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A Large Hadron Electron Collider at CERN

Report on the Physics and Design
Concepts for Machine and Detector

LHeC Study Group

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To be submitted for publication

¹⁴ The Kandinsky painting is taken from a talk on gluon saturation and 5D black hole duality as presented
¹⁵ at the first CERN-ECFA-NuPECC Workshop on the LHeC held at Divonne near to CERN in September
¹⁶ 2008 [1].

Abstract

18 The physics programme and the design are described of a new electron-hadron collider, the LHeC, in which
19 electrons of 60 to possibly 140 GeV collide with LHC protons of 7000 GeV. With an ep design luminosity
20 of about $10^{33} \text{ cm}^{-2}\text{s}^{-1}$, the Large Hadron Electron Collider exceeds the integrated luminosity collected at
21 HERA by two orders of magnitude and the kinematic range by a factor of twenty in the four-momentum
22 squared, Q^2 , and in the inverse Bjorken x . The physics programme is devoted to an exploration of the
23 energy frontier, complementing the LHC and its discovery potential for physics beyond the Standard Model
24 with high precision deep inelastic scattering (DIS) measurements. These are projected to solve a variety of
25 fundamental questions in strong and electroweak interactions. The LHeC thus becomes the world's cleanest
26 high resolution microscope, designed to continue the path of deep inelastic lepton-hadron scattering into
27 unknown areas of physics and kinematics. The physics programme also includes electron-ion (eA) scattering
28 into a $(Q^2, 1/x)$ range extended by four orders of magnitude as compared to previous lepton-nucleus DIS
29 experiments. The LHeC may be realised either as a ring-ring or as a linac-ring collider. Optics and beam
30 dynamics studies are presented for both versions, along with technical design considerations on the interaction
31 region, magnets, cryogenics, RF, civil engineering and further components. A design study is also presented
32 of a detector suitable to perform high precision DIS measurements in a wide range of acceptance using
33 state-of-the art detector technology, which is modular and of limited size enabling its fast installation. The
34 detector includes tagging devices for electron, photon, proton and neutron detection near to the beampipe.
35 The LHeC is designed to be built and operated while the LHC runs. It is a major opportunity for progress
36 in particle physics and further exploits the investment made in the LHC.



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113

Preface

115 Preparations for new, big machines take time. The idea of an electron-proton collider in the LEP-LHC
 116 tunnel was discussed as early as 1984 [2], at the first LHC workshop at Lausanne. This was the time when
 117 the first ever built ep collider, HERA, was approved by the German government. HERA was a machine of
 118 about 30 GeV electron beam energy and nearly 1 TeV proton beam energy, a combination of a warm dipole
 119 electron ring with a superconducting dipole proton ring, in a 6 km circumference tunnel. The machine
 120 started operation 8 years after its approval. It reached luminosities of $10^{31} \text{ cm}^{-2} \text{ s}^{-1}$ in its first phase of
 121 operation which increased by about a factor of 4 in the subsequent, upgraded configuration. HERA never
 122 attempted to collide electrons with deuterons nor with ions.

123 The realisation of HERA had followed a number of attempts to realise ep interactions in collider mode,
 124 mainly driven by the unforgettable Bjoern Wiik: since the late 1960s, he and his colleagues had considered
 125 such machines and proposed to probe the proton's structure more deeply with an ep collider at DORIS [3],
 126 later at PETRA (PROPER) [4] and subsequently at the SPS at CERN (CHEEP) [5]. Further ep collider
 127 studies were made for PEP [6], TRISTAN [7] and also the Tevatron (CHEER) [8].

128 In 1990, at a workshop at Aachen, the combination of LEP with the LHC was discussed, with studies [9–
 129 11] on the luminosity, interaction region, a detector and the physics as seen with the knowledge of that
 130 time, before HERA. Following a request of the CERN Science Policy Committee (SPC), a brief study of
 131 the ring-ring ep collider in the LEP tunnel was performed [12] with the estimated luminosity of about
 132 $10^{32} \text{ cm}^{-2} \text{ s}^{-1}$.

133 At the end of the eighties it had been realised that there was a possible end to the increase of the energy
 134 of ep colliders in the ring-ring configuration, because of the synchrotron radiation losses of an electron ring
 135 accelerator. The classic SLAC fixed target ep experiment had already used a 2 mile linac. For ep linac-ring
 136 collider configurations, two design sketches considering electron beam energies up to a few hundred GeV were
 137 published, in 1988 [13] and in 1990 [14]. As part of the TESLA linear collider proposal, an option (THERA)
 138 was studied [15] to collide electrons of a few hundred GeV energy with protons and ions from HERA at
 139 DESY. Later, in 2003, the possibility was evaluated to combine LHC protons with CLIC electrons [16]. It
 140 was yet realised, that the bunch structures of the LHC and CLIC were not compliant with the need for high
 141 luminosities.

142 In September 2007, the SPC again asked whether one could realise an ep collider at CERN. Some of us
 143 had written a paper [17] in the year before, that had shown in detail, for the first time, that a luminosity
 144 of $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ was achievable. This appeared possible in a ring-ring configuration based on the ultimate
 145 LHC beam, with $1.7 \cdot 10^{11}$ protons in bunches 25 ns apart. Thanks to the small beam-beam tune-shift, it was
 146 found to be feasible to simultaneously operate pp in the LHC and ep in the new machine, which in 2005 was
 147 termed the Large Hadron Electron Collider (LHeC) [18]. Thus it appeared possible to realise an ep collider
 148 that was complementary to the LHC, just as HERA was to the Tevatron. The integrated luminosity was
 149 projected to be $\text{O}(100) \text{ fb}^{-1}$, a factor of hundred more than HERA had collected over its lifetime of 15 years.

150 It was clear that with a centre-of-mass energy of about $\sqrt{s} \simeq 1.5 \text{ TeV}$ an exciting programme of deep
 151 inelastic scattering (DIS) measurements at the energy-frontier was in reach. This would comprise searches
 152 and analyses for physics beyond the Standard Model, novel measurements in QCD and electroweak physics
 153 to unprecedented precision, as well as DIS physics at such low Bjorken x , that all the known laws of parton
 154 and gluon interactions would have to be modified to avoid violating unitarity. It had also been realised that

155 the kinematic region, in terms of four-momentum-transfer-squared, Q^2 , and $1/x$, accessed in lepton-nuclear
156 interactions could be extended by 4 orders of magnitude using the ion beams of the LHC. A salient theme
157 of the LHeC therefore is the precise mapping of the gluon field, over six orders of magnitude in Bjorken x ,
158 in protons, neutrons and nuclei, with unprecedented sensitivity.

159 In the autumn of 2007, (r)ECFA and CERN invited us to work out the LHeC concept to a degree,
160 which would allow one to understand its physics programme, evaluate the accelerator options and their
161 technical realisation. The detector design should be affordable and capable of realising a high precision,
162 large acceptance experimental programme of deep inelastic scattering at the energy frontier. The electron
163 beam energy range was set to be between about 50–150 GeV. The wall plug power consumed for the electron
164 beam was limited to 100 MW.

165 For the installation of the LHC it had been decided to remove LEP from the tunnel and to re-use the
166 injector chain. To realise an ep collider based on the LHC, a new electron accelerator has to be built. The
167 following report details two solutions for the chosen default electron beam energy of $E_e = 60$ GeV. One option
168 is to build and install a new ring, with modern magnet technology, on top of the LHC, using a new 10 GeV
169 injector. Alternatively, one can build a “linac”, actually two 10 GeV superconducting linacs in a racetrack
170 configuration. By employing energy recovery techniques, this configuration could provide the equivalent of
171 about 1 GW available power and reach $10^{33} \text{ cm}^{-2}\text{s}^{-1}$ luminosity. The genuine linac would be of about the
172 same length as the one used for the discovery of quarks at SLAC [19,20], the Q^2 , however, with which parton
173 interactions were studied at the LHeC exceeded that from 1969 by a factor of nearly 10^5 .

174 It was agreed early on to devote a few years to the report, also because none of the people involved
175 could work anything near to full time for this endeavour. Three workshops were held in 2008-2010, that
176 annually assembled about a hundred experts on theory, experiment and accelerator to develop the LHeC
177 design concepts. The project was presented annually to ECFA and in 2008 to ICFA, see [21]. In view
178 of the unique electron-ion scattering programme of the LHeC, the design effort became also supported by
179 NuPECC, and the LHeC is now part of the NuPECC roadmap for European nuclear physics as released in
180 2010 [22]. Following an intermediate report to the Science Policy Committee of CERN, in July 2010, the
181 SPC considered the LHeC “an option for a future project at CERN”.

182 The LHeC by its nature is an upgrade of the LHC. It substantially enriches the physics harvest related to
183 the gigantic investment in the LHC. Whatever the outcome of the searches at the LHC for physics beyond
184 the Standard Model turns out to be, an ep collider operating at the energy frontier is guaranteed to deepen
185 the understanding of TeV scale physics and thus will support the development of the theory of particles and
186 their interactions.

187 The LHeC needs the LHC proton and ion beams to be operational and so the design is made for syn-
188 chronous pp and ep operation, as well as AA and eA , including deuterons. Should the LHC eventually be
189 upgraded to even higher beam energy, beyond 7 TeV per beam [23], it would open an even higher energy
190 reach for ep also. There is a future for deep inelastic scattering at the energy frontier, beginning with the
191 LS3 shutdown of the LHC, envisaged for 2022, likely leading into further decades. As Frank Wilczek put it,
192 “one of the joys of our subject is the continuing of our culture that bridges continents and generations” [24].

193 Our science is driven by curiosity, by theoretical expectations, sometimes too great, but also by experiment
194 and technology, and the authors of this study therefore hope that the LHeC may be given the chance to
195 contribute to the common efforts of our community for a deeper understanding of nature.

196
197 Max Klein (Chair of the LHeC Steering Committee)

198
199 The current, preliminary version of this report, as of August 5th, is handed to the referees appointed by
200 the CERN directorate. Following their reports, and also considering further developments and necessary
201 updates of the current draft, the report will be handed to CERN, ECFA and NuPECC. It is thereby intended
202 to become part of the European deliberations on the future directions of particle physics, which must be
203 seen in the context of the LHC and the results now emerging at half its design energy.

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505

Part I

506

Introduction

507 The present document is a detailed presentation of the physics, the accelerator options and a detector design
508 comprising the LHeC project. It has been developed under the auspices and with support of CERN, ECFA
509 and NuPECC, between 2008 and now. The paper is organised as follows:

510 In the introduction, **Chapter I**, cornerstones of deep inelastic scattering and the main considerations
511 for the design of the LHeC are summarised. The emphasis is on adding a 60 GeV energy electron beam
512 to the existing proton and ion beams of the LHC, in a manner which foresees the simultaneous *ep* and
513 *pp* operation for the realisation of a luminous DIS programme while minimising the interference with the
514 LHC. The introduction contains an executive summary of this report (which will be added before its final
515 publication).

516 **Chapter II** presents major, selected subjects, with related simulation studies and theoretical consider-
517 ations, in order to sketch the physics programme of the LHeC. These subjects are grouped in three areas:
518 high precision QCD and electroweak physics, the potential for searches for phenomena beyond the standard
519 model and its relation to the LHC, and finally the physics of high parton densities at low Bjorken x and in
520 nuclei. It is clear that it has rarely been possible, fortunately, to accurately predict nor to fully simulate
521 the physics of a new machine at much enlarged energies. The subjects here presented are neither supposed
522 to cover the complete field as it is known today. For a new laboratory of particle physics as the LHeC
523 represents, however, a broad view must be taken to what it comprises most likely.

524 **Chapter III** is devoted to the accelerator design studies presenting the ring-ring and linac-ring concepts,
525 optics etc and in a third section the various technical systems which often are common to both accelerator
526 options. The emphasis here is on an understanding of the main challenges and characteristics of both options
527 and not on discussing their relative merits. The accelerator chapter is concluded with separate sections on
528 the civil engineering and a tentative time schedule for the realisation of the LHeC within the next about ten
529 years.

530 **Chapter IV** presents the design considerations for a detector with its challenging central part and further
531 systems to tag forward nucleons and backward scattered electrons and photons, including a study for a high
532 precision measurement of the lepton beam polarisation. The salient feature of the detector baseline design
533 is its silicon tracker surrounded by an electromagnetic liquid argon calorimeter inside a superconducting coil
534 which uses a tile hadron calorimeter for the flux return.

535 The present version of this document (as of July 2011) does not yet contain summary sections. These
536 will be added in the fall when the referee process ended and corresponding updates of this document ¹ are
537 completed. One can not exclude today that this process, also in the light of the rapid increase in LHC
538 luminosity, leads to revisions of not only details of the present draft report. The main characteristics of this
539 *ep* collider, however, its high luminosity and its high cms energy, beyond a TeV, are on firm ground as they
540 are achieved with the unique hadron beams of the LHC. The LHeC technologies require prototyping and
541 preparations but essentially they are at hand which makes the LHeC a realistic opportunity.

542 This report has been organised jointly by a steering group and convenors for the various physics, accel-
543 erator and detector parts of the design. It was accompanied by a scientific advisory committee. The present
544 draft is handed to 24 referees nominated by the CERN directorate for a detailed evaluation of the design
545 and its corresponding update. The composition of these groups is listed in the **Appendix** of the paper.
546 Some members of the steering group, many of the convenors and various members of the advisory committee
547 have made direct scientific contributions to the LHeC design as presented here. They therefore also appear
548 among the authors of this study which are representing a group of about 150 physicists and engineers from
549 50 institutes.

550 It is for the coming phase of the LHeC design to begin its technical development, beyond the initial
551 prototyping of magnets, and to form the appropriate international collaborations, both for the accelerator
552 and the detector.

¹An estimate is underway of the cost of the detector and the accelerator options which will be made available to CERN when available. For a rough cost estimate, an order of magnitude guess, which will be sufficient for most of the purposes, it may suffice to state that the cost of the LHeC is expected to be comparable with the cost of LEP or the XFEL while the detector cost will be a fraction only of the cost of CMS or ATLAS.

Chapter 1

Lepton-Hadron Scattering

1.1 Development and Contributions

It is almost exactly 100 years since the birth of the scattering experiment as a means of revealing the structure of matter. Geiger and Marsden's experiment [25] and its interpretation by Rutherford [26] set the scene for a century of ever-deeper and more precise resolution of the constituents of the atom, the nucleus and the nucleon. Lepton-hadron scattering has played a crucial role in this exploration over the past 55 years. The finite radius of the proton of about 1 fm was first established through elastic electron-proton scattering experiments [27]. Later, through deep inelastic electron proton scattering at Stanford [19, 20], proton structure was understood in terms of quarks, still the smallest known constituents of matter. With the discovery of Bjorken scaling of the proton structure function $F_2(x, Q^2)$, its quark model interpretation, and the subsequent discovery of scaling violation in support of asymptotic freedom [28, 29], deep inelastic scattering (DIS) became a field of fundamental theoretical importance [30] to the understanding of the strong interaction. Precise measurements of the parton momentum distributions of the nucleon became a major testing ground for the selection and development of Quantum Chromodynamics (QCD) [31] as the appropriate theory of the strong interaction. Prior to these developments, the theory of strong interactions was of merely phenomenological nature, built around S matrix theory and general amplitude features and various concepts such as Regge, bootstrap or further models [32].

Quantum Chromodynamics is a Yang-Mills gauge theory, in which the interaction between confined quarks proceeds via coloured gluon exchange. With improved resolution, as provided by increased Q^2 , quarks can be resolved as quarks radiating gluons, whilst gluons may split into quark-antiquark pairs or, due to the non-abelian nature of the underlying gauge field theory, into pairs of gluons [33–35]. The development of QCD calculations beyond leading order [36, 37] is one of the most remarkable recent achievements of particle physics theory supported by experiment. It leads to a consistent description of all perturbatively accessible hadron observables in DIS (and beyond), as has recently been established over the kinematic range accessible to HERA [38]. This includes the unexpected observation of deep inelastic diffractive scattering at HERA, according to which in a significant fraction of violent DIS interactions the proton remains intact, an exchange of vacuum quantum numbers which often is termed “Pomeron exchange”.

Despite previous successes, many fundamental areas of QCD have not been verified experimentally, with instantons [39] as only one example. Even the classic areas related to quarks and gluons have not been exploited as required for limited precision, range and variation of initial conditions. Meanwhile the theory underlying DIS experiences further fundamental developments. Four-dimensional conformal field theory is seen to be related to superstring theory in the anti-de Sitter space in ten dimensions, which relates the $N = 4$ supersymmetric pomeron to the graviton in this space [40]. The evolution of partons is expected to obey different laws than explored hitherto at HERA when at small x their interactions have to be damped for the restoration of unitarity, see [41] for a review.

Particle physics in the past could profit very much from the complementarity of hadron-hadron, DIS and

The 10-100 GeV Energy Scale [1968-1986]

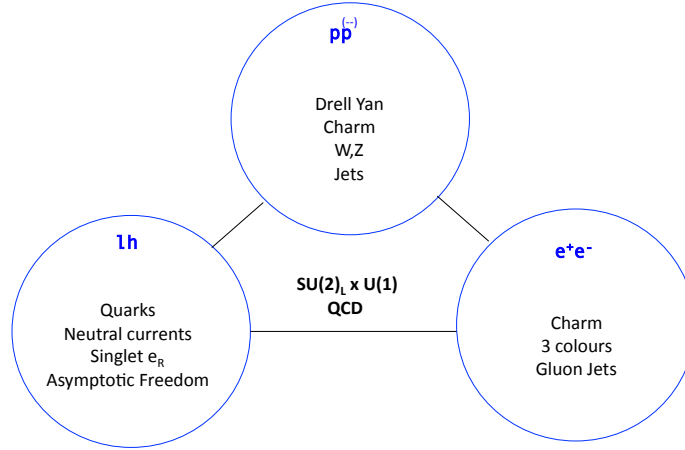


Figure 1.1: Key results of the exploration of the 10 – 100 GeV energy scale in hadron-hadron (top), deep inelastic (bottom left) and e^+e^- scattering (bottom right). These and further important results selected the $SU(2)_L \times U(1)$ and QCD as the appropriate theories for the electroweak and the strong interaction, respectively, of leptons and quarks transmitted by the photon, the W^\pm , Z bosons and gluons.

590 e^+e^- experiments. Key observations were made in all three areas, and the overlap in physics coverage was
 591 used to achieve confidence in new and precision results. This is sketched in Figure 1.1 for the experiments of
 592 the seventies and eighties, which resulted in the birth of the Standard Model. Fig. 1.2 illustrates this for the
 593 experiments of the nineties until now, when the Tevatron, HERA and the SLC/LEP machines determined
 594 the progress in the exploration of particle physics at the energy frontier accessed with colliders. The present
 595 report deals with the reasons and possibility to extend deep inelastic scattering experimentation into an
 596 unexplored range of our knowledge for which the LHC at CERN provides the rare and single opportunity
 597 for the next decades ahead. Simultaneous LHC and LHeC operation would put the ep part of the TeV scale
 598 triangle, as shown in Figure 1.3, on a firm ground.

599 1.2 Open Questions

600 For a project as the LHeC one needs to understand which fundamental properties of nature it promises to
 601 deal with and which possibly specific questions it is expected to answer.

602 The Standard Model of particle physics contains a remarkable, but unexplained, symmetry between
 603 quarks and leptons [42], with three generations, in each of which two quarks and two leptons are embedded.
 604 It was pointed out long ago [43] that it appears somewhat artificial that the basic building blocks of matter
 605 share the electromagnetic and the weak interactions but differ in their sensitivity to the strong interaction.
 606 Many theories which unify the quark and lepton sectors, such as models based on the E6 gauge group [44],
 607 R -parity violating supersymmetry and left-right symmetric extensions of the Standard Model [45], predict
 608 new resonant states with both lepton and baryon numbers, usually referred to as leptoquarks (LQ). In the
 609 technicolour theory, leptoquarks are bound states of technifermions [46, 47]. Although some of the specific
 610 theories have not been supported by experiment, the search for leptoquarks has been a prime motivation for
 611 high energy scattering, especially DIS experiments. The limits for leptoquark states as of the time of EPS11
 612 from the LHC leave the possibility of new LQ states at around 1 TeV mass open while the absence of large

613 missing energy may be seen as being compliant with RPV SUSY states in which there is no LSP. An LHeC,
 614 in combination with the existing LHC programme, can extend this search into a previously unexplored mass
 615 region, with the prospect of deciphering the leptoquark quantum numbers.

616 No analytic proof yet exists that QCD should exhibit the property of colour confinement, though it
 617 is reasonable to assume that it is a consequence of gluon dynamics, as reflected for example in popular
 618 hadronisation models [48] and Monte Carlo simulations on the lattice. Studying the behaviour of gluons
 619 under new extreme conditions and contrasting the conditions under which the proton stays intact with those
 620 in which it is destroyed may help to shed light on the precise mechanism at work.

621 The search for the Higgs boson, which explains the masses of the electroweak bosons, and for the origin
 622 of electroweak symmetry breaking is currently the central focus of particle physics and is expected to be
 623 principally resolved within the near future by the ATLAS and CMS experiments. If there exists a Higgs
 624 particle at masses around 130 GeV, the determination of its properties becomes an important issue. The
 625 LHeC, due to its clean initial state and the absence of pile-up, has an interesting potential to accurately
 626 determine the Higgs particle coupling to $b\bar{b}$, and to also investigate the quartic self-coupling of the scalar
 627 doublet, from the HWW vertex, which provides direct insight into the nature of electroweak symmetry
 628 breaking.

629 The question of hadronic mass deserves similar exploration. The mass of baryons is almost entirely due to
 630 strong interaction field energy, generated through quark and gluon vacuum condensates the self-interaction
 631 of gluons in a manner which is not yet well understood. It may be accessible through a more detailed
 exploration of QCD dynamics.

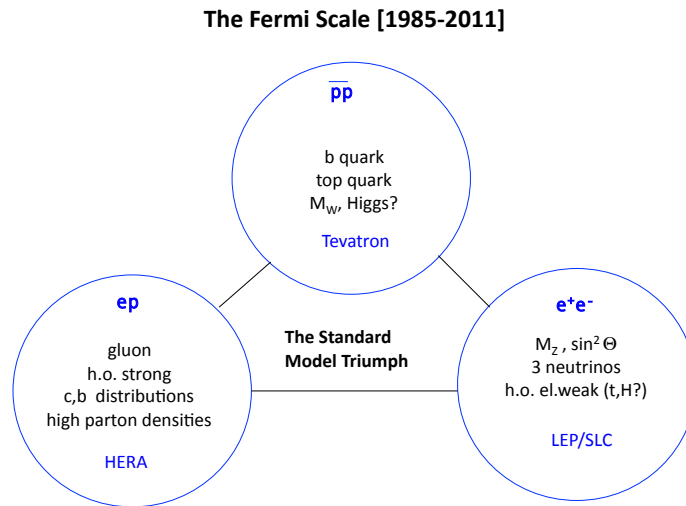


Figure 1.2: Key results of the exploration of the Fermi energy scale in $p\bar{p}$ (top), deep inelastic (bottom left) and e^+e^- scattering (bottom right) with the energy frontier colliders, the Tevatron, HERA and the SLC/LEP, respectively. These and further important results established the Standard Model of particle physics with six types of quarks and leptons in three families, and the development of higher order precision calculations used for the prediction of the top quark and the Higgs mass, based mainly on e^+e^- scattering results, and for the understanding of the partonic contents of the proton to NNLO pQCD, based mainly on the results from HERA and previous DIS fixed target experiments.

632
 633 The salient theme of physics with the LHeC is the mapping of the gluon field. This is achieved with
 634 precision measurements of the evolution of structure functions over an unprecedented range of $\ln Q^2$. It

635 relates inclusive ep DIS with jets and heavy flavour, it concerns the unexplored role of the gluon in nuclei
636 and in deeply virtual Compton scattering. The gluon field is central to QCD but not directly measurable. It
637 may exhibit spots of maximum density (hot spots) and it may also disappear (cold spots) as it does towards
638 low Q^2 and x , and possibly at the scaling point near $x \simeq 0.2$ [49]. Knowing the gluon means understanding
639 the origin of baryonic matter, the production of the Higgs boson and of other new particles and not least
640 important understanding Quantum Chromodynamics.

641 The study of deep inelastic ep scattering is important for the investigation of the nature of the Pomeron
642 and Odderon, which are Regge singularities of the t -channel partial waves $f_j(t)$ in the complex plane of the
643 angular momentum j . The Pomeron is responsible for a growth of total cross sections with energy. The
644 Odderon describes the behaviour of the difference of the cross sections for particle-particle and particle-
645 antiparticle scattering which obey the Pommeranchuk theorem. In perturbative QCD, the Pomeron and
646 Odderon are the simplest colorless reggeons (families of glueballs) constructed from two and three reggeized
647 gluons, respectively. Their wave functions satisfy the generalized BFKL equation. In the next-to-leading
648 approximation the solution of the BFKL equation contains an infinite number of Pomerons and to verify
649 this prediction of QCD one needs to increase the energy of colliding particles. In the N=4 supersymmetric
650 generalization of QCD, in the t'Hooft limit of large N_c , the BFKL Pomeron is equivalent to the reggeized
651 graviton living in the 10-dimensional anti-de-Sitter space. Therefore, the Pomeron interaction describing
652 the screening corrections to the BFKL predictions, at least in this model, should be based on a general
653 covariant effective theory being a generalization of the Einstein-Hilbert action for general relativity. Thus,
654 the investigation of high energy ep scattering could be interesting for the construction of a non-perturbative
655 approach to QCD based on an effective string model in high dimensional spaces.

656 The strong coupling constant α_s decreases as energy scales increase, in contrast to the energy dependence
657 of the weak coupling and the fine structure constant. It appears possible in SUSY theories that the three
658 constants approach a common value at energies of order 10^{15} GeV. The distinctions we make between the
659 electromagnetic, weak and strong interactions may merely be a consequence of the low energy scale at which
660 we live. The possible grand unification of the known interactions has been one of the major goals of modern
661 particle physics theory and experiment. Progress in this area requires that we know α_s , by far the most
662 poorly constrained of the fundamental couplings, much more accurately than is currently the case. The
663 LHeC promises a factor of ten reduction in the uncertainty on α_s based on a major renewal and extension
664 of the experimental and the theoretical basis of the physics of deep inelastic scattering.

665 After quarks were discovered, a distinction was soon made between valence and sea quarks [50]. However,
666 it was not until the high energy colliding beam configuration of HERA became available that the rich partonic
667 structure of the proton was fully realised. Despite the resulting fast development of our knowledge of the
668 parton distribution functions (PDFs) in the proton, there are still many outstanding important questions
669 regarding the quark contents of the nucleon. These regard for example: i) the unresolved question of whether
670 sea quarks and anti-quarks have the same momentum distributions; ii) the clarification of the role of heavy
671 quarks in QCD, including the search for their intrinsic states [51], the precision measurement of the b quark
672 density or, owing to the huge reach in Q^2 , the novel exploration of top production in DIS and the transition
673 of top from a heavy to a light quark, for $Q^2 \gg m_t^2$; iii) the partonic structure of the neutron which is to be
674 resolved over many orders of magnitude in $1/x$, as HERA had no deuteron data taken, and the assumption
675 of isospin symmetry, which relates the neutron down-quark distribution to the proton up-quark distribution.
676 Modern fits of PDFs use quite a number of symmetry assumptions and exploit parameterisations which are
677 to be questioned and overcome by a new basis for the PDF determinations which the LHeC uniquely provides
678 as it constrains all quark distributions, $u_v, d_v, u, \bar{u}, d, \bar{d}, s, \bar{s}, c, b$ and likely t and \bar{t} over an unprecedented
679 range of x and Q^2 . The LHeC will put the whole PDF related physics on new, much firmer ground. That
680 is crucial for searches for physics beyond the standard model. It also is necessary for high precision tests of
681 the electroweak theory, as for the ultimate measurement of the mass of the W boson [52] as a test for the
682 validity of the SM, especially the relation to the masses of the top quark and the Higgs boson.

683 The structure of the neutron at low $x \leq 0.01$ in the DIS region is experimentally unknown. With
684 no data on the scattering of leptons from heavy ions with colliding beam kinematics, the knowledge of the
685 modifications to nucleon parton densities when they are bound inside nuclei, rather than free, is also restricted

686 to high x values. This is reflected in a lack of detailed understanding of shadowing phenomena, particularly
687 for the gluon density and a corresponding lack of knowledge of the initial state of heavy ion collisions at LHC
688 energies. The mechanism of shadowing at low x can be tested for the first time via Gribov's fundamental
689 relation to diffraction and also via measurements with different light nuclei. Antishadowing at larger x [53]
690 may possibly be non-universal and flavour specific. Nuclear corrections at large x may be dealt with in eD
691 scattering at the LHeC by tagging the spectator nucleon and reconstructing its momentum well enough to
692 account for the so far disturbing effects of Fermi motion. This promises to overcome the uncertainty from
693 nuclear corrections which has been an obstacle for decades in the understanding of nucleon structure and
694 represents a formidable experimental task, see e.g. [53] for a recent study. Parton distributions in nuclei,
695 for $x \lesssim 0.01$, presently are based in HERA's proton data convoluted with theoretical expectations. With
696 the LHeC they will be determined down to almost 10^{-6} and largely flavour separated. It is unknown what
697 will be found from an experimental point of view, and it is critical for the understanding of the quark gluon
698 plasma.

699 There are various fundamental properties predicted in QCD which have never been resolved or even tested
700 so far and which will become accessible with the LHeC. While ordinary quark distributions correspond to
701 an incoherent sum of squared amplitudes, a new approach has been developed, which uses quark amplitudes
702 and Generalised Parton Distributions (GPDs) to understand proton structure in a new, three-dimensional
703 way [54,55]. Our understanding of GPDs is limited by the relative paucity of experimental data on exclusive
704 DIS channels. The emission of partons is assumed in PDF fits to be governed by the linear DGLAP evolution
705 equations, an approximation to a full solution to QCD, in which parton cascades are ordered in transverse
706 momentum. There are good reasons to believe that the DGLAP approximation is insufficient to describe
707 the Q^2 evolution of low x partons, even within the x range to which the LHC rapidity plateau corresponds.
708 Inclusive DIS and jet data in an extended low x kinematic regime are required to resolve this situation.

709 The rapid rise of the proton gluon density as x decreases cannot continue indefinitely. At x values
710 within the reach of LHeC ep and eA scattering, a transition takes place from the currently known DIS
711 regime in which the proton behaves as a dilute system to a new low x domain in which parton densities
712 saturate and the proton approaches a 'black disk' limit [56]. This latter region represents a fundamentally
713 new regime of strong interaction dynamics, for which a rich phenomenology has developed, but where the
714 detailed mechanisms and the full consequences are not yet known. Experimental data at sufficiently low x
715 with scales which are large enough to allow a partonic interpretation are required in order to test the models
716 and fully understand the behaviour of partons at high densities. The so well known DGLAP evolution at low
717 x is to break and non-linear evolution equations will determine the parton distributions, for which various
718 untested predictions exist.

719 The high precision and range of the LHeC DIS measurements provide many further opportunities for
720 explorations of fundamental interest. With the ep initial state any new phenomenon singly produced can be
721 investigated with particular sensitivity, as for example the possibility for excited leptons to exist. Variation
722 of beam charge and polarisation lead to resolve quantum numbers of new, so-called contact interactions, of
723 scale up to about 50 TeV, and to novel precision measurements of the scale dependence of the weak mixing
724 angle around the Z pole.

725 Despite its huge success in describing existing high energy data, the Standard Model is known to be in-
726 complete, not only due to the absence of an experimentally established mechanism for electroweak symmetry
727 breaking. As the exploitation of the TeV energy regime and the high luminosities of the LHC era develop
728 further, a full understanding requires to challenge the existing theory through new precision measurements,
729 as broad in scope as possible, with initial states involving leptons as well as quarks and gluons. The LHeC
730 will not just answer some of the currently outstanding questions but represents the opportunity to build a
731 new laboratory for particle physics which owing to its specific configuration, its enlarged DIS energy range
732 and unprecedented precision will accompany the LHC, and possibly built pure lepton machines, in exploring
733 the next layer of the high energy frontier physics.

The TeV Scale [2010-2035..]

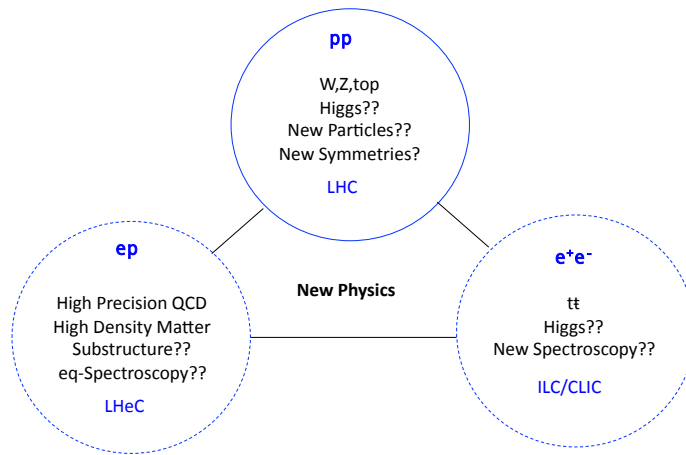


Figure 1.3: The exploration of the TeV energy scale has begun with the LHC. The present document describes one of its compliments, a new TeV scale ep and eA collider, while intense work is continuing on the development of concepts for new e^+e^- and possibly $\mu^+\mu^-$ colliders. While each of the new machines has exciting standard model programmes to pursue with higher precision and range, physics beyond the SM has been elusive at the moment this report is released and 1 fb^{-1} of 7 TeV cms LHC data have been analysed within a very short time for the EPS11 conference at Grenoble.

Chapter 2

Design Considerations

The following sections describe briefly which general considerations have determined the LHeC design as presented in this report. Major changes to the underlying assumptions would naturally require an appropriately changed variation of the design.

2.1 DIS and Particle Physics

Deep inelastic scattering experiments with charged leptons may be classified as low energy, medium and high energy experiments. The pioneering low energy DIS experiment, which discovered quarks, was performed at SLAC. Classic medium energy experiments were the BCDMS and the NMC experiments at CERN, while HERA, the first ep collider ever built, had pushed the DIS energy reach to the Fermi scale. This allowed the field of deep inelastic scattering to develop as part of the energy frontier particle physics, complementary to the Tevatron and LEP. In all three areas, the field of DIS is considering upgrade projects with the 12 GeV upgrade at Jlab, the medium energy colliders at Jlab and/or BNL, possibly fixed target further neutrino experiments and the LHeC.

The LHeC provides the only realistic possibility for an energy frontier ep programme in the coming probably three decades. Owing to the LHC, there is one opportunity to complement the TeV scale pp machine with a TeV energy ep collider, besides a pure lepton collider in this energy range. It took about 30 years for HERA, LEP and the Tevatron to be built, operated and analysed. The exploration of the TeV energy scale is subject to similar time horizons.

2.2 Synchronous pp and ep operation

The intense, energetic hadron beams of the LHC provide the unique possibility to realise a luminous experimental programme of deep inelastic scattering at TeV energies. The LHeC is therefore by its nature an upgrade to the LHC, which gives it its site and in a way determines its dimensions too. The first design consideration builds on the assumption that the LHC still runs in pp mode when an electron beam becomes operational. This has several implications:

- The construction of the LHeC has to be completed in the coming about 10 years.
- The design has to be adapted for synchronous pp and ep (and AA and eA) operation, as with magnets in the IR to steer three beams and with civil engineering and detector modularity requirements to be compliant with the LHC operation and upgrade programme.
- The synchronous operation of pp and ep allows to collect a high integrated luminosity, with the goal of a total of order 100 fb^{-1} , and makes the most efficient use of both the proton beams and the electron beam installation too.

766 It can not realistically be assumed today, that the ep physics would commence only when the pp program
 767 was finished because several key LHC components have a limited lifetime, which is nowadays estimated to
 768 be about 20 years. Planning for an ep run after the pp program finishes therefore implies a significant risk
 769 of additional cost for the project due to a substantial consolidation effort in the LHC.

770 The LHeC can be thought and it is designed to accompany the proton and the ion physics programme
 771 of the LHC in its high luminosity phase, now assumed to begin in 2023.

772 2.3 Choice of Electron Beam Energy

773 The centre of mass energy squared of an ep collider is $s = 4E_e E_p$. It determines the maximum four-
 774 momentum transfer squared, Q^2 , between the electron and the proton because $Q^2 = sxy$, where x is the
 775 fraction of four momentum of the proton carried by the struck parton while y is the inelasticity of the
 776 scattering process which in the laboratory frame is the relative energy transfer, with $0 < x, y \leq 1$.

777 HERA has operated with a proton beam energy of $E_p = 0.92$ TeV and an electron (and positron) beam
 778 energy of $E_e = 27.5$ GeV. With Sokolov-Ternov build-up times of about half an hour, the electron beam
 779 became polarised and mean polarisations of up to 40% were achieved. HERA has not accelerated any
 780 hadron beam other than protons. The LHeC has to surpass these parameters significantly for a unique and
 781 exciting programme to be pursued.

782 The LHeC can use an up to 7 TeV energy proton beam. For this design study the electron beam energy
 783 is set to 60 GeV. This implies that the gain in s , or Q^2 at fixed (x, y) , as compared to HERA will be a
 784 factor of 16.6, or about 4 in \sqrt{s} . The real gain in range of Q^2 and x will even be larger as with the superior
 785 luminosity even the highest Q^2 values and x close to 1 become accessible. The kinematic range of the LHeC
 786 as compared to HERA at low x and at high Q^2 is illustrated in Fig. 2.1.

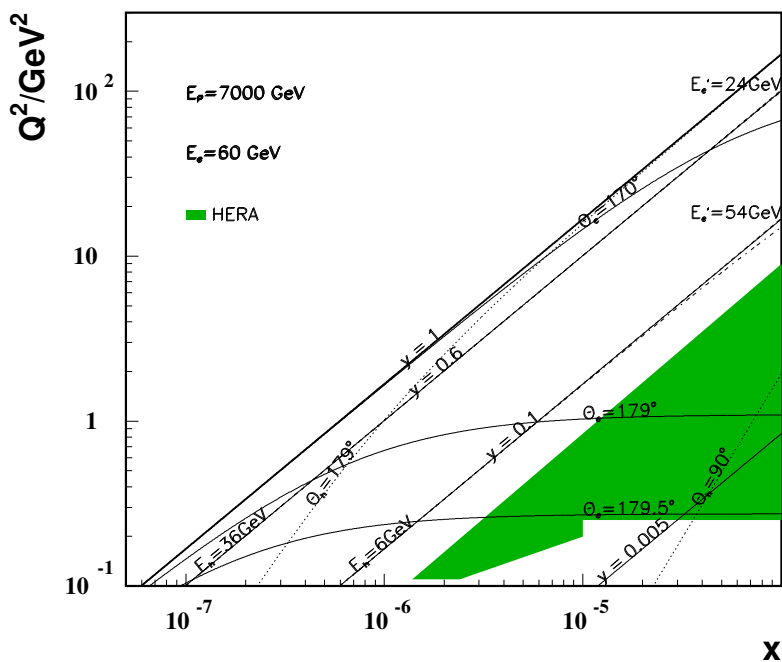
787 The choice of a default $E_e = 60$ GeV for this design report is dictated by physics and by practical
 788 considerations:

- 789 • New physics has been assumed to appear at the TeV energy scale. At the time of completion of this
 790 report, the LHC has excluded much of the sub-TeV physics beyond the Standard Model (SM) but
 791 leaves the possibility open of resonant lepton-parton states with masses of larger than about 500 GeV,
 792 for which the LHeC would be a particularly suitable machine with a range of up to $M \lesssim \sqrt{s}$.
- 793 • High precision QCD and electroweak physics require a maximum range in $\ln Q^2$ and highest Q^2 ,
 794 respectively. The unification of electromagnetic and weak forces takes place at $Q^2 \simeq M_Z^2$ which is much
 795 exceeded by the LHeC energies. Part of the electroweak physics requires lepton beam polarisation.
- 796 • The discovery of gluon saturation requires to measure at typical values of small $x \simeq 10^{-5}$ with $Q^2 \gg$
 797 M_p^2 , where M_p is the mass of the proton. The choice of energies ensures this discovery at the LHeC in
 798 the DIS region, both in ep and in eA .
- 799 • Energy losses by synchrotron radiation, $\propto E_e^4$, both in the ring and the return arcs for the linac, can be
 800 kept at reasonable levels, in terms of the power, P , needed to achieve high luminosity and the radius
 801 of the racetrack return arcs for the linac too.

802 It so appears that 60 GeV is an appropriate and affordable choice. It yet is well possible that the 60 GeV
 803 may not be the final value of the electron beam energy, especially if the LHC would find non-SM physics
 804 just above the now chosen energy range. The design therefore also considers a dedicated high energy beam
 805 of 140 GeV as an option, which yet has not been worked out to any comparable detail ¹.

¹Such a large E_e would also fit better to a future HE LHC, when about 16 TeV proton beam energy might become available in the yet much farther future, as that would keep the $e - p$ beam energy asymmetry tolerable.

LHeC - Low x Kinematics



LHeC - High Q^2 Kinematics

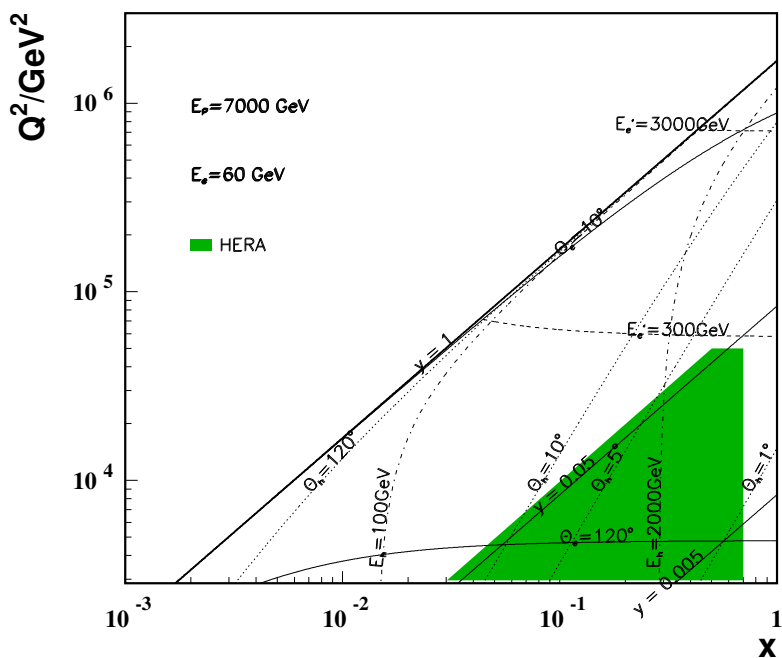


Figure 2.1: Kinematics of ep scattering at the LHeC at low x (top) and high Q^2 (bottom). Solid (dotted) curves correspond to constant polar angles θ_e (θ_h) of the scattered electron (hadronic final state). The polar angle is defined with respect to the proton beam direction. Dashed (dashed-dotted) curves correspond to constant energies E'_e (E_h) of the scattered electron (hadronic final state). The shaded (green) area illustrates the region of kinematic coverage in neutral current scattering at HERA. The energy and angle isochrone lines are discussed in the detector design chapter in detail.

2.4 Detector Constraints

One easily recognises, in Fig. 2.1, that the asymmetry of the electron and proton beam energies poses severe constraints to the detector design: i) the “whole” low Q^2 and low x physics requires to measure the electron, of energy $E'_e \lesssim E_e$, scattered in backward direction between about 170° and 179° , and ii) the forward scattered final state, of energy comparable to E_p , needs to be reconstructed down to very small angles in order to cover the high x region in a range of not too extreme Q^2 .

The current detector design considers an option to have split data taking phases, like HERA I and II, with different interaction region configurations, a high acceptance phase, covering $1^\circ - 179^\circ$, at reduced luminosity and a high luminosity phase, of acceptance limited to $8^\circ - 172^\circ$. In the course of the study, however, an optics was found for the high acceptance configuration with only a factor of two reduced luminosity. It is likely, therefore, that the TDR will lead to a unification of these configurations and correspondingly weakened demands on the modularity of the inner detector region.

Synchronous ep and pp operation implies that at least one of the four IPs, currently occupied by experiments, will have to be free'd for an LHeC detector. It was decided to use for this report IP2 as an example site and to limit the study of bypasses, in the ring option, to IP1 and IP5. There has often been a discussion about the need for two detectors and ambitious detector push-pull concepts are discussed for the Linear Collider. For the LHeC this would imply a major overhead of cost and delay in construction time. The detector envisaged here will be challenging but also be based on known technology. Truly independent reconstruction, simulation and analysis software teams using one common facility may lead to sufficient confidence when it comes to crucial and most precise results.

2.5 Two Electron Beam Options

It was shown a few years ago [17] that an electron beam in the LHC tunnel would allow to achieve an outstanding luminosity of about $10^{33} \text{ cm}^{-2}\text{s}^{-1}$ in ep interactions for both electrons and positrons. It is obvious, however, that while such a ring may be built without any major technical obstacle, installing it on top of the LHC magnet ring would be a non-trivial engineering task. For this reason it was decided to consider besides this “ring-ring (RR)” option also a “linac-ring (LR)” configuration, with a linear electron accelerator tangential to the LHC. For the comparison of RR and LR options, E_e was kept the same 60 GeV. The ring may extend to somewhat higher energies, while only a Linac would allow to exceed 100 GeV E_e largely.

This report presents all major components and considerations for both the RR and the LR configuration. A choice between the two configurations is envisaged soon after the appearance of the CDR. It is important to consider that the RR configuration delivers high electron and positron luminosity, with difficulties for high polarisation, while the LR configuration has a high potential for polarised electrons but difficulties to deliver an intense positron beam, yet offering also a photon beam option. A choice of one over the other option has primarily to be based on physics but as well technical, cost and further considerations, which is why considerable effort had been spent to develop both options to the required detail. No attempt is made in the report to favour one over the other configuration. In the period of this design study both options came into a very fruitful interaction and occasional competition which nicely boosted both designs.

2.6 Luminosity and Power

The relation of the luminosity, power and energy differs for the RR and the LR configurations. In the case of the ring accelerator, as for HERA, the luminosity for matched beams is determined by the number of protons per bunch (N_p), the normalised proton beam emittance (ϵ_p), the x, y coordinates of the proton beam beta function values at the interaction point ($\beta_{x,y}$) and the electron beam current (I_e) as

$$L = \frac{N_p \cdot \gamma}{4\pi\epsilon_p} \cdot \frac{I_e}{\sqrt{\beta_{px}\beta_{py}}}, \quad (2.1)$$

849 with $\gamma = E_p/M_p$. The design luminosity assumes the so-called ultimate proton beam parameters for $E_p =$
 850 7 TeV with $1.7 \cdot 10^{11}$ protons per bunch and $\epsilon_p = 3.8 \mu\text{m}$. It is interesting to note that already the first year of
 851 operating the LHC has indicated that smaller emittance values are in reach and the bunch intensities have
 852 exceeded 10^{11} , for 50 ns spacing. Eq. 2.1 then corresponds to

$$L = 8.2 \cdot 10^{32} \text{cm}^{-2} \text{s}^{-1} \cdot \frac{N_p 10^{11}}{1.7} \cdot \frac{m}{\sqrt{\beta_{px} \beta_{py}}} \cdot \frac{I_e}{50 \text{mA}}, \quad (2.2)$$

853 where the electron beam current is given by

$$I_e = 0.35 \text{mA} \cdot P[\text{MW}] \cdot \left(\frac{100}{E_e[\text{GeV}]} \right)^4. \quad (2.3)$$

854 Consequently one needs to minimize the β functions and gains linearly with P and like E_e^4 when decreasing
 855 the electron beam energy. With $\beta_{x(y)} = 1.8(0.5) \text{m}$, see the optics section, one obtains a typical value of
 856 $10^{33} \text{cm}^{-2} \text{s}^{-1}$ luminosity for $E_e = 60 \text{GeV}$ with 30 MW of beam power. The dependence of $L(E, P)$ is shown
 857 in Fig. 2.2 (top) for the RR configuration. While with the matching requirement for each E_e an evaluation
 858 would have to be done of the β functions, one yet recognises that the RR option has a great potential to
 859 indeed achieve very high luminosities, even exceeding $10^{33} \text{cm}^{-2} \text{s}^{-1}$ if E_e was a bit lowered and P somewhat
 860 enlarged.

861 For this design report on the LHeC the wall-plug power limit was set to 100 MW, about one fifth of what
 862 one is considering for CLIC, for example. With a 10 years running period at such a high luminosity and
 863 N_p probably enlarged, one can consider an integrated luminosity for the LHeC of $O(100) \text{fb}^{-1}$ a realistic
 864 perspective in simultaneous operation with the LHC. This is two orders of magnitude more than HERA
 865 delivered. That is necessary for exploiting the high Q^2 and large x boundaries. It means that the whole
 866 low Q^2 physics program, with the exception of rare processes as DVCS and subject to trigger acceptance
 867 considerations, may yet be pursued in a rather short period of time.

868 A linear electron beam colliding with a storage ring proton beam was considered quite some time ago [13].
 869 Its luminosity, for head-on collisions, can be obtained from the following relation [14], similar to Eq. 2.1

$$L = \frac{N_p \cdot \gamma}{4\pi e \epsilon_p} \cdot \frac{I_e}{\beta^*}, \quad (2.4)$$

870 which scales as

$$L = 8 \cdot 10^{31} \text{cm}^{-2} \text{s}^{-1} \cdot \frac{N_p 10^{11}}{1.7} \cdot \frac{0.2 \text{m}}{\beta^*} \cdot \frac{I_e}{1 \text{mA}}, \quad (2.5)$$

871 where the electron beam current is given by

$$I_e = \text{mA} \cdot \frac{P[\text{MW}]}{(1 - \eta) E_e[\text{GeV}]}. \quad (2.6)$$

872 Here η denotes the efficiency of the energy recovery process. It is easy to see that a pulsed linac without
 873 recovery is short by an order of magnitude in the luminosity to the RR configuration, even for an ambitious
 874 β^* value of 0.1 m, which is introduced in the LR section. With energy recovery, however, and an efficiency
 875 above 90% as is expected to be realistic for the LHeC case, one obtains luminosities of similar value as in
 876 the RR case, see Fig. 2.2. The energy recovery linac (ERL) operates the cavities in CW mode at moderate
 877 gradients of typically 20 MV/m.

878 The recovery of energy requires a racetrack geometry of the linac with return arcs, or possibly two linacs
 879 of opposite orientation as was originally considered [57]. This introduces synchrotron radiation losses as a
 880 parameter of concern to the LR configuration also. With the design here proposed, the arcs have a bending
 881 radius of 764 m, which leads to a LR accelerator of about 9 km length, which is one third of the LHC
 882 circumference, and requires a small compensation stage for the energy losses in the arcs.

883 A straight high energy, pulsed linac is also considered, which at $E_e = 140 \text{GeV}$, reaches a luminosity of
 884 about $5 \cdot 10^{31}$, the design value of the HERA upgrade phase. One can also contemplate about stages of ERL
 885 returns, which provide much higher luminosities in this case, as is briefly demonstrated in this report too.

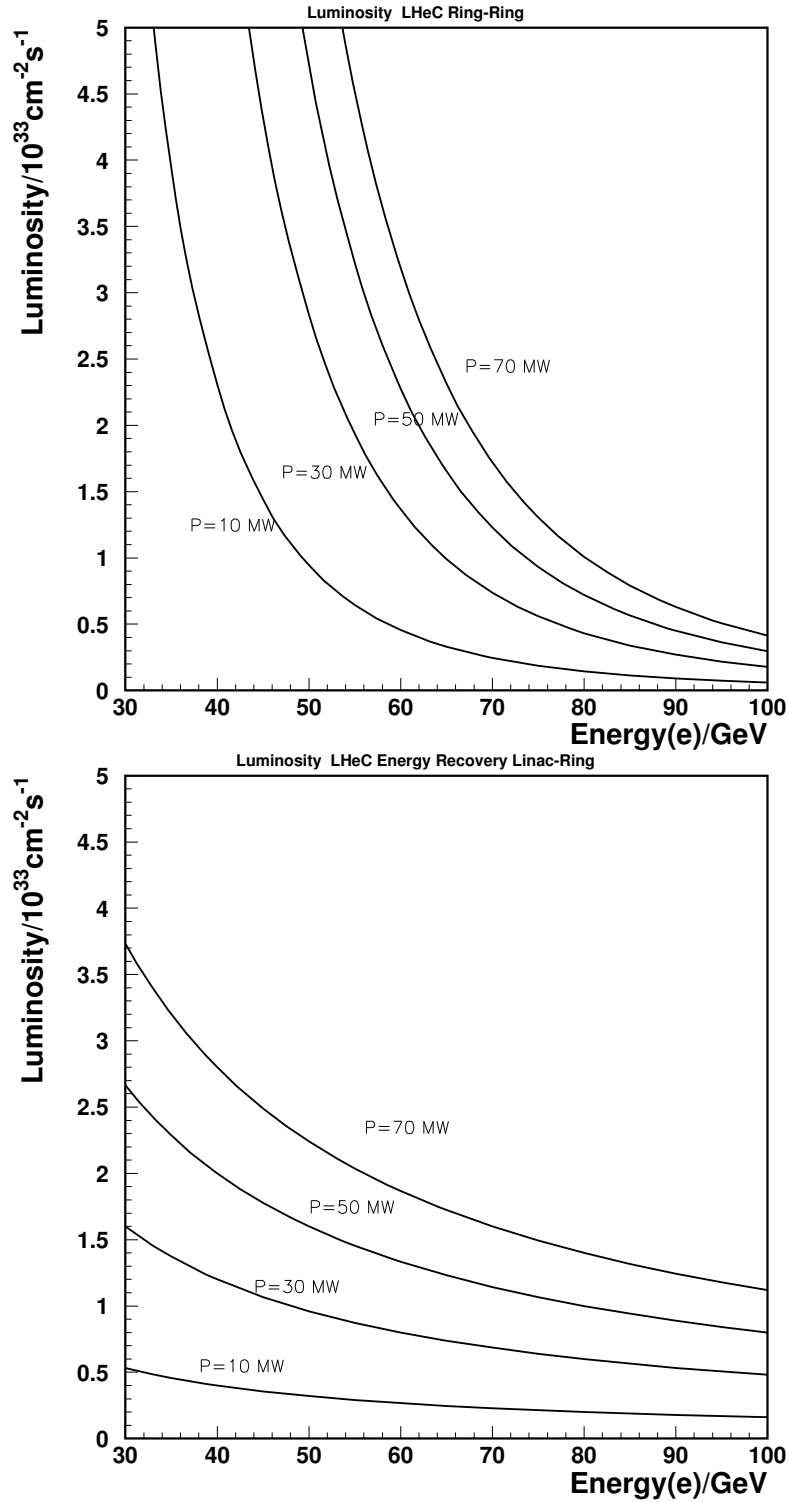


Figure 2.2: Estimated luminosity, in units of $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, for the RR configuration (top) and the LR energy recovery configuration (bottom), displayed as a function of the electron beam energy with the beam power as a parameter, see text.

Chapter 3

Executive Summary

The current version of the CDR, as of early August 2011, is for the referees as listed at the end of the draft to be evaluated. The authors are aware that various aspects of the project and the draft deserve a bit more attention prior to releasing the design report to the public. This concerns for example due consideration of the potential of the ring accelerator to reach higher than the here assumed 60 GeV beam energy, a further pass through physics and detector considerations and certainly various editorial finesses. The referee process will no doubt lead to further improvements and clarifications. The parameter table 3.1 given here may serve as a first overview for what the LHeC project as currently understood comprises. A genuine executive summary will be added after the completion of the referee process.

electron beam	RR	LR	LR ^{*)}	proton beam	RR	LR
e- energy at IP[GeV]	60	60	140	bunch pop. [10^{11}]	1.7	1.7
luminosity [10^{32} cm ⁻² s ⁻¹]	13	10	0.4	tr.emitt. $\gamma\epsilon_{x,y}$ [μ m]	3.75	3.75
polarization [%]	40	90	90	spot size $\sigma_{x,y}$ [μ m]	30, 16	7
bunch population [10^9]	20	1.0	1.5	$\beta^*_{x,y}$ [m]	1.8,0.5	0.1
e- bunch length [mm]	10	0.3	0.3	bunch spacing [ns]	25	25
bunch interval [ns]	25	25	50			
transv. emit. $\gamma\epsilon_{x,y}$ [mm]	0.58, 0.29	0.05	0.1			
rms IP beam size $\sigma_{x,y}$ [μ m]	30, 16	7	7			
e- IP beta funct. $\beta^*_{x,y}$ [m]	0.18, 0.10	0.12	0.14			
full crossing angle [mrad]	1	0	0			
geometric reduction H_{hg}	0.75	0.91	0.94			
repetition rate [Hz]	-	-	10			
beam pulse length [ms]	-	-	5			
ER efficiency	-	94%	-			
average current [mA]	131	6.4	0.27			
tot. wall plug power[MW]	100	100	100			



RR= Ring – Ring LR =Linac –Ring

Ring: with 1° as baseline : L/2
Linac: clearing gap: L*2/3

*) pulsed, but high energy ERL not impossible

Figure 3.1: Parameters of the LHeC in the ring-ring and the linac-ring version as considered in the current report. The LHC proton beam parameters correspond to the “ultimate beam” configuration, to which even the current operation is already close, as with the emittance, β^* , the 50 ns bunch spacing and also the number of protons per bunch. The report has also parts for electron-deuteron and electron-ion scattering.

896

Part II

897

Physics

Chapter 4

Precision QCD and Electroweak Physics

This chapter elucidates the physics prospects which are related to high precision measurements with the LHeC to test and develop QCD and the electroweak theory. Section 4.1 presents inclusive deep inelastic scattering and consists of three parts: NC and CC cross sections and structure functions, the simulation of NC and CC data sets including estimates for the expected systematic uncertainties, and the simulation of LHeC precision measurements of the longitudinal structure function F_L . The LHeC is the first DIS experiment which is able to completely unfold the quark contents of the nucleon. Section 4.2 introduces assumptions for the QCD fit, used for illustrating the expected gain in precision at the LHeC as compared to HERA, BCDMS and precision W charge asymmetry data from the LHC. Results are then presented first for the determination of the valence quark and the strange quark distributions, which are also compared with the current information as contained in modern PDF determinations. A dedicated part is written for top quark physics at the LHeC as at very high Q^2 , t and \bar{t} production in DIS become a new subject of research. Sections 4.3 and 4.4 discuss in detail the expected precision measurements of the gluon distribution and of the strong coupling constant, respectively. Section 4.5 motivates the measurements with electron-deuteron scattering which extend current experimental knowledge on the structure of the neutron (and the deuteron) by nearly four orders of magnitude in Q^2 and $1/x$. Section 4.6 introduces the measurements of the charm and beauty densities. Owing to the much extended range, higher energy (cross section) and dedicated Silicon tracking, high precision measurements of the c and b densities will be provided for the development of the QCD theory of heavy quarks and for the description of new phenomena which may be expected to be related especially to the b density, as the production of the Higgs particle in MSSM SUSY. Sections 4.7 illustrates the precision QCD tests that can be performed at the LHeC with jets in the final state, respectively. With the enlarged energy, new measurements of the total photoproduction cross sections can be performed as are discussed in Section 4.8. The Chapter is concluded with the electroweak physics Section 4.9 which focusses on the precision measurements of the light weak NC quark couplings and on the scale dependence of the electroweak mixing angle, as can be determined from polarisation asymmetries in NC and the NC/CC cross section ratio.

4.1 Inclusive Deep Inelastic Scattering

4.1.1 Cross Sections and Structure Functions

The scattering amplitude for electron-proton scattering is a product of lepton and hadron currents times the propagator characteristic of the exchanged particle, a photon or Z_0 in neutral current scattering, a W^\pm in charged current scattering. The inclusive scattering cross section therefore is given by the product of two

931 tensors,

$$\frac{d^2\sigma}{dx dQ^2} = \frac{2\pi\alpha^2}{Q^4 x} \sum_j \eta_j L_j^{\mu\nu} W_j^{\mu\nu}, \quad (4.1)$$

932 where j denotes the summation over γ , Z_0 exchange and their interference for NC, and $j = W^+$ or W^-
 933 for CC. The leptonic tensor $L_j^{\mu\nu}$ is related to the coupling of the electron with the exchanged boson and
 934 contains the electromagnetic or the weak couplings, such as the vector and axial-vector electron- Z_0 couplings,
 935 v_e and a_e , in the NC case. This leptonic part of the cross section can be calculated exactly in the standard
 936 electroweak $U_1 \times SU_2$ theory. The hadronic tensor, however, describing the interaction of the exchanged
 937 boson with the proton, can only be reduced to a sum of structure functions, $F_i(x, Q^2)$, but not be fully
 938 calculated. Conservation laws reduce the number of basic structure functions in unpolarised ep scattering to
 939 $i = 1 - 3$. In perturbative QCD the structure functions are related to parton distributions f *via* coefficient
 940 functions C

$$[F_{1,3}, F_2] = \sum_i \int_0^1 [1, z] \frac{dz}{z} C_{1,2,3}\left(\frac{x}{z}, \frac{Q^2}{\mu_r^2}, \frac{\mu_f^2}{\mu_r^2}, \alpha_s(\mu_r^2)\right) \cdot f_i(z, \mu_f^2, \mu_r^2), \quad (4.2)$$

941 where i sums the quark q , anti-quark \bar{q} and gluon g contributions and $f_i(x)$ is the probability distribution of
 942 the parton of type i to carry a fraction x of the proton's longitudinal momentum. The coefficient functions
 943 are exactly calculable but depend on the factorisation and renormalisation scales μ_f and μ_r . The parton
 944 distributions are not calculable but have to be determined by experiment. Their Q^2 dependence obeys
 945 evolution equations. A general factorisation theorem, however, has proven the parton distributions to be
 946 universal, i.e. to be independent of the type of hard scattering process. This makes deep inelastic lepton-
 947 nucleon scattering a most fundamental process: the parton distributions in the proton are measured best
 948 with a lepton probe and may be used to predict hard scattering cross sections at, for example, the LHC. The
 949 parton distributions are derived from measurements of the structure functions in NC and CC scattering, as
 950 is discussed below.

951 4.1.2 Neutral Current

952 The neutral current deep inelastic ep scattering cross section, at tree level, is given by a sum of generalised
 953 structure functions according to

$$\frac{d^2\sigma_{NC}}{dx dQ^2} = \frac{2\pi\alpha^2 Y_+}{Q^4 x} \cdot \sigma_{r,NC} \quad (4.3)$$

$$\sigma_{r,NC} = \mathbf{F}_2 + \frac{Y_-}{Y_+} \mathbf{xF}_3 - \frac{y^2}{Y_-} \mathbf{FL}, \quad (4.4)$$

954 where the electromagnetic coupling constant α , the photon propagator and a helicity factor are absorbed in
 955 the definition of a reduced cross section σ_r , and $Y_{\pm} = 1 \pm (1-y)^2$. The functions \mathbf{F}_2 and \mathbf{xF}_3 depend on
 956 the lepton beam charge and polarisation (P) and on the electroweak parameters as [58]

$$\begin{aligned} \mathbf{F}_2^{\pm} &= F_2 + \kappa_Z (-v_e \mp P a_e) \cdot F_2^{\gamma Z} + \kappa_Z^2 (v_e^2 + a_e^2 \pm 2P v_e a_e) \cdot F_2^Z \\ \mathbf{xF}_3^{\pm} &= \kappa_Z (\pm a_e + P v_e) \cdot x F_3^{\gamma Z} + \kappa_Z^2 (\mp 2v_e a_e - P(v_e^2 + a_e^2)) \cdot x F_3^Z. \end{aligned} \quad (4.5)$$

957 In the on-mass shell \overline{MS} scheme the propagator function κ_Z is given by the weak boson masses (M_Z , M_W)

$$\kappa_Z(Q^2) = \frac{Q^2}{Q^2 + M_Z^2} \cdot \frac{1}{4 \sin^2 \Theta \cos^2 \Theta} \quad (4.6)$$

958 with the weak mixing angle $\sin^2 \Theta = 1 - M_W^2/M_Z^2$. In the hadronic tensor decomposition [59] the structure
 959 functions are well defined quantities. In the Quark Parton Model (QPM) the longitudinal structure function

960 is zero [60] and the two other functions are given by the sums and differences of quark (q) and anti-quark
 961 (\bar{q}) distributions as

$$\begin{aligned} (F_2, F_2^{\gamma Z}, F_2^Z) &= x \sum (e_q^2, 2e_q v_q, v_q^2 + a_q^2)(q + \bar{q}) \\ (xF_3^{\gamma Z}, xF_3^Z) &= 2x \sum (e_q a_q, v_q a_q)(q - \bar{q}), \end{aligned} \quad (4.7)$$

962 where the sum extends over all up and down type quarks and $e_q = e_u, e_d$ denotes the electric charge of up-
 963 or down-type quarks. The vector and axial-vector weak couplings of the fermions ($f = e, u, d$) to the Z_0
 964 boson in the standard electroweak model are given by

$$v_f = i_f - e_f 2 \sin^2 \Theta \quad a_f = i_f \quad (4.8)$$

965 where $e_f = -1, 2/3, -1/3$ and $i_f = I(f)_{3,L} = -1/2, 1/2, -1/2$ denotes the left-handed weak isospin charges,
 966 respectively. Thus the vector coupling of the electron, for example, is very small, $v_e = -1/2 + 2 \sin^2 \Theta \simeq 0$,
 967 since the weak mixing angle is roughly equal to $1/4$.

968 At low Q^2 and low y the reduced NC cross section, Eq.4.3, to a very good approximation is given by
 969 $\sigma_r = F_2(x, Q^2)$. At $y > 0.5$, F_L makes a sizeable contribution to $\sigma_{r,NC}$. In the DGLAP approximation of
 970 perturbative QCD, to lowest order, the longitudinal structure function is given by [61]

$$F_L(x) = \frac{\alpha_s}{4\pi} x^2 \int_x^1 \frac{dz}{z^3} \cdot \left[\frac{16}{3} F_2(z) + 8 \sum e_q^2 \left(1 - \frac{x}{z}\right) z g(z) \right], \quad (4.9)$$

971 which at low x is dominated by the gluon contribution. A measurement of F_L requires a variation of the
 972 beam energy.

973 Two further structure functions can be accessed with cross section asymmetry measurements, in which
 974 the charge and/or the polarisation of the lepton beam are varied. A charge asymmetry measurement, with
 975 polarisation values P_{\pm} of the e^{\pm} beam, determines the following structure function combination

$$\sigma_{r,NC}^+(P_+) - \sigma_{r,NC}^-(P_-) = -\kappa_Z a_e (P_+ + P_-) \cdot F_2^{\gamma Z} + \frac{Y_-}{Y_+} \kappa_Z a_e \cdot [2xF_3^{\gamma Z} + (P_+ - P_-) \kappa_Z a_e x F_3^Z] \quad (4.10)$$

976 neglecting terms $\propto v_e$ which can be easily obtained from Eq.4.5. If data are taken with opposite polarisation
 977 and charge, the asymmetry represents a measurement of the difference of quark and anti-quark distributions
 978 in NC, see Eq.4.7. In contrast to what is often stated, the charge asymmetry is a parity conserving quantity
 979 $\propto a_e a_q$. Assuming symmetry between sea and antiquarks, it is a direct measure of the valence quarks,
 980 $xF_3^{\gamma Z} = 2u_v + d_v$ in ep . This function was measured for the first time in μ^{\pm} Carbon scattering by the
 981 BCDMS Collaboration [62] at large $x > 0.2$ and for Q^2 of about 50 GeV^2 . With the LHeC, for the first
 982 time, high precision measurements of xF_3 in NC become possible as is demonstrated in Sect.4.2.2. These
 983 will access the valence quarks at low $x \lesssim 0.001$ for the first time in direct measurements.

984 A genuine polarisation asymmetry measurement, keeping the beam charge fixed, according to eqs.4.3
 985 and 4.5 determines a similar combination of $F_2^{\gamma Z}$ and $xF_3^{\gamma Z}$

$$\frac{\sigma_{r,NC}^{\pm}(P_L) - \sigma_{r,NC}^{\pm}(P_R)}{P_L - P_R} = \kappa_Z [\mp a_e F_2^{\gamma Z} + \frac{Y_-}{Y_+} v_e x F_3^{\gamma Z}] \simeq \mp \kappa_Z a_e F_2^{\gamma Z} \quad (4.11)$$

986 neglecting again the term $\propto v_e$. The product $a_e F_2^{\gamma Z}$ is proportional to combinations $a_e v_q$ and thus a direct
 987 measure of parity violation at very small distances.

988 The structure function $F_2^{\gamma Z}$ accesses a new combination of quark distributions and is measurable for the
 989 first time, and with high precision, at the LHeC, see Fig.4.1, in which the result is shown of its possible
 990 measurement. The remarkable precision on $F_2^{\gamma Z}$ illustrates the huge potential in precision and range which
 991 the LHeC brings. For the study of electroweak effects one clearly desires to have the maximum beam energy
 992 and polarisation available as the comparison of the two results for different beam conditions but the same
 993 luminosity in Fig.4.1 shows.

994 The polarisation asymmetry also permits a high precision measurement of the weak mixing angle at
 995 different Q^2 values, below and to much higher values than M_Z^2 , at which $\sin^2 \Theta$ was precisely measured at
 996 LEP and the SLC, see Sect.4.9.3.

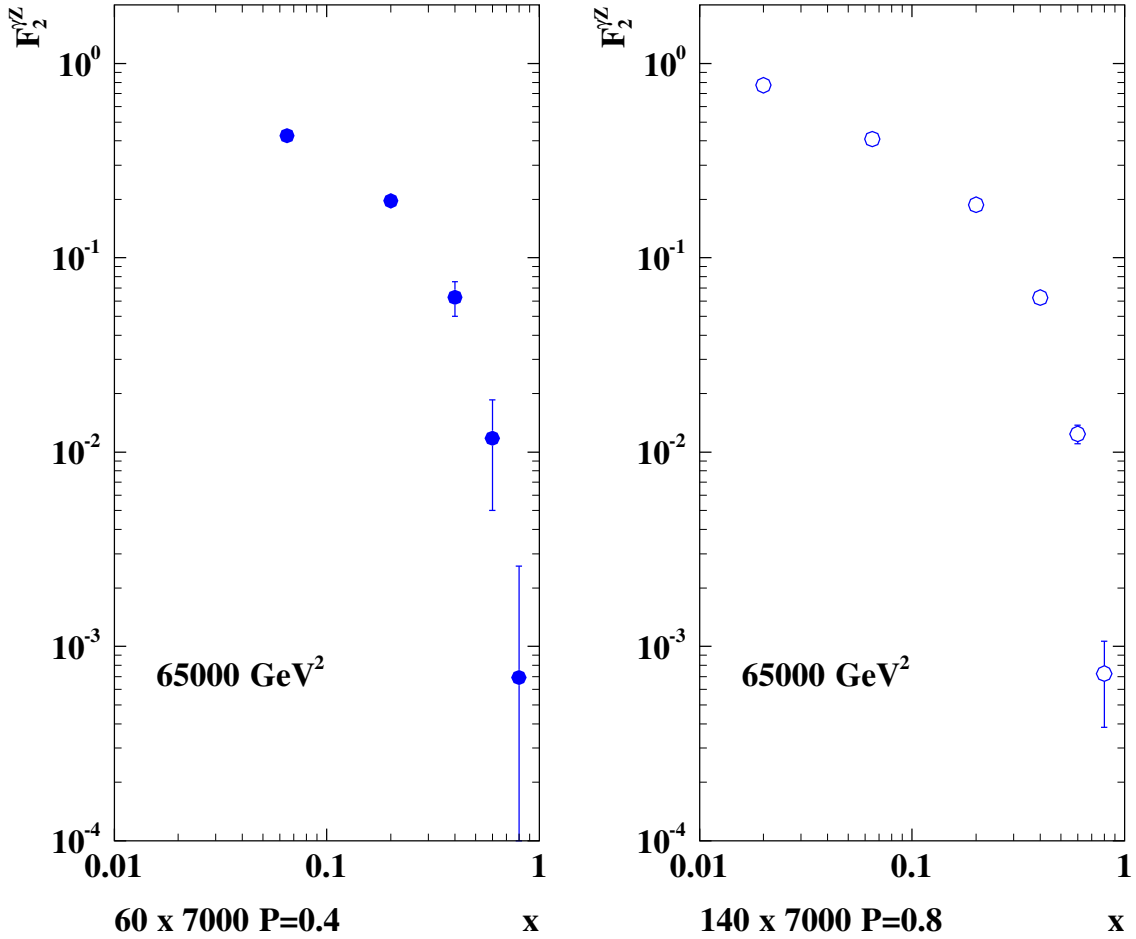


Figure 4.1: Simulation of the measurement of the γZ interference structure function $F_2^{\gamma Z}$, shown as a function of x for a typical high Q^2 value, for two LHeC configurations ($E_e = 60$ GeV and $P = \pm 0.4$, left) and ($E_e = 140$ GeV and $P = \pm 0.9$, right). The proton beam energy is 7 TeV and the luminosity assumed is 10 fb^{-1} per polarisation state. This function is a measure for parity violation and provides additional information on the quark distributions as it is proportional to $e_q v_q$ to be compared with e_q^2 in the lowest order function F_2 . Shown are statistical uncertainties only. The systematic uncertainty can be expected to be small as in the asymmetry many effects cancel and because at the LHeC such asymmetries are large, and the polarisation possibly controlled at the per mille level, as is discussed in the technical part of the CDR.

997 4.1.3 Charged Current

998 The inclusive polarised charged current $e^\pm p$ scattering cross section can be written as

$$\frac{d^2\sigma_{CC}^\pm}{dx dQ^2} = \frac{1 \pm P}{2} \cdot \frac{G_F^2}{2\pi x} \cdot \left[\frac{M_W^2}{M_W^2 + Q^2} \right]^2 Y_+ \cdot \sigma_{r,CC}. \quad (4.12)$$

999 The reduced charged current cross section, analogous to the NC case Eq. 4.3, is a sum of structure function
1000 terms

$$\sigma_{r,CC}^\pm = W_2^\pm \mp \frac{Y_-}{Y_+} xW_3^\pm - \frac{y^2}{Y_+} W_L^\pm. \quad (4.13)$$

1001 In the on-mass shell scheme, the Fermi constant G_F is defined, see for example [63], using the weak boson
1002 masses as

$$G_F = \frac{\pi\alpha}{\sqrt{2}M_W^2 \sin^2\theta(1 - \Delta r)} \quad (4.14)$$

1003 with $\sin^2\theta = 1 - M_W^2/M_Z^2$ as above. The higher order correction term Δr can be approximated [64] as
1004 $\Delta r = 1 - \alpha/\alpha(M_Z) - 0.0094(m_t/173\text{GeV})^2/\tan^2\theta$, and thus introduces a dependence of the DIS cross section
1005 on the mass of the top quark. The choice of G above allows the CC cross section, Eq. 4.12, to be rewritten
1006 as

$$\frac{d^2\sigma_{CC}^\pm}{dx dQ^2} = \frac{1 \pm P}{2} \cdot \frac{2\pi\alpha^2 Y_+}{Q^4 x} \cdot \kappa_W^2 \cdot \sigma_{r,CC}, \quad (4.15)$$

1007 with

$$\kappa_W(Q^2) = \frac{Q^2}{Q^2 + M_W^2} \cdot \frac{1}{4\sin^2\theta}, \quad (4.16)$$

1008 which is convenient for the consideration of NC/CC cross section ratios.

1009 In the QPM (where $W_L^\pm = 0$), the structure functions represent beam charge dependent sums and
1010 differences of quark and anti-quark distributions and are given by

$$W_2^+ = x(\bar{U} + D), \quad xW_3^+ = x(D - \bar{U}), \quad W_2^- = x(U + \bar{D}), \quad xW_3^- = x(U - \bar{D}). \quad (4.17)$$

1011 Using these equations one finds

$$\sigma_{r,CC}^+ \sim x\bar{U} + (1-y)^2 xD, \quad (4.18)$$

$$\sigma_{r,CC}^- \sim xU + (1-y)^2 x\bar{D}. \quad (4.19)$$

1012 Combined with Equation 4.5, which approximately reduces to

$$\begin{aligned} \sigma_{r,NC}^\pm &\simeq [c_u(U + \bar{U}) + c_d(D + \bar{D})] + \kappa_Z[d_u(U - \bar{U}) + d_d(D - \bar{D})] \\ c_{u,d} &= e_{u,d}^2 + \kappa_Z(-v_e \mp Pa_e)e_{u,d}v_{u,d} \quad d_{u,d} = \pm a_e a_{u,d} e_{u,d}, \end{aligned} \quad (4.20)$$

1013 one finds that the NC and CC cross section measurements at the LHeC determine the complete set U, D, \bar{U}
1014 and \bar{D} , i.e. the sum of up-type, of down-type and of their anti-quark-type distributions. Below the b quark
1015 mass threshold, these are related to the individual quark distributions as follows

$$U = u + c \quad \bar{U} = \bar{u} + \bar{c} \quad D = d + s \quad \bar{D} = \bar{d} + \bar{s}. \quad (4.21)$$

1016 Assuming symmetry between sea quarks and anti-quarks, the valence quark distributions result from

$$u_v = U - \bar{U} \quad d_v = D - \bar{D}. \quad (4.22)$$

1017 4.1.4 Cross Section Simulation and Uncertainties

1018 The LHeC extends the kinematic range as compared to HERA in the negative momentum transfer squared
 1019 Q^2 from a maximum of about 0.03 to 1 TeV² and towards low x , e.g. for $Q^2 = 3 \text{ GeV}^2$, from about $4 \cdot 10^{-5}$
 1020 to $2 \cdot 10^{-6}$. The projected increase of integrated luminosity by a factor of 100 allows to also extend the
 1021 kinematic range at large x , in charged currents, from practically about 0.4 to 0.8. Due to the enlarged
 1022 electron beam energy E_e the range of high inelasticity $y \simeq 1 - E'_e/E_e$ should extend closer to 1. A reduced
 1023 noise in the calorimeters may allow to reach lower values of y than at HERA, also because the hadronic y
 1024 is determined as the sum over $E - p_z$ divided by twice the with the LHeC enhanced electron beam energy.
 1025 Very recently it has been observed by H1 that the reconstruction of the hadronic final state with jets rather
 1026 than the full sum of hadronic energy depositions allows to control better the region of low y , i.e. scattering
 1027 close to the beam pipe. At the LHeC these jets are extremely energetic and one would expect, subject to
 1028 detailed simulation studies at a later stage of the project, that kinematic reconstruction for values of y down
 1029 to 0.001 or even below could be trusted.

1030 While the extensions of kinematic coverage and improvements of statistical precision are impressive,
 1031 an estimate of the impact of LHeC NC and CC cross section measurements on derived quantities such as
 1032 structure functions and parton distributions requires to also estimate the expected systematic measurement
 1033 accuracy as may be achieved with the detector described in Chapter 13 below. In the following the assump-
 1034 tions and simulation results are presented for the NC and the CC cross sections, which are subsequently
 1035 used in QCD fit and other analyses throughout this report.

1036 The systematic uncertainties of the DIS cross sections have a number of sources, which at HERA have
 1037 broadly been classified as uncorrelated and correlated across bin boundaries. For the NC case, the uncor-
 1038 related sources, apart from data and Monte Carlo statistics, are a global efficiency uncertainty, due to for
 1039 example tracking or electron identification errors, photoproduction background, calorimeter noise and radi-
 1040 ative corrections. The correlated uncertainties result from imperfect energy scale and angle calibrations. In
 1041 the classic kinematic reconstruction methods used here, and described in Sect. 12.1 one uses the scattered
 1042 electron energy E'_e and polar angle θ_e complemented by the energy of the hadronic final state E_h ¹. The
 1043 correlated errors are due to scale uncertainties of the electron energy E'_e and of the hadronic final state
 1044 energy E_h . There are also systematic errors due to an uncertainty of the measurement of the electron polar
 1045 angle θ_e . The assumptions used in the simulation of pseudodata are summarised in Table 4.1.

1046 In the absence of a detailed detector simulation at this stage, the systematic NC cross uncertainties due
 1047 to E'_e , θ_e and E_h are calculated, following [65], from the derivatives of the NC cross section in the chosen bins
 1048 taking into account the Jacobians where needed. The results have been compared, for the HERA kinematics,
 1049 with the H1 MC simulation of systematic errors [66] and found to be in very good agreement for all three
 1050 sources. The resulting error depends much on the kinematics. At low Q^2 , for example, the systematic cross
 1051 section error due to the uncertainty of θ_e rises because of $\delta Q^2/Q^2 = \delta E'_e/E'_e \oplus \tan(\theta_e/2) \cdot \delta\theta_e$ while at high
 1052 Q^2 it is negligible. Low Q^2 is the backward region, of large electron scattering angles with respect to the
 1053 proton beam direction.

1054 A particular challenge is the measurement at large x because the cross section varies as $(1 - x)^c$, with
 1055 $c \simeq 3$, and thus the relative error is amplified $\propto 1/(1 - x)$ as x approaches 1. At high x the hadronic final
 1056 state is scattered into the forward detector region where the energy calibration becomes challenging. The
 1057 calculated correlated NC cross section errors are illustrated in Figs. 4.2 and 4.3 for $Q^2 = 2$ and 20000 GeV²,
 1058 respectively. In the detector chapter these calculations have been taken to define approximate requirements
 1059 on the scale calibrations in the different detector regions. An example for the resulting cross section
 1060 measurement is displayed in Fig. 4.4 for low x and in Fig. 4.5 for large x .

¹Basically one determines Q^2 best with the electron kinematics and determines x from $y = Q^2/sx$. At large y the inelasticity is essentially measured with the electron energy $y \simeq 1 - E'_e/E_e$. At low y one has $y = E_h \sin^2(\theta_h/2)/E_e$ with the hadronic final state energy E_h and angle θ_h which results in $\delta y/y \simeq \delta E_h/E_h$ to good approximation. There have been various refined methods proposed to determine the DIS kinematics, as the double angle method or the so-called sigma method. For the estimate of the cross section uncertainty behaviour as functions of Q^2 and x , however, the simplest method using Q_e^2, y_e at large y and Q_e^2, y_h at low y is transparent and accurate enough within better than a factor of two. In much of the phase space, moreover, it is rather the uncorrelated efficiency or further specific errors than the kinematic correlations, which dominate the cross section measurement accuracy.

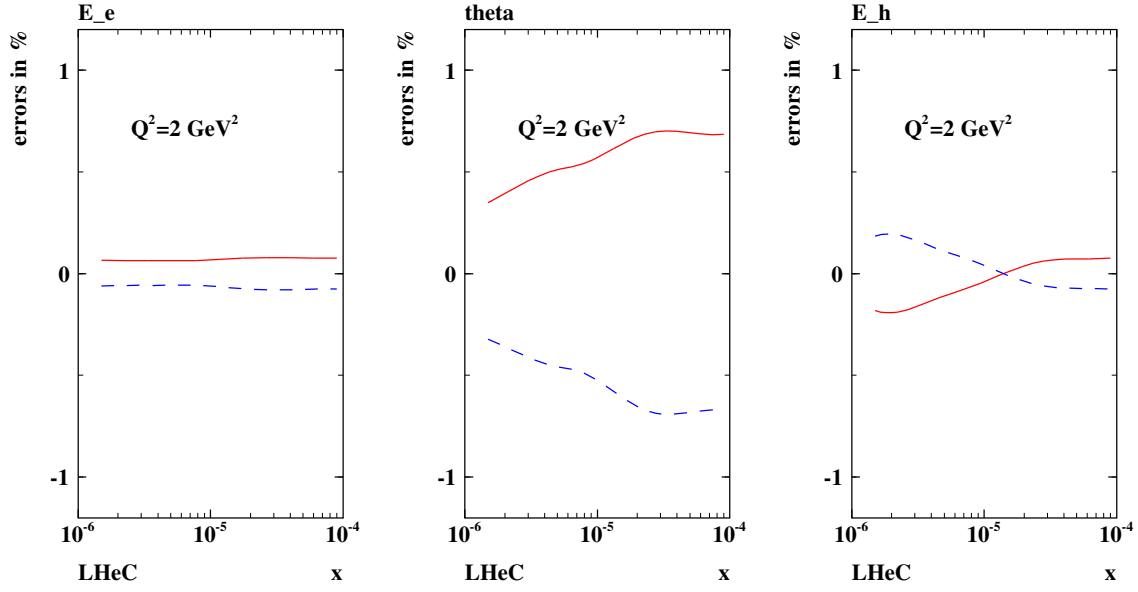


Figure 4.2: Neutral current cross section errors, calculated for $60 \times 7000 \text{ GeV}^2$, as result from scale uncertainties of the scattered electron energy $\delta E'_e/E'_e = 0.1 \%$, of its polar angle $\delta\theta_e = 0.1 \text{ mrad}$ and the hadronic final state energy $\delta E_h/E_h = 0.5 \%$, at low $Q^2 = 2 \text{ GeV}^2$ and correspondingly low x .

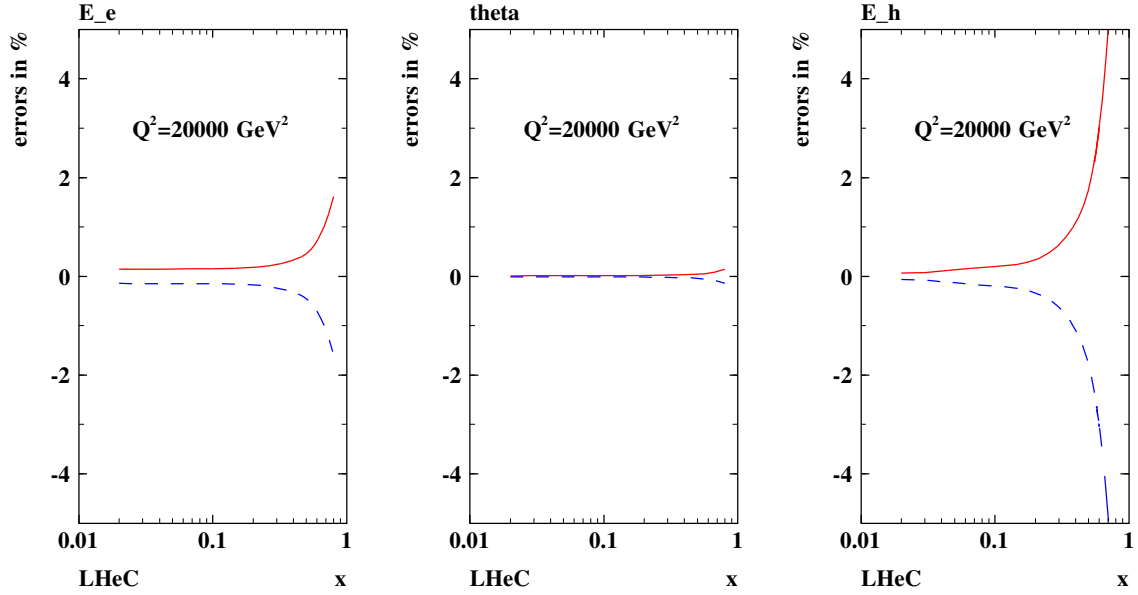


Figure 4.3: Neutral current cross section errors, calculated for $60 \times 7000 \text{ GeV}^2$ unpolarised e^-p scattering, as result from scale uncertainties of the scattered electron energy $\delta E'_e/E'_e = 0.1 \%$, of its polar angle $\delta\theta_e = 0.1 \text{ mrad}$ and the hadronic final state energy $\delta E_h/E_h = 0.5 \%$, at large $Q^2 = 20000 \text{ GeV}^2$ and correspondingly large x . Note that the characteristic behaviour of the relative uncertainty at large x , i.e. to diverge $\propto 1/(1-x)$, is independent of Q^2 , i.e. persistently observed at $Q^2 = 200000 \text{ GeV}^2$ for example too.

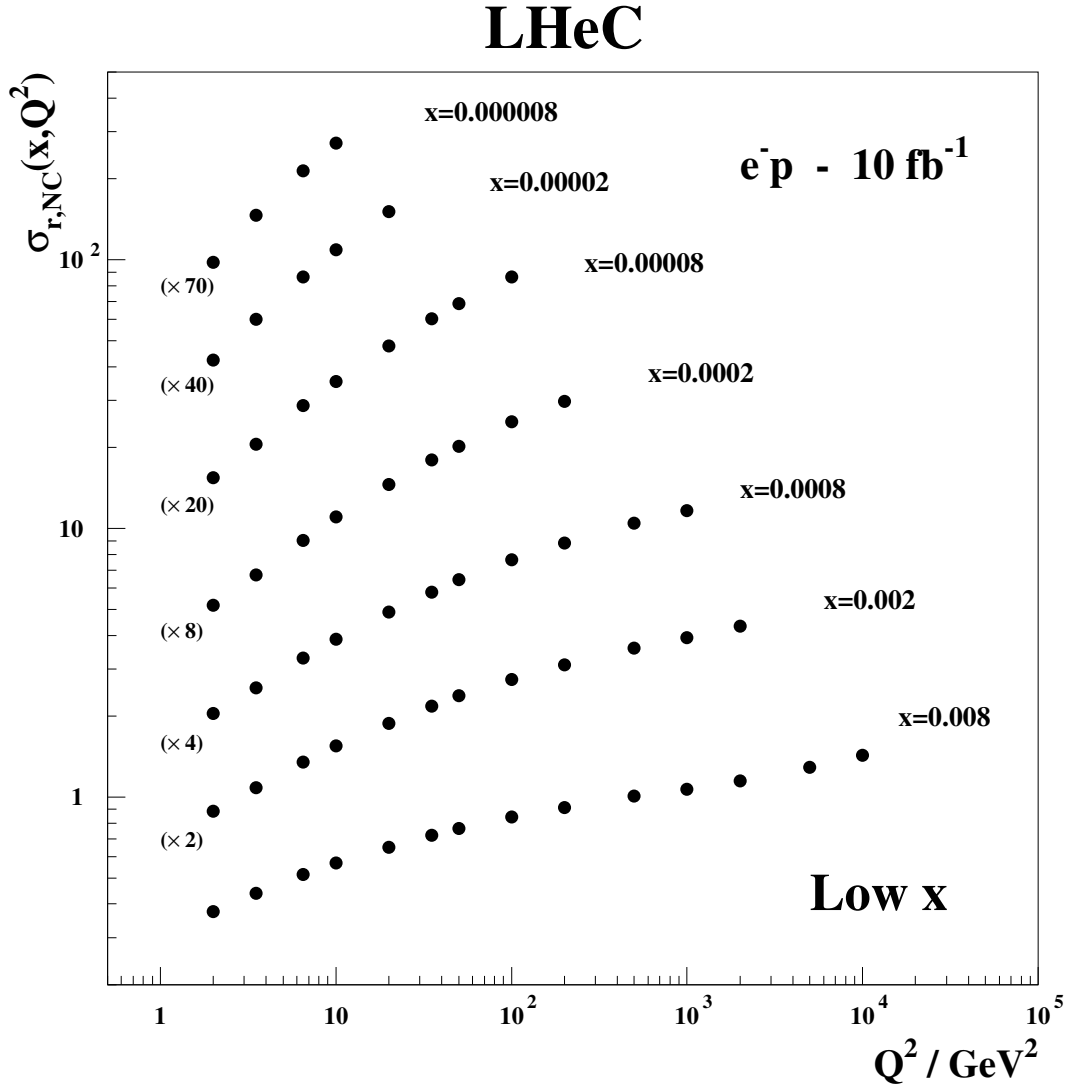


Figure 4.4: Simulated neutral current, inclusive reduced cross section measurement, for an integrated luminosity of 10 fb^{-1} , in unpolarised e^-p scattering at $E_e = 60$ and $E_p = 7000 \text{ GeV}$. The DIS cross section is measurable at unprecedented precision and range. The uncertainty is about or below 1% and thus not visible on this plot. Departures from the strong rise of the reduced cross section, $\sigma_r \simeq F_2$, at very low x and Q^2 are expected to appear due to non-linear gluon-gluon interaction effects in the so-called saturation region.

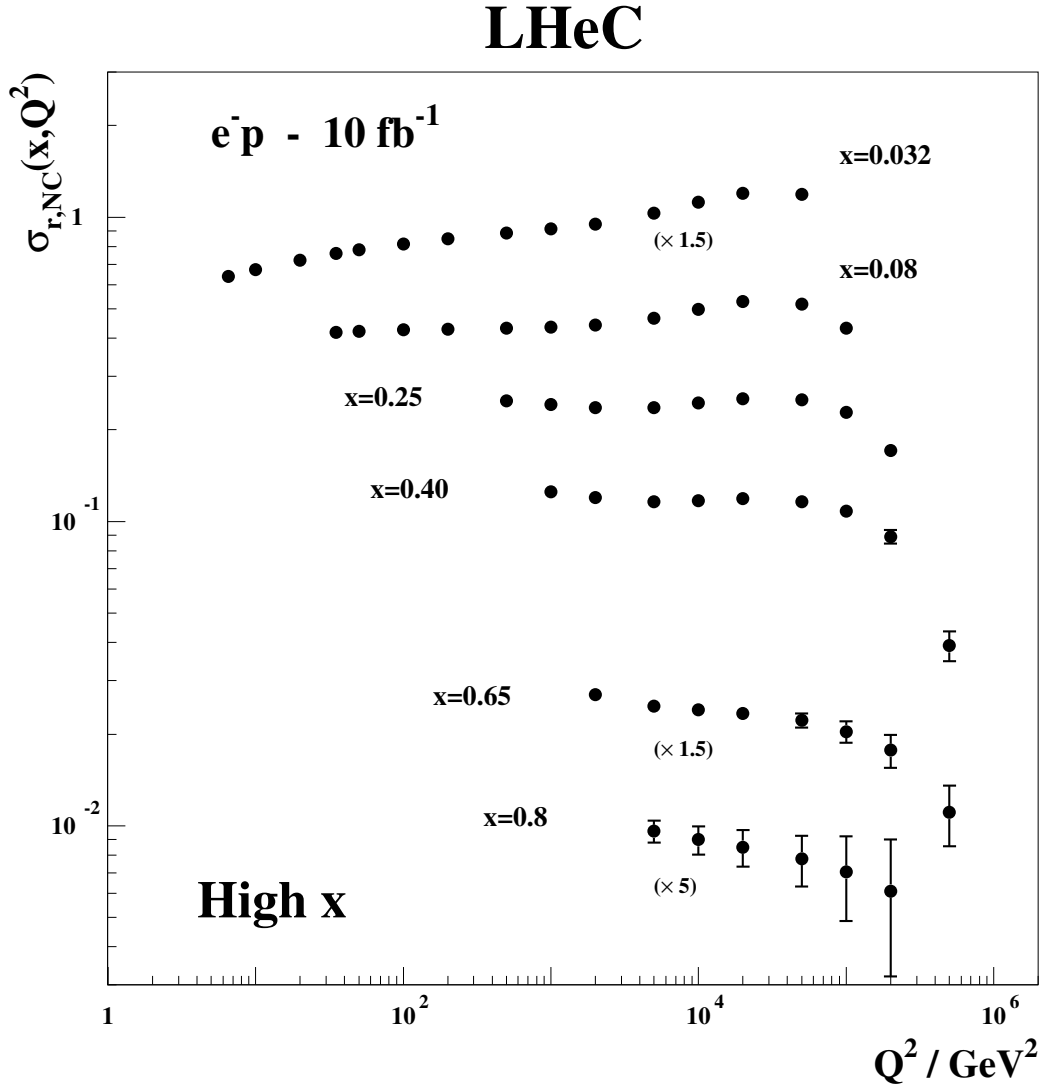


Figure 4.5: Simulated neutral current, inclusive reduced cross section measurement, for an integrated luminosity of 10 fb^{-1} , in unpolarised e^-p scattering at $E_e = 60$ and $E_p = 7000 \text{ GeV}$. The DIS cross section is measurable at unprecedented precision and range. Plotted is the total uncertainty which, where visible at high x and Q^2 , is dominated by the statistical error. Similar data sets are expected with different beam polarisations and charges, and in CC scattering, for $Q^2 \geq 100 \text{ GeV}^2$. The strong variations of σ_r with Q^2 , as at $x = 0.25$, are due to the effects of Z exchange as is discussed and illustrated subsequently.

source of uncertainty	error on the source or cross section
scattered electron energy scale $\Delta E'_e/E'_e$	0.1 %
scattered electron polar angle	0.1 mrad
hadronic energy scale $\Delta E_h/E_h$	0.5 %
calorimeter noise (only $y < 0.01$)	1-3 %
radiative corrections	0.5%
photoproduction background (only $y > 0.5$)	1 %
global efficiency error	0.7 %

Table 4.1: Assumptions used in the simulation of the NC cross sections on the amount of uncertainties from various sources. These assumptions correspond to the typical or best of what was achieved in the H1 experiment. Note that in the cross section measurement the energy scale and angular uncertainties are relative to the Monte Carlo and not to be confused with resolution effects which determine the purity and stability of binned cross sections. The total cross section error due to these uncertainties, e.g. for $Q^2 = 100 \text{ GeV}^2$, is about 1.2, 0.7 and 2.0 % for $y = 0.84, 0.1, 0.004$.

1061 For the CC case, a similar simulation was done, albeit with less numeric effort. An illustration of the
1062 high precision and large range of the inclusive CC cross section measurements is presented in Fig. 4.6. The
1063 systematic cross section error, based on the H1 experience, was set to 2% and for larger $x > 0.3$ a term
1064 was added to allow the error to rise linearly to 10% at $x = 0.9$. For both NC and CC cross sections
1065 the statistical error is given by the number of events but limited to 0.1% from below. With these error
1066 assumptions a number of data sets was simulated, both for NC and CC, which is summarised in Table 4.2.
1067 The energies of these sets had been chosen prior to the final baseline energy choice. For the simulation of
1068 the F_L measurement, described below, a separate set of beam energies is considered.

1069 4.1.5 Longitudinal Structure Function F_L

1070 The inclusive, deep inelastic electron-proton scattering cross section at low Q^2 ,

$$\frac{d^2\sigma}{dx dQ^2} = \frac{2\pi\alpha^2 Y_+}{Q^4 x} [F_2(x, Q^2) - f(y) \cdot F_L(x, Q^2)], \quad (4.23)$$

1071 is defined by two proton structure functions, F_2 and F_L with $y = Q^2/sx$, $Y_+ = 1 + (1-y)^2$ and $f(y) = y^2/Y_+$.
1072 The two functions reflect the transverse and the longitudinal polarisation state of the virtual photon probing
1073 the proton structure, i.e. $F_T = F_2 - F_L$ and F_L , respectively. The positivity of the transverse and longitudinal
1074 cross sections requires $0 \leq F_L \leq F_2$. Since for most of the kinematic range the y dependent factor $f(y)$ is
1075 very small, there follows that F_L causes in most of the kinematic range only a small correction to the reduced
1076 cross section, which is governed by F_2 , apart from the regio of maximum y . At small x , the inelasticity is
1077 given as $y \simeq 1 - E'_e/E_e$. Therefore, in order to extract F_L , DIS has to be measured extremely accurately
1078 at small scattered lepton energies, which is a question of how large E_e is, how to trigger and how to control
1079 the background from particle production at low energies. A variation of the beam energies is required to
1080 separate the two functions measured at the same x and Q^2 by variation of $y = Q^2/sx$.

1081 A first measurement of F_L at low x at HERA has recently been performed by the ZEUS Collaboration [67]
1082 and by the H1 Collaboration [68]. For the study of the gluon distribution at lowest x , the H1 data are crucial
1083 as only H1 has measured F_L below Q^2 of about 10 GeV^2 owing to their backward detector constellation
1084 upgraded in the nineties. The F_L measurement at HERA was performed towards the end of the accelerator
1085 operation and could only extend over a period of three months with about 10 pb^{-1} of integrated luminosity
1086 spent at two reduced proton beam energies, 450 and 565 GeV, besides the nominal 920 GeV. The H1 result is
1087 consistent with pQCD predictions. The ratio $R = F_L/(F_2 - F_L)$ has been found to be independent of x and
1088 Q^2 at 20% accuracy, i.e. $R = 0.26 \pm 0.05$ [68]. This interesting relation deserves a more precise investigation
1089 and may break when the region of saturation is entered at lower x than HERA could access.

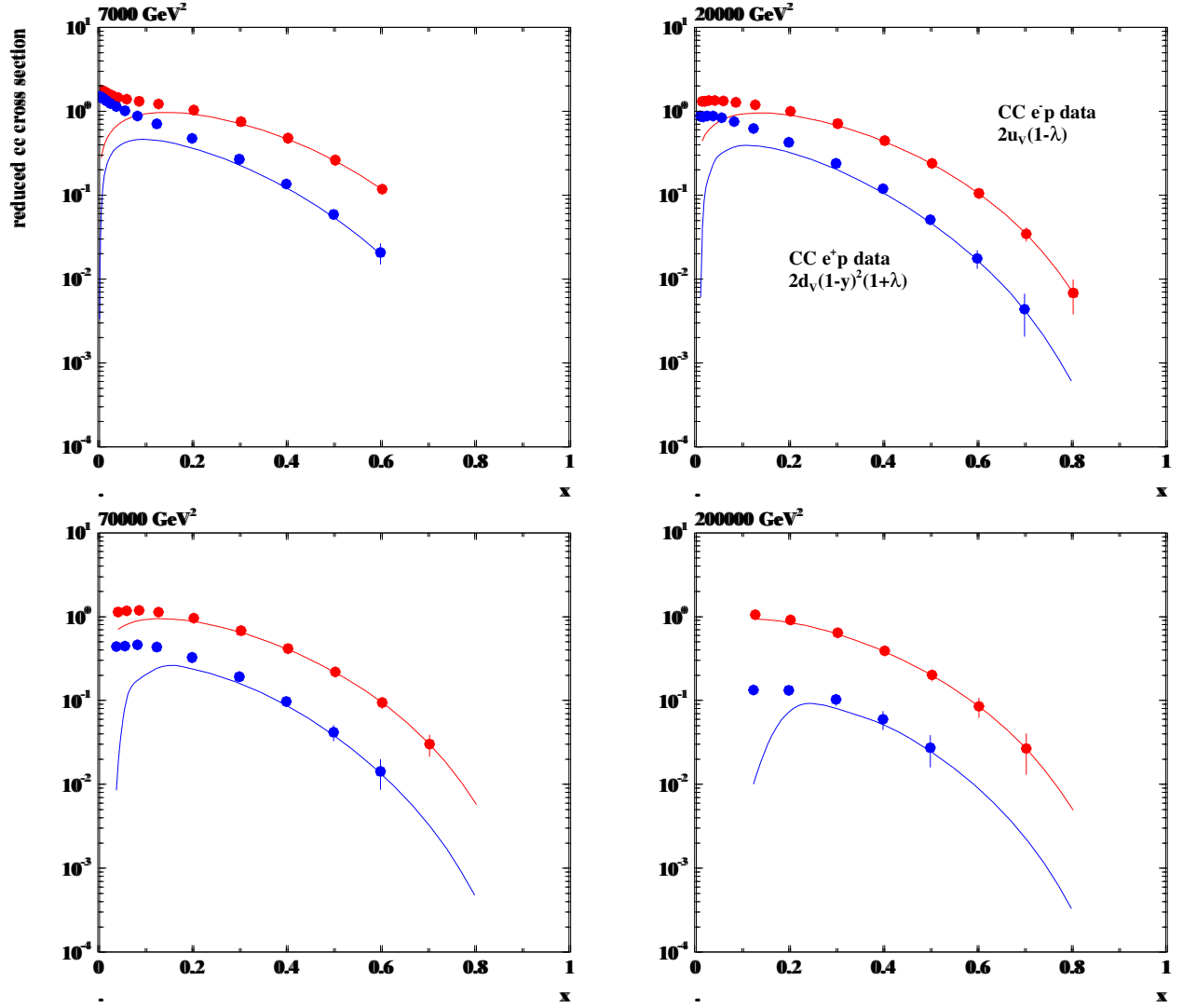


Figure 4.6: Reduced charged current cross sections with statistical uncertainties corresponding to 1 fb^{-1} electron (top data points, red) and positron (lower data points, blue) proton scattering at the LHeC, The curves are determined by the dominant valence quark distributions, u_v for e^-p and d_v for e^+p . In the simulation the lepton polarisation is taken to be zero. The valence-quark approximation of the reduced cross section is seen to hold at $x \geq 0.3$. A precise determination of the u/d ratio up to large x appears to be feasible at very high Q^2 .

Set	E_e/GeV	E_N/TeV	N	L^+/fb^{-1}	L^-/fb^{-1}	Pol
A	20	7	7	1	1	0
B	50	7	7	50	50	0.4
C	50	7	7	1	1	0.4
D	100	7	7	5	10	0.9
E	150	7	7	3	6	0.9
F	50	3.5	7	1	1	0
G	50	2.7	7	0.1	0.1	0.4
H	50	1	7	-	1	0

Table 4.2: Conditions for simulated NC and CC data sets for studies on the LHeC physics. Here, A defines a low electron beam energy option which is of interest to reach lowest Q^2 because Q_{min}^2 decreases $\propto E_e^{-2}$; B is the standard set, with a total luminosity split between different polarisation and charge states. C is a lower luminosity version which was considered in case there was a need for a dedicated low/large angle acceptance configuration, which according to more recent findings could be avoided since the luminosity in the restricted acceptance configuration is estimated, from the β functions obtained in the optics design, to be half of the luminosity in the full acceptance configuration; D is an intermediate energy linac-ring version, while E is the highest energy version considered, with the luminosities as given. It is likely that the assumptions for D and E on the positron luminosity are a bit optimistic. However, even with twenty times lower positron than electron luminosity one would have 0.5 fb^{-1} , i.e. the total HERA luminosity equivalent available in option D for example. F is the deuteron and G the lead option; finally H was simulated for a low proton beam energy configuration as is of interest to maximise the acceptance at large x .

1090 The LHeC will extend this initial measurement by using higher luminosities and dedicated detector
1091 conditions into a much enlarged kinematic range. Since the LHeC is supposed to run synchronously with the
1092 LHC, the simulation presented here has been made with reduced electron beam energies keeping the proton
1093 beam energy untouched. The following set of energies and integrated luminosities: (60, 1), (30, 0.3), (20,
1094 0.1) and (10, 0.05) (GeV, fb^{-1}). Note that the F_L measurement requires to also have data with the opposite
1095 beam charge in order to be able to reliably subtract the non DIS background which at high y is substantial.
1096 This has not been simulated here.

1097 In the low x studies below a similar simulation was used for which the luminosity assumptions were
1098 similar but a set of reduced proton beam energies was considered. The advantage of lowering E_p is that the
1099 maximum y for all beam energy configurations can be high, e.g. 0.95 for $E_e = 60 \text{ GeV}$. When E_e is lowered
1100 instead, one has to accept a lower y_{max} as below a few GeV of energy the background is too high for a
1101 reliable measurement to be performed. The results of both F_L simulations, with reduced E_e or E_p , come
1102 out to be very similar.

1103 The result of the simulation study is shown in Fig. 4.7. The technique applied is the conventional separa-
1104 tion of F_2 and F_L by fitting a straight line to the various reduced cross section data points at fixed Q^2 and
1105 x with $f(y)$ as the parameter and separating the uncorrelated from the correlated systematic uncertainties
1106 which partially cancel in such an analysis. The expected accuracy on F_L is typically 4% at Q^2 of 3.5 GeV^2
1107 or 7% at Q^2 of 25 GeV^2 at a number of points in x , with mainly similar contributions from the calculated
1108 correlated and the assumed uncorrelated systematic uncertainties, and less due to statistics which yet starts
1109 to become important for $Q^2 \geq 100 \text{ GeV}^2$. The LHeC thus will provide the first precision measurement of
1110 $F_L(x, Q^2)$ ever, in a region where the behaviour of the gluon density ought to change significantly and new,
1111 non-linear laws for parton evolution should emerge.

1112 A related measurement of prime interest is the determination of F_L in diffraction, as is discussed below.
1113 A pioneering measurement of F_L^D has been performed by H1 (-cite when published in July-).

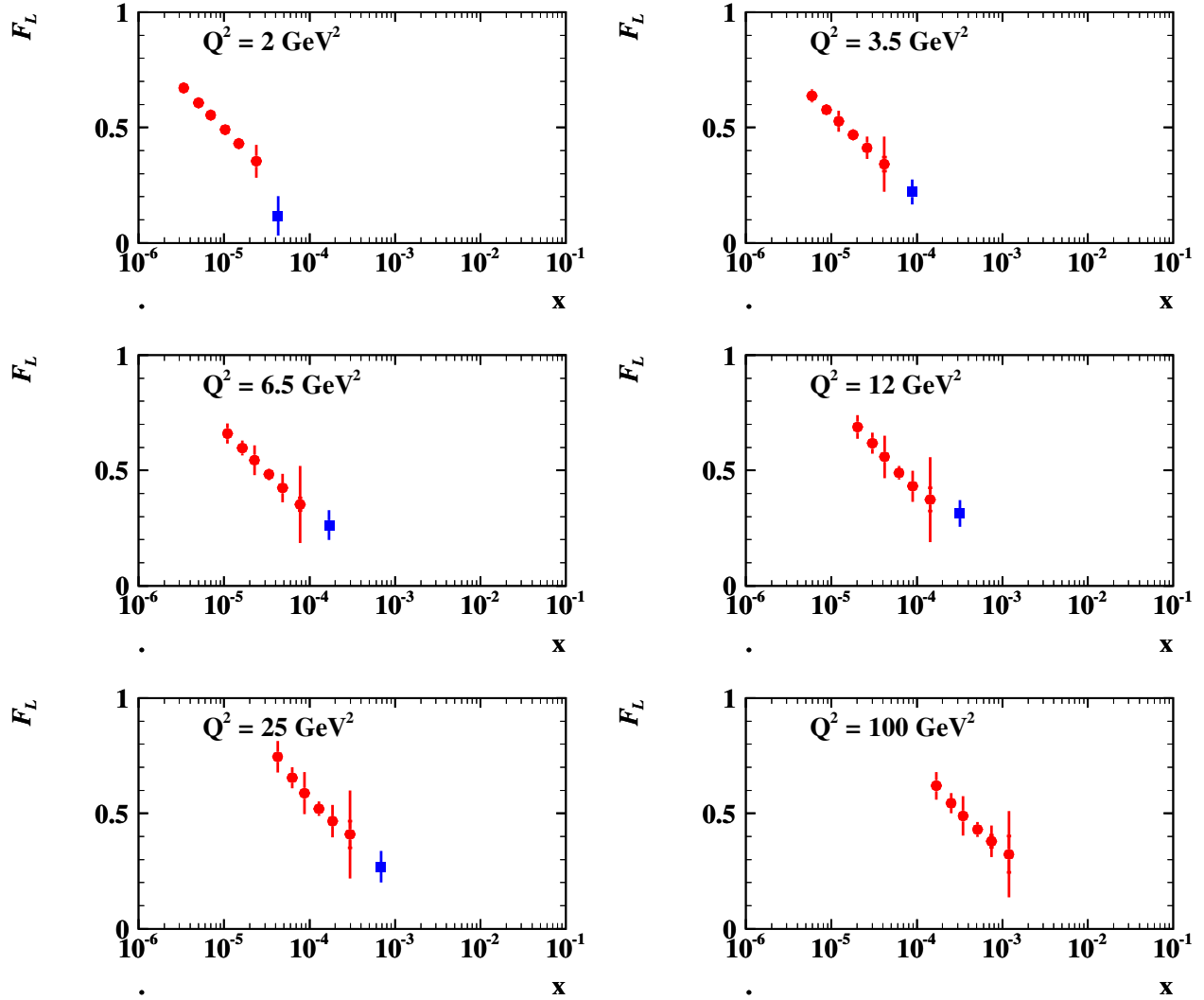


Figure 4.7: Simulated measurement of the longitudinal structure function $F_L(x, Q^2)$ at the LHeC (red closed circles) from a series of runs with reduced electron beam energy, see text. The inner error bars denote the statistical uncertainty, the outer error bars are the total errors with the additional uncorrelated and correlated systematic uncertainties added in quadrature. The blue squares denote the recently published result of the H1 Collaboration, plotting only the x averaged results as the more accurate ones, see [68]. The LHeC extends the measurement towards low x and high Q^2 (not fully illustrated here) with much improved precision.

1114 4.2 Determination of Parton Distributions

1115 Despite a series of deep inelastic scattering experiments with neutrinos, electrons and muons using stationary
 1116 targets and with HERA, despite the addition of some Drell Yan data, the knowledge of the quark distributions
 1117 in the proton is still limited. It often relies on pQCD analyses using various assumptions on the Bjorken
 1118 x dependence of the PDFs and their symmetries. The LHeC has the potential to put the PDF knowledge
 1119 on a qualitatively and quantitatively new and superior basis. This is due to the kinematic range, huge
 1120 luminosity, availability of polarised electron and positron beams, as of proton and deuteron beams, and to
 1121 the anticipated very high precision of the cross section measurements as has been discussed above.

1122 The LHeC has the potential to provide crucial constraints and many determinations of parton distri-
 1123 butions completely or rather independently of the conventional QCD fitting techniques. For example, the
 1124 valence quarks can be measured up to high x , and all heavy quarks be determined from dedicated c and b
 1125 tagging analyses with unprecedented precision. Therefore, the then evolving QCD fits based on real LHeC
 1126 data will be set-up with a massively improved and better constrained input data base. Their eventual effect
 1127 is thus not easy to simulate now, it yet may be illustrated based on the currently used procedures.

1128 The striking potential of the determination of the quark and gluon distributions will be discussed and
 1129 illustrated below. For the various PDFs, the current knowledge is illustrated with a series of plots based
 1130 on the world's best PDF determinations available today. Simulations of essentially direct quark distribution
 1131 measurements, as for the charm quark, will be shown. Moreover, a consistent set of standard QCD fits has
 1132 been performed using the simulated LHeC and further data which is first described in what follows. This is
 1133 used to illustrate the effect the inclusive NC and CC data from the LHeC are expected to have on the PDF
 1134 uncertainties.

1135 Currently extensive work is being performed to test and further constrain PDFs with Drell-Yan scattering
 1136 data from the LHC. This naturally focusses on the Z and W^\pm production and decay. While such tests are
 1137 undoubtedly of interest, they require an extremely high level of precision as at scales $Q^2 \simeq M_{W,Z}^2$ any
 1138 effect due to PDF differences at smaller scales is washed out by the overriding effect of quark-antiquark pair
 1139 production from gluon emission, below the valence quark region. The present QCD fit results also use a set
 1140 of simulated $W^+ - W^-$ asymmetry data of ultimate precision in order to be able to estimate the effect the
 1141 Drell-Yan data will have besides the LHeC in the determination of the PDF's.

1142 4.2.1 QCD Fit Ansatz

1143 NLO QCD fits are performed in order to study the effect of the (simulated) LHeC data on the PDF knowledge.
 1144 Fits are done using the combined HERA data published and so available todate (HERA I), adding BCDMS
 1145 proton data as the most accurate fixed target structure function set of importance at high x , simulated
 1146 precision $W^+ - W^-$ asymmetry LHC data, using the LHeC data alone and in combination. In the fits, for the
 1147 central values of the LHeC data, the Standard Model expectation is used, smeared within the uncorrelated,
 1148 Gaussian distributed uncertainties and taking into account the correlated uncertainties as well.

1149 The procedure used here is adopted from the HERA QCD fit analysis [38]. The QCD fit analysis to extract
 1150 the proton's PDFs is performed imposing a $Q_{min}^2 = 3.5 \text{ GeV}^2$ to restrain to the region where perturbative
 1151 QCD can be assumed to be valid. The fits are extended to lowest x for systematic uncertainty studies, even
 1152 when at such low x values non-linear effects are expected to appear.

1153 The fit procedure consists first in parametrising PDFs at a starting scale $Q_0^2 = 1.9 \text{ GeV}^2$, chosen to
 1154 be below the charm mass threshold. The parametrised PDFs are the valence distributions xu_v and xd_v ,
 1155 the gluon distribution xg , and the $x\bar{U}$ and $x\bar{D}$ distributions, where $x\bar{U} = x\bar{u}$, $x\bar{D} = x\bar{d} + x\bar{s}$. This ansatz
 1156 is natural to the extent that the NC and CC inclusive cross sections determine the sums of up and down
 1157 quark distributions, and their antiquark distributions, as the four independent sets of PDFs, which may be
 1158 transformed to the ones chosen if one assumes $u_v = U - \bar{U}$ and $d_v = D - \bar{D}$, i.e. the equality of anti- and
 1159 sea quark distributions of given flavour.

1160 The following standard functional form is used to parameterise them

$$xf(x) = Ax^B(1-x)^C(1+Dx+Ex^2), \quad (4.24)$$

1161 where the normalisation parameters (A_{uv}, A_{dv}, A_g) are constrained by quark counting and momentum sum
 1162 rules.

1163 The parameters $B_{\bar{U}}$ and $B_{\bar{D}}$ are set equal, $B_{\bar{U}} = B_{\bar{D}}$, such that there is a single B parameter for
 1164 the sea distributions, an assumption the validity of which will be settled with the LHeC. The strange quark
 1165 distribution at the starting scale is assumed to be a constant fraction of \bar{D} , $x\bar{s} = f_s x\bar{D}$, chosen to be $f_s = 0.31$.
 1166 In addition, to ensure that $x\bar{u} \rightarrow x\bar{d}$ as $x \rightarrow 0$, $A_{\bar{U}} = A_{\bar{D}}(1 - f_s)$. The D and E are introduced one by
 1167 one until no further improvement in χ^2 is found. The best fit resulted in a total of 10 free parameters [38],
 1168 while fits with a tested set of 14 parameters lead to very similar results. As discussed above this will change
 1169 considerably when the LHeC data become available and more flexible parameterisations and methods can
 1170 be tested. This has been studied to some extent in the simulation for α_s presented below.

1171 The PDFs are then evolved using DGLAP evolution equations [69] at NLO in the \overline{MS} scheme with the
 1172 renormalisation and factorisation scales set to Q^2 using standard sets of parameters as for $\alpha_s(M_Z)$. These,
 1173 as well as the exact treatment of the heavy quark thresholds, are of no significant influence for the estimates
 1174 of the PDF uncertainties to which the subsequent analysis is only directed. The experimental uncertainties
 1175 on the PDFs are determined using the $\Delta\chi^2 = 1$ criterion.

1176 4.2.2 Valence Quarks

1177 The knowledge of the valence quark distributions, both at large and at low Bjorken x , as derived in the
 1178 current world data QCD fit analyses is amazingly limited, as is illustrated in Fig. 4.8 from a comparison of
 1179 the leading determinations of PDF sets. This has to do, at high x , with the limited luminosity, challenging
 1180 systematics rising $\propto 1/(1-x)$ and nuclear correction uncertainties, and, at low x , with the smallness of the
 valence quark distributions as compared to the sea quarks. The impressive improvement expected from the

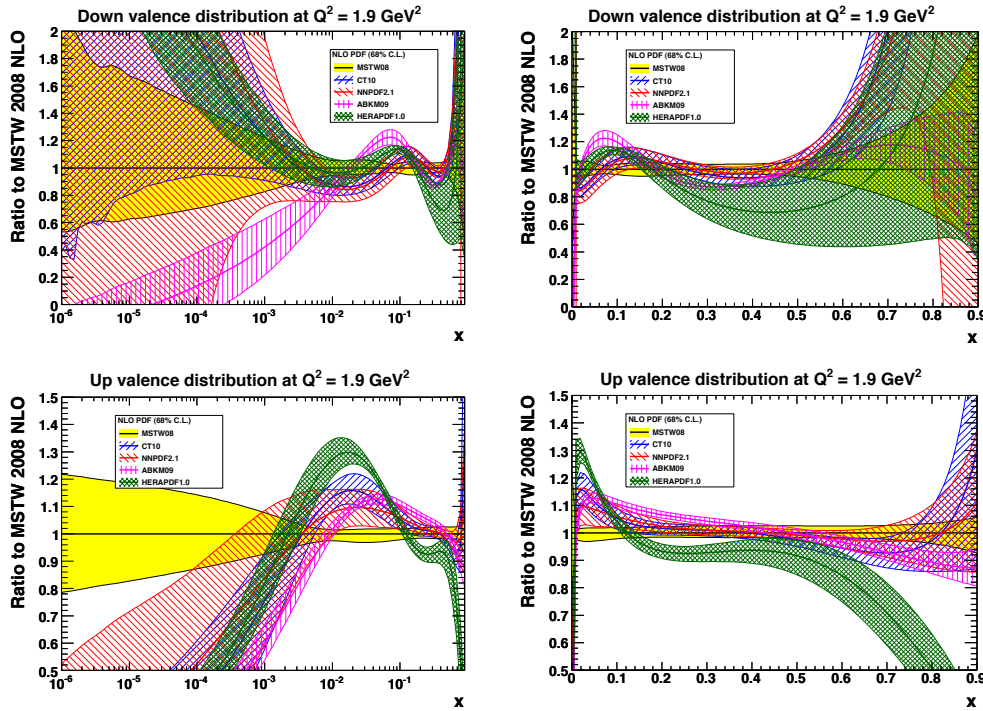


Figure 4.8: Ratios (to MSTW08) and uncertainty bands of valence quark distributions, at $Q^2 = 1.9 \text{ GeV}^2$, for most of the available recent PDF determinations. Top: up valence quark; down: down valence quark; left: logarithmic x , right: linear x .

1181 LHeC is demonstrated in Fig. 4.9. As can be seen, the uncertainty of the down valence quark distribution at,
 1182

1183 for example, $x = 0.7$ is reduced from a level of 50 – 100 % to about 5 %. The up valence quark distribution is
 1184 better known than d_v , because it enters with a four-fold weight in F_2 , due to the electric quark charge ratio
 1185 squared, a big improvement yet is also visible. These huge improvement effects at large x are a consequence
 1186 of the high precision measurements of the NC and the CC inclusive cross sections, which at high x tend to
 1187 $4u_v + d_v$ and u_v (d_v) for electron (positron) scattering, respectively. At HERA the luminosity and range had
 1188 not been high enough to allow a similar measurement as will be possible for the first time with the LHeC.
 1189 This is illustrated in Fig. 4.10 which compares recent results of the ZEUS Collaboration, on the CC cross
 section with the LHeC simulation.

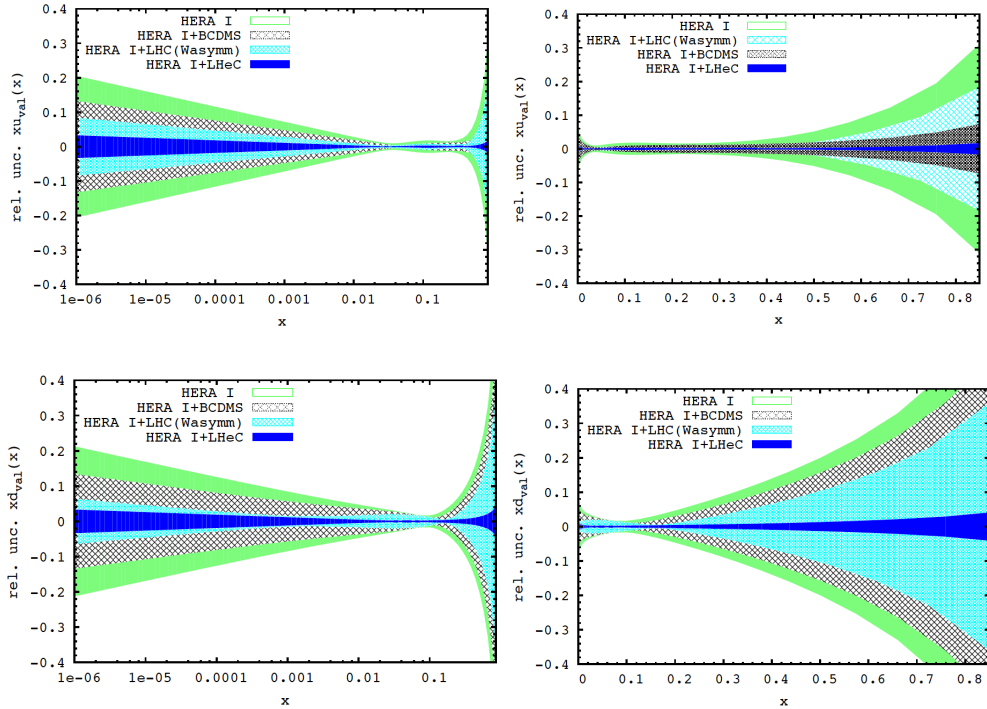


Figure 4.9: Uncertainty of valence quark distributions, at $Q^2 = 1.9 \text{ GeV}^2$, as resulting from an NLO QCD fit to HERA (I) alone (green, outer), HERA and BCDMS (crossed), HERA and LHC (light blue, crossed) and the LHeC added (blue, dark). Top: up valence quark; down: down valence quark; left: logarithmic x , right: linear x .

1190

1191 Access to valence quarks at low x can be obtained from the $e^\pm p$ cross section difference as introduced
 1192 above:

$$\sigma_{r,NC}^- - \sigma_{r,NC}^+ = 2 \frac{Y_-}{Y_+} (-a_e \cdot k x F_3^{\gamma Z} + 2v_e a_e \cdot k^2 x F_3^Z). \quad (4.25)$$

1193 Since the electron vector coupling, v_e , is small and k not much exceeding 1, to a very good approximation the
 1194 cross section difference is equal to $-2kY_- a_e x F_3^{\gamma Z} / Y_+$. In leading order pQCD this “interference structure
 1195 function” can be written as

$$x F_3^{\gamma Z} = 2x [e_u a_u (U - \bar{U}) + e_d a_d (D - \bar{D})], \quad (4.26)$$

1196 with $U = u + c$ and $D = d + s$ for four flavours. The $x F_3^{\gamma Z}$ structure function thus provides information
 1197 about the light-quark axial vector couplings (a_u , a_d) and the sign of the electric quark charges (e_u , e_d).
 1198 Equivalently one can write

$$x F_3^{\gamma Z} = 2x [e_u a_u (u_v + \Delta_u) + e_d a_d (d_v + \Delta_d)]. \quad (4.27)$$

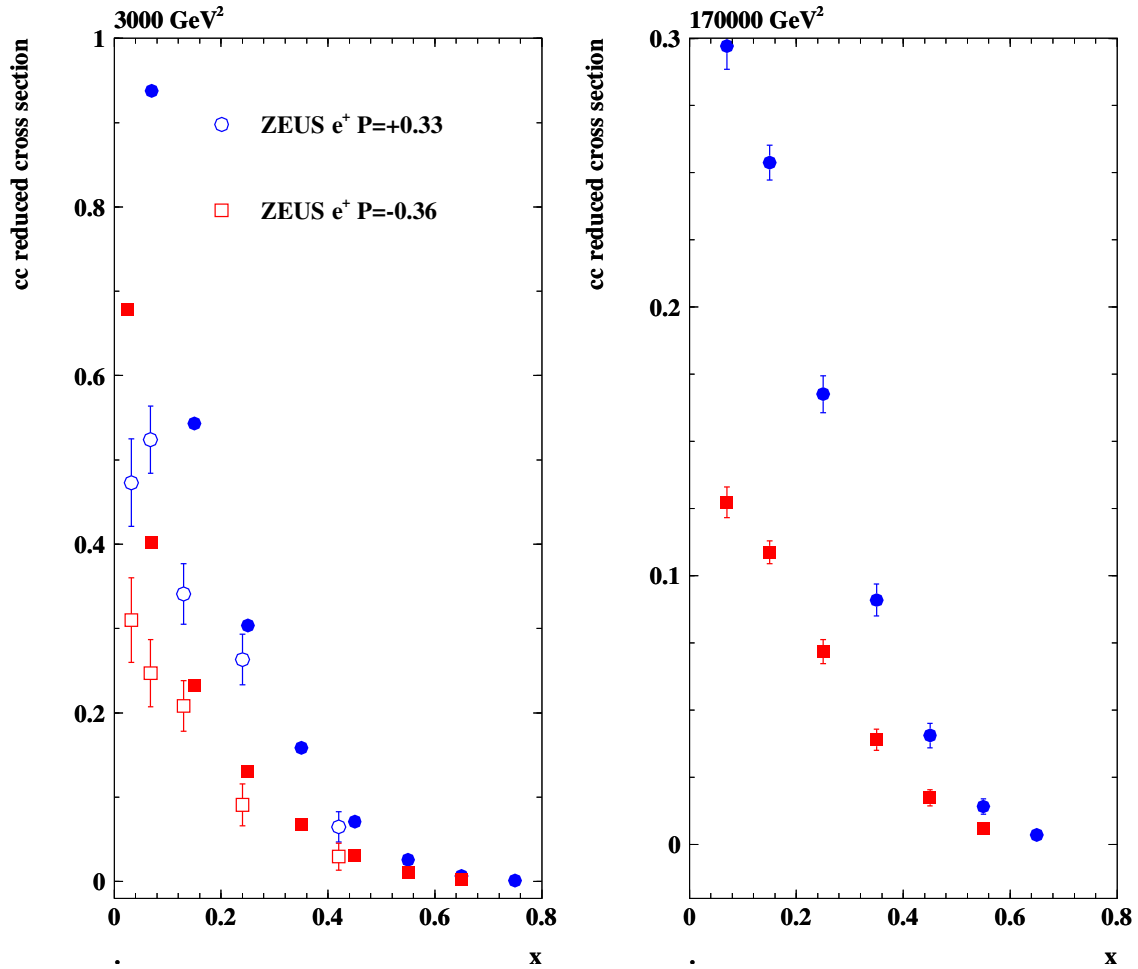


Figure 4.10: Reduced charged current e^+p scattering cross section versus Bjorken x for different polarisations $\pm P$ and values of Q^2 . Closed points: LHeC simulations for 10 fb^{-1} ; open points: ZEUS measurements based on the full HERA statistics of about 0.15 fb^{-1} per polarisation state. Note that the reduced CC cross section at fixed x and Q^2 contains an explicit dependence on the beam energy via the ratio of inelasticity dependent factors Y_-/Y_+ , which is at the origin of the simulated and measured cross section differences apparent at lower x .

1199 In the naive parton model as in conventional perturbative QCD, it is assumed that the differences $\Delta_u =$
 1200 $(u_{sea} - \bar{u} + c - \bar{c})$ and $\Delta_d = (d_{sea} - \bar{d} + s - \bar{s})$ are zero ². Inserting the SM charge and axial coupling values
 1201 one finds

$$xF_3^{\gamma Z} = \frac{x}{3}(2u_v + d_v + \Delta) \quad (4.28)$$

1202 with $\Delta = 2\Delta_u + \Delta_d$. Neglect of Δ leads to a sum rule [70], which in leading order is

$$\int_0^1 xF_3^{\gamma Z} \frac{dx}{x} = \frac{1}{3} \int_0^1 (2u_v + d_v) dx = \frac{5}{3}. \quad (4.29)$$

1203 The $xF_3^{\gamma Z}$ structure function thus is determined by the valence quark distributions and predicted to be only
 1204 very weakly depending on Q^2 . Fig. 4.11 shows a simulation of $xF_3^{\gamma Z}$ and its comparison with the so far most
 1205 accurate measurement from HERA. With such a high precision interesting tests are possible of the relation
 1206 of $xF_3^{\gamma Z}$ to xW_3 , which should only differ by the weak couplings involved in NC and CC.

1207 4.2.3 Strange Quarks

1208 The strange quark distribution $s(x, Q^2)$ has been very difficult to measure. In DIS some information is
 1209 obtained from di-muon production in neutrino-nucleon scattering. Often s is linked to the behaviour of the
 1210 sea quarks. Recently the HERMES Collaboration, from kaon multiplicities, derived an unusual behaviour of
 1211 the strange quark density as compared to previous analyses [71]. Some hints for a difference between the s
 1212 and \bar{s} distributions have been discussed. The existing information on the sum of the strange and anti-strange
 1213 quark distributions is plotted in Fig. 4.12. Obviously there is no real understanding of the strange quark
 1214 distribution in the proton available. This will change with the LHeC. Here s and \bar{s} may be very well measured
 1215 as a function of x and Q^2 from the $W^+s \rightarrow c$ and $W^-\bar{s} \rightarrow \bar{c}$ processes, i.e. with charmed quark tagging
 1216 in CC DIS using electron and positron beams, respectively. The precision for s which may be obtained is
 1217 illustrated in Fig. 4.13. Accurate measurements may be obtained for the first time ever. The simulation of
 1218 \bar{s} obviously leads to the same picture such that over a wide kinematic range possible differences between s
 1219 and \bar{s} may be established.

1220 4.2.4 Top Quarks

1221 The top is the heaviest of the quarks. It decays before hadrons are formed. It has not been explored in
 1222 DIS yet because the cross sections at HERA have been too small [72]. This is different at the LHeC where
 1223 top in charged currents is produced with a cross section of order 5 pb as can easily be estimated from the
 1224 LO calculation of Wb scattering. At the LHeC therefore, for the first time, one can study top quarks in
 1225 deep inelastic scattering. Positron (electron) proton charged current scattering provides a clear distinction
 1226 between top (anti-top) quark production in Wb to t fusion. The rates of this process are very high, as is
 1227 illustrated as a function of Q^2 in Fig. 4.14. Besides the rates and the charge tag it is notable that the
 1228 absence of pile-up and underlying event effects, characteristic for LHC measurements, provide comfortable
 1229 conditions for top quark physics at the LHeC.

1230 Due to its large mass, the top quark may very well play a role in the mechanism of electroweak symmetry
 1231 breaking (EWSB) both in the Standard Model as well as BSM physics. In the Standard Model, a precise
 1232 measurement of single top production in DIS (see for example [73]) is sensitive to the b quark content of
 1233 the proton. In a BSM EWSB scenario, the top quark will couple to the new physics sector and give rise to
 1234 anomalous production modes. The LHeC is expected to provide competitive sensitivity to flavor changing
 1235 neutral currents (FCNC) especially anomalous $tu\gamma$ and tuZ couplings.

1236 In the SM, top is produced dominantly in gluon-boson fusion at $x \lesssim 0.1$. In CC this leads to a top-beauty
 1237 final state while in NC this gives rise to pair produced top-antitop quarks, with a cross section of order 10

²However, in non-perturbative QCD there may occur differences, for example between the strange and anti-strange quark distributions, for which there are some hints in DIS neutrino nucleon di-muon data and corresponding QCD fit analyses, see below.

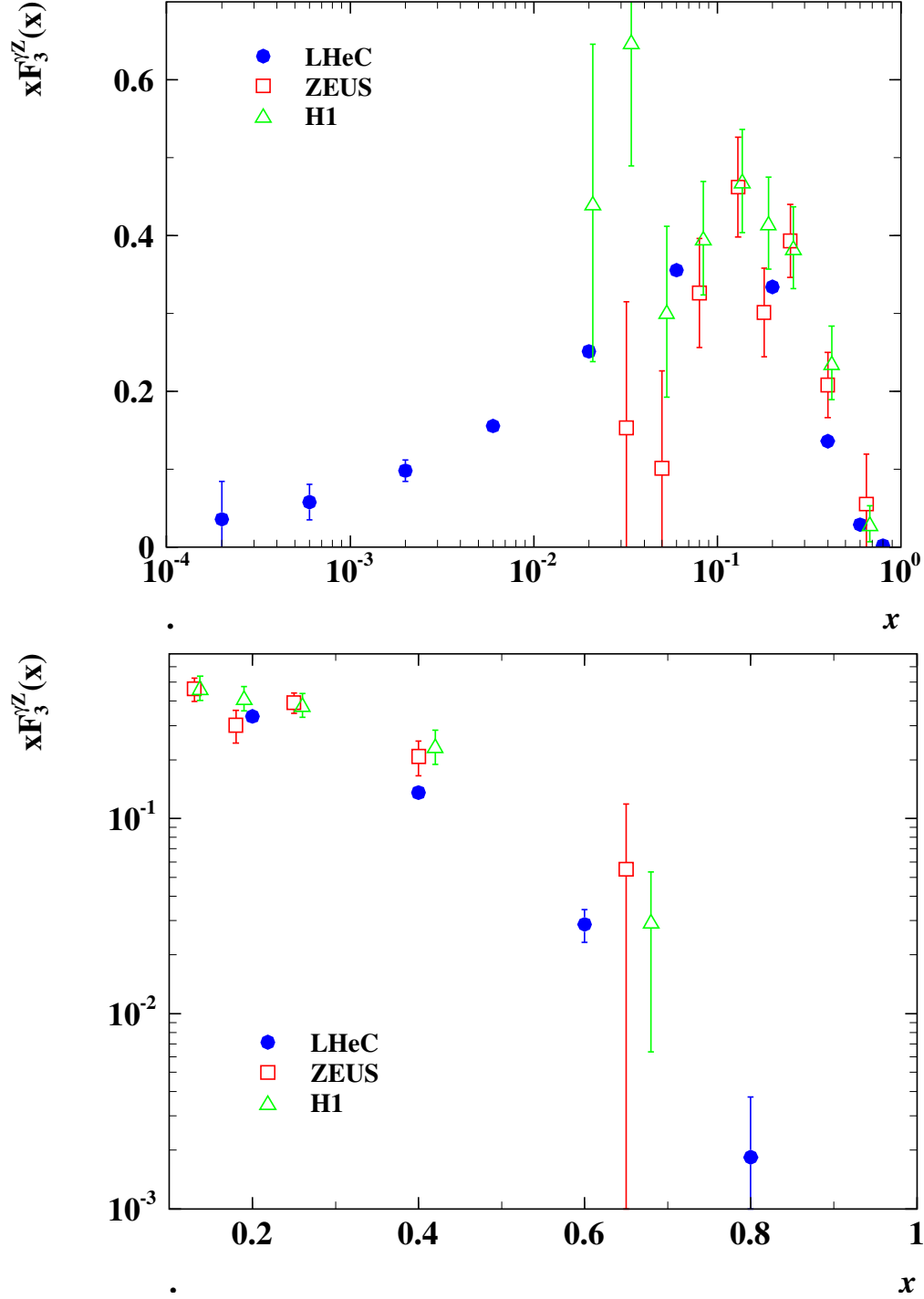


Figure 4.11: Simulation of the LHeC measurement of the interference structure function $xF_3^{\gamma^Z}$ from unpolarised $e^\pm p$ scattering with 10fb^{-1} luminosity per beam (blue, closed points) compared with the HERA II data as obtained by H1 (preliminary, green triangles) and by ZEUS (red squares) with about 0.15fb^{-1} luminosity per beam charge. The H1 x values are enlarged by 10% of their given values for clarity. One should notice that any significant deviation of sea from anti-quarks, see Eq. 4.27, would cause $xF_3^{\gamma^Z}$ at low x to not tend to zero. The top plot shows an average of $xF_3^{\gamma^Z}$ over Q^2 projected to a chosen Q^2 value of 1500GeV^2 exploiting the fact that the valence quarks are approximately independent of Q^2 . The lower plot is a zoom into the high x region.

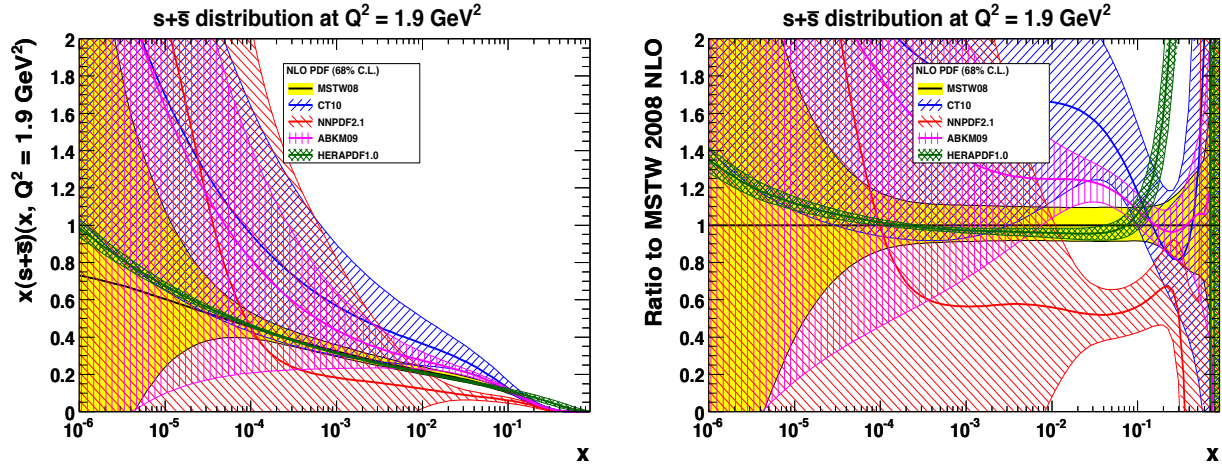


Figure 4.12: Sum of the strange and anti-strange quark distribution as embedded in the NLO QCD fit sets as noted in the legend. Left: $s + \bar{s}$ versus Bjorken x at $Q^2 = 1.9 \text{ GeV}^2$; right: ratio of $s + \bar{s}$ of various PDF determinations to MSTW08. In the HERAPDF1.0 analysis (green) the strange quark distribution is assumed to be a fixed fraction of the down quark distribution which is conventionally assumed to have the same low x behaviour as the up quark distribution, which results in a small uncertainty of $s + \bar{s}$.

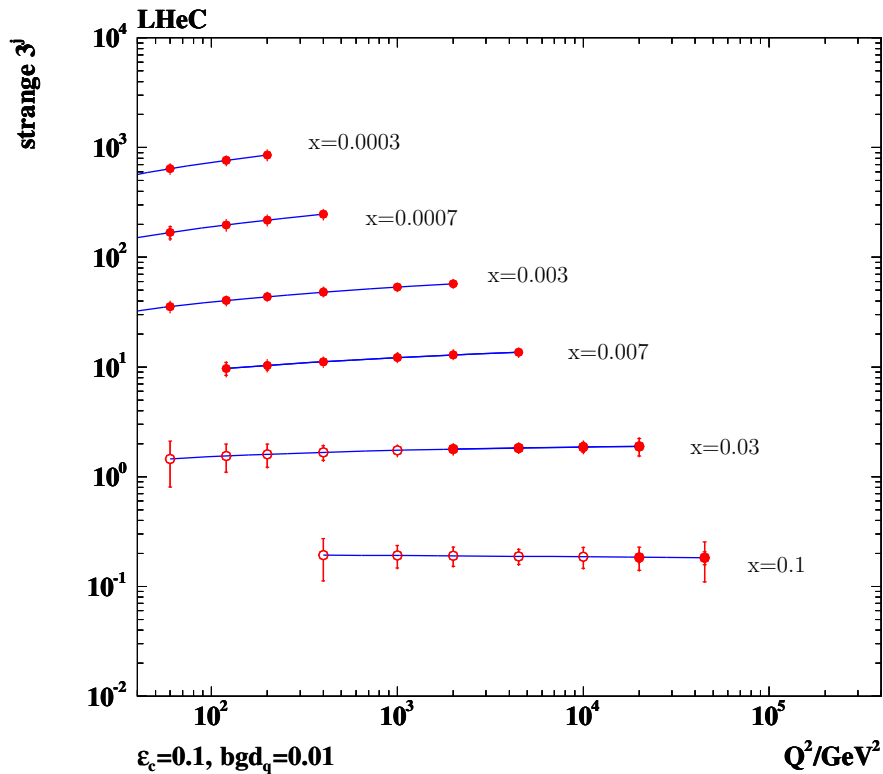


Figure 4.13: Simulated measurement of the strange quark density with the LHeC. Closed (open) points: tagging acceptance down to 10° (1°).

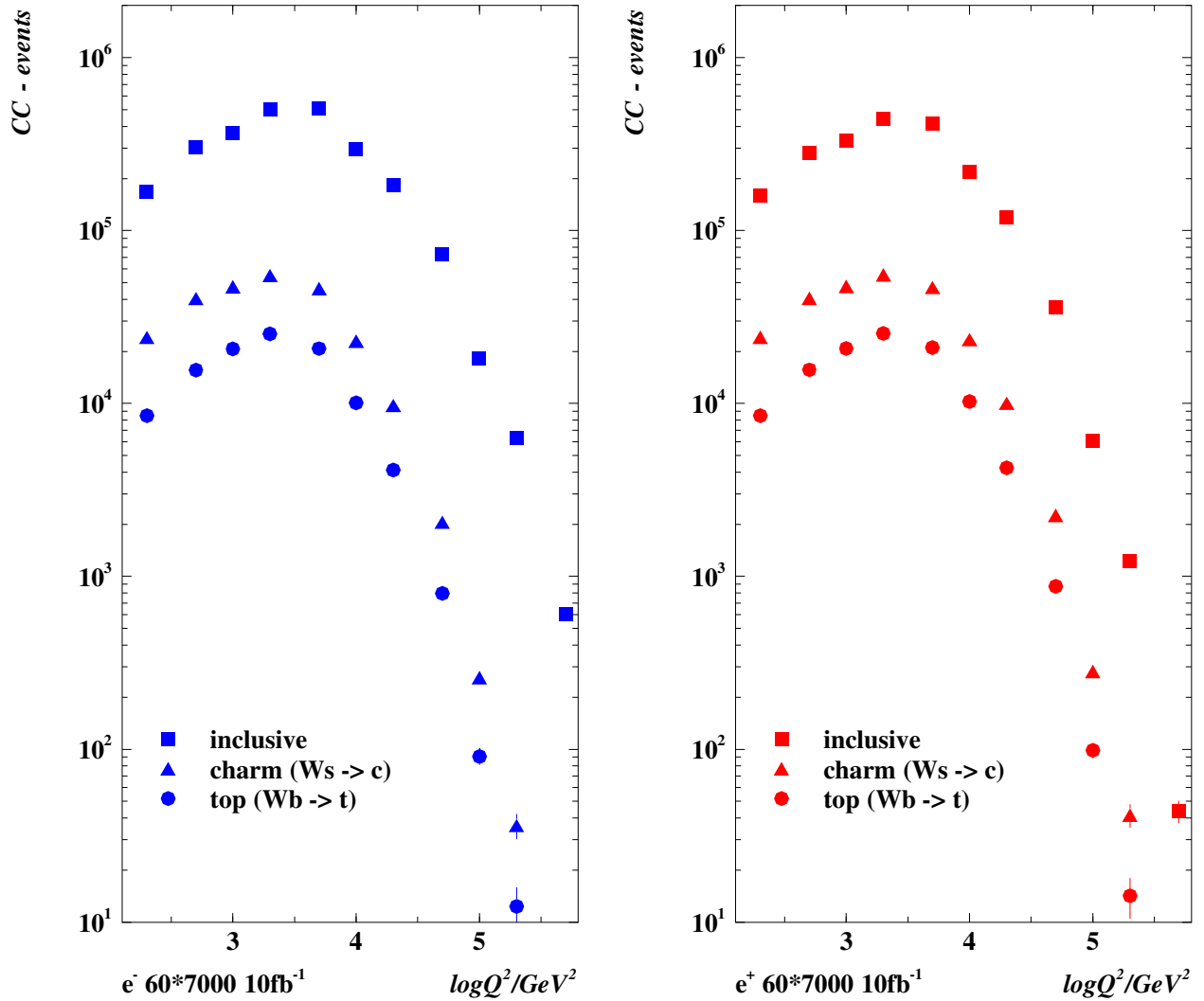


Figure 4.14: Charged current event rates for unpolarised e^-p (left) and e^+p (right) scattering in which \bar{t} and t is produced, respectively. Squares: inclusive CC rate vs. Q^2 ; triangles: charm production from W_s fusion; closed circles: top production from W_b fusion, estimated in a massless heavy flavour treatment. The rates are calculated for the default beam energies for 10 fb^{-1} of integrated luminosity. The errors are only statistical.

1238 times lower than in CC [72]. The electron beam charge distinguishes top and anti-top quark production in
 1239 CC. Thus a unique SM top physics program can be performed at the LHeC. This includes the consideration
 1240 of a top-quark density which at very high scales may be considered “light”. Recently a six-flavour variable
 1241 number scheme has been proposed [74], limited so far to leading order, in which it is predicted that the
 1242 top contribution to proton structure has an on-set much below the threshold of its production in a massless
 1243 scheme. This is illustrated in Fig. 4.15. Due to the very high Q^2 and statistics, the LHeC opens top quark
 PDF physics as a new field of research.

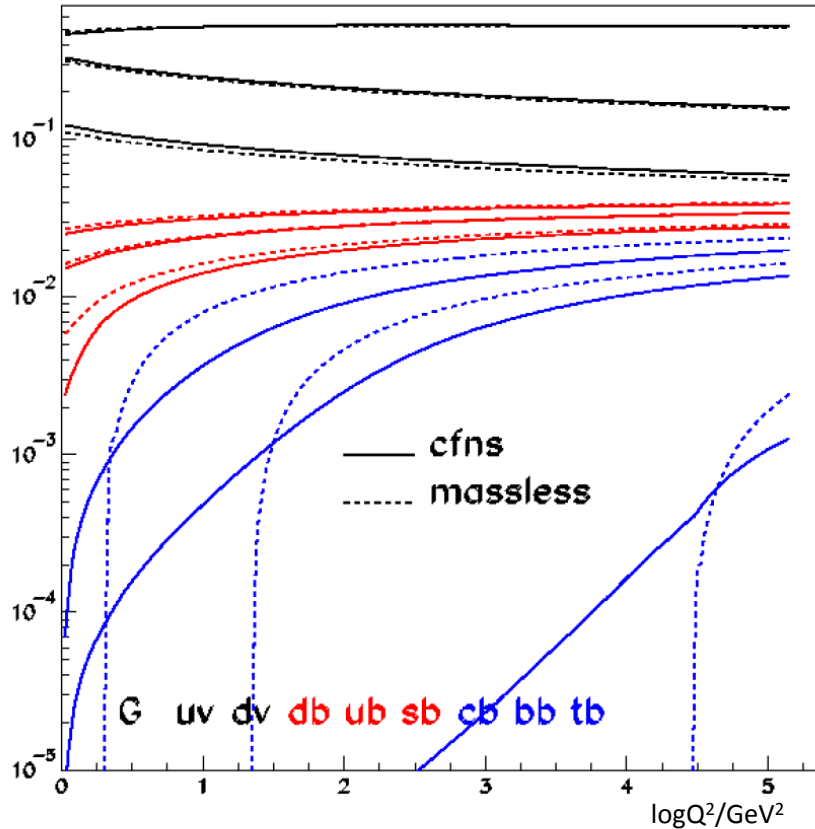


Figure 4.15: Parton momentum fractions as a function of Q^2 in a novel six-flavour variable number scheme (CFNS), solid curves, and in the massless scheme, dashed curves. At HERA one has observed beauty and charm production already below the conventional threshold of $\sqrt{Q^2} = m_Q$. The scheme of [74] suggests that there is a very early onset of top with measurable rates already at Q^2 values of only about one tenth of $m_t^2 \simeq 3 \cdot 10^4 \text{ GeV}^2$. With the LHeC the 'PDF' top physics is expected to commence.

1244

1245 Top, including anomalous couplings, has been considered for the CDR initially [75], based on some
 1246 ANOTOP and PYTHIA studies at generation level. With a detector now simulated in GEANT4 and in
 1247 the light of the first top results provided by the LHC experiments [76], as well as further prospects, the CC
 1248 and NC top physics at the LHeC deserves a more detailed study. This shall include an analysis about the
 1249 possible precision measurement of the top (and anti) top quark mass, which at the LHC may be determined
 1250 with an accuracy of 1 GeV and possibly be better in *ep*. Independently of whether one soon finds the SM
 1251 Higgs particle or it remains elusive, a high precision measurement of m_t is of prime importance.

4.3 Gluon Distribution

There are many fundamental reasons to understand the gluon distribution and the gluon interactions deeper than hitherto. Half of proton’s momentum is carried by gluons. Gluon self-interaction is responsible for the creation of baryonic mass. The Higgs particle, should it exist, is predominantly produced by gluon-gluon interactions. The rise of the gluon density towards low Bjorken x must be tamed for unitarity reasons: there is a new phase of hadronic matter to be discovered, in which gluons interact non-linearly while α_s is smaller than 1.

The LHeC, with precision and range of the most appropriate process (DIS) to explore $xg(x, Q^2)$, will pin down the gluon distribution much more accurately than could be done before. This primarily comes from the extension of range and precision in the measurement of $\partial F_2/\partial \ln Q^2$ which at small x is a measure of xg . The inclusive NC and CC measurements together provide a fully constrained data base for the determination of the quark distributions, which strongly constrains xg . The addition of precision measurements of F_L , discussed above and used in the small x chapter of this document, will unravel the saturating behaviour of xg . High precision measurements of boson-gluon fusion to heavy quark pairs will provide a complementary basis for understanding the gluon and its parton interactions.

The peculiarity of the gluon density is that it is defined and observable only in the context of a theory. Moreover, a crude data base and correspondingly rough fit ansatz can screen local deviations from an otherwise preferred smooth behaviour. It has yet not been settled whether there are gluonic “hot” spots in the proton or not. An example for possible surprises is provided by the analysis [49], in which Chebyshev polynomials have been used to parameterise the parton distributions in contrast to more conventional forms as in Eq. 4.24. Inspection of the gluon distribution obtained there reveals that it seems to be vanishing at $x \simeq 0.2$, i.e. at the point, in which scaling holds for $F_2(x, Q^2)$, which one might term a “cool” spot in the proton. Much more is still to be learned about the gluon, even when one is disregarding the yet to be explored role of the gluon in the theory of generalised and of unintegrated parton distributions.

The current knowledge of the gluon distribution in the proton is astonishingly limited as becomes clear from Fig. 4.16 showing the world determinations, and their uncertainties, of $xg(x, Q^2)$ at a typical initial, low scale, and from Fig. 4.17 expressing this information with ratios to one of the PDF sets. At low x and Q^2 most but not all of the PDF sets predict xg to be of valence like type with very large uncertainties for x below a few times 10^{-4} . At large x inclusive DIS has difficulties to pin down xg because the evolution of valence quarks as non-singlet quantities in QCD is not directly coupled to the gluon and very weak. Yet, even the information from jets, used in some of the PDF sets, does not lead to a clear understanding of xg at large x as is illustrated too. In fact, there is a tendency of obtaining a smaller xg at large x from HERA (I) data alone, see Fig. 4.16, as compared to the other determinations, albeit with large uncertainties.

The determination of xg is predicted to be radically improved with the LHeC precision data which extend up to lowest x near to 10^{-6} and large $x \geq 0.7$. The result of the QCD fit analysis for xg as described above in Sect. 4.2.1 is shown in Fig. 4.18. One observes a dramatic improvement at low x , as must be expected from the extension of the kinematic range, but also at high x , as is attributed to the high x precision measurements of the NC and CC cross sections. At $x = 0.7$, for example, the predicted experimental uncertainty of xg is 5%, which is about ten times more accurate than the results of MSTW08 or of the HERA fit indicate.

It is worth noting that the uncertainties considered here are restricted to those related to the genuine cross section measurement errors. There are further uncertainties, as discussed e.g. in [38], related to the difficulty of parameterising the PDFs and choosing the optimum solution in such a fit analysis. These will be also considerably reduced with the LHeC extended data base. Moreover, this analysis is not making use of the plethora of extra information on xg , which the LHeC will provide with F_L , $F_2^{c,b}$ and jet cross section measurements. The understanding of the gluon and its interactions is a primary task of the LHeC and undoubtedly a new horizon in strong interaction physics will be opened.

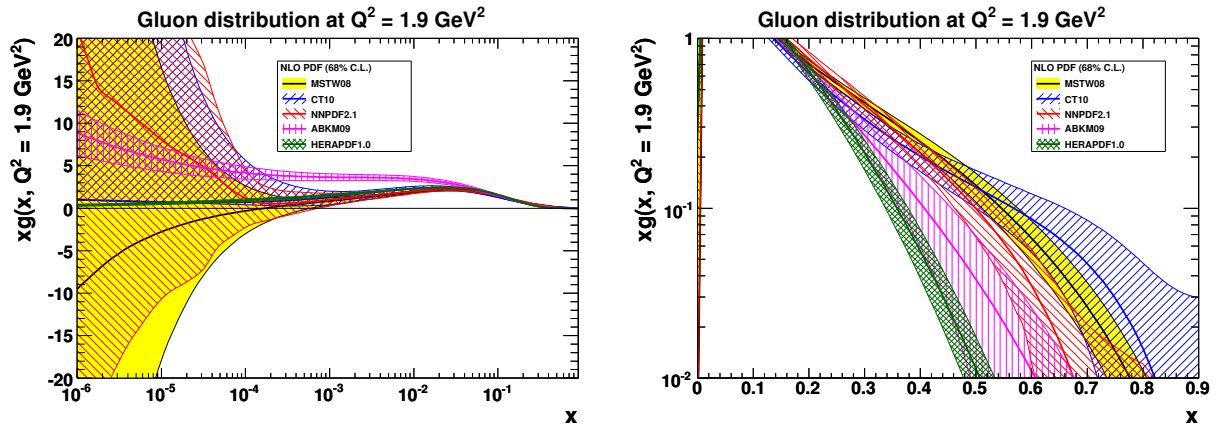


Figure 4.16: Gluon distribution and uncertainty bands, at $Q^2 = 1.9 \text{ GeV}^2$, for most of the available recent PDF determinations. Left: logarithmic x , right: linear x .

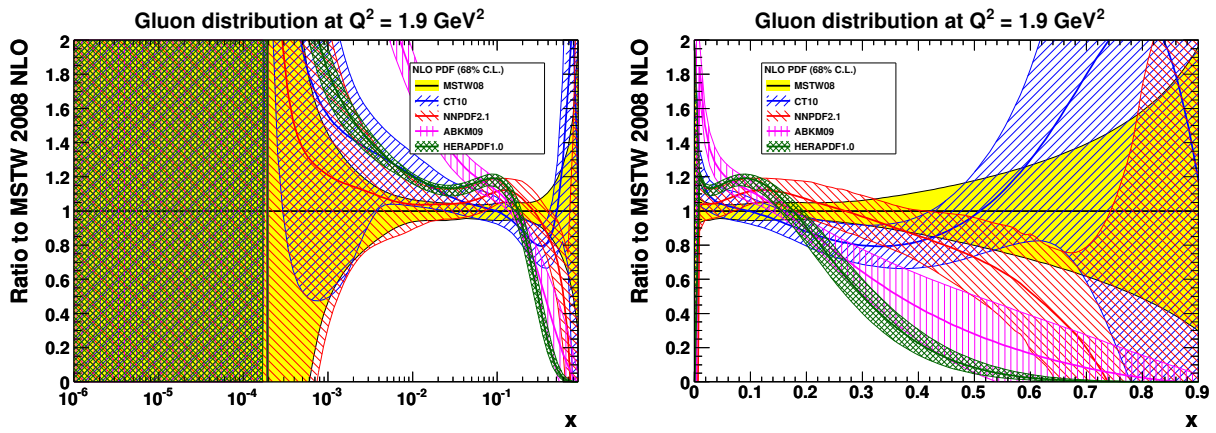


Figure 4.17: Ratios to MSTW08 of gluon distribution and uncertainty bands, at $Q^2 = 1.9 \text{ GeV}^2$, for most of the available recent PDF determinations. Left: logarithmic x , right: linear x .

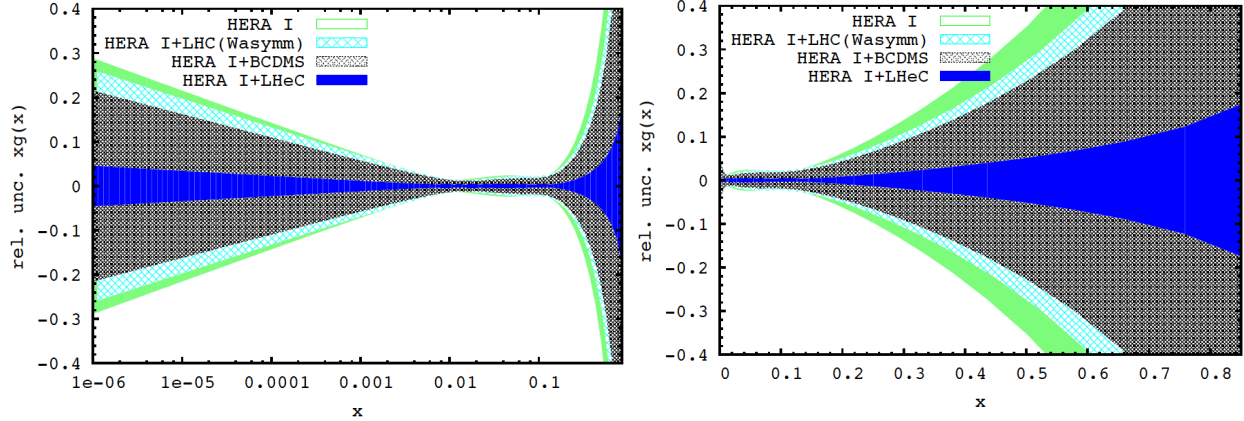


Figure 4.18: Relative uncertainty of the gluon distribution at $Q^2 = 1.9 \text{ GeV}^2$, as resulting from an NLO QCD fit to HERA (I) alone (green, outer), HERA and BCDMS (crossed), HERA and LHC (light blue, crossed) and the LHeC added (blue, dark). Left: logarithmic x , right: linear x .

1298 4.4 Prospects to Measure the Strong Coupling Constant

1299 The precise knowledge of $\alpha_s(M_Z^2)$ is of instrumental importance for the correct prediction of the electro-
 1300 weak gauge boson production cross sections and the Higgs boson cross section at Tevatron and the LHC
 1301 [77]. Independently of such applications, the accurate determination of the coupling constants of the known
 1302 fundamental forces is of importance in the search for their possible unification within a more fundamental
 1303 theory. Among the coupling constants of the forces in the Standard Model, the strong coupling α_s exhibits
 1304 the largest uncertainty, which is currently of the size of $\sim 1\%$. Any future improvement of this accuracy, along
 1305 with the consolidation of the genuine central value, is one of the central issues of contemporary elementary
 1306 particle physics. It demands deep experimental and theoretical efforts to obtain the required precision and
 1307 especially to handle all essential systematic effects.

1308 Experimentation at the LHeC will allow to measure the strong coupling constant $\alpha_s(M_Z^2)$ at much higher
 1309 precision than hitherto, both from the scaling violations of the deep inelastic structure functions, as will be
 1310 demonstrated below, and using ep multiple jet cross sections. For the final inclusion of jet data in global
 1311 pdf analyses, both from ep and from hadron colliders, their description at NNLO is required. At the LHeC,
 1312 similar to HERA, the measurement of the ep jet cross sections will form important data samples ³ for the
 1313 measurement of $\alpha_s(M_Z^2)$.

1314 Subsequently, a brief account will be given on the status and the complexity of determining α_s in DIS,
 1315 followed by a presentation of the study of the α_s measurement uncertainty with the inclusive NC and CC
 1316 data from the LHeC.

1317 4.4.1 Status of the DIS Measurements of α_s

1318 During the last 35 years the strong coupling constant has been measured with increasing accuracy in lepton-
 1319 nucleon scattering in various experiments at CERN, FERMILAB and DESY. The precision, which has
 1320 been reached currently, requires the description of the deep-inelastic scattering structure functions at $O(\alpha_s^3)$
 1321 [36, 78, 79].

³These are presented below but have not been used in this document for a determination of the strong coupling constant. One knows of course that the use of jet data in DIS helps resolving the α_s - xg correlation, especially at large x , and consequently leads to a significant reduction of the uncertainty on the coupling constant. This, however, tends to also change the central value. The LHeC as will be shown below determines α_s to permille precision already in inclusive scattering. Comparison with precise values from jets can be expected to shed light on the yet unresolved question as to whether there is a theoretical or systematic effect which leads to different values in inclusive DIS and jets or not.

	$\alpha_s(M_Z^2)$	
BBG	$0.1134^{+0.0019}_{-0.0021}$	valence analysis, NNLO [80]
GRS	0.112	valence analysis, NNLO [81]
ABKM	0.1135 ± 0.0014	HQ: FFNS $N_f = 3$ [82]
ABKM	0.1129 ± 0.0014	HQ: BSMN-approach [82]
JR	0.1124 ± 0.0020	dynamical approach [83]
JR	0.1158 ± 0.0035	standard fit [83]
MSTW	0.1171 ± 0.0014	[84]
ABM	0.1147 ± 0.0012	FFNS, incl. combined H1/ZEUS data [85]
BBG	$0.1141^{+0.0020}_{-0.0022}$	valence analysis, N ³ LO [80]
world average	0.1184 ± 0.0007	[86]

Table 4.3: Recent NNLO and N³LO determinations of the strong coupling $\alpha_s(M_Z)$ in DIS world data analyses.

As is well known [87], though also questioned [88], the fits at NLO exhibit scale uncertainties for both the renormalization and factorization scales of $\Delta_{r,f}\alpha_s(M_Z^2) \sim 0.0050$, which are too large to cope with the experimental accuracy of $O(1\%)$. Therefore, NNLO analyses are mandatory. In Table 1 recent NNLO results are summarised. NNLO non-singlet data analyses have been performed in [80,81]. The analysis [80] is based on an experimental combination of flavor non-singlet data referring to $F_2^{p,d}(x, Q^2)$ for $x < 0.35$ and using the respective valence approximations for $x > 0.35$. The $\bar{d} - \bar{u}$ distributions and the $O(\alpha_s^2)$ heavy flavor corrections were accounted for. The analysis could be extended to N³LO effectively due to the dominance of the Wilson coefficient in this order [78] if compared to the anomalous dimension, cf. [80,89]. This analysis led to an increase of $\alpha_s(M_Z^2)$ by $+0.0007$ if compared to the NNLO value.

A combined singlet and non-singlet NNLO analysis based on the DIS world data, including the Drell-Yan and di-muon data, needed for a correct description of the sea-quark densities, was performed in [82]. In the fixed flavor number scheme (FFNS) the value of $\alpha_s(M_Z^2)$ is the same as in the non-singlet case [80]. The comparison between the FFNS and the BMSN scheme [90] for the description of the heavy flavor contributions induces a systematic uncertainty $\Delta\alpha_s(M_Z^2) = 0.0006$. One should note that also in the region of medium and lower values of x higher twist terms have to be accounted for within singlet analyses to cover data at lower values of Q^2 . Moreover, systematic errors quoted by the different experiments usually cannot be combined in quadrature with the statistical errors, but require a separate treatment. The NNLO analyses [83] are statistically compatible with the results of [80–82], while those of [84] yield a higher value.

In [85] the combined H1 and ZEUS data were accounted for in an NNLO analysis for the first time, which led to a shift of $+0.0012$. However, running quark mass effects [91] and the account of recent F_L data reduce this value again to the NNLO value given in [82]. Other recent NNLO analyses of precision data, as the measurement of $\alpha_s(M_Z^2)$ using thrust in high energy e^+e^- annihilation data [92,93], result in $\alpha_s(M_Z^2) = 0.1153 \pm 0.0017 \pm 0.0023$, resp. $0.1135 \pm 0.0011 \pm 0.0006$. Also the latter values are lower than the 2009 world average [86] based on NLO, NNLO and N³LO results.

4.4.2 Simulation of α_s Determination

Since nearly twenty years, the α_s determination in DIS is dominated by the most precise data from the BCDMS Collaboration, which hint to particularly low values of $\alpha_s(M_Z) \simeq 0.113$ [94] and exhibit some peculiar systematic error effects, when compared to the SLAC data and in the pQCD analyses as are discussed in [95,96]. Recent analyses seem to indicate that the influence of the BCDMS data is limited, which, however, is possible only when jet and nuclear fixed target data, extending to very low Q^2 , are used. Jet data sometimes tend to increase the value of α_s and certainly introduce extra theoretical problems connected with hadronisation effects in non-inclusive measurements. The use of fixed target data poses problems due to the uncertainty of corrections from higher twists and from nuclear effects, because what is required is an extraordinary precision if indeed one wants to unambiguously determine the strong coupling

case	cut [Q^2 in GeV^2]	α_s	\pm uncertainty	relative precision in %
HERA only (14p)	$Q^2 > 3.5$	0.11529	0.002238	1.94
HERA+jets (14p)	$Q^2 > 3.5$	0.12203	0.000995	0.82
LHeC only (14p)	$Q^2 > 3.5$	0.11680	0.000180	0.15
LHeC only (10p)	$Q^2 > 3.5$	0.11796	0.000199	0.17
LHeC only (14p)	$Q^2 > 20.$	0.11602	0.000292	0.25
LHeC+HERA (10p)	$Q^2 > 3.5$	0.11769	0.000132	0.11
LHeC+HERA (10p)	$Q^2 > 7.0$	0.11831	0.000238	0.20
LHeC+HERA (10p)	$Q^2 > 10.$	0.11839	0.000304	0.26

Table 4.4: Results of NLO QCD fits to HERA data (top, without and with jets) to the simulated LHeC data alone and to their combination. Here 10p or 14p denotes two different sets of parametrisations, one, with 10 parameters, the minimum parameter set used in [38] and the other one with four extra parameters added as has been done for the HERAPDF1.5 fit. The central values of the LHeC based results are obviously of no interest. The result quoted as relative accuracy includes all the statistical and the systematic error sources taking correlations as from the energy scale uncertainties into account.

constant in DIS. These problems have been discussed in detail above, and recently also in presentations by MSTW [97] and in a phenomenological study of the NNPDF group [98].

The question, of how large α_s is, remains puzzling, as has been discussed at a recent workshop [99] and requires a qualitatively and quantitatively new level of experimental input if one wants to progress in DIS.

Following the description of the simulated LHeC data (Sec. 4.1.4) and the QCD fit technique (Sec. 4.2.1) a dedicated study has been performed to estimate the accuracy of an α_s measurement with the LHeC. In the fits, for the central values of the LHeC data, the SM expectation is used smeared within the above uncertainties assuming their Gaussian distribution and taking into account correlated uncertainties as well.

The QCD fit results are summarised in Tab. 4.4. The first two lines give the result of a fit to the HERA I data. One observes that the inclusion of DIS jet data reduces the uncertainty, by a factor of two, but it also increases the central value by more than the uncertainty. The LHeC alone, in sole inclusive DIS, reaches values of better than 0.2% which when complemented with HERA data reaches a one per mille precision. From inspecting the results one finds that enlarging the Q^2 minimum still leads to an impressive precision, as of two per mille in the LHeC plus HERA case, at values which safely are in the DIS region. A Q^2 cut of for example 10 GeV^2 excludes also the lowest x region in which non-linear gluon interaction effects may require to change the evolution equations.

It is obvious that the sole experimental uncertainty, while impressive and promising indeed, is not the only problem in such a complex analysis. That requires all relevant parameters to be correspondingly tuned and understood. For example, the charm mass has to be known at the 10 MeV level to allow an α_s uncertainty of one per mille. The question of the uncertainty of the renormalisation and factorisation scales and their effect on α_s will be posed newly and higher than NNLO approximations of pQCD appear to be necessary. However, as mentioned above there already exist first N³LO results.

From an experimental and phenomenological point of view it appears extremely exciting that with the LHeC the α_s determination in DIS will be put on much more solid grounds, by the high precision and unprecedented kinematic range and but also by the resulting full constraints on the complete set of parton distributions, of light and heavy quarks, often by direct measurements, which hitherto had to be parameterised in an often crude way.

In view of the importance of this result, this analysis has been performed independently twice with separately generated NC and CC pseudodata under somewhat different assumption, albeit using the same simulation program, and using different versions of the QCD fit program. The results obtained before [100] are in good agreement with the numbers presented here.

1387 It is finally worth noting that there is an interest to measure α_s also based on non-singlet quantities. The
 1388 LHeC data provide high precision information both on the valence quarks and also on the proton-neutron
 1389 structure function difference. The accuracy expected from such measurements has not been estimated.

1390 4.5 Electron-Deuteron Scattering

1391 The structure of the deuteron and of the neutron are experimental unknowns over most of the kinematic
 1392 region of deep inelastic scattering. The last time lepton-deuteron scattering was measured occurred in the
 1393 fixed target μD experiments at CERN [101–103], while it had only been considered at HERA [104–106].
 1394 The LHeC so extends the range of these measurements by nearly four orders of magnitude in Q^2 and $1/x$,
 1395 which gives rise to a most exciting programme in QCD and in experimental physics.

1396 DIS and Partons

1397 Electron-deuteron scattering complements ep scattering in that it makes possible accurate measurements of
 1398 neutron structure in the new kinematic range accessed by the LHeC. In a collider configuration, in which
 1399 the hadron “target” has momentum much larger than the lepton probe, the spectator proton can be tagged
 1400 and its momentum measured with high resolution [104]. The resulting neutron structure function data are
 1401 then free of nuclear corrections which have plagued the interpretation of deuteron data, especially at larger
 1402 x , until now [107]. At low x , for the first time, since diffraction is related to shadowing, one will be able to
 1403 control the shadowing corrections⁴ at the per cent level of accuracy as is also discussed below.

1404 Accurate en cross section measurements will resolve the quark flavour decomposition of the sea, i.e. via
 1405 isospin symmetry, unfolding \bar{u} from \bar{d} contributions to the rise of $F_2^p \propto x(4\bar{u} + \bar{d})$ towards low x , and, from
 1406 the full set of $e^\pm p$ and $e^\pm n$ charged current cross section data, a full unfolding of the flavour content of the
 1407 nucleon. For the study of the parton evolution with Q^2 , the measurement of $F_2^N = (F_2^p + F_2^n)/2$ is crucial
 1408 since it disentangles the evolution of the non-singlet and the singlet contributions. Down to x of about 10^{-3}
 1409 the W^+/W^- LHC data will also provide important information on the up-down quark distributions, albeit
 1410 at high Q^2 . With ep , eD and W^+/W^- data, the low x sea will be resolved for the first time, as all the low
 1411 x light quark information from HERA has been restricted to F_2^p only.

1412 A special interest in high precision neutron data at high Q^2 arises from the question of whether there
 1413 holds charge symmetry at the parton level, as has been discussed recently [109]. It may be studied in the
 1414 charged current ep and eD reactions, using both electrons and positrons, by measuring the asymmetry ratio

$$R^- = 2 \frac{W_2^{-D} - W_2^{+D}}{W_2^{-p} + W_2^{+p}}, \quad (4.30)$$

1415 which is directly sensitive to differences of up and down quark distributions in the proton and neutron,
 1416 respectively, which conventionally are assumed to be equal. With the prospect of directly measuring the
 1417 strange and anti-strange quark asymmetry in $e^\pm p$ CC scattering and of tagging the spectator proton and
 1418 thus eliminating the Fermi motion corrections in eD , such a measurement becomes feasible at the LHeC. It
 1419 requires high luminosity of order 1 fb^{-1} in eD scattering.

1420 Hidden Colour

1421 In nuclear physics nuclei are simply the composites of nucleons. However, QCD provides a new perspec-
 1422 tive [110, 111]. Six quarks in the fundamental 3_C representation of $SU(3)$ color can combine into five
 1423 different color-singlet combinations, only one of which corresponds to a proton and neutron. The deuteron
 1424 wavefunction is a proton-neutron bound state at large distances, but as the quark separation becomes

⁴For light nuclei, nuclear shadowing is dominated by the scattering off two nucleons. Since the probability of such double collisions is primarily determined by nuclear geometry, the A -dependence (though not the absolute value) of shadowing in light nuclei ($A \leq 12$) is not sensitive to details of the dynamics. Consequently, one can extract the nuclear shadowing correction for electron-deuteron scattering with a small uncertainty (well below 1 the electron-carbon and electrondeuteron cross sections [108]).

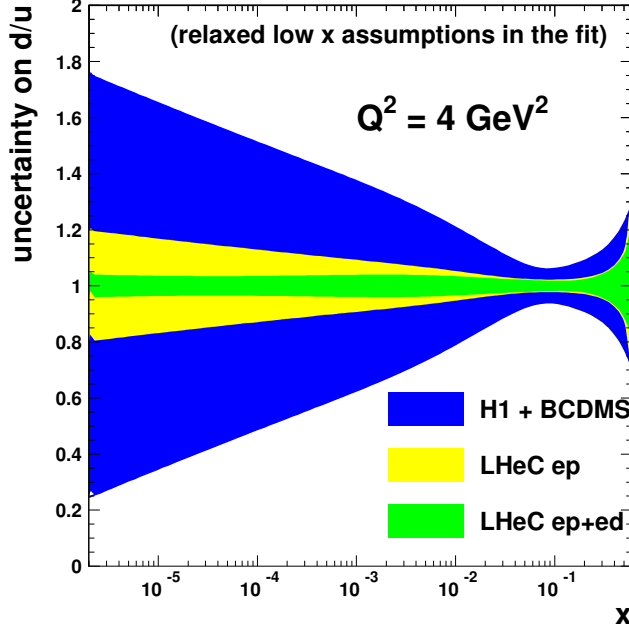


Figure 4.19: Uncertainty of the d/u ratio as a function of x from a QCD fit to H1 and BCDMS data (outer band, blue), to the LHeC proton data (middle band, yellow) and the combined simulated proton and deuteron data from the LHeC (inner band, green). In these fits the constraint of u and d to be the same at low x has been relaxed.

1425 smaller, QCD evolution due to gluon exchange introduces four other “hidden color” states into the deuteron
 1426 wavefunction [112]. The normalization of the deuteron form factor observed at large Q^2 [113], as well as
 1427 the presence of two mass scales in the scaling behavior of the reduced deuteron form factor [110], sug-
 1428 gest sizable hidden-color Fock state contributions in the deuteron wavefunction [114]. The hidden-color
 1429 states of the deuteron can be materialized at the hadron level as $\Delta^{++}(uuu)\Delta^{-}(ddd)$ and other novel quan-
 1430 tum fluctuations of the deuteron. These dual hadronic components become important as one probes the
 1431 deuteron at short distances, such as in exclusive reactions at large momentum transfer. For example, the
 1432 ratio $d\sigma/dt(\gamma d \rightarrow \Delta^{++}\Delta^{-})/d\sigma/dt(\gamma d \rightarrow np)$ is predicted to increase to a fixed ratio 2 : 5 with increasing
 1433 transverse momentum p_T . Similarly, the Coulomb dissociation of the deuteron into various exclusive chan-
 1434 nels $ed \rightarrow e' + pn, pp\pi^{-}, \Delta\Delta, \dots$ will have a changing composition as the final-state hadrons are probed
 1435 at high transverse momentum, reflecting the onset of hidden-color degrees of freedom. The hidden color
 1436 of the deuteron can be probed at the LHeC in electron deuteron collisions by studying reactions such as
 1437 $\gamma^*d \rightarrow npX$ where the proton and neutron emerge in the target fragmentation region at high and opposite
 1438 p_T . In principle, one can also study DIS reactions $ed \rightarrow e'X$ at very high Q^2 where $x > 1$. The production
 1439 of high p_T anti-nuclei at the LHeC is also sensitive to hidden color-nuclear components.

1440 4.6 Charm and Beauty production

1441 4.6.1 Introduction and overview of expected highlights

1442 In this section it is shown that the measurements of charm and beauty production at LHeC provide high
 1443 precision pQCD tests and are crucial to improve the knowledge of the proton structure. Historically the
 1444 HERA charm and beauty studies extended by large amount results from previous fixed target experiments.
 1445 This allowed a great advancement in the understanding of the dynamics of heavy quark production. The
 1446 LHeC is the ideal machine for a further extension of similar historic importance because a higher centre

1447 of mass energy and a much larger integrated luminosity compared to HERA are available. On top of this
 1448 the heavy flavour measurements will greatly benefit from the advanced detector design at LHeC with high
 1449 precision (Silicon or similar) trackers all over the place. At HERA the tagging was restricted to central
 1450 rapidities and effective efficiencies⁵ of only 0.1% (1%) for charm (beauty) were reached. At LHeC efficiencies
 1451 of 10% (50%) should be possible for charm (beauty) and a large rapidity range can be covered from the very
 1452 backward to the very forward regions. Before further elucidating the great measurement prospects the next
 1453 paragraph introduces the main heavy quark production processes, the relevant pQCD theoretical schemes
 1454 and some related open questions.

1455 In leading order, heavy quarks are produced in ep collisions via the Boson Gluon Fusion (BGF) process
 shown in Figure 4.20 on the left. This process provides direct access to the gluon density in the proton.

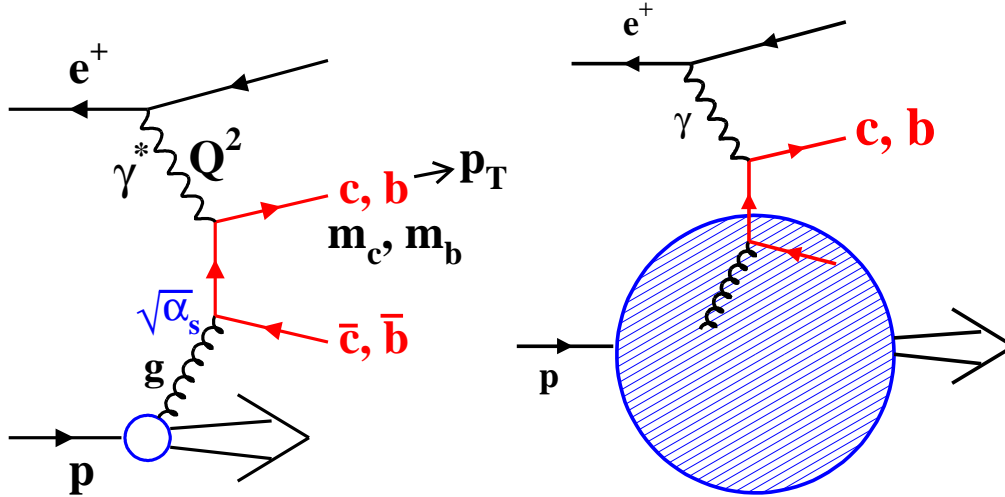


Figure 4.20: Left: Leading order Boson Gluon Fusion (BGF) diagram for charm and beauty production in ep -collisions. Right: Sketch of the leading order process in the massless approach where charm and beauty quarks are treated as massless sea quarks in the proton.

1456 BGF type processes dominate DIS scattering towards lower x , due to the large gluon density. In the high Q^2
 1457 limit, the events with charm and beauty quarks are expected to account for $\sim 36\%$ and $\sim 9\%$ of the BGF
 1458 processes and hence contribute significantly to inclusive DIS. On the theoretical side, the description of heavy
 1459 quark production in the framework of perturbative QCD is complicated due to the presence of several large
 1460 scales like the heavy quark masses, the transverse momentum p_T of the produced quarks and the momentum
 1461 transfer Q^2 . Different calculation schemes have been developed to obtain predictions from pQCD. At low
 1462 scales p_T (or Q^2) the fixed-flavour number scheme (FFNS) [115–117] is expected to be most appropriate
 1463 where the quark masses are fully accounted for. At very high scales the NLO FFNS scheme predictions
 1464 are expected to break down since large logarithms $\ln(p_T^2/m^2)$ are neglected that represent collinear gluon
 1465 radiations from the heavy quark lines. These logarithms can be resummed to all orders in the alternative
 1466 zero-mass variable flavour number (ZM-VFNS) [118–121] schemes. Here the charm and beauty quarks are
 1467 treated above kinematic threshold as massless and appear also as active sea quarks in the proton, as depicted
 1468 in figure 4.20 in the sketch on the right. Most widely used are nowadays the so-called generalised
 1469 variable flavour number schemes (GM-VFNS) [122, 123]. These mixed schemes converge to the massive and
 1470 massless schemes at low and high kinematical scales, respectively, and apply a suitable interpolation in the
 1471 intermediate region. However, the exact modelling of the interpolation and in general the treatment of mass
 1472 dependent terms in the perturbation series are still a highly controversial issue among the various theory
 1473 groups. The different treatments have profound implications for global PDF fits and influence the fitted
 1474

⁵The effective efficiency takes the background pollution into account. It is defined as the efficiency of an equivalent background free sample with the same signal precision as that obtained in the data.

1475 densities of gluons and other quark flavours in the proton. This has direct consequences for many important
 1476 cross section predictions at LHC, for instance for Z and W production. The value of the charm quark mass
 1477 is also an important uncertainty in the calculations. Recently the running charm mass has been fitted [91]
 1478 to fixed target and HERA charm data obtaining a value $m_c(m_c) = 1.01 \pm 0.09(\text{exp}) \pm 0.03(\text{th})$ GeV.

1479 The following main physics highlights are expected for heavy quark production measurements at LHeC:

- 1480 • *Massive vs Massless scheme:* At HERA the charm and beauty production data were found to be well
 1481 described by the NLO FFNS scheme calculations over the whole accessible phase space, up to the
 1482 highest p_T and Q^2 scales. An LHeC collider would allow to extend these studies to a much larger
 1483 kinematical phase space and thus to map the expected transition to the massless regime. Further
 1484 improvements in the determination of the charm quark mass and in the tuning of the GM-VFNS
 1485 schemes are possible and will have strong impacts on global PDF fits.

- 1486 • *Gluon density determination:* At HERA the recorded charm data provide already some interesting
 1487 sensitivity to the gluon density in the proton. However due to the small tagging efficiencies the
 1488 precisions are far below those obtained from the scaling violations of F_2 or those from jet data. At
 1489 LHeC this situation will highly improve and it will be possible to probe the gluon density via the BGF
 1490 process down to proton momentum fractions $x_g \leq 10^{-5}$, where it is currently not well known.

1491 At such low values of x_g a fixed-order perturbative computation becomes unreliable. It is then necessary
 1492 to resum both evolution equations and hard matrix elements. In fact, heavy quark production is the first
 1493 process for which all-order small x resummed terms were computed, and the high-energy factorization,
 1494 on which the whole of perturbative small- x resummation is based, was proven in this context [124,125].
 1495 Heavy quark production at the LHeC, with its high precision, energy and extended kinematic coverage,
 1496 would thus provide an ideal setting for tests of high-energy factorization and small x resummation.

1497 In this context it is also interesting to note that in the BGF process one can reach for charm production
 1498 much smaller x_g values than with flavour inclusive jets since experimentally one can tag charm quarks
 1499 with small transverse momenta. The studies of heavy flavour production sensitive to the gluon density
 1500 can be done both in DIS and in the photoproduction kinematic regime.

- 1501 • *Charm and beauty densities in the proton:* In general the measurements of the structure functions F_2^{cc}
 1502 and F_2^{bb} are of highest interest for theoretical analyses of heavy flavour production in ep collisions.
 1503 These structure functions are describing the parts of F_2 which are due to events with charm or beauty
 1504 quarks in the final state. At sufficiently high $Q^2 \gg m_c^2, m_b^2$, the two structure functions can be directly
 1505 related to effective densities of charm and beauty quarks in the proton, This can be used for predictions
 1506 of many interesting processes at LHC with charm or beauty quarks in the initial state. For instance,
 1507 as discussed in [126], in the minimal supersymmetric extension of the standard model the production
 1508 of the neutral Higgs boson A is driven by $b\bar{b} \rightarrow A$ and for the calculation of this process the PDF
 1509 uncertainties dominate over the theoretical uncertainties of the perturbative calculation. At HERA
 1510 the measurements of F_2^{bb} barely reached the necessary high Q^2 regime and only with modest precision.
 1511 Huge phase space extensions and precision improvements will be possible at LHeC.

- 1512 • *Intrinsic charm component:* Since long it has been suggested [51,127–129] that the proton wave function
 1513 might contain an intrinsic charm component $uudc\bar{c}$. This would show up mainly at large $x > 0.1$
 1514 Unfortunately at HERA this large x region could not be studied mainly due to the limited detector
 1515 acceptance in the forward region. Due to the even larger boost in the forward direction at LHeC the
 1516 situation is also not easy there. However, with a forward tracking acceptance down to small polar
 1517 angles there could be a chance to study this effect, in particular with the planned proton low energy
 1518 runs.

- 1519 • *Strange/antistrange densities:* Events with charm quarks in the final state can be also used as a tool
 1520 for other purposes. The strange and antistrange quark densities in the proton can be analysed via
 1521 the charge current process $sW \rightarrow c$, where the charm quark is tagged in the event. At HERA this
 1522 was impossible due to the small cross sections, but at LHeC the cross sections for CC reactions are

1523 much higher and as noted before the other experimental conditions (luminosities, detector) will greatly
 1524 improve. This leads to the first and precise measurement of both the strange and the anti-strange
 1525 quark densities as is demonstrated in Sect. 4.2.

- 1526 • *Electroweak physics:* There are intriguing possibilities for LHeC electroweak physics studies with charm
 1527 and beauty quarks in the final state. For example one should be able to do a lepton beam polarisation
 1528 asymmetry measurement for neutral current events, where the scattered quark is tagged as a beauty
 1529 quark. This will provide direct access to the axial and vector couplings of the beauty quark to the Z
 1530 boson. Similar measurements are possible for charm.

1531 In summary the measurements of charm and beauty at an LHeC will be extremely useful for high precision
 1532 pQCD tests, in particular for the understanding of the treatment of mass terms in pQCD, to improve the
 1533 knowledge of the proton PDFs: directly for g, c, b, s, \bar{s} densities and indirectly also for u and d. Furthermore
 1534 they provide a great potential for electroweak physics. At the time when the LHeC will be operated, the
 1535 pQCD theory calculations are expected to have advanced considerably. In particular there is hope that full
 1536 massive scheme NNLO calculations of order $o(\alpha_s^3)$ will be available by then. These will allow theory to data
 1537 comparisons for heavy flavour production in ep collisions with unprecedented precision.

1538 In the following subsections several dedicated simulation studies are presented which illustrate some of the
 1539 expected highlights. First total cross sections are presented for various processes involving charm, beauty
 1540 and also top quarks in the final state, showing that LHeC will be a genuine *multi heavy flavour factory*.
 1541 Then the expected measurements of the structure functions F_2^{cc} and F_2^{bb} are discussed and compared to the
 1542 existing HERA data. Next a study is presented of the possibility to measure intrinsic charm with dedicated
 1543 low proton energy runs. Finally predictions for differential charm hadron production cross sections in the
 1544 photoproduction kinematic regime are presented and compared to HERA, demonstrating the large phase
 1545 space extension.

1546 4.6.2 Total production cross sections for charm, beauty and top quarks

1547 This section presents total cross sections for various heavy quark processes at LHeC (with 7 TeV proton
 1548 beam energy) as a function of the lepton beam energy. Predictions are obtained for: charm and beauty
 1549 production in photoproduction and DIS, the charged current processes $sW \rightarrow c$ and $bW \rightarrow t$ and top quark
 1550 pair production in photoproduction and DIS. For comparison the flavour inclusive charged current total
 1551 cross section is also shown. Table 4.5 lists the generated processes, the used Monte Carlo generators and the
 1552 selected parton distribution functions. The resulting cross sections are shown in Figure 4.21. For comparison
 1553 also the predicted cross sections for the HERA collider (with 920 GeV proton energy) are presented. The
 1554 cross sections at LHeC are typically about one order of magnitude larger compared to HERA. Attached to
 1555 the right of the plot are the number of events that are produced per 10 fb^{-1} of integrated luminosity. For
 1556 instance for charm more than 10 billion events are expected in photoproduction and for beauty more than
 1557 100 million events. In DIS the numbers are typically a factor of five smaller. The strange and antistrange
 1558 densities can be probed with some hundred thousands of charged current events with charm in the final state.
 1559 The top quark production is dominated by the single production in the charged current reaction with beauty
 1560 in the initial state and about one hundred thousands tops and a similar number of antitops are expected.
 1561 In summary the LHeC will be the first ep collider which provides access to all quark flavours and with high
 1562 statistics.

1563 4.6.3 Charm and Beauty production in DIS

1564 This section presents predictions for charm and beauty production in neutral current DIS, for Q^2 values
 1565 of at least a few GeV^2 . The predictions are given for the structure functions $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$ which denote
 1566 the contributions from charm and beauty events to F_2 . As explained in section 4.6.1 the two structure
 1567 functions are of large interest for theoretical analyses. Experimentally they are obtained by determining the
 1568 total charm and beauty cross sections in two-dimensional bins of x and Q^2 . The LHeC projections shown
 1569 here were obtained with the Monte Carlo programme RAPGAP [132] which generates charm and beauty

Process	Monte Carlo	PDF
Charm γp Beauty γp tt γp	PYTHIA6.4 [130]	CTEQ6L [131]
Charm DIS Beauty DIS tt DIS	RAPGAP3.1 [132]	CTEQ5L [133]
CC e^+p CC e^-p $sW \rightarrow c$ $\bar{s}W \rightarrow \bar{c}$ $bW \rightarrow t$ $\bar{b}W \rightarrow \bar{t}$	LEPTO6.5 [134]	CTEQ5L
tt DIS	RAPGAP 3.1	CTEQ5L

Table 4.5: Used generator programmes for the predictions of total cross sections at LHeC, shown in Figure 4.21. For all processes with top quarks the top mass was set to a value of 170 GeV. For both photoproduction (labelled as γp) and DIS only direct photon processes were generated and no reactions with resolved photons.

1570 production with massive leading order matrix elements supplemented by parton showers. The proton Parton
1571 Distribution Function set CTEQ5L [133] were used and the heavy-quark masses were set to $m_c = 1.5$ GeV
1572 and $m_b = 4.75$ GeV, respectively. In general at HERA the RAPGAP predictions are known to provide a
1573 reasonable description of the measured charm and beauty DIS production data. The RAPGAP data were
1574 generated for an LHeC collider scenario with 100 GeV electrons colliding with 7 TeV protons. The statistical
1575 uncertainties have been evaluated such that they correspond to an integrated data luminosity of 10 fb^{-1} . All
1576 studies were done at the parton level, hadronisation effects were not taken into account. Tagging efficiencies
1577 of 10% for charm quarks and 50% for beauty quarks have been assumed, respectively. These efficiencies are
1578 about a factor 100 larger compared to the effective efficiencies (including the dilution due to background
1579 pollution) at HERA which may look surprisingly but is explainable. At HERA the charm quarks were tagged
1580 either with full charm meson reconstruction or with inclusive secondary vertexing of charm hadron decays.
1581 The first method suffered from very small branching ratios of suitable decay channels. The second technique
1582 which was also used for the beauty tagging was affected by a large pollution from light quark background
1583 events due to the limited detector capabilities to separate secondary from primary vertices. At LHeC one
1584 can expect a much better secondary vertex identification and thus a very strong background reduction. It is
1585 difficult to predict exactly how much background pollution will remain at LHeC, so for the purpose of this
1586 simulation study it was completely neglected. Systematic uncertainties were also neglected for the studies
1587 presented here. From the experiences at HERA the total systematic uncertainties for charm and beauty
1588 cross sections in the visible ranges can be expected to be of similar size as the statistical ones.

1589 Figures 4.22 and 4.23 show the resulting RAPGAP predictions at LHeC for the structure functions F_2^{cc}
1590 and F_2^{bb} , respectively, compared to recent measurements [135] from HERA. The data are shown as a function
1591 of x for various Q^2 values. The Q^2 values were chosen such that they cover a large fraction of the specific
1592 values for which HERA results are available. Some further values demonstrate the phase space extensions
1593 at LHeC. The projected LHeC data are presented as points with error bars which (where visible) indicate
1594 the estimated statistical uncertainties. For the open points the detector acceptance is assumed to cover the
1595 whole polar angle range. For the grey shaded and black points events are only accepted if at least one charm
1596 quark is found with polar angles $\theta_c > 2^0$ and $\theta_c > 10^0$, respectively. The selected results from HERA are
1597 shown as triangles with error bars indicating the total uncertainty. The HERA F_2^{cc} results in Figure 4.22

Total cross sections in ep collisions

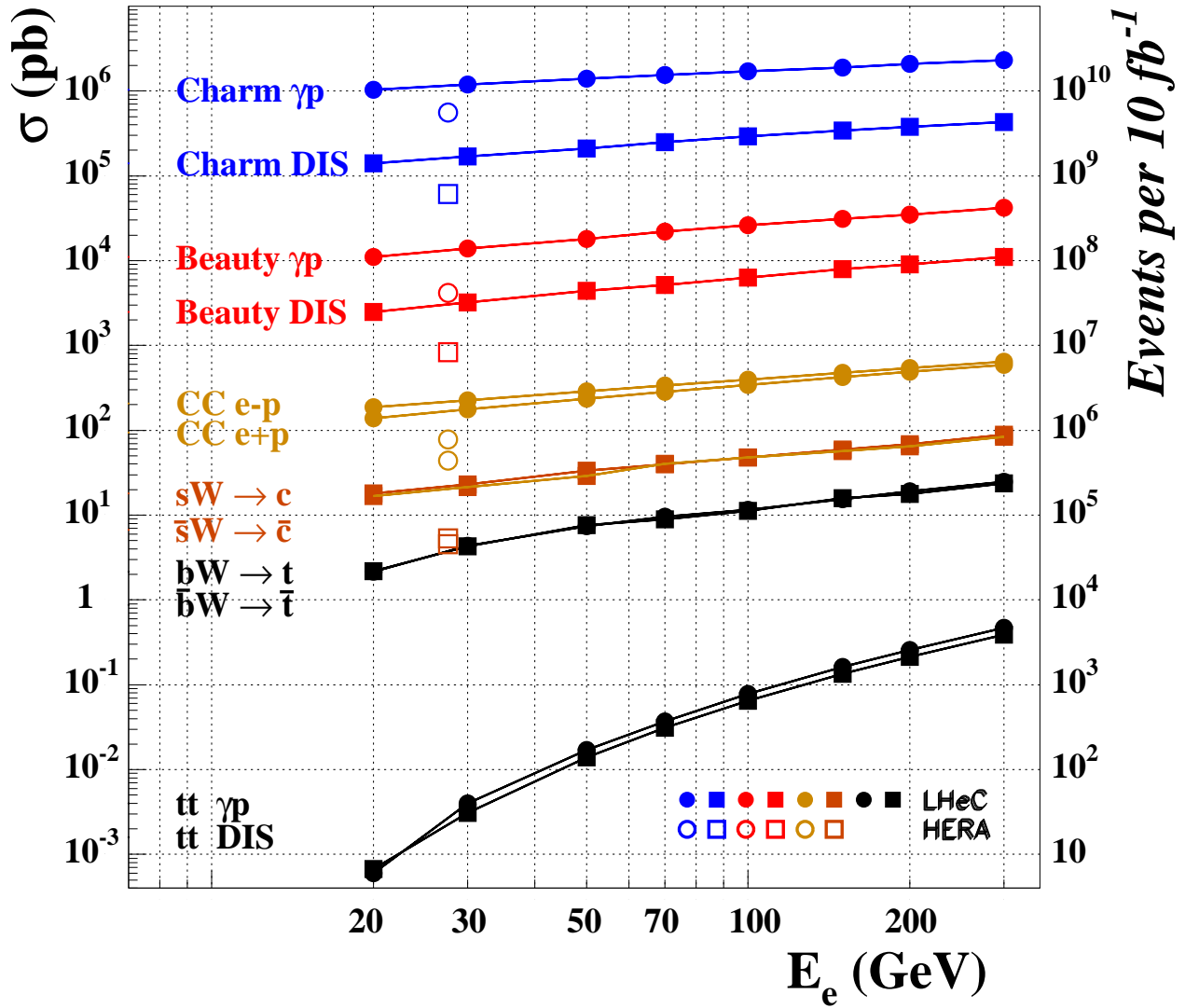


Figure 4.21: Total production cross section predictions for various heavy quark processes at the LHeC (with 7 TeV proton energy), as a function of the lepton beam energy. The following processes are covered: charm and beauty production in photoproduction and DIS, the charged current processes $sW \rightarrow c$ and $bW \rightarrow t$ and top pair production in photoproduction and DIS. The flavour inclusive charged current total cross section is also shown. All predictions are taken from Monte Carlo simulations, the details can be found in Table 4.5. For comparison also the predicted cross sections at HERA (with 920 GeV proton energy) are shown.

1598 are those of a recent weighted average [135] of almost all available measurements from H1 and ZEUS. In a
 1599 large part of the covered phase space these results are already rather accurate, with precisions between 5%
 1600 and 10%. The overlaid LHeC projections show a vast phase space increase to lower and larger x and also
 1601 to much higher Q^2 values. In the kinematic overlap region the expected statistical precisions at LHeC are
 1602 typically a factor ~ 40 better than at HERA which can be easily explained by the 20 times larger integrated
 1603 luminosity and the ~ 100 times better tagging efficiency. For the smaller x not covered by HERA the

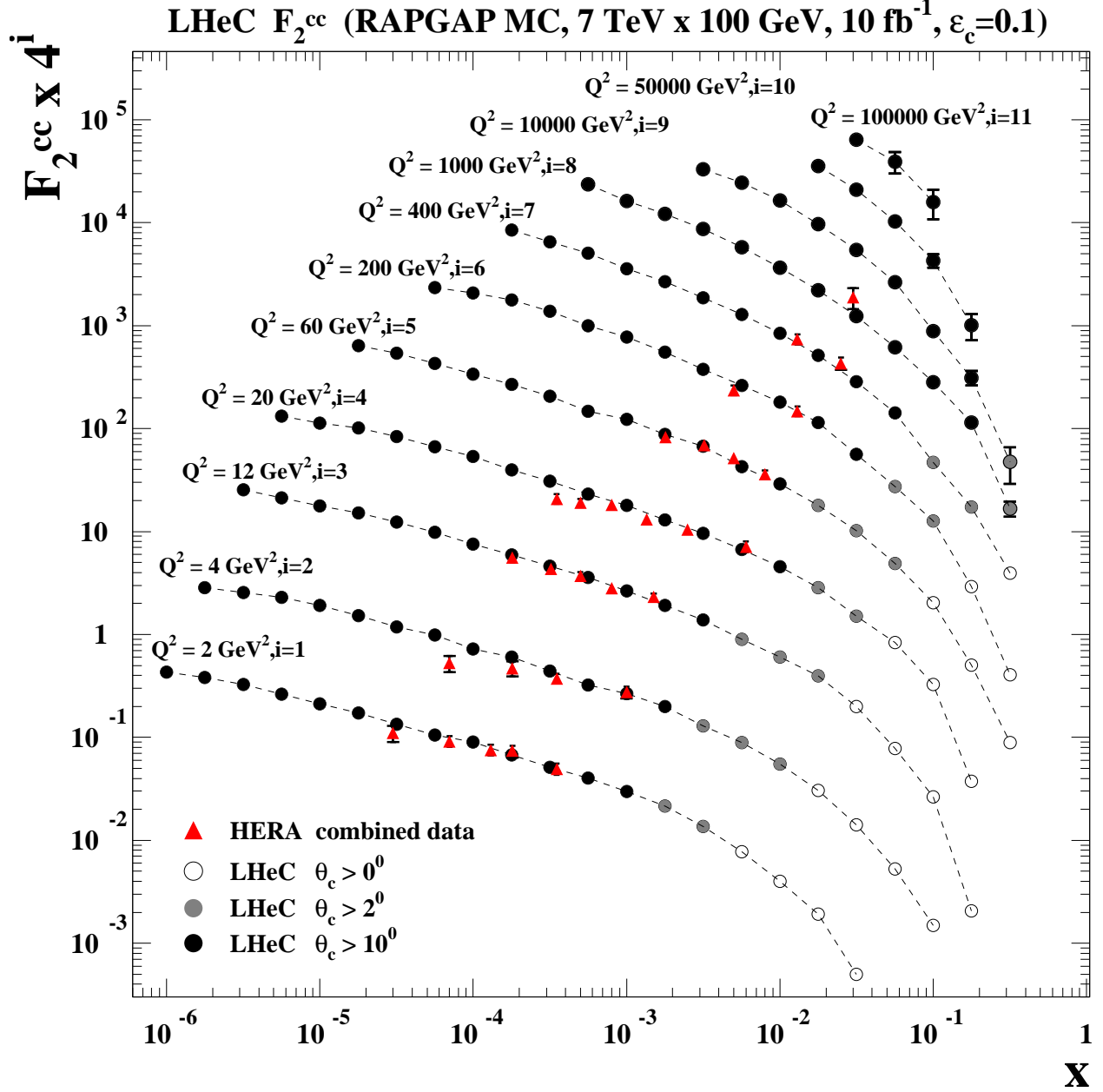


Figure 4.22: F_2^{cc} projections for LHeC compared to HERA data [135], shown as a function of x for various Q^2 values. The expected LHeC results obtained with the RAPGAP MC simulation are shown as points with error bars representing the statistical uncertainties. The dashed lines are interpolating curves between the points. For the open points the detector acceptance is assumed to cover the whole polar angle range. For the grey shaded and black points events are only accepted if at least one charm quark is found with polar angles $\theta_c > 2^0$ and $\theta_c > 10^0$, respectively. For further details of the LHeC simulation see the main text. The combined HERA results from H1 and ZEUS are shown as triangles with error bars representing their total uncertainty.

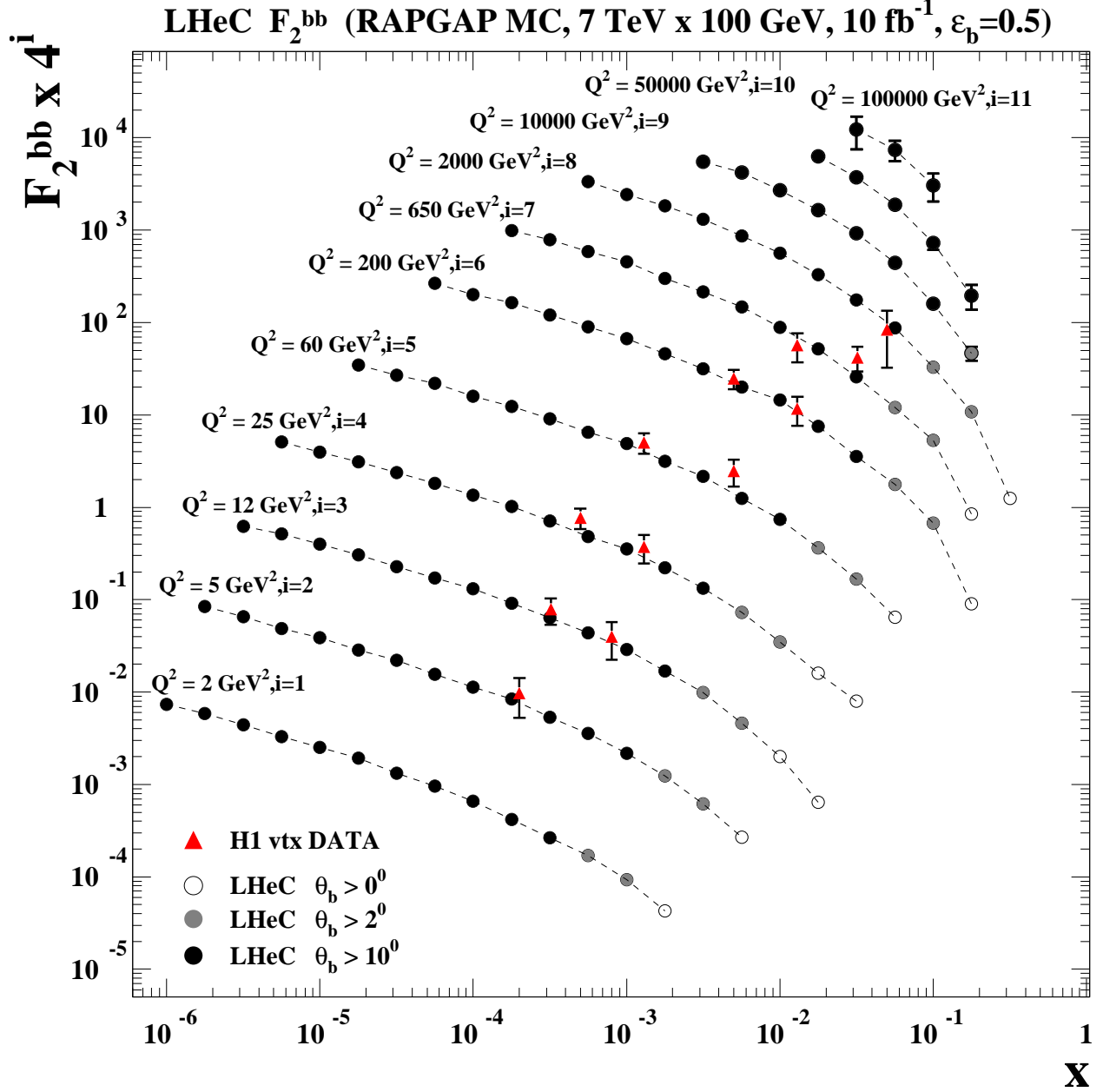


Figure 4.23: F_2^{bb} projections for LHeC compared to HERA data [136] from H1, shown as a function of x for various Q^2 values. The expected LHeC results obtained with the RAPGAP MC simulation are shown as points with error bars representing the statistical uncertainties. The dashed lines are interpolating curves between the points. For the open points the detector acceptance is assumed to cover the whole polar angle range. For the grey shaded and black points events are only accepted if at least one beauty quark is found with polar angles $\theta_b > 2^\circ$ and $\theta_b > 10^\circ$, respectively. For further details of the LHeC simulation see the main text. The HERA results from H1 are shown as triangles with error bars representing their total uncertainty.

1604 precision even improves at LHeC due to the growing cross sections driven by the rise of the gluon density.
 1605 The best statistical precisions in the LHeC simulation are observed at smallest x values and small Q^2 and

reach down to 0.01%. As seen in the simulation (not shown here) the LHeC F_2^{cc} data provide access to the gluon density in the BGF process down to proton momentum fractions $x_g \sim 10^{-5}$. The LHeC data can also provide an substantial extension to higher x compared to HERA where the measurements reached x values of a few percent. As evident from the simulated points with different polar angle cuts this necessitates an excellent forward tagging of charm quarks. In any case values of $x > 0.1$ should be accessible in the medium and large Q^2 domain.

Figure 4.23 show the RAPGAP predictions at LHeC for F_2^{bb} . Also shown are the results from the H1 analysis [136] based on inclusive secondary vertex tagging. Clearly these results and similar ones (not shown) from ZEUS are not very precise, the typical total uncertainties are 20-50%. Again, the LHeC F_2^{bb} projections demonstrate a vast phase space increase, similar as for charm. The best statistical precisions obtained at LHeC for F_2^{bb} are seen in the simulation towards low x and small and medium Q^2 and reach down to 1 permille. The measurements at LHeC will enable a precision mapping of beauty production from kinematic threshold to large Q^2 . In the context of the generalised variable flavour number schemes (GM-VFNS) this will allow to study in detail the onset of the beauty quark density in the proton and to compare it to the charm case. As mentioned in section 4.6.1, for high $Q^2 \gg m_b^2$ the F_2^{bb} results can be directly interpreted in terms of an effective beauty density in the proton. The measurement of this density is of large interest because it can be used to predict beauty quark initiated processes at the LHC. As visible in the figure, HERA covers only a small phase space in this region and with moderate precision. However, at LHeC the prospects for measuring F_2^{bb} in this region are very good.

4.6.4 Intrinsic Heavy Flavour

It is conventional to assume that the charm and bottom quarks in the proton structure function only arise from gluon splitting $g \rightarrow Q\bar{Q}$. In fact, the proton light-front wavefunction contains *ab initio* intrinsic heavy quark Fock state components such as $|uudc\bar{c}\rangle$ [51, 127–129]. The intrinsic heavy quarks carry most of the proton's momentum since this minimizes the off-shellness of the state. The heavy quark pair $Q\bar{Q}$ in the intrinsic Fock state is primarily a color-octet, and the ratio of intrinsic charm to intrinsic bottom scales as $m_c^2/m_b^2 \simeq 1/10$, as can easily be seen from the operator product expansion in non-Abelian QCD [127, 129]. Intrinsic charm and bottom explain the origin of high x_F open-charm and open-bottom hadron production, as well as the single and double J/ψ hadroproduction cross sections observed at high x_F . The factorization-breaking nuclear $A^\alpha(x_F)$ dependence of hadronic J/ψ production cross sections is also explained.

As emphasized recently [137], there are strong indications that the structure functions used to model charm and bottom quarks in the proton at large x have been underestimated, since they ignore intrinsic heavy quark fluctuations of hadron wavefunctions. Furthermore, the neglect of the intrinsic-heavy quark component in the proton structure function will lead to an incorrect assessment of the gluon distribution at larger x if it is assumed that sea quarks always arise from gluon splitting. The anomalous growth of the $p\bar{p} \rightarrow \gamma cX$ inclusive cross section observed by the D0 collaboration [138] at the Tevatron indicates that the charm distribution has been underestimated at $x > 0.1$.

In [139] a novel mechanism for inclusive and diffractive Higgs production $pp \rightarrow pHp$ is proposed, in which the Higgs boson carries a significant fraction of the projectile proton momentum. The production mechanism is based on the subprocess $(Q\bar{Q})g \rightarrow H$ where the $Q\bar{Q}$ in the $|uudQ\bar{Q}\rangle$ intrinsic heavy quark Fock state of the colliding proton has approximately 80% of the projectile protons momentum. A similar mechanism could produce the Higgs at large $x_F \sim 0.8$ in $\gamma p \rightarrow HX$ at the LHeC based on the mechanism $\gamma(Q\bar{Q}) \rightarrow H$ since the heavy quarks typically each carry light-cone momentum fractions $x \sim 0.4$ when they arise from the intrinsic heavy quark Fock states $|uudQ\bar{Q}\rangle$ of the proton.

The LHeC could establish the phenomenology of the charm and bottom structure functions at larger x . In addition to DIS measurements, one can test the charm (and bottom) distributions at the LHeC by measuring reactions such as $\gamma p \rightarrow cX$ where the charm jet is produced at high p_T in the reaction $\gamma c \rightarrow cg$.

In order to access the charm and bottom distributions towards larger Bjorken x , it is required to tag heavy flavour production in the forward direction. As this is difficult in the asymmetric electron-proton beam energy configuration such a measurement can favourably be done with a reduced proton beam energy.

1656 Approximately, as may be derived from Eq. 12.8, the small hadronic scattering angle, θ_h , is obtained from
 1657 the relation, $\theta_h^2 \simeq 2\sqrt{Q^2}/E_p x$. Therefore a reduction by a factor of 7 of the proton beam energy E_p enhances
 1658 x by 7 at fixed Q^2 and θ_h . One also notices that large x is reached at fixed θ_h and E_p only at high Q^2 . The
 1659 attempt to access maximum x thus requires to find an optimum of high luminosity, to reach high Q^2 , and
 1660 low proton beam energy, to access large x . Fig. 4.24 shows a simulated measurement of the charm structure
 1661 function for $E_p = 1$ TeV and a luminosity of 1 fb^{-1} . The two curves illustrate the difference between CTEQ66
 PDF sets with and without an intrinsic charm component, based on [137]. The actual amount of intrinsic

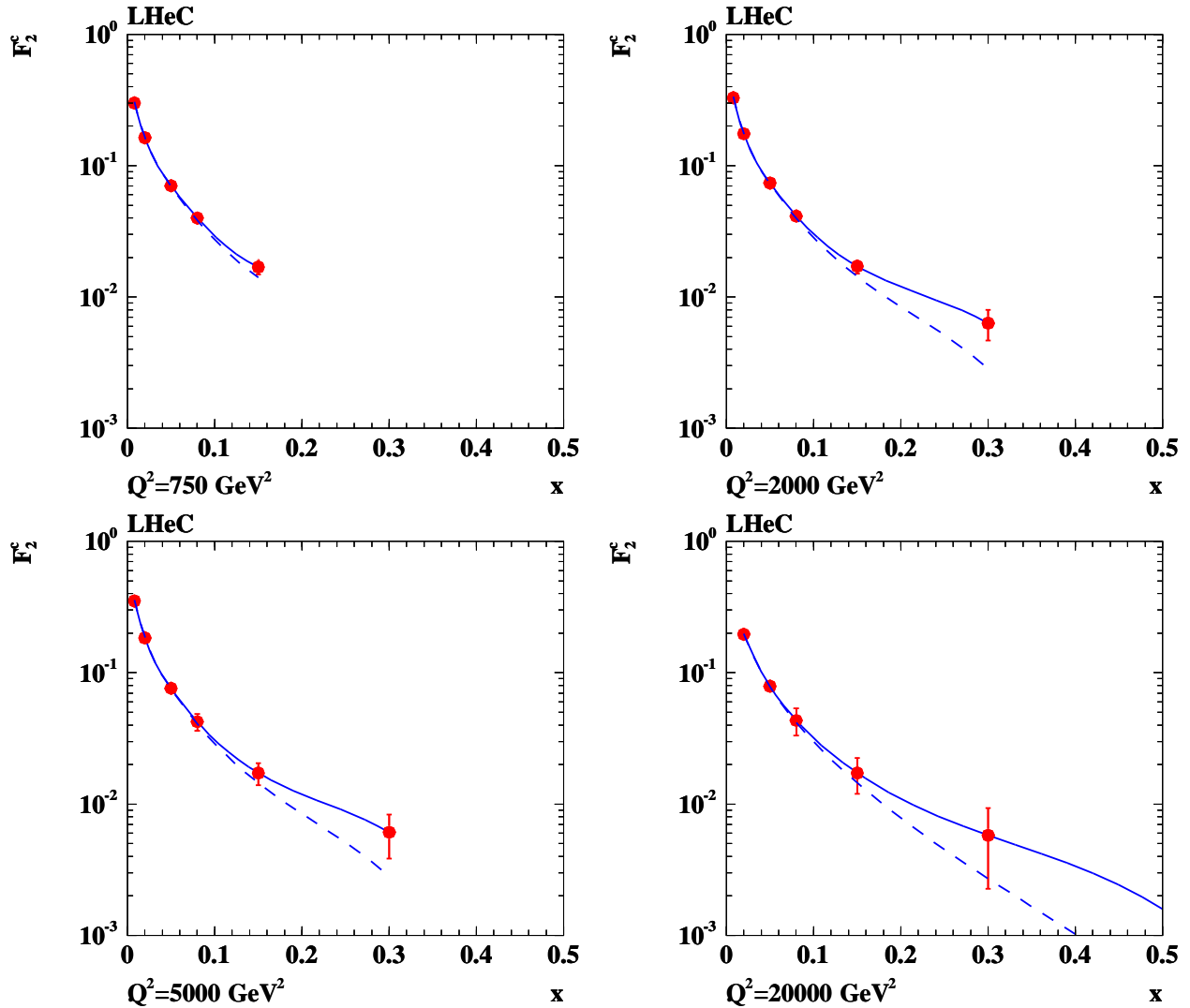


Figure 4.24: Simulation of measurement of the charm structure function at large x , see text. The errors are statistical, taking tagging and background efficiencies into account. The tagging efficiency for charm quarks was assumed to be 10% and the amount of background was estimated to be $0.01 \cdot N_{ev}$, where N_{ev} refers to the total number of expected NC events in the respective (Q^2, x) bin. Solide line: CTEQ66c predictions, including an intrinsic charm component, dashed line: ordinary CTEQ66m.

1662 charm may be larger than in the CTEQ attempt, it may also be smaller. One so finds that a reliable detection
 1663 of an intrinsic heavy charm component at the LHeC may be possible, but will be a challenge for forward
 1664 charm detection and requires high luminosity. The result yet may be rewarding as it would have quite some
 1665

1666 theoretical consequences as sketched above. It would be obtained in a region of high enough Q^2 to be able
 1667 to safely neglect any higher twist effects which may mimic such an observation at low energy experiments.

1668 4.6.5 D^* meson photoproduction study

1669 A study is presented of D^* meson photoproduction at LHeC compared to HERA. It is based on NLO
 1670 predictions in the so-called general-mass variable-flavour-number scheme (GM-VFNS) [122,123] for 1-particle
 1671 inclusive heavy-meson production. Both direct and resolved photon contributions are taken into account.
 1672 The cross section for direct photoproduction is a convolution of the proton PDFs, the cross section for the
 1673 hard scattering process and the fragmentation functions FF for the transition of a parton to the observed
 1674 heavy meson. For the resolved contribution, an additional convolution with the photon PDFs has to be
 1675 performed. For the photoproduction predictions at the ep -colliders HERA and LHeC, the calculated photon
 1676 proton cross sections are convoluted with the photon flux using the Weizsaecker-Williams approximation.

1677 In the GM-VFNS approach the large logarithms $\ln(p_T^2/m^2)$, which appear due to the collinear mass
 1678 singularities in the initial and final state, are factorized into the PDFs and the FFs and summed by the
 1679 well known DGLAP evolution equations. The factorization is performed following the usual $\overline{\text{MS}}$ prescrip-
 1680 tion which guarantees the universality of both PDFs and FFs. At the same time, mass-dependent power
 1681 corrections are retained in the hard-scattering cross sections, as in the FFNS. For the photon PDF the
 1682 parametrization of Ref. [140] with the standard set of parameter values is used and for the proton PDF the
 1683 parametrization CTEQ6.5 [141] of the CTEQ group. For the FFs the set Belle/CLEO-GM of Ref. [142] is
 chosen. Various combinations of beam energies are studied. To compare with the situation at HERA, as

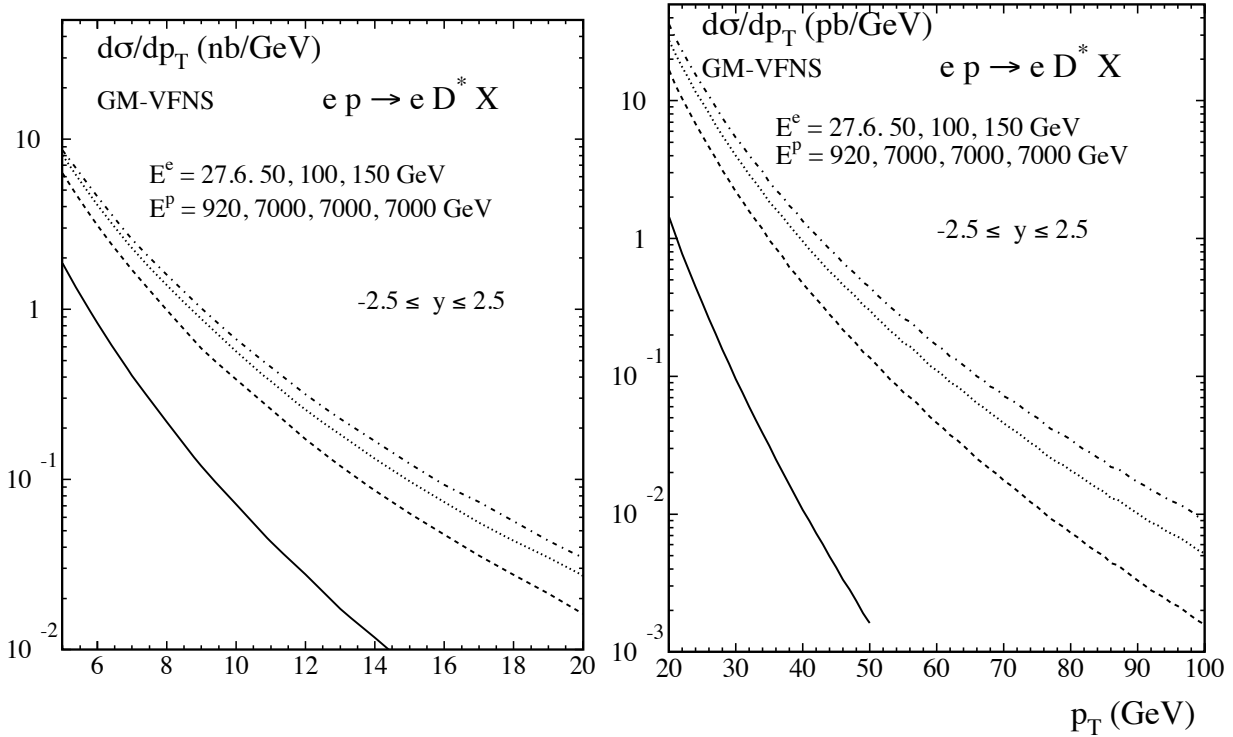


Figure 4.25: The p_T -differential cross section for the production of D^* mesons at LHeC for different beam energies integrated over rapidities $|\eta| \leq 2.5$, for the low- p_T range $5 \text{ GeV} \leq p_T \leq 20 \text{ GeV}$ (left) and for the high- p_T range $20 \text{ GeV} \leq p_T \leq 50 \text{ GeV}$ (right). The curves from bottom to top correspond to the combinations of beam energies as indicated in the figure.

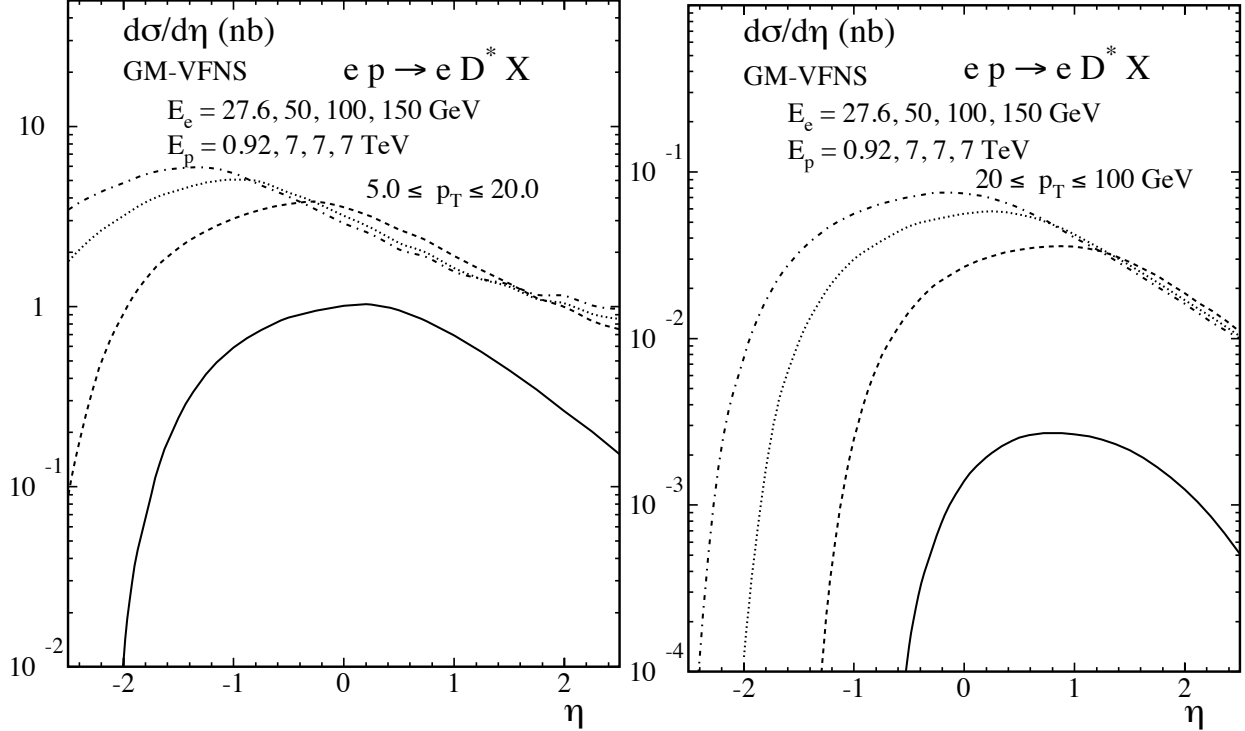


Figure 4.26: Rapidity distribution of the cross section for the production of D^* mesons at LHeC for different beam energies integrated over the low- p_T range $5 \text{ GeV} \leq p_T \leq 20 \text{ GeV}$ (left) and the high- p_T range $20 \text{ GeV} \leq p_T \leq 50 \text{ GeV}$ (right). The curves from bottom to top correspond to the combinations of beam energies as indicated in the figure.

1685 a reference, the values $E^p = 920 \text{ GeV}$ and $E^e = 27.5 \text{ GeV}$ for proton and electron energies, respectively,
 1686 are also included. For the LHeC the proton energy is taken to be always $E^p = 7 \text{ TeV}$ and the options
 1687 $E^e = 50, 100$ and 150 GeV are considered. The exchanged photons are restricted to inelasticities y in the
 1688 range $0.1 < y < 0.9$. The transverse momentum p_T and the rapidity η of the D^* -meson are varied in Fig. 4.25
 1689 in the kinematic ranges $5 < p_T < 20 \text{ GeV}$ or $20 < p_T < 100$ and $|\eta| < 2.5$. Numerical results are shown in Fig. 4.25
 1690 for the differential cross section $d\sigma/dp_T$ integrated over the rapidity $|\eta| \leq 2.5$ and in Fig. 4.26 for $d\sigma/d\eta$,
 1691 integrated over the p_T -ranges $5 \leq p_T \leq 20 \text{ GeV}$ and $20 \leq p_T \leq 100 \text{ GeV}$.

1692 The higher centre-of-mass energies available at the LHeC lead to a considerable increase of the cross
 1693 sections as compared to HERA. Obviously one can expect an increase in the precision of corresponding
 1694 measurements and much higher values of p_T , as well as higher values of the rapidity η , will be accessible.
 1695 Since theoretical predictions also become more reliable at higher p_T , measurements of heavy quark produc-
 1696 tion constitute a promising testing ground for perturbative QCD. One may expect that the experimental
 1697 information will contribute to an improved determination of the (extrinsic and intrinsic) charm content of
 1698 the proton and the charm fragmentation functions.

1699 4.7 High p_t jets

1700 4.7.1 Jets in ep

1701 The study of the jet final states in lepton-proton collisions allows the determination of aspects of the nucleon
 1702 structure which are not accessible in inclusive scattering. Moreover, jet production allows for probing pre-

1703 ditions of QCD to a high accuracy. Depending on the virtuality of the exchanged photon, one distinguishes
1704 processes in photoproduction (quasi-real photon) and deep inelastic scattering.

1705 The photoproduction cross section for di-jet final states can be studied in different kinematical regions,
1706 thereby covering a wide spectrum of physical phenomena, and probing the structure of the proton and the
1707 photon. Two-jet production in deep inelastic scattering is a particularly sensitive probe of the gluon distri-
1708 bution in the proton and of the strong coupling constant α_s . Both processes allow the study of potentially
1709 large enhancement effects in di-jet and multi-jet production.

1710 Jet production in photoproduction proceeds via the direct processes, in which the quasi-real photon
1711 interacts as a point-like particle with the partons from the proton, and the resolved processes, in which
1712 the quasi-real photon interacts with the partons from the proton via its partonic constituents. The parton
1713 distributions in the quasi-real photon are constrained mostly from the study of processes at e^+e^- colliders,
1714 and are less well-determined than their counterparts in the proton. In both the direct and the resolved
1715 process, there are two jets in the final state at lowest-order QCD. The jet production cross section is given in
1716 QCD by the convolution of the flux of photons in the electron (usually estimated via the Weizacker-Williams
1717 approximation), the parton densities in the photon, the parton densities in the proton and the partonic cross
1718 section (calculable in pQCD). Therefore, the measurements of jet cross sections in photoproduction provide
1719 tests of perturbative QCD and the structure of the photon and the proton.

1720 Owing to the large size of the cross section, photoproduction of di-jets can be used for precision physics
1721 in QCD. A measurement at LHeC could improve upon previous HERA results and enter into a much larger
1722 kinematical region. In measurements made by the ZEUS collaboration, the available photon-proton centre-of-
1723 mass energy ranged from 142 to 293 GeV, and jets of a transverse energy of up to 90 GeV could be observed.
1724 By comparing the measured cross section with the theoretical prediction in NLO pQCD, a value of $\alpha_s(M_Z)$
1725 was extracted with a total uncertainty of $\pm 3\%$ and the running of α_s was tested over a wide range of E_t^{jet} in
1726 a single measurement. The limiting factors in this measurement were the theoretical uncertainty inherent
1727 to the NLO prediction (which could be improved by computing NNLO corrections to jet photoproduction)
1728 and the experimental systematic uncertainty in the detector energy calibration.

1729 Another motivation for making new photoproduction experiments is to improve the knowledge of the
1730 parton content of the photon. At present, most information on the photon structure is inferred from the
1731 collision of quasi-real photons with electrons at e^+e^- colliders, resulting in a decent determination of the
1732 total (charge weighted) quark content of the quasi-real photon. Its gluonic content, and the quark flavour
1733 decomposition are on the other hand only loosely constrained. Improvements to the photon structure are of
1734 crucial importance to physics studies at a future linear e^+e^- collider like the ILC or CLIC. Such a collider,
1735 operating far above the Z -boson resonance, will face a huge background from photon-photon collisions.
1736 This background can be suppressed only to a certain extent by kinematical cuts. Consequently, accurate
1737 predictions of it (which require an improved knowledge of the photon's parton content) are mandatory for
1738 the reliable interpretation of hadronic final states at the ILC or CLIC. Several parametrizations of the parton
1739 distributions in the photon are available. They differ especially in the gluon content of the photon. For the
1740 studies presented here, the GRV-HO parametrization [143] is used as default.

1741 The photoproduction studies performed at LHeC were done for three different electron energy scenarios:
1742 $E_e=50, 100$ and 150 GeV. In all cases, the proton energy was set to 7 TeV. PYTHIA MC samples of
1743 resolved and direct processes were generated for these three scenarios. Jets were searched using the k_t -
1744 cluster algorithm in the kinematic region of $0.1 < y < 0.9$ and $Q^2 < 1$ GeV². Inclusive jet cross sections
1745 were done for jets of $E_t^{\text{jet}} > 15$ GeV and $3 < \eta^{\text{jet}} < 3$. Figure 4.27 shows the PYTHIA MC cross sections
1746 as functions of y for the three scenarios plus the corresponding cross section for the HERA regime. It can
1747 be seen that the LHeC cross sections are one to two orders of magnitude larger than the cross section at
1748 HERA.

1749 The full study was complemented with fixed-order QCD calculations at order α_s and α_s^2 using the
1750 program by Klasen et al. [144] with the CTEQ6.1 sets for the proton PDFs, GRV-HO sets for the photon
1751 PDFs, $\alpha_s(M_Z) = 0.119$ and the renormalisation and factorisation scales were set to the transverse energy of
1752 each jet.

1753 Figure 4.28 shows the inclusive jet cross sections at parton level as functions of E_t^{jet} for the three en-

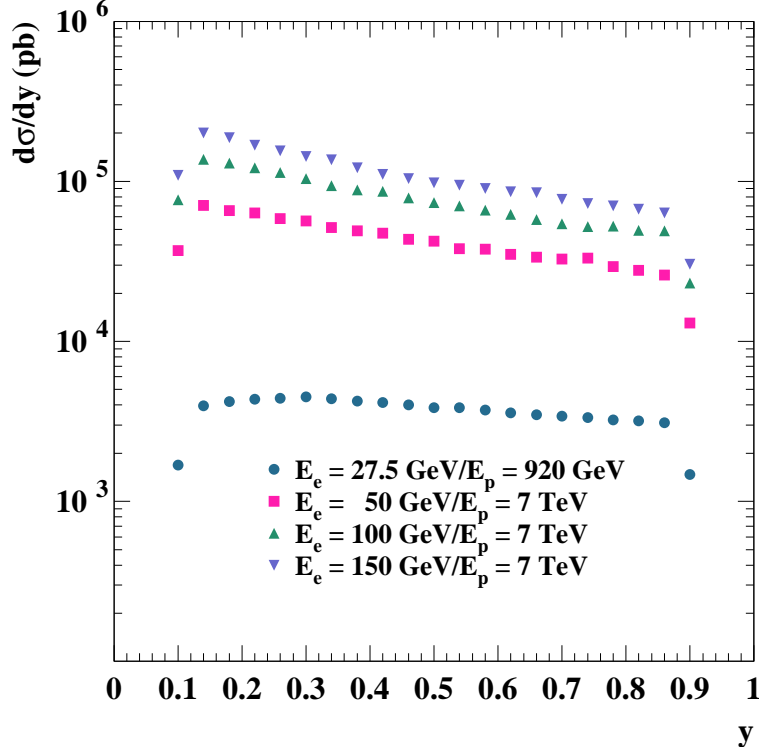


Figure 4.27: PYTHIA predictions for photoproduction cross section at HERA and for three LHeC scenarios.

1754 energy scenarios for the PYTHIA res+dir (red dots), PYTHIA resolved (blue triangles) and PYTHIA direct
 1755 (pink triangles) together with the predictions from the NLO (solid curves) and LO (dashed curves) QCD
 1756 calculations. The calculations predict a sizeable rate for Etjet of at least up to 200 GeV. Resolved processes
 1757 dominate at low E_t^{jet} , but the direct processes become increasingly more important as E_t^{jet} increases. The
 1758 PYTHIA cross sections (which have been normalised to the NLO integrated cross section) agree well in shape
 1759 with the NLO calculations. Investigating the η^{jet} distribution, we find that resolved processes dominate in
 1760 the forward region, while direct processes produce more central jets.

1761 Figure 4.29 show the inclusive jet cross sections at parton level as functions of E_t^{jet} (on the left) and
 1762 η^{jet} (on the right) for the PYTHIA resolved+direct (symbols) and the predictions from the NLO (solid
 1763 curves) and LO (dashed curves) QCD calculations together for the three energy scenarios. For comparison,
 1764 the calculations for the HERA regime are also included. It is seen that the cross sections at fixed E_t^{jet}
 1765 increase and that the jets tend to go more backward as the collision energy increases. The much larger
 1766 photon-proton centre-of-mass energies that could be available at LHeC provide a much wider reach in E_t^{jet}
 1767 and η^{jet} compared to HERA.

1768 Hadronisation corrections for the cross sections shown were investigated. The corrections are predicted
 1769 to be quite small, below +5% for the chosen scenarios. Since the hadronisation corrections are very small,
 1770 the features observed at parton level remain unchanged.

1771 Inclusive-jet and dijet measurements in deep-inelastic scattering (DIS) have since long been a tool to
 1772 test concepts and predictions of perturbative QCD. Especially at HERA, jets in DIS have been thoroughly
 1773 studied, and the results have provided deep insights, giving for example precise values for the strong coupling
 1774 constant, α_s and providing constraints for the proton PDFs.

1775 An especially interesting region for such studies has been the regime of large (for HERA) Q^2 values of, for
 1776 example, $Q^2 > 125 \text{ GeV}^2$. In this regime, the theoretical uncertainties, especially those due to the unknown

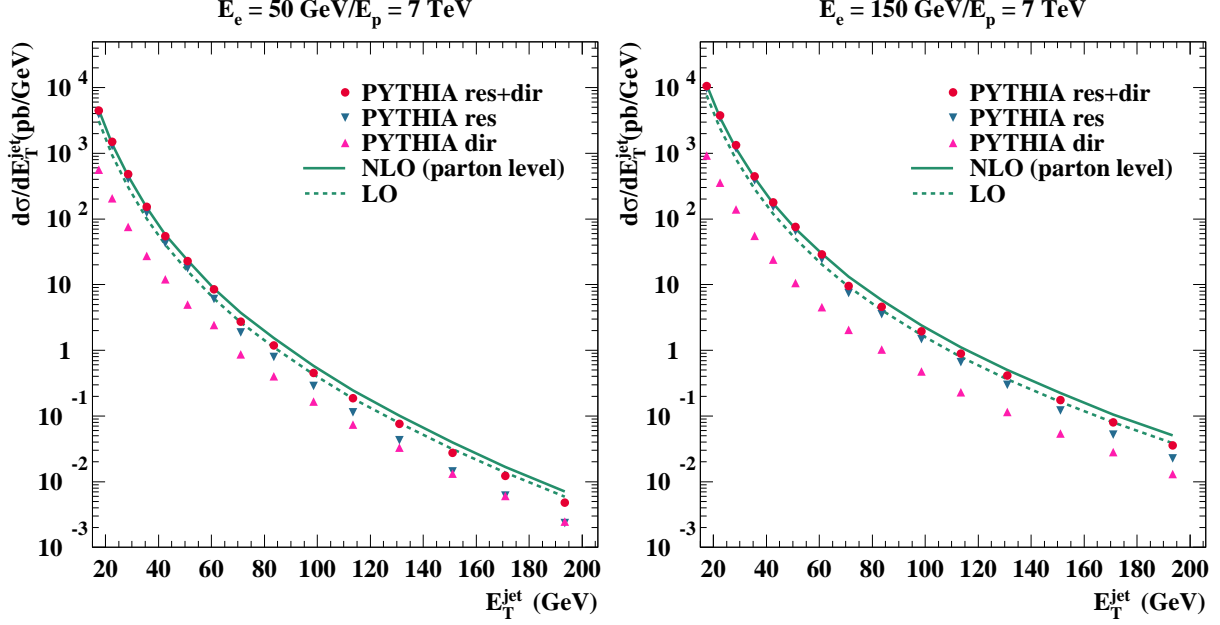


Figure 4.28: Parton level predictions for the inclusive transverse energy distribution in photoproduction.

1777 effects of missing higher orders in the perturbative expansion, are found to be small. Recently, both the H1
 1778 and ZEUS collaborations have published measurements of inclusive-jet and dijet events in this kinematic
 1779 regime.

1780 An extension of such measurements to the LHeC is interesting for two reasons: First, the provided high
 1781 luminosity will allow measurements in already explored kinematic regions with still increased experimental
 1782 precision. Second, the extension in centre-of-mass energy, \sqrt{s} , and thus in boson virtuality, Q^2 , and in jet
 1783 transverse energy, $E_{T,jet}$, will potentially allow to study pQCD at even higher scales, extending the scale
 1784 reach for measurements of the strong coupling or the precision of the proton PDFs at large values of x .

1785 To explore the potential of such a measurement, we investigated DIS jet production for the following LHeC
 1786 scenario: proton beam energy 7 TeV, electron beam energy 70 GeV and integrated luminosity 10 fb^{-1} . The
 1787 study concentrates on the phase space of high boson virtualities Q^2 , with event selection cuts $100 < Q^2 < 500$
 1788 000 GeV^2 and $0.1 < y < 0.7$, where y is the inelasticity of the event. Jets are reconstructed using the k_T
 1789 clustering algorithm in the longitudinally invariant inclusive mode in the Breit reference frame. Jets were
 1790 selected by requiring: a jet pseudorapidity in the laboratory of $-2 < \eta_{lab} < 3$, a jet transverse energy in the
 1791 Breit frame of $E_{T,jet}^{Breit} > 20 \text{ GeV}$ for the inclusive-jet measurement and jet transverse energies in the Breit
 1792 frame of 25(20) GeV for the leading and the second-hardest jet in the case of the dijet selection.

1793 For inclusive-jet production we study cross sections in the indicated kinematic regime as functions of
 1794 Q^2 , x_{Bj} , $E_{T,jet}^{Breit}$ and η_{jet}^{lab} , the jet pseudorapidity in the laboratory frame. For dijet production, studies are
 1795 presented as functions of Q^2 , the logarithm of the proton momentum fraction ξ , $\log_{10} \xi$, the invariant dijet
 1796 mass M_{jj} , the average transverse energy of the two jets in the Breit frame, $\overline{E_{T,jet}^{Breit}}$, and of half of the absolute
 1797 difference of the two jet pseudorapidities in the laboratory frame, η' .

1798 For the binning of the observables shown here, the statistical uncertainties for the indicated LHeC in-
 1799 tegrated luminosity can mostly be neglected, even at the highest scales. The systematic uncertainties were
 1800 assumed to be dominated by the uncertainty on the jet energy scale which was assumed to be known to 1%
 1801 or 3% (both scenarios are indicated with different colours in the following plots), leading to typical effects on
 1802 the jet cross sections between 1 and 15%. A further relevant uncertainty is the acceptance correction that is
 1803 applied to the data which was assumed to be 3% for all observables.

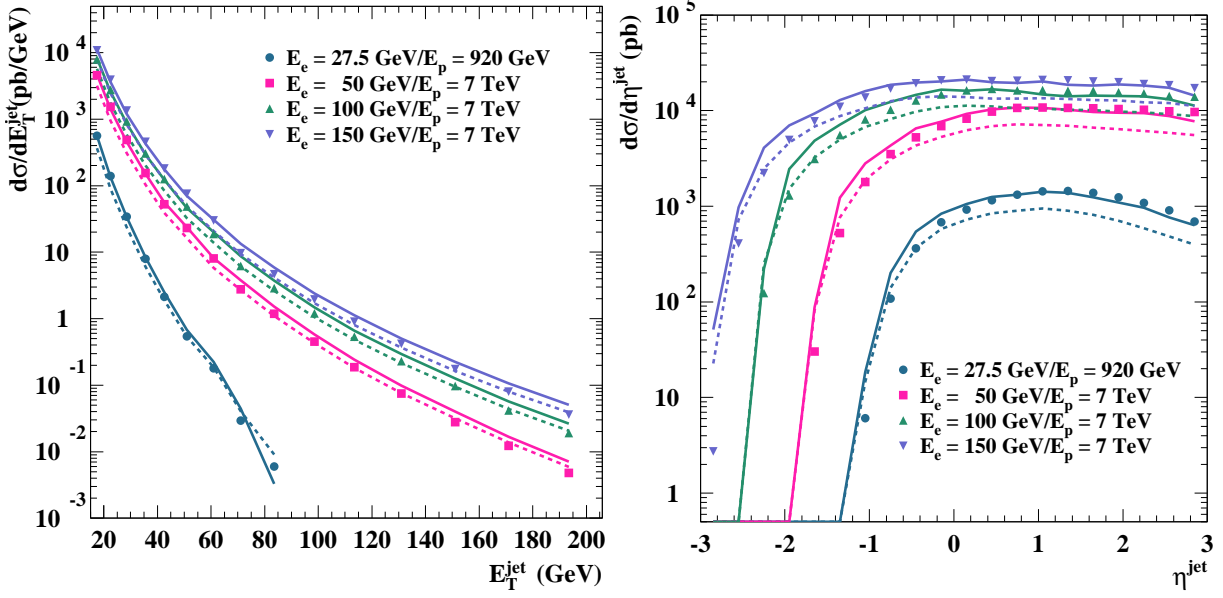


Figure 4.29: Dijet distributions in photoproduction as function of the jet transverse energy (left) and of the jet rapidity (right) for different LHeC energies compared to the HERA kinematic range.

1804 The theoretical calculations were performed with the DISINT program [145] using the CTEQ6.1 proton
 1805 PDFs [131, 146]. The central default squared renormalisation and factorisation scales were set to Q^2 . The
 1806 theory calculations for the LHeC scenario were corrected for the effects of hadronisation and Z^0 exchange
 1807 using Monte Carlo data samples simulated with the LEPTO program [134].

1808 Theoretical uncertainties were assessed by varying the renormalization scale up and down by a factor
 1809 2 (to estimate the potential effect of contributions beyond NLO QCD), by using the 40 error sets of the
 1810 CTEQ6.1 parton distribution functions, and by varying α_s using the CTEQ6AB PDF [147]. The dominant
 1811 theory uncertainty turned out to be due to the scale variations, resulting in effects of a few to up to 20%
 1812 or more, for example for low values of Q^2 or, for the case of the dijet measurement, for low values of the
 1813 invariant dijet mass, M_{jj} , or the logarithm of momentum fraction carried into the hard scattering, $\log_{10} \xi$.

1814 Note that for the inclusive-jet results also the predictions for a HERA scenario with almost the same
 1815 selection are shown in order to indicate the increased reach of the LHeC with respect to HERA. The only
 1816 change is a reduction in centre-of-mass energy to 318 GeV and a reduced Q^2 reach, $125 < Q^2 < 45\,000 \text{ GeV}^2$.
 1817 The HERA predictions shown were also corrected for hadronisation effects and the effects of Z^0 exchange.

1818 Figure 4.30 shows the inclusive jet cross section as function of Q^2 and of the jet transverse energy
 1819 in the Breit frame, while Figure 4.31 shows the dijet cross section as function of Q^2 and of $\xi = x_{Bj}(1 +$
 1820 $M_{jj}^2/Q^2)$. The top parts of the figures show the predicted cross sections together with the expected statistical
 1821 and (uncorrelated) experimental systematic uncertainties as error bars. The correlated jet energy scale
 1822 uncertainty is indicated as a coloured band; the inner, yellow band assumes an uncertainty of 1%, the outer,
 1823 blue band one of 3%. Also shown as a thin hashed area are the theoretical uncertainties; the width of the
 1824 band indicates the size of the combined theoretical uncertainty. In case of inclusive-jet production, also the
 1825 predictions for HERA are indicated as a thin line.

1826 The bottom parts of the figures show the relative uncertainties due to the jet energy scale (yellow band
 1827 for 1%, blue band for 3%), the statistical and uncorrelated experimental systematic uncertainties as inner
 1828 / outer error bars, and the combined theoretical uncertainties as hashed band. The inner part of this band
 1829 indicates the uncertainty due to the variation of the renormalisation scale.

1830 The inclusive-jet cross section as function of Q^2 shows a typical picture: In most region of the phase

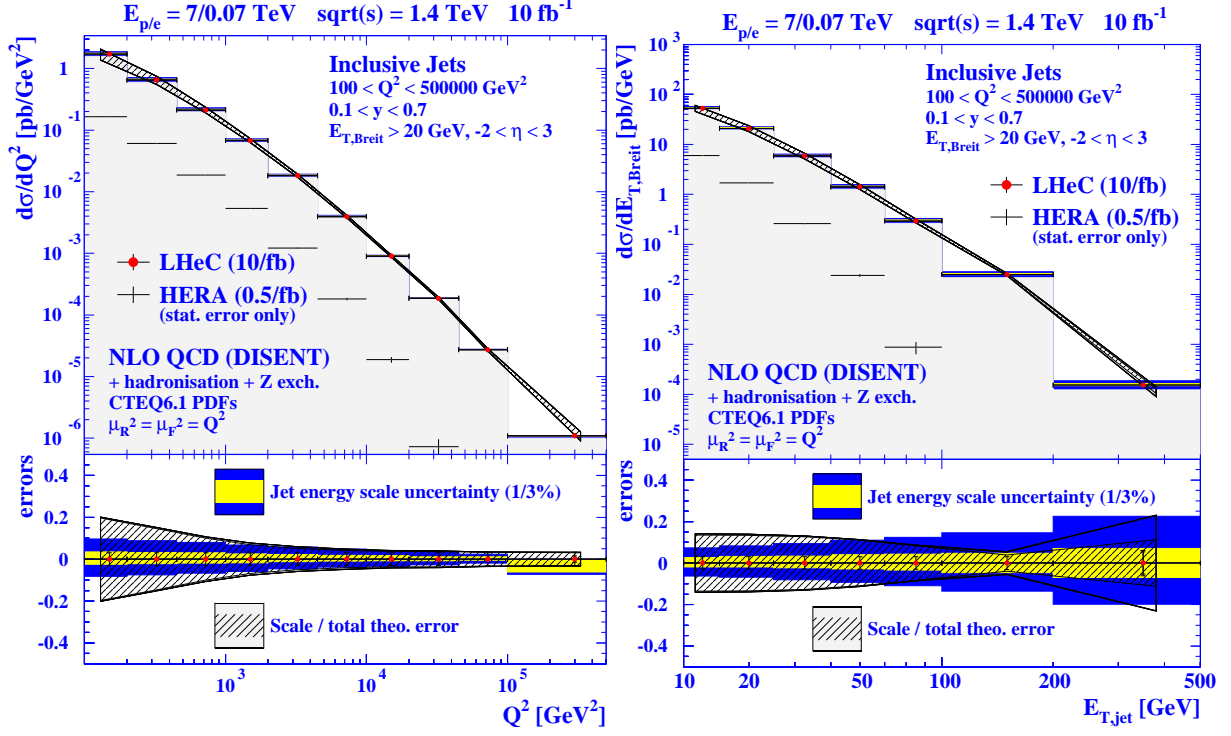


Figure 4.30: Predicted LHeC results for inclusive jet production as function of Q^2 and of E_T in the Breit frame. Predictions for HERA results are also shown.

1831 space, the uncertainties are dominated by the theory uncertainties, and here mainly by the renormalisation
 1832 scale uncertainty. The typical size of experimental uncertainties is of the order of 10%, with larger values
 1833 in regions with low relevant scales — i.e. low invariant dijet masses, low jet transverse energies or low Q^2
 1834 values. The theoretical uncertainties are typically between 5 and 20%, with partially strong variations over
 1835 the typical range of the observable in question.

1836 A comparison with the HERA predictions for inclusive-jet production shows that the LHeC cross sections
 1837 is typically larger by 1 to 3 orders of magnitude. The dijet final state allows for a full reconstruction of the
 1838 partonic kinematics, and can thus be used to probe the parton distribution functions in Q^2 and ξ . It can
 1839 be seen that a measurement at LHeC covers a large kinematical range ranging down to $\xi \approx 10^{-3}$ and up to
 1840 $Q^2 = 10^5 \text{ GeV}^2$. Potentially limiting factors in an extraction of parton distribution functions are especially
 1841 the jet energy scale uncertainty on the experimental side and missing higher order (NNLO) corrections on the
 1842 theory side. The jet energy scale uncertainty can be addressed by the detector design and by the experimental
 1843 setup of the measurement. NNLO corrections to dijet production in deep inelastic scattering are already
 1844 very much demanded by the precision of the HERA data, their calculation is currently in progress [148, 149].

1845 In summary, jet final states in photoproduction and deep inelastic scattering at the LHeC promise a wide
 1846 spectrum of new results on the partonic structure of the photon and the proton. They allow for precision tests
 1847 of QCD by independent determinations of the strong coupling constant over a kinematical range typically
 1848 one to two orders of magnitude larger than what was accessible at HERA. The resulting parton distributions
 1849 will have a direct impact for precision predictions at the LHC and a future linear collider.

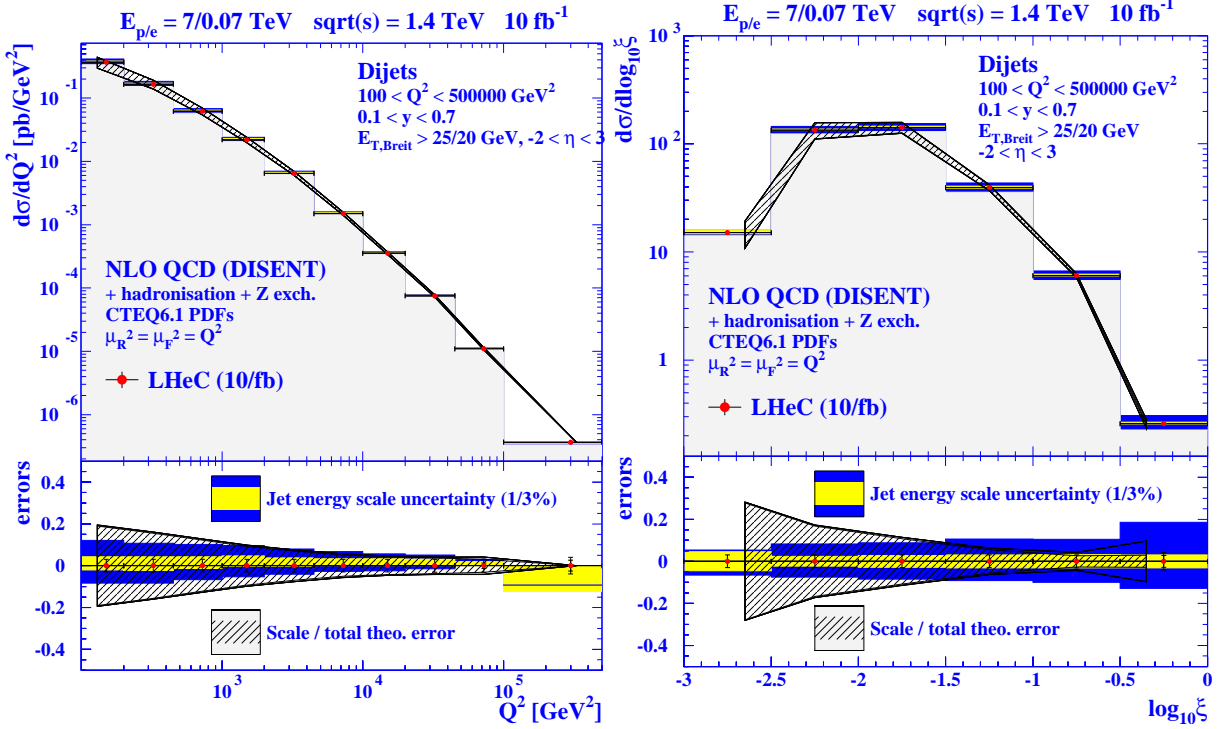


Figure 4.31: Predicted LHeC results for dijet production as function of Q^2 and of ξ .

4.7.2 Jets in γA

1850

1851 For photoproduction in eA collisions, jets provide an abundant yield of high-energy probes of the nuclear
1852 medium. The expected cross sections have been computed using the calculations in [150,151], for an electron
1853 beam of 50 GeV colliding with the LHC beams. For the nuclear case the same integrated luminosity (2 fb^{-1})
1854 was assumed per nucleon as for ep . Only jets with $E_{T,jet} > 20$ GeV are considered, and for the distribution
1855 in $E_{T,jet}$ the pseudorapidity acceptance is $|\eta_{jet}| < 3.1$, corresponding to $5^\circ < \theta_{jet} < 175^\circ$ in polar angle. The
1856 simulations use the Weizsäcker-Williams photon flux from the electron with the standard option in [150,151].
1857 The chosen photon, proton and nuclear modified PDFs are taken from GRV-HO [152], CTEQ6.1M [146] and
1858 EPS09 [153], respectively - see Subsec. 6.1.4 for explanations on the nuclear modifications of PDFs. The
1859 renormalization and factorization scales are taken to be $\mu_R = \mu_F = \sum_{jets} E_{T,jet}/2$ and the inclusive k_T jet
1860 algorithm [154] is used with $D = 1$. The statistical uncertainty in the computation (i.e. in the Monte Carlo
1861 integration) is smaller than 10 % for all results shown. This large statistical uncertainty is reached only
1862 for the largest $E_{T,jet}$, with much smaller uncertainties at lower values of E_T . No attempt has been made
1863 to estimate the uncertainties due to the choices of photons flux, photon or proton parton densities, scales
1864 or jet algorithms (see [155,156] for such considerations at HERA). The issues of background subtraction,
1865 experimental efficiencies in the jet reconstruction or energy calibration have also yet to be addressed. The
1866 only uncertainty studied thus far is that due to the nuclear parton densities, which is extracted in the EPS09
1867 framework [153] using the Hessian method.

1868

1869 The results are shown in Fig. 4.32. One observes that yields of around 10^3 jets per GeV are expected
1870 with $E_{T,jet} \sim 95$ (80) GeV in ep (ePb), for $|\eta_{jet}| < 3.1$ and the considered integrated luminosity of 2 fb^{-1} per
1871 nucleon. The effects of the nuclear modification of parton densities and their uncertainties are smaller than
1872 10 %. The two-peak structure in the η_{jet} -plot results from the sum of the direct plus resolved contributions,
1873 each of which produce a single maximum, located in opposite hemispheres. Positive η_{jet} values are dominated
by direct photon interactions, whereas negative η_{jet} values are dominated by contributions from resolved

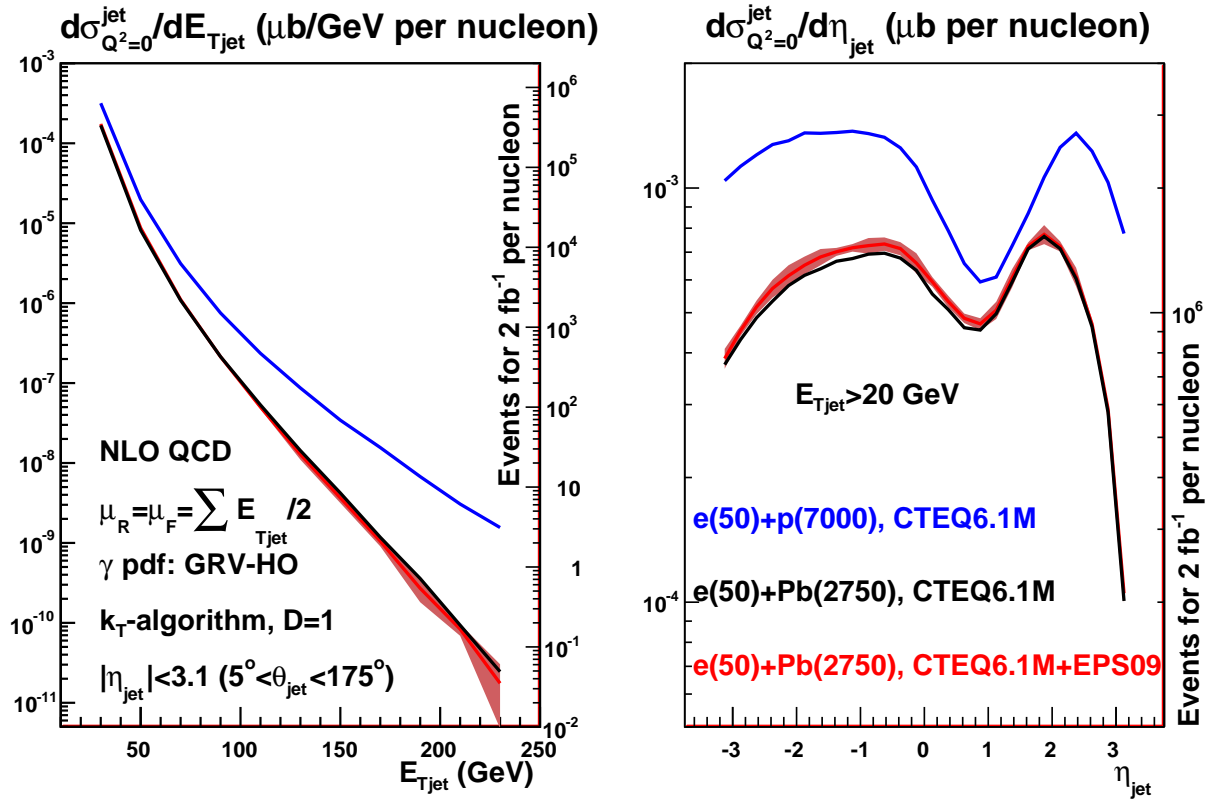


Figure 4.32: Predictions for the inclusive jet distribution in photoproduction, differential in E_{Tjet} (left) and η_{jet} (right) for $e(50)+p(7000)$ (blue, top lines), $e(50)+Pb(2750)$ without nuclear modification of the parton densities (black lines), and $e(50)+Pb(2750)$ with EPS09 nuclear modification of the parton densities (red lines for the central value and bands for the uncertainty coming from the nuclear modification factors). See the text and the legends on the plots for further details of the calculations and kinematic cuts. In both plots, the axis on the left corresponds to the cross section in μb , while the axis on the right provides the number of jets expected for an integrated luminosity of 2 fb^{-1} per nucleon, per unit of E_{Tjet} (η_{jet}) in the plot on the left (right).

1874 photons.

1875 4.8 Total photoproduction cross section

1876 Due to the $1/Q^4$ propagator term, the LHeC ep cross section is dominated by very low Q^2 quasi-real photons.
 1877 With a knowledge of the effective photon flux [157], measurements in this kinematic region can be used to
 1878 obtain real photoproduction (γp) cross sections. The real photon has a dual nature, sometimes interacting
 1879 in a point-like manner and sometimes interacting through its effective partonic structure, resulting from
 1880 $\gamma \rightarrow q\bar{q}$ and higher multiplicity splittings well in advance of the target [158, 159], the details of which are
 1881 fundamental to the understanding of QCD evolution.

1882 The behaviour of the total photoproduction cross section at high energy is a topic of a major interest.
 1883 It is now firmly established experimentally that all hadronic cross sections rise with centre of mass energy
 1884 for large energies. The Froissart-Martin bound has been derived for hadronic probes. It therefore remains

1885 to be seen whether this bound is applicable to γp scattering. For example in Refs. [160, 161] it has been
 1886 argued that the bound for real photon-hadron interactions should be of a different functional form, namely
 1887 $\ln^3 s$. This would imply that the universality of the asymptotic behaviour of hadronic cross sections does
 1888 not hold. Therefore the measurement of the total photoproduction cross section at high energies will bring
 1889 an important insight into the problems of universality of hadronic cross sections, unitarity constraints, the
 1890 role of diffraction and the interface between hard and soft physics.

1891 In Fig. 4.33, available data on the total cross section are shown [64, 162–164]⁶, together with a variety
 1892 of models. More specifically, the dot-dashed black line labelled ‘FF model GRS’ is a minijet model [166],
 1893 the yellow band labelled ‘Godbole et al.’ is an eikonized minijet model with soft gluon resummation [166]
 1894 with the band defined by different choices of the parameters in the model, the red solid line labelled ‘Block
 1895 & Halzen’ is based on a low energy parametrization of resonances joined with Finite Energy Sum Rules and
 1896 asymptotic $\ln^2 s$ -behaviour [167, 168], and the dashed blue line labelled ‘Aspen model’ is a QCD inspired
 1897 model [169].

1898 The theoretical predictions diverge at energies beyond those constrained by HERA data, where cross
 1899 sections were obtained by tagging and measuring the energies of electrons scattered through very small angles
 1900 in dedicated calorimeters located well down the beampipe in the outgoing electron direction [162, 163]. As
 1901 discussed in Chapter 14, the most promising location for similar small angle electron detectors at the LHeC
 1902 is in the region around 62 m from the interaction point, which could be used to tag scattered electrons in
 1903 events with $Q^2 < 0.01 \text{ GeV}^2$ and $y \sim 0.3$. This naturally leads to measurements of the total photoproduction
 1904 cross section at γp center-of-mass energies $W \sim 0.5\sqrt{s}$. The measurements would be strongly limited by
 1905 systematics. In the absence of a detailed simulation of an LHeC detector these uncertainties are hard to
 1906 estimate. For the simulated data in Fig. 4.33, uncertainties of 7% have been assumed, matching the precision
 1907 of the H1 and ZEUS data. This would clearly be more than adequate to distinguish between many of the
 1908 available models. The HERA uncertainties were dominated by the invisible contributions from diffractive
 1909 channels in which the diffractive masses were too small to leave visible traces in the main detector. If detector
 1910 acceptances to 1° are achieved at the LHeC, better precision is expected to be possible.

1911 4.9 Electroweak physics

1912 4.9.1 The context

1913 Precision electroweak measurements at low energy have played a central role in establishing the Standard
 1914 Model (SM) as the theory of fundamental interactions. More recently, measurements at LEP, SLD, and
 1915 the Tevatron have confirmed the SM at the quantum level, verifying the existence of its higher-order loop
 1916 contributions. The sensitivity of these contribution to virtual heavy particles has allowed for an estimate of
 1917 the mass of the top quark prior to its actual discovery in 1995 by the CDF and DØ Collaborations. Now that
 1918 the determination of the top mass at the Tevatron has become quite accurate, reaching the 1% level, and
 1919 M_W is known with an error of 23 MeV, electroweak precision measurements imply significant constraints on
 1920 the mass of the last missing piece of the SM, the Higgs boson. The current situation has been analysed for
 1921 instance in [170, 171] taking into account the results of direct searches for the Higgs boson at LEP-2 and the
 1922 Tevatron, which currently exclude a SM Higgs boson with mass lower than 114 GeV or in a narrow window
 1923 around 160 GeV. At 95% CL, if the SM is correct, the Higgs boson must soon be found with mass below
 1924 155 GeV either at the Tevatron or at the LHC.

1925 Electroweak precision measurements are also very effective in constraining the possible extensions of
 1926 the SM. In general, the observed good quality of the SM fit disfavors new physics at an energy scale of
 1927 $O(100 \text{ GeV})$ that modifies the Higgs mechanism in a drastic way. On the other hand, the fit does present
 1928 a few interesting deviations at the level of $2\text{--}3\sigma$. There is a significant tension between the FB asymmetry
 1929 of $Z \rightarrow b\bar{b}$ measured at LEP, which favors a heavy Higgs, and the LR asymmetry in $Z \rightarrow \ell\bar{\ell}$ and the W
 1930 mass, which both favors a very light Higgs. Unfortunately, the present determination of M_H depends largely

⁶The recent results by ZEUS [165] refer only to the energy behavior of the cross section in the range $194 < W < 296 \text{ GeV}$, but do not provide absolute values.

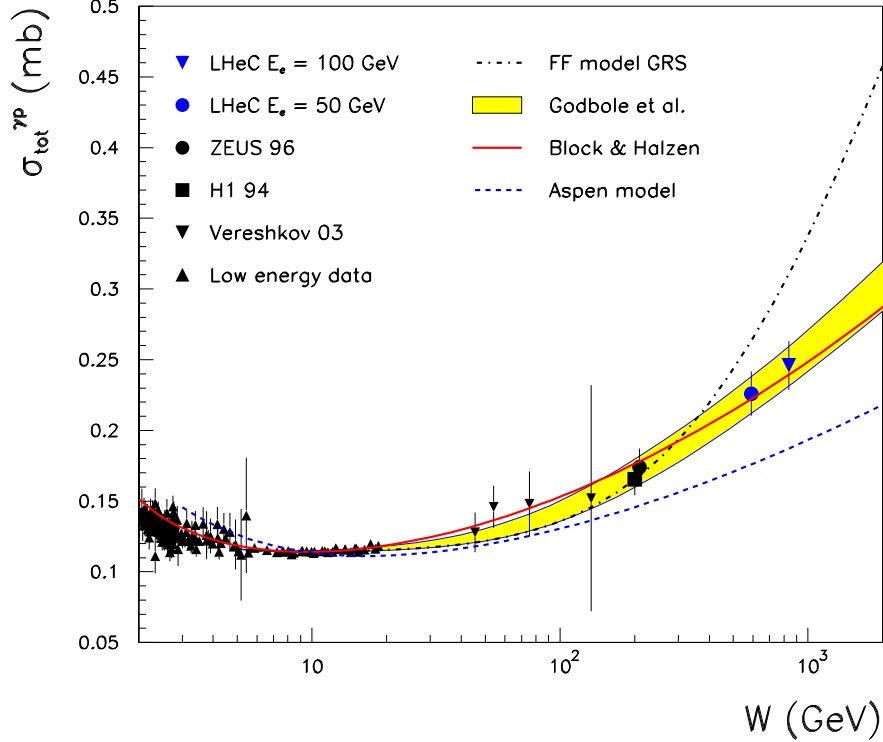


Figure 4.33: Simulated LHeC measurements of the total photoproduction cross section with $E_e = 50$ GeV or $E_e = 100$ GeV, compared with previous data and a variety of models (see text for details). This is derived from a similar figure in [166].

1931 on these conflicting information, whose origin could be either statistical or rooted in new physics around
 1932 the corner [172]. Another plausible $\sim 3\sigma$ hint of physics beyond the SM, without Higgs implications, is the
 1933 discrepancy between the measured magnetic anomalous moment of the muon and its SM prediction [173].

1934 It is unlikely that operating experiments will change significantly the above picture of electroweak precision
 1935 measurements. The Tevatron and LHC will marginally improve the current precision on the top mass
 1936 and reach a combined 15 MeV uncertainty on M_W , while LHCb might be able to achieve an interesting accuracy
 1937 in the measurement of $\sin^2 \theta_W$ [174,175]. Two experiments at Jefferson Lab, Q-weak [176] and (later)
 1938 MOLLER [177], will measure the weak mixing angle from parity violation in ep and e^-e^- scattering at low
 1939 energy: these are interesting measurements complementary to the existing ones; MOLLER, in particular,
 1940 may eventually reach an accuracy similar to that of LEP. It is widely expected that either the Higgs boson
 1941 or further new physics will be discovered at the LHC, if not both. This is the context in which precision
 1942 electroweak measurements at LHeC are set.

1943 The electroweak measurements possible at LHeC are of the kind performed at HERA (see [178,179] for
 1944 an overview). However, they will greatly benefit from the higher energy and larger luminosity, as well as from
 1945 highly polarized lepton beams, and therefore also include processes, as single standard model or anomalous
 1946 top quark production, which were impossible to study in ep before.

1947 A first class of measurements involves polarized charged currents (CC) only. They include a verification
 1948 of the left-handedness of CC from the polarization dependence of the CC cross-section. At HERA this has
 1949 led to a bound on possible right-handed currents, expressed in terms of the mass of a right-handed W_R boson
 1950 that couples to quarks with the same strength as the SM one. While the HERA result, $M_{W_R} > 210$ GeV
 1951 at 95% CL, can be significantly improved at the LHeC, low-energy flavour bounds and direct searches for
 1952 W type new bosons at the LHC are more sensitive. It yet is interesting to verify the universality of space-

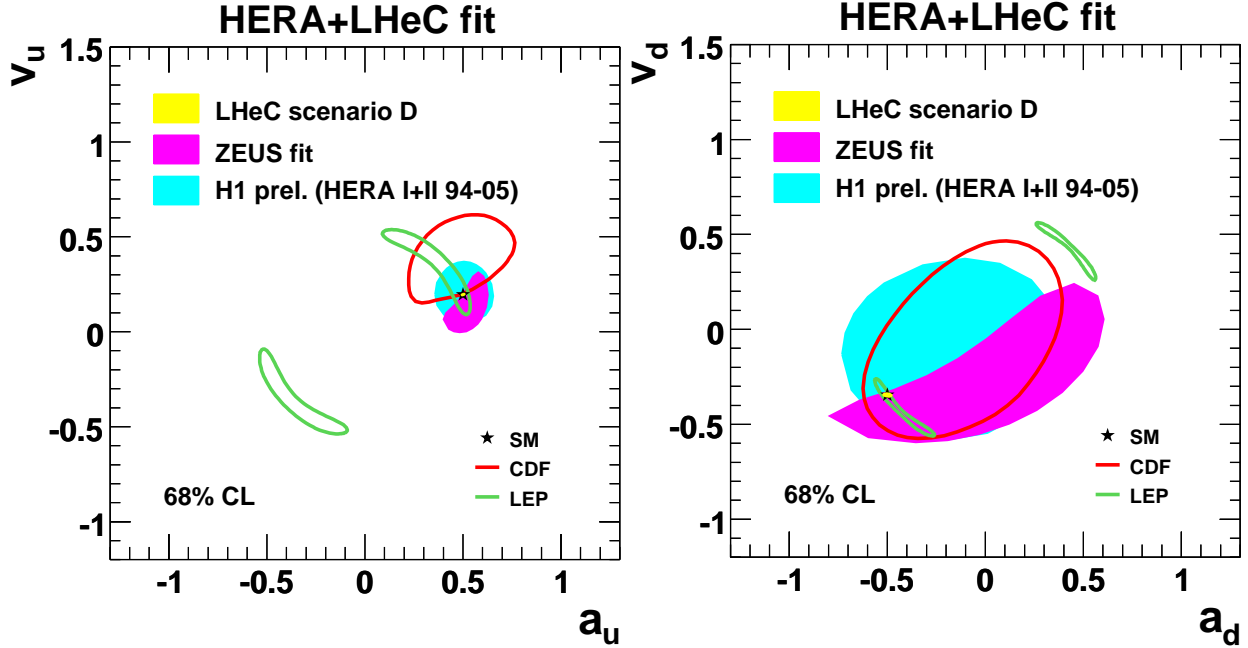


Figure 4.34: Determination of the vector and axial NC couplings of the light quarks at LEP, CDF, HERA and LHeC. - plot to be updated.

1953 and timelike interactions and thus to determine the propagator mass from the CC cross section through its
 1954 Q^2 dependence, $\propto (M_W^2/(M_W^2 + Q^2))^2 \phi(x, Q^2)$. At the LHeC, the HERA W propagator mass uncertainty
 1955 value may be improved by a factor of 10 to about 150 MeV.

1956 4.9.2 Light Quark Weak Neutral Current Couplings

1957 The LHeC will be able to measure the neutral current couplings of the light quarks at unprecedented
 1958 precision. As can be seen in Fig. 4.34, LEP has been able to constrain only an ambiguous combination of
 1959 them as the couplings enter as squares in pure weak NC reactions.

1960 DIS experiments with polarized electron and positron beams can completely disentangle the vector and
 1961 axial couplings of up and down type light quarks. As illustrated in Fig.4.34, the preliminary results by ZEUS
 1962 and H1 have improved on the LEP determination in the case of the up quarks [179–181]. Very recent D0
 1963 results, obtained from the Z/γ^* forward-backward asymmetry in the electron channel, somewhat improve on
 1964 HERA constraints [182]. However, a simultaneous determination of the four light quark couplings, based on
 1965 a luminosity of 5 fb^{-1} with D0, still gives uncertainties of order $0.1 - 0.2$, which are an order of magnitude
 1966 less precise than the expected DIS result at the LHeC.

1967 The sensitivity of the LHeC to the light quark NC couplings has been studied with a QCD fit to the
 1968 simulated data, in which the PDFs and the NC quark couplings are simultaneously determined. Here the
 1969 electron couplings are fixed, as they are very precisely measured at LEP and SLD. The expected resolution
 1970 for scenario D of LHeC is hardly visible on the scale of Fig. 4.34. A comparison among the various LHeC
 1971 scenarios can be found in Fig. 4.35 The accuracy on the vector and axial vector couplings of the u , d quarks
 1972 ranges, in the best possible scenario, between 1 and 4%, with an improvement wrt HERA by a factor 10
 1973 to 40. A better determination of the light quark NC couplings will particularly constrain New Physics
 1974 models that modify significantly the light quark NC couplings, without affecting the well-measured lepton
 1975 and heavy quark couplings. It is not easy to realize such an exotic scenario in a natural way, although
 1976 family non-universal (leptophobic) Z' models (see for instance [183,184] and refs. therein), R-parity violating

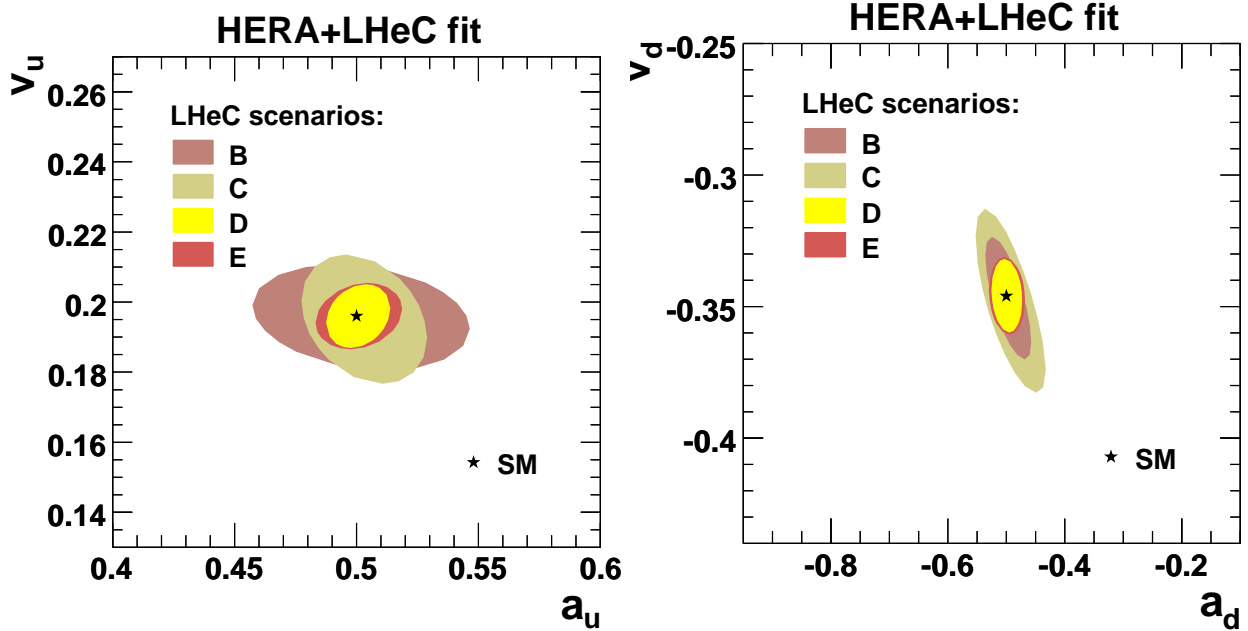


Figure 4.35: Determination of the vector and axial NC couplings of the light quarks at LHeC, comparison different scenarios.

1977 supersymmetry (see [185] for a review) and leptoquarks [186] can in principle succeed. LHeC could therefore
 1978 accurately test a spectrum of interesting new physics models. A specific linear combination of the light quark
 1979 NC vector couplings (v_u and v_d) might be measured at the per cent level by the QWeak Collaboration [176].
 1980 Their results, combined with existing precise measurements of Atomic Parity Violation and DIS, could
 1981 provide a percent determination of v_u and v_d [187] and test the same kind of models, but it will not probe
 1982 the axial quark couplings.

1983 4.9.3 Determination of the Weak Mixing Angle

1984 Cross Section Asymmetries and Ratios

1985 The LHeC is a unique facility for electroweak physics because of the very high luminosity, high measurement
 1986 precision and the extreme range of momentum transfer Q^2 . Fig. 4.36 illustrates the reach and the size of
 1987 the electroweak effects in NC scattering. Depending on the charge and polarisation of the electron beam,
 1988 the contributions from γZ interference and pure Z exchange become comparable to or even exceed the
 1989 photon exchange contribution, i.e. of F_2 , which has dominated hitherto all NC DIS measurements. With the
 1990 availability of two charge and two polarisation states, of neutral and charged current measurements, proton
 1991 and isoscalar targets, a unique menu becomes available for testing the electroweak theory. For example,
 1992 one can very precisely measure light quark weak neutral current couplings, discussed above. One can also
 1993 test the universality of $\gamma - g$ and $Z - g$ fusion by extracting the heavy quark (c , b) contributions from γZ
 1994 interference. A remarkable measurement illustrated in the following regards the energy dependence of the
 1995 weak mixing angle $\sin^2 \Theta$.

1996 Tests of the electroweak theory in DIS require to simultaneously control the parton distribution effects.
 1997 With the outstanding data base from the LHeC, joint QCD and electroweak fits become possible to high
 1998 orders perturbation theory. Cross section asymmetries and ratios can also be used to determine electroweak
 1999 parameters. Particularly useful examples are polarisation and charge asymmetries and also NC to CC cross
 2000 section ratios.

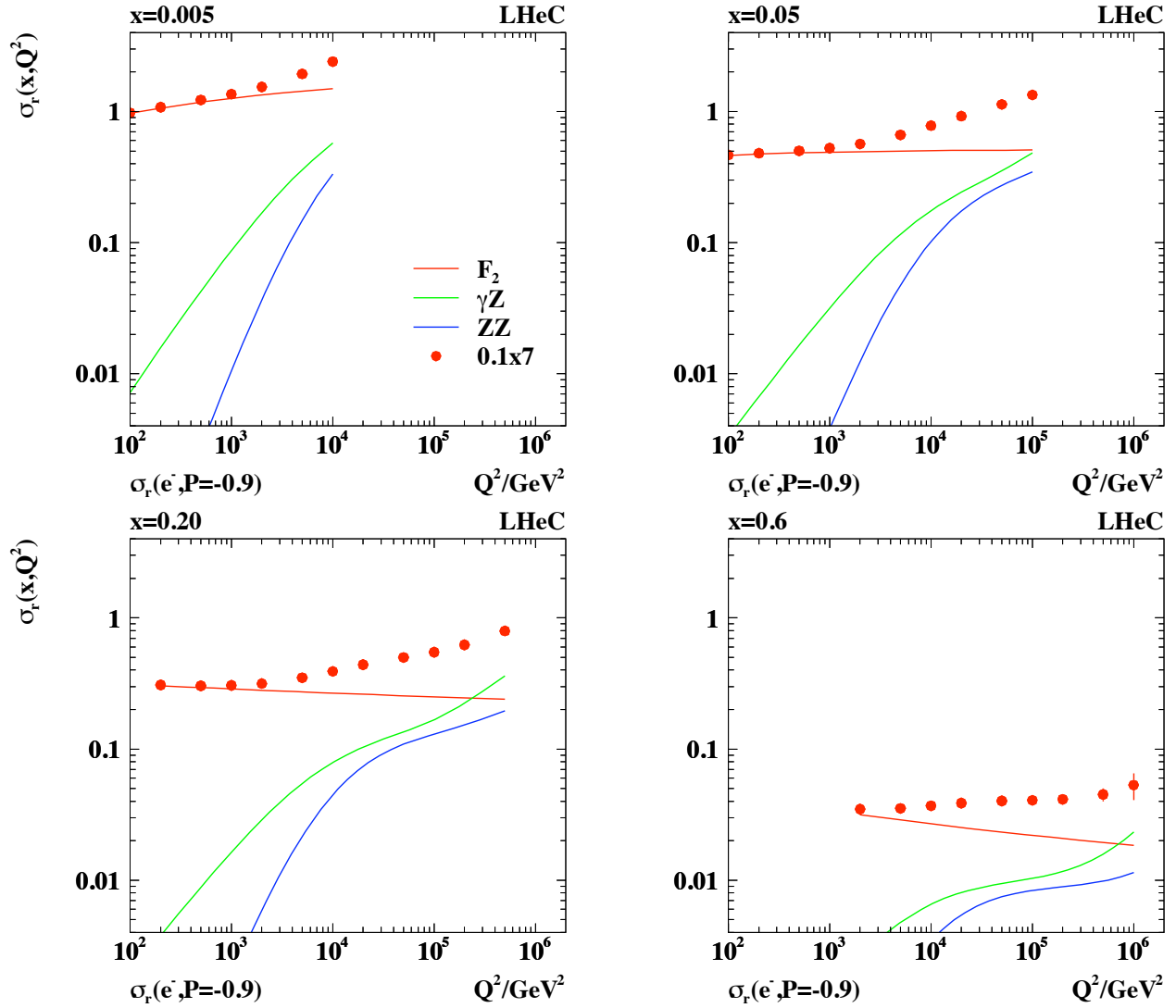


Figure 4.36: Simulated measurement of the neutral current DIS cross section (closed points) with statistical errors for 10 fb^{-1} shown as a function of Q^2 for different values of Bjorken x . The different curves represent the contributions of pure photon exchange (red), γZ interference (green) and pure Z exchange (blue) as prescribed in Eq. 4.5. Note the high precision of the reduced cross section measurement up to large x and Q^2 .

2001 In NC scattering, the polarisation asymmetry

$$A^\pm = \frac{1}{P_R - P_L} \cdot \frac{\sigma_{NC}^\pm(P_R) - \sigma_{NC}^\pm(P_L)}{\sigma_{NC}^\pm(P_R) + \sigma_{NC}^\pm(P_L)} \quad (4.31)$$

2002 served for the decisive confirmation of the left handed weak neutral current doublet structure as was predicted
 2003 by the GWS theory in 1979 [188]. The size of the electroweak asymmetries is given by the relative amount
 2004 of Z to photon exchange $O(10^{-4}Q^2/\text{GeV}^2)$, i.e. it becomes of order 1 at high Q^2 at the LHeC.

2005 To a good approximation the asymmetry measures the structure function ratio

$$A^\pm \simeq \mp \kappa_Z a_e \frac{F_2^{\gamma Z}}{(F_2 + \kappa_Z a_e Y_- x F_3^{\gamma Z} / Y_+)} \simeq \mp \kappa_Z a_e \frac{F_2^{\gamma Z}}{F_2}. \quad (4.32)$$

2006 Thus A^+ is expected to be about equal to $-A^-$ and to be only weakly dependent on the parton distributions.
 2007 The product of the axial coupling of the electron and the vector coupling of the quarks, inherent in $F_2^{\gamma Z}$,
 2008 determines the polarisation asymmetry to be parity violating. A measurement of A^\pm provides a unique and
 2009 precise measurement of the scale dependence of the weak mixing angle, as is discussed below (Sect. 4.9.3).
 2010 At large x the polarisation asymmetry provides an NC measurement of the d/u ratio of the valence quark
 2011 distributions, according to

$$A^\pm \simeq \pm \kappa \frac{1 + d_v/u_v}{4 + d_v/u_v}. \quad (4.33)$$

2012 Further asymmetries of NC cross sections have been discussed in [58].

2013 The neutral-to-charged current cross-section ratio

$$R^\pm = \frac{\sigma_{NC}^\pm}{\sigma_{CC}^\pm} = \frac{2}{(1 \pm P)\kappa_W^2} \cdot \frac{\sigma_{r,NC}^\pm}{\sigma_{r,CC}^\pm} \quad (4.34)$$

2014 is of interest for electroweak physics too as will be demonstrated below. At very high $Q^2 \gg M_Z^2$ and
 2015 neglecting terms in the NC part proportional to v_e it becomes approximately equal to

$$R^\pm \simeq \frac{2a_e^2}{(1 \pm P)\cos^2\theta} \cdot \frac{Y_+ F_2^Z - Y_- P x F_3^Z}{Y_+ W_2^\pm + Y_- x W_3^\pm} \quad (4.35)$$

2016 which reveals the striking similarity of the neutral and charged weak interactions at high energies. One may
 2017 further consider, for example, a quantity which is the eN analogon to the Paschos-Wolfenstein relation [189]
 2018 in νN scattering

$$A_{NCC} = \frac{\sigma_{NC}^+ - \sigma_{NC}^-}{\sigma_{CC}^+ - \sigma_{CC}^-}. \quad (4.36)$$

2019 The very high luminosity and Q^2 range of the LHeC as compared even to HERA will open a completely
 2020 new era of electroweak physics in DIS.

2021 Measurement of the Weak Mixing Angle

2022 Further tests of the SM at the quantum level and indirect searches for new physics require ultimate precision.
 2023 Such corrections occur in the factor $1 - \Delta r$, see Eq. 4.14, which depends on the top mass, logarithmically
 2024 on the Higgs mass and possibly on new, heavy particles. A measurement of the weak mixing angle, $\sin^2\theta$,
 2025 to 0.01% precision should fix the Higgs mass to 5% accuracy. The so far most precise measurements of
 2026 $\sin^2\theta$ have been performed at the Z pole in e^+e^- scattering, using the very high statistics, at LEP, and
 2027 in the case of the SLC, the large beam polarisation of 75% too. The LHeC has the potential to measure
 2028 weak asymmetries and cross section ratios at, below and beyond the M_Z scale by precisely measuring their
 2029 dependence on $\sqrt{Q^2}$.

2030 The accuracy estimated for $\sin^2 \theta$ depends on its definition. The electroweak theory has three independent
 2031 parameters. For the subsequent study, as in a similar study of H1 [180], the values of α and M_Z are fixed,
 2032 which are best known, M_Z to 0.002 %. For the estimate of the sensitivity to electroweak effects as the third
 2033 parameter here $\sin^2 \theta$ is chosen, which is used, together with α and M_Z to calculate G and M_W and also
 2034 occurs in the weak neutral current couplings ⁷. This way both the NC and the CC cross sections are sensitive
 2035 to $\sin^2 \theta$. Equivalently one could have expressed all parameters using α , M_Z and M_W , and determine M_W .
 2036 Due to the relation $\sin^2 \theta = 1 - M_W^2/M_Z^2$, the error of such an indirect measurement of M_W is

$$\Delta M_W = \frac{M_W \delta \sin^2 \theta}{2 \sin^2 \theta}, \quad (4.37)$$

2037 i.e. a one permille accuracy on $\sin^2 \theta$ corresponds to $\Delta M_W = 40$ MeV.

2038 A simulation is done of the NC and CC cross sections depending on the lepton beam charges and
 2039 polarisations based on the formulae presented above. This allows to build a variety of asymmetries and
 2040 cross section ratios and derive their sensitivity to the weak mixing angle. An example is illustrated in
 2041 Fig. 4.37. Here the polarisation asymmetry (left) and the NC/CC ratio (right) are calculated for different
 2042 values of $\sin^2 \Theta$ using two recent sets of leading order parton distributions, CTEQ6LL and MSTW08. The
 2043 measurement accuracy of $\sin^2 \Theta$ has a statistical, a polarisation, a systematic and a pdf uncertainty. One
 2044 derives that the statistical precision is about 0.1 % for the NC asymmetry A^- and even 0.05 % for the NC/CC
 2045 ratio R^- for e^-p scattering with an assumed polarisation of -0.8 and a luminosity of 10 fb^{-1} for default
 2046 beam energies.

2047 At this early stage of consideration one may not present a full error study. However, a few first con-
 2048 siderations are in order: The high luminosity and large Q^2 range move the electroweak physics at this ep
 2049 machine to the level of highest accuracy demands. Most of the systematic errors cancel in asymmetry and
 2050 ratio measurements. A 0.1 % electron energy scale uncertainty, as has been achieved with H1, for example,
 2051 translates at the LHeC to a 0.15 % change of A^- and a negligible change of R^- . This measurement samples
 2052 data in a region of very high cross section accuracy and can exclude the highest x region where uncertainties
 2053 grow like $1/(1-x)$. The desired level of polarisation measurement is obviously about a permille, which seems
 2054 to be possible as is discussed in the detector chapter.

2055 The requirements for A^- and R^- are different. The asymmetry A^- requires frequent changes of the
 2056 polarisation to control the time dependence of the measurement. It measures essentially a ratio of the
 2057 structure functions $F_2^{\gamma Z}/F_2$ and therefore it is rather insensitive to uncertainties related to the parton
 2058 distributions. In fact, one observes in Fig. 4.37 that the predictions of the two PDF sets considered differ
 2059 by less than the statistical uncertainty for A^- . The NC/CC ratio R is less sensitive to time drifts as the
 2060 NC and CC data are taken simultaneously. Its statistical power is highest, as had already been noticed for
 2061 HERA [190]. It yet is sensitive to the PDFs. For the two sets of PDFs considered here, an about two per cent
 2062 difference is calculated of the R^- ratios. This would spoil the extraction of $\sin^2 \Theta$. The high sensitivity of R
 2063 to the mixing angle can only be employed when the PDFs are much better known than so far. This, however,
 2064 is one of the major goals of the LHeC physics programme and large improvements are to be expected as
 2065 is discussed in Sec. 4.2. The potential of measuring $\sin^2 \Theta$ from NC/CC ratios is observed to be particular
 2066 striking. However, for the evaluation of the scale dependence of $\sin^2 \Theta$ below, the results derived from A^-
 2067 are used due to its much smaller PDF sensitivity.

2068 The mixing angle, similar to α_s , is predicted to vary strongly as a function of the scale μ , which in DIS
 2069 is precisely known and given as $\sqrt{Q^2}$. This dependence results from higher order loop effects as calculated
 2070 in [191]. Precise measurements to per mille uncertainty were performed at the Z pole by SLC and LEP
 2071 experiments. Recent low energy experiments have provided measurements of $\sin^2 \Theta$ at very low Q^2 as from
 2072 the parity violation asymmetry due to polarisation conjugation in Moeller scattering at $Q^2 = 0.026 \text{ GeV}^2$
 2073 by the E158 experiment. At scale values of about 5 GeV the NuTeV Collaboration has determined the
 2074 mixing angle which for some time created a substantial experimental and theoretical effort when it appeared

⁷An interesting test is also to fix α , M_Z and G and to determine derived electroweak parameters as M_W or $\sin^2 \Theta$ for precision consistency checks in the search for deviations from the SM. Such a study has not been undertaken so far for the LHeC.

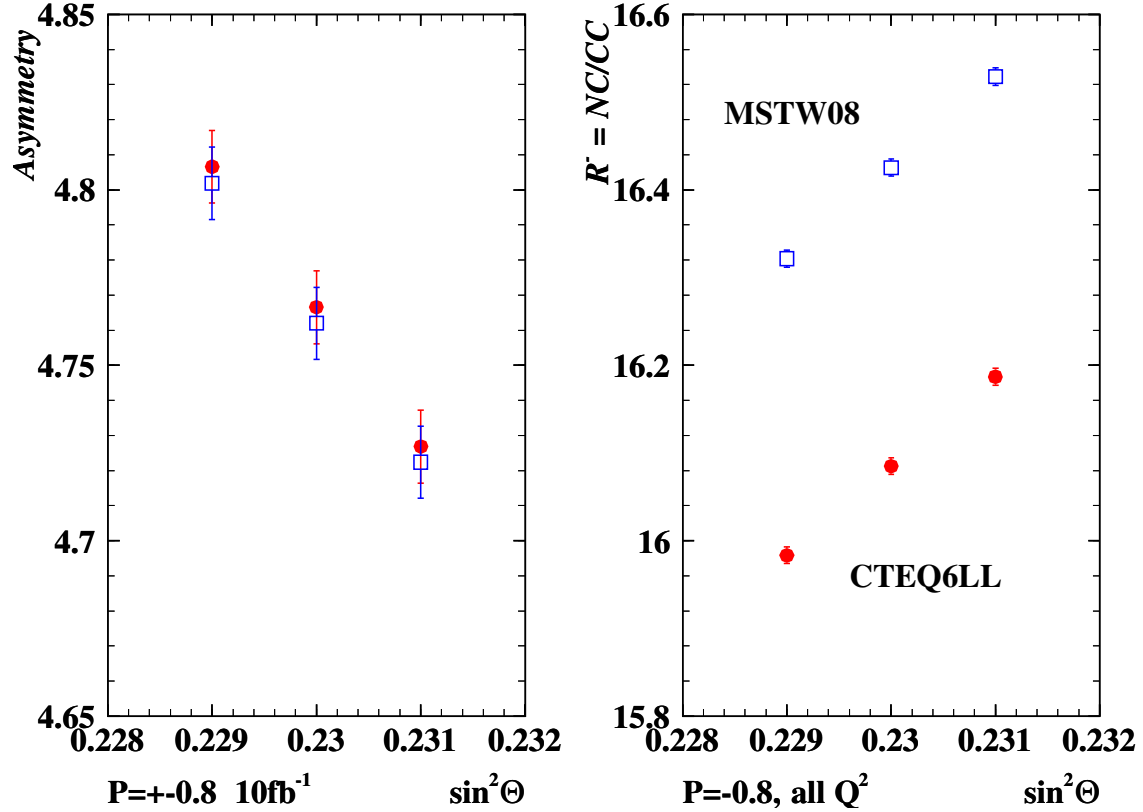


Figure 4.37: Simulated measurement of the polarisation NC cross section asymmetry A^- (left), in per cent for $P = \pm 0.8$, and the ratio of neutral-to-charged current cross sections, $R = NC/CC$ (right), for $P = -0.8$, for different values of $\sin^2 \theta$. The errors are statistical for luminosities of 10 fb^{-1} per beam for polarised electron scattering for $E_e = 60 \text{ GeV}$ and the nominal 7 TeV proton beam. The closed (open) symbols show the simulation for the CTEQ6LL (MSTW08) leading order parameterisations of the parton distributions. The average Q^2 is 1300 GeV^2 for the NC asymmetry A^- , while for the ratio R the average CC Q^2 is about 9500 GeV^2 . Consequently, the mean x in NC and CC differs by a factor of 6, which is at the origin of the large differences in R between the two PDF set predictions.

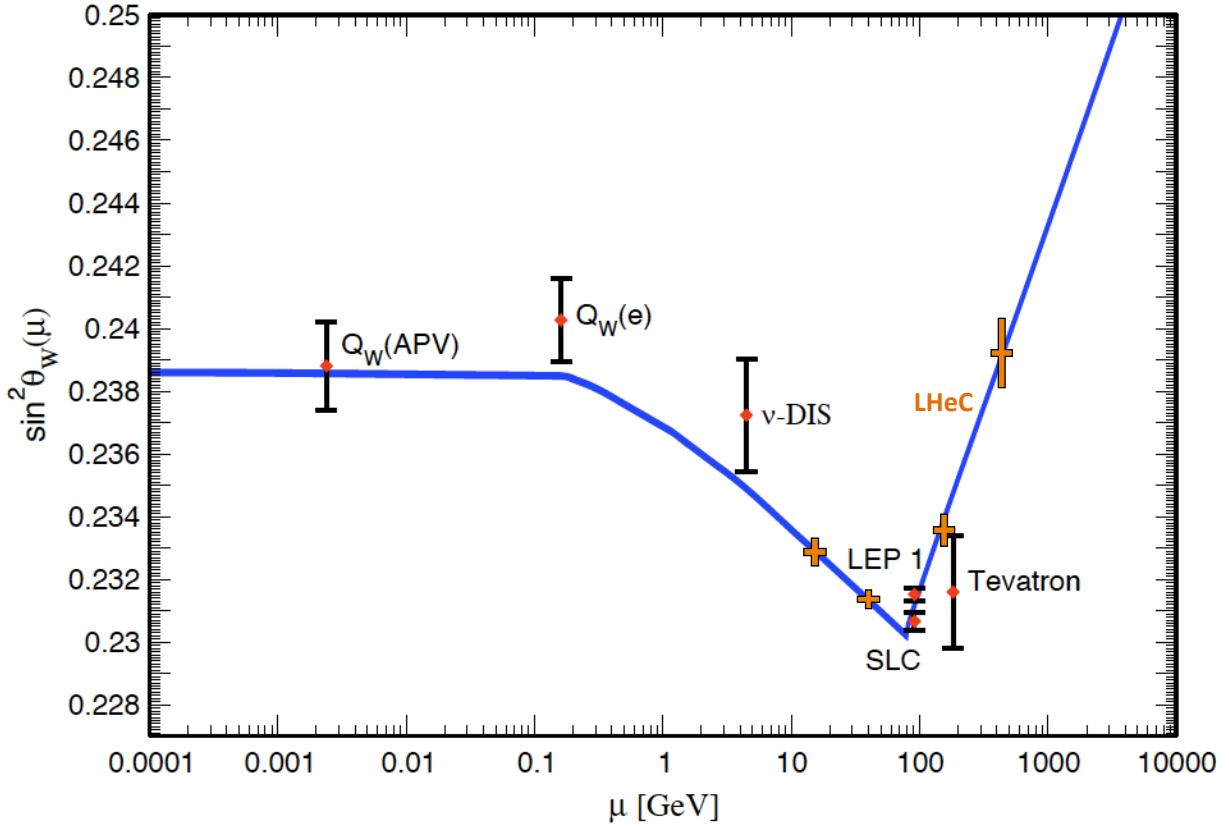


Figure 4.38: Dependence of the weak mixing angle on the energy scale μ , taken from [64]. Four simulated points have been added based on the estimated measurement accuracy using the polarisation asymmetry A^- binned in intervals of $\sqrt{Q^2}$, see text.

Type	Q_1	P_1	Q_2	P_2	$\delta s(A_{12})$	$\delta s(R_1)$	$\delta s(R_2)$
e^- Polarisation Conjugation	-1.	-0.8	-1.	0.8	0.00026	0.00009	0.00024
e^+ Polarisation Conjugation	+1.	-0.8	+1.	0.8	0.00027	0.00040	0.00015
e^- Low P Conjugation	-1.	-0.4	-1.	0.4	0.00052	0.00010	0.00015
Charge Conjugation $P=0$	+1.	0.	-1.	0.	0.01600	0.00019	0.00012
Charge Conjugation $P=\mp 0.8$	+1.	-0.8	-1.	0.8	—	0.00040	0.00024
Charge Conjugation $P=\pm 0.8$	+1.	+0.8	-1.	-0.8	0.00790	0.00015	0.00009
e^- PC Low $Q^2 \sim 300 \text{ GeV}^2$	-1.	-0.8	-1.	0.8	0.00068	0.00029	0.00083
e^- PC Med $Q^2 \sim 1500 \text{ GeV}^2$	-1.	-0.8	-1.	0.8	0.00027	0.00012	0.00029
e^- PC High $Q^2 \sim 22000 \text{ GeV}^2$	-1.	-0.8	-1.	0.8	0.00044	0.00071	0.00055
e^- PC vHigh $Q^2 \sim 130000 \text{ GeV}^2$	-1.	-0.8	-1.	0.8	0.00170	0.00460	0.00200

Table 4.6: Estimated accuracies of the weak mixing angle, $\delta \sin^2 \Theta$ from simulated measurements of the NC asymmetry and the NC/CC cross section ratio for different beam charge and polarisation conditions.

2075 to be above the theoretical expectation by a few standard deviations. Explanations of this “anomaly”
2076 included variations of the strange quark density, effects from QED or nuclear corrections. An ultraprecise
2077 measurement of $\sin^2 \Theta$ is envisaged, yet still at $\mu = M_Z$, if a new Z_0 factory was built.

2078 The current measurements are summarised in Fig.4.38. The plot also contains projected $\sin^2 \Theta$ uncer-
2079 tainty values from the LHeC, as listed in Table4.6, which result from simulations of the parity violation
2080 asymmetry A^- in polarised e^-p scattering, for scales between about 10 and 400 GeV. Due to the high statis-
2081 tics nature of the DIS NC process, the variation of $\sin^2 \Theta$ as a function of $\sqrt{Q^2}$ can be measured for a large
2082 range of $\sqrt{Q^2}$. At low scales the range limited by the sensitivity to the Z exchange effects and at high scales
2083 by the kinematic limit and luminosity. It may deserve a study to understand to how low values of Q^2 the
2084 asymmetry A^- can be determined in a meaningful measurement, which is related to time drifts, polarisation
2085 flip times etc. and likely can only be answered with real data. It is to be noted that previous and planned
2086 fixed target experiments measure this asymmetry at extremely small values of Q^2 as compared to the range
2087 of the LHeC.

2088 From the range considered here, with $Q^2 > 300 \text{ GeV}^2$, it can be concluded, see Fig.4.38, that the expected
2089 measurement accuracy would lead to a decisive test of the scale dependence of $\sin^2 \Theta$.

Chapter 5

New Physics at Large Scales

Although the LHC is expected to be the discovery machine for physics beyond the Standard Model at the TeV scale, it will not always be possible to measure with precision the parameters of the new physics. In this section, it is shown that in many cases the LHeC can probe in detail deviations from the expected electroweak interactions shared by leptons and quarks, thus adding essential information on the new physics. Previous studies [2, 192–194] of the potential of high-energy $e-p$ colliders for the discovery of exotic phenomena have considered a number of processes, most of which are reviewed here.

In some cases, Standard Model processes can also be better measured at the LHeC. Here, the charged and neutral current processes of SM Higgs production by vector boson fusion are investigated with the goal of measuring the $H-b-b$ coupling.

5.1 New Physics in inclusive DIS at high Q^2

The LHeC collider would enable the study of deep inelastic neutral current scattering at very high squared momentum transfers Q^2 , thus probing the structure of eq interactions at very short distances. At large scales new phenomena not directly detectable may become observable as deviations from the Standard Model predictions. A convenient tool to assess the experimental sensitivity beyond the maximal available center of mass energy and to parameterise indirect signatures of new physics is the concept of an effective four-fermion contact interaction. If the contact terms originate from a model where fermions have a substructure, a compositeness scale can be related to the size of the composite object. If they are due to the exchange of a new heavy particle, such as a leptoquark, the effective scale is related to the mass and coupling of the exchanged boson. Contact interaction phenomena are best observed as a modification of the expected Q^2 dependence and all information is essentially contained in the differential cross section $d\sigma/dQ^2$. An alternative way to parameterize the effects of fermion substructure makes use of form factors, which would also lead to deviations of $d\sigma/dQ^2$ with respect to the SM prediction. As a last example, low scale quantum gravity effects, which may be mediated via gravitons coupling to SM particles and propagating into large extra spatial dimensions, could also be observed as a modification of $d\sigma/dQ^2$ at highest Q^2 . These possible manifestations of new physics in inclusive DIS are addressed in this section.

5.1.1 Quark substructure

The remarkable similarities in the electromagnetic and weak interactions of leptons and quarks in the Standard Model, and their anomaly cancellations in the family structure, strongly suggest a fundamental connection. It would therefore be natural to conjecture that they could be composed of more fundamental constituents, or that they form a representation of a larger gauge symmetry group than that of the Standard Model, in a Grand Unified Theory.

2123 A possible method to investigate fermion substructures is to assign a finite size of radius R to the
 2124 electroweak charges of leptons and/or quarks while treating the gauge bosons γ and Z still as pointlike
 2125 particles [195]. A convenient parametrisation is to introduce ‘classical’ form factors $f(Q^2)$ at the gauge
 2126 boson–fermion vertices, which are expected to diminish the Standard Model cross section at high momentum
 2127 transfer

$$f(Q^2) = 1 - \frac{1}{6} \langle r^2 \rangle Q^2, \quad (5.1)$$

$$\frac{d\sigma}{dQ^2} = \frac{d\sigma^{SM}}{dQ^2} f_e^2(Q^2) f_q^2(Q^2). \quad (5.2)$$

2128 The square root of the mean-square radius of the electroweak charge distribution, $R = \sqrt{\langle r^2 \rangle}$, is taken as
 2129 a measure of the particle size. Since the pointlike nature of the electron/positron is already established down
 2130 to extremely low distances in $e^+ e^-$ and $(g-2)_e$ experiments, only the quarks are allowed to be extended
 2131 objects i.e. the form factor f_e can be set to unity in the above equation.

2132 Figure.5.1 shows the sensitivity that an LHeC collider could reach on the “quark radius” [196]. Two
 2133 configurations have been studied ($E_e = 70$ GeV and $E_e = 140$ GeV), and two values of the integrated
 luminosity, per charge, have been assumed in each case. A sensitivity to quark radius below 10^{-19} m could

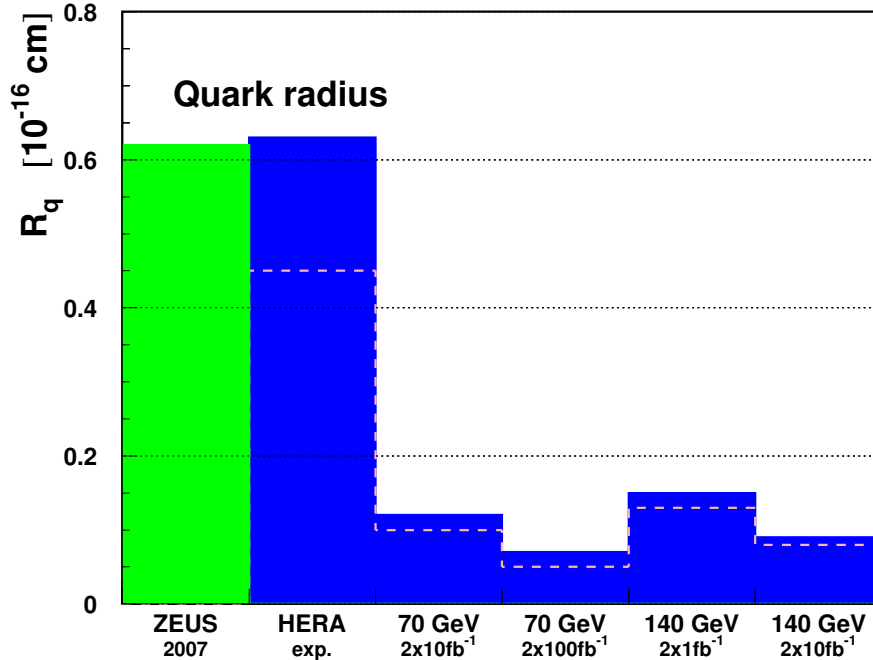


Figure 5.1: Sensitivity (95% confidence level limits) of an LHeC collider to the effective quark radius.

2134 be reached, which is one order of magnitude better than the current constraints, and comparable to the
 2135 sensitivity that the LHC is expected to reach.
 2136

2137 5.1.2 Contact Interactions

2138 New currents or heavy bosons may produce indirect effects through the exchange of a virtual particle inter-
 2139 fering with the γ and Z fields of the Standard Model. For particle masses and scales well above the available
 2140 energy, $\Lambda \gg \sqrt{s}$, such indirect signatures may be investigated by searching for a four-fermion pointlike

2141 $(\bar{e}e)(\bar{q}q)$ contact interaction. The most general chiral invariant Lagrangian for neutral current vector-like
 2142 contact interactions can be written in the form [197–199]

$$\mathcal{L}_V = \sum_{q=u,d} \{ \eta_{LL}^q (\bar{e}_L \gamma_\mu e_L) (\bar{q}_L \gamma^\mu q_L) + \eta_{LR}^q (\bar{e}_L \gamma_\mu e_L) (\bar{q}_R \gamma^\mu q_R) + \eta_{RL}^q (\bar{e}_R \gamma_\mu e_R) (\bar{q}_L \gamma^\mu q_L) + \eta_{RR}^q (\bar{e}_R \gamma_\mu e_R) (\bar{q}_R \gamma^\mu q_R) \}, \quad (5.3)$$

2143 where the indices L and R denote the left-handed and right-handed fermion helicities and the sum extends
 2144 over up -type and $down$ -type quarks and antiquarks q . In deep inelastic scattering at high Q^2 the contributions
 2145 from the first generation u and d quarks completely dominate and contact terms arising from sea quarks s ,
 2146 c and b are strongly suppressed. Thus, there are eight independent effective coupling coefficients, four for
 2147 each quark flavour

$$\eta_{ab}^q \equiv \epsilon \frac{g^2}{\Lambda_{ab}^q{}^2}, \quad (5.4)$$

2148 where a and b indicate the L , R helicities, g is the overall coupling strength, Λ_{ab}^q is a scale parameter and ϵ
 2149 is a prefactor, often set to $\epsilon = \pm 1$, which determines the interference sign with the Standard Model currents.
 2150 The ansatz eq. (5.3) can be easily applied to any new phenomenon, *e.g.* (eq) compositeness, leptoquarks
 2151 or new gauge bosons, by an appropriate choice of the coefficients η_{ab} . Scalar and tensor interactions of
 2152 dimension 6 operators involving helicity flip couplings are strongly suppressed at HERA [199] and therefore
 2153 not considered.

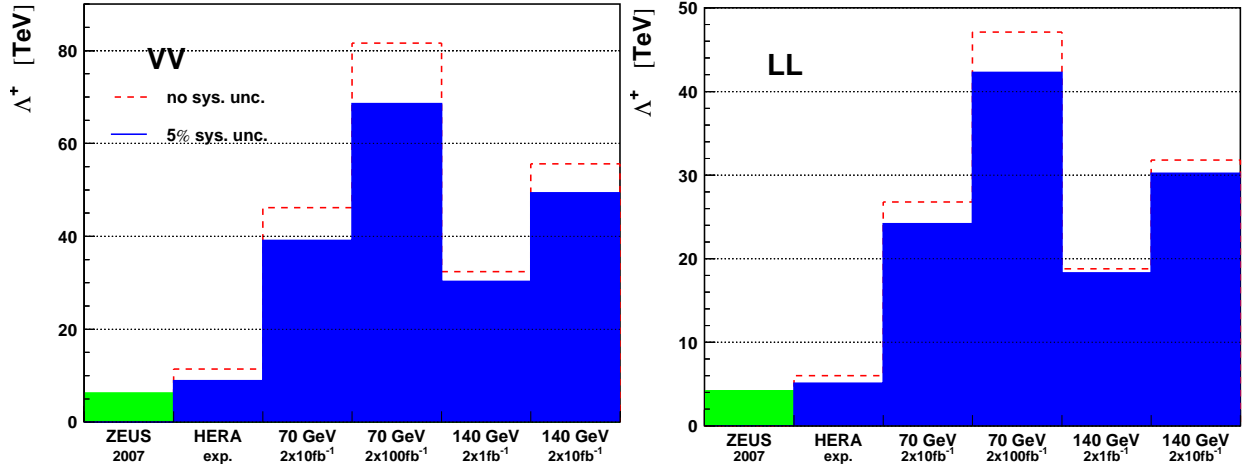


Figure 5.2: Sensitivity (95% confidence level limits) on the scale Λ for two example contact interactions.

2154 Figure 5.2 shows the sensitivity that an LHeC could reach on the scale Λ , for two example cases of contact
 2155 interactions [196]. In general, with 10 fb^{-1} of data, LHeC would probe scales between 25 TeV and 45 TeV,
 2156 depending on the model. The sensitivity of LHC to such $eeqq$ interactions, which would affect the di-electron
 2157 Drell-Yan (DY) spectrum at high masses, is similar.

2158 Figure 5.3 shows how the DY cross-section at LHC would deviate from the SM value, for three examples
 2159 of $eeqq$ contact interactions. In the “LL” model considered here, the sum in eq. (5.3) only involves left-
 2160 handed fermions and all amplitudes have the same phase ϵ . With only pp data, it will be difficult to
 2161 determine simultaneously the size of the contact interaction scale Λ and the sign of the interference of the
 2162 new amplitudes with respect to the SM ones: for example, for $\Lambda = 20 \text{ TeV}$ and $\epsilon = -1$, the decrease of the
 2163 cross-section with respect to the SM prediction for di-electron masses below $\sim 3 \text{ TeV}$, which is characteristic

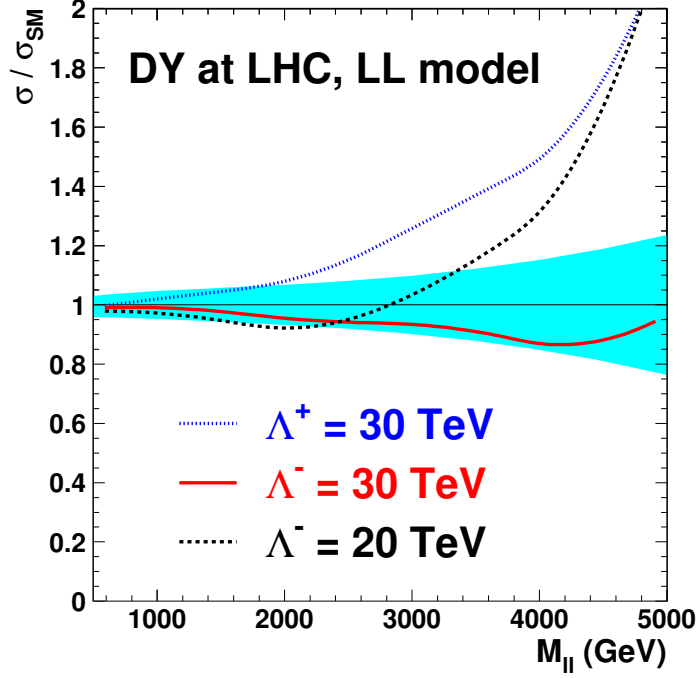


Figure 5.3: Example deviations, from its SM value, of the Drell-Yan cross-section at LHC as a function of the dilepton mass, in the presence of an $eeqq$ contact interaction. The blue band shows the relative uncertainty of the predicted SM cross-sections due to the current uncertainties of the parton distribution functions, as obtained from the CTEQ 6.1 sets.

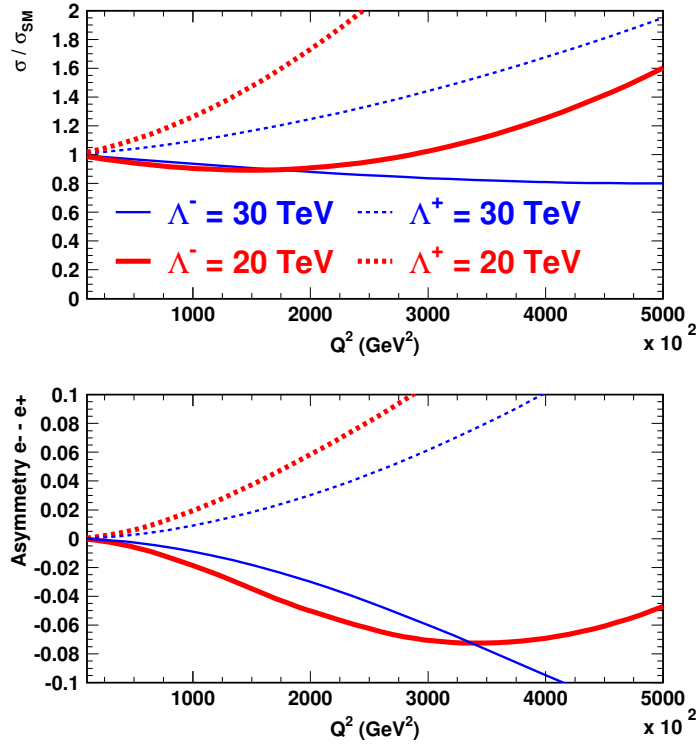


Figure 5.4: (top) Example deviations of the e^-p DIS cross-section at LHeC, in the presence of an $eeqq$ CI. The ratio of the “measured” to the SM cross-sections, $r = \sigma/\sigma_{SM}$, is shown. (bottom) Asymmetry $\frac{r(e^+) - r(e^-)}{r(e^+) + r(e^-)}$ between e^+p and e^-p measurements of σ/σ_{SM} .

2164 of a negative interference, is too small to be firmly established when uncertainties due to parton distribution
2165 functions are taken into account.

2166 For the same “LL” model, the sign of this interference can be unambiguously determined at LHeC from
2167 the asymmetry of σ/σ_{SM} in e^+p and e^-p data, as shown in Fig. 5.4.

2168

2169 Moreover, with a polarised lepton beam, ep collisions would help determine the chiral structure of the
2170 new interaction. More generally, it is very likely that both pp and ep data would be necessary to underpin the
2171 structure of new physics which would manifest itself as an $eeqq$ contact interaction. Such a complementarity
2172 of pp , ep (and also ee) data was studied in [200] in the context of the Tevatron, HERA and LEP colliders.

2173 5.1.3 Kaluza-Klein gravitons in extra-dimensions

2174 In some models with n large extra dimensions, the SM particles reside on a four-dimensional “brane”, while
2175 the spin 2 graviton propagates into the extra spatial dimensions and appears in the four-dimensional world
2176 as a tower of massive Kaluza-Klein (KK) states. The summation over the enormous number of Kaluza-Klein
2177 states up to the ultraviolet cut-off scale, taken as the Planck scale M_S in the $4 + n$ space, leads to effective
2178 contact-type interactions $ff'f'$ between two fermion lines, with a coupling $\eta = O(1)/M_S^4$. In ep scattering,
2179 the exchange of such a tower of Kaluza-Klein gravitons would affect the Q^2 dependence of the DIS cross-
2180 section $d\sigma/dQ^2$. At LHeC, such effects could be observed as long as the scale M_S is below 4 – 5 TeV. While
2181 at the LHC, virtual graviton exchange may be observed for scales up to ~ 10 TeV, and the direct production
2182 of KK gravitons, for scales up to 5 – 7 TeV depending on n , would allow this phenomenon to be studied
2183 further, LHeC data may determine that the new interaction is universal by establishing that the effect in
2184 the $eq \rightarrow eq$ cross-section is independent of the lepton charge and polarization, and, to some extent, of the
2185 quark flavor.

2186 5.2 Leptoquarks and leptogluons

2187 The high energy of the LHeC extends the kinematic range of DIS physics to much higher values of electron-
2188 quark mass $M = \sqrt{sx}$, beyond those of present ep colliders. By providing both baryonic and leptonic
2189 quantum numbers in the initial state, it is ideally suited to a study of the properties of new bosons possessing
2190 couplings to an electron-quark pair in this new mass range. Such particles can be squarks in supersymmetric
2191 models with R -parity violation (\tilde{R}_p), or first-generation leptoquark (LQ) bosons which appear naturally in
2192 various unifying theories beyond the Standard Model (SM) such as: E_6 [44], where new fields can mediate
2193 interactions between leptons and quarks; extended technicolor [47,201], where leptoquarks result from bound
2194 states of technifermions; the Pati-Salam model [45], where the leptonic quantum number is a fourth color of
2195 the quarks or in lepton-quark compositeness models. They are produced as single s -channel resonances via
2196 the fusion of incoming electrons with quarks in the proton. They are generically referred to as “leptoquarks”
2197 in what follows. The case of “leptogluons”, which could be produced in ep collisions as a fusion between the
2198 electron and a gluon, is also addressed at the end of this section.

2199 5.2.1 Phenomenology of leptoquarks in ep collisions

2200 In ep collisions, LQs may be produced resonantly up to the kinematic limit of $\sqrt{s_{ep}}$ via the fusion of
2201 the incident lepton with a quark or antiquark coming from the proton, or exchanged in the u -channel, as
2202 illustrated in Fig. 5.5. The coupling λ at the $LQ - e - q$ vertex is an unknown parameter of the model.

2203 In the narrow-width approximation, the resonant production cross-section is proportional to $\lambda^2 q(x)$ where
2204 $q(x)$ is the density of the struck parton in the incoming proton.

2205 The resonant production or t -channel exchange of a leptoquark gives $e + q$ or $\nu + q'$ final states leading to
2206 individual events indistinguishable from SM NC and CC DIS respectively. For the process $eq \rightarrow LQ \rightarrow eq$,
2207 the distribution of the transverse energy $E_{T,e}$ of the final state lepton shows a Jacobian peak at $M_{LQ}/2$,
2208 M_{LQ} being the LQ mass. Hence the strategy to search for a LQ signal in ep collisions is to look, among

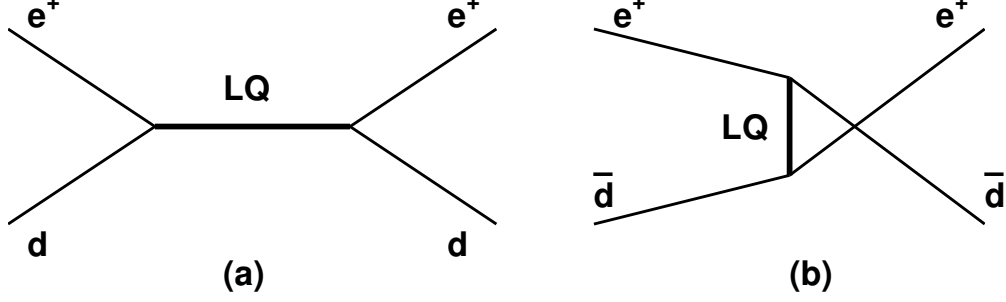


Figure 5.5: Example diagrams for resonant production in the s -channel (a) and exchange in the u -channel (b) of a LQ with fermion number $F = 0$. The corresponding diagrams for $|F| = 2$ LQs are obtained from those depicted by exchanging the quark and antiquark.

2209 high Q^2 (i.e. high $E_{T,e}$) DIS event candidates, for a peak in the invariant mass M of the final $e - q$ pair.
 2210 Moreover, the significance of the LQ signal over the SM DIS background can be enhanced by exploiting the
 2211 specific angular distribution of the LQ decay products (see spin determination, below).

2212 5.2.2 The Buchmüller-Rückl-Wyler Model

2213 A reasonable phenomenological framework to study first generation LQs is provided by the BRW model [202].
 2214 This model is based on the most general Lagrangian that is invariant under $SU(3) \times SU(2) \times U(1)$, respects
 2215 lepton and baryon number conservation, and incorporates dimensionless family diagonal couplings of LQs
 2216 to left- and/or right-handed fermions. Under these assumptions LQs can be classified according to their
 2217 quantum numbers into 10 different LQ isospin multiplets (5 scalar and 5 vector), half of which carry a
 2218 vanishing fermion number $F = 3B + L$ (B and L denoting the baryon and lepton number respectively) and
 couple to $e^+ + q$ while the other half carry $|F| = 2$ and couple to $e^+ + \bar{q}$. These are listed in Table 5.1.

$F = -2$	Prod./Decay	β_e	$F = 0$	Prod./Decay	β_e
Scalar Leptoquarks					
$1/3 S_0$	$e_R^+ \bar{u}_R \rightarrow e^+ \bar{u}$	1/2	$5/3 S_{1/2}$	$e_R^+ u_R \rightarrow e^+ u$	1
	$e_L^+ \bar{u}_L \rightarrow e^+ \bar{u}$	1		$e_L^+ u_L \rightarrow e^+ u$	1
$4/3 \tilde{S}_0$	$e_L^+ \bar{d}_L \rightarrow e^+ \bar{d}$	1	$2/3 S_{1/2}$	$e_L^+ d_L \rightarrow e^+ d$	1
$4/3 S_1$	$e_R^+ \bar{d}_R \rightarrow e^+ \bar{d}$	1	$2/3 \tilde{S}_{1/2}$	$e_R^+ d_R \rightarrow e^+ d$	1
$1/3 S_1$	$e_R^+ \bar{u}_R \rightarrow e^+ \bar{u}$	1/2			
Vector Leptoquarks					
$4/3 V_{1/2}$	$e_L^+ \bar{d}_R \rightarrow e^+ \bar{d}$	1	$2/3 V_0$	$e_L^+ d_R \rightarrow e^+ d$	1
	$e_R^+ \bar{d}_L \rightarrow e^+ \bar{d}$	1		$e_R^+ d_L \rightarrow e^+ d$	1/2
$1/3 V_{1/2}$	$e_L^+ \bar{u}_R \rightarrow e^+ \bar{u}$	1	$5/3 \tilde{V}_0$	$e_L^+ u_R \rightarrow e^+ u$	1
$1/3 \tilde{V}_{1/2}$	$e_R^+ \bar{u}_L \rightarrow e^+ \bar{u}$	1	$5/3 V_1$	$e_R^+ u_L \rightarrow e^+ u$	1
			$2/3 V_1$	$e_R^+ d_L \rightarrow e^+ d$	1/2

Table 5.1: Leptoquark isospin families in the Buchmüller-Rückl-Wyler model. For each leptoquark, the superscript corresponds to its electric charge, while the subscript denotes its weak isospin. β_e denotes the branching ratio of the LQ into $e + q$.

2219
 2220

We use the nomenclature of [203] to label the different LQ states. In addition to the underlying hypotheses

2221 of BRW, we restrict LQs couplings to only one chirality state of the lepton, given that deviations from lepton
 2222 universality in helicity suppressed pseudoscalar meson decays have not been observed [204, 205].

2223 In the BRW model, LQs decay exclusively into eq and/or νq and the branching ratio $\beta_e = \beta(LQ \rightarrow eq)$
 2224 is fixed by gauge invariance to 0.5 or 1 depending on the LQ type.

2225 5.2.3 Phenomenology of leptoquarks in pp collisions

2226 **Pair production** In pp collisions leptoquarks would be mainly pair-produced via gg or qq interactions. As
 2227 long as the coupling λ is not too strong (e.g. $\lambda \sim 0.3$ or below, corresponding to a strength similar to or lower
 2228 than that of the electromagnetic coupling, $\sqrt{4\pi\alpha_{em}}$), the production cross-section is essentially independent
 2229 of λ . At the LHC, LQ masses up to about 1.5 to 2 TeV will be probed [206], independently of the coupling λ .
 2230 However, the determination of the quantum numbers of a first generation LQ in the pair-production mode
 2231 is not possible (e.g. for the fermion number) or ambiguous and model-dependent (e.g. for the spin). Single
 2232 LQ production is much better suited for such studies.

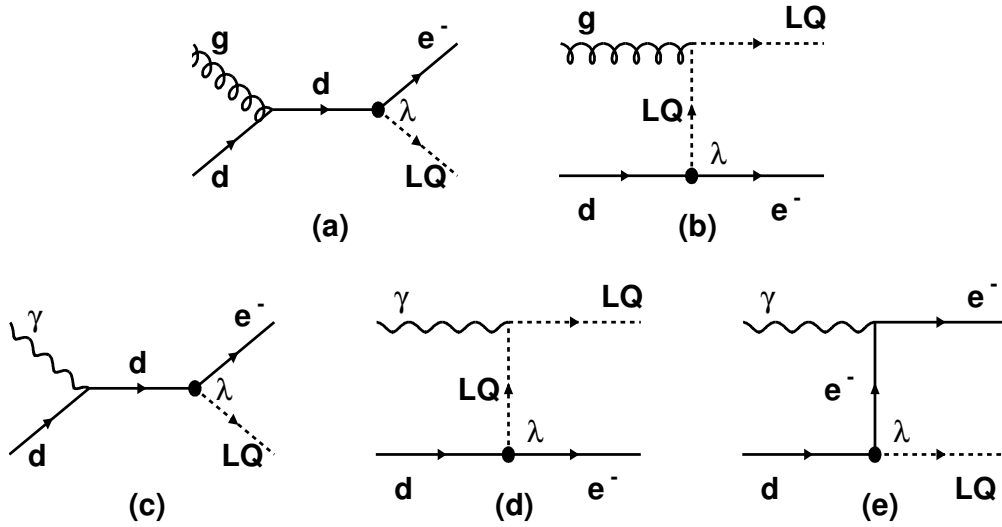


Figure 5.6: Diagrams for single LQ production in pp collisions, shown for the example case of the $\tilde{S}_{1/2}^L$ scalar leptoquark. The production may occur via qq interactions (a and b), or via $q\gamma$ interactions (c, d and e). In the latter case, the photon can be emitted by the proton (elastic regime) or by a quark coming from the proton (inelastic regime).

2233 **Single production** Single LQ production at the LHC is also possible. So far, only the production mode
 2234 $gq \rightarrow e + LQ$ (see example diagrams in Fig. 5.6a and b) has been considered in the literature (see e.g. [206]).
 2235 In the context of this study, the additional production mode $\gamma q \rightarrow e + LQ$ has been considered as well (see
 2236 example diagrams in Fig. 5.6c, d and e). This cross-section has been calculated by taking into account:

- 2237 • the inelastic regime, where the photon virtuality q^2 is large enough and the proton breaks up in a
 2238 hadronic system with a mass well above the proton mass. In that case, the photon is emitted by a
 2239 parton in the proton, and the process $qq' \rightarrow q + e + LQ$ is calculated.
- 2240 • the elastic regime, in which the proton emitting the photon remains intact. This calculation involves
 2241 the elastic form factors of the proton.

2242 As the resonant LQ production in ep collisions, the cross-section of single LQ production in pp collisions
 2243 approximately scales with the square of the coupling, $\sigma \propto \lambda^2$. Figure 5.7 (left) shows the cross-section for
 2244 single LQ production at the LHC as a function of the LQ mass, assuming a coupling $\lambda = 0.1$. While the
 2245 inelastic part of the γq cross-section can be neglected, the elastic production plays an important role at high
 2246 masses; its cross-section is larger than that of LQ production via gq interactions for masses above ~ 1 TeV.
 2247 However, the cross-section for single LQ production at LHC is much lower than that at LHeC, in e^+p or e^-p
 2248 collisions, as shown in Fig.5.7 (right).

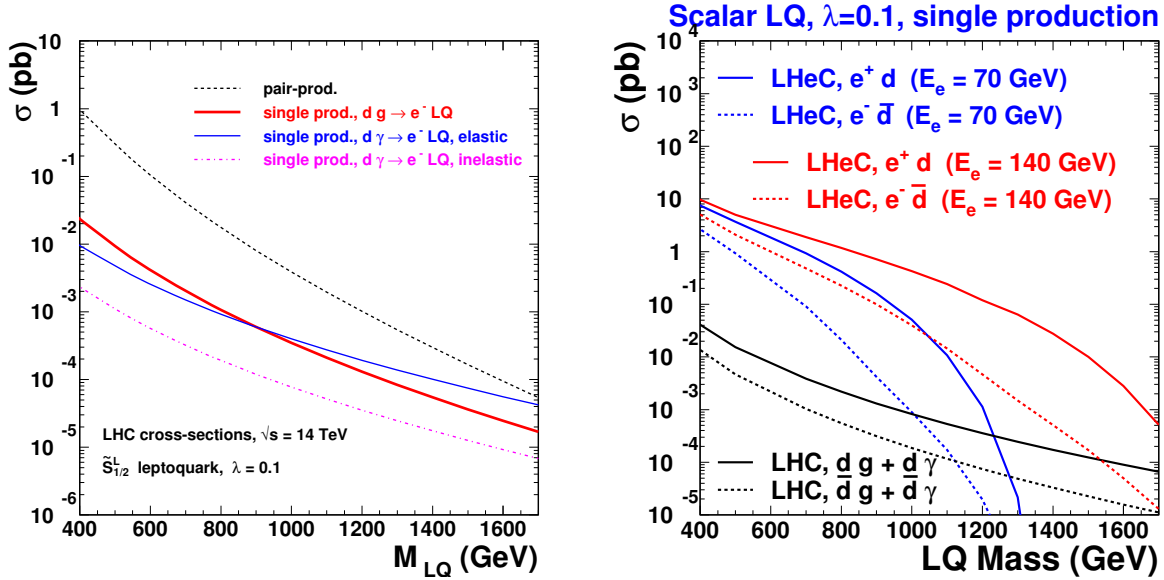


Figure 5.7: left: Single LQ production cross-section at the LHC. right: comparison of the cross-section for single LQ production, at LHC and at LHeC.

2249 **The Contact Term Approach** For LQ masses far above the kinematic limit, the contraction of the
 2250 propagator in the $eq \rightarrow eq$ and $qq \rightarrow ee$ amplitudes leads to a four-fermion interaction. Such interactions are
 2251 studied in the context of general contact terms, which can be used to parameterize any new physics process
 2252 with a characteristic energy scale far above the kinematic limit.

2253 In ep collisions, Contact Interactions (CI) would interfere with NC DIS processes and lead to a distortion
 2254 of the Q^2 spectrum of NC DIS candidate events. The results presented in section 5.1 can be re-interpreted
 2255 into expected sensitivities on high mass leptoquarks.

2256 5.2.4 Current status of leptoquark searches

2257 The H1 and ZEUS experiments at the HERA ep collider have constrained the coupling λ to be smaller than
 2258 the electromagnetic coupling ($\lambda < \sqrt{4\pi\alpha_{em}} \sim 0.3$) for first generation LQs lighter than 300 GeV. The D0 and
 2259 CDF experiments at the Tevatron pp collider set constraints on first-generation LQs that are independent of
 2260 the coupling λ , by looking for pair-produced LQs that decay into eq (νq) with a branching ratio β ($1 - \beta$).
 2261 For a branching fraction $\beta = 1$, masses below 299 GeV are excluded by the D0 experiment [207]. The CMS
 2262 and ATLAS experiments have recently set tighter constraints [208, 209]. Fig. 5.8 shows the bounds obtained
 2263 by the CMS experiment with $\sim 32 \text{ pb}^{-1}$ collected in 2010, in the β versus M_{LQ} plane. For $\beta = 1$ ($\beta = 0.5$),
 2264 masses below 384 GeV (340 GeV) are ruled out.

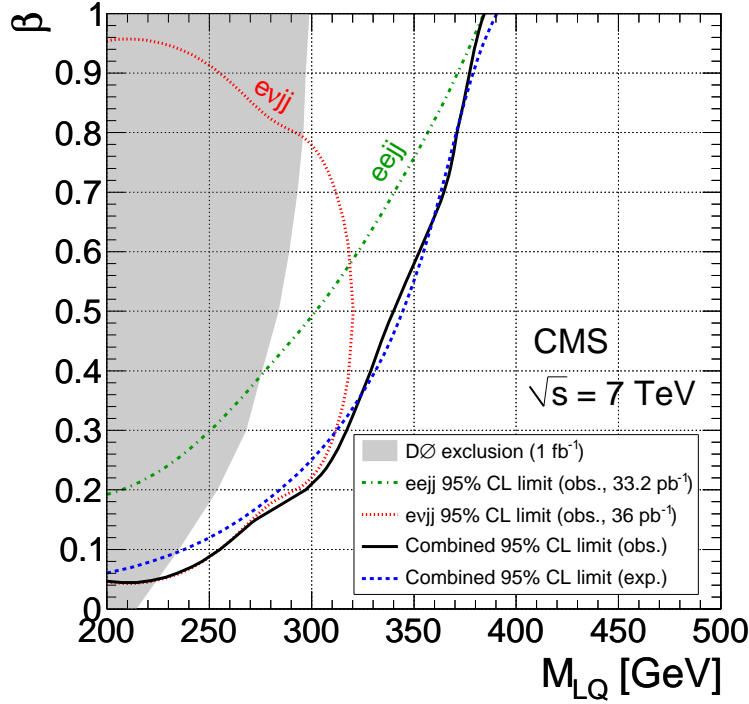


Figure 5.8: Constraints on first generation leptoquarks obtained by the CMS experiment.

5.2.5 Sensitivity on leptoquarks at LHC and at LHeC

Mass - coupling reach Fig. 5.9 shows the expected sensitivity [196] of the LHC and LHeC colliders for scalar leptoquark production. The single LQ production cross section depends on the unknown coupling λ of the LQ to the electron-quark pair. For a coupling λ of $\mathcal{O}(0.1)$, LQ masses up to about 1 TeV could be probed at the LHeC. In pp interactions at the LHC, such leptoquarks would be mainly produced via pair production, or singly produced with a much reduced cross section.

5.2.6 Determination of LQ properties

In ep collisions LQ production can be probed in detail, taking advantage of the formation and decay of systems which can be observed directly as a combination of jet and lepton invariant mass in the final state. It will thereby be possible at the LHeC to probe directly and with high precision the perhaps complex structures which will result in the lepton-jet system and to determine the quantum numbers of new states. Examples of the sensitivity of high energy ep collisions to the properties of LQ production follow. In particular, a quantitative comparison of the potential of LHC and LHeC to measure the fermion number of a LQ is given.

Fermion number (F) Since the parton densities for u and d at high x are much larger than those for \bar{u} and \bar{d} , the production cross section at LHeC of an $F = 0$ ($F = 2$) LQ is much larger in e^+p (e^-p) than in e^-p (e^+p) collisions. A measurement of the asymmetry between the e^+p and e^-p LQ cross sections,

$$\mathcal{A}_{ep} = \frac{\sigma_{prod}(e^+p) - \sigma_{prod}(e^-p)}{\sigma_{prod}(e^+p) + \sigma_{prod}(e^-p)}$$

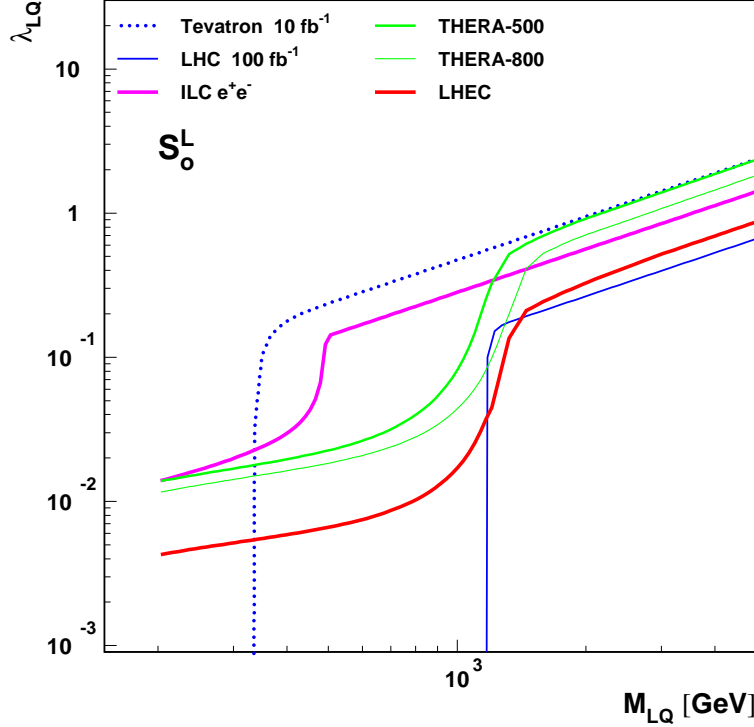


Figure 5.9: Mass-dependent upper bounds on the LQ coupling λ as expected at LHeC for a luminosity of 10 fb^{-1} (full red curve) and at the LHC for 100 fb^{-1} (full blue curve). These are shown for an example scalar LQ coupling to e^-u .

thus determines, via its sign, the fermion number of the produced leptoquark. Pair production of first generation LQs at the LHC will not allow this determination. Single LQ production at the LHC, followed by the LQ decay into e^\pm and q or \bar{q} , could determine F by comparing the signal cross sections with an e^+ and an e^- coming from the resonant state. Indeed, for a $F = 0$ leptoquark, the signal observed when the resonance is made by a positron and a jet corresponds to diagrams involving a *quark* in the initial state (see Fig.5.10a). Hence the corresponding cross-section, $\sigma(e_{out}^+j)$ is larger than that of the signal observed when the resonance is made by an electron and a jet, $\sigma(e_{out}^-j)$, since a high x antiquark is involved in that latter case (see Fig.5.10b). In contrast, for a $F = 2$ LQ, $\sigma(e_{out}^+j)$ is smaller than $\sigma(e_{out}^-j)$. The measurement of (the sign of) the asymmetry

$$\mathcal{A}_{pp} = \frac{\sigma(e_{out}^+j) - \sigma(e_{out}^-j)}{\sigma(e_{out}^+j) + \sigma(e_{out}^-j)}$$

2279 should thus provide a determination of the LQ fermion number. However, the single LQ production cross
 2280 section at the LHC is two orders of magnitude lower than at the LHeC (Fig. 5.7), so that the asymmetry \mathcal{A}_{pp}
 2281 measured at the LHC may suffer from statistics in a large part of the parameter space. For a LQ coupling
 2282 to ed and $\lambda = 0.1$, no information on F can be extracted from 300 pb^{-1} of LHC data for a LQ mass above
 2283 $\sim 1 \text{ TeV}$, while the LHeC can determine F for LQ masses up to 1.5 TeV (Fig. 5.11 and Fig. 5.12). Details
 2284 of the determination of \mathcal{A}_{pp} at the LHC are given in the next paragraph.

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An estimate of the precision with which the fermion number determination of a leptoquark can be determined at the LHC was obtained from a Monte Carlo simulation. First, using the model [210] implemented in CalcHep [211], samples were generated for the processes $g u \rightarrow e^+e^-u$ and $g \bar{u} \rightarrow e^+e^-\bar{u}$, keeping only diagrams involving the exchange of a scalar LQ exchange of charge $1/3$, isospin 0 and fermion number 2.

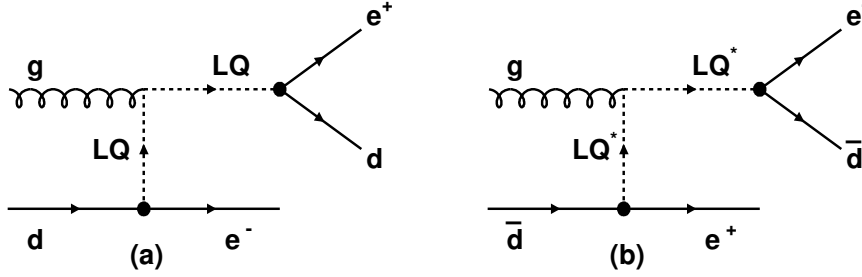


Figure 5.10: Single production of a $F = 0$ leptoquark decaying (a) into a positron and a jet and (b) into an electron and a jet. In (a) (resp. (b)), the jet comes from a quark (an antiquark); conservation of the baryon number implies that the parton involved in the initial state is a quark (an antiquark).

2290 This leptoquark ($^{1/3}S_0$ in the notation of Table 5.1) couples to $e_R^- u_R$. Assuming that it is chiral, only right-
 2291 handed coupling was allowed. The $^{1/3}S_0$ leptoquark was also assumed to couple only to the first generation.
 2292 Masses of 500 GeV, 750 GeV and 1 TeV were considered. The renormalization and factorization scales were
 2293 set at $Q^2 = m_{LQ}^2$ and the coupling parameter $\lambda = 0.1$. A center of mass energy of 14 TeV was assumed at
 2294 the LHC.

2295 High statistics background samples, corresponding to 150 fb^{-1} were also produced by generating the
 2296 same processes $pp \rightarrow e^+e^- + \text{jet}$, including all diagrams except those involving the exchange of leptoquarks.
 2297 Kinematic preconditions were applied at the generation level to both signals and background: (i) $p_T(\text{jet}) >$
 2298 50 GeV , (ii) $p_T(e^\pm) > 20 \text{ GeV}$, (iii) invariant mass of jet- $e^+ - e^-$ system $> 200 \text{ GeV}$. The cross sections for
 2299 the signals and backgrounds under these conditions are: 19.7 fb, 3.4 fb and 0.87 fb for LQ's of mass 500 GeV,
 2300 750 GeV and 1 TeV respectively, and 1780 fb for the background. These events were subsequently passed to
 2301 Pythia [130] to perform parton showering and hadronization, then processed through Delphes [212] for a fast
 2302 simulation of the ATLAS detector. Finally, considering events with two reconstructed electrons of opposite
 2303 sign and, assuming that the leptoquark has already been discovered (at the LHC), the combination of the
 2304 highest p_T jet with the reconstructed e^- or e^+ with a mass closest to the known leptoquark mass is chosen
 2305 as the LQ candidate. The following cuts for $m_{LQ} = 500, 750$ and 1000 GeV , respectively, are applied:

- 2306 • dilepton invariant mass $m_{ll} > 150, 200, 250 \text{ GeV}$. This cut rejects very efficiently the $Z + \text{jets}$ back-
 2307 ground.
- 2308 • $p_T(e_1) > 150, 200, 250 \text{ GeV}$ and $p_T(e_2) > 75, 100, 100 \text{ GeV}$, where e_1 is the reconstructed e^\pm with
 2309 higher p_T and e_2 the lower p_T electron.
- 2310 • $p_T(j_1) > 100, 250, 400 \text{ GeV}$, where j_1 is the reconstructed jet with highest p_T , used for the reconstruction
 2311 of the LQ.

2312 Table 5.2 summarizes the results of the simulation for an integrated luminosity of 300 fb^{-1} . The expected
 2313 number of signal events shown in the table is then simply the number of events due to the leptoquark
 2314 production and decay, falling in the resonance peak within a mass window of width (60, 100, 160 GeV) for
 2315 the three cases studied, respectively. Although this simple analysis can be improved by considering other
 2316 less dominant backgrounds and by using optimized selection criteria, it should give a good estimate of the
 2317 precision with which the asymmetry can be measured. This precision falls rapidly with increasing mass and,
 2318 above $\sim 1 \text{ TeV}$, it becomes impossible to observe simultaneously single production of both $^{1/3}S_0$ and $^{1/3}\bar{S}_0$.
 2319 It must be noted that the asymmetry at the LHC will be further diluted by the abundant leptoquark pair
 2320 production, not taken into account here.

2321 **Flavour structure of the LQ coupling** More generally, using the same charge asymmetry observable,
 2322 the LHeC will be sensitive to the flavour structure of the leptoquark, through the dependence on the parton

LQ mass (GeV)	$^{1/3}S_1 \rightarrow e^+\bar{u}$		$^{1/3}\bar{S}_1 \rightarrow e^-u$		Charge Asymmetry
	Signal	Background	Signal	Background	
500	121	431	771	478	0.73 ± 0.05
750	18.3	137	132	102	$0.76^{+0.16}_{-0.14}$
1000	4.9	57	44	42	$0.77^{+0.23}_{-0.24}$

Table 5.2: Estimated number of events of signal and background, and the charge asymmetry measurement with 300 fb^{-1} at the LHC, for $\lambda = 0.1$.

distribution functions of the interacting quark in the proton. Fig. 5.13 shows the calculated asymmetry for scalar LQs. Provided that the coupling λ is not too small, the accuracy of the measurement of \mathcal{A}_{ep} at LHeC (see Fig. 5.11) would allow the various LQ types to be disentangled, as different LQs lead to values of \mathcal{A}_{ep} that differ by typically 20–30%. A similar measurement at the LHC would be possible only in a very limited part of the phase space (low masses and large couplings), where the statistics would be large enough to yield an accuracy of about 20% on the measured asymmetry \mathcal{A}_{pp} .

Spin At the LHeC, the angular distribution of the LQ decay products is unambiguously related to its spin. Indeed, scalar LQs produced in the s -channel decay isotropically in their rest frame leading to a flat $d\sigma/dy$ spectrum where $y = \frac{1}{2}(1 + \cos\theta^*)$ is the Bjorken scattering variable in DIS and θ^* is the decay polar angle of the lepton relative to the incident proton in the LQ centre of mass frame. In contrast, events resulting from the production and decay of vector LQs would be distributed according to $d\sigma/dy \propto (1-y)^2$. These y spectra from scalar or vector LQ production are markedly different from the $d\sigma/dy \propto y^{-2}$ distribution expected at fixed M for the dominant t -channel photon exchange in neutral current DIS events¹. Hence, a LQ signal in the NC-like channel will be statistically most prominent at high y .

The spin determination will be much more complicated, even possibly ambiguous, if only the LHC leptoquark pair production data are available. Angular distributions for vector LQs depend strongly on the structure of the $gLQ\bar{LQ}$ coupling, i.e. on possible anomalous couplings. For a structure similar to that of the γWW vertex, vector LQs produced via $q\bar{q}$ fusion are unpolarised and, because both LQs are produced with the same helicity, the distribution of the LQ production angle will be similar to that of a scalar LQ. The study of LQ spin via single LQ production at the LHC will suffer from the relatively low rates and more complicated backgrounds.

Neutrino decay modes At the LHeC, there is similar sensitivity for LQ decay into both eq and νq . At the LHC, in pp collisions, LQ decay into neutrino-quark final states is plagued by huge QCD background. At the LHeC, production through eq fusion with subsequent νq decay is thus very important if the complete pattern of LQ decay couplings is to be determined.

Coupling λ In the narrow-width approximation, the production cross-section of a LQ in ep collisions can be written as, depending on the LQ spin :

$$\sigma_{prod} = \frac{\lambda^2}{16\pi} q(x = M^2/s_{ep}) \quad (J = 0) \quad \text{or} \quad \sigma_{prod} = \frac{\lambda^2}{8\pi} q(x = M^2/s_{ep}) \quad (J = 1).$$

At LHeC, the determination of:

- the LQ spin, via the analysis of the angular distribution of its decay products;
- the flavor of the quark q involved in the $e-q-LQ$ vertex, via the charge asymmetry described above;

¹At high momentum transfer, Z^0 exchange is no longer negligible and contributes to less pronounced differences in the y spectra between LQ signal and DIS background.

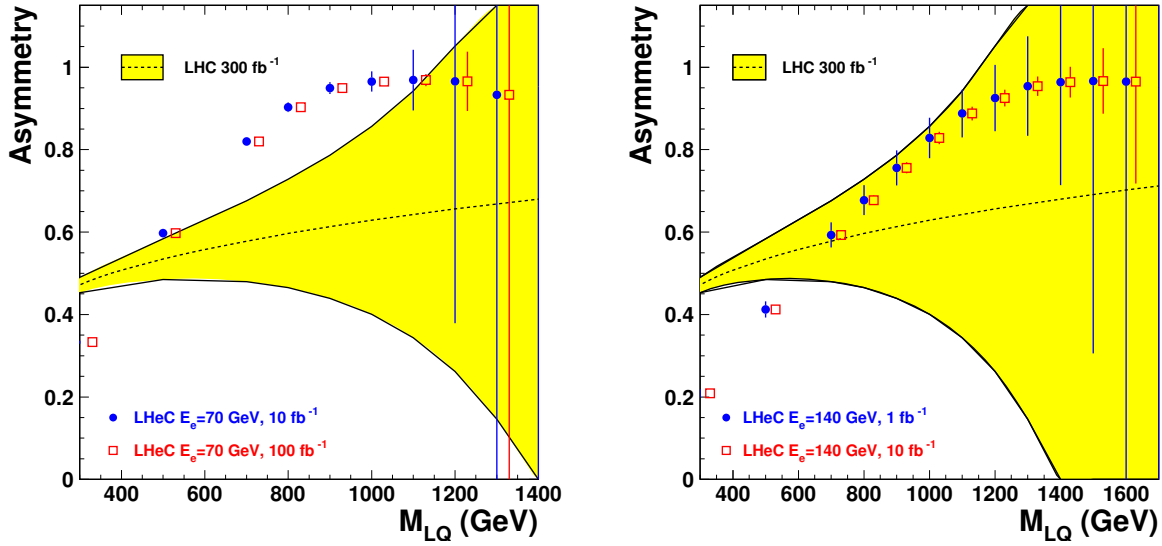


Figure 5.11: *Asymmetries which would determine the fermion number of a LQ , the sign of the asymmetry being the relevant quantity. The dashed curve shows the asymmetry that could be measured at the LHC; the yellow band shows the statistical uncertainty of this quantity, assuming an integrated luminosity of 300 fb^{-1} . The red and blue symbols, together with their error bars, show the asymmetry that would be measured at LHeC, assuming $E_e = 70 \text{ GeV}$ (left) or $E_e = 140 \text{ GeV}$ (right). Two values of the integrated luminosity have been assumed. These determinations correspond to the $\hat{S}_{1/2}^L$ (scalar LQ coupling to $e^+ + d$), with a coupling of $\lambda = 0.1$.*

2351 • the production cross-section, via the cross-sections measured in the eq and νq decay modes

2352 allows the value of the coupling λ to be determined, from the above formula.

2353 **Chiral structure of the LQ coupling** Chirality is central to the SM Lagrangian. Polarised electron and
 2354 positron beams² at the LHeC will shed light on the chiral structure of the LQ - e - q couplings. Measurements
 2355 of a similar nature at LHC are impossible.

2356

2357 In summary, would a first generation leptoquark exist in the TeV mass range with a coupling λ of $\mathcal{O}(0.1)$,
 2358 the LHeC would allow a rich program of “spectroscopy” to be carried out, resulting in the determination of
 2359 most of the LQ properties.

2360 5.2.7 Leptogluons

2361 While leptoquarks and excited fermions are widely discussed in the literature, leptogluons have not received
 2362 the same attention. However, they are predicted in all models with colored preons [213–218]. For example,
 2363 in the framework of fermion-scalar models, leptons would be bound states of a fermionic preon and a scalar
 2364 anti-preon $l = (F\bar{S}) = 1 \oplus 8$ (both F and S are color triplets), and each SM lepton would have its own colour
 2365 octet partner [218].

²Whether it is possible to achieve longitudinal polarisation in a 70 GeV e^\pm beam in the LHC tunnel remains to be clarified.

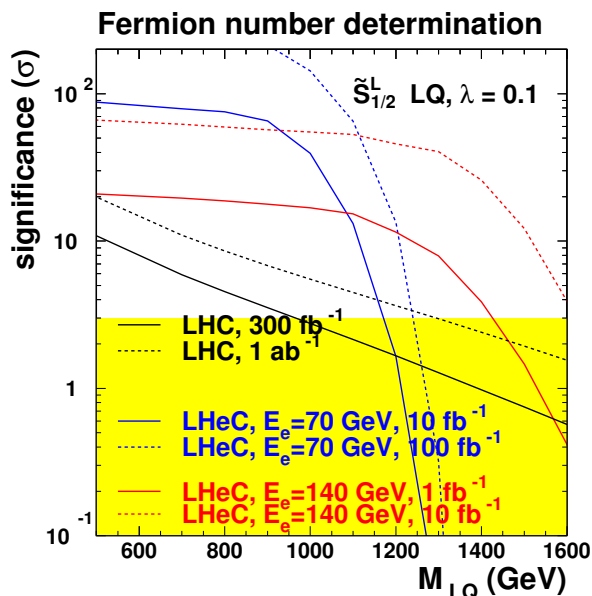


Figure 5.12: Significance of the determination of the fermion number of a LQ, at the LHC (black curve) and at the LHeC (blue and red curves). This corresponds to a $\tilde{S}_{1/2}^L$ leptoquark, assuming a coupling of $\lambda = 0.1$.

2366 A study of leptogluons production at LHeC is presented in [219]. It is based on the following Lagrangian:

$$L = \frac{1}{2\Lambda} \sum_l \{ \bar{l}_8^\alpha g_s G_{\mu\nu}^\alpha \sigma^{\mu\nu} (\eta_L l_L + \eta_R l_R) + h.c. \} \quad (5.5)$$

2367 where $G_{\mu\nu}^\alpha$ is the field strength tensor for gluon, index $\alpha = 1, 2, \dots, 8$ denotes the color, g_s is gauge coupling,
 2368 η_L and η_R are the chirality factors, l_L and l_R denote left and right spinor components of lepton, $\sigma^{\mu\nu}$ is the
 2369 anti-symmetric tensor and Λ is the compositeness scale. The leptonic chiral invariance implies $\eta_L \eta_R = 0$.

2370 The phenomenology of leptogluons at LHC and LHeC is very similar to that of leptoquarks, despite
 2371 their different spin (leptogluons are fermions while leptoquarks are bosons) and their different interactions.
 2372 Figure 5.14 shows typical cross-sections for single leptogluon production at the LHeC, assuming Λ is equal
 2373 to the leptogluon mass. It is estimated that, for example, a sensitivity of to a compositeness scale of 200
 2374 TeV, at 3σ level can be achieved with LHeC having $E_e = 70$ GeV and with 1 fb^{-1} . The mass reach for M_{e8}
 2375 is 1.1 TeV for $\Lambda = 10$ TeV.

2376 As for leptoquarks, would leptogluons be discovered at the LHC, LHeC data would be of highest value
 2377 for the determination of the properties of this new particle.

2378 5.3 Excited leptons and other new heavy leptons

2379 The three-family structure and mass hierarchy of the known fermions is one of the most puzzling charac-
 2380 teristics of the Standard Model (SM) of particle physics. Attractive explanations are provided by models
 2381 assuming composite quarks and leptons [220]. The existence of excited states of fermions (F^*) is a natural
 2382 consequence of compositeness models. More generally, various models predict the existence of fundamental
 2383 new heavy leptons, which can have similar experimental characteristics as excited leptons. They could, for
 2384 example, be part of a fourth Standard model family. They arise also in Grand Unified Theories, and appear
 2385 as colorless fermions in technicolor models.

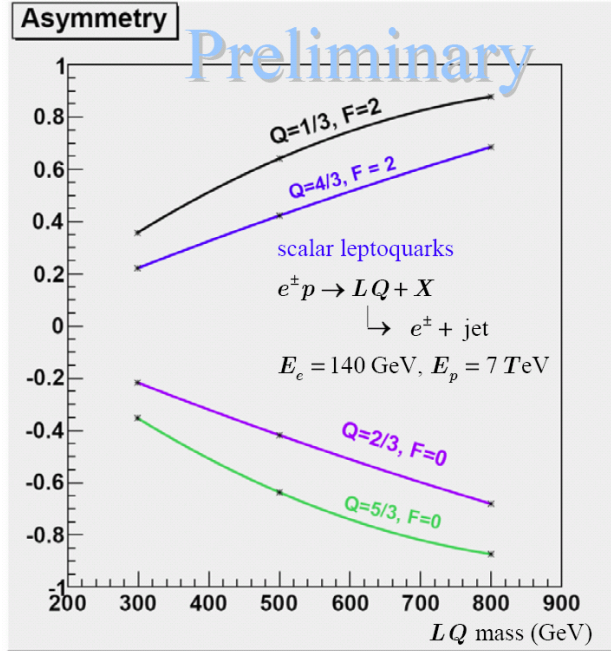


Figure 5.13: Charge asymmetry vs LQ mass for different types of scalar LQ's.

2386 New heavy leptons could be pair-produced at the LHC up to masses of $\mathcal{O}(300)$ GeV. As for the case
 2387 of leptoquarks, pp data from pair-production of new leptons may not allow for a detailed study of their
 2388 properties and couplings. Single production of new leptons is also possible at the LHC, but is expected to
 2389 have a larger cross-section at LHeC, via $e\gamma$ or eW interactions. The case of excited electrons is considered
 2390 in the following, with more details being given in [221].

2391 Single production of excited leptons at the LHC (\sqrt{s} up to 14 TeV) may happen via the reactions
 2392 $pp \rightarrow e^\pm e^* \rightarrow e^+ e^- V$ and $pp \rightarrow \nu e^* + \nu^* e^\pm \rightarrow e^\pm \nu V$. The LHC should be able to tighten considerably the current
 2393 constraints on these possible new states and to probe excited lepton masses of up to 1 TeV [222]. A sensitivity
 2394 similar to the LHC could be reached at the ILC [223], with different e^+e^- , $e\gamma$ and $\gamma\gamma$ collisions modes and
 2395 a centre of mass energy of $\sqrt{s} \geq 500$ GeV.

2396 Recent results of searches for excited fermions [224–226] at HERA using all data collected by the H1
 2397 detector have demonstrated that ep colliders are very competitive to pp or e^+e^- colliders. Indeed limits
 2398 set by HERA extend at high mass beyond the kinematic reach of LEP searches [227, 228] and to higher
 2399 compositeness scales than those obtained at the Tevatron [229] using 1 fb^{-1} of data. Therefore a future
 2400 LHeC machine, with a centre of mass energy of 1 – 2 TeV, much higher than at the HERA ep collider,
 2401 would be ideal to search for and study excited fermions. This has motivated us to examine excited electron
 2402 production at a future LHeC collider and compare it to the potential of other types of colliders at the TeV
 2403 scale, the LHC and the ILC.

2404

2405 5.3.1 Excited Fermion Models

2406 Compositeness models attempt to explain the hierarchy of masses in the SM by the existence of a substructure
 2407 within the fermions. Several of these models [230–232] predict excited states of the known fermions, in which
 2408 excited fermions are assumed to have spin 1/2 and isospin 1/2 in order to limit the number of parameters
 2409 of the phenomenological study. They are expected to be grouped into both left- and right-handed weak
 2410 isodoublets with vector couplings. The existence of the right-handed doublets is required to protect the

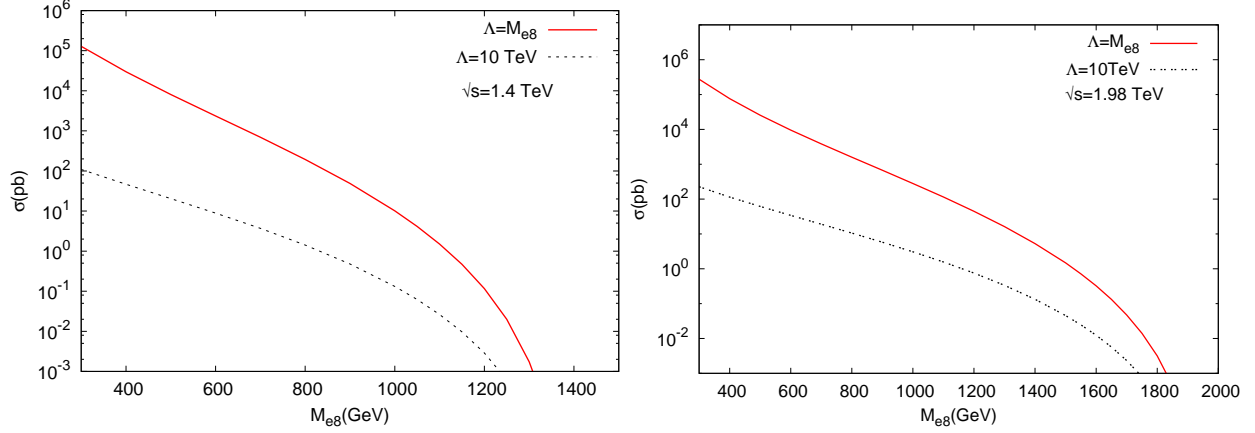


Figure 5.14: Resonant e_8 production at the LHeC, for two values of the center-of-mass energy.

2411 ordinary light fermions from radiatively acquiring a large anomalous magnetic moment via F^*FV interaction
 2412 (where V is a γ, Z or W).

2413 Interactions between excited and ordinary fermions may be mediated by gauge bosons, as described by
 2414 the effective Lagrangian:

$$\mathcal{L}_{GM} = \frac{1}{2\Lambda} \bar{F}_R^* \sigma^{\mu\nu} \left[g f \frac{\vec{\tau}}{2} \vec{W}_{\mu\nu} + g' f' \frac{Y}{2} B_{\mu\nu} + g_s f_s \frac{\vec{\lambda}}{2} \vec{G}_{\mu\nu} \right] F_L + h.c., \quad (5.6)$$

2415 where Y is the weak hypercharge, g_s , $g = \frac{e}{\sin \theta_W}$ and $g' = \frac{e}{\cos \theta_W}$ are the strong and electroweak gauge
 2416 couplings, where e is the electric charge and θ_W is the weak mixing angle; $\vec{\lambda}$ and $\vec{\tau}$ are the Gell-Mann
 2417 matrices and the Pauli matrices, respectively. $G_{\mu\nu}$, $W_{\mu\nu}$ and $B_{\mu\nu}$ are the field strength tensors describing
 2418 the gluon, the $SU(2)$, and the $U(1)$ gauge fields. f_s , f and f' are the coupling constants associated to each
 2419 gauge field. They depend on the composite dynamics. The parameter Λ has units of energy and can be
 2420 regarded as the compositeness scale which reflects the range of the new confinement force.

2421 In addition to gauge mediated (GM) interactions, novel composite dynamics may be visible as contact
 2422 interactions (CI) between excited fermions and ordinary fermions. Such interactions can be described by an
 2423 effective four-fermion Lagrangian [232]:

$$\mathcal{L}_{CI} = \frac{4\pi}{2\Lambda^2} j^\mu j_\mu, \quad (5.7)$$

2424 where Λ is here assumed to be the same parameter as in the gauge interaction Lagrangian (5.6) and j_μ is
 2425 the fermion current

$$j_\mu = \eta_L \bar{F}_L \gamma_\mu F_L + \eta'_L \bar{F}_L^* \gamma_\mu F_L^* + \eta''_L \bar{F}_L^* \gamma_\mu F_L + h.c. + (L \rightarrow R). \quad (5.8)$$

2426 By convention, the η factors of left-handed currents are set to ± 1 , while the factors of right-handed currents
 2427 are considered to be zero.

2428

2429 5.3.2 Simulation and Results

2430 In the following study, excited electron (e^*) production and decays via both GM and CI are considered. For
 2431 GM interactions, the e^* production cross section under the assumption $f = -f'$ becomes much smaller than
 2432 for $f = +f'$ and therefore only the case $f = +f'$ is studied.

2433 Considering pure gauge interactions, excited electrons could be produced in ep collisions at the LHeC
 2434 via a t -channel γ or Z bosons exchange. The Monte Carlo (MC) event generator COMPOS [233] is used for
 2435 the calculation of the e^* production cross section and the simulation of signal events. The production cross
 2436 sections of excited neutrinos at the LHeC is also shown in figure 5.15. These results are obtained with the
 2437 assumption $f = +f'$ and $M_{e^*} = \Lambda$ and are compared to production cross section at HERA and also at the
 2438 LHC [222]. In the mass range accessible by the LHeC, the e^* production cross section is clearly much higher
 2439 than at the LHC.

2440 Considering gauge and contact interactions together, formulae for the e^* production cross section via
 2441 CI and of the interference term between contact and gauge interactions have been incorporated into COM-
 2442 POS [224, 234]. For simplicity, the relative strength of gauge and contact interactions are fixed by setting
 2443 the parameters f and f' of the gauge interaction to one. Comparisons of the e^* production cross section
 2444 via only gauge interactions and via GM and CI together, as a function of the e^* mass, are presented in
 2445 figure 5.16(a) for $M_{e^*} = \Lambda$ and figure 5.16(b) for $\Lambda = 10$ TeV, respectively. These results for the LHeC
 2446 at $\sqrt{s} = 1.4$ TeV are compared to the cross section at an LHC operating at $\sqrt{s} = 14$ TeV. These plots
 2447 demonstrate that at the LHeC the ratio of the contact and gauge cross sections (proportional to \hat{s}/Λ^4 and
 2448 $1/\Lambda^2$ respectively) decreases as Λ and M_{e^*} increase differently than for the LHC where contact interactions
 2449 may be an important source of production of excited electrons. In the mass range accessed at the LHeC, e^*
 2450 decays are dominated by gauge decays, provided that Λ is large enough. Therefore, only gauge decays are
 2451 looked for in the present study.

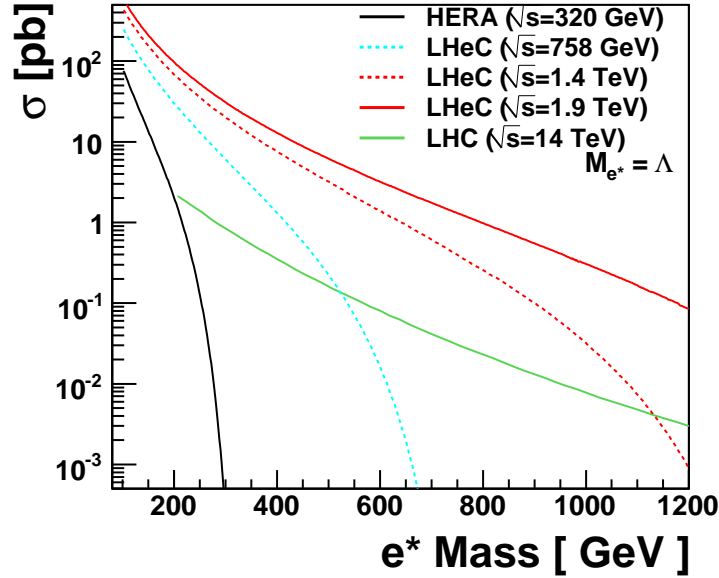


Figure 5.15: The e^* production cross section for different design scenarios of the LHeC electron-proton collider, compared to the cross sections at HERA and at the LHC.

2452 In order to estimate the sensitivity of excited electron searches at the LHeC, the e^* production followed
 2453 by its decay in the channel $e^* \rightarrow e\gamma$ is considered. This is the key channel for excited electron searches in ep
 2454 collisions as it provides a very clear signature and has a large branching ratio. Only the main sources of
 2455 backgrounds from SM processes are considered here, namely neutral currents (NC DIS) and QED-Compton
 2456 ($e\gamma$) events. Other possible SM backgrounds are negligible. The MC event generator WABGEN [235] is used
 2457 to generate these background events. Figure 5.17 compares the e^* production cross section to the total cross
 2458 section of SM backgrounds. Background events dominate in the low e^* mass region. Hence to enhance the
 2459 signal, candidate events are selected with two isolated electromagnetic clusters with a polar angle between

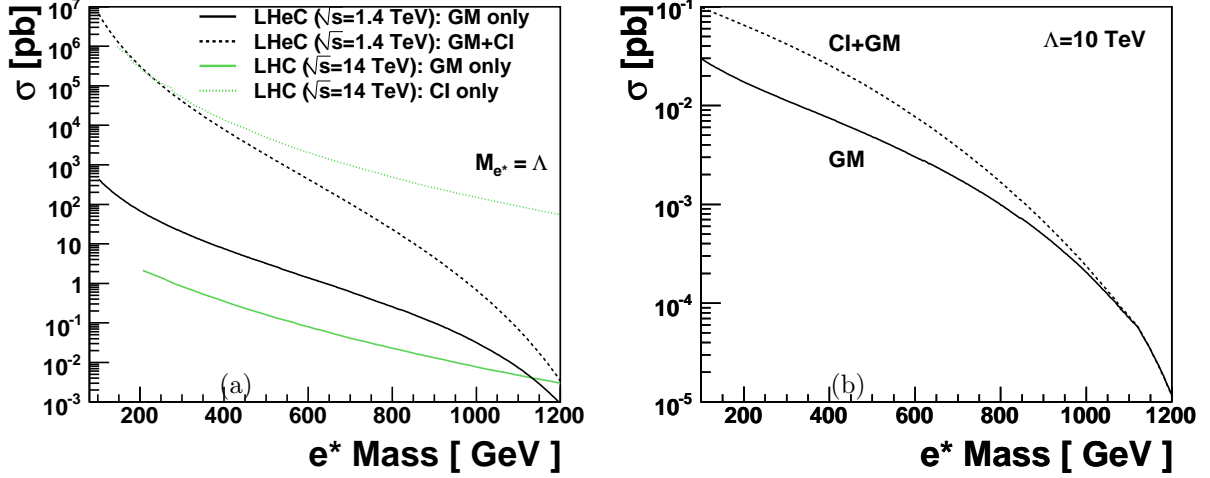


Figure 5.16: Comparison of the e^* production cross section via gauge and contact interactions. In figure (a), the results for the LHeC ($\sqrt{s} = 1.4$ TeV) and for the LHC ($\sqrt{s} = 14$ TeV) are compared. Production cross sections for a fixed Λ value of 10 TeV are shown in figure (b) for the LHeC.

2460 5° and 145° and transverse energies greater than 15 GeV and 10 GeV, respectively.

2461 To translate the results into exclusion limits, expected upper limits on the coupling f/Λ are derived at
 2462 95% Confidence Level (CL) as a function of excited electron masses.

2463 In case of gauge interaction, the attainable limits at the LHeC on the ratio f/Λ are shown in figure 5.18
 2464 for excited electrons, for the hypothesis $f = +f'$ and different integrated luminosities $L = 10 \text{ fb}^{-1}$ for
 2465 \sqrt{s} up to 1.4 TeV and $L = 1 \text{ fb}^{-1}$ for \sqrt{s} up to 2 TeV. They are compared to the upper limits obtained
 2466 at LEP [227, 228], HERA [224] and also to the expected sensitivity of the LHC [222]. Considering the
 2467 assumption $f/\Lambda = 1/M_{e^*}$ and $f = +f'$, excited electrons with masses up to 1.2(1.5) TeV, corresponding
 2468 to centre of mass energies of $\sqrt{s} = 1.4(1.9)$ TeV of the LHeC, are excluded. Under the same assumptions,
 2469 LHC ($\sqrt{s} = 14$ TeV) could exclude e^* masses up to 1.2 TeV for an integrated luminosity of 100 fb^{-1} . In
 2470 the accessible mass range of LHeC, the LHeC would be able to probe smaller values of the coupling f/Λ
 2471 than the LHC. Similarly to leptoquarks (see section 5.2), if an excited electron is observed at the LHC with
 2472 a mass of $\mathcal{O}(1 \text{ TeV})$, the LHeC would be better suited to study the properties of this particle, thanks to the
 2473 larger single production cross-section (see Fig. 5.15).

2474 5.3.3 New leptons from a fourth generation

2475 New leptons from a fourth generation (l_4, ν_4) may have anomalous couplings to the standard leptons, as
 2476 given by the following effective Lagrangian:

$$\begin{aligned}
 \mathcal{L}_{nc} &= \left(\frac{\kappa_\gamma^{\ell_4 l_i}}{\Lambda} \right) e_\ell g_e \bar{\ell}_4 \sigma_{\mu\nu} \ell_i F^{\mu\nu} \\
 &+ \left(\frac{\kappa_Z^{\ell_4 l_i}}{2\Lambda} \right) g_Z \bar{\ell}_4 \sigma_{\mu\nu} \ell_i Z^{\mu\nu} + \left(\frac{g_Z}{2} \right) \bar{\nu}_i \frac{i}{2\Lambda} \kappa_Z^{\nu_4 \nu_i} \sigma_{\mu\nu} q^\nu P_L \nu_4 Z^\mu + h.c. \\
 \mathcal{L}_{cc} &= \left(\frac{g_W}{\sqrt{2}} \right) \bar{l}_i \left[\frac{i}{2\Lambda} \kappa_W^{\nu_4 l_i} \sigma_{\mu\nu} q^\nu \right] P_L \nu_4 W^\mu + h.c.
 \end{aligned}$$

2477 In that case, the single production of l_4 and ν_4 would be similar to that of excited electrons and neutrinos. For
 2478 a study of the properties and couplings of such a new lepton, an ep machine would offer the same advantages

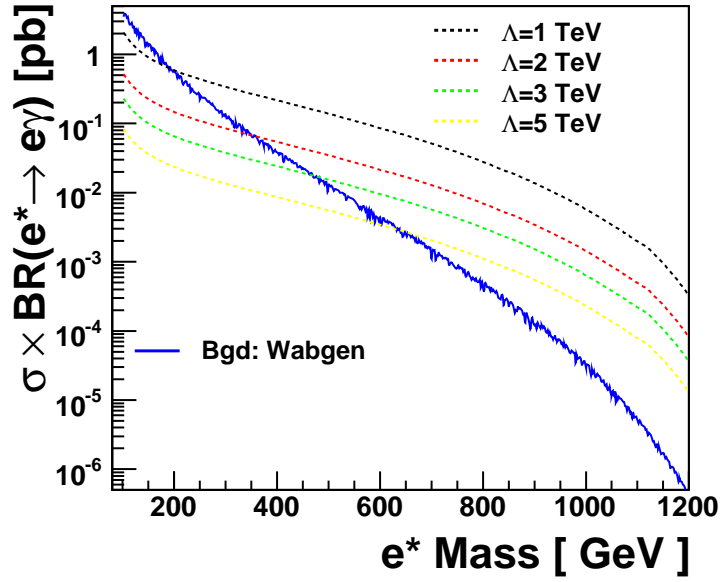


Figure 5.17: Electromagnetic production cross section for e^* ($e^* \rightarrow e\gamma$) for different values of Λ .

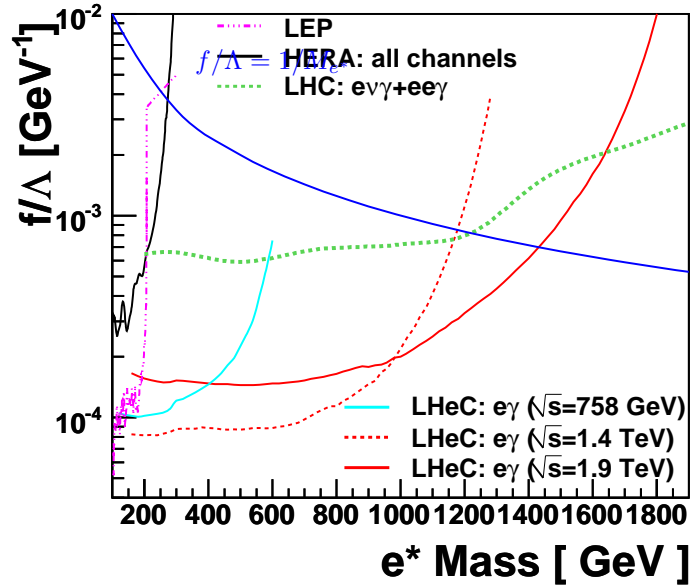


Figure 5.18: Sensitivity to excited electron searches for different design scenarios of the LHeC electron-proton collider, compared to the expected sensitivity of the LHC ($\sqrt{s} = 14$ TeV, $L = 100$ fb $^{-1}$). Different integrated luminosities at the LHeC ($L = 10$ fb $^{-1}$ for \sqrt{s} up to 1.4 TeV and $L = 1$ fb $^{-1}$ for \sqrt{s} up to 2 TeV) are assumed. The curves present the expected exclusion limits on the coupling f/Λ at 95% CL as a function of the mass of the excited electron with the assumption $f = +f'$. Areas above the curves are excluded. Present experimental limits obtained at LEP and HERA are also represented.

2479 as presented above in the case of excited electrons. A study of the processes $ep \rightarrow l_4 X \rightarrow Ze(\gamma\mu)X$
 2480 and $ep \rightarrow \nu_4 X \rightarrow W(e, \mu)X$ at the LHeC is presented in [236]. For example, for an anomalous coupling
 2481 $\kappa/\Lambda = 1 \text{ TeV}^{-1}$, LHeC would be able to cover l_4 masses up to $\sim 900 \text{ GeV}$.

2482 5.4 New physics in boson-quark interactions

2483 Several extensions of the Standard Model predict new phenomena that would be directly observable in boson-
 2484 quark interactions. For example, the top quark may have anomalous couplings to gauge bosons, leading to
 2485 Flavour Changing Neutral Current (FCNC) vertices $tq\gamma$, where q is a light quark. Similarly, excited quarks
 2486 (q^*) or quarks from a fourth generation (Q) could be produced via $\gamma q \rightarrow q^*$ or $\gamma q \rightarrow Q$. The transitions
 2487 $\gamma q \rightarrow t, q^*, Q$ can be studied in ep collisions at the LHeC, but a much larger cross-section would be achieved
 2488 at a γp collider, due to the much larger γp centre-of-mass energy. The single production of q^* , Q or of a top
 2489 quark via anomalous couplings is also possible at the LHC, but it involves an anomalous coupling together
 2490 with an electroweak coupling and the main background processes involve the strong interaction. The signal
 2491 to background ratio will thus be much more challenging at the LHC, and any constraints on anomalous
 2492 couplings would therefore be obtained from the decay channels of these quarks. The example of anomalous
 2493 single top production is detailed in the following.

2494 5.4.1 An LHeC-based γp collider

2495 The possibility to operate the LHeC as a γp collider is described in 8.1.6. If the electron beam is accelerated
 2496 by a linac, it can be converted into a beam of high energy real photons, by backscattering off a laser pulse.
 2497 The energy of these photons would be about 80% of the energy of the initial electrons.

2498 5.4.2 Anomalous Single Top Production at the LHeC Based γp Collider

2499 The top quark is expected to be most sensitive to physics beyond the Standard Model (BSM) because
 2500 it is the heaviest available particle of the Standard Model (SM). A precise measurement of the couplings
 2501 between SM bosons and fermions provides a powerful tool for the search of BSM physics allowing a possible
 2502 detection of deviations from SM predictions [237]. Anomalous tqV ($V = g, \gamma, Z$ and $q = u, c$) couplings can
 2503 be generated through dynamical mass generation [73], sensitive to the mechanism of dynamical symmetry
 2504 breaking. They have a similar chiral structure as the mass terms, and the presence of these couplings would
 2505 be interpreted as signals of new interactions. This motivates the study of top quark flavour changing neutral
 2506 current (FCNC) couplings at present and future colliders.

2507 Current experimental constraints at 95% C.L. on the anomalous top quark couplings are [238]: $BR(t \rightarrow$
 2508 $\gamma u) < 0.0132$ and $BR(t \rightarrow \gamma u) < 0.0059$ from HERA; $BR(t \rightarrow \gamma q) < 0.041$ from LEP and $BR(t \rightarrow \gamma q) <$
 2509 0.032 from CDF. The HERA has much higher sensitivity to $u\gamma t$ than $c\gamma t$ due to more favorable parton
 2510 density: the best limit is obtained from the ZEUS experiment.

2511 The top quarks will be produced in large numbers at the Large Hadron Collider (LHC), allowing great
 2512 precision measurement of the coupling. For a luminosity of 1 fb^{-1} (100 fb^{-1}) the expected ATLAS sensitivity
 2513 to the top quark FCNC decay is $BR(t \rightarrow q\gamma) \sim 10^{-3}(10^{-4})$ [239, 240]. The production of top quarks by
 2514 FCNC interactions at hadron colliders has been studied in [241–253], e^+e^- colliders in [73, 254–257] and
 2515 lepton-hadron collider in [73, 258–260]. LHC will give an opportunity to probe $BR(t \rightarrow ug)$ down to
 2516 5×10^{-3} [261]; ILC/CLIC has the potential to probe $BR(t \rightarrow q\gamma)$ down to 10^{-5} [262].

2517 A linac-ring type collider presents the sole realistic way to TeV scale in γp collisions [263–268]. Recently
 2518 this opportunity has been widely discussed in the framework of the LHeC project [17]. Two stages of the
 2519 LHeC were considered: QCD Explorer ($E_e = 50 - 100 \text{ GeV}$) and Energy Frontier ($E_e > 250 \text{ GeV}$). The po-
 2520 tential of the LHeC as a γp collider to search for anomalous top quark interactions has been investigated [269].
 2521 The effective Lagrangian involving anomalous $t\gamma q$ ($q = u, c$) interactions is given by [261].

$$L = -g_e \sum_{q=u,c} Q_q \frac{\kappa_q}{\Lambda} \bar{t} \sigma^{\mu\nu} (f_q + h_q \gamma_5) q A_{\mu\nu} + h.c. \quad (5.9)$$

2522 where $A_{\mu\nu}$ is the usual photon field tensor, $\sigma_{\mu\nu} = \frac{i}{2}(\gamma_\mu \gamma_\nu - \gamma_\nu \gamma_\mu)$, Q_q is the quark charge, in general f_q and
 2523 h_q are complex numbers, g_e is the electromagnetic coupling constant, κ_q is a real and positive anomalous
 2524 FCNC coupling constant and Λ is the new physics scale. The neutral current magnitudes in the Lagrangian
 2525 satisfy $|(f_q)^2 + (h_q)^2| = 1$ for each term. The anomalous decay width can be calculated as

$$\Gamma(t \rightarrow q\gamma) = \left(\frac{\kappa_q}{\Lambda}\right)^2 \frac{2}{9} \alpha_{em} m_t^3 \quad (5.10)$$

2526 Taking $m_t = 173$ GeV and $\alpha_{em} = 0.0079$, the anomalous decay width ≈ 9 MeV for $\kappa_q/\Lambda = 1$ TeV⁻¹
 2527 while the SM decay width is about 1.5 GeV.

2528 For numerical calculations anomalous interaction vertices are implemented into the CalcHEP pack-
 2529 age [211] using the CTEQ6M [131] parton distribution functions. The Feynman diagrams for the subprocess
 2530 $\gamma q \rightarrow W^+ b$, where $q = u, c$ are shown in Fig. 5.19. The first three diagrams correspond to irreducible back-
 2531 grounds and the last one to the signal. The main background comes from associated production of W boson
 2532 and the light jets.

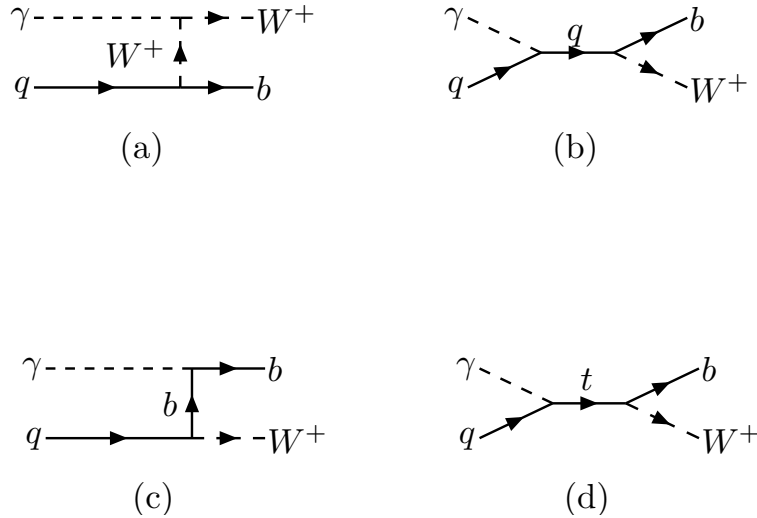


Figure 5.19: Feynman diagrams for $\gamma q \rightarrow W^+ b$, where $q = u, c$.

2533 The differential cross sections for the final state jets are given in Fig. 5.20 ($\kappa/\Lambda = 0.04$ TeV⁻¹) for
 2534 $E_e = 70$ GeV and $E_p = 7000$ GeV assuming $\kappa_u = \kappa_c = \kappa$. It is seen that the transverse momentum
 2535 distribution of the signal has a peak around 70 GeV.

2536 Here, b-tagging efficiency is assumed to be 60% and the mistagging factors for light (u, d, s) and c quarks
 2537 are taken as 0.01 and 0.1, respectively. A p_T cut reduce the signal (by $\sim 30\%$ for $p_T > 50$ GeV), whereas
 2538 the background is essentially suppressed (by a factor 4-6). In order to improve the signal to background
 2539 ratio further, one can apply a cut on the invariant mass of $W + jet$ around top mass. In Table 5.3, the cross
 2540 sections for signal and background processes are given after having applied both a p_T and an invariant mass
 2541 cuts ($M_{Wb} = 150 - 200$ GeV).

2542 In order to calculate the statistical significance (SS) we use following formula [270] :

$$SS = \sqrt{2 \left[(S + B) \ln\left(1 + \frac{S}{B}\right) - S \right]} \quad (5.11)$$

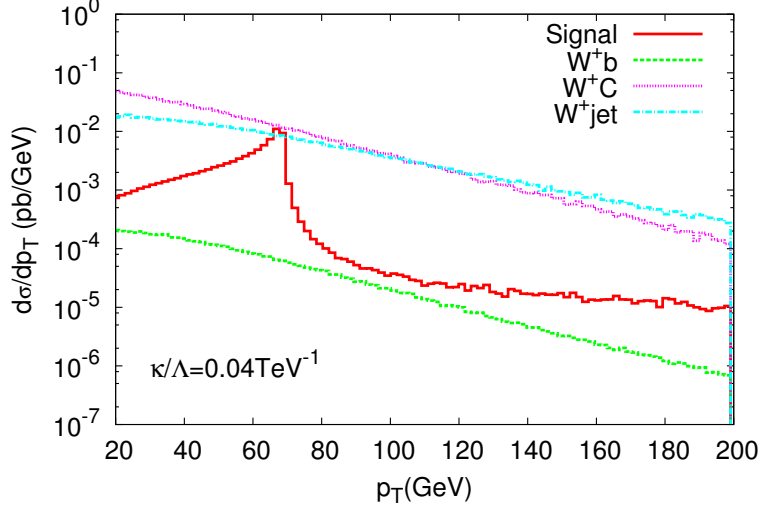


Figure 5.20: The transverse momentum distribution of the final state jet for the signal and background processes. The differential cross section includes the b -tagging efficiency and the rejection factors for the light jets. The center of mass energy $\sqrt{s_{ep}} = 1.4$ TeV and $\kappa/\Lambda = 0.04$ TeV $^{-1}$.

$\kappa/\Lambda = 0.01$ TeV $^{-1}$	$p_T > 20$ GeV	$p_T > 40$ GeV	$p_T > 50$ GeV
Signal	8.86×10^{-3}	7.54×10^{-3}	6.39×10^{-3}
Background: W^+b	1.73×10^{-3}	1.12×10^{-3}	7.69×10^{-4}
Background: W^+c	3.48×10^{-1}	2.30×10^{-1}	1.63×10^{-1}
Background: W^+jet	1.39×10^{-1}	9.11×10^{-2}	6.38×10^{-2}

Table 5.3: The cross sections (in pb) according to the p_T cut and invariant mass interval ($M_{Wb} = 150 - 200$ GeV) for the signal and background at γp collider based on the LHeC with $E_e = 70$ GeV and $E_p = 7000$ GeV.

2543 where S and B are the numbers of signal and background events, respectively. Results are presented in Table
 2544 5.4 for different κ/Λ and luminosity values. It is seen that even with 2 fb $^{-1}$ the LHeC based γp collider will
 2545 provide 5σ discovery for $\kappa/\Lambda = 0.02$ TeV $^{-1}$.

2546 Up to now, we have assumed $\kappa_u = \kappa_c = \kappa$. However, it would be interesting to analyze the case
 2547 $\kappa_u \neq \kappa_c$. Indeed, at HERA, valence u -quarks dominate whereas at LHeC energies the c -quark and u -quark
 2548 contributions become comparable. Therefore, the sensitivity to κ_c will be enhanced at LHeC comparing to
 2549 HERA. In Fig. 5.21 contour plots for anomalous couplings in $\kappa_u - \kappa_c$ plane are presented. For this purpose,
 2550 a χ^2 analysis was performed with

$$\chi^2 = \sum_{i=1}^N \left(\frac{\sigma_{S+B}^i - \sigma_B^i}{\Delta\sigma_B^i} \right)^2 \quad (5.12)$$

2551 where σ_B^i is the cross-section for the SM background in the i^{th} bin, including both b -jet and light-jet
 2552 contributions with their corresponding efficiency factors. In the σ_{S+B} calculations, we take into account the
 2553 different values for κ_u and κ_c as well as the signal-background interference. Figs. 5.20-5.21 show that the
 2554 sensitivity is enhanced by a factor of 1.5 when the luminosity changes from 2 fb $^{-1}$ to 10 fb $^{-1}$. Concerning the
 2555 energy upgrade, increasing electron energy from 70 GeV to 140 GeV results in 20% improvement for κ_c [269].
 2556 Increasing the electron energy further (energy frontier ep collider) does not give an essential improvement in

SS	$L = 2 \text{ fb}^{-1}$	$L = 10 \text{ fb}^{-1}$
$\kappa/\Lambda = 0.01 \text{ TeV}^{-1}$	2.58 (2.88)	5.79 (6.47)
$\kappa/\Lambda = 0.02 \text{ TeV}^{-1}$	5.26 (5.92)	11.78 (13.25)

Table 5.4: The signal significance (SS) for different values of κ/Λ and integral luminosity for $E_e = 70 \text{ GeV}$ and $E_p = 7000 \text{ GeV}$ (the numbers in parenthesis correspond to $E_e = 140 \text{ GeV}$).

2557 the sensitivity to anomalous couplings [271].

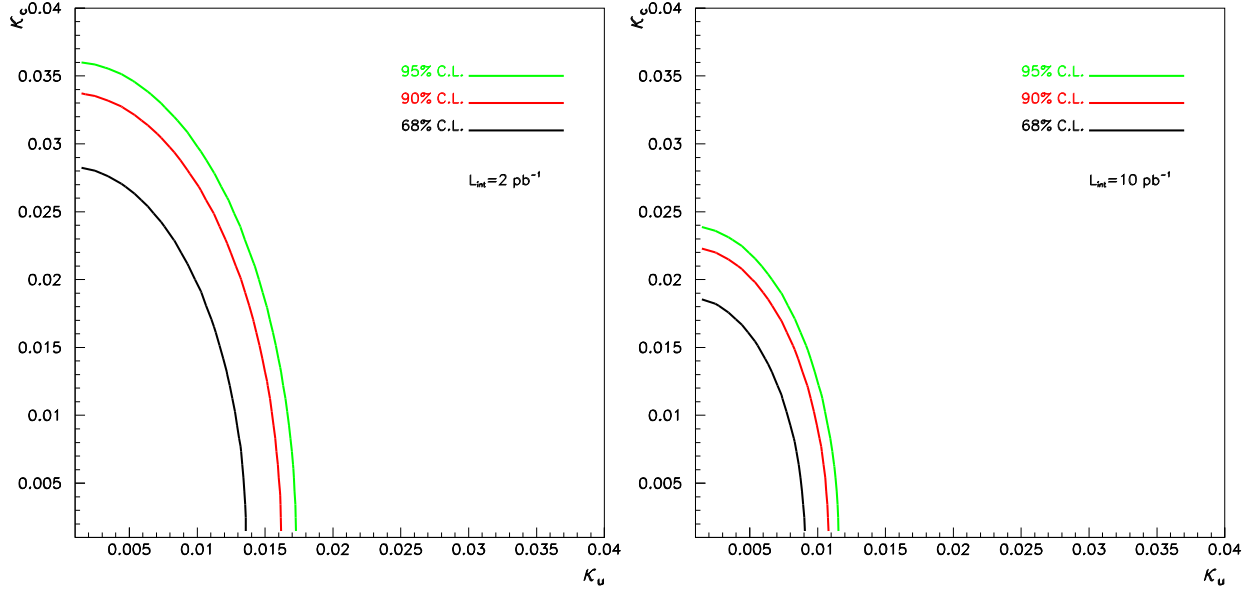


Figure 5.21: Contour plot for the anomalous couplings reachable at the LHeC based γp collider with the center of mass energy $\sqrt{s_{ep}} = 1.4 \text{ TeV}$ and integrated luminosity of $L_{int} = 2 \text{ fb}^{-1}$ (left) or $L_{int} = 10 \text{ fb}^{-1}$ (right)

2558 Table 5.4 shows that a sensitivity to anomalous coupling κ/Λ down to 0.01 TeV^{-1} could be reached.
 2559 Noting that the value of $\kappa/\Lambda = 0.01 \text{ TeV}^{-1}$ corresponds to $BR(t \rightarrow \gamma u) \approx 2 \times 10^{-6}$ which is two orders
 2560 smaller than the LHC reach with 100 fb^{-1} , it is obvious that even an upgraded LHC will not be competitive
 2561 with LHeC based γp collider in the search for anomalous $t\gamma q$ interactions. Different extensions of the SM
 2562 (SUSY, technicolor, little Higgs, extra dimensions etc.) predict branching ratio $BR(t \rightarrow \gamma q) = O(10^{-5})$, hence
 2563 the LHeC will provide an opportunity to probe these models. The top quark could provide very important
 2564 information for the Standard Model extensions due to its large mass close to the electroweak symmetry
 2565 breaking scale.

2566 5.4.3 Excited quarks in γp collisions at LHeC

2567 Excited quarks will have vertices with SM quark and gauge bosons (photon, gluon, Z or W bosons). They
 2568 can be produced at ep and γp colliders via quark photon fusion. Interactions involving excited quark are
 2569 described by the Lagrangian of eq. 5.6 (where F is now a quark q)

2570 A sizeable f_s coupling would allow for resonant q^* production at the LHC via quark-gluon fusion. In that
 2571 case, the LHC would offer a large discovery potential for excited quarks and would be well suited to study
 2572 the properties and couplings of these new quarks. However, if the coupling of excited quarks to gq happens

2573 to be suppressed, the LHC would mainly produce q^* via pair-production and would have little sensitivity to
 2574 couplings f/Λ or f'/Λ . Such couplings would be better studied, or probed down to much lower values, via
 2575 single-production of q^* at the LHeC. A study of the LHeC potential for excited quarks is presented in [272].
 2576 An example of the 3σ discovery reach, assuming $f = f' = f_s$ and setting Λ to be equal to the q^* mass, is
 given in Fig. 5.22. Both decays $q^* \rightarrow q\gamma$ and $q^* \rightarrow qg$ have been considered here.

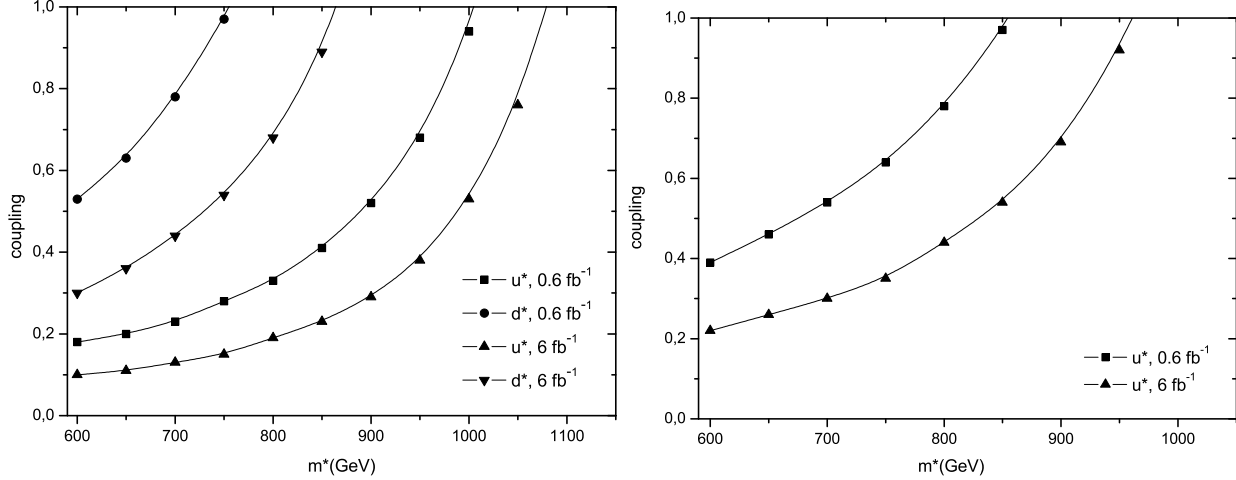


Figure 5.22: Observation reach at 3σ for coupling and excited quark mass at a γp collider with $\sqrt{s} = 1.27$ TeV from an analysis of (left) the jj channel and (right) the γj channel.

2577

2578 5.4.4 Quarks from a fourth generation at LHeC

2579 The case of fourth generation quarks with magnetic FCNC interactions to gauge bosons and standard quarks,

$$\mathcal{L} = \left(\frac{\kappa_\gamma^{q_4 q_i}}{\Lambda} \right) e_q g_e \bar{q}_4 \sigma_{\mu\nu} q_i F^{\mu\nu} + \left(\frac{\kappa_Z^{q_4 q_i}}{2\Lambda} \right) g_Z \bar{q}_4 \sigma_{\mu\nu} q_i Z^{\mu\nu} + \left(\frac{\kappa_g^{q_4 q_i}}{\Lambda} \right) g_s \bar{q}_4 \sigma_{\mu\nu} T^a q_i G_a^{\mu\nu} + h.c. \quad (5.13)$$

2580 is very similar to that of excited quarks. A γp collider based on LHeC would have a better sensitivity than
 2581 LHC to anomalous couplings κ_γ and κ_Z . A detailed study is presented in [236] and example results are
 2582 shown in Fig. 5.23. These figures also show the clear advantage of a γp collider compared to an ep collider,
 2583 for the study of new physics in γq interactions.

2584 5.4.5 Diquarks at LHeC

2585 The case of diquark production at LHeC has been studied in [273]. The production cross-section can be
 2586 sizeable at a high energy ep machine, especially when operated as a γp collider. The measurement of the
 2587 $\gamma p \rightarrow DQ + X$ cross-section, for a diquark DQ of known mass and known coupling to the diquark pair³
 2588 would provide a measurement of the electric charge of the diquark. It would thus be complementary to
 2589 the pp data, which offer no simple way to access the DQ electric charge. However, the diquark masses and
 2590 couplings that could be accessible at LHeC appear to be already excluded by the recent search for dijet
 2591 resonances at the LHC [274].

³The LHC would observe diquark as di-jet resonances, and could easily determine its mass, width and coupling to the quark pair.

2592 5.4.6 Quarks from a fourth generation in Wq interactions

2593 In case fourth generation quarks do not have anomalous interactions as in Eq. 5.13, they (or vector-like quarks
2594 coupling to light generations [275,276]) could be produced in ep collisions by Wq interactions provided that
2595 the V_{Qq} elements of the extended CKM matrix are not too small, via the usual vector WqQ interactions. An
2596 example of the sensitivity that could be reached at LHeC is presented in [277], assuming some values for the
2597 V_{Qq} parameters. Measurements of single Q production at LHeC would provide complementary information
2598 to the LHC data, that could help in determining the extended CKM matrix.

2599 5.5 Sensitivity to a Higgs boson

2600 Understanding the mechanism of electroweak symmetry breaking is a key goal of the LHC physics programme.
2601 In the SM, the symmetry breaking is realized via a scalar field (the Higgs field) which, at the minimum of the
2602 potential, develops a non-zero vacuum expectation value. The breaking of the $SU(2)_L \times U(1)_Y$ symmetry
2603 gives mass to the electroweak gauge bosons via the Higgs mechanism while the fermions obtain their mass
2604 via Yukawa couplings with the Higgs field. The LHC experiments should be able to discover a Higgs boson
2605 within the full allowable mass range, with an integrated luminosity of less than 10 fb^{-1} . Following its
2606 discovery, it will be crucial to measure the couplings of this Higgs boson to the SM particles, in particular
2607 to the fermions, in order to:

- 2608 • establish that the Higgs field is indeed accounting for the fermion masses, via Yukawa couplings $y_f H \bar{f} f$;
- 2609 • disentangle between the SM and (some of) its extensions. For example, despite the richer content of
2610 the Higgs sector in the Minimal Supersymmetric Standard Model, only the light SUSY Higgs boson h
2611 would be observable at the LHC in certain regions of parameter space. Its properties are very similar
2612 to those of the SM Higgs H , and precise measurements of ratios $BR(\Phi \rightarrow VV)/BR(\Phi \rightarrow ff)$ will be
2613 essential in determining whether or not the observed boson, Φ , is the SM Higgs scalar.

2614 Electroweak precision measurements strongly suggest that the SM Higgs boson should be light, in which
2615 case it would decay into a $b\bar{b}$ pair with a branching ratio of $\sim 70\%$, but a measurement of the $Hb\bar{b}$ coupling
2616 will be very challenging at the LHC [239,270,278]. Indeed, the observation of $H \rightarrow b\bar{b}$ in the inclusive
2617 production mode is made very difficult by the huge QCD background, although a possible search channel
2618 would be associated WH and ZH production, with highly boosted Higgs, leading to a high mass jet with
2619 substructure [279]. The observability of the signal in the $t\bar{t}H$ production mode also suffers from a large
2620 background, including background of combinatorics origin, and from experimental systematic uncertainties.

2621 The signal $H \rightarrow b\bar{b}$ may be observed in the exclusive production mode, thanks to the much cleaner
2622 environment in a diffractive process. However, the production cross-section in this mode suffers from large
2623 theoretical uncertainties, such that this measurement, if feasible at all, would not translate into a precise
2624 measurement of the $Hb\bar{b}$ coupling.

2625 At the LHeC, a light Higgs boson could be produced via WW or ZZ fusion with a sizeable cross-section.
2626 This section focusses on the observability of the signal $ep \rightarrow H + X \rightarrow b\bar{b} + X$ at LHeC, which may be the
2627 first observation of the $H \rightarrow b\bar{b}$ decay. A recent similar study can be found in [280].

2628 5.5.1 Higgs production at LHeC

2629 In ep collisions, the Higgs boson could be produced in neutral current (NC) interactions via the ZZH
2630 coupling, and in charged current (CC) interactions via the WWH coupling. The corresponding diagrams
2631 are shown in Fig. 5.24, and the production cross-sections, as a function of the Higgs mass, is displayed
2632 in Fig. 5.25. The WWH production largely dominates the total cross-section. As is the case for the
2633 inclusive CC DIS interactions, the cross-section is much larger in e^-p collisions than in e^+p collisions, due
2634 to the more favorable density of the valence quark that is involved (u in e^-p , d in e^+p), and to the more
2635 favorable helicity factors. Table 5.5 shows the Higgs production cross-section (at leading order) via CC
2636 interactions in e^-p collisions, for various values of the Higgs mass and three example values of the electron

2637 beam energy. The scale dependency of these leading order estimate is of $\mathcal{O}(10\%)$. Next-to-leading order
 2638 corrections were calculated in [281, 282]. They are small, but can affect within $\mathcal{O}(20\%)$ the shape of some
 2639 kinematic distributions.

M_H in GeV :	100	120	160	200	240	280
$E_e = 50$ GeV	102	81	50	32	20	12
$E_e = 100$ GeV	201	165	113	79	55	39
$E_e = 150$ GeV	286	239	170	123	90	67

Table 5.5: Production cross-section in fb of a SM Higgs boson via charged current interactions in e^-p collisions, for three example values of the electron beam energy.

2640 5.5.2 Observability of the signal

2641 The dominating source of background at large missing transverse energy is coming from multi-jet production
 2642 in CC DIS interactions. In particular, a good rejection of the background coming from single top production
 2643 ($e^-b \rightarrow \nu t$), where the top decays hadronically, puts severe constraints on the acceptance and the resolution
 2644 of the detector, as will be seen below. The background due to multijet production in NC interactions is also
 2645 considered.

2646 MadGraph [283] has been used to generate SM Higgs production, CC and NC DIS background events.
 2647 Calculations of cross-sections and generation of final states of outgoing particles are performed by MadGraph,
 2648 given the beam parameters, considering all possible tree-level Feynman diagrams in the SM. In the case of
 2649 NC, since the cross section is very high, diverging at low scattering angle, only processes producing two or
 2650 more b quarks were generated in order to have sufficient MC statistics. By artificially increasing the mistag
 2651 probability, it was possible to verify that, after the selection, essentially all the remaining NC background is
 2652 indeed due to events with two truly b-quark jets in the final state. Fragmentation and hadronization processes
 2653 were simulated by PYTHIA [130] with custom modifications to apply for ep collisions. Finally, particles were
 2654 passed through a generic detector using the PGS [284] fast detector simulation tool. We assumed tracking
 2655 coverage of $|\eta| < 3$ and calorimeter coverage of $|\eta| < 5$ with electromagnetic calorimeter resolution of
 2656 $5\%/\sqrt{E(\text{GeV})}$ (plus 1% of constant term) and hadronic calorimeter resolution of $60\%/\sqrt{E(\text{GeV})}$. Jets
 2657 were reconstructed by a cone algorithm with a cone size of $\Delta R = 0.7$. The efficiency of b-flavor tagging was
 2658 assumed to be 60% and flat within the calorimeter coverage, whereas mistagging probabilities of 10% and
 2659 1% for charm-quark jets and for light-quark jets, respectively, were taken into account.

2660 We set 150 GeV of electron beam energy with 7 TeV of proton beam energy as the reference beam
 2661 configuration and assumed 120 GeV of SM Higgs boson mass in the MC simulation study. The results were
 2662 compared with those with a different beam energy and Higgs mass.

2663 The following selection criteria were applied, based on observable variables generated by the PGS detector
 2664 simulation, to distinguish $H \rightarrow b\bar{b}$ from the CC and NC DIS backgrounds.

2665 • cut (1): Primary cuts

- 2666 – Exclude electron-tagged events
- 2667 – $E_{T,miss} > 20$ GeV
- 2668 – $N_{jet}(P_{T,jet} > 20 \text{ GeV}) \geq 3$
- 2669 – $E_{T,total} > 100$ GeV
- 2670 – $y_{JB} < 0.9$, where $y_{JB} = \Sigma(E - p_z)/2E_e$
- 2671 – $Q_{JB}^2 > 400$ GeV, where $Q_{JB}^2 = E_{T,miss}^2/(1 - y_{JB})$

2672 • cut (2): b-tag requirement

2673 – $N_{b\text{-jet}}(P_{T,\text{jet}} > 20 \text{ GeV}) \geq 2$, where b-jet means a b-tagged jet

2674 • **cut (3): Higgs invariant mass cut**

2675 – $90 < M_H < 120 \text{ GeV}$; due to the energy carried by the neutrino from b decays, the mass peaks
2676 are slightly lower than the true Higgs mass

2677 Fig. 5.26 shows the missing E_T and number of b-tagged jets for $H \rightarrow b\bar{b}$ events together with the CC and
2678 NC DIS background. The NC background is strongly suppressed by the missing E_T cut and electron-tag
2679 requirement. We required at least two b-tagged jets, and reconstructed the Higgs invariant mass using the
2680 two b-tagged jets with lowest and second lowest η . After cuts (1) + (2) + (3) were applied, 44.4% of the
2681 remaining CC background was due to single top production. The following cuts were further applied.

2682 • **cut (4): rejection of single top production** Single top events result in a final state with two b-jets
2683 and a W decaying into two light-quark jets. The following cuts were found to be efficient in suppressing
2684 this background.

2685 – $M_{jjj,\text{top}} > 250 \text{ GeV}$, where the three-jet invariant mass ($M_{jjj,\text{top}}$) was reconstructed from two
2686 b-jets with the lowest η and any third jet with the lowest η regardless of b-tag

2687 – $M_{jj,W} > 130 \text{ GeV}$, where di-jet invariant mass ($M_{jj,W}$) was reconstructed from one b-jet with the
2688 lowest η and any second jet with the lowest η regardless of b-tag but excluding the second lowest
2689 η b-jet

2690 • **cut (5): forward jet tagging**

2691 – $\eta_{\text{jet}} > 2$ for the lowest- η jet excluding the two b -jets

2692 Fig. 5.27 shows the reconstructed three-jet ($M_{jjj,\text{top}}$) and di-jet ($M_{jj,W}$) invariant masses after cuts (1) and
2693 (2) are applied. It is seen that, for CC background, the former peaks at the top mass and the latter peaks
2694 at the W mass. The last cut is motivated by the fact that the jet from light quark participating in the CC
2695 reaction for the signal is kinematically boosted to forward rapidity (in the proton beam direction), as shown
2696 in Fig. 5.28.

2697 Fig. 5.29 shows the reconstructed Higgs mass distribution for an integrated luminosity of 10 fb^{-1} , after all
2698 selection criteria except for the Higgs mass cut have been applied. The results are summarized in Table 5.6.
2699 After the selection, 85 $H \rightarrow b\bar{b}$ events are expected for 10 fb^{-1} luminosity with a 150 GeV electron beam.
2700 The signal to background ratio is 1.79 and the significance of the signal $S/\sqrt{N} = 12.3$. For a higher Higgs
2701 mass, $m_H=150 \text{ GeV}$, the production cross section decreases and the $b\bar{b}$ branching ratio also decreases. The
2702 expected number of signal events becomes 25 and S/N and S/\sqrt{N} are 0.52 and 3.60, respectively. On
2703 the other hand, with 60 GeV electron beam and five times larger luminosity (50 fb^{-1}), for 120 GeV Higgs,
2704 124 $H \rightarrow b\bar{b}$ events are expected after the same cuts have been applied. Considering the CC and NC DIS
background, S/N and S/\sqrt{N} are 1.05 and 11.4, respectively.

	Higgs production	CC DIS	NC $b\bar{b}j$	S/N	S/\sqrt{N}
cut (1)	816	123000	4630	6.38×10^{-3}	2.28
cut (1) + (2) + (3)	178	1620	179	9.92×10^{-2}	4.21
All cuts	84.6	29.1	18.3	1.79	12.3

Table 5.6: Expected $H \rightarrow b\bar{b}$ signal and background events with 150 GeV electron beam for an integrated luminosity of 10 fb^{-1} . Contents of the cuts are listed in text.

2705 The results shown here are subject to large uncertainties. First, as mentioned above, the very large NC
2706 background cross section at forward scattering angles makes it impossible to simulate a sufficient number
2707

2708 of events to limit the Monte Carlo statistical uncertainty. It is estimated that the background evaluation,
 2709 with the above method where only events with at least two b quarks were simulated, has an uncertainty of
 2710 about a factor 3. With a full simulation, it can be expected to be negligible when the true measurement
 2711 is realized. Neglecting, therefore, this source of uncertainty, the systematic errors which will dominate are
 2712 expected to be the theoretical estimates of signals and backgrounds and instrumental effects: efficiency and
 2713 acceptance of lepton and jet reconstruction, b-tagging and mistagging probabilities. They are difficult to
 2714 estimate without real data and a real detector. The statistical uncertainty on the cross section can, however,
 2715 be estimated: 15% for the reference case of 150 GeV \times 7 TeV beams and a Higgs of mass 120 GeV. This
 2716 represents a direct measure of the statistical uncertainty on the product of the squares of couplings Hbb and
 2717 HWW .

2718 5.5.3 Probing Anomalous HWW Couplings at the LHeC

2719 The HWW vertex is an excellent handle on the quartic self-coupling of the scalar doublet. Its measurement
 2720 provides a direct insight into the nature of electroweak symmetry-breaking. Parametrising the $H(k) -$
 2721 $W_\mu^+(p) - W_\nu^-(q)$ vertex in the form $i\Gamma^{\mu\nu}(p, q) \epsilon_\mu(p) \epsilon_\nu^*(q)$, any deviations from the simple SM formula
 2722 $\Gamma_{(\text{SM})}^{\mu\nu}(p, q) = gM_W \lambda^{\mu\nu}$ at a level incompatible with SM loop corrections would immediately indicate the
 2723 presence of new physics. Following Ref. [285], we can parametrize these deviations using two dimension-5
 2724 operators

$$\Gamma_{\mu\nu}^{(\text{BSM})}(p, q) = \frac{-g}{M_W} [\lambda(p \cdot q \lambda_{\mu\nu} - p_\nu q_\mu) + i \lambda' \epsilon_{\mu\nu\rho\sigma} p^\rho q^\sigma] \quad (5.14)$$

2725 where λ and λ' are, respectively, effective coupling strengths for the CP -conserving and the CP -violating
 2726 parts.

2727 An ep collider has a unique advantage in the fact that the HWW vertex gives rise to the process
 2728 $e + p \rightarrow \nu_e + X + H(bb)$ though the single Feynman diagram shown in Figure 5.24(left). The final state
 2729 has, therefore, missing transverse energy (MET) and three jets J_1, J_2 and J_3 , of which two (say J_2 and J_3)
 2730 are tagged as b -jets. It can be shown [285] that in the limit when there is practically no energy transfer
 2731 to the W bosons and the final states are very forward, the CP -conserving (CP -violating) coupling λ (λ')
 2732 contributes to the matrix element for this process a term of the form which goes through zero when the
 2733 missing transverse momentum is perpendicular to the p_T of the jet:

$$\mathcal{M} \sim +\lambda \vec{p}_T \cdot \vec{p}_T^{J_1} \quad \widetilde{\mathcal{M}} \sim -\lambda' \vec{p}_T \cdot \vec{p}_T^{J_1} . \quad (5.15)$$

2734 This explains the general trend illustrated in Figure 5.30, for an exact calculation of the $2 \rightarrow 3$ process
 2735 $eq \rightarrow \nu_e q' H$ at the parton level, with parton density functions from the CTEQ-6L1 set [131]. In the case
 2736 considered, 140 GeV electrons collide with 7 TeV protons and the Higgs boson mass is set to 120 GeV.

2737 A detailed simulation of the charged current process was discussed above in Sect. 5.5.2. Here, the analysis
 2738 is based on the kinematic cuts and efficiencies adopted in Ref. [280]. The azimuthal distribution has been
 2739 simulated in 10 bins, each of width $\pi/5$, and the signal and SM backgrounds have been calculated in each
 2740 bin using the same formulae used to create Figure 5.30, followed by a detailed simulation of fragmentation,
 2741 jet identification and detector effects. Assuming statistical errors dependent on the integrated luminosity
 2742 L , we then determine the sensitivity, for a given L , of the experiment to λ, λ' by making a log-likelihood
 2743 analysis. Our results are exhibited in Figure 5.31, where we present 95% exclusion plots for the λ and λ'
 2744 couplings as a function of L . It is clear from this figure that by the time the LHeC has collected 10 fb $^{-1}$
 2745 of data, we will be able to exclude the anomalous couplings to the level of 0.3 or lower. The experimental
 2746 set-up is somewhat more sensitive to the CP -even coupling, as evidenced by the narrower inaccessible region
 2747 indicated on the left panel.

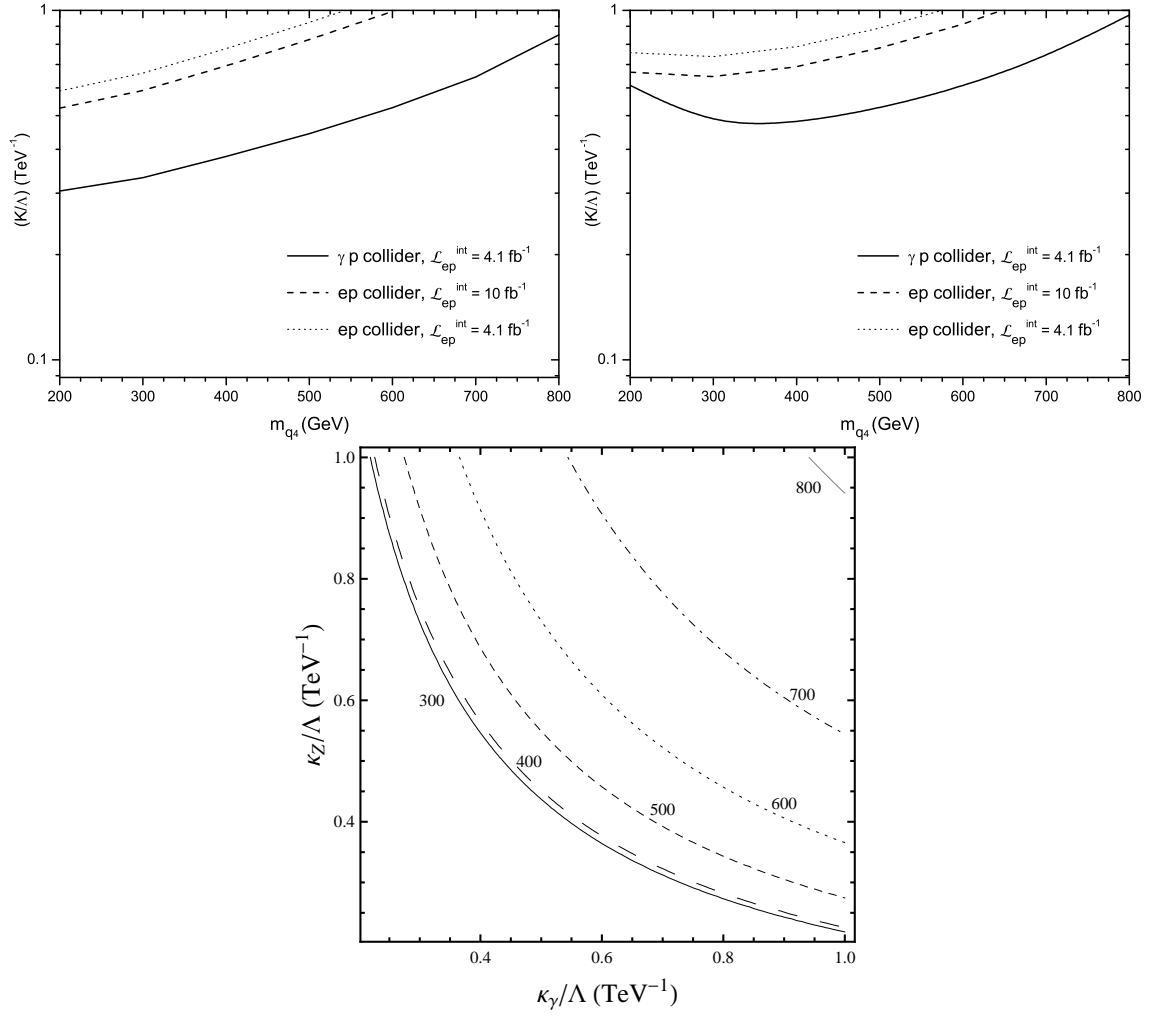


Figure 5.23: The achievable values of the anomalous coupling strength at ep and γp colliders for a) $q_4 \rightarrow \gamma q$ anomalous process and (b) $q_4 \rightarrow Zq$ anomalous process as a function of the q_4 mass; (c) the reachable values of anomalous photon and Z couplings with $L_{int} = 4.1 \text{ fb}^{-1}$.

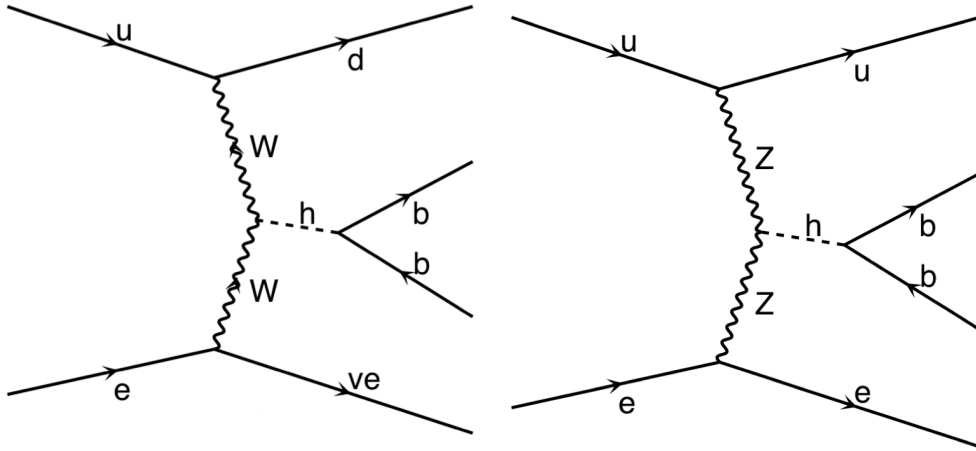


Figure 5.24: Feynman diagrams for CC(left) and NC(right) Higgs production at the LHeC.

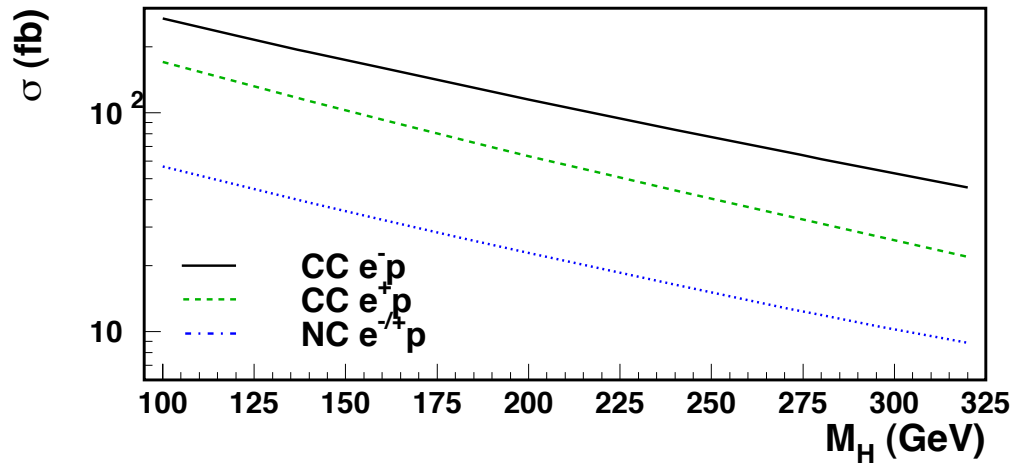


Figure 5.25: Production cross-section of a SM Higgs boson in ep collision with $E_e=150$ GeV and $E_p=7$ TeV, as a function of the Higgs mass.

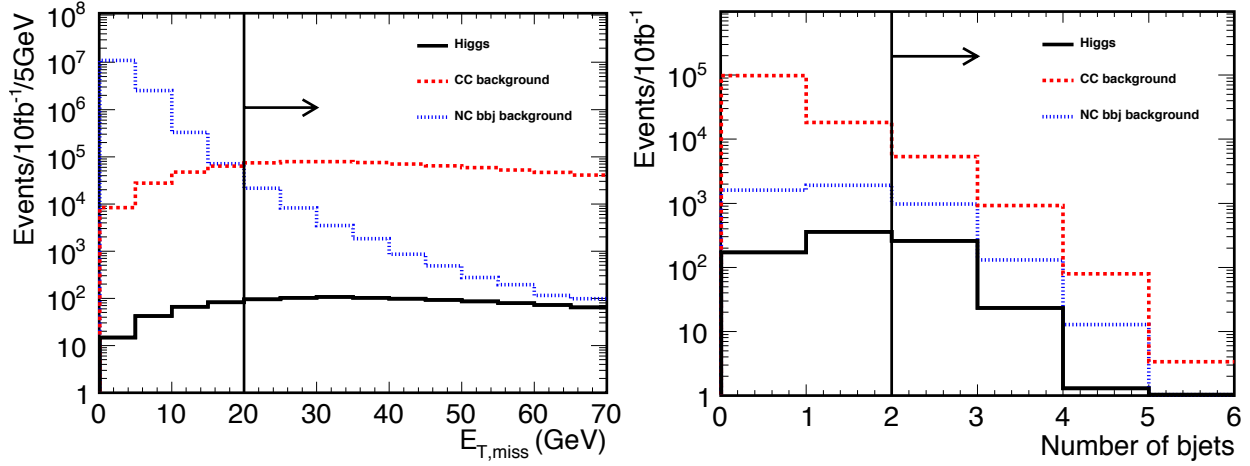


Figure 5.26: Missing E_T (left) and number of b-tagged jets (right). Solid (black), dashed (red) and dotted (blue) histograms show $H \rightarrow b\bar{b}$, CC and NC DIS background, respectively. The right plot is for events passing cut (1) in the text.

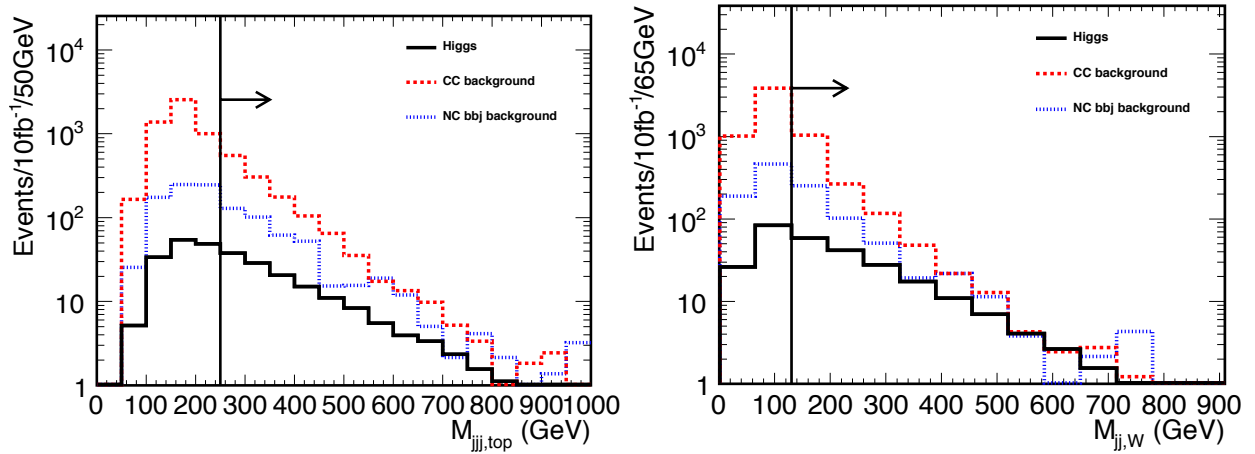


Figure 5.27: Three-jet (left) and di-jet (right) invariant masses. Solid (black), dashed (red) and dotted (blue) histograms show $H \rightarrow b\bar{b}$, CC and NC DIS background, respectively.

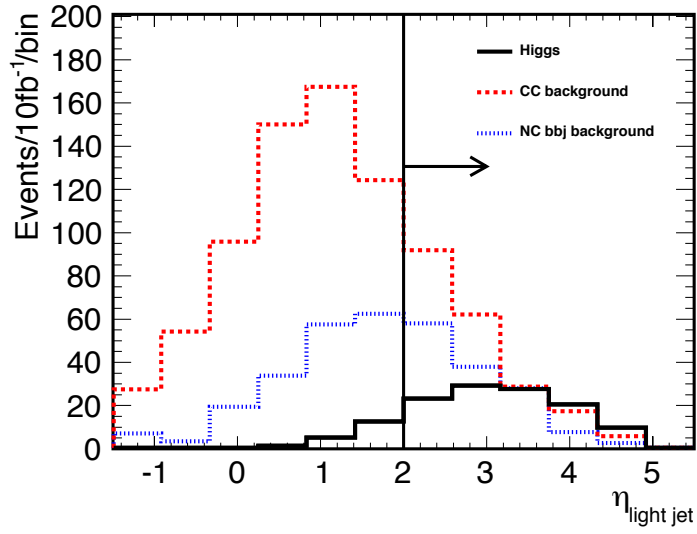


Figure 5.28: η_{jet} distribution for the lowest- η jet excluding the two b -tagged jets. Solid (black), dashed (red) and dotted (blue) histograms show $H \rightarrow b\bar{b}$, CC and NC DIS background, respectively.

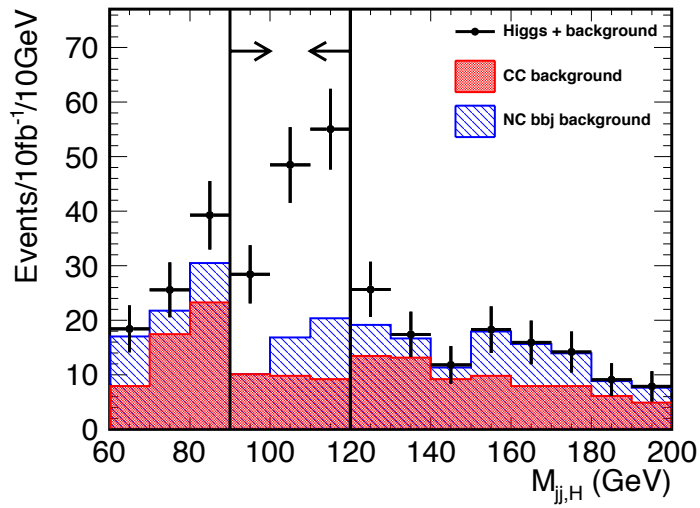


Figure 5.29: Reconstructed invariant Higgs mass after all selection criteria, except for the Higgs mass cut, have been applied. Points with error bars (black) show the $H \rightarrow b\bar{b}$ signal added to the CC (red histogram) and NC (hatched blue histogram) DIS background for an integrated luminosity of 10 fb^{-1} .

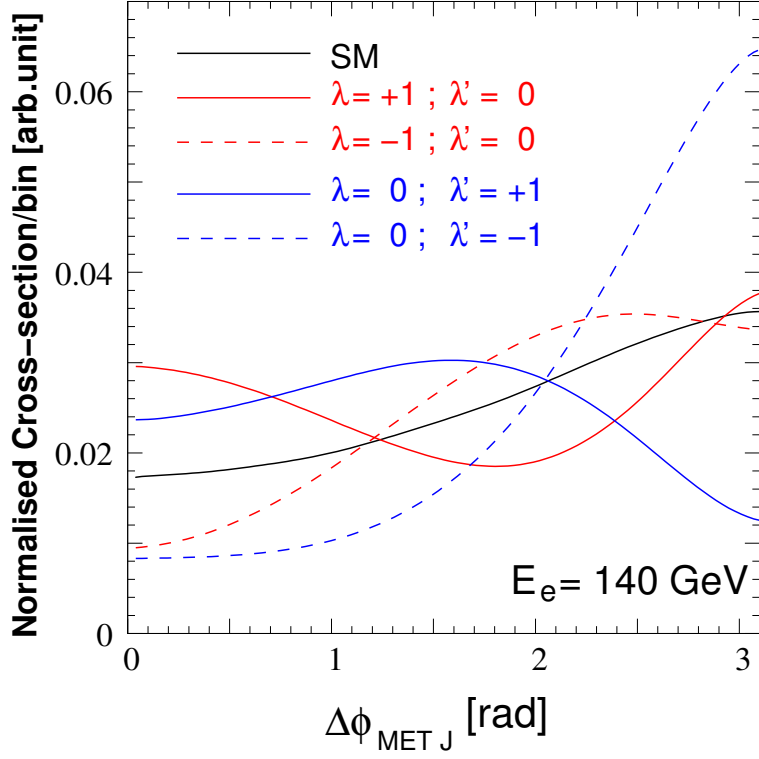


Figure 5.30: Illustrating the SM distribution in azimuthal angle and deviations therefrom which are due to anomalous HWW couplings.

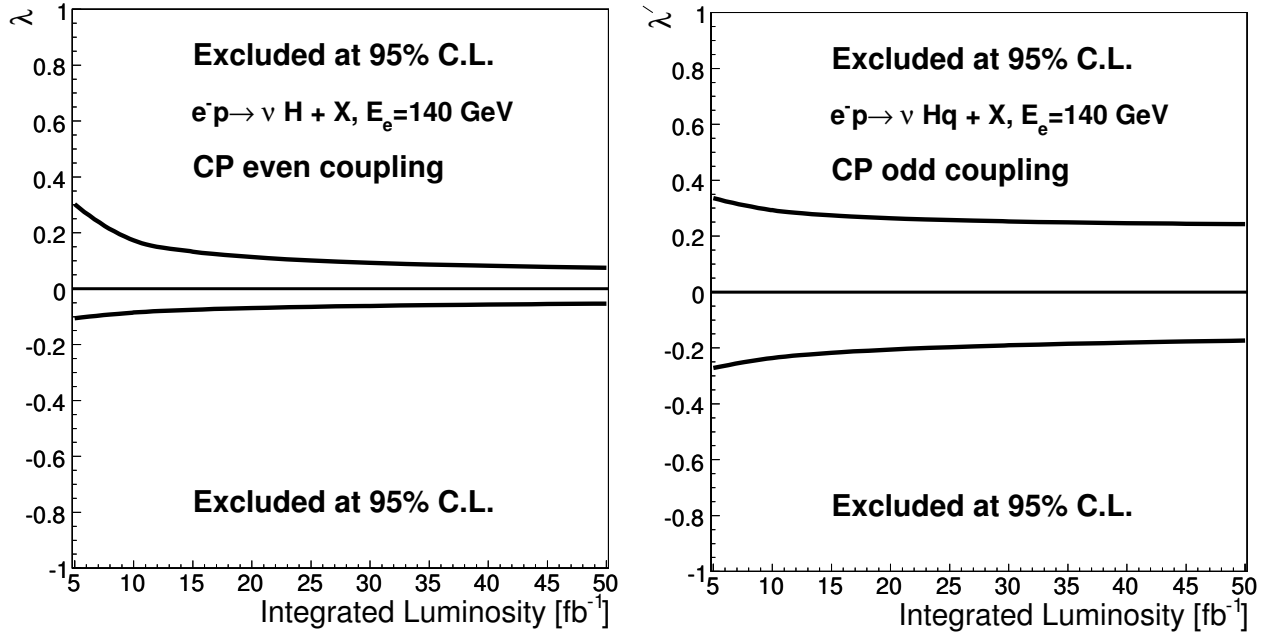


Figure 5.31: Exclusion plots obtainable by a study of the azimuthal angle distributions at the LHeC for the CP -even coupling λ and the CP -odd coupling λ' . Note that this study is for $M_H = 120$ GeV.

Chapter 6

Physics at High Parton Densities

6.1 Physics at small x

6.1.1 Unitarity and QCD

Introduction

QCD [31] is the fundamental theory of the strong interaction that has been extensively tested in the last 38 years. Still, many open questions remain to be solved. One of them, which can be addressed at high energies, is the transition between the regimes in which the strong coupling constant is either large or small - the so-called *strong and weak coupling* regimes. In the former, standard perturbation theory techniques are not applicable and exact analytical results are not yet within the reach of current knowledge. Therefore various models, *effective* theories, whose parameters cannot yet be derived from QCD, or numerical lattice computations, have to be employed. One example of such an effective theory which has been used through the years and actually predates QCD, is the Regge-Gribov [286–288] theory.

The weak coupling regime has been well tested in high-energy experiments through a selected class of measurements - often referred to as *hard processes* - where weak and strong coupling effects can be cleanly separated. There exists a well-defined theoretical concept which has been derived from first principles and probed in the weak coupling regime, namely the collinear factorization theorem (for a comprehensive review see [289] and references therein). It allows a separation of the cross sections involving hadrons into: (i) parts that can be computed within perturbation theory, corresponding to the cross section for parton scattering, and (ii) pieces which cannot be calculated using weak coupling techniques, but whose evolution is still perturbative. The latter are universal, process-independent distributions that either characterize the partonic content of the hadron - *parton densities* on which we will mainly focus the discussion - or the eventual projection of partons onto hadrons. Together with their corresponding (DGLAP) linear evolution equations [33,35,290], they have been used to describe experimental data to high accuracy. Examples include total DIS cross sections, the production of jets with large transverse momenta and final states with heavy quarks.

In recent years high-energy experiments have become sensitive to kinematic regions in which the coupling is small but the factorization assumption may no longer be valid. As an example, several HERA DIS measurements at small longitudinal momentum fractions x where parton densities are large, indicate deviations from the behavior expected within the standard collinear factorization. Similarly, hadronic or nuclear collisions involving partons with small x may also show such deviations. At the same time, in these small- x regions the cross sections grow rapidly, so contributions from such regions dominate hadronic cross sections in sufficiently high energy scattering. Experiments sensitive to this kinematic region thus provide a way to test QCD in the new regime where the parton densities become very large and novel effects are expected. We will refer to this region as the high parton density domain.

From a theoretical viewpoint, this situation offers both opportunities and challenges. The fact that, at

small- x , there is no abrupt transition between the dilute and dense regimes, allows the use of techniques which, while still being weak coupling, go beyond those used in the dilute limit. The usual parton multiplication processes have to be supplemented by processes in which partons recombine - thus adding non-linear terms to the evolution equations [291]. There are deep theoretical questions arising in this new dense partonic regime of QCD. At high energies the scattering amplitudes are close to the unitarity limit, and one expects that unitarity will be preserved by the taming of parton densities due to recombination effects - this phenomenon is generically referred to as *saturation*. Thus, in the weak coupling limit the physics responsible for satisfying unitarity in QCD is expected to be describable in partonic language. Theoretical calculations [292–295] in high-energy QCD justify these generic expectations. Furthermore, the experimental exploration of this transition region where the standard perturbative description based on collinear factorization and linear evolution equations requires large corrections, provides new possibilities of further understanding the strong coupling regime.

Deep inelastic lepton-hadron scattering has already been shown to address these questions in the most efficient manner. It provides the cleanest way of measuring the parton densities, including the small- x region in which, as indicated above, the border between the dilute and dense regimes of QCD should occur within the weak coupling region where calculations can be done. Approaching this transition region from the dilute side by decreasing x or by increasing the number of nucleons in the target, one should observe features which cannot be understood within the framework of linear QCD evolution equations but, using more elaborate tools (non-linear evolution equations) can still be analyzed in terms of weak coupling techniques. In fact, within the standard framework of the leading-twist linear QCD evolution equations (DGLAP) the parton densities are predicted to rise at small x , and this rise has been seen very clearly at HERA. However, unitarity prevents such a rise from continuing indefinitely, leading to saturation of gluon densities. In hadron-hadron scattering it is unitarity which limits the growth of the total cross sections as a function of energy: according to Froissart and Martin [296, 297]

$$\sigma_{\text{tot}} \leq \text{const.} \ln^2 s/s_0, \quad (6.1)$$

where s_0 is a typical hadronic scale. This bound comes from two fundamental assumptions. The first is that the amplitude for the scattering at fixed value of impact parameter is bounded by unity and the second is the finite range of the strong interaction. The bound on the amplitude has a simple physical interpretation that the probability for the interaction becomes very high, so the target (or more precisely the interaction region) is completely absorptive. This situation is usually referred to as a *black disk* regime. The description of this regime is very challenging theoretically and it is expected that new phenomena will occur which are direct manifestations of a new state in QCD which is characterized by a high parton density. The LHeC will uniquely offer the possibility of exploring the transition towards this new state of dense QCD matter, as it can pursue a two-pronged approach: high center-of-mass energy, extending the kinematic range to lower x , and the possibility of deep inelastic scattering off heavy nuclei.

In the rest of this section we will present the different approaches that are currently under discussion to describe the high-energy regime of QCD. We will recall the ideas that lead from linear evolution equations to non-linear ones. On the former, we will discuss both cases in which the evolution equations are computed within fixed-order perturbation theory (the DGLAP evolution equations) and where they include some kind of resummation - thus going beyond any fixed order in the perturbative expansion in the QCD coupling constant. The most famous example is the Balitsky-Fadin-Kuraev-Lipatov (BFKL) equation [298, 299]. Concerning the latter, non-linear evolution leads to the phenomenon of saturation of partonic densities in the hadron or nucleus. We will briefly review the realizations of saturation of parton densities both at strong coupling and, mainly, at weak coupling. We will end by discussing the importance of diffractive observables and of the use of nuclear targets for the investigation of the small- x behavior of the hadron or nucleus wave function.

From DGLAP to non-linear evolution equations in QCD: saturation

In DIS the structure function $F_2(x, Q^2)$ is proportional to the total cross section σ_{tot} for the scattering of a virtual photon on a hadron h , $\gamma^* h \rightarrow X$. The growth of F_2 at small x translates into the rise of σ_{tot} as a

function of the energy of the virtual photon-hadron system. Although the Froissart-Martin bound, derived for hadron-hadron scattering, cannot be applied to a process involving a virtual photon, direct calculations based on the evaluation of the QCD diagrams demonstrate unambiguously that, at small x , large corrections exist and need to be resummed. These corrections suppress the leading-twist results and there is no doubt that, for F_2 , the rise with $1/x$ predicted by DGLAP is modified by contributions which are not included in the framework of leading-twist linear evolution equations. The corrections which become numerically important in the small- x limit are also important for the restoration of the unitarity bound. As a result of these modifications parton saturation is reached for sufficiently large energies or small values of Bjorken- x .

In deep inelastic electron-proton scattering, the virtual photon emitted by the incoming electron interacts with partons inside the proton whose properties are specified by the kinematics of the photon. In particular, the transverse size of the partons is (roughly) inversely proportional to the square root of the virtuality of the photon, $\langle r_T^2 \rangle \sim 1/Q^2$. The deep inelastic cross section, parametrized through parton densities, thus counts the numbers of quarks and gluons per unit of phase space. For sufficiently large photon virtualities Q^2 and not too small x , the improved QCD parton model works well because the partons forming the hadron, on the distance scale defined by the small photon, are in a dilute regime, and they interact only weakly. This is a direct consequence of the property of asymptotic freedom, which makes the strong coupling constant small. This diluteness condition is not satisfied if the density of partons increases. This happens if either the number of partons increases (large structure function) or the interaction between the partons becomes strong (large α_s). The former situation is realized at small x , the latter for small photon virtuality Q^2 which sets the scale of the strong coupling $\alpha_s(Q^2)$. This simple qualitative argument shows that corrections to the standard QCD parton picture can be described in terms of quarks and gluons and their interactions as long as Q^2 is not too small ($\alpha_s(Q^2) \ll 1$) and the gluon density is large (small x). Combining these two conditions one arrives at the picture shown in Fig. 6.1: there is an approximately diagonal line in the $\ln Q^2 - \ln 1/x$ plane below which the parton distributions are dilute, and the standard QCD parton picture applies. In this regime linear evolution equations provide the correct description of parton dynamics. In the vicinity of the line, non-linear QCD corrections become important, and above the line partons are in a high-density state. Well above the line, interactions become strong, and standard perturbation theory is not valid. The division between the two regimes is usually defined in terms of a saturation line, which is specified by a dynamically generated saturation scale, growing with decreasing x . Within this picture one easily understands which type of corrections can be expected. Once the density of gluons increases sufficiently, it becomes probable that, prior to their interaction with the photon, gluons undergo recombination processes.

Saturation in perturbative QCD

While unitarity is an unavoidable feature of any quantum field theory, the microscopic dynamics which lead to it in QCD are not very well understood. There are several proposals to implement unitarity in strong interactions, which can be roughly classified into those which use non-perturbative models and those based on perturbative QCD calculations.

The usual non-perturbative framework to implement unitarity are Regge-Gribov based models [56, 287, 300]. Though they are quite successful in describing existing data on inclusive and diffractive ep and eA scattering (see e.g. [301, 302] and references therein), they lack theoretical foundations within QCD.

On the other hand, attempts have been going on for the last 30 years to implement parton rescattering or recombination¹ in perturbative QCD in order to describe its high-energy behaviour. In the pioneering work in [291, 303], a non-linear evolution equation in $\ln Q^2$ was proposed to provide the first correction to the linear equations. A non-linear term appeared, which was proportional to the local density of color charges seen by the probe (the virtual photon).

An alternative, independent approach was developed in [304], where the amplitudes for diffractive processes in the triple Regge limit were calculated. This resulted in the extraction of the triple Pomeron vertex in QCD at small x , which is responsible for the non-linear term in the evolution equations.

¹Note that the rescattering and recombination concepts correspond to the same physical mechanism viewed in the rest frame and the infinite momentum frame of the hadron, respectively.

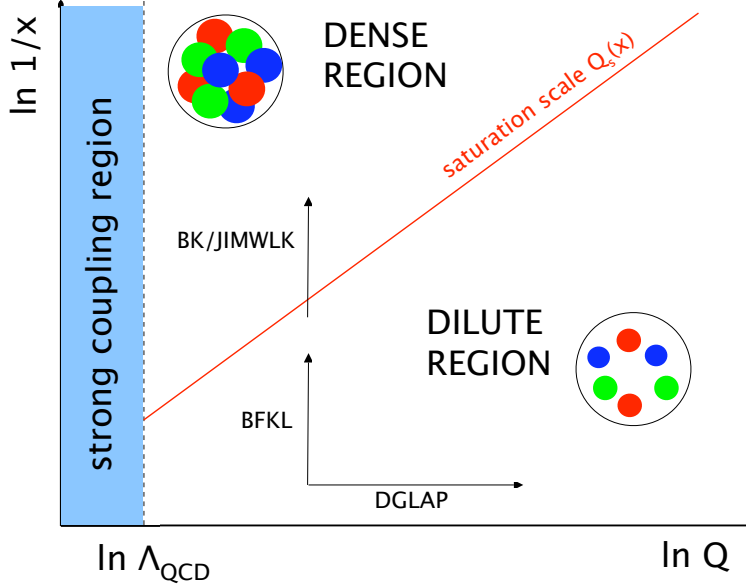


Figure 6.1: Schematic view of the different regions for the parton densities in the $\ln Q^2 - \ln 1/x$ plane. See the text for comments.

2879 Later on these ideas were developed to include all corrections enhanced by the local density, to constitute
 2880 what is called the Color Glass Condensate (CGC) [292–295, 305–312] (see also the most recent developments
 2881 in [313–316]). The CGC provides a non-perturbative, but weak-coupling, realization of the parton saturation
 2882 ideas within QCD. The linear limit of the basic CGC equation is the BFKL equation, which is the generally
 2883 accepted linear evolution equation for the high-energy limit. As illustrated in Fig. 6.1, the evolution in the
 2884 $\ln Q^2 - \ln 1/x$ plane is driven by both linear equations: along $\ln Q^2$ for DGLAP and along $\ln 1/x$ for BFKL.

2885 The basic framework in which saturation ideas are discussed is illustrated in Fig. 6.2. One is considering
 2886 the hadron wave function at high energy. Its partonic components can be separated into those with a
 2887 large momentum fraction x and those with small x . The large- x components are dilute and provide color
 2888 sources for the corresponding small- x components. Due to multiple splittings of the small- x gluons, a dense
 2889 system is eventually formed. One can then construct within this formalism an evolution equation for the
 2890 gluon correlators in the hadron wave function which is a renormalization group equation with respect to the
 2891 rapidity separating large- and small- x partons. This renormalization procedure assumes perturbative gluon
 2892 emissions from the large- x partons which imply a redefinition of the source at each step in rapidity.

2893 The mean field version of the CGC, the Balitsky-Kovchegov (BK) equation [294, 295], provides a non-
 2894 linear evolution equation for unintegrated gluon densities. It turns out that the BK approach results in
 2895 a gluon density which, for a fixed resolution of the probe, is saturated for small longitudinal momentum
 2896 fractions x , whereas at large values of x , the non-linear term is negligible. The separation between these two
 2897 limits is given by a dynamically generated saturation momentum $Q_s(x)$ which increases with decreasing x
 2898 (c.f. figure 6.1), and therefore saturation is determined by the condition $Q_s(x) > Q$. Then, for large energies
 2899 or small x , the system is in a dense regime of high gluon fields (thus non-perturbative) but the typical gluon
 2900 momentum, $\sim Q_s$, is large (thus the coupling constant which determines gluon interactions is weak). The
 2901 qualitative behavior of the saturation scale with energy and nuclear size can be argued as follows. The
 2902 transition from a dilute to a dense regime is marked by the packing factor (in this case, the product of the
 2903 density of gluons per unit transverse area times the gluon-gluon cross section) becoming of the order unity
 2904 i.e.

$$\frac{A \times xg(x, Q_s^2)}{\pi A^{2/3}} \times \frac{\alpha_s(Q_s^2)}{Q_s^2} \sim 1 \implies Q_s^2 \sim A^{1/3} Q_0^2 \left(\frac{1}{x}\right)^\lambda, \quad (6.2)$$

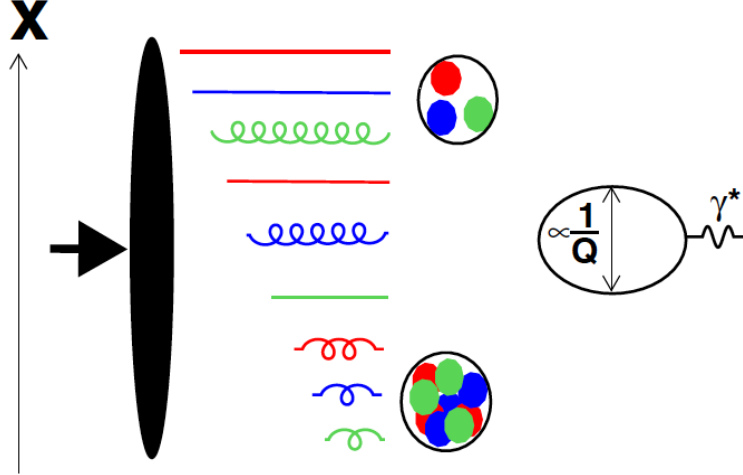


Figure 6.2: Illustration of saturation ideas. The hadron is moving very fast to the right, and its wave function contains many partonic components. Specifically, it includes partons with both large and small fractions of its longitudinal momentum x . The former are in a dilute regime, while the latter become densely packed due to multiple splitting. The photon with virtuality Q^2 is moving to the left and it constitutes a probe of the hadron wave function with a spatial resolution proportional to $1/Q$.

2905 where the growth of the gluon density at small x has been approximated by a power law, $xg(x, Q^2) \sim x^{-\lambda}$,
 2906 logarithms are neglected and the nucleus is considered a simple superposition of independent nucleons. The
 2907 exponent $\lambda \simeq 0.3$ can be derived from QCD, whereas the scale Q_0^2 has to be taken from experiment.

2908 The BK equation was derived under several simplifying assumptions such as the scattering of a dilute
 2909 projectile on a dense target, a large number of QCD colours and the absence of correlations in the target.
 2910 At present, the discussion is concentrated on how to overcome these difficulties [313, 317, 318]. Possible
 2911 phenomenological implications [319–321], are being considered. Also, the proposed relation between high-
 2912 energy QCD and Statistical Mechanics [317, 322] is under investigation.

2913 In the CGC formalism, the resummed terms are those enhanced by the energy and by the local density
 2914 of partons, and the saturation scale depends on the matter (colour charge) density at the impact parameter
 2915 probed by the virtual photon. For a nucleus, the nuclear size plays the role of an enhancement factor, see
 2916 Eq. (6.2), in a manner which is analogous to impact parameter scanning. Therefore, it is expected that when
 2917 scanning the impact parameter from the center to the periphery of the hadron at high energy, one should go
 2918 from a non-linear to a linear regime. Analogously, non-linear effects will become more important for large
 2919 nuclei than for smaller ones or for nucleons. Thus, a study of the variation of parton densities with impact
 2920 parameter and with the nuclear size, will provide an exacting test of our ideas on parton saturation.

2921 Resummation at low x

2922 The generic challenges that the small- x region bears in QCD are inherently related to the divergence of the
 2923 gluon number density with decreasing values of x . As is well known, deep-inelastic partonic cross sections
 2924 and parton splitting functions receive large corrections in the small- x limit due to the presence of powers of
 2925 $[\alpha_s \log x]$ to all orders in the perturbative expansion [33, 125, 298, 299, 323]. It thus suggests dramatic effects
 2926 from logarithmically enhanced corrections, so the success of fixed order NLO perturbation theory at HERA
 2927 has been very hard to explain in regions where x becomes small. Recently, hints have been found that
 2928 indeed the DGLAP fits tend to deteriorate systematically in the region of small x and Q^2 [38, 324]. Direct
 2929 calculations at next-to-leading logarithmic accuracy in the BFKL framework were performed [325, 326], and
 2930 showed a slow convergence of the perturbative series in the high-energy, or small- x regime. Therefore,
 2931 generically one expects deviations from fixed-order DGLAP evolution in the small- x and small- Q regime

2932 which call for resummation of higher orders in perturbation theory.

2933 Extensive analyses have been performed in the last few years [327–332], which indeed point to the
2934 importance of resummation to all orders. Resummation should embody important constraints like kinematic
2935 effects, momentum sum rules and running coupling effects.

2936 Several important questions arise here, such as the relation and interplay of the resummation and the
2937 non-linear effects, and possibly the role of resummation in the transition between the perturbative and non-
2938 perturbative regimes in QCD. Precise experimental measurements in extended kinematic regions are needed
2939 to explore the deviations from standard DGLAP evolution and to quantify the role of resummation at small
2940 x .

2941 **The importance of diffraction**

2942 It was observed at HERA that a substantial fraction, about 10%, of deep inelastic interactions are diffractive
2943 events i.e. events in which the interacting proton stays intact, despite the inelasticity of the interaction.
2944 Moreover, the proton appears well separated from the rest of the hadronic final state by a large rapidity gap.
2945 The events otherwise look similar to normal deep inelastic events.

2946 Diffraction has been extensively analyzed at HERA, with a variety of measurements in bins of x and Q^2 ,
2947 as well as more differential analyses which include the dependence on the momentum transfer t . Physically,
2948 for the diffractive event to occur, there must be an exchange of a coherent, color neutral cluster of partons
2949 (a quasiparticle) which leaves the interacting proton intact. This color neutral cluster is often called the
2950 *pomeron*, and it can be characterised via a factorisation theorem [333] by a set of partonic densities analogous
2951 to those for the proton or nucleus. At lowest order, the QCD realisation of the pomeron is a pair of
2952 gluons [334,335], which leads to enhanced sensitivity to saturation phenomena compared to the single gluon
2953 exchange in the bulk of non-diffractive processes.

2954 There are strong theoretical indications that diffraction is closely linked with the phenomenon of partonic
2955 saturation. From a wide range of calculations, mostly based on the so-called dipole model, see for example
2956 [336,337], it is known that diffractive DIS events involve softer effective scales than non-diffractive events
2957 at the same Q^2 . Thus, the exploration of diffractive phenomena offers a unique window to analyze the
2958 transition between perturbative and non-perturbative dynamics in QCD.

2959 LHeC will provide a widely extended kinematic coverage for diffractive events. By their study one could
2960 extract diffractive parton densities for a larger range in Q^2 than at HERA, and thus provide crucial tests
2961 of parton dynamics in diffraction as well as of the factorization theorems. The high energy involved also
2962 enables the production of diffractive states with large masses which could include W and Z bosons as well
2963 as states with heavy flavours or even exotic states with quantum numbers 1^- .

2964 Of particular importance is exclusive diffractive production of vector mesons, for which differential mea-
2965 surements as a function of squared four-momentum transfer, t , are most easily performed. It has been
2966 demonstrated that in this case, information about the momentum transfer of the cross section can be trans-
2967 lated into the dependence of the scattering amplitude on impact parameter. As a result, a profile in impact
2968 parameter of the interaction region, illustrated in Fig. 6.3, can be extracted. The precise determination of
2969 the dynamics governing the high parton density regime requires a detailed picture of the spatial distribution,
2970 in impact parameter space, of partons in the interaction region. As mentioned previously, by selecting small
2971 impact parameter values (large t), one is probing the regions of higher parton density where the saturation
2972 phenomenon is more likely to occur. One can then extract the value of the saturation scale as a function of
2973 energy and impact parameter.

2974 Even more inclusive measurements of the diffractive production of vector mesons can provide valuable
2975 information about parton dynamics. For example, the measurement of the energy dependence of the diffrac-
2976 tive cross section for the production of J/ψ at the LHeC can distinguish between different scenarios for
2977 parton evolution and thus explore parton saturation to a greater accuracy than ever before.

2978 **The importance of nuclei**

2979 In the context of small- x physics, studying lepton-nucleus collisions has a two-fold importance:

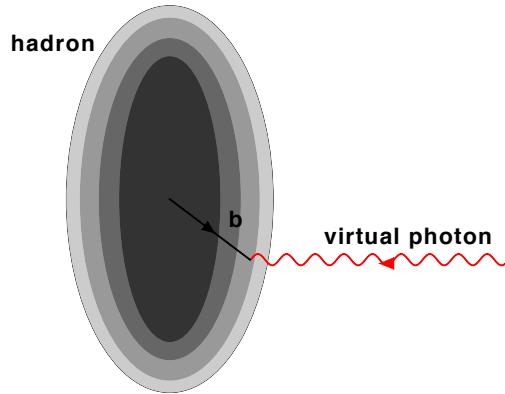


Figure 6.3: Illustration of the transverse profile of the hadron as explored by a virtual photon at impact parameter b .

- On the one hand and as discussed in sections 6.1.4 and 6.2.2, the nuclear structure functions and parton densities are basically unknown at small x . The main reason for this lack of knowledge comes from the rather small area in the $\ln Q^2 - \ln 1/x$ plane covered by presently available experimental data, see Fig. 6.4. Current theoretical and phenomenological analyses [338] point to the importance of non-linear dynamics in DIS off nuclei at small and moderate Q^2 and small x , which needs to be tested experimentally. In this respect, a relation exists, as reviewed in Sec. 6.2.4, between diffraction in lepton-proton collisions and the small- x behavior of nuclear structure functions. Such relation relies on basic properties of Quantum Field Theory and its verification provides stringent tests of our understanding of these phenomena.
- Non-linear effects in parton evolution are enhanced by increasing the density of partons. Such an increase can be achieved (see Fig. 6.5) either by increasing the energy of the collision (decreasing x), or by increasing the nuclear mass number A . The latter can be accomplished by either using the largest nuclei possible, or by selecting subsets of collisions with small impact parameters b (i.e. more central collisions) between the relatively light nuclei and the virtual photon, such that more nucleons are involved. The ideal situation would be to Map out the dependence of the saturation scale on x , b and A as fully as possible (see Eq. (6.2). This is a key observable in formulations which resum multiple interactions and result in parton saturation. As such it must be checked in experiment in order to clearly settle the mechanism underlying non-linear parton dynamics.

Also, the study of lepton-nucleus collisions has strong implications on the understanding of the experimental data from ultrarelativistic nucleus-nucleus collisions, as discussed later in Subsec. 6.1.4.

6.1.2 Status following HERA data

As discussed in the previous Section, in the low- x region a high parton density can be achieved in DIS and various novel phenomena are predicted. Ultimately, unitarity constraints become important and a ‘black disk’ limit is approached [300], in which the cross section reaches the geometrical bound given by the transverse proton or nucleus size. When α_s is small enough for quarks and gluons to be the right degrees of freedom, parton saturation effects are therefore expected to occur within the theoretically controllable weak coupling regime. In this small- x limit, many striking observable effects are predicted, such as Q^2 dependences of the cross sections which differ fundamentally from the usual logarithmic variations, and diffractive cross sections approaching 50% of the total [339]. This fairly good phenomenological understanding of the onset of unitarity effects is, unfortunately, not very quantitative. In particular, the precise location of the saturation scale line in the DIS kinematic plane (see Fig. 6.1) is to be determined experimentally. The search for parton saturation effects has therefore been a major issue throughout the lifetime of the HERA project.

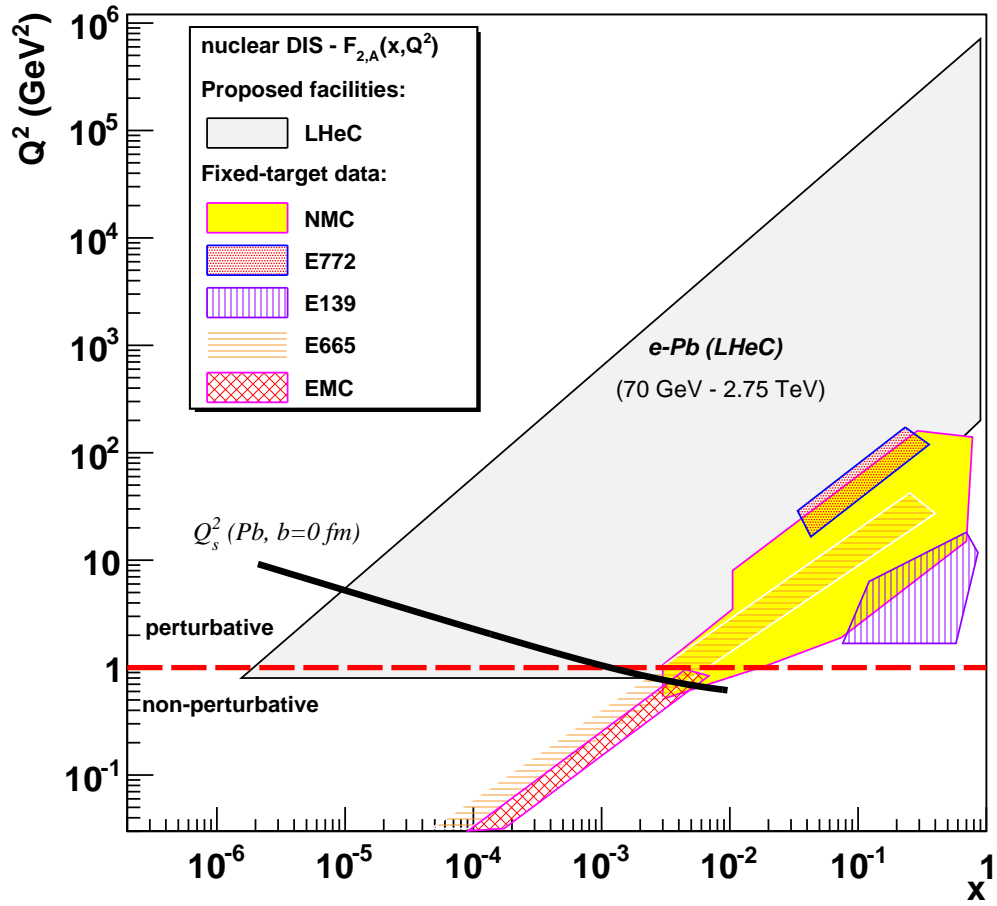


Figure 6.4: Kinematical coverage of the LHeC in the $\ln Q^2 - \ln 1/x$ plane for nuclear beams, compared with existing nuclear DIS and Drell-Yan experiments.

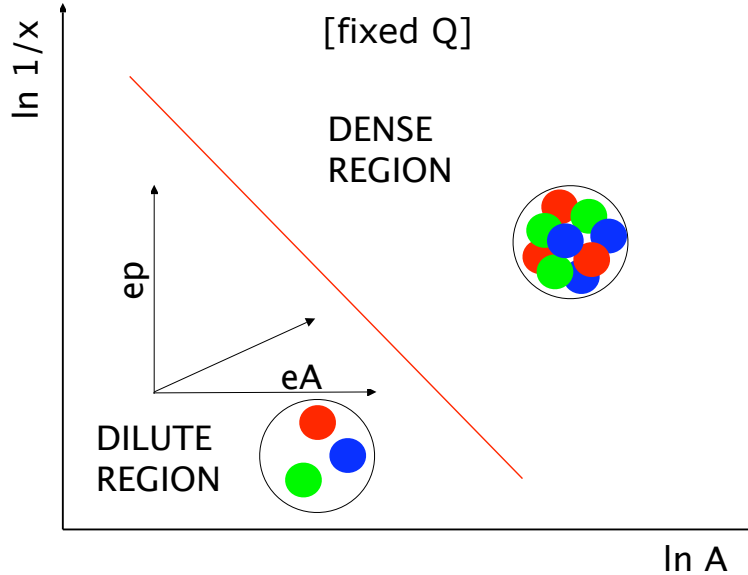


Figure 6.5: Schematic view of the different regions for the parton densities in the $\ln 1/x - \ln A$ plane, for fixed Q^2 . See the text for comments.

3012 Although no conclusive saturation signals have been observed in parton density fits to existing HERA
 3013 data, various hints have been obtained, for example, by studying the change in fit quality as low- x and Q^2
 3014 data are progressively omitted, in the NNPDF [324] and HERAPDF [38] analyses (see below).

3015 A more common approach is to fit the data to dipole models [336, 337, 340, 341], which are applicable at
 3016 very low Q^2 values beyond the range in which quarks and gluons can be considered to be good degrees of
 3017 freedom. The typical conclusion [341] is that HERA data in the perturbative regime exhibit at best weak
 3018 evidence for saturation. However, when data in the $Q^2 < 1 \text{ GeV}^2$ region are included, models which include
 3019 saturation effects are quite successful in the description of the wide variety of experimental data.

3020 The ‘geometric scaling’ [342] feature of the HERA data (Fig. 6.6left) reveals that, to a good approxima-
 3021 tion, the low- x cross section is a function of a single combined variable $\tau = Q^2/Q_s^2(x)$, where $Q_s^2 = Q_0^2 x^{-\lambda}$ is
 3022 the saturation scale, see Eq. (6.2). This parameterisation works well for scattering off both protons and ions,
 3023 as shown in Fig. 6.6right [342, 343]. Geometric scaling is observed not only for the total γ^*p cross section,
 3024 but also for other, more exclusive observables in γ^*p collisions [344, 345] and even in hadron production in
 3025 proton-proton collisions at the LHC [346] and nucleus-nucleus collisions at RHIC [343]. This feature supports
 3026 the view (Subsec. 6.1.1) of the cross section as being invariant along lines of constant ‘gluon occupancy’.
 3027 When viewed in detail (Fig. 6.6), there is a change in behaviour in the geometric scaling plot near $\tau = 1$,
 3028 which has been interpreted as a transition to the saturation region shown in Fig. 6.1. However, data with
 3029 $\tau < 1$ exist only at very low, non-perturbative, Q^2 values to date, precluding a partonic interpretation. Also,
 3030 the fact that the scaling extends to large values of τ which characterize the dilute regime, has prompted
 3031 theoretical explanations of this phenomenon which do not invoke the physics of saturation [347].

3032 Dipole models

3033 As mentioned previously, one of the interesting observations at HERA is the success of the description of
 3034 many aspects of the experimental data within the framework of the so-called dipole picture [292, 348, 349] with
 3035 models that include unitarisation or saturation effects [350, 351]. These models are based on the assumption
 3036 that the relevant degrees of freedom at high energy are colour dipoles. Dipole models in DIS are closely
 3037 related to the Good-Walker picture [352] previously developed for soft processes in hadron-hadron collisions.
 3038 In DIS, dipoles are shown to be the eigenstates of high-energy scattering in QCD, and the photon wave

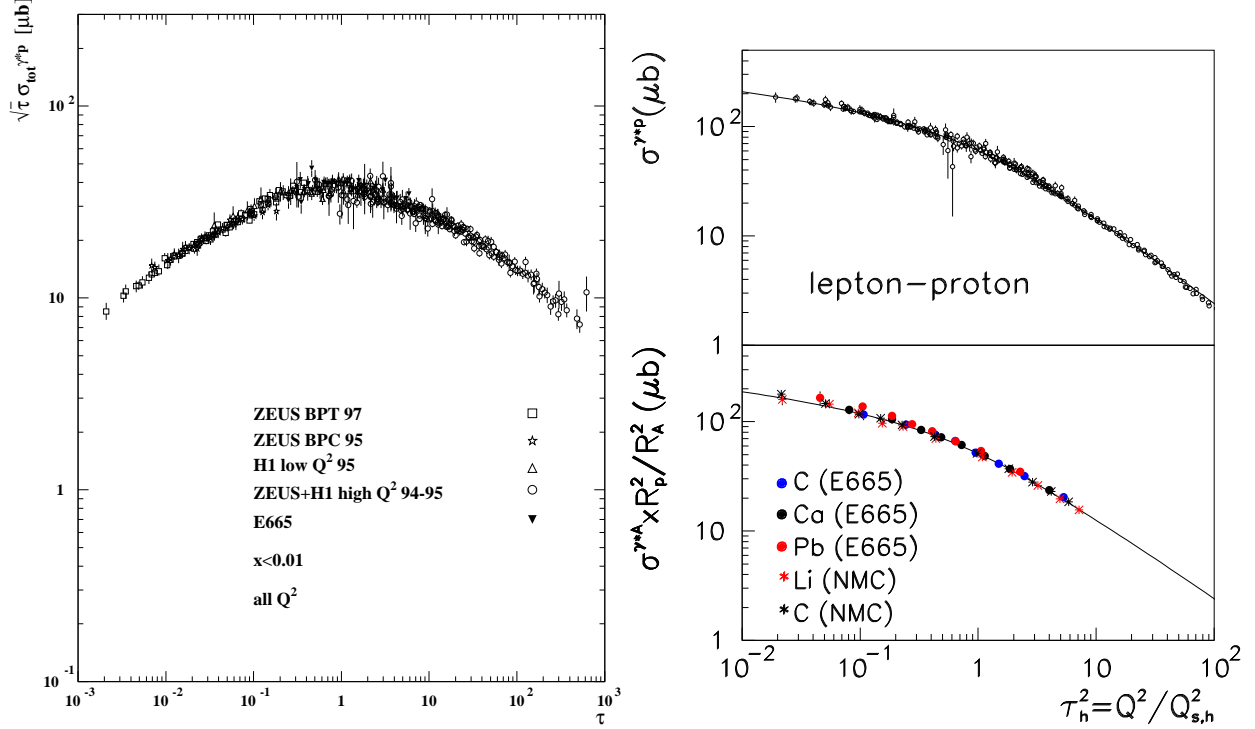


Figure 6.6: (left) Geometric scaling plot [342], in which low x data on the $\gamma^* p$ cross section from HERA and E665 are plotted as a function of the dimensionless variable τ (see text). The cross sections are scaled by $\sqrt{\tau}$ for visibility. (right) Geometric scaling plot showing cross sections for electron scattering off nuclei as well as off protons [343].

3039 function can be expanded onto the dipole basis.

3040 The dipole factorization for the inclusive cross section in DIS is illustrated in Fig. 6.7. It differs from
 3041 the usual picture of the virtual photon probing the parton density of the target in that here the partonic
 3042 structure of the probed hadron is not evident. Instead, one chooses a particular Lorentz frame where the
 3043 photon fluctuates into a quark-antiquark pair with a transverse separation r and at impact parameter b with
 3044 respect to the target. For sufficiently small $x \ll (2m_N R_h)^{-1}$, with m_N the nucleon mass and R_h the hadron
 3045 or nuclear radius, the lifetime of the $q\bar{q}$ fluctuation is much longer than the typical time for interaction with
 3046 the target. The interaction of the $q\bar{q}$ dipole with the hadron or nucleus is then described by a scattering
 3047 matrix $S(r, b; x)$ such that $|S(r, b; x)| < 1$. The unitarity constraints can be incorporated naturally in this
 3048 picture [353] by the requirement that $|S(r, b; x)| \geq 0$, with $S(r, b; x) = 0$ corresponding to the black disk
 3049 limit. Integrating $1 - S(r, b; x)$ over the impact parameter b one obtains the dipole cross section $\sigma^{q\bar{q}}(r, x)$,
 3050 which depends on the dipole size and the energy (through the dependence on $x = x_{Bj}$). The transverse size
 3051 of the partons probed in this process is roughly proportional to the inverse of the virtuality of the photon
 3052 Q^2 . This statement is most accurate in the case of a longitudinally polarized photon, while in the case of a
 3053 transversely polarized one, the distribution of the probed transverse sizes of dipoles is broadened due to the
 3054 so-called aligned jet configurations.

3055 At small values of the dipole size, such that $r \ll 1/Q$, the dipole cross section can be shown to be related
 3056 to the integrated gluon distribution function

$$\sigma^{q\bar{q}}(r, x) \sim r^2 \alpha_s(C/r^2) xg(x, C/r^2), \quad (6.3)$$

3057 where C is a constant. In this regime, where r is small, the dipole cross section is small and consequently

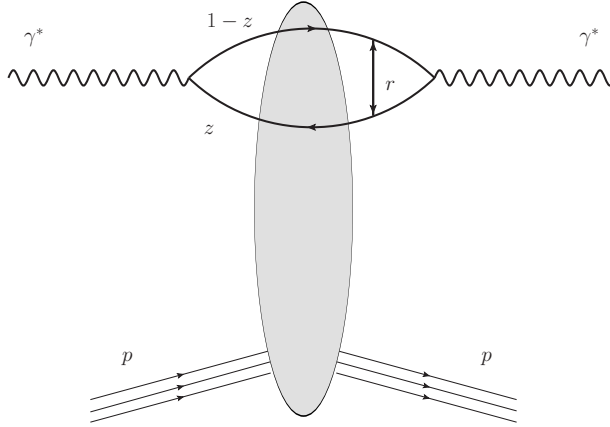


Figure 6.7: Schematic representation of dipole factorisation at small x in DIS. The virtual photon fluctuates into a quark-antiquark pair and subsequently interacts with the target. All the details of the dynamics of the interaction are encoded in the dipole scattering amplitude.

the amplitude is far from the unitarity limits. With increasing energy the dipole cross section grows and saturation corrections must be taken into account in order to guarantee the unitarity bound on $S(r, b; x)$. The transition region between the two limits is characterised by the saturation scale $Q_s(x)$. Several models [336, 340, 354] have been proposed which successfully describe the HERA data on the structure function F_2 .

Once the dipole cross section has been constrained by the data on the inclusive structure functions, it can be used to predict, with almost no additional parameters, the cross sections for diffractive production at small x . Inclusive diffraction has been computed within the dipole picture in [337], and exclusive diffraction of vector mesons in [355, 356]. One of the interesting aspects of these models is that they naturally lead to a constant ratio of the diffractive to total cross sections as a function of energy [337]. In models with saturation this is related to the fact that the saturation scale provides a natural x -dependent cut-off and gives the same leading-twist behavior for inclusive and diffractive cross sections. As a result the ratio of inclusive to diffractive cross sections is almost constant as a function of the energy.

In spite of the fact that this approach has been able to successfully describe inclusive data and predict diffraction at small values of x , there is still important conceptual progress to be made. Certainly there are important hints from dipole models about the nature of the perturbative–non-perturbative transition in QCD. Nevertheless, dipole models should be rather regarded as effective phenomenological approaches. As such they only parametrize the essential dynamics at small x . For instance, the transverse impact parameter dependence of the dipole scattering amplitude $S(r, b; x)$ is very poorly constrained. Indeed, it is possible simultaneously to describe F_2 and F_2^D with a rather wide range of impact parameter dependences. On the theoretical side, it has not been possible so far to fully predict the realistic profile of the interaction region in transverse size. It is therefore of vital importance to measure accurately the t -dependencies of the diffractive cross sections in an extended kinematic range to pin down the impact parameter distribution of the proton at high energies.

Hints of deviations from fixed-order linear DGLAP evolution in inclusive HERA data

As discussed in previous sections, the experimental data on the inclusive structure functions F_2 and F_L measured at HERA have been successfully described - with $\chi^2/d.o.f. \sim 1$ - by fits which use linear fixed-order DGLAP evolution, see [38, 68, 131, 133, 357–363]. The current status of the calculations is fixed order at next-to-next-to-leading accuracy. On the other hand, see Subsec. 6.1.1, there are several theoretical reasons to expect that at small x and/or at small Q^2 the fixed-order DGLAP framework needs to be extended. Possible relevant phenomena predicted by perturbative QCD are linear small- x resummation, non-linear

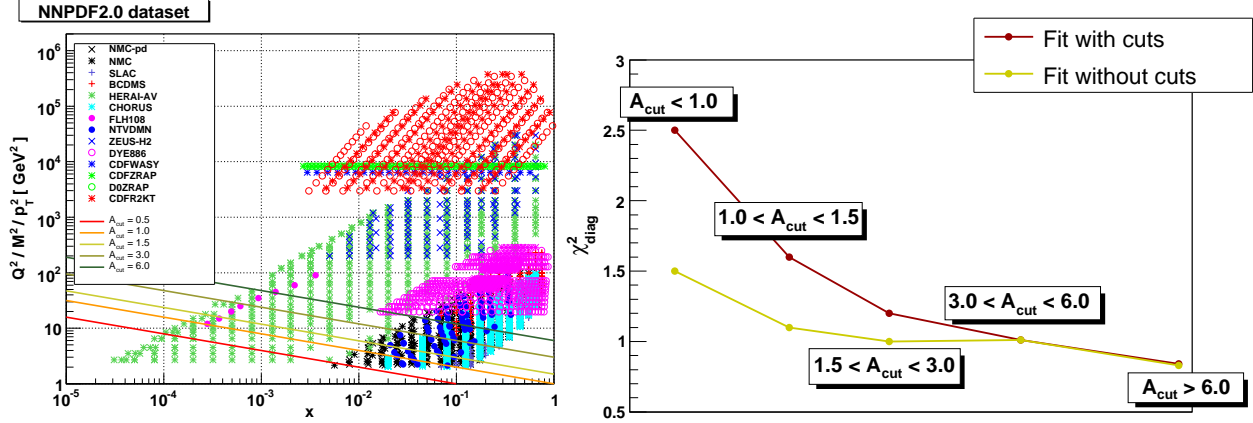


Figure 6.8: Left plot: the kinematic coverage of the data used in the NNPDF2.0 analysis, indicating the different choices of A_{cut} used to probe deviations from DGLAP. Right plot: the diagonal χ^2_{diag} evaluated in kinematic slices corresponding to the different A_{cut} cuts, where χ^2_{diag} has been computed using both the reference NNPDF2.0 fit without kinematic cuts (yellow line) and the NNPDF2.0 with the maximum $A_{\text{cut}} = 1.5$ cut (red line).

3088 evolution and parton saturation or other higher-twist effects. Although the exact kinematic regime in which
 3089 these effects should become important remains unclear, it is evident that at some point they will lead to
 3090 deviations from fixed-order DGLAP evolution. Therefore, an important question is whether these deviations
 3091 are already present in HERA data. Several analyses have been performed which aimed to address this
 3092 question.

3093 In one analysis [341], HERA $F_2(x, Q^2)$ data are subjected to three fits in the framework of a dipole model.
 3094 In one of the fits, the parameterisation of the dipole cross section does not contain saturation properties,
 3095 whereas in the other two, saturation effects are included using two rather different models [340, 341]. All
 3096 three dipole fits are able to describe the HERA data adequately in the perturbative region $Q^2 \geq 2 \text{ GeV}^2$.
 3097 However, a clear preference for the models containing saturation effects becomes evident when data in the
 3098 range $0.045 < Q^2 < 1 \text{ GeV}^2$ are added [341]. Similar conclusions are drawn when the same dipole cross
 3099 section models are applied to various less inclusive observables at HERA [364]. These observations provide
 3100 an intriguing hint that saturation effects may already be present in HERA data. However, due to the non-
 3101 perturbative nature of the low Q^2 kinematic region in which the effects appear, there is no clear interpretation
 3102 in terms of perturbative QCD degrees of freedom and firm conclusions cannot be drawn on the existence
 3103 and nature of parton recombination effects.

3104 In another analysis [324], possible indications of deviations from linear DGLAP evolution were discussed.
 3105 It was based on an unbiased PDF analysis of the inclusive HERA data. Here we present briefly an up-
 3106 dated version of this study which uses the most precise inclusive DIS data to date, the combined HERA-I
 3107 dataset [38] in the framework of the global NNPDF2.0 fitting framework. The key idea is to perform global
 3108 fits only in the large- x , large- Q^2 region, where NLO DGLAP is expected to be reliable. This way one can
 3109 determine *safe* parton distributions which are not contaminated by possible non-DGLAP effects. These
 3110 PDFs are then evolved backwards into the potentially *unsafe* low- x and low- Q^2 kinematic region, and are
 3111 used to compute physical observables, which are compared with data. A deviation between the predicted
 3112 and observed behavior in this region can then provide a signal for effects beyond NLO DGLAP.

3113 The PDFs were determined within the *safe* kinematic region in which $Q^2 \geq A_{\text{cut}} \cdot x^{-\lambda}$, where $\lambda = 0.3$
 3114 and A_{cut} is a variable parameter (see the left plot in Fig. 6.8 and [324] for details on the procedure). The
 3115 NNPDF2.0 analysis [363] was repeated for different choices of the kinematic cuts, one for each choice of
 3116 A_{cut} , and the results were compared with experimental data. As shown in Fig. 6.9, at high $Q^2 = 15 \text{ GeV}^2$
 3117 one does not see any significant deviation from NLO DGLAP. In this region all PDF sets agree with data
 3118 and with one another, the only difference between them being that as A_{cut} increases the PDF uncertainty
 3119 bands grow as expected due to the experimental information removed by the cuts. The situation is different

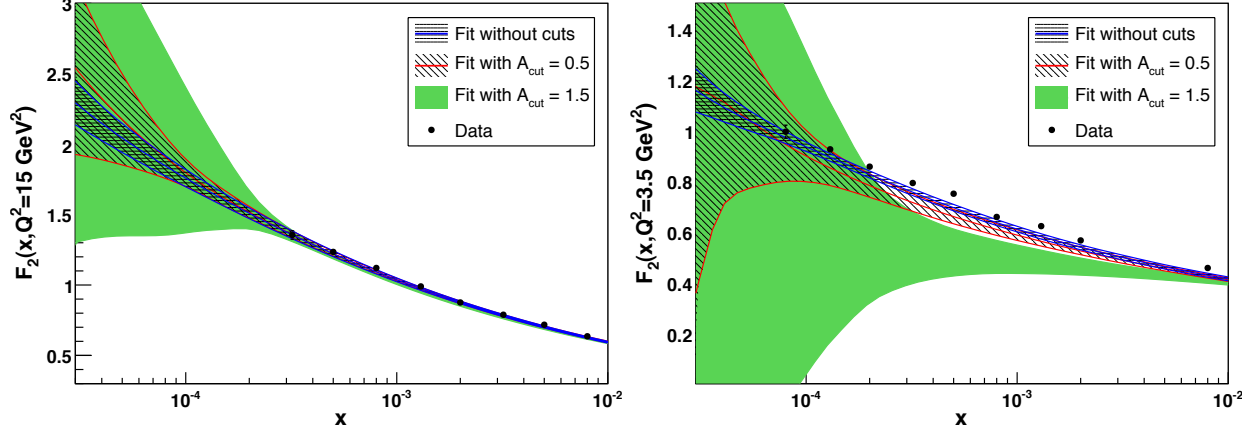


Figure 6.9: Left: the proton structure function $F_2(x, Q^2 = 15 \text{ GeV}^2)$ at small- x , computed from PDFs obtained from the NNPDF2.0 fits with different values of A_{cut} . Right: the same but at a lower $Q^2 = 3.5 \text{ GeV}^2$ scale.

3120 at a lower $Q^2 = 3.5 \text{ GeV}^2$: the prediction obtained from the backwards evolution of the data above the
3121 cut exhibits a systematic downward trend, becoming more evident with increasing A_{cut} . These results are
3122 indicative of deficiencies in the description of HERA data at low- x and low- Q^2 by NLO DGLAP evolution².
3123 Specifically, the NLO DGLAP approach suggests a faster evolution with Q^2 than is present in the data.
3124 To be sure that one is observing a genuine small- x effect, one needs to check that it becomes less and less
3125 relevant as x and Q^2 increase. To this aim the diagonal χ^2_{diag} was computed, see the right plot in Fig. 6.8, in
3126 different kinematic slices, both from the fit without cuts and from that with the maximum cut $A_{\text{cut}} = 1.5$.
3127 The expectation is that at larger x and Q^2 the difference between the two fits becomes smaller, as deviations
3128 from NLO DGLAP should become negligible. The data support this expectation: the contribution to the
3129 χ^2 from the region with $A_{\text{cut}} \geq 3$ is comparable for the fits with and without cuts, in contrast to the lower x
3130 and Q^2 region, where the χ^2 is substantially larger in the version of the fit with cuts applied. Nevertheless, it
3131 should be noted that there is no general consensus on the origins of these effects. e.g. in [365] it is suggested
3132 that their origin lies in bias due to the chosen initial conditions for DGLAP evolution

3133 In summary, there are hints that the low- Q^2 -low- x region covered by HERA may exhibit deviations from
3134 fixed-order linear evolution. These hints are obtained from the success of dipole models with saturation
3135 features to describe the experimental data in this region, and from the fact that the quality of fixed-order
3136 DGLAP fits seems to deteriorate there. However, the region in which such effects may be present corresponds
3137 to rather small Q^2 , preventing a clear interpretation in terms of perturbative QCD degrees of freedom. In
3138 addition, the overall quality of the fixed-order DGLAP fits to HERA data remains high. It is therefore
3139 premature to draw any firm conclusion on the failure of fixed-order linear evolution as the appropriate tool
3140 to describe all HERA data. In any case, it is clear that the methods discussed in this Subsection should be
3141 used to analyse LHeC inclusive structure function data, and would allow a detailed characterization of any
3142 new high-energy QCD dynamics unveiled by the LHeC. If the hints in the HERA data are correct, the novel
3143 phenomena should appear at the LHeC in a higher Q^2 perturbative region where they can be established
3144 cleanly and understood in terms of parton dynamics.

3145 Linear resummation schemes

3146 The deviations from DGLAP evolution could be caused by higher order effects at small x and small Q
3147 which need to be resummed to all orders of perturbation theory. As mentioned previously, the problem
3148 of resummation at small x has been extensively studied in recent years, see for example [327–332]. It has

²This problem cannot be solved by NNLO corrections which work in the opposite direction, see in this respect [361]. Also, in the HERAPDF framework [38, 68] the fit quality tends to worsen when low- Q^2 data are included.

3149 been demonstrated that the small- x resummation framework accounts for running coupling effects, kinematic
 3150 constraints, gluon exchange symmetry and other physical constraints. The results were shown to be very
 3151 robust with respect to scale changes and different resummation schemes. As a result, the effect of the
 3152 resummation of terms which are enhanced at small x is perceptible but moderate - comparable in size to
 3153 typical NNLO fixed order corrections in the HERA region.

3154 A major development for high-energy resummation was presented in [329], where the full small- x re-
 3155 summation of deep-inelastic scattering (DIS) anomalous dimensions and coefficient functions was obtained
 3156 including the quark contribution. This allowed for the first time a consistent small- x resummation of DIS
 3157 structure functions. These results are summarized in Fig. 6.10, taken from Ref. [329], where the K -factors
 3158 for F_2 and F_L for the resummed results are compared. As is evident from this figure, resummation is quite
 3159 important in the region of low x for a wide range of Q^2 values. One observes, for example, that the fixed order
 3160 NNLO contribution leads to an enhancement of F_2 with respect to NLO, whereas the resummed calculation
 3161 leads to a suppression. This means that a truncation at any fixed order is very likely to be insufficient for
 3162 the description of the LHeC data and therefore the fixed-order perturbative expansion becomes unreliable
 3163 in the low- x region, which calls for the resummation. Furthermore, the resummation of hard partonic cross
 3164 sections has been performed for several LHC processes such as heavy quark production [366], Higgs pro-
 3165 duction [367, 368], Drell-Yan [369, 370] and prompt photon production [371, 372]. The LHC is thus likely to
 3166 provide a testing ground in the near future.

3167 We refer to the recent review in Ref. [373] as well as to the HERA-LHC workshop proceedings [374] for
 3168 a more detailed summary of recent theoretical developments in high-energy resummation.

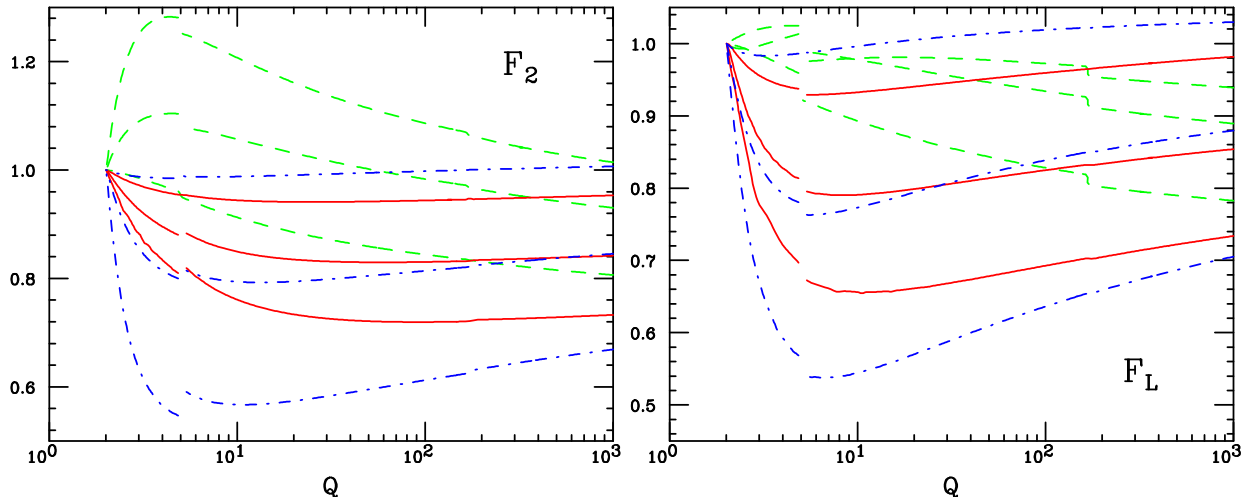


Figure 6.10: The K -factors, defined as the ratio of the fixed-order NNLO or resummed calculation to the NLO fixed-order results for the singlet F_2 and F_L structure functions, with F_2 and F_L kept fixed for all x at $Q_0 = 2$ GeV. Results are shown at fixed $x = 10^{-2}$, 10^{-4} or 10^{-6} as a function of Q in the range $Q = 2 - 1000$ GeV with α_s running and n_f varied in a zero-mass variable flavour number scheme. The breaks in the curves correspond to the b and t quark thresholds. The curves are: fixed order perturbation theory NNLO (green, dashed); resummed NLO in the $Q_0\overline{\text{MS}}$ scheme (red, solid), resummed NLO in the $\overline{\text{MS}}$ scheme (blue, dot-dashed). Curves with decreasing x correspond to those going from bottom to top for NNLO and from top to bottom in the resummed cases.

3169 To summarise, small- x resummation is becoming a very important component for precision LHC physics,
 3170 and will become a crucial ingredient of the LHeC small- x physics program [375, 376]. The LHeC extended
 3171 kinematic range will enhance the differences between the resummed predictions with respect to fixed-order
 3172 DGLAP calculations.

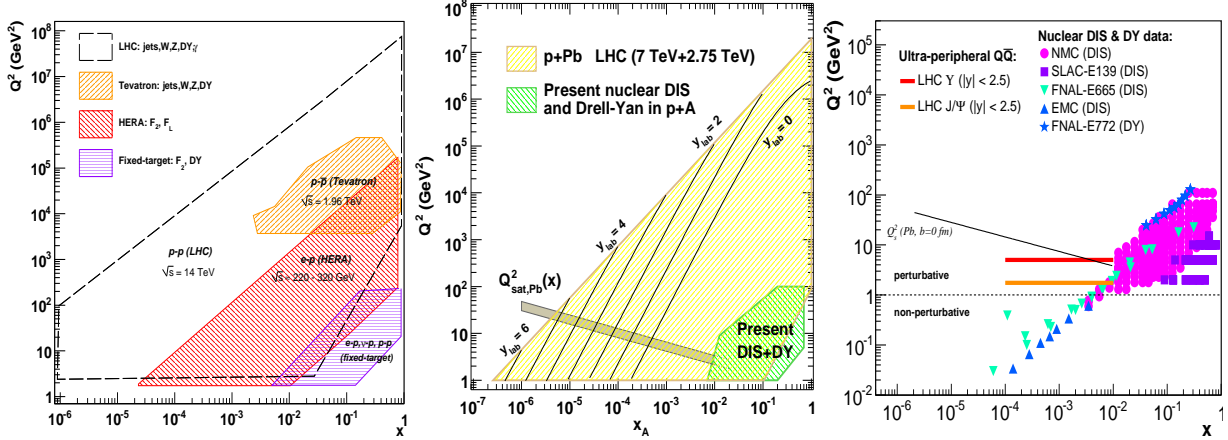


Figure 6.11: Kinematic reaches in the (x, Q^2) plane covered in proton-proton (left), proton-nucleus (center) [377] and ultraperipheral nucleus-nucleus (right) [378] collisions at the LHC. Also shown are the regions studied so far in collider and fixed-target experiments. Estimates of the saturation scale for lead are also shown.

6.1.3 Low- x physics perspectives at the LHC

The low- x regime of QCD can also be analyzed in hadron and nucleus collisions at the LHC. The experimentally accessible values of x range from $x \sim 10^{-3}$ to $x \sim 10^{-6}$ for central and forward rapidities respectively. The estimates for the corresponding saturation scale at $x \sim 10^{-3}$, based on Eq. (6.2), result in $Q_s^2 \approx 1 \text{ GeV}^2$ for proton and $Q_s^2 \approx 5 \text{ GeV}^2$ for lead.

The significant increase in the center-of-mass energy and the excellent rapidity coverage of the LHC detectors will extend the kinematic reach in the x - Q^2 plane by orders of magnitude compared to previous measurements at fixed-target and collider energies (see Fig. 6.11). Such measurements are particularly important in the nuclear case since, due to the scarcity of nuclear DIS data, the gluon PDF in the nucleus is virtually unknown at fractional momenta below $x \approx 10^{-2}$ [153]. In addition, due to the dependence of the saturation scale on the hadron transverse size, non-linear QCD phenomena are expected to play a central role in the phenomenology of collisions involving nuclei. We succinctly review here the experimental possibilities to study saturation physics in pp , pA and AA collisions at the LHC.

Low- x studies in proton-proton collisions

The LHC experiments feature detection capabilities at forward rapidities ($|\eta| \gtrsim 3$), which will allow measurements of various perturbative processes sensitive to the underlying parton structure and its dynamical evolution in the proton. The *minimum* parton momentum fractions probed in a $2 \rightarrow 2$ process with a particle of momentum p_T produced at pseudo-rapidity η is

$$x_{min} = \frac{x_T e^{-\eta}}{2 - x_T e^{\eta}}, \quad \text{where } x_T = 2p_T/\sqrt{s}, \quad (6.4)$$

i.e. x_{min} decreases by a factor ~ 10 every 2 units of rapidity. The extra e^{η} lever-arm motivates the interest in *forward* particle production measurements to study the PDFs at small values of x . From Eq. (6.4) it follows that the measurement at the LHC of particles with transverse momentum $p_T = 10 \text{ GeV}$ at rapidities $\eta \approx 5$ probes x values as low as $x \approx 10^{-5}$ (Fig. 6.11, left). Various experimental measurements have been proposed at forward rapidities at the LHC to constrain the low- x PDFs in the proton and to look for possible evidence for non-linear QCD effects. These include forward jets and Mueller-Navelet dijets in ATLAS and CMS [379]; and forward isolated photons [380] and Drell-Yan (DY) [381] in LHCb.

3198 Low- x studies in proton-nucleus collisions

3199 Until an electron-ion collider becomes available, proton-nucleus collisions will be the best available tool to
3200 study small- x physics in a nuclear environment without the strong influence of the final-state medium, as
3201 expected in the AA case. Though proton-nucleus collisions are not yet scheduled at the LHC, detailed feasi-
3202 bility studies exist [382] and strategies to define the accessible physics programme are being developed [377].
3203 The pA programme at the LHC serves a dual purpose [377]: to provide “cold QCD matter” benchmark
3204 measurements for the physics measurements of the AA programme without significant final-state effects,
3205 and to study the nuclear wavefunction in the small- x region. In Fig. 6.11 (center) we show how dramatically
3206 the LHC will extend the region of phase space in the (x, Q^2) plane³ by orders of magnitude compared with
3207 those studied at present. The same figure also shows the scarcity of nuclear DIS and DY measurements and,
3208 correspondingly, the lack of knowledge of nuclear PDFs in the regions needed to constrain the initial state
3209 for the AA programme - there is almost no information at present in the region $x \lesssim 10^{-2}$ [153].

3210
3211 Nuclear PDF constraints, checks of factorization (universality of PDFs) and searches for saturation
3212 of partonic densities will be performed in pA collisions at the LHC by studying different production cross
3213 sections for e.g. inclusive light hadrons [383], heavy flavour particles [384], isolated photons [385], electroweak
3214 bosons [386] and jets. Additional opportunities also appear in the so-called ultra-peripheral collisions in which
3215 the coherent electromagnetic field created by the proton or the large nucleus effectively acts as one of the
3216 colliding particles with photon-induced collisions at centre of mass energies higher than those reached in
3217 photoproduction at the HERA collider [387] (see next subsection).

3218 At this point it is worth mentioning that particle production in the forward (proton) rapidity region
3219 in dAu collisions at RHIC shows features suggestive of saturation effects, although no consensus has been
3220 reached so far, see [388–393] and references therein. The measurements at RHIC suffer from the limitation
3221 of working at the edge of the available phase space in order to study the small- x region in the nuclear wave
3222 function. This limitation will be overcome by the much larger available phase space at the LHC.

3223 Low- x studies in nucleus-nucleus collisions

3224 Heavy-ion (AA) collisions at the LHC aim at the exploration of collective partonic behaviour both in the
3225 initial wavefunction of the nuclei as well as in the final produced matter, the latter being a hot and dense
3226 QCD medium (see the discussions in Subsection 6.1.4). The nuclear PDFs at small x define the number of
3227 parton scattering centers and thus the initial conditions of the system which then thermalises.

3228 A possible means of obtaining direct information on the nuclear parton distribution functions is through
3229 the study of final state particles which do not interact strongly with the surrounding medium, such as
3230 photons [394] or electroweak bosons [386]. Beyond this, global properties of the collision such as the total
3231 multiplicities or the existence of long-range rapidity structures (seen in AuAu collisions at RHIC [395] and
3232 in pp and PbPb collisions at the LHC [396, 397]) are sensitive to the saturation momentum which at the
3233 LHC is expected to be well within the weak coupling regime [398], $Q_{\text{sat, Pb}}^2 \approx 5 - 10 \text{ GeV}^2$. CGC predictions
3234 for charged hadron multiplicities in central Pb-Pb collisions at 5.5 TeV per nucleon are $dN_{ch}/d\eta|_{\eta=0} \approx$
3235 1500–2000 [399]. (Note that the predictions done before the start of RHIC in 2000 were 3 times higher).
3236 Recent data from ALICE [400] give $dN_{ch}/d\eta|_{\eta=0} \approx 1600$ in central Pb-Pb at 2.76 TeV per nucleon, in rough
3237 agreement with CGC expectations.

3238 As already noted for the pA case, one of the cleanest ways to study the low- x structure of the Pb nucleus
3239 at the LHC may be via ultra-peripheral collisions (UPCs) [387] in which the strong electromagnetic fields
3240 (the equivalent flux of quasi-real photons) generated by the colliding nuclei can be used for photoproduction
3241 studies at maximum energies $\sqrt{s_{\gamma N}} \approx 1 \text{ TeV}$, that is 3–4 times larger than at HERA. In particular, exclu-
3242 sive quarkonium photoproduction offers an attractive opportunity to constrain the low- x gluon density at
3243 moderate virtualities, since in such processes the gluon couples *directly* to the c or b quarks and the cross
3244 section is proportional to the gluon density *squared*. The vector meson mass M_V introduces a relatively

³Asymmetric colliding systems imply a rapidity shift in the two-in-one magnet design of the LHC. This shift has been taken into account in the figure: the quoted y values are those in the laboratory frame.

3245 large scale, amenable to a perturbative QCD treatment. In $\gamma A \rightarrow J/\psi(\Upsilon) A^{(*)}$ processes at the LHC, the
 3246 gluon distribution can be probed at values as low as $x = M_V^2/W_{\gamma A}^2 e^y \approx 10^{-4}$, where $W_{\gamma A}$ is the γA centre
 3247 of mass energy (Fig. 6.11 right). Full simulation studies [378, 401] of quarkonium photoproduction tagged
 3248 with very-forward neutrons, show that ALICE and CMS can carry out detailed p_T, η measurements in the
 3249 dielectron and dimuon decay channels.

3250 In summary, pp , pA and AA collisions at the LHC have access to the small- x regime, and will certainly
 3251 help to unravel the complex parton dynamics in this region. However, the excellent precision of a high
 3252 energy electron-proton (ion) collider cannot be matched in hadronic collisions. The deep inelastic scattering
 3253 process is much cleaner experimentally and under significantly better theoretical control. The description
 3254 of hadron-hadron and heavy ion collisions in the regime of small x suffers from a variety of uncertainties,
 3255 such as the question of the appropriate factorization, if any, and the large indeterminacy of fragmentation
 3256 functions in the relevant kinematic region. Thus, the precise measurement of physical observables and parton
 3257 densities and their interpretation in terms of QCD dynamics is only possible at an electron-hadron (ion)
 3258 collider.

3259 6.1.4 Nuclear targets

3260 As discussed in Subsection 6.1.1, the use of nuclei offers a means of modifying the parton density both
 3261 through colliding different nuclear species and by varying the impact parameter of the collision. Therefore,
 3262 the study of DIS on nuclear targets is of the utmost importance for our understanding of the dynamics
 3263 which control the behaviour of hadron and nuclear wave functions at small x . On the other hand, the
 3264 characterization of parton densities inside nuclei and the study of other aspects of lepton-nucleus collisions
 3265 such as particle production, are of strong interest both fundamentally and because they are crucial for a
 3266 correct interpretation of the experimental results from ultrarelativistic ion-ion collisions. In the rest of this
 3267 section we focus on these last two aspects.

3268 Additionally, nuclear effects have to be better understood in order to improve the constraints on nucleon
 3269 PDF in analyses which include DIS data with neutrino beams (e.g. [361, 363]). Due to the smallness of the
 3270 cross section, such neutrino experiments use nuclear targets, so corrections for nuclear effects are a significant
 3271 source of uncertainty in the extraction of parton densities even for the proton.

3272 Comparing nuclear parton density functions

3273 The nuclear modification of structure functions has been extensively studied since the early 70's [402, 403].
 3274 It is usually characterized through the so-called nuclear modification factor which, for a given structure
 3275 function or parton density f , reads

$$R_f^A(x, Q^2) = \frac{f^A(x, Q^2)}{A \times f^N(x, Q^2)}. \quad (6.5)$$

3276 In this equation, the superscript A refers to a nucleus of mass number A , while N denotes the nucleon (either
 3277 a proton or a neutron, or their average as obtained from deuterium). The absence of nuclear effects would
 3278 result in $R = 1$.

3279 The nuclear modification factor for F_2 shows a rich structure: an enhancement ($R > 1$) at large $x > 0.8$,
 3280 a suppression ($R < 1$) for $0.3 < x < 0.8$, an enhancement for $0.1 < x < 0.3$, and a suppression for $x < 0.1$
 3281 where isospin effects can be neglected. The latter effect is called shadowing [338], and is the dominant
 3282 phenomenon at high energies (the kinematical region $x < 0.1$ will determine particle production at the LHC,
 3283 see Sec. 6.1.3 and [404]).

3284 The modifications in each region are believed to be of different dynamical origin. In the case of shadowing,
 3285 the explanation is usually given in terms of a coherent interaction involving several nucleons, which reduces
 3286 the nuclear cross section from the totally incoherent situation, $R = 1$, towards a region of total coherence.
 3287 In the region of very small x , small-to-moderate Q^2 and for large nuclei, the unitarity limit of the nuclear
 3288 scattering amplitudes is expected to be approached and some mechanism of unitarisation such as multiple

scattering should come into play. Therefore, in this region nuclear shadowing is closely related to the onset of the unitarity limit in QCD and the transition from coherent scattering of the probe off a single parton to coherent scattering off many partons. The different dynamical mechanisms proposed to deal with this problem should offer a quantitative explanation for shadowing, with the nuclear size playing the role of a density parameter in the way discussed in Subsection 6.1.1.

At large enough Q^2 the generic expectation is that the parton system becomes dilute and the usual leading-twist linear DGLAP evolution equations should be applicable to nuclear PDFs. In this framework, global analyses of nuclear parton densities (in exact analogy to those of proton and neutron parton densities) have been developed up to NLO accuracy [153, 405, 406]. In these global analyses, the initial conditions for DGLAP evolution are parametrized by flexible functional forms but they lack theoretical motivation in terms of e.g. the dynamical mechanisms for unitarization mentioned above. On the other hand, the relation between diffraction and nuclear shadowing [56, 300] can in principle be employed to constrain the initial conditions for DGLAP evolution, as has been explored previously at both LO [302] and NLO [407]⁴ accuracy, see Subsec. 6.2.4. All nuclear PDF analyses [153, 405, 406] include data from NC DIS and DY experiments, and [153] also uses particle production data at mid-rapidity in deuterium-nucleus collisions at RHIC. Error sets obtained through the Hessian method are provided in [153]. CC DIS data have been considered only recently [53, 409]⁵ in this context.

Results from the different nuclear PDF analyses performed at NLO accuracy are shown in Fig. 6.12, with the band indicating the uncertainty obtained using the error sets in [153]. In addition to the discrepancies concerning the existence of an enhancement/suppression at large x , the different approaches lead to clear differences at small x , both in magnitude and in shape, usually within the large uncertainty band shown. With nuclear effects vanishing logarithmically in the DGLAP analysis, the corresponding differences and uncertainties diminish, although they remain sizable until rather large Q^2 .

These large uncertainties are due to the lack of experimental data on nuclear structure functions for $Q^2 > 2 \text{ GeV}^2$ and x smaller than a few times 10^{-2} . The constraints on the small x gluon are particularly poor. Particle production data at mid-rapidity coming from deuterium-nucleus collisions at RHIC offer an indirect constraint on the small- x sea and glue [153], but these data are bound to contain sizable uncertainties intrinsic to particle production in hadronic collisions at small and moderate scales. Therefore, only high-accuracy data on nuclear structure functions at smaller x , with a large lever arm in Q^2 , as is achievable at the LHeC, will be able to substantially reduce the uncertainties and clearly distinguish between the different approaches.

Requirements for the ultra-relativistic heavy ion programs at RHIC and the LHC

The LHeC will offer extremely valuable information on several aspects of high-energy hadronic and nuclear collisions. On the one hand, it will characterize hard scattering processes in nuclei through a precise determination of initial state. On the other hand, it will provide quantitative constraints on theoretical descriptions of initial particle production in ultra-relativistic nucleus-nucleus collisions and the subsequent evolution into the quark-gluon plasma, the deconfined partonic state of matter whose production and study offers key information about confinement. Such knowledge will complement that coming from pA collisions and self-calibrating hard probes in nucleus-nucleus collisions (see [377, 394, 404, 410, 411]) regarding the correct interpretation of the findings of the heavy-ion programme at RHIC (see e.g. [412, 413] and refs. therein) and at the LHC. Beyond the qualitative interpretation of such findings, the LHeC will greatly improve the quantitative characterization of the properties of QCD extracted from such studies. The relevant information can be classified into three items:

a. Parton densities inside nuclei:

⁴In the approach in [407] predictions are provided only for sea quarks and gluons, with the valence taken from the analysis in [408].

⁵The analysis in [409] shows the compatibility of the nuclear corrections as extracted in [153] with CC DIS data on nuclear targets, while in [53] some tension is found between NC and CC DIS data.

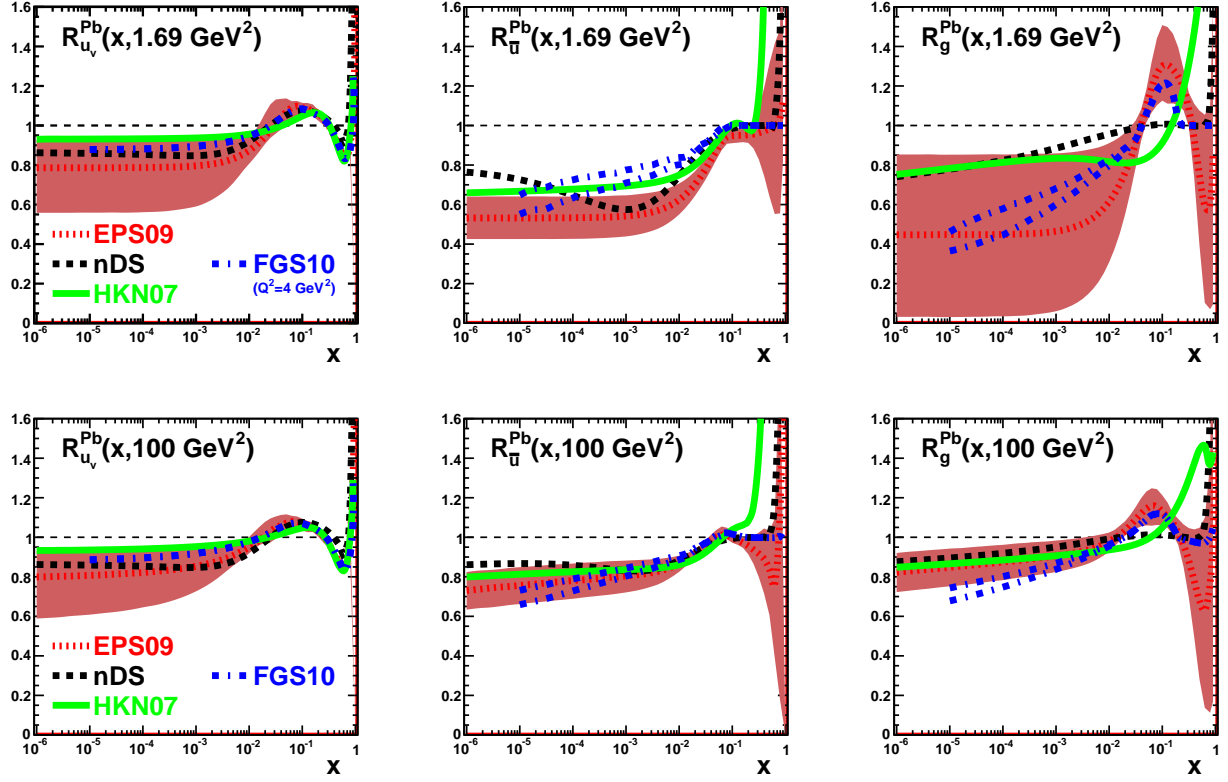


Figure 6.12: Ratio of parton densities in a bound proton in Pb to those in a free proton scaled by $A = 207$, for valence u (left), \bar{u} (middle) and g (right), at $Q^2 = 1.69$ (top) and 100 (bottom) GeV^2 . Results are shown from [405] (nDS, black dashed), [406] (HKN07, green solid), [153] (EPS09, red dotted) and [407] (FGS10, blue dashed-dotted; in this case the lowest Q^2 is 4 GeV^2 and two lines are drawn reflecting the uncertainty in the predictions). The red bands indicate the uncertainties according to the EPS09 analysis [153].

3333 The knowledge of parton densities inside nuclei is an essential piece of information for the analysis of
3334 the medium created in ultra-relativistic heavy-ion collisions using hard probes, i.e. those observables
3335 whose yield in nucleon-nucleon collisions can be predicted in pQCD (see [394, 404, 410, 411]). The
3336 comparison between the expectation from an incoherent superposition of nucleon-nucleon collisions
3337 and the measurement in nucleus-nucleus collision characterises the nuclear effects. However, we need
3338 to disentangle those effects which originate from the creation of a hot medium in nucleus-nucleus
3339 collisions, from effects arising only from differences in the partonic content between nucleons and
3340 nuclei.

3341 Our present knowledge of parton densities inside nuclei is clearly insufficient in the kinematic regions of
3342 interest for RHIC and, above all, for the LHC (see [404] and Subsection 6.1.3). Such ignorance reflects
3343 in uncertainties larger than a factor 3–4 for the calculation of different cross sections in nucleus-nucleus
3344 collisions at the LHC (see Fig. 6.12 and [383]), thus weakening strongly the possibility of extracting
3345 quantitative characteristics of the produced hot medium. While the pA program at the LHC will offer
3346 new constraints on the nuclear parton densities (e.g. [377, 383]), measurements at the LHeC would be
3347 far more constraining and would reduce the uncertainties in nucleus-nucleus cross sections to less than
3348 a factor two.

3349 b. Parton production and initial conditions for a heavy-ion collision:

3350 The medium produced in ultra-relativistic heavy-ion collisions develops very early a collective behavior,
3351 usually considered as that of a thermalized medium and describable by relativistic hydrodynamics. The
3352 initial state of a heavy-ion collision for times prior to its eventual thermalization, and the thermalisation
3353 or isotropisation mechanism, play a key role in the description of the collective behavior. Such an
3354 initial condition for hydrodynamics or transport is presently modelled and fitted to data. But it
3355 should eventually be determined by a theoretical formalism of particle production within a saturation
3356 framework which embodies the both aspects: parton fluxes inside nuclei - discussed in the previous
3357 item, and particle production and evolution, eventually leading to isotropization.

3358 The CGC offers a well-defined framework in which the initial condition and thermalization mechanism
3359 can be computed from QCD, see Subsection 6.1.1 and e.g. [414] and refs. therein. Although our
3360 theoretical knowledge is still incomplete, electron-nucleus collisions are considerably less complex than
3361 the nucleus-nucleus collisions in which these CGC-based calculations already exist and can be tested.
3362 In this way, electron-ion collisions offer a testing ground for ideas on parton production in a dense
3363 environment, which is required for a first principles calculation of the initial conditions for the collective
3364 behavior in ultra-relativistic heavy-ion collisions. The LHeC offers the possibility of studying particle
3365 production in the kinematic region relevant for experiments at RHIC and the LHC.

3366 c. Parton fragmentation and hadronization inside the nuclear medium:

3367 The mechanism through which a highly virtual parton evolves from an off-shell coloured state to a final
3368 state consisting of colourless hadrons, is still subject to great uncertainties. Electron-ion experiments
3369 offer a testing ground for our ideas and understanding of such phenomena, see [415] and refs. therein,
3370 with the nucleus being a medium of controllable extent and density which modifies the radiation and
3371 hadronization processes.

3372 The LHeC will have capabilities for particle identification and jet reconstruction for both nucleon and
3373 nuclear targets. Its kinematic reach will allow the study of partons traveling through the nucleus
3374 from low energies, for which hadronization is expected to occur inside the nucleus, to high energies
3375 with hadronization outside the nucleus. Therefore the modification of the yields of energetic hadrons,
3376 observed at RHIC⁶ and usually attributed to in-medium energy loss - the so-called jet quenching
3377 phenomenon - will be investigated. With jet quenching playing a key role in the present discussions
3378 on the production and characterisation of the hot medium produced in ultra-relativistic heavy-ion

⁶LHC experiments have already observed the jet quenching phenomenon both at the level of single-particle spectra [416] and through the study of jets [417, 418], which will play a central role in heavy-ion physics at these energies.

3379
3380

collisions, the LHeC will offer most valuable information on effects in cold nuclear matter of great importance for clarifying and reducing the existing uncertainties.

3381 6.2 Prospects at the LHeC

3382 6.2.1 Strategy: decreasing x and increasing A

3383 As discussed previously, in order to analyse the regime of high parton densities at small x , we propose a
3384 two-pronged approach which is illustrated in Fig. 6.5. To reach an interesting novel regime of QCD one can
3385 either decrease x by increasing the center-of-mass energy or increase the matter density by increasing the
3386 mass number A of the nucleus. In addition, we will see that diffraction, and especially exclusive diffraction,
3387 will play a special role in unravelling the new dense partonic regime of QCD.

3388 The LHeC will offer a huge lever arm in x and also a possibility of changing the matter density at
3389 fixed values of x . This will allow us to pin down and compare the small x and saturation phenomena both
3390 in protons and nuclei and will offer an excellent testing ground for theoretical predictions. Thus, in the
3391 following, LHeC simulations of electron-proton collisions are paralleled by those in electron-lead wherever
3392 possible. For a complementary perspective on the opportunities for novel QCD studies offered by the LHeC,
3393 see [88].

3394 6.2.2 Inclusive measurements

3395 Predictions for the proton

3396 The LHeC is expected to provide measurements of the structure functions of the proton with unprecedented
3397 precision, which will allow detailed studies of small- x QCD dynamics. In particular, it will be highly sensitive
3398 to departures of the inclusive observables, F_2 and F_L from the fixed-order DGLAP framework, in the region
3399 of small x and Q^2 . These deviations are expected by several theoretical arguments, as discussed in detail
3400 previously.

3401 In Fig. 6.13 we show several predictions for the proton structure functions, F_2 and F_L , in ep collisions at
3402 $Q^2 = 10 \text{ GeV}^2$ and for $10^{-6} \leq x \leq 0.01$ i.e. $F_{2(L)}(x, Q^2 = 10 \text{ GeV}^2)$. The different curves correspond to the
3403 extrapolation of models that reproduce correctly the available HERA data for the same observables in the
3404 small- x region. They are classified into two categories: those based on linear evolution approaches and those
3405 that include non-linear small- x dynamics. Among the linear approaches we include extrapolation from the
3406 NLO DGLAP fit as performed by the NNPDF collaboration [419] (solid yellow bands) and the results from a
3407 combined DGLAP/BFKL approach, which includes resummation of small- x effects [420] (black-dotted-dotted
3408 lines). The non-linear calculations shown here are all formulated within the dipole model. We distinguish
3409 two categories: those based on the eikonalization of multiple scatterings together with DGLAP evolution of
3410 the gluon distributions [354, 355] (blue dashed-dotted lines) and those relying in the Color Glass Condensate
3411 effective theory of high-energy QCD scattering (red dashed lines). The latter include calculations based
3412 on solutions of the running coupling Balitsky-Kovchegov equation [421] and other more phenomenological
3413 models of the dipole amplitude without [340], or with [356] impact parameter dependence. Finally, we also
3414 include a hybrid approach, where initial conditions based on Regge theory and including non-linearities are
3415 evolved in Q^2 according to linear DGLAP evolution [301] (green dotted line). In all cases the error bands
3416 are generated by allowing variations of the free parameters in each subset of models. The green filled squares
3417 correspond to the subset of the simulated LHeC pseudodata at $Q^2 = 10 \text{ GeV}^2$ (see subsection 4.1.4).

3418 Clearly, the accuracy of the data at the LHeC will offer huge possibilities for discriminating between
3419 different models and for constraining the dynamics underlying the small- x region.

3420 Constraining small- x dynamics

3421 The potential impact of the LHeC on low x parton densities within the framework of an NLO DGLAP analysis
3422 is assessed by adding the pseudodata introduced in subsection 4.1.4 into the NNPDF fitting analysis. The

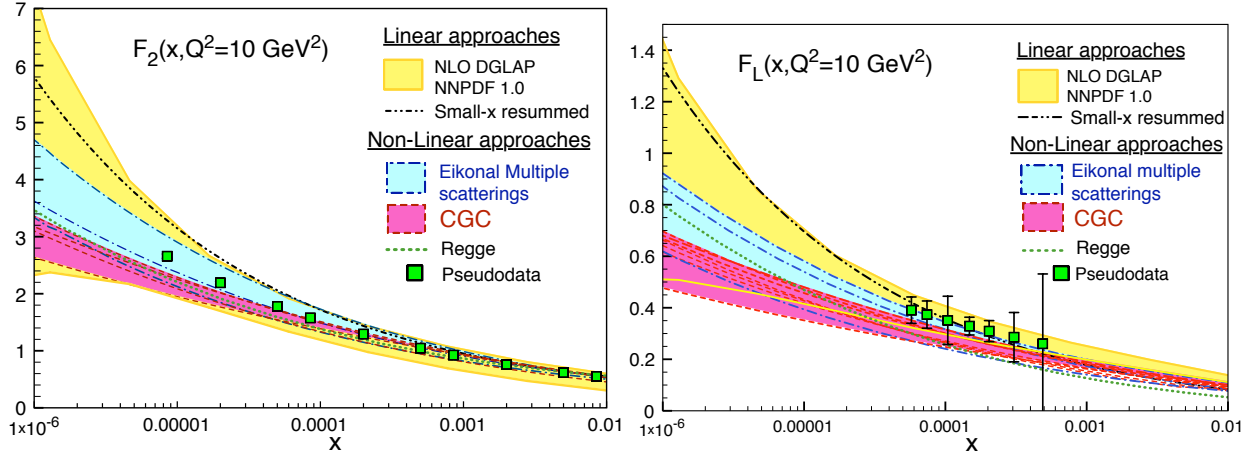


Figure 6.13: Predictions from different models for $F_2(x, Q^2 = 10 \text{ GeV}^2)$ (plot on the left) and $F_L(x, Q^2 = 10 \text{ GeV}^2)$ (plot on the right) versus x , together with the corresponding pseudodata. See the text for explanations.

3423 pseudodata are first generated at the extrapolated central values according to the existing NNPDF fits.

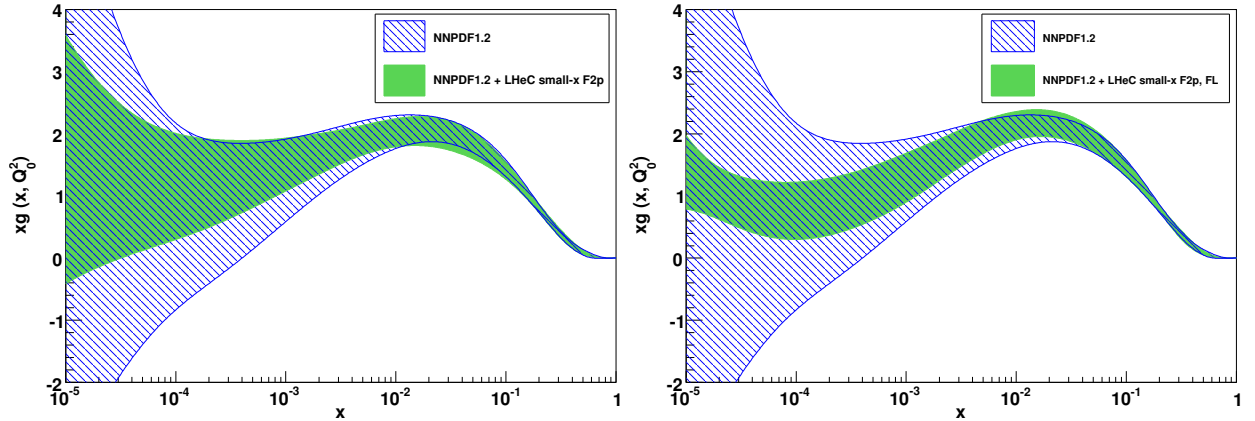


Figure 6.14: The results for the gluon distribution in the standard NNPDF1.2 DGLAP fit [419], together with the results when additionally including LHeC pseudodata for F_2 (left) and for both F_2 and F_L (right). The results are shown at the starting scale for DGLAP evolution, $Q_0^2 = 2 \text{ GeV}^2$.

3424 The extrapolated NNPDF1.2 gluon density and its uncertainty band are shown at the starting scale for
 3425 QCD evolution, $Q_0^2 = 2 \text{ GeV}^2$ in Fig. 6.14, where it can be seen that the lack of experimental constraints for
 3426 $x \lesssim 10^{-4}$ leads to an explosion in the uncertainties. When the LHeC F_2 pseudodata are included in addition,
 3427 the uncertainties improve considerably, but remain rather large at the lowest x values, due to the lack of a
 3428 large lever-arm in Q^2 to constrain the evolution. However, when the LHeC pseudodata on the longitudinal
 3429 structure function F_L are included in addition, the additional constraints lead to a much more substantial
 3430 improvement in the uncertainties on the gluon density.

3431 As is well known from experience at HERA, the measurement of the longitudinal structure function
 3432 presents many experimental challenges and involves possibly undesirable modifications to the beam energies.
 3433 An alternative constraint on the gluon density from the charmed structure function F_2^c has therefore also
 3434 been investigated. As discussed in detail in Subsec. 4.6.1, the LHeC will offer unique precision in the

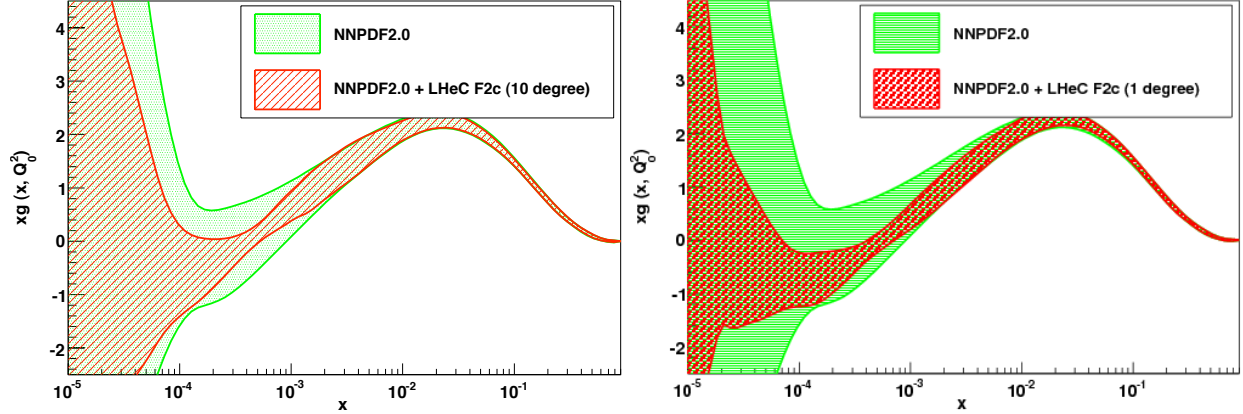


Figure 6.15: The effect on the extracted gluon distribution function of the inclusion of the LHeC pseudodata on the charmed structure function in the NNPDF global analysis. Left plot: scattered electron acceptance extending to within 10° of the beampipe. Right plot: 1° acceptance. The results are shown at the starting scale for DGLAP evolution, $Q_0^2 = 2 \text{ GeV}^2$.

determination of the charm and beauty structure functions, extending to very small x .

In Fig. 6.15 the gluon distribution function is shown, as obtained from the NNPDF2.0 analysis. The green band corresponds to the standard analysis. The red band shows the modified analysis where additionally F_2^c pseudodata from the LHeC are included, using a novel technique based on Bayesian reweighting [422]. It is observed that the charmed structure function considerably improves the constraints on the gluon density at small values of x , especially between $3 \times 10^{-5} - 10^{-2}$, provided that the scattered electron acceptance extends to within around 1° of the beampipe. With a sufficiently good theoretical understanding, heavy flavour production data from the LHeC may thus offer an alternative to F_L for precision constraints on the gluon density at all but the lowest x values.

Given that for all models considered in Fig. 6.13 there are significant flexibilities in the initial parametrisations, it is conceivable that upon suitable changes of parameters it would be possible to obtain satisfactory fits of a wide range of models to the LHeC data. It is therefore essential to analyse in more detail the ability of the LHeC to distinguish unambiguously between different evolution dynamics. With this aim, a PDF analysis is performed including LHeC pseudodata which are generated using different scenarios for small- x QCD dynamics. Pseudodata for $F_2(x, Q^2)$ and $F_L(x, Q^2)$ at small x are considered in a scenario in which the LHeC machine has electron energy $E_e = 70 \text{ GeV}$ and electron acceptance for $\theta_e \leq 179^\circ$, for an integrated luminosity of 1 fb^{-1} . The study is carried out in the framework of the NNPDF1.0 analysis [423] and includes all HERA and fixed target data used in that analysis, in addition to LHeC pseudodata. The kinematics of the LHeC pseudodata included in the fit (together with other data included in the original NNPDF1.0 analysis) are shown in Fig. 6.16. In order to avoid correlations between low x and high x data e.g. through the momentum sum rule constraint, only LHeC pseudodata with $x < 10^{-2}$ are considered. The average total uncertainty of the simulated F_2 pseudodata is $\sim 2\%$, while that of F_L is $\sim 8\%$.

For the NNPDF fits, the input LHeC pseudodata are generated not within the DGLAP framework, but rather using two different models which include saturation effects in the gluon density: the AAMS09 model [421], which is based on non-linear Balitsky-Kovchegov evolution with a running coupling, and the FS04 dipole model [341]. Both of these models deviate significantly from linear DGLAP evolution in the LHeC regime.

The global fit using the NNPDF1.0 framework with fixed-order DGLAP evolution is repeated, now including LHeC pseudodata generated using the scenarios including saturation effects. By assessing the quality of the fit with saturated LHeC pseudodata included, this study tests the sensitivity to parton dynamics beyond fixed-order DGLAP. The conclusions are the same for both the AAMS09 and the FS04 models. The

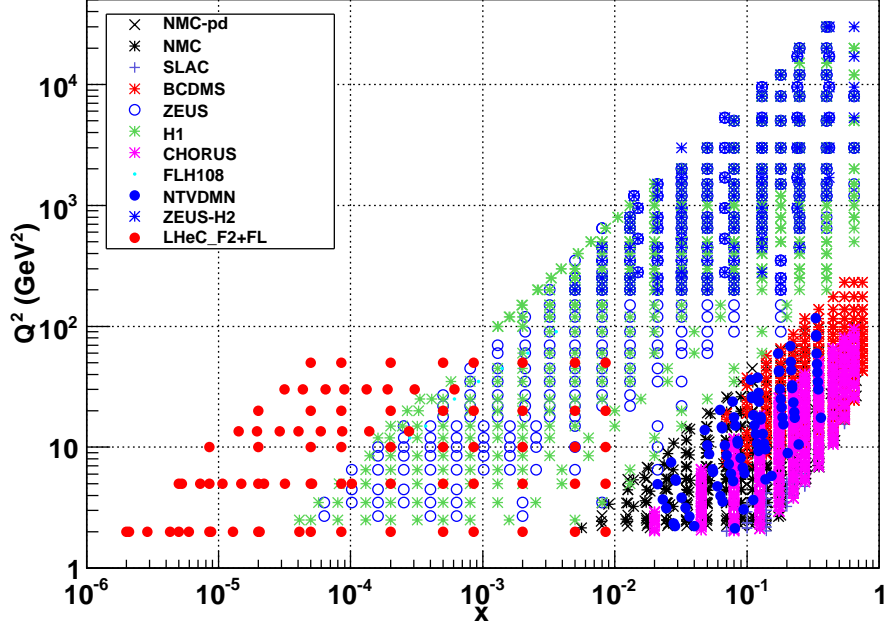


Figure 6.16: The kinematic coverage of the LHeC pseudodata used in the present studies, together with the data already included in the reference NNPDF1.0 dataset.

3466 DGLAP analysis yields an acceptable fit when only the $F_2(x, Q^2)$ LHeC pseudodata are included. This
 3467 implies that although the underlying physical theories are different, the small- x extrapolations of AAMS09
 3468 and FS04 for F_2 are sufficiently similar to DGLAP-based extrapolations for the differences to be absorbed as
 3469 modifications to the shapes of the non-perturbative initial conditions for the PDFs at the starting scale Q_0^2
 3470 for DGLAP evolution. More sophisticated analyses, based for example on sequential kinematical cuts and
 3471 backwards DGLAP evolution, as presented in Subsec. 6.1.2, could still be applied. However, it seems likely
 3472 that it will not be possible unambiguously to establish non-linear effects using LHeC data on F_2 alone.

3473 The situation is very different when data on the longitudinal structure function $F_L(x, Q^2)$ are included
 3474 in the NNPDF fit, provided the lever-arm in Q^2 is large enough for the gluon sensitivity through the Q^2
 3475 evolution of F_2 to conflict with that through F_L . The analysis based on linear DGLAP evolution fails to
 3476 reproduce simultaneously F_2 and F_L in all the Q^2 bins, and thus the overall χ^2 is very large. The effect is
 3477 illustrated in Fig. 6.17, where the best fits from the NNPDF DGLAP analysis are compared with the LHeC
 3478 F_L pseudodata generated from the AAMS09 model. This is a clear signal for a departure from fixed-order
 3479 DGLAP of the simulated pseudodata. This analysis shows that the combined use of F_2 and F_L data is
 3480 a very sensitive probe of novel small- x QCD dynamics, and that their measurement would be very likely
 3481 to discriminate between different theoretical scenarios. Using F_2^c data in place of F_L may offer a similarly
 3482 powerful means of establishing deviations from fixed-order linear DGLAP evolution at small x .

3483 Predictions for nuclei: impact on nuclear parton distribution functions

3484 The LHeC, as an electron-ion collider in the TeV regime, will have an enormous potential for measuring the
 3485 nuclear parton distribution functions at small x . Let us start by a brief explanation of how the pseudodata
 3486 for inclusive observables in e Pb collisions are obtained: To simulate an LHeC measurement of F_2 in electron-
 3487 nucleus collisions, the points (x, Q^2) , generated for $e(50) + p(7000)$ collisions for a high acceptance, low
 3488 luminosity scenario, as explained in subsection 4.1.4, are considered. Among them, we keep only those
 3489 points at small $x \leq 0.01$ and not too large $Q^2 < 1000 \text{ GeV}^2$ with $Q^2 \leq sx$, for a Pb beam energy of

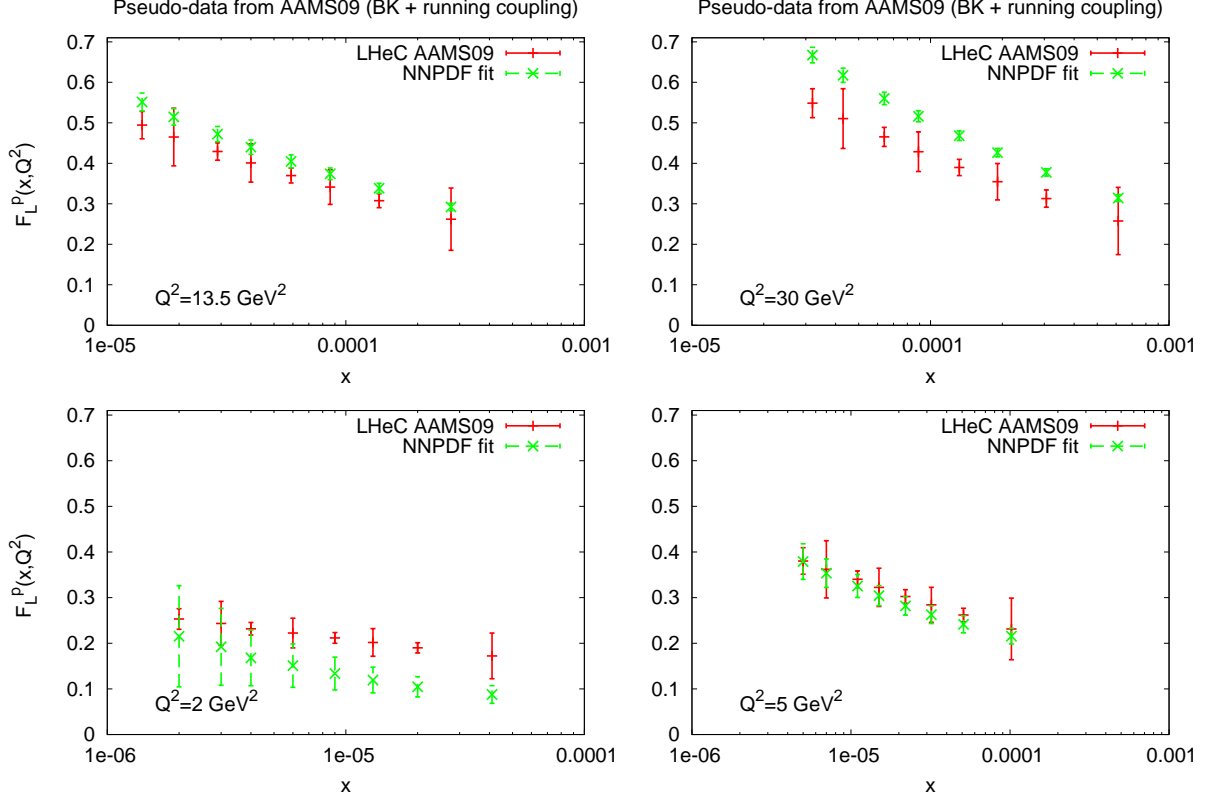


Figure 6.17: The results for F_L obtained from the best NLO DGLAP fit to the standard NNPDF1.2 data set, together with the LHeC pseudodata for $F_2(x, Q^2)$ and $F_L(x, Q^2)$ generated with the (saturating) AAMS09 model. The fit results are compared with the input AAMS09 F_L pseudodata.

2750 GeV per nucleon⁷. Under the assumption that the instantaneous luminosity per nucleon is the same in ep and eA [424], the number of events is scaled by a factor $1/(5 \times 50 \times A)$, with 50 coming from the transition from a high luminosity to a low luminosity scenario, and 5 being a crudely estimated reduction factor accounting for the shorter running time for ions than for proton.

At each point of the grid, σ_r and F_2 are generated using the dipole model of [336, 425] to get the central value. Then, for every point, the statistical error in ep is scaled by the previously mentioned factor $1/(5 \times 50 \times A)$, and corrected for the difference in F_2 or σ_r between the (Glauberized) 5-flavor GBW model [425] and the model used for the ep simulation. The fractional systematic errors are taken to be the same as for ep - as has been achieved in previous DIS experiments on nuclear targets⁸. An analogous procedure is applied when obtaining the nuclear pseudodata for F_2^c and F_2^b , considering the same tag and background rejection efficiencies as in the ep simulation.

To generate LHeC F_L pseudodata for a heavy ion target, a dedicated simulation of $e + p(2750)$ collisions has been performed, at three different energies: 10, 25 and 50 GeV for the electron, with assumed luminosities 5, 10 and 100 pb^{-1} respectively, see subsec. 4.1.5. Then, for each point in the simulated grid, F_L values for protons and nuclei are generated using the (Glauberized) 5-flavor GBW model [425]. The relative uncertainties are taken to be exactly the same as in the ep simulation, as explained above.

⁷In this document we have restricted the discussion and results to Pb because it is the presently accelerated ion at the LHC. But simulations also exist for a Ca nucleus of 3500 GeV per nucleon, and they can be easily produced for other nuclei as Ar (3150 GeV per nucleon), whose acceleration at the LHC has been discussed as part of the AA program [382].

⁸A significant difference in the systematics may eventually come from the different size of the QED radiative corrections for protons and nuclei, an important point which remains to be addressed in future studies.

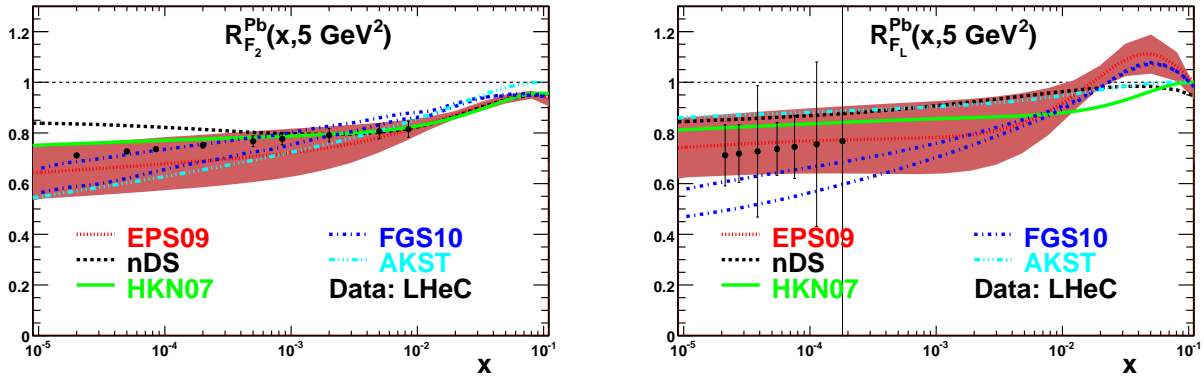


Figure 6.18: Predictions from different models for the nuclear modification factor, Eq. (6.5) for Pb with respect to the proton, for $F_2(x, Q^2 = 5 \text{ GeV}^2)$ (plot on the left) and $F_L(x, Q^2 = 5 \text{ GeV}^2)$ (plot on the right) versus x , together with the corresponding LHeC pseudodata. Dotted lines correspond to the nuclear PDF set EPS09 [153], dashed ones to nDS [405], solid ones to HKN07 [406], dashed-dotted ones to FGS10 [407] and dashed-dotted-dotted ones to AKST [302]. The band corresponds to the uncertainty in the Hessian analysis in EPS09 [153].

3506 In Fig. 6.18 we show several predictions for the nuclear suppression factor, Eq. (6.5), with respect
 3507 to the proton, for the total and longitudinal structure functions, F_2 and F_L respectively,
 3508 at an example $Q^2 = 5 \text{ GeV}^2$ and for $10^{-5} < x < 0.1$. Predictions based on global DGLAP analyses of
 3509 existing data at NLO: nDS, HKN07 and EPS09 [153, 405, 406], plus those from models using the relation
 3510 between diffraction and nuclear shadowing, AKST and FGS10 [302, 407], are shown together with the LHeC
 3511 pseudodata. Brief explanations on the different models can be found in Subsec. 6.1.4. Clearly, the accuracy
 3512 of the data at the LHeC will offer huge possibilities for discriminating between different models and for
 3513 constraining the dynamics underlying nuclear shadowing at small x .

3514 In order to better quantify how the LHeC would improve the present situation concerning nuclear PDFs
 3515 in global DGLAP analyses (see the uncertainty band in Fig. 6.12), nuclear LHeC pseudodata have been
 3516 included in the global EPS09 analysis [153]. The DGLAP evolution was carried out at NLO accuracy, in the
 3517 variable-flavor-number scheme (SACOT prescription) with the CTEQ6.6 [359] set for free proton PDFs as a
 3518 baseline. See [153] and references therein for further details. The only difference compared with the original
 3519 EPS09 setup is that one additional gluon parameter, x_a , has been varied (this parameter was originally
 3520 frozen in EPS09), and the only additionally weighted data set was the PHENIX data on π^0 production at
 3521 mid-rapidity [426] in dAu collisions at RHIC.

3522 Two different fits have been performed: the first one (Fit 1) includes pseudodata on the total reduced
 3523 cross section. The results of the fit are shown in Fig. 6.19 in terms of the nuclear modification factors for
 3524 the parton densities. A large improvement in the determination of sea quark and gluon densities at small x
 3525 is evident.

3526 The second fit (Fit 2) includes not only nuclear LHeC pseudodata on the total reduced cross section
 3527 but also on its charm and beauty components. These data provide direct information on the nuclear effects
 3528 on charm and beauty parton densities, which are generated mainly dynamically from the gluons through
 3529 DGLAP evolution. Thus, the inclusion of such pseudodata further improves the determination of the nuclear
 3530 effects on the gluon at small x , as illustrated in Fig. 6.20.

3531 In both Figs. 6.19 and 6.20 a sizable reduction of the uncertainties in the sea quark and gluon nuclear
 3532 parton distributions at large $x > 0.1$ can also be observed. This improvement is basically due to the
 3533 constraints imposed by sum rules and to the fact that DGLAP evolution links large and small x . Although
 3534 the study of parton distributions at large x is not the subject of this chapter, it is worth commenting
 3535 that F_2 could be measured in eA collisions at the LHeC with a statistical accuracy better than a few

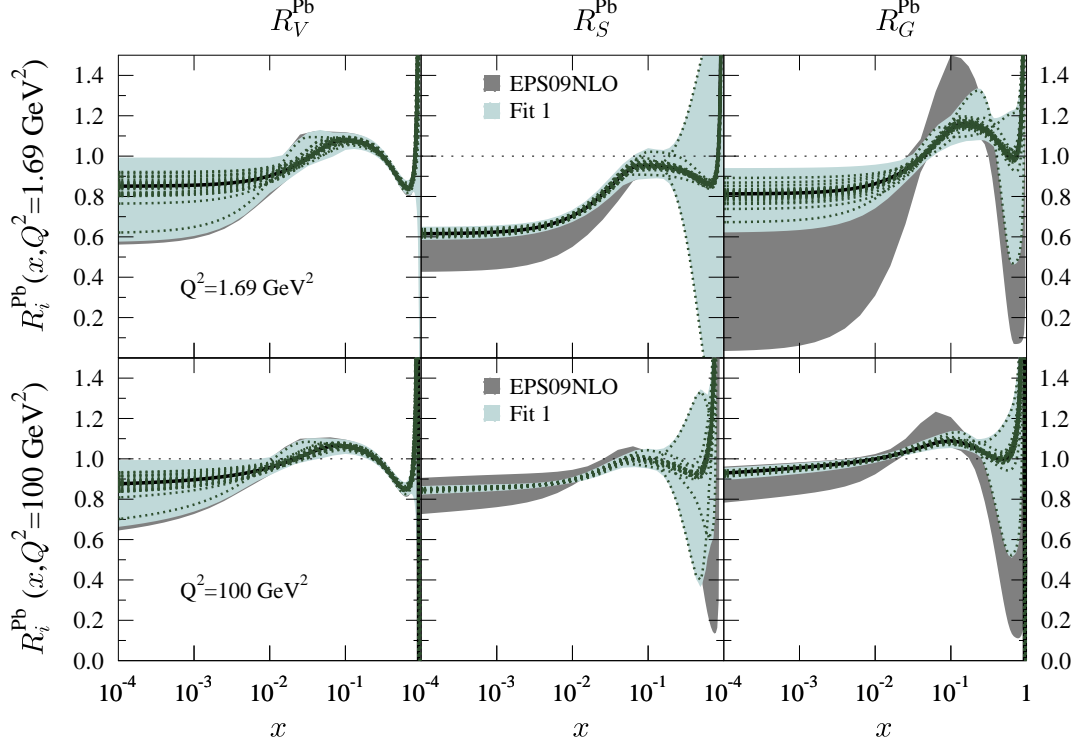


Figure 6.19: Ratio of parton densities for protons bound in Pb to those in a free proton, for valence u (left), \bar{u} (middle) and g (right), at $Q^2 = 1.69$ (top) and 100 (bottom) GeV^2 . The dark grey band corresponds to the uncertainty band using the Hessian method in the original EPS09 analysis [153], while the light blue band corresponds to the uncertainty obtained after including nuclear LHeC pseudodata on the total reduced cross sections (Fit 1). The dotted lines indicate the values corresponding to the different nPDF sets in the EPS09 analysis [153].

3536 percent up to $x \sim 0.6$ but for large $Q^2 > 1000 \text{ GeV}^2$. On the other hand, flavor decomposition will only
 3537 be accessible for $x < 0.1$. Therefore, the LHeC will provide additional information on the antishadowing
 3538 ($R > 1$, $0.1 < x < 0.3$) and - with less precision - on the EMC-effect ($R < 1$, $0.3 < x < 0.8$) regions. The
 3539 latter is valence-dominated and there exist data from fixed target experiments, though at much smaller Q^2 ,
 3540 so at the LHeC the validity of leading-twist DGLAP evolution will be tested.

3541 Furthermore, the large lever-arm in Q^2 opens the possibility of measuring CC events in electron scattering
 3542 on nuclear targets, thus helping to improve the loose constraints on the flavour decomposition of the nuclear
 3543 parton densities coming from existing DIS and DY data. In this respect (see the comments in Subsec.
 3544 6.1.4) the LHeC may help to clarify the issue of the compatibility of the nuclear corrections extracted in
 3545 neutrino-nucleus collisions with those coming from electron- or muon-nucleus collisions⁹.

3546 In conclusion, the precision and large lever-arm in x and Q^2 of the nuclear data at the LHeC will offer huge
 3547 possibilities for discriminating different models and for constraining the parton densities in global DGLAP
 3548 analyses. Besides measurements of the reduced cross section, data on its charm and bottom components
 3549 and on F_L will help to constrain the nuclear effects on PDFs, see e.g. the recent work in [428, 429].

⁹Note that the nuclear modifications of the structure function F_2 in these two types of process are expected to differ due to the different coupling to quarks [427].

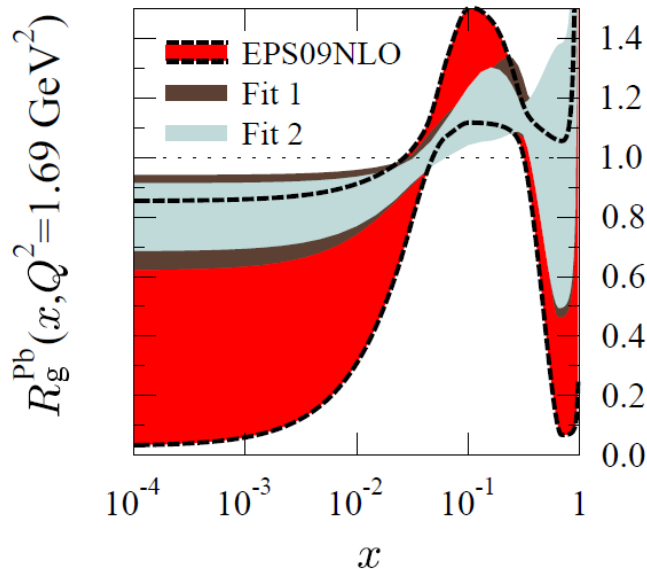


Figure 6.20: Ratio of the gluon density for protons bound in Pb to that of a free proton at $Q^2 = 1.69 \text{ GeV}^2$. The red band corresponds to the uncertainty using the Hessian method in the original EPS09 analysis [153], while the dark brown band corresponds to the uncertainty obtained after including nuclear LHeC pseudodata on the total reduced cross sections (Fit 1), and the light blue band shows the uncertainty obtained after further including pseudodata on charm and beauty reduced cross sections (Fit 2).

3550 6.2.3 Exclusive Production

3551 Introduction

3552 Exclusive processes such as the electroproduction of vector mesons and photons, $\gamma^*N \rightarrow VN (V = \rho^0, \phi, \gamma)$, or
 3553 photoproduction of heavy quarkonia, $\gamma N \rightarrow VN (V = J/\psi, \Upsilon)$ - see Fig. 6.21 - provide information on nucleon
 3554 structure and small- x dynamics which is complementary to that obtained in inclusive measurements [339].
 3555 The exclusive production of J/ψ and ρ mesons in ep collisions and Deeply-Virtual Compton Scattering
 3556 (DVCS, $ep \rightarrow e\gamma p$), have been particularly prominent in the development of our understanding of HERA
 3557 physics [430].

3558 Diffractive channels such as these are favourable, since the underlying exchange crudely equates to a
 3559 pair of gluons, making the process sensitive to the square of the gluon density [431], in place of the linear
 3560 dependence for F_2 or F_L . With a sufficiently good theoretical understanding of the exclusive production
 3561 mechanism, this may enhance substantially the sensitivity to non-linear evolution and saturation phenomena.
 3562 As already shown at HERA, J/Ψ production in particular is a potentially very clean probe of the gluonic
 3563 structure of the hadron [356, 431]. The same exclusive processes can be measured in deep inelastic scattering
 3564 off nuclei, where the gluon density is modified by nuclear effects [432]. In addition, exclusive processes
 3565 give access to the spatial distribution of the gluon density, parametrized by the impact parameter [433]
 3566 of the collision. The correlations between the gluons coupling to the proton contain information on the
 3567 three-dimensional structure of the nucleon or nucleus, which is encoded in the Generalised Parton Densities
 3568 (GPDs). The GPDs combine aspects of parton densities and elastic form factors and have emerged as a key
 3569 concept for describing nucleon structure in QCD (see [55, 434, 435] for a review).

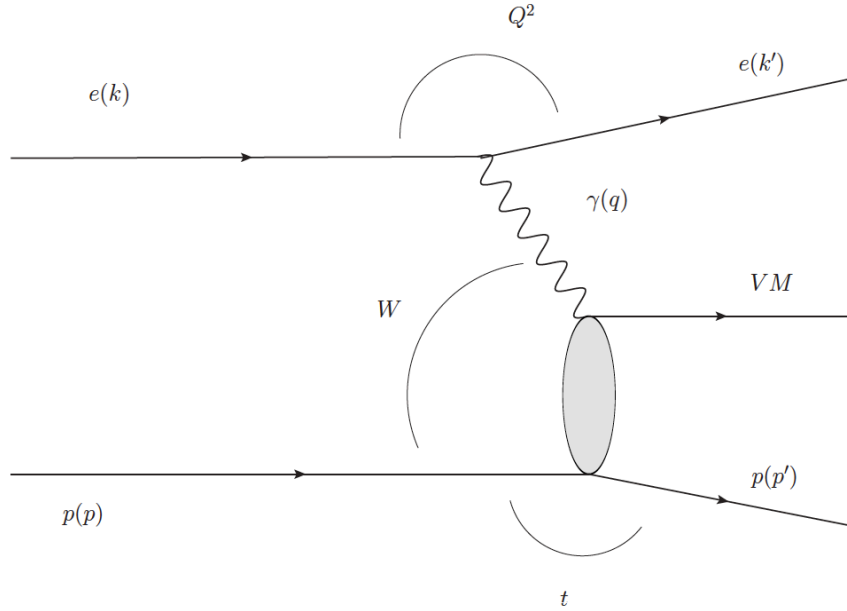


Figure 6.21: Schematic illustration of the exclusive vector meson production process and the kinematic variables used to describe it in photoproduction ($Q^2 \rightarrow 0$) and DIS (large Q^2). The outgoing particle labelled ‘VM’, may be either a vector meson with $J^{PC} = 1^{--}$ or a photon.

3570 Exclusive processes can be treated conveniently within the dipole picture described in Subsec. 6.1.2. In
 3571 this framework, the cross section can be represented as a product of three factorisable terms: the splitting
 3572 of an incoming photon into a $q\bar{q}$ dipole; the ‘dipole’ cross section for the interaction of this $q\bar{q}$ pair with the
 3573 proton and, in the case of vector mesons, a wave function term for the projection of the dipole onto the
 3574 meson. As discussed in Subsec. 6.1.2 the dipole formalism is particularly convenient since saturation effects
 3575 can be easily incorporated.

3576 Generalised Parton Densities and Spatial Structure

3577 At sufficiently large Q^2 the exclusively produced meson or photon is in a configuration of transverse size
 3578 much smaller than the typical hadronic size, $r_{\perp} \ll R_{\text{hadron}}$. As a result its interaction with the target can
 3579 be described using perturbative QCD [436]. A QCD factorisation theorem [437] states that the exclusive
 3580 amplitudes in this regime can be factorised into a perturbative QCD scattering process and certain universal
 3581 process-independent functions describing the emission and absorption of the active partons by the target,
 3582 the generalized parton distributions (GPDs).

3583 The Fourier transform of the GPDs with respect to the transverse momentum transferred to the nucleon
 3584 describes the transverse spatial distribution of partons (illustrated in Fig. 6.3) with a given longitudinal
 3585 momentum fraction x [438]. The transverse spatial distributions of quarks and gluons are fundamental
 3586 characteristics of the nucleon, which reveal the size of the configurations in its partonic wave function and
 3587 allow the study of the non-perturbative dynamics governing their change with x , such as Gribov diffusion,
 3588 chiral dynamics, and other phenomena. The nucleon transverse gluonic size is also an essential input in
 3589 studies of saturation at small x . It determines the initial conditions of the non-linear QCD evolution equations
 3590 and thus directly influences the impact parameter dependence of the saturation scale for the nucleon [355,
 3591 439], which in turn predicates its nuclear enhancement [440]. Information on the nucleon transverse quark
 3592 and gluon distributions is further required in the phenomenology of high-energy pp collisions with hard
 3593 processes, including those with new particle production, where it determines the underlying event structure

(centrality dependence) in inclusive scattering [441] and the rapidity gap survival probability in hard single diffraction [442] and central exclusive diffraction [443,444]. In view of its considerable interest, the transverse quark/gluon imaging of the nucleon with exclusive processes has been recognized as an important objective of nucleon structure and small- x physics.

Mapping the transverse spatial distribution of quarks and gluons requires measurement of the t -dependence of hard exclusive processes up to large values of $|t|$, of the order of 1 GeV^2 . Studies of the Q^2 -dependence and comparisons between different channels provide crucial tests of the reaction mechanism and the universality of GPDs. Vector meson production at small x and heavy quarkonium photoproduction at high energies probe the gluon GPD of the target, while real photon production (DVCS) involves the singlet quark as well as the gluon GPDs. Measurements of exclusive J/ψ photo/electroproduction [445,446] and ρ^0 and ϕ electroproduction at HERA have confirmed the applicability of the factorized QCD description through several model-independent tests, and have provided basic information on the nucleon gluonic size in the region $10^{-4} < x < 10^{-2}$ and its change with x [339]. Measurements of DVCS at HERA [447,448] hint that the transverse distribution of singlet quarks may extend further than that of gluons. While these experiments have given important insight into transverse nucleon structure, the interpretation of the HERA data is limited by the low statistics which preclude a fully differential analysis. A major source of systematic uncertainty at larger t arises from the lack of a complete separation between elastically scattered protons and proton excitations, illustrating the importance of good scattered proton detection at the LHeC.

As discussed in the following, the LHeC would enable a comprehensive program of gluon and singlet quark transverse imaging through exclusive processes, with numerous applications to nucleon structure and small- x physics. The high statistics would permit fully differential measurements of exclusive channels, as needed to understand the reaction mechanism. For example, measurements of the t -distributions for fixed x differentially in Q^2 are needed to confirm the dominance of small-size configurations. The LHeC would also push such measurements to the region $Q^2 \sim \text{few} \times 10 \text{ GeV}^2$ where finite-size (higher-twist) effects are small and the effects of QCD evolution can be cleanly identified. Measurements of gluonic exclusive channels ($J/\psi, \phi, \rho^0$) at the LHeC would provide gluonic transverse images of the nucleon down to $x \sim 10^{-6}$ with unprecedented accuracy, testing theoretical ideas about diffusion dynamics in the wave function. Because exclusive cross sections are proportional to the square of the gluon GPD (i.e. the gluon density), such measurements would also offer new insight into non-linear effects in QCD evolution, and enable new tests of the approach to saturation by measuring the impact parameter dependence of the saturation scale. Along these lines, saturation effects in the exclusive vector meson production on protons and nuclei have been studied in [432,449–451]. Furthermore, measurements of DVCS would provide additional information on the nucleon singlet quark size and its dependence on x . Besides its intrinsic interest for nucleon structure and small- x physics, this information would greatly advance our theoretical understanding of the transverse geometry of high-energy pp collisions at the LHC. We note that these exclusive measurements at the LHeC would complement similar measurements at moderately small x ($0.003 < x < 0.2$) with the COMPASS experiment at CERN and in the valence region $x > 0.1$ with the JLab 12 GeV Upgrade, providing a comprehensive picture of the nucleon spatial structure.

Further interesting information comes from hard exclusive measurements accompanied by the diffractive dissociation of the nucleon, $\gamma^* N \rightarrow V + Y$ ($Y = \text{low-mass proton dissociation state}$). The ratio of inelastic to elastic diffraction in these processes provides information on the quantum fluctuations of the gluon density, which reveals the quantum-mechanical nature of the non-perturbative colour fields in the nucleon and can be related to dynamical models of low-energy nucleon structure [452]. HERA results are in qualitative agreement with such model predictions but do not permit a quantitative analysis. These measurements of exclusive diffraction at the LHeC, and similar ones for eA collisions, would allow for detailed quantitative studies of all these new aspects of nucleon and nuclear structure.

3640 Exclusive Production Formalism in the Dipole Approach

3641 For the exclusive production of vector mesons, a QCD factorization theorem has been demonstrated (for σ_L)
 3642 in [436]. The dipole model follows from this QCD factorization theorem in the LO approximation. Within
 3643 the dipole model, see Subsec. 6.1.2, the amplitude for the exclusive diffractive production of a particle E ,

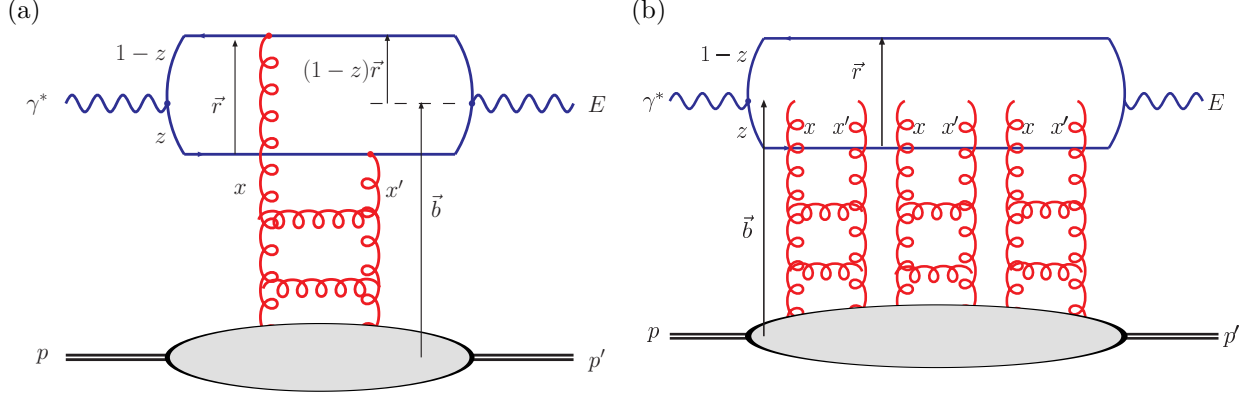


Figure 6.22: Parton level diagrams representing the γ^*p scattering amplitude proceeding via (a) single-Pomeron and (b) multi-Pomeron exchange, where the perturbative QCD Pomeron is represented by a gluon ladder. For exclusive diffractive processes, such as vector meson production ($E = V$) or DVCS ($E = \gamma$), we have $x' \ll x \ll 1$ and $t = (p - p')^2$. These diagrams are related through the optical theorem to inclusive DIS, where $E = \gamma^*$, $x' = x \ll 1$ and $p' = p$.

3644 $\gamma^*p \rightarrow Ep$, shown in Fig. 6.22(a), can be expressed as

$$\mathcal{A}_{T,L}^{\gamma^*p \rightarrow E+p}(x, Q, \Delta) = i \int d^2\mathbf{r} \int_0^1 \frac{dz}{4\pi} \int d^2\mathbf{b} (\Psi_E^* \Psi)_{T,L} e^{-i[\mathbf{b} - (1-z)\mathbf{r}] \cdot \Delta} \frac{d\sigma_{q\bar{q}}}{d^2\mathbf{b}}. \quad (6.6)$$

3645 Here $E = V$ for vector meson production, or $E = \gamma$ for deeply virtual Compton scattering (DVCS). In Eq.
 3646 (6.6), z is the fraction of the photon's light-cone momentum carried by the quark, $r = |\mathbf{r}|$ is the transverse
 3647 size of the $q\bar{q}$ dipole, while \mathbf{b} is the impact parameter, that is, $b = |\mathbf{b}|$ is the transverse distance from the centre
 3648 of the proton to the centre-of-mass of the $q\bar{q}$ dipole; see Fig. 6.22(a). The transverse momentum lost by the
 3649 outgoing proton, Δ , is the Fourier conjugate variable to the impact parameter \mathbf{b} , and $t \equiv (p - p')^2 = -\Delta^2$.
 3650 The forward overlap function between the initial-state photon wave function and the final-state vector meson
 3651 or photon wave function in Eq. (6.6) is denoted $(\Psi_E^* \Psi)_{T,L}$, while the factor $\exp[i(1-z)\mathbf{r} \cdot \Delta]$ originates from
 3652 the non-forward wave function [453]. The differential cross section for an exclusive diffractive process is
 3653 obtained from the amplitude, Eq. (6.6), by

$$\frac{d\sigma_{T,L}^{\gamma^*p \rightarrow E+p}}{dt} = \frac{1}{16\pi} \left| \mathcal{A}_{T,L}^{\gamma^*p \rightarrow E+p} \right|^2, \quad (6.7)$$

3654 up to corrections from the real part of the amplitude and from skewedness ($x' \ll x \ll 1$ for the variables
 3655 shown in figure 6.22a). Taking the imaginary part of the forward scattering amplitude immediately gives
 3656 the formula for the total γ^*p cross section (or equivalently, the proton structure function $F_2 = F_T + F_L$) via
 3657 the optical theorem:

$$\sigma_{T,L}^{\gamma^*p}(x, Q) = \text{Im} \mathcal{A}_{T,L}^{\gamma^*p \rightarrow \gamma^*p}(x, Q, \Delta = 0) = \sum_f \int d^2\mathbf{r} \int_0^1 \frac{dz}{4\pi} (\Psi^* \Psi)_{T,L}^f \int d^2\mathbf{b} \frac{d\sigma_{q\bar{q}}}{d^2\mathbf{b}}. \quad (6.8)$$

3658 The dipole picture therefore provides a unified description of both exclusive diffractive processes and inclusive
 3659 deep-inelastic scattering (DIS) at small x .

3660 The unknown quantity common to Eqs. (6.6) and (6.8) is the b -dependent dipole–proton cross section,

$$\frac{d\sigma_{q\bar{q}}}{d^2\mathbf{b}} = 2 \mathcal{N}(x, r, b), \quad (6.9)$$

3661 where \mathcal{N} is the imaginary part of the dipole–proton scattering amplitude, which can vary between zero and
 3662 one, with $\mathcal{N} = 1$ corresponding to the unitarity (“black disk”) limit. The scattering amplitude \mathcal{N} encodes the

3663 information about the details of the strong interaction between the dipole and the target (proton or nucleus).
 3664 It is generally parameterised according to some theoretically-motivated functional form, with the parame-
 3665 ters fitted to data. Most dipole models assume a factorised b dependence, $\mathcal{N}(x, r, b) = T(b)\mathcal{N}(x, r)$, with
 3666 $\mathcal{N}(x, r) \in [0, 1]$ and, for example, $T(b) = \Theta(R_p - b)$, so that the b -integrated $\sigma_{q\bar{q}} = (2\pi R_p^2)\mathcal{N}(x, r)$. However,
 3667 the “saturation scale” is strongly dependent on impact parameter and the chosen of b -dependence must be
 3668 made consistent with the t -dependence of exclusive diffraction at HERA. This matching is complicated by
 3669 the the non-zero effective “Pomeron slope” α'_p measured at HERA, which implies a correlation between the
 3670 x - and b - dependences of $\mathcal{N}(x, r, b)$. Therefore, for accurate results, $\mathcal{N}(x, r, b)$ should be determined from
 3671 the simultaneous description of inclusive DIS and exclusive diffractive processes.

3672 An impact-parameter-dependent saturation (“b-sat”) model [355, 356] has been shown to describe very
 3673 successfully a broad range of HERA data on exclusive diffractive vector meson (J/ψ , ϕ , ρ) production and
 3674 DVCS (see also the rather different approach in [454]), including almost all aspects of the Q^2 , W and t
 3675 dependence with the exception of α'_p , together with the inclusive structure functions F_2 , $F_2^{c\bar{c}}$, $F_2^{b\bar{b}}$ and F_L .
 3676 The “b-Sat” parameterisation is based on LO DGLAP evolution of an initial gluon density, $xg(x, \mu_0^2) =$
 3677 $A_g x^{-\lambda_g} (1 - x)^{5.6}$, with a Gaussian impact parameter dependence, $T(b) \propto \exp(-b^2/2B_G)$. The dipole
 3678 scattering amplitude is parametrized as

$$\mathcal{N}(x, r, b) = 1 - \exp\left(-\frac{\pi^2}{2N_c} r^2 \alpha_S(\mu^2) xg(x, \mu^2) T(b)\right), \quad (6.10)$$

3679 where the scale $\mu^2 = 4/r^2 + \mu_0^2$, $B_G = 4 \text{ GeV}^{-2}$ was fixed from the t -slope of exclusive J/ψ photoproduction
 3680 at HERA, and the other three parameters ($\mu_0^2 = 1.17 \text{ GeV}^2$, $A_g = 2.55$, $\lambda_g = 0.020$) were fitted to ZEUS
 3681 F_2 data with $x_{Bj} \leq 0.01$ and $Q^2 \in [0.25, 650] \text{ GeV}^2$ [356]. The eikonalised dipole scattering amplitude of
 3682 Eq. (6.10) can be expanded as

$$\mathcal{N}(x, r, b) = \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n!} \left[\frac{\pi^2}{2N_c} r^2 \alpha_S(\mu^2) xg(x, \mu^2) T(b) \right]^n, \quad (6.11)$$

3683 where the n -th term in the expansion corresponds to n -Pomeron exchange; for example, the case $n = 3$ is
 3684 illustrated in Fig. 6.22(b). The terms with $n > 1$ are necessary to ensure unitarity.

3685 Simulations of LHeC Elastic J/ψ and Υ Production

3686 Due to the extremely clean final states produced, the relatively low effective x -values ($x_{\text{eff}} \sim (Q^2 + m_V^2)/(Q^2 +$
 3687 $W^2)$) and scales ($Q_{\text{eff}}^2 \sim (Q^2 + m_V^2)/4$) accessed [431, 455], and the experimental possibility of varying both
 3688 W and t over wide ranges, J/ψ photoproduction ($Q^2 \rightarrow 0$) may offer the cleanest available signature to study
 3689 the transition between the dilute and dense regimes of small- x partons. It should be possible to detect the
 3690 muons from J/ψ or Υ decays with acceptances extending to within 1° of the beampipe with dedicated muon
 3691 chambers on the outside of the experiment. Depending on the electron beam energy, this makes invariant
 3692 photon-proton masses W of well beyond 1 TeV accessible.

3693 For the analysis presented here we concentrate on the photoproduction limit, where the HERA data are
 3694 most precise due to the large cross sections and where unitarity effects are most important. Studies have
 3695 also been made at larger Q^2 [456], where the extra hard scale additionally allows a perturbative treatment
 3696 of exclusive light vector meson (e.g. ρ , ω , ϕ) production. Again, perturbative unitarity effects are expected
 3697 to be important for light vector meson production when $Q^2 \gtrsim 1 \text{ GeV}^2$ is not too large.

3698 LHeC pseudodata for elastic J/ψ and Υ photoproduction and electroproduction have been generated
 3699 using the DIFFVM Monte Carlo generator [457] under the assumption of 1° acceptance and a variety
 3700 of luminosity scenarios. The DIFFVM generator involves a simple Regge-based parameterization of the
 3701 dynamics and a full treatment of decay angular distributions. Statistical uncertainties are estimated for
 3702 each data point. Systematic uncertainties are hard to estimate without a detailed simulation of the muon
 3703 identification and reconstruction capabilities of the detector, but are likely to be at least as good as the 10%
 3704 measurements typically achieved for the elastic J/ψ at HERA.

3705 The plots in Fig. 6.23 show t -integrated predictions for exclusive J/ψ photoproduction ($Q^2 = 0$) obtained
 3706 from Eqs. (6.6) and (6.7), using the eikonalsed “b-Sat” dipole scattering amplitude given in Eq. (6.10)
 3707 together with a “boosted Gaussian” vector meson wave function [356,458]. Also shown is the single-Pomeron
 3708 exchange contribution obtained by keeping just the first ($n = 1$) term in the expansion of Eq. (6.11), such
 3709 that the scattering amplitude is linearly dependent on the gluon density, without refitting any of the input
 3710 parameters.

3711 The difference between the “eikonalsed” and “1-Pomeron” predictions therefore indicates the importance
 3712 of unitarity corrections, which increase significantly with rising γp centre-of-mass energy W . The maximum
 3713 kinematic limit accessible at the LHeC, $W = \sqrt{s}$, is indicated with different options for electron beam
 3714 energies (E_e) and not accounting for the angular acceptance of the detector. The most precise HERA
 3715 data [446,459] are overlaid, together with sample LHeC pseudodata points, assuming 1° muon acceptance,
 3716 with the errors (statistical only) given by an LHeC simulation with $E_e = 150$ GeV. The central values of the
 3717 LHeC pseudodata points were obtained from a Gaussian distribution with the mean given by extrapolating
 3718 a power-law fit to the HERA data [446,459] and the standard deviation given by the statistical errors
 3719 from the LHeC simulation. The plots in Fig. 6.23 show that the errors on the LHeC pseudodata are much
 3720 smaller than the difference between the “eikonalsed” and “1-Pomeron” predictions. Therefore, exclusive
 3721 J/ψ photoproduction at the LHeC may be an ideal observable for investigating unitarity corrections at a
 3722 perturbative scale provided by the charm-quark mass.

3723 Similar plots for exclusive Υ photoproduction are shown in Fig. 6.24. Here, the unitarity corrections are
 3724 smaller than for J/ψ production due to the larger scale provided by the bottom-quark mass and therefore the
 3725 smaller typical dipole sizes r being probed. The simulated LHeC pseudodata points also have larger statistical
 3726 errors than for J/ψ production due to the much smaller cross sections. Nonetheless, the simulations indicate
 3727 that a huge improvement in kinematic range and precision is possible compared with the very sparse Υ data
 3728 from HERA [460–462].

3729 In order to achieve a satisfactory description of the experimental data on exclusive Υ photoproduction,
 3730 an additional normalization factor of ~ 2 has to be included in the dipole calculation (a similar factor is
 3731 required for other calculations using the dipole model, see for example Ref. [463]). This normalization factor
 3732 does not arise from any theoretical considerations. Therefore, the dipole model prediction for the Υ in
 3733 diffractive exclusive processes in DIS still poses significant theoretical questions which cannot be resolved
 3734 without LHeC data.

3735 The cross sections shown in Figs. 6.23 and 6.24 are integrated over $t \equiv (p - p')^2 = -\Delta^2$, where Δ is
 3736 the Fourier conjugate variable to the impact parameter \mathbf{b} . One expects that at high center-of-mass energies
 3737 (small x), saturation effects are most important close to the centre of the proton (small b), where the
 3738 interaction region is densest. This is illustrated in Fig. 6.25(a) where the b-Sat model dipole scattering
 3739 amplitude is shown as a function of b for various x values. By measuring exclusive diffraction in bins of $|t|$
 3740 one can extract the impact parameter profile of the interaction region. This is illustrated in Fig. 6.25(b)
 3741 where the integrand of Eq. (6.6) is shown for different values of t as a function of impact parameter. Clearly
 3742 for large values of $|t|$, small values of b are probed in the impact parameter profile., corresponding to the most
 3743 densely populated region, where saturation effects should be most clearly visible. Indeed, the eikonalsed
 3744 dipole model of Eq. (6.10) leads to “diffractive dips” in the t -distribution of exclusive J/ψ photoproduction
 3745 at large $|t|$ (reminiscent of the dips seen in the t -distribution of the proton-proton elastic cross section),
 3746 departing from the exponential fall-off in the t -distribution seen with single-Pomeron exchange [355]. The
 3747 HERA experiments have only been able to make precise measurements of exclusive J/ψ photoproduction at
 3748 relatively small $|t| \lesssim 1$ GeV², and no significant departure from the exponential fall-off, $d\sigma/dt \sim \exp(-B_D|t|)$,
 3749 has been observed.

3750 In Fig. 6.26, LHeC pseudodata on the differential cross section $d\sigma/dt$ is shown as a function of the
 3751 energy W in different bins of t for the case of exclusive J/Ψ production. Again two different b-Sat model
 3752 scenarios are shown, with unitarisation effects and with single Pomeron exchange. Already for small values of
 3753 $|t| \sim 0.2$ GeV² and low values of electron energies there is a large discrepancy between the models. The LHeC
 3754 simulated data still have very small errors in this regime, and can clearly distinguish between the different
 3755 models. The differences are of course amplified for large t and large electron beam energies. However the

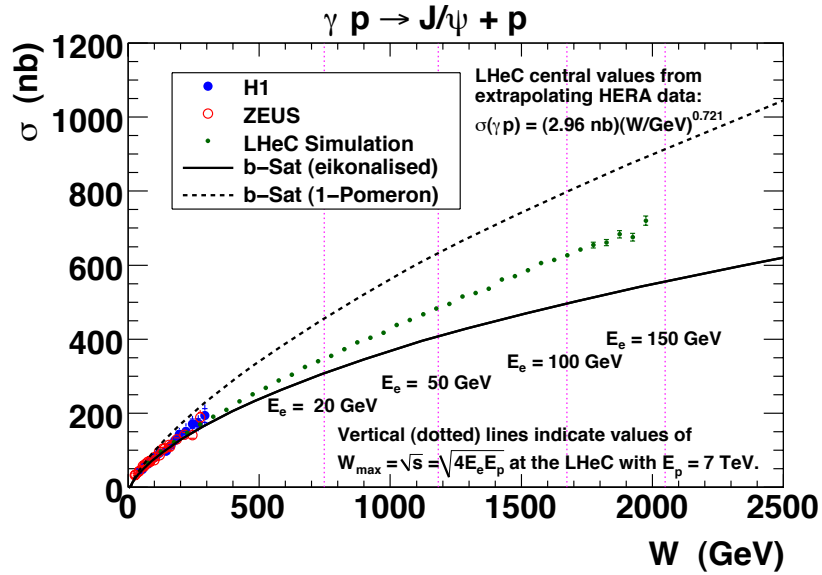
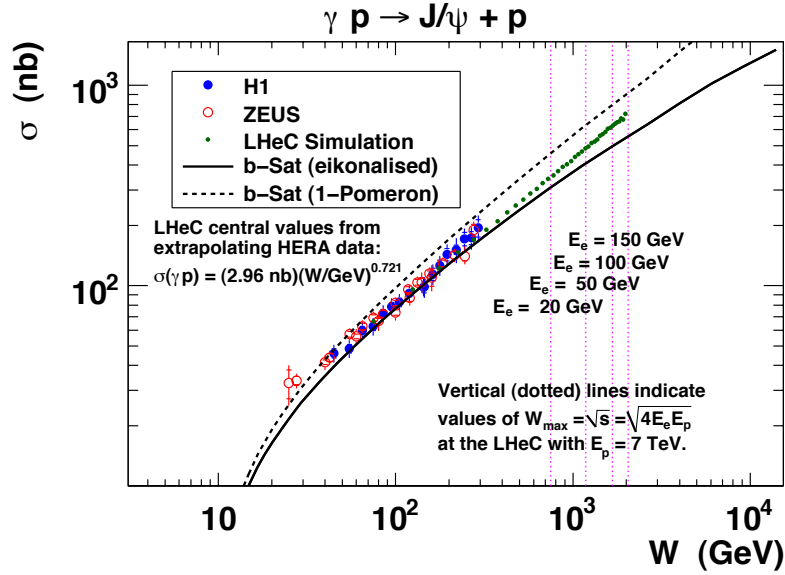


Figure 6.23: LHeC exclusive J/ψ photoproduction pseudodata, as a function of the γp centre-of-mass energy W , plotted on a (top) log–log scale and (bottom) linear–linear scale. The difference between the solid and dashed curves indicates the size of unitarity corrections according to the b-Sat dipole model.

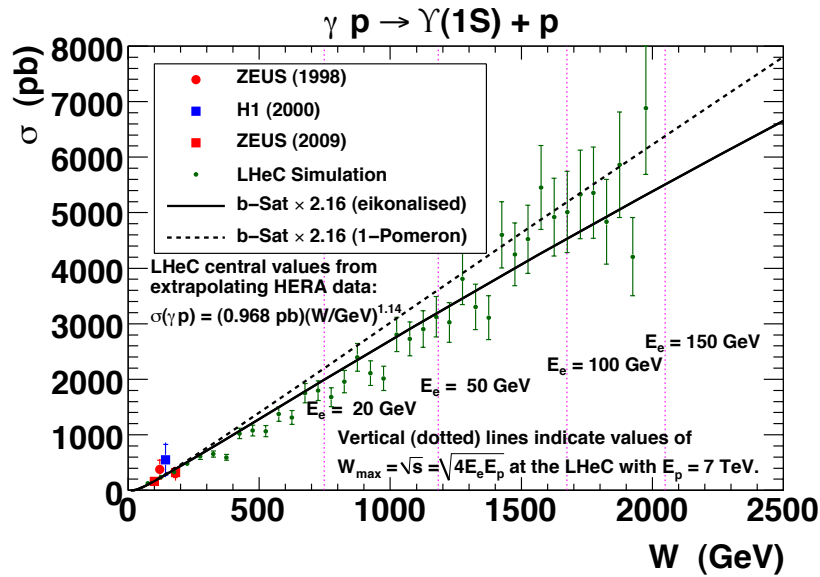
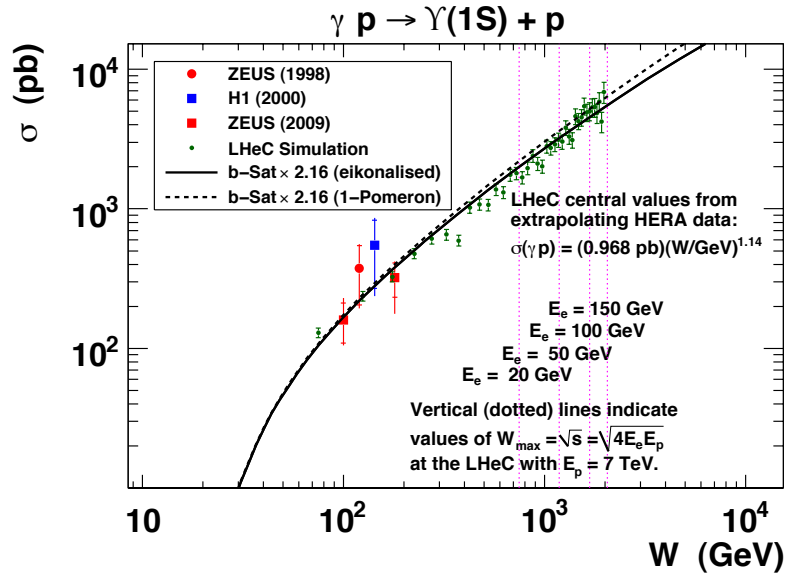


Figure 6.24: LHeC exclusive Υ photoproduction pseudodata, as a function of the γp centre-of-mass energy W , plotted on a (a) log-log scale and (b) linear-linear scale. The difference between the solid and dashed curves indicates the size of unitarity corrections according to the b-Sat model. The b-Sat theory predictions have been scaled by a factor 2.16 to best-fit the existing HERA data.

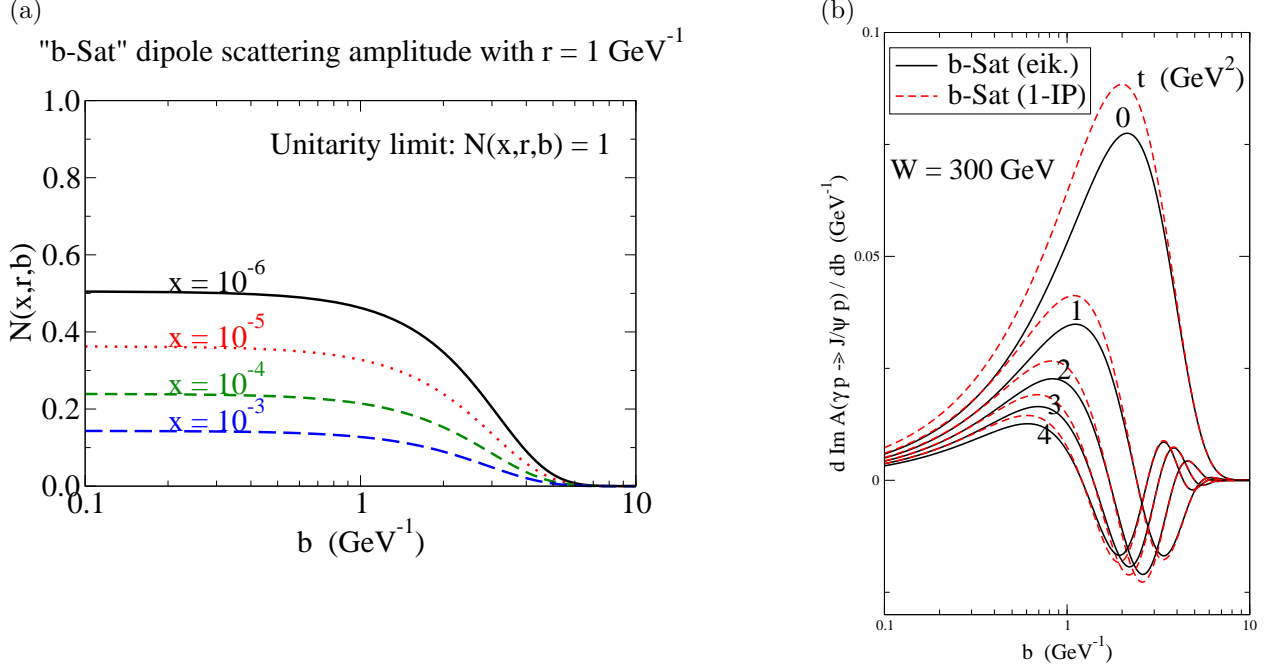


Figure 6.25: (a) The imaginary part of the dipole scattering amplitude, $\mathcal{N}(x, r, b)$, as a function of the impact parameter b , for fixed values of dipole size $r = 1 \text{ GeV}^{-1}$ (typical for exclusive J/ψ photoproduction) and different x values. (b) The (r -integrated) amplitude - the integrand of Eq. (6.6) - for exclusive J/ψ photoproduction as a function of b , for $W = 300 \text{ GeV}$ and $|t| = 0, 1, 2, 3, 4 \text{ GeV}^2$.

3756 precision of the data deteriorates at large t .

3757 Summarising, it is clear that the precise measurements of large- $|t|$ exclusive J/ψ photoproduction at the
 3758 LHeC would have significant sensitivity to unitarity effects.

3759 Simulations of Deeply Virtual Compton Scattering at the LHeC

3760 Simulations of the DVCS measurement possibilities with the LHeC have been made using the Monte Carlo
 3761 generator MILOU [464], in the 'FFS option', for which the DVCS cross section is estimated using the model
 3762 of Frankfurt, Freund and Strikman [465]. A t -slope of $B = 6 \text{ GeV}^{-2}$ is assumed.

3763 The $ep \rightarrow e\gamma p$ DVCS cross section is estimated in various scenarios for the electron beam energy and
 3764 the statistical precision of the measurement is estimated for different integrated luminosity and detector
 3765 acceptance choices. Detector acceptance cuts at either 1° or 10° are placed on the polar angle of the final
 3766 state electron and photon. Based on experience with controlling backgrounds in HERA DVCS measurements
 3767 [447, 448, 466], an additional cut is placed on the transverse momentum P_T^γ of the final state photon.

3768 The kinematic limitations due to the scattered electron acceptance follow the same patterns as for the
 3769 inclusive cross section (see Subsec. 6.2.2). The photon P_T^γ cut is found to be a further important factor in the
 3770 Q^2 acceptance, with measurements at $Q^2 < 20 \text{ GeV}^2$ almost completely impossible for a cut at $P_T^\gamma > 5 \text{ GeV}$,
 3771 even in the scenario with detector acceptances reaching 1° . If this cut is relaxed to $P_T^\gamma > 2 \text{ GeV}$, it opens
 3772 the available phase space towards the lowest Q^2 and x values permitted by the electron acceptance.

3773 A simulation of a possible LHeC DVCS measurement double differentially in x and Q^2 is shown in
 3774 Fig. 6.27 for a very modest luminosity scenario (1 fb^{-1}) in which the electron beam energy is 50 GeV ,
 3775 the detector acceptance extends to 1° and photon measurements are possible down to $P_T^\gamma = 2 \text{ GeV}$. High
 3776 precision is possible throughout the region $2.5 < Q^2 < 40 \text{ GeV}^2$ for x values extending down to $\sim 5 \times 10^{-5}$.
 3777 The need to measure DVCS therefore places constraints on the detector performance for low transverse

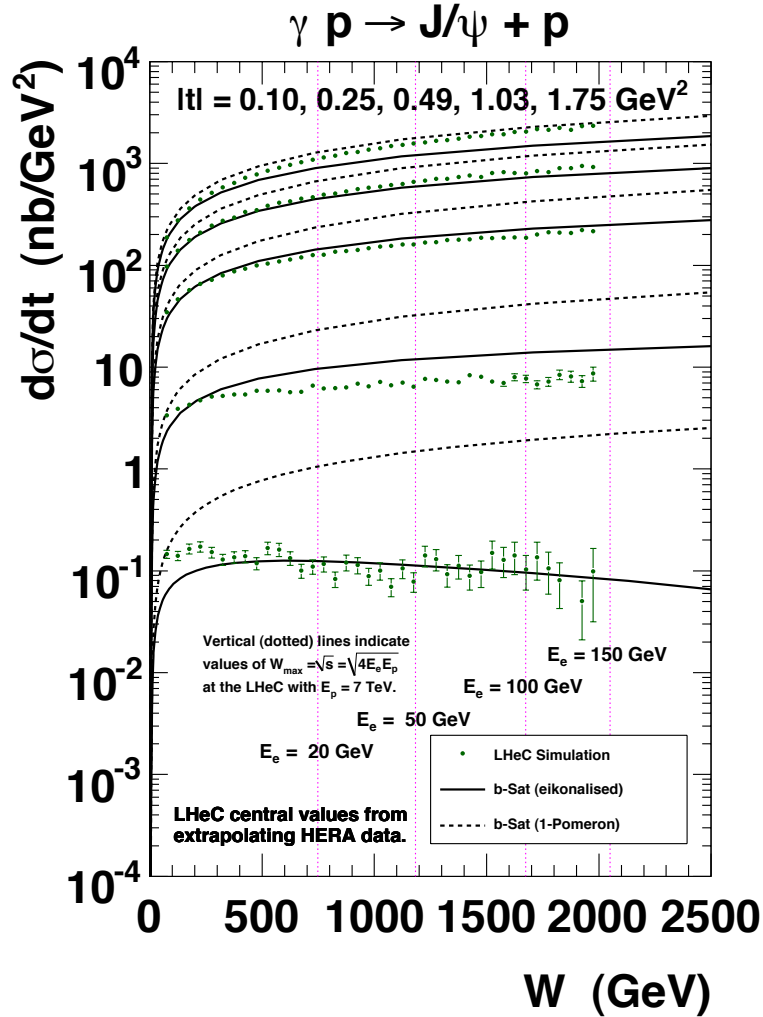


Figure 6.26: Simulated LHeC measurements of the W -dependence of exclusive J/ψ photoproduction at the LHeC, differentially in bins of $|t| = 0.10, 0.20, 0.49, 1.03, 1.75$ GeV². The difference between the solid and dashed curves indicates the size of unitarity corrections according to the b-Sat dipole model. The central values of the LHeC pseudodata points were obtained from a Gaussian distribution with the mean given by extrapolating a parameterization of HERA data and the standard deviation given by the statistical errors from the LHeC simulation with $E_e = 150$ GeV. The t -integrated cross section (σ) as a function of W for the HERA parameterization was obtained from a power-law fit to the data from both ZEUS [459] and H1 [446], then the t -distribution was assumed to behave as $d\sigma/dt = \sigma \cdot B_D \exp(-B_D|t|)$, with $B_D = [4.400 + 4 \cdot 0.137 \log(W/90 \text{ GeV})]$ GeV⁻² obtained from a linear fit to the values of B_D versus W given by both ZEUS [459] and H1 [446].

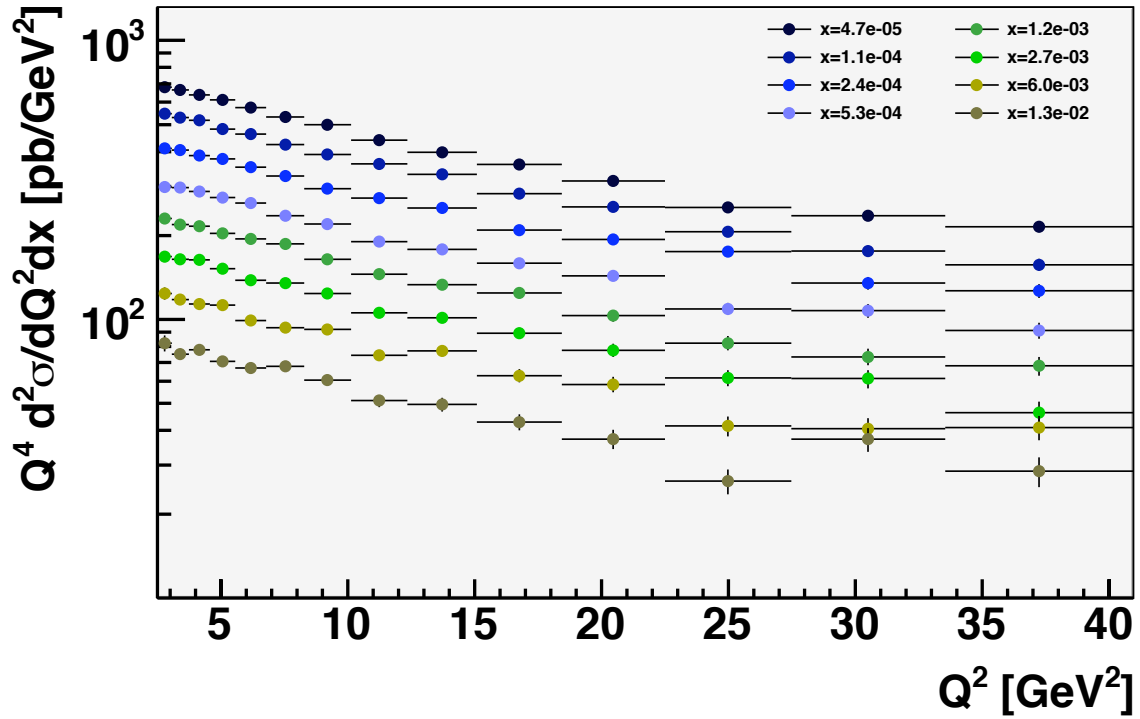


Figure 6.27: Simulated LHeC measurement of the DVCS cross section multiplied by Q^4 for different x values for a luminosity of 1 fb^{-1} , with $E_e = 50 \text{ GeV}$, and electron and photon acceptance extending to within 1° of the beam pipe with a cut at $P_T^\gamma = 2 \text{ GeV}$. Only statistical uncertainties are considered.

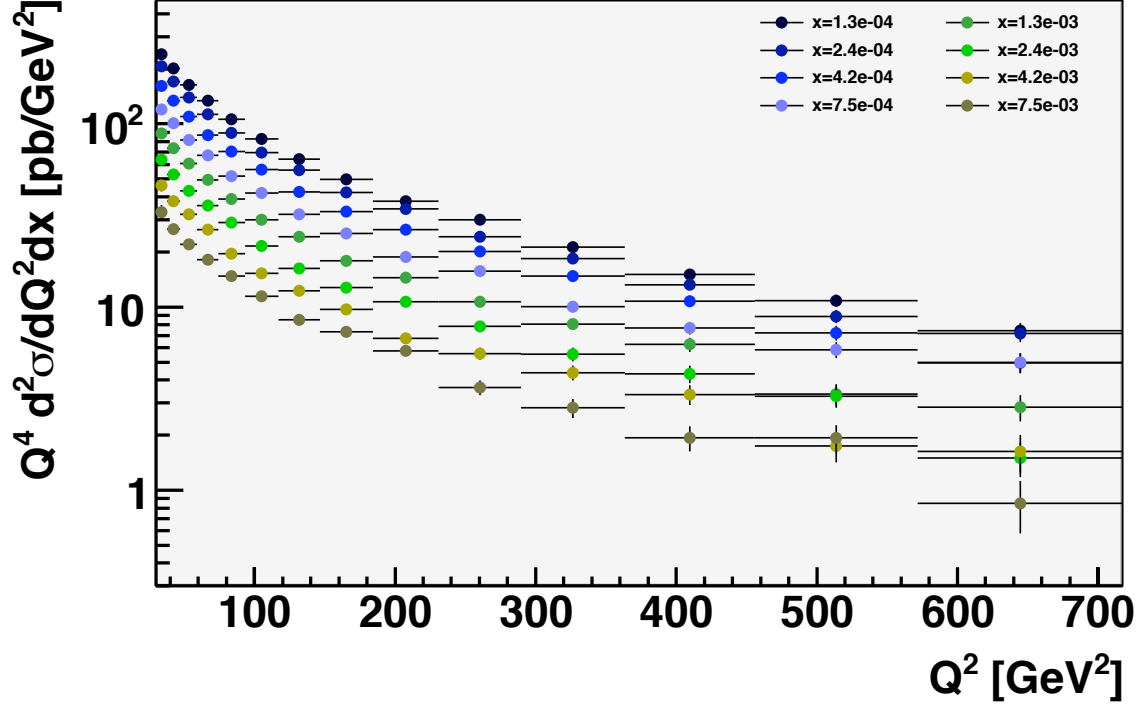


Figure 6.28: Simulated LHeC measurement of the DVCS cross section multiplied by Q^4 for different x values for a luminosity of 100 fb^{-1} , with $E_e = 50 \text{ GeV}$, and electron and photon acceptance extending to within 10° of the beampipe with a cut at $P_T^\gamma = 5 \text{ GeV}$. Only statistical uncertainties are considered.

3778 momentum photons, which in practice translates into the electromagnetic calorimetry noise conditions and
 3779 response linearity at low energies.

3780 If the detector acceptance extends to only 10° , the P_T^γ cut no longer plays such an important role.
 3781 Although the low Q^2 acceptance is lost in this scenario, the larger luminosity will allow precise measurements
 3782 for $Q^2 \gtrsim 50 \text{ GeV}^2$, a region which is not well covered in the 1° acceptance scenario due to the small cross
 3783 section. In the simulation shown in Fig. 6.28, a factor of 100 increase in luminosity is considered, resulting
 3784 in precise measurements extending to $Q^2 > 500 \text{ GeV}^2$, well beyond the range explored for DVCS or other
 3785 GPD-sensitive processes to date.

3786 Maximising the lepton beam energy potentially gives access to the largest W and smallest x values,
 3787 provided the low P_T^γ region can be accessed. However, the higher beam lepton energy boosts the final state
 3788 photon in the scattered lepton direction, resulting in an additional acceptance limitation.

3789 Further studies of this process will require a better understanding of the detector in order to estimate
 3790 systematic uncertainties. A particularly interesting extension would be to investigate possible beam charge
 3791 [447, 466] and polarisation asymmetry measurements at lower x or larger Q^2 than was possible at HERA.
 3792 With the addition of such information, a full study of the potential of the LHeC to constrain GPDs could
 3793 be performed.

3794 Diffractive Vector Meson Production off Nuclei

3795 Exclusive diffractive processes are similarly promising as a source of information on the gluon density in
 3796 the nucleus [432]. Quasi-elastic scattering of photons from nuclei at small x can be treated within the
 3797 same dipole model framework as for ep scattering, making the comparisons with the proton case relatively

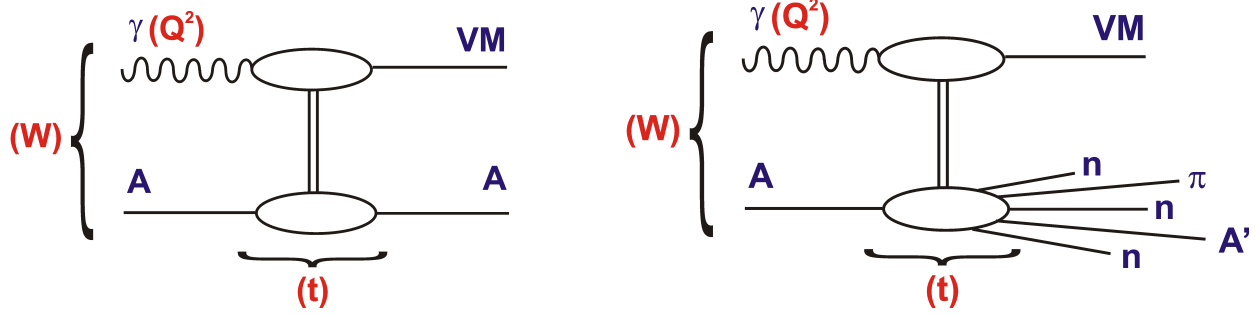


Figure 6.29: Diagrams illustrating the different types of exclusive diffraction in the nuclear case: coherent (plot on the left) and incoherent (plot on the right). While the diagrams have been drawn for the case of exclusive vector meson production, they equally apply to an arbitrary diffractively produced state.

straightforward. The interaction of the dipole with the nucleus can be viewed as a sum of dipole scatterings off the nucleons forming the nucleus. Nuclear effects can be incorporated into the dipole cross section by modifying the transverse gluon distribution and adding the corrections due to Glauber rescattering from multiple nucleons [355,432]. Previous experimental data on exclusive production from nuclei exist [467,468], but are limited in both kinematic range and precision.

There is one aspect of diffraction which is specific to nuclei. The structure of incoherent diffraction with nuclear break-up ($eA \rightarrow eXY$) is more complex than with a proton target, and it can also be more informative. In the case of a target nucleus, we expect the following qualitative changes in the t -dependence. First, the low- $|t|$ regime of coherent diffraction illustrated in Fig. 6.29 left, in which the nucleus scatters elastically and remains in its ground state, will be dominant up to a smaller value of $|t|$ (about $|t| = 0.05 \text{ GeV}^2$) than in the proton case, reflecting the larger size of the nucleus. The nuclear dissociation regime (incoherent case), see Fig. 6.29 right, will consist of two parts: an intermediate regime in momentum transfer up to perhaps $|t| = 0.7 \text{ GeV}^2$, where the nucleus will predominantly break up into its constituent nucleons, and a large- $|t|$ regime where the nucleons inside the nucleus will also break up, implying - for instance - pion production in the Y system. While these are only qualitative expectations, it is crucial to study this aspect of diffraction quantitatively in order to complete our understanding of the transverse structure of nuclei.

Fig. 6.30 shows the diffractive cross sections for exclusive J/Ψ production off a lead nucleus with (b-Sat) and without (b-NonSat) saturation effects. The figure shows both the coherent and incoherent cross sections. According to both models shown, the cross section for $t \sim 0$ is dominated by coherent production, whereas the nuclear break-up contribution becomes dominant for $|t| \gtrsim 0.01 \text{ GeV}^2$, leading to a relatively flat t distribution. The coherent cross section exhibits a characteristic multiple-dip structure at these relatively large t values, the details of which are sensitive to gluon saturation effects. Resolving these dips requires a clean separation between the coherent and nuclear break-up contributions, which may be possible with sufficient forward instrumentation. In particular, preliminary studies suggest that the detection of neutrons from the nuclear break-up in the Zero Degree Calorimeter (Section 14.3) reduces the incoherent backgrounds dramatically. Assuming that it is possible to obtain a relatively clean sample of coherent nuclear diffraction, resolving the rich structure at large t should be possible based on the measurement of the transverse momentum of the elastically produced J/ψ according to $t = -p_T^2(J/\psi)$. The resolution on the t measurement is thus related to that on the J/ψ by $\Delta t = 2\sqrt{-t} \Delta p_T(J/\psi)$, amounting to $\Delta t < 0.01 \text{ GeV}^2$ throughout the range shown in Fig. 6.30 assuming $\Delta p_T(J/\psi) < 10 \text{ MeV}$, as has been achieved at HERA. The pseudodata for the coherent process shown in the figure are consistent with this resolution and correspond to a modest integrated luminosity of order 10 pb^{-1} .

Independently of the large $|t|$ behaviour, important information can be obtained from the low $|t|$ region alone. Coherent production for $t \sim 0$ can easily be related to the properties of dipole-nucleon interactions, because all nuclear effects can be absorbed into the nuclear wave functions, such that only the average gluon density of the nucleus enters the calculation. For this forward cross section, the exact shape of the nuclear

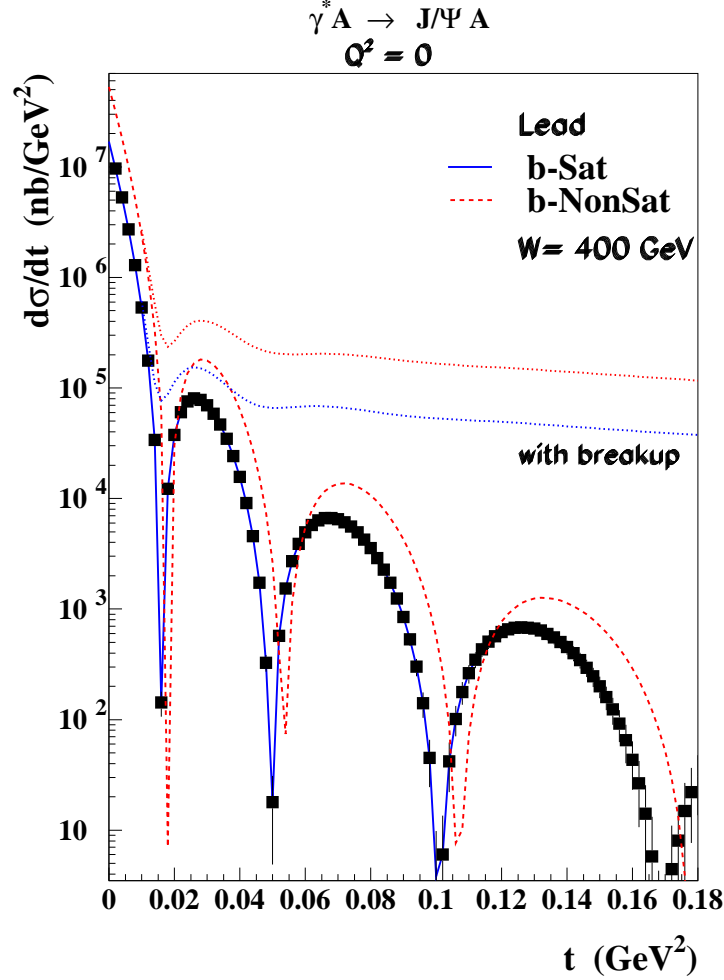


Figure 6.30: Differential cross section for the diffractive production of J/Ψ on a lead nucleus, as a function of the momentum transfer $|t|$. The dashed-red and solid-blue lines correspond to the b-Sat model predictions for coherent production without and with saturation effects, respectively. The dotted lines correspond to the predictions for the incoherent case. The pseudodata shown for the coherent case are explained in the text.

3834 wave function is not important, in contrast to what happens at larger $|t|$ where the distribution reflects the
3835 functional form of the nuclear density.

3836 Saturation effects can be studied in a very clean way using the t -averaged gluon density obtained in this
3837 way from the forward coherent cross section. Fig. 6.31 shows this cross section for J/Ψ production as a
3838 function of W for different nuclei. The cross section varies substantially as a function of the γ^*p centre of
3839 mass energy W and the nuclear mass number A . It is also very sensitive to shadowing or saturation effects
3840 due to the fact that the differential cross section at $t = 0$ has a quadratic dependence on the gluon density
3841 and A . Due to this fact, the ratios of the cross sections for nuclei and protons are roughly proportional to the
3842 ratios of the gluon densities squared. This has been exploited in the calculation [469] presented in Fig. 6.32,
3843 where the nuclear modification factor R for the square of the gluon density is shown. The predictions are
3844 consistent with those obtained from the b-Sat model (Fig. 6.31). Therefore, a precise measurement of the
3845 J/ψ cross section around $t = 0$ is an invaluable source of information on the gluon density and in particular
3846 on non-linear effects.

3847 Another region of interest is the measurement at larger $|t|$, $|t| \gtrsim 0.15 \text{ GeV}^2$. Here the reaction is fully

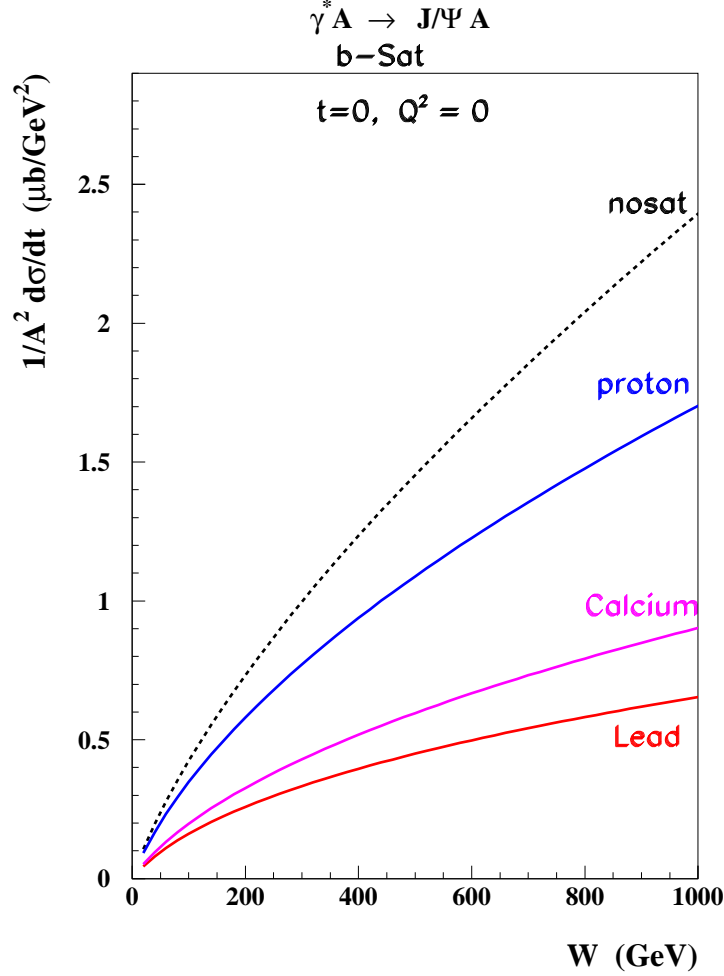


Figure 6.31: Energy dependence of the coherent photoproduction of the J/Ψ on a proton and different nuclei in the forward case $t = 0$ according to the b-Sat model. The cross sections are normalized by a factor $1/A^2$, corresponding to the dependence on the gluon density squared if no nuclear effects are present.

3848 dominated by the incoherent processes in which the nucleus breaks up. The shadowing or saturation effects
 3849 should be stronger in this region than in the coherent case [440] and the shape of the diffractive cross
 3850 section should be only weakly sensitive to nuclear effects [432]. Finally, the intermediate region between
 3851 $|t| \sim 0.01 \text{ GeV}^2$ and $|t| \sim 0.1 \text{ GeV}^2$ is also very interesting because here the barely known gluonic nuclear
 3852 effects can be studied.

3853 Searching for the Odderon

3854 Exclusive processes in photoproduction and DIS offer unique sensitivity to rare exchanges in QCD. One
 3855 prominent example is that of exclusive pseudoscalar meson production, which could proceed via the exchange
 3856 of the Odderon. The Odderon is the postulated Reggeon which is the C-odd partner of the Pomeron. The
 3857 exchange of an Odderon should contribute with different signs to particle-particle and particle-antiparticle
 3858 scattering. Therefore, in the case of hadron-hadron collisions it could lead, via the optical theorem, to a
 3859 finite difference between proton-proton and proton-antiproton total cross sections at high energies, provided
 3860 the intercept of the Odderon is close to unity. Despite many searches, no evidence for Odderon exchange
 3861 has been found so far, see for example [470]. Nevertheless, the existence of the Odderon is a firm prediction

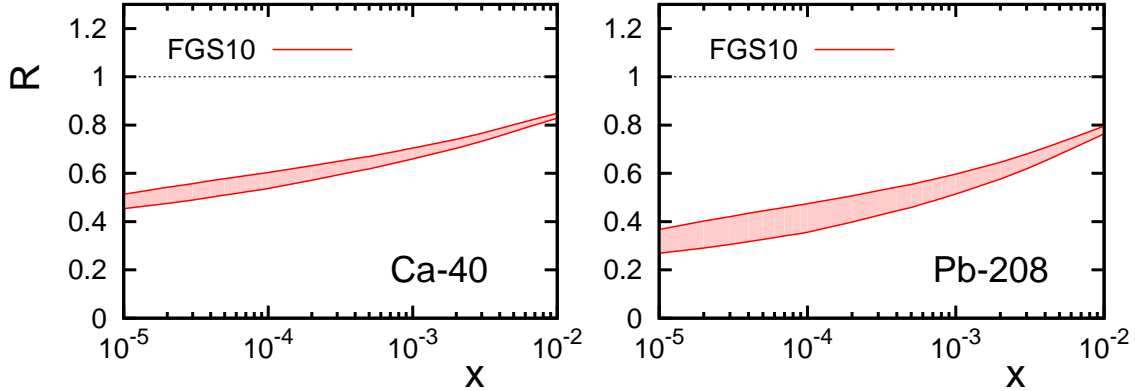


Figure 6.32: The x dependence of the nuclear modification ratio for the gluon density squared, from nuclei to protons (rescaled by A^2), for the scale corresponding to the exclusive production of the J/Ψ . Calculations obtained from the model described in [469].

3862 of high-energy QCD, for a comprehensive review see [471]. At lowest order in perturbation theory it can
 3863 be described as a system of three non-interacting gluons. In the leading logarithmic approximation in x its
 3864 evolution is governed by the Bartels-Kwieciński-Praszalowicz (BKP) equations [472–474]. Up to now, two
 3865 solutions to the BKP equations are known, one with intercept slightly below one [475] and the other with
 3866 intercept exactly equal to one [476].

3867 Several channels involving Odderon exchange are possible at the LHeC, leading to the exclusive production
 3868 of pseudoscalar mesons, $\gamma^{(*)}p \rightarrow Cp$, where $C = \pi^0, \eta, \eta', \eta_c \dots$. Searches for the Odderon in the reaction
 3869 $ep \rightarrow e\pi^0 N^*$ were performed by the H1 collaboration at HERA [477] at an average γp c.m.s energy $\langle W \rangle =$
 3870 215 GeV. No signal was found and an upper limit on the cross section was derived, $\sigma(ep \rightarrow e\pi^0 N^*, 0.02 <$
 3871 $|t| < 0.3 \text{ GeV}^2) < 49$ nb at the 95 % confidence level. Although the predicted cross sections for processes
 3872 governed by Odderon exchange are rather small, they are not suppressed with increasing centre-of-mass
 3873 energy and the large luminosities offered by the LHeC may be exactly what is required for a discovery. In
 3874 addition to π^0 production, Odderon searches at the LHeC could be based on other exclusive channels, for
 3875 example with heavier mesons η_c, η_b [478]. An even more sensitive test, ideal for study at the LHeC, is the
 3876 measurement of the difference between charm and anti-charm angular or energy distributions in $\gamma^* p \rightarrow c\bar{c}N^*$.
 3877 An asymmetry arises from the interference of pomeron and Odderon exchange amplitudes [479].

3878 6.2.4 Inclusive diffraction

3879 Introduction to Diffractive Deep Inelastic Scattering

3880 Approximately 10% of low- x DIS events are of the diffractive type, $ep \rightarrow eXp$, with the proton surviving the
 3881 collision intact despite the large momentum transfer from the electron (Fig. 6.33). This process is usually
 3882 interpreted as the diffractive dissociation of the exchanged virtual photon to produce any hadronic final state
 3883 system X with mass much smaller than W and the same net quantum numbers as the exchanged photon
 3884 ($J^{PC} = 1^{--}$). Due to the lack of colour flow, diffractive DIS events are characterised by a large gap in the
 3885 rapidity distribution of final state hadrons between the scattered proton and the diffractive final state X .

3886 As discussed in section 6.2.3, similar processes exist in electron-ion scattering, where they can be sub-
 3887 divided into fully coherent diffraction, where the nucleus stays intact ($eA \rightarrow eXA$) and incoherent diffraction,
 3888 where the nucleons within the nucleus are resolved and the nucleus breaks up ($eA \rightarrow eXY$, Y being a system
 3889 produced via nuclear or nucleon excitation, with the same quantum numbers as A).

3890 Theoretically, rapidity gap production is usually described in terms of the exchange of a net colourless
 3891 object in the t -channel, which is often referred to as a pomeron [480, 481]. In the simplest models [482, 483],
 3892 this pomeron has a universal structure and its vertex couplings factorise, such that it is applicable for

3893 example to proton-(anti)proton scattering as well as DIS. One of the main achievements at HERA has been
 3894 the development of an understanding of diffractive DIS in terms of parton dynamics and QCD [484]. Events
 3895 are selected using the experimental signatures of either a leading proton [485–487] or the presence of a large
 3896 rapidity gap [486,488]. The factorisable pomeron picture has proved remarkably successful for the description
 3897 of most of these data.

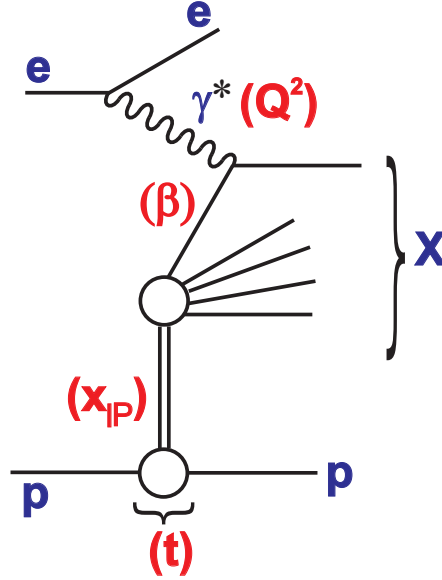


Figure 6.33: Illustration of the kinematic variables used to describe the inclusive diffractive DIS process $ep \rightarrow eXp$.

3908 The kinematic variables used to describe diffractive DIS are illustrated in Fig. 6.33. In addition to x , Q^2
 3909 and the squared four-momentum transfer t , the mass M_X of the diffractively produced final state provides
 3900 a further degree of freedom. In practice, the variable M_X is often replaced by

$$\beta = \frac{Q^2}{Q^2 + M_X^2 - t}. \quad (6.12)$$

3901 Small values of β refer to events with diffractive masses much bigger than the photon virtuality, while values
 3902 of β close to unity are associated with small M_X values. In models based on a factorisable pomeron, β may
 3903 be interpreted as the fraction of the pomeron longitudinal momentum which is carried by the struck parton.
 3904 The variable

$$x_{\mathbb{P}} = \frac{x}{\beta} = \frac{Q^2 + M_X^2 - t}{Q^2 + W^2 - M^2}, \quad (6.13)$$

3905 with M the nucleon mass, is then interpreted as the longitudinal momentum fraction of the Pomeron with
 3906 respect to the incoming proton or ion. It also characterises the size of the rapidity gap as $\Delta\eta \simeq \ln(1/x_{\mathbb{P}})$.

3907 Measuring Diffractive Deep Inelastic Scattering at the LHeC

3908 Diffractive DIS (DDIS) can be studied in a substantially increased kinematic range at the LHeC, which will
 3909 allow a whole new level of investigations of the factorisation properties of inclusive diffraction, will lead to
 3910 new insights into low- x dynamics and will provide a subset of final states with known quantum numbers for
 3911 use in searches for new physics and elsewhere.

3912 As shown in [333], collinear QCD factorisation holds in the leading-twist approximation in diffractive
 3913 DIS and can be used to define diffractive parton distribution functions for the proton or ion. That is, within

the collinear framework, the diffractive structure functions [489] can be expressed as convolutions of the appropriate coefficient functions with diffractive quark and gluon distribution functions, which in general depend on all of β , Q^2 , $x_{\mathbb{P}}$ and t . The diffractive parton distribution functions (DPDFs) are physically interpreted as probabilities for finding a parton with a small fraction of the proton momentum $x = \beta x_{\mathbb{P}}$, under the condition that the proton stays intact with a final state four-momentum which is specified up to an azimuthal angle by $x_{\mathbb{P}}$ and t . The DPDFs may then be evolved in Q^2 with the DGLAP evolution equations, with β playing the role of the Bjorken x variable. The other two variables $x_{\mathbb{P}}$ and t play the role of external parameters to the DGLAP evolution.

In various extractions using HERA DIS data [488,490–492] the DPDFs have been found to be dominated by gluons. Proton vertex factorisation holds to good approximation, such that the DPDFs vary only in normalisation with the four-momentum of the final state proton, the normalisation being well modelled using Regge phenomenology [481].

The LHeC will offer the opportunity to study diffractive DIS in an unprecedented kinematic range. The diffractive kinematic plane is illustrated in Fig. 6.34 for two different values of the Pomeron momentum fraction, $x_{\mathbb{P}} = 0.01$ and $x_{\mathbb{P}} = 0.0001$. In each plot, accessible kinematic ranges are shown for three different electron energies in collision with the 7 TeV proton beam. Figure 6.34a corresponds to the coverage that will be possible based on leading proton detection (see Chapter 14). Figure 6.34b is more representative of the possibilities using the large rapidity gap technique (see the following). It is clear that the LHeC will have a much increased reach compared with HERA towards low values of $x_{\mathbb{P}}$, where the interpretation of diffractive events is not complicated by the presence of sub-leading meson exchanges, rapidity gaps are large and diffractive event selection systematics are correspondingly small. The range in the fractional struck quark momentum β extends by a factor of around 20 below that accessible at HERA.

Figure 6.35 further illustrates the achievable kinematic range of diffractive DIS measurements at the LHeC for the example of a 150 GeV electron beam combining large rapidity gap and proton tagging acceptance, compared with an estimation of the final HERA performance. For ease of illustration, a binning scheme is chosen in which the β dependence is emphasized and very large bins in $x_{\mathbb{P}}$ and Q^2 are taken. There is a large difference between the kinematically accessible ranges with backward acceptance cuts of 1° and 10° . Statistical uncertainties are typically much smaller than 1% for a luminosity of 2 fb^{-1} , so a much finer binning is possible, as required. The data points are plotted according to the H1 Fit B DPDF predictions [488], which amounts to a crude extrapolation based on dependences in the HERA range.

Systematic uncertainties are difficult to estimate without a detailed knowledge of the forward detectors and their acceptances. At HERA, sub-5% systematics have been achieved in the bulk of the phase space and it is likely that the LHeC could do at least as well.

The limitations in the kinematic range accessible with the large rapidity gap technique are investigated in Fig. 6.36. This shows the correlation between $x_{\mathbb{P}}$ and the pseudorapidity η_{max} of the most forward particle in the hadronic final state system X , in simulated samples with LHeC and HERA beam energies, according to the RAPGAP event generator [132]. This correlation depends only on the proton beam energy and is thus the same for all LHeC running scenarios. At HERA, a cut at $\eta_{\text{max}} \sim 3.2$ has been used to select diffractive events. Assuming LHeC forward instrumentation extending to around $\theta = 1^\circ$, a cut at $\eta_{\text{max}} = 5$ may be possible, which would allow measurements to be made comfortably up to $x_{\mathbb{P}} \sim 0.001$, with some limited sensitivity at larger $x_{\mathbb{P}}$, a region where the proton tagging acceptance takes over (see Chapter 14). The two methods are thus complementary, and offer some common acceptance in an overlap region of $x_{\mathbb{P}}$. This redundancy could be used for cross-calibration of the two methods and their systematics, as has been done at HERA.

3958 Diffractive Parton Densities and Final States

3959 The previously unexplored diffractive DIS region of very low β is of particular interest. Here, diffractively
 3960 produced systems will be created with unprecedented invariant masses. Figure 6.37a shows a comparison
 3961 between HERA and the LHeC in terms of the M_X distribution which could be produced in diffractive
 3962 processes with $x_{\mathbb{P}} < 0.05$ (using the RAPGAP Monte Carlo model [132]). Figure 6.37a compares the
 3963 expected M_X distributions for one year of running at three LHeC electron beam energy choices. Diffractive

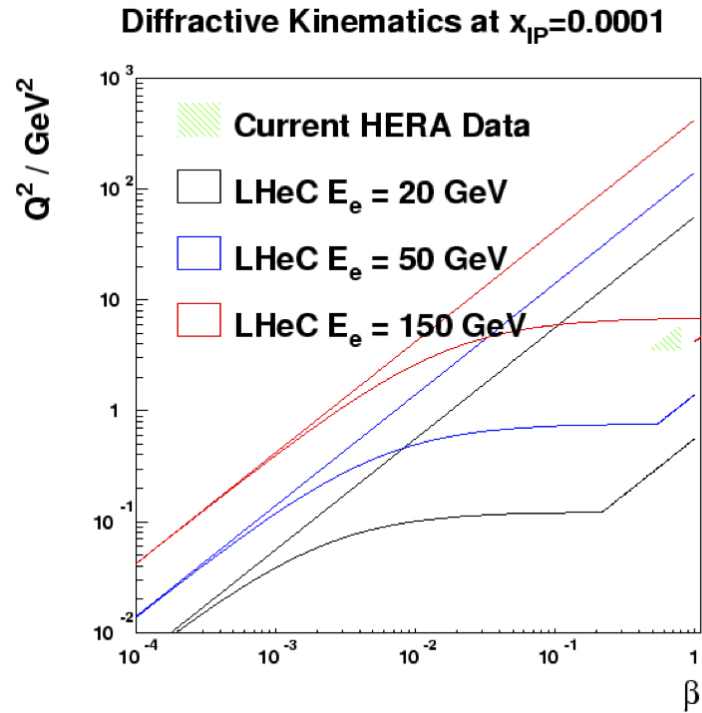
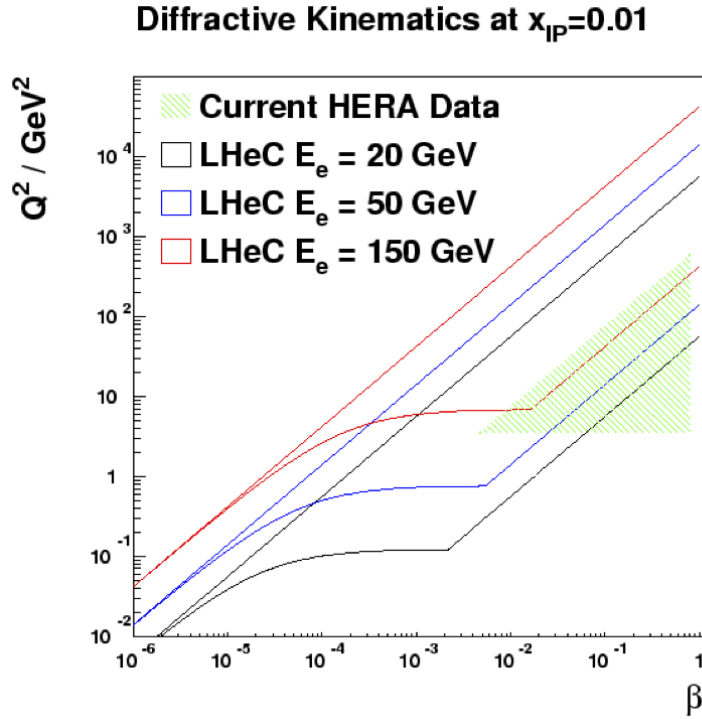


Figure 6.34: Diffractive DIS kinematic ranges in Q^2 and β of HERA and of the LHeC for different electron energies $E_e = 20, 50, 150 \text{ GeV}$ at $x_{\text{P}} = 0.01$ (left plot), and $x_{\text{P}} = 0.0001$ (right plot). In both cases, 1° acceptance is assumed for the scattered electron and the typical experimental restriction $y > 0.01$ is imposed. No rapidity gap restrictions are applied.

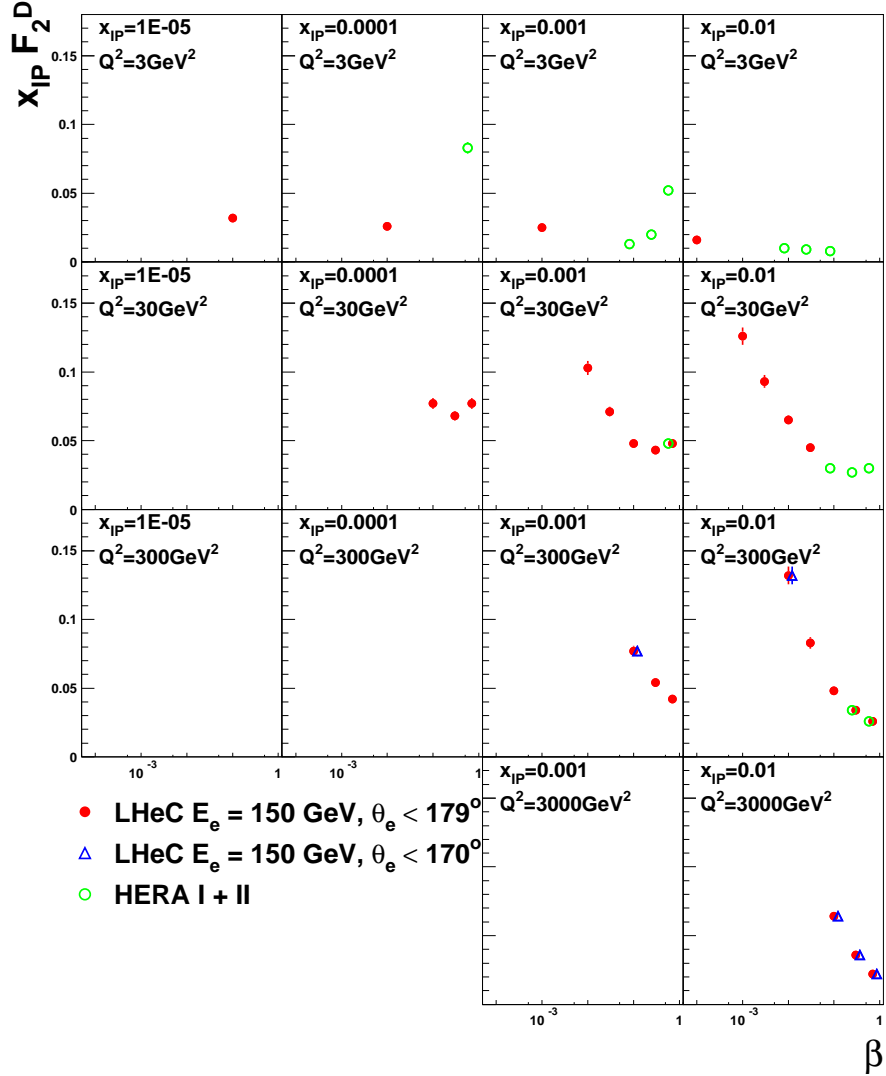


Figure 6.35: Simulation of a possible LHeC measurement of the diffractive structure function, F_2^D using a 2 fb^{-1} sample, compared with an estimate of the optimum results achievable at HERA using the full luminosity for a single experiment (500 pb^{-1}). The loss of kinematic region if the LHeC scattered electron acceptance extends to within 10° of the beam-pipe, rather than 1° is also illustrated.

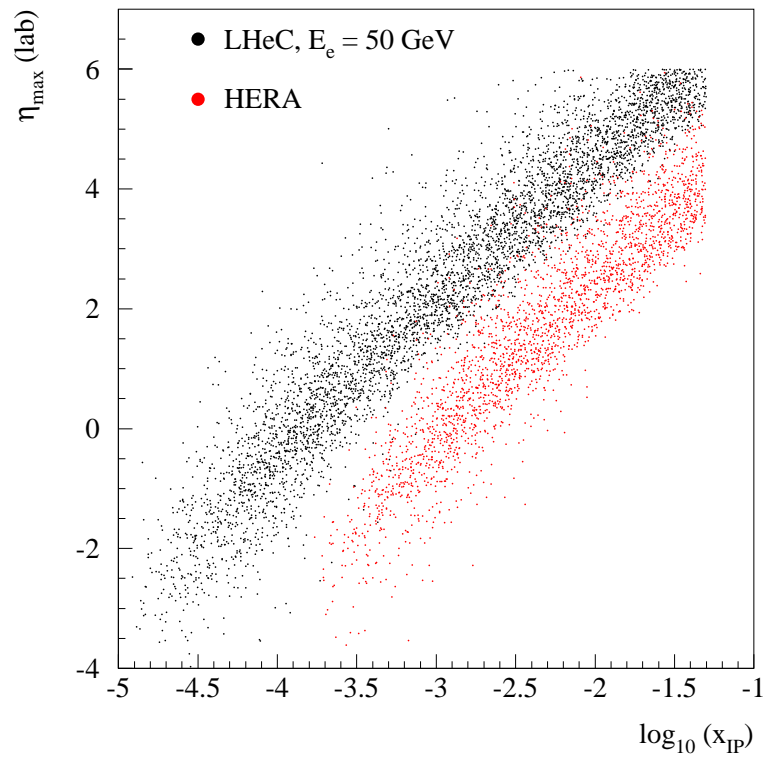


Figure 6.36: Comparison of the correlation between the rapidity gap selection variable, η_{\max} and x_{P} at HERA and at the LHeC, using events simulated with the RAPGAP Monte Carlo generator.

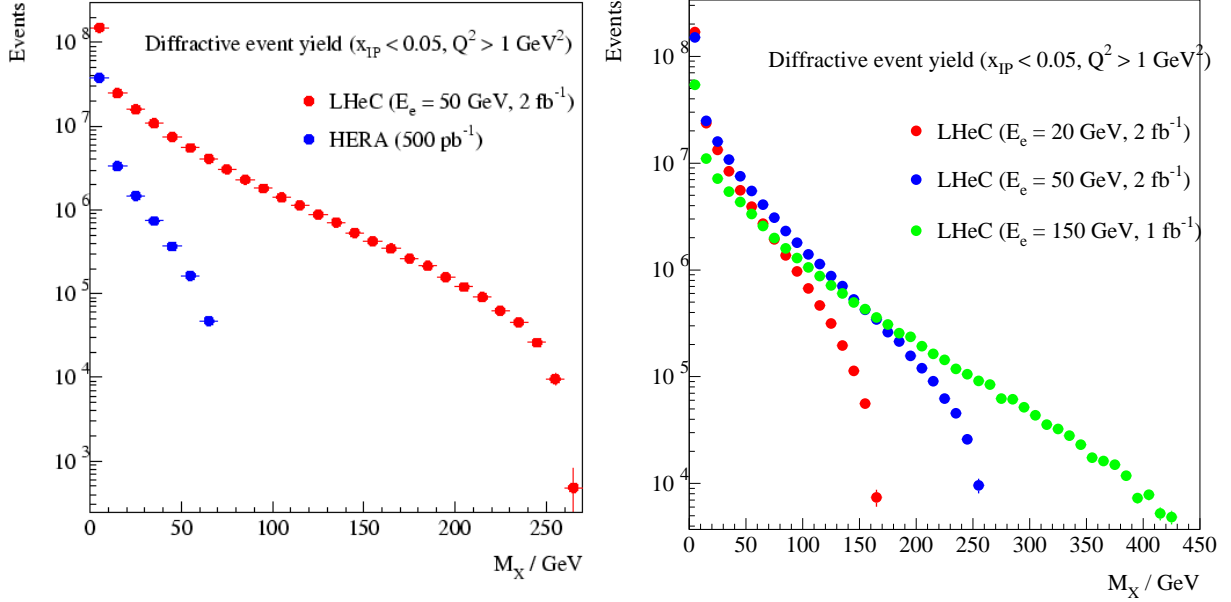


Figure 6.37: Simulated distributions in the invariant mass M_X according to the RAPGAP Monte Carlo model for samples of events obtainable with $x_{\text{P}} < 0.05$ (a) One year of high acceptance LHeC running at $E_e = 50 \text{ GeV}$ compared with HERA (full luminosity for a single experiment). (b) Comparison between three different high acceptance LHeC luminosity and E_e scenarios.

3964 masses up to several hundred GeV are accessible with reasonable rates, such that diffractive final states
 3965 involving beauty quarks and W and Z bosons, or even exotic states with 1^- quantum numbers, could be
 3966 produced.

3967 Large improvements in DPDFs are likely to be possible from NLO DGLAP fits to LHeC diffractive
 3968 structure function data. In addition to the extended phase space in β , the extension of the kinematic range
 3969 towards larger Q^2 increases the lever-arm for extracting the diffractive gluon density and opens the possibility
 3970 of significant weak gauge boson exchange, which would allow a quark flavour decomposition for the first time.

3971 Proton vertex factorisation can be tested precisely by comparing the LHeC β and Q^2 dependences at
 3972 different small x_{P} values in their considerable regions of overlap. The production of dijets or heavy quarks as
 3973 components of the diffractive system X will provide a means of testing QCD collinear factorisation. These
 3974 processes are driven by boson-gluon fusion ($\gamma^* g \rightarrow q\bar{q}$) and thus provide complementary sensitivity to the
 3975 diffractive gluon density to be compared with that from the scaling violations of the inclusive cross section.
 3976 Factorisation tests of this sort have been carried out on many occasions at HERA, with NLO calculations
 3977 based on DPDFs predicting jet and heavy flavour cross sections which are in good agreement with data at
 3978 large Q^2 [493, 494]. However, due to the relatively small accessible jet transverse momenta at HERA, the
 3979 precision is limited by scale uncertainties on the theoretical predictions. At the LHeC, much larger diffractive
 3980 jet transverse momenta are measurable ($p_T \lesssim M_X/2$), which should lead to much more precise tests [495].

3981 The simulated measurement of the longitudinal proton structure function, F_L described in subsec-
 3982 tion 4.1.5, could also be extended to extract the diffractive analogue, F_L^D . At small β , where the cross
 3983 section for longitudinally polarised photons is expected to be dominated by a leading twist contribution, an
 3984 F_L^D measurement provides further complementary constraints on the role of gluons in the diffractive PDFs.
 3985 As $\beta \rightarrow 1$, a higher twist contribution from longitudinally polarised photons, closely related to that driving
 3986 vector meson electroproduction, dominates the diffractive cross section in many models [496] and a mea-
 3987 surement to even modest precision would give considerable insight. A first measurement of this quantity has

3988 recently been reported by the H1 Collaboration [497], though the precision is strongly limited by statistical
3989 uncertainties. The LHeC provides the opportunity to explore it in much finer detail.

3990 In contrast to leading proton production, the production of leading neutrons in DIS ($ep \rightarrow eXn$) requires
3991 the exchange of a net isovector system. Data from HERA have supported the view that this process is
3992 driven dominantly by charged pion exchange over a wide range of neutron energies [498]. With the planned
3993 emphasis on zero degree calorimetry for leading neutron measurements (see Chapter 14), LHeC data will
3994 thus constrain the structure of the pion at much lower x and larger Q^2 values than has been possible hitherto.
3995 Note also that the combination of rapidity gap detection and zero degree calorimetry offers the possibility
3996 of disentangling coherent from incoherent nuclear diffraction.

3997 **Diffraction DIS, Dipole Models and Sensitivity to Non-linear Effects**

3998 Diffraction DIS at the LHeC will give us an opportunity to test the predictions of collinear factorisation
3999 and the possible onset of non-linear or higher-twist effects in the evolution. Of particular importance is the
4000 semi-hard regime $Q^2 < 10 \text{ GeV}^2$ and x as small as possible. It is possible that the non-linear saturation
4001 regime will be easier to reach with diffractive than with inclusive measurements, since diffractive processes
4002 are mostly sensitive to quantum fluctuations in the proton wave function that have a virtuality of order of
4003 the saturation scale Q_s^2 , instead of Q^2 . As a result, power corrections (not the generic Λ_{QCD}^2/Q^2 corrections,
4004 but rather the sub-class of them of order Q_s^2/Q^2) are expected to come into play starting from a higher
4005 value of Q^2 in diffractive than in inclusive DIS. Indeed, there is already a hint of this at HERA: collinear
4006 factorization starts to fail below about 3 GeV^2 in the case of F_2 [38], while it breaks down already around
4007 8 GeV^2 in the case of F_2^D [488]. This fact can alternatively be observed in the feature that models which
4008 in principle should only work for small Q^2 , can in practice be used up to larger Q^2 for diffractive than for
4009 inclusive observables (see e.g. [301]).

4010 With the sort of measurement precision for F_2^D possible at the LHeC, it ought to be possible to distinguish
4011 between different models, as illustrated in Fig. 6.38. For the simulated data shown here, a conservative
4012 situation is assumed, in which the electron beam energy is 50 GeV and only the rapidity gap selection
4013 method is used, such that the highest x_p bin is at 0.001. H1 Fit B [488] extrapolations (as in Fig. 6.35) are
4014 compared with the “b-sat” [355,356] and bCGC [499] dipole models. As has been found to be necessary to
4015 describe HERA data, photon fluctuations to $q\bar{q}g$ states are included in addition to the usual $q\bar{q}$ dipoles used
4016 to describe inclusive and vector meson cross sections. Both dipole models differ substantially from the H1
4017 Fit B extrapolation. The LHeC simulated precision and kinematic range are sufficient to distinguish between
4018 a range of models with and without saturation effects, and also between different models which incorporate
4019 saturation.

4020 **Predicting nuclear shadowing from inclusive diffraction in ep**

4021 The connection between nuclear shadowing and diffraction was established a long time ago by Gribov [300].
4022 Its key approximation is that the nucleus can be described as a dilute system of nucleons in the nucleus rest
4023 frame. The accuracy of this approximation for hadron-nucleus interactions is on the level of a few %, which
4024 reflects the small admixture of non-nucleonic degrees of freedom in nuclei and the small off-shellness of the
4025 nucleons in nuclei as compared to the soft strong interaction scale. Gribov’s result can be derived using the
4026 AGK cutting rules [500] and hence it is a manifestation of unitarity [501,502]. The formalism can be used
4027 to calculate directly cross sections of $\gamma(\gamma^*)$ -nucleus scattering for the interaction with $N = 2$ nucleons, but
4028 has to be supplemented by additional considerations to account for the contribution of the interactions with
4029 $N \geq 3$ nucleons.

4030 In this context, nuclear PDFs at small x can be calculated [501,502] combining unitarity relations for
4031 different cuts of the shadowing diagrams corresponding to diffractive and inelastic final states, with the QCD
4032 factorisation theorem for hard diffraction [333]. A *model-independent* expression for the nuclear PDF at fixed

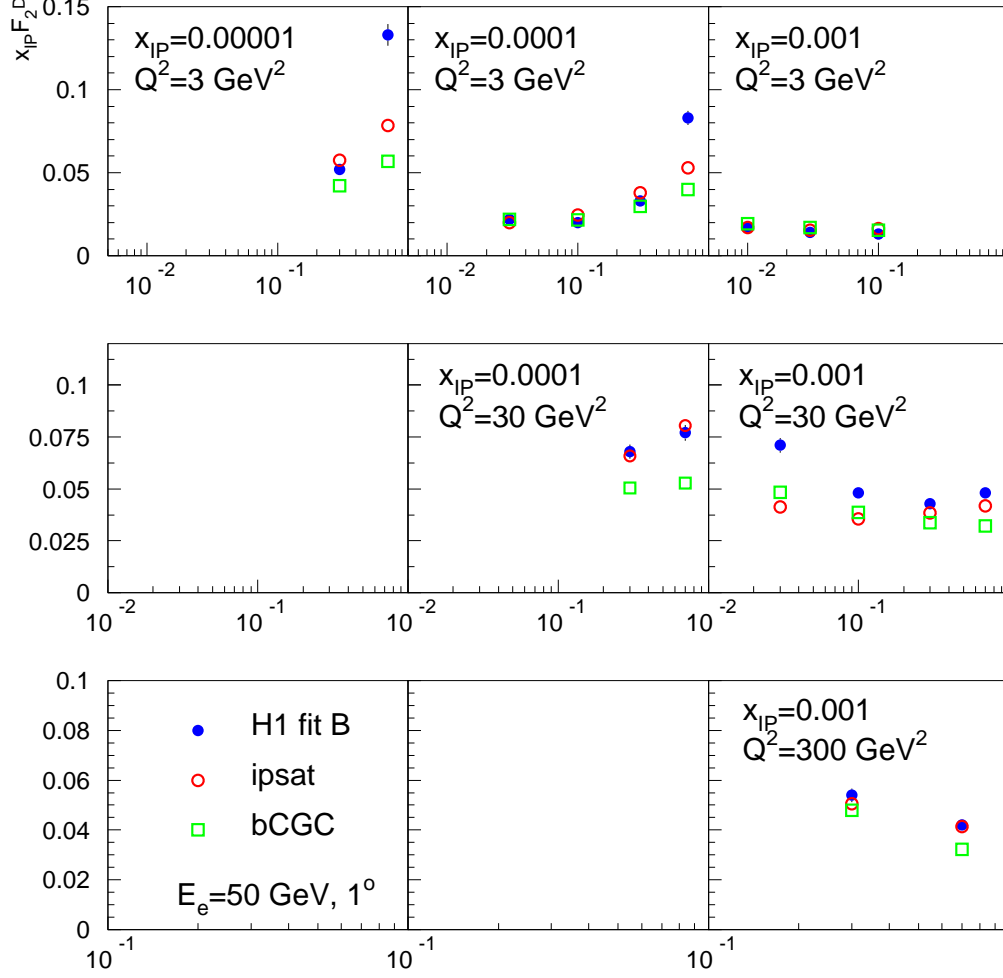


Figure 6.38: Simulated F_2^D measurements in selected $x_{\mathbb{P}}$, β and Q^2 bins. An extrapolation of the H1 Fit B DPDF fit to HERA data is compared with two different implementations of the dipole model, both of which contain saturation effects and include $q\bar{q}g$ photon fluctuations in addition to $q\bar{q}$ ones.

4033 impact parameter b , valid for the case $N = 2$ [501], reads:

$$\begin{aligned}
\Delta [x f_{j/A}(x, Q^2, b)] &= x f_{j/N}(x, Q^2, b) - x f_{j/A}(x, Q^2, b) \\
&= 8\pi A(A-1) \Re e \left[\frac{(1-i\eta)^2}{1+\eta^2} \int_x^{0.1} dx_{\mathbb{P}} \beta f_j^{D(4)}(\beta, Q^2, x_{\mathbb{P}}, t_{\min}) \right. \\
&\quad \times \left. \int_{-\infty}^{\infty} dz_1 \int_{z_1}^{\infty} dz_2 \rho_A(\vec{b}, z_1) \rho_A(\vec{b}, z_2) e^{i(z_1 - z_2)x_{\mathbb{P}} m_N} \right], \tag{6.14}
\end{aligned}$$

4034 where $f_{j/A}(x, Q^2)$, $f_{j/N}(x, Q^2)$ are nuclear and nucleon PDFs respectively, $f_j^{D(4)}(\beta, Q^2, x_{\mathbb{P}}, t_{\min})$ are diffractive
4035 nucleon PDFs, $\eta = \Re e A^{diff} / \Im m A^{diff} \approx 0.17$, $\rho_A(r)$ is the nuclear matter density, and $t_{\min} = -m_N^2 x_{\mathbb{P}}^2$
4036 with m_N the nucleon mass. Eq. (6.14) satisfies the QCD evolution equations to all orders in α_s . Numerical
4037 studies indicate that the dominant contribution to the shadowing probed by present experiments - corre-
4038 sponding to not very small x - comes from the region of relatively large β , for which small- x approximations
4039 which involve resummation of $\ln x$ terms are not important.

In Eq. (6.14), the interaction of different configurations of the hard probe (e.g. $q\bar{q}$, $q\bar{q}g$, vector meson resonances, . . .) are encoded in $f_j^{D(4)}(\beta, Q^2, x_{\mathbb{P}}, t_{\min})$. For the case of more than $N = 2$ nucleons, there are two or more intermediate nucleon diffractive states which may be different and thus result in a different interaction between the virtual photon and the nucleus. Therefore the interaction of the hard probe with $N \geq 3$ nucleons is sensitive to finer details of the diffractive dynamics, namely the interplay between the interactions of the hard probe with N nucleons with different cross sections. This (colour) fluctuation effect is analogous to the inelastic shadowing phenomenon for the scattering of hadrons from nuclei, with the important difference that the dispersion of the interaction cross sections for the configurations in the projectile is much smaller in the hadronic case than in DIS.

In order to estimate this effect, one should note that, experimentally, the energy dependence of hard diffraction is close to that observed for soft Pomeron dynamics (the soft Pomeron intercept $\alpha_{\mathbb{P}} \approx 1.11$) with the hard Pomeron contribution ($\alpha_{\mathbb{P}} \approx 1.25$) being a small correction. This fact indicates that hadron-like (aligned jet) configurations [503], evolved via DGLAP evolution to large Q^2 , dominate hard diffraction in DIS, while point-like configurations give an important, and increasing with Q^2 , contribution to small- x PDFs. This reduces the uncertainties in the treatment of $N \geq 3$ contributions [407,469]. Calculations show that the difference between two extreme scenarios of colour fluctuations is $\leq 20\%$ for $A \sim 200$ and much smaller for lighter nuclei, see the two FGS10 curves in Figs. 6.12 and 6.18. Besides, fluctuations tend to reduce the shadowing somewhat compared with the approximations neglecting them [302, 501, 504, 505] (compare the FGS10 results in Fig. 6.18 left with those labelled AKST). The gluon density is more sensitive to the magnitude of fluctuations than F_2 , as can be inferred from Fig. 6.12 and Fig. 6.18 right.

Finally, the AGK technique also allows the calculation of the nuclear diffractive PDFs, see below, and fluctuations of multiplicity in non-diffractive DIS [469, 501, 506]. Both observables turn out to be sensitive to the pattern of colour fluctuations.

Predictions for inclusive diffraction on nuclear targets

Diffractive DIS events were first discovered in ep collisions at the HERA collider. Since no eA collider has ever been built, inclusive diffraction in eA has simply never been measured. Thus, DDIS off nuclei at the LHeC will be a completely unexplored territory throughout the whole kinematic domain accessed, implying a huge discovery potential.

Despite this lack of experimental information on DDIS off nuclei, we have expectations, based on our current understanding of QCD, of how it should look. For instance, the theory of nuclear shadowing allows us to construct nuclear diffractive PDFs for large Q^2 (see the previous item) while, within the Color Glass Condensate framework, nuclear diffractive structure functions can be predicted at small x . Depending on kinematics and the heavy ion species, different patterns of nuclear shadowing or antishadowing are expected as a function of β and $x_{\mathbb{P}}$. This is just one of many examples of what should be checked with an eA collider. Others are the impact parameter dependence introduced in the models, or the relation between nuclear shadowing and diffraction in ep which relies on what we know on DDIS from HERA. Therefore, in the larger kinematic domain accessible at the LHeC there are many things to discover about the structure of nuclei with diffractive measurements.

Predictions from a variety of models for nuclear coherent diffraction (see comments on different types of diffractive process on nuclei in Subsection on diffractive vector meson production), are shown in Figs. 6.39 and 6.40. The chosen models here are FGS10 [469] and KLMV [507, 508]. Both plots show selected LHeC pseudodata for $x_{\mathbb{P}}F_2^D$ as a function of β in bins of Q^2 and $x_{\mathbb{P}}$. Statistical and systematic errors are added in quadrature, with systematic errors estimated to be at the level of 5%. The models give very different predictions both in absolute value and in their detailed dependence on x_{IP} and Q^2 , which cannot be resolved without LHeC data.

Also shown in Fig. 6.41 are predicted diffractive-to-total ratios of the structure functions as a function of the collision energy W . It was demonstrated in [337] that the constancy with energy of this ratio for the proton can be naturally explained in the models which include saturation effects, because in the black disk regime the ratio of the diffractive to total cross sections tends to a constant value. At fixed impact parameter the ratio may grow as large as 50%, but the integration in impact parameter results in a smaller value. HERA

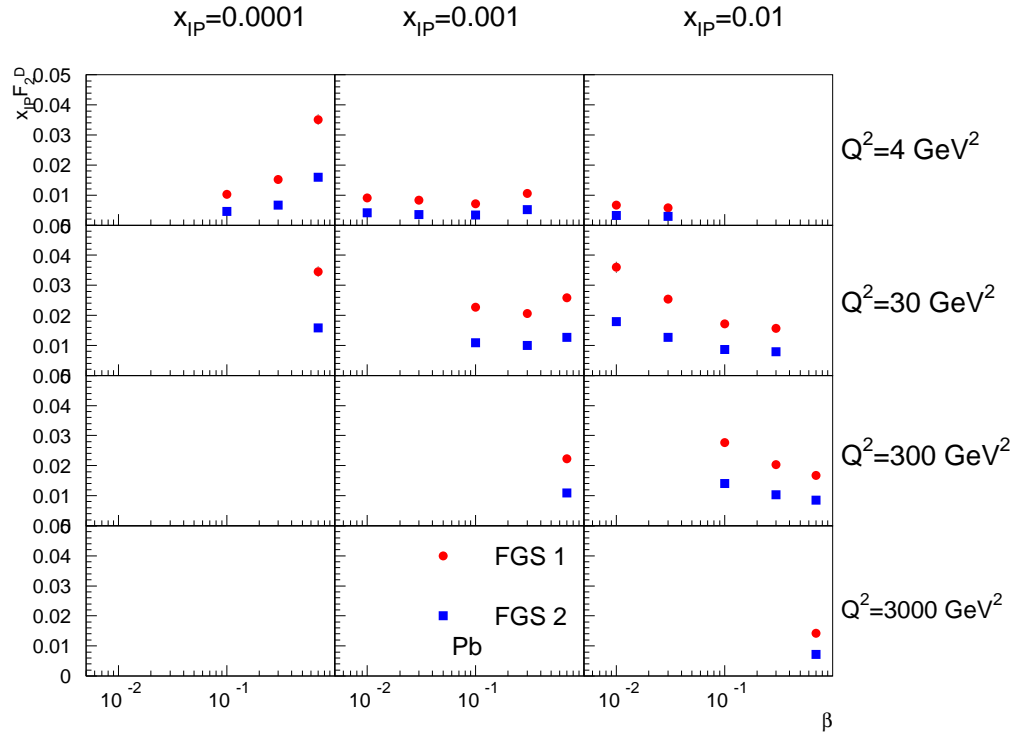


Figure 6.39: Diffractive structure function $x_{\mathbb{P}}F_2^D$ for Pb in bins of Q^2 and $x_{\mathbb{P}}$ as a function of β . Model calculations are taken from [469].

4090 data showed approximate energy independence of this ratio, which could be easily obtained within the GBW
 4091 saturating dipole model [337]. Within the given energy range the models shown in figure 6.41 predict a slight
 4092 variation with energy. Note however the rather substantial difference between predictions coming from the
 4093 different models. The uncertainty in modelling the impact parameter is one of its main sources. LHeC data
 4094 are required for clarification.

4095 6.2.5 Jet and multi-jet observables, parton dynamics and fragmentation

4096 Introduction

4097 Inclusive measurements provide essential information about the integrated distributions of partons in a
 4098 proton. However, as was discussed in previous sections, more exclusive measurements are needed to pin
 4099 down the essential details of the small- x dynamics. For example, a central prediction of the BFKL framework
 4100 at small x is the diffusion of the transverse momenta of the emitted partons between the photon and the
 4101 proton. In the standard collinear approach with integrated parton densities the information about the
 4102 transverse momentum is not accessible. However, it can be recovered within a different framework which
 4103 utilizes unintegrated parton distribution functions, dependent on parton transverse momentum as well as x
 4104 and Q^2 . Unintegrated PDFs are natural in the BFKL approach to small- x physics. A general, fundamental
 4105 expectation is that as x decreases, the distribution in transverse momentum of the emitted partons broadens,
 4106 resulting in diffusion.

4107 The specific parton dynamics can be tested by a number of exclusive measurements. These in turn can
 4108 provide valuable information about the distribution of transverse momentum in the proton. As discussed
 4109 in [509], for many inclusive observables the collinear approximation with integrated PDFs is completely
 4110 insufficient, and even just including parton transverse momentum effects by hand may not be sufficient to
 4111 describe many observables. In DIS, for example, processes needing unintegrated distributions include the

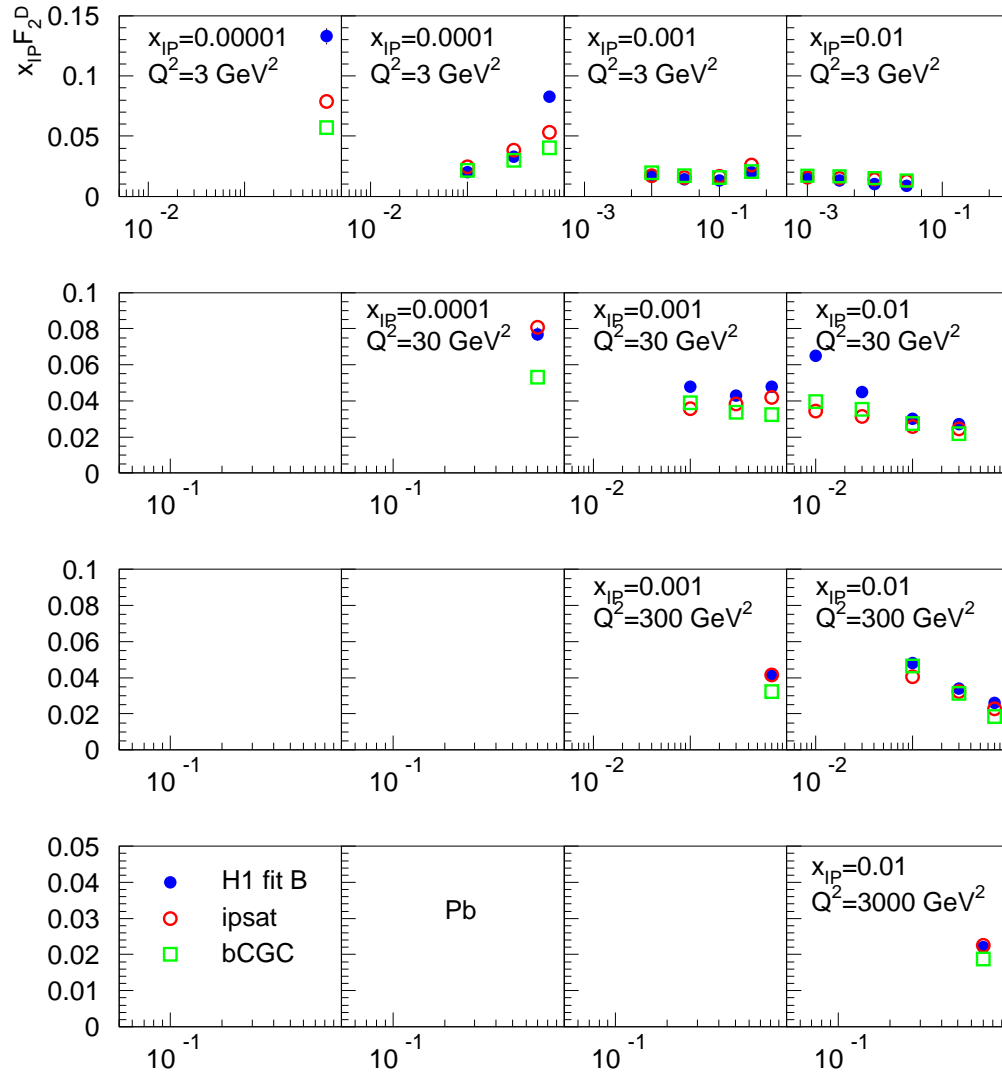


Figure 6.40: Diffractive structure function $x_{\mathbb{P}} F_2^D$ for Pb in bins of Q^2 and $x_{\mathbb{P}}$ as a function of β . Model calculations are based on the dipole framework [507, 508].

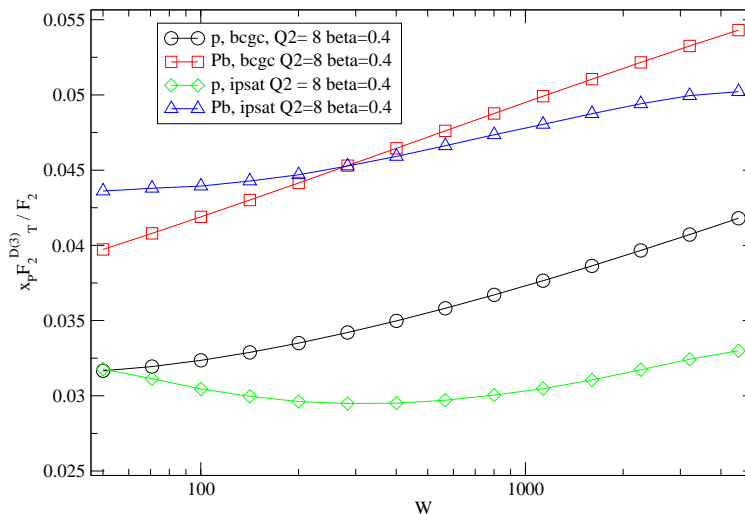


Figure 6.41: Ratio of the transversely polarised photon contribution to the diffractive structure function $x_p F_2^D$ to the inclusive structure function in p and Pb for fixed values of Q^2 and β as a function of the energy W . The model calculations are based on the dipole framework [507, 508].

4112 transverse momentum distribution of heavy quarks. Similar problems are encountered in hadron collisions
 4113 when studying heavy quark and Higgs production. The natural framework using unintegrated PDFs gives a
 4114 much more reliable description. Furthermore, lowest-order calculations in the framework with unintegrated
 4115 PDFs provide a much more realistic description of cross sections concerning kinematics. This may well lead
 4116 to NLO and higher corrections being much smaller numerically than they typically are at present in standard
 4117 collinear factorization, since the LO description is better.

4118 This approach, however, calls for precise measurements of a variety of relatively exclusive processes in
 4119 a wide kinematic range. As discussed below, measurements of dijets, forward jets and particles, as well as
 4120 transverse energy flow, are required to constrain the unintegrated PDFs and will give valuable information
 4121 about parton dynamics at small x . While we will discuss the case of DIS on a proton, all conclusions can be
 4122 paralleled for DIS on nuclei.

4123 Unintegrated PDFs

4124 The standard integrated parton densities are functions of the longitudinal momentum fraction of a parton
 4125 relative to its parent hadron, with an integral over the parton transverse momentum. In contrast, uninte-
 4126 grated, or transverse-momentum-dependent (TMD), parton densities depend on both parton longitudinal
 4127 momentum fraction and parton transverse momentum. Processes for which unintegrated densities are natural
 4128 include the Drell-Yan process (and its generalization to Higgs production), and semi-inclusive DIS (SIDIS).
 4129 In SIDIS, we need TMD fragmentation functions as well as TMD parton densities.

4130 In the literature there are several apparently different approaches to TMD parton densities, with varying
 4131 degrees of explicitness in the definitions and derivations.

- 4132 • The CSS approach [510–513] and some further developments [514].
- 4133 • The CCFM approach [515–518] for small x .
- 4134 • Related BFKL associated works [316, 519].

4135 Central to this subject is the concrete definition of TMD densities, and complications arise because QCD
 4136 is a gauge theory. A natural initial definition uses light-front quantization: the unintegrated density of

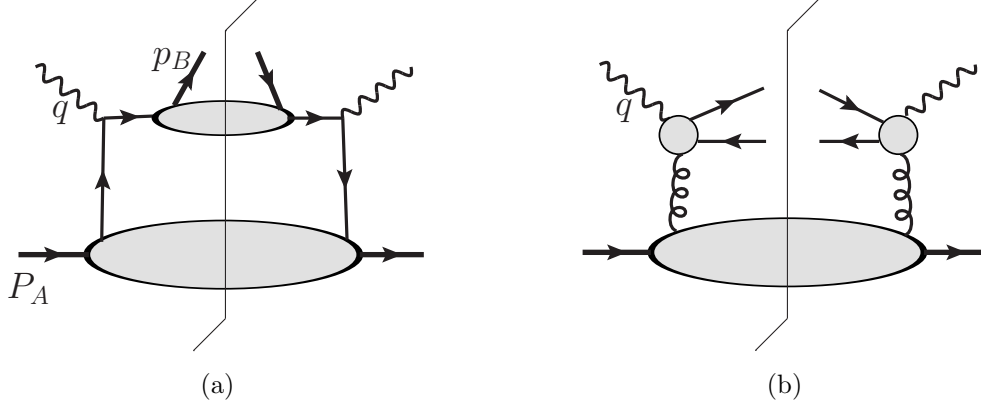


Figure 6.42: (a) Parton model factorisation for a SIDIS cross section. (b) Factorization for high-energy $q\bar{q}$ photoproduction.

4137 parton j in hadron h would be

$$f_{j/h}(x, \mathbf{k}_\perp) \stackrel{?}{=} \frac{1}{2x(2\pi)^3} \sum_\lambda \frac{\langle P, h | b_{k, \lambda, j}^\dagger b_{k, \lambda, j} | P, h \rangle_c}{\langle P, h | P, h \rangle}, \quad (6.15)$$

4138 where $b_{k, \lambda, j}$ and $b_{k, \lambda, j}^\dagger$ are light-front annihilation and creation operators, j and λ label parton flavor and
 4139 helicity, while $k = (k^+, \mathbf{k}_\perp)$ is its momentum, and only connected graphs ‘c’ are considered. The ‘?’ over the
 4140 equality sign warns that the formula does not apply literally in QCD. Expressing $b_{k, \lambda, j}$ and $b_{k, \lambda, j}^\dagger$ in terms
 4141 of fields gives the TMD density as the Fourier transform of a light-front parton correlator. For example, for
 4142 a quark

$$f_j(x, \mathbf{k}_\perp) \stackrel{?}{=} \int \frac{dw^- d^2\mathbf{w}_\perp}{(2\pi)^3} e^{-ixP^+w^- + i\mathbf{k}_\perp \cdot \mathbf{w}_\perp} \langle P | \bar{\psi}_j(0, w^-, \mathbf{w}_\perp) \frac{\gamma^+}{2} \psi_j(0) | P \rangle_c. \quad (6.16)$$

4143 One can similarly define a TMD fragmentation function [511] $d_{h/j}(z, \mathbf{p}_\perp)$, for the probability density of
 4144 final-state hadron h in an outgoing parton j .

4145 The corresponding factorization formula for SIDIS $e + A(P_A) \rightarrow e + B(p_B) + X$ is [514]

$$\frac{d\sigma}{dx dQ^2 dz d^2\mathbf{P}_{B\perp}} = \sum_j \int d^2\mathbf{k}_\perp H_j f_{j/A}(x, \mathbf{k}_\perp) d_{B/j}(z, \mathbf{p}_{B\perp} + z\mathbf{k}_\perp), \quad (6.17)$$

4146 where z and $\mathbf{P}_{B\perp}$ are the fractional longitudinal momentum and the transverse momentum of the detected
 4147 hadron relative to the simplest parton-model calculation of the outgoing jet, while H_j is the hard-scattering
 4148 factor for electron-quark elastic scattering; see Fig. 6.42(a). In the fragmentation function $d_{B/j}$ in Eq. (6.17),
 4149 the use of $z\mathbf{k}_\perp$ with its factor of z is because the transverse-momentum argument of the fragmentation
 4150 function is a transverse momentum of the outgoing hadron relative to the parton initiating the jet, whereas
 4151 \mathbf{k}_\perp is the transverse momentum of a parton relative to a hadron.

4152 The most obvious way of applying (6.16) in QCD is to define the operators in light-cone gauge $A^+ = 0$,
 4153 or, equivalently, to attach Wilson lines to the quark fields with a light-like direction for the Wilson lines.
 4154 One minor problem in QCD is that, because the wave function is infinite (see below), the exact probability
 4155 interpretation of parton densities cannot be maintained.

4156 A much harder problem occurs because QCD is a gauge theory. Evaluating TMD densities defined by
 4157 (6.16) in light-cone gauge gives divergences where internal gluons have infinite negative rapidity [510]. These
 4158 cancel only in the integrated density. The physical problem is that any coloured parton entering (or leaving)
 4159 the hard scattering is accompanied by a cloud of soft gluons, and the soft gluons of a given transverse

4160 momentum are distributed uniformly in rapidity. A parton density defined in light-cone gauge corresponds
 4161 to the asymptotic situation of infinite available rapidity.

4162 A quark in a realisable hard scattering can be considered as having a transverse recoil against the soft
 4163 gluons, but with a physically restricted range of rapidity. So a proper definition of a TMD density must
 4164 implement a rapidity cut-off in the gluon momenta. Evolution equations must take into account the rapidity
 4165 cut-off. The CSS formalism [510] has an explicit form of the rapidity cut-off and an equation for the
 4166 dependence of TMD functions on the cut-off. But in any alternative formalism the need in the definitions
 4167 for a cut-off to avoid rapidity divergences is non-negotiable.

4168 Parton densities and fragmentation functions are only useful because they appear in factorisation the-
 4169 orems, so a useful definition must allow useful factorisation theorems to be formulated and derived. An
 4170 improved definition involving Wilson line operators has recently been given in [520]; see also [521].

4171 A second train of argument leads to a related kind of factorisation (the so-called k_{\perp} -factorisation) for
 4172 processes at small x [125]. A classic process is photo- or electro-production of charm pairs $\gamma(p_1) + h(p_2) \rightarrow$
 4173 $Q(p_3) + \bar{Q}(p_4) + X$, for which k_{\perp} -factorisation has the form

$$4M^2\sigma_{\gamma g}(\rho, M^2/Q_0^2) = \int d^2\mathbf{k}_{\perp} \int_0^1 \frac{dz}{z} \hat{\sigma}(\rho/z, \mathbf{k}_{\perp}^2/M^2) f_{g/h}(x, \mathbf{k}_{\perp}), \quad (6.18)$$

4174 see Fig. 6.42(b). Here $\rho = M^2/(p_1 + p_2)^2 \ll 1$, and M is the mass of the heavy quark. The corresponding
 4175 definition of the TMD gluon density [515] is said to use light-cone gauge, but there is in fact a hidden rapidity
 4176 cut-off resulting from the use of the BFKL formalism.

4177 Although both (6.17) and (6.18) use k_{\perp} -dependent parton densities, there are important differences. In
 4178 (6.18), the hard scattering cross section $\hat{\sigma}$ has the incoming gluon *off*-shell, whereas in (6.17), the hard
 4179 scattering H_j uses on-shell partons. This is associated with a substantial difference in the kinematics. In
 4180 (6.17) for SIDIS, the transverse momenta of the partons relative to their hadrons are less than Q , which allows
 4181 the neglect of parton virtuality in the hard scattering. This approximation fails at large partonic transverse
 4182 momentum, $\mathbf{k}_{\perp} \sim Q$, but ordinary collinear factorisation is valid in that region. So the factorisation formula
 4183 is readily corrected, by adding a suitable matching term [510].

4184 In contrast, in the small- x formula (6.18), the gluon transverse momentum is comparable with the hard
 4185 scale M . So it is not appropriate to neglect \mathbf{k}_{\perp} with respect to M , and the hard scattering is computed with
 4186 an off-shell gluon. Factorisation is actually obtained from BFKL physics, where the gluons in Fig. 6.42(b)
 4187 couple the charm quark subgraph to a subgraph where the lines have much larger rapidity.

4188 The evolution equation of the CS-style TMD functions used in (6.17) gives the dependence of the TMD
 4189 functions on the rapidity difference between the hadron and the virtual photon momenta. The results for
 4190 TMD functions and for the cross sections can finally be obtained [514] in terms of (a) ordinary integrated
 4191 parton densities and fragmentation functions, (b) perturbatively calculable quantities, and (c) a restricted set
 4192 of non-perturbative quantities. The most important of these non-perturbative quantities is the distribution
 4193 in recoil transverse momentum per unit rapidity against the emission of the soft interacting gluons, which
 4194 is exponentiated after evolution. Importantly, it is independent of x and z , and it is universal between
 4195 processes [522], and different only between gluons (color octet) and quarks (color triplet). There is also
 4196 what can be characterised as a non-perturbative intrinsic transverse momentum distribution in both parton
 4197 densities and fragmentation functions. In the quark sector, all but the fragmentation function are well
 4198 measured in Drell-Yan processes [523].

4199 On the other hand, evolution for the small- x formalism in (6.18) is given by the BFKL method.

4200 The avenues for further improvement on this subject are both theoretical and experimental. On the
 4201 theory side, these concern the relation between different formalisms for evolution [316, 510, 514, 519, 524], the
 4202 extension of factorisation theorems to a larger number of particles in the final state, and the matching to
 4203 Monte Carlo generators. On the experimental side, the sensitivity to TMD functions is linked to a sensitivity
 4204 to parton transverse momentum. This is the case of SIDIS at low transverse momentum. Another interesting
 4205 process which would enable the TMD gluon functions to be probed is $ep \rightarrow e\pi\pi X$, with the pions being in
 4206 different directions (different jets), but such that they are close to back-to-back in the (q, p_i) (the so-called
 4207 brick wall) frame.

4208 Finally, measuring SIDIS and dijet production off protons or nuclei at the LHeC will allow detailed
 4209 investigations of non-linear parton evolution in QCD. In this respect, the SIDIS cross section [525] and
 4210 dihadron production [526] have been studied in the CGC framework. It turns out that, for small x , one is
 4211 sensitive to the saturation regime of the target (proton or nucleus) wave function if the transverse momentum
 4212 of the produced hadron is of the order of the saturation momentum.

4213 Dijet production and angular decorrelation

4214 Dijet production in high energy deep inelastic electron-proton scattering is a very valuable process for the
 4215 study of small- x behavior in QCD. The dominant process is illustrated in Fig. 6.43, which is that of the
 4216 $\gamma^* g \rightarrow q\bar{q} \rightarrow$ dijet production. The incoming gluon can have sizeable transverse momentum accumulated
 4217 from diffusion in k_T along the gluon chain. As Bjorken- x becomes smaller, and therefore the longitudinal
 4218 momentum of the gluon also decreases, larger values of the transverse momentum k_T can be sampled. This
 4219 will lead to an azimuthal decorrelation between the jets which increases with decreasing x . The definition of
 4220 $\Delta\phi$ is indicated in Fig. 6.43. That is, the jets are no longer back-to-back since they must balance the sizable
 4221 transverse momentum k_T of the incoming virtual gluon.

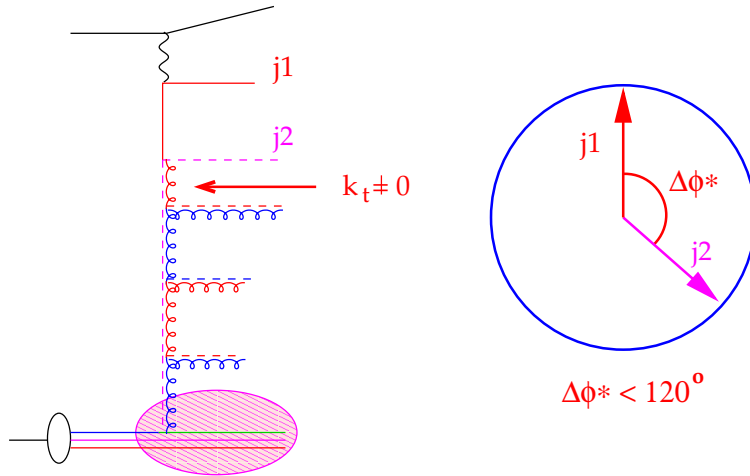


Figure 6.43: Schematic representation of the production of a system of two jets in the process of virtual photon-gluon fusion. The incoming gluon has non-vanishing transverse momentum $k_T \neq 0$ which leads to the decorrelation of the jets. $\Delta\phi$ is the angle between two jets.

4222 This picture of dijet production is to be contrasted with the conventional picture which uses integrated
 4223 parton distributions, and typically leads to a narrow distribution about the back-to-back jet configuration.
 4224 Higher orders usually broaden the distribution. However, as shown by direct measurements of DIS dijet
 4225 data [527], NLO DGLAP calculations are not able to accommodate the pronounced effect of the decorrelation.

4226 Explicit calculations for HERA kinematics show that the models which include the resummation of
 4227 powers of $\log 1/x$ compare favourably with the experimental data [528–532]. The proposal and calculations
 4228 to extend such studies to diffractive DIS also exist [533, 534].

4229 In Fig. 6.44 we show the differential cross section as a function of $\Delta\phi$ for jets in the region $-1 < \eta_{jet} <$
 4230 2.5 with $E_{T,jet1} > 7$ GeV and $E_{T,jet2} > 5$ GeV found with the k_t jet algorithm in the kinematic range
 4231 $Q^2 > 5$ GeV, $0.1 < y < 0.6$ for different regions in x . The ‘MEPS’ prediction comes from a Monte Carlo
 4232 generator [132] using $\mathcal{O}(\alpha_s)$ matrix elements with a DGLAP-type parton shower. The ‘CDM prediction
 4233 uses the same generator [132], but with higher order parton radiation simulated with the Colour Dipole
 4234 Model [535], thus effectively including some k_t diffusion. Finally, the CASCADE Monte Carlo prediction
 4235 [536], uses off-shell matrix elements convoluted with an unintegrated gluon distribution (CCFM set A), with

4236 subsequent parton showering according to the CCFM evolution equation.

4237 At large x all predictions agree reasonably well, in both shape and normalisation. At smaller x the
 4238 $\Delta\phi$ -distribution becomes flatter for CDM and CASCADE, indicating higher order effects leading to a larger
 4239 decorrelation of the produced jets. Whereas a decorrelation is observed, its size depends on the details of the
 4240 parton evolution and thus a measurement of the $\Delta\phi$ cross section provides a direct measurement of higher
 order effects which need to be taken into account at small x .

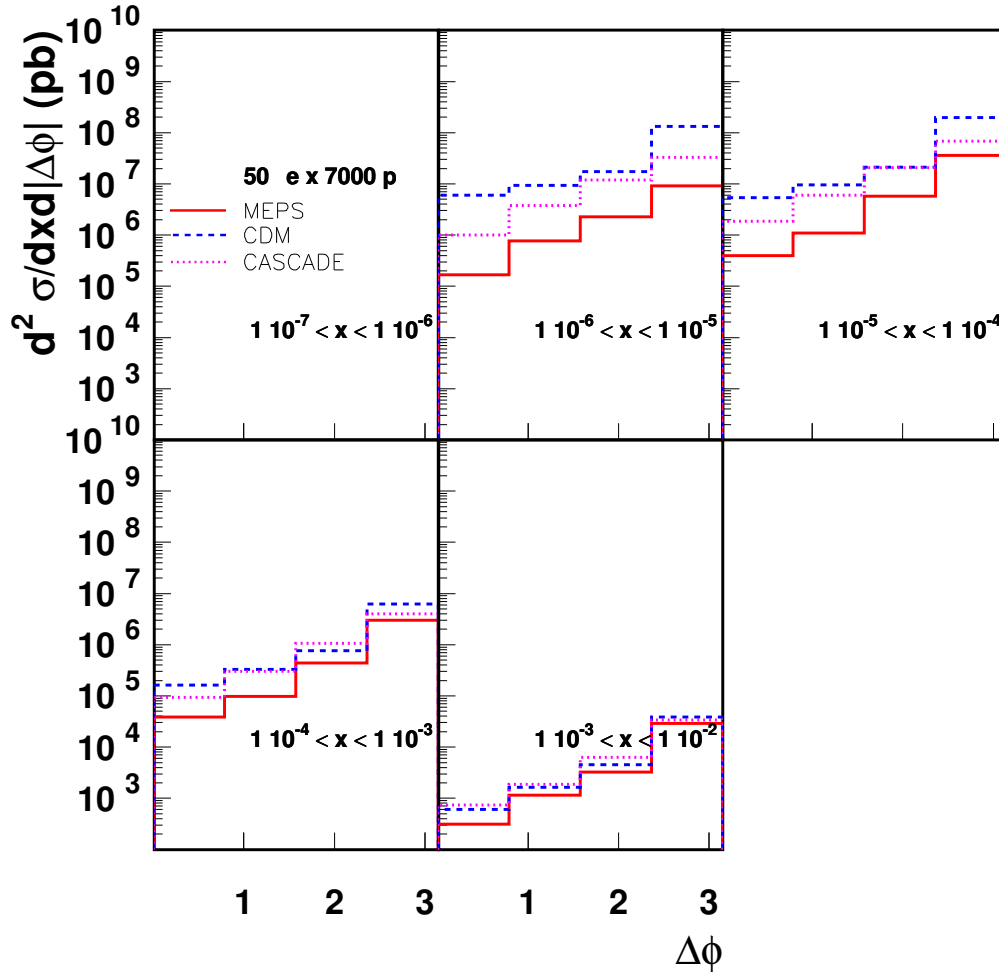


Figure 6.44: Differential cross section for dijet production as a function of the azimuthal separation $\Delta\phi$ for dijets with $E_{T,\text{jet}1} > 7$ GeV and $E_{T,\text{jet}2} > 5$ GeV.

4241

4242 Thus, in principle, a measurement of the azimuthal dijet distribution offers a direct determination of
 4243 the k_T -dependence of the unintegrated gluon distribution. When additionally supplemented by inclusive
 4244 measurements, it can serve as an important constraint for the precise determination of the fully unintegrated
 4245 parton distribution, with the transverse momentum dynamics in the proton completely unfolded.

4246 Forward observables

4247 It was proposed some time ago [537,538] that a process which would be very sensitive to the parton dynamics
 4248 and the transverse momentum distribution was the production of forward jets in DIS. According to [537,538],
 4249 DIS events containing identified forward jets provide a particularly clean window on small- x dynamics. The

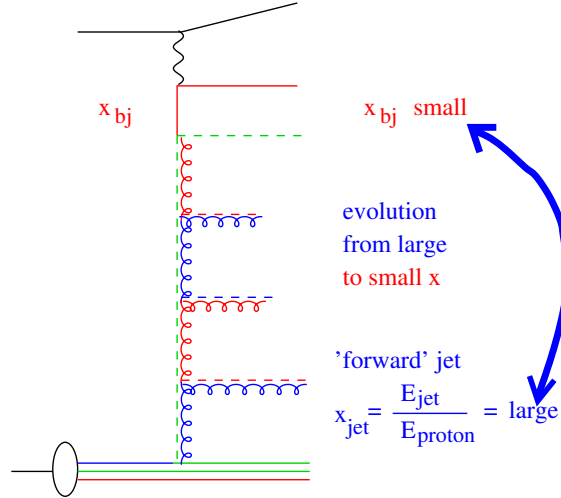


Figure 6.45: Schematic representation of the production of a high transverse momentum forward jet in DIS.

4250 schematic view of the process is illustrated in Fig. 6.45. The forward jet transverse momentum provides
 4251 the second hard scale p_T . Hence one has a process with two hard scales: the photon virtuality Q and
 4252 the transverse momentum of the forward jet p_T . As a result the collinear (DGLAP) configurations (with
 4253 no diffusion and strongly ordered transverse momenta) can be eliminated by choosing the scales to be
 4254 of comparable size, $Q^2 \simeq p_T^2$. Additionally, the jet is required to be produced in the forward direction by
 4255 demanding that x_J , the longitudinal momentum fraction of the produced jet, is as large as possible, and x/x_J
 4256 is as small as possible. This requirement selects events with a large sub-energy between the jet and the virtual
 4257 photon, such that the BFKL framework should be applicable. There have been dedicated measurements of
 4258 forward jets at HERA [539–544], which demonstrated that DGLAP dynamics at NLO are indeed incompatible
 4259 with the experimental measurements. On the other hand, calculations based on resummations of powers of
 4260 $\log 1/x$ (BFKL and others) [545–551] are consistent with the data. The azimuthal dependence of forward
 4261 jet production has also been studied [552, 553] as a sensitive probe of the small- x dynamics.

4262 Another observable that provides a valuable insight into the features of small- x physics is the transverse
 4263 energy (E_T -flow) accompanying DIS events at small x . The diffusion of the transverse momenta in this
 4264 region leads to a strongly enhanced distribution of E_T at small x . As shown in [554, 555], small- x evolution
 4265 results in a broad Gaussian E_T -distribution as a function of rapidity. This should be contrasted with the
 4266 much smaller E_T -flow obtained assuming strong k_T -ordering as in DGLAP-based approaches, which give an
 4267 E_T -distribution that narrows with decreasing x , for fixed Q^2 .

4268 The first experimental measurements of the E_T -flow in small- x DIS events indicate that there is signifi-
 4269 cantly more E_T than is given by conventional QCD cascade models based on DGLAP evolution. Instead we
 4270 find that they are in much better agreement with estimates which incorporate dynamics beyond fixed-order
 4271 DGLAP [535, 550, 556] such as BFKL evolution. The latter dynamics are characterized by an increase of the
 4272 E_T -flow in the central region with decreasing x .

4273 However, the experimental data from HERA do not enable a detailed analysis due to their constrained
 4274 kinematics. At the LHeC one could perform measurements with large separations in rapidity and for different
 4275 selections of the scales (Q, p_T). In particular, there is a possibility of varying scales to test systematically
 4276 the parton dynamics from the collinear (strongly ordered) regime $Q^2 \gg p_T^2$ to the BFKL (equal scale, Regge
 4277 kinematics) regime $Q^2 \simeq p_T^2$. Measurements of the energy flow in different x -intervals, in the small- x regime,
 4278 should therefore allow a definitive check of the applicability of BFKL dynamics and of the eventual presence
 4279 of more involved, non-linear effects.

4280 A simulation of forward jet production at the LHeC is shown in Figs. 6.46 and 6.47. The jets are required
 4281 to have $E_T > 10$ GeV with a polar angle $\Theta_{jet} > 1^\circ$ or 3° in the laboratory frame. Jets are found with the

4282 SISCone jet-algorithm [557]. The DIS phase space is defined by $Q^2 > 5 \text{ GeV}$, $0.05 < y < 0.85$.

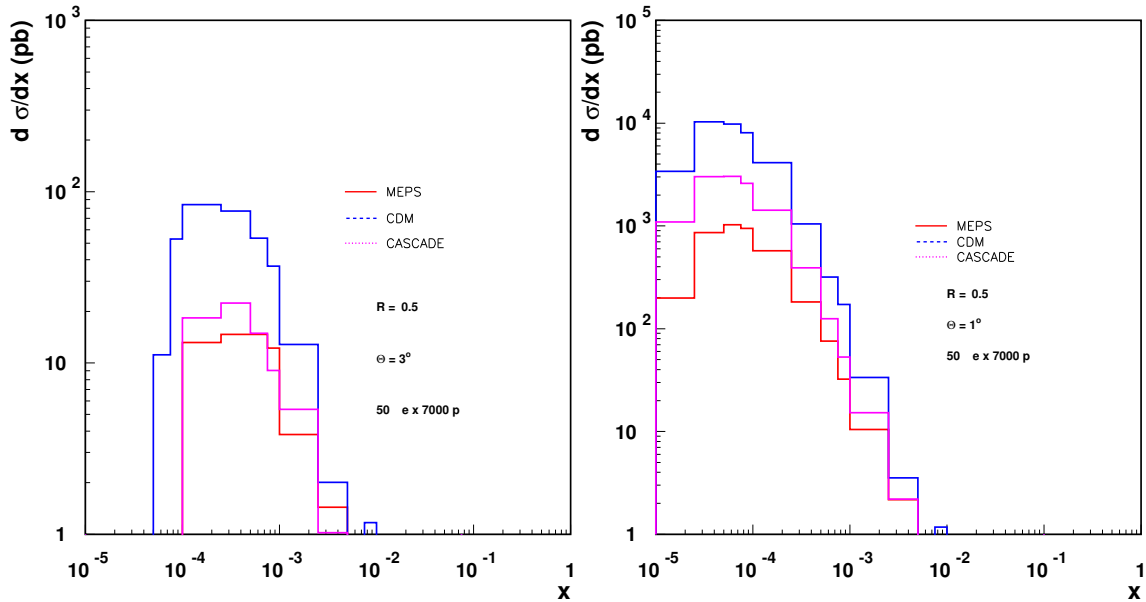


Figure 6.46: Cross section for forward jets with $\Theta_{jet} > 3^\circ$ (left) and $\Theta_{jet} > 1^\circ$ (right). Predictions from MEPS, CDM and CASCADE are shown. Jets are found with the SISCone algorithm using $R = 0.5$.

4283 In Fig. 6.46 the differential cross section is shown as a function of Bjorken x for an electron energy of
 4284 $E_e = 50 \text{ GeV}$. The calculations are obtained from the MEPS [132], CDM [535] and CASCADE [550] Monte
 4285 Carlo models, as described in the previous section. Predictions for $\Theta_{jet} > 3^\circ$ and $\Theta_{jet} > 1^\circ$ are shown. One
 4286 can clearly see that the small- x range is explored in detail with the small angle scenario. In Fig. 6.47 the
 4287 forward jet cross section is shown when using $R = 1$ instead of $R = 0.5$ (Fig. 6.46). It is important to note
 4288 that good forward acceptance of the detector is crucial for the measurement of forward jets. The dependence
 4289 of the cross section on the acceptance angle is very strong as is evident from comparisons between the cross
 4290 sections for different Θ_{jet} cuts Figs. 6.46 and 6.47.

4291 A complementary reaction to that of forward jets is the production of forward π^0 mesons in DIS. Despite
 4292 having a lower rate, this process offers some advantages over forward jet production. By looking onto
 4293 single particle production the dependencies on the jet finding algorithms can be eliminated. Also, the
 4294 non-perturbative hadronisation effects can be effectively encompassed into fragmentation functions [546].

4295 Perturbative and non-perturbative aspects of final state radiation and hadronization

4296 The mechanism through which a highly virtual parton produced in a hard scattering gets rid of its virtuality
 4297 and colour and finally projects onto an observable final state hadron, is unknown to a great extent (see [415]
 4298 and references therein). The different postulated stages of the process are illustrated in Fig. 6.48. The
 4299 coloured parton undergoes QCD radiation before forming first a coloured excited bound state (pre-hadron),
 4300 then a colourless pre-hadron and ultimately a final state hadron. These sub-processes are characterised by
 4301 different time scales. While the first stage can be described in perturbative QCD [558], subsequent ones
 4302 require models (e.g. the QCD dipole model for the pre-hadron stages) and non-perturbative information.

4303 The LHeC offers great opportunities to study these aspects and improve our understanding of all of
 4304 them. The energy of the parton which is struck by the virtual photon implies a Lorentz dilation of the
 4305 time scales for each stage of the radiation and hadronisation processes. All of them are influenced by the
 4306 fact that they do not take place in the vacuum, but within the QCD field created by the other components

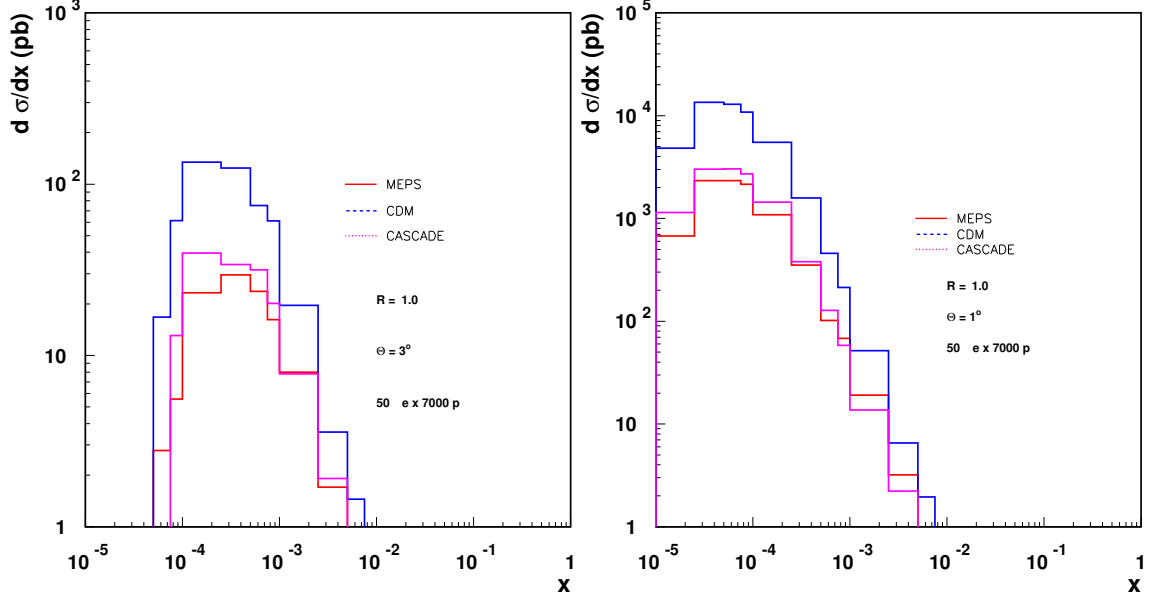


Figure 6.47: Cross section for forward jets with $\Theta_{jet} > 3^\circ$ (left) and $\Theta_{jet} > 1^\circ$ (right). Predictions from MEPS, CDM and CASCADE are shown. Jets are found with the SIScone algorithm using $R = 1.0$.

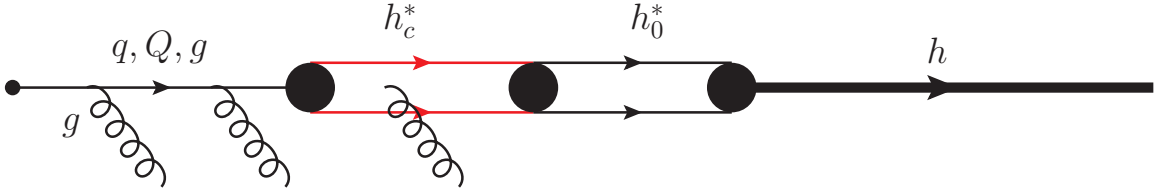


Figure 6.48: Sketch of the different postulated stages in the hadronisation of a highly virtual parton. From left to right: radiating parton; radiating coloured pre-hadron, colourless pre-hadron and final state hadron.

4307 of the hadron or nucleus. While at fixed target SIDIS or DY experiments, the lever arm in energy is
 4308 relatively small (energy transfer to the struck parton in its rest frame, $\nu < 100$ GeV), at the LHeC this lever
 4309 arm will be huge ($\nu < 10^5$ GeV; see also in Subsec. 4.7.2 the abundant yield of expected high transverse
 4310 momentum jets in photoproduction), implying that the different stages can be considered to happen in
 4311 or out of the hadron field depending on the parton energy. Furthermore, the fact that we can introduce
 4312 a piece of coloured matter of known length and density - a nucleus - by doing ePb collisions at different
 4313 centralities, allows a controllable variation of the influence of the different processes. The induced differences
 4314 in the final distributions of hadrons, both in terms of their momenta and of their relative abundance, will
 4315 provide important information about the time scales and the detailed physical mechanisms at work in each
 4316 stage. Dramatic effects are predicted in some models [160], with a significant suppression of the forward
 4317 hadron spectra due to the creation of the dense partonic system. Note that SIDIS experiments already
 4318 provide information for the determination of standard fragmentation functions (see [559, 560] for a recent
 4319 analysis). The other pieces of information, coming mainly from e^+e^- experiments, will not be improved
 4320 until next-generation linear colliders become available.

4321 Furthermore, these studies will shed light on two aspects already discussed in Subsec. 6.1.4, related
 4322 to the study of ultrarelativistic heavy-ion collisions: the characterization of the medium created in such
 4323 collisions through hard probes, and the details of particle production in a dense situation which will define

4324 the initial conditions for the collective behavior of this medium. Concerning the latter, our theoretical tools
 4325 for computing particle production in eA collisions are more advanced e.g. within the CGC framework, and
 4326 on a safer ground than in nucleus-nucleus collisions (see Subsec. 6.1.1 and e.g. [414] and refs. therein). The
 4327 possibility of disentangling the different mechanisms through which the factorisation that is used in dilute
 4328 systems - collinear factorisation [289] - becomes broken by density effects (e.g. initial and final state energy
 4329 loss or final state absorption) will be possible at the LHeC and will complement existing studies done at
 4330 much smaller energies in fixed target SIDIS and DY experiments [415].

4331 6.2.6 Implications for ultra-high energy neutrino interactions and detection

The stringent constraints of the parton distributions at very small x from a future LHeC will have important
 implications for neutrino astronomy. Ultra-high energy neutrinos can provide important information about
 distant astronomical objects and the origin of the Universe. They have attracted a lot of attention during
 recent years, see the reviews [561, 562]. Neutrino astronomy has many advantages over conventional photon
 astronomy. This is due to the fact that neutrinos, unlike photons, interact only weakly, so they can travel
 long distances being practically undisturbed. The typical interaction lengths for neutrinos and photons at
 energy $E \sim 1$ TeV are about

$$\mathcal{L}_{int}^{\nu} \sim 250 \times 10^9 \text{ g/cm}^2, \quad \mathcal{L}_{int}^{\gamma} \sim 100 \text{ g/cm}^2.$$

4332 Thus, very energetic photons with energy bigger than ~ 10 TeV cannot reach the Earth from the very distant
 4333 corners of our Universe without being rescattered. In contrast, neutrinos can travel very long distances
 4334 without interacting. They are also not deflected by galactic magnetic fields, and therefore at ultra-high
 4335 energies the angular distortion of the neutrino trajectory is very small. As a result, highly energetic neutrinos
 4336 reliably point back to their sources. The interest in the neutrinos at these high energies has led to the
 4337 development of several neutrino observatories, see [562] and references therein.

4338 For reliable observations based on neutrino detection, precise knowledge about their production rates
 4339 and interactions is essential to estimate the background, the expected fluxes and the detection probabilities.
 4340 Even though neutrinos interact only weakly with other particles, strong interactions play an essential role in
 4341 the calculations of their production rates and interaction cross sections. This is due to the fact that neutrinos
 4342 are produced in the decays of various mesons such as π , K , D and even B , which are produced in high-energy
 4343 proton-proton (or proton-nucleus or nucleus-nucleus) collisions. These hadronic processes occur mainly in
 4344 the atmosphere though possibly also in the accretion discs of remote Active Galactic Nuclei. Further, the
 4345 interactions of highly energetic neutrinos with matter are dominated by the deep inelastic cross section with
 4346 nucleons or nuclei. Hence, low x information from high-energy collider experiments such as HERA, Tevatron,
 4347 LHC and, most importantly, the future LHeC, is invaluable.

4348 One of the main uncertainties (if not the dominant one) in the current limits on high-energy neutrino
 4349 production is due to the neutrino-nucleon (nucleus) cross section. In fact, event rates are proportional to
 4350 the neutrino cross section in many experiments. This cross section involves the gluon distribution probed
 4351 at very small values of Bjorken x , down to even $\sim 10^{-9}$, which corresponds to a very high centre of mass
 4352 energy.

4353 To visualize the kinematic regime probed in ultra-high energy neutrino-nucleon interactions, contour
 4354 plots of the differential cross section $\frac{d^2\sigma}{d\ln 1/x d\ln Q^2/\Lambda^2}$ in the (x, Q^2) plane are shown in Fig. 6.49. The
 4355 contours enclose regions with different contributions to the total cross section $\sigma(E_{\nu})$. For very high energy
 4356 $E_{\nu} = 10^{11}$ GeV the dominant contribution comes from the domain $Q^2 \simeq M_W^2$ and $x_{\min} \simeq M_W^2/(2M_N E) \sim$
 4357 $10^{-8} - 10^{-7}$ where M_N is the nucleon mass, inaccessible to any current or proposed accelerators. However,
 4358 at lower neutrino energy $E_{\nu} = 10^7$ GeV the relevant domain of (x, Q^2) could be very well covered by the
 4359 LHeC, thus providing important new constraints on the neutrino-nucleon cross section.

4360 On the other hand, another process which has been proposed for neutrino detection comes from the
 4361 discovery of neutrino flavor oscillations, which makes it possible that high rates of τ neutrinos reach the
 4362 Earth, despite being heavily suppressed in most postulated production mechanisms. The possibility to
 4363 search for ν_{τ} 's by looking for τ leptons that exit the Earth, Earth-skimming neutrinos, has been shown to be

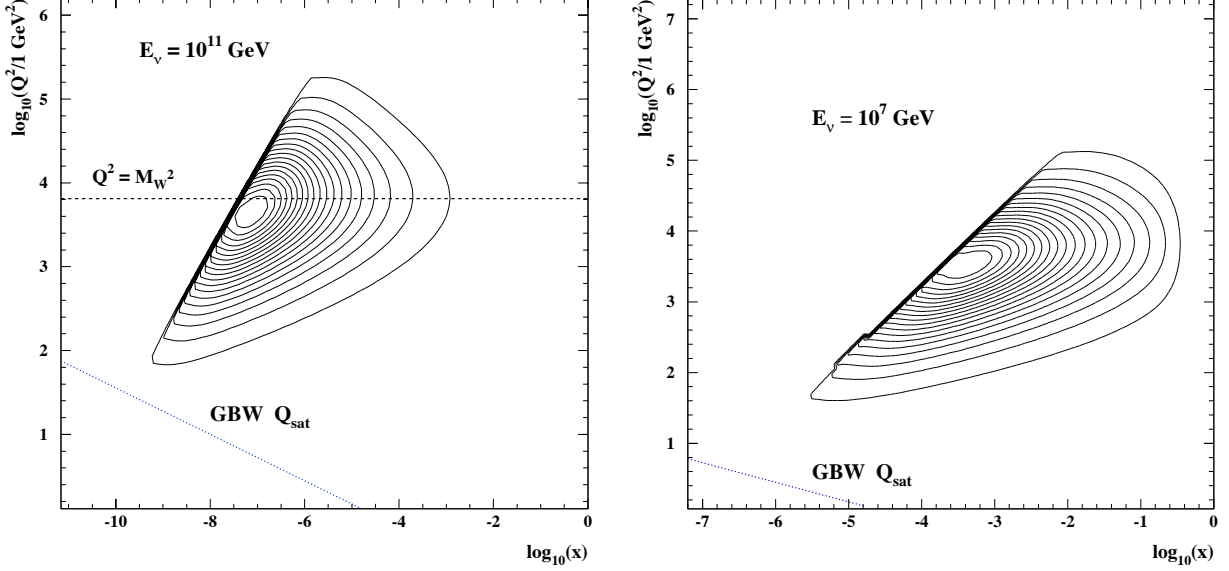


Figure 6.49: Contour plot showing the x, Q^2 domain of the dominant contribution to the differential cross section $d\sigma/d\ln(1/x)d\log Q^2$ for the total ν -nucleon interaction at neutrino laboratory energies of $E_\nu = 10^{11}$ GeV (left plot) and $E_\nu = 10^7$ GeV (right plot). The 20 contours enclose contributions of 5, 10, 15 \dots 100 % of the cross section. The saturation scale according to the model in [336] is shown as a dashed line. See the text for further explanation.

4364 particularly advantageous to detect neutrinos of energies in the EeV (10^{18} eV) range [563]. The short lifetime
 4365 of a τ lepton originating a neutrino charged current interaction allows the τ to decay in flight while still close
 4366 to the Earth's surface, producing an outgoing air shower, detectable in principle by various techniques. This
 4367 channel suffers from negligible contamination for other neutrino flavors. The sensitivity to ν_τ 's through the
 4368 Earth-skimming channel directly depends both on the neutrino charged current cross section and on the τ
 4369 range (the energy loss) which is determined by the amount of matter with which the neutrino has to interact
 4370 to produce an emerging τ . It turns out that the τ energy loss is also determined by the behavior of the
 4371 proton and nucleus structure functions at very small values of x , see e.g. [564]. The average energy loss per
 4372 unit depth, X , is conveniently represented by:

$$-\left\langle \frac{dE}{dX} \right\rangle = a(E) + b(E)E, \quad b(E) = \frac{N_A}{A} \int dy y \int dQ^2 \frac{d\sigma^{LA}}{dQ^2 dy}, \quad (6.19)$$

4373 where the $a(E)$ term is due to ionization, $b(E)$ is the sum of fractional losses due to e^+e^- pair production,
 4374 Bremsstrahlung and photonuclear interactions, N_A is Avogadro's number and A is the mass number. The
 4375 parameter $a(E)$ is nearly constant and the term $b(E)E$ dominates the energy loss above a critical energy
 4376 that for τ leptons is a few TeV, with the photonuclear interaction being dominant for τ energies exceeding
 4377 $E = 10^7$ GeV (as already assumed in Eq. (6.19)). In Fig. 6.50 the relative contribution to $b(E)$ of different
 4378 x and Q^2 regions is shown. It can be observed that the energy loss is dominated by very small x and, in
 4379 contrast to the case of the neutrino cross section, by small and moderate $Q^2 \lesssim m_\tau^2$.

4380 As the LHeC will be able to explore a new regime of low x and high Q^2 and constrain the parton
 4381 distributions, the measurements performed at this collider will be invaluable for the precise evaluation of
 4382 the neutrino-nucleon (or nucleus) scattering cross sections and τ energy loss necessary for ultra-high energy
 4383 neutrino astronomy.

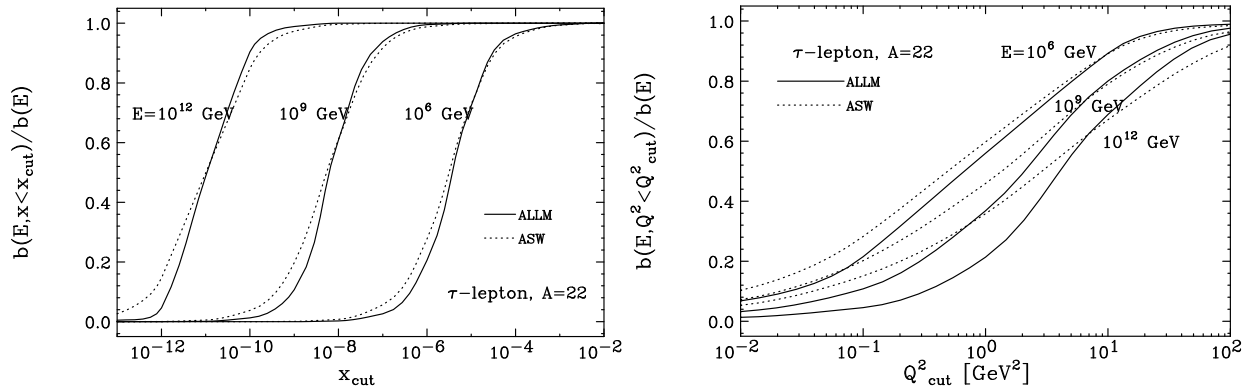


Figure 6.50: The relative contribution of $x < x_{cut}$ (plot on the left) and of $Q^2 < Q_{cut}^2$ (plot on the right) to the photonuclear energy loss rate, $b(E)$, for different neutrino energies $E = 10^6, 10^9$ and 10^{12} GeV, in two different models for the extrapolation of structure functions to very small x . See the text and [564] - from which these plots were taken - for explanations.

Part III

Accelerator

4384

4385

Chapter 7

Ring-Ring Collider

7.1 Baseline Parameters and Configuration

Intense electron-proton beam interactions in the LHC tunnel can be realised with an electron storage ring and the LHC, as has been discussed already at the Lausanne workshop back in 1984. This solution was revived [17] when it had been seen that a hundred fold higher luminosity can be achieved than with HERA, owing to the intense proton beams available with the LHC. With an electron beam energy set between about 50 and 100 GeV and the 7 TeV proton beam energy one can realise a new ep collider of cms energy, $\sqrt{s} = 2\sqrt{E_e E_p}$ beyond 1 TeV. The advantages of a ring-ring (RR) configuration are that one uses known technology, with much experience from HERA and LEP, and that intense beams of both lepton charges are readily available.

For the present design study the electron beam energy has been set to 60 GeV as is discussed above, Sect. 2.3. With extra efforts and higher investments one may double that energy, as had been achieved for LEP [565], should there be strong physics requirements. One yet has to see that power losses vary $\propto E_e^{-4}$ and much higher synchrotron radiation occurs, which causes the operation and technical conditions to be increasingly demanding as E_e increases. A 60 GeV e^\pm beam may be polarised while, following the calculations presented below, that becomes questionable when E_e increases.

Due to the smallness of the ep tuneshift, synchronous pp and ep interactions can be realised with the LHC and the LHeC. This requires to bypass the active pp experiments with separate tunnels which, in adjacent caverns, can house the rf. Excavation of such tunnels may proceed in parallel to LHC operation, like the CMS cavern was excavated while LEP ran. Due to machine hardware or unfortunate geological conditions, none of the 4 machine points (3,4 and 6,7) could house the LHeC interaction region. For the present study IP2 was chosen as the ep IR, currently housing ALICE, and bypasses were considered for ATLAS and CMS.

Maximum luminosity can be achieved with focussing magnets placed close to the interaction point. This limits, however, the polar angle acceptance. Two principal interaction optics solutions have been developed, the high luminosity optics, with acceptance down to about 8° , and the large acceptance optics, covering polar angles down to 1° . As is shown below, there is only a factor of 4 difference in the product of the β functions. It then is likely that one further develops the large acceptance solution only, but both are fully described here.

A complete lattice has been designed for the new ring. This takes into account some peculiarities due to the LHC. In particular, an asymmetric FODO cell, of half the LHC FODO cell length, had to be designed to account for LHC service modules and the DFBS. Similarly, a non-standard solution for the dispersion matching had to be developed, using 8 individually powered quadrupoles instead of regulating the position of dipoles which is too constrained by the LHC.

A further baseline parameter is the injection energy. The LHeC electron storage ring differs from LEP in its bunch structure. The LHeC has a maximum of about $2 \cdot 10^{10}$ electrons per bunch in a much higher repetition rate than LEP, which had a bunch intensity of $4 \cdot 10^{11}$. The smaller intensity allows to inject at

4423 lower energy than LEP. For the current design a new injector is considered, using linac technology with high
4424 frequency cavities, of energy of 10 GeV. This poses constraints on the quality of the main dipole magnets,
4425 which have to ensure a magnetic field reproducibility of about 10^{-4} . C - (and H) shape prototype magnets
4426 have been developed, built and successfully tested at BINP Novosibirsk. Alternative magnets have been built
4427 and are being tested also at CERN. Besides the magnetic field properties, attention was given to small outer
4428 dimensions (of about 35 cm^2 compared to 50 cm^2 at LEP) and to a reduction of the weight (from 800 kg/m
4429 at LEP to 250 kg/m for the LHeC) in order to facilitate the installation. The total number of magnets is
4430 less than 4000. Such an amount is large, but it may be obtained within a few years production, following
4431 1 : 1 prototyping within the technical design phase.

4432 The key question for the storage ring is its possible installation in the LHC tunnel without posing too
4433 harsh constraints on the LHC operation schedule. A first inspection has been made of the various elements
4434 of concern, as described below, with the conclusion that installation of the LHeC was possible but very
4435 demanding. For a TDR of the ring-ring solution, a detailed 3D CAD integration study of both accelerators
4436 is mandatory.

4437 The subsequent chapter describes the studies dedicated to characterize the RR option. It is followed by a
4438 similar chapter on the LR option. Much of the system hardware is common or similar and thus it is contained
4439 in a following chapter. From today's perspective both options may be realised within the coming ten years,
4440 albeit the differences which distinguish them. It is part of the referee process to understand the relative
4441 merits in terms of physics, technics, operation, infrastructure and future developments, which is expected
4442 to lead to a sufficiently deep consideration and comparison of the storage ring versus the linac options, such
4443 that the TDR can be developed for just one of them. Since, however, the cavities, for the ring injector and
4444 for the linac, the dipole magnets, for the ring and for the linac return arcs, and the 3 beam superconducting
4445 triplet of magnets near the interaction point, all have very similar constraints, a next phase of prototyping
4446 and design has been possible to already prepare.

4447 7.2 Geometry

4448 All lattice descriptions in this chapter are based on the LHeC lattice Version 1.1.

4449 7.2.1 General Layout

4450 The general layout of the LHeC consists of eight arcs, six straight sections and two bypasses around the
4451 experiments in Point 1 and Point 5. The e-p collision experiment is assumed to be located in Point 2, the
4452 only foreseen interaction point of the electron and proton beams. All straight sections except those in the
4453 bypasses have the same length as the LHC straight sections: 538.8 m at even points and 537.8 m at odd
4454 points.

4455 The insertions shared with the LHC are already used for the experiments or for LHC equipment.
4456 Therefore the RF for the electron ring is installed in the straight sections of the bypasses. For the same
4457 reason the beam is injected in the bypass around Point 1. Point 1 is preferred over Point 5 for geological
4458 and infrastructural reasons. The overall layout of the LHeC is shown in Figure 7.1.

4459 The insertions shared with the LHC are already used for the experiments or for LHC equipment.
4460 Therefore the RF for the electron ring is installed in the straight sections of the bypasses (see section 9.2.1).
4461 For the same reason the beam is injected in the bypass around Point 1. Point 1 is preferred over Point 5 for
4462 geological and infrastructural reasons. The overall layout of the LHeC is shown in Figure 7.1.

4463 7.2.2 Electron Ring Circumference

4464 The LHeC electron beam collides only in one point (assumed to be Point 2) with the protons of the LHC.
4465 This leaves the options to either exactly match the circumferences of the proton and electron rings or to
4466 allow a difference of a multiple of the LHC bunch spacing. In the case of different circumferences the proton

4467 beam could become unstable due to beam-beam interactions with the electrons [566]. To avoid this possible
4468 effect in the LHeC, the electron ring circumference is matched exactly to the proton ring circumference.

4469 The circumference can be adjusted in two ways:

- 4470 1. Different bypass designs, e.g. inner and outer bypass, which compensate each other in length.
- 4471 2. Radial displacement of the electron ring to the inside or outside of the LHC in the places where the
4472 two rings share the same tunnel to compensate for the path length difference caused by the bypasses.

4473 The various design possibilities for the bypasses are discussed in Sec. 7.2.4. Considering their characteristics,
4474 the best choice seems to be outer bypasses around both experiments.

4475 7.2.3 Idealised Ring

4476 In the following the average between LHC Beam1 and Beam2 is taken as reference geometry for the LHC.

4477 General Layout

4478 To compensate the path length differences from the bypasses, the electron ring is placed on average 61 cm
4479 to the inside of the LHC in the sections where both rings share the tunnel. For this a complete ring with an
4480 ideally constant radial offset of 61 cm to the LHC was designed. In the following we refer to this ring as the
4481 *Idealised Ring*.

4482 In addition to the horizontal displacement, the electron ring is set 1 m above the LHC in order to minimise
4483 the interference with the LHC elements. The main remaining conflicts in the arc are then the service modules
4484 as shown in Figure 7.49 and the DFBs in the insertions shown in Figure 7.57. A representative cross section
4485 of the LHC tunnel is shown in Figure 7.47.

4486 In the main arcs the service modules have a length of 6.62 m and are installed at the beginning of each
4487 LHC arc cell. The insertions host a different number of DFBs with a varying placement and length. The
4488 idealised ring lattice is designed to avoid overlaps of magnet elements with all service modules in the main
4489 arcs. In order to show that it is possible to design an optics with no e-ring elements at any DFB positions in
4490 the insertions, the dispersion suppressors of the even and odd insertions were adapted to the DFB positions
4491 and lengths in IR2 and IR3 respectively. For simplicity all straight sections are filled with a regular FODO
4492 cell structure.

4493 Geometry

4494 To adjust the beam optics to the regular reappearance of the service modules at the beginning of each LHC
4495 arc cell it was suggested to use a multiple, n , or sub-multiple $1/n$ ($n \in \mathbb{N}$) of the LHC arc cell length as LHeC
4496 FODO cell length. Beside the integration constraints, the cell has to provide the right emittance. Taking
4497 half the LHC arc cell length as LHeC FODO cell length already fulfils this second criterion (Sec. 7.3.1).

4498 As the LHC arc cell is symmetric, the best geometrical alignment with the LHC main arc would be
4499 achieved, if the LHeC cell also had a symmetrical layout. Because of the service modules, no elements can
4500 be placed in the first 6.9 m of two consecutive cells. If all cells had the same layout, another 6.9 m would be
4501 lost in the second FODO cell. This would result in additional unwanted synchrotron radiation losses as the
4502 energy loss in a dipole magnet is proportional to the inverse length of the dipole

$$U_{\text{dipole}} = \frac{C_\gamma}{2\pi} E_0^4 \frac{\theta^2}{l}, \quad C_\gamma = \frac{4\pi}{3} \frac{r_e}{(m_e c^2)^3} \quad (7.1)$$

4503 where θ is the bending angle, l the length of the dipole and E_0 the beam energy. In order to avoid this, the
4504 LHeC arc cell is a double FODO cell, symmetric in the positioning of the quadrupoles but asymmetric in
4505 the placement of the dipoles (Figure 7.2).

4506 The bending angle in the arc cells and also in the DS is determined by the LHC geometry. In the
4507 following we refer to the LHC DS as the section from the end of the arc to the beginning of the LSS. With

4508 this definition the LHC DS consists of two cells. Keeping the same conversion rule as in the arc (one LHC
 4509 FODO cell corresponds to two LHeC FODO cells), the LHeC DS would then ideally consist of 4 equal cells.
 4510 For consistency the ratio between the LHeC DS and arc cell lengths is the same as between the LHC DS
 4511 and arc cell. For the LHC this ratio is 2/3. This leaves the following choices for the number of dipoles in
 4512 the arc and DS cell:

$$N_{\text{Dipole, arc cell}} = \frac{3}{2} N_{\text{Dipole, DS cell}} = 3, 6, 9, 12, 15 \dots \quad (7.2)$$

4513 A good compromise between a reasonable dipole length and optimal use of the available space for the bending
 4514 is 15 dipoles per arc cell. The dipoles are then split up in packages of 3 + 4 + 4 + 4 in one arc cell and 2 + 3
 4515 in one DS cell.

4516 Beside the bending angle, the module length of the electron ring has to be matched to the LHC geometry.
 4517 As the electron ring is radially displaced to the inside of the proton ring, all e-ring modules are slightly shorter
 4518 than their proton ring equivalents (Table 7.1).

	Proton Ring	Electron Ring
Arc Cell Length	106.9 m	106.881 m
DSL Length (even points)	172.80 m	172.78 m
DSR Length (even points)	161.60 m	161.57 m
DSL Length (odd points)	173.74 m	173.72 m
DSR Length (odd points)	162.54 m	162.51 m

Table 7.1: Proton and Electron-Ring Module Lengths

4519 The above considerations already fix the bending angle of the dipoles, which leaves only position and
 4520 length as free parameters. Ideally the dipole length would be chosen as long as possible, but because of the
 4521 asymmetry of the arc cell, the dipoles have to be shortened and moved to the right in order to fit the LHC
 4522 geometry.

4523 The LHeC DS layout would ideally be similar to the LHC DS layout (Figure 7.3), but has to be modified in
 4524 order to leave space for the DFBS in the DS region. In the final design the dipoles are placed as symmetrically
 4525 as possible between the regular arrangement of the quadrupoles (Figure 7.4, 7.5).

4526 The difference between the LHC proton ring and the idealised LHeC electron ring is shown in Figure 7.6
 4527 and 7.7.

4528 7.2.4 Bypass Options

4529 In the design of the e-ring geometry, it is foreseen to bypass the LHC experiments at Point 1 and Point
 4530 5. The main requirements for both bypasses are that all integration constraints are respected, synchrotron
 4531 radiation losses are not significantly increased and that the change in circumference can be compensated by
 4532 increasing or decreasing the radius of the ring.

4533 Three different options are considered as basic bypass designs:

4534 **Vertical Bypass:** A vertical bypass would have to be a vertically upward bypass as downward would
 4535 imply crossing the LHC magnets and other elements. For this a separation of about 20 to 25 m is
 4536 required [567]. This can only be achieved by strong additional vertical bending. In general a vertical
 4537 bypass would therefore be rather long, increase the synchrotron radiation due to the additional vertical
 4538 bends and decrease the polarization compared to a horizontal bypass. A vertical bypasses is therefore
 4539 only considered as an option if horizontal bypasses are not possible.

4540 **Horizontal Inner Bypass:** A horizontal inner bypass can be constructed by simply decreasing the bending
 4541 radius of the main bends. Consequently the synchrotron radiation losses for an inner bypass are larger
 4542 than for a comparable outer bypass. The advantage of an inner bypass is, if used in combination with

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4544

an outer one, that it reduces the circumference and the two bypasses could compensate each other's path length differences.

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4546
4547

Horizontal Outer Bypass: A horizontal outer bypass uses the existing curvature of the ring instead of additional or stronger dipoles and consequently does not increase the synchrotron radiation losses. In general this is the preferred option.

4548

7.2.5 Bypass Point 1

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The cavern in Point 1 reaches far to the outside of the LHC, so that a separation of about 100 m would be necessary in order to fully bypass the experimental hall. For a bypass on the inside, a smaller separation of about 39 m would be required. For an inner bypass with minimal separation, the bending strength in three normal arc cells would have to be doubled resulting in a bypass of more than 2 km length. A sketch of such an inner bypass is shown in Figure 7.8.

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Instead of a long inner bypass, an outer bypasses using the existing survey gallery is chosen as final design. With this design the separation is brought down to 16.25 m. The RF is installed in the straight section next to the straight section of the proton ring. The electron beam is injected into the arc on the right side of the bypass. The design is shown in Figure 7.9.

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7.2.6 Bypasses Point 5

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Due to the compact design of the cavern in Point 5 a separation of only about 20 m is needed to completely bypass the experiment on the outside (Figure 7.10). The separation in the case of an inner horizontal bypass or a vertical bypass would be the same or larger and therefore, as in the case of Point 1, the horizontal outer bypass is preferred over an inner or vertical one. The RF is installed in the centre straight section parallel to the proton ring.

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7.2.7 Matching Proton and Electron Ring Circumference

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Both bypasses in Point 1 and Point 5 require approximately the same separation and a similar design was chosen for both. To obtain the necessary separation Δ_{BP} a straight section of length s_{BP} is inserted into the lattice of the idealised ring (Sec. 7.2.3) in front of the last two arc cells. The separation Δ_{BP} , the remaining angle θ_{BP} and the inserted straight section s_{BP} are related by (Figure 7.11):

$$\Delta_{\text{BP}} = s_{\text{BP}} \sin \theta_{\text{BP}} \quad (7.3)$$

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As indicated in Figure 7.11 the separation could be increased by inserting a S-shaped chicane including negative bends. The advantage of additional bends would be the faster separation of the electron and proton ring. On the other hand the additional bends would need to be placed in the LHC tunnel, the straight sections of the bypass would be reduced and the synchrotron radiation losses increased.

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In the following, estimates for the current bypass design, which does not include any extra bends, are presented. Given the separation, angle and length of the inserted straight section, the induced change in circumference is then:

$$\Delta s_{\text{BP}} = s_{\text{BP}} - x_{\text{BP}} = 2\Delta_{\text{BP}} \tan\left(\frac{\theta_{\text{BP}}}{2}\right) \quad (7.4)$$

4576

This change can be compensated by a change in radius of the idealised ring by:

$$\Delta s_{\text{BP}} = 2\pi\Delta R \quad (7.5)$$

4577
4578

Taking the change in radius into account, the separation Δ_{BP} has to be substituted by $\Delta_{\text{BP,tot}} := \Delta_{\text{BP}} + \Delta R$. The radius change and the total separation are then related by:

$$\Delta R = \frac{\Delta_{\text{BP}}}{\pi \cot\left(\frac{\theta_{\text{BP}}}{2}\right) - 2}, \quad \text{with } \Delta_{\text{BP}} = \Delta_{\text{BP1}} + \Delta_{\text{BP5}} \quad (7.6)$$

4579 As the bypass in Point 1 passes through the existing survey gallery, the geometry and with it the separation
 4580 in Point 1, cannot be changed. The bypass in Point 5, on the other hand, is fully decoupled from the existing
 4581 LHC cavern and tunnel and is therefore used for the fine adjustment of the circumference. The design values
 4582 of both bypasses are summarised in Table 7.2.

	Point 1	Point 5
Total bypass length	1303.3 m	1303.7 m
Separation	16.25 m	20.56 m
Dispersion free straight section	172 m	297 m
Ideal radius change of the idealised ring	61 cm	

Table 7.2: Lengths characterising the bypasses.

4583 7.3 Layout and Optics

4584 Throughout the whole electron ring lattice, the choice of the optics is strongly influenced by the geometrical
 4585 constraints and shortage of space in the LHC tunnel. The main interference with the LHC beside Point 1
 4586 and Point 5, which have to be bypassed, are the service modules and DFBs in the tunnel, where no electron
 4587 ring elements can be placed.

4588 7.3.1 Arc Cell Layout and Optics

4589 The LHC service modules are placed at the beginning of each LHC main arc cell. In order to obtain a
 4590 periodic solution of the lattice, the electron ring arc cell length can only be a multiple or $1/n$ th, $n \in \mathbb{N}$, of
 4591 the LHC FODO cell length. Given the same phase advance and bending radius, the emittance increases
 4592 with increasing cell length L of a FODO cell. In the case of the LHeC electron ring a FODO cell length
 4593 corresponding to half the LHC FODO cell length delivers an emittance close to the design value. The
 4594 emittance of a cell with the full LHC FODO cell length is about a factor of 4 too large.

4595 Choosing half the LHC FODO cell length divides the arc into 23 equal double FODO cells with a
 4596 symmetric configuration of the quadrupoles and an asymmetric distribution of the dipoles, namely 8 dipoles
 4597 in the first FODO cell and 7 in the second. The dipole configuration is asymmetric in order to use all
 4598 available space for the bending of the e-beam and consequently minimise the synchrotron radiation losses.
 4599 With a phase advance of 180° horizontally and 120° vertically over the complete double FODO cell, which
 4600 corresponds to a phase advance of $90^\circ/60^\circ$ per FODO cell, the horizontal emittance of 4.70 nm lies well
 4601 below the design value of 5 nm. Because of the asymmetry of the dipole configuration, the phase advance in
 4602 the horizontal plane is also not equally distributed. In the first half it is, at $90.6^\circ/60^\circ$, slightly larger than
 4603 in the second half with $89.4^\circ/60^\circ$. The optics of one arc cell is shown in Figure 7.2 and the parameters are
 4604 listed in Table 7.3.

4605 7.3.2 Insertion Layout and Optics

4606 For simplicity all even and all odd insertions of the electron ring have the same layout as described in Sec.
 4607 7.2.1. Each insertion is divided in three parts: the dispersion suppressor on the left side (DSL), the straight
 4608 section and the dispersion suppressor on the right side (DSR).

4609 Dispersion Suppressor

4610 Various well known standard DS designs like the missing bend or half bend scheme exist, but they are all
 4611 based on specific placement of the dipoles. In the case of the LHeC the position of the dipoles is strongly
 4612 determined by the LHC geometry and does not match any of the standard schemes. Therefore the dispersion

Beam energy	60 GeV
Phase advance per cell	180°/120°
Cell length	106.881 m
Dipole fill factor	0.75
Damping partition $J_x/J_y/J_e$	1.5/1/1.5
Coupling constant κ	0.5
Horizontal emittance (no coupling)	4.70 nm
Horizontal emittance ($\kappa = 0.5$)	3.52 nm
Vertical emittance ($\kappa = 0.5$)	1.76 nm

Table 7.3: Optics parameters of one LHeC arc cell with a phase advance of 180°/120°.

4613 matching is achieved by 8 individually powered quadrupoles and not with the positioning of the dipoles. The
4614 DS on the left side is split into two DS sections, reaching from the first DFB to the second and from the
4615 second to the beginning of the straight section. In the DSL the quadrupoles are distributed equally in each
4616 section. In the DSR they are placed with equal distances from each other throughout the complete DS. This
4617 layout turned out to be better for the right side due to the different arrangement of the DFBs. The DSs of
4618 the even and odd points differ slightly in their length but have the same general layout. The lengths of the
4619 DSs are listed in Table 7.1. The DS optics are shown in Figure 7.4 and 7.5.

4620 Straight Section

4621 For simplicity the straight sections consist of a regular FODO lattice with a phase advance of 90°/60°. In a
4622 later stage the lattice and optics of the straight sections will have to be adjusted to the various insertions.

4623 7.3.3 Bypass Layout and Optics

4624 The general layout and nomenclature of the bypasses is illustrated in Figure 7.12. The straight sections
4625 LSSL, LSSR and IR are dispersion free sections reserved for the installation of RF, wiggler(s), injection etc.
4626 Two normal arc cells (4 FODO cells) with 8 individual quadrupoles are used as dispersion suppressor before
4627 the first straight section LSSL and after the last straight section LSSR. In the sections TLIR and TRIR
4628 the same configuration of dipoles is kept as in the idealised lattice for geometric reasons. Among this fixed
4629 arrangement of dipoles 14 matching quadrupoles per side are placed as equally as possible.

4630 The straight sections consist of a regular FODO lattice with a phase advance of 90°/60°.

4631 The complete bypass optics in Point 1 and Point 5 are shown in Figure 7.13 and 7.14.

4632 7.3.4 Chromaticity Correction

4633 The phase advance of one LHeC FODO cell is approximately 90°/60°. The traditional choice would be to
4634 correct the chromaticity with two interleaved families in the horizontal and three in the vertical plane, but
4635 this scheme leads to one strong and one weak sextupole in the horizontal plane, which is undesirable for the
4636 suppression of resonances. An interleaved scheme with 6 sextupoles yields to approximately similar strength
4637 for all sextupoles and should therefore lead to more stability. More detailed studies have to be carried out to
4638 find the best correction scheme, but chromaticity correction is not expected to be a problem in this machine.

4639 7.3.5 Working Point

4640 Because of the bypasses and the single interaction region, the LHeC lattice has no reflection or rotation
4641 symmetry. As 50% emittance ratio is required, betatron coupling resonances may be excited and must be

4642 taken into account for the choice of the working point. In addition the beam will suffer a maximum beam-
 4643 beam tune shift of 0.086 in the horizontal and 0.088 in the vertical plane in the case of the 1° option and 0.085
 4644 in the horizontal and 0.090 in the vertical plane in the case of the 10° option. Taking all this into account, a
 4645 possible working point could be $Q_x = 122.1/Q_y = 83.13$ for the 1° optics and $Q_x = 122.1011/Q_y = 83.1283$
 4646 for the 10° optics. The working point diagrams for both cases are shown in Figs. 7.15 and 7.16.

4647 7.3.6 Aperture

4648 The current LHeC e-ring magnet apertures (see section 9.2.1) are based on the experience from LEP applied
 4649 on the LHeC arc cells. They correspond to minimum 23.0 σ hor./39.9 σ ver. in the arc dipoles, 31 σ hor./59
 4650 σ ver. in the arc quadrupoles, 9.7 σ hor./34.3 σ ver. in the insertion dipoles and 14.3 σ hor./51.0 σ ver.
 4651 in the insertion quadrupoles. In the estimate all insertions were included except the interaction region.
 4652 All values are summarised in Table 7.4, 7.5, 7.6, 7.7. The hor. aperture in the insertion dipoles could be
 4653 slightly to tight, but can be probably extended without problems over the current 20 mm half aperture.
 4654 In all calculations a gaussian profile in all three dimensions was assumed and the maximum beam size is
 4655 consequently given by:

$$\sigma_{x,y} = \sqrt{\beta_{x,y}\epsilon_{x,y} + D_{x,y}^2\sigma_E^2} \quad (7.7)$$

4656 where $\epsilon_{x,y}$ are the design emittances of 5 respectively 2.5 nm.

Hor. half apert. dipole	30 mm
Ver. half apert. dipole	20 mm
Max. hor. beta function	82.7 m
Max. hor. dispersion	0.51 m
Max. ver. beta function	100.5 m
Max. hor. beam size	0.87 mm
Max. ver. beam size	0.50 mm
Hor. apert./max. beam size	34.5
Ver. apert./max. beam size	39.9

Table 7.4: Aperture and beam sizes for the arc dipoles

Hor. half aperture dipole	30 mm
Ver. half aperture dipole	20 mm
Max. hor. beta function	126.9 m
Max. hor. dispersion	1.64 m
Max. ver. beta function	136.2 m
Max. hor. beam size	2.06 mm
Max. ver. beam size	0.58 mm
Hor. aperture/max. beam size	14.6
Ver. aperture/max. beam size	34.3

Table 7.5: Aperture and beam sizes for the insertion dipoles

Apert. radius arc quad.	30 mm
Max. hor. beta function	99.2 m
Max. hor. dispersion	0.56 m
Max. ver. beta function	103.3 m
Max. hor. beam size	0.96 mm
Max. ver. beam size	0.51 mm
Hor. apert./max. beam size	31.4
Ver. apert./max. beam size	59.0

Table 7.6: Aperture and beam sizes for the arc quadrupoles

Apert. radius quad.	30 mm
Max. hor. beta function	141.9 m
Max. hor. dispersion	1.66 m
Max. ver. beta function	138.4 m
Max. hor. beam size	2.10 mm
Max. ver. beam size	0.59 mm
Hor. apert./max. beam size	14.3
Ver. apert./max. beam size	51.0

Table 7.7: Aperture and beam sizes for the insertion quadrupoles

4657 **7.3.7 Complete Lattice and Optics**

4658 Combining all the lattice parts discussed in section 7.3.1 to 7.3.3 one obtains a lattice with the parameters
 4659 listed in Table 7.8

Beam energy	60 GeV
No. of particles per bunch	1.98×10^{10}
No. of bunches	2808
Circumference	26658.8832 m
Syn. rad. loss per turn	437.2 mev
Power	43.72 MW
Damping partition $j_x/j_y/j_e$	1.5/1/1.5
Coupling constant κ	0.5
Damping time τ_x	0.016 s
Damping time τ_y	0.024 s
Damping time τ_e	0.016 s
Polarization time	61.7 min
Horizontal emittance (no coupling)	5.53 nm
Horizontal emittance ($\kappa = 0.5$)	4.15 nm
Vertical emittance ($\kappa = 0.5$)	2.07 nm
RF voltage V_{RF}	500 MV
RF frequency f_{RF}	721.421 MHz
Energy spread	0.00116
Momentum compaction	0.00008084
Synchrotron tune	0.058
Bunch length	6.88 mm
Max. hor. beta	141.94 m
Max. ver. beta	138.43 m
Max. hor. dispersion	1.66 m
Vert. dispersion	0 m
Max. hor. beam size (5/2.5 nm emittance)	2.1 mm
Max. ver. beam size (5/2.5 nm emittance)	0.59 mm

Table 7.8: LHeC Optics Parameters

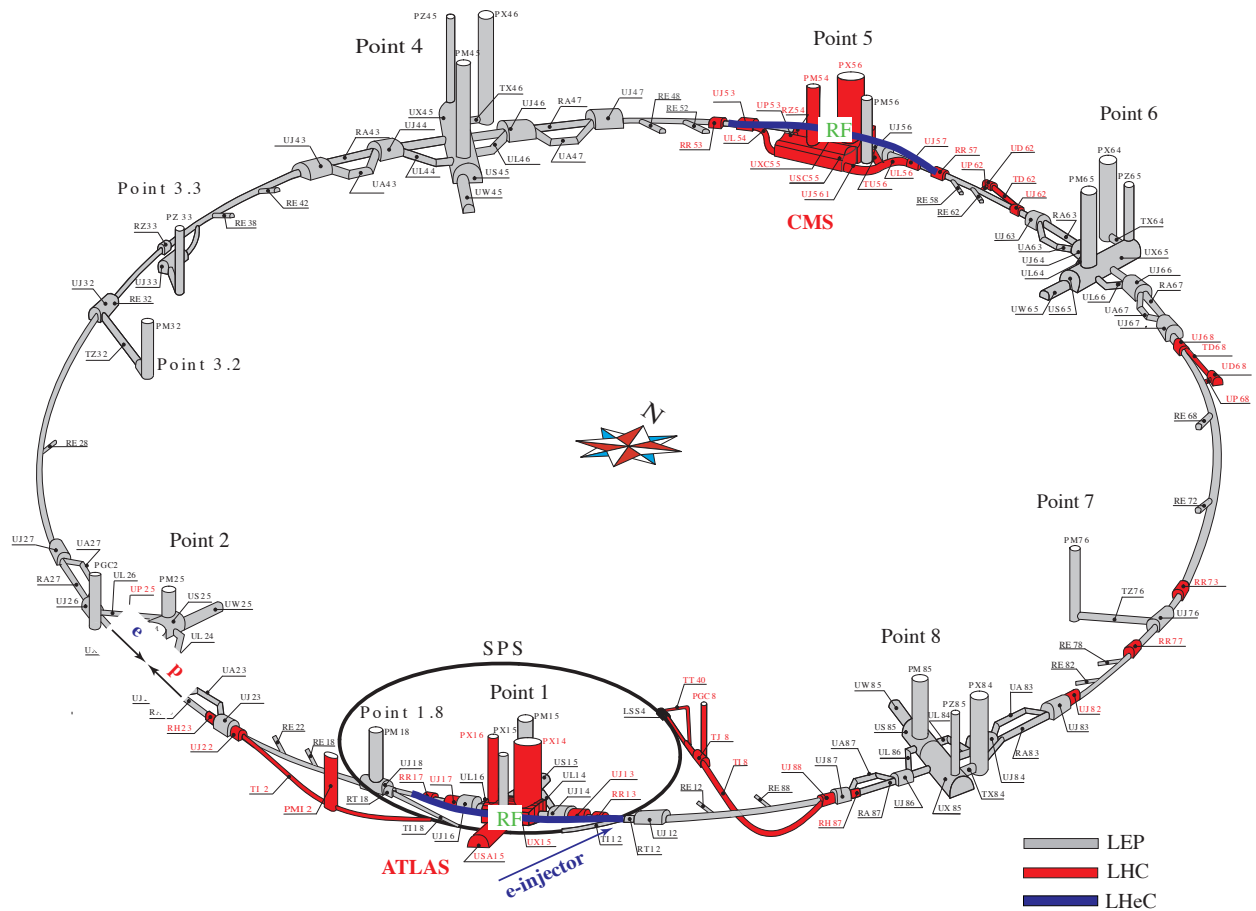


Figure 7.1: Schematic Layout of the LHeC: In grey the LEP tunnel now used for the LHC, in red the LHC extensions. The two LHeC bypasses are shown in blue. The RF is installed in the central straight section of the two bypasses. The bypass around Point 1 hosts in addition the injection.

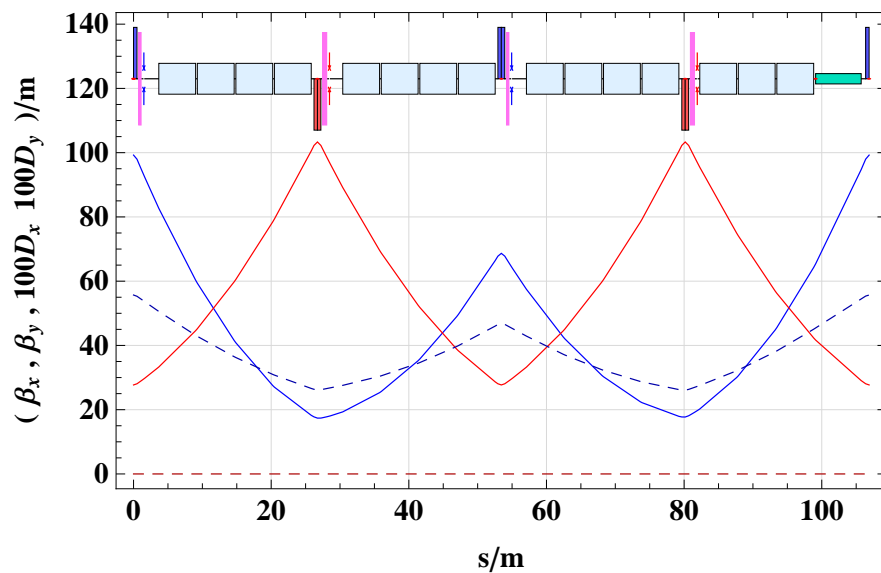


Figure 7.2: Electron ring arc cell optics. One arc cell consists of two FODO cells symmetric in the placement of the quadrupoles and asymmetric for the dipoles.

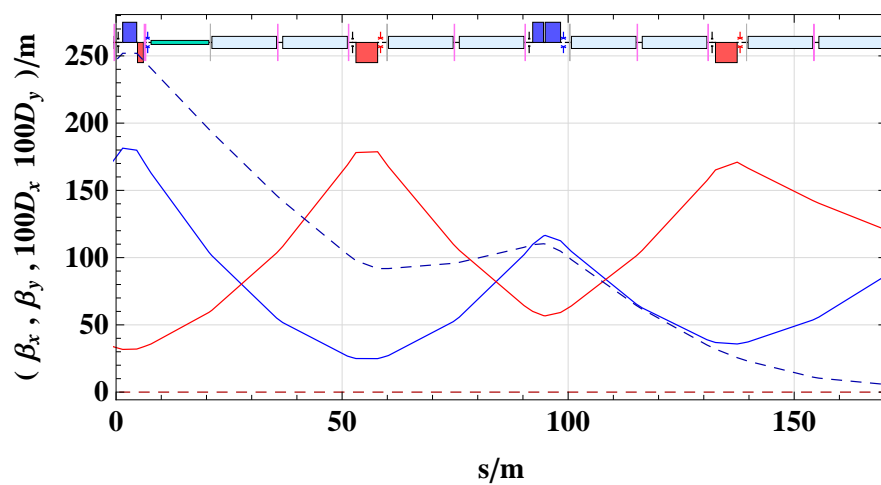


Figure 7.3: LHC DS on the left side of IP2.

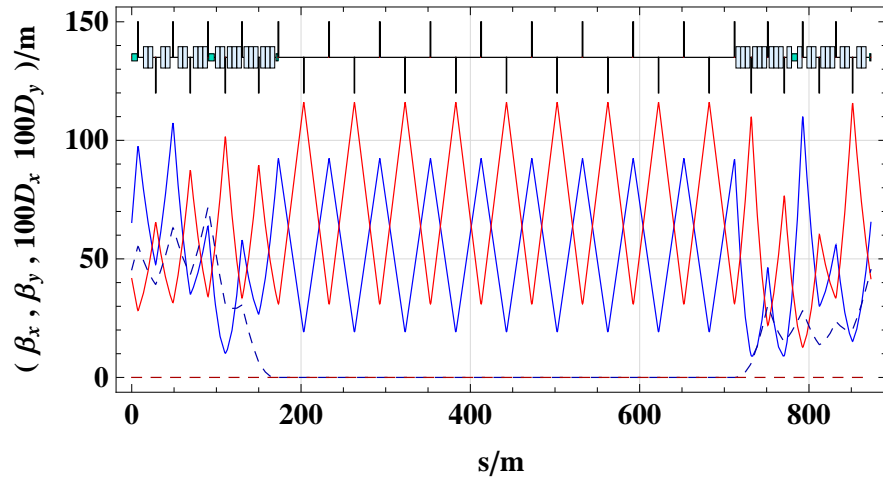


Figure 7.4: LHeC IR for even IRs, based on the DFB configuration in Point 2.

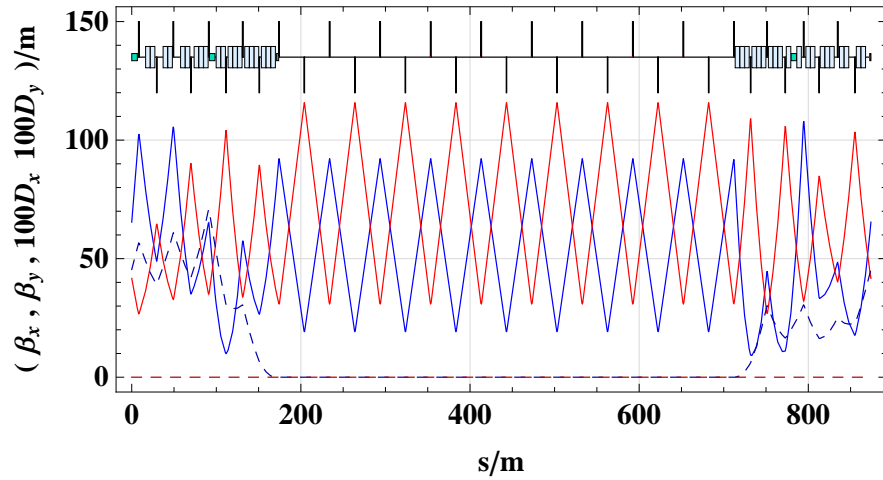


Figure 7.5: LHeC IR for odd IRs, based on the DFB configuration in Point 3.

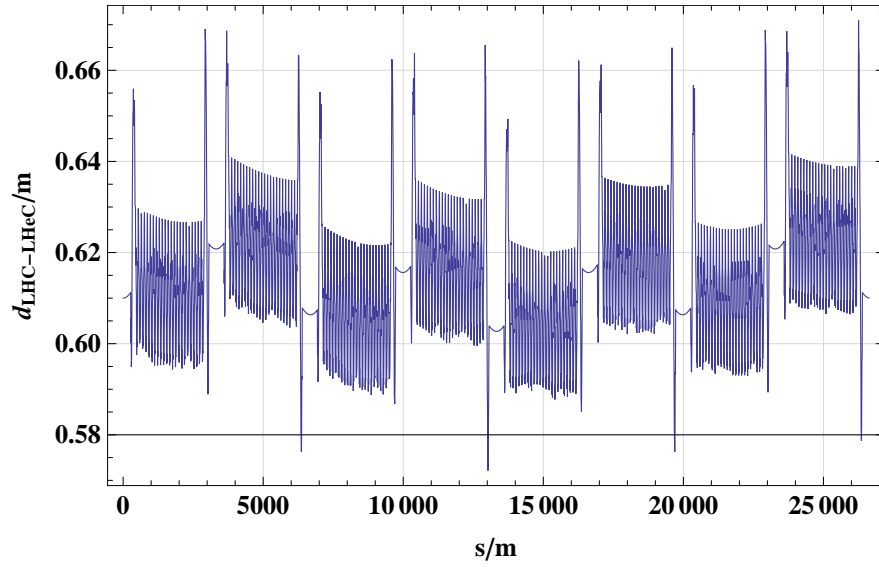


Figure 7.6: Radial distance between the idealised electron ring and the proton ring

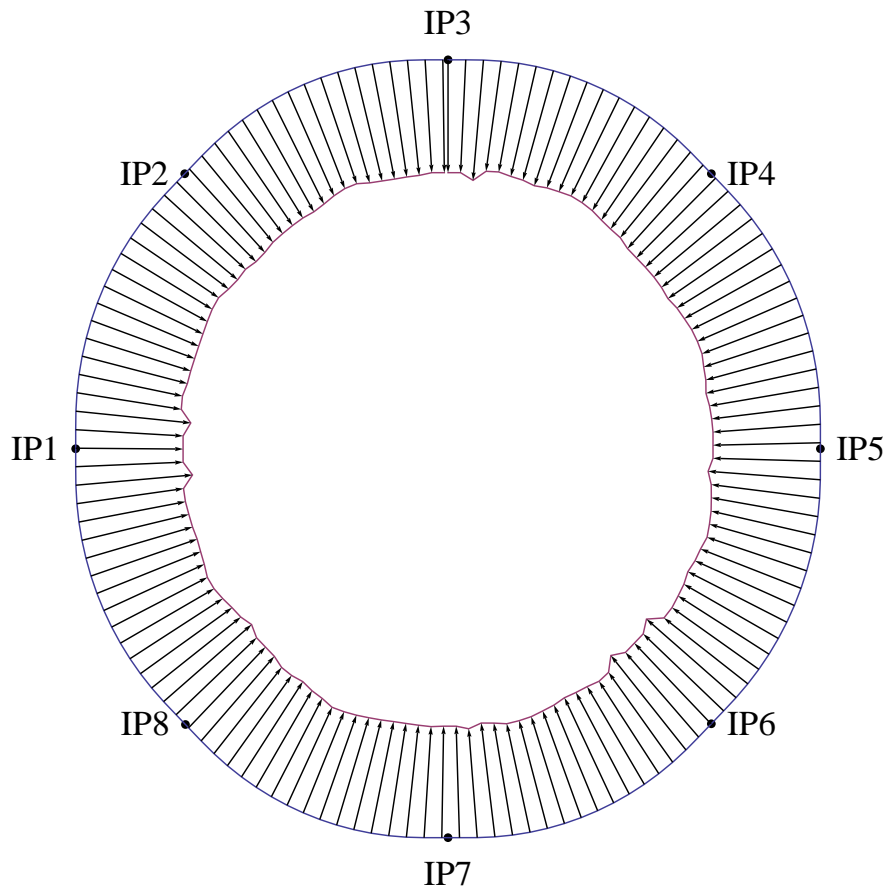


Figure 7.7: LHC and LHeC. The distance between the two rings is exaggerated by a factor 2000.

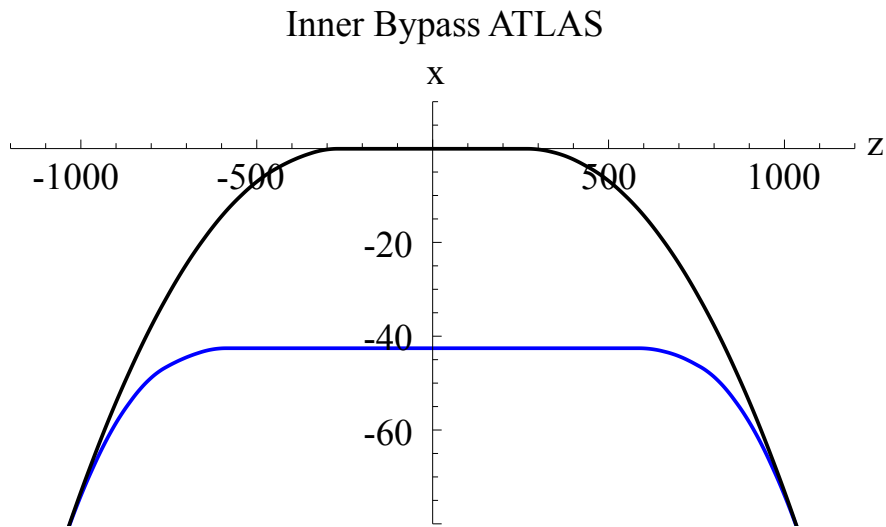


Figure 7.8: Example of an inner Bypass around Point 1. The Bypass is shown in blue, The LHC proton ring in black.

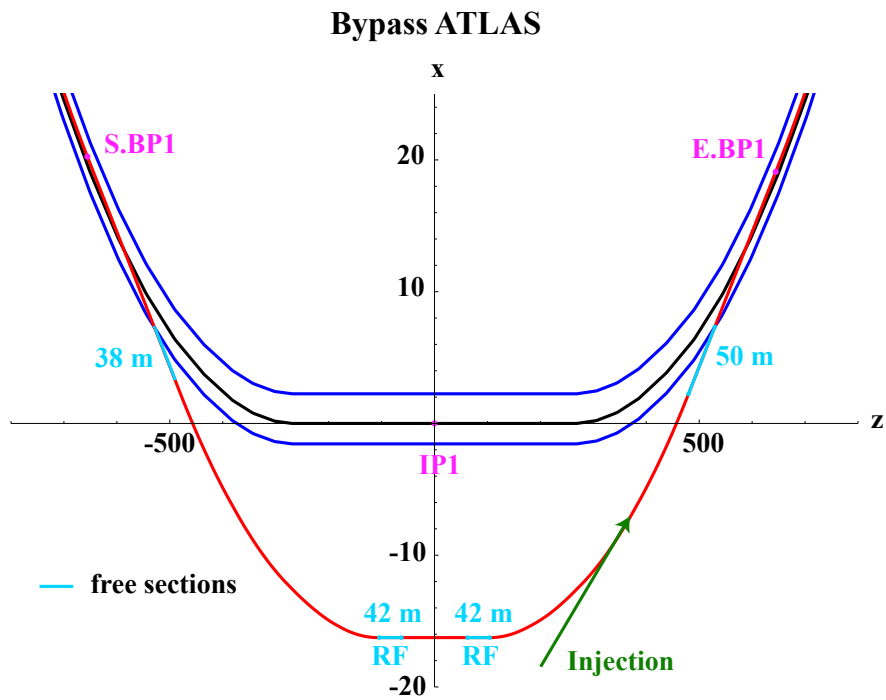


Figure 7.9: Final bypass design using the survey gallery in Point 1. The LHC proton ring is shown in black, the electron ring in red and the tunnel walls in blue. Dispersion free sections reserved for the installation of RF, wiggler(s), injection and other equipment are marked in light blue. The injection is marked in green and is located in the right arc of the bypass. Beginning and end of the bypass are marked with S.BP1 and E.BP1

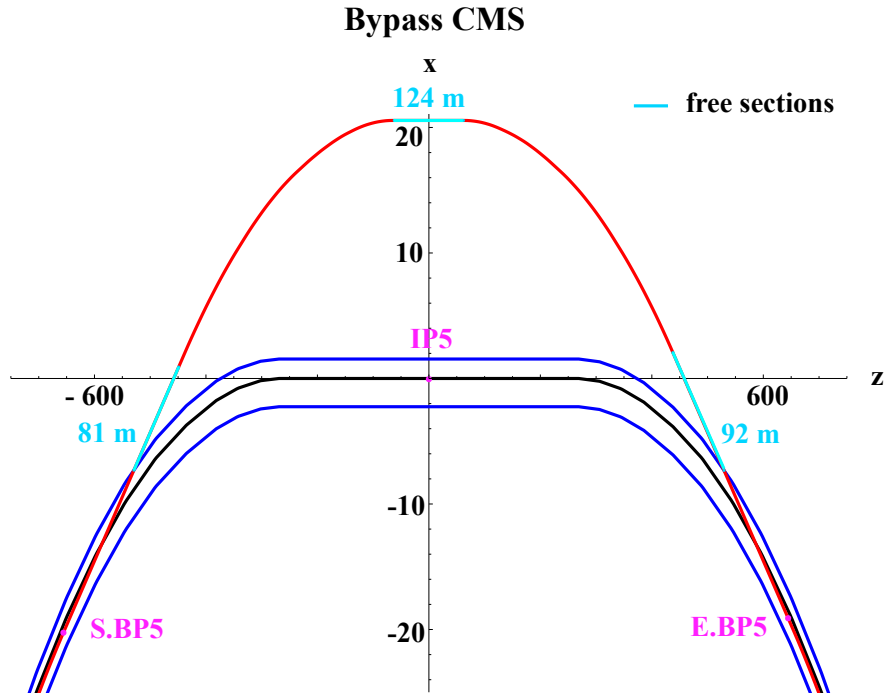


Figure 7.10: Horizontal outer bypass in Point 5. The LHC proton ring is shown in black, the electron ring in red and the tunnel walls in blue. Dispersion free sections reserved for the installation of RF, wiggler(s), injection and other equipment are marked in light blue. Beginning and end of the bypass are marked with S.BP5 and E.BP5

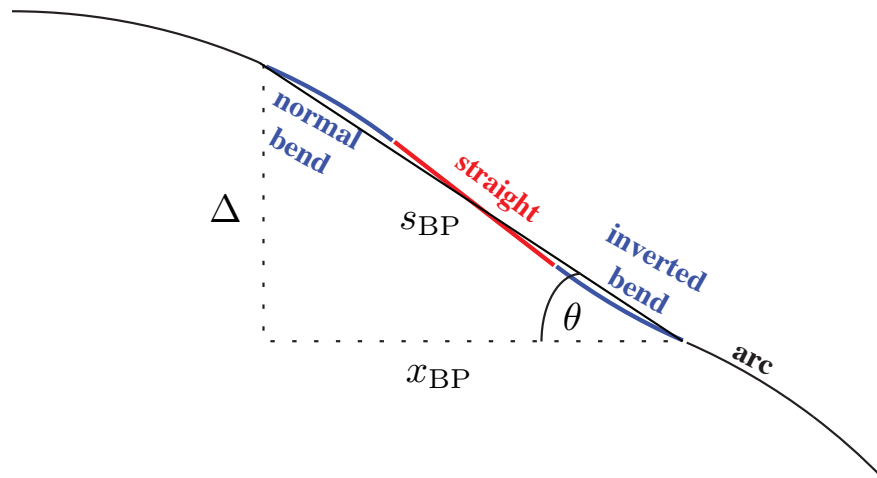


Figure 7.11: Outer bypass: a straight section is inserted to obtain the required separation. A larger separation could be achieved by inserting inverted bends.

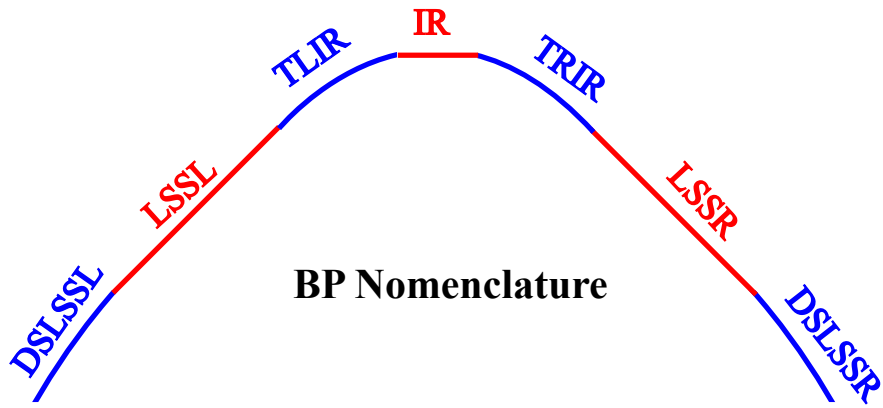


Figure 7.12: Bypass layout and nomenclature.

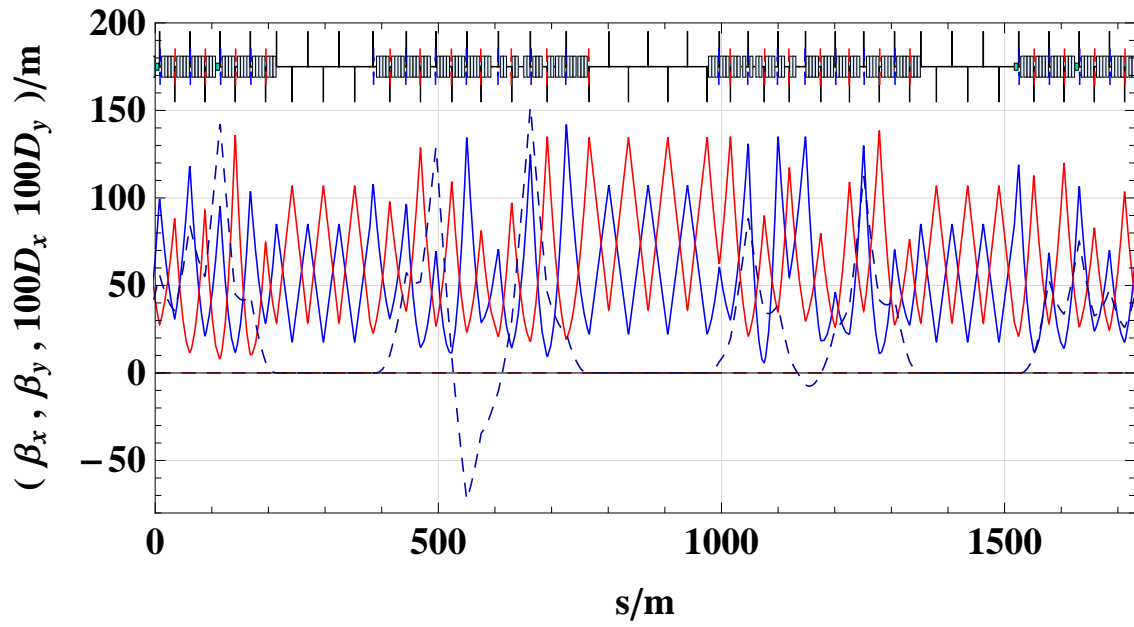


Figure 7.13: Bypass optics Point 1.

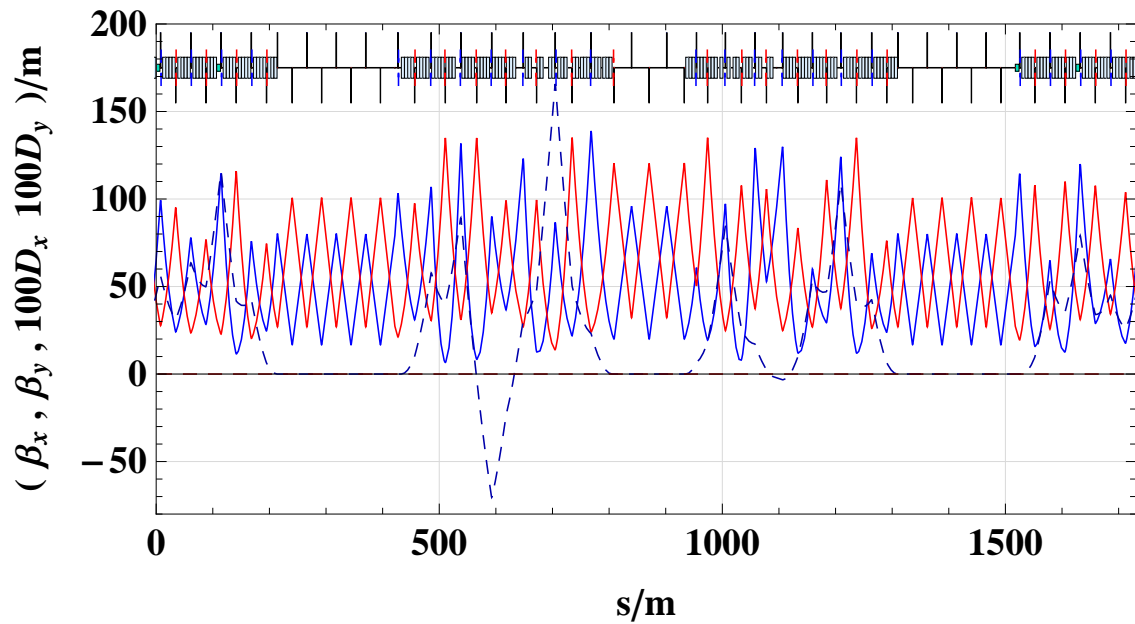


Figure 7.14: Bypass Optics Point 5.

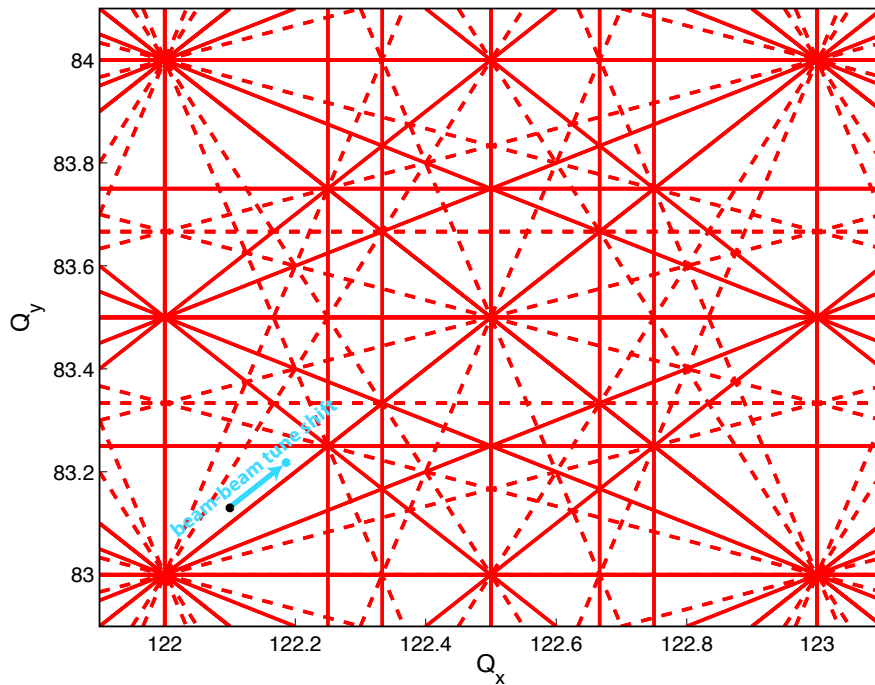


Figure 7.15: Working Point for the 1° optics. The dashed lines are the coupling resonances up to 4th order, the solid lines the constructive resonances up to 4th order. The black dot indicates the working point without beam-beam tune shift and the blue one with beam-beam tune shift.

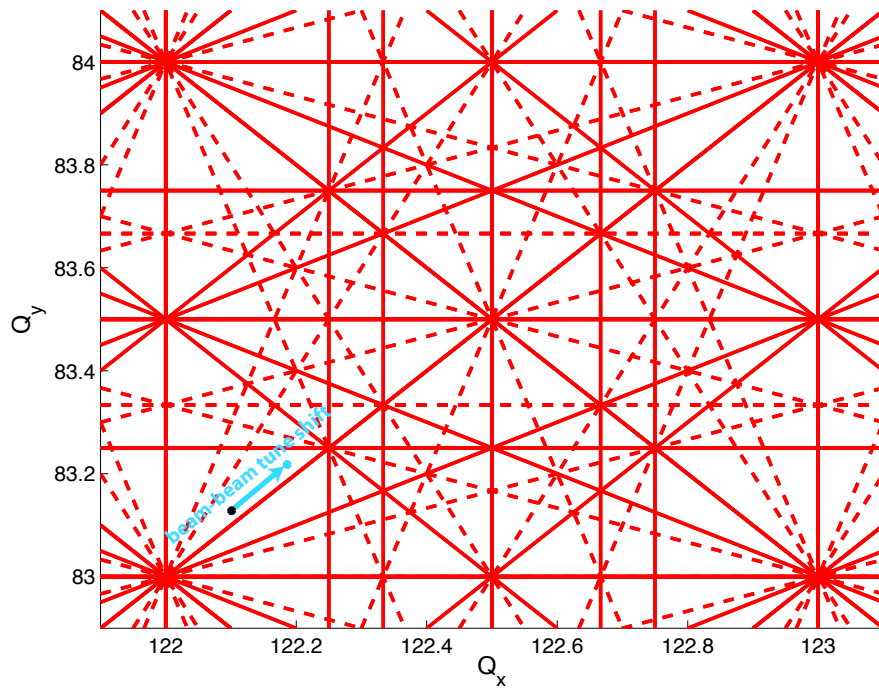


Figure 7.16: Working Point for the 10° optics. The dashed lines are the coupling resonances up to 4th order, the solid lines the constructive resonances up to 4th order. The black dot indicates the working point without beam-beam tune shift and the blue one with beam-beam tune shift.

4660 7.4 Interaction Region Layout

4661 The design of the Interaction Region (IR) of the LHeC is particularly challenging as it has to consider
4662 boundary conditions from

- 4663 • The lattice design and beam optics of the electron and proton beam
- 4664 • The geometry of the LHC experimental cavern and the tunnel
- 4665 • The beam separation scheme which is determined by the bunch pattern of the LHC standard proton
4666 operation and related to this the optimization of the synchrotron light emission and collimation
- 4667 • The technical feasibility of the hardware.

4668 Therefore the IR has to be optimized with respect to a well matched beam optics that adapts the optical
4669 parameters from the new electron-proton interaction point to the standard LHC proton beam optics in the
4670 arc and to the newly established beam optics of the electron ring. At the same time the two colliding
4671 beams as well as the non-colliding proton beam of LHC have to be separated efficiently and guided into their
4672 corresponding magnet lattices. As a general rule that has been established in the context of this study any
4673 modification in the standard LHC lattice and any impact on the LHC proton beam parameters had to be
4674 chosen moderately to avoid detrimental effects on the performance of the LHC proton-proton operation.

4675 The layout and parameters of the new e/p interaction point are defined by the particle physics require-
4676 ments. At present the physics program that has been proposed for the LHeC [568] follows two themes - a
4677 high luminosity, high Q^2 program requiring a forward and backward detector acceptance of around 10° and
4678 a low x, low Q^2 program, which requires an increased detector acceptance in forward and backward direction
4679 of at least 1° and could proceed with reduced luminosity. Accordingly two machine scenarios have been
4680 studied for the interaction region design. Firstly, a design that has been optimised for high luminosity with
4681 an acceptance of 10° and secondly, a high acceptance design that allows for a smaller opening angle of the
4682 detector. In both cases the goal for the machine luminosity is in the range of $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ but the layouts
4683 differs in the magnet lattice, the achievable absolute luminosity and mainly the synchrotron radiation that
4684 is emitted during the beam separation process. Both options will be presented here in detail and the corre-
4685 sponding design luminosity, the technical requirements and the synchrotron radiation load will be compared.
4686 In both cases however, a well matched spot size of the electron and proton beam had to be established at
4687 the collision point: Experience in SPS and HERA [569] [570] showed that matched beam cross sections have
4688 to be established between the two colliding beams to guarantee stable beam conditions. Considering the
4689 different nature of the beams, namely the emittances of the electron beam in the two transverse planes, the
4690 interaction region design has to consider this boundary condition and the beam optics has to be established
4691 to achieve equal beam sizes $\sigma_x(p) = \sigma_x(e)$, $\sigma_y(p) = \sigma_y(e)$ at the IP.

4692 The basic beam parameters however like energy, particle intensity and beam emittances are identical
4693 for both designs, determined by the electron and proton ring lattices and the pre-accelerators. They are
4694 summarised in Table 7.9.

4695 Colliding two beams of different characteristics, the luminosity obtained is given by the equation

$$L = \sum_{i=1}^{n_b} (I_e * I_p) \frac{1}{e^2 f_0 2\pi \sqrt{\sigma_{xp}^2 + \sigma_{xe}^2} \sqrt{\sigma_{yp}^2 + \sigma_{ye}^2}}, \quad (7.8)$$

4696 where $\sigma_{x,y}$ denotes the beam size of the electron and proton beam in the horizontal and vertical plane and
4697 I_e , I_p the electron and proton single bunch currents. In all IR layouts, the proton beam size at the IP is
4698 matched to the electron beam size in order to optimise the delivered luminosity and minimise detrimental
4699 beam beam effects.

4700 The main difference of the IR design for the electron proton collisions with respect to the existing LHC
4701 interaction regions is the fact that the two beams of LHeC cannot be focussed and / or guided at the
4702 same time: The different nature of the two beams, the fact that the electrons emit synchrotron radiation

Quantity	unit	e	p
Beam energy	GeV	60	7000
Total beam current	mA	100	860
Number of bunches		2808	2808
Particles/bunch N_b	10^{10}	2.0	17
Horiz. emittance	nm	5.0	0.5
Vert. emittance	nm	2.5	0.5
Bunch distance	ns	25	

Table 7.9: Main parameters for e/p collisions.

and mainly the large difference in the particle momentum make a simultaneous focusing of the two beams impossible. The strong gradients of the proton quadrupoles in the LHC triplet structure cannot be tolerated nor compensated for the electron lattice and a stable optical solution for the electrons is not achievable under the influence of the proton magnet fields. The electron beam therefore has to be separated from the proton beam after the collision point before any strong “7 TeV like” magnet field is applied.

In order to obtain still a compact design and to optimize the achievable luminosity of the new e/p interaction region, the beam separation scheme has to be combined with the electron mini-beta focusing structure.

Figure 7.17 shows a schematic layout of the interaction region. It refers to the 10 degree option and shows a compact triplet structure that is used for early focusing of the electron beam. The electron mini beta quadrupoles are embedded into the detector opening angle and in order to obtain the required separation effect they are shifted in the horizontal plane and act effectively as combined function magnets: Thus focusing and separation of the electron beam are combined in a very compact lattice structure, which is the prerequisite to achieve luminosity values in the range of $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$.

7.4.1 Beam Separation Scheme

The separation scheme of the two beams has to be optimised with respect to an efficient (i.e. fast) beam separation and a synchrotron radiation power and critical energy of the emitted photons that can be tolerated by the absorber design. Two main issues have to be accomplished: a sufficient horizontal distance between the beams has to be generated at the position of the first proton (half) quadrupole, located at a distance of $s = 22\text{m}$ from the interaction point (the nominal value of the LHC proton lattice). In addition to that, harmful beam beam effects have to be avoided at the first parasitic bunch encounters which will take place at $s = 3.75\text{m}$, as the nominal bunch distance in LHC corresponds to $\Delta t = 25\text{ns}$. These so-called parasitic bunch crossings have to be avoided as they would lead to intolerable beam-beam effects in the colliding beams. As a consequence the separation scheme has to deliver a sufficiently large horizontal distance between the two counter rotating bunches at these locations.

To achieve the first requirement a separation effect is created inside the mini beta quadrupoles of the electron beam: The large momentum difference of the two colliding beams provides a very elegant way to separate the lepton and the hadron beams: Shifting the mini-beta quadrupoles of the electron beam and installing a 15.8m long, but weak separator dipole magnet close to the IP provides the gentle separation that is needed to keep the synchrotron radiation level in the IR within reasonable limits.

The nearest proton quadrupole to the IP is designed as a half-quadrupole to ease the extraction of the outgoing electron beam. At this location (at $s=22\text{m}$) a minimum separation of $\Delta x = 55\text{mm}$ is needed to guide the electron beam along the mirror plate of a sc. proton half quadrupole (see section 9.1). A first layout of this magnet is sketched in figure 7.18

The horizontal offsets of the mini beta lenses are chosen individually in such a way that the resulting bending strength in the complete separation scheme (quadrupole triplet / doublet and separator dipole) is constant. In this way a moderate separation strength is created with a constant bending radius of $\rho = 6757\text{m}$

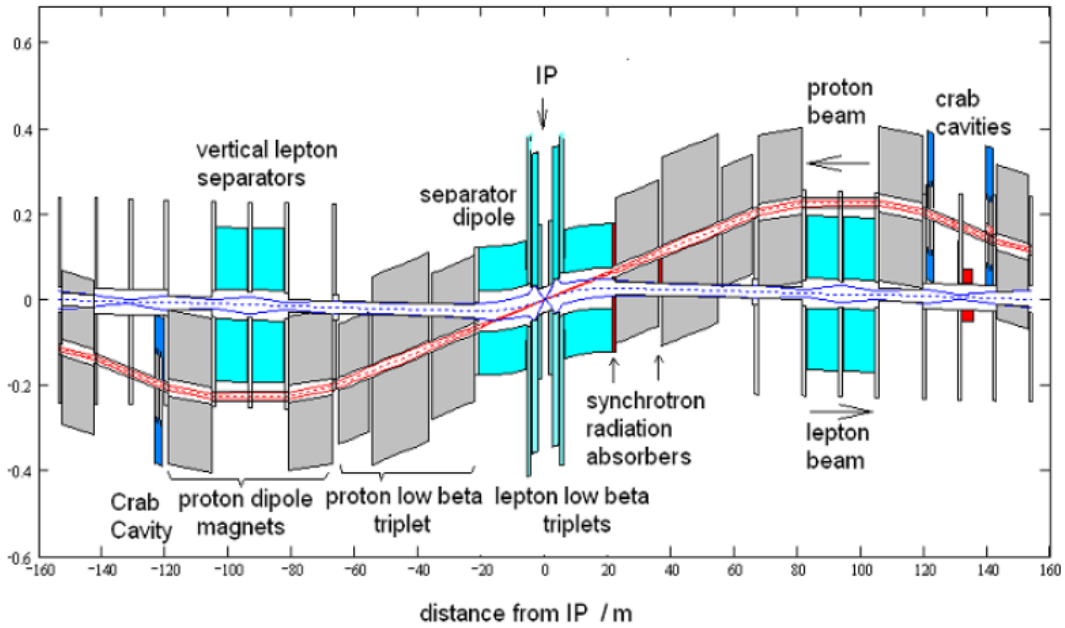


Figure 7.17: Schematic layout of the LHeC interaction region

Ring-ring option half-quadrupole, 4900 A, Gradient 137 T/m,
+ 2.5 T dipole field from feeddown

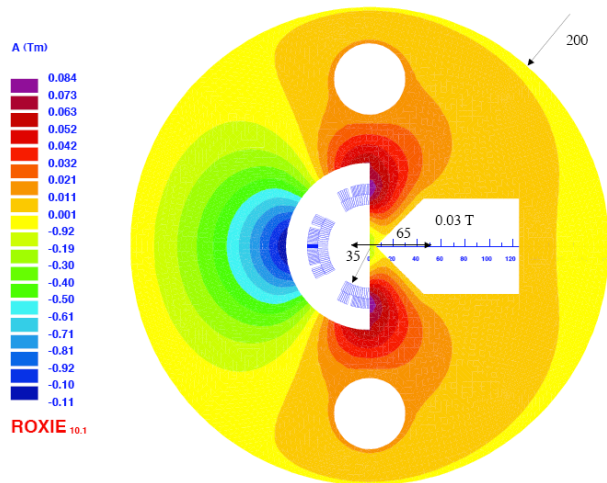


Figure 7.18: Super conducting half quadrupole in the proton lattice: The electron beam will pass on the right hand side of the mirror plate in a quasi field free region (see section 9.1).

Detector Option Quantity	unit	1°		10°	
		electrons	protons	electrons	protons
Number of bunches		2808			
Particles/bunch N_b	10^{10}	1.96	17	1.96	17
Horiz. beta-function	m	0.4	4.0	0.18	1.8
Vert. beta-function	m	0.2	1.0	0.1	0.5
Horiz. emittance	nm	5.0	0.5	5.0	0.5
Vert. emittance	nm	2.5	0.5	2.5	0.5
Distance to IP	m	6.2	22	1.2	23
Crossing angle	mrad	1.0		1.0	
Synch. Rad. in IR	kW	51		33	
absolute Luminosity	$\text{cm}^{-2} \text{s}^{-1}$	$8.54 * 10^{32}$		$1.8 * 10^{33}$	
Loss-Factor S		0.86		0.75	
effective Luminosity	$\text{cm}^{-2} \text{s}^{-1}$	$7.33 * 10^{32}$		$1.34 * 10^{33}$	

Table 7.10: Parameters of the mini beta optics for the 1° and 10° options of the LHeC Interaction Region.

4739 for the 10 degree option. In the case of the 1 degree option the quadrupole lenses of the electron lattice
4740 cannot be included inside the detector design as the opening angle of the detector does not provide enough
4741 space for the hardware of the electron ring lattice. Therefore a much larger distance between the IP and the
4742 location of the first electron lens had to be chosen ($\Delta s = 6.2\text{m}$ instead of $\Delta s = 1.2\text{m}$). As a consequence
4743 - in order to achieve the same overall beam separation - stronger magnetic separation fields have to be
4744 applied resulting in a bending radius of $\rho = 4057\text{m}$ in this case. In both cases the position of the electron
4745 quadrupoles is following the design orbit of the electron beam to avoid local strong bending fields and keep
4746 the synchrotron radiation power to a minimum. This technique has already been succesfully applied at the
4747 layout of the HERA electron-proton collider [571].
4748

4749 Still the separation at the location of the first proton magnet is small and a half quadrupole design for
4750 this super conducting magnet has been chosen at this point. The resulting beam parameters - including the
4751 expected luminosity for this ring ring option - are summarised in Table 2.

4752 It has to be pointed out in this context that the arrangement of the off centre quadrupoles as well as
4753 the strength of the separator dipole depend on the beam optics of the electron beam. The beam size at the
4754 parasitic crossings and at the proton quadrupole will determine the required horizontal distance between the
4755 electron and proton bunches. The strength and position of these magnets however will determine the optical
4756 parameters, including the dispersion function that is created during the separation process itself. Therefore
4757 a self-consistent layout concerning optics, beam separation and geometry of the synchrotron light absorbers
4758 has to be found.

4759 It is obvious that these boundary conditions have to be fulfilled not only during luminosity operation of
4760 the e/p rings. During injection and the complete acceleration procedure of the electron ring the influence
4761 of the electron quadrupoles on the proton beam has to be compensated with respect to the proton beam
4762 orbit (as a result of the separation fields) as well as to the proton beam optics: The changing deflecting
4763 fields and gradients of the electron magnets will require correction procedures in the proton lattice that will
4764 compensate this influence at any moment.

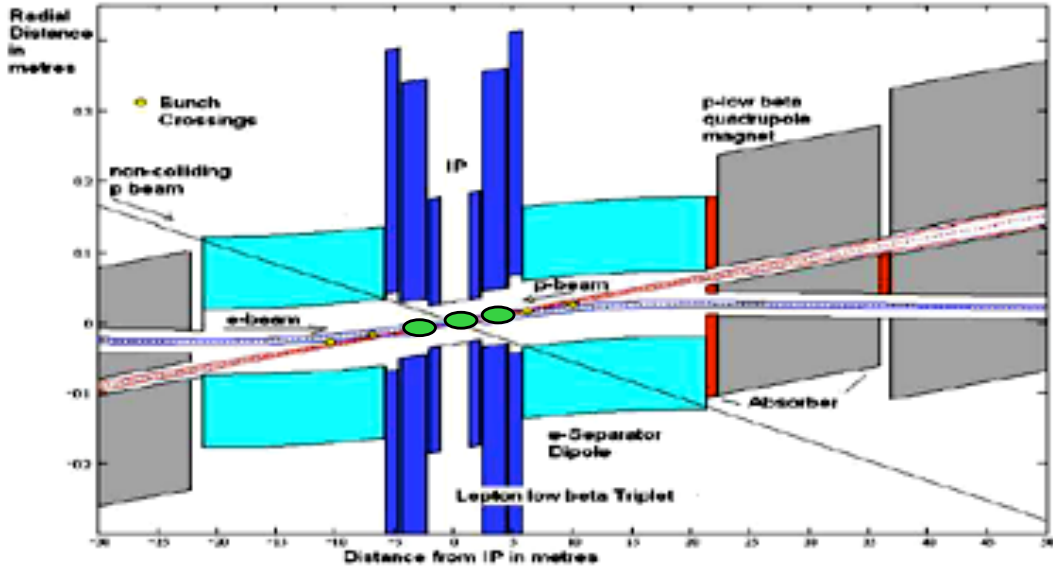


Figure 7.19: LHeC interaction region including the location of the first parasitic bunch encounters where a sufficient beam separation is achieved by a crossing angle of 1 mrad. The location of the parasitic encounters is indicated by green ovals.

7.4.2 Crossing Angle

A central aspect of the LHeC IR design is the beam-beam interaction of the colliding electron and proton bunches. The bunch structure of the electron beam will match the pattern of the LHC proton filling scheme for maximal luminosity, giving equal bunch spacings of 25 ns to both beams. The IR design therefore is required to separate the bunches as quickly as possible to avoid additional bunch interactions at these positions and limit the beam-beam effect to the desired interactions at the IP. The design bunch distance in the LHC proton bunch chain corresponds to $\Delta t = 25$ ns or $\Delta s = 7.5$ m. The counter rotating bunches therefore meet after the crossing at the interaction point at additional, parasitic collision points in a distance $s = 3.75$ m from the IP. To avoid detrimental effects from these parasitic crossings the above mentioned separation scheme has to be supported by a crossing angle that will deliver a sufficiently large horizontal distance between the bunches at the first parasitic bunch crossings. This technique is used in all LHC interaction points. In the case of the LHeC however, the crossing angle is determined by the emittance of the electron beam and the resulting beam size which is considerably larger than the usual proton beam size in the storage ring. In the case of the LHeC IR a crossing angle of $\theta = 1$ mrad is considered as sufficient in the 1° as well as in the 10° option to avoid beam-beam effects from this parasitic crossings. Figure 7.19 shows the position of the first possible parasitic encounters and the effect of the crossing angle to deliver a sufficient separation at these places.

The detailed impact of one beam on another is evaluated by a dedicated beam-beam interaction study which is included in this report, based on a minimum separation of $5\sigma_e + 5\sigma_p$ at every parasitic crossing node. Due to the larger electron emittance the separation is mainly dominated by the electron beam parameters, and as a general rule it can be stated that the rapid growth of the β -function in the drift around the IP,

$$\beta(s) = \beta^* + \frac{s^2}{\beta^*}, \quad (7.9)$$

makes it harder to separate the beams if small β^* and a large drift space s is required in the optical design.

In any design for the LHeC study, a crossing angle is used to establish an early beam separation, reduce

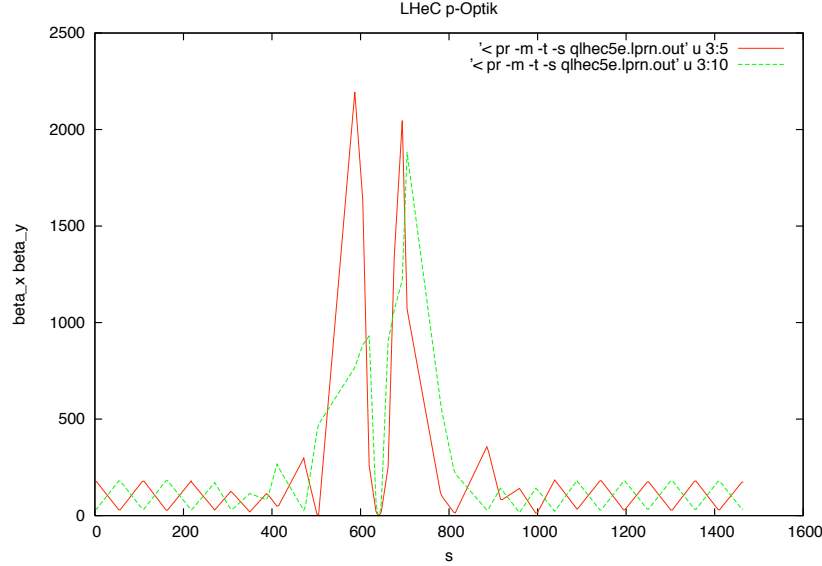


Figure 7.20: Proton optics for the LHeC interaction region. The gradients of the antisymmetric triplet lattice in the standard LHC have been modified to adopt for the requirements of the LHeC flat beam parameters.

4788 the required strength in the separation magnets and minimise the synchrotron radiation power that is created
 4789 inside the interaction region.

4790 As a draw back however the luminosity is reduced due to the fact that the bunches will not collide
 4791 anymore head on. This reduction is expressed in a geometric luminosity reduction factor “S”, that depends
 4792 on the crossing angle θ , the length of the electron and proton bunches σ_{ze} and σ_{zp} and the transverse beam
 4793 size in the plane of the bunch crossing σ_x^* :

$$S(\theta) = \left[1 + \left(\frac{\sigma_{sp}^2 + \sigma_{se}^2}{2\sigma_x^{*2}} \right) \tan^2 \frac{\theta}{2} \right]^{-\frac{1}{2}} . \quad (7.10)$$

4794

4795

4796 Accordingly, the effective luminosity that can be expected for a given IR layout is obtained by

$$L = S(\theta) * L_0 \quad (7.11)$$

4797

4798

4799 For the two beam optics that have been chosen for this design study (the 1° and the 10° option) and a
 4800 crossing angle of $\theta = 1\text{mrad}$ the loss factor amounts to $S = 74\%$ and $S = 85\%$ respectively.

4801 7.4.3 Beam Optics and Luminosity

4802 A special boundary condition had to be observed in the design of the proton beam optics of the LHeC:
 4803 For the layout of the four present proton-proton interaction regions in the LHC machine an anti-symmetric
 4804 option had been chosen: A solution that is appropriate for a round beam optics ($\sigma_x^* = \sigma_y^*$). An optimised
 4805 design for collisions with the flat e^\pm beams however requires unequal β -functions for the hadron beam at
 4806 the IP and the existing LHC optics can no longer be maintained. Therefore the optical layout of the existing
 4807 triplet structure in the LHC had to be modified to match the required beta functions ($\beta_x = 1.8\text{m}$, $\beta_y =$
 4808 0.5m) at the IP to the regular optics of the FODO structure in the arc (Figure 7.20).

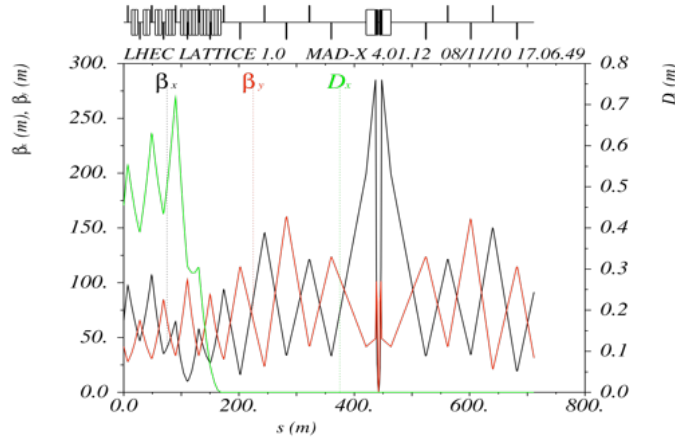


Figure 7.21: Electron optics for the LHeC interaction region. The plot corresponds to the 10 degree option where a triplet structure combined with a separation dipole has been chosen to separate the two beams.

4809 In the case of the electron beam optics, two different layouts of the interaction region are considered: One
 4810 optical concept for highest achievable luminosity and a solution for maximum detector acceptance. In the
 4811 first case an opening angle of 10° is available inside the detector geometry and allows to install an embedded
 4812 magnet structure where the first electron quadrupole lenses can be placed as close as $s = 1.2\text{m}$ from the IP.
 4813 This early focusing scheme leads to moderate values of the β function inside the mini beta quadrupoles and
 4814 therefore allows for a smaller spot size at the IP and larger luminosity values can be achieved. Still however
 4815 the quadrupoles require a compact design: While the gradients required by the optical solution are small
 4816 (for a super conducting magnet design) the outer radius of the first electron quadrupole has been limited to
 4817 $r_{max} = 210\text{mm}$.

4818 In the case of the 1° option the detector design is optimised for largest detector acceptance. Accordingly
 4819 the opening angle of the detector hardware is too small to deliver space for accelerator magnets. The mini
 4820 beta quadrupoles therefore have to be located outside the detector, and a distance $s = 6\text{m}$ from the IP had
 4821 to be chosen in this case. Even if the magnet dimensions are not limited by the detector design in this case,
 4822 the achievable luminosity is about a factor of two smaller than in the 10° case.

4823 The two beam optics that are based on these considerations are discussed in detail in the next chapter of
 4824 this report. In the case of the 10° option a triplet structure has been chosen to allow for moderate values
 4825 of the beta functions inside the mini beta quadrupoles. As a special feature of the optics that is shown in
 4826 Figure 7.21 the focusing effect of the first quadrupole magnet is moderate: Its gradient has been limited
 4827 as it has to deliver mainly the first beam separation. Table 7.10 includes as well the overall synchrotron
 4828 radiation power that is produced inside the IR. Due to the larger bending radius (i.e. smaller bending forces)
 4829 in the case of the 10° option the produced synchrotron radiation power is limited to about 30 kW, while the
 4830 alternative - high acceptance - option has to handle 50kW of synchrotron light.

4831 The details of the synchrotron light characteristics are covered in the next chapters of this report for both
 4832 cases, including the critical energies and the design of the required absorbers.

4833 For the 1° option the mini beta focusing is based on a quadrupole doublet as the space limitations in
 4834 the transverse plane are much more relaxed compared to the alternative option and the main issue here
 4835 was to find a compact design in the longitudinal coordinate: Due to the larger distance of the focusing
 4836 and separating magnets from the IP the magnet structure has to be more compact and the separating
 4837 field stronger to obtain the required horizontal beam distance at the location $s = 22\text{m}$ of the first proton
 4838 quadrupole. The corresponding beam optics for both options are explained in full detail below.

4839 Once the beams are separated into independent beam pipes, the electron beam must be transported into
 4840 the ring lattice. Quadrupoles are used in the electron machine LSS to transport the beam from the IP to
 4841 the dispersion suppressor and match twiss parameters at either end. This matching must be smooth and
 4842 not require infeasible apertures. In addition the first electron quadrupoles will be located inside the detector
 4843 hardware and therefore a compact design is required within the limited space available.

4844
 4845 The complete design of the long straight section "LSS", that includes the mini beta insertion, the matching
 4846 section and the dispersion suppressor must be designed around a number of further constraints. As well as
 4847 beam separation, the electron beam must be steered from the electron ring into the IR and back out again.
 4848 The colliding proton beam must be largely undisturbed by the electron beam. The non-colliding proton
 4849 beam must be guided through the IR without interacting with either of the other beams.

4850 7.4.4 High Luminosity IR Layout

4851 Parameters

4852 Table 7.11 details the interaction point parameters and other parameters for this design. To optimise for
 4853 luminosity, a small l^* is desired. An acceptance angle of 10° is therefore chosen, which gives an l^* of 1.2m
 4854 for final focusing quadrupoles of reasonable size.

$L(0)$	1.8×10^{33}
θ	1×10^{-3}
$S(\theta)$	0.746
$L(\theta)$	1.34×10^{33}
β_x^*	0.18 m
β_y^*	0.1 m
σ_x^*	3.00×10^{-5} m
σ_y^*	1.58×10^{-5} m
SR Power	33 kW
E_c	126 keV

Table 7.11: Parameters for the High Luminosity IR.

4855 SR calculations are detailed in section [7.4.7]. The total power emitted in the IR is similar to that in the
 4856 HERA-2 IR [reference] and as such appears to be reasonable, given enough space for absorbers.

4857 Layout

4858 Due to the relatively round beam spot aspect ratio of 1.8:1, a final quadrupole triplet layout has been chosen
 4859 for this design. The relatively weak horizontal focussing quadrupole used as first magnet lens is mainly
 4860 needed for beam separation, followed by two strong, nearly doublet like quadrupoles. The focusing strength
 4861 Figure 7.22 and table 7.12 detail the layout.

4862
 4863 The l^* of 1.2 m allows both strong focusing of the beam, and constant bending of the beam from 1.2 m to
 4864 21.5 m. This is achieved with offset quadrupoles and a separation dipole.

4865
 4866 Figure 7.23 shows the β functions of the beam in both planes from the IP to the face of the final proton
 4867 quadrupole at $s = 23$ m.

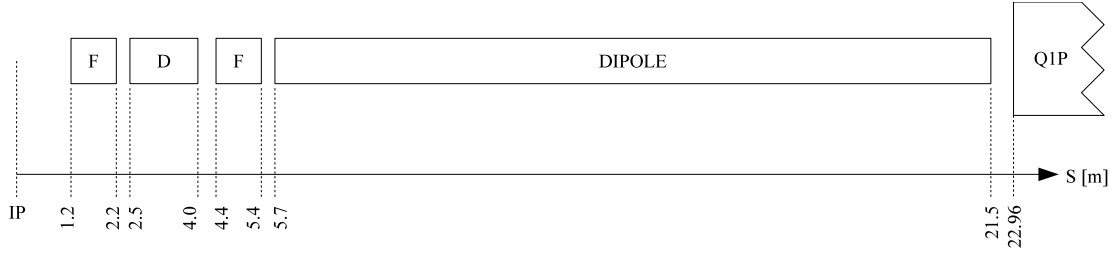


Figure 7.22: Layout of machine elements in the High Luminosity IR. Note that the left side of the IR is symmetric.

Element	S_{entry} [m]	L [m]	Gradient [T/m]	Dipole Field [T]	Offset [m]
BS.L	-21.5	15.8	-	-0.0296	-
Q3E.L	-5.4	1.0	89.09229	-0.0296	-3.32240×10^{-4}
Q2E.L	-4	1.5	-102.2013	-0.0296	2.89624×10^{-4}
Q1E.L	-2.2	1.0	54.34071	-0.0296	-5.44711×10^{-4}
IP	0.0	-	-	-	-
Q1E.R	1.2	1.0	54.34071	0.0296	5.44711×10^{-4}
Q2E.R	2.5	1.5	-102.2013	0.0296	-2.89624×10^{-4}
Q3E.R	4.4	1.0	89.09229	0.0296	3.32240×10^{-4}
BS.R	5.7	15.8	-	-0.0296	-

Table 7.12: Machine elements for the High Luminosity IR. S_{entry} gives the leftmost point of the idealised magnetic field of an element. Note that S is relative to the IP.

4868 Separation Scheme

4869 As described above a quadrupole triplet configuration is used for the first focusing of the electron beam. This
 4870 has the effect of generating a larger peak in β_x , between parasitic crossings but leads to smaller horizontal
 4871 beam sizes at these locations and therefore reduces the necessary beam separation. The first F quadrupole
 4872 reduces β_x at $s = 3.75$ m compared to an initial D quadrupole. The third F quadrupole then brings β_x down
 4873 from the peak sufficiently to avoid large beam-beam interactions at the second parasitic crossing, $s = 7.5$ m.

4874

4875 Separation is provided by the bending effect of the offset quadrupoles, and also the IP crossing angle of
 4876 1 mrad. These elements ensure that the separation between the beams, normalised to beam size, increases
 4877 at each parasitic crossing. Note that 1 mrad is not a minimum crossing angle required by beam-beam in-
 4878 teraction separation criteria; it is however a chosen balance between luminosity loss and minimising bend
 4879 strength. In theory, this layout could support an IP with no crossing angle; however the bend strength
 4880 required to achieve this would generate an undesirable level of SR power.

4881 Optics Matching and IR Geometry

4882 The IR is matched into the ring arc lattice by means of matching quads in the LSS. The quads are roughly
 4883 evenly placed, with sufficient space left after the IR section to accommodate the proton optics and the re-
 4884 maining electron ring geometry, which has yet to be designed fully. The solution is nearly symmetric about
 4885 the IP; however due to the geometry of the LHC lattice, the electron ring itself is not exactly symmetric. As
 4886 such the solution differs slightly on either side of the LSS. Table 7.13 details the layout of machine elements

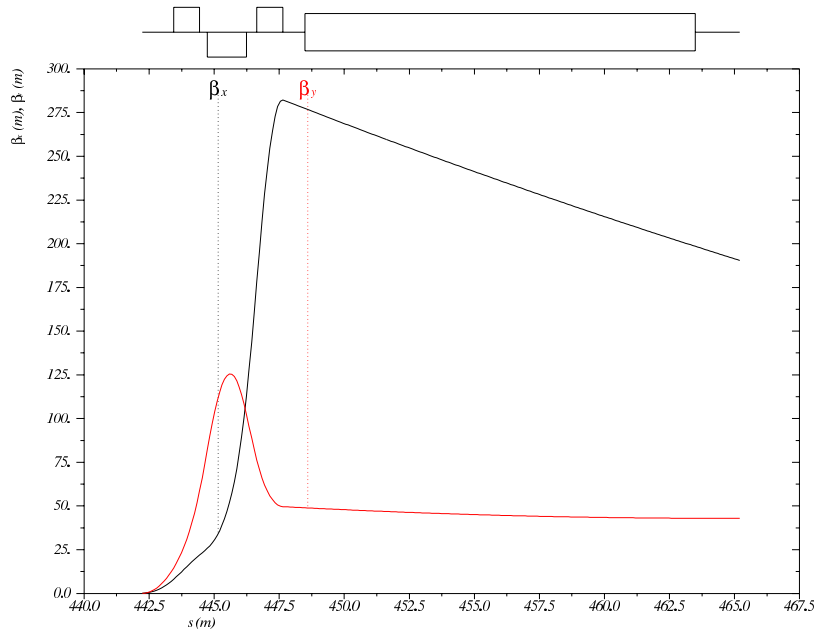


Figure 7.23: β functions in both planes for the High Luminosity IR layout, from the IP to the face of the final proton quadrupole at $s = 23$ m. Note that s is relative to the ring, which begins at the left side of the left dispersion suppressor of IP2.

4887 in the LSS. Five matching quadrupoles are used on either side of the IP. A sixth quadrupole is used on the
 4888 left side, next to the dispersion suppressor. Due to the asymmetric design of the dispersion suppressors,
 4889 a quadrupole (MQDSF.L2) is included at the same distance from the IP on the right side as part of the
 4890 dispersion suppressor. MQDSF.L2 is required to match the optics, but is more constrained than the other
 4891 matching quadrupoles. Figure 7.24 shows the β functions of the matching from the IP to the dispersion
 4892 suppressor, on both sides of the IP (Figure 7.25)

4893

4894 A smooth matching is obtained, where the maximum beta functions are well controlled and continuously
 4895 reduced to the values of the arc structure. The beam envelopes in the LSS are of reasonable size and do not
 4896 require excessive aperture.

4897

4898 Note that this solution is not yet matched for dispersion as the rest of the ring geometry in the LSS and IR
 4899 areas is yet to be designed.

4900 Plans for the remaining IR geometry include a second horizontal dipole, and quadrupoles, on either side to
 4901 turn each separation dipole into a dispersion-free S-shaped bend. This will be used to extract the beam into
 4902 the electron machine.

4903 7.4.5 High Acceptance IR Layout

4904 Parameters

4905 Table 7.14 details the design parameters for this option. The chosen detector opening angle for this layout
 4906 is 1° . All elements, especially the mini beta quadrupoles of the electron ring, therefore have to be placed
 4907 outside the limits of the detector, at $z = \pm 6.2$ m, where z is the longitudinal axis of the detector. As such,
 4908 the actual acceptance of the layout is limited by the beam pipe rather than the size of machine elements.
 4909 This also gives further flexibility in the strengths and designs of the final focusing quadrupoles, although

Element	S_{entry} [m]	L [m]	Gradient [T/m]
MQDSF.L2	-268.8944	1.0	8.451030
MQDM5.L2	-240.5	1.0	-7.306991
MQFM4.L2	-199.5	1.0	6.529028
MQDM3.L2	-162.5	1.0	-6.561684
MQFM2.L2	-120.5	1.0	6.140239
MQDM1.L2	-82.5	1.0	-5.127192
MQDM1.R2	81.5	1.0	-5.286055
MQFM2.R2	119.5	1.0	6.171258
MQDM3.R2	161.5	1.0	-6.641329
MQFM4.R2	198.5	1.0	7.058192
MQDM5.R2	239.5	1.0	-7.26769

Table 7.13: Machine elements for the High Luminosity LSS layout. S_{entry} gives the leftmost point of the idealised magnetic field of an element. Note that S is relative to the IP.

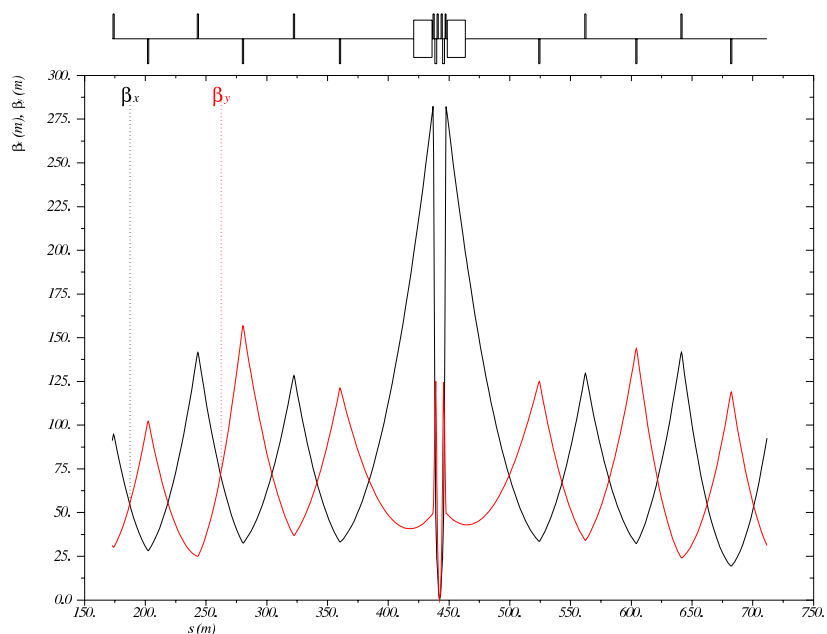


Figure 7.24: β functions in both planes for the High Luminosity IR layout, from the end of the left dispersion suppressor to the start of the right dispersion suppressor. Note that s is relative to the ring, which begins at the left side of the left dispersion suppressor of IP2.

4910 this flexibility is not exploited in the design.

4911

4912 SR calculations are discussed in detail in section [7.4.7]. The total power emitted in the IR is similar to
 4913 that in the HERA-2 IR [reference] and as such appears to be reasonable, given enough space for absorbers.
 4914 However it is significantly higher than that in the high luminosity layout. As discussed in section [7.4.7], an
 4915 option exists to reduce the total SR power by including a dipole field in the detector, thus mitigating the
 4916 limitation imposed on dipole length by the larger l^* .

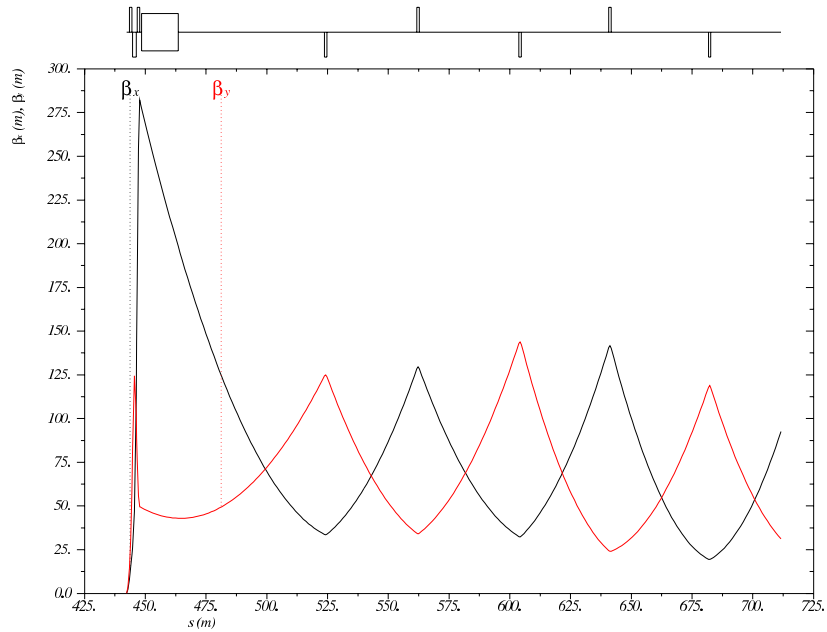


Figure 7.25: β functions in both planes for the High Luminosity IR layout, from the IP to the start of the right dispersion suppressor. Note that s is relative to the ring, which begins at the left side of the left dispersion suppressor of IP2.

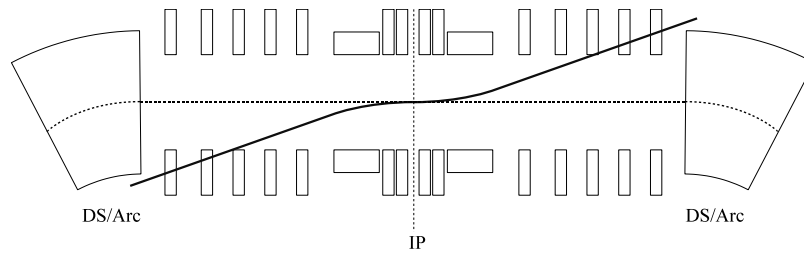


Figure 7.26: Graphical representation of misaligned LSS/IR geometry. With beam steering in the IR and no compensation in the LSS, the electron beam no longer lines up with the ring lattice reference orbit. Diagram is not to scale and does not represent the correct optical layout of the IR nor the LSS.

4917 **Layout and separation scheme**

4918 A symmetric final quadrupole doublet layout has been chosen for this design. The beam spot aspect ratio of
 4919 2:1 is marginally flatter than the High Luminosity layout, and as such a triplet is less suitable. Figure 7.27
 4920 and table 7.15 detail the layout.

4921
 4922 The l^* of 6.2m imposes limitations on focusing and bending in this layout. Focusing is limited by quadratic
 4923 β growth through a drift space, which is increased for smaller β^* . As such, lower instantaneous luminosity
 4924 is attainable.

4925
 4926 As in the high luminosity option the beam separation will be achieved by a combination of a adequate
 4927 crossing angle and the separation fields of off-centre quadrupole magnets. However, due to the large free

$L(0)$	8.54×10^{32}
θ	1×10^{-3}
$S(\theta)$	0.858
$L(\theta)$	7.33×10^{32}
β_x^*	0.4 m
β_y^*	0.2 m
σ_x^*	4.47×10^{-5} m
σ_y^*	2.24×10^{-5} m
SR Power	51 kW
E_c	163 keV

Table 7.14: Parameters for the High Acceptance IR.

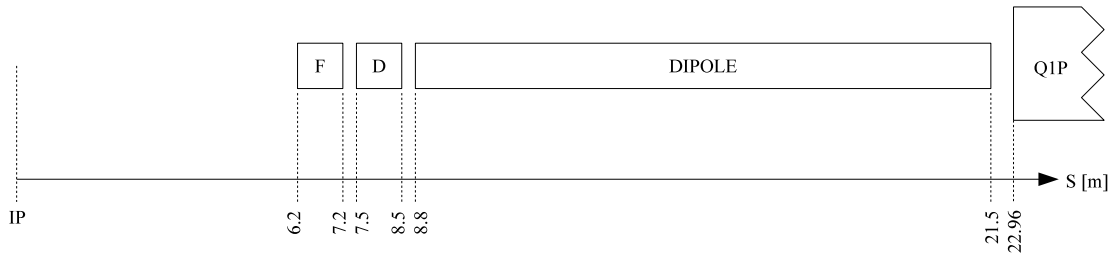


Figure 7.27: Layout of machine elements in the High Acceptance IR. Note that the left side of the IR is symmetric.

Element	S_{entry} [m]	L [m]	Gradient [T/m]	Dipole Field [T]	Offset [m]
BS.L	-21.5	12.7	-	-0.0493	-
Q2E.L	-8.5	1.0	-77.30906	-0.0493	6.37700×10^{-4}
Q1E.L	-7.2	1.0	90.38473	-0.0493	-5.45446×10^{-4}
IP	0.0	-	-	-	-
Q1E.R	6.2	1.0	90.38473	0.0493	5.45446×10^{-4}
Q2E.R	7.5	1.0	-77.30906	0.0493	-6.37700×10^{-4}
BS.R	8.8	12.7	-	0.0493	-

Table 7.15: Machine elements for the High Acceptance IR. S_{entry} gives the leftmost point of the idealised magnetic field of an element. Note that S is relative to the IP.

4928 space of $z=6$ m to the IP, stronger fields have to be applied to obtain the same geometric separation at the
 4929 first proton quadrupole.

4930 Figure 7.28 shows the β functions of the beam in both planes from the IP to the face of the final proton
 4931 quadrupole at $s = 23$ m.

4932 Optics Matching and IR Geometry

4933 The lattice that is used to match the IR optics to the periodic arc structure corresponds to a large extent to
 4934 the one presented for the high luminosity option. Figure 7.29 shows the β functions of the matching from

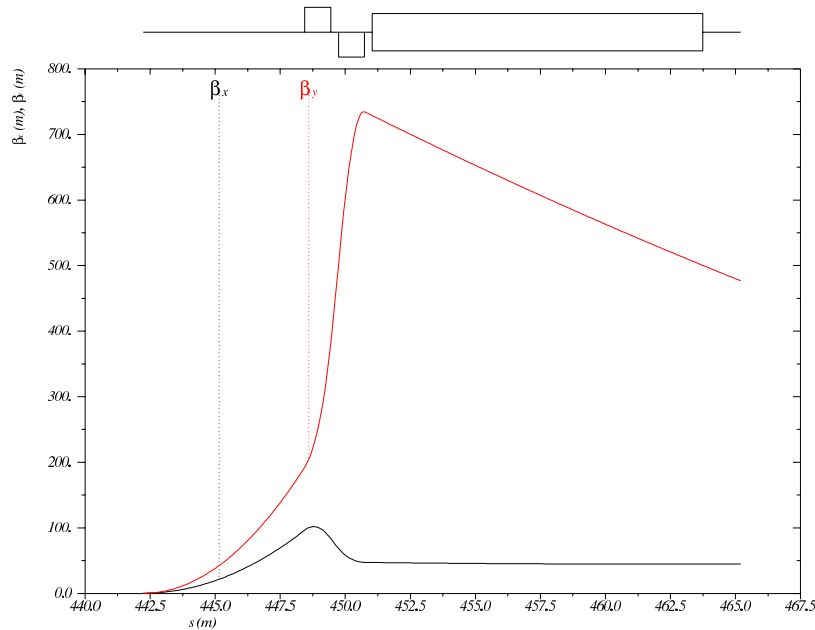


Figure 7.28: β functions in both planes for the High Acceptance IR layout, from the IP to the face of the final proton quadrupole at $s = 23$ m. Note that s is relative to the ring, which begins at the left side of the left dispersion suppressor of IP2.

4935 the IP to the dispersion suppressor, on both sides of the IP (Figure 7.30).

4936

4937 As with the High Luminosity layout, a smooth matching is obtained, with the IR β peaks being brought
 4938 down and controlled before being matched into the arc solution. The beam envelopes in the LSS are of
 4939 reasonable size and do not require excessive aperture.

4940

4941 Other geometric issues must again be addressed, which are briefly discussed in section 7.4.4.

4942 7.4.6 Comparison of High Luminosity and High Acceptance Options

4943 Table 7.17 shows a direct comparison of various parameters of the two layouts.

4944

4945 The difference in luminosity after considering the loss factor S due to the crossing angle, is a factor of 1.8.
 4946 However it should be noted that this design strives for technical feasibility and both layouts could be squeezed
 4947 further to decrease β^* in both planes. The High Luminosity layout could likely be squeezed further than the
 4948 High Acceptance layout due to the large difference in l^* , as shown in figure 7.31 which compares the two IR
 4949 layouts. At this stage both designs deliver their required IP parameters of luminosity and acceptance and
 4950 appear to be feasible.

4951

4952 The High Acceptance design generates a higher level of SR power. This still appears to be within rea-
 4953 sonable limits and is discussed in section [7.4.7]. Furthermore, an option is discussed to install a dipole
 4954 magnet in the detector. This early separation would reduce the required strength of the dipole fields in the
 4955 IR, significantly reducing total SR power.

Element	S_{entry} [m]	L [m]	Gradient [T/m]
MQDSF.L2	-268.8944	1.0	9.635332
MQFM6.L2	-237.5	1.0	-7.436781
MQDM5.L2	-205.5	1.0	7.676403
MQFM4.L2	-174.5	1.0	-6.025603
MQDM3.L2	-143.5	1.0	6.396806
MQFM2.L2	-111.5	1.0	-9.183061
MQDM1.L2	-80.5	1.0	5.786843
MQDM1.R2	79.5	1.0	5.786843
MQFM2.R2	110.5	1.0	-9.183061
MQDM3.R2	142.5	1.0	6.396806
MQFM4.R2	173.5	1.0	-5.894718
MQDM5.R2	204.5	1.0	7.289766
MQFM6.R2	236.5	1.0	-7.150586

Table 7.16: Machine elements for the High Acceptance LSS layout. S_{entry} gives the leftmost point of the idealised magnetic field of an element. Note that S is relative to the IP.

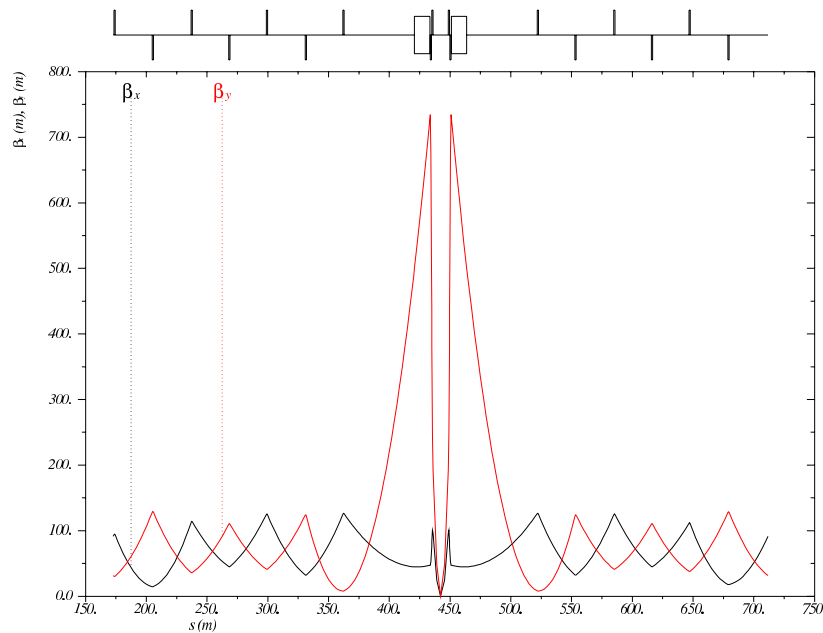


Figure 7.29: β functions in both planes for the High Acceptance IR layout, from the end of the left dispersion suppressor to the start of the right dispersion suppressor. Note that s is relative to the ring, which begins at the left side of the left dispersion suppressor of IP2.

4956 7.4.7 Synchrotron radiation and absorbers

4957 Introduction

4958 The synchrotron radiation (SR) in the interaction region has been analyzed in three ways. The SR was

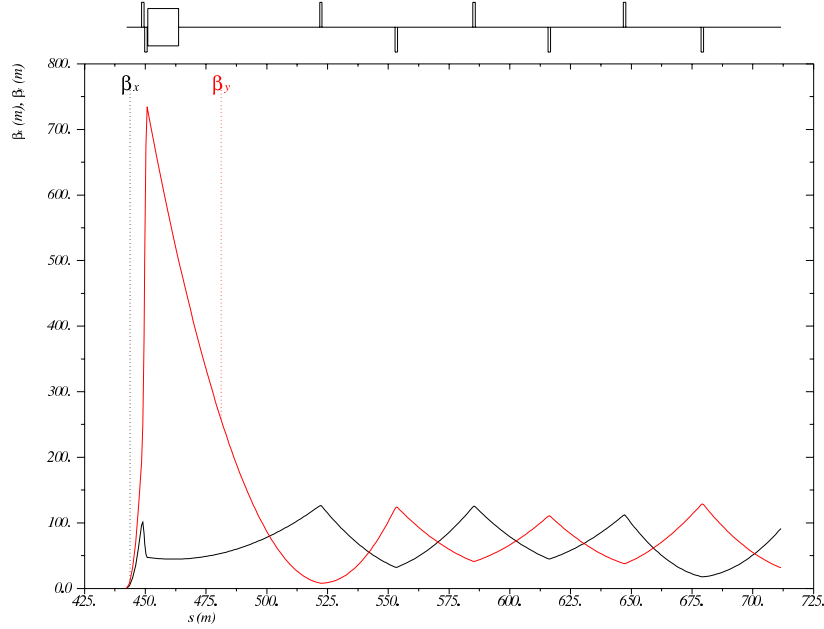


Figure 7.30: β functions in both planes for the High Luminosity IR layout, from the IP to the start of the right dispersion suppressor. Note that s is relative to the ring, which begins at the left side of the left dispersion suppressor of IP2.

Parameter	HL	HA
$L(0)$	1.8×10^{33}	8.54×10^{32}
θ	1×10^{-3}	1×10^{-3}
$S(\theta)$	0.746	0.858
$L(\theta)$	1.34×10^{33}	7.33×10^{32}
β_x^*	0.18 m	0.4 m
β_y^*	0.1 m	0.2 m
σ_x^*	3.00×10^{-5} m	4.47×10^{-5} m
σ_y^*	1.58×10^{-5} m	2.24×10^{-5} m
SR Power	33 kW	51 kW
E_c	126 keV	163 keV

Table 7.17: Parameters for the High Luminosity IR.

4959 simulated in depth using a program made with the Geant4 (G4) toolkit. In addition a cross check of the
 4960 total power and average critical energy was done in IRSYN, a Monte Carlo simulation package written by
 4961 R. Appleby. [572] A final cross check has been made for the radiated power per element using an analytic
 4962 method. These other methods confirmed the results seen using G4. The G4 program uses Monte Carlo
 4963 methods to create gaussian spatial and angular distributions for the electron beam. The electron beam is
 4964 then guided through vacuum volumes that contain the magnetic fields for the separator dipoles and electron
 4965 final focusing quadrupoles.

4966 The SR is generated in these volumes using the appropriate G4 process classes. The G4 SR class was
 4967 written for a uniform magnetic field, and therefore the quadrupole volumes were divided such that the

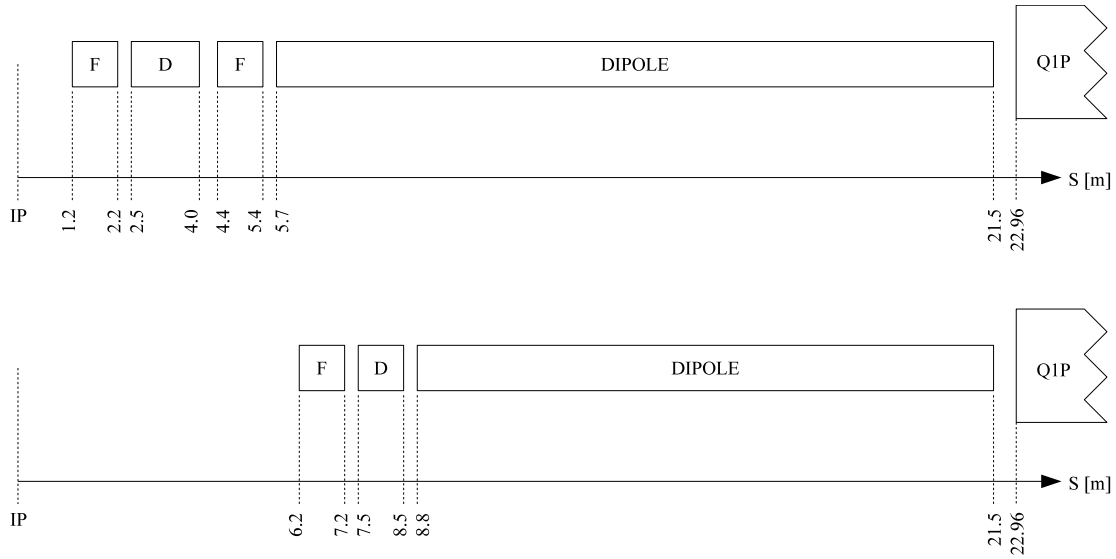


Figure 7.31: Scale comparison of the layouts for the High Luminosity and High Acceptance designs. Note the large difference in l^* .

4968 field remained approximately constant in each volume. This created agreement between upstream and
 4969 downstream quadrupoles since for a downstream quadrupole the beta function at the entrance and exit are
 4970 reversed from its upstream counterpart. This agreement confirms that the field was approximately constant
 4971 in each volume.

4972 The position, direction, and energy of each photon created is written as n-tuples at user defined Z values.
 4973 These n-tuples are then used to analyze the SR fan as it evolves in Z. The analysis was done primarily
 4974 through the use of MATLAB scripts. It was necessary to make two versions of this program. One for the
 4975 high luminosity design and one for the high detector acceptance design.

4976 Before going further I will explain some conventions used for this section. I will refer to the electron
 4977 beam as *the beam* and the proton beams will be referred to as either the interacting or non interacting
 4978 proton beams. The beam propagates in the $-Z$ direction and the interacting proton beam propagates in the
 4979 $+Z$ direction, I will use a right handed coordinate system where the X axis is horizontal and the Y axis is
 4980 vertical. The beam centroid always remains in the $Y = 0$ plane. The *angle of the beam* will be used to refer
 4981 to the angle between the beam centroid's velocity vector and the Z axis, in the $Y = 0$ plane. This angle is
 4982 set such that the beam propagates in the $-X$ direction as it traverses Z.

4983 The SR fans extension in the horizontal direction is driven by the angle of the beam at the entrance
 4984 of the upstream separator dipole. Because the direction of emitted photons is parallel to the direction of
 4985 the electron that emitted it, the angle of the beam and the distance to the absorber are both greatest at
 4986 the entrance of the upstream separator dipole and therefore this defines one of the edges of the synchrotron
 4987 fan on the absorber. The other edge is defined by the crossing angle and the distance from the IP to the
 4988 absorber. The S shaped trajectory of the beam means that the smallest angle of the beam will be reached
 4989 at the IP. Therefore the photons emitted at this point will have the lowest angle and for this given angle the
 4990 smallest distance to the absorber. This defines the other edge of the fan in the horizontal direction.

4991 The SR fans extension in the vertical direction is driven by the beta function and angular spread of the
 4992 beam. The beta function along with the emittance defines the r.m.s. spot size of the beam. The vertical
 4993 spot size defines the Y position at which photons are emitted. On top of this the vertical angular spread
 4994 defines the angle between the velocity vector of these photons and the Z axis. Both of these values produce
 4995 complicated effects as they are functions of Z. These effects also affect the horizontal extension of the fan

4996 however are of second order when compared to the angle of the beam. Since the beam moves in the $Y = 0$
 4997 plane these effects dominate the vertical extension of the beam.

4998 The number density distribution of the fan is a complicated issue. The number density at the absorber
 4999 is highest between the interacting beams. The reason for this is that although the separator dipoles create
 5000 significantly more photons the number of photons generated per unit length in Z is much lower for the dipoles
 5001 as opposed to the quadrupoles due to the high fields experienced in the quadrupoles. The position of the
 5002 quadrupole magnets then causes the light radiated from them to hit the absorber in the area between the
 5003 two interacting beams.

5004 High Luminosity

5005 **Parameters:** The parameters for the high luminosity option are listed in Table 7.18. The separation refers
 5006 to the displacement between the two interacting beams at the face of the proton triplet.

Characteristic	Value
Electron Energy [GeV]	60
Electron Current [mA]	100
Crossing Angle [mrad]	1
Absorber Position [m]	-21.5
Dipole Field [T]	0.0296
Separation [mm]	55
γ/s	5.39×10^{18}

Table 7.18: High Luminosity: Parameters

5007 The energy, current, and crossing angle (θ_c) are common values used in all RR calculations. The dipole
 5008 field value refers to the constant dipole field created throughout all dipole elements in the IR. The direction
 5009 of this field is opposite on either side of the IP. The quadrupole elements have an effective dipole field created
 5010 by placing the quadrupole off axis, which is the same as this constant dipole field. The field is chosen such
 5011 that 55 mm of separation is reached by the face of the proton triplet. This separation was chosen based on
 5012 S. Russenschuck's SC quadrupole design for the proton final focusing triplet. [573] The separation between
 5013 the interacting beams can be increased by raising the constant dipole field. However, for a dipole magnet
 5014 $P_{SR} \propto |B^2|$, [574] therefore an optimization of the design will need to be discussed. The chosen parameters
 5015 give a flux of 5.39×10^{18} photons per second at $Z = -21.5$ m.

5016 **Power and Critical Energy:** Table 7.19 shows the power of the SR produced by each element along
 5017 with the average critical energy produced per element. This is followed by the total power produced in the
 5018 IR and the average critical energy. Since the G4 simulations utilize Monte Carlo, multiple runs should be
 5019 made with various seeds to get an estimate for the standard error.

5020 The power from the dipoles is greater than any one quadrupole however the critical energies of the
 5021 quadrupoles are significantly higher than in the dipoles. It is expected that the dipole and quadrupole
 5022 elements can create power on the same order however have very different critical energies. This is because
 5023 the dipole is an order of magnitude longer than the quadrupole elements. Since the SR power created for
 5024 both the quadrupole and dipoles are linearly dependent on length [574] one needs to have a much higher
 5025 average critical energy to create comparable amounts of power.

5026 **Comparison:** The IRSYN cross check of the power and critical energies is shown in Table 7.20. This
 5027 comparison was done for the total power and the average critical energy.

Element	Power [kW]	Critical Energy [keV]
DL	6.4	71
QL3	5.3	308
QL2	4.3	218
QL1	0.6	95
QR1	0.6	95
QR2	4.4	220
QR3	5.2	310
DR	6.4	71
Total/Avg	33.2	126

Table 7.19: High Luminosity: Power and Critical Energies as calculated with Geant4.

	Power [kW]		Critical Energy [keV]	
	Geant4	IRSYN	Geant4	IRSYN
Total/Avg	33.2	33.7	126	126

Table 7.20: High Luminosity: Geant4 and IRSYN comparison

5028 A third cross check to the G4 simulations was made for the power as shown in Table 7.21. This was done
5029 using an analytic method for calculating power in dipole and quadrupole magnets. [574] This was done for
5030 every element which provides confidence in the distribution of this power throughout the IR.

Element	Power [kW]	
	Geant4	Analytic
DL	6.4	6.3
QL3	5.3	5.4
QL2	4.3	4.6
QL1	0.6	0.6
QR1	0.6	0.6
QR2	4.4	4.6
QR3	5.2	5.4
DR	6.4	6.3
Total/Avg	33.2	33.8

Table 7.21: High Luminosity: Geant4 and Analytic method comparison

5031 **Number Density and Envelopes:** The number density of photons as a function of Z is shown in Figure
5032 7.32. Each graph displays the density of photons in the $Z = Z_o$ plane for various values of Z_o . The first three
5033 figures give the growth of the SR fan inside the detector area. This is crucial for determining the dimensions
5034 of the beam pipe. Since the fan grows asymmetrically in the $-Z$ direction an asymmetric elliptical cone
5035 geometry will minimize these dimensions, allowing the tracking to be placed as close to the beam as possible.
5036 The horizontal extension of the fan in the high luminosity case is the minimum for the two Ring Ring options
5037 as well as the Linac Ring option, which is most important inside the detector region. This is due to the

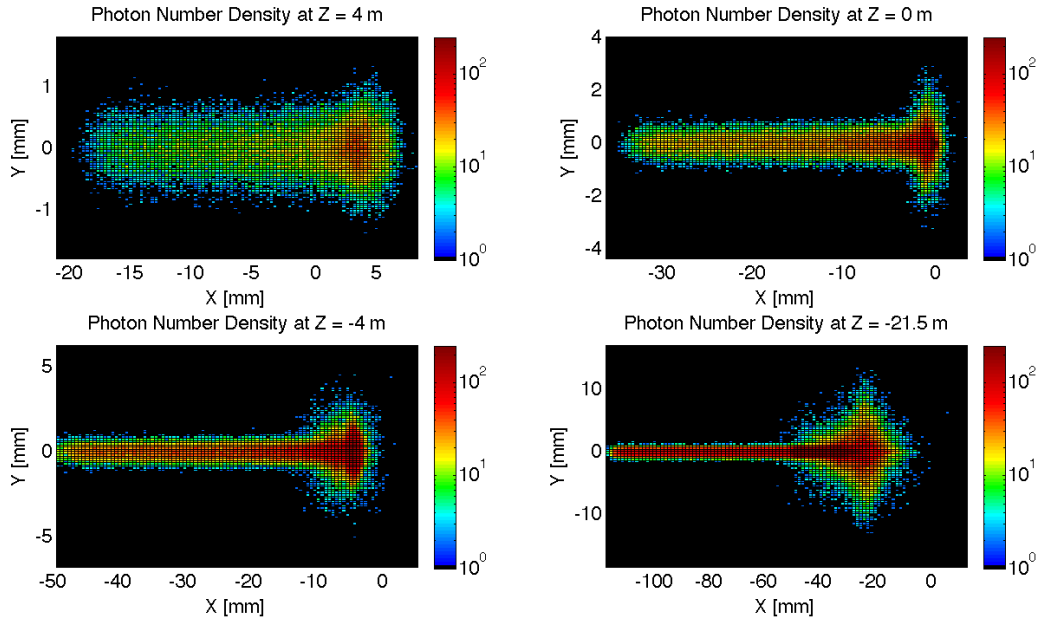


Figure 7.32: High Luminosity: Number Density Growth in Z

5038 lower value of l^* . Because the quadrupoles are closer to the IP and contain effective dipole fields the angle
 5039 of the beam at the entrance of the upstream dipole can be lower as the angle of the beam doesn't need to
 5040 equal the crossing angle until $Z = l^*$. The number density of this fan appears as expected. There exists the
 5041 highest density between the two beams at the absorber.

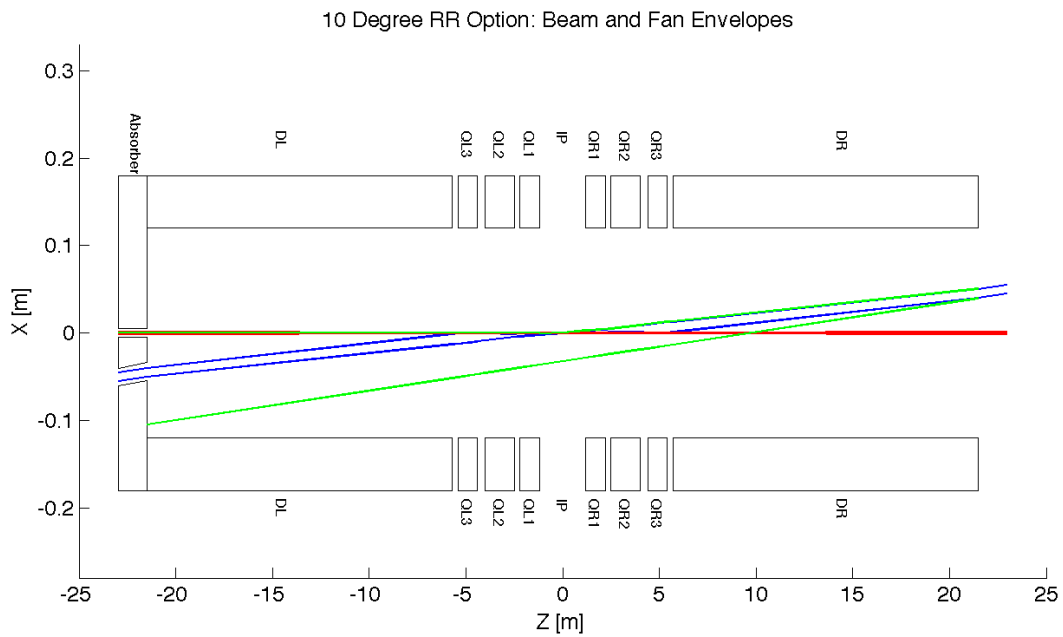


Figure 7.33: High Luminosity: Beam Envelopes in Z

5042 In Figure 7.32 the distribution was given at various Z values however a continuous envelope distribution is
 5043 also important to see everything at once. This can be seen in Figure 7.33, where the beam and fan envelopes
 5044 are shown in the Y = 0 plane. This makes it clear that the fan is antisymmetric which comes from the S
 5045 shape of the electron beam as previously mentioned.

5046 **Critical Energy Distribution:** The Critical Energy is dependent upon the element in which the SR is
 5047 generated, and for the quadrupole magnets it is also dependent upon Z. This is a result of the fact that the
 5048 critical energy is proportional to the magnetic field component that is perpendicular to the particle direction.
 5049 i.e. $E_c \propto B_{\perp}$. [575] Since the magnitude of the magnetic field is dependent upon x and y, then for a gaussian
 5050 beam in position particles will experience different magnetic fields and therefore have a spectrum of critical
 5051 energies. In a dipole the field is constant and therefore regardless of the position of the particles as long as
 5052 they are in the uniform field area of the magnet they have a constant critical energy. Since the magnetic
 5053 field is dependent upon x and y it is clear that as the r.m.s. spot size of the beam decreases there will be a
 5054 decrease in critical energies. The opposite will occur for an increasing spot size. This is evident from Figure
 5055 7.34.

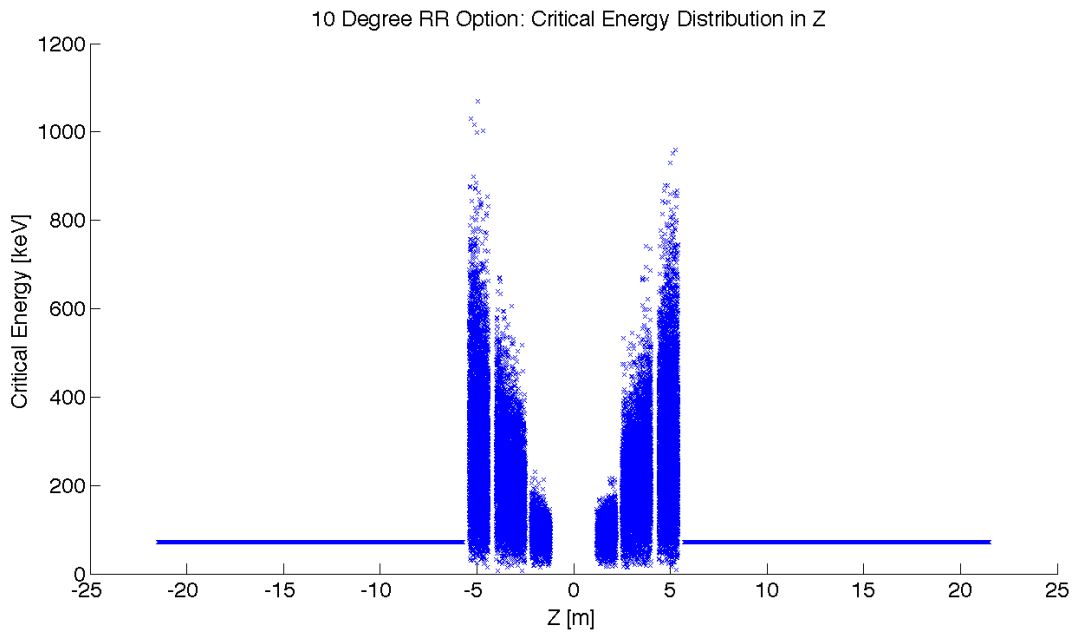


Figure 7.34: High Luminosity: Critical Energy Distribution in Z

5056 **Absorber:** The Photon distribution on the absorber surface is crucial. The distribution decides how the
 5057 absorber must be shaped. The shape of the absorber in addition to the distribution on the surface then
 5058 decides how much SR is backscattered into the detector region. In HERA backscattered SR was a significant
 5059 source of background that required careful attention. [576] Looking at Figure 7.35 it is shown that for the
 5060 high luminosity option 19.2 kW of power from the SR light will fall on the face of the absorber which is
 5061 58% of the total power. This gives a general idea of the amount of power that will be absorbed. However,
 5062 backscattering and IR photons will lower the percent that is actually absorbed.

5063 **Proton Triplet:** The super conducting final focusing triplet for the protons needs to be protected from
 5064 radiation by the absorber. Some of the radiation produced upstream of the absorber however will either pass
 5065 through the absorber or pass through the apertures for the two interacting beams. This is most concerning

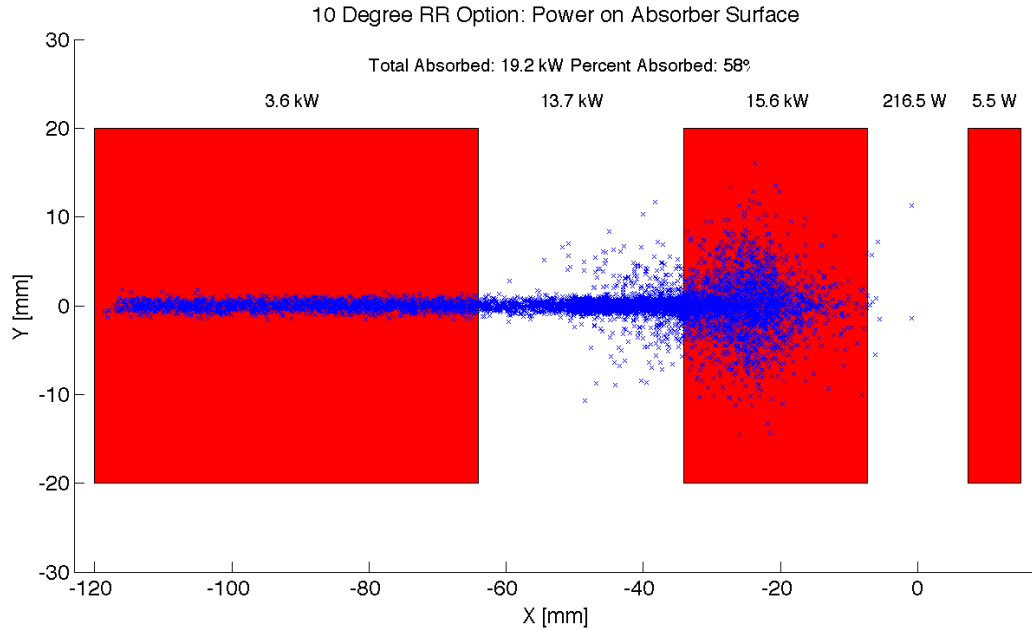


Figure 7.35: High Luminosity: Photon distribution on Absorber Surface

5066 for the interacting proton beam aperture which will have the superconducting coils. A rough upper bound
 5067 for the amount of power the coils can absorb before quenching is 100W [577]. There is approximately 217
 5068 W entering into the interacting proton beam aperture as is shown in Figure 7.35. This doesn't mean that
 5069 all this power will hit the coils but simulations need to be made to determine how much of this will hit the
 5070 coils. The amount of power that will pass through the absorber can be disregarded as it is not enough to
 5071 cause any effects. The main source of power moving downstream of the absorber will be the photons passing
 5072 through the beams aperture. This was approximately 13.7 kW as can be seen from Figure 7.35. Most of
 5073 this radiation can be absorbed in a secondary absorber placed after the first downstream proton quadrupole.
 5074 Overall protecting the proton triplet is important and although the absorber will minimize the radiation
 5075 continuing downstream this needs to be studied in depth.

5076 **Backscattering:** Another Geant4 program was written to simulate the backscattering of photons into the
 5077 detector region. The ntuple with the photon information written at the absorber surface is used as the
 5078 input for this program. An absorber geometry made of copper is described, and general physics processes
 5079 are set up. A detector volume is then described and set to record the information of all the photons which
 5080 enter in an ntuple. The first step in minimizing the backscattering was to optimize the absorber shape.
 5081 Although the simulation didnt include a beam pipe the backscattering for different absorber geometries was
 5082 compared against one another to find a minimum. The most basic shape was a block of copper that had
 5083 cylinders removed for the interacting beams. This was used as a benchmark to see the maximum possible
 5084 backscattering. In HERA a wedge shape was used for heat dissipation and minimizing backscattering [576].
 5085 The profile of two possible wedge shapes in the YZ plane is shown in Figure 7.36. It was found that this is
 5086 the optimum shape for the absorber. The reason for this is that a backscattered electron would have to have
 5087 its velocity vector be almost parallel to the wedge surface to escape from the wedge and therefore it works
 5088 as a trap. As can be seen from Table 7.22 utilizing the wedge shaped absorber did not reduce the power by
 5089 much. This appears to be a statistical limitation. This needs to be redone with higher statistics to get a
 5090 better opinion on the difference between the two geometries.

5091 After the absorber was optimized it was possible to set up a beam pipe geometry. An asymmetric

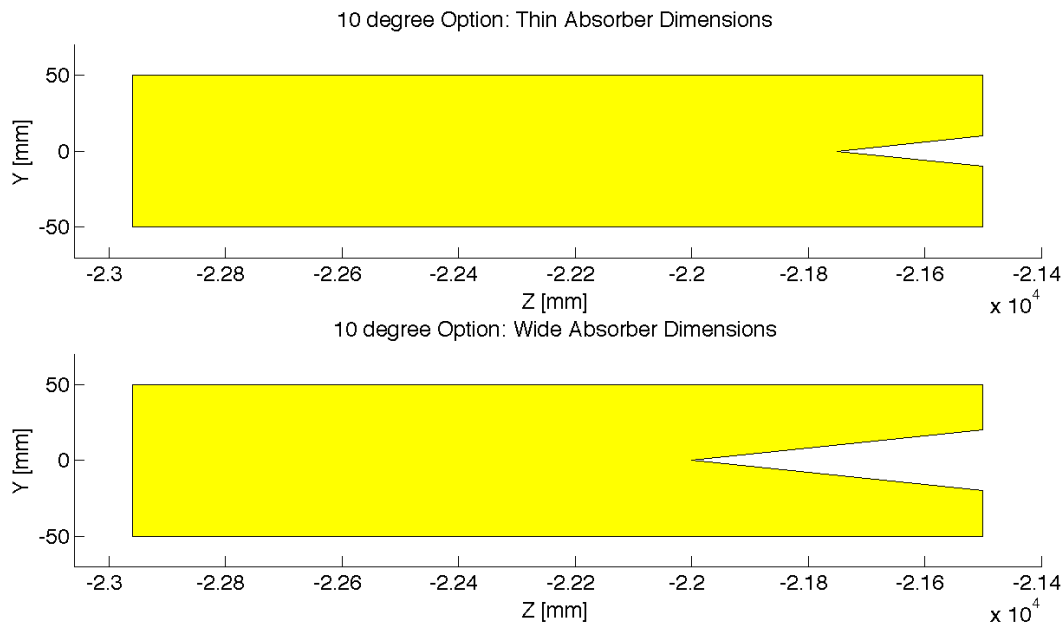


Figure 7.36: 10 deg: Absorber Dimensions

5092 elliptical cone beam pipe geometry made of beryllium was used since it would minimize the necessary size
 5093 of the beam pipe as previously mentioned. The next step was to place the lead shield and masks inside this
 5094 beam pipe. To determine placement a simulation was run with just the beam pipe. Then it was recorded
 5095 where each backscattered photon would hit the beam pipe in Z. A histogram of this data was made. This
 5096 determined that the shield should be placed in the Z region ranging from -20 m until the absorber (-21.5
 5097 m). The shields were then placed at -21.2 m and -20.5 m. This decreased the backscattered power to zero as
 5098 can be seen from Table 7.22. Although this is promising this number should be checked again with higher
 5099 statistics to judge its accuracy. Overall there is still more optimization that can occur with this placement.

Absorber Type	Power [W]
Flat	22
Wedge	18.5
Wedge & Mask/Shield	0

Table 7.22: High Luminosity: Backscattering/Mask

5100 Cross sections of the beam pipe in the $Y = 0$ and $X = 0$ planes with the shields and masks included can
 5101 be seen in Figure 7.37.

5102 High Detector Acceptance

5103 **Parameters:** For the Ring Ring high acceptance option the basic parameters are listed in Table 7.23. The
 5104 separation refers to the displacement between the two interacting beams at the face of the proton triplet.

5105 The energy, current, and crossing angle (θ_c) are common values used in all RR calculations. The dipole
 5106 field value refers to the constant dipole field created throughout all dipole elements in the IR. The separation
 5107 is the same as in the high luminosity case and can be altered for the same reasons with the same ramifica-
 5108 tions. The chosen parameters give a flux of 6.41×10^{18} photons per second at $Z = -21.5$ m, which is slightly

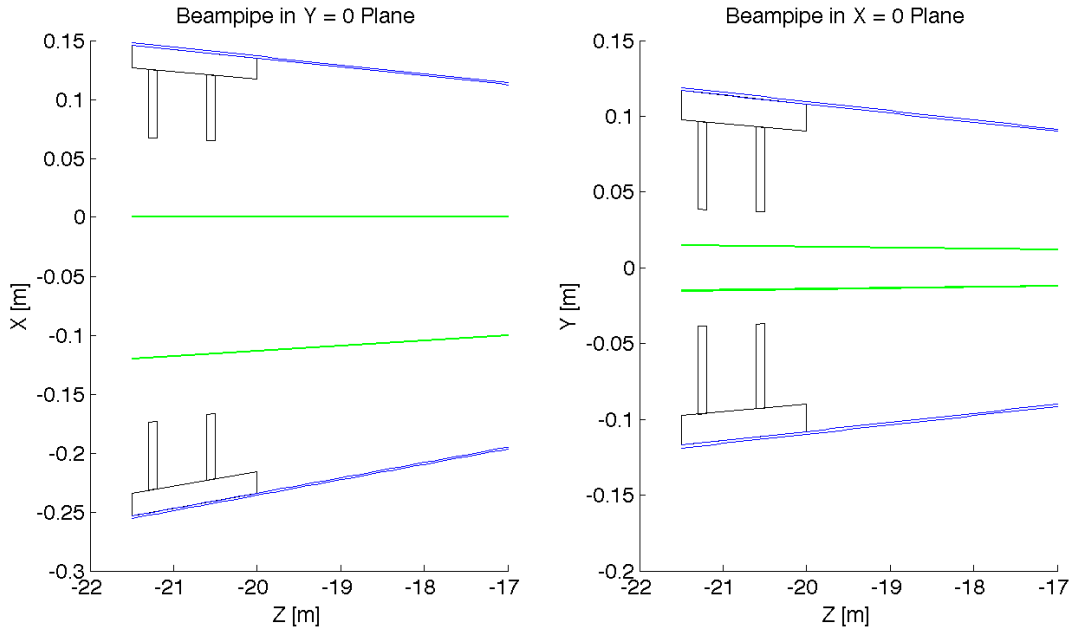


Figure 7.37: High Luminosity: Beampipe Cross Sections

Characteristic	Value
Electron Energy [GeV]	60
Electron Current [mA]	100
Crossing Angle [mrad]	1
Absorber Position [m]	-21.5
Dipole Field [T]	0.0493
Separation [mm]	55.16
γ/s	6.41×10^{18}

Table 7.23: High Acceptance: Parameters

5109 higher than in the high luminosity case. This is expected as the fields experienced in the high acceptance
 5110 case are higher.

5111 **Power and Critical Energy:** Table 7.24 shows the power of the SR produced by each element along
 5112 with the average critical energy produced per element. This is followed by the total power produced in the
 5113 IR and the average critical energy. Since the G4 simulations utilize Monte Carlo, multiple runs should be
 5114 made with various seeds to get an estimate for the standard error.

5115 The distribution of power and critical energy over the IR elements is similar to that of the high acceptance
 5116 option with the exception of the upstream and downstream separator dipole magnets. The power and
 5117 critical energies are significantly higher than before. This is due to the higher dipole field and the quadratic
 5118 dependence of power on magnetic field and linear dependence of critical energy on magnetic field. [575]

5119 **Comparison:** The IRSYN cross check of the power and critical energies is shown in Table 7.25. This
 5120 comparison was done for the total power and the critical energy.

Element	Power [kW]	Critical Energy [keV]
DL	13.9	118
QL2	6.2	318
QL1	5.4	294
QR1	5.4	293
QR2	6.3	318
DR	13.9	118
Total/Avg	51.1	163

Table 7.24: High Acceptance: Power and Critical Energies [Geant4]

	Power [kW]		Critical Energy [keV]	
	Geant4	IRSYN	Geant4	IRSYN
Total/Avg	51.1	51.3	163	162

Table 7.25: High Acceptance: Geant4 and IRSYN comparison

5121 A third cross check to the G4 simulations was also made for the power as shown in Table 7.26. This
5122 was done using an analytic method for calculating power in dipole and quadrupole magnets. [574] This
5123 comparison provides confidence in the distribution of the power throughout the IR.

Element	Power [kW]	
	Geant4	Analytic
DL	13.9	14
QL2	6.2	6.2
QL1	5.4	5.3
QR1	5.4	5.3
QR2	6.3	6.2
DR	13.9	14
Total	51.1	51

Table 7.26: High Acceptance: Geant4 and Analytic method comparison

5124 **Number Density and Envelopes:** The number density of photons as a function of Z is shown in Figure
5125 7.38. The horizontal extension of the fan in the high acceptance case is larger than in the high luminosity
5126 case however still lower than in the LR option. Since the beam stays at a constant angle for the first 6.2 m
5127 after the IP it requires larger fields to bend in order to reach the desired separation. This means that an
5128 overall larger angle is reached near the absorber, and since the S shaped trajectory is symmetric in Z the
5129 angle of the beam at the entrance of the upstream quadrupoles is also larger and therefore the fan extends
5130 further in X.

5131 The envelope of the SR fan can be seen in Figure 7.39, where the XZ plane is shown at the value $Y = 0$.
5132 Once again the fan is antisymmetric due to the S shape of the electron beam.

5133 **Critical Energy Distribution:** The critical energy distribution in Z is similar to that of the high lumi-
5134 nosity case. This is due to the focusing of the beam in the IR. This is evident from Figure 7.40.

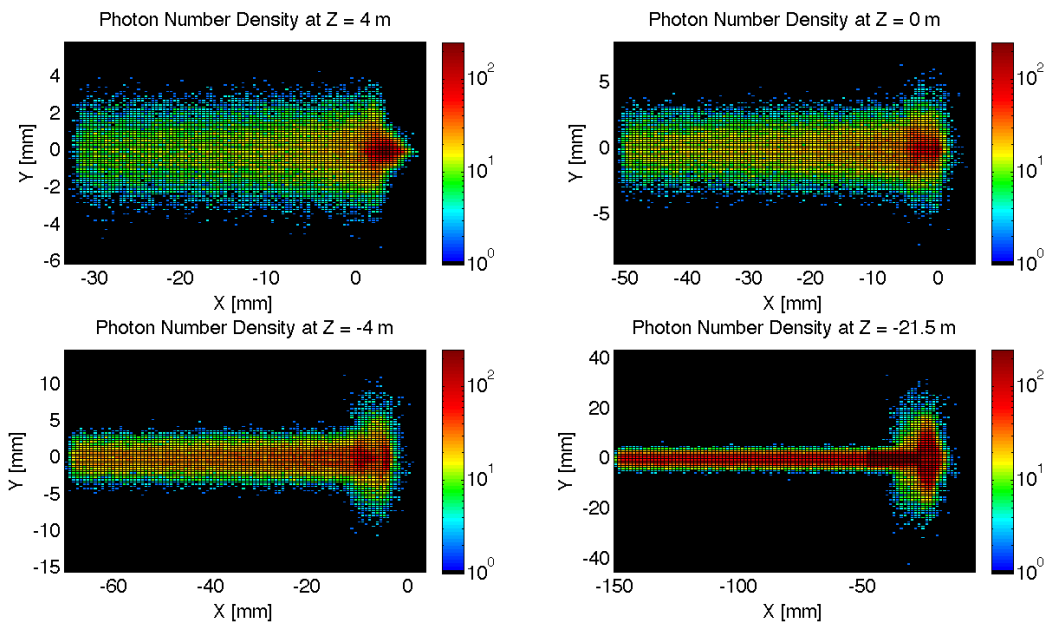


Figure 7.38: High Acceptance: Number Density Growth in Z

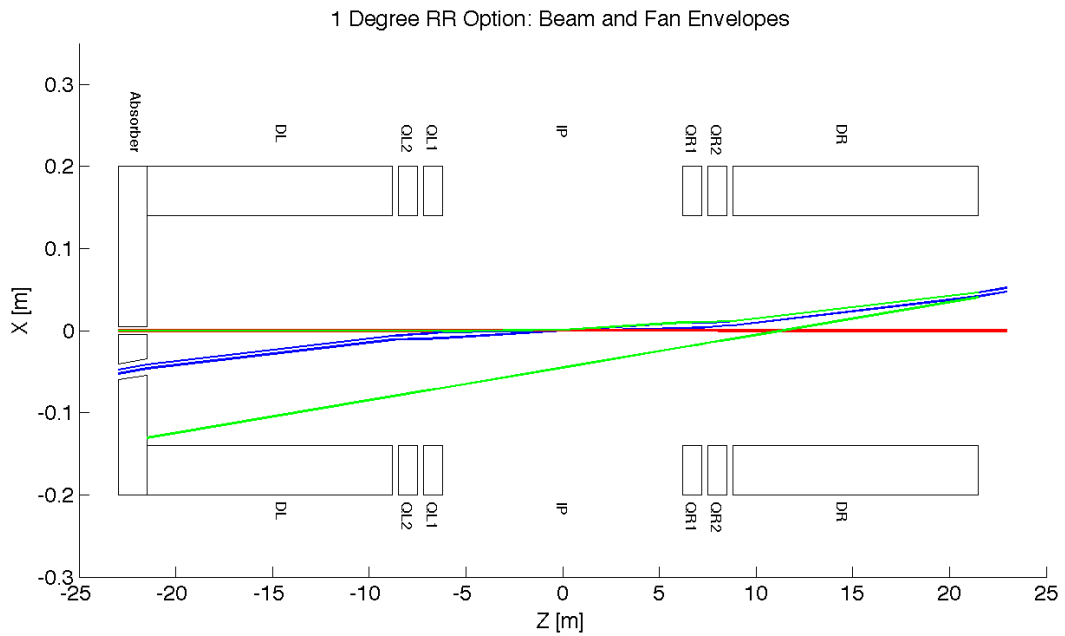


Figure 7.39: High Acceptance: Beam Envelopes in Z

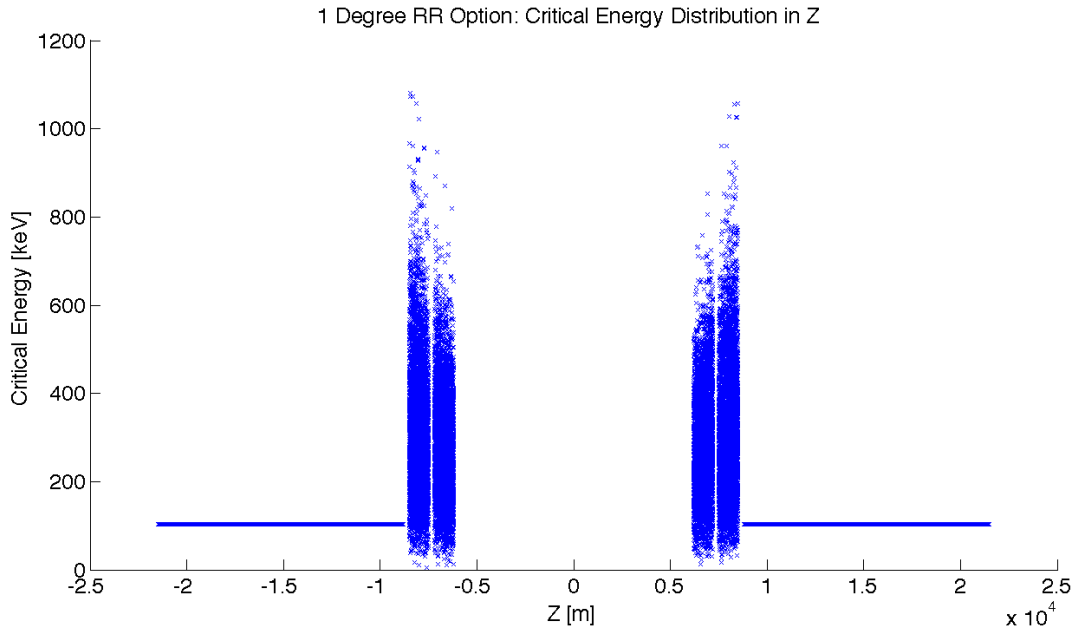


Figure 7.40: High Acceptance: Critical Energy Distribution in Z

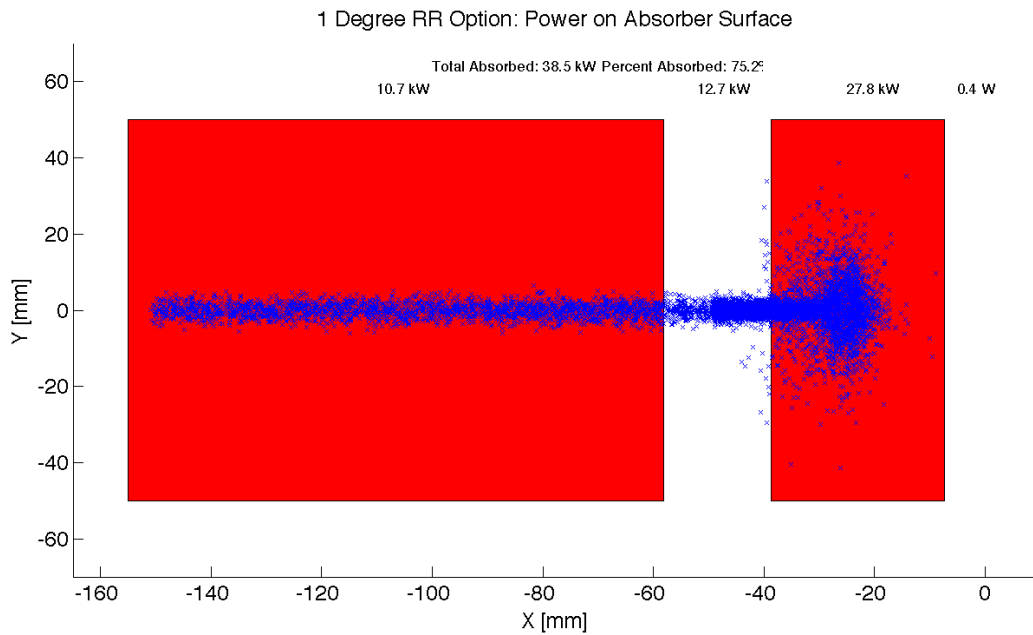


Figure 7.41: High Acceptance: Photon distribution on Absorber Surface

5135 **Absorber:** Looking at Figure 7.41 it is shown that for the high acceptance option 38.5 kW of power from
 5136 the SR light will fall on the face of the absorber which is 75% of the total power. This gives a general idea of
 5137 the amount of power that will be absorbed. However, backscattering and IR photons will lower the percent
 5138 that is actually absorbed.

5139 **Proton Triplet:** The super conducting final focusing triplet for the protons needs to be protected from
 5140 radiation by the absorber. Some of the radiation produced upstream of the absorber however will either pass
 5141 through the absorber or pass through the apertures for the two interacting beams. This is most concerning
 5142 for the interacting proton beam aperture which will have the superconducting coils. A rough upper bound
 5143 for the amount of power the coils can absorb before quenching is 100 W. [577] In the high acceptance option
 5144 there is approximately 0.4 W entering into the interacting proton beam aperture as is shown in Figure 7.41.
 5145 Therefore for the high acceptance option this is not an issue. The amount of power that will pass through
 5146 the absorber can be disregarded as it is not enough to cause any significant effects. The main source of
 5147 power moving downstream of the absorber will be the photons passing through the beams aperture. This
 5148 was approximately 12.7 kW as can be seen from Figure 7.41. Most of this radiation can be absorbed in
 5149 a secondary absorber placed after the first downstream proton quadrupole. Overall protecting the proton
 5150 triplet is important and although the absorber will minimize the radiation continuing downstream this needs
 5151 to be studied in depth.

5152 **Backscattering:** Another Geant4 program was written to simulate the backscattering of photons into the
 5153 detector region. The ntuple with the photon information written at the absorber surface is used as the
 5154 input for this program. An absorber geometry made of copper is described, and general physics processes
 5155 are set up. A detector volume is then described and set to record the information of all the photons which
 5156 enter in an ntuple. The first step in minimizing the backscattering was to optimize the absorber shape.
 5157 Although the simulation didnt include a beam pipe the backscattering for different absorber geometries was
 5158 compared against one another to find a minimum. The most basic shape was a block of copper that had
 5159 cylinders removed for the interacting beams. This was used as a benchmark to see the maximum possible
 5160 backscattering. In HERA a wedge shape was used for heat dissipation and minimizing backscattering. [576]
 5161 The profile of two possible wedge shapes in the YZ plane is shown in Figure 7.42. It was found that this is
 5162 the optimum shape for the absorber. The reason for this is that a backscattered electron would have to have
 5163 its velocity vector be almost parallel to the wedge surface to escape from the wedge and therefore it works
 5164 as a trap. As can be seen from Table 7.27 utilizing the wedge shaped absorber decreased the backscattered
 5165 power by a factor of 9.

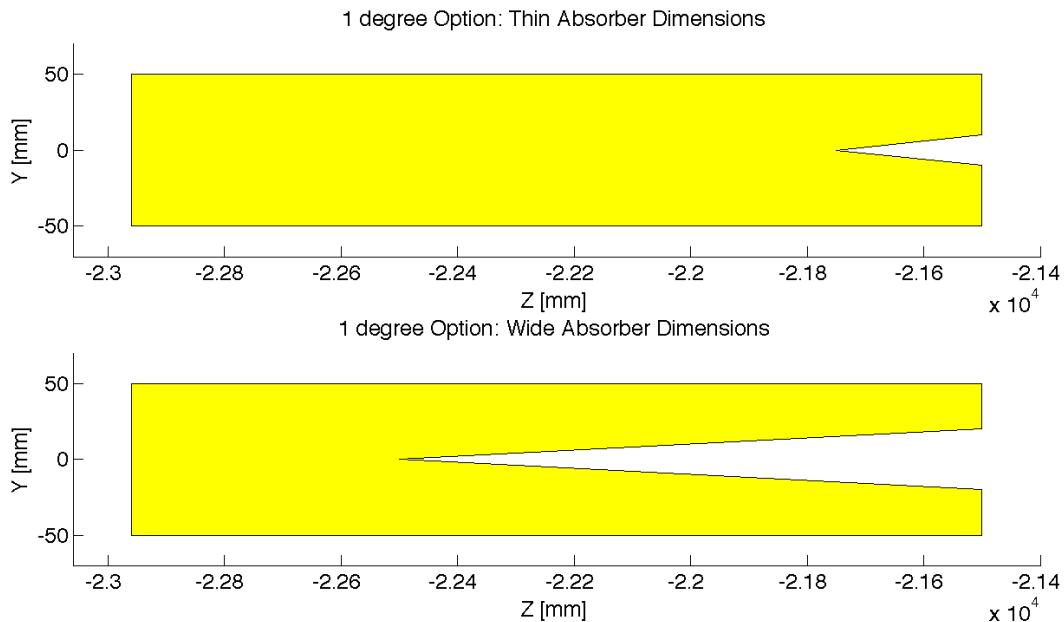


Figure 7.42: 1 deg: Absorber Dimensions

5166 After the absorber was optimized it was possible to set up a beam pipe geometry. An asymmetric
 5167 elliptical cone beam pipe geometry made of beryllium was used since it would minimize the necessary size
 5168 of the beam pipe as previously mentioned. The next step was to place the lead shield and masks inside this
 5169 beam pipe. To determine placement a simulation was run with just the beam pipe. Then it was recorded
 5170 where each backscattered photon would hit the beam pipe in Z. This determined that the shield should be
 5171 placed in the Z region ranging from -20 m until the absorber (-21.5 m). The shields were then placed at -21.2
 5172 m and -20.6 m. This decreased the backscattered power to zero as can be seen from Table 7.27. Although
 5173 this is promising this number should be checked again with higher statistics to judge its accuracy. Overall
 5174 there is still more optimization that can occur with this placement.

Absorber Type	Power [W]
Flat	91.1
Wedge	10
Wedge & Mask/Shield	0

Table 7.27: High Acceptance: Backscattering/Mask

5175 Cross sections of the beam pipe in the $Y = 0$ and $X = 0$ planes with the shields and masks included can
 5176 be seen in Figure 7.43.

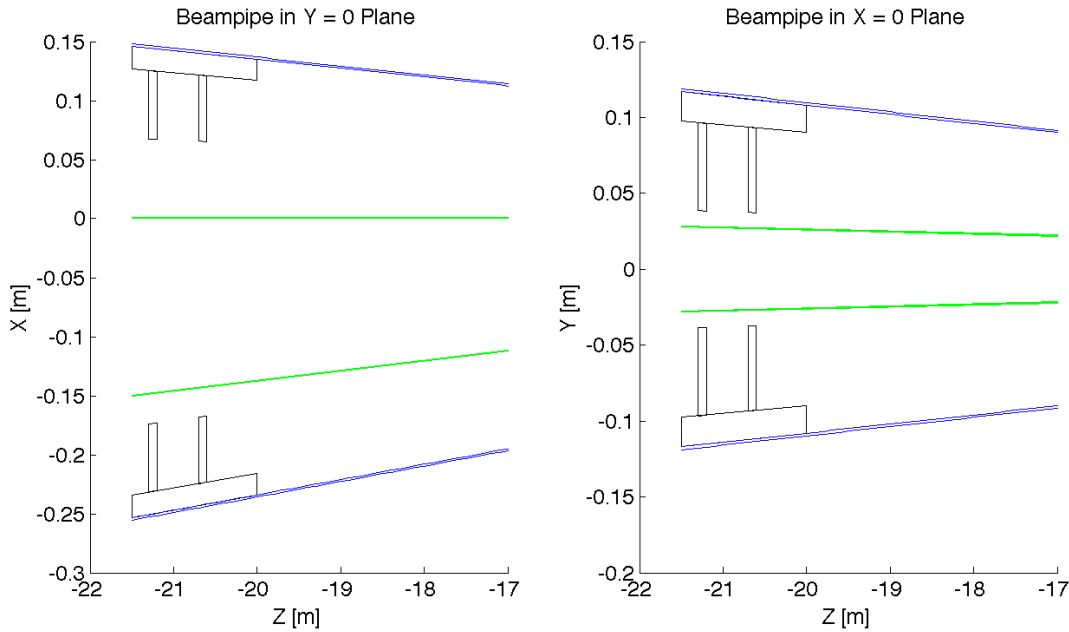


Figure 7.43: High Acceptance: Beampipe Cross Sections

5177 7.5 Beam-beam effects in the LHeC

5178 In the framework of the Large Hadron electron Collider a ring-ring option is considered where protons of
 5179 one beam collide with the protons of the second proton beam as well as with leptons from a separate ring.
 5180 To deduce possible limitations the present knowledge of the LHC beam-beam effects from proton-proton
 5181 collisions are fundamental to define parameters of an interaction point with electron-proton collisions. From

5182 past experience it is known that the maximum achievable luminosity in a collider is limited by beam-beam
 5183 effects. These are often quantified by the maximum beam-beam tune shifts in each of the two beams. An
 5184 important aspect in electron-proton collisions is that the proton beam, more sensitive to transverse noise,
 5185 could be perturbed by a higher level of noise in the electron beam. In this section we will assess some limits
 5186 to the possible tune shift achievable in collision based on experience from past colliders as CESR [578] and
 5187 LEP [579] and more recent ones like the LHC [580].

5188 7.5.1 Head-on beam-beam effects

5189 A first important performance issue in beam-beam interaction comes from the restricted choice of the β -
 5190 function at the interaction point to keep the transverse beam sizes equal for the two beams since proton and
 5191 electron emittances are different. The choice of beta functions at the interaction point has to be different
 5192 for the two beams in order to keep $\sigma_x^e = \sigma_x^p$ and $\sigma_y^e = \sigma_y^p$ for the reasons explained in detail in [581]. In a
 5193 mismatched collision the larger bunch may suffer more because a large part of the particle distribution will
 5194 experience the non-linear beam-beam force of the other bunch. With this in mind it is preferable to keep
 5195 the electron beam slightly larger than the proton beam since the electron beam may be less sensitive due
 5196 to strong radiation damping. This matching implies that the electron emittances must be controlled during
 5197 operation and kept as constant as possible (i.e. H/V coupling). For the proton beam the beam-beam effects
 5198 from the electron beam will be different for the two planes. Optical matching of the beam sizes at the IP is
 5199 the first constraint for any interaction region layout proposed.

5200
 5201 Another important issue is the achievable tune shift and how this relates to the linear beam-beam pa-
 5202 rameter which is normally the parameter used to evaluate the strength of the beam-beam interaction.

5203
 5204 The linear beam-beam parameter is defined as ξ_{bb} and is expressed for the case of round beams like in
 5205 proton-proton collision at the LHC as:

$$\xi_{bb} = \frac{Nr_p\beta^*}{4\pi\gamma\sigma^2} \quad (7.12)$$

5206 where r_p is the proton classical radius, β^* is the optical amplitude function (β -function) at the interaction
 5207 point, $\sigma = \sigma_{x,y}$ is the transverse beam size in meters at the interaction point, N_p is the bunch intensity and
 5208 γ is the relativistic factor. For proton-proton collisions where ξ_{bb} does not reach too large values and the
 5209 operational tune is far enough away from linear resonances, this parameter is about equal to the linear tune
 5210 shift ΔQ expected from the head-on beam-beam interaction. This is the case for the LHC proton-proton
 5211 collisions at IP1 and IP5 where the linear tune shift per IP is of the order of 0.0034/0.0037 for nominal beam
 5212 parameters as summarized in Table 7.28 and corresponds to the linear beam-beam parameter ξ_{bb} . This is in
 5213 general not true for lepton colliders where the operational scenario differs from hadron colliders and other
 5214 effects become dominant and have to be taken into account.

5215 In the case of electron beams the transverse shape of the beams is normally elliptical with $\sigma_x > \sigma_y$. In this
 5216 configuration one can generalize the linear beam-beam parameter calculation with the following formula [582]:

$$\xi_{x,y} = \frac{Nr_e\beta_{x,y}^*}{2\pi\gamma\sigma_{x,y}(\sigma_x + \sigma_y)} \quad (7.13)$$

5217 with r_e is the electron classical radius.

5218 In the case of electron-proton collisions one has to also take into account the different species during
 5219 collision and the beam-beam parameters become:

$$\xi_{(x,y),b_1} = \frac{N_{b_2}r_{b_1}\beta_{(x,y),b_1}^*}{2\pi\gamma_{b_1}\sigma_{(x,y),b_2}(\sigma_{x,b_2} + \sigma_{y,b_2})} \quad (7.14)$$

5220 Here b_1 and b_2 refer to Beam1 and Beam2 respectively. The linear beam-beam parameter ξ is often used
 5221 to quantify the strength of the beam-beam interaction, however it does not reflect the non-linear nature of

Parameter	LEP	LHC (nominal)
Beam sizes	180 μm \cdot 7 μm	16.6 μm \cdot 16.6 μm
Intensity N	4.0 \cdot 10 ¹¹ /bunch	1.15 \cdot 10 ¹¹ /bunch
Energy	100 GeV	7000 GeV
$\beta_x^* \cdot \beta_y^*$	1.25 m \cdot 0.05 m	0.55 m \cdot 0.55 m
Crossing angle	0.0	0/285 μrad
Beam-beam parameter(ξ)	0.0700	0.0037/0.0034

Table 7.28: Comparison of parameters for the LEP collider and the LHC.

5222 the electromagnetic interaction. Nevertheless, it can be used for comparison and as a scaling parameter.
5223 Since a general beam-beam limit cannot be found and will be different from one collider to the next, the
5224 interpretation should be conservative.

5225 In Table 7.28 we compare LEP and LHC beam parameters and achieved linear beam-beam parameters.
5226 Some of the differences are striking: while the beams in the LHC are round at the interaction point, they are
5227 very flat in LEP. This is due to the excitation of the beam in the horizontal plane by the strong synchrotron
5228 radiation and damping in the vertical plane. Another observation is the much larger beam-beam parameter
5229 in LEP.

5230 One reason for the larger achievable beam-beam parameter in lepton colliders is due to a significant
5231 dynamic beta effect when operating at a working point close to integer tune. This is considered more
5232 difficult with proton beams. In Equation 7.15 the perturbed β^* is expressed as a function of the beam-beam
5233 parameter and the phase advance between two interaction points $2\pi Q^i$. The tune shift becomes a function
5234 of the tune which can be chosen to keep the actual shift small.

$$\beta^*(Q) = \frac{\beta}{\sqrt{1 + 4\pi\xi(\cot(2\pi Q^i)) - 4\pi^2\xi^2}} \quad (7.15)$$

5235 From experience it is known that electrons have a bigger range for the linear head-on beam-beam param-
5236 eter: LEP II has proved a beam-beam parameter of 0.07 corresponding to a measured ΔQ of 0.03 as also
5237 confirmed in other lepton colliders. CESR demonstrated the possibility to achieve tune shifts of the order
5238 of 0.09. A second and most important reason for a higher acceptable tune shift in lepton colliders is the
5239 synchrotron radiation damping. Furthermore, while for lepton colliders a clear indication for a "beam-beam
5240 limit" exists, not such criteria can be easily defined for hadron machines [580]. With this brief resume on the
5241 head-on linear beam-beam parameters reached so far it is clear that the beam which will have some limits
5242 on the choice of beam-beam parameters ξ_{bb} is the proton beam.

5243 The LHC as a proton-proton collider has confirmed previous experience from SppS and Tevatron that
5244 a total linear tune shift of 0.018 (0.006 per IP) is tolerable with neither important losses nor reduction
5245 of beam lifetime during normal operation. It is generally admitted that ξ_{bb} could reach a value of 0.01
5246 per interaction point. Recent experiments at the LHC with very high intensity beams beyond ultimate
5247 and reduced beam transverse sizes demonstrated the possibility of reaching head-on tune shifts well beyond
5248 the nominal values [580]. At the LHC tune shifts per IP close to 0.02 have been achieved. Total tune
5249 shift exceeding 0.034 have also been achieved with stable beams for two symmetric crossings at IP1 and
5250 IP5. These latest experiments demonstrate the possibility to operate with larger than nominal beam-beam
5251 parameters.

5252 The calculated beam-beam parameters for the electron and proton beams due to an electron-proton
5253 collision in the LHeC are summarized in Table 7.29 for the two interaction region options (1 Degree Option
5254 and 10 Degree Option).

5255 The two proposed interaction region options will give for the proton beams a maximum beam-beam
5256 parameter in the horizontal plane of about $8 \cdot 10^{-4}$. This effect is in the shadow of the proton-proton
5257 collision at IP1 and IP5 which will give a beam-beam parameter of $5.5 \cdot 10^{-3}$ per single IP for nominal

IR Option	1 degree		10 degree	
	Electrons	Protons	Electrons	Protons
Beams	Electrons	Protons	Electrons	Protons
Energy	60 GeV	7 TeV	60 GeV	7 TeV
Intensity	$2 \cdot 10^{10}$	$1.7 \cdot 10^{11}$	$2 \cdot 10^{10}$	$1.7 \cdot 10^{11}$
β_x^*	0.4 m	4.05 m	0.18 m	1.8 m
β_y^*	0.2 m	0.97 m	0.1 m	0.5 m
ϵ_x	5 nm	0.5 nm	5 nm	0.5 nm
ϵ_y	2.5 nm	0.5 nm	2.5 nm	0.5 nm
σ_x	45 μm		30 μm	
σ_y	22 μm		15.8 μm	
Cross angle	1 mrad		1 mrad	
$\xi_{bb,x}$	0.086	0.0008	0.085	0.0008
$\xi_{bb,y}$	0.088	0.0004	0.090	0.0004
Luminosity	$7.33 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$		$1.34 \cdot 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$	

Table 7.29: Beam parameters for the interaction region options and the relative linear beam-beam parameter ξ .

	Nominal		Upgrade	
	Electrons	Protons	Electrons	Protons
$\xi_{bb,x}$	0.016	0.0013	0.027	0.0017
$\xi_{bb,y}$	0.018	0.0012	0.041	0.0005

Table 7.30: Linear beam-beam parameters for HERA, nominal machine and upgrade parameters.

IR Option	1 degree		10 degree	
Beams	Electrons	Protons	Electrons	Protons
β_x^*	0.4 m	4.05 m	0.18 m	1.8 m
β_y^*	0.2 m	0.97 m	0.1 m	0.5 m
ϵ_x	5 nm	0.5 nm	5 nm	0.5 nm
ϵ_y	2.5 nm	0.5 nm	2.5 nm	0.5 nm
Cross angle	1 mrad		1 mrad	
d_x	90 σ_e	8.94 σ_p	60 σ_e	6.0 σ_p

Table 7.31: Normalized distance of beam-beam long range encounter for the two interaction region options.

beam emittances and assuming intensities of $1.7 \cdot 10^{11}$ protons/bunch which was already achieved during 2010 operation at the LHC with reduced emittances and nominal beam intensities. One should not expect important effects of the head-on tune shifts coming from the electron beam apart from a potential coupling of noise from the electron into the proton beam.

For the electron beam, on the contrary, the beam-beam parameter of $8.6 \cdot 10^{-2}$ is large and represents a value at the limit of what has been achieved so far in other lepton machines (LEP at 90 GeV energy achieved a beam-beam parameter of 0.07 while KEK and HERA a maximum $\xi_{bb} = 0.04$ during operation, CESR achieved a beam-beam parameter of 0.09 for single IP but with lower luminosity). The beam-beam tuneshifts achieved at HERA for the nominal and upgrade version are summarized in Table 7.30 for comparison.

7.5.2 Long range beam-beam effects

So far we have discussed head-on beam-beam interactions but an important issue are the long range interactions which will occur at the electron-proton collision and their interplay with the proton-proton crossings at IP1 and IP5. The two interaction points IP1 and IP5 will give up to 60 proton-proton long-range interactions which should be added to the two interaction region options which will give two additional parasitic encounters. The beam separation at this encounters should be as large as possible to reduce any non-linear perturbation. The parasitic encounters occur every 3.75 m from the interaction point for a bunch spacing of 25 ns. The proposed optics will then lead to parasitic beam-beam interactions which will occur at a transverse separation d as:

$$d(s)_{x,y} = \alpha \frac{s}{\sqrt{\epsilon_{x,y} \beta(s)_{x,y}}} \quad (7.16)$$

with $\epsilon_{x,y}$ are the beam emittance in the separation plane and $\beta(s)$ is the betatron function at a distance s from the interaction point.

In Table 7.31 the distances of the parasitic encounters in units of the transverse beam sizes are shown for both interaction region layouts.

The 1 degree option gives long range interactions at larger separation with respect to the 10 degree option which results in small separations of $\approx 6 \sigma$ for the proton beam. Particles in the tail of the proton beam particles will experience the non linearity of the electron beam electromagnetic force. The presence of two long range at 6σ separation may be acceptable since it is shown experimentally that few encounters also at smaller separation do not affect the beams dramatically [583]. However, the interplay of these two encounters with the long-range interactions from IP1 and IP5 should be studied in detail with numerical simulation to highlight possible limitations. In this framework future experiments at the LHC will help defining a possible beam parameters space for the control of the long-range effects from proton-proton collisions. If encounters at 6σ present a limitation to the collider performance then a possible cure to increase the long-range separation could be a further increase of the crossing angle and using crab cavities can recover the increased geometric luminosity reduction factor. In this case a study of the crab cavities effects on the proton beam would be essential to define the effects of transverse noise on colliding beams.

5292 For any reliable study of the LHeC project one has to address other possible beam-beam issues with extensive
5293 numerical simulations of the operational scenario of the LHeC. This is fundamental since there is no other
5294 possible simplification which can be adopted in evaluating the non-linear parts of the beam-beam forces.
5295 For this reason a detailed and full interaction layout with crossing schemes matched in thin lens version
5296 is needed. With the complete optic layout beam-beam effects which still need further studies by means of
5297 numerical simulation campaign are the following:

- 5298 • Long-range tune shifts and orbit effects.
- 5299 • Self-consistent study of the proton-proton and electron-proton beam dynamics interplay.
- 5300 • Dynamic aperture tracking studies.
- 5301 • Multi-bunch effects.
- 5302 • Noise coupling from the electron to the proton beam.

5303 The evaluation of the non-linear effects of the beam-beam interactions with self-consistent calculations will
5304 define a set of parameters for operation [584].

5305 7.6 Performance as an electron-ion collider

5306 7.6.1 Heavy nuclei, e-Pb collisions

5307 With the first collisions of lead nuclei ($^{208}\text{Pb}^{82+}$) in 2010 [382, 585], the LHC has already demonstrated
5308 its capability as a heavy-ion collider and this naturally opens up the possibility of electron-nucleus (e-A)
5309 collisions in the LHeC.

5310 In order to avoid interference with the high luminosity proton-proton operation, this mode of operation
5311 would naturally be included in the annually-scheduled ion operation period of the LHC. In principle, the
5312 CERN complex could provide A-A (or even p-A) collisions to the LHC experiments while the LHeC operates
5313 with e-A collisions. The lifetime of the nuclear beam would depend mainly on whether it was exposed to
5314 the losses from A-A luminosity in the LHC (in this case it would be at least a few hours).

5315 In the first decade or so of LHC operation, the ion injector chain is expected to provide mainly $^{208}\text{Pb}^{82+}$,
5316 but also other species such as $^{40}\text{Ar}^{18+}$ or $^{129}\text{Xe}^{54+}$, either to the LHC or from the SPS to fixed target
5317 experiments in the North Area. These beams could also be collided with electrons in the LHeC but solid
5318 intensity estimates are not yet available for the lighter ions. For simplicity, we shall estimate LHeC perfor-
5319 mance in e-Pb collisions with the design performance values of the ion injector chain as described in [586]
5320 and the assumption of a single nuclear beam in one ring of the LHC with parameters as recalled from [587]
5321 in Table 7.32. It is assumed that present uncertainties about the Pb intensity limits at full energy in the
5322 LHC will have been resolved, if necessary, by installation of new collimators in the dispersion suppressors of
5323 the collimation insertions in the LHC. This simplifies the discussion because the design emittances of Pb and
5324 proton beams in the LHC are such that both species have the same geometric beam sizes and considerations
5325 of optics and aperture can be taken over directly. The “Ultimate Pb” value of the Pb single bunch intensity
5326 was already attained in 2010 [585] using a simplified injection scheme but not yet with the nominal filling
5327 scheme for 592 bunches; it can be considered an optimistic goal. At present, there are no prospects for
5328 increasing the number of bunches significantly. Lower Pb emittances may be possible but would not increase
5329 e-Pb luminosity unless matched with smaller optical functions or emittances for the electron beam.

5330 Assume that the injection system can create an electron bunch train matching the 592-bunch train of Pb
5331 nuclei in the LHC so that every Pb bunch finds a collision partner in the electron beam. Assuming further
5332 that the hadron optics can be adjusted to match the sizes of the electron and Pb beams, the luminosity
5333 can be expressed in terms of the interaction point optical functions and emittances of the electron beam.
5334 Since the e-A physics is focused on low- x these are taken from Table 7.14 describing the Ring-Ring High
5335 Acceptance optics, which reduces the luminosity by a factor 2 as compared with the High-Luminosity optics.

		Design Pb	Ultimate Pb
Energy	E_{Pb}	574. TeV	
Energy per nucleon	E_N	2.76 TeV	
No. of bunches	n_b	592	
Ions per bunch	N_{Pb}	$7. \times 10^7$	1.2×10^8
Normalised emittance	ε_n	1.5 μm	

Table 7.32: Parameters for the $^{208}\text{Pb}^{82+}$ beam according to Chapter 21 of [587].

5336 In e-p mode, the intensity of the 2808 electron bunches, N_e is limited for the Ring-Ring version of the
5337 LHeC by the total RF power available to compensate the synchrotron radiation loss. For the same power
5338 (some 44 MW for $N_e = 2 \times 10^{10}$ of Table 7.8), the intensity of the $n_b = 592$ bunches required to collide
5339 with the Pb nuclei can be increased by a factor 2808/592 to $N_e = 9.5 \times 10^{10}$. Electron beam parameters
5340 for the LHeC Ring-Ring option other than the single bunch intensity can be taken from Table 7.8. Present
5341 experience with beam-beam effects in the LHC suggests that the additional electron intensity would not
5342 present any problem for the proton beam. The single-bunch intensity is still well below that achieved in
5343 LEP although the feasibility of these values should be confirmed by further analysis of the ring impedance
5344 and collective effects.

5345 Neglecting the geometric reduction factor due to the crossing angle and the hourglass effect, the *electron-*
5346 *nucleon* luminosity, $L_{eN} = AL_{eA}$, is then given by

$$L_{eN} = \frac{n_b f_0 N_e (A N_{\text{Pb}})}{4\pi \sqrt{\beta_{xe}^* \varepsilon_x} \sqrt{\beta_{ye}^* \varepsilon_y}} = \begin{cases} 2.6 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1} & \text{(Nominal Pb)} \\ 4.5 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1} & \text{(Ultimate Pb)} \end{cases} \quad (7.17)$$

5347 This gives an indication of the range of peak luminosities that can be expected. A factor of 2 could be gained
5348 by switching to the high-luminosity interaction region optics.

5349 By the time the LHeC comes into operation, it is not unreasonable to hope that ways to increase the
5350 number of Pb bunches and perhaps to reduce their emittance (by cooling) may be implemented. Therefore,
5351 on an optimistic view, the luminosity could be even higher than the value quoted here.

5352 Finally, we note that the dependence of luminosity on electron beam energy ($\propto E_e^{-6}$) is very strong at
5353 the power limit so that a trade-off between energy and luminosity may be of interest.

5354 7.6.2 Electron-deuteron collisions

5355 As discussed in [377], deuteron beams are not presently available in the CERN complex. Meanwhile it has
5356 been clearly demonstrated [588] that it would not be feasible to set up a D^- source and accelerate them
5357 via Linac4. The present proton Linac2 is due to be shut down so the only way to accelerate them would
5358 be via the heavy ion Linac3. However this would require a new source, RFQ and switch-yard at the input
5359 to Linac3. The study of practical feasibility, space limitations, design and potential performance of these
5360 modifications to the injector complex will start only in late 2011 with a view to supplying D and other light
5361 ions to fixed target experiments and the LHC in several years' time.

5362 Assuming that a practical design can be implemented, the intensity of bunches in the LHC ring can be
5363 estimated as follows.

5364 The present GTS-LHC source delivers $^{208}\text{Pb}^{29+}$ ions with a charge-to-mass ratio $Q/A = 1/7.2$. A
5365 safe estimate of the space-charge limit at the entrance of Linac3 is 200 μA . To accelerate deuterons with
5366 $Q/A = 1/2$, all magnetic and electric fields would have to be reduced by a factor 3.6, leading to a space-charge
5367 limited current of 55 μA .

5368 However there is then a very comfortable margin in the electric and magnetic fields and deuterons are
5369 not subject to the loss factors associated with the subsequent stripping stages for Pb. If enough deuteron

5370 current is available from the source (say 5 mA), and one accepts losses in the linac and a somewhat degraded
 5371 beam quality at the end, then a current in the range of 200-500 μA would probably be available at the end
 5372 of the linac.

5373 As a caveat, early measurements of poor transmission of helium ions in Linac3 [589] should be mentioned.
 5374 However the explanation is unclear due to the lack of appropriate diagnostics.

5375 The bunch number and filling pattern in the LHC would be similar to that of the Pb beam. A naive
 5376 transposition of the scaling of the ratios of Linac3 output current (50 μA) to LHC bunch intensity (7×10^7)
 5377 from Pb to deuterons would suggest that the deuteron single-bunch intensity in the LHC could be $N_D \approx$
 5378 1.5×10^{10} .

5379 However this does not consider the differences in performance of the remainder of the injector chain (the
 5380 LEIR cooling ring, PS and SPS synchrotrons). A proper evaluation of these requires a more detailed study.
 5381 To be safe, we can apply a factor 5 reduction to this value.

5382 Then, assuming that we collide such a beam with the electron beam described in the preceding sub-
 5383 section, we see that *electron-nucleon* luminosities of order $L_{eN} \gtrsim 10^{31} \text{ cm}^{-2}\text{s}^{-1}$ could be accessible in e-D
 5384 collisions at the LHeC.

5385 7.7 Spin polarisation – an overview

5386 Before describing concepts for attaining electron and positron spin polarisation for the ring-ring option of
 5387 the LHeC we present a brief overview of the theory and phenomenology. We can then draw on this later as
 5388 required. This overview is necessarily brief but more details can be found in [590, 591].

5389 7.7.1 Self polarisation

5390 The spin polarisation of an ensemble of spin-1/2 fermions with the same energies travelling in the same
 5391 direction is defined as

$$\vec{P} = \langle \frac{2}{\hbar} \vec{\sigma} \rangle \quad (7.18)$$

5392 where $\vec{\sigma}$ is the spin operator in the rest frame and $\langle \rangle$ denotes the expectation value for the mixed spin
 5393 state. We denote the single-particle rest-frame expectation value of $\frac{2}{\hbar} \vec{\sigma}$ by \vec{S} and we call this the “spin”.

5394 The polarisation is then the average of \vec{S} over an ensemble of particles such as that of a bunch of particles.

5395 Electrons and positrons circulating in the (vertical) guide field of a storage ring emit synchrotron radiation
 5396 and a tiny fraction of the photons can cause spin flip from up to down and vice versa. However, the up-
 5397 to-down and down-to-up rates differ, with the result that in ideal circumstances the electron (positron)
 5398 beam can become spin polarised anti-parallel (parallel) to the field, reaching a maximum polarisation, P_{st} ,
 5399 of $\frac{8}{5\sqrt{3}} = 92.4\%$. This, the Sokolov-Ternov (S-T) polarising process, is very slow on the time scale of other
 5400 dynamical phenomena occurring in storage rings, and the inverse time constant for the exponential build up
 5401 is [592]:

$$\tau_{\text{st}}^{-1} = \frac{5\sqrt{3}}{8} \frac{r_e \gamma^5 \hbar}{m_e |\rho|^3} \quad (7.19)$$

5402 where r_e is the classical electron radius, γ is the Lorentz factor, ρ is the radius of curvature in the magnets
 5403 and the other symbols have their usual meanings. The time constant is usually in the range of a few minutes
 5404 to a few hours.

5405 However, even without radiative spin flip, the spins are not stationary but precess in the external fields.
 5406 In particular, the motion of \vec{S} for a charged particle travelling in electric and magnetic fields is governed by
 5407 the Thomas-BMT equation $d\vec{S}/ds = \vec{\Omega} \times \vec{S}$ where s is the distance around the ring [591, 593]. The vector $\vec{\Omega}$
 5408 depends on the electric (\vec{E}) and magnetic (\vec{B}) fields, the energy and the velocity (\vec{v}) which evolves according

5409 to the Lorentz equation:

$$\vec{\Omega} = \frac{e}{m_e c} \left[- \left(\frac{1}{\gamma} + a \right) \vec{B} + \frac{a\gamma}{1+\gamma} \frac{1}{c^2} (\vec{v} \cdot \vec{B}) \vec{v} + \frac{1}{c^2} \left(a + \frac{1}{1+\gamma} \right) (\vec{v} \times \vec{E}) \right] \quad (7.20)$$

$$= \frac{e}{m_e c} \left[- \left(\frac{1}{\gamma} + a \right) \vec{B}_\perp - \frac{g}{2\gamma} \vec{B}_\parallel + \frac{1}{c^2} \left(a + \frac{1}{1+\gamma} \right) (\vec{v} \times \vec{E}) \right]. \quad (7.21)$$

5410 Thus $\vec{\Omega}$ depends on s and on the position of the particle $u \equiv (x, p_x, y, p_y, l, \delta)$ in the 6-D phase space of
 5411 the motion. The coordinate δ is the fractional deviation of the energy from the energy of a synchronous
 5412 particle (“the beam energy”) and l is the distance from the centre of the bunch. The coordinates x and y are
 5413 the horizontal and vertical positions of the particle relative to the reference trajectory and $p_x = x', p_y = y'$
 5414 (except in solenoids) are their conjugate momenta. The quantity g is the appropriate gyromagnetic factor
 5415 and $a = (g - 2)/2$ is the gyromagnetic anomaly. For e^\pm , $a \approx 0.0011596$. \vec{B}_\parallel and \vec{B}_\perp are the magnetic fields
 5416 parallel and perpendicular to the velocity.

5417 In a simplified picture, the majority of the photons in the synchrotron radiation do not cause spin flip but
 5418 tend instead to randomise the e^\pm orbital motion in the (inhomogeneous) magnetic fields. Then, if the ring is
 5419 insufficiently-well geometrically aligned and/or if it contains special magnet systems like the “spin rotators”
 5420 needed to produce longitudinal polarisation at a detector (see below), the spin-orbit coupling embodied in
 5421 the Thomas-BMT equation can cause spin diffusion, i.e. depolarisation. Compared to the S-T polarising
 5422 effect the depolarisation tends to rise very strongly with beam energy. The equilibrium polarisation is then
 5423 less than 92.4% and will depend on the relative strengths of the polarisation and depolarisation processes. As
 5424 we shall see later, even without depolarisation certain dipole layouts can reduce the equilibrium polarisation
 5425 to below 92.4%.

5426 Analytical estimates of the attainable equilibrium polarisation are best based on the Derbenev-Kondratenko
 5427 (D-K) formalism [594, 595]. This implicitly asserts that the value of the equilibrium polarisation in an e^\pm
 5428 storage ring is the same at all points in phase space and is given by

$$P_{\text{dk}} = \mp \frac{8}{5\sqrt{3}} \frac{\oint ds \left\langle \frac{1}{|\rho(s)|^3} \hat{b} \cdot \left(\hat{n} - \frac{\partial \hat{n}}{\partial \delta} \right) \right\rangle_s}{\oint ds \left\langle \frac{1}{|\rho(s)|^3} \left(1 - \frac{2}{9} (\hat{n} \cdot \hat{s})^2 + \frac{11}{18} \left| \frac{\partial \hat{n}}{\partial \delta} \right|^2 \right) \right\rangle_s} \quad (7.22)$$

5429 where $\langle \rangle_s$ denotes an average over phase space at azimuth s , \hat{s} is the direction of motion and $\hat{b} = (\hat{s} \times \dot{\hat{s}})/|\dot{\hat{s}}|$.
 5430 \hat{b} is the magnetic field direction if the electric field vanishes and the motion is perpendicular to the magnetic
 5431 field. $\hat{n}(u; s)$ is a unit 3-vector field over the phase space satisfying the Thomas-BMT equation along particle
 5432 trajectories $u(s)$ (which are assumed to be integrable), and it is 1-turn periodic: $\hat{n}(u; s + C) = \hat{n}(u; s)$ where
 5433 C is the circumference of the ring.

5434 The field $\hat{n}(u; s)$ is a key object for systematising spin dynamics in storage rings. It provides a reference
 5435 direction for spin at each point in phase space and it is now called the “invariant spin field” [591, 596, 597].
 5436 At zero orbital amplitude, i.e. on the periodic (“closed”) orbit, the $\hat{n}(0; s)$ is written as $\hat{n}_0(s)$. For e^\pm rings
 5437 and away from spin-orbit resonances (see below), \hat{n} is normally at most a few milliradians away from \hat{n}_0 .

5438 A central ingredient of the D-K formalism is the implicit assumption that the e^\pm polarisation at each
 5439 point in phase space is parallel to \hat{n} at that point. In the approximation that the particles have the same
 5440 energies and are travelling in the same direction, the polarisation of a bunch measured in a polarimeter at
 5441 s is then the ensemble average

$$\vec{P}_{\text{ens,dk}}(s) = P_{\text{dk}} \langle \hat{n} \rangle_s. \quad (7.23)$$

5442 In conventional situations in e^\pm rings, $\langle \hat{n} \rangle_s$ is very nearly aligned along $\hat{n}_0(s)$. The *value* of the ensemble
 5443 average, $P_{\text{ens,dk}}(s)$, is essentially independent of s .

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Equation 7.22 can be viewed as having three components. The piece

$$P_{\text{bk}} = \mp \frac{8}{5\sqrt{3}} \frac{\oint ds \left\langle \frac{1}{|\rho(s)|^3} \hat{b} \cdot \hat{n} \right\rangle_s}{\oint ds \left\langle \frac{1}{|\rho(s)|^3} (1 - \frac{2}{9} (\hat{n} \cdot \hat{s})^2) \right\rangle_s} \approx \mp \frac{8}{5\sqrt{3}} \frac{\oint ds \frac{1}{|\rho(s)|^3} \hat{b} \cdot \hat{n}_0}{\oint ds \frac{1}{|\rho(s)|^3} (1 - \frac{2}{9} n_{0s}^2)}. \quad (7.24)$$

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gives the equilibrium polarisation due to radiative spin flip. The quantity n_{0s} is the component of \hat{n}_0 along the closed orbit. The subscript “bk” is used here instead of “st” to reflect the fact that this is the generalisation by Baier and Katkov [598, 599] of the original S-T expression to cover the case of piecewise homogeneous fields. Depolarisation is then accounted for by including the term with $\frac{11}{18} |\frac{\partial \hat{n}}{\partial \delta}|^2$ in the denominator. Finally, the term with $\frac{\partial \hat{n}}{\partial \delta}$ in the numerator is the so-called kinetic polarisation term. This results from the dependence of the radiation power on the initial spin direction and is not associated with spin flip. It can normally be neglected but is still of interest in rings with special layouts.

In the presence of radiative depolarisation the rate in Eq. 7.19 must be replaced by

$$\tau_{\text{dk}}^{-1} = \frac{5\sqrt{3}}{8} \frac{r_e \gamma^5 \hbar}{m_e C} \oint ds \left\langle \frac{1 - \frac{2}{9} (\hat{n} \cdot \hat{s})^2 + \frac{11}{18} |\frac{\partial \hat{n}}{\partial \delta}|^2}{|\rho(s)|^3} \right\rangle_s. \quad (7.25)$$

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This can be written in terms of the spin-flip polarisation rate, τ_{bk}^{-1} , and the depolarisation rate, τ_{dep}^{-1} , as:

$$\frac{1}{\tau_{\text{dk}}} = \frac{1}{\tau_{\text{bk}}} + \frac{1}{\tau_{\text{dep}}}, \quad (7.26)$$

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where

$$\tau_{\text{dep}}^{-1} = \frac{5\sqrt{3}}{8} \frac{r_e \gamma^5 \hbar}{m_e C} \oint ds \left\langle \frac{\frac{11}{18} |\frac{\partial \hat{n}}{\partial \delta}|^2}{|\rho(s)|^3} \right\rangle_s \quad (7.27)$$

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and

$$\tau_{\text{bk}}^{-1} = \frac{5\sqrt{3}}{8} \frac{r_e \gamma^5 \hbar}{m_e C} \oint ds \left\langle \frac{1 - \frac{2}{9} (\hat{n} \cdot \hat{s})^2}{|\rho(s)|^3} \right\rangle_s. \quad (7.28)$$

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The time dependence for build-up from an initial polarisation P_0 to equilibrium is

$$P(t) = P_{\text{ens,dk}} \left[1 - e^{-t/\tau_{\text{dk}}} \right] + P_0 e^{-t/\tau_{\text{dk}}}. \quad (7.29)$$

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In perfectly aligned e^\pm storage rings containing just horizontal bends, quadrupoles and accelerating cavities, there is no vertical betatron motion and $\hat{n}_0(s)$ is vertical. Since the spins do not “see” radial quadrupole fields and since the electric fields in the cavities are essentially parallel to the particle motion, \hat{n} is vertical, parallel to the guide fields and to $\hat{n}_0(s)$ at all u and s . Then the derivative $\frac{\partial \hat{n}}{\partial \delta}$ vanishes and there is no depolarisation. However, real rings have misalignments. Then there is vertical betatron motion so that the spins also see radial fields which tilt them from the vertical. Moreover, $\hat{n}_0(s)$ is also tilted and the spins can couple to vertical quadrupole fields too. As a result \hat{n} becomes dependent on u and “fans out” away from $\hat{n}_0(s)$ by an amount which usually increases with the orbit amplitudes. Then in general $\frac{\partial \hat{n}}{\partial \delta}$ no longer vanishes in the dipoles (where $1/|\rho(s)|^3$ is large) and depolarisation occurs. In the presence of skew quadrupoles and solenoids and, in particular, in the presence of spin rotators, $\frac{\partial \hat{n}}{\partial \delta}$ can be non-zero in dipoles even with perfect alignment. The deviation of \hat{n} from $\hat{n}_0(s)$, and the depolarisation, tend to be particularly large near to the spin-orbit resonance condition

$$\nu_0 = k_0 + k_I Q_I + k_{II} Q_{II} + k_{III} Q_{III}. \quad (7.30)$$

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Here $k_0, k_I, k_{II}, k_{III}$ are integers, Q_I, Q_{II}, Q_{III} are the three tunes of the synchrotron motion and ν_0 is the spin tune on the closed orbit, i.e. the number of precessions around $\hat{n}_0(s)$ per turn, made by a spin on

5471 the closed orbit ¹. In the special case, or in the approximation, of no synchrotron coupling one can make
5472 the associations: $I \rightarrow x$, $II \rightarrow y$ and $III \rightarrow s$, where, here, the subscript s labels the synchrotron mode.
5473 In a simple flat ring with no closed-orbit distortion, $\nu_0 = a\gamma$ where γ is the Lorentz factor for the nominal
5474 beam energy. For e^\pm , $a\gamma$ increments by 1 for every 441 MeV increase in beam energy. In the presence of
5475 misalignments and special elements like rotators, ν_0 is usually still approximately proportional to the beam
5476 energy. Thus an energy scan will show peaks in τ_{dep}^{-1} and dips in $P_{\text{ens,dk}}(s)$, namely at around the resonances.
5477 Examples can be seen in figures 7.44 and 7.45 below. The resonance condition expresses the fact that the
5478 disturbance to spins is greatest when the $|\vec{\Omega}(u; s) - \vec{\Omega}(0; s)|$ along a trajectory is coherent (“in step”) with
5479 the natural spin precession. The quantity $(|k_I| + |k_{II}| + |k_{III}|)$ is called the order of the resonance. Usually,
5480 the strongest resonances are those for which $|k_I| + |k_{II}| + |k_{III}| = 1$, i.e., the first-order resonances. The next
5481 strongest are usually the so-called “*synchrotron sideband resonances*” of parent first-order resonances, i.e.
5482 resonances for which $\nu_0 = k_0 \pm Q_{I,II,III} + \tilde{k}_{III} Q_{III}$ where \tilde{k}_{III} is an integer and mode III is associated with
5483 synchrotron motion. All resonances are due to the non-commutation of successive spin rotations in 3-D and
5484 they therefore occur even with purely linear orbital motion.

5485 We now list some keys points.

- 5486 • The approximation on the r.h.s. of Eq. 7.24 makes it clear that if there are dipole magnets with fields
5487 not parallel to \hat{n}_0 , as is the case, for example, when spin rotators are used, then P_{bk} can be lower than
5488 the 92.4% attainable in the case of a simple ring with no solenoids and where all dipole fields and $\hat{n}_0(s)$
5489 are vertical.
- 5490 • If, as is usual, the kinetic polarisation term makes just a small contribution, the above formulae can
5491 be combined to give

$$P_{\text{ens,dk}} \approx P_{\text{bk}} \frac{\tau_{\text{dk}}}{\tau_{\text{bk}}} . \quad (7.31)$$

5492 From Eq. 7.26 it is clear that $\tau_{\text{dk}} \leq \tau_{\text{bk}}$.

- 5493 • The underlying rate of polarisation due to the S-T effect, τ_{bk}^{-1} , increases with the fifth power of the
5494 energy and decreases with the third power of the bending radii.
- 5495 • It can be shown that as a general rule the “normalised” strength of the depolarisation, $\tau_{\text{dep}}^{-1}/\tau_{\text{bk}}^{-1}$,
5496 increases with beam energy according to a tune-dependent polynomial in even powers of the beam
5497 energy. So we expect that the attainable equilibrium polarisation decreases as the energy increases.
5498 This was confirmed LEP, where with the tools available, little polarisation could be obtained at 60
5499 GeV [600].

5500 7.7.2 Suppression of depolarisation – spin matching

5501 Although the S-T effect offers a convenient way to obtain stored high energy e^\pm beams, it is only useful in
5502 practice if there is not too much depolarisation. Depolarisation can be significant if the ring is misaligned,
5503 if it contains spin rotators or if it contains uncompensated solenoids or skew quadrupoles. Then if $P_{\text{ens,dk}}$
5504 and/or τ_{dk} are too small, the layout and the optic must be adjusted so that $(|\frac{\partial \hat{n}}{\partial \delta}|)^2$ is small where $1/|\rho(s)|^3$
5505 is large. So far it is only possible to do this within the linear approximation for spin motion. This technique
5506 is called “*linear spin matching*” and when successful, as for example at HERA [601], it immediately reduces
5507 the strengths of the first-order spin-orbit resonances. Spin matching requires two steps: “*strong synchrobeta*
5508 *spin matching*” is applied to the optics and layout of the perfectly aligned ring and then “*harmonic closed-*
5509 *orbit spin matching*” is applied to soften the effects of misalignments. This latter technique aims to adjust
5510 the closed orbit so as to reduce the tilt of \hat{n}_0 from the vertical in the arcs. Since the misalignments can
5511 vary in time and are usually not sufficiently well known, the adjustments are applied empirically while the
5512 polarisation is being measured.

5513 Spin matching must be approached on a case-by-case basis. An overview can be found in [590].

¹In fact the resonance condition should be more precisely expressed in terms of the so-called amplitude dependent spin tune [591, 596, 597]. But for typical e^\pm rings, the amplitude dependent spin tune differs only insignificantly from ν_0 .

7.7.3 Higher order resonances

Even if the beam energy is chosen so that first-order resonances are avoided and in linear approximation $P_{\text{ens,dk}}$ and/or τ_{dk} are expected to be large, it can happen that that beam energy corresponds to a higher order resonance. As mentioned above, in practice the most intrusive higher order resonances are those for which $\nu_0 = k_0 \pm Q_k + \tilde{k}_s Q_s$ ($k \equiv I, II$ or III). These synchrotron sideband resonances of the first-order parent resonances are due to modulation by energy oscillations of the instantaneous rate of spin precession around \hat{n}_0 . The depolarisation rates associated with sidebands of isolated parent resonances ($\nu_0 = k_0 \pm Q_k$) are related to the depolarisation rates for the parent resonances. For example, if the beam energy is such that the system is near to a dominant Q_y resonance we can approximate τ_{dep}^{-1} in the form

$$\tau_{\text{dep}}^{-1} \propto \frac{A_y}{(\nu_0 - k_0 \pm Q_y)^2}. \quad (7.32)$$

This becomes

$$\tau_{\text{dep}}^{-1} \propto \sum_{\tilde{k}_s=-\infty}^{\infty} \frac{A_y B_y(\zeta; \tilde{k}_s)}{(\nu_0 - k_0 \pm Q_y \pm \tilde{k}_s Q_s)^2}$$

if the synchrotron sidebands are included. The quantity A_y depends on the beam energy and the optics and is reduced by spin matching. The proportionality constants $B_y(\zeta; \tilde{k}_s)$ are called *enhancement factors*, and they contain modified Bessel functions $I_{|\tilde{k}_s|}(\zeta)$ and $I_{|\tilde{k}_s|+1}(\zeta)$ which depend on Q_s and the energy spread σ_δ through the *modulation index* $\zeta = (a\gamma \sigma_\delta / Q_s)^2$. More formulae can be found in [602, 603].

Thus the effects of synchrotron sideband resonances can be reduced by doing the spin matches described above. Note that these formulae are just meant as a guide since they are approximate and explicitly neglect interference between the first-order parent resonances. To get a complete impression, the Monte-Carlo simulation mentioned later must be used. The sideband strengths generally increase with the energy spread and the beam energy and the sidebands are a major contributor to the increase of $\tau_{\text{dep}}^{-1} / \tau_{\text{bk}}^{-1}$ with energy.

7.7.4 Calculations of the e^\pm polarisation in the LHeC

As a first step towards assessing the attainable polarisation we have considered an early version of the LHeC lattice: a flat ring with no rotators, no interaction point and no bypasses. The tunes are $Q_x = 123.83$ and $Q_y = 85.62$. The horizontal emittance is 8 nm. The ring is therefore typical of the designs under consideration. With perfect alignment, \hat{n}_0 is vertical everywhere and there is no vertical dispersion. The polarisation will then reach 92.4%. At ≈ 60 GeV, $\tau_{\text{bk}} \approx 60$ minutes.

For the simple flat ring these values can be obtained by hand from Eq. 7.24 and Eq. 7.28. However, in general, e.g., in the presence of misalignments or rotators, the calculation of polarisation requires special software and for this study, the thick-lens code SLICKTRACK was used [604]. This essentially consists of four sections which carry out the following tasks:

- (1) Simulation of misalignments followed by orbit correction with correction coils.
- (2) Calculation of the optical properties of the beam and the beam sizes.
- (3) Calculation of $\partial\hat{n}/\partial\delta$ for linearised spin motion with the thick-lens version (SLICK [605]) of the SLIM algorithm [590].
The equilibrium polarisation is then obtained from Eq. 7.22. This provides a first impression and only exhibits the first order resonances.
- (4) Calculation of the rate of depolarisation beyond the linear approximation of item 3.

In general, the numerical calculation of the integrand in Eq. 7.27 beyond first order represents a difficult computational problem. Therefore a pragmatic approach is adopted, whereby the rate of depolarisation

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is obtained with a Monte-Carlo spin-orbit tracking algorithm which includes radiation emission. The algorithm employs full 3-D spin motion in order to see the effect of the higher order resonances. The Monte-Carlo algorithm can also handle the effect on the particles and on the spins of the non-linear beam-beam forces. An estimate of the equilibrium polarisation is then obtained from Eq. 7.31.

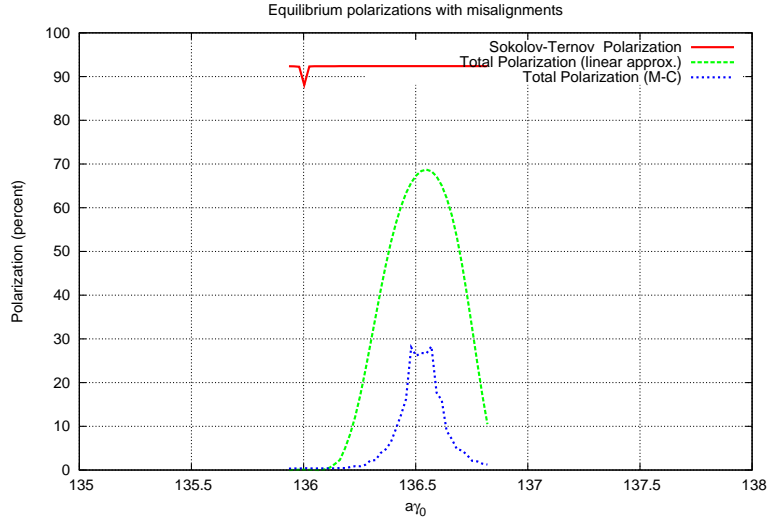


Figure 7.44: Estimated polarisation for the LHeC without spin rotators, $Q_s = 0.06$.

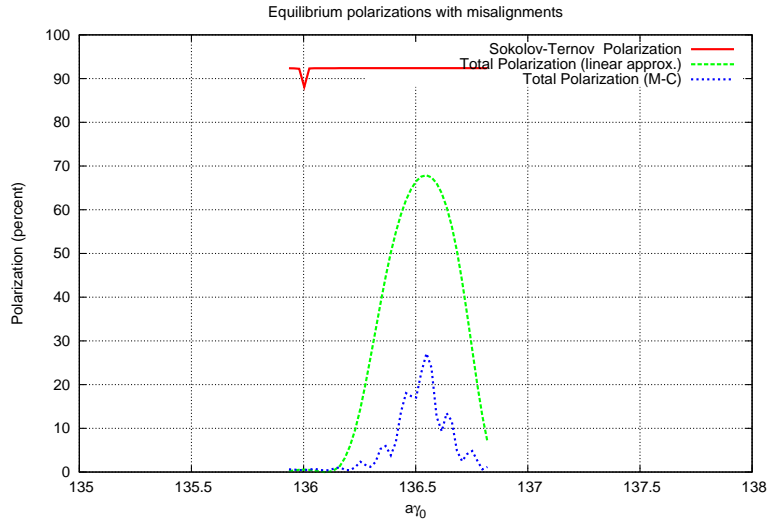


Figure 7.45: Estimated polarisation for the LHeC without spin rotators, $Q_s = 0.1$.

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Some basic features of the polarisation for the misaligned flat ring are shown in figures 7.44 and 7.45 where polarisations are plotted against $a\gamma$ around 60 GeV. In both cases the r.m.s. vertical closed-orbit deviation is about $75\mu\text{m}$. This is obtained after giving the quadrupoles r.m.s. vertical misalignments of $150\mu\text{m}$ and assigning a correction coil to every quadrupole. The vector \hat{n}_0 has an r.m.s. tilt of about 4 milliradians from the vertical near $a\gamma = 136.5$. For figure 7.44 the synchrotron tune, Q_s , is 0.06 so that $\xi \approx 5$. For figure 7.45, $Q_s = 0.1$ so that $\xi \approx 1.9$.

5562 The red curves depict the polarisation due to the Sokolov-Ternov effect alone. The dip to below 92.4%
 5563 at $a\gamma = 136$ is due to the characteristic very large tilt of \hat{n}_0 from the vertical at an integer value of $a\gamma$.
 5564 See [590].

5565 The green curves depict the equilibrium polarisation after taking into account the depolarisation associ-
 5566 ated with the misalignments and the consequent tilt of \hat{n}_0 . The polarisation is calculated with the linearised
 5567 spin motion as in item 3 above. In these examples the polarisation reaches about 68 %. The strong fall off
 5568 on each side of the peak is mainly due to first-order “synchrotron” resonances $\nu_0 = k_0 \pm Q_s$. Since Q_s is
 5569 small these curves are similar for the two values of Q_s .

5570 The blue curves show the polarisation obtained as in item 4 above. Now, by going beyond the linearisa-
 5571 tion of the spin motion, the peak polarisation is about 27 %. The fall from 68 % is mainly due to synchrotron
 5572 sideband resonances. With $Q_s = 0.06$ (Fig. 7.44) the resonances are overlapping. With $Q_s = 0.1$, (Fig. 7.45)
 5573 the sidebands begin to separate. In any case these curves demonstrate the extreme sensitivity of the attain-
 5574 able polarisation to small tilts of \hat{n}_0 at high energy. Simulations for $Q_s = 0.1$ with a series of differently
 5575 misaligned rings, all with r.m.s. vertical closed-orbit distortions of about $75\mu\text{m}$, exhibit peak equilibrium
 5576 polarisations ranging from about about 10 % to about 40 %. Experience at HERA suggests that harmonic
 5577 closed-orbit spin matching can eliminate the cases of very low polarisation.

5578 Figure 7.46 shows a typical energy dependence of the peak equilibrium polarisation for a fixed rf voltage
 5579 and for one of the misaligned rings. The synchrotron tune varies from $Q_s = 0.093$ at 40 GeV to $Q_s = 0.053$
 5580 at 65 GeV due to the change in energy loss per turn. As expected the attainable polarisation falls steeply
 5581 as the energy increases. However, although with this good alignment, a high polarisation is predicted at 45
 5582 GeV, τ_{bk} would be about 5 hours as at LEP. A small τ_{bk} is not only essential for a programme of particle
 physics, but essential for the application of empirical harmonic closed-orbit spin matching.

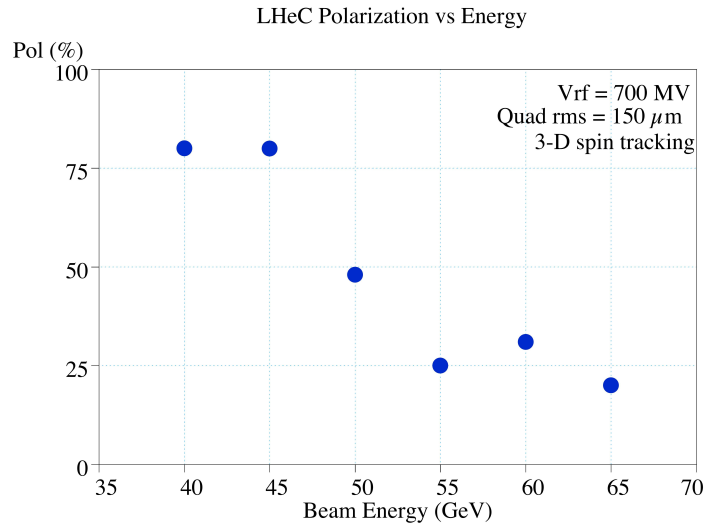


Figure 7.46: Equilibrium polarisation *vs* ring energy, full 3-D spin tracking results

5583
 5584 As mentioned above, it was difficult to get polarisation at 60 GeV at LEP. However, these calculations
 5585 suggest that by adopting the levels of alignment that are now standard for synchrotron-radiation sources
 5586 and by applying harmonic closed-orbit spin matching, there is reason to hope that high polarisation in a flat
 5587 ring can still be obtained.

7.7.5 Spin rotator concepts for the LHeC

The LHeC, like all analogous projects involving spin, needs longitudinal polarisation at the interaction point. However, if the S-T effect is to be the means of producing and maintaining the polarisation, then as is clear from Eq. 7.24, \hat{n}_0 must be close to vertical in most of the dipoles. We have seen at Eq. 7.23 that the polarisation is essentially parallel to \hat{n}_0 . So to get longitudinal polarisation at a detector, it must be arranged that \hat{n}_0 is longitudinal at the detector but vertical in the rest of the ring. This can be achieved with magnet systems called spin rotators which rotate \hat{n}_0 from vertical to longitudinal on one side of the detector and back to vertical again on the other side.

Spin rotators use sequences of magnets which generate large spin rotations around different axes and exploit the non-commutation of successive large rotations around different axes. According to the T-BMT equation, the rate of spin precession in longitudinal fields is inversely proportional to the energy. However, for motion perpendicular to a magnetic field spins precess at a rate essentially proportional to the energy: $\delta\theta_{\text{spin}} = (a\gamma + 1)\delta\theta_{\text{orb}}$ in obvious notation. Thus for the high-energy ring considered here, spin rotators should be based on dipoles as in HERA [601]. In that case the rotators consisted of interleaved horizontal and vertical bending magnets set up so as to generate interleaved, closed, horizontal and vertical bumps in the design orbit. The individual orbit deflections were small but the spin rotations were of the order of a radian. The success in obtaining high longitudinal polarisation at HERA attests to the efficacy of such rotators.

Eq. 7.24 shows that P_{bk} essentially scales with the cosine of the angle of tilt of \hat{n}_0 from the vertical in the arc dipoles. Thus a rotation error resulting in a tilt of \hat{n}_0 of even a few degrees would not reduce P_{bk} by too much. However, as was mentioned above, a tilt of \hat{n}_0 in the arcs can lead to depolarisation. In fact the calculations below show that at 60 GeV, tilts of more than a few milliradians cause significant depolarisation. Thus well-tuned rotators are essential for maintaining polarisation.

Dipole rotators require a significant amount of space in the ring. To minimise the power density as well as to preserve the polarisation, the amount of synchrotron radiation from the rotators needs to be kept to a minimum, in direct conflict with the desire to keep the dipole magnets as short as possible. In addition, longer dipole magnets lead to larger orbit excursions. A numerical example for HERA-type spin rotators in the LHeC with a bending radius of each dipole equal to that of the arc dipoles yields a length of each spin rotator of about 150 m. The net space appears to be available; the challenge being the integration of the string of dipoles and the vertical magnet movers in an already crowded area of the LHC tunnel. Note that the rotator incorporates a certain amount of bending angle. The excursion away from the nominal orbit is about 0.3 m.

A scheme using two Siberian Snakes has been considered by Derbenev and Grote [606] (see below) that would integrate the IR rotators with the vertical dogleg required to bring the beams into collision. For this the horizontal bends are all of the same polarity and contribute to the overall 360° bend so that the added dipole strength in the IR is minimised.

Table 7.33 gives an indication of possible parameters for LHeC spin rotators. These are subject to change as the specific geometry in the IR is being further refined. Note that the effect of these rotators on the degree of polarisation remains to be evaluated (but see below for further comments on the Derbenev-Grote scheme).

7.7.6 Further work

We now list the next steps towards obtaining longitudinal polarisation at the interaction point.

- (1) A harmonic closed-orbit spin matching algorithm must be implemented for the LHeC to try to correct the remaining tilt of \hat{n}_0 and thereby increase the equilibrium polarisation.
- (2) Practical spin rotators must be designed and appropriate strong synchrobeta spin matching must be implemented. The design of the rotators and spin matching are closely linked. Some preliminary numerical investigations (below) show, as expected, that without this spin matching, little polarisation will be obtained.

Table 7.33: Possible Parameters for LHeC Spin Rotators

Parameter	Unit	HERA-type	Derbenev-Grote (IP only)
No. of vertical dipole magnets		12	10
No. of horizontal dipole magnets		12	10
Bending angle/magnet	°	0.110	0.132
Length of magnet	m	5.45	5.45
Total length of rotator	m	170	80
Net bending angle	°	0.66	1.32
Vertical offset	m	0	1.25

- (3) If synchrotron sideband resonances are still overwhelming after items 1 and 2 are implemented, a scheme involving Siberian Snakes could be tried. Siberian Snakes are arrangements of magnets which manipulate spin on the design orbit so that the closed-orbit spin tune is independent of beam energy. Normally the spin tune is then 1/2 and heuristic arguments suggest that the sidebands should be suppressed. However, the two standard schemes [607] either cause \hat{n}_0 to lie in the machine plane (just one snake) or ensure that it is vertically up in one half of the ring and vertically down in the other half (two snakes). In both cases Eq. 7.24 shows that P_{bk} vanishes. In principle, this problem can be overcome for two snakes by again appealing to Eq. 7.24 and having short strong dipoles in the half of the ring where \hat{n}_0 points vertically up and long weaker dipoles in the half of the ring where \hat{n}_0 points vertically down (or vice versa). Of course, the dipoles must be chosen so that the total bend angle is π in each half of the ring. Moreover, Eq. 7.24 shows that the pure Sokolov-Ternov polarisation would be much less than 92.4%. One version of this concept [606] uses a pair of rotators which together form a snake while a complementary snake is inserted diametrically opposite to the interaction point. Each rotator comprises interleaved strings of vertical and horizontal bends which not only rotate the spins from vertical to horizontal, but also bring the e^\pm beams down to the level of the proton beam and then up again. However, the use of short dipoles in the arcs increases the radiation losses.

Note that because of the energy dependence of spin rotations in the dipoles, \hat{n}_0 is vertical in the arcs at just one energy. This concept has been tested with SLICKTRACK but in the absence of a strong synchrobeta spin match, the equilibrium polarisation is very small as expected. Nevertheless the effects of misalignments and of the tilt of \hat{n}_0 away from design energy, have been isolated by imposing an artificial spin match using standard facilities in SLICKTRACK. The snake in the arc has been represented as a thin element that has no influence on the orbital motion. Then it looks as if the synchrotron sidebands are indeed suppressed in the depolarisation associated with tilts of \hat{n}_0 . In contrast to the rotators in HERA, this kind of rotator allows only one helicity for electrons and one for positrons.

- (4) If a scheme can be found which delivers sufficient longitudinal polarisation, the effect of non-linear orbital motion, the effect of beam-beam forces and the effect of the magnetic fields of the detector must then be studied.

7.7.7 Summary

We have investigated the possibility of polarisation in the LHeC electron ring. At this stage of the work it appears that a polarisation of between 25 and 40% at 60 GeV can be reasonably aimed for, assuming the efficacy of harmonic closed-orbit spin matching. Attaining this degree of polarisation will require precision alignment of the magnets to better than $150\mu\text{m}$ rms, a challenging but achievable goal. The spin rotators necessary at the IP need to be properly spin matched to avoid additional depolarisation and this work is in progress. An interesting alternative involving the use of Siberian Snakes to try to avoid the depolarising

5670 synchrotron sideband resonances is being investigated. At present, this appears to potentially yield a similar
5671 degree of polarisation, at the expense of increased energy dissipation in the arcs arising from the required
5672 differences of the bending radii in the two halves of the machine.

5673 7.8 Integration and machine protection issues

5674 7.8.1 Space requirements

5675 The integration of an additional electron accelerator into the LHC is a difficult task. Firstly, the LEP tunnel
5676 was designed for LEP and not for the LHC, which is now using up almost all space in the tunnel. It is
5677 not evident, how to place another accelerator into the limited space. Secondly, the LHC will run for several
5678 years, before the installation of a second machine can start. Meanwhile the tunnel will be irradiated and all
5679 installation work must proceed as fast as possible to limit the collective and individual doses. The activation
5680 after the planned high-luminosity-run of the LHC and after one month of cool-down is expected to be around
5681 $0.5...1\mu Sv/h$ [608] on the proton magnets and many times more at exposed positions. Moreover the time
5682 windows for installation will be short and other work for the LHC will be going on, maybe with higher
5683 priority. Nevertheless, with careful preparation and advanced installation schemes an electron accelerator
5684 can be fitted in.

5685 For the installation of the LHC machine proper, all heavy equipment had to pass the UJ2, while entering
5686 the tunnel. There the equipment had to be moved from TI2, which comes in from the outside, to the
5687 transport zone of LHC, which is on the inner side of the ring. Clearly, applying this procedure to the
5688 installation of the LHeC everything above the cold dipoles has to be removed. The new access shafts and
5689 the smaller size of the equipment for the electron ring may render this operation unnecessary.

5690 **General** The new electron accelerator will be partially in the existing tunnel and partially in specially
5691 excavated tunnel sections and behind the experiments in existing underground areas. The excavation work
5692 will need special access shafts in the neighborhood of the experiments from where the stub-tunnels can be
5693 driven. The connection to the existing LEP tunnels will be very difficult. The new tunnel enters with a very
5694 small grazing angle, which means over a considerable length. Very likely the proton installation will have to
5695 be removed while the last meters of the new tunnel is bored.

5696 Figure 7.47 shows a typical cross section of the LHC tunnel, where the two machines are together. The
5697 LHC dipole dominates the picture. The transport zone is indicated at the right (inside of the ring). The
5698 cryogenic installations (QRL) and various pipes and cable trays are on the left. The dipole cross section
5699 shows two concentric circles. The larger circle corresponds to the largest extension at the re-enforcement
5700 rings and marks a very localized space restriction on a very long object. The inner circle is relevant for
5701 items shorter than about 10 m longitudinally. A hatched square above the dipole labeled 30 indicates the
5702 area, which was kept free in the beginning for an electron machine. Unfortunately, the center of this space
5703 is right above the proton beam. Any additional machine will, however, have to avoid the interaction points
5704 1 and 5. In doing so additional length will be necessary, which can only be compensated for by shifting
5705 the electron machine in the arc about 60 cm to the inside (right), as indicated by the red square in Figure
5706 7.47. The limited space for compensation puts a constraint on the extra length created by the bypasses.
5707 The transport zone will, however, be affected. This requires an unconventional way to mount the electron
5708 machine. Nevertheless, there is clearly space to place an electron ring into the LHC, for most of the arc.
5709 Figure 7.48 gives the impression that the tunnel for most of its length is not too occupied.

5710 **In the arc** In Fig. 7.48 one sees the chain of superconducting magnets and in the far distances the *QRL*
5711 *Service Module* with its jumper, the cryogenic connection between the superconducting machine and the
5712 cryogenic distribution line. The service modules come always at the position of every second quadrupole and
5713 have a substantial length. The optics of the LHeC foresees no e-ring magnet at these positions. A photo of
5714 service modules in the workshop is shown in figure 7.49 (courtesy CERN) illustrating that the QRL extends
5715 substantially in the vertical direction above the LHC arc cryostat and cryo line. The picture 7.48, taken in

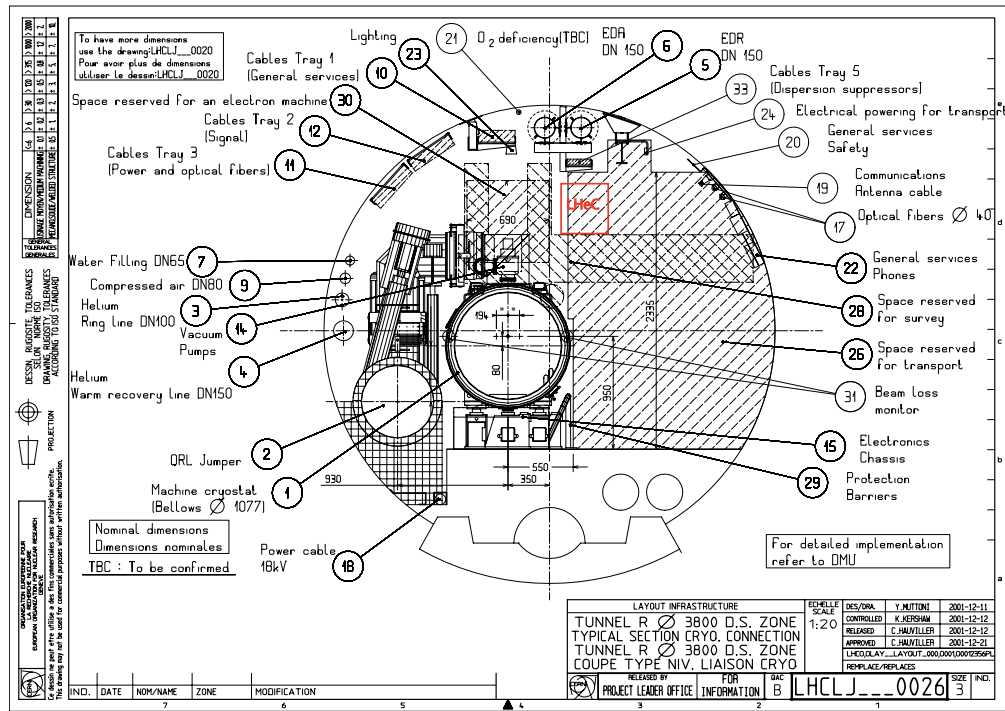


Figure 7.47: Cross-section of the LHC tunnel with the original space holder for the electron beam installation directly above the LHC cryostat and the shifted new required space due to the additional bypass in IR1 and IR5 and the need to keep the overall circumference of the electron ring identical to that of the proton beams.

5716 sector 3, shows also the critical tunnel condition in this part of the machine. Clearly, heavy loads cannot
 5717 be suspended from the tunnel ceiling. The limit is set to 100 kg per meter along the tunnel. The e-ring
 5718 components have to rest on stands from the floor wherever possible. Normally there is enough space between
 5719 the LHC dipoles and the QRL to place a vertical 10 cm quadratic or rectangular support. Alternatively a
 5720 steel arch bolted to the tunnel walls and resting on the floor can support the components from above. This
 5721 construction is required wherever the space for a stand is not available.

5722 The electron machine, though partially in the transport zone, will be high up in the tunnel, high enough
 5723 not to interfere with the transport of a proton magnet or alike. The transport of cryogenic equipment may
 5724 need the full height. Transports of that kind will only happen, when part of the LHC are warmed up. This
 5725 gives enough time to shift the electron ring to the outside by 30 cm, if the stands are prepared for this
 5726 operation. The outside movement causes also a small elongation of the inter-magnet connections. This effect
 5727 is locally so small that the expansion joints, required anyway, can accommodate it. One could even think
 5728 of moving large sections of the e-machine outwards in a semi-automatic way. Thus the time to clear the
 5729 transport path can be kept in the shadow of the warm-up and cool-down times.

5730 **Dump area** The most important space constraints for the electron machine are in the proton dump area,
 5731 the proton RF cavities, point 3, and in particular the collimator sections.

5732 Figure 7.50 [609] shows the situation at the dump kicker. The same area is also shown in a photo in Figure
 5733 7.51, while Figure 7.52 shows one of the outgoing dump-lines. The installation of the e-machine requires
 5734 the proper rerouting of cables (which might be damaged by radiation and in need of exchange anyhow),
 5735 eventually turning of pumps by 90 degrees or straight sections in the electron optics to bridge particularly
 5736 difficult stretches with a beam pipe only.



Figure 7.48: View of sector 4 showing the chain of superconducting magnets in the arc.



Figure 7.49: Sideview of a QRL service module with the jumper that extends vertically above the LHC cryostat and the cryogenic distribution line.

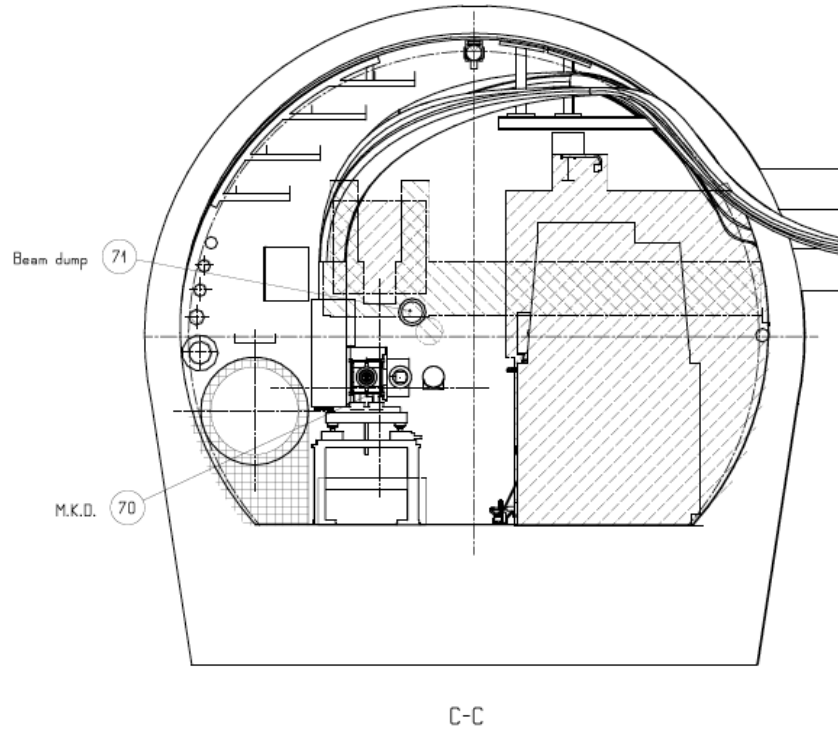


Figure 7.50: Dump kicker [609]

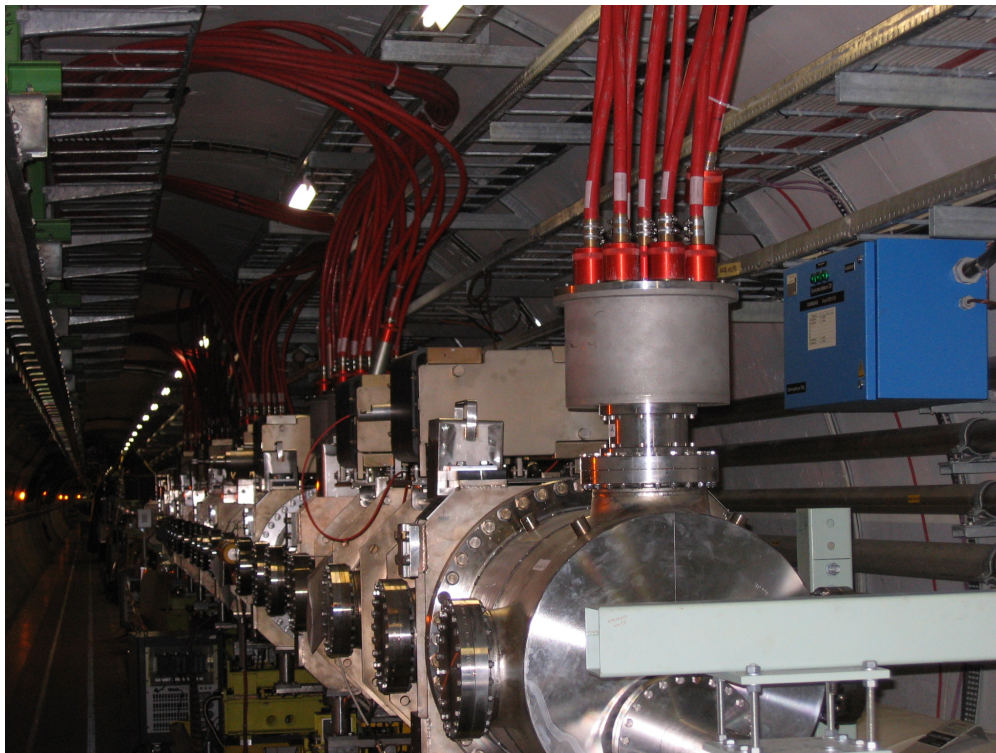


Figure 7.51: Dump kicker installation in IR6 for one of the two LHC proton rings.

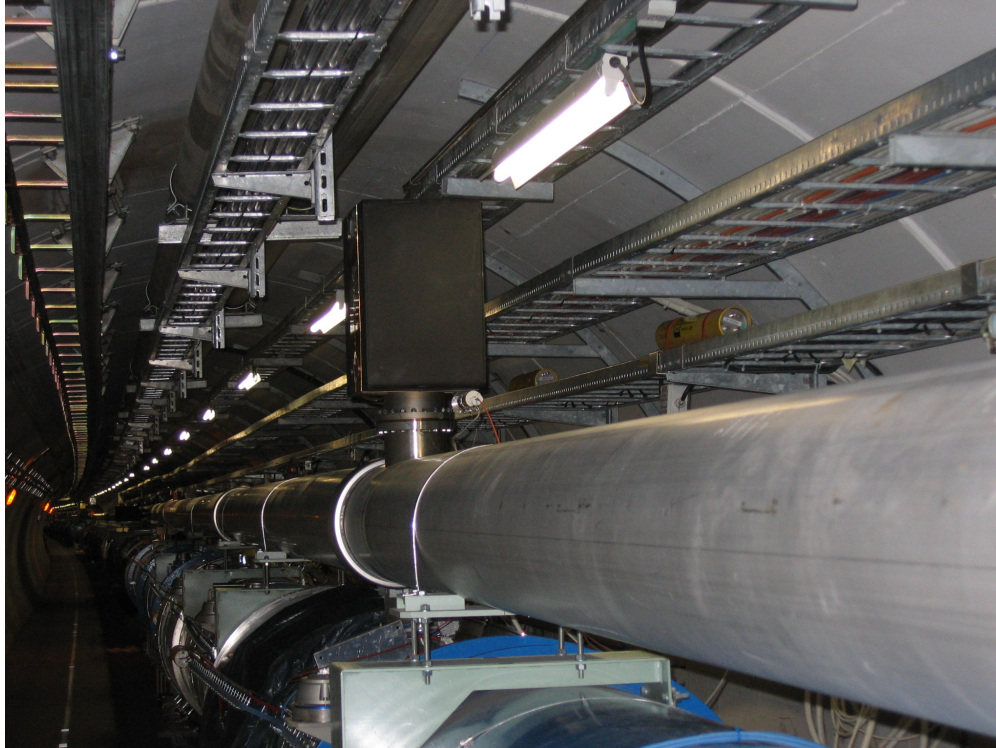


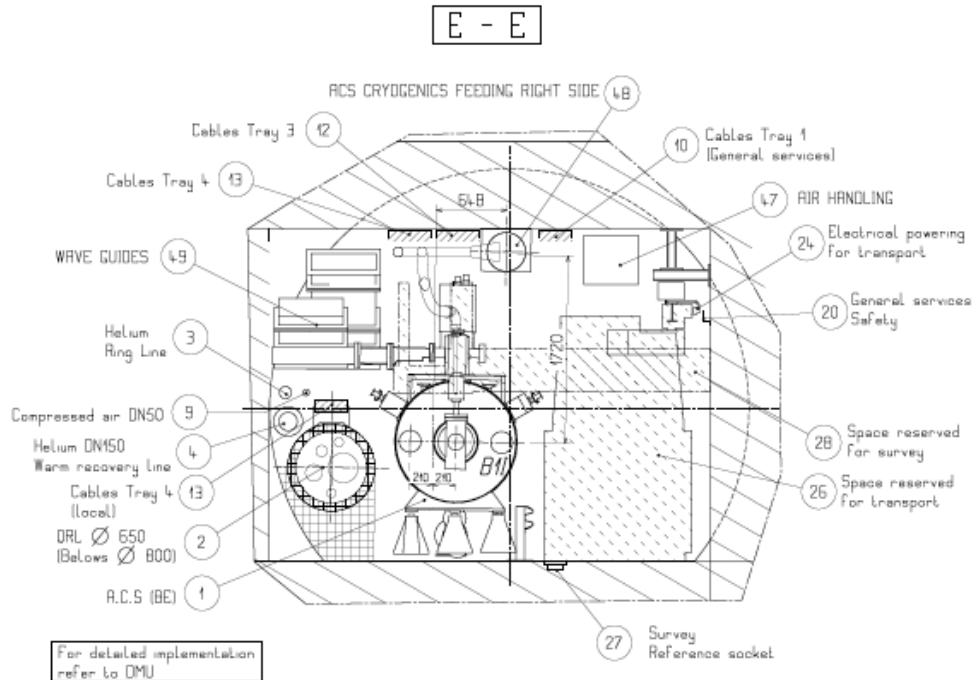
Figure 7.52: Dump line of one of the LHC proton rings.

5737 **Point 4, proton RF** The Figures 7.53 [610] and 7.54 illustrate the situation at the point 4, where the
 5738 LHC RF is installed. Fortunately, the area is not very long. A short straight section could be created for
 5739 the electron ring. This would allow to pass the area with just a shielded beam pipe.

5740 **Cryolink in point 3** The geography around point 3 did not permit to place there a cryoplant. The
 5741 cryogenic cooling for the feedboxes is provided by a cryolink, as is shown in the figures 7.55 and 7.56. In
 5742 particular above the Q6 proton quadrupole changes have to be made. There are other interferences with the
 5743 cryogenics, as for example at the DFBA's (main feedboxes). An example is shown in figure 7.57. Eventually
 5744 the electron optics has to be adapted to allow the beampipe to pass the cables, which may have to be moved
 5745 a bit.

5746 **Long straight section 7** An extra air duct is mounted in the long straight section 7 (LSS7) as is indicated
 5747 in Fig. 7.58 (labelled Plenum de ventilation) avoiding the air pollution of the area above point 7. The duct
 5748 occupies the space planned for the electron machine. The air duct has to be replaced by a slightly different
 5749 construction mounted further outside (to the right in the figure). There are also air ducts at points 1 and 5,
 5750 but they are not an issue. The electron ring is passing behind the experiments in these points

5751 **Proton collimation** The areas around Point 3 (-62...+177m) and Point 7 (-149...+205m) [611] are heavily
 5752 used for the collimation of the proton beam. The high dose rate in the neighborhood of a collimator
 5753 makes special precautions for the installation of new components or the exchange of a collimator necessary.
 5754 Moreover, the collimator installation needs the full height of the tunnel. Hence, the electron ring installation
 5755 has to be suspended from the re-enforced tunnel roof. The electron machine components must be removable
 5756 and installable, easy and fast. The re-alignment must be well prepared and fast, possibly in a remote fashion.



h

Figure 7.53: Schematic tunnel cross section with the LHC Proton Proton RF in point 4 [610].

5757 It is uncommon to identify fast mounting and demounting as a major issue. However, with sufficient emphasis
 5758 during the R&D phase of the project, this problem can be solved.

5759 7.8.2 Impact of the synchrotron radiation on tunnel electronics

5760 It is assumed that the main power converters of the LHC will have been moved out of the RRs because of
 5761 the single event upsets, caused by proton losses.

5762 The synchrotron radiation has to be intercepted at the source, as in all other electron accelerators. A few
 5763 millimeter of lead are sufficient for the relatively low (critical) energies around 100 to 200 keV. The K-edge
 5764 of lead is at 88 keV, the absorption coefficient is above 80/cm at this energy [612]. One centimeter of lead is
 5765 sufficient to suppress 300 keV photons by a factor of 100. Detailed calculations of the optics will determine
 5766 the amount of lead needed in the various places. The primary shielding needs an effective water cooling to
 5767 avoid partial melting of the lead.

5768 The electronics is placed below the proton magnets. Only backscattered photons with correspondingly
 5769 lower energy will reach the electronics. If necessary, a few millimeter of extra shielding could be added here.

5770 The risk for additional single event upsets due to synchrotron radiation is negligible.

5771 7.8.3 Compatibility with the proton beam loss system

5772 The proton beam loss monitoring system works very satisfactory. It has been designed to detect proton
 5773 losses by observing secondaries at the outside of the LHC magnets. The sensors are ionization chambers.
 5774 Excessive synchrotron radiation (SR) background will presumably trigger the system and dump the proton
 5775 beam. The SR background at the monitors has to be reduced by careful shielding of either the monitors or
 5776 the electron ring. Alternatively, the impact of the photon background can be reduced by using a new loss
 5777 monitoring system which is based on coincidences (as was done elsewhere [613]).

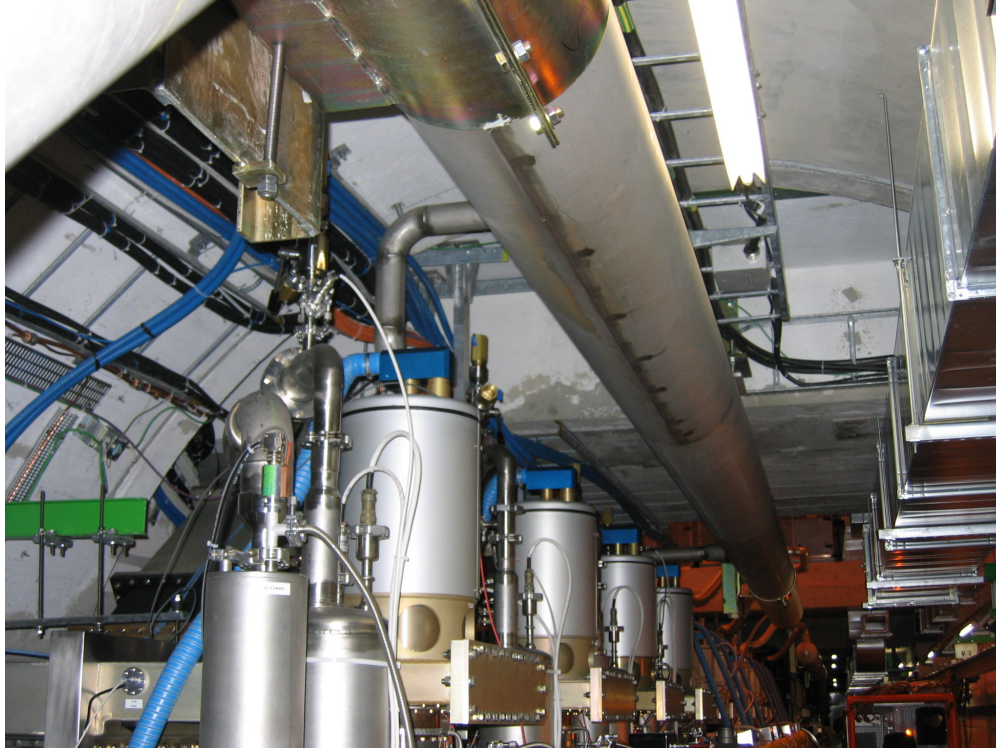


Figure 7.54: Tight space restriction in Point 4 due to the LHC proton RF installation.

7.8.4 Space requirements for the electron dump

The electron beam of the LHeC installation requires a dedicated dump section. Potential interference of the losses during or after an electron beam dump with equipment of the LHC proton rings still needs to be studied and a suitable space still needs to be found in the LHC tunnel.

7.8.5 Protection of the p-machine against heavy electron losses

The existing proton loss detectors are placed, as mentioned above, at the LHC magnets. The trigger threshold requires certain number of detectors to be hit by a certain number of particles. The assumption is that the particles come from the inside of the magnets and the particle density there is much higher. Electron losses, creating a similar pattern in the proton loss detectors will result in a much lower particle density in the superconducting coils. Hence, still tolerable electron losses will unnecessarily trigger the proton loss system and dump the proton beam. The proton losses are kept at a low level by installing an advanced system of collimators and masks. Fast changes of magnet currents, which will result in a beam loss, are detected. A similar system is required for the electrons. An electron loss detection system, like the one mentioned in Ref. [613], combined with the proton loss system can be used to identify the source of the observed loss pattern and to minimize the electron losses by improved operation. It seems very optimistic to think of a hardware discrimination system, which determines very fast the source of the loss and acts correspondingly. Such a system could be envisaged only after several years of running.

7.8.6 How to combine the Machine Protection of both rings?

The existing machine-protection system combines many different subsystems. The proton loss system, the quench detection system, cryogenics, vacuum, access, and many other subsystems may signal a dangerous

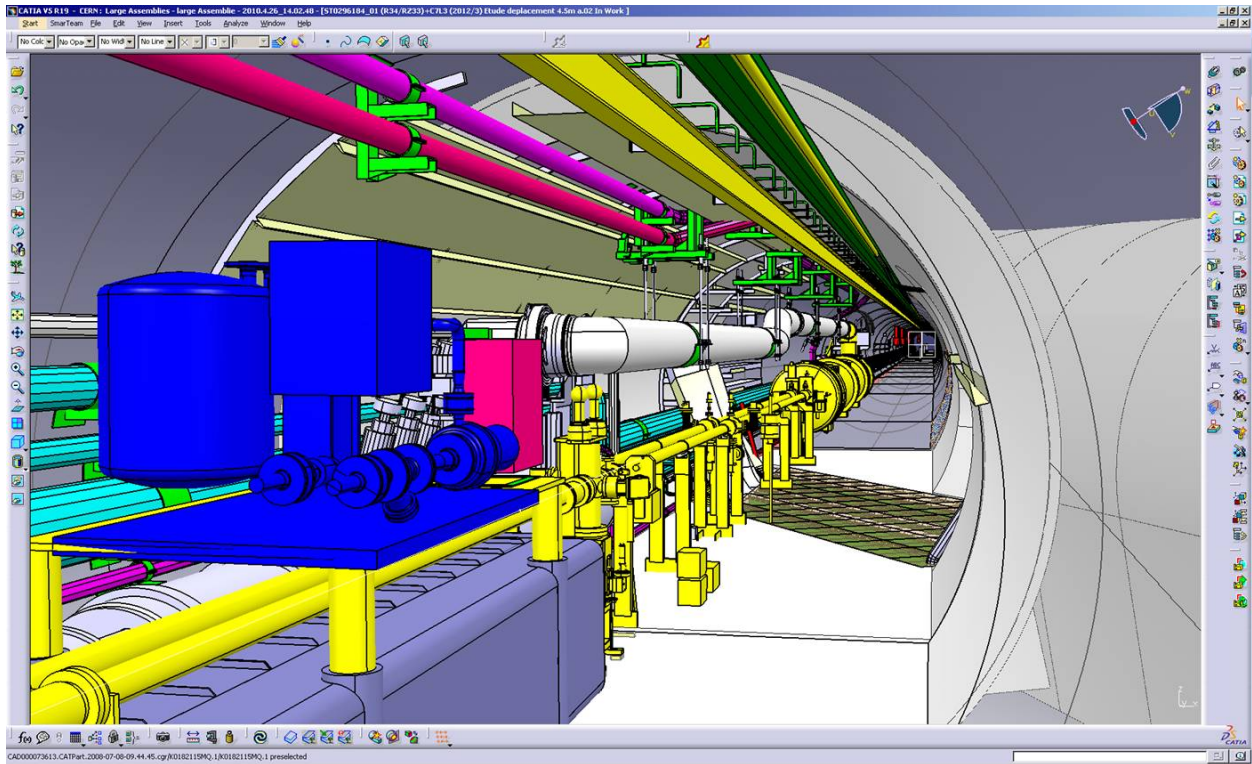


Figure 7.55: The cryogenic connection in point 3

5798 situation. This requirement lead to a very modular architecture, which could be expanded to include the
 5799 electron accelerator.

5800 7.9 LHeC Injector for the Ring-Ring option

5801 7.9.1 Injector

5802 The LEP pre-injectors have been dismantled and the infrastructure re-used for the CLIC test facility CTF3.
 5803 The RF cavities that accelerated leptons in the SPS have been removed to reduce its impedance. Re-
 5804 installation of an injector chain similar to LEP's through the PS and SPS would be costly and potentially
 5805 limit the proton performance.

5806 The LHeC e-ring therefore requires new lepton injectors.

5807 In the 30 years from the design of the LEP injectors, there has been substantial progress in accelerator
 5808 technology. This is particularly true in the field of superconducting radio frequency technology which was
 5809 very successfully used for LEP2 on a large scale and which has been further developed for TESLA and the
 5810 ILC. It makes it feasible to design a very compact and efficient 10 GeV injector based on the principle of a
 5811 recirculating LINAC and to take advantage of the studies for ELFE at CERN [614].

5812 7.9.2 Required performance

5813 The main requirements for the LHeC ring-ring electron and positron injectors are summarized in Table 7.34.

5814 Polarization is not required from the ring injectors. It would be very difficult to maintain the polarization
 5815 during the acceleration in the main ring. Instead, polarization can be built up at top energy from synchrotron
 5816 radiation.

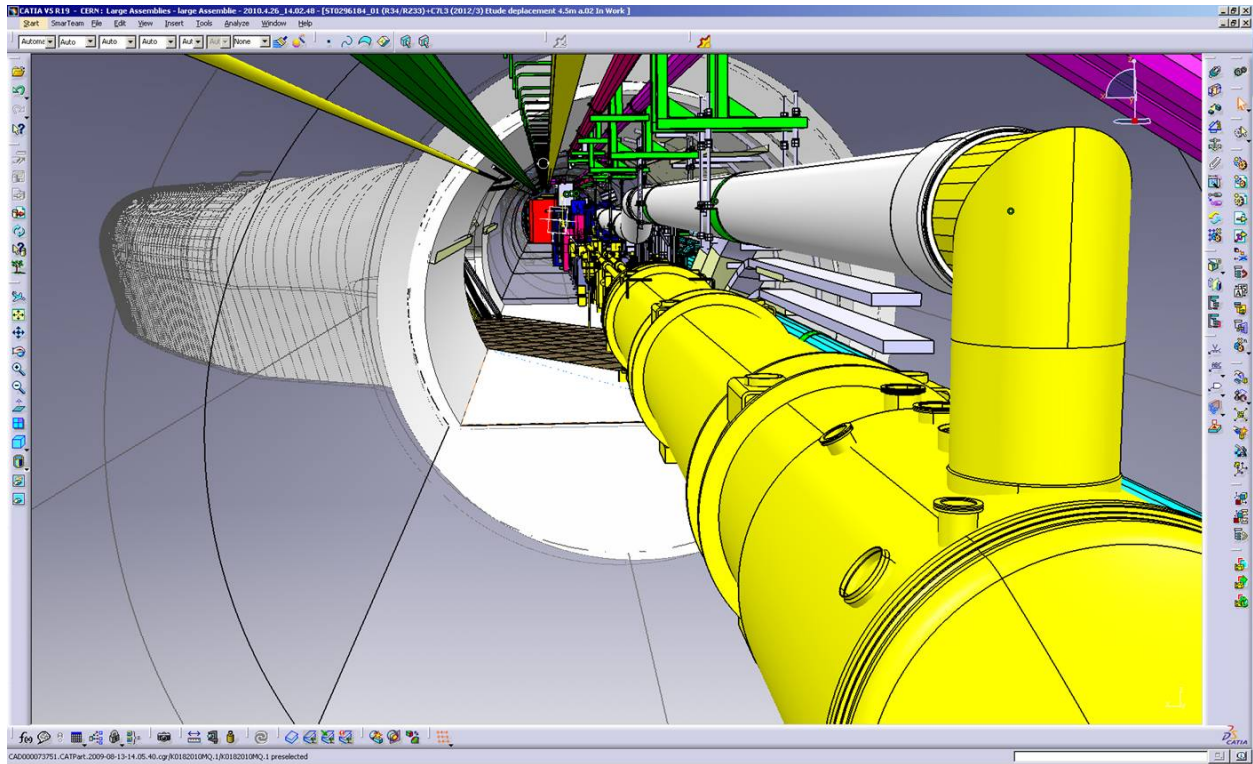


Figure 7.56: The cryogenic connection in point 3 (grey tube passing above the two LHC proton beam vacuum tubes [yellow]).

5817 The electron bunch intensity for nominal LHeC performance is 1.4×10^{10} . The target intensity for the
 5818 injector is taken as 2×10^{10} which includes a safety factor and allows for losses at injection and during the
 5819 ramp. Higher single-bunch intensities may be useful, with a smaller number of bunches, for the e-A mode of
 5820 operation. LEP was operated with much higher bunch intensities up to 4×10^{11} limited by the transverse
 5821 mode coupling instability (TMCI). The TMCI threshold current can be estimated from [615]

$$I_{th} = \frac{\omega_s E}{e \sum \beta k_{\perp}(\sigma_s)} \quad (7.33)$$

5822 where $\omega_s = 2\pi Q_s f_{rev}$ is the synchrotron frequency, e the elementary charge, E is the beam energy, β the
 5823 beta function value at the location of the impedance and k_{\perp} the loss factor which accounts for the transverse
 5824 impedance of the machine. LEP had a design injection energy of 20 GeV. It was raised to 22 GeV to increase
 5825 the TMCI threshold.

5826 The relatively low bunch intensity required for the LHeC allows for direct injection without accumulation
 5827 and for a lower injection energy compared to LEP. The LHeC transverse impedance will be similar to LEP,
 5828 with a smaller contribution from the reduced number of cavities and an increased impedance contribution
 5829 from the more compact beam-pipe cross-section. Lowering the beam energy results in weak bending fields
 5830 and loss of synchrotron radiation damping. A beam energy of a few GeV may still be tolerable for transverse
 5831 mode coupling but would not be practical for magnet stability and require strong wigglers to get a significant
 5832 radiation damping (otherwise this requires a minimum beam energy of the order of 10 GeV).

5833 A pulse frequency of on average 5 Hz is required, to fill the LHeC electron ring with 2808 bunches in
 5834 10 minutes.

5835 The injector requirements summarized in Table 7.34 are within the reach of proven technology and con-
 5836 cepts. An example is the FACET facility at SLAC which provides 2×10^{10} electrons of 23 GeV energy at

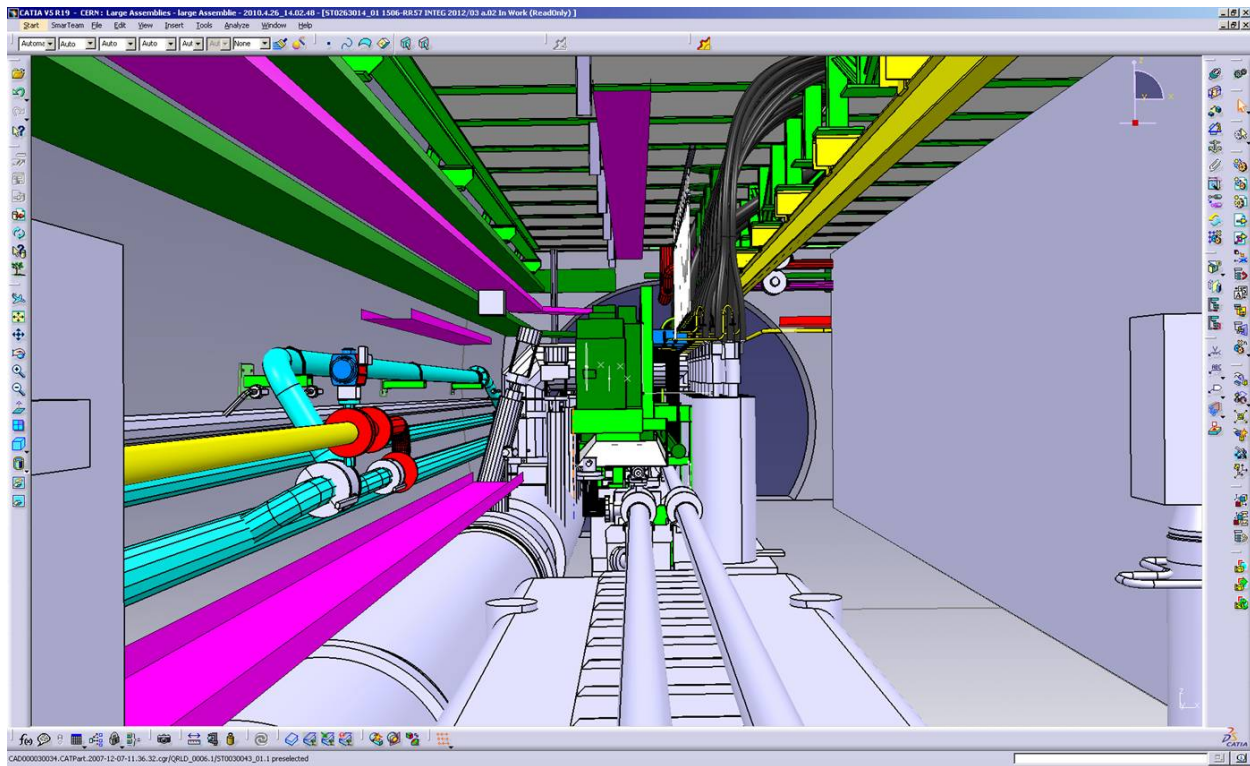


Figure 7.57: A typical big current feed-box (DFBA) on top of (green) and next to (grey shafts with black power lines) the two proton beam pipes.

5837 30 Hz repetition frequency [616].

5838 The intensities and repetition frequency required here match well with the performance of the LIL, the
 5839 first part of the LEP pre-injectors, which we reconsider here for the source, positron accumulation and pre-
 5840 acceleration to 0.6 GeV. For the acceleration to 10 GeV we propose a new, superconducting recirculating
 5841 LINAC.

5842 **7.9.3 Source, accumulator and acceleration to 0.6 GeV**

5843 Figure 7.59 shows the layout of the LPI (LEP Pre-Injector) as it was working in 2000. The LPI was composed
 5844 of the LIL (LEP Injector Linac) and the EPA (Electron Positron Accumulator).

5845 Table 7.35 gives the beam characteristics at the end of LIL.

5846 Table 7.36 gives the electron and positron beam parameters at the exit of EPA.

5847 With 8 bunches in the EPA for a 1.14 s cycle, the 2808 bunches required for the LHeC could be filled in
 5848 6.7 min which is perfectly adequate. According to the original LEP injector design report [617–619] Vol.I,
 5849 the cycle length for positrons is 11.22 s which would allow the 2808 bunches to be filled in 66 minutes. We
 5850 conclude that the LIL+EPA performance is fully adequate for the LHeC. A reduction of the cycle length for
 5851 positrons would be useful to reduce the filling time.

5852 **Timing considerations**

5853 EPA was planned for 1 to 8 bunches compatible with the LEP RF-frequency. The EPA circumference of
 5854 125.665 m corresponds to $t_{\text{rev}} = 419.173$ ns, which is 16.75×25 ns and would in theory allow for 16 bunches

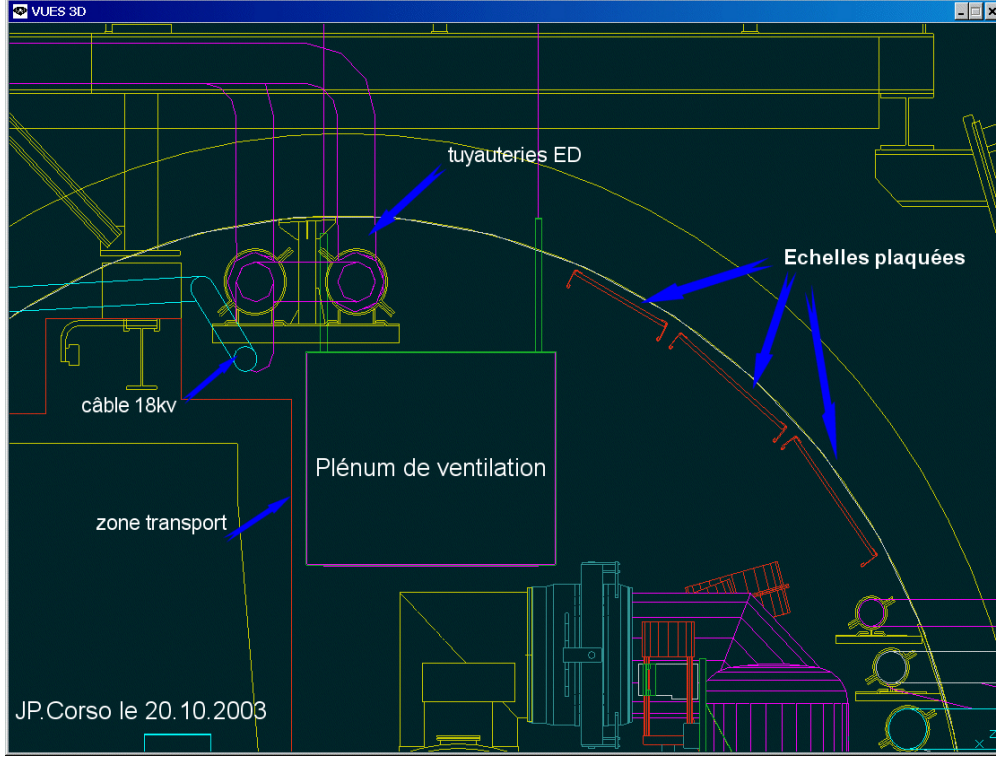


Figure 7.58: Air-duct in LSS7 indicated by the box labelled 'Plenum de ventilation' [610].

5855 spaced by 25 ns as relevant for the LHeC. Injection in batches of 72 bunches as possible for protons into the
 5856 LHC would require a five times larger damping ring which would be rather expensive.

5857 EPA had an RF-frequency $f_{rf} = 19.0852$ MHz. It will be increased to 40 MHz to allow for a bunch spacing
 5858 of 25 ns. For the injection into the LHC we propose a fast kicker system with a kicker rise-time below 25 ns.
 5859 This conserves the dimensions of EPA and gives full flexibility to place the bunches into the LHeC electron
 5860 ring as required to collide with the proton or ion bunches [586, 587].

5861 7.9.4 10 GeV injector

5862 For the acceleration to 10 GeV we propose a re-circulating LINAC, designed as a downscaled, low energy
 5863 version of the 25 GeV ELFE at CERN design [614] using modern ILC-type RF-technology.

5864 A sketch of the proposed machine is shown in Fig. 7.61. The acceleration is provided by 4 RF-units of
 5865 the ILC type, providing together 3.13 GV acceleration.

5866 The acceleration from 0.6 GeV to 10 GeV is achieved in three passages through the LINAC. This requires
 5867 only two re-circulation arcs which can be constructed in the horizontal plane. The maximum energy in the
 5868 last re-circulation arc is $10 - 3.13 = 6.87$ GeV.

5869 For a beam energy E and bending radius ρ , the energy loss U_0 by synchrotron radiation in the single
 5870 passage through a re-circulation arc is

$$U_0 = C_\gamma \frac{E^4}{\rho} \quad (7.34)$$

5871 where

$$C_\gamma = \frac{e^2}{3\epsilon_0} \frac{1}{(mc^2)^4} = 8.846 \times 10^{-5} \text{ m GeV}^{-3} .$$

Table 7.34: Main parameters for the LHeC RR injector

particle types	e^+, e^-
polarized	no
injection energy	$E_b = 10 \text{ GeV}$
bunch intensity	$2 \times 10^{10} e = 3.2 \text{ nC}$
pulse frequency	$\geq 5/s$

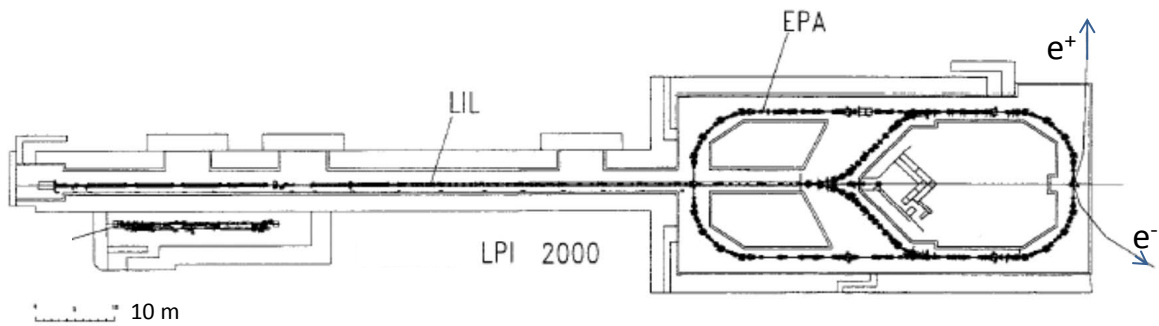


Figure 7.59: Layout of the LPI in 2000.

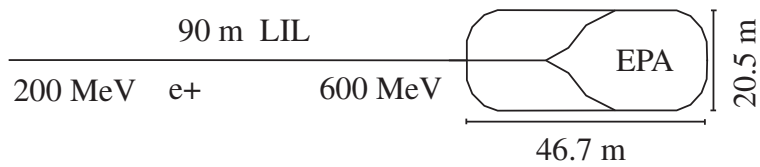


Figure 7.60: LIL and EPA

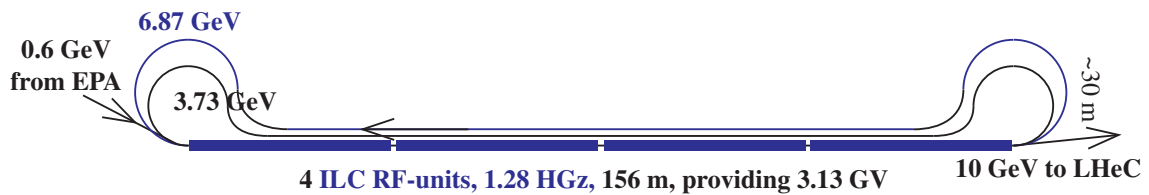


Figure 7.61: Recirculator using 4 ILC modules.

Beam energy	200 to 700 MeV
Charge	5×10^8 to $2 \times 10^{10} e^-$ / pulse
Pulse length	10 to 40 ns (FWHM)
Repetition frequency	1 to 100 Hz
Beam sizes (rms)	3 mm

Table 7.35: LIL beam parameters.

Energy	200 to 600 MeV
Charge	up to $4.5 \times 10^{11} e^\pm$
Intensity	up to 0.172 A
Number of bunches	1 to 8
Emittance	0.1 mm.mrad
Tune	$Q_x = 4.537, Q_y = 4.298$

Table 7.36: The electron and positron beam parameters at the exit of EPA.

5872 where e is the elementary charge and m the electron mass. The relative energy spread is increased by the
5873 synchrotron radiation in a single passage by

$$\sigma_e = r_e c_f \frac{\gamma^{5/2}}{\rho} \quad (7.35)$$

5874 where r_e is the classical electron radius and

$$c_f = \frac{3}{2} \sqrt{\frac{55\pi}{27\sqrt{3}\alpha}} = 33.75. \quad (7.36)$$

5875 A bending radius of $\rho = 2$ m at $E = 6.87$ GeV would result in an energy loss by recirculation of $U_0 = 98$ MeV
5876 and an energy spread of 10^{-3} . This would both be tolerable, but require very strong superconducting 11 tesla
5877 magnets for the 6.87 GeV recirculation.

5878 At this stage, we propose the use of warm 2 tesla magnets, resulting in a bending radius of $\rho = 11.5$ m
5879 for the 6.87 GeV recirculation and $\rho = 6.2$ m for the 3.73 GeV recirculation. The values for the energy loss
5880 and spread are listed in Table 7.37.

Table 7.37: Energy, bending field and radius, energy loss and energy spread in the recirculator magnets.

E GeV	B tesla	ρ m	U_0 MeV	σ_e
6.87	2	11.45	17.1	1.7×10^{-4}
3.73	2	6.23	2.8	7×10^{-5}

5881 To save space and allow for a single LINAC tunnel, we propose a dogbone-like shape for the recirculators
5882 as shown in Fig. 7.61.

Chapter 8

Linac-Ring Collider

8.1 Basic Parameters and Configurations

8.1.1 General Considerations

A high-energy electron-proton collider can be realized by accelerating electrons (or positrons) in a linear accelerator (linac) to 60–140 GeV and colliding them with the 7-TeV protons circulating in the LHC. Except for the collision point and the surrounding interaction region, the tunnel and the infrastructure for such a linac are separate and fully decoupled from the LHC operation, from the LHC maintenance work, and from other LHC upgrades (e.g., HL-LHC and HE-LHC).

The technical developments required for this type of collider can both benefit from and be used for many future projects. In particular, to deliver a long or continuous beam pulse, as required for high luminosity, the linac must be based on superconducting (SC) radio frequency (RF) technology. The development and industrial production of its components can exploit synergies with numerous other advancing SC-RF projects around the world, such as the European XFEL at DESY, eRHIC, ESS, ILC, CEBAF upgrade, CESR-ERL, JLAMP, and the CERN HP-SPL.

For high luminosity operation at a beam energy of 50–70 GeV the linac should be operated in continuous wave (CW) mode, which restricts the maximum RF gradient through the associated cryogenics power, to a value of about 20 MV/m or less. In order to limit the active length of such a linac and to keep its construction and operating costs low, the linac should, and can, be recirculating. For the sake of energy efficiency and to limit the overall site power, while boosting the luminosity, the SC recirculating CW linac can be operated in energy-recovery (ER) mode. A 60-GeV recirculating energy-recovery linac represents the baseline scenario for a linac-ring LHeC.

Electron-beam energies higher than 70 GeV, e.g. 140 GeV, can be achieved by a pulsed SC linac, similar to the XFEL, ILC or SPL. In this case the accelerating gradient can be larger than for CW operation, i.e. above 30 MV/m, which minimizes the total length, but recirculation is no longer possible at this beam energy due to prohibitively high synchrotron-radiation energy losses in any return arc of reasonable dimension. As a consequence the standard energy recovery scheme using recirculation cannot be implemented and the luminosity of such a higher-energy lepton-hadron collider would be more than an order of magnitude lower than the one of the lower-energy CW ERL machine, at the same wall-plug power. An advanced energy-recovery option for the pulsed straight linac would employ two-beam technology, as developed for CLIC, in this case based on a decelerating linac and multiple energy-transfer beams, to boost the luminosity potentially by several orders of magnitude [620]. Such novel type of energy-recovery linac could later be converted into a linear collider, or vice versa.

While for a linac it is straightforward to deliver a 80–90% polarized electron beam, the production of a sufficient number of positrons is extremely challenging for a linac-ring collider. A conceivable path towards decent proton-positron luminosities would include a recycling of the spent positrons, together with the recovery of their energy.

5920 The development of a CW SC recirculating energy-recovery linac (ERL) for LHeC would prepare the
 5921 ground, the technology and the infrastructure for many possible future projects, e.g., for an International
 5922 Linear Collider, for a Muon Collider¹, for a neutrino factory, or for a proton-driven plasma wake field
 5923 accelerator. A ring-linac LHeC would, therefore, promote any conceivable future high-energy physics project,
 5924 while pursuing an attractive forefront high-energy physics programme in its own right.

5925 8.1.2 ERL Performance and Layout

5926 Particle physics imposes the following performance requirements. The lepton beam energy should be 60
 5927 GeV or higher and the electron-proton luminosity of order $10^{33} \text{ cm}^{-2}\text{s}^{-1}$. Positron-proton collisions are
 5928 also required, with at least a few percent of the electron-proton luminosity. Since the LHeC should operate
 5929 simultaneously with LHC pp physics, it should not degrade the pp luminosity. Both electron and positron
 5930 beams should be polarized. Lastly, the detector acceptance should extend down to 1° or less. In addition,
 5931 the total electrical power for the lepton branch of the LHeC collider should stay below 100 MW.

5932 For round-beam collisions, the luminosity of the linac-ring collider [13] is written as

$$L = \frac{1}{4\pi e} \frac{N_{b,p}}{\epsilon_p} \frac{1}{\beta_p^*} I_e H_{hg} H_D, \quad (8.1)$$

5933 where e denotes the electron charge, $N_{b,p}$ the proton bunch population, β_p^* the proton IP beta function, I_e the
 5934 average electron beam current, H_{hg} the geometric loss factor arising from crossing angle and hourglass effect,
 5935 and H_D the disruption enhancement factor due to the electron pinch in collision, or luminosity reduction
 5936 factor from the anti-pinch in the case of positrons. In the above formula, it is assumed that the electron
 5937 bunch spacing is a multiple of the proton beam bunch spacing. The latter could be equal to 25, 50 or 75 ns,
 5938 without changing the luminosity value.

5939 The ratio $N_{b,p}/\epsilon_p$ is also called the proton beam brightness. Among other constraints, the LHC beam
 5940 brightness is limited by the proton-proton beam-beam limit. For the LHeC design we assume the brightness
 5941 value obtained for the ultimate bunch intensity, $N_{p,p} = 1.7 \times 10^{11}$, and the nominal proton beam emittance,
 5942 $\epsilon_p = 0.5 \text{ nm}$ ($\gamma\epsilon_p = 3.75 \mu\text{m}$). This corresponds to a total pp beam-beam tune shift of 0.01. More than two
 5943 times higher values have already been demonstrated, with good pp luminosity lifetime, during initial LHC
 5944 beam commissioning, indicating a potential for higher ep luminosity.

5945 To maximize the luminosity the proton IP beta function is chosen as 0.1 m. This is considerable smaller
 5946 than the 0.55 m for the pp collisions of the nominal LHC. The reduced beta function can be achieved by
 5947 reducing the free length between the IP and the first proton quadrupole (10 m instead of 23 m), and by
 5948 squeezing only one of the two proton beams, namely the one colliding with the leptons, which increases the
 5949 aperture available for this beam in the last quadrupoles. In addition, we assume that the final quadrupoles
 5950 could be based on Nb₃Sn superconductor technology instead of Nb-Ti. The critical field for Nb₃Sn is almost
 5951 two times higher than for Nb-Ti, at the same temperature and current density, allowing for correspondingly
 5952 larger aperture and higher quadrupole gradient. Nb₃Sn quadrupoles are presently under development for
 5953 the High-Luminosity LHC upgrade (HL-LHC).

5954 The geometric loss factor H_{hg} needs to be optimized as well. For round beams with $\sigma_{z,p} \gg \sigma_{z,e}$ (well
 5955 fulfilled for $\sigma_{z,p} \approx 7.55 \text{ cm}$, $\sigma_{z,e} \approx 300 \mu\text{m}$) and $\theta_c \ll 1$, it can be expressed as²

$$H_{hg} = \frac{\sqrt{\pi} z e^{z^2} \text{erfc}(z)}{S}, \quad (8.2)$$

5956 where

$$z \equiv 2 \frac{(\beta_e^*/\sigma_{z,p})(\epsilon_e/\epsilon_p)}{\sqrt{1 + (\epsilon_e/\epsilon_p)^2}} S$$

¹The proposed Muon Collider heavily relies on SC recirculating linacs for muon acceleration as well as on a SC-linac proton driver.

²The derivation of this formula is similar to the one for the LHC in Ref. [621], with the difference that here the two beams have different emittances and IP beta functions, and the electron bunch length is neglected. Curves obtained with formula (8.2) were first reported in [622].

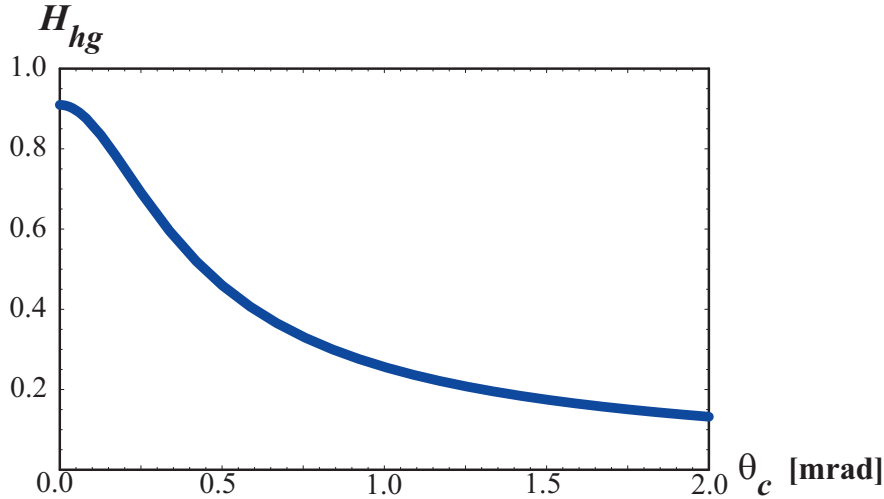


Figure 8.1: Geometric luminosity loss factor H_{hg} , (8.2), as a function of the total crossing angle

5957 and

$$S \equiv \sqrt{1 + \frac{\sigma_{x,p}^2 \theta_c^2}{8\sigma_p^{*2}}}.$$

5958 Luminosity loss from a crossing angle is avoided by head-on collisions. The luminosity loss from the hourglass
 5959 effect, due to the long proton bunches and potentially small electron beta functions, is kept small, thanks
 5960 to a “small” linac electron beam emittance of 0.43 nm ($\gamma\epsilon_e = 50 \mu\text{m}$). We note that the assumed electron-
 5961 beam emittance, though small when compared with a storage ring of comparable energy, is still very large
 5962 by linear-collider standards.

5963 The disruption enhancement factor for electron-proton collisions is about $H_D \approx 1.35$, according to
 5964 Guinea-Pig simulations [623] and a simple estimate based on the fact that the average rms size of the
 5965 electron beam during the collision approaches a value equal to $1/\sqrt{2}$ of the proton beam size. This additional
 5966 luminosity increase from disruption is not taken into account in the numbers given below. On the other
 5967 hand, for positron-proton collisions the disruption of the positrons leads to a significant luminosity reduction,
 5968 by roughly a factor $H_D \approx 0.3$, similar to the case of electron-electron collisions [624].

5969 The final parameter determining the luminosity is the average electron (or positron) beam current I_e . It
 5970 is closely tied to the total electrical power available (taken to be 100 MW).

5971 Crossing Angle and IR Layout

5972 The colliding electron and proton beams need to be separated by 7 cm at a distance of 10 m from the
 5973 IP in order to enter through separate holes in the first proton quadrupole magnet. This separation could
 5974 be achieved with a crossing angle of 7 mrad and crab cavities. The required crab voltage would, however,
 5975 need to be of order 200 MV, which is 20–30 times the voltage needed for pp crab crossing at the HL-LHC.
 5976 Therefore, crab crossing is not considered an option for the L-R LHeC. Without crab cavities, any crossing
 5977 angle should be smaller than 0.3 mrad, as is illustrated in Fig. 8.1. Such small a crossing angle is not useful,
 5978 compared with the 7 mrad angle required for the separation. The R-L interaction region (IR), therefore, uses
 5979 detector-integrated dipole fields around the collision point, to provide head-on ep collisions ($\theta_c = 0$ mrad)
 5980 and to separate the beams by the required amount. A dipole field of about 0.3 T over a length of ± 9 m
 5981 accomplishes these goals.

5982 The IR layout with separation dipoles and crossing angle is sketched in Fig. 8.2. Significant synchrotron
 5983 radiation, with 48 kW average power, and a critical photon energy of 0.7 MeV, is emitted in the dipole

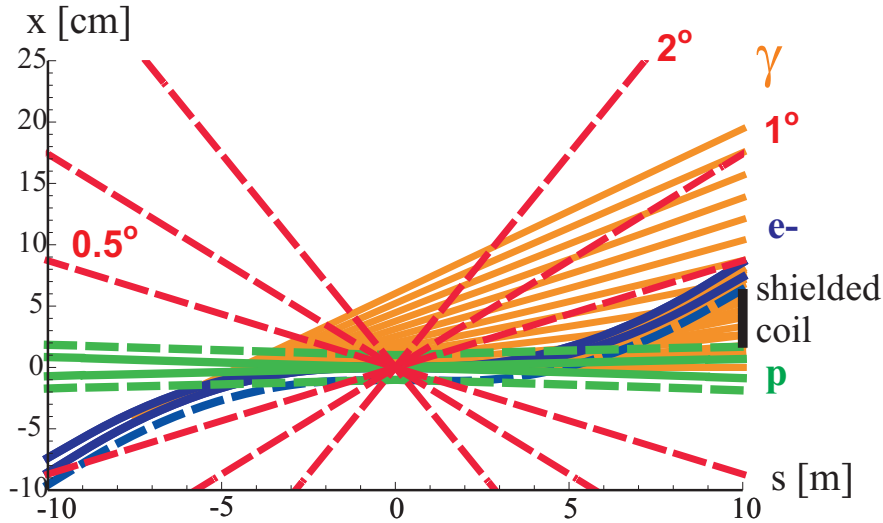


Figure 8.2: Linac-ring interaction-region layout. Shown are the beam envelopes of 10σ (electrons) [solid blue] or 11σ (protons) [solid green], the same envelopes with an additional constant margin of 10 mm [dashed], the synchrotron-radiation fan [orange], the approximate location of the magnet coil between incoming protons and outgoing electron beam [black], and a “1 degree” line.

5984 fields. A large portion of this radiation is extracted through the electron and proton beam pipes. The SC
 5985 proton magnets can be protected against the radiation heat load by an absorber placed in front of the first
 5986 quadrupole and by a liner inside the beam pipe. Backscattering of synchrotron radiation into the detector
 5987 is minimized by shaping the surface of absorbers and by additional masking.

5988 The separation dipole fields modify, and enhance, the geometric acceptance of the detector. Figure 8.3
 5989 illustrates that scattered electrons with energies of 10–50 GeV might be detected at scattering angles down
 5990 to zero degrees.

5991 Electron Beam and the Case for Energy Recovery

5992 The electron-beam emittance and the electron IP beta function are not critical, since the proton beam size is
 5993 large by electron-beam standards (namely about $7 \mu\text{m}$ rms compared with nm beam-sizes for linear colliders).
 5994 The most important parameter for high luminosity is the average beam current, I_e , which linearly enters
 5995 into the luminosity formula (8.1). In addition to the electron beam current, also the bunch spacing (which
 5996 should be a multiple of the LHC 25-ns proton spacing) and polarization (80–90% for the electrons) need
 5997 to be considered. Having pushed all other parameters in (8.1), Fig. 8.4 illustrates that an average electron
 5998 current of about 6.4 mA is required to reach the target luminosity of $10^{33} \text{ cm}^{-2}\text{s}^{-1}$.

5999 For comparison, the CLIC main beam has a design average current of 0.01 mA [625], so that it falls
 6000 short by a factor 600 from the LHeC requirement. For other applications it has been proposed to raise the
 6001 CLIC beam power by lowering the accelerating gradient, raising the bunch charge by a factor of two, and
 6002 increasing the repetition rate up to three times, which raises the average beam current by a factor 6 to about
 6003 0.06 mA (this type of CLIC upgrade is described in [268]). This ultimate CLIC main beam current is still
 6004 a factor 100 below the LHeC target. On the other hand, the CLIC drive beam would have a sufficiently
 6005 high current, namely 30 mA, but at the low energy 2.37 GeV, which would not be useful for high-energy ep
 6006 physics. Due to this low energy, also the drive beam power is still a factor of 5 smaller than the one required
 6007 by LHeC. Finally, the ILC design current is about 0.04 mA [626], which also falls more than a factor 100
 6008 short of the goal.

6009 Fortunately, SC linacs can provide higher average current, e.g. by increasing the linac duty factor 10–100
 6010 times, or even running in continuous wave (CW) mode, at lower accelerating gradient. Example average

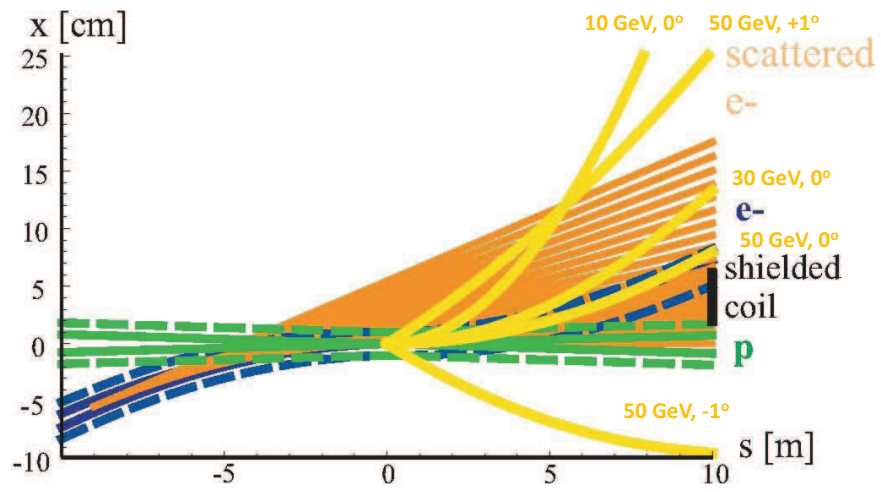


Figure 8.3: Example trajectories in the detector dipole fields for electrons of different energies and scattering angles, demonstrating an enhancement of the detector acceptance by the dipoles.

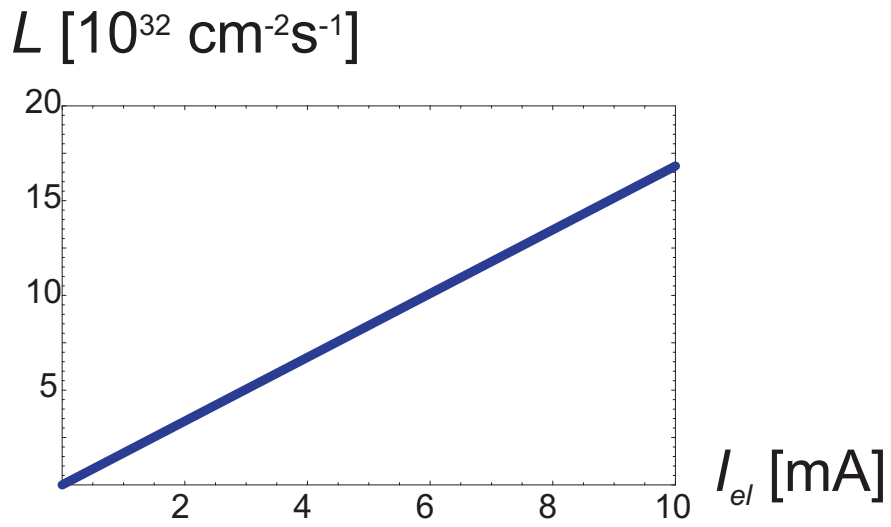


Figure 8.4: Linac-ring luminosity versus average electron beam current, according to (8.1).

6011 currents for a few proposed designs illustrate this point: The CERN High-Power Superconducting Proton
6012 Linac aims at about 1.5 mA average current (with 50 Hz pulse rate) [627], the Cornell ERL design at 100
6013 mA (cw) [628], and the eRHIC ERL at about 50 mA average current at 20 GeV beam energy (cw) [629].
6014 All these designs are close to, or exceed, the LHeC requirements for average beam current and average beam
6015 power (6.4 mA at 60 GeV). It is worth noting that the JLAB UV/IR 4th Generation Light Source FEL is
6016 routinely operating with 10 mA average current (135 pC pulses at 75 MHz) [630].

6017 The target LHeC IP electron-beam power is 384 MW. With a standard wall-plug-power to RF conversion
6018 efficiency around 50%, this would imply about 800 MW electrical power, far more than available. This
6019 highlights the need for energy recovery where the energy of the spent beam, after collision, is recuperated
6020 by returning the beam 180° out of phase through the same RF structure that had earlier been used for its
6021 acceleration, again with several recirculations. An energy recovery efficiency η_{ER} reduces the electrical power
6022 required for RF power generation at a given beam current by a factor $(1 - \eta_{ER})$. We need an efficiency η_{ER}
6023 above 90% or higher to reach the beam-current goal of 6.4 mA with less than 100 MW total electrical power.

6024 The above arguments have given birth to the LHeC Energy Recovery Linac high-luminosity baseline
6025 design, which is being presented in this chapter.

6026 Choice of RF Frequency

6027 Two candidate RF frequencies exist for the SC linac. One possibility is operating at the ILC and XFEL RF
6028 frequency around 1.3 GHz, the other choosing a frequency of about 720 MHz, close to the RF frequencies of
6029 the CERN High-Power SPL, eRHIC, and the European Spallation Source (ESS).

6030 The ILC frequency would have the advantage of synergy with the XFEL infrastructure, of profiting from
6031 the high gradients reached with ILC accelerating cavities, and of smaller structure size, which could reduce
6032 the amount of high-purity niobium needed by a factor 2 to 4.

6033 Despite these advantages, the present LHeC baseline frequency is 720 MHz, or, more precisely, 721 MHz
6034 to be compatible with the LHC bunch spacing. The arguments in favor of this lower frequency are the
6035 following:

- 6036 • A frequency of 721 MHz requires less cryo-power (about two times less than at 1.3 GHz according to
6037 BCS theory; the exact difference will depend on the residual resistance [631]).
- 6038 • The lower frequency will facilitate the design and operation of high-power couplers [632], though the
6039 couplers might not be critical [633].
- 6040 • The smaller number of cells per module (of similar length) at lower RF frequency is preferred with
6041 regard to trapped modes [634].
- 6042 • The lower-frequency structures reduce beam-loading effects and transverse wake fields.
- 6043 • The project can benefit from synergy with SPL, eRHIC and ESS.

6044 In case the cavity material costs at 721 MHz would turn out to be a major concern, they could be reduced
6045 by applying niobium as a thin film on a copper substrate, rather than using bulk niobium. The thin film
6046 technology may also enhance the intrinsic cavity properties, e.g. increase the Q value.

6047 Linac RF parameters for both 720 MHz and 1.3 GHz in CW mode as well as for a pulsed 1.3-GHz
6048 option are compared in Table 8.1. The 721 MHz parameters are derived from eRHIC [635]. Pulsed-linac
6049 applications for LHeC are discussed in subsections 8.1.4 and 8.1.6.

¹The range of heat-load values quoted for 721 MHz reflects the measured parameters of eRHIC prototype cavity BNL-I and an extrapolation to the improved cavity BNL-III [636].

²The range of heat-load values indicated for 1.3 GHz refers to different assumptions on the cavity Q at 18 MV/m (or to two different extrapolations from [626]).

	ERL 721 MHz	ERL 1.3 GHz	Pulsed
duty factor	CW	CW	0.05
RF frequency [GHz]	0.72	0.72	1.3
cavity length [m]	1	~1	~1
energy gain / cavity [MeV]	18	18	31.5
R/Q [100Ω]	400–500	1200	1200
Q_0 [10^{10}]	2.5–5.0	2	1
power loss stat. [W/cav.]	5	< 0.5	< 0.5
power loss RF [W/cav.]	8–32 ¹	13–27 ²	< 10
power loss total [W/cav.]	13–37	13–27	11
“W per W” (1.8 K to RT)	700	700	700
power loss / GeV at RT [MW]	0.51–1.44	0.6–1.1	0.24
length / GeV [m] (filling=0.57)	97	97	56

Table 8.1: Linac RF parameters for two different RF frequencies and two modes of operation.

6050 ERL Electrical Site Power

6051 The cryopower for two 10-GeV accelerating SC linacs is 28.9 MW, assuming pessimistically 37 W/m heat
6052 load at 1.8 K and 18 MV/m cavity gradient (this is a pessimistic estimate since the heat load could be up to
6053 3 times smaller; see Table 8.1), and 700 “W per W” cryo efficiency as for the ILC. The RF power needed to
6054 control microphonics for the accelerating RF is estimated at 22.2 MW, considering that 10 kW/m RF power
6055 may be required, as for eRHIC, with 50% RF generation efficiency. The electrical power for the additional
6056 RF compensating the synchrotron-radiation energy loss is 24.1 MW, with an RF generation efficiency of 50%.
6057 The cryo power for the compensating RF is 2.1 MW, provided in additional 1.44 GeV linac sections, and
6058 the microphonics control for the compensating RF requires another 1.6 MW. In addition, with an injection
6059 energy of 50 MeV, 6.4 mA beam current, and as usual 50% efficiency, the electron injector consumes about
6060 6.4 MW. A further 3 MW is budgeted for the recirculation-arc magnets [637]. Together this gives a grand
6061 total of 88.3 MW electrical power, some 10%.below the 100 MW limit.

6062 ERL Configuration

6063 The ERL configuration is depicted in Fig. 8.5. The shape, arc radius and number of passes have been
6064 optimized with respect to construction cost and with respect to synchrotron-radiation effects [638].

6065 The ERL is of racetrack shape. A 500-MeV electron bunch coming from the injector is accelerated in each
6066 of the two 10-GeV SC linacs during three revolutions, after which it has obtained an energy of 60 GeV. The
6067 60-GeV beam is focused and collided with the proton beam. It is then bent by 180° in the highest-energy arc
6068 beam line before it is sent back through the first linac, at a decelerating RF phase. After three revolutions
6069 with deceleration, re-converting the energy stored in the beam to RF energy, the beam energy is back at its
6070 original value of 500 MeV, and the beam is now disposed in a low-power 3.2-MW beam dump. A second,
6071 smaller (tune-up) dump could be installed behind the first linac.

6072 Strictly speaking, with an injection energy into the first linac of 0.5 GeV, the energy gain in the two
6073 accelerating linacs need not be 10 GeV each, but about 9.92 GeV, in order to reach 60 GeV after three
6074 passages through each linac. Considering a rough value of 10 GeV means that we overestimate the electrical
6075 power required by about 1%.

6076 Each arc contains three separate beam lines at energies of 10, 30 and 50 GeV on one side, and 20, 40 and
6077 60 GeV on the other. Except for the highest energy level of 60 GeV, at which there is only one beam, in
6078 each of the other arc beam lines there always co-exist a decelerating and an accelerating beam. The effective

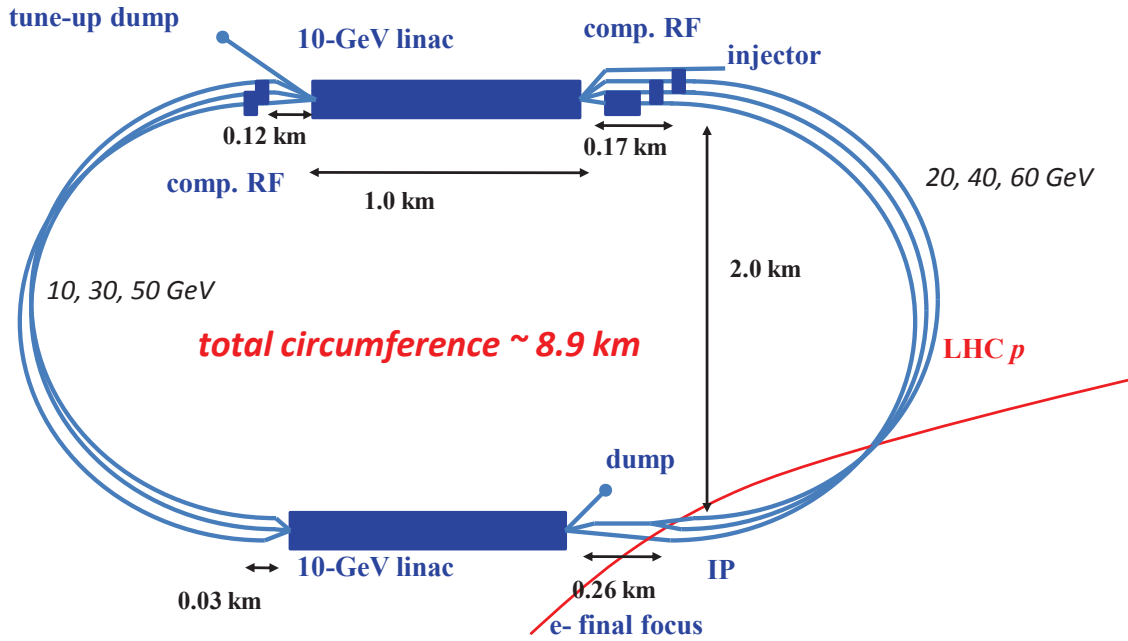


Figure 8.5: LHeC ERL layout including dimensions.

6079 arc radius of curvature is 1 km, with a dipole bending radius of 764 m [639].

6080 The two straight sections accommodate the 1-km long SC accelerating linacs. In addition to the 1km
 6081 linac section, there is an additional space of 290 m in each straight section of the racetrack. In one straight
 6082 of the racetrack 260 m of this additional length is allocated for the electron final focus (plus matching and
 6083 splitting), the residual 30 m on the other side of the same straight allows for combining the beam and
 6084 matching the optics into the arc. In the second straight section of the racetrack the additional length of
 6085 the straight sections houses the additional linacs for compensating the 1.44 GeV energy loss in the return
 6086 arcs [640]. For the highest energy, 60 GeV, there is a single beam and the compensating RF (750 MV) can
 6087 have the same frequency, 721 MHz, as in the main linac [640]. For the other energies, a higher harmonic RF
 6088 system, e.g. at 1.442 GHz, can compensate the energy loss for both decelerating and accelerating beams,
 6089 which are 180° out of phase at 721 MHz. On one side of the second straight one must compensate a total
 6090 of about 907 MV ($=750+148+9$ MV, corresponding to the energy loss at 60, 40 and 20 GeV, respectively),
 6091 which should easily fit within a length of 170 m. On the other side one has to compensate 409 MV ($=362+47$
 6092 MV), corresponding to SR energy losses at 50 and 30 GeV), for which a length of 120 m is available.

6093 The total circumference of the ERL racetrack is chosen as 8.9 km, equal to one third of the LHC
 6094 circumference. This choice has the advantage that one could introduce ion-clearing gaps in the electron
 6095 beam which would match each other on successive revolutions (e.g. for efficient ion clearing in the linacs
 6096 that are shared by six different parts of the beam) and which would also always coincide with the same proton
 6097 bunch locations in the LHC, so that in the latter a given proton beam would either always collide or never
 6098 collide with the electrons [641]. Ion clearing may be necessary to suppress ion-driven beam instabilities. The
 6099 proposed implementation scheme would remove ions while minimizing the proton emittance growth which
 6100 could otherwise arise when encountering collisions only on some of the turns. In addition, this arrangement
 6101 can be useful for comparing the emittance growth of proton bunches which are colliding with the electrons
 6102 and those which are not.

6103 The length of individual components is as follows. The exact length of the 10-GeV linac is 1008 m. The
 6104 individual cavity length is taken to be 1 m. The optics consists of 56-m long FODO cells with 32 cavities.
 6105 The number of cavities per linac is 576. The linac cavity filling factor is 57.1%. The effective arc bending
 6106 radius is set to be 1000 m. The bending radius of the dipole magnets is 764 m, corresponding to a dipole

6107 filling factor of 76.4% in the arcs. The longest SR compensation linac has a length of 84 m (replacing the
6108 energy lost by SR at 60 GeV). Combiners and splitters between straights and arcs require about 20–30 m
6109 space each. The electron final focus may have a length of 200–230 m.

6110 IP Parameters and Beam-Beam Effects

6111 Table 8.2 presents interaction-point (IP) parameters for the electron and proton beams.

	protons	electrons
beam energy [GeV]	7000	60
Lorentz factor γ	7460	117400
normalized emittance $\gamma\epsilon_{x,y}$ [μm]	3.75	50
geometric emittance $\epsilon_{x,y}$ [nm]	0.40	0.43
a IP beta function $\beta_{x,y}^*$ [m]	0.10	0.12
rms IP beam size $\sigma_{x,y}^*$ [μm]	7	7
initial rms IP beam divergence $\sigma_{x',y'}^*$ [μrad]	70	58
beam current [mA]	≥ 430	6.4
bunch spacing [ns]	25 or 50	(25 or) 50
bunch population [ns]	1.7×10^{11}	(1 or) 2×10^9

Table 8.2: IP beam parameters

6112 Due to the low charge of the electron bunch, the proton head-on beam-beam tune shift is tiny, namely
6113 $\Delta Q_p = +0.0001$, which amounts to only about 1% of the LHC pp design tune shift (and is of opposite
6114 sign). Therefore, the proton-beam tune spread induced by the ep collisions is negligible. In fact, the electron
6115 beam acts like an electron lens and could conceivably increase the pp tune shift and luminosity, but only
6116 by about 1%. Long-range beam-beam effects are equally insignificant for both electrons and protons, since
6117 the detector-integrated dipoles separate the electron and proton bunches by about $36\sigma_p$ at the first parasitic
6118 encounter, 3.75 m away from the IP.

6119 One further item to be looked at is the proton beam emittance growth. Past attempts at directly
6120 simulating the emittance growth from ep collisions were dominated by numerical noise from the finite number
6121 of macroparticles and could only set an upper bound [642], nevertheless indicating that the proton emittance
6122 growth due to the pinching electron beam might be acceptable for centered collisions. Proton emittance
6123 growth due to electron-beam position jitter and simultaneous pp collisions is another potential concern. For
6124 a 1σ offset between the electron and proton orbit at the IP, the proton bunch receives a deflection of about
6125 10 nrad (approximately $10^{-4}\sigma_{x',y'}^*$). Beam-beam simulations for LHC pp collisions have determined the
6126 acceptable level for random white-noise dipole excitation as $\Delta x/\sigma_x \leq 0.1\%$ [643]. This translates into a very
6127 relaxed electron-beam random orbit jitter tolerance of more than 1σ . The tolerance on the orbit jitter will
6128 then not be set by beam-beam effects, but by the luminosity loss resulting from off-center collisions, which,
6129 without disruption, scales as $\exp(-(\Delta x)^2/(4\sigma_{x,y}^{*2}))$. The random orbit jitter observed at the SLAC SLC had
6130 been of order 0.3–0.5 σ [644, 645]. A 0.1 σ offset at LHeC would reduce the luminosity by at most 0.3%, a
6131 0.3 σ offset by 2.2%. Disruption further relaxes the tolerance.

6132 The strongest beam-beam effect is encountered by the electron beam, which is heavily disrupted. The
6133 electron disruption parameter is $D_{x,y} \equiv N_{b,p} r_e \sigma_{z,p} / (\gamma_e \sigma^{*2}) \approx 6$, and the “nominal disruption angle” $\theta_0 \equiv$
6134 $D\sigma^*/\sigma_{z,p} = N_{b,p} r_e / (\gamma_e \sigma^*)$ [646] is about 600 μrad (roughly $10\sigma_{x',y'}^*$), which is huge. Simulations show that
6135 the actual maximum angle of the disrupted electrons is less than half θ_0 .

6136 Figure 8.6 illustrates the emittance growth and optics-parameter change for the electron beam due to
6137 head-on collision with a “strong” proton bunch. The intrinsic emittance grows by only 15%, but there is a
6138 180% growth in the mismatch parameter “ B_{mag} ” (defined as $B_{\text{mag}} = (\beta\gamma_0 - 2\alpha\alpha_0 + \beta_0\gamma)/2$, where quantities

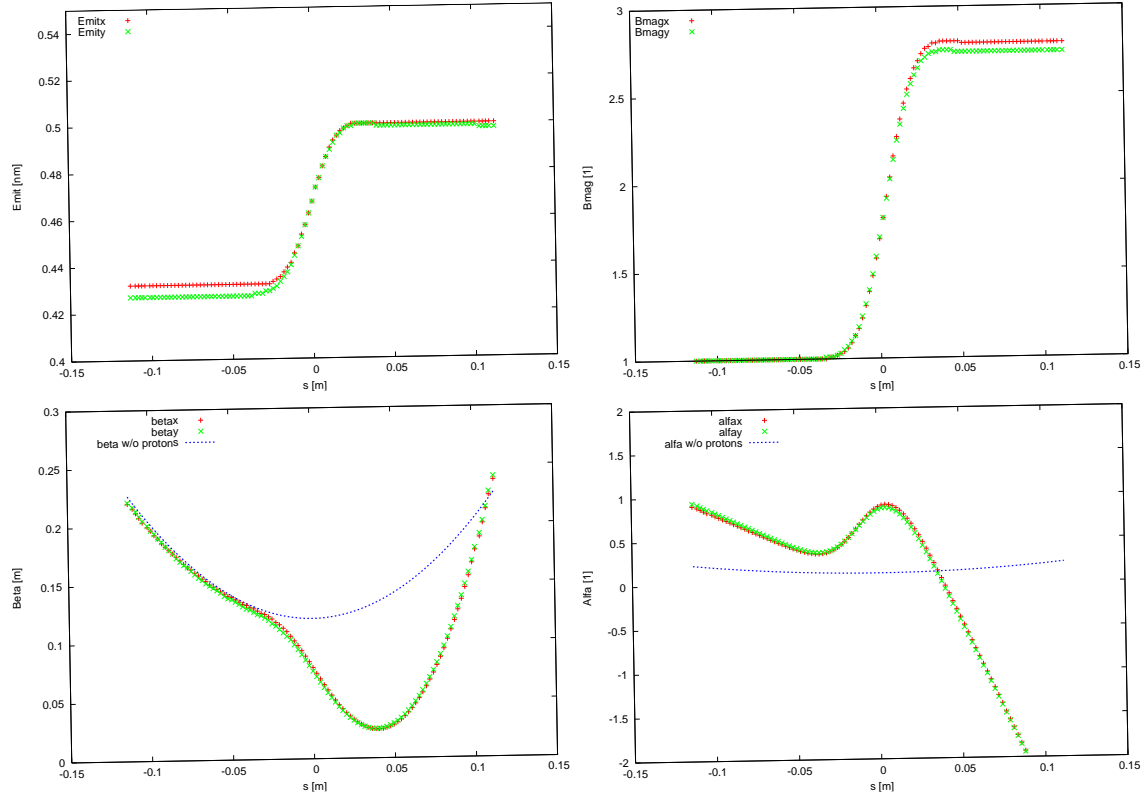


Figure 8.6: Simulated evolution of the electron beam emittance (top left), mismatch factor B_{mag} (top right) beta function (bottom left) and alpha function (bottom right) during the collision with a proton bunch, as a function of distance from the IP.

6139 with and without subindex “0” refer to the optics without and with collision, respectively. Without adjusting
 6140 the extraction line optics to the parameters of the mismatched beam the emittance growth will be about
 6141 200%. This would be acceptable since the arc and linac physical apertures have been determined assuming
 6142 up to 300% emittance growth for the decelerating beam [639]. However, if the optics of the extraction line
 6143 is rematched for the colliding electron beam (corresponding to an effective β^* of about 3 cm rather than the
 6144 nominal 12 cm; see Fig.8.6 bottom left), the net emittance growth can be much reduced, to only about 20%.
 6145 The various optics parameters shown in Fig. 8.6 vary by no more than 10–20% for beam-beam orbit offsets
 6146 up to 1σ .

6147 Figure 8.7 presents the average electron deflection angle as a function of the beam-beam offset. The
 6148 extraction channel for the electron beam must have sufficient aperture to accommodate both the larger
 6149 emittance due to disruption and the average trajectory change due to off-center collisions.

6150 8.1.3 Polarization

6151 The electron beam can be produced from a polarized DC gun with about 90% polarization, and with,
 6152 conservatively, 10–50 μm normalized emittance [647]. Spin-manipulation tools and measures for preserving
 6153 polarization, like Wien filter and/or spin rotators, and polarimeters should be included in the optics design
 6154 of the injector, the final focus, and the extraction line.

6155 As for the positrons, up to about 60% polarization can be achieved either with an undulator [648] or
 6156 with a Compton-based e^+ source [649,650]³.

³The primary challenge for positrons is to produce them in sufficient number and with a small enough emittance.

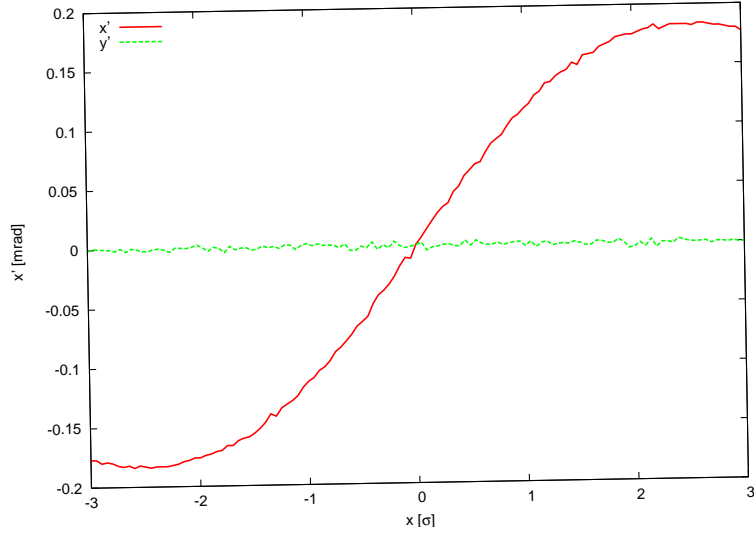


Figure 8.7: Simulated electron horizontal center-of-mass deflection angle as a function of the horizontal beam-beam offset.

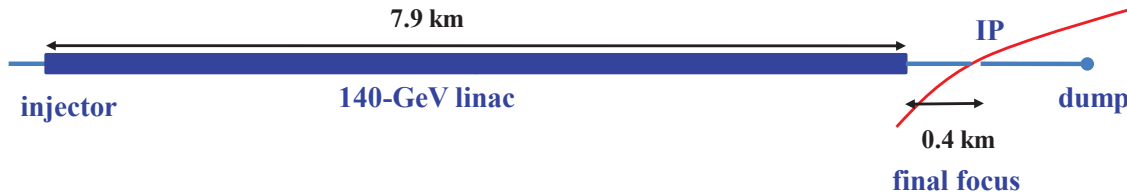


Figure 8.8: Pulsed single straight 140-GeV linac for highest energy ep collisions.

6157 8.1.4 Pulsed Linacs

6158 For beam energies above about 140 GeV, due to the growing impact of synchrotron radiation, the construction
 6159 of a single straight linac is cheaper than that of a recirculating linac [638]. Figure 8.8 shows the schematic of
 6160 an LHeC collider based on a pulsed straight 140-GeV linac, including injector, final focus, and beam dump.
 6161 The linac could be either of ILC type (1.3 GHz RF frequency) or operate at 721 MHz as the preferred ERL
 6162 version. In both cases, ILC values are assumed for the cavity gradient (31.5 MV/m) and for the cavity
 6163 unloaded Q value ($Q_0 = 10^{10}$). This type of linac would be extendable to ever higher beam energies and
 6164 could conceivably later become part of a linear collider. In its basic, simplest and conventional version no
 6165 energy recovery is possible for this configuration, since it is impossible to bend the 140-GeV beam around.
 6166 The lack of energy recovery leads to significantly lower luminosity. For example, with 10 Hz repetition rate,
 6167 5 ms pulse length (longer than ILC), a geometric reduction factor $H_g = 0.94$ and $N_b = 1.5 \times 10^9$ per bunch,
 6168 the average electron current would be 0.27 mA and the luminosity $4 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1}$.

6169 The construction of the 140-GeV pulsed straight linac could be staged, e.g. so as to first feature a pulsed
 6170 linac at 60 GeV, which could also be used for γ - p/A collisions (see subsection 8.1.6). The linac length
 6171 decreases directly in proportion to the beam energy. For example, at 140-GeV the pulsed linac measures 7.9
 6172 km, while at 60 GeV its length would be 3.4 km. For a given constant wall-plug power, of 100 MW, both
 6173 the average electron current and the luminosity scale roughly inversely with the beam energy. At 60 GeV
 6174 the average electron current becomes 0.63 mA and the pulsed-linac luminosity, without any energy recovery,
 6175 would be more than $9 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1}$.

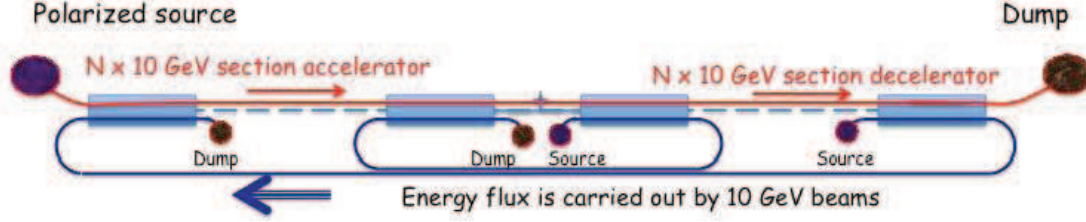


Figure 8.9: Highest-energy high-luminosity ERL option based on two straight linacs and multiple 10-GeV energy-transfer beams [651].

8.1.5 Highest-Energy LHeC ERL Option

The simple straight linac layout of Fig. 8.8 can be expanded as shown in Fig. 8.9 [651]. The main electron beam propagates from the left to the right. In the first linac it gains about 150 GeV, then collides with the hadron beam, and is then decelerated in the second linac. By transferring the RF energy back to the first accelerating linac, with the help of multiple, e.g. 15, 10-GeV “energy-transfer beams,” a novel type of energy recovery linac is realized without bending the spent beam. With two straight linacs facing each other this configuration could easily be converted into a linear collider, or vice versa, pending on geometrical and geographical constraints of the LHC site. As there are no synchrotron-radiation losses the energy recovery can be nearly 100% efficient. Such novel form of ERL could push the LHeC luminosity to the $10^{35} \text{ cm}^{-2}\text{s}^{-1}$ level. In addition, it offers ample synergy with the CLIC two-beam technology.

8.1.6 γ - p/A Option

In case of a (pulsed) linac without energy recovery the electron beam can be converted into a high-energy photon beam, by backscattering off a laser pulse, as is illustrated in Fig. 8.10. The rms laser spot size at the conversion point should be similar to the size of the electron beam at this location, that is $\sigma_\gamma \approx 10 \mu\text{m}$.

With a laser wavelength around $\lambda_\gamma \approx 250 \text{ nm}$ ($E_{\gamma,0} \approx 5 \text{ eV}$), obtained e.g. from a Nd:YAG laser with frequency quadrupling, the Compton-scattering parameter x [652, 653],

$$x \approx 15.3 \left[\frac{E_{e,0}}{\text{TeV}} \right] \left[\frac{E_{\gamma,0}}{\text{eV}} \right], \quad (8.3)$$

is close to the optimum value 4.8 for an electron energy of 60 GeV (for $x > 4.8$ high-energy photons get lost due to the creation of e^+e^- pairs). The maximum energy of the Compton scattered photons is given by $E_{\gamma,\text{max}} = x/(x+1)E_0$, which is larger than 80% of the initial electron-beam energy $E_{e,0}$, for our parameters. The cross section and photon spectra depend on the longitudinal electron polarization λ_e and on the circular laser polarization P_c . With proper orientation ($2\lambda_e P_c = -1$) the photon spectrum is concentrated near the highest energy $E_{\gamma,\text{max}}$.

The probability of scattering per individual electron is [654]

$$n_\gamma = 1 - \exp(-q) \quad (8.4)$$

with

$$q = \frac{\sigma_c A}{E_{\gamma,0} 2\pi\sigma_\gamma^2}, \quad (8.5)$$

where σ_c denotes the (polarized) Compton cross section and A the laser pulse energy. Using the formulae in [655], the Compton cross section for $x = 4.8$ and $2\lambda_e P_c = -1$ is computed to be $\sigma_c = 3.28 \times 10^{-25} \text{ cm}^2$. The pulse energy corresponding to $q = 1$, i.e. to a conversion efficiency of 65%, is estimated as $A \approx E_{\gamma,0} 2\pi\sigma_\gamma^2 / \sigma_c \approx 16 \text{ J}$. To set this into perspective, for a $\gamma\gamma$ collider at the ILC, Ref. [656] considered a pulse energy of 9 J at a four times longer wavelength of $\lambda \approx 1 \mu\text{m}$.

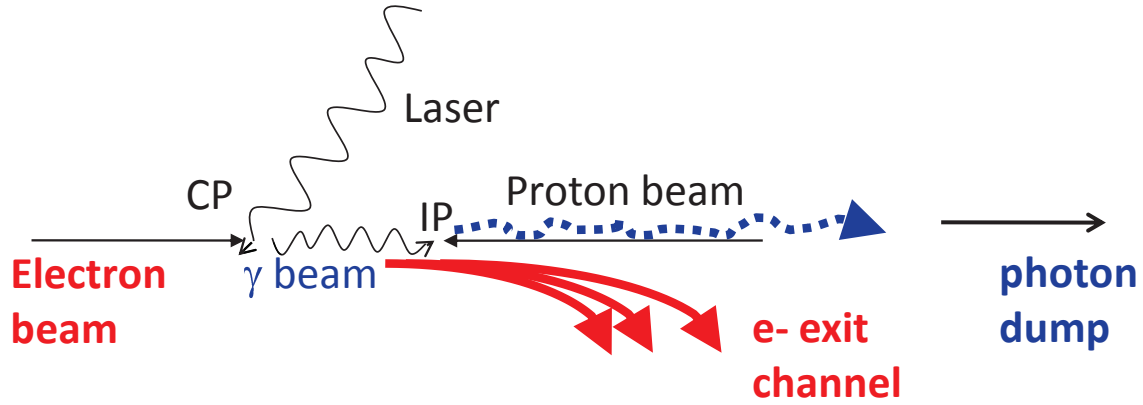


Figure 8.10: Schematic of γ - p/A collision; prior to the photon-hadron interaction point (IP), the electron beam is scattered off a several-J laser pulse at the conversion point (CP).

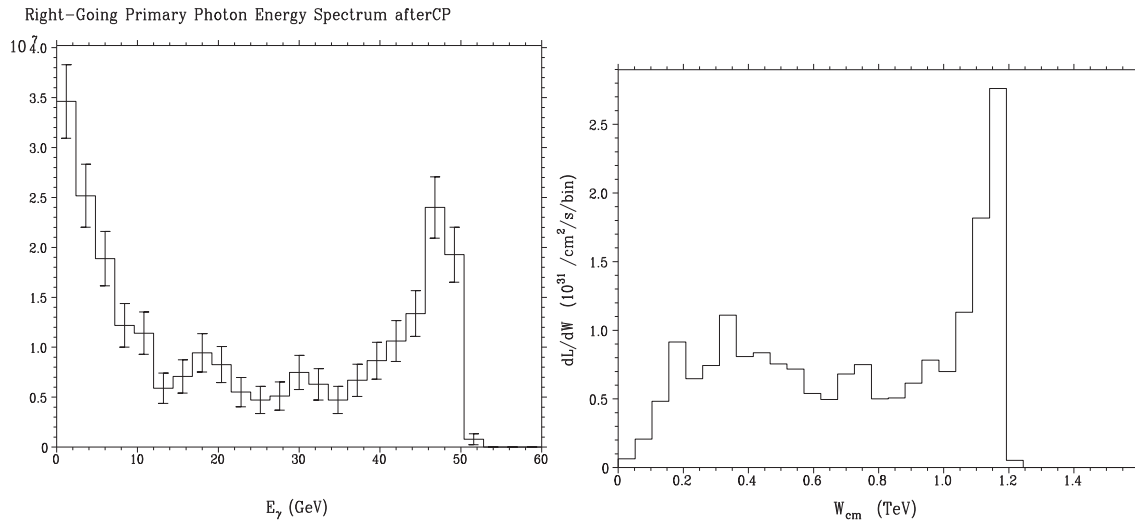


Figure 8.11: Simulated example photon spectrum after the conversion point (left) and γ - p luminosity spectrum [657].

6205 The energies of the leftover electrons after conversion extend from about 10 to 60 GeV. This spent
 6206 electron beam, with its enormous energy spread, must be safely extracted from the interaction region. The
 6207 detector-integrated dipole magnets will assist in this process. They will also move the scattered electrons
 6208 away from the interaction point. A beam dump for the neutral photons should also be installed, behind the
 6209 downstream quadrupole channel.

6210 Figure 8.11 presents an example photon energy spectrum after the conversion and a luminosity spectrum
 6211 [657], obtained from a simulation with the Monte-Carlo code CAIN [658].

6212 Differently from $\gamma\gamma$ collisions at a linear collider, thanks to the much larger IP spot size and smaller
 6213 beam energy, the conversion point can be a much larger distance $\Delta s \approx \beta^* \sim 0.1$ m away from the interaction
 6214 point, which could simplify the integration in the detector, and is also necessary as otherwise, with e.g. a
 6215 mm-distance between CP and IP, the conversion would take place inside the proton bunch.

6216 To achieve the required laser pulse energy, external pulses can be stacked in a recirculating optical cavity.
 6217 For an electron bunch spacing of e.g. 200 ns, the path length of the recirculation could be 60m. A schematic
 6218 of a possible mirror system is sketched in Fig. 8.12 (adapted from [656]).

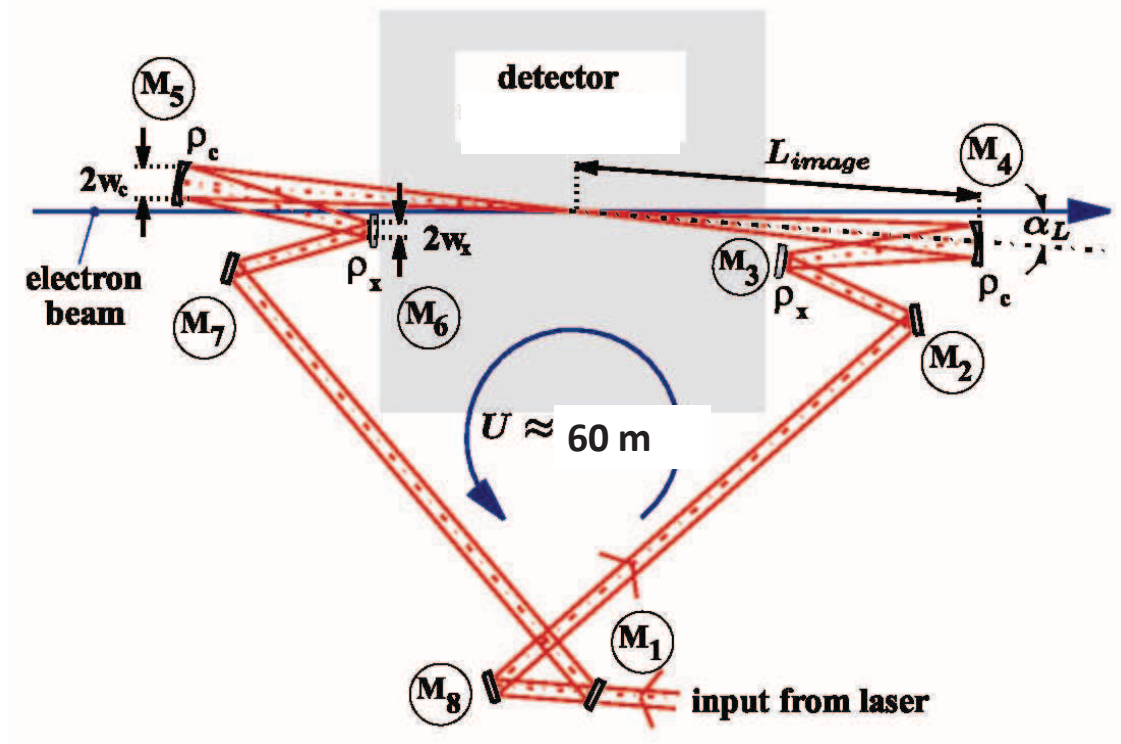


Figure 8.12: Recirculating mirror arrangement providing a laser-pulse path length of 60 m for pulse stacking synchronously with the arriving electron bunches (adapted from [656]).

8.1.7 Summary of Basic Parameters and Configurations

The baseline 60-GeV ERL option presented here can provide a ep luminosity of $10^{33} \text{ cm}^{-2}\text{s}^{-1}$, at less than 100 MW total electrical power for the electron branch of the collider, and with less than 9 km circumference. The 21 GV of SC-RF installation represents its main hardware component.

A pulsed 140-GeV linac, without energy recovery, could achieve a luminosity of $1.4 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1}$, at higher c.m. energy, again with less than 100 MW electrical power, and shorter than 9 km in length. The pulsed linac can accommodate a γ - p/A option. An advanced, novel type of energy recovery, proposed for the single straight high-energy linac case, includes a second decelerating linac, and multiple 10-GeV “energy-transfer beams”. This type of collider could potentially reach luminosities of $10^{35} \text{ cm}^{-2}\text{s}^{-1}$.

High polarization is possible for all linac-ring options. Beam-beam effects are benign, especially for the proton beam, which will not be affected by the presence of the electron beam.

Producing the required number of positrons needed for high-luminosity proton-positron collisions is the main open challenge for a linac-ring LHeC. Recovery of the positrons together with their energy, as well as fast transverse cooling schemes, are likely to be essential ingredients for any linac-based high-luminosity ep collider involving positrons.

8.2 Interaction region

This section presents a first conceptual design of the LHeC linac-ring Interaction Region (IR). The merits of the IR are a very low β^* of 0.1m with proton triplets as close as possible to the IP to minimize chromaticity. Head-on proton-electron collisions are achieved by means of dipoles around the Interaction Point (IP). The Nb_3Sn superconductor has been chosen for the proton triplets since it provides the largest gradient. If this technology proves not feasible in the timescale of the LHeC a new design of the IR can be pursued using standard technology.

The main goal of this first design is to evaluate potential obstacles, decide on the needs of special approaches for chromaticity correction and evaluate the impact of the IR synchrotron radiation.

8.2.1 Layout

A crossing angle of 6 mrad between the non-colliding proton beams allows enough separation to place the proton triplets. Only the proton beam colliding with the electrons is focused. A possible configuration in IR2 could be to inject the electrons parallel to the LHC Beam1 and collide them head-on with Beam2, see Fig. 8.13. The signs of the separation and recombination dipoles (D1 and D2) have to be changed to allow for the large crossing angle at the IP. The new D1 has one aperture per beam and is 4.5 times stronger than the LHC design D1. The new D2 is 1.5 times stronger than the LHC design D2. Both dipoles feature about a 6 T field. The lengths of the nominal LHC D1 and D2 dipoles have been left unchanged, 23 m and 9 m, respectively. However the final IR design will need to incorporate an escape line for the neutral particles coming from the IP, probably requiring to split D1 into two parts separated by tens of meters.

Bending dipoles around the IP are used to make the electrons collide head-on with Beam2 and to safely extract the disrupted electron beam. The required field of these dipoles is determined by the L^* and the minimum separation of the electron and the focused beam at the first quadrupole (Q1). A 0.3 T field extending over 9 m allows for a beams separation of 0.07 m at the entry of Q1. This separation distance is compatible with mirror quadrupole designs using Nb_3Sn technology; see Section 9.1. The electron beam radiates 48 kW in the IR dipoles. A sketch of the 3 beams, the synchrotron radiation fan and the proton triplets is shown in Fig. 8.14.

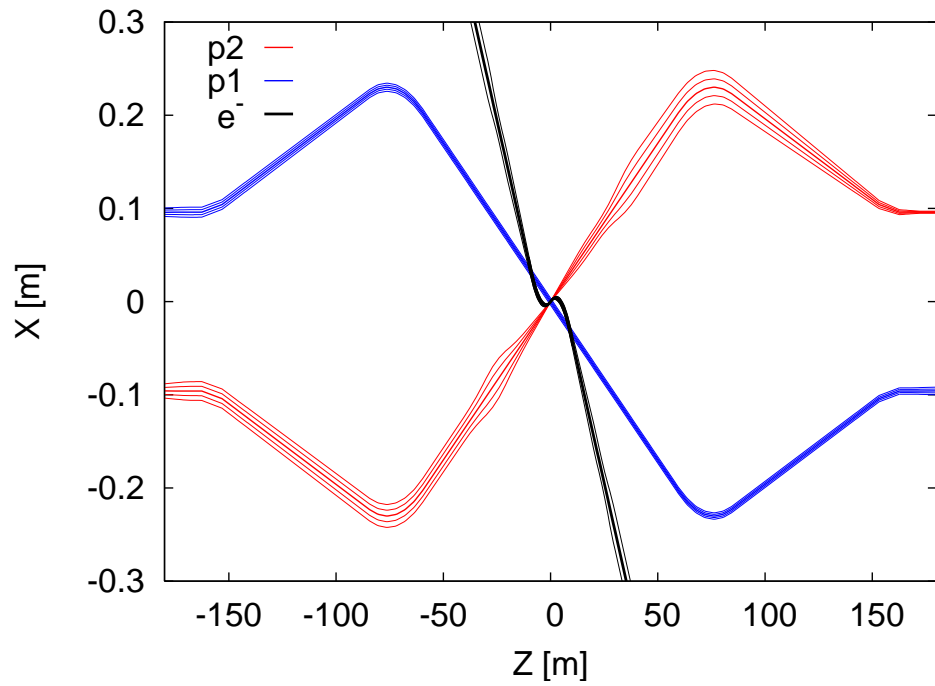


Figure 8.13: LHeC interaction region displaying the two proton beams and the electron beam trajectories with 5σ and 10σ envelopes.

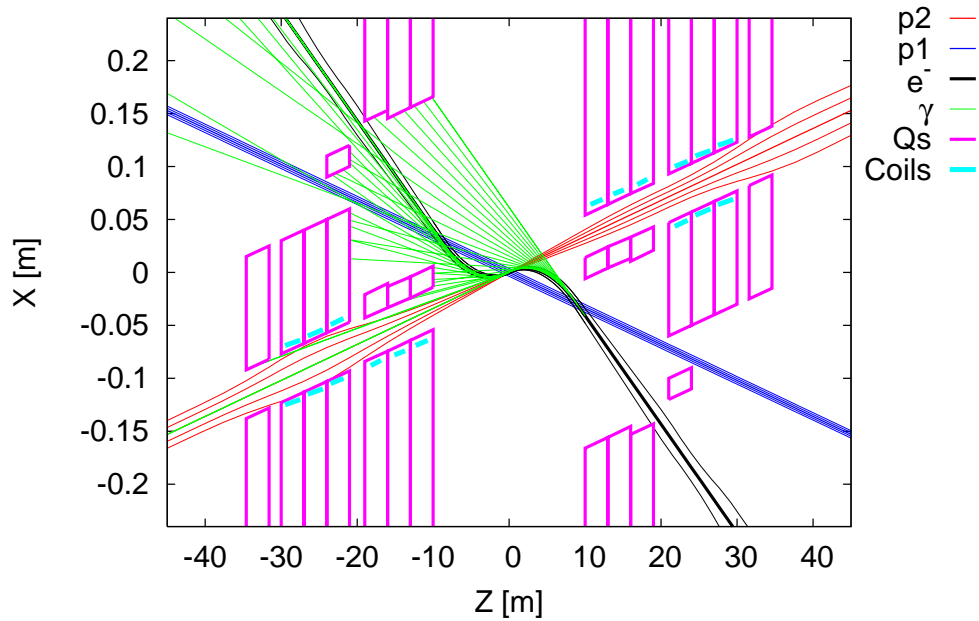


Figure 8.14: LHeC interaction region with a schematic view of synchrotron radiation. Beam trajectories with 5σ and 10σ envelopes are shown. The parameters of the Q1 and Q2 quadrupole segments correspond to the Nb₃Sn half-aperture and single-aperture (with holes) quadrupole of Fig. 9.5.

Name	Gradient [T/m]	Length [m]	Radius [mm]
Q1	187	9	22
Q2	308	9	30
Q3	185	9	32

Table 8.3: Parameters of the proton triplet quadrupoles. The radius is computed as $11\max(\sigma_x, \sigma_y) + 5$ mm.

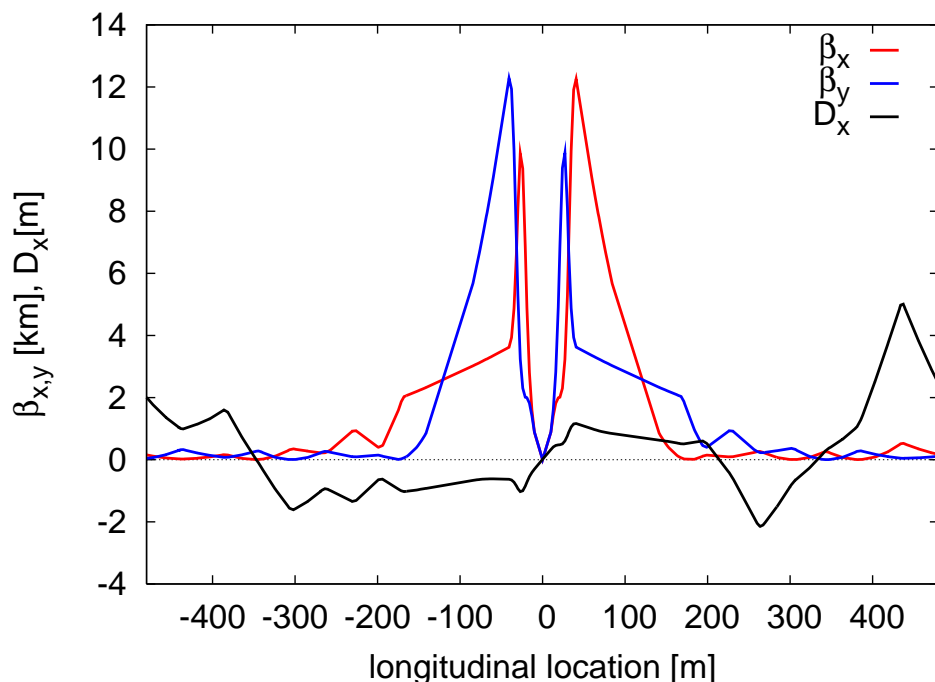


Figure 8.15: Optics functions for main proton beam.

8.2.2 Optics

Colliding proton optics

The colliding beam triplet starts at $L^*=10$ m from the IP. It consists of 3 quadrupoles with main parameters given in Table 8.3. The quadrupole aperture is computed as $11\max(\sigma_x, \sigma_y) + 5$ mm. The 5 mm split into 1.5 mm for the beam pipe, 1.5 mm for mechanical tolerances and 2 mm for the closed orbit. The magnet parameters for the first two quadrupoles correspond to Nb₃Sn design described in Section 9.1. The total chromaticity from the two IP sides amounts to 960 units. The optics functions for the colliding beam are shown in Fig. 8.15

It was initially hoped that a compact Nb₃Sn triplet with $L^*=10$ m would allow for a normal chromaticity correction using the arc sextupoles. However after matching this triplet to the LHC and correcting linear chromaticity the chromatic β -beating at $dp/p=0.001$ is about 100% (see Fig. 8.16). This is intolerable regarding collimation and machine protection issues. Therefore a dedicated chromaticity correction scheme has to be adopted. A large collection of studies exist showing the feasibility of correcting even larger chromaticities in the LHC [659–661]. Other local chromatic correction approaches as [662], where quadrupole doublets are used to provide the strong focusing, could also be considered for the LHeC.

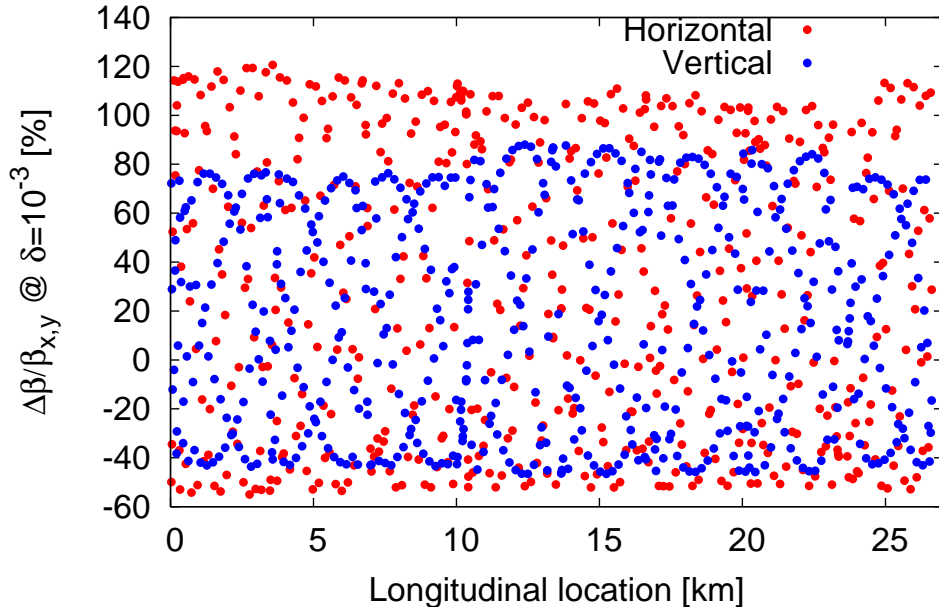


Figure 8.16: Chromatic beta-beating at $dp/p=0.001$.

6275 Since LHeC anyhow requires a new dedicated chromaticity correction scheme, current NbTi technology
 6276 could be pursued instead of Nb₃Sn and the L* could also be slightly increased. The same conceptual three-
 6277 beam crossing scheme as in Fig. 8.13 could be kept.

6278 To achieve L* below 23 m requires a cantilever supported on a large mass as proposed for the CLIC
 6279 QD0 [663] to provide sub-nanometer stability at the IP. The LHeC vibration tolerances are much more
 6280 relaxed, being on the sub-micrometer level.

6281 Non-colliding proton optics

6282 The non-colliding beam has no triplet quadrupoles since it does not need to be focused. The LHC “alignment
 6283 optics” [664] was used as a starting point. Figure 8.17 shows the optics functions around the IP. The LHeC
 6284 IP longitudinal location can be chosen so as to completely avoid unwanted proton-proton collisions.

6285 The non-colliding proton beam travels through dedicated holes in the proton triplet quadrupoles, in Q1
 6286 together with the electron beam. The Q1 hole dimensions are determined by the electron beam, see below.
 6287 By contrast, the non-colliding proton beam travels alone through the first module of the Q2, requiring about
 6288 30 mm full aperture. No fields are assumed in these apertures but the possible residual fields could easily
 6289 be taken into account for the proton optics.

6290 Electron optics

6291 The electron L* = 30 m has been chosen to allow for enough separation between the proton and the electron
 6292 final focusing quadrupoles. A first design of the optics already matched to the exit of the linac is shown in
 6293 Fig. 8.18. The electron focusing quadrupoles feature moderately low gradients as shown in Table 8.4. The
 6294 IP beam size aberration versus the relative rms energy spread of the beam is shown in Fig. 8.19. Chromatic
 6295 correction is mandatory for relative energy spreads above 3×10^{-4} . It is recommended to design a chromatic
 6296 correction section. About 200 m are available between the exit of the linac and the IP while the current
 6297 electron final focus is using only 90 m, leaving space for collimation and beam diagnostics.

6298 The electrons shares a hole with the non-colliding proton beam in the first half-quadrupole, Q1, and
 6299 then travels through a dedicated hole in the cryostat of Q2. The common hole in the proton Q1 must

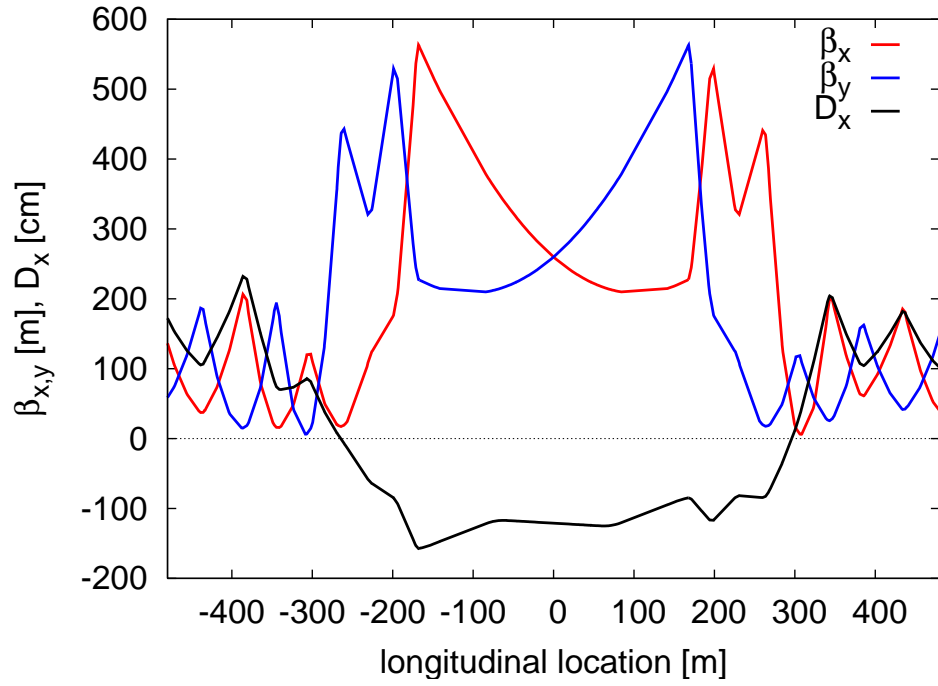


Figure 8.17: Optics functions for the non-colliding proton beam without triplets.

Name	Gradient [T/m]	Length [m]	Radius [mm]
Q1	19.7	1.34	20
Q2A	38.8	1.18	32
Q2B	3.46	1.18	20
Q3	22.3	1.34	22

Table 8.4: Parameters of the electron triplet quadrupoles. The radius is computed as $11\max(\sigma_x, \sigma_y) + 5$ mm.

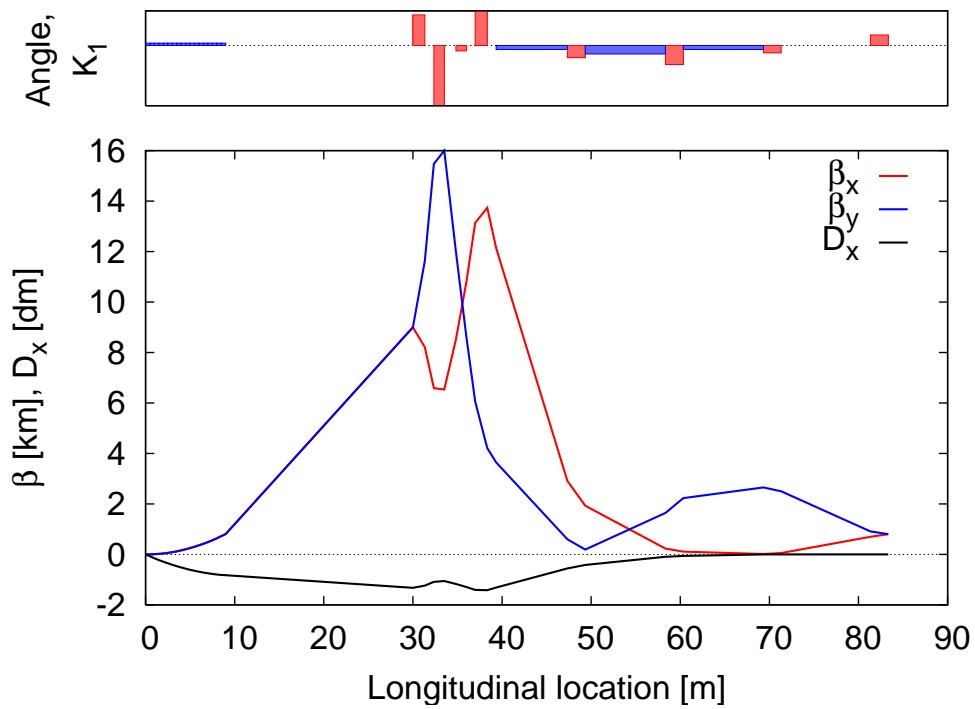


Figure 8.18: Optics of the electron beam.

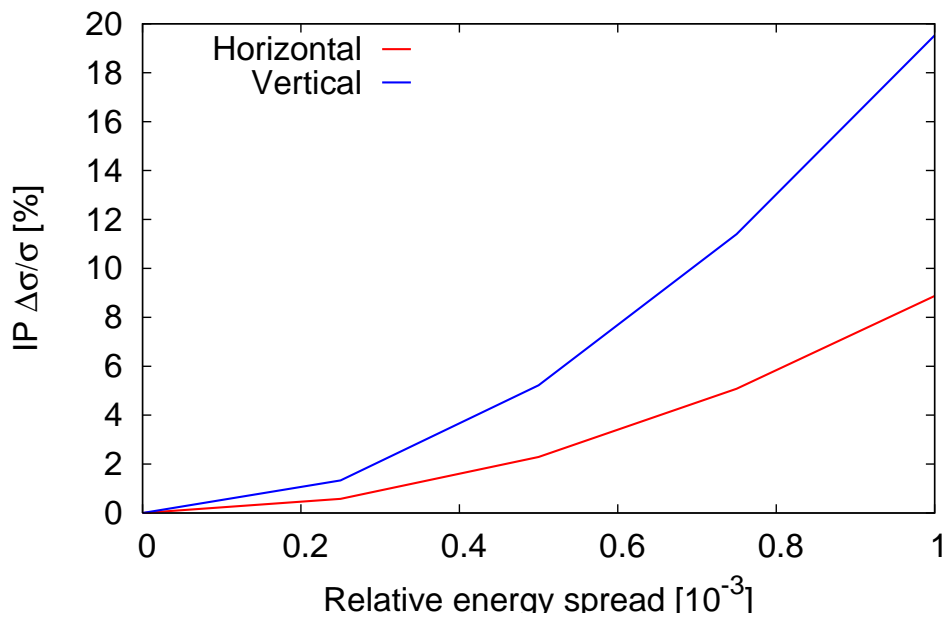


Figure 8.19: IP electron beam size versus relative energy spread of the beam.

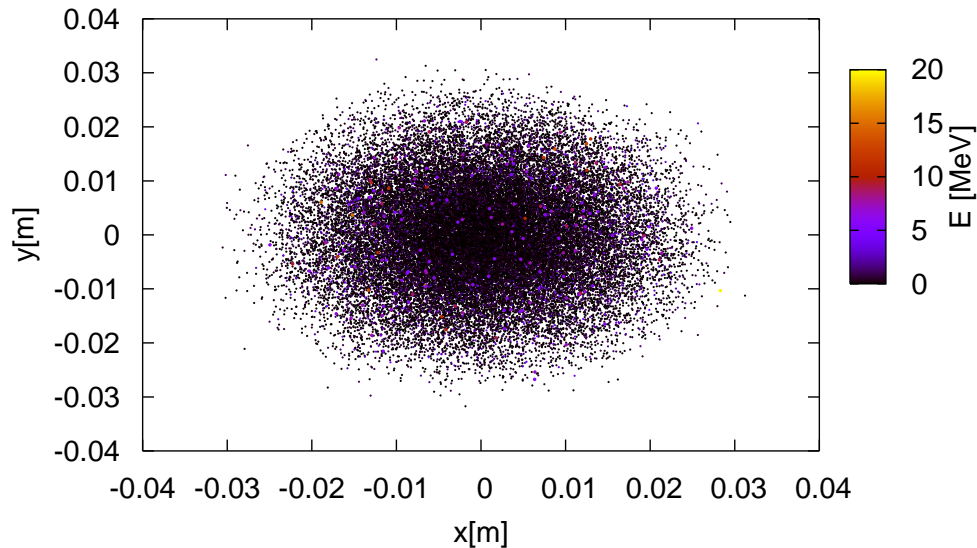


Figure 8.20: Distribution of the spent electron beam at 10 m from the IP. The Gaussian and rms sigmas are shown on the plot.

6300 have about 160 mm full horizontal aperture to allow for the varying separation between the electron and
 6301 non-colliding proton orbit (120 mm) with the usual electron-beam aperture assumptions (± 20 mm). First
 6302 design of mirror magnets for Q1 feature a field of 0.5 T in the electron beam pipe. This value is considered
 6303 too large when compared to the IR dipole of 0.3 T, but new designs with active isolation or dedicated coils
 6304 could considerably reduce this field. Migrating to NbTi technology would automatically reduce this field
 6305 too.

6306 Spent electron beam

6307 The proton electromagnetic field provides extra focusing to the electron beam. This increases the divergence
 6308 of the electron. Figure 8.20 shows the horizontal distribution of the electrons at 10 m from the IP (entry of
 6309 Q1) as computed by Guineapig [665]. The contribution of dispersion and energy spread to the transverse size
 6310 of the exiting collided beam can be neglected. Therefore, it is possible to linearly scale the sigmas at 10 m to
 6311 estimate both the horizontal and vertical sigmas at any other longitudinal location. The simulation used 10^5
 6312 particles. No particles are observed beyond 4.5 mm from the beam centroid at 10 m from the IP and beyond
 6313 9 mm at 20 m. A radial aperture of 10 mm has been reserved for the beam size at the incoming electron Q1
 6314 hole. The same value of 10 mm seem to be enough to also host the spent electron beams, although it might
 6315 be worth to allocate more aperture margin in the last block of Q1.

6316 8.2.3 Modifications for γp or γ -A

6317 The electron beam can be converted into photons by Compton scattering off a high-power laser pulse, as
 6318 discussed Section 8.1.6. For this option a laser path and high-finesse optical cavities must be integrated into
 6319 the interaction region. A multiple mirror arrangement has been sketched in Fig. 8.12. The 0.3-T dipole field
 6320 after the (now) γ -p interaction point will help to separate the Compton-scattered spent electron beam from
 6321 the high-energy photons. The high-energy photons propagate straight into the direction of the incoming

6322 proton beam through the main openings of Q1 and Q2, while the spent electrons will be extracted through
6323 the low-field exit holes shared with the non-colliding proton beam, as for electron-proton collisions.

6324 8.2.4 Synchrotron radiation and absorbers

6325 Introduction

6326 The synchrotron radiation (SR) in the linac-ring interaction region has been analyzed by three different
6327 approaches. The SR was simulated using a program made with the Geant4 (G4) toolkit. In addition, a cross
6328 check of the total power and average critical energy was done in IRSYN, a Monte Carlo simulation package
6329 written by R. Appleby [572]. A final cross check of the radiated power has been performed using an analytic
6330 method. The latter two checks confirmed the results obtained from G4. The G4 program uses Monte Carlo
6331 methods to create the desired Gaussian spatial and angular distributions of an electron beam. This electron
6332 beam distribution is then transported through a “vacuum system,” including the magnetic fields for the
6333 separator dipoles. In a non-zero magnetic field SR is generated using the appropriate G4 process classes.
6334 The position, direction, and energy of each photon emitted is written as ntuples at user defined longitudinal
6335 positions (Z values). These ntuples are then used to analyze the SR fan as it evolves in Z . The latter
6336 analysis was done primarily through MATLAB scripts.

6337 This section uses the following conventions. The electron beam is being referred to as *the beam* and the
6338 proton beams will be called either the interacting or non interacting proton beams. The (electron) beam
6339 propagates in the $-Z$ direction and the interacting proton beam propagates in the $+Z$ direction. At the
6340 collision point both beams propagate up the straight Z (or $-Z$) direction. A right-handed coordinate system
6341 is used where the X axis is horizontal and the Y axis vertical. The beam centroid always remains in the
6342 $Y = 0$ plane. The *angle of the beam* will be used to refer to the angle between the beam centroid’s direction
6343 and the Z axis, in the $Y = 0$ plane. This angle is defined such that the beam propagates in the $-X$ direction
6344 when it passes through the dipole field as it moves along Z .

6345 The SR fans extension in the horizontal direction is determined by the angle of the beam at the entrance
6346 of the upstream separator dipole. Because the direction of the photons is parallel to the direction of the
6347 electron from which it is emitted, the angle of the beam and the X -distance to the interacting proton beam
6348 at the Z location of the last proton quadrupole are both greatest for photons generated at the entrance of
6349 the upstream separator dipole and, therefore, this angle defines one of the edges of the synchrotron fan on
6350 the absorber in front of the proton quadrupole. The other edge is defined by the crossing angle, which is
6351 zero for the linac-ring option. The S shaped trajectory of the beam means that the smallest angle of the
6352 beam will be reached at the IP. Therefore, the photons emitted at this point will move exactly along the Z
6353 axis. This defines the other edge of the fan in the horizontal direction.

6354 The SR fans extent in the vertical direction is determined by the beta function and angular spread of
6355 the beam. The beta function along with the emittance defines the local rms beam size. The vertical rms
6356 beam size characterizes the range of Y positions at which photons are emitted. Possibly more importantly,
6357 the vertical angular spread defines the angle between the velocity vector of these photons and the Z axis.
6358 Both of these dependencies are functions of Z . Similar effects also affect the horizontal extension of the SR
6359 fan, however, in the horizontal plane they are of second order when compared to the horizontal deflection
6360 angle in the strong dipole field.

6361 The number density distribution of the SR fan is inferred from the simulations. The number density at
6362 the location of the absorber is highest in the region between the two interacting beams. This is due to the
6363 S shaped trajectory of the beam.

6364 Parameters

6365 The parameters for the Linac Ring option are listed in Table 8.5. The separation refers to the displacement
6366 between the two interacting beams at the face of the proton triplet.

6367 The energy, current, and crossing angle (θ_c) are the common values used in all LR calculations. The B
6368 value refers to the constant dipole field created throughout the two dipole magnets in the IR. The direction

Characteristic	Value
Electron Energy [GeV]	60
Electron Current [mA]	6.6
Crossing Angle [mrad]	0
Absorber Position [m]	-9
Dipole Field [T]	0.3
Separation [mm]	75
γ/s	1.37×10^{18}

Table 8.5: LR: Parameters

6369 of this field is opposite on either side of the IP. The field is chosen such that 75 mm of separation is reached
6370 by the face of the proton triplet. This separation was chosen based on S. Russenschuck’s SC quadrupole
6371 design. [573] The separation between the interacting beams can be increased by raising the constant dipole
6372 field however for a dipole magnet $P_{SR} \propto |B^2|$, [574] therefore an optimization of the design will need to be
6373 discussed. The chosen parameters give a flux of 1.37×10^{18} photons per second at $Z = -9$ m.

6374 Power and Critical Energy

6375 Table 8.6 shows the power of the SR produced in the IR along with the critical energy. This is followed by
6376 the total power produced in the IR and the critical energy. Since the G4 simulations utilize Monte Carlo,
6377 multiple runs were used to provide a standard error. This only caused fluctuations in the power since the
6378 critical energy is static for a constant field and constant energy.

Element	Power [kW]	Critical Energy [keV]
DL	24.4 +/- 0.1	718
DR	24.4 +/- 0.1	718
Total	48.8 +/- 0.1	718

Table 8.6: LR: Power and Critical Energies as calculated with Geant4.

6379 These magnets have strong fields and therefore produce high critical energies and a substantial amount
6380 of power. Although the power is similar to that of the RR design the critical energy is much larger. This
6381 comes from the linear dependence of critical energy on magnetic field (*i.e.* $E_c \propto B$) [575]. With the dipole
6382 field in the LR case being an order of magnitude larger than the dipole fields in the RR case the critical
6383 energies from the dipole magnets are also an order of magnitude larger in the LR case.

6384 Comparison

6385 The IRSYN cross check of the power and critical energies is shown in Table 8.7. This comparison was done
6386 for the total power and the critical energy.

	Power [kW]		Critical Energy [keV]	
	Geant4	IRSYN	Geant4	IRSYN
Total	48.8 +/- 0.1	48.8	718	718

Table 8.7: LR: Geant4 and IRSYN comparison.

6387
6388

A third cross check to the Geant4 simulations was made for the power as shown in Table 8.8. This was done using an analytic method for calculating power in dipole magnets [574].

	Power [kW]	
Element	Geant4	Analytic
DL	24.4 +/- 0.1	24.4
DR	24.4 +/- 0.1	24.4
Total/Avg	48.8 +/- 0.1	48.8

Table 8.8: LR: Geant4 and Analytic method comparison.

6389

Number Density and Envelopes

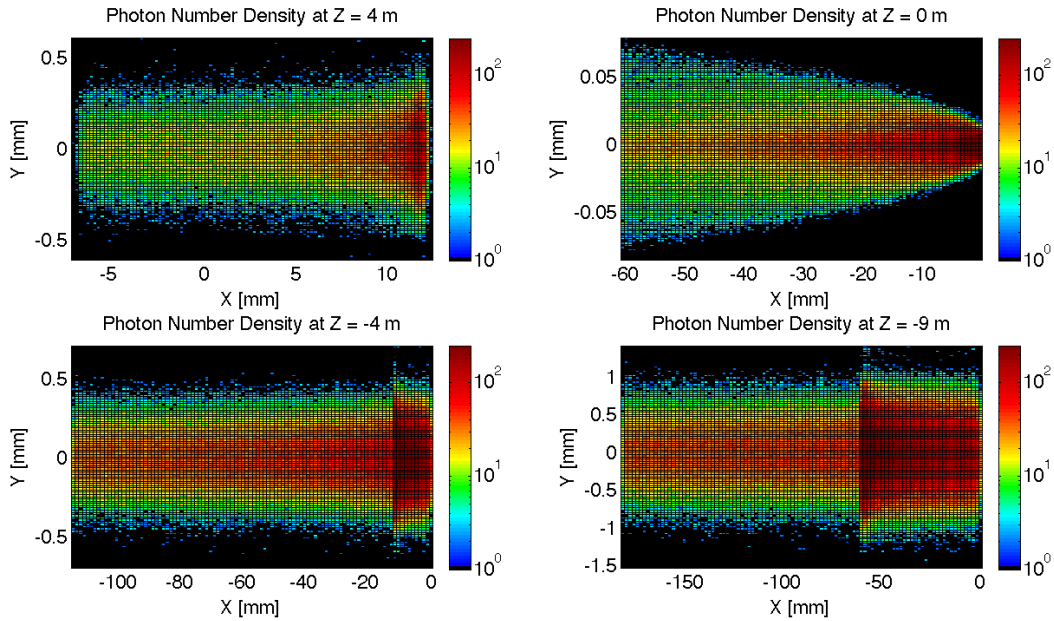


Figure 8.21: LR: Number Density of photons Growth in Z direction.

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The number density of photons at different Z values is shown in Figure 8.21. Each graph displays the density of photons in the $Z = Z_o$ plane for various values of Z_o . The first three graphs give the growth of the SR fan inside the detector area. This is crucial for determining the dimensions of the beam pipe inside the detector area. Since the fan grows asymmetrically in the $-Z$ direction an asymmetric elliptical cone shaped beam pipe will minimize these dimensions, allowing the tracking to be placed as close to the beam as possible. The horizontal extension of the fan in the LR option is larger than in the RR case. This is due to the large angle of the beam at the entrance of the upstream separator dipole. As mentioned in the introduction this angle defines the fans extension, and in the LR case this angle is the largest, hence the largest fan. The number density of this fan appears as expected. There exists the highest density between the two beams at the absorber.

In Figure 8.21 the distribution was given at various Z values however a continuous envelope distribution is also important to see everything at once. This can be seen in Figure 8.22, where the beam and fan envelopes

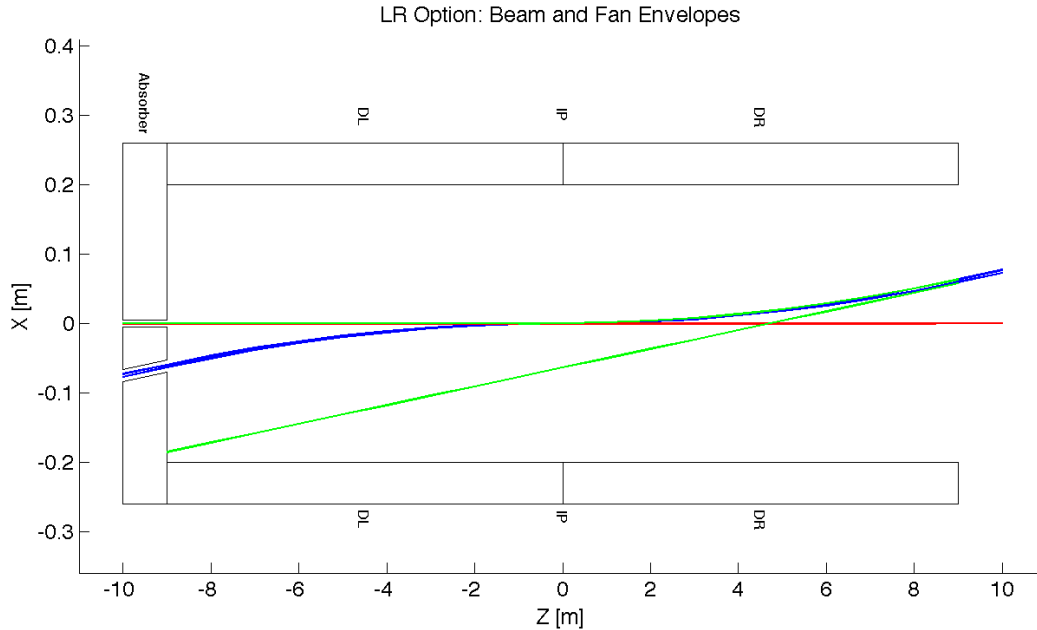


Figure 8.22: LR: Beam Envelopes in Z direction.

6402 are shown in the $Y = 0$ plane. This makes it clear that the fan is antisymmetric which comes from the S
 6403 shape of the electron beam as previously mentioned.

6404 Absorber

6405 The Photon distribution on the absorber surface is crucial. The distribution decides how the absorber must
 6406 be shaped. The shape of the absorber in addition to the distribution on the surface then decides how
 6407 much SR is backscattered into the detector region. In HERA backscattered SR was a significant source of
 6408 background that required careful attention [576]. Looking at Figure 8.23 it is shown that for the LR option
 6409 35.15 kW of power from the SR light will fall on the face of the absorber which is 73% of the total power.
 6410 This gives a general idea of the amount of power that will be absorbed. However, backscattering and IR
 6411 photons will lower the percent that is actually absorbed.

6412 **Proton Triplet:** The super conducting final focusing triplet for the protons needs to be protected from
 6413 radiation by the absorber. Some of the radiation produced upstream of the absorber however will either pass
 6414 through the absorber or pass through the apertures for the two interacting beams. This is most concerning
 6415 for the interacting proton beam aperture which will have the superconducting coils. A rough upper bound
 6416 for the amount of power the coils can absorb before quenching is 100 W. [577] There is approximately 2 kW
 6417 entering into the interacting proton beam aperture as is shown in Figure 8.23. This doesn't mean that all
 6418 this power will hit the coils but simulations need to be made to determine how much of this will hit the coils.
 6419 The amount of power that will pass through the absorber (0.25 W) can be disregarded as it is not enough
 6420 to cause any significant effects. The main source of power moving downstream of the absorber will be the
 6421 photons passing through the beams aperture. This was approximately 11 kW as can be seen from Figure
 6422 8.23. Most of this radiation can be absorbed in a secondary absorber placed after the first downstream proton
 6423 quadrupole. Overall protecting the proton triplet is important and although the absorber will minimize the
 6424 radiation continuing downstream this needs to be studied in depth.

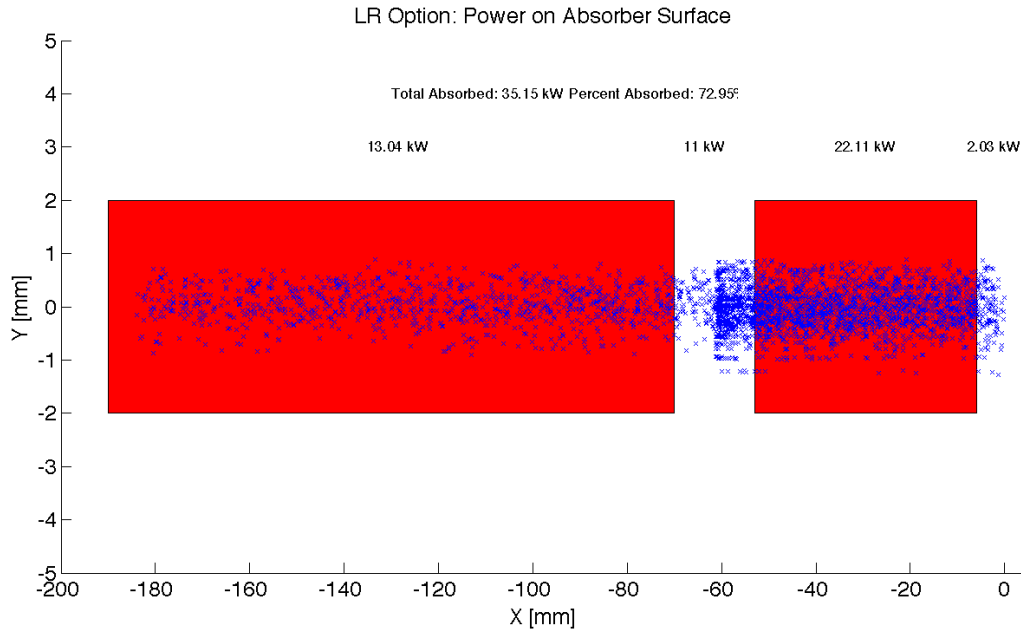


Figure 8.23: LR: Photon distribution on the Absorber Surface.

6425 **Beamstrahlung** The beamstrahlung photons travel parallel to the proton beam until the entrance of D1
 6426 without impacting the triplets. Figure 8.24 shows the transverse and energy distributions of the beamstrahlung
 6427 photons at the entry of D1 as computed with Guineapig [665]. The maximum photon energy is about 20 MeV
 6428 the average photon energy is 0.4 MeV. The beamstrahlung power is 980 W. D1 has to be designed to properly
 6429 dispose the neutral debris from the IP. Splitting D1 into two parts could allow an escape line for the neutral
 6430 particles.

6431 **Backscattering** Another G4 program was written to simulate the backscattering of photons into the
 6432 detector region. The ntuple with the photon information written at the absorber surface is used as the
 6433 input for this program. An absorber geometry made of copper is described, and general physics processes
 6434 are set up. A detector volume is then described and set to record the information of all the photons which
 6435 enter in an ntuple. The first step in minimizing the backscattering was to optimize the absorber shape.
 6436 Although the simulation didnt include a beampipe the backscattering for different absorber geometries was
 6437 compared against one another to find a minimum. The most basic shape was a block of copper that had
 6438 cylinders removed for the interacting beams. This was used as a benchmark to see the maximum possible
 6439 backscattering. In HERA a wedge shape was used for heat dissipation and minimizing backscattering [576].
 6440 The profile of this geometry in the YZ plane is shown in Figure 8.25. It was found that this is the optimum
 6441 shape for the absorber. The reason for this is that a backscattered electron would have to have its
 6442 velocity vector be almost parallel to the wedge surface to escape from the wedge and therefore it works as
 6443 a trap. One can be seen from Table 8.9 utilizing the wedge shaped absorber decreased the backscattered
 6444 power by a factor of 4. The energy distribution for the backscattered photons can be seen in Figure 8.26.

6445 After the absorber was optimized it was possible to set up a beam pipe geometry. An asymmetric
 6446 elliptical cone beam pipe geometry made of beryllium was used since it would minimize the necessary size
 6447 of the beam pipe as previously mentioned. The next step was to place the lead shield and masks inside this
 6448 beam pipe. To determine placement a simulation was run with just the beam pipe. Then it was recorded
 6449 where each backscattered photon would hit the beam pipe in Z. A histogram of this data was made as shown
 6450 in Figure 8.27. This determined that the shield should be placed in the Z region ranging from -8 m until the

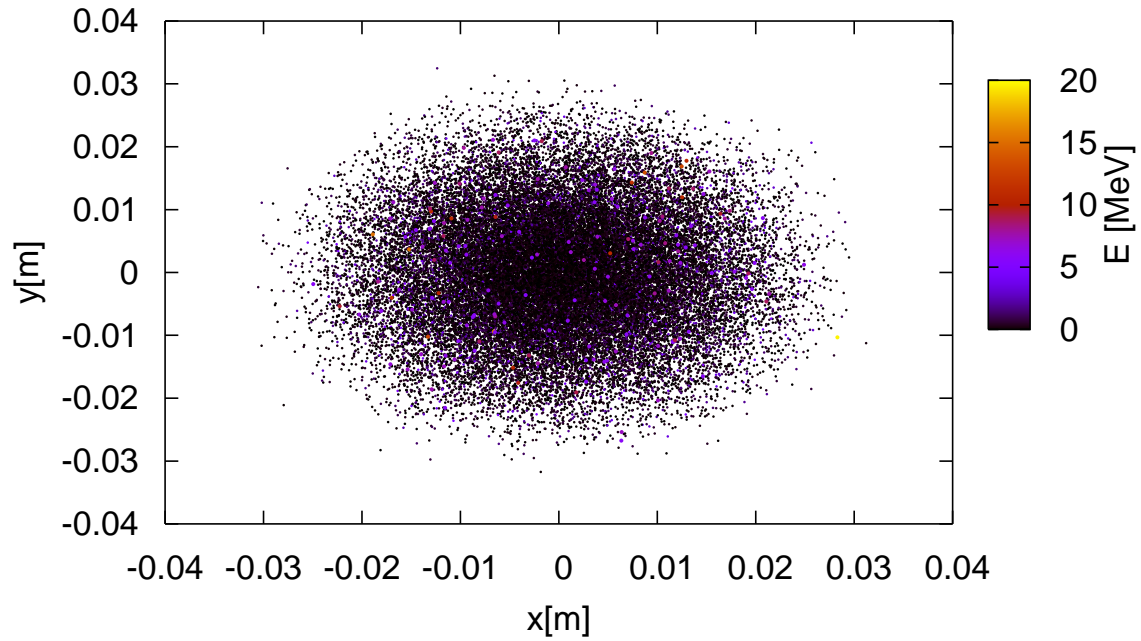


Figure 8.24: Beamstrahlung photons at the entrance of D1.

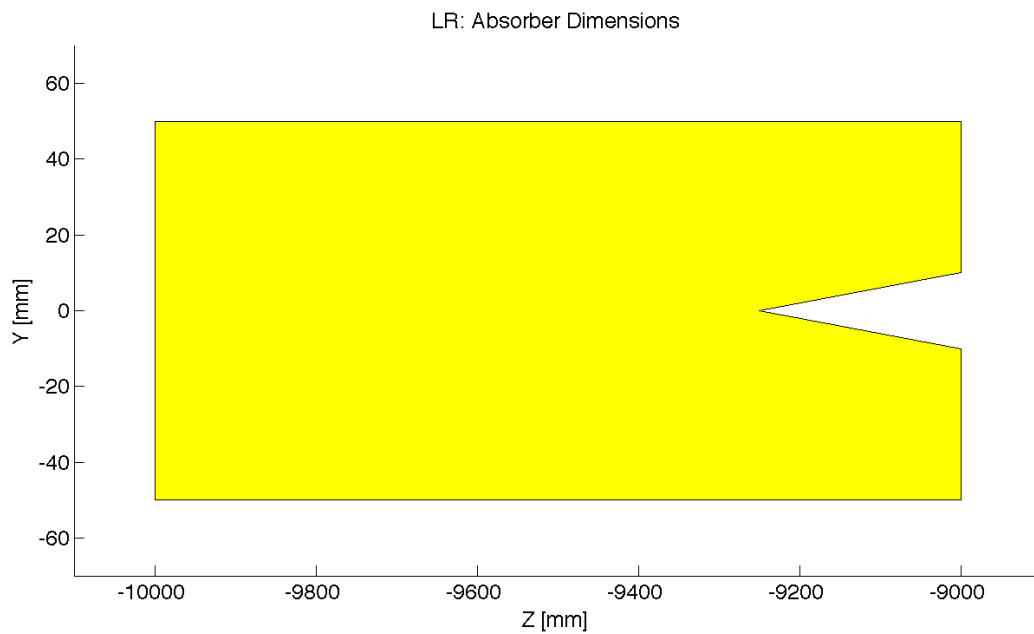


Figure 8.25: LR: Absorber Dimensions.

6451 absorber (-9 m). The masks were then placed at -8.9 m and -8.3 m. This decreased the backscattered power
 6452 by a factor of 40 as can be seen from Table 8.9. Overall there is still more optimization that can occur with
 6453 this placement.

6454 Cross sections of the beam pipe in the $Y = 0$ and $X = 0$ planes with the shields and masks included can
 6455 be seen in Figure 8.28.

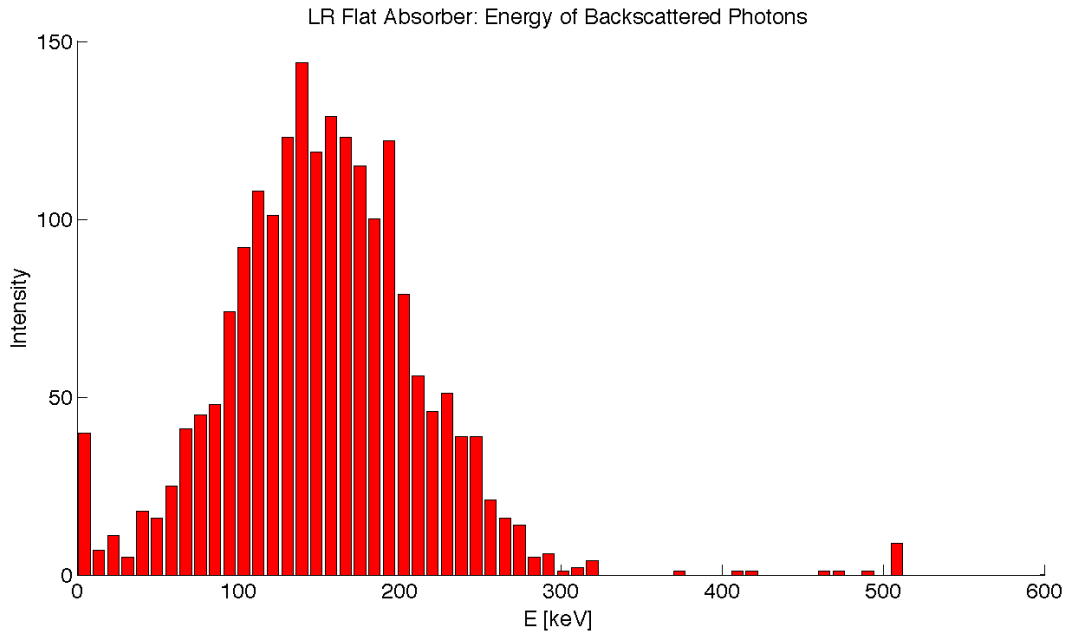


Figure 8.26: LR: Backscattered Energy Distribution.

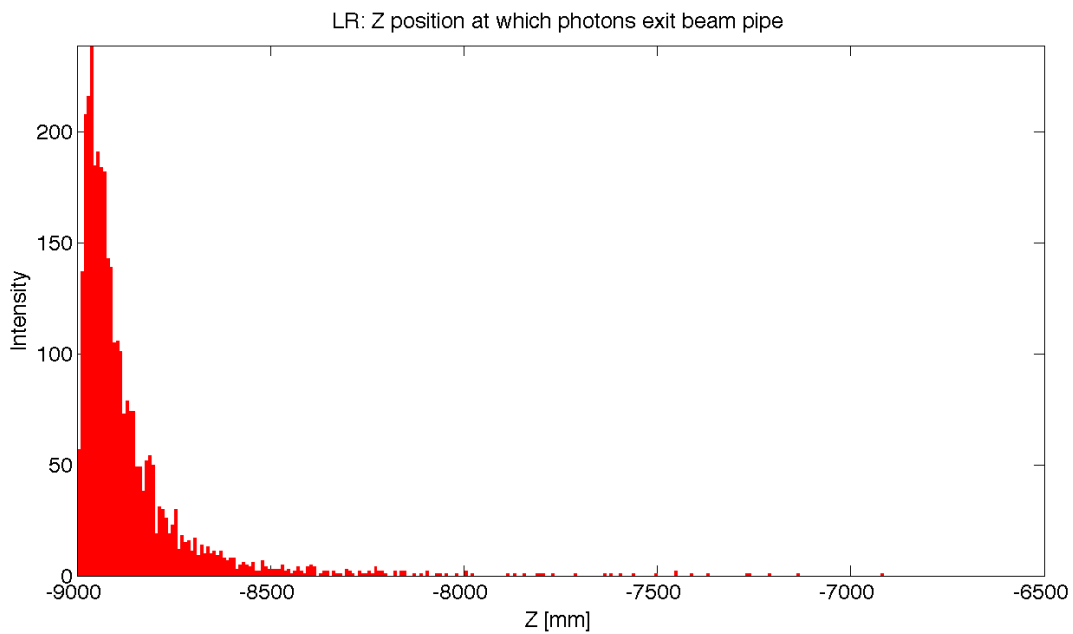


Figure 8.27: LR: Backscattered Photons Exiting the Beam Pipe.

6456 8.3 Linac Lattice and Impedance

6457 8.3.1 Overall Layout

6458 The proposed layout of the recirculating linear accelerator complex (RLA) is illustrated schematically in
 6459 Fig. 8.29. It consists of the following components:

Absorber Type	Power [W]
Flat	645.9
Wedge	159.1
Wedge & Mask/Shield	4.3

Table 8.9: LR: Power deposition due to Backscattered photons.

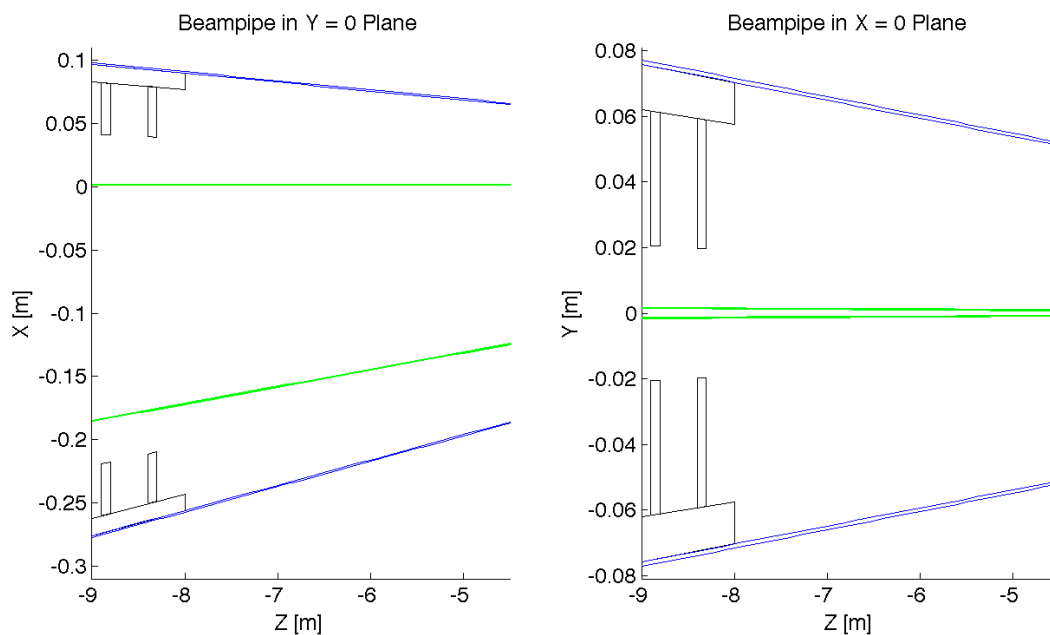


Figure 8.28: LR: Beampipe Cross Sections.

- 6460 • A 0.5 GeV injector with an injection chicane.
- 6461 • A pair of 721.44MHz SCRF linacs. Each linac is one kilometer long with an energy gain 10GeV per
6462 pass.
- 6463 • Six 180° arcs. Each arc has a radius of one kilometer.
- 6464 • For each arc one re-accelerating station that compensates the synchrotron radiation emitted in this
6465 arc.
- 6466 • A switching station at the beginning and end of each linac to combine the beams from different arcs
6467 and to distribute them over different arcs.
- 6468 • An extraction dump at 0.5 GeV.

6469 After injection, the beam makes three passes through the linacs before it collides with the LHC beam.
6470 The beam will then perform three additional turns in which the beam energy is almost completely extracted.
6471 The size of the complex is chosen such that each turn has the same length and that three turns correspond
6472 to the LHC circumference. This choice is motivated by the following considerations:

- 6473 • To avoid the build-up of a significant ion density in the accelerator complex, clearing gaps may be
6474 required in the beam.

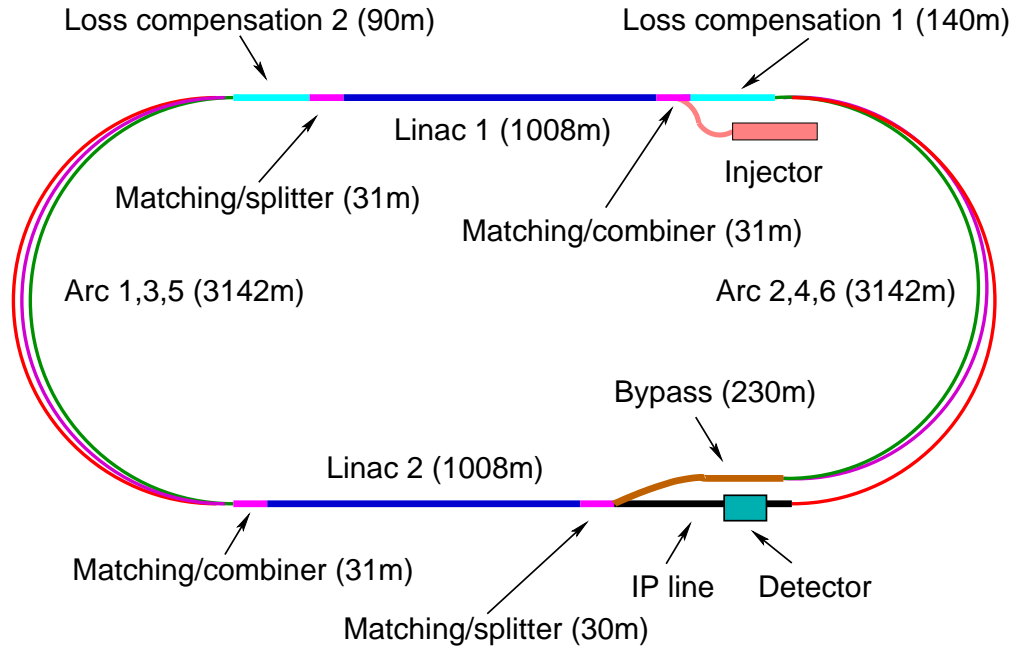


Figure 8.29: The schematic layout of the recirculating linear accelerator complex.

Parameter	Symbol	Value
Particles per bunch	N	$2 \cdot 10^9$
Initial normalised transverse emittance	ϵ_x, ϵ_y	$30 \mu\text{m}$
Normalised transverse emittance at IP	ϵ_x, ϵ_y	$50 \mu\text{m}$
Bunch length	σ_z	$600 \mu\text{m}$

Table 8.10: Key beam parameters.

- The longitudinal position of these gaps must coincide for each of the six turns that a beam performs. This requires that the turns have the same length.
- Due to the gaps some LHC bunches will collide with an electron bunch but some will not. It is advantageous to have each LHC bunch either always collide with an electron bunch or to never collide. The choice of length for one turn in the RLA allows to achieve this.

Some key beam parameters are given in table 8.10.

8.3.2 Linac Layout and Lattice

The key element of the transverse beam dynamics in a multi-pass recirculating linac is an appropriate choice of multi-pass linac optics. The focusing strength of the quadrupoles along the linac needs to be set such that one can transport the beam at each pass. Obviously, one would like to optimize the focusing profile to accommodate a large number of passes through the RLA. In addition, the requirement of energy recovery puts a constraint on the exit/entrance Twiss functions for the two linacs. As a baseline we have chosen a FODO lattice with a phase advance of 130° for the beam that passes with the lowest energy and a quadrupole spacing of 28m [666]. Alternative choices are possible. An example is an optics that avoids any quadrupole in the linacs [667].

6490 **Linac Module Layout**

6491 The linac consists of a series of units, each consisting of two cryomodules and one quadrupole pack. Each
6492 cryomodule is 12.8m and contains eight 1m-long accelerating cavities. The interconnect between two adjacent
6493 cryomodules is 0.8m long. The quadrupole pack is 1.6m long, including the interconnects to the adjacent
6494 cryomodules. The whole unit is 28m long.

6495 Each quadrupole pack contains a quadrupole, a beam position monitor and a vertical and horizontal
6496 dipole corrector, see section 2.9.

6497 **Linac Optics**

6498 The linac consists of 36 units with a total length of 1008m. In the first linac, the strength of the quadrupoles
6499 has been chosen to provide a phase advance per cell of 130° for the beam in its first turn. In the second
6500 linac, the strength has been set to provide a phase advance of 130° for the last turn of the beam. The initial
6501 Twiss parameters of the beam and the return arcs are optimised to minimise the beta-functions of the beams
6502 in the following passages. The criterion used has been to minimise the integral

$$\int_0^L \frac{\beta}{E} ds \tag{8.6}$$

6503 Single bunch transverse wakefield effects and multi-bunch effects between bunches that have been injected
6504 shortly after each other are proportional to this integral [668]. The final solution is shown in Fig. 8.30. A
6505 significant beta-beating can be observed due to the weak focusing for the higher energy beams.

6506 **Return Arc Optics**

6507 At the ends of each linac the beams need to be directed into the appropriate energy-dependent arcs for
6508 recirculation. Each bunch will pass each arc twice, once when it is accelerated before the collision and once
6509 when it is decelerated after the collision. The only exception is the arc at highest energy that is passed
6510 only once. For practical reasons, horizontal rather than vertical beam separation was chosen. Rather than
6511 suppressing the horizontal dispersion created by the spreader, the horizontal dispersion can be smoothly
6512 matched to that of the arc, which results in a very compact, single dipole, spreader/recombiner system.

6513 The initial choice of large arc radius (1 km) was dictated by limiting energy loss due to synchrotron
6514 radiation at top energy (60.5 GeV) to less than 1%. However other adverse effects of synchrotron radiation
6515 on beam phase-space such as cumulative emittance and momentum growth due to quantum excitations
6516 are of paramount importance for a high luminosity collider that requires normalized emittance of 50 mm
6517 mrad. Energy losses from resistive wall and from coherent synchrotron radiation have both been shown to
6518 be negligible compared with the energy loss due to incoherent synchrotron radiation [667].

6519 Three different arc designs have been developed [666]. In the design for the lowest energy turns, the beta-
6520 functions are kept small in order to limit the required vacuum chamber size and consequently the magnet
6521 aperture. At the highest energy, the lattice is optimised to keep the emittance growth limited, while the
6522 beta-functions are allowed to be larger. A cell of the lowest and one of the highest energy arc is shown in
6523 Fig. 8.31 All turns have a bending radius of 764m. The beam pipe diameter is 25mm, which corresponds to
6524 more than 12σ aperture.

6525 An interesting alternative optics, which pushes towards a smaller beam pipe, has also been devel-
6526 oped [667].

6527 **Synchrotron Radiation in Return Arcs**

6528 Synchrotron radiation in the arcs leads to a significant beam energy loss. This loss is compensated by the
6529 small linacs that are incorporated before or after each arc when the beams are already or still separated
6530 according to their energy, see Fig. 8.29. The energy loss at the 60GeV turn-round can be compensated by
6531 a linac with an RF frequency of 721.44MHz. The compensation at the other arcs is performed with an RF

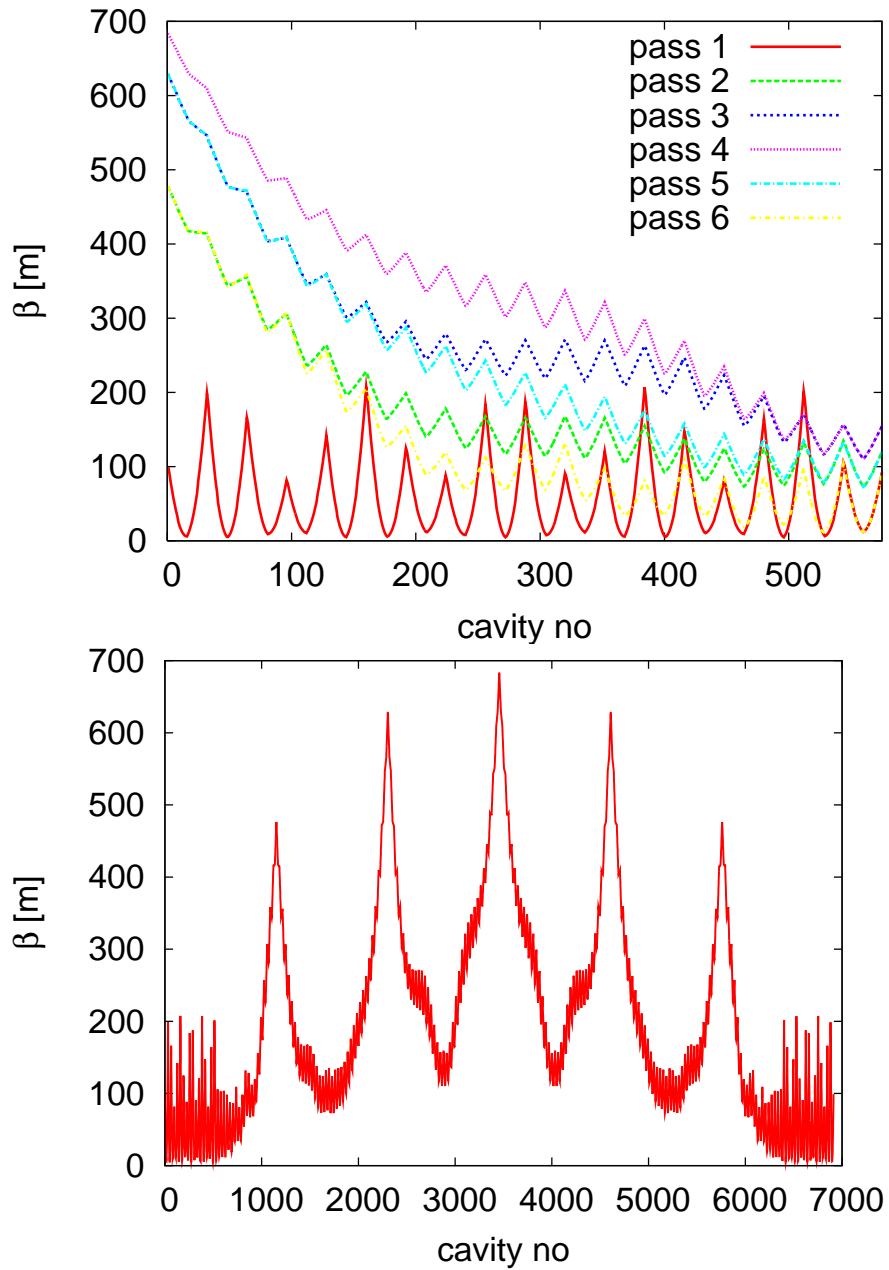


Figure 8.30: Beta-functions in the first linac. On the top, the beta-functions of the six different beam passages in the first linac are shown. On the bottom, the beta-function as seen by the beam during his stay in the linacs are shown.

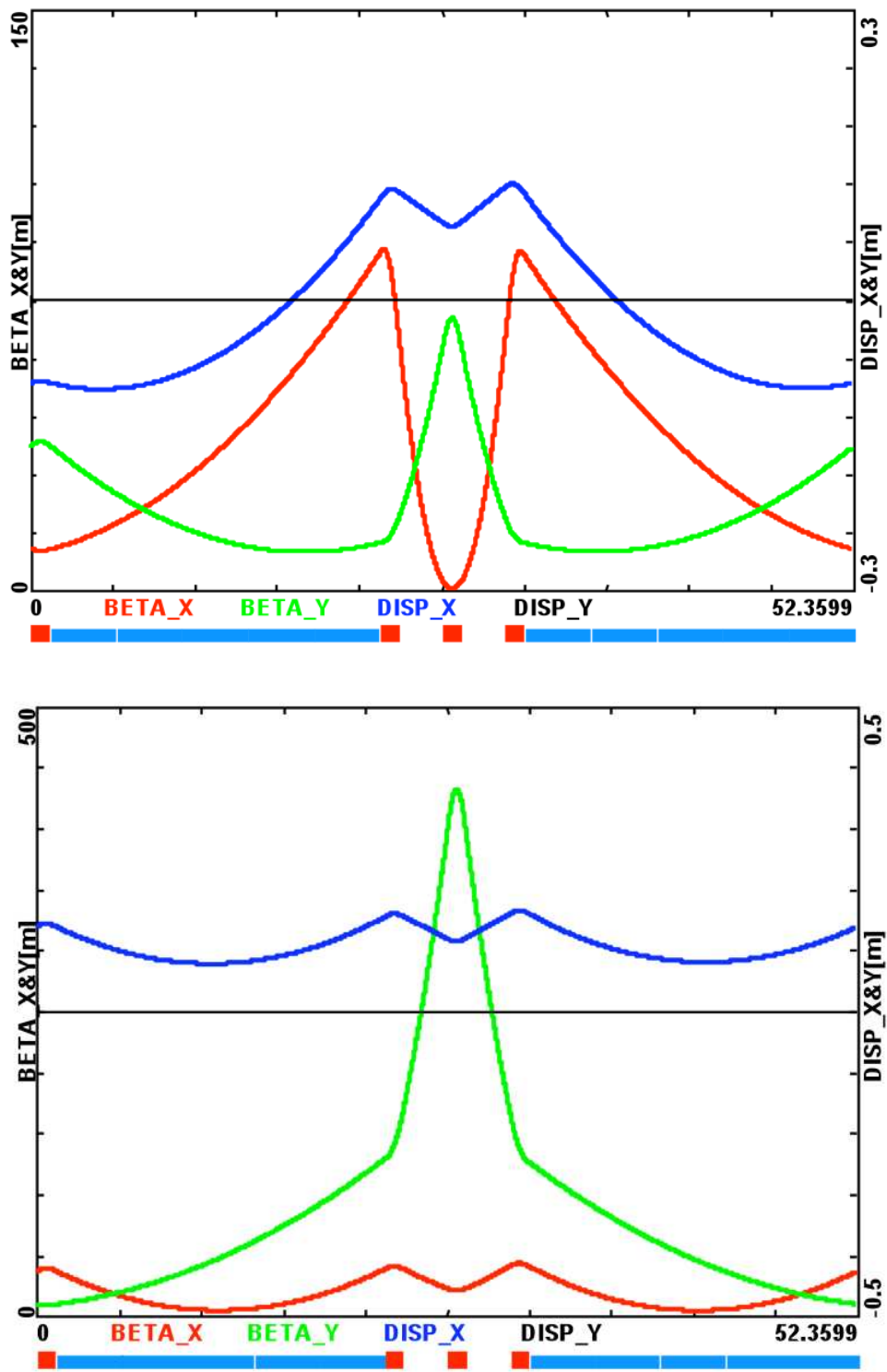


Figure 8.31: The optics of the lowest (top) and the highest (bottom) energy return arcs.

turn no	E [GeV]	ΔE [MeV]	σ_E/E [%]
1	10.5	0.7	0.00036
2	20.5	10.2	0.0019
3	30.5	49.8	0.0053
4	40.5	155	0.011
5	50.5	375	0.020
6	60.5	771	0.033
7	50.5	375	0.044
8	40.5	155	0.056
9	30.5	49.8	0.074
10	20.5	10.2	0.11
11	10.5	0.7	0.216
dump	0.5	0.0	4.53

Table 8.11: Energy loss due to synchrotron radiation in the arcs as a function of the arc number. The integrated energy spread induced by synchrotron radiation is also shown.

6532 frequency of 1442.88MHz. In this way the bunches that are on their way to the collision point and the ones
6533 that already collided can both be accelerated. This ensures that the energy of these bunches are the same
6534 on the way to and from the interaction point, which simplifies the optics design. If the energy loss were not
6535 compensated the beams would have a different energy at each turn, so that the number of return arcs would
6536 need to be doubled.

6537 The synchrotron radiation is also generating an energy spread of the beam. In Tab. 8.11 the relative
6538 energy spread is shown as a function of the arc number that the beam has seen. At the interaction point,
6539 the synchrotron radiation induced RMS energy spread is only 2×10^{-4} , which adds to the energy spread of
6540 the wakefields. At the final arc the energy spread reaches about 0.22%, while at the beam dump it grows to
6541 a full 4.5%.

6542 The growth of the normalised emittance is given by

$$\Delta\epsilon = \frac{55}{48\sqrt{3}} \frac{\hbar c}{mc^2} r_e \gamma^6 I_5 \quad (8.7)$$

6543 Here, r_e is the classical electron radius, and I_5 is given by

$$I_5 = \int_0^L \frac{H}{|\rho|^3} ds = \frac{\langle H \rangle \theta}{\rho^2} \quad H = \gamma D^2 + 2\alpha DD' + \beta D'^2 \quad (8.8)$$

6544 For a return arc with a total bend angle $\theta = 180^\circ$ one finds

$$\Delta\epsilon = \frac{55}{48\sqrt{3}} \frac{\hbar c}{mc^2} r_e \gamma^6 \pi \frac{\langle H \rangle \theta}{\rho^2} \quad (8.9)$$

6545 The synchrotron radiation induced emittance growth is shown in table 8.12. Before the interaction point
6546 a total growth of about $7\mu\text{m}$ is accumulated. The final value is $26\mu\text{m}$. While this growth is significant
6547 compared to the target emittance of $50\mu\text{m}$ at the collision point, it seems acceptable.

6548 Matching Sections and Energy Compensation

6549 Currently we do not have a design of the matching sections. However, we expect these sections to be
6550 straightforward. For the case of the linac optics without quadrupoles and the alternative return arc lattice

turn no	E [GeV]	$\Delta\epsilon_{arc}$ [μm]	$\Delta\epsilon_t$ [μm]
1	10.5	0.0025	0.0025
2	20.5	0.140	0.143
3	30.5	0.380	0.522
4	40.5	2.082	2.604
5	50.5	4.268	6.872
6	60.5	12.618	19.490
5	50.5	4.268	23.758
4	40.5	2.082	25.840
3	30.5	0.380	26.220
2	20.5	0.140	26.360
1	10.5	0.0025	26.362

Table 8.12: The emittance growth due to synchrotron radiation in the arcs.

design matching sections designs exist and exhibit no issues [667]. Also the sections that compensate the energy loss in the arcs have not been designed. But this again should be straightforward.

8.3.3 Beam Break-Up

Single-Bunch Wakefield Effect

In order to evaluate the single bunch wakefield effects we used PLACET [669]. The full linac lattice has been implemented for all turns but the arcs have each been replaced by a simple transfer matrix, since the matching sections have not been available.

Single bunch wakefields were not available for the SPL cavities. We therefore used the wakefields in the ILC/TESLA cavities [670]. In order to adjust the wakefields to the lower frequency and larger iris radius (70mm vs. 39mm for the central irises) we used the following scaling

$$W_{\perp}(s) \approx \frac{1}{(70/39)^3} W_{\perp,ILC}(s/(70/39)) \quad W_L(s) \approx \frac{1}{(70/39)^2} W_{L,ILC}(s/(70/39)) \quad (8.10)$$

First, the RMS energy spread along the linacs is determined. An initial uncorrelated RMS energy spread of 0.1% is assumed. Three different bunch lengths were studied, i.e. 300 μm , 600 μm and 900 μm . This longest value yields the smallest final energy spread. The energy spread along during the beam life-time can be seen in Fig. 8.32. The wakefield induced energy spread is between 1×10^{-4} and 2×10^{-4} at the interaction point, $1-2 \times 10^{-3}$ at the final arc and 3.5–4.5% at the beam dump.

Second, the single bunch beam-break-up is studied by tracking a bunch with an initial offset of $\Delta x = \sigma_x$. The resulting emittance growth of the bunch is very small, see Fig. 8.33.

Multi-Bunch Transverse Wakefield Effects

For a single pass through a linac the multi-bunch effects can easily be estimated analytically [668]. Another approach exists in case of two passes through one cavity [671]. It is less straightforward to find an analytic solution for multiple turns in linacs with wakefields that vary from one cavity to the next. In this case the also phase advance from one passage through a cavity to the next passage depends on the position of the cavity within the linac.

We therefore have developed a code to simulate the multi-bunch effect in the case of recirculation and energy recovery [672]. It assumes point-like bunches and takes a number of dipole wake field modes into

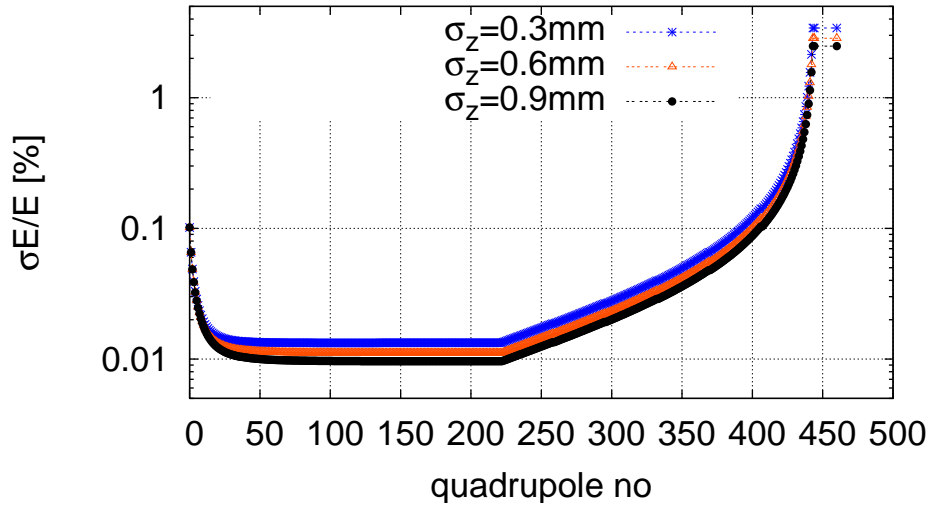


Figure 8.32: The RMS energy spread due to single bunch wakefields along the linacs. The bunch has been cut longitudinally at $\pm 3\sigma_z$ and at $\pm 3\sigma_E$ in the initial uncorrelated energy spread.

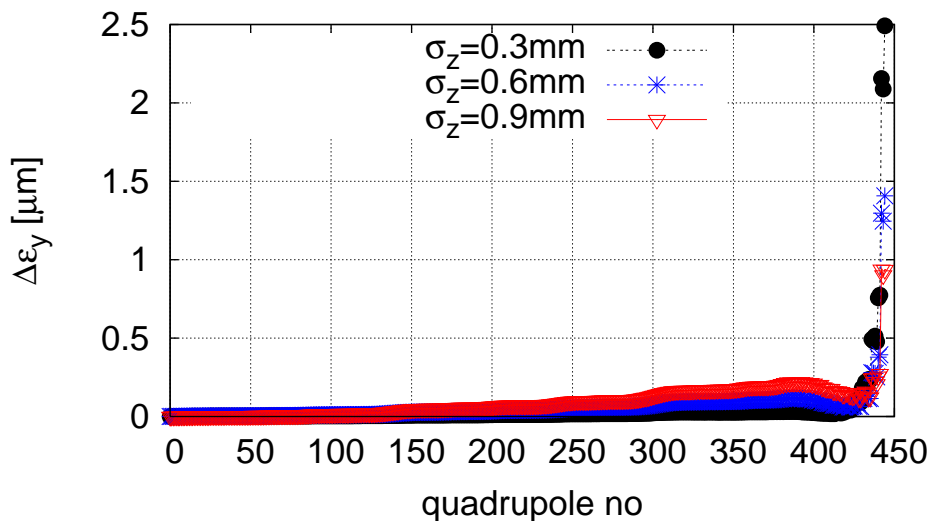


Figure 8.33: The single-bunch emittance growth along the LHeC linacs for a bunch with an initial offset of $\Delta x = \sigma_x$. The arcs have been represented by a simple transfer matrix.

f [GHz]	k [V/pCm ²]	f [GHz]	k [V/pCm ²]
0.9151	9.323	1.675	4.160
0.9398	19.095	2.101	1.447
0.9664	8.201	2.220	1.427
1.003	5.799	2.267	1.377
1.014	13.426	2.331	2.212
1.020	4.659	2.338	11.918
1.378	1.111	2.345	5.621
1.393	20.346	2.526	1.886
1.408	1.477	2.592	1.045
1.409	23.274	2.592	1.069
1.607	8.186	2.693	1.256
1.666	1.393	2.696	1.347
1.670	1.261	2.838	4.350

Table 8.13: The considered dipole modes of the SPL cavity design.

6576 account. A cavity-to-cavity frequency spread of the wakefield modes can also be modeled. The arcs are
6577 replaced with simple transfer matrices. In the simulation, we offset a single bunch of a long train by one
6578 unit and determine the final position in phase space of all other bunches.

6579 We evaluated the beam stability using the wakefield modes that have been calculated for the SPL cavity
6580 design [673]. The level of the Q -values of the transverse modes is not yet known. We assume $Q = 10^5$ for all
6581 modes, which is comparable to the larger of the Q -values found in the TESLA cavities. A random variation
6582 of the transverse mode frequencies of 0.1% has been assumed, which corresponds to the target for ILC [670].
6583 The results in Fig. 8.34 indicate that the beam remains stable in our baseline design. Even in the alternative
6584 lattice with no focusing in the linacs, the beam would remain stable but with significantly less margin. An
6585 independent beam-breakup analysis for linacs without focusing, based on measurements and simulations for
6586 the BNL 5-cell cavity, demonstrated as well that for all practical scenarios with a HOM frequency spread
6587 above 0.2% the instability threshold current is well above the design beam current [667].

6588 We also performed simulations, assuming that either only damping or detuning were present, see Fig. 8.35.
6589 The beam is unstable in both cases. Based on our results we conclude

- 6590 • One has to ensure that transverse higher order cavity modes are detuned from one cavity to the next.
6591 While this detuning can naturally occur due to production tolerances, one has to find a method to
6592 ensure its presence. This problem exists similarly for the ILC.
- 6593 • Damping of the transverse modes is required.

6594 Further studies can give more precise limits on the maximum required Q and minimum mode detuning.

6595 Multi-Pass Beam Breakup Instability (BBU)

6596 **BBU model for ERL** To gain confidence that electron current of 6.5 mA, required for the LHeC lumi-
6597 nosity is feasible, one needs to look into multi-pass beam breakup stability for our ERL design. Here, we will
6598 summarize results of a recent numerical study of 6-pass (3 passes “up” and 3 passes “down”) BBU due to
6599 the transverse higher order modes (HOMs) excited in the RF cavities. The beam travelling along each linac
6600 experiences cumulative transverse deflection from each cavity HOMs. They add up for all 3 accelerating
6601 passes in both linacs and continue for another 3 decelerating passes (energy recovery). Therefore, one needs
6602 to study transverse dynamics of the beam interacting with cavity HOMs for the entire passage through ERL
6603 using specific linac optics for each of six passes, as well as linear transfer maps of the 6 return arcs. In case

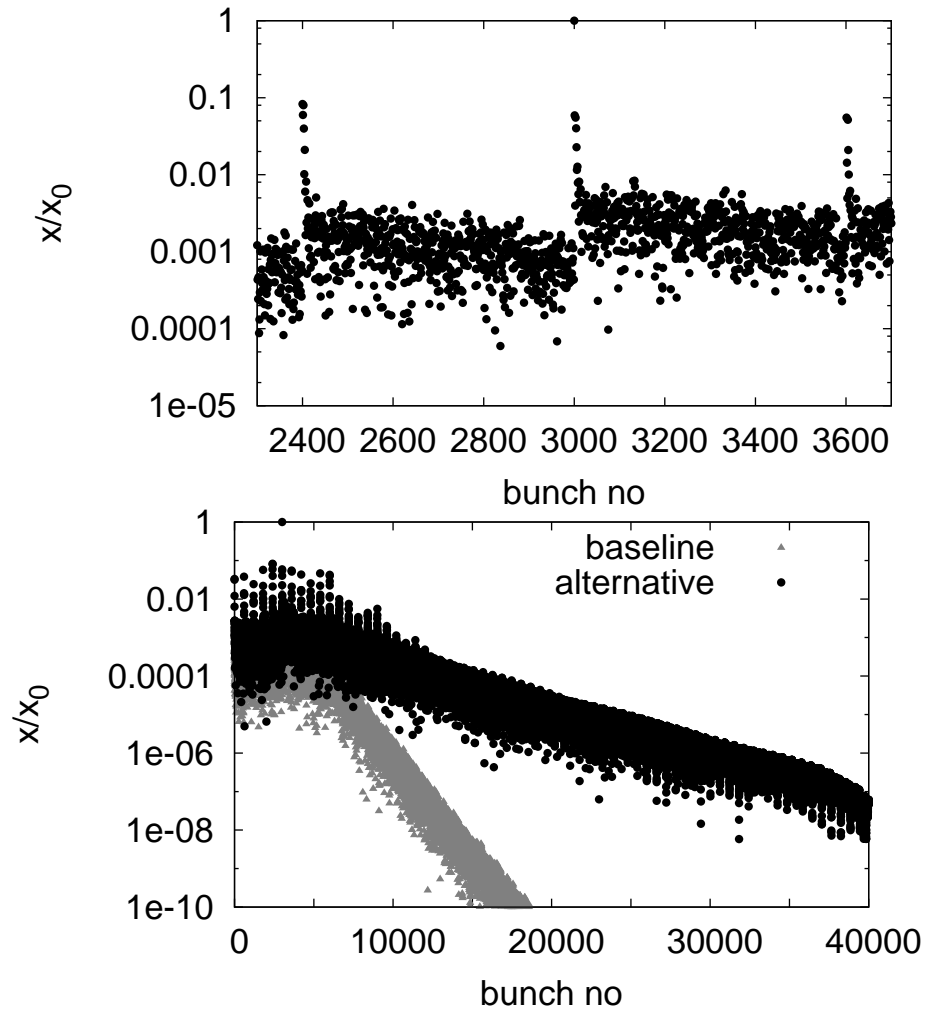


Figure 8.34: Multi-bunch beam break-up assuming the SPL cavity wakefields. One bunch has been offset at the beginning of the machine and the normalised amplitudes of the bunch oscillations are shown along the train at the end of the last turn. The upper plot shows a small number of bunches before and after the one that has been offset (i.e. bunch 3000). The lower plot shows the amplitudes along the full simulated train for the baseline lattice and the alternative design with no quadrupole focusing. One can see the fast decay of the amplitudes.

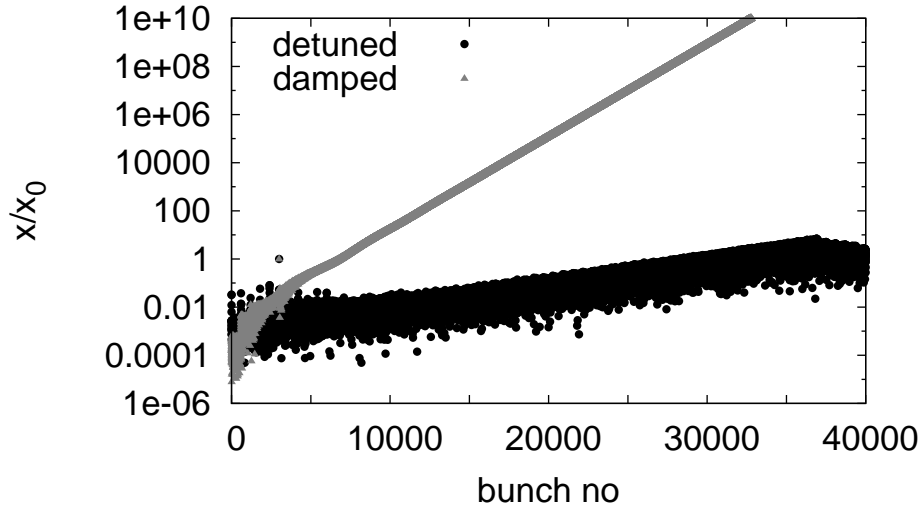


Figure 8.35: Multi-bunch beam break-up for the SPL cavities. In one case only damping, in the other case only cavity-to-cavity mode detuning is present.

6604 of BBU instability the transverse particle positions would increase exponentially and finally the particles
 6605 would hit a beam pipe.

6606 The following analytic formula describes the BBU threshold current for a single cavity with one HOM
 6607 excitation only, and one recirculation (one pass in each linac):

$$I_{th} = -\frac{2pc}{q} \frac{1}{(R/Q)Q_l M^* k \sin(\omega T_r)} \quad (8.11)$$

6608 where

- 6609 • $M^* = M_{12} \cos^2 \alpha + (M_{14} + M_{32}) \sin \alpha \cos \alpha + M_{34} \sin^2 \alpha$
- 6610 • p - particle momentum on the second pass
- 6611 • q - particle charge
- 6612 • R/Q - shunt impedance of the dipole mode
- 6613 • Q_l - quality factor of the dipole mode
- 6614 • k - wave number of dipole mode
- 6615 • T_r - recirculation time
- 6616 • α - polarization angle (0 - horizontal, 90 - vertical)

6617 The TDBBU code applies the above formalism, formulated in the time domain (TD), for each cavity
 6618 along the entire ERL.

6619 **HOM Data** LHeC ERL is designed with 720 MHz RF cavities. Since such cavities have not been fabri-
 6620 cated yet, the BNL3 5-cell SRF cavity data would serve as close reference for the HOM data even though
 6621 BNL3 fundamental mode frequency, 703.79 MHz, is slightly different. The summary of measured HOMs is
 6622 illustrated in Figure 8.36.

6623 One can notice that all the Q values are less than $1 \cdot 10^6$ and most of them are smaller than $1 \cdot 10^4$. For
 6624 our BBU simulation, we consider the worst case of $Q_l = 1 \cdot 10^6$. Out of all HOMs collected in Figure 8.36, we
 6625 selected three most offending HOMs with relatively high R/Q values. They are summarized in table 8.14.

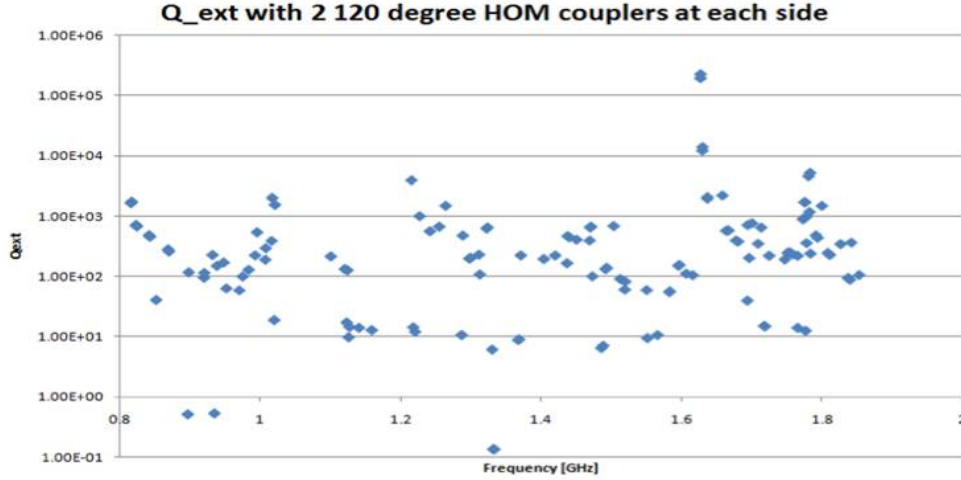


Figure 8.36: Quality factor of BNL3 cavity per “High Current SRF Cavity Design for SPL and eRHIC”, S. Belomestnykh et al., Proceedings of 2011 Particle Accelerator Conference, New York, NY, USA.

Frequency[MHz]	Q_l	R/Q[Ohm]
1003	$1 \cdot 10^6$	32
1337	$1 \cdot 10^6$	32
1820	$1 \cdot 10^6$	32

Table 8.14: The most offending HOMs selected into BBU simulation.

6626 **ERL multi-pass Optics** A concise representation of multi-pass ERL linac Optics for all six passes,
 6627 with constraints imposed on Twiss functions by “sharing” the same return arcs by the accelerating and
 6628 decelerating passes is presented in Figure 8.37.

6629 All six return arcs have to satisfy, by design, the following features:

- 6630 • No coupling
- 6631 • Double Achromat ($D_{x,y} = 0 = D'_{x,y}$)
- 6632 • Isochronous ($M_{56} = 0$)
- 6633 • Mirror symmetric ends ($\beta_{x,y}^1 = \beta_{x,y} = \beta_{x,y}^2$ and $\alpha_{x,y}^1 = \alpha_{x,y} = -\alpha_{x,y}^2$)

6634 Assuming the above design features of arc optics and knowing the Twiss parameters at the end of each
 6635 linac, as well as, the betatron phase advances, f_x and f_y , we can construct the arc Transfer matrices ad hoc
 6636 using the following formula:

$$M^i = \begin{pmatrix} M_x^i & 0 & 0 \\ 0 & M_y^i & 0 \\ 0 & 0 & 1 \end{pmatrix}, M_{x,y}^i = \begin{pmatrix} \cos \phi_{x,y}^i + \alpha_{x,y}^i \sin \phi_{x,y}^i & \beta_{x,y}^i \sin \phi_{x,y}^i \\ \frac{2\alpha_{x,y}^i}{\beta_{x,y}^i} \cos \phi_{x,y}^i - \frac{1-(\alpha_{x,y}^i)^2}{\beta_{x,y}^i} \sin \phi_{x,y}^i & \cos \phi_{x,y}^i + \alpha_{x,y}^i \sin \phi_{x,y}^i \end{pmatrix} \quad (8.12)$$

6637 **TDBBU Simulation** For each cavity along the linac, the three offending HOM frequencies are randomly
 6638 distributed with the full width of 2 MHz. In practice, the HOM frequencies are generated using random
 6639 numbers in that range and these are distributed at each cavity. Twenty samples for different HOM frequency

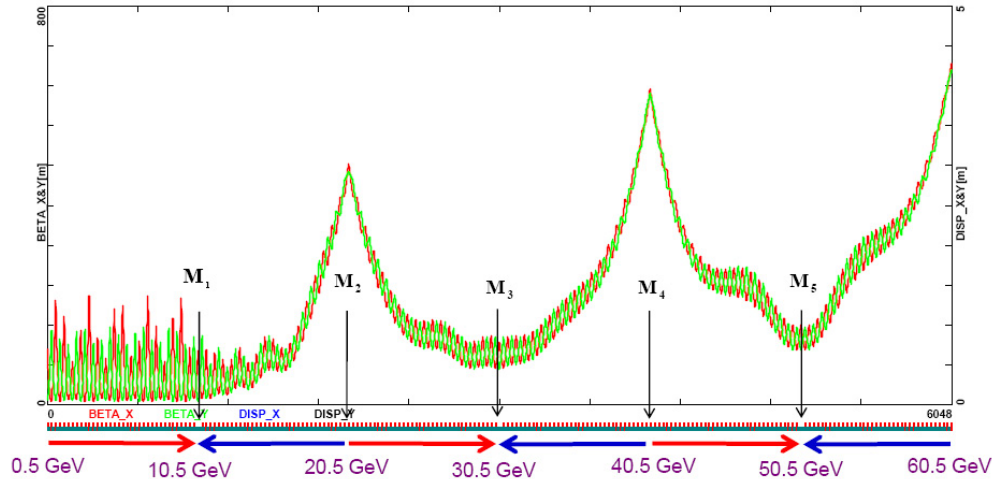


Figure 8.37: Multi-pass linac optics optimized for 3-pass ERL As a virtue of ER, Linac 2 Optics is a mirror reflection of Linac 1.

6640 distributions are generated. The plots below show the beam behavior near the threshold. The horizontal
 6641 axis corresponds to a bunch number and can be considered as an axis of time (if the bunch numbers are
 6642 divided by frequencies). The vertical axis represents the transverse beam position at the end of the second
 6643 linac. We plot the transverse positions of every 1117th particles. The number 1117 is somehow arbitrary;
 6644 however it is a large prime number chosen to avoid an unexpected sub-harmonic redundancy in the data
 6645 sampling. The simulation results for various beam currents: 4, 5 and 6 mA are illustrated in Figure 8.38.

6646 **BBU stability** As illustrated in Figure 8.38, the beam is stable at 4 mA. At 5 mA the transverse position
 6647 is increasing, which indicate onset of the instability. Finally, at 6 mA one explicitly observes an exponential
 6648 increase in transverse beam position - a vivid case of beam instability. Therefore, we could infer that the
 6649 BBU threshold current is somewhere around 5 mA. One needs to keep in mind, our study assumed the worst
 6650 case interpretation of HOM's measurement for a cavity with limited HOM suppression, only one pair 1200
 6651 HOM dampers per cavity. This suggests more extended HOM damping will bring the stability threshold
 6652 above 6.5 mA. Further BBU study with more realistic HOM selection extracted from the same measurement,
 6653 summarized in Figure 8.36, is under way.

6654 Fast Beam-Ion Instability

6655 Collision of beam particles with the residual gas in the beam pipe will lead to the production of positive
 6656 ions. These ions can be trapped in the beam. Their presence modifies the betatron function of the beam
 6657 since the ions focus the beam. They can also lead to beam break-up, since bunches with an offset will induce
 6658 a coherent motion in the ions. This can in turn lead to a kick of the ions on following bunches.

6659 **Trapping Condition in the beam pulse** In order to estimate whether ions are trapped or not, one can
 6660 replace each beam with a thin focusing lens, with the strength determined by the charge and transverse
 6661 dimension of the beam. In this case the force is assumed to be linear with the ion offset, which is a good
 6662 approximation for small offsets.

6663 The coherent frequency f_i of the ions in the field of a beam of with bunches of similar size is given

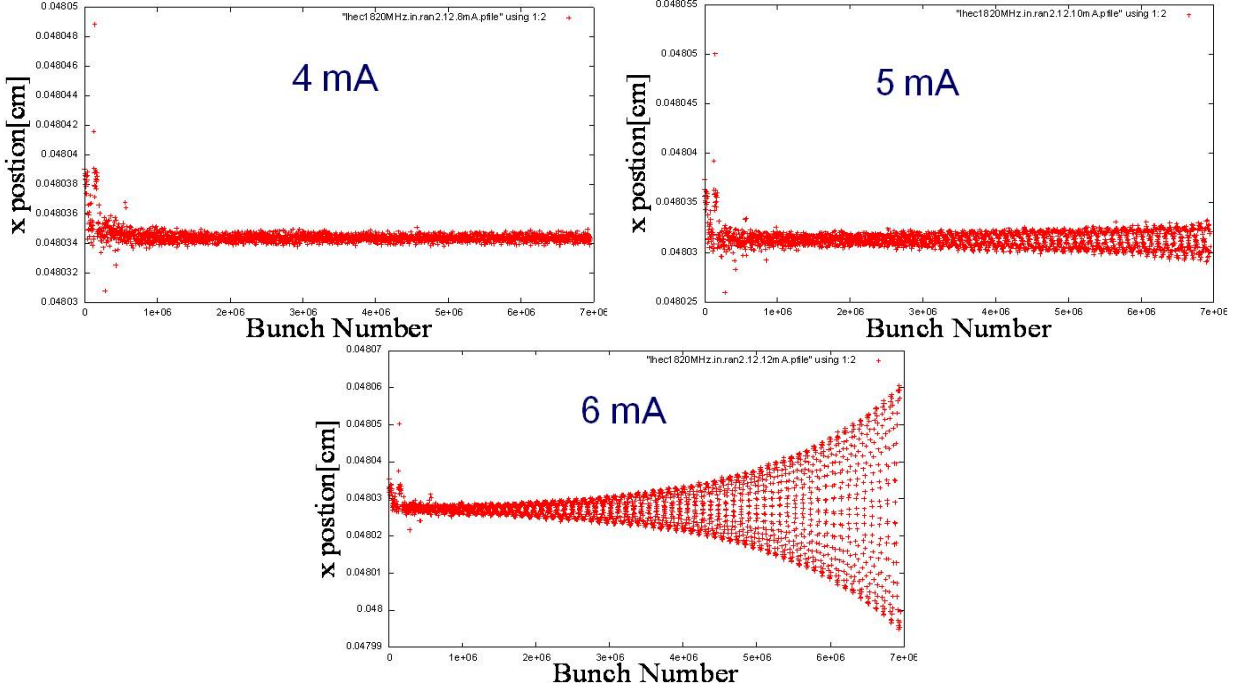


Figure 8.38: Large scale TDBBU simulation results for various beam currents: 4 (top left), 5 (top right) and 6 mA.

6664 by [674]:

$$f_i = \frac{c}{\pi} \sqrt{\frac{Q_i N r_e \frac{m_e}{A m_p}}{3 \sigma_y (\sigma_x + \sigma_y) \Delta L}} \quad (8.13)$$

6665 Here, N is the number of electrons per bunch, ΔL the bunch spacing, r_e the classical electron radius, m_e
 6666 the electron mass, Q_i the charge of the ions in units of e and A is their mass number and m_p the proton
 6667 mass. The beam transverse beam size is given by σ_x and σ_y . The ions will be trapped in the beam if

$$f_i \leq f_{limit} = \frac{c}{4 \Delta L} \quad (8.14)$$

6668 In the following we will use $\Delta L \approx 2.5\text{m}$, i.e. assume that the bunches from the different turns are almost
 6669 evenly spaced longitudinally.

6670 In the linacs, the transverse size of the beam changes from one passage to the next while in each of
 6671 the return arcs the beams have (approximately) the same size at both passages. But the variation from
 6672 one turn to the next is not huge, so we use the average focusing strength of the six turns. The calculation
 6673 shows that ions will be trapped for a continuous beam in the linacs. Since we are far from the limit of the
 6674 trapping condition, the simplification in our model should not matter. As can be seen in Fig. 8.39 CO_2^+
 6675 ions are trapped all along the linacs. Even hydrogen ions H_2^+ would be trapped everywhere. If one places
 6676 the bunches from the six turns very close to each other longitudinally, the limit frequency f_{limit} is reduced.
 6677 However, the ratio f_c/f_{limit} is not increased by more than a factor 6, which is not fully sufficient to remove
 6678 the H_2^+ .

6679 **Impact and Mitigation of Ion Effects** Without any methods to remove ions, a continuous beam would
 6680 collect ions until they neutralise the beam current. This will render the beam unstable. Hence one needs to

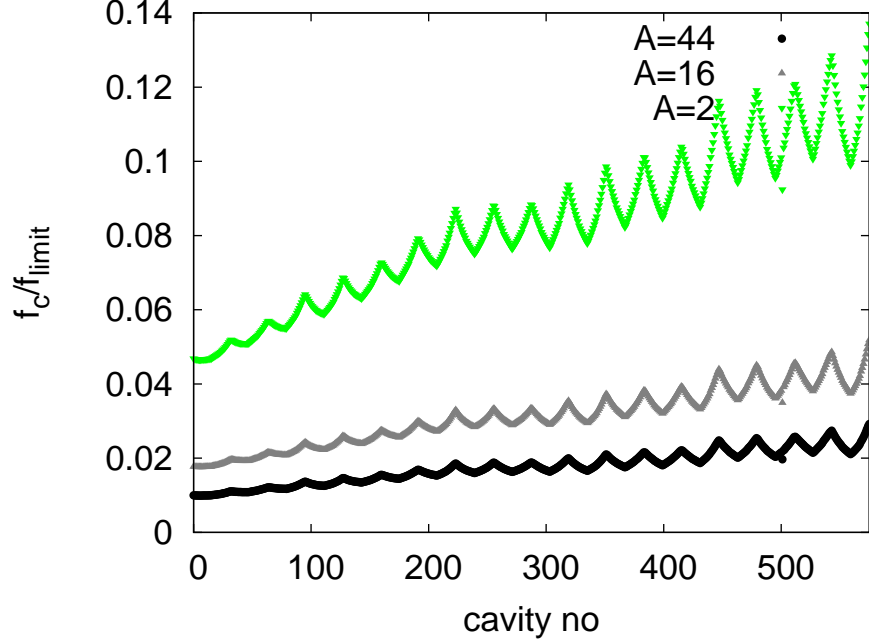


Figure 8.39: The oscillation frequency f_c of ions of different mass number A in the linacs using the average focusing strength of the bunches at different energy. The frequency is normalised to the limit frequency f_{limit} above which the ions would not be trapped any more.

6681 find methods to remove the ions. We will first quickly describe the mitigation techniques and then give a
 6682 rough estimate of the expected ion effect.

6683 A number of techniques can be used to reduce the fast beam-ion instability:

- 6684 • An excellent vacuum quality will slow down the build-up of a significant ion density.
- 6685 • Clearing gaps can be incorporated in the electron beam. During these gaps the ions can drift away
 6686 from the beam orbit.
- 6687 • Clearing electrodes can be used to extract the ions. They would apply a bias voltage that lets the ions
 6688 slowly drift out of the beam.

6689 **Clearing Gaps** In order to provide the gap for ion cleaning, the beam has to consist at injection of short
 6690 trains of bunches with duration τ_{beam} separated by gaps τ_{gap} . If each turn of the beam in the machine takes
 6691 τ_{cycle} , the beam parameters have to be adjusted such that $n(\tau_{beam} + \tau_{gap}) = \tau_{cycle}$. In this case the gaps of
 6692 the different turns fall into the same location of the machine. This scheme will avoid beam loading during
 6693 the gap and ensure that the gaps are fully empty. By choosing the time for one round trip in the electron
 6694 machine to be an integer fraction of the LHC roundtrip time $\tau_{LHC} = m\tau_{cycle}$, one ensures that each bunch
 6695 in the LHC will either always collide with an electron bunch or never. We chose to use $\tau_{cycle} = 1/3\tau_{LHC}$
 6696 and to use a single gap with $\tau_{gap} = 1/3\tau_{cycle} \approx 10 \mu\text{s}$.

6697 In order to evaluate the impact of a clearing gap in the beam, we model the beam as a thick focusing lens
 6698 and the gap as a drift. The treatment follows [675], except that we use a thick lens approach and correct a
 6699 factor two in the force. The focusing strength of the lens can be calculated as

$$k = \frac{2Nr_em_e}{A_{ion}m_p\sigma_y(\sigma_x + \sigma_y)\Delta L} \quad (8.15)$$

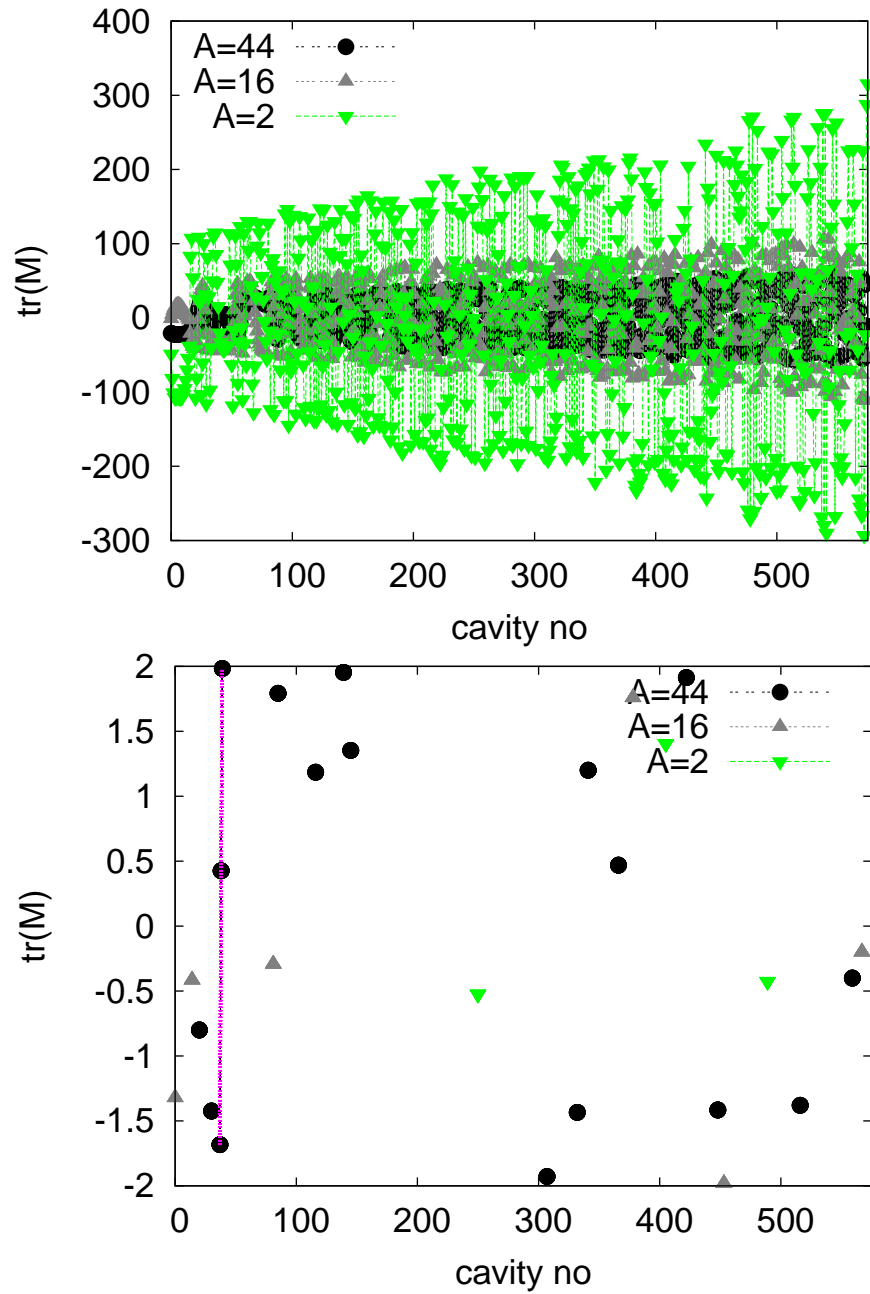


Figure 8.40: The trace of the transfer matrix for H_2^+ , CH_4^+ and CO_2^+ ions in presence of a clearing gap. Values above 2 or below -2 indicate that the ions will not be trapped.

6700 The ions will not be collected if the following equation is fulfilled

$$\left| 2 \cos(\sqrt{k}(L_{erl} - L_g)) - \sqrt{k}L_g \sin(\sqrt{k}(L_{erl} - L_g)) \right| \geq 2 \quad (8.16)$$

6701 Since the beam size will vary as a function of the number of turns that the beam has performed, we replace
6702 the above defined k with the average value over the six turns using the average bunch spacing ΔL ,

$$k = \frac{1}{n} \sum_{i=1}^n \frac{2Nr_e m_e}{A_{ion} m_p \sigma_{y,i} (\sigma_{x,i} + \sigma_{y,i}) \Delta L}. \quad (8.17)$$

6703 The results of the calculation can be found in Fig. 8.40. As can be seen, in most locations the ions are not
6704 trapped. But small regions exist where ions will accumulate. More study is needed to understand which ion
6705 density is reached in these areas. Longitudinal motion of the ions will slowly move them into other regions
6706 where they are no longer trapped.

6707 **Ion Instability** While the gap ensures that ions will be lost in the long run, they will still be trapped
6708 at least during the full train length of $20\mu s$. We therefore evaluate the impact of ions on the beam during
6709 this time. This optimistically ignores that ions will not be completely removed from one turn to the next.
6710 However, the stability criteria we employ will be pessimistic. Clearly detailed simulations will be needed in
6711 the future to improve the predictive power of the estimates.

6712 Different theoretical models exist for the rise time of a beam instability in the presence of ions. A
6713 pessimistic estimate is used in the following. The typical rise time of the beam-ion instability for the n th
6714 bunch can be estimated to be [674]

$$\tau_c = \frac{\sqrt{27}}{4} \left(\frac{\sigma_y(\sigma_x + \sigma_y)}{Nr_e} \right)^{\frac{3}{2}} \sqrt{\frac{A_{ion} m_p}{m} \frac{kT}{p\sigma_{ion}} \frac{\gamma}{\beta_y c n^2 \sqrt{L_{sep}}}} \quad (8.18)$$

6715 This estimate does not take into account that the ion frequency varies with transverse position within the
6716 bunch and along the beam line.

6717 We calculate the local instability rise length $c\tau_c$ for a pressure of $p = 10^{-11}$ hPa at the position of the
6718 beam. As can be seen in Fig. 8.41 this instability rise length ranges from a few kilometers to several hundred.
6719 One can estimate the overall rise time of the ion instability by averaging over the local ion instability rates:

$$\left\langle \frac{1}{\tau_c} \right\rangle = \frac{\int \frac{1}{\tau_c(s)} ds}{\int ds} \quad (8.19)$$

6720 For the worst case in the figure, i.e. CH_4^+ , one finds $c\tau_c \approx 14$ km and for H_2^+ $c\tau_c \approx 25$ km. The beam
6721 will travel a total of 12 km during the six passes through each of the two linacs. So the typical time scale
6722 of the rise of the instability is longer than the life time of the beam and we expect no issue. This estimate
6723 is conservative since it does not take into account that ion frequency varies within the beam and along the
6724 machine. Both effects will stabilise the beam. Hence we conclude that a partial pressure below 10^{-11} hPa is
6725 required for the LHeC linacs.

6726 In the cold part of LEP a vacuum level of 0.5×10^{-9} hPa has been measured at room temperature, which
6727 corresponds to 0.6×10^{-10} hPa in the cold [676]. This is higher than required but this value “represents
6728 more the outgassing of warm adjacent parts of the vacuum system” [676] and can be considered a pessimistic
6729 upper limit. Measurements in the cold at HERA showed vacuum levels of 10^{-11} hPa [677], which would be
6730 sufficient but potentially marginal. Recent measurements at LHC show a hydrogen pressure of 5×10^{-12} hPa
6731 measured at room temperature, which corresponds to about 5×10^{-13} hPa in the cold [678]. For all other
6732 gasses a pressure of less than 10^{-13} hPa is expected measured in the warm [678], corresponding to 10^{-14} hPa
6733 in the cold. These levels are significantly better than the requirements. The shortest instability rise length
6734 would be due to hydrogen. With a length of $c\tau_c \approx 500$ km which is longer than 40 turns. Hence we do not

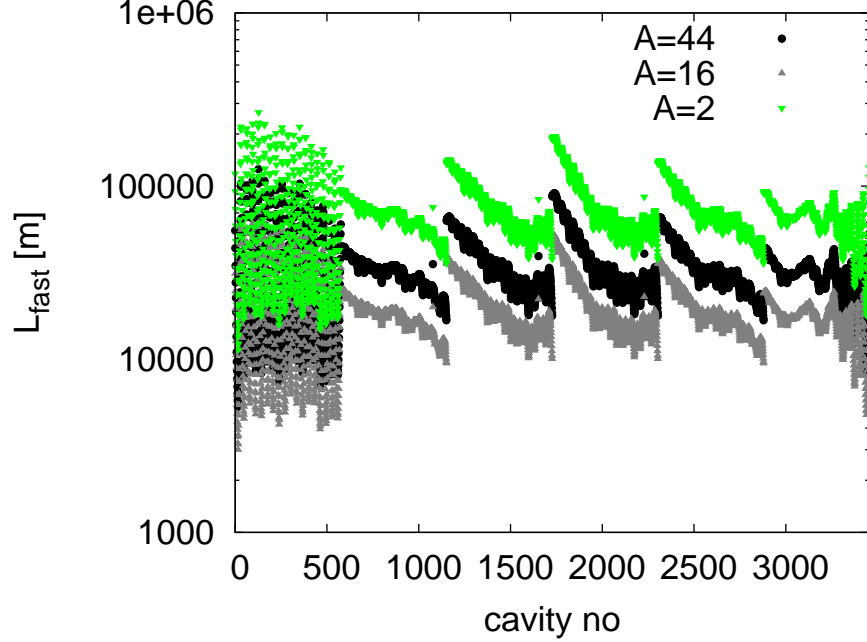


Figure 8.41: The instability length of the beam-ion instability assuming a very conservative partial pressure of 10^{-11} hPa for each gas.

6735 expect a problem with the fast beam-ion instability in the linacs provided the vacuum system is designed
 6736 accordingly.

6737 The effect of the fast beam-ion instability in the arcs has been calculated in a similar way, taking into
 6738 account the reduced beam current and the baseline lattice for each arc. Even H_2^+ will be trapped in the
 6739 arcs. We calculate the instability rise length $c\tau_c$ for a partial pressure of 10^{-9} hPa for each ion mass and find
 6740 $c\tau_c \approx 70$ km for H_2^+ , $c\tau_c \approx 50$ km for N_2^+ and CO^+ and $c\tau_c \approx 60$ km for CO_2^+ . The total distance the beam
 6741 travels in the arcs is 15km. Hence we conclude that a partial pressure below 10^{-9} hPa should be sufficient
 6742 for the arcs. More detailed work will be needed in the future to fully assess the ion effects in LHeC but we
 6743 remain confident that they can be handled.

Ion Induced Phase Advance Error The relative phase advance error along a beam line can be calculated
 using [675] for a round beam:

$$\frac{\Delta\phi}{\phi} = \frac{1}{2} \frac{Nr_e}{\Delta L \epsilon_y} \frac{\theta}{\langle \beta_y^{-1} \rangle}$$

6744 Here θ is the neutralisation of the beam by the ions. We use the maximum beta-function in the linac to
 6745 make a conservative approximation $\langle \beta_y^{-1} \rangle = 1/700$ m. At the end of the train we find $\rho \approx 3.3 \times 10^{-5}$ for
 6746 $p = 10^{-11}$ hPa in the cold and $p = 10^{-9}$ hPa in the warm parts of the machine. This yields $\Delta\Phi/\Phi \approx 7 \times 10^{-4}$.
 6747 Hence the phase advance error can be neglected.

6748 **Impact of the Gap on Beam Loading** It should be noted that the gaps may create some beam-loading
 6749 variation in the injector complex. We can estimate the associated gradient variation assuming that the same
 6750 cavities and gradients are used in the injector as in the linacs. We use

$$\frac{\Delta G}{G} \approx \frac{1}{2} \frac{R}{Q} \omega \frac{\tau_{gap} \tau_{beam} I}{\tau_{gap} + \tau_{beam}} \frac{1}{G} \quad (8.20)$$

6751 In this case the $10\mu\text{s}$ gaps in the bunch train correspond to a gradient variation of about 0.6%. This seems
 6752 very acceptable.

6753 8.3.4 Imperfections

6754 Static imperfections can lead to emittance growth in the LHeC linacs and arcs. However, one can afford an
 6755 emittance budget that is significantly larger than the one for the ILC, i.e. $10\mu\text{m}$ vs. 20nm . If the LHeC
 6756 components are aligned with the accuracy of the ILC components, one would not expect emittance growth
 6757 to be a serious issue. In particular in the linacs dispersion free steering can be used and should be very
 6758 effective, since the energies of the different probe beams are much larger than they would be in ILC.

6759 Gradient Jitter and Cavity Tilt

Since the cavities have tilts with respect to the beam line axis, dynamic variations of the gradient will lead to transverse beam deflections. This effect can be easily calculated using the following expression:

$$\frac{\langle y^2 \rangle}{\sigma_y^2} = \frac{\langle (y')^2 \rangle}{\sigma_{y'}^2} = \frac{1}{2} \frac{1}{\epsilon} \int \frac{\beta}{E} ds \frac{L_{cav} \langle \Delta G^2 \rangle \langle (y'_{cav})^2 \rangle}{mc^2}$$

For an RMS cavity tilt of $300\mu\text{radian}$, an RMS gradient jitter of 1% and an emittance of $50\mu\text{m}$ we find

$$\frac{\langle y^2 \rangle}{\sigma_y^2} = \frac{\langle (y')^2 \rangle}{\sigma_{y'}^2} \approx 0.0125$$

6760 i.e. an RMS beam jitter of $\approx 0.07\sigma_y$. At the interaction point the beam jitter would be $\approx 0.05\sigma_{y'}$.

6761 8.4 Performance as a Linac-Ring electron-ion collider

6762 The performance as an e-A collider can be evaluated on a basis similar to the Ring-Ring version of the LHeC
 6763 discussed in Section 7.6. Again, this relies on the fact that the nominal emittances for Pb beams in the LHC
 6764 imply equal geometric beam sizes, at the IP in particular.

6765 8.4.1 Heavy nuclei, e-Pb collisions

6766 The Pb beam is specified in Table 7.32. Assuming that the 60 GeV electron beam specified in Table 8.5 can
 6767 be adapted to the irregular 100 ns spacing of the Pb beam, the luminosity follows from Eq. 8.1 (including
 6768 the additional factor of $A = 208$ to obtain the electron-nucleon luminosity):

$$L_{eN} = \begin{cases} 9 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1} & \text{(Nominal Pb)} \\ 1.6 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1} & \text{(Ultimate Pb)} \end{cases} \quad (8.21)$$

6769 where we assume $H_{hg} = H_D = 1$ for the additional factors in Eq. 8.1.

6770 8.4.2 Electron-deuteron collisions

6771 An estimate of the parameters for deuteron beams in the LHC is also given in Section 7.6. Proceeding in the
 6772 same manner as above, we find that *electron-nucleon* luminosities of order $L_{eN} \gtrsim 3 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1}$ could
 6773 be accessible in e-D collisions in a Linac-Ring LHeC.

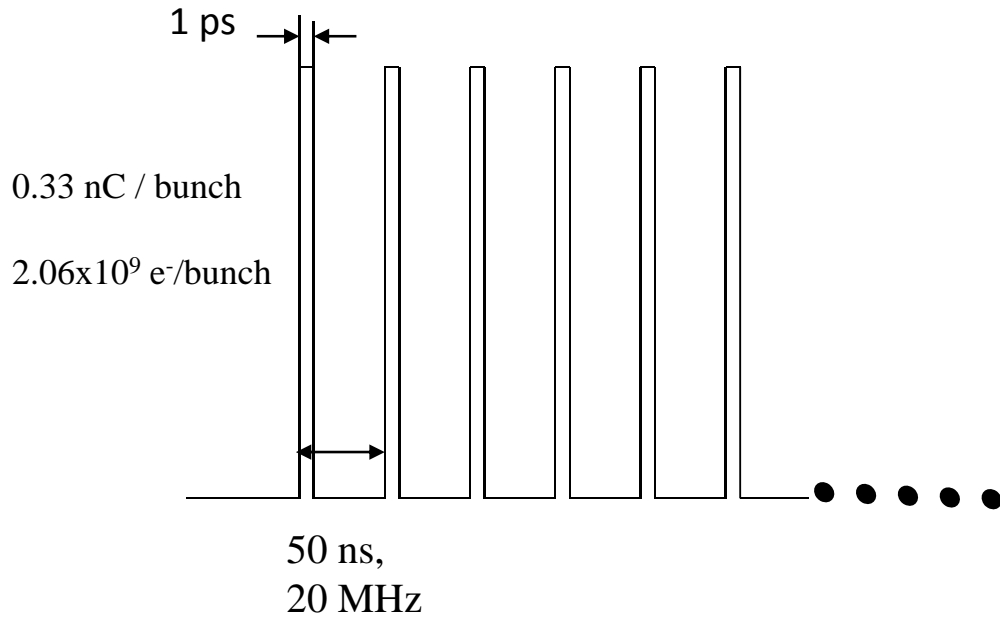


Figure 8.42: Beam pattern at IP

8.5 Polarized-Electron Injector for the Linac-Ring LHeC

We present the injector for the polarized electron beam. The issue of producing a sufficient number of polarized or unpolarized positrons is discussed in section 8.7.

The Linac-Ring option is based on an ERL machine where the beam pattern, at IP, is shown in Figure 8.42.

With this bunch spacing, one needs 20×10^9 bunches/second and with the requested bunch charge, the average beam current is 20×10^9 b/s \times 0.33 nC/b = 6.6 mA.

Figure 8.43 shows a possible layout for the injector complex, as source of polarized electron beam.

The injector is composed of a DC gun where a photocathode is illuminated by a laser beam. Then a linac accelerates electron beam up to the requested energy before injection into the ERL. Downstream a bunch compressor system allows to compress the beam to 1 ps and finally a spin rotator, brings the spin in the vertical plane.

Assuming 90% of transport efficiency between the source and the IP, the bunch charge at the photocathode should 2.2×10^9 e⁻/b. According to the laser and photocathode performance, the laser pulse width, corresponding to the electron bunch length, will be between 10 and 100 ps.

Table 8.15 summarises the electron beam parameters at the exit of the DC gun.

The challenges to produce the 7 mA beam current are the following:

- a very good vacuum ($< 10^{-12}$ mbar) is required in order to get a good lifetime.
- the issues related to the space charge limit and the surface charge limit should be considered. A peak current of 10 A with 4 ns pulse length has been demonstrated. Assuming a similar value for the DC gun, a laser pulse length of 35 ps would be sufficient to produce the requested LHeC charge.
- the high voltage (100 kV to 500 kV) of the DC gun could induce important field emissions.
- the design of the cathode/anode geometry is crucial for a beam transport close to 100%.
- the quantum efficiency should be as high as possible for the photocathode ($\sim 1\%$ or more).

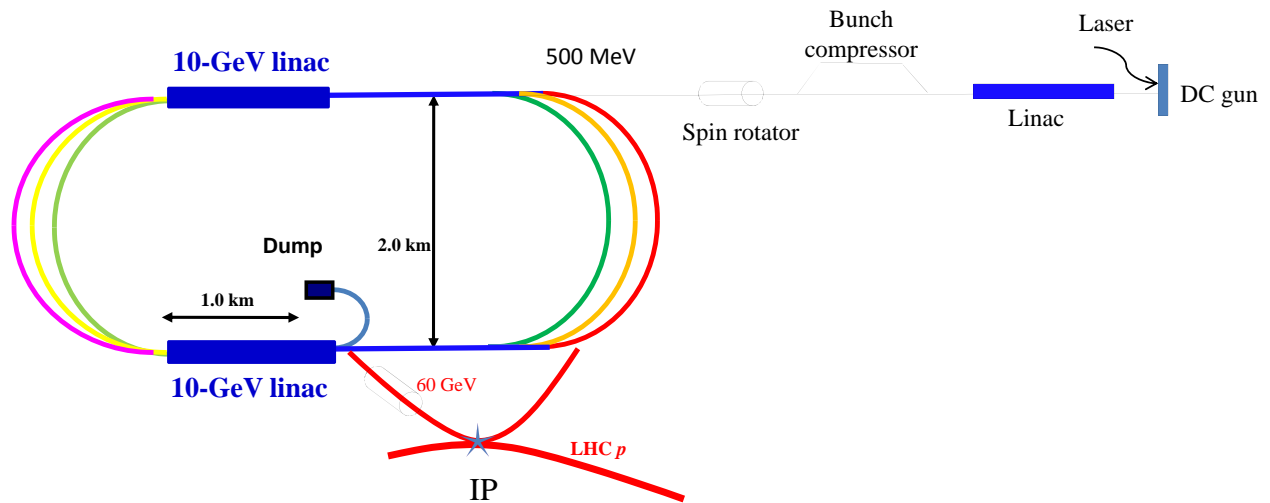


Figure 8.43: Layout of the injector (not to scale).

Parameters	60 GeV ERL
Electrons /bunch	2.2×10^9
Charge /bunch	0.35 nC
Number bunches / s	20×10^9
Bunch length	10 – 100 ps
Bunch spacing	50 ns
Pulse repetition rate	CW
Average current	7 mA
Peak current of the bunch	3.5 – 350 A
Current density (1 cm)	1.1 – 110 A/cm ²
Polarization	> 90%

Table 8.15: Beam parameters at the source.

- 6798 • the laser parameters (300 nJ/pulse on the photocathode, 20 MHz repetition rate) will need some R&D
6799 according to what is existing today on the market.
- 6800 • the space charge could increase the transverse beam emittances.

6801 In conclusion, a tradeoff between the photocathode, the gun and the laser seems reachable to get accept-
6802 able parameters at the gun exit. A classical Pre-Injector Linac accelerates electron beam to the requested
6803 ERL energy. Different stages of bunch compressor are used to compensate the initial laser pulse and the
6804 space charge effects inducing bunch lengthening. A classical spin rotator system rotates the spin before
6805 injection into the ERL.

6806 8.6 Spin Rotator

6807 The LHeC physics requires polarized electrons with spin aligned longitudinally at the collision point [679].
6808 In the electron accelerator of LHeC, consisting of two 10-GeV superconducting linear accelerators linked

6809 with six 180° arc paths, the depolarization due to the arcs is negligible if the spin is aligned vertically in the
 6810 arcs.

6811 The motion of the spin vector \vec{S} is governed by Thomas-BMT equation [680] shown in Eq. 8.22

$$\frac{d\vec{S}}{dt} = \frac{e}{m\gamma} \vec{S} \times [(1 + G\gamma)\vec{B}_\perp + (1 + G)\vec{B}_\parallel] \quad (8.22)$$

6812 where e , m and γ are the electric charge, mass and Lorentz factor of the particle. G is the anomalous
 6813 g-factor. For protons, $G = 1.7928474$ and for electrons, $G = 0.00115$. \vec{B}_\perp and \vec{B}_\parallel are the magnetic field
 6814 perpendicular and parallel to the particle velocity direction, respectively. In Eq. 8.22, magnetic field is in the
 6815 laboratory frame while the spin vector \vec{S} is in the particle's rest frame. In a bending dipole, a spin vector
 6816 precesses $G\gamma$ times of the particle's orbital rotation in the particle's moving frame. It is also evident that
 6817 solenoid field is less effective to manipulate spin motion at high energies.

6818 For the LHeC physics program, the polarization of 60 GeV electron beam needs to be aligned longitu-
 6819 dinally at the collision point which is after the last arc and the acceleration. The most economical way to
 6820 control the spin direction at the collision point is to control the spin direction of the low energy electron
 6821 beam at the early stage of injector using a Wien Filter, a traditional low energy spin rotator. Since spin
 6822 vector rotates $G\gamma\pi$ each time it passes through a 180° arc, the goal of the Wien Filter is to put the spin
 6823 vector in the horizontal plane with an angle to the direction of the particle's velocity to compensate the
 6824 amount of spin rotations before collision.

6825 For the layout of LHeC, i.e. two linear accelerators linked with two arcs, spin vector rotates

$$\phi_{arc} = G\pi[\gamma_i(2n - 1) + \Delta\gamma n(2n - 1)] \quad (8.23)$$

6826 after its n th path. Here, γ_i is the initial Lorentz factor of the beam and $\Delta\gamma$ is the energy gain of each linear
 6827 accelerator. In addition, LHeC also employs two horizontal bending dipoles on either side of the collision
 6828 point to separate the electrons from the protons. Each of this bending dipole is 0.3 T and spans 9 m from
 6829 the collision point. For 60 GeV electron beam, it rotates the spin vector by $\phi_{IP} = 104.4^\circ$. For initial
 6830 energy of 10 GeV and each linear accelerator energy gain of 10 GeV, Table 8.16 lists the amount of spin
 6831 rotation through the arcs and the amount of spin rotation through the final bending dipole at the collision
 point for 20 GeV, 40 GeV and 60 GeV beam, respectively. Here, the amount of spin rotation is the net

beam energy [GeV]	# of path n	ϕ_{arc} [degrees]	ϕ_{IP} [degrees]
20	1	8101.8	34.8
40	2	36457.9	69.6
60	3	81017.6	104.4

Table 8.16: total spin rotation from arcs and final bending dipole at collision point

6832 spin rotations in the range of 2π . Since the spin rotation is proportional to beam energy, for a beam of
 6833 particles with non-zero momentum spread, different amount of spin rotation then generates a spread of spin
 6834 vector directions. This results in an effective polarization loss due to the spread of the spin vector. Fig. 8.44
 6835 shows the angle spread of the spin vector for an off-momentum particle at 20GeV, 40GeV and 60GeV. The
 6836 calculation assumes the initial energy before the electron beam enters the arc is 10 GeV and energy gain of
 6837 each linear accelerator is 10 GeV. It shows that for 60 GeV electron beam, a momentum spread of 3×10^{-4}
 6838 can cause about 10% polarization loss effectively due to the spread of the spin vectors. This may not be able
 6839 to satisfy the requirement on high polarization.
 6840

6841 In order to provide the desirable polarization direction without sacrificing polarization, one can take the
 6842 traditional approach of high energy polarized beams at HERA and RHIC, i.e. to rotate the spin vector
 6843 to vertical direction before it gets accelerated to high energy. Since the spin vector aligns with the main
 6844 bending magnetic fields' direction, this prevents the spread of the spin vector due to the momentum spread.

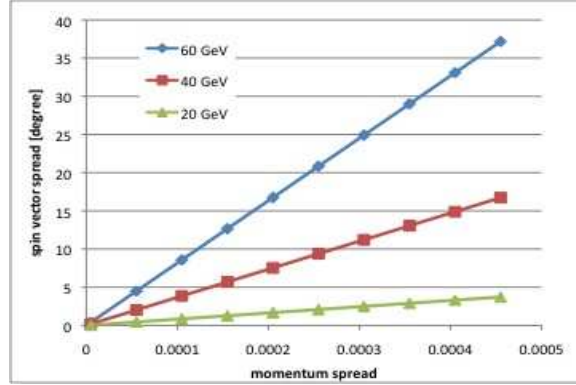


Figure 8.44: Calculated spin vector spread as function of momentum spread. The effective polarization loss is the cosine of spin vector spread angle, i.e. for an angle of 30 degrees, the effective polarization is 86% of initial beam polarization

6845 After the last arc and acceleration, at 60 GeV beam energy, the spin vector must be rotated back so as
 6846 to be longitudinally aligned at the collision point. To this end, for the current compact LHeC design, we
 6847 propose to use a RHIC type spin rotator [681, 682] at the LHeC. Besides saving space of being compact,
 6848 this approach also provides the advantage of independent control of the spin vector orientation, as well as
 6849 nearly energy independent spin rotation for the same magnetic field. The four helical dipoles are arranged
 6850 in a similar fashion as the RHIC spin rotator, i.e. with alternating helicity. Fig. 8.45 shows the schematic
 6851 layout. Each helical dipole is 3.3 m long and the helicity alternates between right hand to left hand between
 6852 each helical dipole. The two inner helical dipoles have the same magnetic field but opposite helicity. Same
 applies to the two outer helical dipoles.

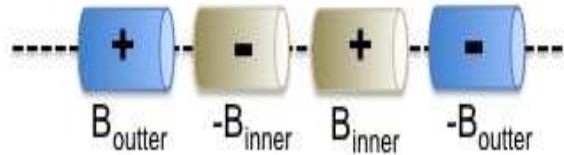


Figure 8.45: Schematic layout of LHeC spin rotator. A total of four helical dipoles with alternating helicity marked as + and -. The polarity of two outer helical dipole fields are also opposite. And so is the polarity of the two inner helical dipoles.

6853 For each helical dipole, the magnetic field is given by
 6854

$$B_x = B \cos kz; B_y = B \sin kz; B_z = 0.0 \quad (8.24)$$

6855 where, B_x, y, z are the horizontal, vertical and longitudinal component of the magnetic field, respectively. Z
 6856 is the longitudinal distance along the helical dipole axis. $|k| = \frac{2\pi}{\lambda}$ and λ are wave number and wave length
 6857 of the helical field, respectively.

6858 For spin roator, all helical dipoles are chosen to be one period, i.e. $\lambda = L$, where L is the length of each
 6859 helical dipole. Depending on the direction of the helicity, $\frac{k}{|k|} = \pm 1$. Fig. 8.46 shows the correlation of the
 6860 magnetic field for the inner and outer helical magnets of a spin rotator which brings the spin vector from
 6861 vertical direction to be in the horizontal plane. Fig. 8.47 shows the calculated angle of the spin vector for

each outer helical magnet field. Both plots show that this design provides a flexible choice of the direction of spin vector by adjusting the outer and inner helical magnetic fields respectively.

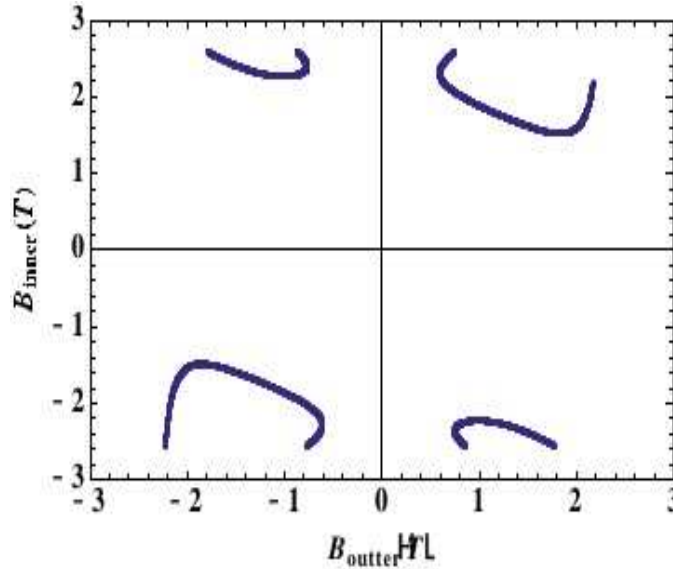


Figure 8.46: correlation of the outer and inner helical dipole magnetic field strength for a spin rotator which is designed to bring a vertically aligned spin vector to the horizontal plane.

This rotator will be placed in the straight section of between LINAC and final focusing section (FFS). This is upstream of the final bending dipole at the collision point as well as three bends right upstream of the triplet. The 0.3 T final bending dipole rotates spin vector by 104.4 degrees for 60 GeV electron beam, while the other three bends rotates spin vector by -1.8 degrees. In order to bring the spin vector of polarized electron along longitudinal direction, it requires that spin rotator to put the spin vector from vertical direction to the horizontal plane with an angle of 102.6 degrees away from longitudinal direction. This requirement then yields the magnetic field of the inner pair and outer pair to be 1.92 T and 0.93 T, respectively. The maximum orbital excursion is 17 mm in horizontal and 8.5mm in vertical. The fine tuning of the direction of spin vector can be achieved by empirically adjusting the helical dipole magnetic field strength based on the measurements of the polarimeters before and after the collision point.

Detailed calculations including helical dipole design, orbital and spin tracking of spin rotator are in working progress.

8.7 Positron Options for the Linac-Ring LHeC

8.7.1 Motivation

It is known that the generation of an intense positron beam with a linac configuration is a particular challenge. This raises the question as to how crucial the availability of positron-proton scattering to the LHeC is. Reasons for the importance of e^+p scattering are given in the physics chapters and have been summarized in an introduction to a topical meeting [683] in May 2011 at CERN, the technical results of which are summarized below. For the physics program, the following topics may serve as important example processes which require very high statistics positron (and electron) data:

- If there exist so far unknown resonant states of leptons and partons, quarks or/and gluons, the asymmetry between the e^+p and e^-p cross sections determines the fermion number of the produced leptoquark

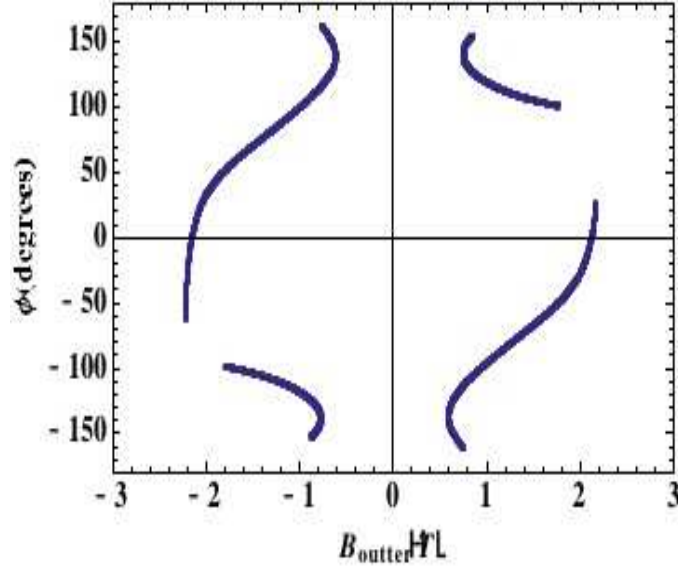


Figure 8.47: spin vector direction in the horizontal plane as function of outer helical magnet field strength

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to be $F = 2$, as for an $e_L u$ state of charge $-1/3$, or $F = 0$ for an $e_L \bar{u}$ state of charge $-5/3$.

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- If there appears a new contact interaction, its nature may be disentangled by considering its charge dependence. If there was an excited electron observed, one surely would like to check whether the positron has the same structure.

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- It has been a long standing question whether the strange quark and anti-quark distributions are different, for which neutrino-nucleon data provide certain hints. With electron and positron charged current data, this can be resolved and both s and \bar{s} can be measured. Similarly one will be able to measure single top and single anti-top quark distributions for the first time.

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- Access to valence quarks at low x is possible with the precision measurement of the $x F_3^{\gamma Z}$ structure function, which can be accessed only with high statistics NC cross section asymmetry data.

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- High statistics beam charge asymmetry data are essential to access generalized parton distributions at low Q^2

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An example for the importance of e^+p scattering with high but perhaps not maximum luminosity is the precision measurement of the longitudinal structure function F_L , in which the charge symmetric background at low scattered electron energies has to be experimentally determined and subtracted in order to safely reach the region of highest sensitivity to F_L . One would finally like to note that if the positron-proton luminosity was significantly lower than the electron-proton luminosity, there would always be a tendency to preferentially run with electrons in order to collect a maximum integrated luminosity for those processes and topics which are less or not dependent on the availability of both beam charge configurations. Examples here are the precision measurement in polarized e^-p scattering of the weak mixing angle, the physics at low x or the precision measurement of α_s . It is the physics beyond the standard model, and the searches for it, which has the highest demands on the e^+p luminosity. One concludes that the physics demands for the availability of intense e^+p scattering are very strong. A further aspect regards the importance of positron beam polarization which may deserve further consideration.

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6910 8.7.2 LHeC Linac-Ring e^+ Requirements

6911 Table 8.17 compares the e^+ beam flux foreseen for LHeC with those obtained at the SLC, and targeted for
6912 CLIC and the ILC.

	SLC	CLIC (3 TeV)	ILC (500 GeV)	LHeC (p= 140)	LHeC (ERL)
Energy (GeV)	1.19	2.86	4	140	60
e^+ /bunch at IP ($\times 10^9$)	40	3.72	20	1.6	2
Norm. emittance (mm.mrad)	30 (H) 2 (V)	0.66 (H) 0.02 (V)	10 (H) 0.04 (V)	100	50
Longit. rms emittance (eV-m)	7000	5000	60000	10000	5000
e^+ /bunch after capture ($\times 10^9$)	50	7.6	30	1.8	2.2
Bunches / macropulse	1	312	2625	10^5	NA
Macropulse repetition rate	120	50	5	10	CW
Bunches / second	120	15600	13125	10^6	20×10^6
e^+ / second ($\times 10^{14}$)	0.06	1.1	3.9	18	440

Table 8.17: Comparison of the e^+ flux.

6913 The SLC (Stanford Linear Collider) was the only linear-collider type machine which has produced e^+ for
6914 a high-energy particle physics experiment. The flux for the CLIC project (a factor 20 compared to SLC)
6915 is already considered challenging and possible options with hybrid targets are under investigation on paper.
6916 Even more positrons would be required for the ILC. The requested LHeC flux for pulsed operation at 140
6917 GeV (a factor 300 compared to SLC) could be obtained, in a first approximation, with 10 e^+ target stations
6918 working in parallel. Several more advanced solutions are proposed to meet the requested LHeC flux for the
6919 CW option (a factor 7300 compared to SLC).

6920 8.7.3 Mitigation Schemes

6921 Two main approaches can be considered to reduce the rate of positrons that needs to be produced at the
6922 source, namely

- 6923 • Recycling the positrons after the collision, with implied considerations on e^+ emittance after collision,
6924 emittance growth in the 60-GeV return arc due to synchrotron radiation, and the possible introduction
6925 of a cooling scheme, e.g. laser cooling à la Telnov at lower beam energy, introducing a tri-ring recovery
6926 scheme with fast laser cooling in central ring. (see below), or a using a large damping ring. If 90% of
6927 the positrons are recycled the requirement for the source drops by an order of magnitude.
- 6928 • Repeated collisions on multiple turns, e.g. using a (pulsed) 180-degree phase-shift chicane in order to
6929 recover 60 GeV in the second return arc after the collision.

6930 Reuse and Cooling of Positrons

6931 One of the most challenging problems associated with the continuous production of positrons is cooling
6932 (damping) of the positron beam emerging from a source or recycled after the collision. The cooling process
6933 in a storage ring requires many synchrotron and betatron oscillation periods as well as the emission of many
6934 photons. The direct connection of the ERL's output and input aiming at a reuse of the positron beam does
6935 not solve the problem of beam cooling, since the electron suffers from noticeable disruption.

6936 Beam cooling, that is at least an e-fold reduction of energy spread and transverse emittances, usually
6937 requires at least thousand turns of beam in a damping ring. The employment of a novel idea of fast

cooling [684] may reduce this period, down to 200...500 turns. Even further reduction of the cooling period might be attained by designing a damping ring with multiple, S , superperiods, each of which of the double chicane scheme (to provide about $S/2$ synchrotron oscillations per full turn). In this latter case, the number of turns needed for cooling would be reduced by another factor of S .

The next section presents considerations on the pushed performance of a conventional damping ring, and it estimates the damping that could be obtained in a ring with the size of the SPS. An elegant complementary or alternative solution to relax the damping requirements — the tri-ring scheme — is described in the following section.

Damping-Ring Considerations

The main parameter driving the circumference choice of a positron damping ring for the LHeC complex is the train length (for the pulsed option) and the structure. For 10^5 bunches with separation of 25 ns the damping ring has to be unreasonably long (around 750 km). The bunch train has thus to be compressed in the damping ring and uncompressed by extracting individual bunches every 25 ns using a fast extraction kicker or RF deflector. The minimum bunch spacing in the ring is determined by the fastest achievable rise time of the extraction systems. A fast kicker can probably pulse with rise/fall times of around 2.5 ns and an RF deflector may be reduced even further (0.5 ns). Both systems have to present a stability of the order of a few 10^{-4} . Given the larger emittance the kicker stability requirement may be relaxed compared with the damping rings of CLIC and ILC. Considering a 2.5-ns bunch spacing, the ring circumference can be reduced by a factor of 10 but remains still very large. A further order-of-magnitude reduction can be obtained by considering either ten times less bunches (with correspondingly higher charge) or an order of magnitude increase of the repetition rate, i.e. 100 Hz instead of 10 Hz. Indeed, with a 100-Hz repetition rate, the ring becomes 7.5 km, which is very close to the circumference of the SPS of $C = 2200\pi = 6911.5$ m.

In this respect, a parameter set can be deduced by taking as base a damping ring in the SPS tunnel ⁴, where a train of 9221 bunches with 2.5 ns can fit. The high repetition rate option demands that the bunches are damped and then extracted within 10 ms. Considering that at least 5 damping times are needed to reach equilibrium, the transverse damping time should be less than 2 ms. This number is assumed in the following. We note, however, that a damping time of 10 or 20 ms, with much relaxed constraints on the ring, may already be sufficient for recycling spent positrons and recovering their original emittance.

The transverse damping time is given by

$$\tau_{x,y} = \frac{2EC}{cJ_{x,y}U} , \quad (8.25)$$

with E the energy, $J_{x,y} \approx 1$ the damping partition numbers, c the speed of light and U the energy loss per turn:

$$U = \frac{C_\gamma E^4}{\rho} (1 + F_w) , \quad (8.26)$$

with $\rho = E/(eB)$ the bending radius and F_w the wiggler damping factor:

$$F_w = \frac{L_w B_w^2}{4\pi B^2 \rho} , \quad (8.27)$$

with L_w and B_w the wiggler length and field respectively. The transverse damping time can be rewritten as

$$\tau = \frac{8\pi C}{ceC_\gamma E(eB_w^2 L_w + 4\pi B E)} , \quad (8.28)$$

connecting it directly with the ring energy and radiating magnet characteristics. Considering a maximum bending field of 1.8 T and wiggler field of 1.9 T, there is a parametric interdependence between beam energy,

⁴A damping ring in the SPS tunnel has already been considered as early as 1988 by L. Evans and R. Schmidt, in CLIC Note 58, although their parameter set has been far away from present LHeC and CLIC requirements.

6973 the total wiggler length and the damping time. Figure 8.48 shows the dependence of the damping ring
 6974 energy on the total wiggler length for a damping time of 2 ms (red curve). Without wigglers, the ring has
 6975 to run at 22 GeV, whereas for around 10 GeV, wigglers with a total length of 800 m are needed. The blue
 6976 curve represents the same dependence when the low repetition rate is considered which indeed increases the
 6977 damping time by an order of magnitude. In that case, the ring energy without any wigglers can be reduced
 6978 to 7 GeV and it can be dropped to less than 4 GeV for a total wiggler length of 200 m.

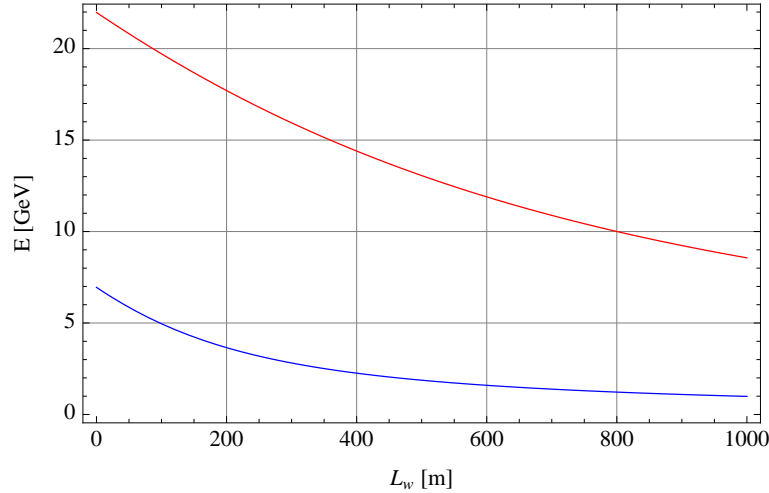


Figure 8.48: Dependence of the damping ring energy on the total wiggler length for a transverse damping time of 2 ms (red curve) and 20 ms (blue curve).

6979 A tentative parameter list for the low and high repetition rate option can be found in table 8.18. This
 6980 example considers for both cases, 234 bending magnets of 0.5m-long dipoles with 1.8T bending field. The
 6981 wiggler field of 1.9 T and a period of 5 cm is within the reach of modern hybrid wiggler technology. A big
 6982 challenge is the longitudinal parameters driven from the high energy loss per-turn, especially in the high
 6983 repetition rate case, where around 300 MV of total RF voltage is needed to restore the high-energy loss/turn.
 6984 In addition, the bunch has to be kept short (around 5 mm) in order to achieve the longitudinal emittance
 6985 target of 10 keV-m, which necessitates a quasi-isochronous ring, with momentum compaction factor, close
 6986 to 10^{-6} . This may be a challenge for lattice design as low momentum compaction factors are achieved for
 6987 strong focusing conditions, which increase chromaticity, and necessitate strong sextupoles with detrimental
 6988 effects for the dynamic aperture of the ring. The average beam power of 25 MW indicates that the wall-plug
 6989 power would be quite high and may necessitate the use of super-conducting RF system to increase efficiency.
 6990 In the low repetition case, the RF voltage and power are an order of magnitude more relaxed.

6991 Tri-Ring Scheme

6992 A possible solution to cool down a continuous positron beam, both the recycled beam and/or a new beam
 6993 from a source, is the tri-ring scheme illustrated in Fig. 8.49.

6994 The operation cycle of the system is as follows:

- 6995 • The basic cycle lasts N turns
 - 6996 – N -turn injection from ERL into the accumulating ring (bottom)
 - 6997 – N -turn cooling in the cooling ring (middle); fast laser cooling may be employed here
 - 6998 – N -turn slow extraction from the extracting ring (top) into the ERL
- 6999 • One-turn transfer from the cooling ring into the extracting ring
- 7000 • One-turn transfer from the accumulating ring into the cooling ring

7001 The average current in the cooling ring is $N \times$ average ERL current. The number of turns of the main cycle
 7002 is limited by the efficiency of multi-turn injection and the maximum current which can be stored (and cooled)
 7003 in the cooling ring.

7004 Laser cooling may generate a new low-emittance positron beam to compensate for losses and emittance
 7005 growth of the recycled beam.

7006 Reusing and/or cooling of positrons relaxes the requirements for all types of positron sources discussed in
 7007 the following. The cooling period is limited by the maximal stored current in the ring and by the multi-turn
 7008 injection. Fast laser cooling may be employed for compensating positron emittance growth when reusing
 7009 positrons or to compensate losses (without a dedicated high-current positron source). A slow extraction
 7010 process would be capable of further reducing the energy spread (chromatic extraction) or, alternatively, the
 7011 transverse emittance (using resonant extraction).

7012 8.7.4 Positron Production Schemes

7013 Positrons can be produced by pair creation when high-energy electrons or photons hit a target. Conventional
 7014 sources, as used at the SLC, send a high-energy electron beam on a conversion target. Alternatively, a high-
 7015 energy electron beam can first be used to create high-energy photons, which are then sent onto a target.
 7016 The prior conversion into photons reduces the heat load of the target for a given output intensity and it may
 7017 also improve the emittance of the generated positrons.

7018 There exist a number of schemes that can accomplish the conversion of electrons into photons. Several
 7019 of them employ Compton scattering off a high-power laser pulse stacked in an optical cavity. According to
 7020 the electron-beam accelerator employed, one distinguishes Compton rings, Compton linacs, and Compton
 7021 ERLs. An alternative scheme uses the photons emitted by an electron beam of very high energy (of order

Parameter [unit]	High Rep-rate	Low Rep-rate
Energy [GeV]	10	7
Bunch population [10^9]	1.6	1.6
Bunch spacing [ns]	2.5	2.5
Number of bunches/train	9221	9221
Repetition rate [Hz]	100	10
Damping times trans./long. [ms]	2/1	20/10
Energy loss/turn [MeV]	230	16
Horizontal norm. emittance [μm]	20	100
Optics detuning factor	80	80
Dipole field [T]	1.8	1.8
Dipole length [m]	0.5	0.5
Wiggler field [T]	1.9	-
Wiggler period [cm]	5	-
Total wiggler length [m]	800	-
Dipole length [m]	0.5	0.5
Longitudinal norm. emittances [keV.m]	10	10
Momentum compaction factor	10^{-6}	10^{-6}
RF voltage [MV]	300	35
rms energy spread [%]	0.20	0.17
rms bunch length [mm]	5.2	8.8
average power [MW]	23.6	3.6

Table 8.18: CLIC versus NLC parameters driving the DRs design.

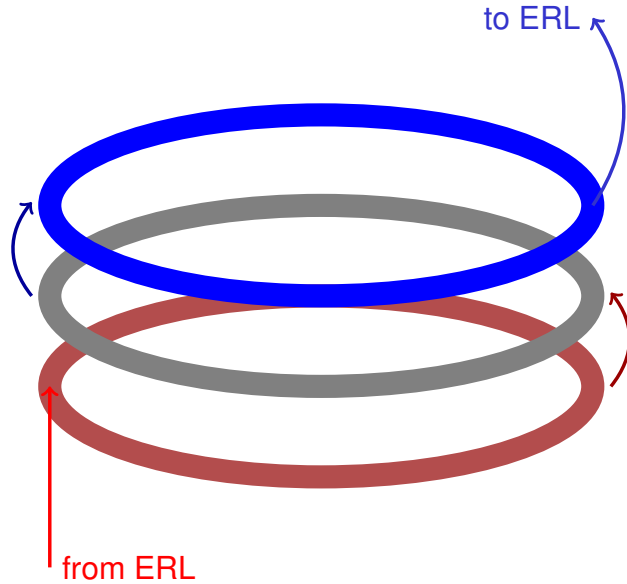


Figure 8.49: Tri-ring scheme

7022 100 GeV) when passing through a short-period undulator.

7023 Finally, there even exists a simpler scheme where a high-power laser pulse itself serves as the target for
 7024 (coherent) pair creation.

7025 Applications of the various possible schemes to the LHeC are discussed in the following sections.

7026 8.7.5 Targets

7027 For the positron flux considered for the LHeC the heating and possible destruction of the target are important
 7028 concerns. Different target schemes and types can address these challenges:

- 7029 • Multiple targets operating in parallel (Section 8.7.6).
- 7030 • He-cooled granular W-sphere targets (Section 8.7.6).
- 7031 • Rotating-wheel targets (Section 8.7.6).
- 7032 • Sliced-rod W tungsten conversion targets (Section 8.7.7);
- 7033 • Liquid mercury targets (Section 8.7.7).
- 7034 • Running tape with annealing process (Section 8.7.7).

7035 8.7.6 Conventional Scheme based on e^- Beam Hitting Target

7036 The LHeC ERL option requires a positron current of 6 mA or $4 \times 10^{16} e^+/s$, with normalized emittance of
 7037 $\leq 50 \mu\text{m}$ and longitudinal emittance $\leq 5 \text{ MeV}\cdot\text{mm}$.

7038 For a conversion target with optimized length the power of the primary beam is converted as follows
 7039 $P_{\text{primary}}(100\%) = P_{\text{thermal}}(30\%) + P_{\gamma}(50\%) + P_{e^-}(12\%) + P_{e^+}(8\%)$. The average kinetic energy of the
 7040 newly generated positrons is $\langle T_{e^+} \rangle \approx 5 \text{ MeV}$, which allows estimating the total power incident on the
 7041 target as $P_{\text{target}} = 5 \text{ MV} \times 6 \text{ mA} / 0.08 = 375 \text{ kW}$. Assuming an electron linac efficiency of $\eta_{\text{acc}} \approx 20\%$ we
 7042 find $P_{\text{wall}} = P_{\text{target}}/0.2 = 1.9 \text{ MW}$. This wall-plug power level looks feasible and affordable.

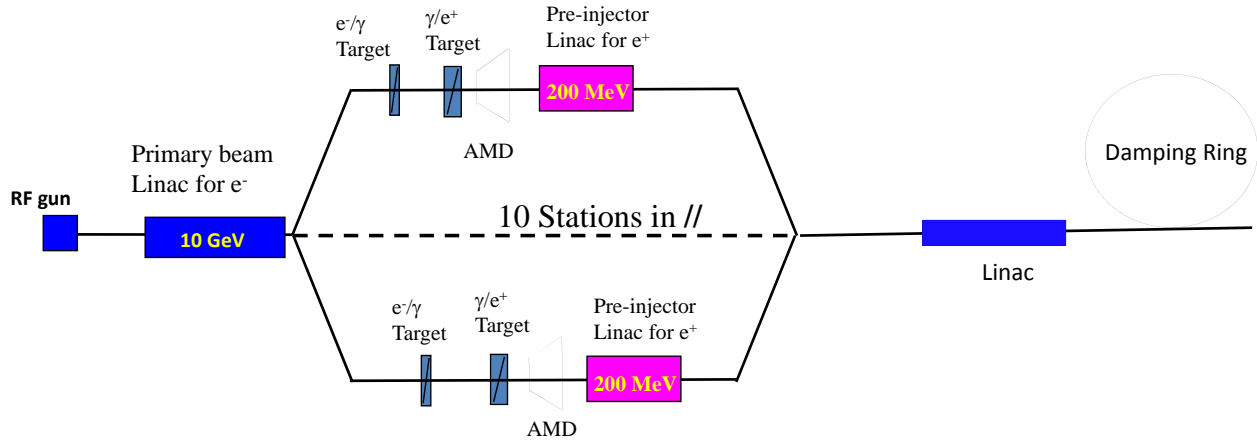


Figure 8.50: Possible layout with unpolarised e^+ for the LHeC injector (p-140 GeV).

7043 Figure 8.50 illustrates a possible option, which alone would already meet the requirements for the 140-
 7044 GeV single-linac case, where the repetition rate is 10 Hz. The idea is to use 10 e^+ target stations in
 7045 parallel. This implies installing 2 RF deflectors upstream and the same downstream. Experience exists for
 7046 RF deflectors at 3 GHz and with operating 2 lines in parallel. Assuming that this configuration is acceptable
 7047 from the beam-optics point-of-view, it would be necessary to implement a fast damping scheme because the
 7048 bare emittances from the target will be too high for the injection into the ERL.

7049 Table 8.19 shows the beam characteristics at the end of the 10 GeV Primary beam Linac for electrons,
 7050 before splitting the beam.

Primary beam energy (e^-)	10 GeV
Number e^- / bunch	1.2×10^9
Number of bunches / pulse	100000
Number e^- / pulse	1.2×10^{14}
Pulse length	5 ms
Beam power	1900 kW
Bunch length	1 ps

Table 8.19: Electron beam parameters before splitting.

7051 Table 8.20 shows the beam parameters at each e^+ target. Energy of 5.6 kW is deposited in each target
 7052 and the Peak Energy Deposition Density (PEDD) is around 30 J/g. This value has been chosen, in order
 7053 to be below the breakdown limit for tungsten (W) target. It is based on recent simulations [685] with
 7054 conventional W targets. A new study has been done [686], assuming a target made out of an assembly of
 7055 densely packed W spheres (density about 75% of solid tungsten) with diameters of 1–2 mm. The cooling is
 7056 provided by blowing He-gas through the voids between the spheres. Such He-cooled granular targets have
 7057 been considered for neutrino factories and recently for the European Spallation Source ESSS.

7058 To achieve the required cooling and the corresponding mass flow of the cooling fluid, we consider pres-
 7059 surized He at 10 bar entering the target volume at a velocity of 10 m/s, i.e. a mass flow 1.8 g/s is required
 7060 for each target. From this a convection coefficient of about $\alpha = 1 \text{ W/cm}^2/\text{K}$ can be expected and a cooling
 7061 time constant τ (exponential decay time after an adiabatic temperature rise of a sphere) of 185 ms will
 7062 result. Clearly, not much cooling during a pulse of 5 ms duration will occur, but cooling will set in during
 7063 the off-beam time of 95 ms between the pulses. The peak temperature after each pulse will stabilize at about

Yield (e^+/e^-)	1.5
Beam power (for e^-)	190 kW
Deposited power / target	5.6 kW
PEDD	30 J/g
Number e^+ / bunch	1.8×10^9
Number bunches / pulse	10,000
Number e^+ / pulse	1.8×10^{13}

Table 8.20: Beam parameters at each e^+ target.

500 K above that of the cooling fluid. An average exit temperature of the He-gas of about 600 °C will have still to be added, which drives the maximum temperature of the spheres up to about 1100 °C. Although compatible with W in an inert atmosphere, it should be attempted to reach lower temperatures. This could be achieved by increasing the He-pressure to 20 bar and the velocity of He to 20 m/s which might reduce the maximum temperature in a sphere to 500 °C. Thus, a He-cooled granular 10-W-target system could be a viable solution.

Another approach has been considered. To achieve, as in the previous case, a reduction of the energy deposition density by a factor of 10, a fast rotating wheel could be designed. The beam pulse of 5 ms duration is spread over the rim of the rotating wheel and a linear velocity of the rotating rim of 20 m/s would be required. This would lead to a repetition rate of about 1000 rpm, assuming a wheel diameter of 0.4 m. Such a solution is actually under investigation for the ILC with a rotation speed of 1800 rpm.

Here tungsten spheres, again, are contained in a structure, similar to a care tyre, as is illustrated in Fig. 8.51. The container is possibly made of light Ti-alloy where the sides, facing the beam entrance and exit should be made of Beryllium, compatible with the beam heating. The helium for the cooling is injected from the rotating axle through spokes into the actual target ring and is recuperated in the same way.

If the beam pulse duration is extended by a factor 10, i.e. 50 ms duration, maintaining of course the same average power, then the rotation time could be reduced. The velocity of the wheel is such that over the duration of 5 ms the rim is displaced by one beam width, i.e. 1 cm. This leads to much reduced rotation speeds of 2 m/s, which can readily be achieved in a wheel with a diameter of 16 cm, rotating at 240 rpm.

By choosing appropriately the rotation velocity, the average time between two hits of the same spot on the rim of the wheel, is about 0.5 s. With the aforementioned cooling time constant for the He-circuit of 185 ms, the adiabatic temperature rise during one hit over 5 ms of 211 K will have dropped close to zero before the next hit. Since we assume to simultaneously cool the whole rim of the wheel, a He-flow of 90 g/s must be provided. Taking into account the temperature increase in the cooling fluid, a maximum tungsten temperature in the W-spheres of about 350°C can be expected, which is rather comfortable.

Using a continuous D.C.-beam with no gaps will further alleviate the structure and performance of the target wheel.

The interference of the rotating wheel with the downstream flux concentrator will have to be assessed. One may, however, expect considerably less forces than presently considered for the ILC, due to the much lower velocity of the wheel. Moreover, proper choice of materials with high electrical resistivity and laminating the structure may be considered.

Clearly, the W-granules must be contained inside the beam vacuum within a structure which is He-leak tight at the selected He-pressure. As material for the upstream and downstream beam windows, Beryllium must be considered which, due to its large radiation length (34 cm as compared to W with 0.34 cm), should resist to the thermal loads. This, however, has to be verified.

Also, radiation damage and life time issues will still have to be assessed.

It is believed that rotating “Air to Vacuum” seals at 240 rpm are commercially available or can be adapted to the radiation environment. Rotating “High Pressure He to Air” seals may have to be developed, where small He-leaks can be tolerated.

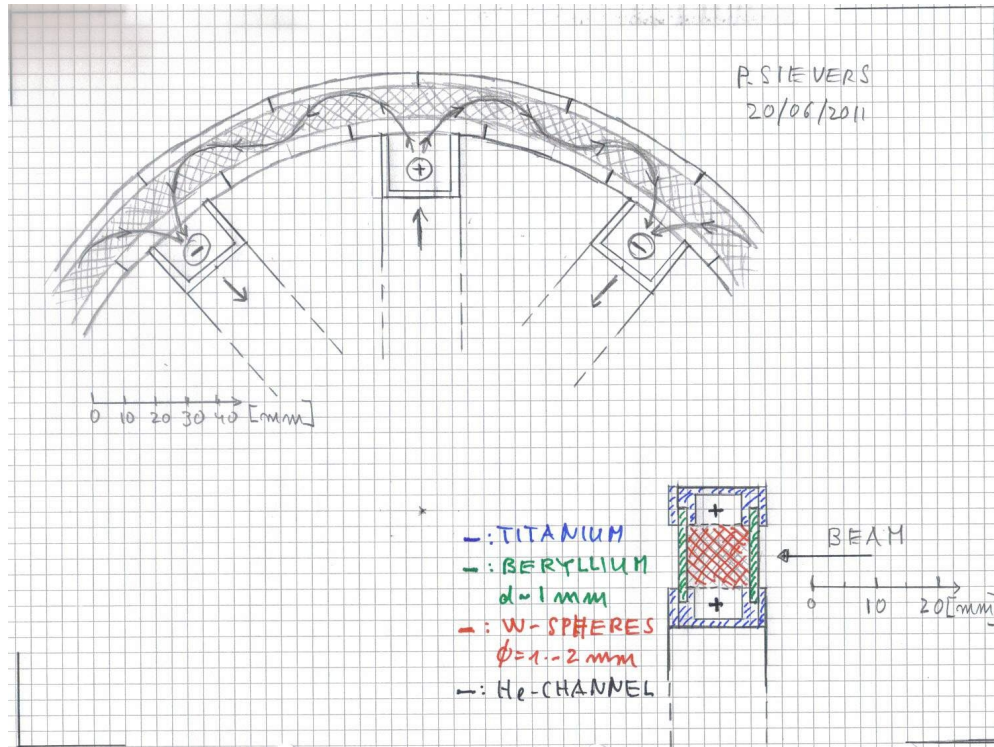


Figure 8.51: Artist's view of rotating wheel containing W spheres with He cooling.

7103 This last approach is focused on e^+ targets. Presently with conventional targets, the transverse normal-
 7104 ized rms beam emittances, in both planes, are in the range of 6000 to 10 000 mm.mrad. With the new type
 7105 of target, we do not know yet by how much the transverse emittances will be changed. In any case, a strong
 7106 reduction of emittances is mandatory for the requested LHeC performance.

7107 Assuming that large or small emittances could be recombined, Table 8.21 shows a possible e^+ flux after
 7108 recombination.

7109 Finally, if a solution is found for the emittances, it will be necessary to design and implement a linac
 7110 accelerating the positron beam up to 500 MeV, the energy for the ERL injection.

Secondary beam energy (e^+)	200 MeV
Number e^+ bunch	1.8×10^9
Number of bunches / pulse	100000
Number of e^+ / pulse	1.8×10^{14}
Bunch spacing	50 ns
Repetition rate	10 Hz

Table 8.21: Positron beam parameters after recombination.

7111 8.7.7 Compton Sources

7112 In Compton sources, (polarized) positrons are produced as a result of the following processes:

- 7113 1. Electron beam (current I_{e^-}) scatters off polarized laser photons (energy in pulse W).

	unit	SLC	CLIC (3TeV)	LHeC p-140	LHeC ERL
I_{e+} at IP	μA	0.96	18	290	7050
typical I_{e-}	A	1.4E-2	0.26	4.3	105.7
I_{e-} with 5 J	A	1.5E-3	2.8E-2	0.46	11.2
I_{e-} with 5 J+1 m rod	A	2.2E-4	4.0E-3	6.5E-2	1.6

Table 8.22: IP positron current and the implied minimum electron beam current in a Compton Ring

7114 2. Gamma flux, $\sim I_{e-} \times W$, is first collimated and then impinging on a conversion target.

7115 3. Produced positrons lose a fraction of energy while traversing the target.

7116 4. Postselection: low-energy positrons are discarded to attain the required polarization.

7117 Three principal factors limit the performance of polarized positron sources based on Compton scattering.
7118 They are:

7119 1. Limited average current of electrons scattering off laser photons (world record $I_{e-} = 5 \text{ A}$ – PEP ring).

7120 2. Limited energy of pulses stored in optical resonators (fast progress, an array of resonators may be
7121 employed, 1...5 J assumed maximal accepted: higher energy of pulses violates electron dynamics).

7122 3. Limited power density of gammas, to which the conversion target is tolerable (sliced-rod convertor
7123 reduces positron losses and increases the current).

7124 The polarization degree of positrons is determined by the cut-off energy of positrons exiting from the target:
7125 the higher the polarization required the higher the energy threshold for discarding low-energy positrons (and
7126 the lower the yield). The optimal target thickness that maximizes the yield also decreases with the increase
7127 of the polarization requested, along with a decrease in the yield of positrons (but with an improved quality
7128 of the positron beam: a smaller energy spread, and a smaller transverse emittance).

7129 For a CLIC source of polarized positrons [687] (1 GeV electron energy, $1 \mu\text{m}$ YAG laser system, and,
7130 correspondingly, 20 MeV maximal energy of the Compton spectrum) “envelopes” describing the limiting
7131 number of positrons from the conversion target per scattered gamma and the associated polarization are
7132 presented in Fig. 8.52.

7133 Compton Ring

7134 A typical Compton-ring gamma source (the CLIC ring) with the parameters listed in [687], and modified
7135 to accommodate an entire array of optical resonators, namely 10 units with 50 mJ of laser energy stored in
7136 each, installed in the dispersive section, is capable of producing 0.01 gammas per electron-turn. This scheme
7137 can be enhanced by increasing the laser energy by a factor of 10, up to 5 J, and by halving the collision
7138 angle, to 4 degrees, which increases the yield by an order of magnitude, up to 0.1 gammas per electron-turn.

7139 A typical tungsten convertor optimized for Compton gammas with a maximal energy of 20 MeV can
7140 deliver 0.01 positrons with 60% polarization per incident scattered gamma. The converter can be enhanced
7141 as well: a sliced-rod convertor target produces 0.07/0.13 positrons per gamma for a 1 m or 3 m long rod,
7142 respectively [688].

7143 Including a 50% overhead, for either the standard scheme and with the two types of enhancements,
7144 various projects require the minimal circulating currents in Compton rings listed in Table 8.22.

7145 Table 8.22 illustrates that a Compton-ring source equipped with an array of optical resonators yielding a
7146 total laser-pulse energy of 5 Joule, together with a sliced-rod conversion target, will produce the desired flux
7147 of polarized positrons even for the LHeC ERL option.

7148 In conclusion, according to the present understanding and simulations, a Compton positron source
7149 may produce sufficient average positron beam current for all LHeC options. The conversion of gammas to

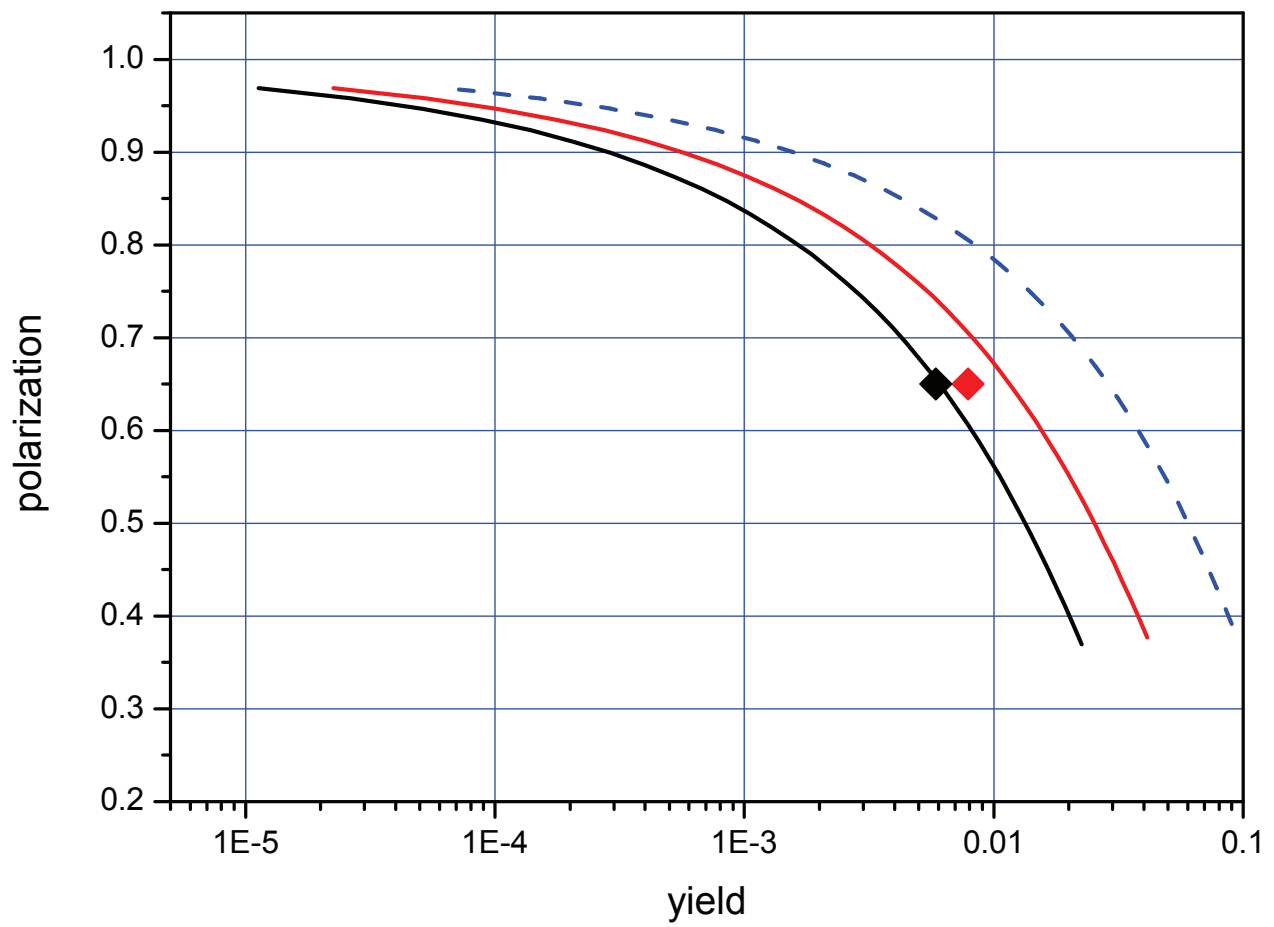


Figure 8.52: Limits for Ti (black) and W (red) conversion targets. Diamonds: simulations (A.Schalicke, S.Riemann). Blue Dashed curve: a sliced-rod conversion target.

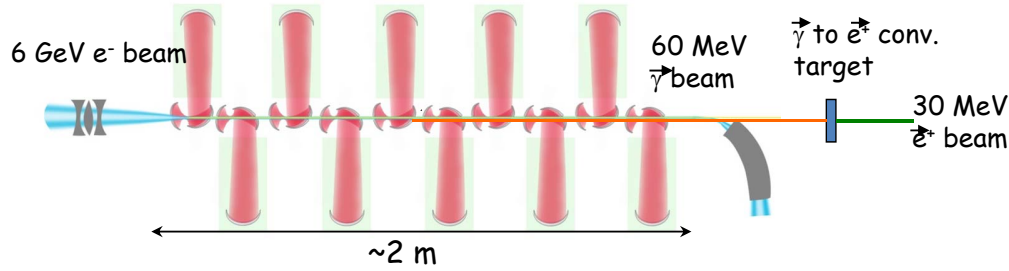


Figure 8.53: Layout based on Compton Linac.

7150 positrons is a bottleneck, which requires a study and optimization of effective converter targets such as the
 7151 sliced-rod converter.

7152 Compton Linac

7153 Positrons, even polarized, can be generated by the Compton scattering process of high-power laser pulses
 7154 stacked in optical cavities with a high-energy electron beam from a linac. Figure 8.53 present a possible
 7155 layout for such configuration.

7156 At BNL, a ratio photon/electron close to 1 has been demonstrated. Assuming that a ratio pho-
 7157 ton/positron close to 2% is achievable, then 50 photons are required to produce 1 e^+ . For LHeC, one
 7158 needs 0.35 nC/bunch (for the e^+ to be produced). Based on above estimations, it implies ~ 18 nC/bunch
 7159 (for the e^- beam). Then with 10 optical cavities, the requested e^- charge is about 1.8 nC / bunch which is
 7160 a reasonable value.

7161 Power Analysis for Compton Schemes and Compton ERL

7162 A number of pertinent technologies have been investigated, but are not yet established:

- 7163 1. 1.3 Ampere ERL (R&D at BNL)
- 7164 2. Mercury target or annealing target (Muon collider collaboration)
- 7165 3. High finesse optical stacking cavities with factor 1000 enhancement, 1 kW pump (France, KEK, ...)

7166 This section considers different Compton-based options for an LHeC positron source including power con-
 7167 siderations. The following source requirements were taken into account:

- 7168 • 6mA average current or 4×10^{16} e^+ /sec.
- 7169 • 2×10^7 bunches with 2×10^9 e^+ /bunch.
- 7170 • Normalized rms emittance of 50 microns.
- 7171 • Longitudinal emittance 5 MeV-mm or 10 mm normalized.

7172 The **power analysis** for the different schemes can be done backwards:

- 7173 1. Power of the captured positron beam.
- 7174 2. \rightarrow Power of the gamma beam entering the conversion target and generating electron positron pairs.
- 7175 3. \rightarrow Electron drive beam generating the gamma beam.
- 7176 4. \rightarrow Klystron accelerating the electron drive beam.

7177

5. → Wall plug power.

7178

Scattering of the multi MeV gammas on the target produces the electrons and positrons. The optimal gamma beam energy range of 30-60 MeV is selected as a compromise between conversion efficiency and capture efficiency as well as longitudinal emittance. Beam power of the captured positron beam is estimated at 6 mA × 30 MeV or 180 kW.

7182

The conversion efficiency of gamma beam into captured positrons ranges from 0.3 to 2% for different schemes of the ILC positron source. This (optimistically) sets a requirement for the gamma beam entering the target at 9 MW. A 2–6 GeV electron beam is used in different schemes to generate a gamma beam by Compton scattering of the powerful laser beam. The efficiency of electron beam power conversion is at most 10%, for the scheme with a CO2 laser. This puts a lower limit on the drive beam power at 90 MW. A CLIC type driver can optimistically generate the drive beam at approximately 50 percent efficiency and, therefore, an overall power requirement to generate a 6 mA positron beam with pulsed linac (CLIC type) and the CO2 laser can be estimated at 180 MW.

7190

To summarize:

7191

• 6 mA × 30 MeV → 180 kW e⁺ beam (Output of conversion target).

7192

• γ → e⁺ efficiency about 2% → 9 MW γ beam (conversion efficiency).

7193

• e⁻ → γ about 10%, 90 MW e⁻ beam

7194

• Wall → e⁻ about 50% or 180 MW wall power.

7195

The wall plug power for the electron beam alone exceeds the limit of 100 MW set for the entire project. On the other hand, the energy spread of the circulating beam would be prohibitive in a Compton ring scheme subjected to the requirement to generate 9 MW from a 30-MeV gamma beam. Both issues can be handled by exploring the energy recovery linac option. A 3-GeV 1.3-Ampere ERL with 2 micron laser enhancement cavities has the potential of generating the required positron beam with only 50 MW of wall plug power, as follows:

7200

7201

• 6 mA x 30MeV → 180kW e+ beam (Output of conversion target).

7202

• γ → e⁺ about 1% → 18 MW γ beam (Conversion efficiency).

7203

• e⁻ → γ about 0.5% 4 GW e⁻ beam (99.9% efficient ERL).

7204

• Wall → e⁻ about 50% of 0.001×4 GW + 18 MW.

7205

• Total ≈50 MW wall power.

7206

The major challenge of a pulsed linac scheme is in the cost of driving the linac. A high wall power requirement combined with long pulse format make the CO2 laser/pulse linac combination an unlikely solution. The challenge of the ERL scheme lies in the development of the recirculating cavities and target/capture system that would be able to perform the CW mode of operation.

7210

Emittances: The upper estimate on the transverse and longitudinal emittances in the case of 2 GeV ERL for the captured positron beams can be estimated as follows:

7211

7212

• Normalized positron beam emittance, expressed through its energy, RMS beam size and angular divergence at the target exit: $\epsilon_N \approx \gamma_{e^+} \sigma \sigma'$.

7213

• Acquired angular spread in the length target (typically selected at 0.4 radiation length) can be estimated as

$$\sigma_{e^+} \approx \frac{1}{\sqrt{2}} \frac{14\text{MeV}}{E_{e^+}} \sqrt{\frac{L_{target}}{X_0}} \approx \frac{10}{\gamma_{e^+}} .$$

7214

• Three components contribute to the beam size:

1. Scattering in the target:

$$\sigma_{e^+,sc} \approx \frac{\sqrt{2}}{3} \sigma'_{e^+} L_{\text{target}} \approx \frac{\sqrt{2}}{3} 0.3 \cdot 1.2 \text{ mm} \approx 150 \text{ } \mu\text{m} .$$

2. Beam size due to gamma beam divergence:

$$\sigma_{\gamma,div} \approx \frac{1}{2\gamma_{e^-}} \frac{L_{IR}}{\sqrt{2}} \approx \frac{1}{2 \times 4000} \frac{0.1 \text{ m}}{\sqrt{2}} \approx 15 \text{ } \mu\text{m} .$$

3. and e- beam size on target:

$$\sigma_{\gamma e^-} \approx \sqrt{\frac{\epsilon_{Ne^-}}{\gamma_{e^-}} \beta_{e^-}} \approx \sqrt{\frac{10 \text{ } \mu\text{m}}{4000}} 1 \text{ m} \approx 50 \text{ } \mu\text{m} .$$

This results in the normalized transverse emittance of 1.5 mm. The strong magnetic field in which the target would likely be immersed will lower this estimate. The estimate for the longitudinal emittance is:

$$\epsilon_{||,N} \approx \Delta\gamma_{e^+} \sigma_{\tau e^-} \approx \frac{60 - 30}{4} 60 \text{ } \mu\text{m} \approx 450 \text{ } \mu\text{m} .$$

7215 **Compton-ERL Target:** Charged particle beams exiting the conversion target generate most of the
 7216 heat. The deposited power can be estimated (roughly) as $6 \text{ mA} \times 5 \text{ MeV} \times 2 \times 2$, or 120 kW. 5 MeV is
 7217 estimated for the energy loss and factors of 2 are attributed to equal parts of captured and non-captured low
 7218 energy positrons, and to the equal number of electrons and positrons. This suggests that a liquid mercury
 7219 target may be an important candidate.

7220 **Compton ERL Summary:** High current ERL seems the most promising approach, e.g. a 3-GeV 1.3-A
 7221 ERL with 2-micron wavelength optical enhancement cavities.

7222 Target is going to be a very difficult consideration (candidates would be a liquid mercury target or running
 7223 tape with annealing process). The desired emittances are not reached from any Compton scheme source,
 7224 even if the target is immersed in a strong magnetic field. Therefore, cooling or scraping would be required.

7225 Laser Pulses and Optical Cavities

7226 Different experimental programs presently underway aim at achieving a very important photon pulse intensity
 7227 by direct production in a laser system and stacking in a passive optical resonator. This laser-stacking scheme
 7228 allows increasing the available average power in the optical cavity without requiring impossible performances
 7229 to the drive laser system. As far as Compton-source developments are concerned, depending on the purpose
 7230 of the application, the stored pulse length ranges from a few hundreds of femtoseconds to a few picoseconds,
 7231 the repetition frequency (which determines the cavity length) from 20 to 200 MHz, and the wavelength from
 7232 0.5 to 1.1 μm .

7233 When trying to achieve storing a very high power in a Fabry-Perot optical resonator the state of the
 7234 art of the present technology has to be taken into account. As far as the laser is concerned, in the last
 7235 years an impressive increase in the available average power has been provided by the development of the
 7236 fiber amplifiers. The best performances have been obtained by combining the development of large core
 7237 single mode photonic crystal fibers with the chirped-pulse amplification (CPA) technique. For example, a
 7238 200-fs, 1048-nm wavelength, 78-MHz oscillator pulse after a first stretching to 800 ps, has been amplified
 7239 in a system composed of a two-stage double-clad photonic crystal fiber preamplifier (30 μm mode field and
 7240 170 μm pump cladding diameter) pumped at 976-nm wavelength, and a main-amplifier double-clad water
 7241 cooled fibre (27- μm mode field and 500 μm air clad). After this phase a recompression of the pulse to 640
 7242 fs has yielded an “incredible” average power of 830 W and about 10 μJ per puls [689].

7243 To stack many short laser pulses in a Fabry Perot resonator, and obtain an important pulse enhancement,
 7244 it is necessary to lock the cavity characteristic comb with the laser one. This implies to act on two degrees
 7245 of freedom given by the repetition frequency and by the carrier to phase envelope (Φ_{ce}). In this context the

Pound Driver Hall locking techniques is employed in the LAL cavity [690]. This technique has attained the best performances in gain, as far as pulses of few ps are concerned. A gain of about 10000 was achieved, storing a laser pulse of close to 20 kW in a confocal two mirror cavity. However, the best result, as far as the stored power is concerned, has been achieved by the MPQ laboratory using the Hansch-Couillaud locking technique [691]. With a pulse length of 200 fs an average power of 18 kW was obtained in a 78-MHz tie bow cavity with an enhancement factor of 1800. After this achievement, thermal problems were noticed due to the very high-power density of the pulse. Stretching the pulse to 2 ps the stacking process was efficient up to 72 kW with an estimated gain of 1400. In the cavity waist this corresponded to a 10^{14} W/cm² power density. At this power level the coupling between the laser power and the cavity was near 50%.

In the framework of the Compton facilities another important experimental effort is carried out jointly by LAL Orsay (France) and KEK Tsukuba (Japan) [692]. In fact, to validate the use of optical passive cavities, different tests have to be performed also taking into account the reliability and the compatibility of a given optical cavity with the accelerator environment. A 176 MHz, a four-mirror vacuum-compatible optical cavity has been designed, realized and installed in the KEK-ATF ring. A four-mirror configuration was chosen instead of a two-mirror one, because with the former it is possible to achieve very small laser-waists without losing in mechanical stability. An estimated stored power of 2 kW has been achieved during the commissioning of the system at the end of 2010. A future program to explore the 100kW range is envisaged. At the ATF beam energy, Compton collision will produce gamma rays near 20 MeV resulting in the world's first beam-driven gamma factory.

8.7.8 Undulator Source

Another positron production option would be an undulator process, based on the main high-energy electron (or positron) beam. The LHeC undulator scheme can benefit from the pertinent development work done for the ILC. The beam energy at LHeC would be lower, e.g. 60 GeV, which might possibly be compensated by more ambitious undulator magnets, e.g. ones based on Nb₃Sn or HTS. However, the requested photon flux calls for a careful investigation. The undulator parameters needed for 60 GeV, the expected positron production rate, and technical feasibility all require further study.

8.7.9 Source based on Coherent Pair Creation

The normalized transverse emittance of all positrons from a target is of order $\epsilon_N \approx 1 - 10$ mm, to be compared with a requested emittance of $\epsilon_N = 0.05$ mm. Therefore, a factor 100 emittance reduction is required.

Solution 1 would be to simply cut the phase space. However, this would give rise to an unrealistic increase of the primary beam power.

Solution 2 would be to collect all positrons, accelerate them to 1 GeV and damp them for $\text{Log}(100) \sim 5$ damping times, with an implied RF power of $P_{RF} = 1 \text{ GeV} \times 5 \text{ mA} \times 5/0.6 = 60 \text{ MW}$, where an RF efficiency of 50% was assumed.

Solution 3 would be to produce positrons in a smaller phase space volume. Indeed the inherent transverse emittance from pair production is small. The large phase space volume only comes from multiple scattering in the production target.

Pair production from relativistic electrons in a strong laser field would not need any solid target, since the laser itself serves as the target, and it would not suffer from multiple scattering. This process has been studied in the 1960's and 1990's [693–695]. It should be reconsidered with 2011 state of the art TiSa lasers and X-ray FELs [696].

8.7.10 Conclusions

The challenging requirements for the LHeC Linac-Ring positron source are relaxed if positrons can be collided several times before deceleration, if they can be reused over several acceleration/deceleration cycles, and/or

7291 if they can be cooled. The compact tri-ring scheme is an attractive proposal for recooling the spent and
7292 recycled positrons. A conventional damping ring in the SPS tunnel would be an alternative.

7293 Assuming some of the aforementioned measures are taken to reduce the required positron intensity, which
7294 needs to be generated, by at least an order of magnitude, and also assuming that an advanced target, e.g.
7295 W-granules, rotating wheel, sliced-rod converter, or liquid metal jet, can be used, several of the proposed
7296 source and cooling concepts could provide the intensity and the beam quality required by the LHeC ERL.

7297 For example, the Compton-ring source and the Compton ERL are viable candidates for the Linac-
7298 Ring LHeC positron source. Coherent pair production and an advanced undulator represent other possible
7299 schemes, still to be explored for LHeC in greater detail. The coherent pair production would have the
7300 appealing feature of generating positrons with an inherently small emittance.

7301 In conclusion, it does seem technically possible to meet the very demanding requirements for the LHeC
7302 positron source by a combination of approaches. A serious and concerted R&D effort will be required to
7303 determine the optimum linac-ring positron configuration.

Chapter 9

System Design

9.1 Magnets for the Interaction Region

9.1.1 Introduction

The technical requirements for the ring-ring options are easily achieved with superconducting magnets of proven technology. It is possible to make use of the wire and cable development for the LHC inner triplet magnets. We have studied all-together seven variants of which two are selected for this CDR. Although these magnets will require engineering design efforts, there are no challenges because the mechanical design will be very similar to the MQXA [697] magnet built for the LHC [587].

The requirements in terms of aperture and field gradient are much more difficult to obtain for the linac-ring option. We reverse the arguments and present the limitations for the field gradient and septum size, that is, the minimum distance between the proton and electron beams, for both Nb-Ti and Nb₃Sn superconducting technology. Here we limit ourselves to the two most promising conceptual designs.

9.1.2 Magnets for the ring-ring option

The interaction region requires a number of focussing magnets with apertures for the two proton beams and field-free regions to pass the electron beam after the collision point. The lattice design was presented in Sections 7.2 and 8.45; the schematic layout is shown in Fig. 7.17.

The field requirements for the ring-ring option (gradient of 127 T/m, beam stay clear of 13 mm (12 σ), aperture radius of 21 mm for the proton beam, 30 mm for the electron beam) allow a number of different magnet designs using the well proven Nb-Ti superconductor technology and making use of the cable development for the LHC. In the simulations presented here, we have used the parameters (geometrical, critical surface, superconductor magnetization) of the cables used in the insertion quadrupole MQY of the LHC.

Fig. 9.1 shows a superferric magnet as built for the KEKb facility [698]. This design comes to its limits due to the saturation of the iron poles. Indeed, the fringe field in the aperture of the electron beam exceeds the limit tolerable for the electron beam optics, and the field quality required for proton beam stability, on the order of one unit in 10^{-4} at a reference radius of 2/3 the aperture, is difficult to achieve.

The magnetic flux density in the low-field region of the design shown in Fig. 9.1 (right) is about 0.3 T. We therefore disregard this design as well. Moreover, the engineering design work required for the mechanical structure of this magnet would be higher than for the proven designs shown in Fig. 9.2.

Fig. 9.2 shows the three alternatives based on LHC magnet technology. In the case of the double aperture version the aperture for the proton beams is 21 mm in radius, in the single aperture version the beam pipe radius is 26 mm. In all cases the 127 T/m field gradient can be achieved with a comfortable safety margin to quench (exceeding 30%) and using the cable(s) of the MQY magnet of the LHC. The operation temperature is supposed to be 1.8 K, employing superfluid helium technology. The cable characteristic data are given in

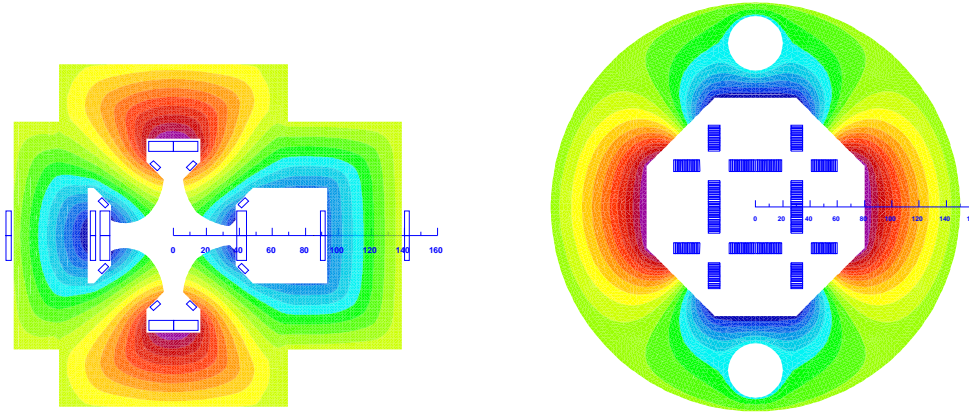


Figure 9.1: Cross-sections of insertion quadrupole magnets with iso-surfaces of the magnetic vector potential (field-lines). Left: Super-ferric, similar to the design presented in [698]. Right: Superconducting block-coil magnet as proposed in [699] for a coil-test facility.

7339 Table 9.1. The outer radii of the magnet coldmasses do not exceed the size of the triplet magnets installed
 7340 in the LHC (diameter of 495 mm). The fringe field in the aperture of the electron beam is in all cases below
 7341 0.05 T.

7342 Fig. 9.3 shows half-aperture quadrupoles (single and double-aperture versions for the proton beams) in a
 7343 similar design as proposed in [17]. The reduced aperture requirement in the double-aperture version makes
 7344 it possible to use a single layer coil and thus to reduce the beam-separation distance between the proton and
 7345 the electron beams. The field-free regions is large enough to also accommodate the counter rotating proton
 7346 beam. The version shown in Fig. 9.3 (left) employs a double-layer coil. In all cases the outer diameter of
 7347 the coldmasses do not exceed the size of the triplet magnets currently installed in the LHC tunnel.

7348 For this CDR we retain only the single aperture version for the Q2 (shown in Fig. 9.2, left) and the
 7349 half-aperture quadrupole for the Q1 (shown in Fig. 9.3, top left). The separation distance between the
 7350 electron and proton beams in Q1 requires the half-aperture quadrupole design to limit the overall synchrotron
 7351 radiation power emitted by bending of the 60 GeV electron beam. The single aperture version for Q2 is
 7352 retained in the present layout, because the counter rotating proton beam can be guided outside the Q2
 7353 triplet magnet. The design of Q3 follows closely that of Q2, except for the size of the septum between the
 7354 proton and the electron beams.

7355 The coils in all three triplet magnets are made from two layers, using both Nb-Ti composite cables as
 7356 specified in Table 9.1. The layers are individually optimized for field quality. This reduces the sensitivity
 7357 to manufacturing tolerances and the effect of superconductor magnetization [700]. The mechanical design
 7358 will be similar to the MQXA magnet where two kinds of interleaved yoke laminations are assembled under
 7359 a hydraulic press and locked with keys in order to obtain the required pre-stress of the coil/collar structure.
 7360 The main parameters of the magnets are given in Table 9.2.

7361 9.1.3 Magnets for the linac-ring option

7362 The requirements in terms of aperture and field gradient are more difficult to obtain for the linac-ring option.
 7363 Consequently we present the limitations for the field gradient and septum size achievable with both Nb-Ti
 7364 and Nb₃Sn superconducting technologies. We limit ourselves to the two conceptual designs already chosen
 7365 for the ring-ring option. For the half quadrupole, shown in Fig. 9.5 (right), the working points on the
 7366 load-line are given for both superconducting technologies in Fig. 9.4.

7367 However, the conductor size must be increased and in case of the half quadrupole, a four layer coil must

Table 9.1: Characteristic data for the superconducting cables and strands. OL = outer layer, IL = inner layer

Magnet	MQY (OL)	MQY (IL)
Diameter of strands (mm)	0.48	0.735
Copper to SC area ratio	1.75	1.25
Filament diameter (μ m)	6	6
B_{ref} (T) @ T_{ref} (K)	8 @ 1.9	5 @ 4.5
$J_c(B_{\text{ref}}, T_{\text{ref}})$ (A mm^{-2})	2872	2810
$-dJ_c/dB$ ($\text{A mm}^{-2} \text{T}$)	600	606
$\rho(293 \text{ K})/\rho(4.2 \text{ K})$ of Cu	80	80
Cable width (mm)	8.3	8.3
Cable thickness, thin edge (mm)	0.78	1.15
Cable thickness, thick edge (mm)	0.91	1.40
Keystone angle (degree)	0.89	1.72
Insulation thicken. narrow side (mm)	0.08	0.08
Insulation thicken. broad side (mm)	0.08	0.08
Cable transposition pitch length (mm)	66	66
Number of strands	34	22
Cross section of Cu (mm^2)	3.9	5.2
Cross section of SC (mm^2)	2.2	4.1

7368 be used; see Fig. 9.5. The thickness of the coil is limited by the flexural rigidity of the cable, which will
7369 make the coil-end design difficult. Moreover, a thicker coil will also increase the beam separation between
7370 the proton and the electron beams. The results of the field computation are given in Table 9.2, column 3
7371 and 4. Because of the higher iron saturation, the fringe fields in the electron beam channel are considerably
7372 higher than in the magnets for the ring-ring option.

7373 For the Nb_3Sn option we assume composite wire produced with the internal Sn process (Nb rod extru-
7374 sions), [701]. The non-Cu critical current density is 2900 A/mm^2 at 12 T and 4.2 K. The filament size of 46
7375 μm in Nb_3Sn strands give rise to higher persistent current effects in the magnet. The choice of Nb_3Sn would
7376 impose a considerable R&D and engineering design effort, which is however, not more challenging than other
7377 accelerator magnet projects employing this technology [702].

7378 Fig. 9.6 shows the conceptual design of the mechanical structure of these magnets. The necessary
7379 prestress in the coil-collar structure, which must be high enough to avoid unloading at full excitation, cannot
7380 be exerted with the stainless-steel collars alone. For the single aperture magnet as shown in Fig. 9.6 left,
7381 two interleaved sets of yoke laminations (a large one comprising the area of the yoke keys and a smaller,
7382 floating lamination with no structural function) provide the necessary mechanical stability of the magnet
7383 during cooldown and excitation. Preassembled yoke packs are mounted around the collars and put under
7384 a hydraulic press, so that the keys can be inserted. The sizing of these keys and the amount of prestress
7385 before the cooldown will have to be calculated using mechanical FEM programs. This also depends on the
7386 elastic modulus of the coil, which has to be measured with a short-model equipped with pressure gauges.
7387 Special care must be taken to avoid nonallowed multipole harmonics because the four-fold symmetry of the
7388 quadrupole will not entirely be maintained.

7389 The mechanical structure of the half-quadrupole magnet is somewhat similar, however, because of the
7390 left/right asymmetry four different yoke laminations must be produced. The minimum thickness of the
7391 septum will also have to be calculated with structural FEM programs.

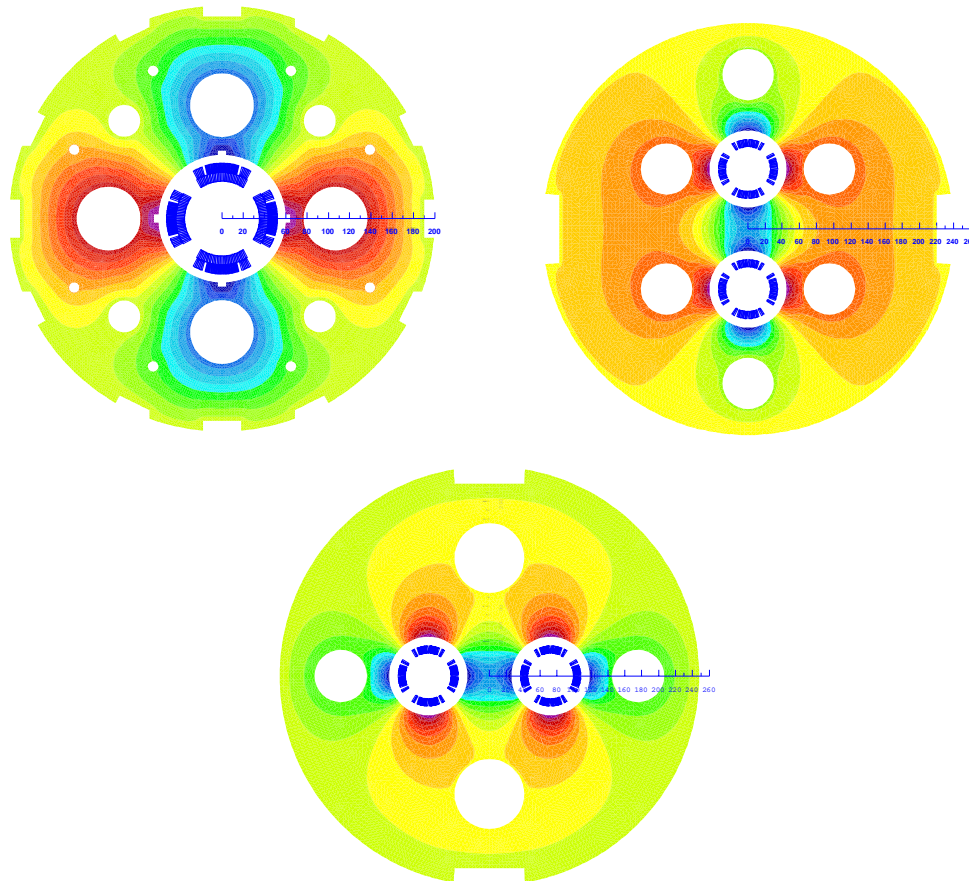


Figure 9.2: Cross-sections with field-lines of insertion quadrupole magnets. Classical designs similar to the LHC magnet technology. Top left: Single aperture with a double layer coil employing both cables listed in Table 9.1. Design chosen for Q2. Top right: Double aperture vertical. Bottom: Double aperture horizontal. The double-aperture magnets can be built with a single layer coil using only the MQY inner layer cable; see the right column of Table 9.1.

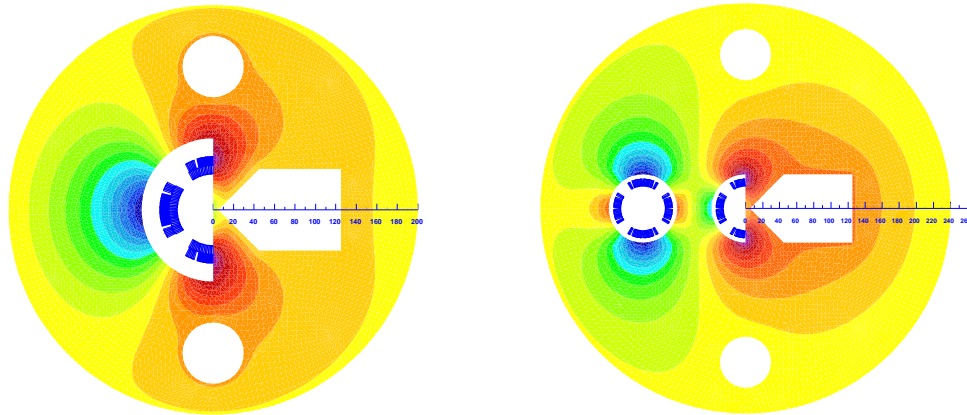


Figure 9.3: Cross-sections of insertion quadrupole magnets with field-lines. Left: Single half-aperture quadrupole with field-free domain [17]; design selected for Q1. Right: Double-aperture magnet composed of a quadrupole and half quadrupole.

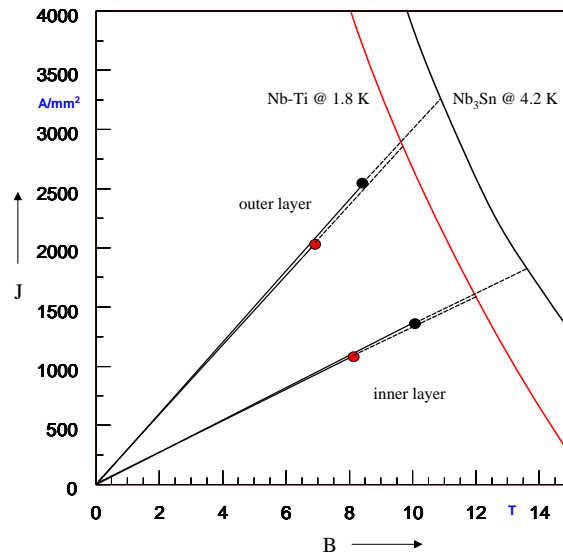


Figure 9.4: Working points on the load-line for both Nb-Ti and Nb₃Sn variants of the half quadrupole for Q1.

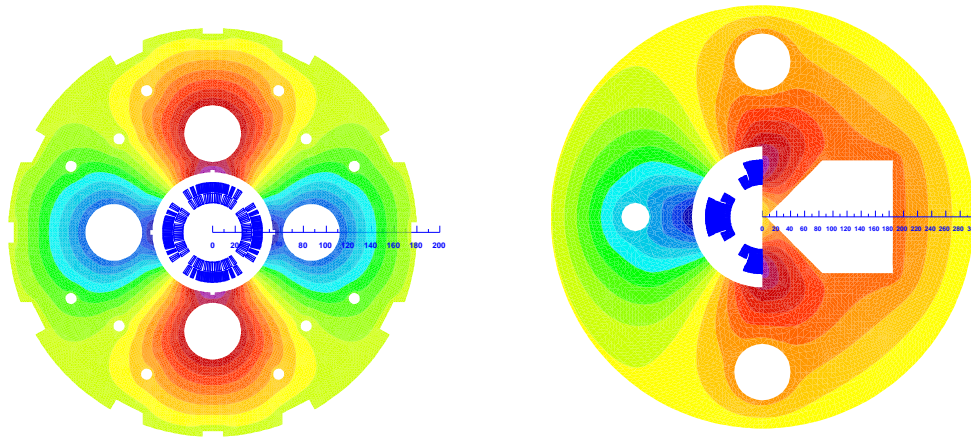


Figure 9.5: Cross-sections of the insertion quadrupole magnets for the linac-ring option. Left: Single aperture quadrupole. Right: Half quadrupole with field-free region.

Table 9.2: SC = type of superconductor, g = field gradient, R = radius of the aperture (without coldbore and beam-screen), LL = operation percentage on the load line of the superconductor material, I_{nom} = operational current, B_0 = main dipole field, S_{beam} = beam separation distance, B_{fringe} = fringe field in the aperture for the electron beam, g_{fringe} = gradient field in the aperture for the electron beam.

Type		Ring-ring single aperture	Ring-ring half-quad	Linac-ring single aperture	Linac-ring half-quad
Function		Q2	Q1	Q2	Q1
SC		Nb-Ti at 1.8 K			
R	mm	36	35	23	46
I_{nom}	A	4600	4900	6700	4500
g	T/m	137	137	248	145
B_0	T	-	2.5	-	3.6
LL	%	73	77	88	87
S_{beam}	mm	107	65	87	63
B_{fringe}	T	0.016	0.03	0.03	0.37
g_{fringe}	T/m	0.5	0.8	3.5	18
SC		Nb ₃ Sn at 4.2 K			
I_{nom}	A			6700	4500
g	T/m			311	175
B_0	T			-	4.7
LL	%			83	82
B_{fringe}	T			0.09	0.5
g_{fringe}	T/m			9	25

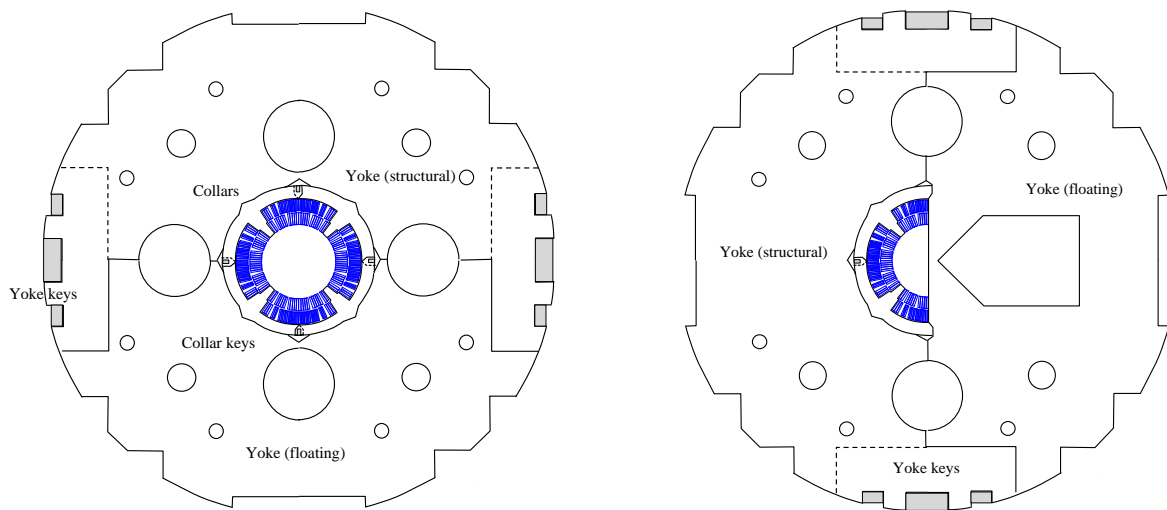


Figure 9.6: Sketch of the mechanical structure. Left: Single aperture magnet. Right: Half quadrupole with field-free region.

7392 **9.2 Accelerator Magnets**

7393 **9.2.1 Dipole Magnets**

7394 Two different types of bending magnets are considered in this document: the ones for the LR Option, used
 7395 in the arcs of the recirculator, and the ones for the RR Option, to be installed in the LHC ring.

7396 **Dipole Magnets for the LR Option**

7397 Each of the 6 arcs of the recirculator needs 600 four-meter-long bending magnets, providing a magnetic field
 7398 from 0.046 T to 0.264 T depending on the arc energy from 10.5 GeV to 60.5 GeV.

7399 Considering the relatively low field strength required even for the highest energy arc, and the small
 7400 required physical aperture of 25 mm only, it is proposed here to adopt the same cross section for all magnets,
 7401 possibly with smaller conductors for the lowest energies.

7402 This allows the design of very compact and relatively cheap magnets, running at low current densities to
 7403 minimize the power consumption.

7404 Table 9.3 summarizes the main parameters of the proposed magnet design illustrated in Figure 9.7.

Parameter	Value	Units
Beam Energy	10.5-60.5	GeV
Magnetic Length	4.0	Meters
Magnetic Field	0.046-0.264	Tesla
Number of magnets	6 x 600 = 3600	
Vertical aperture	25	mm
Pole width	80	mm
Number of turns	2	
Current @ 0.264 T	2200	Ampere
Conductor material	copper	
Magnet inductance	0.10	milli-Henry
Magnet resistance	0.10	milli-Ohm
Power @ 10.5 GeV	15	Watt
Power @ 20.5 GeV	55	Watt
Power @ 30.5 GeV	125	Watt
Power @ 40.5 GeV	225	Watt
Power @ 50.5 GeV	350	Watt
Power @ 60.5 GeV	500	Watt
Total power consumption 10-60 GeV	762	kW
Cooling	air or water	depends on energy

Table 9.3: Main parameters of bending magnets for the LR recirculator. Resistance and power refer to the same conductor size, however for the lowest energies conductors may be smaller.

7405 **Dipole Magnets for the RR Option**

7406 3040 bending magnets, 5.35-meter-long each, are needed in the LHC tunnel for the RR option. They shall
 7407 provide a magnetic field ranging from 0.0127 T at 10 GeV to 0.0763 T at 60 GeV. Additionally, about 40
 7408 magnets will be needed in the Interaction Regions totalling about 3080 magnets. The main issues in the
 7409 design of these magnets are:

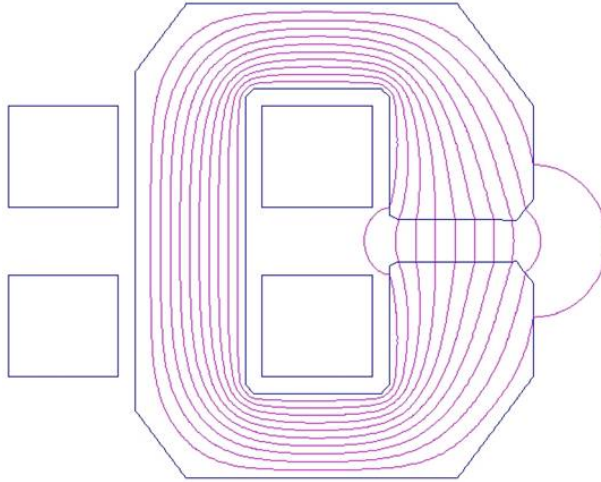


Figure 9.7: Bending magnets for the LR re-circulator

- 7410 • The field range, situated in low field region, and in particular the very low injection field constitute
7411 a challenge for achieving a satisfactory field reproducibility from cycle to cycle and for making field
7412 quality relatively constant during the field ramp. These specific issues will be discussed further in the
7413 paragraphs dealing with the experimental work carried out at BINP and at CERN.
- 7414 • Compactness, to fit in the present LHC tunnel.
- 7415 • Compatibility with synchrotron radiation power.

7416 The proposed design is constituted by compact C-Type dipoles, with the C-aperture on the external side
7417 of the ring to possibly allow the use of a vacuum pre-chamber and in any case to avoid the magnet intercepting
7418 the synchrotron radiation. The unusual pole shape allows minimizing the difference of flux line length over
7419 the horizontal aperture, making magnetic field quality less dependent on the iron characteristics than in a
7420 C-type dipole of conventional shape. The coils are constituted by solid single bars of conductor, which after
7421 insulation are individually slit inside the magnet. The conductor can be in aluminum or in copper depending
7422 from economical reasons coming from a correct balance between investment cost and operation. The present
7423 design is based on an aluminum conductor, which among other has the advantage of making the magnet
7424 lighter than with a copper conductor. The conductor size is sufficiently large to reduce the dissipated power
7425 within levels which can be dealt with by ventilation in the LHC tunnel: this is a considerable advantage in
7426 terms of simplicity of magnet manufacture, connections and reliability.

7427 Table 9.4 summarizes the main parameters of the proposed magnet design illustrated in Figure 9.8.

7428 9.2.2 BINP Model

7429 Two different types of models have been manufactured, both aiming at demonstrating that a cycle-to-cycle
7430 reproducibility of the relatively low injection field (only 127 Gauss at an injection energy of 10 GeV) better
7431 than 0.1 Gauss can be achieved. Both models, pictured in Figure 9.9, showed a magnetic field reproducibility
7432 at injection field within ± 0.075 Gauss when cycled between injection and maximum field. To achieve such
7433 results both models make use of the same iron laminations, which are 3408 type silicon steel grain oriented
7434 0.35 mm thick. Their coercive force in the direction of the orientation is about 6 A/m, and perpendicular
7435 to the direction of the orientation remains relatively low at about 22 A/m. The C-type model has been
7436 assembled in two variants, with the central iron part with grains oriented vertically and with grain oriented
7437 horizontally (both blocks are as shown in the picture). The relevant magnetic measurements did not show
7438 differences between the two versions.

Parameter	Value	Units
Beam Energy	10-60	GeV
Magnetic Length	5.35	Meters
Magnetic Field	0.0127-0.0763	Tesla
Number of magnets	3080	
Vertical aperture	40	mm
Pole width	150	mm
Number of turns	2	
Current @ 0.763 T	1300	Ampere
Conductor material	copper	
Magnet inductance	0.15	milli-Henry
Magnet resistance	0.16	milli-Ohm
Power @ 60 GeV	270	Watt
Total power consumption @ 60 GeV	0.8	MW
Cooling	air or water	depends on tunnel ventilation

Table 9.4: Main parameters of bending magnets for the RR Option.

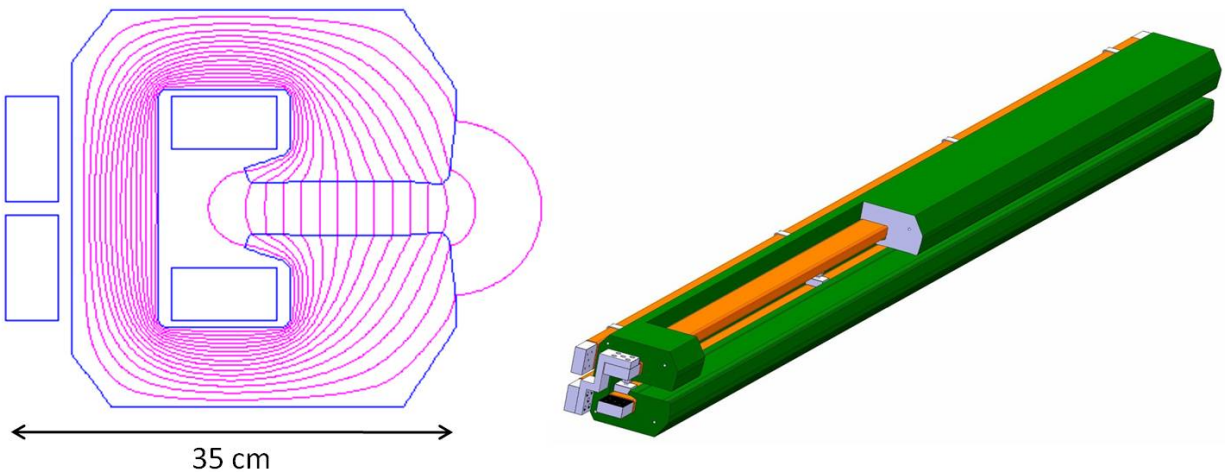


Figure 9.8: Bending magnets for the RR Option

7439 9.2.3 CERN Model

7440 As a complementary study to the one made by BINP, the CERN model explores the manufacture of lighter
7441 magnets, with the yoke made by interleaved iron and plastic laminations. The magnetic flux produced in the
7442 magnet aperture is concentrated in the iron only, with a thickness ratio between plastic and iron of about
7443 2:1 the magnetic field in the iron is about 3 times that in the magnet gap. In addition to a lighter assembly,
7444 this solution has the advantage of increasing the magnetic working point of the iron at injection fields, thus
7445 being less sensitive to the quality of the iron and in particular to the coercive force. To explore the whole
7446 potential of this solution three different lamination materials have been explored: an expensive NiFe 50 steel
7447 (Hc 3A/m) which will act as reference, a conventional grain oriented steel with similar characteristics as the
7448 one used by BINP, and a conventional low carbon steel with Hc 70 A/m. The model cross section reproduces
7449 the reference one described for the RR dipoles.

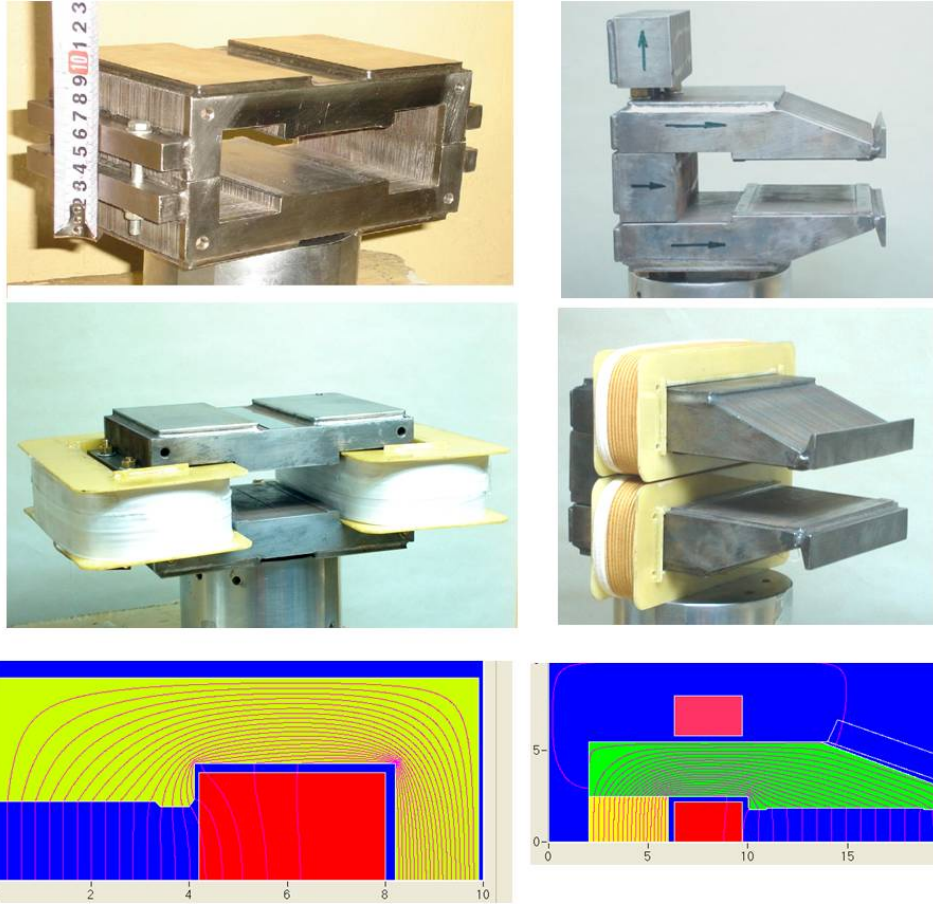


Figure 9.9: H and C-Type model magnets made by BINP at Novosibirsk.

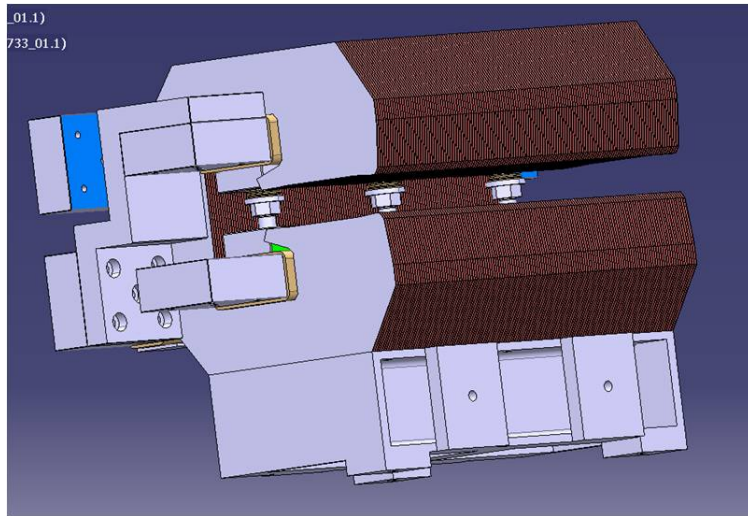


Figure 9.10: 400 mm long RR dipole model under consideration at CERN with interleaved laminations

7450 **9.2.4 Quadrupole and Corrector Magnets**

7451 In case of the RR option we need, in the LHC tunnel:

- 7452 • In the arcs, 336 QF each providing 10.28T integrated strength, and 336 QD each providing 8.40T
7453 integrated strength.
- 7454 • In the insertion and by-pass, 97 QF each providing 18T integrated strength, and 97 QD each providing
7455 12.6T integrated strength.

7456 In case of the LR option we need:

- 7457 • In the two 10 GeV linacs, 37+37 quadrupoles each providing 2.5T integrated strength.
- 7458 • Again in the two 10 GeV linacs, 37+37 correctors each providing 10mTm integrated strength in both
7459 vertical and horizontal direction.
- 7460 • In the recirculator arcs 4 different quadrupole types, the Q0, Q1 and Q3 each providing about 35 T
7461 integrated strength, and the Q2 each providing about 50T integrated strength.

7462 **RR: 336+336 quadrupoles in the arcs**

7463 Considering the integrated strength of QD and QF are not much different, we propose having the same
7464 type of magnets: the relevant parameters are summarized in Table 9.5 and the cross section is illustrated in
7465 Figure 9.11.

Parameter	Value	Units
Beam Energy	10-60	GeV
Magnetic Length	1.0	Meters
Field gradient @ 60 GeV	10.28 (QF) - 8.40 (QD)	T/m
Number of magnets	336 + 336	
Aperture radius	30	mm
Total length	1.2	meters
Weight	700	kg
Number of turns/pole	10	
Current @ 10.28 T/m	390	Ampere
Conductor material	copper	
Current density	4	A/mm ²
Magnet inductance	3	milli-Henry
Magnet resistance	16	milli-Ohm
Power @ 60 GeV	2500	Watt
Cooling	water	

Table 9.5: Main parameters of arc quadrupole magnets for the RR Option.

7466 **RR: 148 + 148 quadrupoles in the insertion and by-pass**

7467 In total 148 QF and 148 QD quadrupoles are needed in the insertion and by-pass. The required integrated
7468 strength is 18T for the QF and 13T for the QD. We propose having the same magnet cross section with two
7469 different length, 1.0 m the QF and 0.7 m the QD, capable of producing a gradient of up to 19 T/m. The
7470 relevant parameters are summarized in Table 9.9 and the cross section is illustrated in Figure 9.12.

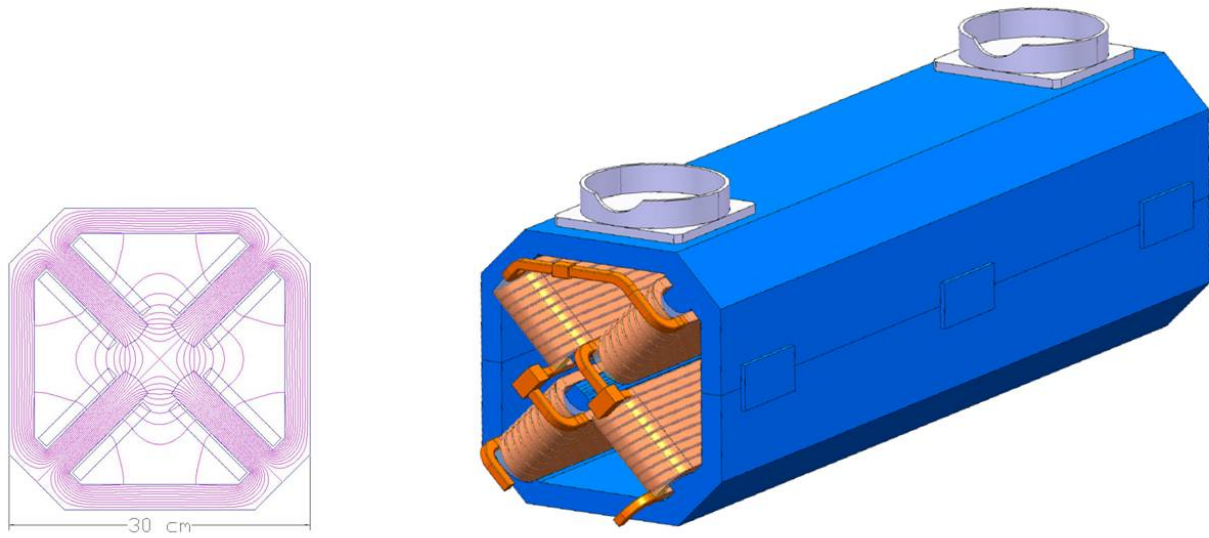


Figure 9.11: Arc quadrupole magnets for the RR Option

Parameter	Value	Units
Beam Energy	10-60	GeV
Magnetic Length (QD/QF)	1.0/0.7	Meters
Field gradient @ 60 GeV	19	T/m
Number of magnets (QD+QF)	148 + 148	
Aperture radius	30	mm
Total length (QD/QF)	1.2/0.9	meters
Weight (QD/QF)	700/500	kg
Number of turns/pole	17	
Current @ 19 T/m	410	Ampere
Conductor material	copper	
Current density	5	A/mm ²
Magnet inductance (QD/QF)	12/9	milli-Henry
Magnet resistance (QD/QF)	40/30	milli-Ohm
Power @ 60 GeV (QD/QF)	7/5	kWatt
Cooling	water	

Table 9.6: Main parameters of insertion and by-pass quadrupole magnets for the RR Option.

7471 **LR: 37 + 37 quadrupoles for the two 10 GeV Linacs**

7472 The present design ¹ considers 70 mm aperture radius magnets to be compatible with any possible aperture
 7473 requirement. The relevant parameters are summarized in table 9.7 and the cross section is illustrated in
 7474 Figure 9.13.

¹Considerations as space and warm/cold connections suggest to eventually make the Linac quadrupoles superconducting and integrate them in the combined cavity-quadrupole cryo module, as has also been opted for with the XFEL at DESY.

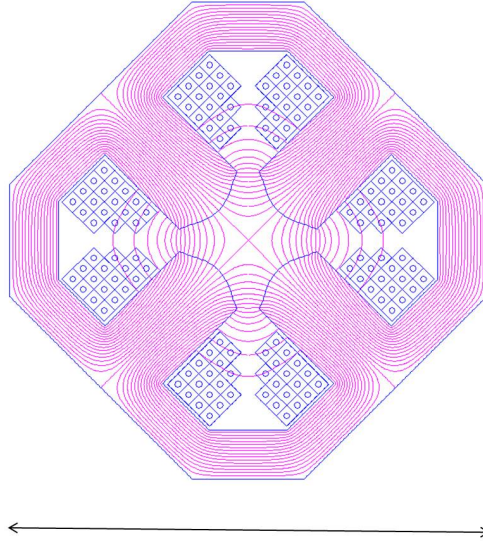


Figure 9.12: Insertion and by-pass quadrupole magnets for the RR Option

Parameter	Value	Units
Magnetic Length	250	mm
Field gradient	10	T/m
Number of magnets	37 + 37	
Aperture radius	70	mm
Weight (QD/QF)	300	kg
Number of turns/pole	44	
Current @ 10 T/m	500	Ampere
Conductor material	copper	
Current density	5	A/mm ²
Magnet inductance	12	milli-Henry
Magnet resistance	24	milli-Ohm
Power @ 500 A	6	kWatt
Cooling	water	

Table 9.7: Main parameters of quadrupoles for the 10 GeV linacs of the LR option

7475 **LR: 37 + 37 correctors for the two 10 GeV Linacs**

7476 The combined function correctors shall provide an integrated field of 10 mTm in an aperture of 140 mm.

7477 The relevant parameters are summarized in table 9.8 and the cross section is illustrated in Figure 9.14.

7478 **LR: 360 Q0 + 360 Q1+ 360 Q2 + 360 Q3 quadrupoles for the recirculator arcs**

7479 In each of the 6 arcs there are 4 types of quadrupoles, each type in 60 units, making 240 quadrupoles per
 7480 arc. The required integrated strength can be met with one type of quadrupole manufactured in two different
 7481 length: 1200 mm the Q2 and 900 mm the Q0-Q1-Q3. The quadrupoles of the low energy arcs may use
 7482 a smaller conductor or less turns or the same conductor as the higher energy quadrupoles showing then
 7483 ecological friendly power consumption. The relevant parameters are summarized in table ?? and the cross

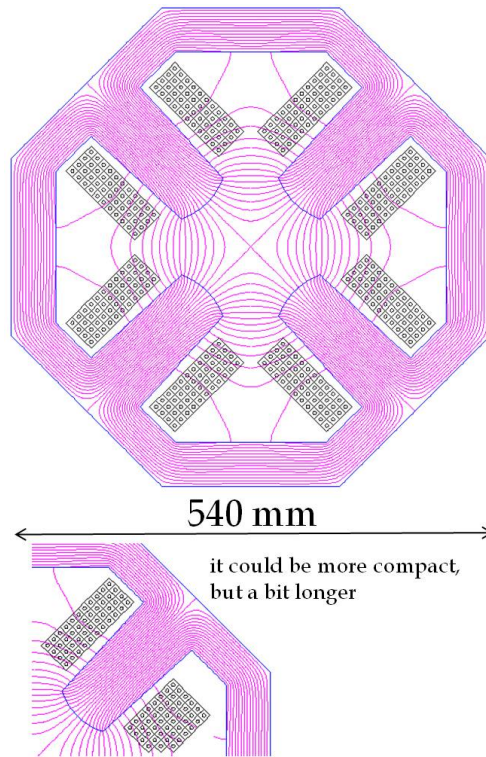


Figure 9.13: Quadrupoles for the 10 GeV linacs of the LR option

Parameter	Value	Units
Magnetic Length	400	mm
Field induction	25	mT
Number of magnets (QD+QF)	37 + 37	
Free aperture	140 x 140	mm x mm
Yoke length	250	mm
Total length	350	mm
Weight	100	kg
Number of turns/circuit	2x100	
Current	40	Ampere
Conductor material	copper	
Current density	1.5	A/mm ²
Magnet inductance per circuit	10	milli-Henry
Magnet resistance per circuit	0.1	Ohm
Power per circuit	160	Watt
Cooling	air	

Table 9.8: Main parameters of combined function corrector magnets for the LR Option.

7484 section is illustrated in Figure 9.15.

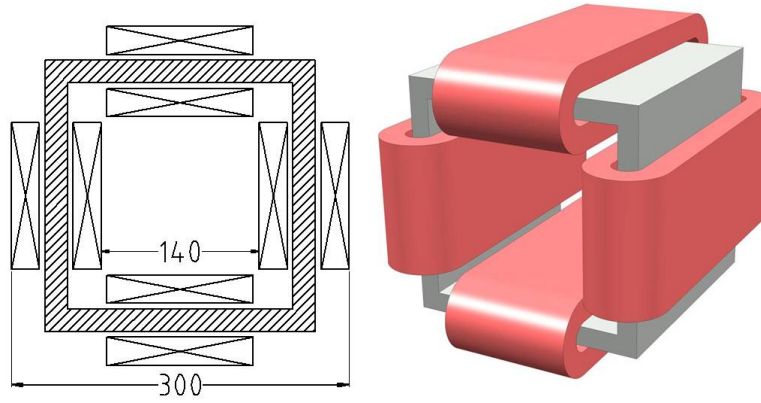


Figure 9.14: Combined function corrector magnets for the LR Option

Parameter	Value	Units
Beam Energy	10-60	GeV
Magnetic Length	0.9/1.2	Meters
Field gradient	41	T/m
Number of magnets (Q0+Q1+Q2+Q3)	1440	
Aperture radius	20	mm
Weight (QD/QF)	550/750	kg
Number of turns/pole	17	
Current @ 41 T/m	410	Ampere
Conductor material	copper	
Current density	5	A/mm ²
Magnet inductance	15/20	milli-Henry
Magnet resistance	30/40	milli-Ohm
Power @ 410 A	5/7	kWatt
Cooling	water	

Table 9.9: Main parameters of quadrupoles for the recirculators of the LR option

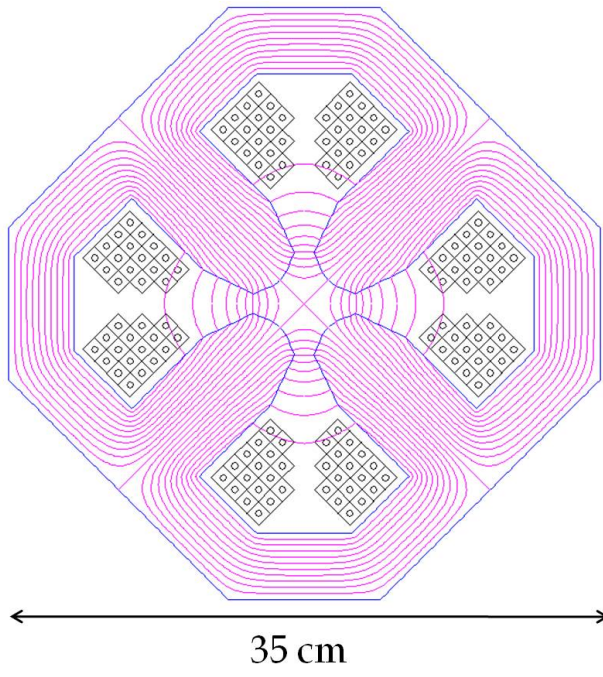


Figure 9.15: Quadrupoles for the recirculators of the LR option

9.3 Ring-Ring RF Design

9.3.1 Design Parameters

The RF system parameters for the e-ring are listed in Table 9.10. For a beam energy of 60 GeV the synchrotron losses are 437 MeV/turn. With a nominal beam current of 100 mA the rather significant amount of power of 47.3 MW is lost due to synchrotron radiation. For the voltages needed superconducting RF is the only choice.

9.3.2 Cavities and klystrons

Cavity design

The most important issue determining the RF design is not so much in achieving high accelerating gradient but rather the need to handle large powers through the power coupler. The choice of RF frequency is based on relatively compact cavities which are able to handle the relatively high beam intensities and allowing fitting of power couplers of sufficient dimensions to handle the RF power. A frequency in the range 600 to 800 MHz is the most appropriate. Cavities of frequency of 704 MHz are currently being developed at CERN in the context of the study of a Superconducting Proton Linac (SPL) [703] [704] [705]. The same frequency is also used at BNL for ERL cavities for the RHIC upgrade project [706]. Both cavities are 5-cell and can achieve gradients greater than 20 MV/m. For the present study we take an RF frequency of 721.42 MHz, which is compatible with the minimum 25 ns bunch spacing in the LHC. An RF voltage of 500 MV gives a quantum lifetime of 50 hours; this is taken as the minimum operating voltage. An RF voltage of 560 MV gives infinite quantum lifetime and a margin of 60 MV which permits feedback system voltage excursions and provides tolerance to temporary failure of part of the RF system without beam loss.

5-cell cavities would require too much RF power transferred through the power coupler, therefore we use 2-cell cavities here in keeping the cell shape. Then with a total of 112 cavities, the power per cavity supplied to the beam to compensate the synchrotron radiation losses is 390 kW. This level of power handling is only just reached for the power couplers of the larger 400 MHz cavities of the LHC. It is therefore proposed to use two power couplers per cavity and split the power. In terms of voltage, only 5 MV per cavity is required to make 560 MV, hence it is sufficient to use cavities with two cells instead of five. The resulting cavity active length is 0.42 m and the gradient is a conservative 11.9 MV/m. Under these conditions the matched loaded Q is $2.8 \cdot 10^5$. Over-coupling by 50 % to $1.9 \cdot 10^5$ provides a stability margin and incurs relatively small power overhead. Under this condition the average forward power through the coupler is just under 200 kW. This nevertheless remains challenging for the design of power coupler.

Cryomodule layout

With 8 cavities per cryomodule there are a total of 14 cryomodules. The estimated cryomodule length, scaled from the 8 5-cell cavity of SPL to two cells per cavity is 10 m. There are 8 double cell cavities in 14 10m cryomodules, the total RF cryomodule length is therefore 140 m, but space must be allowed for quadrupoles, vacuum equipment and beam instrumentation. A total of 208 m is available in the by-passes: 124 m at CMS and 2 x 42m at ATLAS. Eight cryomodules can therefore be installed in the CMS bypass and six, three on each side, in the ATLAS by-passes. The distance between the modules can be taken as 3 m to allow space for the other equipment. The positioning of the RF tunnels in the CMS and ATLAS bypasses is shown in Figure 9.16.

RF Power System

The configuration for powering the eight cavities within one cryomodule is shown in figure 9.17. Each klystron feeds two cavities with power being split near the cavity to its two couplers. Taking two cavities per klystron with an estimated 7 % losses in the waveguide system gives a mean required klystron output power of 870 kW. A 15 % margin for the feedbacks gives a klystron rated power of 1 MW. The total number

Energy	GeV	60
Beam current	mA	100
Synchrotron losses	MeV/turn	437
Power loss to synchrotron radiation	MW	43.70
Bunch frequency (25 ns spacing)	MHz	40.08
Multiplying factor		18
RF frequency	MHz	721.42
Harmonic number		64152
RF Voltage for 50 hour quantum lifetime	MV	500.00
Nominal RF voltage (MV)	MV	560.00
Synchronous phase angle	degrees	129
Quantum lifetime at nominal RF voltage	hrs	infinite
Number of cavities		112
Number of 8-cavity cryomodules		14
Power couplers per cavity		2
Average RF power to beam per power coupler	kW	195
Voltage per cavity at nominal voltage	MV	5.00
Cells per cavity		2
Cavity active length	m	0.42
Cavity R/Q		114
Cavity Gradient	MV/m	11.90
Cavity loaded Q (Matched)		$2.8 \cdot 10^5$
Cavity forward power (nom. current, nom. voltage) for matched condition	kW	390
Nominal cavity loaded Q (matched for 50 % more beam)		$1.9 \cdot 10^5$
Cavity forward power (nominal current, voltage & loaded Q)	kW	406
Forward power per coupler	kW	203
Number of cavities per klystron		2
Waveguide losses	%	7
Klystron output power	kW	870
Feedbacks & detuning power margins	%	15
Klystron rated power	kW	1000
Total number of klystrons		56
Total average operating klystron RF power	MW	49
DC power to klystrons assuming 65% klystron efficiency	%	75
Grid power for RF, assuming 95% efficiency of power converters	MW	79

Table 9.10: RF system parameters for the electron ring.

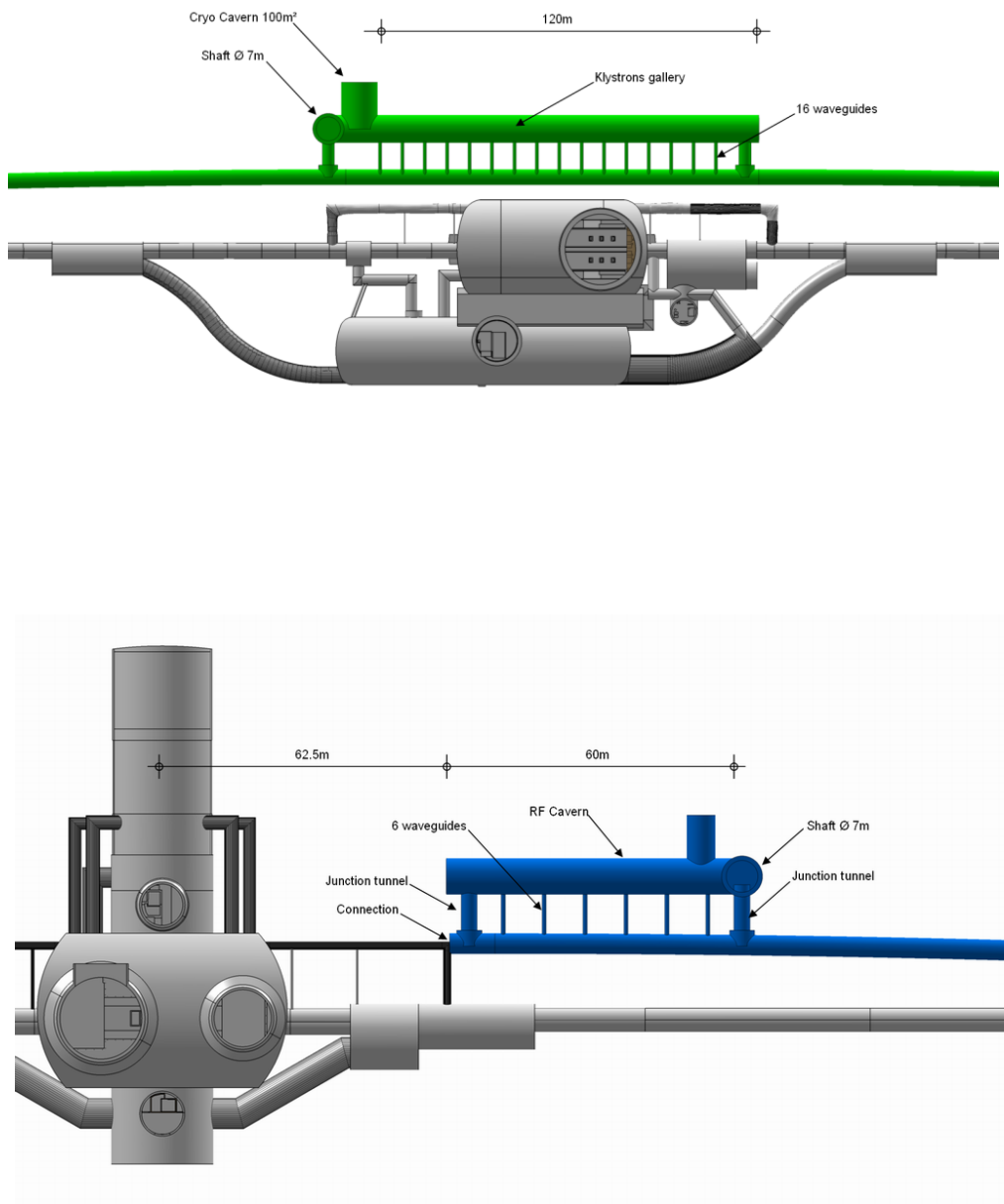


Figure 9.16: RF tunnel Layouts at CMS and ATLAS bypasses. Note only the right hand side at ATLAS shown.

7529 of klystrons is 56, delivering an average total RF power of 49 MW. Taking 65 % klystron efficiency and 95 %
 7530 efficiency in the power converters gives roughly 79 MW grid power needed for the RF power system.

7531 **RF Power System Layout**

7532 The klystrons are installed in the additional tunnels parallel to the by-passes. An estimated surface area of
 7533 100 m^2 is needed for the two klystrons, circulators, HV equipment and Low Level RF and controls racks for
 7534 each 8 cavity module in adjacent RF gallery. This defines the tunnel width over the 13 m module interval
 7535 (length + spacing) to be 8 m. Waveguide ducts are needed between the by-passes and the RF tunnels. With
 7536 one waveguide per klystron into the tunnel, and two waveguides per duct, there are 16 ducts in the CMS
 7537 tunnels, spaced roughly 6.5 m apart. At ATLAS there would be six ducts on either side with the same
 7538 spacing. The required diameter of the duct tunnel is 90cm.

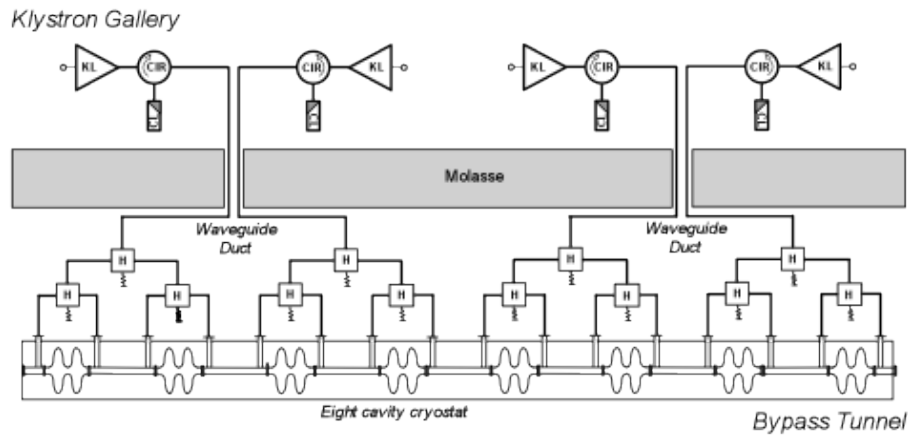


Figure 9.17: Layouts of RF power equipment in bypass and in RF gallery for one cryomodule.

7539 **Surface Installations**

7540 One HV Power Converter rated at 6 MVA is needed per 4 klystrons. These are housed in surface buildings:
 7541 eight converters at CMS, and six at ATLAS.

7542 **Conclusions**

7543 721.4 MHz RF systems can be just fitted in the two bypasses nearest ATLAS and CMS. Detailed studies need
 7544 to be done on the optimization of the cavity geometry for the high beam current and ensuring acceptable
 7545 transverse impedance. The RF power system is large. Further work is needed on integration to exactly
 7546 define tunnel and cavity cavern layouts and quantify the space requirements. Phased installation with
 7547 gradual energy build-up, as was done for LEP, is an interesting possibility. The power needed for RF is
 7548 79 MW. To this must be added power for RF controls, cryogenics and all other machine equipment.

7549 **9.4 Linac-Ring RF Design**

7550 **9.4.1 Design Parameters**

7551 The ERL design [707] [708] [709] is based on two 10 GeV linacs, with a 0.3 GeV injection energy and 6 linac
 7552 passes to reach 60 GeV. This is shown in Figure 8.5.

Arc	Arc energy [GeV]	Energy loss per arc passage [MeV]	Number of passages	Total energy loss per arc [MeV]
6	60	570.0	1	570.0
5	50	275.0	2	550.0
4	40	115.0	2	230.0
3	30	35.0	2	70.0
2	20	7.0	2	14.0
1	10	0.4	2	0.8
				1434.8

Table 9.11: Energy losses in the arcs on a half circle of 1 km radius

The overall parameters are given in Table 8.1. With a beam current of 6.6 mA produced, there are currents of nearly 20 mA in both directions in the linacs. Significant power, greater than the injection energy, is lost in the passages through the arcs due to synchrotron radiation as shown in Table 9.11.

The energy loss in the arcs can be compensated by independent RF systems operating at twice the normal RF frequency. As proposed by [667, 710] it could be envisaged to let the main linacs replace the energy lost to synchrotron radiation. However, this scheme significantly restricts operational freedom and is not tested yet. Therefore we keep it only as one possible option. For the present report both options are presented - Case 1 for additional RF systems in the arcs to compensate synchrotron losses and Case 2 for this energy supplied by the linacs.

Linac design

High accelerating gradient is needed. First tests on cavities at similar frequency at BNL have already reached 20 MV at Q_0 of $2.5 \cdot 10^{10}$. Improved cavity design and careful cavity processing should allow meeting the specifications. The optimum number of cavities and the gradient is an overall compromise taking into account cost, cryogenics consumption and operational reliability. The RF power system needs to compensate energy loss and non-ideal energy recovery due to beam losses, phasing errors, transients, ponderomotive effects and noise. It also needs to allow testing and processing of the cavities at full gradient without circulating beam. The main RF parameters are given in Table 9.12, for the two cases described above.

The linac RF design is based on 5-cell cavities operating at 721.42 MHz, this frequency being compatible with 25 ns bunch spacing in LHC, as for the electron ring option. A gradient of 20 MV/m can be taken. This is a conservative estimate based on SPL type cavities presently being developed, with a design aim of 25 MV/m. The unloaded Q (Q_0) is taken as $2.5 \cdot 10^{10}$. This is presently a challenging figure, but recent tests on cavities at this frequency for e-RHIC have been very encouraging. With an active cavity length of 1.06 m the voltage is 21.2 MV per cavity. This requires 944 cavities in total, or 472 cavities per linac. The cavity external Q (Q_{ext}) is derived from optimum coupling to the required beam power to compensate the 4 energy losses in Case 1 and this plus the synchrotron radiation losses in the arcs in Case 2. It should be noted that the 300 MeV injection linac, with nearly 2 MW beam power will also take grid power of between 3 and 4 MW.

9.4.2 Layout and RF powering

Cryomodule and RF power system layout

With eight cavities in a cryomodule of 14 m length, there are 59 cryomodules per linac. Allowing a further 2 m per cryomodule for other linac equipment the total linac length is 944 m. This is summarized in table

Parameter	Unit	Separate Arc RF	No Arc RF
Beam energy	GeV	60.0	60.0
Injection energy	GeV	0.3	0.3
Average beam current out	mA	6.6	6.6
Av. accelerated beam current in linacs	mA	19.8	19.8
Required total voltage in both linacs	GV	20.0	20.0
Energy recovery efficiency	%	96	96
Total power needed to compensate recovery losses	MW	15.8	15.8
Total energy loss per cycle in arcs	MeV	1434.8	1434.8
Total power needed to compensate arc losses	MW	0.0	9.5
RF frequency	MHz	721.42	721.42
Gradient	MV/m	20	20
Cells per cavity		5	5
Cavity length	m	1.06	1.06
Cavity voltage	MV	21.2	21.2
Number of cavities		944	944
Power to compensate recovery losses per cavity	kW	16.8	16.8
Power to compensate synch. rad. losses per cavity	kW	0.0	10.0
Cavity R/Q	circuit Ω	285	285
Cavity unloaded Q [Q_o]	10^{10}	2.5	2.5
Loaded Q [Q_{ext}]	10^6	47	29
Cavity forward power	kW	16.8	26.8
Cavity forward power - no beam		4.2	6.7
Number of cavities per solid state amp.		1	1
Transmission losses	%	7	7
Amplifier output power per cavity	kW	17.9	28.7
Feedbacks power margin	%	15	15
Amplifier rated power	kW	21	33
Total number of amplifiers		944	944
Total average amplifier output power	MW	17	27
Assumed overall conversion efficiency grid to amplifier RF output	%	70	70
Grid power for linacs RF	MW	24	39

Table 9.12: Linac RF parameters.

Parameter	Unit	Value
Cavities per cryomodule		8
Number of cavities		472
Number of cryomodules per linac		59
Cryomodule length	m	14
Spacing of cryomodules	m	2
Linac length	m	944

Table 9.13: ERL cryomodule numbers, length and spacing.

7584 9.13.

7585 RF power system

7586 Assuming optimum coupling the forward power per cavity is approximately 17.9 kW and 28.7 kW for Cases
7587 1 and 2 respectively. The available power per cavity must be somewhat higher to allow margin for operation
7588 of RF the feedback systems; i.e. 21 kW and 33 kW per cavity. These levels can certainly be achieved with
7589 solid state amplifiers, avoiding the need for high voltage power supplies and associated protection equipment.
7590 The grid to RF conversion efficiency is also somewhat higher; 70 % can be taken. The total supplied average
7591 RF powers are approximately 17 MW and 27 MW for the two cases and the grid power required for powering
7592 of the linacs is 24 MW and 39 MW respectively.

7593 RF Power system layout

7594 The RF amplifiers and RF feedback and controls racks are housed in a separate parallel powering gallery.
7595 There is one RF amplifier per cavity, the power being fed by WR1150 standard waveguides, each 11.5 inches
7596 by 5.75 inches (30 cm by 15 cm). The number of holes between the powering and linac tunnels can be limited
7597 to one per four cavities, i.e. two per cryomodule, spaced 8 m apart giving 118 holes per linac. The diameter
7598 is 90cm. The diameters could be reduced if half height waveguides or coax lines are used.

7599 9.4.3 Arc RF systems

7600 Table 9.11 shows the synchrotron radiation losses in the arcs; they are negligible in the 10 GeV arc. In the
7601 20, 30, 40 and 50 GeV arc both the accelerated and decelerated beams pass the same arc RF system with
7602 180^0 phase shift at the basic frequency of 721.42 MHz; hence to accelerate both beams, the arc RF system
7603 is operated at twice the frequency, i.e. at 1442.82 MHz. The 60 GeV arc carries only the decelerated beam
7604 and there one can use the linac RF cavities at 721.42 MHz. However, since here the required power per
7605 cavity is much larger the solid state amplifiers of the main linac cannot be used but a klystron or IOT must
7606 be applied. Overall parameters for these RF systems are given in Table 9.14.

7607 The arc systems provide very different voltages. Parameters for the individual systems are given in table
7608 9.15. Use of cavities and cryostats scaled to those in the linacs is assumed; however short cryostats containing
7609 four cavities could be used in the 20 and 40 GeV arc systems. Powering would be by klystrons, a total of 36
7610 rated at a maximum of 360 kW, with one klystron supplying up to four cavities.

7611 It can be noted that the overall grid power is less if the arc energy recovery is supplied by the main linacs.
7612 (39 MW compared to 24 plus 18 = 42 MW). This is partly due to the assumed higher efficiency of the solid
7613 state amplifiers in the linacs compared to the klystrons in the arc RF systems.

Parameter	Unit	Value
Total energy loss in 20-60GeV arcs	MeV	1434
Power loss in 20-60GeV arcs	MW	9.5
Arc RF frequency	MHz	1442/721
Number of cavities		49/28
Number of klystrons		25/7
Total average supplied klystron RF power	MW	10.8
Assumed overall conversion efficiency - grid to klystrons RF out	%	60
Grid power for arc RF systems	MW	18

Table 9.14: Arc RF systems overall parameters.

Parameter	Unit	Arc 2	Arc 3	Arc 4	Arc 5	Arc 6	Totals
Arc energy	GeV	20	30	40	50	60	
Energy lost per arc passage	MeV	7	35	115	275	570	
Number of passes		2	2	2	2	1	
Total energy loss in arc	MeV	14	70	230	550	570	1434
Power loss in arc	MW	0.1	0.5	1.5	3.6	3.8	9.5
RF frequency 1442 MHz	MHz	x	x	x	x		
RF frequency 721 MHz	MHz					x	
Cavities at 1442 MHz		1	4	12	32		49
Cavities at 721 MHz						28	28
Required voltage/cavity	MV	7.2	9.1	9.9	8.9	21.1	
RF Power/cavity	kW	92	116	127	113	134	
Nominal RF power/cavity	kW	96	120	132	118	140	
Klystron output power/cavity	kW	103	129	141	126	150	
Kl. rated power/cavity	kW	120	150	170	150	180	
Cavities/klystron		1	2	2	2	4	
Klystron rated power	kW	120	300	340	300	720	
Klystrons at 1442 MHz		1	2	6	16		25
Klystrons at 721 MHz						7	7
Total average supplied klystron RF power	MW	0.1	0.5	1.7	4.0	4.2	10.5
Assumed overall conversion efficiency grid to klystrons total RF power	%	60	60	60	60	60	
Grid power arc RF systems	MW	0.2	0.9	2.8	6.7	7.0	18

Table 9.15: Parameters of the individual arc RF systems.

9.5 Crab crossing for the LHeC

Due to the very high electron beam energies in the LHeC and the associated interaction region design, the emitted synchrotron radiation and the required RF power are challenging. The IR layout for the RR option consists of a crossing angle to mitigate parasitic interactions and allows for a simple scheme to accommodate the synchrotron radiation fan. A crab crossing scheme for the proton beam is highly desirable to recover the geometric luminosity loss due to this crossing angle. Some issues associated with the complexity of the IR design and the associated synchrotron radiation can be relaxed with the implementation of crab crossing near the IR. A crab crossing scheme would also provide a natural knob for regulating the beam-beam parameter if required. Although the linac-ring option plans to employ separation dipoles and mirrors for synchrotron radiation, crab crossing can prove to be a simpler option if the technology is viable.

9.5.1 Luminosity Reduction

In the nominal LHC with proton-proton collision, the two beams share a common vacuum chamber for approximately a 100m from the IP. Therefore, a crossing angle is required in the IRs to avoid parasitic interactions. Consequently, the luminosity is reduced by a geometrical reduction factor which can be expressed as

$$R = \frac{1}{\sqrt{1 - \Phi^2}} \quad (9.1)$$

where $\Phi = \sqrt{\theta\sigma_z/2\sigma_x}$ is the Piwinski parameter, which is proportional to ratio of the longitudinal and transverse beam sizes in the plane of the crossing.

Reducing β^* at a constant beam-to-beam separation in the IRs ($\sim 10\sigma$), the luminosity reduction factor can become quite significant. To compensate for this reduction from the crossing angle, a crab crossing scheme is proposed and R&D is moving rapidly to realize the technology [711, 712].

For the electron-proton collisions, the Piwinski parameter can be redefined as

$$\Phi_p = \frac{\theta_c}{2\sqrt{2}\sigma_x^*} \sqrt{\sigma_{z,p}^2 + \sigma_{z,e}^2} \quad (9.2)$$

where $\sigma_{z,p}$ and $\sigma_{z,e}$ are the proton and electron bunch lengths. Table 9.16 lists the relevant parameters of the crossing schemes in the LHeC as compared to some other machines.

	KEK-B	LHC		LHeC		eRHIC
		Nominal	Upgrade	RR	LR	
θ_c [mrad]	22.0	0.285	0.4-0.6	1.0	0.0 (4.0)	0.0 (5.0)
σ_z [cm]	0.7	7.55		7.55 (0.7†)		20/1.2†
σ_x^* [μm]	103	16.6	11.2	30 (15.8*)	-	32
Φ	0.75	0.64	1-1.4	0.9 (1.6*)	0.0	0.0 (11.0)

Table 9.16: Relevant parameters of the crossing schemes in the LHeC compared to LHC, KEK-B and eRHIC. Note † corresponds to electrons and * corresponds vertical plane.

9.5.2 Crossing Schemes

Since the bunch length of the electrons are significantly smaller (at least factor 10) than that of the protons, the geometrical overlap due to crossing angle is mainly dominated by the angle of the proton bunches. Four different cases (see Fig. 9.18) were simulated to determine the luminosity gain in the different cases with crab cavities and comparing it to the nominal case (see Table 9.17).

The luminosity gains strongly depend on the choice of RF frequency as the reduction factor due to the RF curvature at frequencies of interest (0.4-0.8 GHz) is non-negligible.

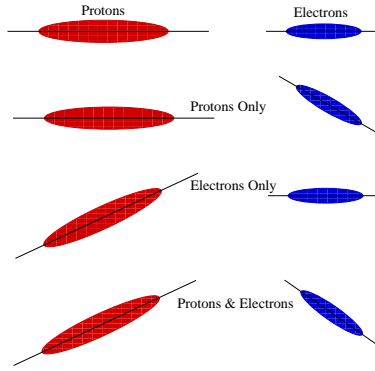


Figure 9.18: Schematic of different crossing schemes using crab cavities on either proton or electron beams as compared to the head-on collision. Top: Crabbing of both beams; Second from top: crabbing of the proton beam only; Third from top: crabbing of electron beam only; Bottom: no crabbing at all.

Scenario	L/L ₀	
	400 MHz	800 MHz
X-Angle (1 mrad)	1.0	
Uncross both e^- and p^+	1.88%	1.48
Uncross only e^-	1.007	
Uncross only p^+	1.88	1.48

Table 9.17: Luminosity gains computed for different crossing schemes with crab cavities and a crossing angle of 1 mrad.

9.5.3 RF Technology

The required cavity voltage can be calculated using

$$V_{crab} = \frac{2cE_0 \tan(\theta_c/2) \sin(\mu_x/2)}{\omega_{RF} \sqrt{\beta_{crab} \beta^*} \cos(\psi_{cc \rightarrow ip}^x - \mu_x/2)} \quad (9.3)$$

where E_0 is the beam energy, ω_{RF} is the RF frequency of the cavity, β_{crab} and β^* are the beta-functions at the cavity and the IP respectively, $\psi_{cc \rightarrow ip}^x$ is the phase advance from the cavity to the IP and μ_x is the betatron tune. The nominal scenarios for both proton-proton and electron-proton IRs are anticipated to have local crab crossing with two cavities per beam to create a local crab-bump within the IR. Since the β -functions are typically large in the location of the crab cavities, a voltage of approximately 20 MV should suffice for crossing angles of approximately 1-2 mrad. The exact voltage will depend on the final interaction region optics of both the proton and the electron beams.

To accommodate the crab cavities within the IR region, deflecting structures with a compact footprint are required. Conventional pill-box type elliptical cavities at frequencies of 400 MHz are too large to fit within the LHC interaction region constraints. The effort to compress the cavity footprint recently resulted in several TEM type deflecting mode geometries [712]. Apart from being significantly smaller than its elliptical counterpart, the deflecting mode is the primary mode of the TEM type cavity, paving the way to a new class of cavities at lower frequencies (400 MHz) which is preferred from the RF curvature point of view.

Demonstration of a robust operation of such novel RF concepts with high deflecting gradients within the LHC constraints is the prerequisite for exploiting the crab crossing concept for the LHeC IR design. R&D on these novel concepts is already underway for the LHC upgrade. The issues of impedance, collimation and machine protection are similar to that of the implementation of the proton-proton IRs.

9.6 Vacuum

9.6.1 Vacuum requirements

In particle accelerators, beams are traveling under vacuum to reduce beam-gas interactions i.e. the scattering of beam particles on the molecules of the residual gas. The beam-gas interaction is dominated by the bremsstrahlung on the nuclei of gas molecules and therefore depends on the partial pressure, the weight and the radiation length [g/cm²] of the gas species. In presence of a photon-stimulated desorption, the residual gas is dominated by hydrogen (75%) followed by CO/CO₂ (24%) and 1% CH₄. Argon normally represents less than 1% of the residual gas if welding best practice for UHV applications is applied. It is to be noted that Argon is 67 times more harmful than hydrogen (H₂); CO₂, CO and N₂ are about 30 times worse than hydrogen and Methane is 10 times worse than hydrogen.

The beam-gas interactions are responsible for machine performance limitations such as reduction of beam lifetime (nuclear scattering), machine luminosity (multiple coulomb scattering), intensity limitation by pressure instabilities (ionization) and for positive beams only, electron (ionization) induced instabilities (beam blow up). The heat load induced by scattered protons and ions can also be an issue for the cryomagnets since local heat loads can lead to a magnet quench i.e. a transition from the superconducting to the normal state. The heavy gases are the most dangerous because of their higher ionization cross-sections. In the case of the LHeC, this limitation exists only in the experimental areas where the two beams travel in the same beam pipe. The beam-gas interactions can also increase the background to the detectors in the experimental areas (non-captured particles or nuclear cascade generated by the lost particles upstream the detectors) and the radiation dose rates in the accelerator tunnels. Thus, leading to material activation, dose rates to intervention crews, premature degradation of tunnel infrastructures like cables and electronics and finally higher probability of electronic single events induced by neutrons which can destroy the electronics in the tunnel but also in the service galleries.

The design of the vacuum system is also driven by severe additional constraints which have to be considered at the design stage since retrofitting mitigation solutions is often impossible or very expensive. Among them, the vacuum system has to be designed to minimise beam impedance and higher order modes (HOM) generation while optimising beam aperture in particular in the magnets. It has to provide also enough ports for the pumps and vacuum diagnostics. For accelerators with cryogenic magnets, the beampipe has to be designed to intercept heat loads induced by synchrotron radiation, energy loss by nuclear scattering, image currents, energy dissipated during the development of electron clouds, the latter building up only in presence of positively charged beams.

The integration of all these constraints often lead to a compromise in performances and in the case of the LHeC, the compromise will differ between the Linac-Ring and the Ring-Ring options.

9.6.2 Synchrotron radiation

The presence of a strong synchrotron radiation has two major implications for the vacuum system: it has to be designed to operate under the strong photon-induced stimulated desorption while being compatible with the significant heat loads onto the beampipes. In the common beampipe, the photo-electrons generated by the synchrotron radiation will dramatically enhance the electron cloud build-up and mitigation solutions shall be included at the design stage. Furthermore, experience with LEP has shown that the Compton scattering of the beam on photons coming from Blackbody radiation can have a significant effect on the beam lifetime [713] [714]. In the following analysis, we have neglected this effect, assuming that a technical solution can be found for keeping the beam vacuum chamber at sufficiently low temperatures. While this does not impose a principle problem to the vacuum system design, it still requires a detailed technical study for identifying a suitable solution for cooling the vacuum system in the presence of ca. 3 kW/m synchrotron radiation power.

7708 **Synchrotron radiation power**

7709 The synchrotron radiation power is an issue for the heat load deposited on the beam pipes and for its
 7710 evacuation and will be the driving factor for the mechanical engineering of the beam pipes. Indeed, the
 7711 heated surfaces will have a higher outgassing rates, the increase being exponentially dependent with the
 7712 surface temperature (factor 10 for a $\Delta T = 50^\circ\text{C}$ increase). The synchrotron radiation power can be calculated
 7713 with equation 9.4. Since scaling linearly with the beam intensity, I , with the power of 4 for energy, E , and
 7714 inversely to power of 2 of the bending radius, the synchrotron radiation power in the Ring-Ring option is
 7715 expected to be 45 times higher than LEP and locally at the by-passes, the power can be about 180 times
 7716 higher. To be compared with the factor 10 expected in the bending and injection sections of the Linac-Ring
 7717 option.

$$P[\text{W/m}] = 1.24 \times 10^3 \frac{E^4 I}{\rho^2} \tag{9.4}$$

7718 **Photon-induced desorption**

7719 The desorption rate depends on critical energy of the synchrotron light, ϵ_c , the energy which divides in two
 7720 the emitted power. For most materials, the desorption rates vary quasi linearly with the critical energy
 7721 (equation 9.5).

$$\epsilon_c(\text{eV}) = \frac{3 \cdot 10^{-7}}{R} \left(\frac{E_B}{E_0} \right)^3 \tag{9.5}$$

7722 $E_0 = 5.10^{-4}$ GeV for electrons, E_B is the energy of the beam and R the bending radius.

7723 For the LHeC, the beam energies will be equivalent to the LEP at start. Then, a similar value of the
 7724 critical energy can be assumed allowing the comparison with LEP pressure observations. Figure 9.19 shows
 7725 typical photo-desorption yields measured on copper and stainless steel samples. But the beam intensities
 7726 being by far larger, the linear photon flux which scales linearly (equation 3) with energy and intensity and
 7727 inversely with bending radius will increase significantly.

$$\Gamma[\text{photons/s/m}] = 7 \times 10^{19} \frac{EI}{\rho} \tag{9.6}$$

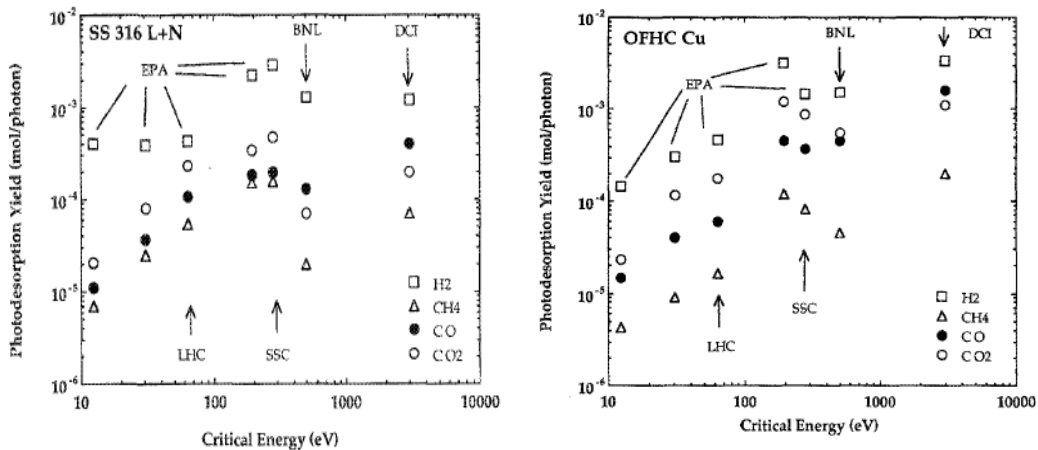


Figure 9.19: Photodesorption yields measured on copper and stainless steel surfaces. To be noted that the desorption yields of methane, η_{CH_4} , is 50 times lower than η_{H_2} .

7728 For the Ring-Ring option (bending sections and by-passes), the linear photon flux is expected to be 45
7729 times larger than in LEP, to be compared to the factor 5 expected for the Linac-Ring option.

7730 The photon stimulated pressure rise, ΔP , depends linearly on the critical energy, on the beam energy and
7731 beam intensity as shown by equation 9.7. The temperature affecting the dependence of the desorption yield
7732 (equation 9.8 and 9.9), η , to the critical energy, ϵ_c the pressure rises will differ between surfaces at ambient
7733 temperature (equation 9.8) and at cryogenic temperature (equation 9.9).

$$\Delta P \propto \eta(\epsilon_c)EI \quad (9.7)$$

$$\text{at room temperature : } \eta \propto \epsilon_c \text{ and } \epsilon_c \propto E^3 \text{ such that } \Delta P \propto E^4I \quad (9.8)$$

$$\text{at cryogenic temperature : } \eta \propto \epsilon_c^{2/3} \text{ and } \epsilon_c \propto E^3 \text{ such that } \Delta P \propto E^3I \quad (9.9)$$

7734 Therefore, the photon stimulated pressure rise is expected to be 45 times higher than LEP for the Ring-
7735 Ring option, to be compared with the factor 30 for the Linac-Ring option.

7736 Vacuum cleaning and beam scrubbing

7737 The dynamic pressure i.e. the pressure while operating the accelerator with beams will be dominated by the
7738 beam-induced dynamic effects like stimulated desorption due to beam losses or synchrotron radiations or by
7739 electron stimulated desorption in case an electron cloud is building-up.

7740 In presence of synchrotron radiation, the vacuum cleaning process which characterises the reduction of
7741 the desorption yields (η) of a surface resulting from the bombardment of the surface by electrons, photons
7742 or ions, significantly decreases the induced gas loads (3 – 4 orders of magnitude observed in LEP) improving
7743 the dynamic pressure at constant pumping speed. This results in a progressive increase of the beam lifetime.

7744 In presence of an electron cloud, the beam scrubbing which characterises the reduction of the secondary
7745 electron yield (SEY, δ) of a surface resulting from the bombardment of the surface by electrons, photons or
7746 ions, significantly decreases the induced gas loads (2 – 3 orders of magnitude observed in SPS) improving
7747 the dynamic pressure at constant pumping speed. Similarly to what happens with the vacuum cleaning, this
7748 results also in a progressive increase of the beam lifetime.

7749 By default and mainly driven by costs and integration issues, the vacuum system of an accelerator
7750 dominated by beam-induced dynamic effects is never designed to provide the nominal performances as from
7751 “day 1”. Indeed, vacuum cleaning and beam scrubbing are assumed to improve the beampipe surface
7752 characteristics while the beam intensity and beam energy are progressively increased during the first years
7753 of operation.

7754 This implies accepting a shorter beam lifetime or reduced beam current during the initial phase; about
7755 500 h of operation with beams were required for LEP to achieve the nominal performances. New technical
7756 developments such as Non-Evaporable Coatings (NEG) shall be considered since significantly decreasing the
7757 time required to achieve the nominal performances (Figures 9.20 and 9.21).

7758 9.6.3 Vacuum engineering issues

7759 The engineering of the vacuum system has to be integrated right from the beginning of the project. This
7760 becomes imperative for the Ring-Ring option since it has to take into account the constraints of the LHC and
7761 allow for future consolidations and upgrades. For the Linac-Ring option, the tangential injection and dump
7762 lines will be in common with the LHC beam vacuum over long distances. The experience has shown that
7763 the vacuum engineering shall proceed in parallel on the following topics: expertise provided to beam-related
7764 components (magnets, beam instrumentation, radio-frequency systems, etc.), engineering of vacuum related
7765 components (beampipes, bellows, pumping ports, etc.) and machine integration including the cabling and
7766 the integration of the services.

7767 Basically, the vacuum system is designed to interconnect the beam related equipments installed on the
7768 beam line (magnets, kickers, RF cavities, beam absorbers, beam instrumentation, etc.) and to provide
7769 the adequate pumping speed and vacuum instrumentation. The vacuum components are often composed

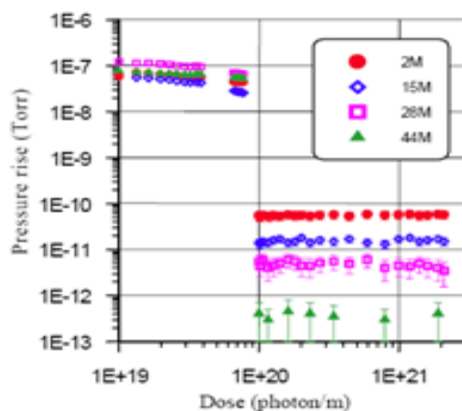
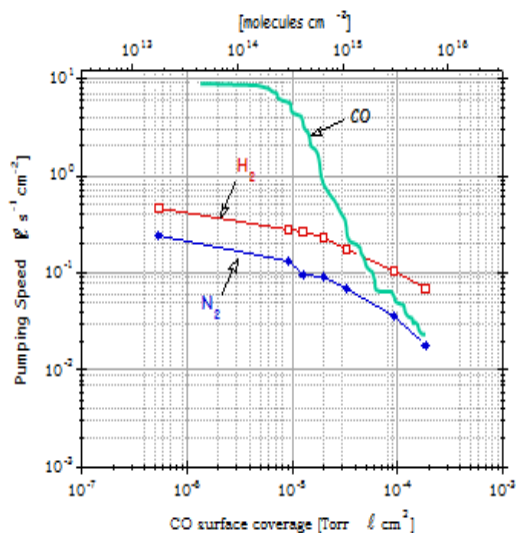
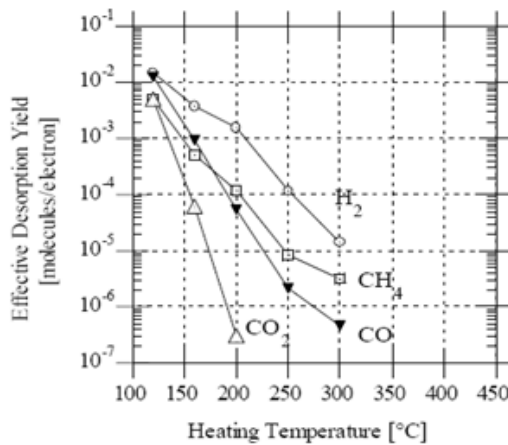


Figure 2: Pressure rise measured in the centre of the TiZrV coated test chamber before activation ($<1 \cdot 10^{20}$ photons/m) and after activation ($>1 \cdot 10^{20}$ photons/m).

Figure 9.20: NEG pumping speed for different gas species and pressure rises measured in presence of a photon flux before and after NEG activation.

Table 2: Summary of results from the activated test chamber

Gas	Sticking probability	Photodesorption yield (molecules/photon)
H ₂	~0.007	$\sim 1.5 \cdot 10^{-5}$
CH ₄	0	$2 \cdot 10^{-7}$
CO (28)	0.5	$< 1 \cdot 10^{-5}$
C _x H _y (28)	0	$< 3 \cdot 10^{-8}$
CO ₂	0.5	$< 2 \cdot 10^{-6}$



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Figure 9.21: Photon (left) and Electron (right) desorption yields.

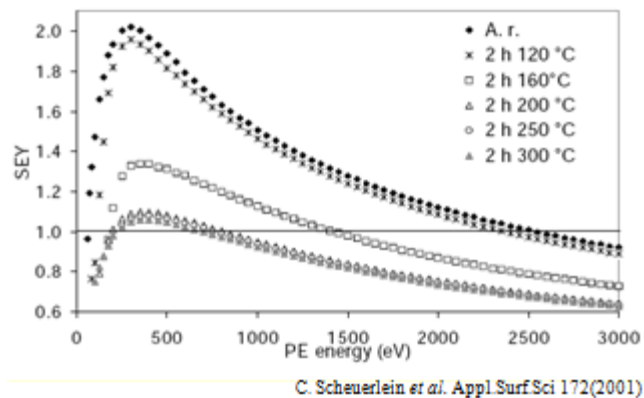


Figure 9.22: Reduction of the secondary electron yield (SEY, δ) by Photons a) and Electron b) desorption yields.

7770 by vacuum pipes, interconnection bellows, diagnostics, pumping ports and sector valves. The number of
 7771 pumps, vacuum diagnostics, bellows and ports will differ significantly between the two options discussed in
 7772 this CDR and also between vacuum sectors of the same accelerator.

7773 Vacuum pumping

7774 The vacuum system of the LHeC will be mainly operated at ambient temperature. These systems rely more
 7775 and more on NEG coatings since they provide a distributed pumping and huge pumping speed (Fig.2) and
 7776 capacity and reduce the outgassing and desorption yields (Fig.3-4). These coatings are compatible with
 7777 copper, aluminium and stainless steel beam pipes. An alternative could be to use the LEP configuration
 7778 with NEG strips. This alternative solution has only the advantage of avoiding the bake out constraints for
 7779 the activation of the NEG coatings. A configuration of a distributed ion pumps is not considered since less
 7780 performing and only applicable in dipole magnets i.e. bending sections. In any case, ion pumps are required
 7781 as a complement of the NEG coatings to pump the noble gasses and methane to avoid the ion beam-induced
 7782 instability. Sublimation pumps are not excluded in case of local huge outgassing rates, NEG cartridges being
 7783 an interesting alternative since recent developments made by manufacturers include an ion pump and a NEG
 7784 cartridge in the same body.

7785 The roughing from atmosphere down to the UHV range will be obtained using mobile turbo-molecular
 7786 pumping stations. These pumps are dismantled prior to beam circulations.

7787 The part of the vacuum system operated at cryogenic temperature, if any, could rely on gas condensation if
 7788 the operating temperatures are below 2 K. Additional cryosorbing material could be required if an important
 7789 hydrogen gas load is expected. This issue still needs to be addressed. As made for the LHC, the parts at
 7790 cryogenic temperature must be isolated from the NEG coated part by sector valves when not at their
 7791 operating temperature to avoid the premature saturation of the NEG coatings.

7792 The pumping layout will be simpler for the Ring-Ring option since more space is available around the
 7793 beam pipes. The tighter tolerances for the Linac-Ring option make the integration and pumping layout
 7794 more delicate. However, the vacuum stability will be easier to ensure in the Linac-Ring option since only
 7795 the bending sections are exposed to the synchrotron radiation.

7796 Vacuum Diagnostics

7797 For both options, the radiation level expected will be too high to use pressure sensors with onboard electron-
 7798 ics. Therefore, passive gauges shall be used, inducing additional cabling costs and need for gauge controllers.

7799 Vacuum Sectorisation

7800 The sectorisation of the beam vacuum system results from the integration of various constraints, the major
7801 being: venting and bake-out requirements, conditioning requirements (RF and HV devices), protection
7802 of fragile and complex systems (experimental areas and ceramic chambers), decoupling of vacuum parts at
7803 room temperature from upstream and downstream parts at cryogenic temperature thus non-baked, radiation
7804 issues, etc.

7805 For UHV beam vacuum systems, all-metal gate valves shall be preferred in order to allow for bake-out at
7806 temperature above 250°C. VITON-sealed valves even though the VITON has been submitted to a special
7807 treatment are not recommended nearby NEG coatings or NEG pumps since minor outgassing of Fluor will
7808 degrade the pump characteristics.

7809 In the injection and extraction regions, the installation of the sector valves will lead to integration issues
7810 since the space left between the beampipes with a tangential injection/extraction and the circulating beams
7811 is often limited. This could result in a long common beam vacuum which implies that the LHC beam vacuum
7812 requirements will apply to the LHeC part shared with LHC.

7813 Vacuum protection

7814 The distribution of the vacuum sector valves will be made in order to provide the maximum protection to
7815 the beam vacuum in case of failure (leak provoked or not). Interlocking the sector valves is not an obvious
7816 task. Indeed, increasing the number of sensors will provide more pressure indications but often results in
7817 a degradation of the overall reliability. The protection at closure (pressure rise, leaks) is treated differently
7818 from the protection while recovering from a technical stop with parts of the accelerator beampipe vented or
7819 being pumped down.

7820 The vacuum protections of the common beampipes between LHeC and LHC shall fulfill the strong LHC
7821 requirements. Indeed, any failure in the LHeC propagating to the LHC could lead to long machine downtime
7822 (several months) in case of an accidental venting of an LHC beam vacuum sector.

7823 HOM and Impedance implications

7824 The generation and trapping of higher order mode (HOM) resulting from the changes in beampipe cross-
7825 sections are severe issues for high intensity electron machines. Thus, the engineering design of LHeC must
7826 be inspired on new generation of synchrotron radiation light sources instead of the simple LEP design. All
7827 bellows and gaps shall be equipped with optimised RF fingers, designed to avoid sparking resulting from bad
7828 electrical continuity. Indeed, these effects could induce pressure rises and machine performance limitations.

7829 Bake-out of vacuum system

7830 An operating pressure in the UHV range (10^{-10} Pa) will be required for both options. This implies the use
7831 of a fully baked-out beam vacuum system. Two options are possible: permanent and dismountable bake out.
7832 The permanent solution could be an option for the Linac-Ring but has to be excluded for the Ring-Ring
7833 option for cost reasons. As done for the dipole chambers (bending sections) of LEP, hot pressurised water can
7834 be used but the limit at 150°C is a constraint for the activation of NEG coatings. Developments are being
7835 carried on at CERN to lower the activation temperature from 180°C down to 150°C but this technology is
7836 not yet available.

7837 Shielding issues

7838 The synchrotron radiation power is an engineering challenge for the beam pipes. Indeed, 50% of the radiation
7839 power hitting the vacuum chamber is absorbed in the beam pipe chamber (case of LEP aluminum chamber).
7840 The remainder 50%, mainly the high-energy part of the spectrum, escapes into the tunnel and creates severe
7841 problems like degradation of organic material and electronics due to high dose rates and formation of ozone
7842 and nitric acid could lead to severe corrosion problems in particular with aluminum and copper materials.

7843 In this respect, the Ring-Ring option is less favorable since the synchrotron radiation will be localized at
7844 the plane of the existing LHC cable trays and electrical distribution boxes in the tunnel. Similar constraints
7845 exist also for the Linac-Ring option but these zones are localized at the bending sections of the LHeC.

7846 Detailed calculations are still to be carried on but based on LEP design, a lead shielding of 3 to 8 mm
7847 soldered directly on the vacuum chamber would be required for 70 GeV beams. Higher energies could require
7848 more thickness. The evacuation of the synchrotron radiation induced heat load on the beam pipe wall and
7849 on lead shielding is a critical issue which needs to be studied. In case of insufficient heat propagation and
7850 cooling, the lead will get melted as observed in LEP in the injection areas. The material fatigue shall also
7851 be investigated since running at much higher beam current as compared to LEP, will increase the induced
7852 stress to the material and welds of the beampipes.

7853 As made in LEP, the best compromise to fulfill the above mentioned constraints is the use of aluminum
7854 beam pipes, covered by a lead shielding layer. The complex beam pipe cross-section required to optimize
7855 the water cooling of the beam pipe and shielding is feasible by extrusion of aluminum billets and the costs
7856 are acceptable for large productions. The large heat conductivity helps also the heat exchange. However,
7857 extruded aluminum beam pipes induce limitations for the maximum bake out temperature and therefore
7858 for the NEG coatings activation. Special grades of aluminum shall be used. The reliability of vacuum
7859 interconnections based on aluminum flanges is a concern at high temperature ($>150^{\circ}\text{C}$) and corrosion issues
7860 shall be addressed. The stainless steel beam pipes do not have these limitations but they have poorer heat
7861 conductivity and they are more difficult and costly to machine and shape.

7862 The LEP 110 GeV operation has shown the criticality of unexpected synchrotron radiations heating
7863 vacuum components and in particular the vacuum connections between pipes or equipments. Indeed, the
7864 flanges, by “offering” a thick path, are behaving as photon absorbers and heat up very quickly. Hence, at
7865 cool down and due to the differential dilatation, leaks are opening. In LEP, these unexpected SR induced
7866 heat loads resulted from orbit displacement in quadrupoles during the ramp in energy and of the use of the
7867 wigglers also during the ramp. In LHeC, resulting from the much higher beam current, these issues shall be
7868 carefully studied.

7869 Corrosion issues

7870 In vacuum systems, feedthroughs and bellows are particularly exposed to corrosion. The feedthroughs,
7871 particularly those of the ion pumps where high voltage is permanently present, are critical parts. A demon-
7872 strated and cheap solution to prevent the risk of corrosion consists in heating directly the protective cover
7873 to reduce the relative humidity around the feedthrough.

7874 The bellows are critical due to their thickness, often between 0.1 – 0.15 mm. PVC material must be
7875 prohibited in the tunnel. Indeed, in presence of radiations, it can generate hydrochloric acid (HCl) which
7876 corrodes stainless steel materials. This corrosion has the particularity to be strongly penetrating, once seen
7877 at the surface, it is often too late to mitigate the effects. Aluminum bellows are exposed to corrosion by
7878 nitric acid (HNO_3) which is generated by the combination of O_3 and NO.

7879 Humidity is the driving factor and shall be kept 50%. However, in the long term, accidental spillage can
7880 compromise locally the conditions and therefore, corrosion-resistant design are strongly recommended.

7881 9.7 Beam Pipe Design

7882 9.7.1 Requirements

7883 The vacuum system inside the experimental sector has a number of different and sometimes conflicting
7884 requirements. Firstly, it must allow normal operation of the LHC with two circulating beams in the cham-
7885 ber. This implies conformity with aperture, impedance, RF, machine protection as well as dynamic vacuum
7886 requirements. The addition of the incoming electron beam adds constraints in terms of geometry for the
7887 associated synchrotron radiation (SR) fan and the addition of SR masks in the vacuum. Finally, optimization
7888 of the surrounding detector for high acceptance running means that all materials for chambers, instrumen-
7889 tation and supports must be optimized for transparency to particles and the central chamber must be as

7890 small and well aligned as possible to allow detectors to approach the beam aperture limit at the interaction
7891 point.

7892 9.7.2 Choice of Materials for beampipes

7893 LHC machine requirements imply an inner beam pipe wall that has low impedance (good electrical conduc-
7894 tivity) along with low desorption yields for beam stimulated emissions and resistance to radiation damage.

7895 Ideal materials for transparency to particles have low radiation length (Z) and hence low atomic mass.
7896 These materials either have poor (i.e. high) desorption yields (eg. aluminum, beryllium) or are not vacuum
7897 and impedance compatible (eg. carbon). Solutions to this problem typically include thin film coatings to
7898 improve desorption yields and composite structures to combine good mechanical properties with vacuum
7899 and electrical properties.

7900 The LHC experimental vacuum systems, along with most other colliders currently use metallic beryllium
7901 vacuum chambers around the interaction points due to a very favourable combination of Z , electrical conduc-
7902 tivity, vacuum tightness, radiation resistance, plus mechanical stiffness and strength. High desorption yields
7903 are suppressed by a thin film TiNiV non-evaporable getter (NEG) coating. This coating also gives a high
7904 distributed vacuum pumping speed, allowing long, small aperture vacuum chambers to be used that would
7905 otherwise be conductance-limited. Activation of this coating requires periodic heating of the chamber to
7906 $180 - 220^\circ\text{C}$ under vacuum for a few hours. This means that the chamber and environment must be designed
7907 for these temperatures. This activation is scheduled in annual LHC shutdowns. Long-term development is
7908 in progress for low desorption yield coatings that do not require high temperature activation [715]. These
7909 may have applications for LHeC.

7910 Production technology developed for the LHC uses beryllium sections machined from hot-pressed blocks
7911 and electron beam welded to produce chambers. This has the advantage that a wide range of vacuum
7912 chamber forms can be manufactured. Cylindrical and conical chamber sections are installed in the LHC
7913 experiments.

7914 Disadvantages of beryllium include high cost, fragility and toxicity in the powder form, as well as limited
7915 availability. For this reason, long-term development of other technologies for experimental beam pipes is
7916 under way at CERN which may yield applications for LHeC.

7917 Composite beam pipe structures made from carbon and other low- Z materials have been developed for
7918 colliders. These typically use a thin inner membrane to comply with vacuum and impedance requirements.
7919 Composite structure pipes were eventually rejected for LHC application for reasons of temperature and
7920 radiation resistance and the risk of de-lamination due to mismatch of thermal expansion coefficients. Lower
7921 luminosity in LHeC experiments combined with new low temperature coatings may allow these materials to
7922 be re-evaluated.

7923 9.7.3 Beampipe Geometries

7924 The proposed geometry has a cross section composed of a half-circle intersecting with a half-ellipse. Cylin-
7925 drical cross-sections under external pressure fail by elastic instability (buckling) whereas elliptical sections
7926 can (depending on the geometry) fail by plastic collapse (yielding).

7927 Figure 9.23 and 9.24 show optimizations of the proposed geometries for the LINAC-Ring (LR) and Ring-
7928 Ring (RR) beam pipes assuming a long chamber of constant cross section made from beryllium metal.
7929 Preliminary analyses have been performed using the ANSYS finite element code. The wall thickness was
7930 minimized for the criteria of yield strength and buckling load multiplier. The LR geometry considered has
7931 a circular section radius of 22 mm and elliptical major radius of 100 mm. The RR geometry has a circular
7932 section radius of 22 mm and elliptical major radius of 55 mm. This preliminary analysis suggests that a
7933 constant wall thickness of $2.5 - 3\text{ mm}$ for the LR and 1.3 to 1.5 mm for the RR would be sufficient to resist
7934 the external pressure. Failure for both of these sections would be expected to occur by plastic collapse.

7935 At this stage of the project, these geometries represent the most optimized forms that fulfill the LHC
7936 machine requirements. However, for 1 degree tracks this corresponds to $X/X_0 \approx 21-25\%$ for the LR and
7937 $\approx 41-49\%$ for the RR designs. This suggests that additional effort must be put into beam pipe geometries

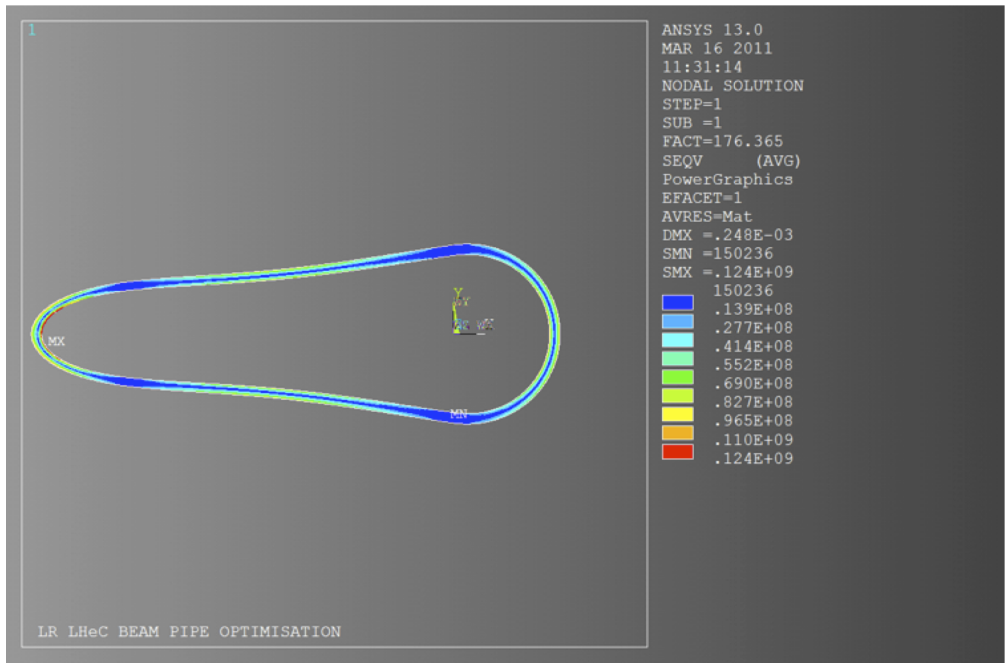


Figure 9.23: Section through the LR geometry showing contours of Von Mises equivalent stress (Pa).

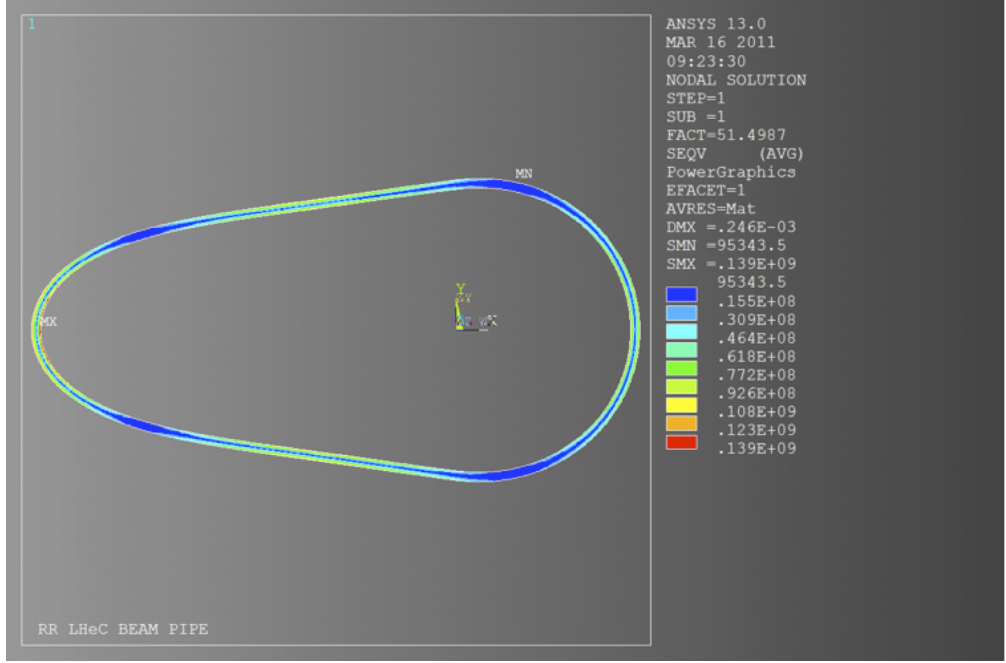


Figure 9.24: Section through the RR geometry showing contours of Von Mises equivalent stress (Pa).

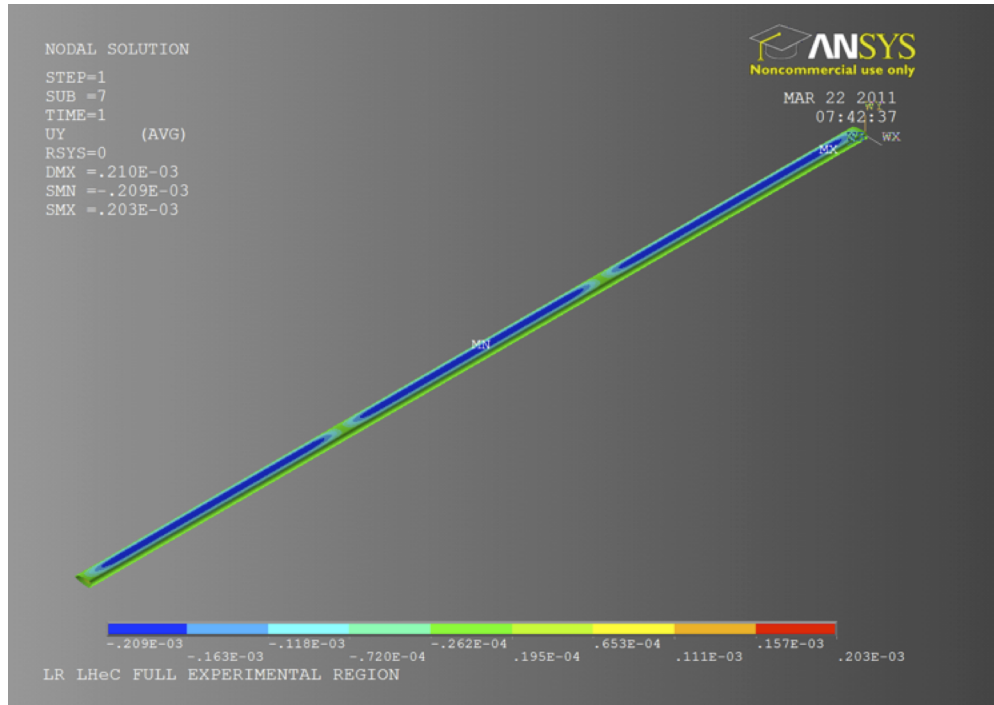


Figure 9.25: 3-D view of the LR geometry showing contours of bending displacement [m].

7938 optimized for low angles. Composite beam pipe concepts suggested for machines such as the LEP [716]
 7939 should be re-considered in the light of advances in lightweight materials and production techniques.

7940 The optimized section of the experimental chamber is 6.1 m in length. This length will require a number of
 7941 optimized supports. These supports function to reduce bending deflection and stresses to within acceptable
 7942 limits and to control the natural frequency of chamber vibration. The non-symmetric geometry will lead to
 7943 a torsional stress component between supports which must be considered in their design. Figure 9.25 shows
 7944 a preliminary analysis of bending displacement for the LR chamber geometry. With 2 intermediate supports
 7945 the maximum calculated displacement (without bakeout equipment) is 0.21 mm.

7946 9.7.4 Vacuum Instrumentation

7947 If, as assumed, this chamber is coated with a NEG film on the inner surfaces, then a high pumping speed of
 7948 chemically active gasses will be available. Additional lumped pumps will be required for non-gettered gasses
 7949 such as CH_4 and noble gasses; however, outgassing rates for these gasses are typically very low.

7950 The vacuum sector containing the experiment will be delimited from the adjacent machine by sector
 7951 valves. These will be used to allow independent commissioning of machine and experiment vacuum. The
 7952 experimental vacuum sector will require pressure gauges covering the whole range from atmospheric to UHV,
 7953 these are used both for monitoring the pressure in the experimental chamber and as interlocks for the machine
 7954 control system.

7955 9.7.5 Synchrotron Radiation Masks

7956 LHeC experimental sector will require a moveable SR mask upstream of the interaction. From the vacuum
 7957 perspective, this implies a system for motion separated from atmosphere by UHV bellows. The SR flux on
 7958 the mask will generate a gas load that should be removed by a local pumping system dedicated to the mask.
 7959 As the load due to thermally stimulated desorption increases exponentially with the temperature, cooling

7960 may be required. However, cooling the mask would significantly complicate the vacuum system design. The
7961 generation of photo-electrons must also be avoided since these photo-electrons can interact with the proton
7962 beam and lead to an electron cloud build-up.

7963 **9.7.6 Installation and Integration**

7964 The installation of the vacuum system is closely linked to the detector closure sequence. Therefore, the
7965 design has to be validated in advance to prevent integration issues which would lead to significant delay
7966 and increase of costs. Temporary supports and protections are required at each stage of the installation.
7967 Indeed, as compared to the size of the detectors, the beam pipe are small, fragile and need to be permanently
7968 supported and protected while moving the detector components. Leak tightness and bake-out testing are
7969 compulsory at each step of the installation since all vacuum systems are subsequently enclosed in the detector,
7970 preventing any access or repair. Their reliability is therefore critical. Precise survey procedures must also
7971 be developed and incorporated in the beam pipe design to minimize the mechanical component of the beam
7972 aperture requirement. Engineering solutions for bake out also has to be studied in details since the equipment
7973 (heaters, probes and cables) must fit within the limited space available between beam pipes and the detector
7974 components.

9.8 Cryogenics

9.8.1 Ring-Ring Cryogenics Design

Introduction

The Ring-Ring version foresees the 60 GeV accelerator to be installed in the existing LHC tunnel. Acceleration of the particles is done with 0.42 m long 5 MV superconducting (SC) cavities housed in fourteen 10 m long cryomodules. They will be placed at two opposite locations in by-passes of point 1 (ATLAS) and, point 5 (CMS). While at CMS a continuous straight by-pass can be built, at ATLAS two straight sections are conceived on each side of the detector cavern (“left” and “right”) with a connecting beam pipe crossing the detector hall. Lay-outs and detailed RF description see Chapter 9.3. The three separate cryomodules locations require three dedicated 2 K cryo-systems. Injection to the Ring at 10 GeV is done with a 1.3 GHz pulsed three-pass re-circulating high field injector. A dedicated cryoplant provides 2 K cooling of its SC cavities. In total four independent cryoplants with their respective distribution systems are needed for the Ring-Ring version. For the LHeC detector the high gradient focusing insertion magnets will be SC and housed in LHC dipole type cryostats. The cooling principle is the same as for LHC dipoles and, the existing cryogenic infrastructure can be used with comparatively small adaptations of the feed boxes. More detailed engineering studies are beyond the scope of this report. This chapter describes the cryosystems of the e-Ring accelerator and the related injector.

Ring-Ring cryogenics

The cavities operate at 2 K superfluid helium temperatures and dissipate an estimated 4 W per cavity at 5 MV. The 8-cavity cryomodule has three temperature levels; a 2 K saturated bath containing the cavities, a 5 – 8 K combined thermal shield and heat intercept for couplers and other equipment and, a 40 – 80 K thermal shield. The thermal loss estimates are listed in Table 9.18 . With efficiencies of modern state of the art cryoplants reaching 1/COP values of 1000 W/W at 2 K, 250 W/W at 5 K and 20 W/W at 40 – 80 K the minimum plant powers are calculated. To the equivalent cooling power at 4.5 K we add a 50% contingency for the distribution system with transfer lines running parallel to the cryomodules. In Table 9.19 the equivalent cooling powers of the three cryoplants are given.

Temperature (K)	2	5 – 8	40 – 80
One cryomodule			
Static loss (W)	5	15	100
Dynamic loss (W)	32	15	80
Sum (W)	37	30	180
8 modules (CMS site) (W)	296	240	1440(2160)
3 modules (ATLAS left) (W)	111	90	720(1080)
3 modules (ATLAS right) (W)	111	90	720(1080)

Table 9.18: Thermal loss estimate of cryomodules. In brackets the values with ultimate thermal losses (50% contingency) which are taken into account for the cryoplant sizing.

At CMS site a dedicated 3 kW @ 4.2 K cryoplant is needed. Except for some general infrastructure equipment like e.g. gas tanks it will be separated from the existing CMS cryoplant used to cool the solenoid magnet. Comparatively modest cooling powers suggest the use of a single compact refrigerator cold box, in contrast to split versions as proposed in this CDR for the Linac-Ring version described below. (The split version is based on LHC technology with a combined surface and underground cold box.) The cold box will be installed directly in the underground cavern at proximity to the cryomodule string. Ambient temperature high and low pressure lines make the link to the compressor stations on surface. For the 2 K

Site	Plant power @ 4.2 K (kW)
CMS site	3.0
ATLAS left	1.2
ATLAS right	1.2

Table 9.19: Cryoplant equivalent cooling powers.

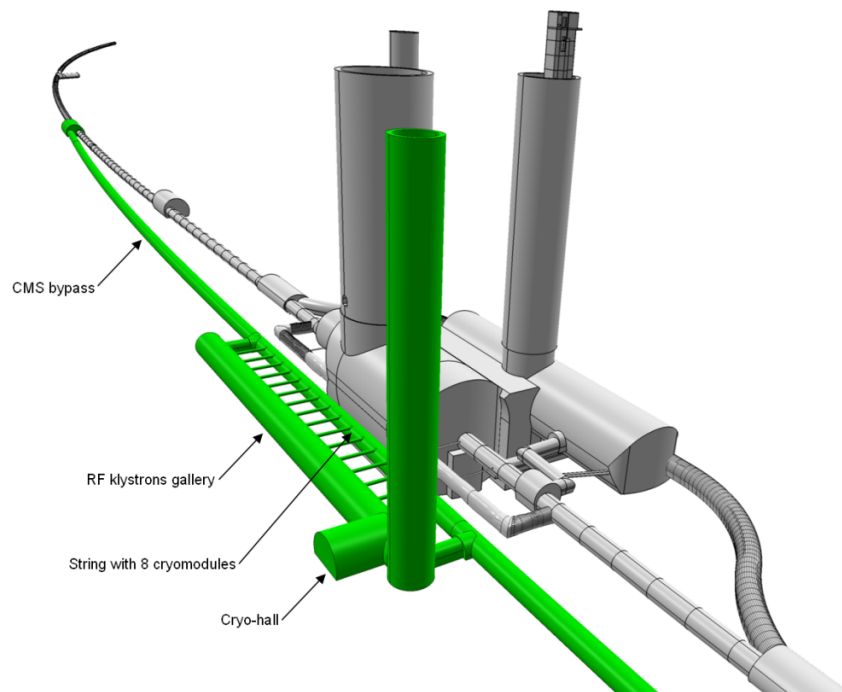


Figure 9.26: Lay-out of the CMS by-pass with location of the cryomodules and the 3 kW @ 4.5 K cryoplant.

8008 temperature level two cold compressors with a total compression ratio of 10 are proposed followed by warm
8009 compressors to compress the gas to ambient pressure. Figure 9.26 shows the lay-out of the CMS by-pass
8010 region. At the two ATLAS sites (left, right) with three cryomodules each, two options are conceivable. The
8011 first consists of connecting to the LHC QRL transfer lines and their terminal feedboxes at vicinity for a
8012 “parasitic” use of excessive cooling power of the LHC cryoplants. For this two additional 10 – 15 m long
8013 perpendicular tunnels to connect the LHC tunnel with the LHeC by-pass would have to be constructed. The
8014 feasibility of this option and potential (negative) impacts have to be studied in more detail in a subsequent
8015 report. The second option is to use two dedicated cryoplants as proposed for the CMS site, however, with
8016 reduced capacity. Also in this case the cold box will be installed at proximity to the cryomodule strings in
8017 the cryo-hall. The two refrigerators are of the same design principle as for CMS, except for their size and
8018 capacity which is smaller. Their location will be on ATLAS terrain which allows to potentially use already
8019 existing cryogenic infrastructure of the large cryo-system for the cooling of the ATLAS toroidal and solenoid
8020 magnets. Among these are the gas storage tanks, the compressor hall and control rooms. Figure 9.27 shows
8021 the lay-out of the ATLAS by-pass region.

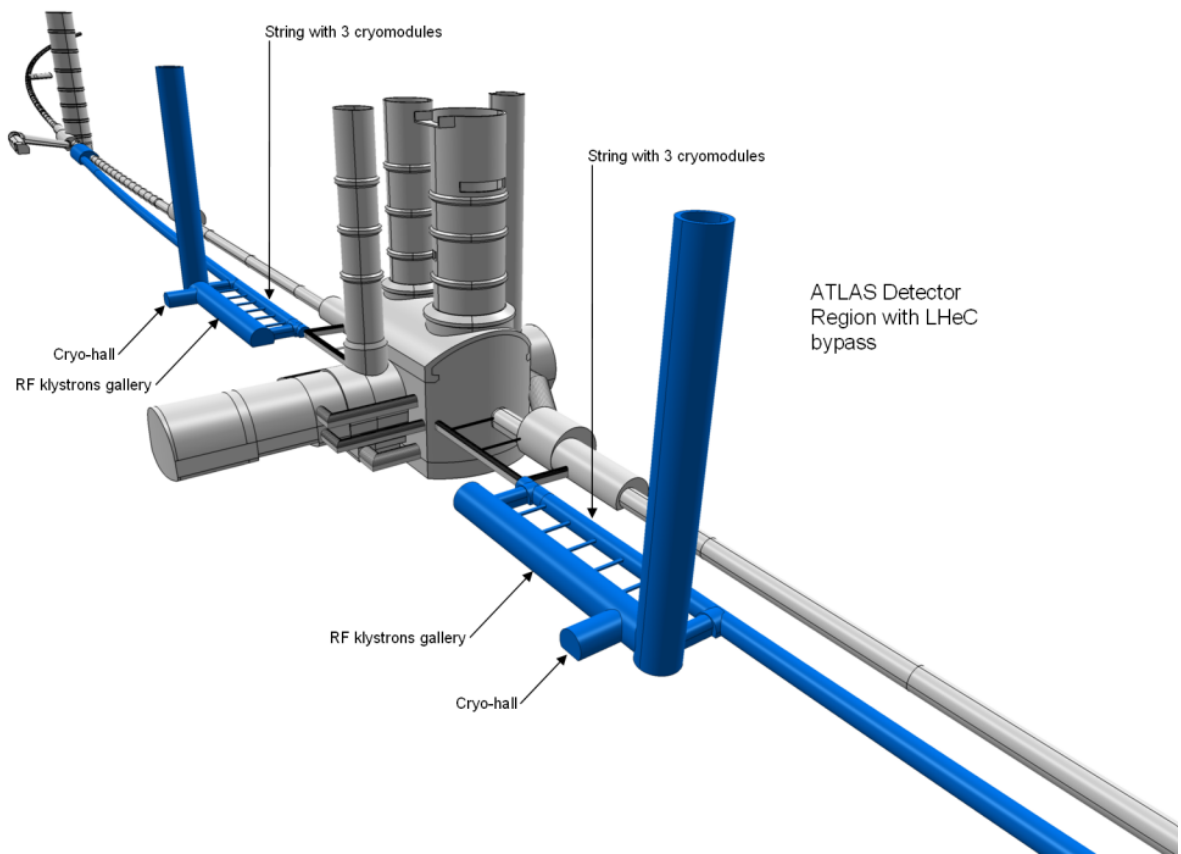


Figure 9.27: Lay-out of the ATLAS by-pass with locations of the cryomodules and the two 1.2 kW @ 4.5 K cryoplants.

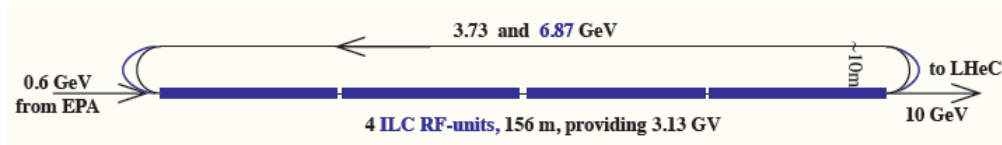


Figure 9.28: Principle of the 10 GeV re-circulating Injector with high gradient pulsed SC cavities (23 MV/m) and 12 cryomodules of the ILC/XFEL type operating at 2 K.

Cryogenics for the 10 GeV Injector

The injector is a three-pass recirculating pulsed 10 Hz machine providing leptons at injection energies of 10 GeV to the LHeC Ring machine. Figure 9.28 shows its basic principle. Cryomodules of the XFEL (ILC) type with 1.3 GHz superconducting cavities are proposed which allow the application of already existing technology requiring little adaptation effort for LHeC. A 146 m long string will be composed of in total 12 cryomodules each 12.2 m long. Cryogen distribution is done within the volume of the cryostats. Bath cooling is at 2 K saturated superfluid helium. Adopted from XFEL the common pump line of 300 mm runs within the cryomodules envelope to collect vapor of all individual cavity baths. Therefore no external transfer line is required which simplifies the overall design. The suction pressure of 30 mbar is provided by cold compressors in the cold box and subsequent ambient temperature compressors. Two more temperature levels of 5–8 K and 40–80 K are used for intercepts and thermal shielding. The operation of the injector at LHeC is in part comparable to XFEL, this during the injection and loading phase of leptons into the LHeC ring. During all other operation phases of a complete LHeC cycle (ramping to final particle energies in the LHC/LHeC tunnel and subsequent physics runs) the injector machine is “idle”. Only static heat losses of the cryomodules and the cryogenic infrastructure have to be intercepted during this time period. Principally a reduced power cryogenic system operating with an “economizer” could be conceived, i.e. a large liquid helium storage is filled during low demands which in turn boosts the cryomodules during the injection phases. A simpler approach, however, is the design for constant (maximum) cooling power when active and, during idle periods, internal electric heaters in the 2 K bath are switched on to keep the load constant. This principle is adopted for these initial studies. A compact single refrigerator cold box providing temperatures from 300 K to 2 K will be installed in a protected area at vicinity to the extraction region of the cryomodule string while the compressor set is at surface. For the estimation of power consumption and cooling performances we shall use the experience gained at DESY during testing of XFEL cryomodules. With a final energy of 10 GeV and three pass operation the acceleration field required is 23 MV/m. At DESY power consumption measurements have been made with cryomodules for a similar acceleration field of 23.8 MV/m and 10 Hz operation. Our estimates as shown in the Table 9.20 are based on these recent data. With 1/COP values as used in above chapter and a 50% margin for additional thermal losses we estimate the required cooling power of the plant to 2 kW @ 4.5 K.

Temperature (K)	2	5 – 8	40 – 80
Static loss (W)	5	15	100
Dynamic loss (W)	8	3	40
Sum (W)	11	18	140
Sum 12 modules (W)	132(198)	216(324)	1680(2520)

Table 9.20: Thermal loss estimate of the 146 m long string built of 12 XFEL type cryo-modules. In brackets values with 50% contingency. Cryoplant equivalent cooling power; 2 kW @ 4.5 K.

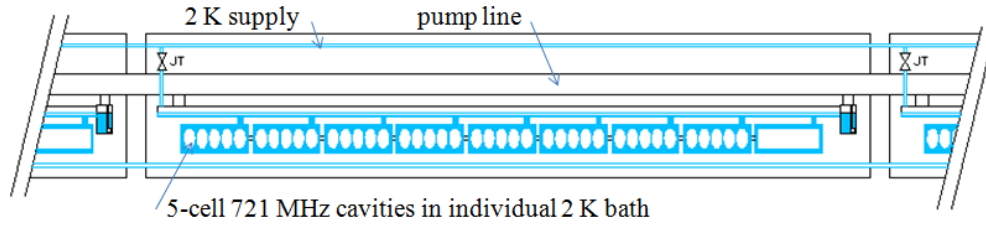


Figure 9.29: Schematic proposal of the 14 m long cryomodules with eight 5-cell 721 MHz cavities operating at 2 K. Supply pipes and the 30 mbar pump line are within cryostat envelope. For the case with inclination right part is lower (only 2 K circuits are shown).

9.8.2 Linac-Ring Cryogenics Design

Location and basic lay-out

The ERL (Energy Recovery Linac) is of racetrack shape with two 1 km long straight SC acceleration sections and, two arcs of 1 km radius with normal conducting magnets. Location and lay-out studies made are described in chapter 10. The currently favored position is within the LHC perimeter (see Figure 10.9) versus the external version being largely under St. Genis community. For the “inside” version more of the newly required surface areas could be located on existing CERN grounds comprising SM18, North Area and, Point 2. Next steps following this CDR will require more detailed combined studies of civil engineering, RF, cryogenics and other services to try optimize the lay-out also, and in particular, for the cryogenic equipment having impact on its own complexity and costs. As base in this study we propose a symmetric lay-out with a sub-division of the respective 1 km long straight sections in four equally spaced sections each housing four 250 m long cryomodule strings. As indicated in chapter 10, the ERL will be inclined towards the Lake of Geneva by 1.4%, however, due to its orientation the tilt in longitudinal direction relevant to the cryogenics is smaller.

Cryomodules

Eight 721 MHz SC 5-cell cavities of length 1.04 m long will be housed in 14 m long cryomodules. Bath cooling of the cavities is done with slightly subcooled saturated superfluid helium at 2 K. Each cryostat is equipped with a J.T. valve located upstream to expand the 2 K supply helium to the 30 mbar bath pressure and the liquid is brought gravity assist to the downstream individual 8 cavity bath volumes via an interconnecting header pipe. This principle is similar to the SPL preliminary design which has to cope with a tilt of 1.7% [717]. Heat intercept and thermal shielding is at 5-8 K and 40-80 K. The final LHeC L-R cryomodule design can be based on extensive previous work and studies of both existing SC linear accelerators and, such being under construction or planned ones. Among these are CEBAF, ILC, XFEL, SPL, e-RHIC. For this study adapted TESLA/XFEL type cryomodules are proposed. Figure 9.29 shows a design proposal of a module with the eight cavities and the cold correction magnets in their individual bath. All cryogen distribution is done within the cryostat module which interconnects to the adjacent ones with the pipe runs throughout a 250 m long cryomodule string. Also the pump line is proposed to be within the cryostat envelope. The expected mass flow rate of 180 g/s at 2 K of a 250 m long section with 15 cryomodules (see calculations next chapter) is approximately comparable to XFEL for its entire machine for which the corresponding pump line diameter has been designed and tested [718]. The parameters of the LHeC SC cavities and cooling requirements are listed in Table 9.21.

Parameter	Value
Two linacs	length 1 km
5-cell cavities	length 1.04 m
Number	944
Cavities/ cryomodule	8
Number cryomodules	118
Length cryomodule	14 m
Voltage per cavity	21.2 MV
R/Q	285 Ω
Cavity Q_0	$2.5 \cdot 10^{10}$
Operation	CW
Bath cooling	2 K
Cooling power/cav.	32 W @ 2 K
Total cooling power (2 linacs)	30 kW @ 2 K

Table 9.21: Parameters and cooling requirements of the ERL (Linac-Ring version).

8081 Cryogenic System

8082 The estimated thermal loads per cavity are based on a voltage of 21.2 MV, an R/Q of 285 Ω and a Q_0
8083 of $2.5 \cdot 10^{10}$. With CW operation the dissipated heat per cavity will be 32 W, respectively 256 W per
8084 cryomodule. This consists of a very high load. The 1 km long straight sections are sub-divided in four 250 m
8085 long sub-sections each with 15 interconnecting cryomodules forming a string which are individually supplied
8086 by a respective refrigerator through local distribution boxes. Eight dedicated refrigerators supply the eight
8087 strings. Figure 9.30 gives a basic lay-out of the cryo-system with its sectorisation. The refrigerator cold boxes
8088 will be of the so-called “split” type with a surface cold box and a connecting underground cold box as explored
8089 and implemented first for LEP2 and later at a larger scale for LHC. The surface cold box will be installed
8090 close to the compressor set and produce temperature levels between 300 K and 4.5 K. The underground
8091 cold box will be installed at proximity to the respective cryomodule string in a protected area and produce
8092 the 2 K with cold compressors. Figure 9.31 gives a principle lay-out of the refrigerator configuration. The
8093 final location of the ERL will dictate civil engineering constraints and the “ideal” symmetric configuration
8094 of placement of the refrigerators as done here will have to be reviewed accordingly and, hence, partially
8095 deviate from this proposal. Also in case only one access shaft per linac can be conceived the four surface
8096 cold boxes may be installed in form of clusters around the pit while the four related 2 K underground cold
8097 boxes will be installed remotely close to the respective cryomodule string to be supplied as described above
8098 and shown in Figure 9.30. The total dynamic cooling power of the ERL with 944 cavities amounts to 30 kW
8099 @ 2 K. For the calculation of the cooling performances of the refrigerators in this document only the largely
8100 dominating dynamic thermal loads of the cavities are taken into account dwarfing all other thermal losses
8101 of the cryomodules which become negligible in a first order approach. Recent developments and industrial
8102 design of large scale refrigerator systems as for LHC [719] indicate the feasibility of a 1/COP of 700 W/W
8103 for 2 K large scale cryoplants. Hence, with this figure the total electric grid power amounts to 21 MW. The
8104 total equivalent refrigerator power at 4.5 K is estimated to 80 kW. This corresponds to about half of the
8105 installed cooling power at LHC. In case contingencies are taken into account in the engineering design the
8106 cooling capacity could approach LHC. For this preliminary study contingencies are omitted, this also in view
8107 of expected future improved cavity performances. Eight cryoplants with 10 kW @ 4.5 K each are proposed
8108 for the ERL. The technology to design and construct such units as well as the overall systems engineering is
8109 largely available today and can be based on experience from LHC, CEBAF, XFEL. Nevertheless it consists
8110 of an engineering challenge due to its sheer size and the large performance capacities required. Development
8111 work will have to be done for the cold compressors units together with detailed combined CERN/industrial

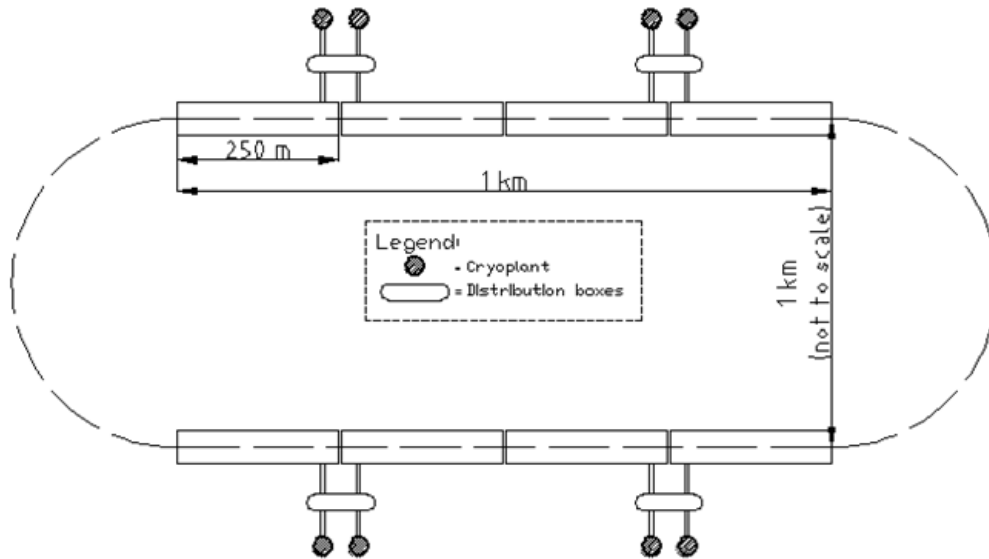


Figure 9.30: Basic lay-out of the 6 pass ERL. Two 1 km long SC acceleration sections with a 10 GeV linac each. Eight 10 kW @ 2 K cryoplants. Configuration such that each plant supplies a cryomodule string of 250 m length (figure not to scale).

8112 engineering design of the refrigerator cold boxes. Implementation and operation of such large systems will
 8113 consist of a complex task. Further cavities and cryomodules will require a limited R&D program. From this
 8114 we expect improved quality factors with respect to today's state of the art. The cryogenics of the L-R version
 8115 consists of a formidable engineering challenge, however, it is feasible and, CERN disposes of the respective
 8116 know-how.

Parameter	Value
Number of Refrigerators	8
1/COP @ 2 K	700
Minimum cooling capacity/refrigerator	10 kW @ 4.5 K
Contingency	none
Minimum total cooling power	80 kW @ 4.5 K
Grid power consumption	21 MW

Table 9.22: Refrigerator cooling capacity and power consumption (minimum cooling power).

8117 9.8.3 General Conclusions Cryogenics for LHeC

8118 These conclusions reference to the complete cryogenic contributions, i.e. for the detector cryogenics, the R-R
 8119 and the L-R version;

8120 The striking advantage of an extension from LHC to a LHeC lies, apart from the new physics, in the
 8121 comparatively small investment cost, the possibility of quasi undisturbed continuation of LHC hadron physics
 8122 and the fact that the technologies are largely already at hand today. This applies also to the cryogenic part.
 8123 No so-called "show-stoppers" could be detected during these studies. For the detector SC magnet and

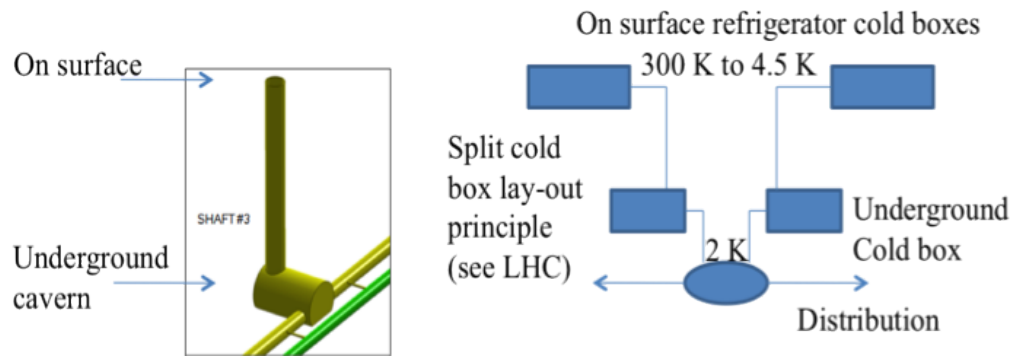


Figure 9.31: Basic principle of a Split Cold Box lay-out (comparable to LHC accelerator cryogenics).

8124 LArgon cryogenics technologies developed and implemented at the ATLAS experiment can be used in a
 8125 “down-scaled” way. For the accelerator cryogenics the two options Ring-Ring and Linac-Ring differ strongly
 8126 in principle and investment. While for the R-R only four small to medium sized 2 K refrigerators are
 8127 required, for the cryomodules of the injector and the three LHC tunnel bypasses, the L-R option with two
 8128 1 km long CW operated 2 K SC cavities is extremely demanding. The total installed cryogenic power will
 8129 likely exceed 100 kW @ 4.5 K equivalent, approaching values of the LHC. However, these estimates are only
 8130 based on currently proved data of the cavity Q_0 . The development of high Q SC cavities is being pursued
 8131 in several laboratories and new encouraging results are on the horizon indicating improvement of quality
 8132 having positive and direct impact for cryogenic requirements and respective plant sizes.

9.9 Beam Dumps and Injection Regions

9.9.1 Injection Region Design for Ring-Ring Option

A 10 GeV recirculating Linac will be used to inject the electrons in the LHeC. This will be built on the surface or underground and a transfer line will connect the linac to the LHeC injection region. At this stage a purely horizontal injection is considered, since this will be easier to integrate into the accelerator. The electron beam will be injected in the bypass around ATLAS, with the baseline being injection into a dispersion free region (at the right side of ATLAS). Bunch-to-bucket injection is planned, as the individual bunch intensities are easily reachable in the injector and accumulation is not foreseen. Two options are considered: a simple septum plus kicker system where single bunches or short trains are injected directly onto the closed orbit; and a mismatched injection, where the bunches are injected with either a betatron or dispersion offset.

Injection onto the closed orbit

The baseline option is injection onto the orbit, where a kicker and a septum would be installed in the dispersion free region at the right side of ATLAS bypass (see Fig. 9.32). Injecting the beam onto the closed orbit has the advantage that the extra aperture requirements around the rest of the machine from injection oscillations or mismatch are minimised. The kicker and septum can be installed around a Defocusing

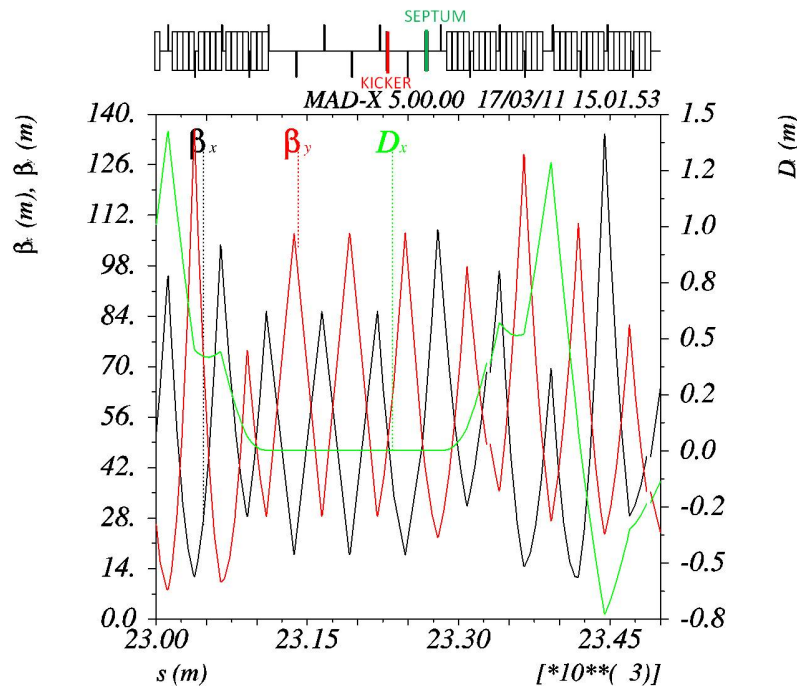


Figure 9.32: Injection optics is shown. The sequence starts ($s=0$) at the beginning of the dispersion suppressor at the left side of IP2 and proceeds clockwise, while the electron beam rotates counterclockwise (from right to left in the figure). The injection kicker and septum are installed in the dispersion free region of the bypass at the right side of ATLAS.

quadrupole to minimise the kicker strength required. The kicker-septum phase advance is 75° .

Some assumptions made to define the required element apertures are made in Table 9.23.

For the septum, an opening between injected and circulating beam of 47 mm is required, taking into account some pessimistic assumptions on orbit, tolerances and with a 4 mm thick septum. This determines

8153 the kicker strength of about 1 mrad.

Orbit variation	± 4 mm
Injection precision	± 3 mm
Mechanical/alignment tolerance	± 1 mm
Horizontal normalised emittance $\varepsilon_{n,x}$	0.58 mm
Vertical normalised emittance $\varepsilon_{n,y}$	0.29 mm
Injection mismatch (on emittance)	100 %
β_x, β_y @ Kicker	61.3 m, 39.7 m
β_x, β_y @ Septum	57.3 m, 42.3 m
σ_x, σ_y @ Kicker and Septum	0.8 mm, 0.4 mm

Table 9.23: Assumptions for beam parameters used to define the septum and kicker apertures

8154 The septum strength should be about 33 mrad to provide enough clearance for the injected beam at the
 8155 upstream lattice quadrupole, the yoke of which is assumed to have a full width of 0.6 m. This requires about
 8156 1.1 T m, and a 3.0 m long magnet at about 0.37 T is reasonable, of single turn coil construction with a
 8157 vertical gap of 40 mm and a current of 12 kA.

8158 The RF frequency of the linac is 1.3 GHz and a bunch spacing of 25 ns is considered, as the LHeC electron
 8159 beam bunch structure is assumed to match with the LHC proton beam structure. Optimally a train of 72
 8160 bunches would be injected, which would require a 1.8 μ s flattop for the kickers and a very relaxed 0.9 μ s
 8161 rise time (as for the LHC injection kickers [720]). However, this train length is too long for the recirculating
 8162 linac to produce, and so the kicker rise time and fall time requirements are therefore assumed to be about
 8163 23 ns, to allow for the bunch length and some jitter.

8164 For a rise time $t_m = 23$ ns, a system impedance Z of 25 Ω is assumed, and a rather conservative system
 8165 voltage U of 60 kV.

8166 Assuming a full vertical opening h of 40 mm, and a full horizontal opening w of 60 mm (which allow ± 6
 8167 σ beam envelopes with pessimistic assumptions on various tolerances and orbit), the magnetic length l_m of
 8168 the individual magnets is:

$$l_m = ht_m Z / \mu_0 w = 0.31 \text{ m}$$

8169 For a terminated system the gap field B is simply:

$$B = \frac{\mu_0 U}{2hZ} = 0.037 \text{ T}$$

8170 As 0.03 Tm are required, the magnetic length should be 0.8 m, which requires 3 magnets. Assuming each
 8171 magnet is 0.5 m long, including flanges and transitions the total installed kicker length is therefore about
 8172 1.5 m.

8173 Mismatched injection

8174 A mismatched injection is also possible, Figure 9.33 with a closed orbit bump used to bring the circulating
 8175 beam orbit close to the septum, and then switched off before the next circulating bunch arrives.

8176 The injected beam then performs damped betatron or synchrotron oscillations, depending on the type of
 8177 mismatch used. In LHeC the damping time is about 3 seconds, so that to achieve the suggested 0.2 s period
 8178 between injections, a damping wiggler would certainly be needed - the design of such a wiggler needs to be
 8179 investigated.

8180 Three kickers (KICKER 1, KICKER 2 and KICKER 3 in Fig. 9.33) are used to generate a closed orbit
 8181 bump of 20 mm at the injection point. The kicker parameters are summarized in table 9.24. In case of

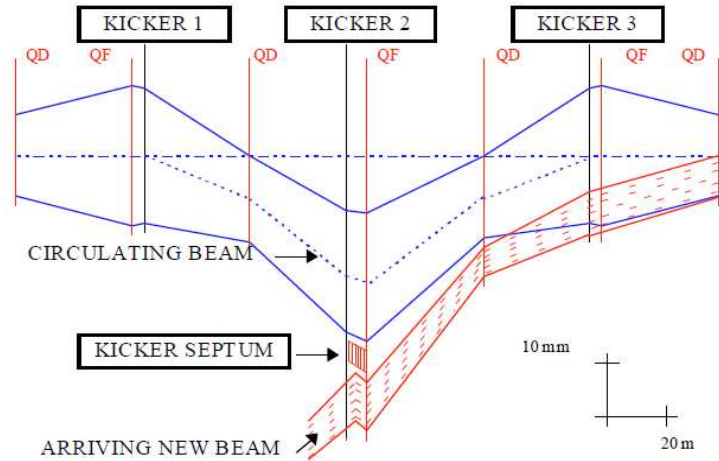


Figure 9.33: layout of mismatched injection system. To minimise kicker strengths the magnets are located near focusing quadrupoles.

Magnet	θ_x [mrad]	B dl [Tm]
KICKER1	1.35	0.04
KICKER2	2.37	0.08
KICKER3	0.55	0.02

Table 9.24: Kickers strength and integrated magnetic field needed to generate an orbit bump of 20 mm at the injection point.

8182 betatron mismatch, the bumpers can be installed in the dispersion free region considered for the injection
 8183 onto the closed orbit case discussed in the previous section (see Fig. 9.34). The installed magnet lengths of
 8184 the kickers should be 2 m, 3.5 m and 1 m respectively, for the kickers size, Z and U parameters given above.
 8185 Overall the kicker system is not very different to the system needed to inject onto the orbit.

8186 To allow for the possibility of synchrotron injection, the injection kicker-septum would need to be located
 8187 where the horizontal dispersion D_x is large. The beam is then injected with a position offset x and a
 8188 momentum offset δp , such that:

$$x = D_x \delta p$$

8189 The beam then performs damped synchrotron oscillations around the ring, which can have an advantage
 8190 in terms of faster damping time and also smaller orbit excursions in the long straight sections, particularly
 8191 experimental ones, where the dispersion functions are small.

8192 As an alternative to the fast (23 ns rise time) kicker for both types of mismatched injection, the kicker
 8193 rise- and fall-time could be increased to almost a full turn, so that the bump is off when the mismatched
 8194 bunch arrives back at the septum. This relaxes considerably the requirements on the injection kicker in
 8195 terms of fall time. However, this does introduce extra complexity in terms of synchronizing the individual
 8196 kicker pulse lengths and waveform shapes, since for the faster kicker once the synchronization is reasonably
 8197 well corrected only the strengths need to be adjusted to close the injection bump for the single bunch.

8198 9.9.2 Injection transfer line for the Ring-Ring Option

8199 The injection transfer line from the 10 GeV injection recirculating linac is expected to be straightforward.
 8200 A transfer line of about 900 m, constituted by 15 FODO cells, has been considered. The phase advance of

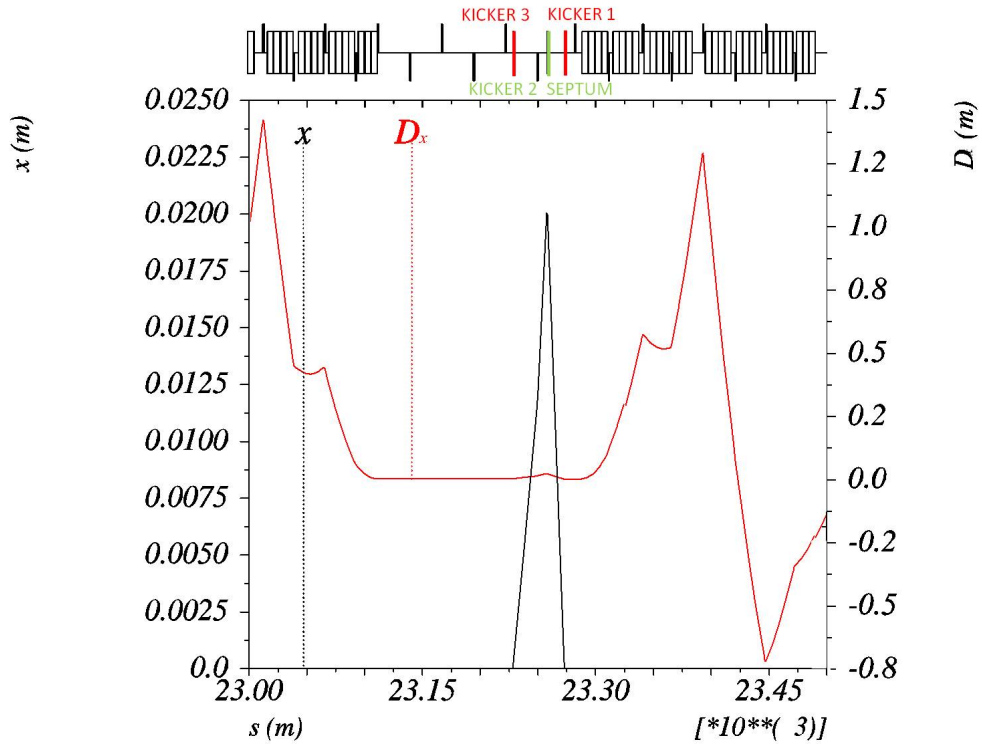


Figure 9.34: A closed orbit bump of 20 mm is generated by three kickers installed in the dispersion free region located at the right side of the bypass around ATLAS (electron beam moves from right to left in the Figure).

8201 each cell corresponds to about 100° .

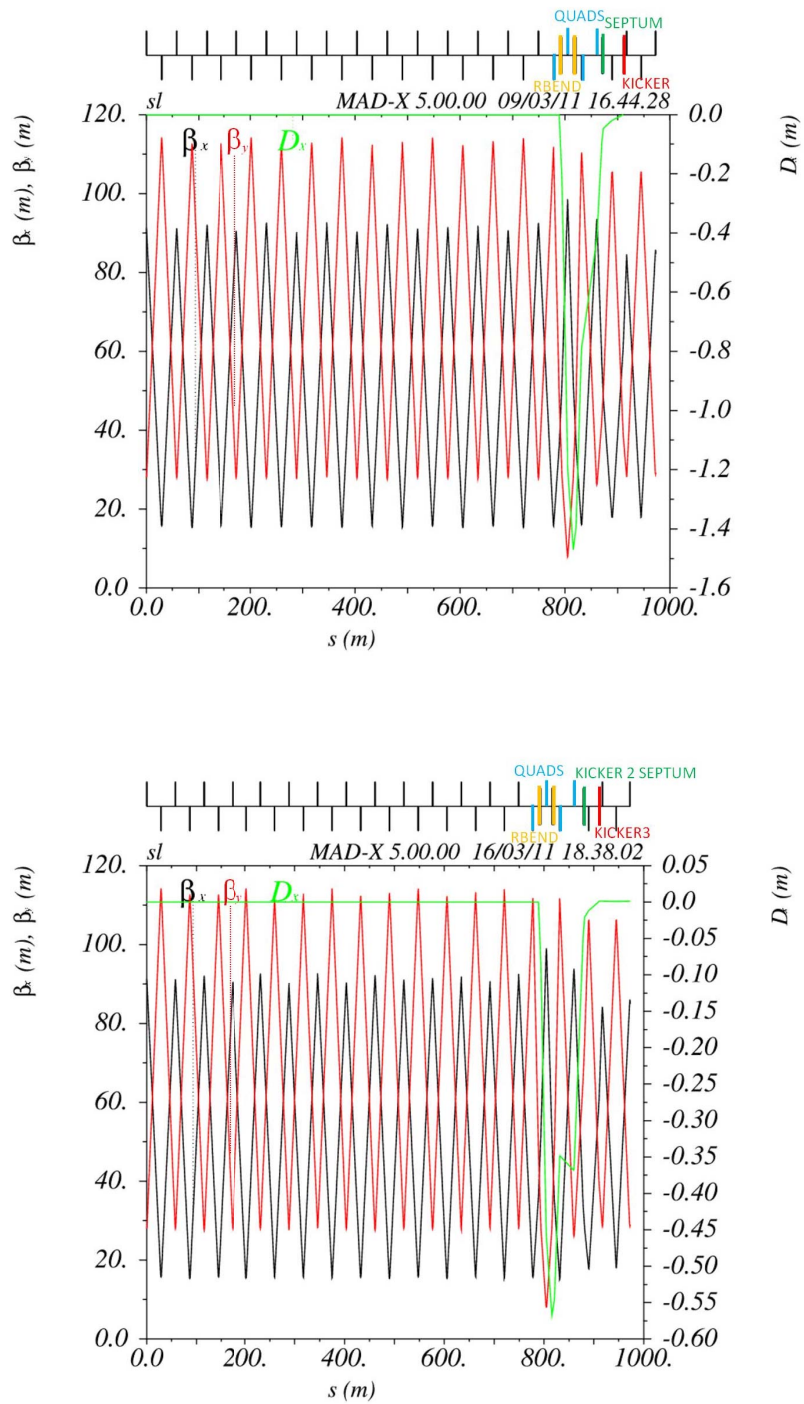


Figure 9.35: Transfer line optics for the injection onto orbit case (top) and mismatched injection case (bottom).

8202 The last two cells are used for optics matching. In particular, four quadrupoles, 1 m long each, are used
 8203 for β_x and β_y matching, while two rectangular bending magnets, 5 m long each, are used for matching the
 8204 horizontal dispersion D_x to 0 (maximum $D_x = -1.48$ m for the injection onto closed orbit case and maximum
 8205 $D_x = -0.57$ m for the mismatched injection case). The “good field region” for a 6σ beam envelope requires
 8206 a minimum half-aperture, in the matching insertion, of 15 mm and 10 mm for the focusing and defocusing
 8207 quadrupoles respectively, corresponding to a pole tip field of about 0.02 T. The maximum strength of the
 8208 bending magnets, which are used for dispersion matching, corresponds to about 39 mrad. This requires
 8209 1.3 T m and a maximum field of 0.3 T. A single turn coil of 9.5 kA with a vertical gap of 40 mm could be
 8210 used.

8211 9.9.3 60 GeV internal dump for Ring-Ring Option

8212 An internal dump will be needed for electron beam abort. The design for LEP [721] consisted of a boron
 8213 carbide spoiler and an Aluminum alloy (6% copper, low magnesium) absorbing block (0.4 m \times 0.4 m \times 2.1 m
 8214 long). A fast kicker was used to sweep eight bunches, of 8.3×10^{11} electrons at 100 GeV, onto the absorber.
 8215 The first bunch was deflected by 65 mm and the last by 45 mm, inducing a temperature increase ΔT of
 8216 165° .

8217 The bunch intensity for the LHeC is about a factor of 20 lower than for LEP and beam size is double (σ
 8218 $= 0.5$ mm in LEP and $\sigma = 1$ mm in LHeC).

8219 The lower energy (60 GeV) and energy density permit to dump 160 bunches in 20 mm to obtain the
 8220 same ΔT as for LEP. However, in total LHeC will be filled with 2808 bunches, which means that significant
 8221 additional dilution will be required. A combination of a horizontal and a vertical kicker magnet can be
 8222 used, as an active dilution system, to paint the beam on the absorber block and increase the effective sweep
 8223 length. The kickers and the dump can be located in the bypass around CMS, in a dispersion free region (see
 8224 fig. 9.36).

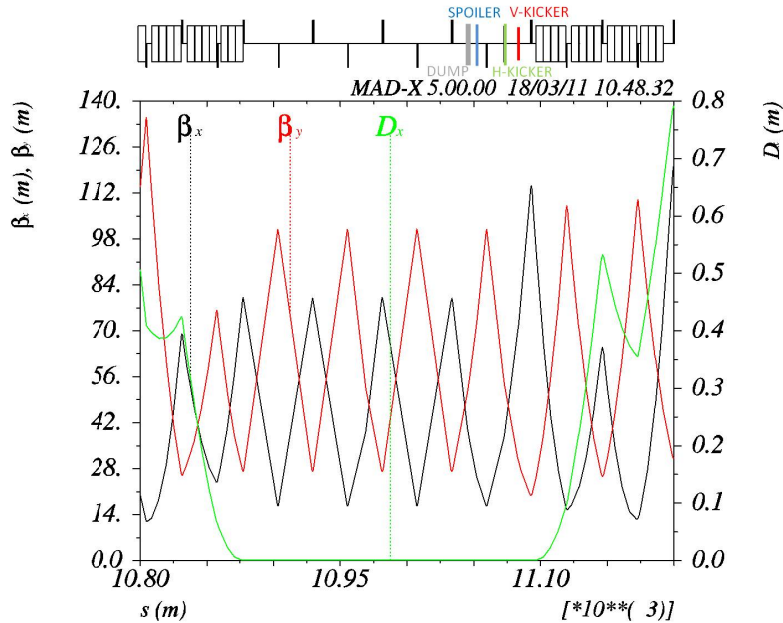


Figure 9.36: The optics in the region of the CMS bypass where the beam dump system could be installed is shown. The system consists of two kickers, one spoiler and a Carbon-composite absorber which are installed in the dispersion free region of the bypass at the right side of CMS (beam proceeds from right to left in the Figure).

8225 It is envisaged to use Carbon-composite for the absorber block, since this has much better thermal and
 8226 mechanical properties than aluminum. The required sweep length is then assumed to be about 100 mm,
 8227 from scaling of the LEP design. The minimum sweep speed in this case is about 0.6 mm per μs , which
 8228 means about 54 bunches per mm. Taking into account the energy and the beam size, this represents less
 8229 than a factor 2 higher energy density on the dump block, compared to the average determined by the simple
 8230 scaling, that should be feasible using carbon. More detailed studies are required to optimise the diluter and
 8231 block designs. Vacuum containment, shielding and a water cooling system has to be incorporated. A beam
 8232 profile monitor can be implemented in front of each absorber to observe the correct functioning of the beam
 8233 dump system.

8234 The vertical kicker would provide a nominal deflection of about 55 mm (see fig.9.37), modulated by
 8235 $\pm 13\%$ for three periods during the 100 μs abort (see fig.9.38), while the horizontal kicker strength would
 8236 increase linearly from zero to give a maximum deflection at the dump of about 55 mm (see Fig.9.37 and
 8237 Fig.9.38). This corresponds to system kicks of 2.7 and 1.6 mrad respectively.

8238 Parameters characterizing the kicker magnets are presented in Table 9.25.

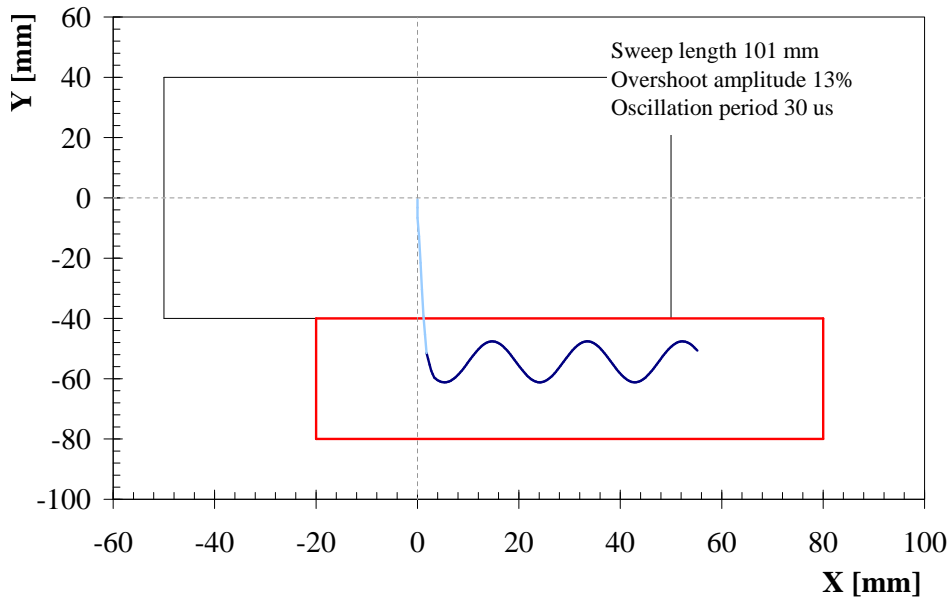


Figure 9.37: A vertical and a horizontal kicker are used to dilute the beam on the dump absorbing block.

8239 In the present lattice the dump is placed ~ 30 m downstream of the kickers, corresponding to a phase
 8240 advance of about 63° in the horizontal plane and 35° in the vertical plane. The minimum horizontal and
 8241 vertical aperture at the dump are 26 mm and 22 mm respectively (at the dump: $\beta_x = 37$ m and $\beta_y = 55$ m,
 8242 using the same beam and machine parameter assumptions, as presented in Table 9.23). The kicker system
 8243 field rise time is assumed to be at most 3 μs (abort gap) and the kicker field flat-top at least 90 μs as for the
 8244 LHC proton beam. Same design as for the LHC dump kicker magnets MKD can be used: a steel yoke with
 8245 a one-turn HV winding. These magnets can provide a magnetic field in the gap of 0.34 T. For a magnetic
 8246 length of 0.31 m ($Z = 25 \Omega$ and $U = 60$ kV), a total installed kicker length of 1.5 m for the horizontal system
 8247 and 2.5 m for the vertical system has to be considered.

8248 A spoiler (one-side single graphite block: 0.3 m \times 0.10 m \times 0.5 m long) can be installed 5 m upstream
 8249 of the dump at the extraction side to provide further dilution.

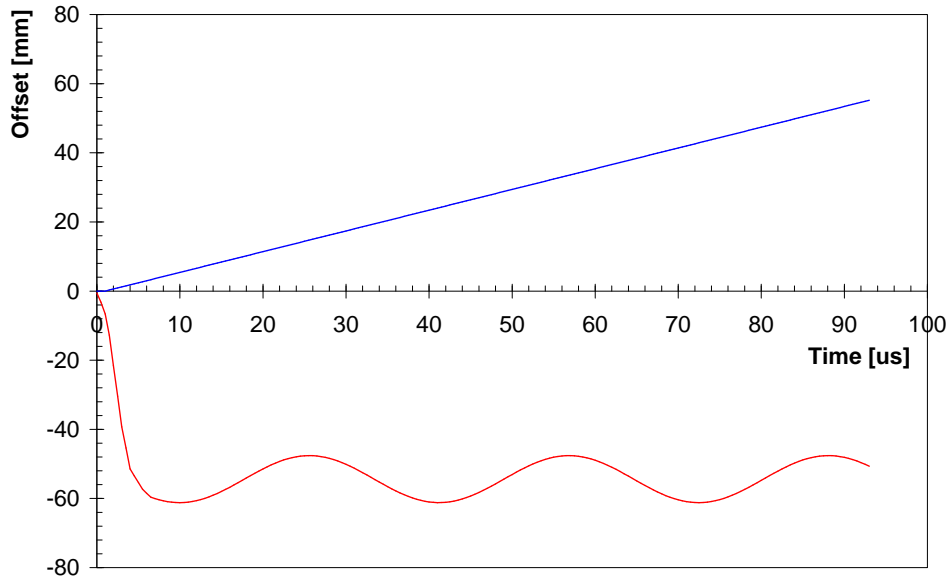


Figure 9.38: The strength of the vertical kicker oscillates in time by $\pm 13\%$ around its nominal value. The deflection provided by the horizontal kicker increases almost linearly in time.

	MKDV	MKDH
Length [m]	2.5	1.5
Maximum angle [mrad]	2.7	1.6
Maximum field [T]	0.34	0.34
Rise/Fall time [ns]	800	800
Flat top length [μ s]	90	90

Table 9.25: Parameters characterising vertical and horizontal kicker magnets of the extraction system.

9.9.4 Post collision line for 140 GeV Linac-Ring option

The post collision line for the 140 GeV Linac option has to be designed taking care of minimizing beam losses and irradiation. The production of Beamstrahlung photons and e^-e^+ pairs is negligible and the energy spread limited to 2×10^{-4} . A standard optics with FODO cells and a long field-free region allowing the beam to naturally grow before reaching the dump can be foreseen. The aperture of the post collision line is defined by the size of the spent beam and, in particular, by its largest horizontal and vertical angular divergence (to be calculated). A system of collimators could be used to keep losses below an acceptable level. Strong quadrupoles and/or kickers should be installed at the end of the line to dilute the beam in order to reduce the energy deposition at the dump window. Extraction line requirements:

- Acceptable radiation level in the tunnel.
- Reasonably big transverse beam size at the dump window and energy dilution.
- Beam line aperture big enough to host the beam: beta function and energy spread must be taken into account.
- Elements of the beam line must have enough clearance.

9.9.5 Absorber for 140 GeV Linac-Ring option

Nominal operation with the 140 GeV Linac foresees to dump a 50 MW beam. This power corresponds to the average energy consumption of 69000 Europeans. An *Eco Dump* could be used to recover that energy; detailed studies are needed and are not presented here. Another option is to start from the concept of the ILC water dump and scale it linearly to the LHeC requirements. The ILC design is based on a water dump with a vortex-like flow pattern and is rated for 18 MW beam of electrons and positrons [722]. Cold pressurized water (18 m³ at 10 bar) flows transversely with respect to the direction of the beam. The beam always encounters fresh water and dissipates the energy into it. The heat is then transmitted through heat exchangers. Solid material plates (Cu or W) are placed beyond the water vessel to absorb the tail of the beam energy spectrum and reduce the total length of the dump. This layer is followed by a stage of solid material, cooled by air natural convection and thermal radiation to ambient, plus several meters of shielding. The size of the LHeC dump, including the shielding, should be 36 m longitudinally and 21 m transversely and it should contain 36 m³ of water. The water is separated from the vacuum of the extraction line by a thin Titanium Alloy (Ti-6Al-4V) window which has high temperature strength properties, low modulus of elasticity and low coefficient of thermal expansion. The window is primarily cooled by forced convection to water in order to reduce temperature rise and thermal stress during the passage of the beam. The window must be thin enough to minimise the energy absorption and the beam spot size of the undisturbed beam must be sufficiently large to prevent window damage. A combination of active dilution and optical means, like strong quadrupoles or increased length of the transfer line, can be use on this purpose. Further studies and challenges related to the dump design are:

- Pressure wave formation and propagation into the water vessel.
- Remotely operable window exchange.
- Handling of tritium gas and tritiated water.

9.9.6 Energy deposition studies for the Linac-Ring option

Preliminary estimates, of the maximum temperature increase in the water and at the dump window, have been defined according to FLUKA simulation results performed for the ILC dump [723]. A 50 MW steady state power should induce a maximum temperature increase ΔT of 90° corresponding to a peak temperature of 215°. The water in the vessel should be kept at a pressure of about 35 bar in order to insure a 25° margin from the water boiling point.

FLUKA studies have been carried out for a 1 mm thick Ti window with a hemispherical shape. The beam size at the ILC window is $\sigma_x = 2.42$ mm and $\sigma_y = 0.27$ mm; an extraction line with 170 m drift and 6 cm sweep radius for beam dilution have been considered. A beam power of 25 W with a maximum heat source of 21 W/cm³ deposited on the window have been calculated. This corresponds to a maximum temperature of 77° for the minimum ionisation particle ($dE/dx = 2$ MeV \times cm²/g), no shower is produced because the thickness of the window is significantly smaller than the radiation length. A maximum temperature lower than 100° would require a minimum beam size of $\sigma_{x,y} = 1.8$ mm. A minimum β function of 8877 m would be needed being the beam emittance $\varepsilon_{x,y} = 0.37$ nm for the undisturbed beam. The radius of the dump window depends on the size of the disrupted beam. The emittance of the disrupted beam is $\varepsilon_{x,y} = 0.74$ nm corresponding to a beam size $\sigma_{x,y}$ of 2.56 mm (for $\beta = 8877$ m); a radius $R = 5$ cm could then fit a 10σ envelope. The yield strength of the Ti alloy used for the window is $\sigma_{Ti} = 830$ MPa, this, according to the formula:

$$\sigma_{Ti} = 0.49 \times \Delta P \frac{R^2}{d^2} \quad (9.10)$$

where $\Delta P = 3.5$ MPa, imposes that the thickness of the window d is bigger than 2.3 mm.

Length of the transfer line drift space and possible dilution have to be estimated together with possible cooling.

9.9.7 Beam line dump for ERL Linac-Ring option

The main dump for the ERL Linac-ring option will be located downstream of the interaction point. Splitting magnets and switches have to be installed in the extraction region and the extracted beam has to be tilted away from the circulating beam by 0.03 rad to provide enough clearance for the first bending dipole of the LHeC arc (see Fig. 9.39). A 90 m transfer line, containing two recombination magnets and dilution kickers, is considered to be installed between the LHeC and the LHC arcs(see Fig. 9.40). The beam dump will be

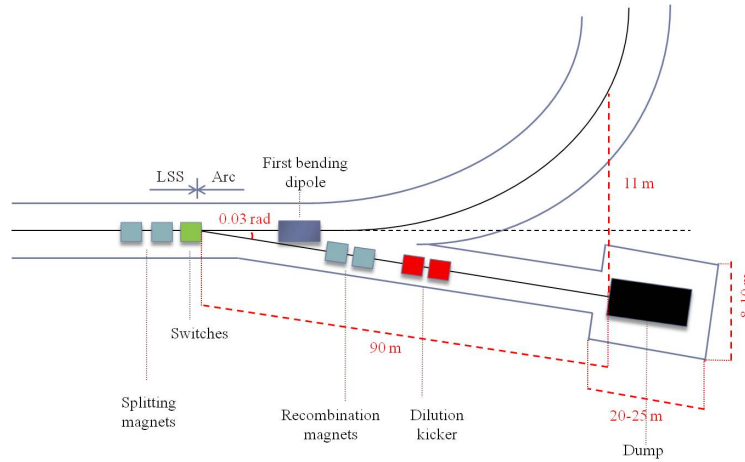


Figure 9.39: Scheme of the transfer line from end of long straight section of the linac and beam dump.

housed in a UD62/UD68 like cavern at the end of the TL and the option of having service caverns for water treatment and heat exchange is explored. An additional dump, and its extraction line, could be installed at the end of the first linac(see Fig. 9.40) for beam setup purposes at intermediate energy. The same design as for the nominal dump and extraction line would be applied.

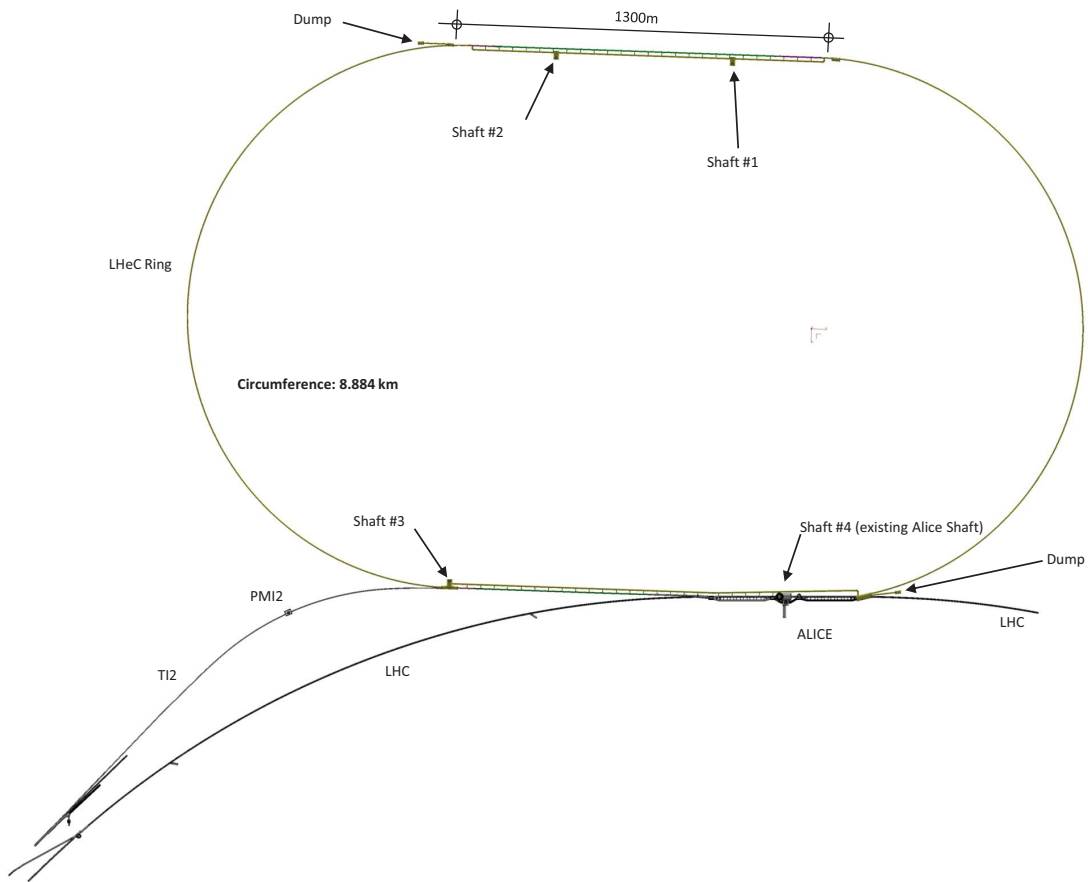


Figure 9.40: Two beam dumps are installed 90 m downstream the end of the long straight section of each linac for nominal operation and beam setup. Note that this drawing is only indicative for the beam dump positions: the currently preferred location of the Linac is 'mirrored' such that it is inside the LHC.

8318 **9.9.8 Absorber for ERL Linac-Ring option**

8319 During nominal operation a 0.5 GeV beam has to be dumped with a current of 6.6 mA. The setup beam
8320 will have a maximum current of 0.05 mA and an energy varying from 10 GeV to 60 GeV (10 GeV step size).
8321 Globally, a maximum beam power of 3 MW has to be dumped. The same design as for the 140 GeV option
8322 can be used by scaling linearly. In this case, a 3 m³ water dump (0.5 m diameter and 8 m length) with a
8323 3 m × 3 m × 10 m long shielding has to be implemented. No show stopper has been identified for the 18
8324 MW ILC dump, same considerations are valid in this less critical case.

Chapter 10

Civil Engineering and Services

10.1 Overview

Infrastructure costs for projects such as LHeC, typically represent approximately one third of the overall budget. For this reason, particular emphasis has been placed on Civil Engineering and Services studies, to ensure a cost efficient conceptual design. This chapter provides an overview of the designs adopted for the key infrastructure cost driver, namely, civil engineering. The costs for the other infrastructure items such as cooling & ventilation, electrical supply, transport & installation will be pro-rated for the CDR and studied in further detail during the next phase of the project. For the purposes of this conceptual design report, the Civil Engineering (CE) studies have assumed that the Interaction Region (IR) for LHeC will be at LHC Point 2, which currently houses the ALICE detector. As far as possible, any surface facilities have been situated on existing CERN land. Both the Ring-Ring and Linac-Ring underground works will be discussed in this Chapter. Surface buildings/structures have not been considered for the CDR.

10.2 Location, Geology and Construction Methods

This section describes the general situation and geology that can be expected for both the Ring-Ring and Linac Ring options.

10.2.1 Location

The proposed siting for the LHeC project is in the North-Western part of the Geneva region at the existing CERN laboratory. The proposed Interaction Region is fully located within existing CERN land at LHC Point 2, close to the village of St.Genis, in France. The CERN area is extremely well suited to housing such a large project, with the very stable and well understood ground conditions having several particle accelerators in the region for over 50 years. The civil engineering works for the most recent machine, the LHC were completed in 2005, so excellent geological records exist and have been utilised for this study to minimise the costs and risk to the project. Any new underground structures will be constructed in the stable Molasse rock at a depth of 100-150m in an area with little seismic activity. CERN and the Geneva region have all the necessary infrastructure at their disposal to accommodate such a project. Due to the fact that Geneva is the home of many international organizations excellent transport and communication networks already exist. Geneva Airport is only 5km from the CERN site, with direct links and a newly constructed tramway, shown in Figure 10.1, gives direct access from the Meyrin Site to the city centre.

The governments of France and Switzerland have long standing agreements concerning the support of particle accelerators in the Geneva region, which make it very likely that the land could be made available free of charge, as it was for previous CERN projects.



Figure 10.1: Tram stop outside CERN Meyrin Site.

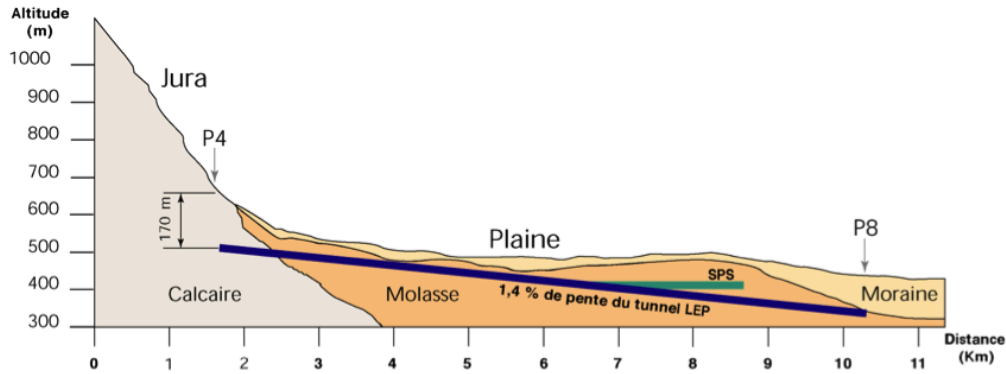


Figure 10.2: Simplified cross section of the LHC housed mostly in Molasse Rock

10.2.2 Land Features

The proposed location for the accelerator is situated within the Swiss midlands embedded between the high mountain chains of the Alps and the lower mountain chain of the Jura. CERN is situated at the feet of the Jura mountain chain in a plain slightly inclined towards the lake of Geneva. The surface terrain was shaped by the Rhone glacier which once extended from the Alps to the valley of the Rhone. The water of the area flows to the Mediterranean Sea. The absolute altitude of the surface ranges from 430 to 500m with respect to sea level. The physical positioning for the project has been developed based on the assumption that the maximum underground volume possible should be housed within the Molasse Rock and should avoid as much as possible any known geological faults or environmentally sensitive areas. The shafts leading to any on-surface facilities have been positioned in the least populated areas, however, as no real discussions have taken place with the local authorities, the presented layouts can only be regarded as indicative, for costing purposes only.

10.2.3 Geology

The LHeC project is within the Geneva Basin, a sub-basin of the large North Alpine Foreland (or Molasse) Basin. This is a large basin which extends along the entire Alpine Front from South-Eastern France to Bavaria, and is infilled by Molasse deposits of Oligocene and Miocene age. The basin is underlain by crystalline basement rocks and formations of Triassic, Jurassic and Cretaceous age. The Molasse, comprising an alternating sequence of marls and sandstones (and formations of intermediate compositions) is overlain by Quaternary glacial moraines related to the Würmian and Rissian glaciations. Figure 10.2 shows a simplified layout of the LHC.

10.2.4 Site Development

As most of the new works are on a close to existing facilities, it is assumed for the CDR that the existing facilities such as restaurant, main access, road network etc are sufficient and have not been costed. However, for the parts located outside the existing fence line, but within CERN property, the following items will have to be included in the costs:

- Roads and car parks.
- Drainage networks.
- Landscaping and planting.
- Spoil dumps.



Figure 10.3: TBM Gripper type machine used for Neutrino tunnel at CERN (left) and roadheader type machine (right).

8386 All temporary facilities needed for the construction works have also been included in the cost estimate.

8387 10.2.5 Construction Methods

8388 It is envisaged that Tunnel Boring Machines (TBMs) will be utilised for the main tunnel excavation greater
 8389 than approximately 2km in length. In the Molasse rock, a shielded TBM will be utilised, with single pass pre-
 8390 cast segmental lining, followed by injection grouting behind the lining. For planning and costing exercises,
 8391 an average TBM advancement of 25m per day, or 150m per week is predicted.

8392 The second phase excavation will be executed using a roadheader type machine. Both machine types are
 8393 shown in Figure 10.3. Any new shafts that have to pass through substantial layers of water bearing moraines
 8394 (for example at CMS) will have to utilize the ground freezing technique. This involves freezing the ground
 8395 with a primary cooling circuit using ammonia and a secondary circuit using brine at -23C, circulating in
 8396 vertical tubes in pre-drilled holes at 1.5 metre intervals. This frozen wall allows excavation of the shafts in
 8397 dry ground conditions and also acts as a retaining wall. Figure 10.4 shows this method being utilized for
 8398 LHC shaft excavation at CMS.

8399 10.3 Civil Engineering Layouts for Ring-Ring

8400 The Ring-Ring solution will require new bypass tunnels at both Point 5 (currently housing the CMS detector)
 8401 and Point 1 (ATLAS). Both of the bypass tunnels are on the outside of the LHC ring.

8402 The Bypass around CMS Point 5 is 1km long with an internal tunnel diameter of 4.5m. Only one new
 8403 shaft is required for excavation works. A roadheader type machine will be used for excavation, with the new
 8404 tunnel position as close as possible to the LHC tunnel as not to induce movements or create operational
 8405 problems to the existing facilities. Figure 10.5 shows the new bypass tunnel and service cavern required
 8406 around CMS.

8407 Figure 10.6 shows the bypass tunnel in blue needed around Point 1. This tunnel is 730 m long and has
 8408 an internal diameter of 4.5 m. Two new 12 m diameter shafts are required to allow access to construct the
 8409 underground areas with minimum disruption to LHC operations. Underground areas are made available for
 8410 RF/Cryogenic and general services. Two junction caverns will be excavated to create a liaison with the LHC
 8411 tunnel.

8412 Waveguides ducts (0.9 m diameter) will connect the LHeC Bypass tunnel to the RF cavern, as shown in
 8413 Figure 10.7. In order to position the bypass as close as possible to the LHC ring, it has been assumed that

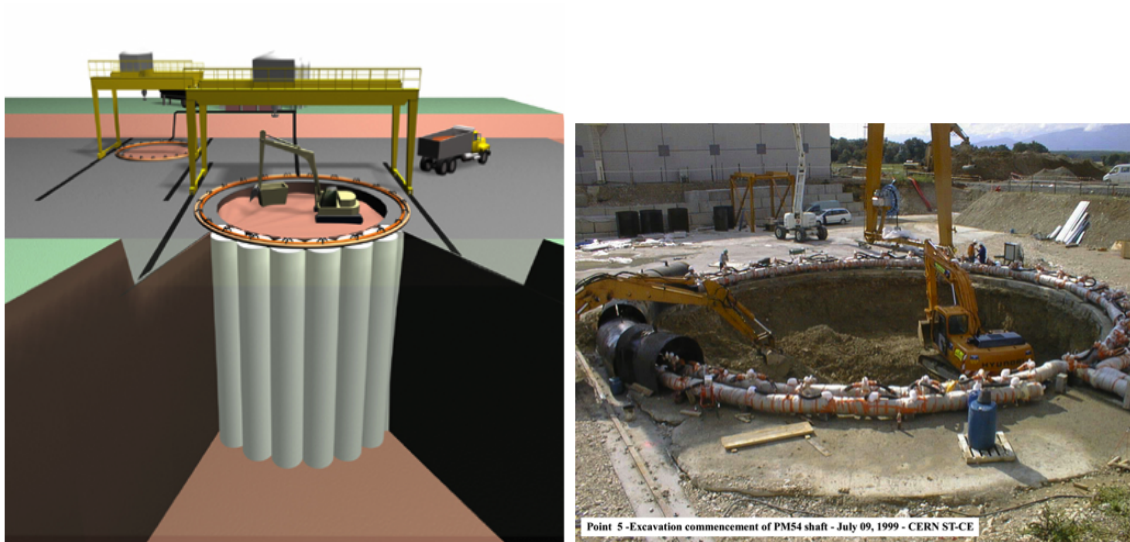


Figure 10.4: LHC Shaft PM54, linking up cylinders of ice to construct a temporary wall.

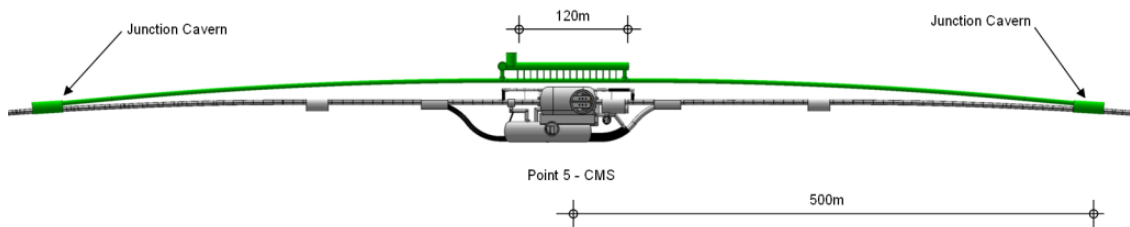


Figure 10.5: Ring-Ring Bypass around CMS Point 5.

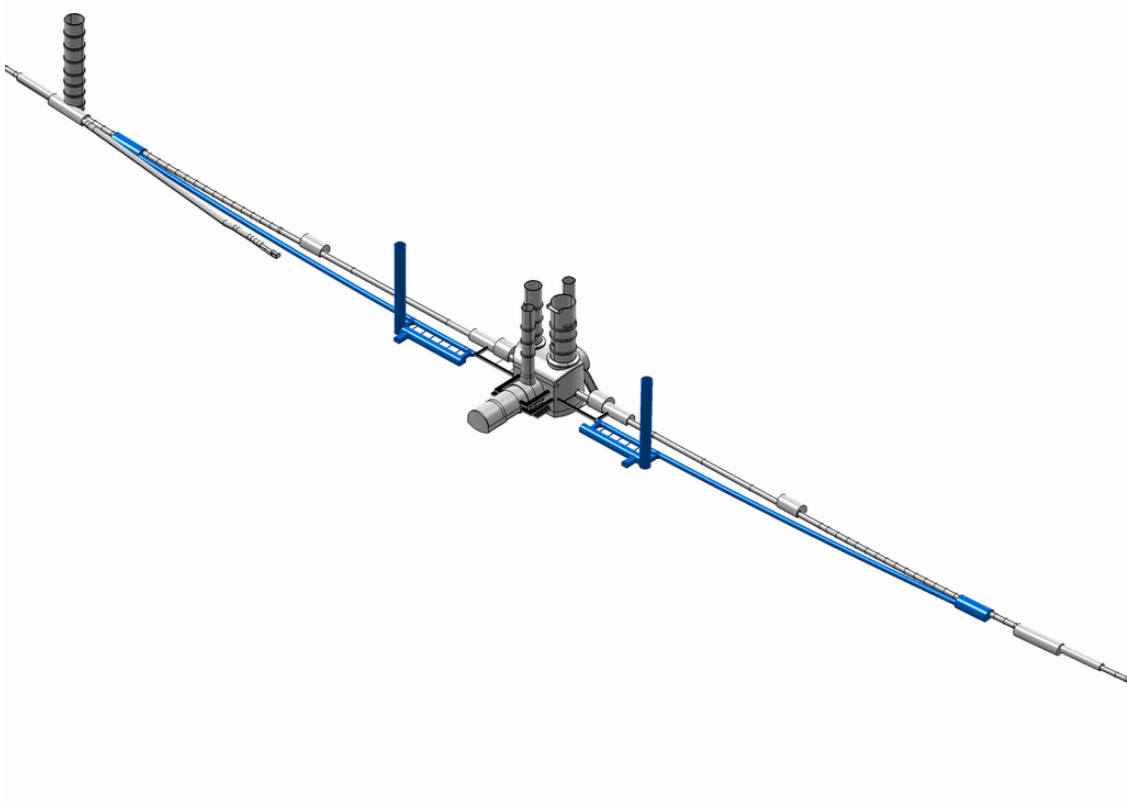


Figure 10.6: Ring-Ring Bypass around ATLAS Point 1.

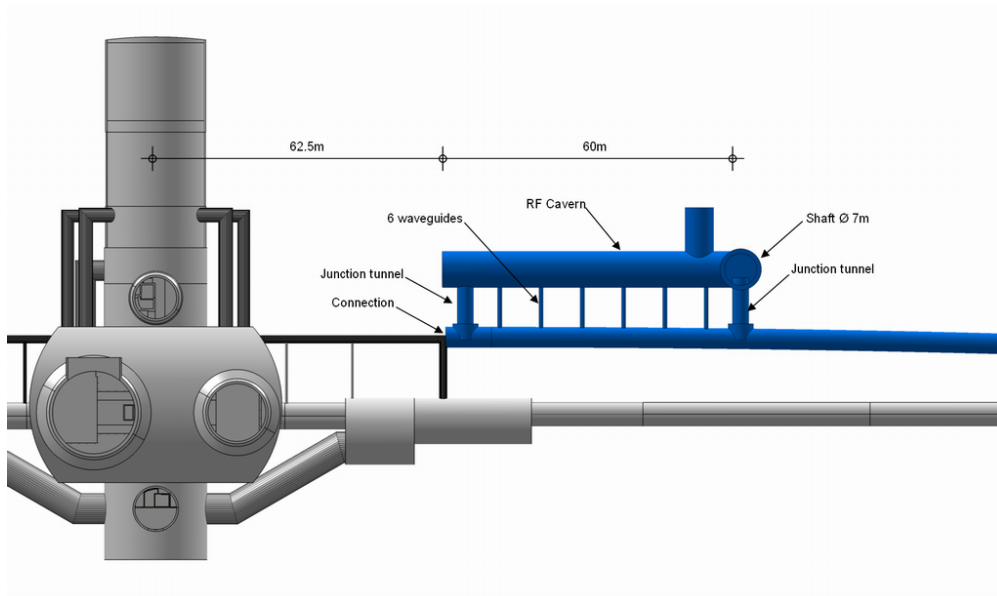


Figure 10.7: Cryo and RF Cavern (one side only) at Point 1.

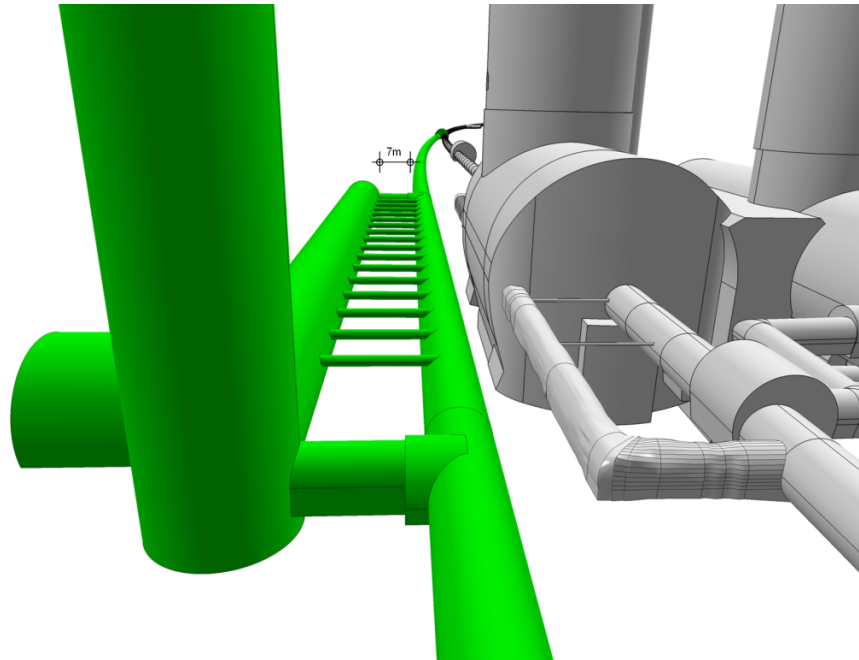


Figure 10.8: 3d model of Ring-Ring Bypass around CMS Point 5.

8414 the LHeC beampipe can be accommodated within the existing survey gallery, and pass through the ATLAS
 8415 experimental hall.

8416 Figure 10.8 shows a 3d model of the bypass around the CMS Point 5. The new excavations will have a
 8417 minimum of 7m of Molasse rock separating the new works from existing LHC structures. This is to avoid
 8418 any unwanted deformation or vibration problems on the existing LHC structures.

8419 The civil engineering for the electron beam injection complex for the Ring-Ring option has not been
 8420 studied for the CDR.

8421 10.4 Civil Engineering Layouts for Linac-Ring

8422 For the CDR it has been assumed that the 60 GeV Energy Recovery Linac (ERL) will be located around
 8423 the St.Genis area of France, injecting directly into the LHC ALICE Cavern at Point 2. Approximately
 8424 10 km of new tunnels (5 m and 6 m diameter), 2 shafts and 9 caverns will be required. The majority of civil
 8425 engineering works can be completed while LHC is operational. Figure 10.9 highlights the area on the LHC
 8426 where the new ERL will be situated.

8427 The ERL will be positioned inside the LHC Ring, in order to ensure that new surface facilities are
 8428 located, as much as possible, on existing CERN land. Secondary tunnels running alongside the long straight
 8429 sections will house RF, Cryogenic and Services for the machine. One of the long straight sections is shown
 8430 in Figure 10.10. The entire ERL, illustrated in Figure 10.11, will be tilted in order to follow a suitable layer
 8431 of Molasse rock. On average the ERL will be tilted approximately 1.4%, dipping towards Lake Geneva, as
 8432 per LHC.

8433 10.5 Summary

8434 From a civil engineering point of view, both the Ring-Ring and Linac-Ring options are feasible. The Ring-
 8435 Ring option will provide a cheaper solution, however, with a marginally increased risk to LHC activity, due

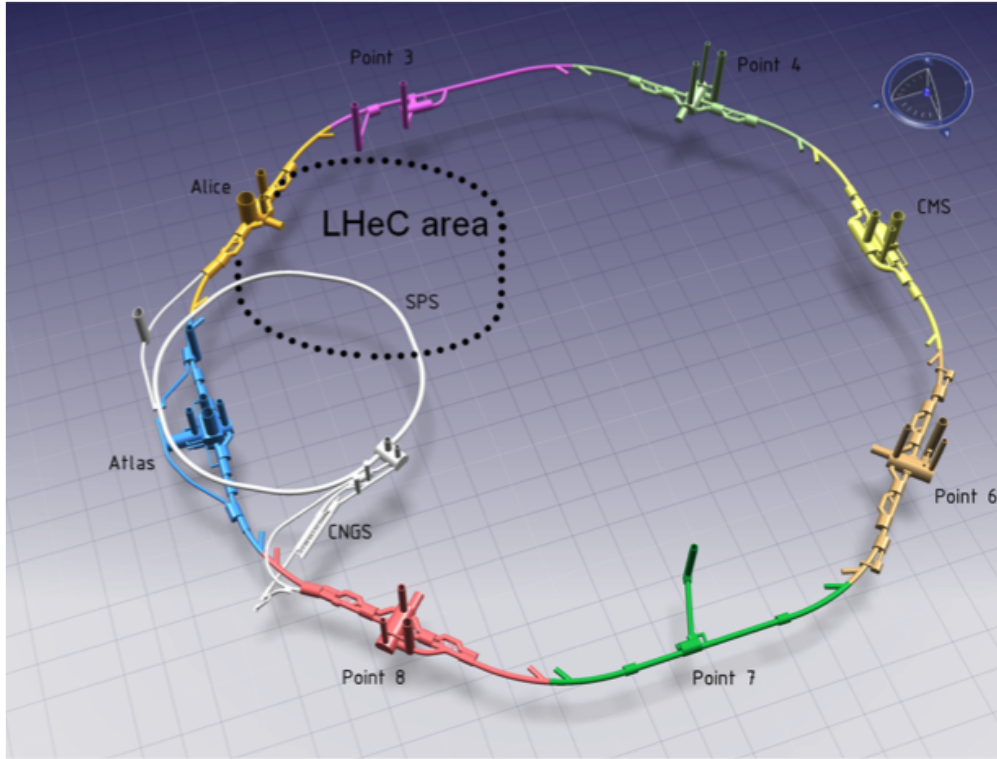


Figure 10.9: Schematic model of ERL position injecting into IP2.

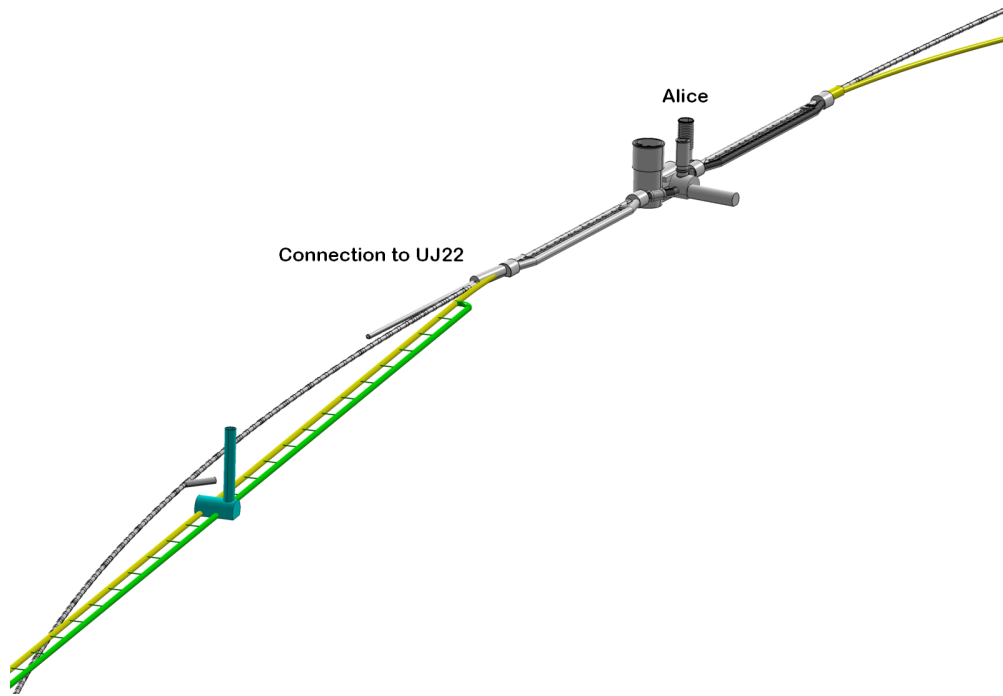


Figure 10.10: ERL Injection area into IP2 and RF/Cryo/Services Cavern (yellow & green).

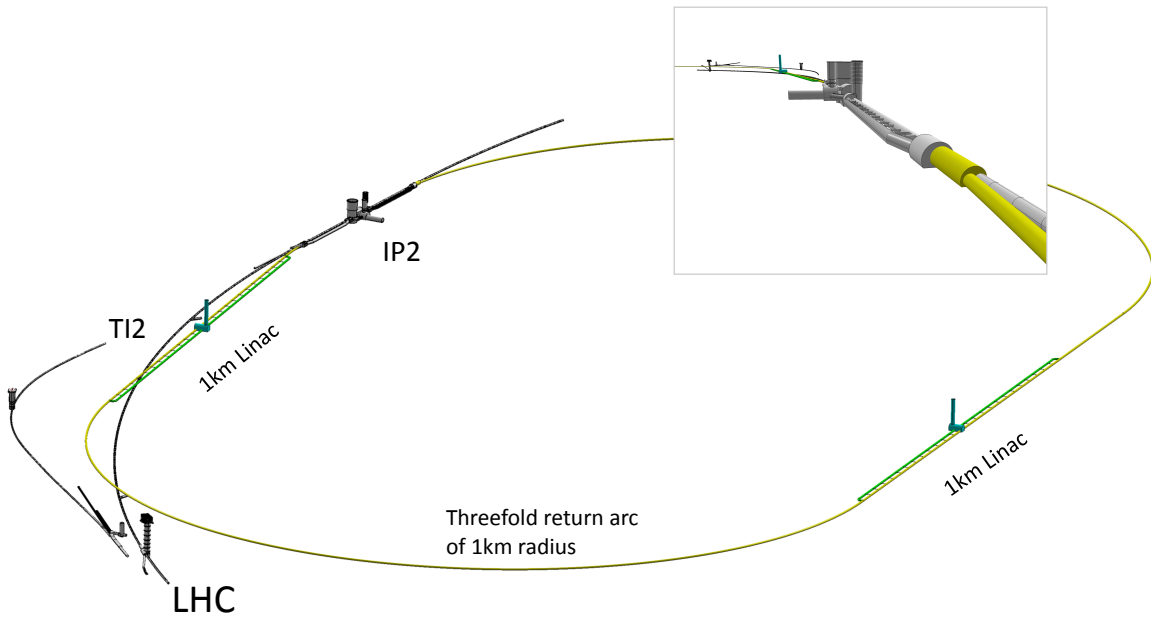


Figure 10.11: View on the ERL placed inside the LHC ring and tangential to IP2. TI2 is the injection line into the LHC. The insert shows the view towards IP2, which currently houses the ALICE experiment, from the direction of the protons colliding with the electron beam incoming from behind.

8436 to the fact that most of the excavation works being in close proximity to the existing installations. The
8437 Linac-Ring option is the cleaner solution from a civil engineering point of view, with much less risk to LHC,
8438 but with substantial extra cost and greater time needed for environmental and building permit procedures.

Chapter 11

Project Planning

We base the planning of the LHeC project on the assumption that the LHC machine will reach the end of its lifetime when the High Luminosity LHC project reaches its design goal of $3000fb^{-1}$. Figure 11.1 shows the current status of the CERN planning for the LHC related upgrade projects. The current planning foresees three long shutdowns:

- Long Shutdown 1 (LS1) for repairing the faulty splice connections in the LHC and allowing operations at nominal energy of 7 TeV.
- Long Shutdown 2 (LS2) for consolidating the LHC for operation above nominal beam intensities
- Long Shutdown 3 (LS3) for implementing the HL-LHC upgrade installations.

Figure 11.2 shows the resulting evolution of the integrated luminosity per experiment over time assuming the LHC performance stabilizes at nominal luminosity after LS1. Figure 11.3 shows a similar evolution of the integrated luminosity assuming the LHC performance stabilizes at ultimate luminosity after LS1.

In both scenarios, the LHC reaches a total integrated luminosity of ca. $200fb^{-1}$ before LS3 and the installation of the HL-LHC upgrade. The HL-LHC project aims at a generation of $200fb^{-1}$ to $300fb^{-1}$ per year [725] and one can assume that the HL-LHC design goal can be reached by between 9 and 13 years after the LS3. Assuming a one year long shutdown for LS3, this implies the accumulation of $3000fb^{-1}$ by ca. 2030 to 2035. Aiming for the LHeC at an exploitation time of 10 years the LHeC operation should therefore start together with the HL-LHC operation after the LS3 in 2022.

We base our estimates for the project time line on the experience of other projects, such as (LEP, LHC and LINAC4 at CERN and the European XFEL at DESY and the PSI XFEL). In the following we will analyze separately the required time line for the project construction for the RF system development, the production of the magnet system, the required civil engineering and the installation of the accelerator components in the tunnel.

The superconducting RF development for LEP and LHC both required approximately 2 to 3 years for the cavity prototyping and testing and approximately 5 to 6 years of test stand operation of the superconducting RF cavity modules adding up to a total time of approximately 6 to 8 years from first prototype to final installation. The first LHC cavity prototypes were constructed in 2000 with a final installation of the 4 cryo modules in the LHC tunnel in 2006. The first LEP superconducting RF cavity was tested in LEP in 1991. LEP2 operation started in 1996 but still required 2 years of progressively commissioning all cryo modules in building B180 before their final installation in the LEP tunnel. The last cryo module of the 73 4-cell LEP cryo modules was installed in the LEP tunnel in 1999. Both RF installations featured extensive test stand operations. The LEP RF system had cavity test stands in building SM18 and a separate power test in building B180 which were operated from 1994 until 1999. The LHC RF system had both, the cavity and the power test stands, in SM18. The LHC test stands were operated from 2002 until 2006 (the test stand operation was slowed down at the end due to difficulties with the RF coupler design). In both cases, LEP

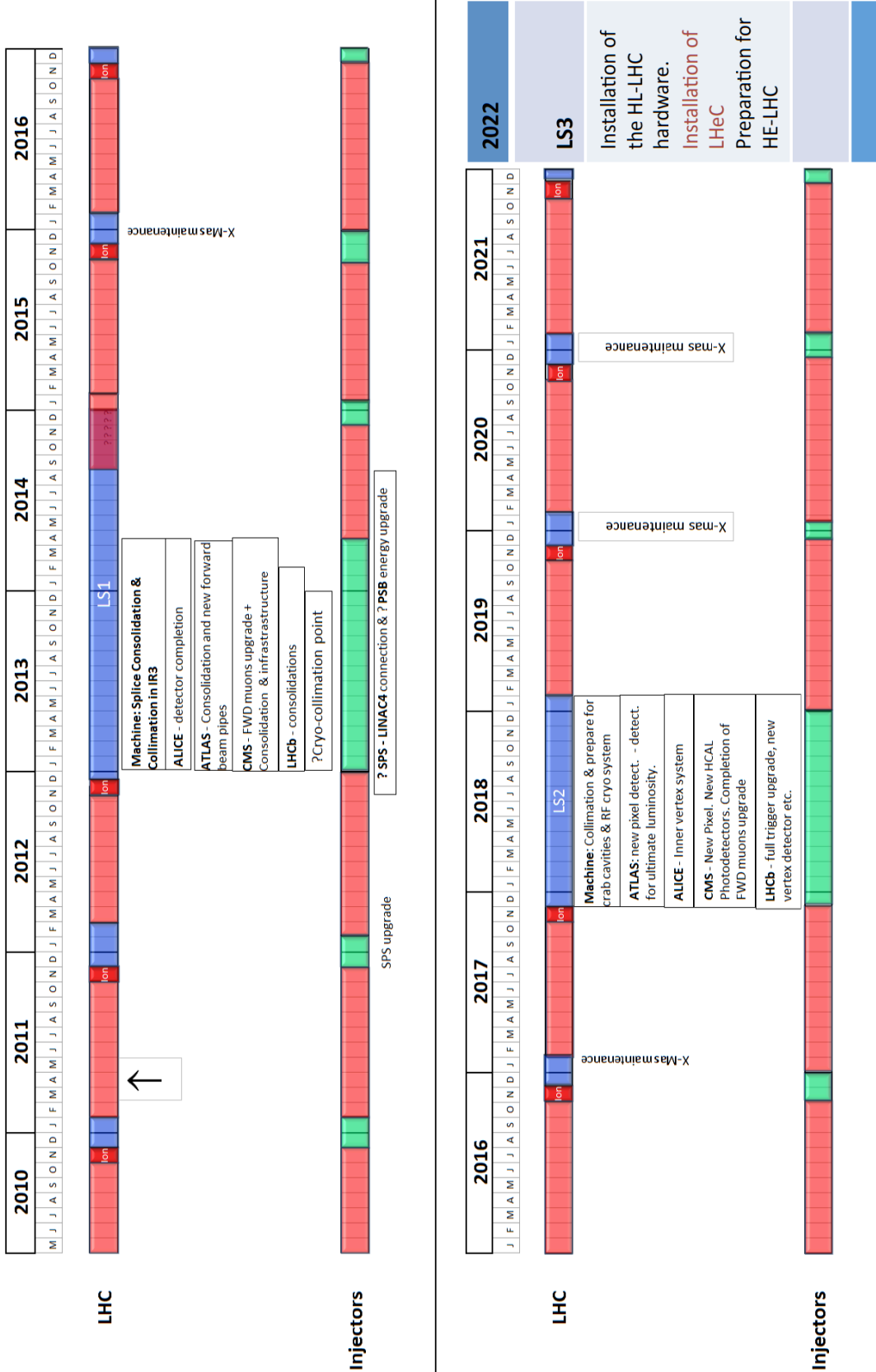


Figure 11.1: CERN medium term plan (MTP), draft as of July 2011, from [724].

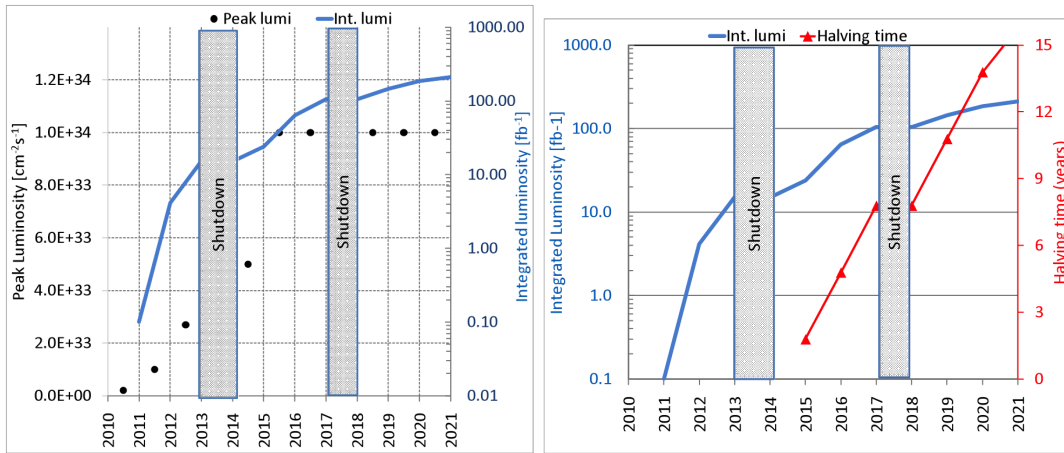


Figure 11.2: Left: Projected luminosity evolution for the LHC assuming the LHC reaches nominal performance levels after the first long shutdown (LS1) and then remains at nominal performance after 2016. Right: The resulting evolution of the integrated luminosity for the LHC experiments. [725].

8475 and LHC, the RF system installation was therefore accompanied by a 5 to 6 year test stand operation which
 8476 overlapped with the actual installation period in the tunnel [726].

8477 The LHeC linac-ring RF system requires 118 cryomodules of eight 721 MHz 5-cell superconducting RF
 8478 structures, amounting to a total of approximately 950 structures or thirteen times the number of LEP RF
 8479 structures. It seems therefore reasonable to assume for the LHeC linac-ring RF system a total time of
 8480 10 years from first prototype construction to final installation in the tunnel with a dedicated test stand
 8481 operation for approximately 8 years. ¹ The LHeC ring-ring RF system corresponds approximately to the
 8482 LEPII RF system in terms of total power and overall length of the RF installation and it seems reasonable
 8483 to assume for the LHeC ring-ring RF system a slightly shorter time scale. Here we assume the same time
 8484 scale as for LEPII: a total time of 8 years from first prototype construction to final installation in the tunnel
 8485 with a dedicated test stand operation for approximately 6 years.

8486 For the magnet system we base a first order estimate of the required timescale for the magnet production
 8487 and installation on the experience with LHC transfer lines. The LHC transfer lines have a total length of 6 km
 8488 and feature a total of ca. 350 normal conducting magnets. The magnet production extended over 3 years
 8489 with a production rate of ca. 10 magnets per month [728]. It is, however, important to underline that the
 8490 production rate was not limited by production capacity but rather, was following the project requirements
 8491 and the CERN ability for magnet testing after reception at CERN. Both LHeC options feature a relatively
 8492 large number of magnets, approximately 4000 magnets. Compared to the LHC transfer line magnets, these
 8493 magnets are much more compact and one can assume that the magnet production rate can be significantly
 8494 larger than that for the LHC transfer lines. The LHeC magnet production requires therefore industrial
 8495 production rates featuring several contractors and production lines. The price to pay for such an industrial
 8496 production scheme will be the requirement for a pre-series production and a thorough quality assurance

¹Faster production rates could be possible by using several manufacturers in parallel as it is, for example, planned for the ILC. The ILC project requires approximately 15000 cavities and aims at a 10 to 15 times faster production rate as compared to the XFEL cavity production. But such an approach requires long preparation studies for the industrialization (the ILC assumes more than 3 years for such studies [727]), dedicated production test facilities (the ILC has production test facilities at three different laboratories: DESY, KEK and FNAL), an extensive pre-series production and test bench operation for verifying the cavity and cryomodule design before launching the mass production (the ILC project has more than 20 years experience of pre-series production and test bench operation in form of the TTF, FLASH and XFEL installations) and a large production volume so that it is lucrative for several manufacturers to split the overall production while still undertaking significant investments for the production lines. Such an approach may not apply to a 'small' project like the LHeC and may therefore not lead to a much faster production time line.

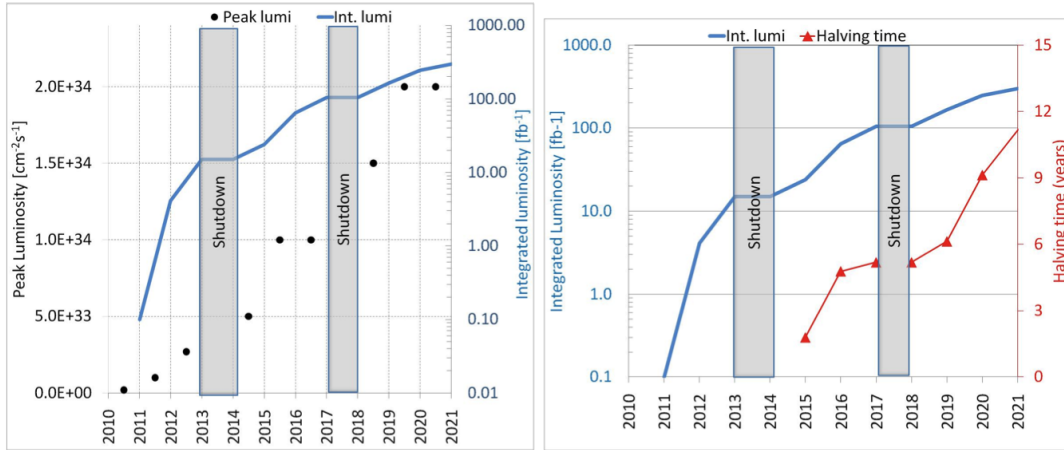


Figure 11.3: Left: Optimistic projection of the luminosity evolution for the LHC assuming the LHC reaches ultimate performance levels after the first long shutdown (LS2). Right: The resulting evolution of the integrated luminosity for the LHC experiments. [725].

8497 over the whole production process. All LHeC magnets will require furthermore a detailed geometry and
 8498 field quality measurement program after reception at CERN. In the following we assume 1-2 years for the
 8499 pre-series production and first testing followed by potential design modifications and a peak production rate
 8500 of ca. 60 dipoles and 20 quadrupoles per month (ca. ten times the production rate of the LHC transfer
 8501 lines). These assumptions lead to a total construction time of ca. 4 to 6 years and a total of 6 to 8 years
 8502 from magnet design to final installation in the tunnel.

8503 For the civil engineering we base our first order estimate for the time line on the estimates for the CLIC
 8504 500 GeV option which features a total length that is comparable to the 60 GeV linac-ring option. The
 8505 civil engineering work requires for the LHeC linac-ring option the construction of ca. 10 km underground
 8506 installations which is estimated to take approximately 4 years construction time (the required underground
 8507 construction for the ring-ring solution is smaller but will occur in the direct vicinity of the main LHC tunnel).
 8508 The installation of the technical infrastructure (water, electricity etc.) will take approximately 2 years and
 8509 the final installation of the machine elements in the tunnel another 2 years. All three activities can partially
 8510 overlap, leading to an estimate of the total construction time of ca. 6 years [729].

8511 For all other components (cryogenics, injector complex, detector etc.) we assume for the moment that
 8512 their development and installation can be done in the shadow of the three components mentioned above.

8513 In summary, we estimate:

- 8514 • Between 8 and 10 years for the production of the RF system (time from prototype to final installation
 8515 in the tunnel) with dedicated test stand operation over 6 to 8 years.
- 8516 • Between 6 and 8 years for the production of the magnet system (time from prototype to final installation
 8517 in the tunnel) with several production lines and test facilities for the quality assurance during the
 8518 magnet production.
- 8519 • Approximately 6 years for the civil engineering work and actual installation in the tunnel.
- 8520 • All other components such as injector complex, cryogenics installation, detector construction etc, are
 8521 assumed to lie in the shadow of the above components.

8522 The above time estimates appear as reasonable estimates compared to the planning of other projects like
 8523 the European XFEL at DESY, the European Spallation Source (ESS) in Sweden, LINAC4 at CERN and
 8524 the PSI XFEL facilities:

- 8525 • The European XFEL project features a 3 km long superconducting linear accelerator (comparable in
8526 size to the linac section of the LHeC linac-ring option) started the civil engineering in January 2009
8527 and plans for completing the civil engineering work in end 2012 (\rightarrow 4 years of bare civil engineering
8528 work) [730]. The project had in form of the FLASH (TTF) installation a pre-series production of
8529 150 1.3 GHz 9-cell cavity modules that went from 1993 to 2005 (12 years) and an extended test stand
8530 operation. The XFEL project plans for an industrial production of more than 600 1.3 GHz 9-cell cavity
8531 module from 2010 until 2014 (4 to 5 year production time) [731].
- 8532 • The ESS facility features ca. 300 m superconducting RF sections and plans for a construction phase
8533 of 9 years (2009 until 2017) with first operation in 2018 and full performance reach in 2025 [732].
- 8534 • The LINAC4 project is a ca. 200 m long normal conducting linac installation which has a ca. 3 year
8535 long civil engineering construction period, followed by one year of infrastructure installation and 1.5
8536 years of waveguide and accelerator component installation, amounting to a total construction period of
8537 ca. 5.5 years (start of civil engineering in beginning 2008 and end of the accelerator installation by mid
8538 2013) which seems rather long compared to the civil engineering estimates for the LHeC (installation
8539 length of ca. 10 km and ca. 100 m underground; ca. 50 times the LINAC4 installation length which
8540 is mainly above surface) [733].
- 8541 • The PSI XFEL project features an approximately 1 km long normal conducting linac and plans for
8542 2 years for the generation of a TDR, a 5 year test stand operation, a 4 year construction period and
8543 an installation period of 3 years leading to a total project time line of 6 years from start of the test
8544 facilities to the start of the actual project [734].

8545 Except for the European XFEL project, which has a longer superconducting RF section than both LHeC
8546 versions, all of the above reference facilities are smaller in scale than the LHeC project and plan between
8547 6 and 9 years from beginning of construction (civil engineering) until the start of operation. All facilities
8548 with superconducting cavities plan for an RF production time of ca. 5 years for their key components and a
8549 substantial period of test bench operation and pre-series production for critical elements (5 years or more).

8550 Figure 11.4 summarizes the above considerations in form of a schematic outline of the project planning.
8551 The planning in Fig. 11.4 addresses only aspects related to the accelerator complex and does not address
8552 additional constraints coming from the detector installation in the cavern. Furthermore, it does not include
8553 additional constraints arising from the LHC operation, logistics constraints and resource limitations due to
8554 the planning for the long shutdowns of the LHC and does therefore certainly not attempt to be an accurate
8555 project projection. Rather than presenting an accurate timeline for the LHeC installation, the presented
8556 planning aims at illustrating that a start of the LHeC operation in 2023 requires the start of first prototype
8557 development and testing already by 2012. Meeting the milestone of an LHeC operation start in 2023 requires
8558 a rather swift project launch starting with the generation of a proper TDR and the launch of first RF R&D
8559 activities by 2012. This ambitious goal can only be achieved if the project receives adequate resource
8560 allocations in 2012. Potential first activities for the prototype development and testing could focus around
8561 the development of superconducting RF cavities, where synergies with ESS and SPL studies exist, with the
8562 goal of setting up an ERL test facility. It could also include the development of electron and positron sources
8563 where synergies with the CLIC and ILC projects exist. Because of their synergies with the ESS, SPL and
8564 the linear collider projects, a start of R&D activities for the LHeC by 2012 appears to be quite timely. In
8565 case the Ring-Ring installation turns out to be the better option for the LHeC, a ERL test facility could in
8566 the end also serve as an injector complex for the Ring-Ring option of the LHeC. It represents therefore a
8567 reasonable investment into the LHeC project independent of a the final implementation choice.

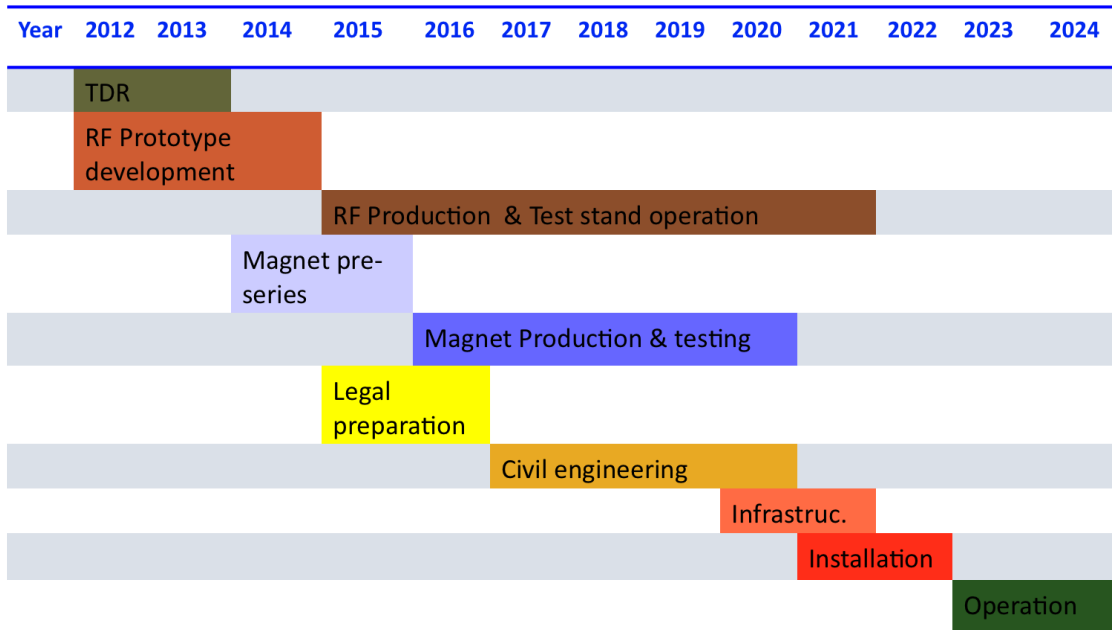


Figure 11.4: Planning considerations for the LHeC, where we assumed a partial overlap of the time lines for the various LHeC project steps (for example a partial overlap of the civil engineering for the tunnel construction and the installation of the technical infrastructure and accelerator components). The overall planning goal of completion by the LS3 seems quite ambitious even with such a partial overlap of individual activities and requires first prototype development as soon as by 2012. The presented planning discusses only aspects related to the accelerator complex and does not address additional constraints coming from the detector installation in the cavern.

8568

Part IV

8569

Detector

Chapter 12

Detector Requirements

In this chapter the core aspects of the main detector design for the LHeC are discussed. The physics requirements are illustrated along with the boundary conditions from the accelerator options and the interaction region design. These considerations converge in chapter 13 where a first picture of the main detector is presented along with a discussion on the choice for the detector elements and the overall detector assembly. Aspects involving the design of the interaction region, the beam pipe, the particle backgrounds, the magnets and the simulation environment are discussed in the later sections. Finally the single detector components are presented starting from the innermost ones, tracking, calorimetry and muon detectors. Detector components not located in the proximity of the interaction region are described in chapter 14.

12.1 Requirements on the LHeC Detector

The new ep/A detector at the LHeC has to basically be a precision instrument of maximum acceptance. The physics program depends on a high level of precision, as for the measurement of α_s , and in the reconstruction of complex final states, like the charged current single top production and decay or the precision measurement of the b -quark density. The acceptance has to extend as close as possible to the beam axis because of the interest in the physics at low and at large Bjorken x . The dimensions of the detector are constrained by the radial extension of the beam pipe in combination with maximum polar angle coverage¹, desirably down to about 1° and 179° for forward going final state particles and backward scattered electrons at low Q^2 , respectively. A further general demand is a high modularity enabling much of the detector construction to be performed above ground for keeping the installation time at a minimum, and to be able to access inner detector parts within reasonable shut down times.

The time schedule of the project demands to have a detector ready within about ten years. This prevents any significant R&D program to be performed. The choice of components fortunately can rely on the vast experience obtained at HERA, the LHC, including its detector upgrades to come, and on ILC detector development studies. The next few sections outline the acceptance and measurement requirements on the detector in detail. Then follow more detailed technical considerations, including alternative solutions, which taken together illustrate the feasibility of experimentation at the LHeC.

12.1.1 Installation and Magnets

The LHeC project represents an upgrade of the LHC. The experiment would be the fifth large experiment, and the detector the third multi-purpose 4π acceptance detector. It requires a cavern, which for the purpose

¹This CDR adopts the HERA convention of the coordinate system, which has been defined with the z axis given by the proton beam direction. This implies that Rutherford "backscattering" of the electron is viewed as scattering into small angles. When the partons are essentially at rest, at very small x , the electrons are scattered "forward" as in fixed target forward spectrometers. The somewhat unfortunate HERA convention calls this backwards. The x and y coordinates are defined such that there is a right handed coordinate system formed with y pointing upwards and x to the center of the proton ring.

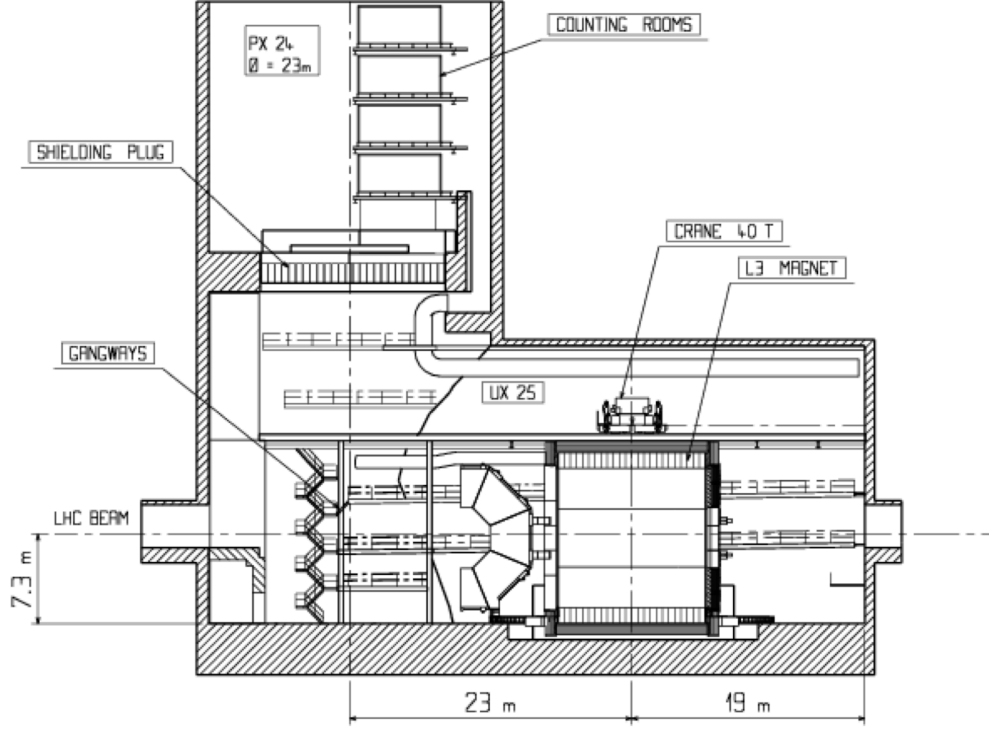


Figure 12.1: Cross section of the IP2 cavern with the ALICE detector inside the L3 magnet. Round access shaft of 23m diameter, cavern about 50m along the beam-line.

8600 of the design study has been considered to be the ALICE cavern in IP2, see Fig. 12.1. The installation of the
 8601 detector has to proceed as fast as possible in order not to introduce large extra delays to the LHC program.
 8602 High modularity and pre-assembly above ground are therefore inevitable demands for the design.

8603 The cost has to be limited in order for the project to be fundable in parallel to when the large upgrade
 8604 investments are presumably made for the ATLAS and CMS detectors in the high luminosity phase of the
 8605 LHC. The cost is related to technology choices, the detector granularity and its size. Crucial parameters of
 8606 the detector are the beam pipe dimensions, when combined with the small angle acceptance constraint, see
 8607 below this section, and the parameters of the solenoid. The cost C of a solenoid can be represented as a
 8608 function of the energy density, ρ_E , $C \simeq 0.5(\rho_E/MJ)^{0.66}$ [64], which is determined as

$$\rho_E = \frac{1}{2\mu_0} \cdot \int B^2 dV \simeq \frac{1}{2\mu_0} \cdot \pi r^2 \cdot l \cdot B^2. \quad (12.1)$$

8609 From these relations one derives roughly that the solenoid cost scales linearly with the radius r and field
 8610 strength B and with the length l to the power 0.66. The solenoid radius influences the track length in the
 8611 transverse plane, which determines $\propto r^{-2}$ the transverse momentum resolution whereas field strength enters
 8612 linearly $\propto B^{-1}$.

8613 The Linac-Ring version of the LHeC requires to put an extended dipole field of 0.3T into the detector
 8614 for ensuring head-on ep collisions and for separating the beams.

8615 A balance between a strong magnetic field for optimal tracking resolution and an affordable sized magnet
 8616 has to be found, knowing that the magnets themselves represent one source of inactive material and that
 8617 the energy stored in the magnets and their return flux require an outer shielding proportional to the field
 8618 and to the square of the solenoid radius.

8619 In the current design the solenoid is placed in between the electromagnetic and the hadron calorime-

8620 ter^2 at a radius of about 1 m. The magnetic field is set to 3.5 T in order to compensate the small radial
 8621 extension of the tracker, the focus of which in the LHeC environment is on the forward direction. The cho-
 8622 sen design position with dipoles and solenoid placed outside the electromagnetic calorimeter ensures good
 8623 electromagnetic calorimetry and high dipole field quality near to the beam line. Fig. 12.2 shows such the
 magnet arrangement inside the detector volume schematically. The total material budget of the solenoid

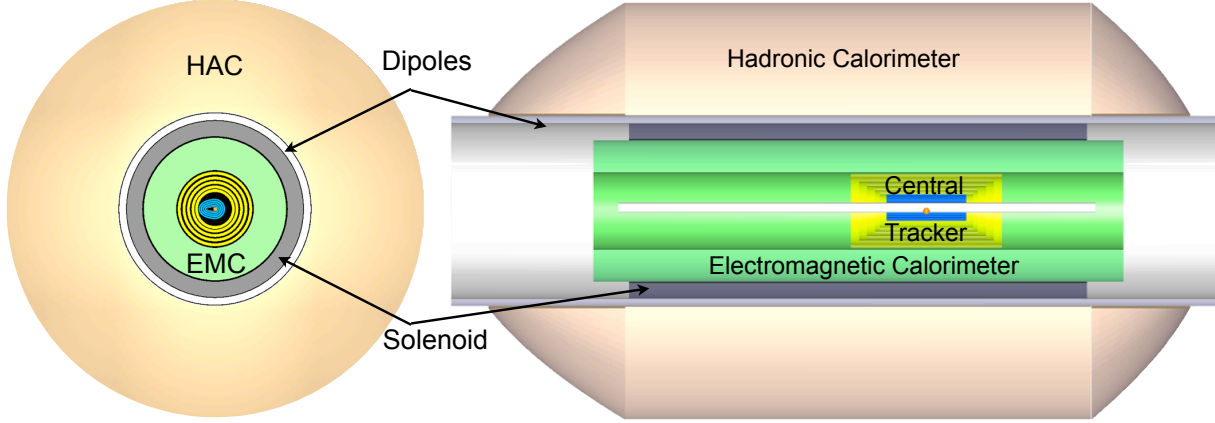


Figure 12.2: Schematic xy and rz views of the magnets and barrel calorimeter arrangement for the baseline layout.

8624 and the dipole, at perpendicular crossing, may be represented by about 16 cm of Aluminum, corresponding
 8625 to about one quarter of an interaction length (λ_I) and about 1 radiation length (X_0). This further supports
 8626 the choice of the magnets located outside of the electromagnetic calorimeter, yet placed before the hadronic
 8627 calorimeter in order to limit the radial dimensions. More details on the design study of the detector magnets
 8628 are addressed in Sect.13.2.

8630 12.1.2 Kinematic reconstruction

8631 The inclusive ep DIS kinematics are defined by the negative four-momentum transfer squared, Q^2 , and
 8632 Bjorken x . Both are related to the cms energy squared s via the inelasticity y through the relation $Q^2 = sxy$,
 8633 which implies $Q^2 \leq s$. The energy squared s is determined by the product of the beam energies, $s = 4E_p E_e$,
 8634 for head-on collisions and large energies compared to the proton mass.

8635 The kinematics are determined from the scattered electron with energy E'_e and polar angle θ_e and from
 8636 the hadronic final state of energy E_h and scattering angle θ_h . The variables Q^2 and y can be calculated from
 8637 the scattered electron kinematics as

$$\begin{aligned} Q_e^2 &= 4E_e E'_e \cos^2\left(\frac{\theta_e}{2}\right) \\ y_e &= 1 - \frac{E'_e}{E_e} \sin^2\left(\frac{\theta_e}{2}\right) \end{aligned} \quad (12.2)$$

8638 and from the hadronic final state kinematics as

$$\begin{aligned} Q_h^2 &= \frac{1}{1 - y_h} \cdot E_h^2 \sin^2(\theta_h) \\ y_h &= \frac{E_h}{E_e} \sin^2\left(\frac{\theta_h}{2}\right) \end{aligned} \quad (12.3)$$

²An option is also considered of placing the solenoid outside the calorimeters, at about 2.5 m radius, combined with a second, bigger solenoid for the flux return, with the muon detector in between. A two-solenoid solution was considered already in the fourth detector concept for the ILD [735].

8639 and x is given as Q^2/sy . The kinematic reconstruction in neutral current scattering therefore is redundant,
8640 which is one reason why DIS experiments at ep colliders are precise. An important example is the calibration
8641 of the electromagnetic energy scale from the measurements of the electron and the hadron scattering angles.
8642 At HERA, this led to energy calibration accuracies for E'_e at the per mil level. In a large part of the phase
8643 space, around $x = E_e/E_p$, the scattered electron energy is approximately equal to the beam energy, $E'_e \simeq E_e$,
8644 which causes a large “kinematic peak” in the scattered electron energy distribution. The hadronic energy
8645 scale can be obtained from the transverse momentum balance in neutral current scattering, $p_t^e \simeq p_t^h$. It is
8646 determined to about 1% at HERA.

8647 Following Eq.12.3, the kinematics in charged current scattering is reconstructed from the transverse and
8648 longitudinal momenta and energy of the final state particles according to

$$\begin{aligned} Q_h^2 &= \frac{1}{1-y_h} \sum p_t^2 \\ y_h &= \frac{1}{2E_e} \sum (E - p_z). \end{aligned} \quad (12.4)$$

8649 There have been many refinements used in the reconstruction of the kinematics, as discussed e.g. in [736],
8650 which for the principle design considerations, however, are of less importance.

8651 12.1.3 Acceptance regions - scattered electron

8652 The positions of isolines of constant energy and angle of the scattered electron in the (Q^2, x) plane are given
8653 by the relations:

$$\begin{aligned} Q^2(x, E'_e) &= sx \cdot \frac{E_e - E'_e}{E_e - xE_p} \\ Q^2(x, \theta_e) &= sx \cdot \frac{E_e}{E_e + xE_p \tan^2(\theta_e/2)}. \end{aligned} \quad (12.5)$$

8654 Following these relations, an acceptance limitation of the scattered electron angle, as due to the beam pipe
8655 or focussing magnets, to a maximum value θ_e^{max} defines a constant minimum Q^2 which independently of E_p
8656 is given as

$$Q_{min}^2(x, \theta_e^{max}) \simeq [2E_e \cot(\theta_e^{max}/2)]^2. \quad (12.6)$$

8657 apart from the smallest x . This is illustrated in Fig.12.3. There follows that a 179° (170°) angular cut
8658 corresponds to a minimum Q^2 of about 1 (100) GeV^2 at nominal electron beam energy. One easily recognizes
8659 in Fig.12.3 that the physics at low x and Q^2 requires to measure electrons scattered backwards from about
8660 135° up to 179° . Their energy in this θ_e region does not exceed E_e significantly. At lower x to very good
8661 approximation $y = E'_e/E_e$ (as can be seen from the lines $y = 0.5$ and $E'_e = 30 \text{ GeV}$ in Fig.12.3).

8662 Following Eq.12.6, Q_{min}^2 varies $\propto E_e^2$. It thus is as small as 0.03 GeV^2 for $E_e = 10 \text{ GeV}$, the injection
8663 energy of the ring accelerator but increases to 6.0 GeV^2 for $E_e = 140 \text{ GeV}$, the maximum electron beam
8664 energy considered in this design report, apart from smallest x , if $\theta_e^{max} = 179^\circ$. While Q_{min}^2 decreases $\propto E_e^2$,
8665 the acceptance loss towards small x is only $\propto E_e$. The measurement of the transition region from hadronic
8666 to partonic behavior, from 0.1 to 10 GeV^2 , therefore requires to take data at lower electron beam energies³.
8667 These variations are illustrated in Fig.12.4 for an electron beam energy of 10 GeV , the injection energy for
8668 the ring and a one-pass linac energy, and for the highest E_e of 140 GeV considered in this report.

³The requirement of acceptance up to 179° determines the length of the backward detector. It could be tempting to utilize this E_e dependence in the design: if one limited the backward electron acceptance to for example 178° instead of 179° this would reduce the backward detector extension in $-z$. With data taken at reduced E_e one would come back to lower Q^2 . From Eq.12.6 one derives that $E_e = 30 \text{ GeV}$ and 178° is leading to the same Q_{min}^2 of about 1.1 GeV^2 , at not extremely small x , as is $E_e = 60 \text{ GeV}$ and 179° . However, one would loose in acceptance to the lowest x , linearly with E_e . Moreover, for the present design the (inner) beam pipe radius in vertical direction is 2.2 cm . This results in an extension of about 1.5 m for the first tracker plane to register an electron scattered at 179° . If one adds about 1 m for the tracker length, and 1 m for the backward calorimeter following the tracker, one arrives at about 3.5 m backward detector length. Obviously for 178° one could reduce

LHeC - electron kinematics

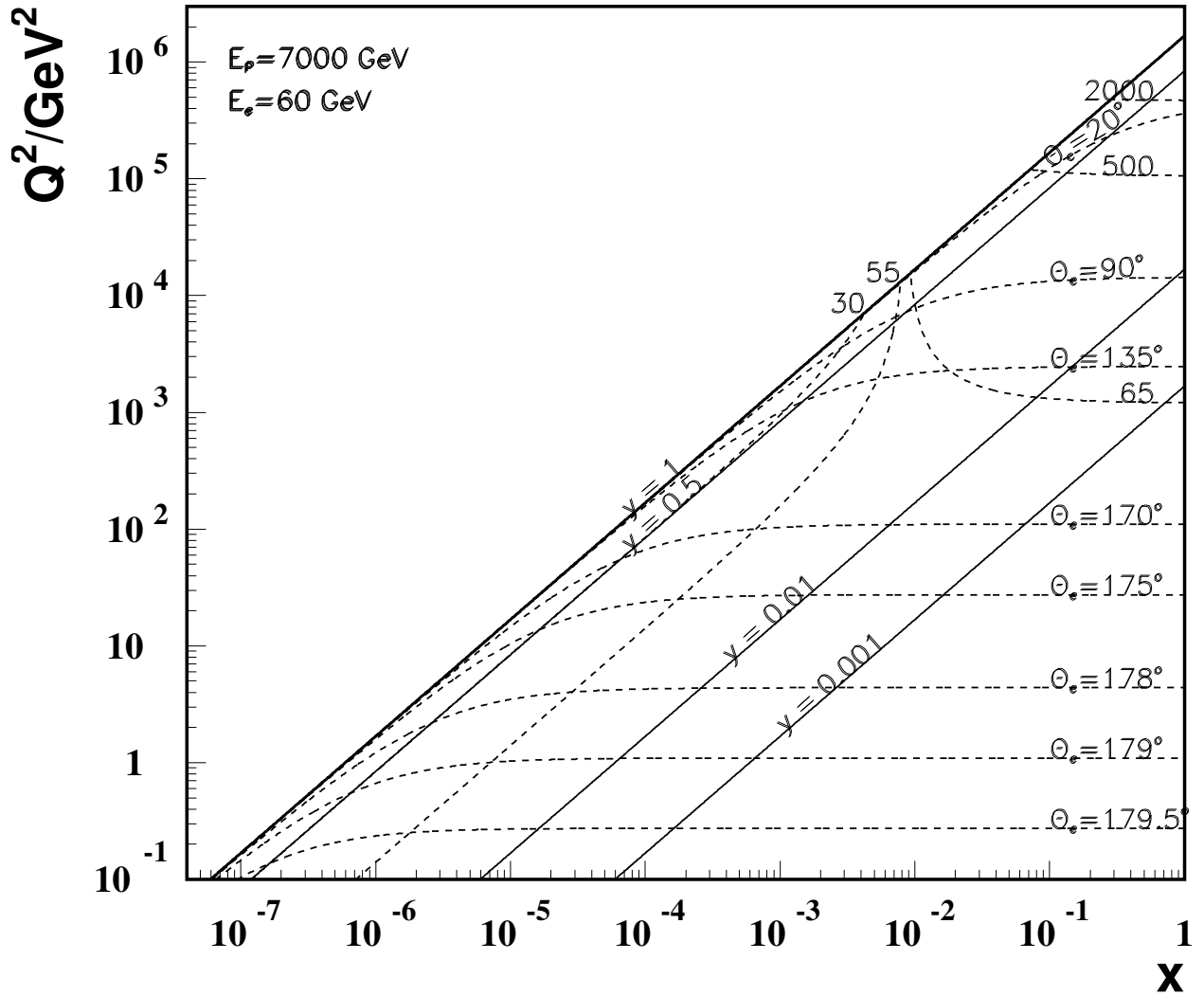


Figure 12.3: Kinematics of electron detection at the LHeC. Lines of constant scattering angle θ_e and energy, in GeV, are drawn. The region of low $Q^2 \lesssim 10^2 \text{ GeV}^2$, comprising the lowest x region, requires to measure electrons scattered backwards with energies not exceeding E_e . At small energies, for $y \lesssim 0.5$ a good e/h separation is important to suppress hadronic background, as from photoproduction. The barrel calorimeter part, of about $90 \pm 45^\circ$, measures scattered electrons of energy not exceeding a few hundreds of GeV, while the forward calorimeter has to reconstruct electron energies of a few TeV. Both the barrel and the forward calorimeters measure the high x part, which requires very good scale calibration as the uncertainties diverge $\propto 1/(1-x)$ towards large x .

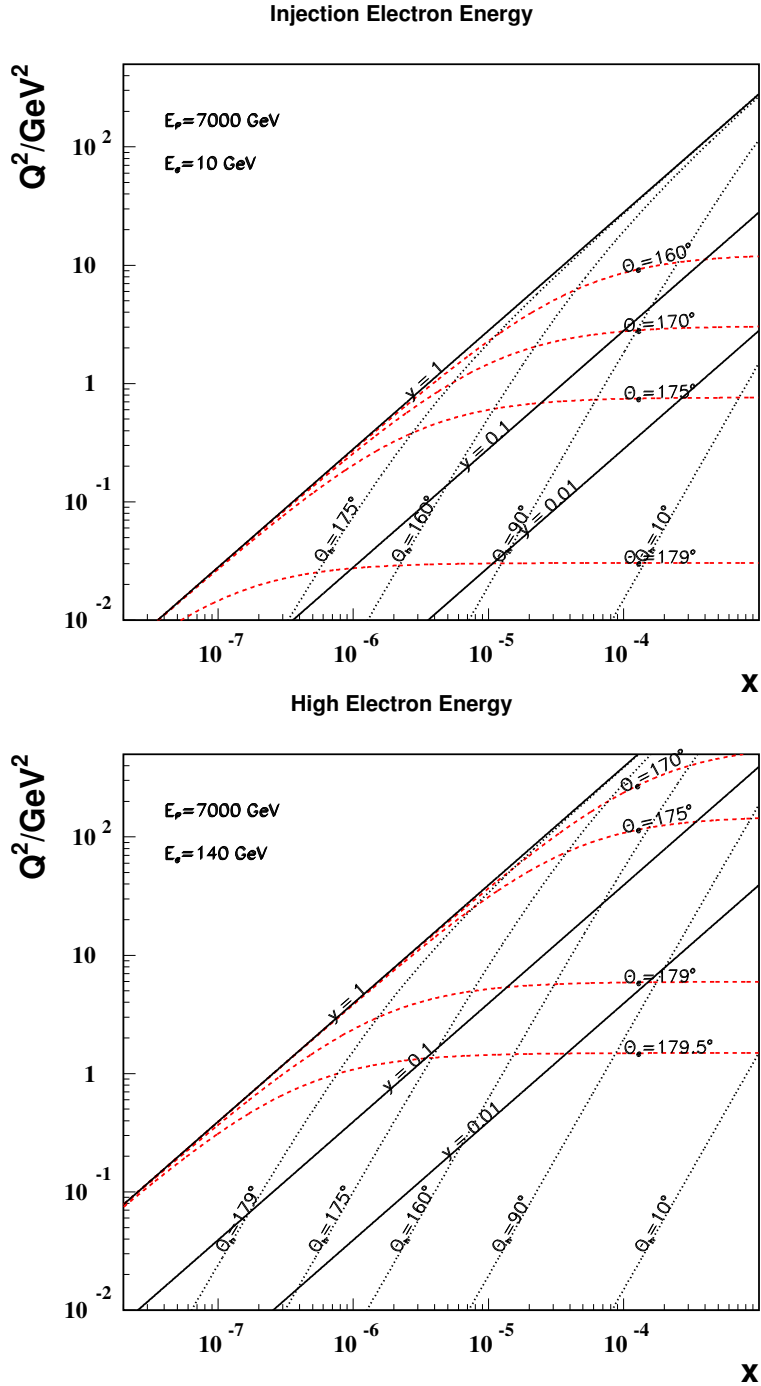


Figure 12.4: Kinematics at low x and Q^2 of electron and hadronic final state detection at the LHeC with an electron beam energy of 10 GeV (top) as compared to 140 GeV (bottom). At larger x , the iso- θ_e lines are at about constant $Q^2 \propto E_e^2$. At low x , the scattered energies, not drawn here, are approximately at $E'_e \simeq (1 - y) \cdot E_e$, and at lower Q^2 and x one has $E_h \simeq E_e - E'_e \simeq y \cdot E_e$. At very high E_e part of the very low Q^2 region may be accessible with the electron tagged along the e beam direction, outside the central detector, and the kinematics measured with the hadronic final state.

8669 Electrons scattered forward correspond to scattering at large $Q^2 \geq 10^4 \text{ GeV}^2$, as is illustrated in the
 8670 zoomed kinematic region plot Fig. 12.5. The energies in the very forward region, $\theta_e \lesssim 10^\circ$, exceed 1000 GeV.
 8671 For large E_e and x , Eq. 12.5 simplifies to $Q^2 \simeq 4E_e E'_e$, i.e. a linear relation of Q^2 and E'_e which is independent
 of x and of E_p , apart from the fact that $Q_{max}^2 = s$.

LHeC - electron kinematics

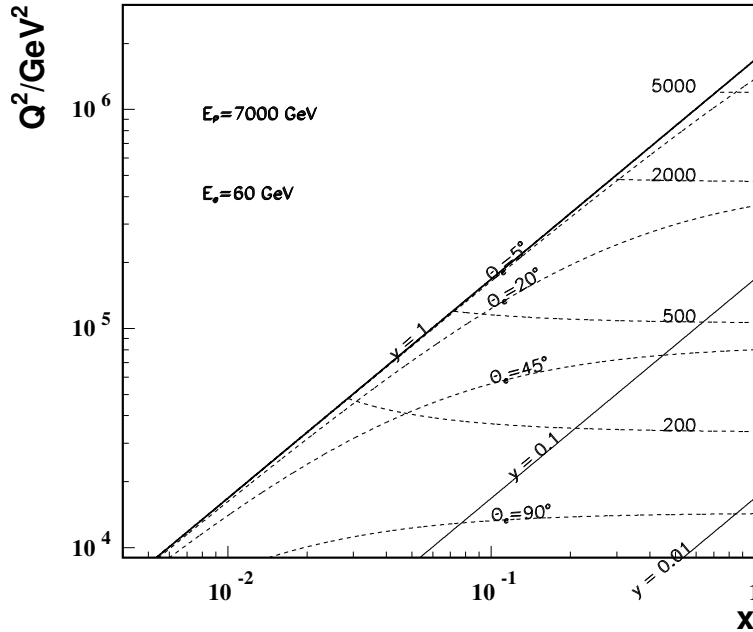


Figure 12.5: Kinematics of electron detection in the forward detector region corresponding to large $Q^2 \geq 10^4 \text{ GeV}^2$. The energy values are given in GeV. At very high Q^2 the iso- E'_e lines are rather independent of x , i.e. $Q^2(x, E'_e) \simeq 4E_e E'_e$.

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8673 12.1.4 Acceptance regions - hadronic final state

8674 The positions of isolines in the (Q^2, x) plane of constant energy and angle of the hadronic final state,
 8675 approximated here by the current jet or struck quark direction, are given by the relations:

$$\begin{aligned}
 Q^2(x, E_h) &= sx \cdot \frac{x E_p - E_h}{x E_p - E_e} \\
 Q^2(x, \theta_h) &= sx \cdot \frac{x E_p}{x E_p + E_e \cot^2(\theta_h/2)}
 \end{aligned}
 \tag{12.7}$$

8676 and are illustrated in Fig. 12.6. At low $x \lesssim 10^{-4}$, the hadronic final state is emitted backwards, $\theta_h > 135^\circ$,
 8677 with energies of a few GeV to a maximum of E_e . Lines at constant y at low x are approximately at
 8678 $y = 1 - E'_e/E_e$ and $E'_e + E_h = E_e$, i.e. $y = E_h/E_e$. Final state physics at lowest $x \lesssim 3 \cdot 10^{-6}$ requires access
 8679 to the backward region within a few degrees of the beam pipe (Fig. 12.6). This is the high y region in which
 8680 the longitudinal structure function is measured.

the first 1.5 m to say 80 cm but one would still like to have a sizable tracker length for achieving some sagitta to determine the charge of the scattered electron and perhaps arrive at an overall backward detector length of about 2.5 m. While this is an interesting reduction one loses the lowest x corner which opens $\propto E_e$. The access to lowest x in the DIS region is a fundamental part of the LHeC physics program and thus the about 179° design requirement has been kept. There are reasons to take data with reduced E_e as for F_L , thus the LHeC detector will access the region below 1 GeV^2 too.

LHeC - hadronic final state kinematics

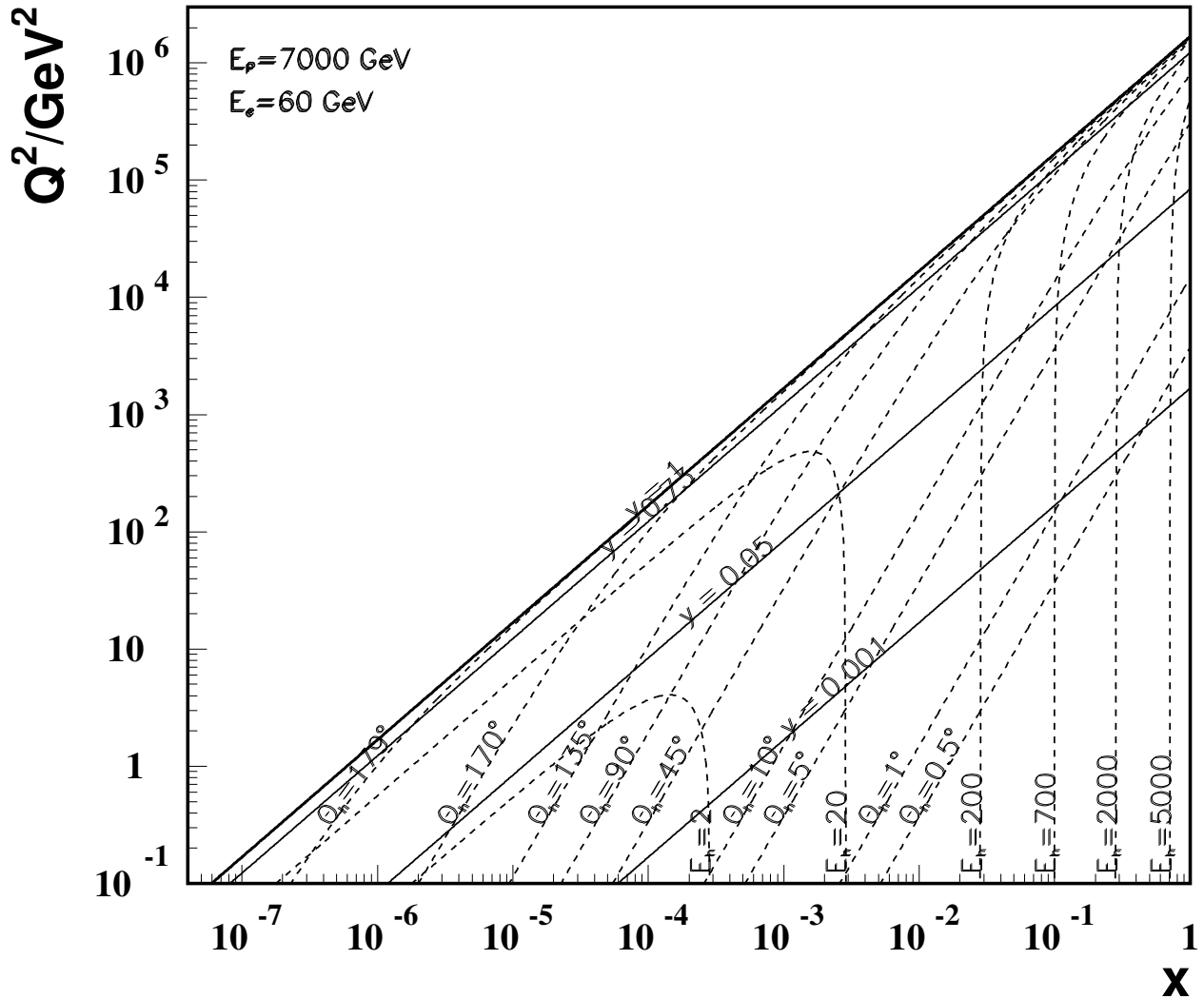


Figure 12.6: Kinematics of hadronic final state detection at the LHeC. Lines of constant energy and angle of the hadronic final state are drawn, as represented by simple kinematics of the struck quark. One easily recognizes that the most demanding region is the large x domain, where very high energetic final state particles are scattered close to the (forward) direction of the proton beam. The barrel region, of about $90 \pm 45^\circ$, is rather modest in its requirements. At low x the final state is not very energetic, $E_h + E'_e \simeq E_e$, and scattered into the backward detector region.

8681 The x range accessed with the barrel calorimeter region, of θ_h between 135° and 45° , is typically around
 8682 10^{-4} and smaller than a decade for each Q^2 , as can be seen in Fig. 12.6. The hadronic energies in this
 8683 part do not exceed typically 200 GeV. The detector part which covers this region is quite large but the
 8684 requirements are modest. One might even be tempted to consider a two-arm spectrometer only. However,
 8685 the measurement of missing transverse energy and the importance of using the longitudinal momentum
 8686 conservation for background and radiative correction reductions, with the $E - p_z$ criterion, demand the
 8687 detector to be hermetic and complete.

8688 For the measurement of the hadronic final state the forward detector is most demanding. Due to the
 8689 high luminosity, the large x region will be populated and a unique physics program at large x and high Q^2
 8690 may be pursued. In this region the relative systematic error increases like $1/(1-x)$ towards large x , see
 8691 below this section. At high x and not extreme Q^2 the $Q^2(x, E_h)$ line degenerates to a line $x = E_h/E_p$ as
 8692 can be derived from Eq. 12.7 and be seen in Fig. 12.6. High x coverage thus demands the registration of up
 8693 to a few TeV of energy close to the beam pipe, i.e. a dedicated high resolution calorimeter is mandatory for
 8694 the region below about $5 - 10^\circ$ extending to as small angles as possible. A minimum angle cut $\theta_{h,min}$ in the
 8695 forward region, the direction of the proton beam, would exclude the large x region from the hadronic final
 8696 state acceptance (Fig. 12.6), along a line

$$Q^2(x, \theta_{h,min}) \simeq [2E_p x \tan^2(\theta_{h,min}/2)]^2, \quad (12.8)$$

8697 which is linear in the $\log Q^2, \log x$ plot and depends on E_p only. Thus at $E_p = 7$ TeV the minimum Q^2
 8698 is roughly $(1000[100]x)^2$ at a minimum angle of $10[1]^\circ$. Since the dependence in Eq. 12.8 is quadratic with
 8699 E_p , lowering the proton beam energy is of considerable interest for reaching the highest possible x and
 8700 overlapping with the large x data of previous experiments or searches for specific phenomena as intrinsic
 8701 heavy flavour.

8702 12.1.5 Acceptance at the High Energy LHC

8703 Presently one considers to build a high energy (HE) LHC in the thirties with proton beam energies of
 8704 16 TeV [737]. Such an accelerator would better be combined with an electron beam of energy exceeding the
 8705 60 GeV, considered as default here, in order to profit from the doubled proton beam energy and to limit the
 8706 asymmetry of the two beam energies. Choosing the 140 GeV beam mentioned above in this section as an
 8707 example, Figure 12.7 displays the kinematics and acceptance regions for given scattering angles and energies
 8708 of the electron (dashed green and red) and of the hadronic final state (black, dotted and dashed dotted).
 8709 The cms energy in this case is enhanced by about a factor of five. The maximum Q^2 reaches 10 TeV^2 , which
 8710 is 10^6 times higher than the typical momentum transfer squared covered by the pioneering DIS experiment
 8711 at SLAC. The kinematic constraints in terms of angular acceptance would be similar to the present detector
 8712 design as can be derived from the Q^2, x plot. At very high x (Q^2) the energy E_h (E'_e) to be registered would
 8713 be doubled. With care in the present design, one would probably be able to use the main LHeC detector
 8714 components also in the HE phase of the LHC.

8715 12.1.6 Energy Resolution and Calibration

8716 The LHeC detector is dedicated to most accurate measurements of the strong and electroweak interaction
 8717 and to the investigation of new phenomena. The calorimetry therefore requires:

- 8718 • Optimum scale calibrations, as for the measurement of the strong coupling constant. This is much
 8719 helped by the redundant kinematic reconstruction and kinematic relations, as $E'_e \simeq E_e$ at low Q^2 ,
 8720 $E'_e + E_h \simeq E_e$ at small x , the double angle reconstruction [738] of E'_e and the transverse momentum
 8721 balance of p_T^e and p_T^h . From the experience with H1 and the much increased statistics it is assumed
 8722 that E'_e may be calibrated to $0.1 - 0.5\%$ and E_h to $1 - 2\%$ accuracy. The latter precision will be most
 8723 crucial in the forward, high x part of the calorimeter because the uncertainties diverge $\propto 1/(1-x)$
 8724 towards large x .

Kinematics at HE-LHeC

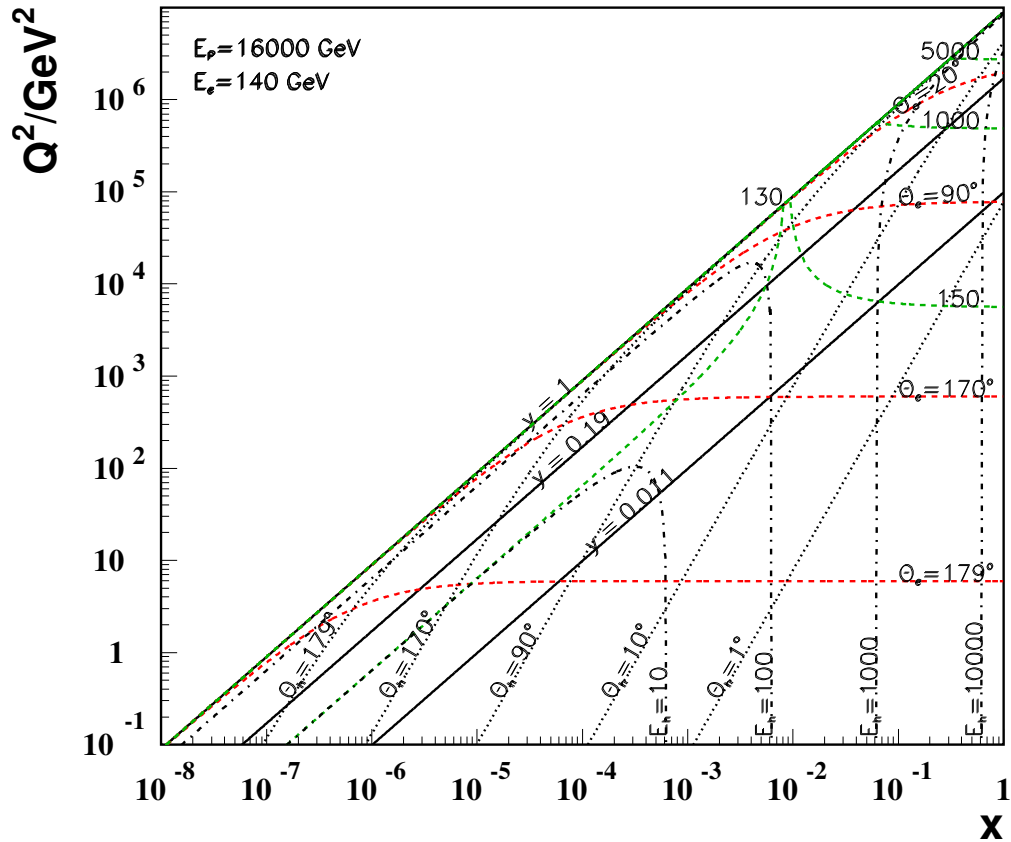


Figure 12.7: Scattered electron and hadronic final state kinematics for the HE-LHC at $E_p = 16$ TeV coupled with a 140 GeV electron beam. Lines of constant scattering angles and energies are plotted. The line $y = 0.011$ defines the edge of the HERA kinematics and $y = 0.19$ defines the edge of the default machine considered in this report ($E_e = 60$ GeV and $E_p = 7$ TeV).

- 8725 • High resolution, for the reconstruction of multi-jet final states as from the $H \rightarrow b\bar{b}$ decay. This is
8726 a particular challenge for the forward calorimeter. While detailed simulations are still ongoing one
8727 may assume that $(10 - 15)/\sqrt{E/GeV}$ % resolutions for E'_e and $(40 - 50)/\sqrt{E/GeV}$ % for E_h are
8728 appropriate, with small linear terms. These requirements are very similar to the ATLAS detector
8729 which quotes electromagnetic resolutions of $10/\sqrt{E/GeV} \oplus 0.007$ % and hadronic energy resolutions of
8730 $50/\sqrt{E/GeV} \oplus 0.03$ %. The basic electromagnetic calorimeter choice for the LHeC can be for Liquid
8731 Argon (LAr)⁴. The hadronic calorimeter is outside the magnets and serving also for the magnetic flux
8732 return may be built as a tile calorimeter with the additional advantage of supporting the whole detector.
8733 The first year of operating the ATLAS combined LAr/TileCal calorimeter has been encouraging. Some
8734 special calorimeters are needed in the small angle forward region ($\theta \lesssim 5^\circ$) where the deposited energies
8735 are extremely large, and also in the backward region ($\theta \geq 135^\circ$) where the electron detection of modest
8736 energy is a special task.

⁴In H1 very good experience has been collected with the longterm stability of the LAr calorimeter. A special demand is the low noise performance because the measurements at small inelasticity y are crucial for reaching large Bjorken x . In this region a small misidentified deposition of energy in the backward part of the detector can spoil the measurement at low $y \lesssim 0.01$, as can be seen from Eq. 12.4.

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- Good electron-hadron separation, as for the electron identification at high y and low Q^2 (backwards) or high Q^2 (in the extreme forward direction). This is a requirement on the segmentation of the calorimeters and on building trackers in front also of the forward and backward calorimeters to support the energy measurements and the electron identification in particular.

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Obviously the calorimetry needs to be hermetic for the identification of the charged current process and good measurement of $E_{T,miss}$. These considerations are also summarised in Tab.12.1.

region of detector approximate angular range / degrees	backward 179 - 135	barrel 135 -45	forward 45-1
scattered electron energy/GeV	3-100	10-400	50-5000
x_e	$10^{-7} - 1$	$10^{-4} - 1$	$10^{-2} - 1$
elm scale calibration in %	0.1	0.2	0.5
elm energy resolution $\delta E/E$ in % $\cdot \sqrt{E/GeV}$	10	15	15
hadronic final state energy/GeV	3-100	3-200	3-5000
x_h	$10^{-7} - 10^{-3}$	$10^{-5} - 10^{-2}$	$10^{-4} - 1$
hadronic scale calibration in %	2	1	1
hadronic energy resolution in % $\cdot \sqrt{E/GeV}$	60	50	40

Table 12.1: Summary of calorimeter kinematics and requirements for the default design energies of $60 \times 7000 \text{ GeV}^2$, see text. The forward (backward) calorimetry has to extend to 1° (179°).

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12.1.7 Tracking Requirements

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The tracking detector has to enable

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- Accurate measurements of the transverse momenta and polar angles
- Secondary vertexing in a maximum polar angle acceptance range
- Resolution of complex, multiparticle and highly energetic final states in forward direction
- Charge identification of the scattered electron
- Distinction of neutral and charged particle production
- Measurement of vector mesons, as the J/ψ or Υ decay into muon pairs

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The transverse momentum resolution in a solenoidal field can be approximated by

$$\frac{\delta p_T}{p_T^2} = \frac{\Delta}{0.3BL^2} \cdot \sqrt{\frac{720}{N+4}} \quad (12.9)$$

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where B is the field strength, Δ is the spatial hit resolution and L the track length in the plane transverse to the beam direction, and N being the number of measurements on a track, which enters as prescribed in [739]. As an example, for $B = 3.5 \text{ T}$, $\Delta = 10 \mu\text{m}$, $N = 4 + 5$ and $L = 0.42 \text{ m}$ one obtains a transverse momentum measurement accuracy of about $3 \cdot 10^{-4}$. A simulation, using the LICTOY program [740], of the transverse momentum, transverse impact parameter and polar angle resolutions is shown in Fig. 12.8. One can see that the estimate following Eq. 12.9 is approximately correct for larger momenta where the multiple scattering becomes negligible. This momentum resolution, in terms of $\delta p_T/p_T^2$ is about ten times better than the one achieved with the H1 central drift chamber. It is similar to the ATLAS momentum resolution for central tracks and thus considered to be adequate for the enlarged momenta at LHeC as compared to

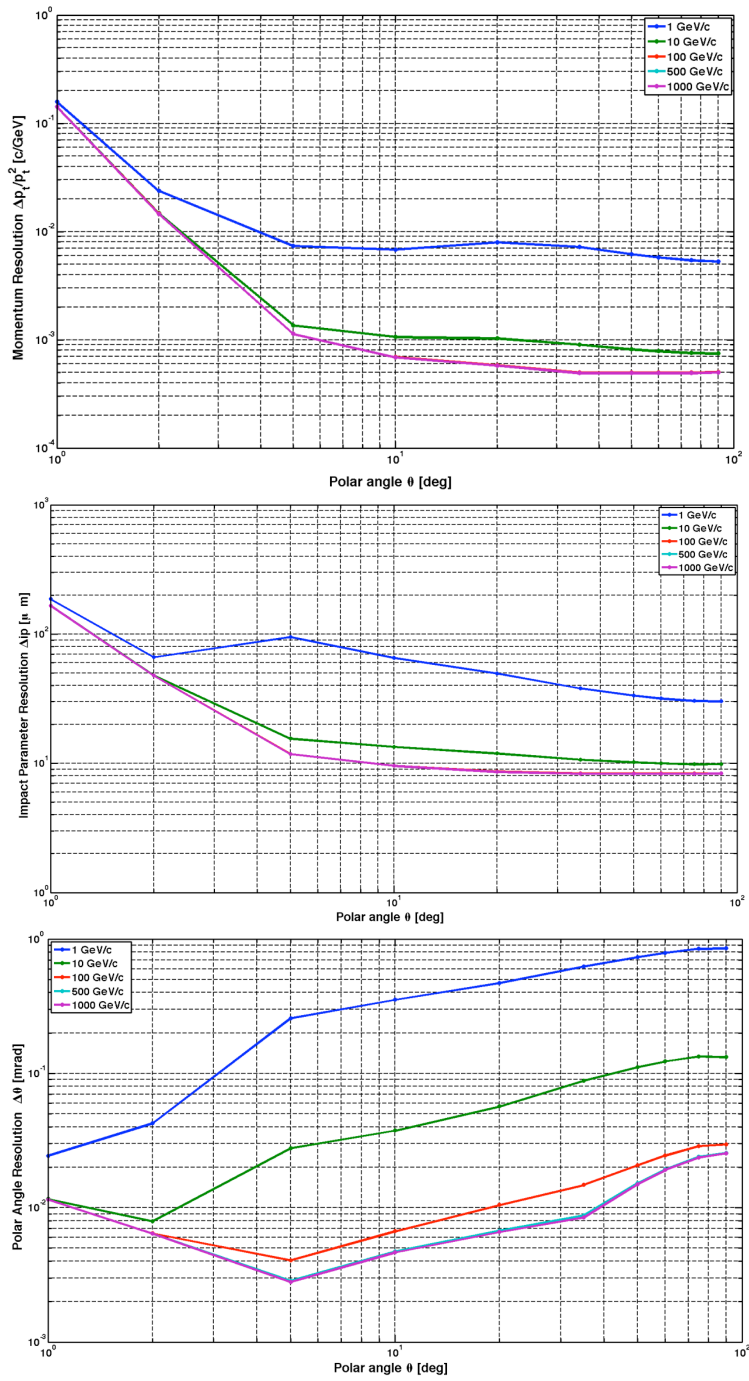


Figure 12.8: Transverse momentum (top), impact parameter (middle) and polar angle (bottom) measurement resolutions as function of the polar angle for the default detector design for four values of track transverse momentum.

8761 HERA and the goal of high precision vertex tagging. One finds that the impact parameter resolution, for
8762 high momenta, is a factor of eight improved over the H1 or ZEUS result.

8763 In backward direction, a main tracking task is to determine the charge of the scattered electron or
8764 positron, which has momenta $E'_e \leq E_e$, down to a few GeV for DIS at high $y \simeq 1 - E'_e/E_e$. With a beam
8765 spot as accurate as about $10 \times 30 \mu\text{m}^2$ and the beam pipe radius of a few cm only, the backward Silicon strip
8766 tracker will allow a precise E/p determination when combined with the backward calorimeter, even better
8767 than has been achieved with the H1 backward silicon detector [68].

8768 In the forward region, $\theta < 5^\circ$, as may be deduced from Figs. 12.5, 12.6, the hadronic final state, for all Q^2 ,
8769 and the scattered electron, when scattered "back" at high Q^2 , are very energetic. This requires a dedicated
8770 calorimeter. Depending on the track path and momentum, the track sagitta becomes very small, for example
8771 about $10 \mu\text{m}$ for a 1 TeV track momentum and a 1 m track length. In such extreme cases of high momenta,
8772 the functionality of the tracker will be difficult to achieve: the sagitta becoming small means that there will
8773 be limits to the transverse momentum measurement while the ability to distinguish photons and electrons
8774 will be compromised by the high probability of showering and conversion when the pipe is passed under very
8775 small angles. A forward tracker yet is considered to be useful down to small angles for the reconstruction
8776 of the event structure, the rejection of beam induced background and the reconstruction of forward going
8777 muons. This region requires detailed simulation studies in a next phase of the project.

8778 12.1.8 Particle Identification Requirements

8779 The requirements on the identification of particles focus on the identification of the scattered electron, a
8780 reliable missing energy measurement and precision tracking for measuring the decay of charm and beauty
8781 particles, the latter rather on a statistical basis than individually. Classic measurements as the identification
8782 of the D meson from the $K\pi\pi$ decay with a slow pion or the identification of B production from high p_T
8783 leptons require a very precise track detector. The tracker should determine some dE/dX properties but
8784 there is no attempt to distinguish strange particles, as kaons from pions, as the measurement of the strange
8785 quark distribution is traced back to charm tagging in CC events. The identification of muons, apart from
8786 some focus on the forward and backward direction, is similar to that of pp detectors. In addition a number
8787 of taggers is foreseen to tag

- 8788 • electrons scattered near the beam pipe in backward direction to access low Q^2 events and control the
8789 photoproduction background;
- 8790 • photons scattered near the beam pipe in backward direction to measure the luminosity from Bethe
8791 Heitler scattering;
- 8792 • protons scattered in forward direction to measure diffractive DIS in ep scattering and to tag the
8793 spectator proton in en scattering in electron-deuteron runs;
- 8794 • neutrons scattered in forward direction to measure pion exchange in ep scattering and to tag the
8795 spectator neutron in ep scattering in electron-deuteron runs;
- 8796 • deuterons scattered in forward direction in order to discover diffraction in lepton-nucleus scattering.

8797 From the perspective of particle identification therefore no unusual requirements are derived. One needs a
8798 state of the art tracker with a very challenging forward part and a tagger system with the deuteron as a new
8799 component in forward direction.

8800 12.1.9 Summary of the Requirements on the LHeC Detector

8801 The considerations discussed in this chapter along with the constraints from machine operation and the
8802 physics program let to following main items for the detector design.

- 8803 1. The LHeC experiment has to be operated in parallel to the other LHC experiments and has to be set
8804 up in accordance to CERN regulations.

- 8805 2. The detector realization requires a modular design and construction with the assembly process done in
8806 parallel partly at surface level and partly in the experimental area following the LHC machine running
8807 and maintenance periods.
- 8808 3. The beam pipe will host the electron beam along with the two LHC counter rotating proton beams.
8809 The non interacting proton/ion beam has to bypass the IP region guided through the same beam pipe
8810 housing the electron and interacting proton/ion beam.
- 8811 4. The detector should be modular and flexible to accommodate the high acceptance as well as the high
8812 luminosity running foreseen for the two main physics programs. The flexibility should accommodate
8813 reducing/enhancing the energy asymmetry of the beams - section 13.3.
- 8814 5. The detector design can profit from the experience at HERA and the LHC and will be based on the
8815 recent detector developments in order to meet the ambitious physics requirements, summarized in pre-
8816 vious chapter, using settled technology, avoiding extended R&D programs and being of comparatively
8817 reasonable cost.
- 8818 6. Mechanics/services have to be optimized minimizing the amount of material in sensitive regions of the
8819 experimental setup.
- 8820 7. The detector has to be operated in a high luminosity environment L . High \bar{L} is anticipated with small
8821 beam spot sizes ($\sigma_x \approx 30\mu m$, $\sigma_y \approx 16\mu m$), small β^* and relatively large IP angles (see acc. part). On
8822 the other hand β^* has to be chosen to eliminate effects of parasitic bunch crossings. The machine and
8823 detector requirements near the IP is an optimization problem.
- 8824 8. The detector must experience acceptable backgrounds. The design has to be background insensitive as
8825 far as possible and the machine has to incorporate masks, shielding's and an appropriate optics design
8826 that minimizes background sources and a vacuum profile that reduces backgrounds.
- 8827 9. It might be necessary to have insertable/removable shielding protecting the detector against injection
8828 and poor machine performance.
- 8829 10. Special Interaction Region (IR) instrumentation for tuning of the machine with respect to background
8830 and luminosity is needed. Radiation detectors e.g. near mask and tight apertures are useful for fast
8831 identification of background sources. Fast bunch related informations are useful for beam optimization
8832 in that context.
- 8833 11. Good vertex resolution for decay particle secondary vertex tagging is required, which implies a small
8834 radius and thin beam pipe optimized in view of synchrotron radiation and background production -
8835 see section 9.7.
- 8836 12. The detector will have one solenoid in its default version building a homogenous field in the tracking
8837 area of 3.5 T extending over $z = +370cm, -200cm$. Solenoid options are described in section 13.2.
- 8838 13. The tracking and calorimetry in the forward and backward direction has to be set up such that the
8839 extreme asymmetry of the production kinematics are taken into account by layout and choice of
8840 technology for the detector design and ensure high efficiency measurements. The detectors have to be
8841 radiation hard.
- 8842 14. Very forward/backward detectors have to be set up to access the diffractive produced events and
8843 measuring the luminosity with high precision, respectively - chapter 14.

Chapter 13

Central Detector

Following the considerations of the physics requirements and the technical and operational constraints outlined in chapter 12.1, a detector design for high precision and large acceptance Deep Inelastic Scattering is presented. The detectors for the Linac-Ring or the Ring-Ring options are nearly identical: the two notable differences are the dipoles in the Linac-Ring case for separating the e and the p beams and the larger beam pipe due to the wider synchrotron radiation fan. For practical reasons of this report the more complicated Linac-Ring detector has been chosen as the baseline, termed version A. This evidently affects the solenoid-dipole configuration and the inner shape of the tracker but is of no severe concern. For the Ring-Ring case the luminosity may be maximised by inserting focussing quadrupoles near to the IP. This causes the inner detector to be designed modular such that a transition could be made between the two phases, with the quadrupoles to achieve maximum luminosity and without, to ensure maximum polar angle acceptance ¹.

13.1 Basic Detector Description

The LHeC detector is asymmetric in design, reflecting the beam energy asymmetry and reducing cost. It is a general purpose 4π detector, which consists of an inner silicon tracker, with extended forward and backward parts, surrounded by an electromagnetic calorimeter, which is separated from the hadronic calorimeter by a solenoid with 3.5 T field incorporating dipoles, in the Linac-Ring case, Fig. 13.1, or not, in the Ring-Ring case, Fig. 13.2. The hadron calorimeter is enclosed in a muon tracker system, not shown here but discussed in section 13.7. The main detector is complemented by hadron tagging detectors in the forward direction and a polarimeter and luminosity measurement system backwards, as is also presented below. Its longitudinal extension is determined by the need to cover polar angles down to 1° at the given beam pipe dimension. Its radial size is mainly determined by the requirement of full energy containment of hadronic showers in the calorimeter.

The dipoles for the Linac-Ring IR cannot be of a too large radius to act on the beam and be affordable. Their bulk material should also not compromise tracking and electromagnetic energy measurements and thus have to be placed outside the electromagnetic calorimeter, chosen to be Liquid Argon. The solenoid cost scales, as discussed above (see Eq.12.1), approximately with its radius which in absolute allows tens of millions CHF to be economised, with the solenoid placed inside the hadronic calorimeter also considering the cost of the 10 kt of iron needed for shielding. In order to minimize cost and material, it appears appropriate to foresee a single cryostat housing the electromagnetic calorimeter and the solenoid and dipole magnets. This leads also to some modification of the forward and backward calorimeter inserts, which can be seen

¹The very recent optics design results suggest that there is only a factor of two difference between the luminosity achievable with and without the quadrupoles. That is not enough to justify considering two measurement phases, in particular having in mind that such a transition, as happened at HERA, may take much more time than one would estimate beforehand. If the Ring-Ring solution was chosen, therefore, it would most likely only require one unchanged main detector configuration. The baseline considered here would be fully adequate for this case, with less complication of the magnets and a narrower pipe.

8875 comparing the Linac-Ring Fig. 13.1 with the Ring-Ring Fig. 13.2. Since for the physics performance it is
 8876 evidently advantageous to place the solenoid outside the hadronic calorimeter, this option, termed B, has
 8877 also been studied and is discussed in section 13.2. The radius of the large coil would be about 2.5 m which
 8878 still compares well with for example the H1 and the CMS coils but is an option for the Ring-Ring machine
 design only and not the baseline currently.

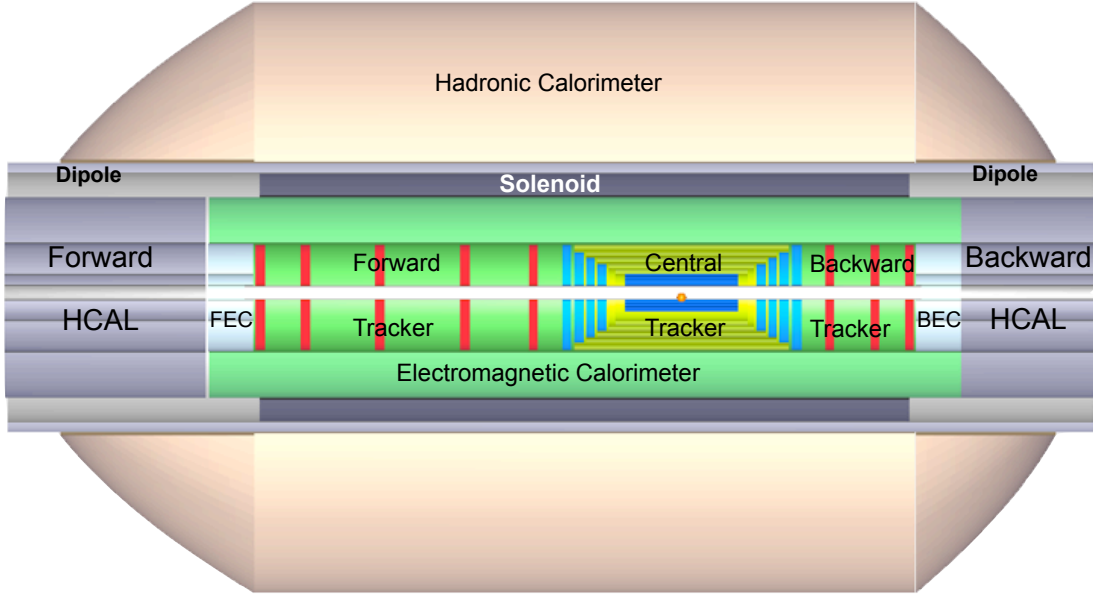


Figure 13.1: Schematic rz view of the detector design for the Linear-Ring machine option showing the characteristic dipole and solenoid placement between the electromagnetic and the hadronic calorimeters. The proton beam, from the right, collides with the electron beam, from the left, at the IP which is surrounded by a central tracker system complemented by large forward and backward tracker telescopes followed by sets of calorimeters. The detector as sketched here, i.e. without the muon tracking system, has a radius of 2.6 m and extends from about $z = -3.6$ m to $z = +5.9$ m in the direction of the proton beam.

8879 The Ring-Ring configuration possibly requires separate data taking phases with maximum polar angle
 8880 acceptance, for physics at low and high x , and with ultimate luminosity, for electroweak physics and the search
 8881 for rare phenomena. Correspondingly, the LHeC inner detector is designed here with a modular structure as
 8882 is illustrated in Figs. 13.3 and 13.4 which show the detector without and with the low β quadrupoles inserted
 8883 to accommodate for either configuration, respectively. This requires the removal of the forward/backward
 8884 tracking setup (shown in red in Fig. 13.3) and the subsequent reinstallation of the external forward/backward
 8885 electromagnetic and hadronic calorimeter plugins near to the vertex. The high luminosity apparatus would
 8886 have a polar angle acceptance coverage of about 8° - 172° for an estimated gain in luminosity of slightly
 8887 higher than a factor of two with respect to the large acceptance configuration. The Ring-Ring and Linac-
 8888 Ring detectors also differ due to the different optics and the beam pipe geometry.

8890 In the Ring-Ring design the e and p/A beams collide with a small non-zero crossing angle, large enough
 8891 to avoid parasitic crossings, which for a 25 ns bunch crossing occur at ± 3.75 m from the IP. Additional
 8892 masks are used to shield the inner part of the detector from synchrotron radiation generated upstream of
 8893 the detector.

8894 For the Linac-Ring design, the dipole field in the detector area which allow for head-on collisions and
 8895 provide the required separation, produces additional synchrotron radiation which has to pass through the
 8896 interaction region requiring a larger beam pipe. This difference results in a factor of two wider extension of
 8897 the horizontal beam pipe in the outer region in the Linac-Ring case, which in this regard is the unfavourable

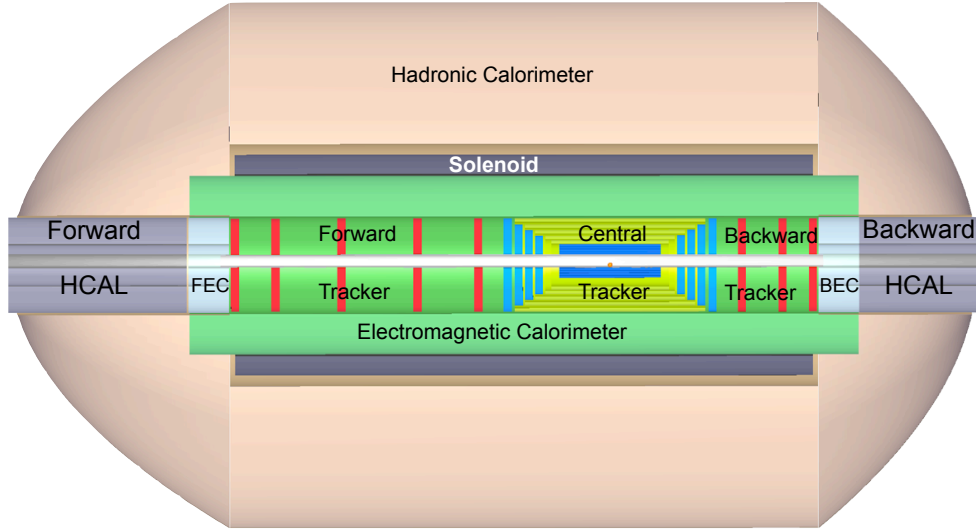


Figure 13.2: Schematic rz view of the detector design for the Ring-Ring machine option. Note that the outer part of the forward and backward calorimeters ends at smaller radii, as compared to the Linac-Ring case, since there are no dipole magnets foreseen.

8898 solution but unavoidable and necessary fully containing the synchrotron radiation fan. The radius of the
 8899 circular part has been chosen according to tentative choices of the LHC upgrade beam pipe dimensions.

8900 According to a first estimate of the synchrotron radiation and an initial placement of masks, shielding
 8901 the Ring-Ring detector from direct and backscattered photons, the beam pipe geometries have been chosen
 8902 as shown in Fig. 13.5 for the Ring-Ring case and in Fig. 13.6 for the Linac-Ring case.

8903 As already mentioned, the necessity to register particle production down to 1 and 179° poses severe
 8904 constraints on the material and the thickness of the pipe. In the design as shown here, a beryllium pipe
 8905 would have 3.0 (1.5) mm thickness in the Linac-Ring (Ring-Ring) case. An extensive R&D program is
 8906 needed aiming for higher stability of the beam pipe at given dimensions and for thinner/lighter beam wall
 8907 construction resulting in higher transparency for all final state particles. This R&D program is necessary
 8908 regardless of which machine option for the LHeC facility is selected. It may also turn out to be advantageous
 8909 to use a trumpet shaped beampipe when this problem gets revisited in a more advanced phase of the LHeC
 8910 design when more detailed simulations will be available and results of pipe material developments become
 8911 known.

8912 In order to ensure optimal polar angle acceptance, the innermost subdetector dimensions have to be
 8913 adapted to the beam pipe shape. Fig. 13.7 illustrates the configuration that a circular silicon tracker would
 8914 imply and the corresponding acceptance losses. These can be reduced as shown in Fig. 13.8 if the detector
 8915 acceptance follows as close as possible the elliptic-circular shape of the pipe. Electrons scattered at high
 8916 polar angle, corresponding to small $Q^2 \sim 1 \text{ GeV}^2$, will only be registered in the inner part of the azimuthal
 8917 angle region for the nominal electron beam energy. As had been shown in chapter 12.1 (Eq. 12.6), the lowering
 8918 of the electron beam energy effectively reduces the strong requirement of measuring up to about 179° , at
 8919 the expense however, of a somewhat reduced acceptance towards lowest Bjorken x .

8920 The optimum configuration of the inner detector will be revisited when the choice between the Linac-Ring
 8921 and the Ring-Ring option is made. It represents in any case one of the most challenging problems to be
 8922 solved for the LHeC.

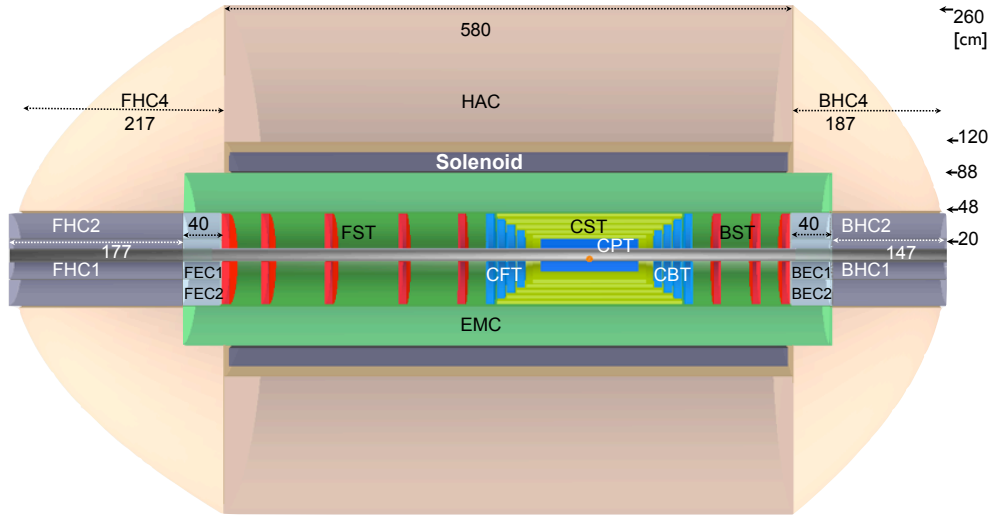


Figure 13.3: An rz cross section and dimensions of the main detector (muon detector not shown) for the Ring-Ring detector version (no dipoles) extending the polar angle acceptance to about 1° in forward and 179° in backward direction.

Detector Module	Abbreviation
Central Silicon Tracker	CST
Central Pixel Tracker	CPT
Central Forward Tracker	CFT
Central Backward Tracker	CBT
Forward Silicon Tracker	FST
Backward Silicon Tracker	BST
Electromagnetic Barrel Calorimeter	EMC
Hadronic Barrel Calorimeter	HAC
Hadronic Barrel Calorimeter Forward	FHC4
Hadronic Barrel Calorimeter Backward	BHC4
Forward Electromagnetic Calorimeter Insert 1/2	FEC1/FEC2
Backward Electromagnetic Calorimeter Insert 1/2	BEC1/BEC2
Forward Hadronic Calorimeter Insert 1/2	FHC1/FHC2
Backward Hadronic Calorimeter Insert 1/2	BHC1/BHC2

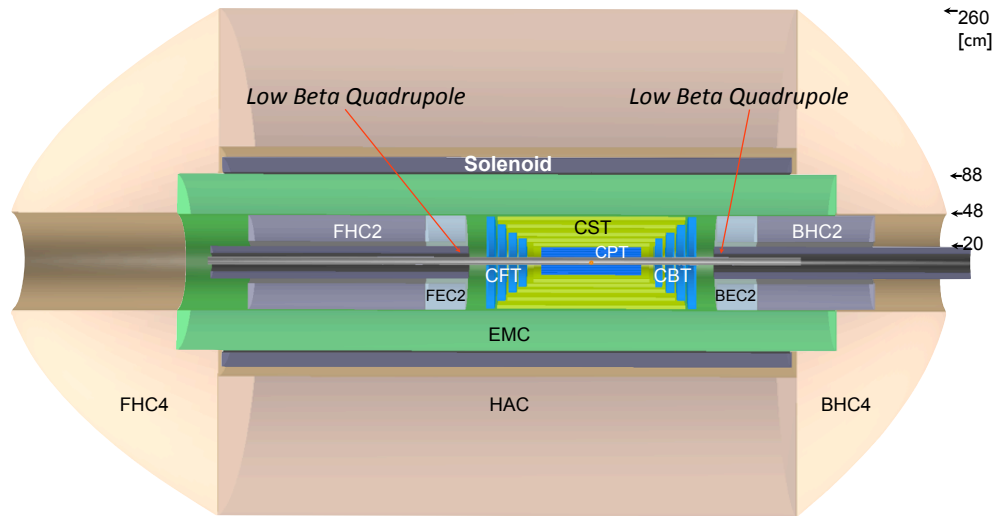


Figure 13.4: An rz cross section and dimensions of the main detector (muon detector not shown) for the Ring-Ring detector version (no dipoles) in which the luminosity is maximised by replacing the forward and backward tracker telescopes by focusing, low β quadrupole magnets at $\pm 1.2\text{m}$ away from the nominal interaction point. The polar angle acceptance is thus reduced to about $8 - 172^\circ$. As compared to the high acceptance detector (Fig. 13.3), the outer forward/backward calorimeter inserts have been moved nearer to the interaction point.

RR - Inner Dimensions
 Circular(x)=2.2cm; Elliptical(-x)=-5.5, y=2.2cm

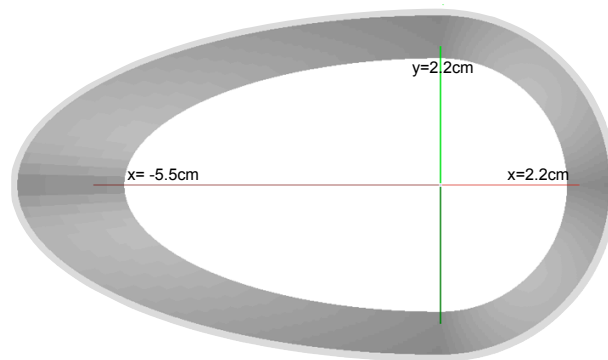


Figure 13.5: Perspective drawing of the beam pipe and its dimensions in the ring-ring configuration. The dimensions consider a 1 cm safety margin around the synchrotron radiation envelope with masks (not shown) for primary synchrotron radiation suppression placed at $z = 6, 5, 4\text{m}$.

LR - Inner Dimensions
 Circular(x)=2.2cm; Elliptical(-x)=-10., y=2.2cm

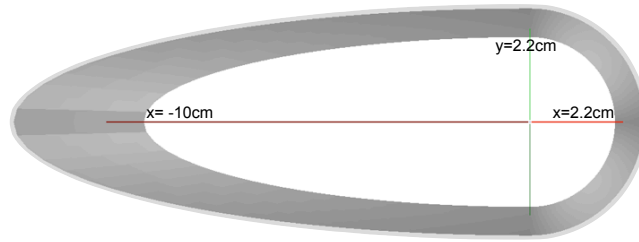


Figure 13.6: Perspective drawing of the beam pipe and its dimensions in the linac-ring configuration. The dimensions consider a 1 cm safety margin around the synchrotron radiation envelope.

8923 13.1.1 Baseline Detector Layout

8924 The baseline configuration (A) of the main detector has the solenoid in between the two calorimeters,
 8925 combined with a dipole field in the Linac-Ring case. The configuration B makes sense only for the Ring-
 8926 Ring machine design since an outer dipole would be a bad practice for that functionality and a second cryostat
 8927 with inner dipole between electromagnetic and hadronic calorimeter is bad practice as well, obviously. The
 8928 main detector is subdivided into a central barrel and the forward and backward end-cap regions, which
 8929 differ in their design because the forward region sees the remnant and the highly energetic ($E_h \lesssim E_p$)
 8930 jet from the struck quark while the backward region sees the scattered electron of energy $E'_e \leq E_e$. The
 8931 detector configuration is sketched in Fig. 13.9 with component abbreviations and some dimensions given.
 8932 More detailed dimensions are given in Fig. 13.10.

8933 For the purpose of this design, technologies had to be chosen in line with the detector requirements,
 8934 see Sect. 12.1, and based on an evaluation of the technologies available or under development for the LHC
 8935 experiments or foreseen for a linear collider detector. Due to its compactness and proven technological
 8936 feasibility, the complete inner tracker is considered to be made of silicon. This allows to keep the radius of
 8937 the magnets small, about 1 m. Based on experience with H1 and ATLAS the EMC is chosen to be a Liquid
 8938 Argon (LAr) Calorimeter. The superconducting dipoles (light grey in Fig. 13.9) are placed in a common
 8939 cryostat with the detector solenoid (dark grey) and the LAr EMC (green). The use of common cryostat
 8940 is optimum for reducing the amount of material present in front of the hadronic barrel calorimeter. The
 8941 HAC is an iron-scintillator tile calorimeter, which also guides the return flux of the magnetic field, as in
 8942 ATLAS [741, 742]. In the baseline design (A) the muon detectors are placed outside of the magnetic field
 8943 with the function of tagging muons, the momentum of which is determined mainly by the inner tracker.

8944 For the Ring-Ring machine, in order to maximize the luminosity, extra focusing magnets must be placed
 8945 near to the interaction point ². This would mean replacing the FST and the BST tracking detectors by the
 8946 low- β quadrupoles (see Fig. 13.4), at the expense of loosing about 8° of polar angle acceptance. The modular
 8947 design of the forward and backward trackers and the corresponding calorimeter modules allow the trackers
 8948 to be mounted/unmounted and the calorimeter inserts to be moved in and out of position as required. The
 8949 inner electromagnetic and hadronic endcap inserts, FEC1/BEC1 and FHC1/BHC1, respectively, will be
 8950 removed allowing the insertion of the low β -magnets and only partially put back in. Particular attention is
 8951 needed for the mechanical support structures of the quadrupoles. The structure must ensure the stability of
 8952 reproducible beam steering, while interfering as little as possible with the detector. The presence of strong
 8953 focussing magnets close to the interaction point was one issue experienced during HERA2 running [743].

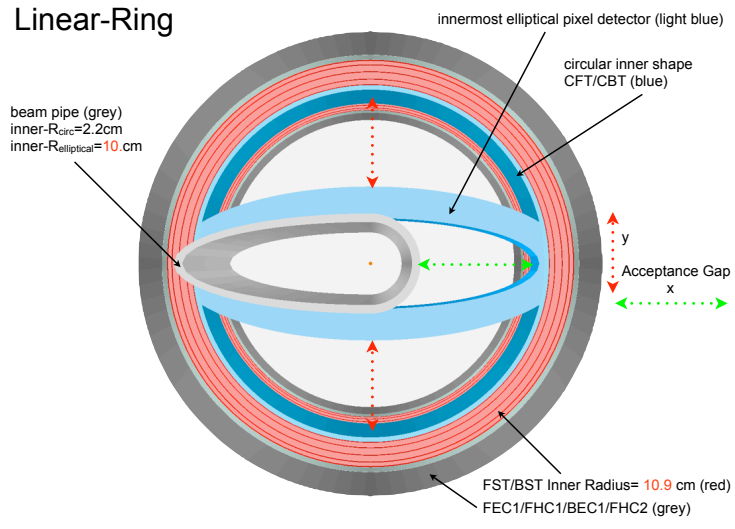


Figure 13.7: Linac-Ring beam pipe design and acceptance gaps due to deviations of inner shapes of the forward/backward tracking detectors FST/BST (circular) and the innermost central pixel detector layer (elliptical) from the pipe shape.

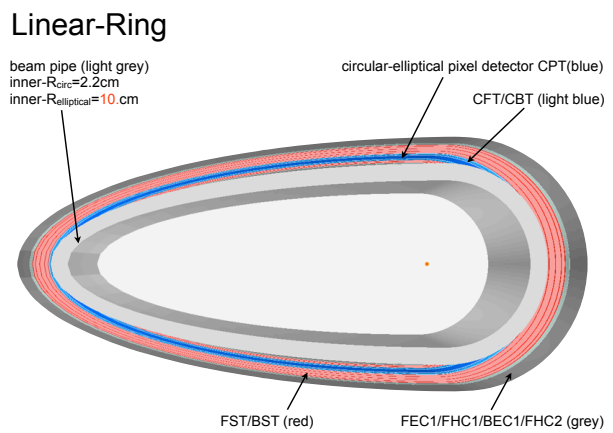


Figure 13.8: Beam pipe design for Linac-Ring and optimized circular-elliptical shape following the beam pipe for all adjacent detector parts.

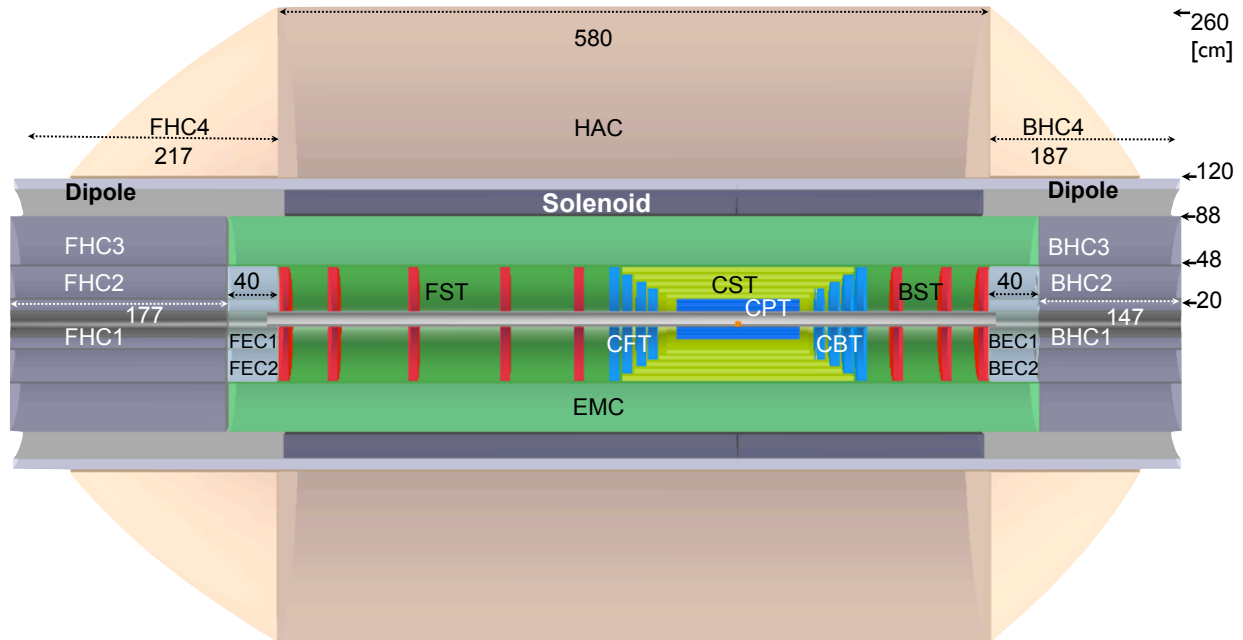


Figure 13.9: An rz cross section of the LHeC detector in its baseline configuration (A). In the central barrel, the following components are considered: a central silicon pixel detector (CPT); silicon tracking detectors (CST,CFT/CBT) of different technology; an electromagnetic calorimeter (EMC) surrounded by the magnets and followed by a hadronic calorimeter (HAC). Not shown is the muon detector. The electron at low Q^2 is scattered into the backward silicon tracker (BST) and its energy measured in the BEC and BHC calorimeters. In the forward region similar components are placed for tracking (FST) and calorimetry (FEC, FHC).

13.1.2 An Alternative Solenoid Placement - Option B

The configuration A is determined by the intention to keep the detector ‘small’: it uses the HAC as flux return for an inside solenoid which, for the Linac-Ring case, is combined with long dipoles. This is not ideal for the hadronic energy measurement. Therefore a second configuration (B) has been considered, to much less detail, in which the solenoid is placed outside the HAC. Option B might be of interest only for the Ring-Ring case as otherwise, the requirement of the bending dipoles to be placed right after the EMC would anyhow compromise the design requiring anyhow similar cryogenics and support structures as in option A.

In considering a solenoid around the HAC one finds, as from the CMS geometry, that the return iron would be massive, of order 10000 tons, and extend by several meters further out in radius, which may pose problems when one has the IP2 cavern in mind. One then is lead to consider using a second solenoid for an active flux return, which gives a good muon momentum reconstruction. A strong magnetic field of 3.5 T covering the barrel calorimeter (HAC) leads to a better separation of charged hadron induced showers in the HAC area compared to the sole fringe field effect in case of the inner solenoid baseline design A. The HAC would have to be designed very carefully as there would be no muon-iron return yoke following for catching shower tails. A warm EMC design with no need for a cryostat would become an option worth considering. Also extending the tracker by an extra more conventional layer of tracking chambers in front of the EMC would be an interesting possibility, with which the amount and radius of the Silicon detector may be somewhat reduced.

An overview of the detector configuration B is given in Fig.13.11. A two solenoid configuration is proposed as an innovative solution with many advantages. A similar design was proposed earlier for the 4th

²See chapter 7.4 for an evaluation of that possibility.

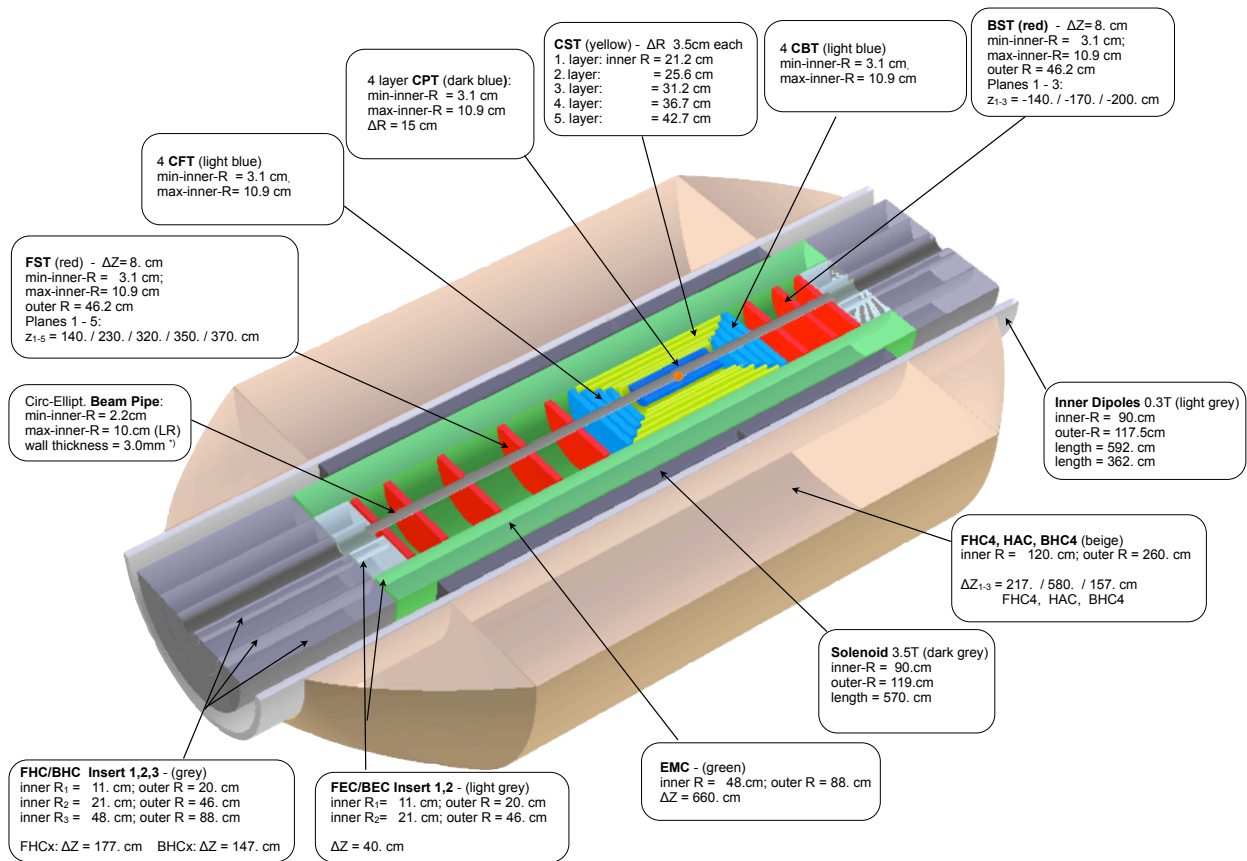


Figure 13.10: View of the baseline detector configuration (A) with some dimensions for each of the main detector components.

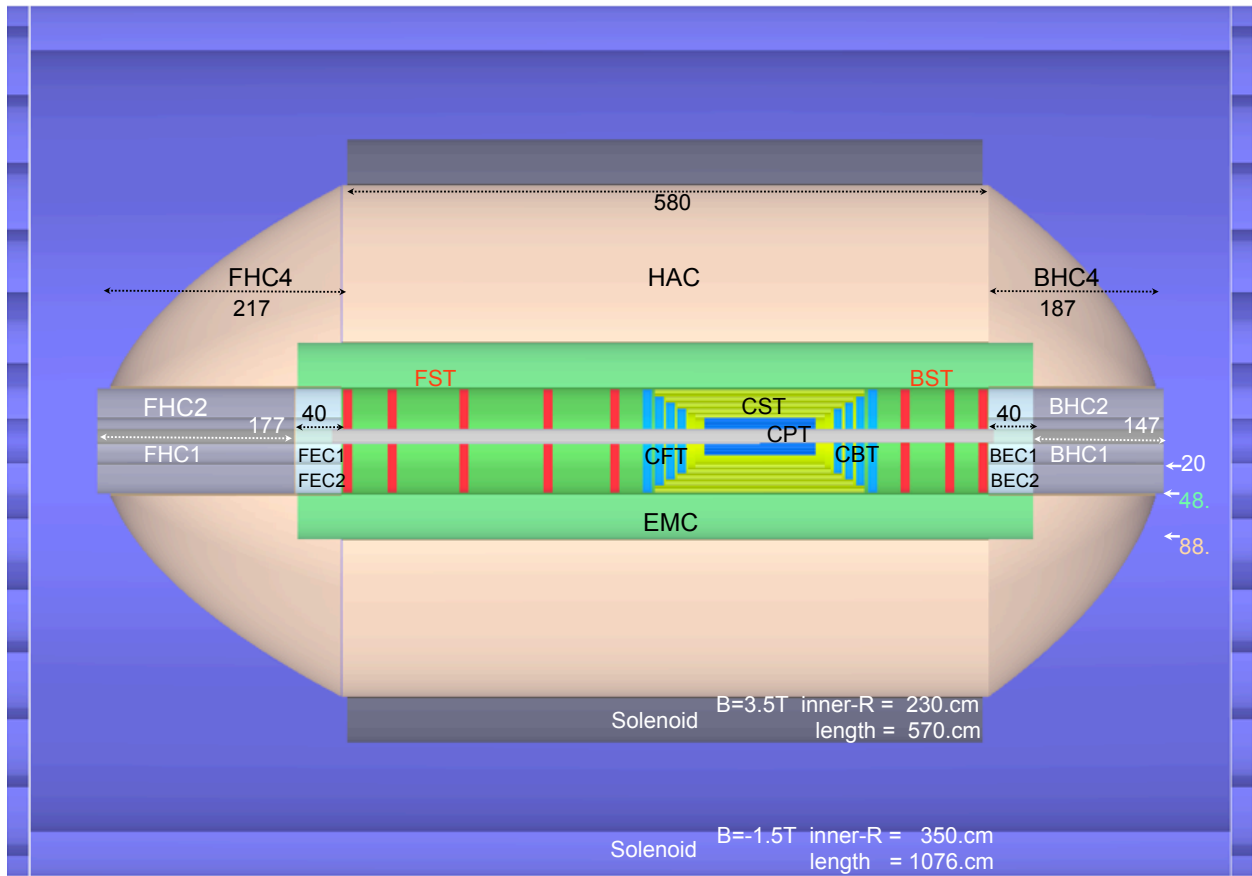


Figure 13.11: An rz cross section of the LHeC detector, option B, in which the solenoid is placed outside the HAC. A compensating larger solenoid is considered, see text. The muon detector is not shown but would be placed inside the second solenoid. The overall dimensions of this detector configuration are about 11 m length and 8 m diameter.

8974 Concept for an ILC Detector [735]. The second outer solenoid keeps the overall dimensions of the detector
8975 limited. A detailed consideration of option B has not been intended at this stage of the project, however,
8976 the statement is made that the option B magnet system is technically feasible and can be chosen if physics
8977 arguments require to do so and the required extra budget is made available.

8978 13.2 Magnet Design

8979 The principle magnet configuration in the Linac-Ring baseline option is introduced and the principle design
8980 of solenoid and dipole magnets as well as their cryogenic services are described. In section 13.2.5, the twin
8981 solenoid system option (detector option B) providing 3.5 T in the entire calorimeter space in combination
8982 with a 1.5 T space for a high precision muon tracking detector is addressed briefly.

8983 13.2.1 Magnets configuration

8984 The LHeC magnet system provides a 3.5 T solenoid with a free bore of 1.8 m and a coil length of 5.7 m
8985 for the bending of the particles produced in the collisions. The bore is dimensioned to provide space for
8986 the Pixel (CPT) and Strip (CST) detectors as well as the electromagnetic Liquid Argon calorimeter (EMC)
8987 immersed in a magnetic field while the hadronic tile calorimeter (HAC) and muon tagging detectors are left
8988 outside. The layout of the magnets in the baseline detector is shown in Figure 13.12. The iron present in
8989 the hadronic calorimeter also provides the return path for the solenoid magnetic field. In the Linac-Ring
8990 option also a set of 18 m long e-beam bending dipoles are required that provide 0.3 T on axis, a plus and
8991 a minus dipole of 9 m length each, respectively. The first dipole is to bring the e-beam into the collision
8992 point and the second to guide the beam away after the collision point. In the Ring-Ring option this set is
8993 obsolete. The Linac-Ring option obviously is more demanding and thus taken as the reference design and
8994 presented here. The introduction of the set of dipoles requires choosing a radial position and radial gap
8995 for these coils. Since cryogenic space is required for the solenoid as well, an elegant solution is to combine
8996 within the detector volume the dipoles and the solenoid in one cryostat, thereby minimizing the total radial
8997 gap as well as maximizing particle transparency. A second combination of cryogenic objects can be made
8998 by also housing the liquid argon electromagnetic calorimeter in the same cryostat which would reduce the
8999 radial built up of material significantly. Since a combination is easier the separate option is more demanding
9000 and therefore engineered and described here. Since the set of dipoles is 18 m long to provide the 2·2.5 Tm
9001 magnetic field integral, and the detector is 10 m long, each of the two dipoles are split in two sections. The
9002 inner superconducting sections sit with the solenoid in the same cryostat and the outer normal conducting
9003 iron based electromagnetic sections with much smaller bore of 0.3 m are positioned on the beam line at
9004 either side of the detectors, see Figure 13.12.

9005 13.2.2 Detector Solenoid

9006 The conceptual design of the solenoid is presented and where necessary some details on the dipoles are
9007 mentioned as well. The position of the solenoid with respect to the other detector components and the
9008 envelopes respected have been shown before in Figure 13.9. The longitudinal section of the LHeC baseline
9009 detector for the default detector configuration and the Linac-Ring option are shown; indicated are the
9010 position of the 3.5 T solenoid and the 0.3 T inner superconducting dipole sections. Solenoid and dipoles are
9011 on a common support cylinder and housed in a single cryostat with a free bore of 1.8 m and extending along
9012 the entire detector with a length of ≈ 10 m.

9013 The design of the solenoid is based on the very successful experience with the many detector magnets built
9014 over the past 30 years, in particular the most recent ATLAS and CMS solenoids [744], [745], [746], [747].
9015 The dimensions of the LHeC solenoid (3.5 T, 5.7 m long and 0.96 m inner radius) are about those of the
9016 ATLAS solenoid (2.0 T, 5.3 m long with 1.25 m radius) while it has to provide the magnetic field of the much
9017 larger CMS solenoid. Since the requested magnetic field is 1.75 times higher than in the ATLAS solenoid a

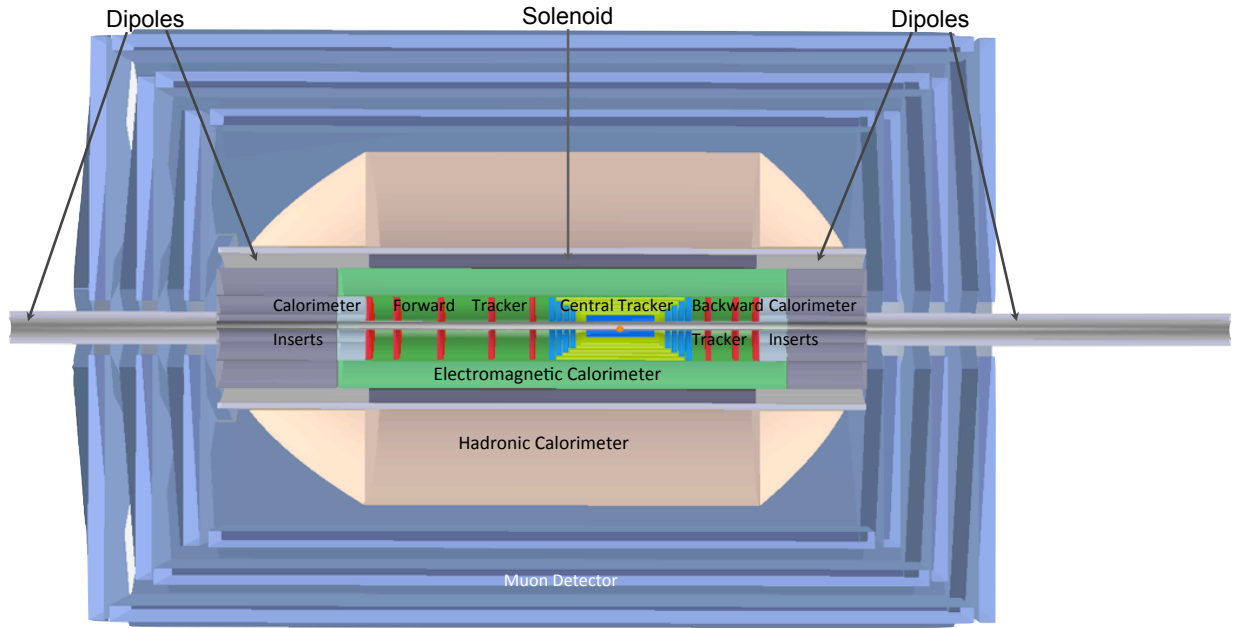


Figure 13.12: Configuration of the solenoid and electron beam bending dipoles in the baseline Linac-Ring detector. Longitudinal r-z section showing the position to solenoid and the two dipoles, each split in two sections, a superconducting inner section incorporated with the solenoid in one cryostat and a normal conducting iron based outer section magnet with smaller bore.

9018 double layer coil will be needed. Using well established design codes with proven records on earlier detector
 9019 magnets, the main solenoid parameters are determined and are listed in Table 13.1.

9020 The solenoid is wound in two layers internally in an Al5083 alloy support cylinder with 30 mm wall
 9021 thickness and a length of about 6 m. When finished two extensions cylinders are flanged to the central
 9022 solenoid section at either end for supporting the inner superconducting dipole sections, see Figure 13.13. In
 9023 this way the solenoid can be produced as a 6 m long coil unit in a company, transported to the integration
 9024 site where the adjacent sections are coupled and the dipoles sections can be introduced.

9025 The magnetic field generated by the system of solenoid and internal dipoles is shown in Figure 13.13.
 9026 The peaks in magnetic field in the solenoid and dipole windings as results of their combined operation at
 9027 nominal current are 3.9 and 2.6 T respectively. The B_z and B_y components of the magnetic field are shown
 9028 in Figure 13.14.

9029 The superconductor used for the solenoid is an Al stabilized NbTi/Cu Rutherford cable based on state-of-
 9030 the-art NbTi strands featuring 3000 A/mm² critical current density at 5 T and 4.2 K. A 20 strands Rutherford
 9031 cable carries the nominal current of 10 kA which is 30% of its critical current.

9032 The conductor has a comfortable temperature margin of 2.0 K when operating the coil with a forced
 9033 Helium flow enabling 4.6 K in the solenoid windings. The high purity Al used for the co-extrusion of Al
 9034 and cable is mechanically reinforced by micro-alloying with either Ni or Zn, or another qualified material, a
 9035 technology qualified for the ATLAS solenoid. Two conductor units of 5.4 km would be perfect, corresponding
 9036 to the two layers in the coil windings. Eventually internal splices are acceptable and can be made reliably
 9037 by overlapping a full turn and performing welding on the two adjacent thin edges of the conductors.
 9038 The conductor insulation is a double layer of 0.3 mm thick polyimide/glass tape (or similar product) featuring
 9039 a high breakdown voltage of more than 2 kV and robustness for coil winding damage in order to limit the
 9040 risk of turn-to-turn shorts. Coil winding can be performed either using the wet winding technique with
 9041 pre-impregnated tape or a vacuum impregnation technique may be applied. Both techniques are appropriate
 9042 provided fully qualified with the coil winding contractor.

Property	Parameter	value	unit
Dimensions	Cryostat inner radius	0.900	m
	Length	10.000	m
	Outer radius	1.140	m
	Coil windings inner radius	0.960	m
	Length	5.700	m
	Thickness	60.0	mm
	Support cylinder thickness	0.030	m
	Conductor section, Al-stabilized NbTi/Cu + insulation	30.0×6.8	mm^2
	Length	10.8	km
	Superconducting cable section, 20 strands	12.4×2.4	mm^2
Masses	Superconducting strand diameter Cu/NbTi ratio = 1.25	1.24	mm
	Conductor windings	5.7	t
	Support cylinder, solenoid section + dipole sections	5.6	t
	Total cold mass	12.8	t
	Cryostat including thermal shield	11.2	t
Electro-magnetics	Total mass of cryostat, solenoid and small parts	24	t
	Central magnetic field	3.50	T
	Peak magnetic field in windings (dipoles off)	3.53	T
	Peak magnetic field in solenoid windings (dipoles on)	3.9	T
	Nominal current	10.0	kA
	Number of turns, 2 layers	1683	
	Self-inductance	1.7	H
	Stored energy	82	MJ
	E/m, energy-to-mass ratio of windings	14.2	kJ/kg
	E/m, energy-to-mass ratio of cold mass	9.2	kJ/kg
Margins	Charging time	1.0	hour
	Current rate	2.8	A/s
	Inductive charging voltage	2.3	V
	Coil operating point, nominal / critical current	0.3	
	Temperature margin at 4.6 K operating temperature	2.0	K
Mechanics	Cold mass temperature at quench (no extraction)	~ 80	K
	Mean hoop stress	~ 55	MPa
Cryogenics	Peak stress	~ 85	MPa
	Thermal load at 4.6 K, coil with 50% margin	~ 110	W
	Radiation shield load width 50% margin	~ 650	W
	Cooling down time / quench recovery time	4 and 1	day
	Use of liquid helium	~ 1.5	g/s

Table 13.1: Main parameters of the baseline LHeC Solenoid providing 3.5 T in a free bore of 1.8 m.

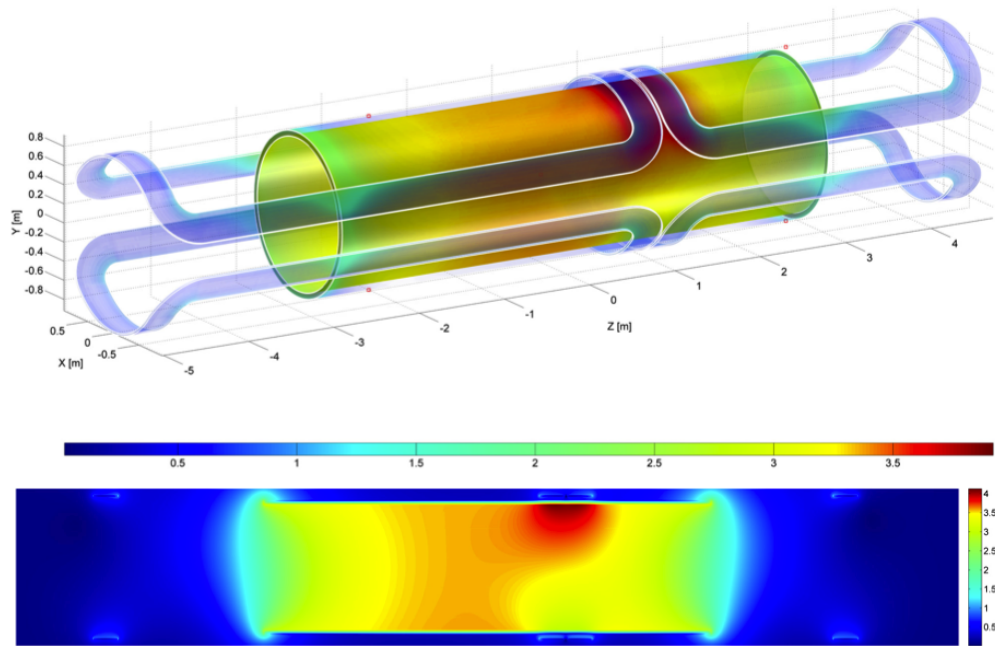


Figure 13.13: Magnetic field of the magnet system of solenoid and the two internal superconducting dipoles at nominal currents (effect of iron ignored). The position of the peak magnetic field of 3.9 T is local due to the adjacent current return heads on top of the solenoid where all magnetic fields add up.

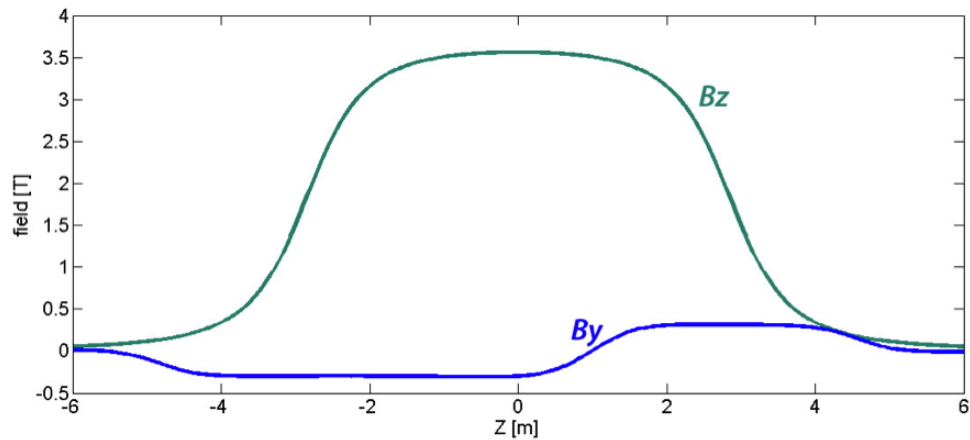


Figure 13.14: Magnetic field components B_z (solenoid) and B_y (set of internal dipoles) on the beam axis across 12 m in z . Note, the magnetic field of the external electromagnets are not included here.

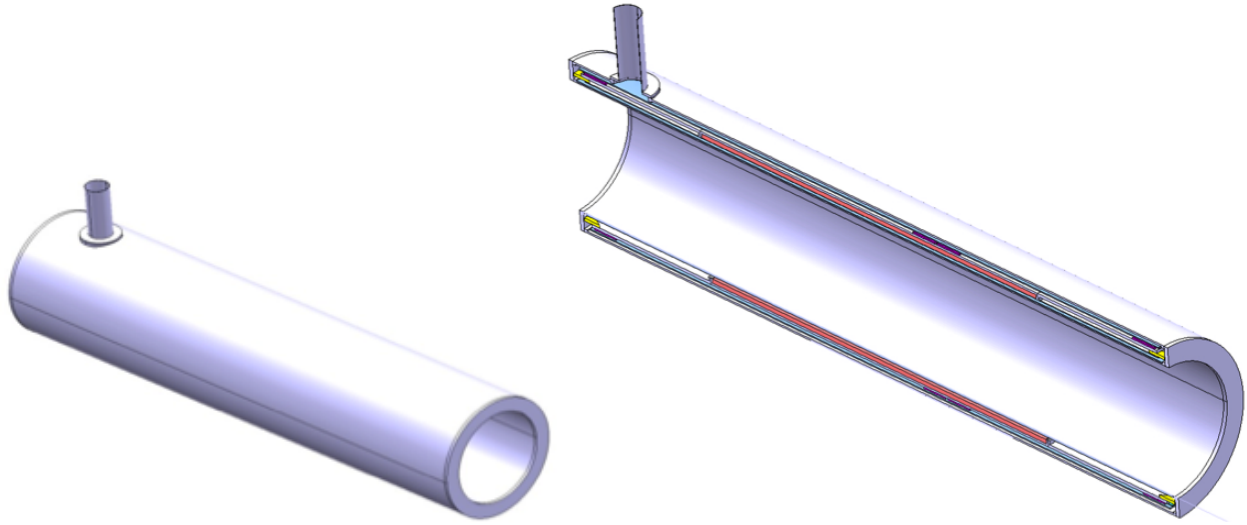


Figure 13.15: Cryostat of the magnet system. Left: the integrated cryostat, and right: longitudinal cut through the cryostat comprising a single cold mass of solenoid and internal superconducting dipole sections.

9043 Once the solenoid windings are finished and delivered to the coil integration site, the dipole coil sections
 9044 are inserted in slots milled into the outer surface of the support cylinder, see section 13.2.3. The four dipole
 9045 upper and lower coil sections are separately produced as flat racetrack coils and then bent onto the fully
 9046 assembled support cylinder. Next all interconnections and bus connections to the current leads are laid down
 9047 and the cold mass is inserted in the cryostat.

9048 The cryostat design is shown in Figure 13.15. The cold mass is supported from the cryostat with a system of
 9049 triangle brackets, a proven technique providing a very compact solution [744], [745]. The cryostat is equipped
 9050 with thermal shields and multi-layer super-insulation in the usual way.

9051 The coil windings of both solenoid and dipole sections are cooled by conduction by forced flow liquid helium
 9052 circulating in 14 mm sized cooling tubes that are attached to the outer surface of the integrated support
 9053 cylinder. The two layer winding pack of 60 mm radial built and fully bonded to the support cylinder is
 9054 sufficiently thin to warrant a thermal gradient in the winding pack of less than 0.1 K. The total radial
 9055 material built of essentially Al alloys is about 150 mm featuring an acceptable effective radiation thickness.
 9056 Quench protection of the solenoid with 82 MJ stored energy in a cold mass with 9 kJ/kg can be done
 9057 safely. The stored energy is absorbed by the cold mass enthalpy (no energy extraction) and the cold mass
 9058 temperature will raise to a safe 80 K level. Heat drains are incorporated in the coil windings to accelerate
 9059 quench propagation and in addition an active heater system will implemented for the same purpose.

9060 13.2.3 Detector integrated e-beam bending dipoles

9061 The two e-beam bending dipoles are positioned symmetrically around the beams intersection point. As
 9062 outlined before each 9 m long dipole is split into a superconducting section integrated with the central
 9063 solenoid and a normal conducting iron based electro-magnet positioned around the beam outside the main
 9064 detector envelope. The external dipole magnets are conventional and will not be further detailed here. The
 9065 principle parameters of the superconducting dipole sections are listed in Table 13.2.

9066 13.2.4 Cryogenics for magnets and calorimeter

9067 The cryogenic operating conditions are achieved by circulating forced flow two-phase helium in cooling pipes
 9068 attached to the Al-alloy coil support cylinder. Electric powering of the solenoid and dipole magnets at 10
 9069 and 2 kA, respectively, is through two pairs of low-loss high-temperature superconducting current leads. The

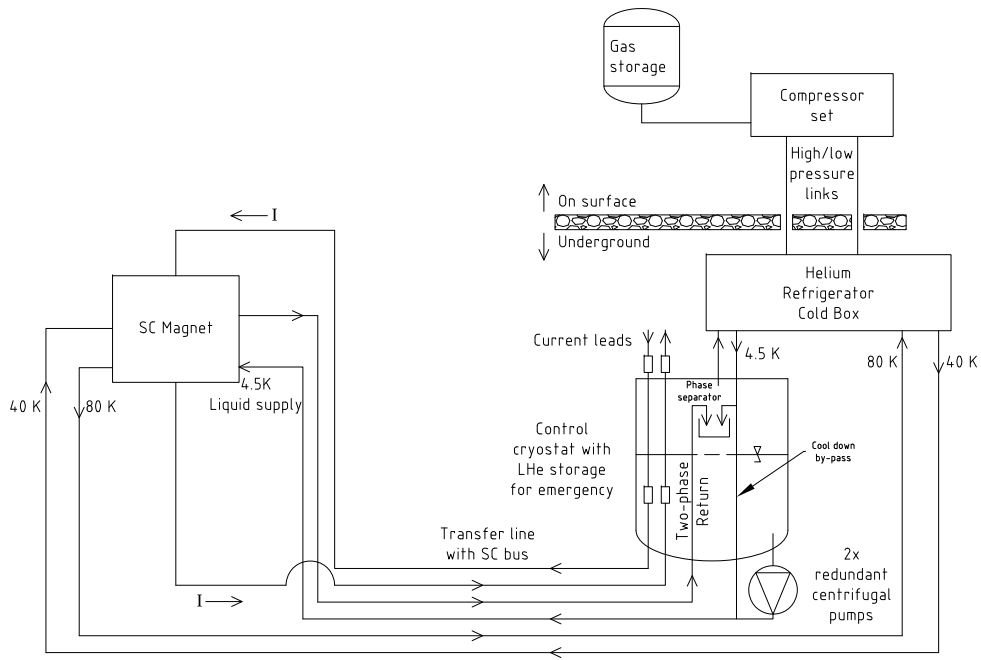


Figure 13.16: Principle cryogenic flow scheme for the cooling of the superconducting magnets.

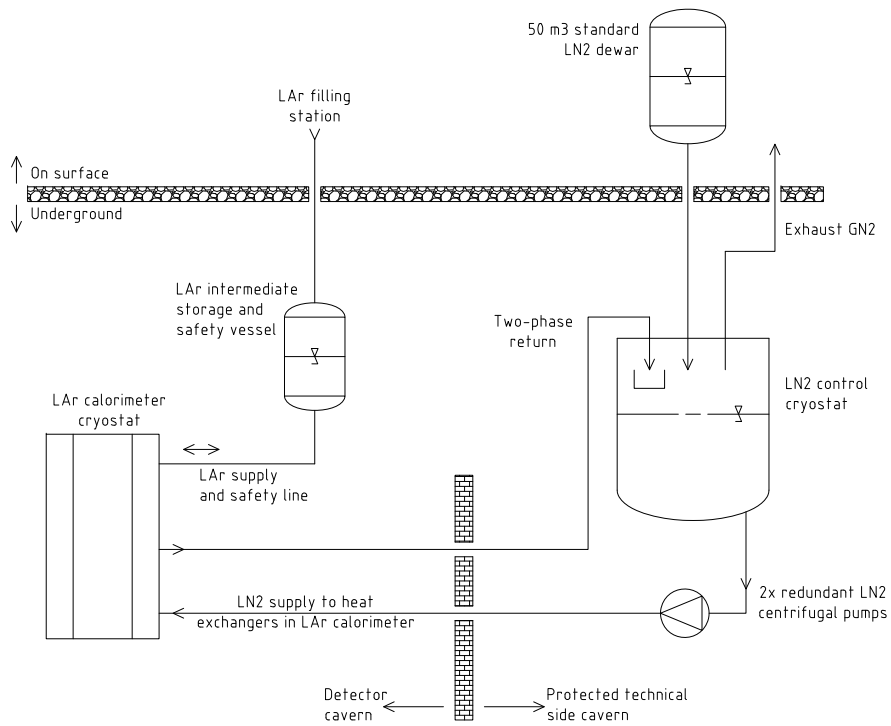


Figure 13.17: Principle cryogenic flow scheme for the cooling of the liquid argon calorimeter.

	Plus coil	Minus coil	
Magnetic field on axis	0.3		T
Peak magnetic field in windings (solenoid off)	0.7		T
Peak magnetic field in windings (solenoid on)	2.6		T
Dipole length (including external sections)	9.0		m
Field integral internal section (sc dipole)	1.6	1.0	Tm
Field integral external section (iron magnet)	1.1	1.7	Tm
Operating current	2.0		kA
Stored Energy	1.9	1.2	MJ
Coil inductance	0.50		H
Coil inner / outer radius	1.042/1052		m
Coil length	6.00	3.70	m
NbTi/Cu conductor diameter (12 strands Rutherford cable)	2.0		mm
Conductor length	5.4	3.6	km

Table 13.2: Main design parameters of the set of superconducting electron beam bending dipoles.

9070 current leads are housed in a separate service cryostat installed at distance in a side cavern, a non-radiation
9071 environment. The service cryostat contains a larger amount of helium sufficient for a safe 1-2 hours ramp
9072 down in the case of refrigerator failure as well as to maintain the magnets at operating temperature for a
9073 few hours. Redundant centrifugal pumps provide for circulation of the slightly sub-cooled liquid helium to
9074 the magnets. The two-phase return flow is brought to a phase separator in the service cryostat. A combined
9075 superconducting link and helium transfer line connects the service cryostat with the current leads and helium
9076 buffer to the magnets. For this circuit static and dynamic losses of the magnets and transfer lines have to be
9077 taken into account, which are about 85 W. With 50% contingency the losses amount to 130 W. For reasons
9078 of flow stability the vapor quality of the return flow shall not exceed 10%.
9079 The mass flow rate of the pump is calculated to 65 g/s maximum. We assume a thermo-hydraulic efficiency of
9080 the pump of 35%, a value based on measurements on already running similar systems. The pump introduces
9081 an additional 40 W to the system.
9082 The refrigerator is at proximity to the cryostat and the compressor set is installed on surface. The expected
9083 modest thermal loss of the magnet system and its proximity cryogenics like service cryostat and transfer lines
9084 amounts to some 200 W@4.5 K. The estimated overall system loss suggest a small sized standard refrigerator
9085 in the class of 300 to 400 W@4.5 K. The thermal load of the system is summarized in Table 13.3. Figure 13.16
9086 shows the simplified flow scheme of the helium cryogenic system.

Component heat load at temperature	4.5 K	20-300 K	40-80 K
Magnets static	45 W		430 W
Magnets dynamic	30 W		
Transfer line/bus static	10 W		150 W
Valve box cryostat static	10 W		150 W
Helium pump static	40 W		
Current leads static		1.0 g/s	
Sums with and extra 50% contingency	200 W	1.5 g/s	1100 W

Table 13.3: Thermal load of the cryogenics system including magnets and helium distribution.

9087 A liquid Argon calorimeter is envisaged as part of an EMC. As mentioned before, it can be installed

9088 in a separate cryostat or preferably share the cryostat with the solenoid. In the latter case the systems
9089 compactness is increased and the inner thermal shield can be omitted. The calorimeter will have an overall
9090 18 m^3 volume from which approximately 12 m^3 will be slightly sub-cooled liquid argon. Cooling is with two-
9091 phase liquid nitrogen in longitudinal pipe runs and its circulation is provided by two redundant small sized
9092 liquid nitrogen pumps. The liquid nitrogen is supplied from a standard dewar on surface to an intermediate
9093 cryostat which serves also as the phase separator. For the liquid argon filling, a line connects from the surface
9094 to an intermediate dewar from which it is transferred to the LAr cryostat in the detector. This dewar also
9095 serves as emergency volume in the case of vacuum loss or leak problems to which the liquid argon can be
9096 transferred from the cryostat. Figure 13.17 shows the functional principle of the Argon cooling units.

9097 The cooling principles of both cryogenic systems proposed in this paper are based on previous design and
9098 experience from the much more complex ATLAS detector cryogenics.

9099 13.2.5 Twin Solenoid System

9100 Being written.

9101 13.3 Tracking Detector

9102 The constraints given by the magnet system (dipole/solenoid) force the tracking detectors to be kept as
9103 small as possible in radius.

9104 According to equation 12.9, the momentum resolution is proportional to $1/L^2$ and is therefore limited
9105 by the tracker radius. For a given magnetic field strength, the only other parameters left to improve are
9106 the intrinsic detector resolution, Δ , and the number of points sampled along the track trajectory. The
9107 forward/backward tracking extensions provide additional measurement points in these regions. Hence, a
9108 balance of number of track points (number of sensitive detector layers), material economy and costs must
9109 be found.

9110 The design adopted here is an all-Silicon detector, with very high resolution. The readout scheme must
9111 be such that a signal weighting using analog information is possible without losing the advantages of digital
9112 signal processing and on-chip zero suppression. All of the components need power and cooling, influencing
9113 the material budget of the tracker system which should be kept as low as possible. The technology used
9114 must be advanced at the industrial level, radiation hard and relatively cheap. A good candidate are n_in_p
9115 single sided sensors [748].

9116 In the following, the layout of a tracker system for the baseline detector configuration A is defined, along
9117 with the design criteria and possible solutions for a tracker which provides high resolution impact parameter
9118 measurement, momentum determination (as far as possible) and optimal support of the calorimetry.

9119 13.3.1 Tracking Detector - Baseline Layout

9120 The tracking detectors (Fig. 13.22) inside the electromagnetic calorimeter are all-Silicon devices. The tracker
9121 covers the pseudorapidity range $-4.8 < \eta < 5.5$ and is located inside the solenoidal field of 3.5T. Addition-
9122 ally a dipole field of 0.3T, resulting from the steering dipoles required for the Linac-Ring configuration, is
9123 superimposed.

9124 The tracker is subdivided into central (CPT, CST, CFT/CBT) and forward/backward parts (FST, BST).
9125 Fig. 13.22 shows the tracker configuration for LHeC operation at maximal acceptance in the baseline (A)
9126 detector design. More details are summarized in Tab. 13.4³. The shape of the CPT and the inner dimensions
9127 of all near-beam detectors have been chosen to maximise detector acceptance by measuring as close to the
9128 beam-line as possible (see Fig. 13.19 which shows the xy view of the circular-elliptical CPT and the cylindrical
9129 CST detectors).

³The item *project area* in table 13.4 describes the area which has to be equipped with appropriate Si-sensors (e.g. single-sided or double-sided sensors). An alternative would be the usage of Si-Gas detectors providing track segment information instead of track points, e.g. in the CST cylinders (Ref. [749], [750], [751])

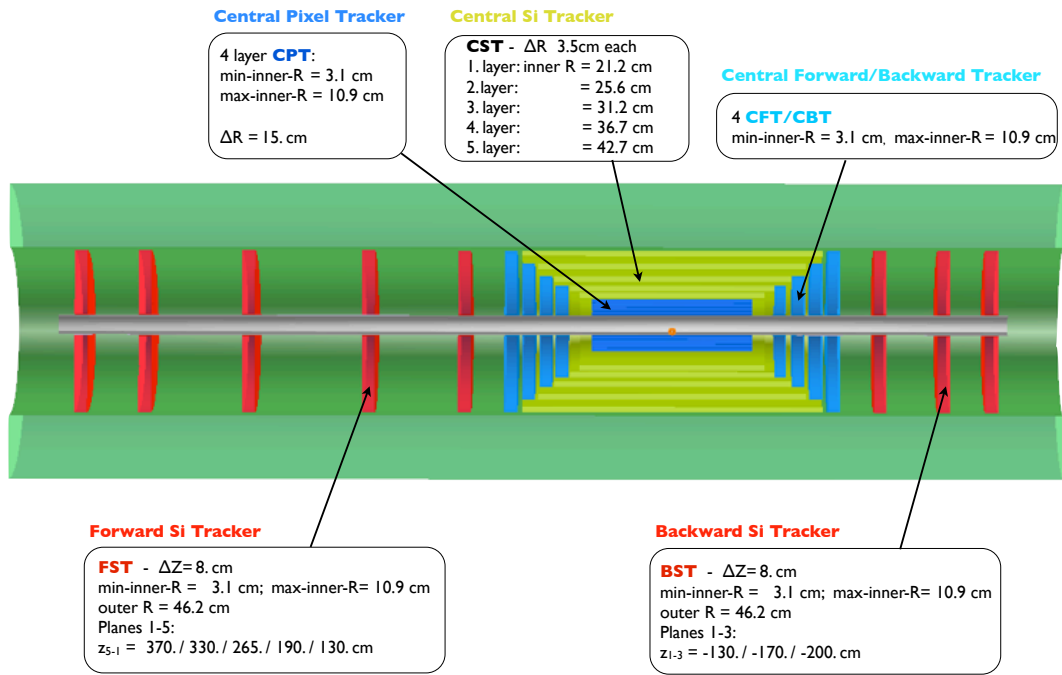


Figure 13.18: Tracker and barrel Electromagnetic-Calorimeter rz view of the baseline detector (Linac-Ring case).

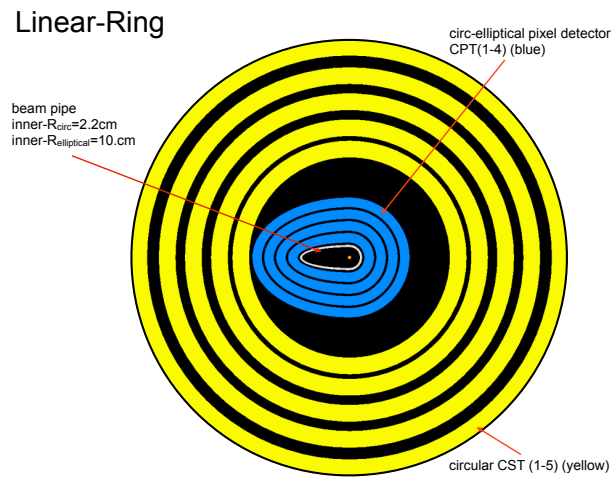


Figure 13.19: XY cut away view of the Central Pixel (CPT) and Central Strixel Tracker (CST) (Linac-Ring layout).

Central Barrel	CPT1	CPT2	CPT3	CPT4	CST1	CST2	CST3	CST4	CST5
Min. Radius R [cm]	3.1	5.6	8.1	10.6	21.2	25.6	31.2	36.7	42.7
Min. Polar Angle θ [°]	3.6	6.4	9.2	12.0	20.0	21.8	22.8	22.4	24.4
Max. $ \eta $	3.5	2.9	2.5	2.2	1.6	1.4	1.2	1.0	0.8
ΔR [cm]	2	2	2	2	3.5	3.5	3.5	3.5	3.5
$\pm z$ -length [cm]	50	50	50	50	58	64	74	84	94
Project Area [m ²]	1.4				8.1				
Central Endcaps	CFT4	CFT3	CFT2	CFT1		CBT1	CBT2	CBT3	CBT4
Min. Radius R [cm]	3.1	3.1	3.1	3.1		3.1	3.1	3.1	3.1
Min. Polar Angle θ [°]	1.8	2.0	2.2	2.6		177.4	177.7	178	178.2
at z [cm]	101	90	80	70		-70	-80	-90	-101
Max./Min. η	4.2	4.0	3.9	3.8		-3.8	-3.9	-4.0	-4.2
Δz [cm]	7	7	7	7		7	7	7	7
Project Area [m ²]	1.8					1.8			
Fwd/Bwd Planes	FST5	FST4	FST3	FST2	FST1		BST1	BST2	BST3
Min. Radius R [cm]	3.1	3.1	3.1	3.1	3.1		3.1	3.1	3.1
Min. Polar Angle θ [°]	0.48	0.54	0.68	0.95	1.4		178.6	178.9	179.1
at z [cm]	370	330	265	190	130		-130	-170	-200
Max./Min. η	5.5	5.4	5.2	4.8	4.5		-4.5	-4.7	-4.8
Outer Radius R [cm]	46.2	46.2	46.2	46.2	46.2		46.2	46.2	46.2
Δz [cm]	8	8	8	8	8		8	8	8
Project Area [m ²]	3.3						2.0		

Table 13.4: Summary of tracker dimensions. The 4 Si-Pixel-Layers CPT1-CPT4 (resolution of $\sigma_{\text{pix}} \approx 8\mu\text{m}$) are positioned as close to the beam pipe as possible. Si-strixel (CST1-CST5) (resolution of $\sigma_{\text{strixel}} \approx 12\mu\text{m}$) form the central barrel layers. An alternative is the 2_in_1 single sided Si-strip solution for these barrel cylinders ($\sigma_{\text{strip}} \approx 15\mu\text{m}$) [752]. The endcap Si-strip detectors CFT/CBT(1-4) complete the central tracker. The tracker inserts, 5 wheels of Si-Strip detectors in forward direction (FST) and 3 wheels in backward direction (BST), are based on single sided Si-strip detectors of 2_in_1-design ($\sigma_{\text{strip}} \approx 15\mu\text{m}$). They have to be removed in case of high luminosity running for the Ring-Ring option of the accelerator configuration (see Fig. 13.4).

9130 **13.3.2 Performance**

9131 Some results of preliminary tracker performance simulations using the LicToy-2.0 program [740] for the
 9132 tracker setup (see table 13.4 and Fig. 13.20), and with parameters given in table 13.5 are summarised in
 Fig. 13.21. The detector performance is very good, as expected. For 1° tracks the bending solenoidal field

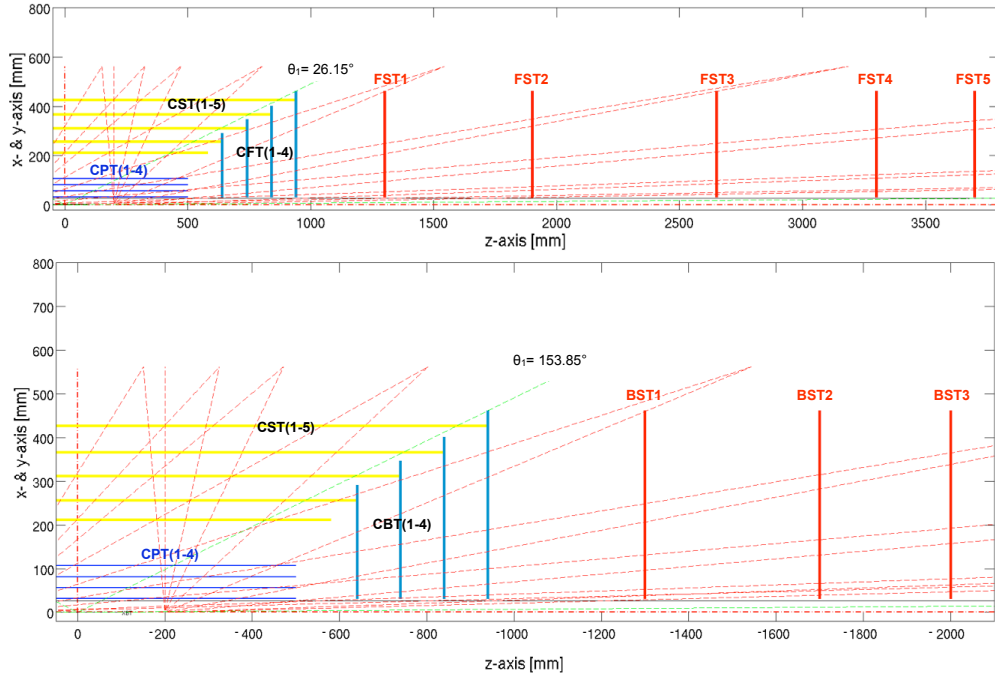


Figure 13.20: LicToy2.0 tracker design of the central/forward FST(top) and central/backward direction BST(bottom).

9133 component (0.36T) is of the same order as the dipole field and the resulting track sagitta only reaches the
 9134 mm range when particles of momentum < 100 GeV have a track length of 250cm (see Fig.13.22). The
 9135 tracker described here measures 1° tracks over a distance of ≈ 180 cm, and therefore high momentum tracks
 9136 will have a poor momentum determination. Nevertheless, the position information can be used to match a
 9137 track to a calorimeter deposit with high precision.
 9138

9139 The backward measurement is characterised by even shorter track lengths and in this case the analysis
 9140 has to rely on the energy measurement in the calorimeters matched to a well defined track. Thanks to
 9141 the much reduced particle flux in the backward direction due to kinematics, the performance and precision
 9142 achievable is expected to be higher. Very low Q^2 /low x processes will be more easily accessible by reducing the
 9143 electron beam energy, thus measuring at larger angles in the backward direction (see Fig. 12.3 and Fig. 12.4
 9144 and discussion in chapter 12.1).

9145 **13.3.3 Tracking detector design criteria and possible solutions**

9146 The experience of former attempts for an optimal detector design suggest that some criteria should be
 9147 discussed as early as possible.
 9148 The main items to consider [748, 753] are discussed in the following.

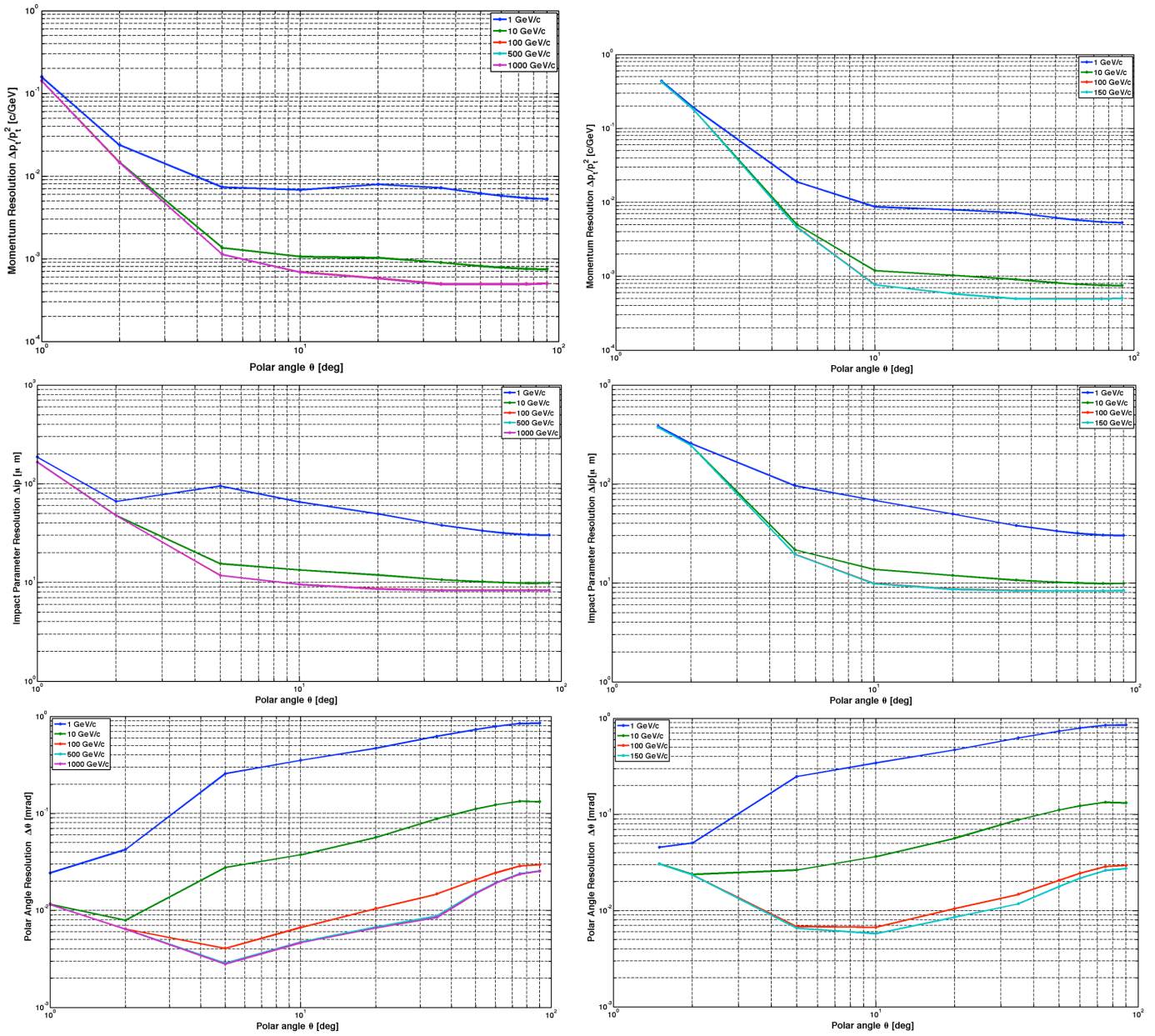


Figure 13.21: Scaled momentum, impact parameter and polar angle resolution as function of polar angle θ resulting from tracker design simulation using LiCToy2 for the FST(left) and BST(right) side. Tracker setup used as shown in Fig. 13.20.

Parameters	
B	3.5T
X/X_0^{beampipe}	0.002
$X/X_0^{\text{det-parts}}$	0.005
efficiency	0.99%
Minimal inner radius	3.15cm
σ_{CPT}	8 μm
$\sigma_{\text{CST,CFT,CBT}}$	12 μm
$\sigma_{\text{FST,BST}}$	15 μm

Table 13.5: The main parameters assumed in the tracking simulation.

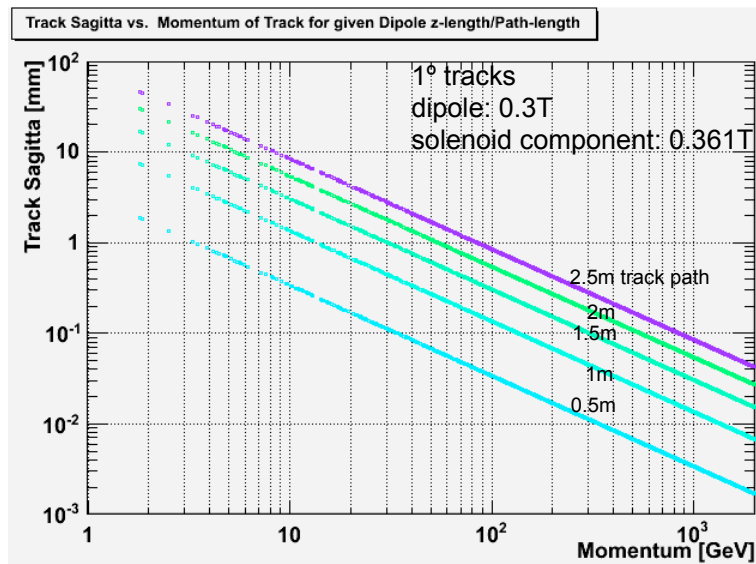


Figure 13.22: Track Sagitta vs. Momentum of 1° tracks in a superposed dipole/solenoidal field.

9149 **Optimising cost for all components**

9150 The technology developments for HL-LHC/ILC experiments [754–767] should be used as far as possible
 9151 while relying on existing technologies because of time constraints. The sensors, integrated electronics, read-
 9152 out/trigger circuitry, mechanics, cooling, etc. available today have to be used in order to meet the goal of
 9153 installation in the early 2020’s.

9154 **Choice of sensor type**

9155 The default tracker design is based on the silicon microstrip detector technology developed for the experiments
 9156 at LHC, ILC, TEVATRON, b-factories etc. within the last 20 years. The final decision for sensor types
 9157 (pixel, strixel, strip) depend on many factors and will be taken according to their functionality.

9158 **Radiation hardness** The expected radiation load is defined and influenced by the interaction rate (25ns),
 9159 luminosity ($\approx 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$), particle rate per angle interval, fluence n_{eq} and ionisation dose. Some data
 9160 will be better defined after evaluation of more detailed simulations. Specifically the radiation impact on
 9161 tracker wheels, calorimeter inserts and the inner tracker-barrel layer has to be studied. The tools for those
 9162 simulations are being prepared. First estimates are discussed in section 13.8 in more detail, but there is
 9163 as yet no indication for extremely high radiation load into the detectors adjacent to the beam pipe. The
 9164 expected levels are far below what the LHC experiments have to withstand.

9165 A side remark is related to the active parts of the forward/backward calorimeter. For safety reasons those
 9166 calorimeter inserts should be equipped with radiation hard silicon-based sensors according to LHC/HL-LHC
 9167 standards. Relatively small in volume but still large in terms of layer area $\mathcal{O}(\text{m}^2)$, the use of Si-strip/Si-pad
 9168 based calo-inserts might turn out as a sizeable investment which is anyhow needed in order to guarantee
 9169 for a stable performance and a sufficient detector lifetime. A final decision will only be possible after more
 9170 detailed **FLUKA** [768, 769] simulations are complete.

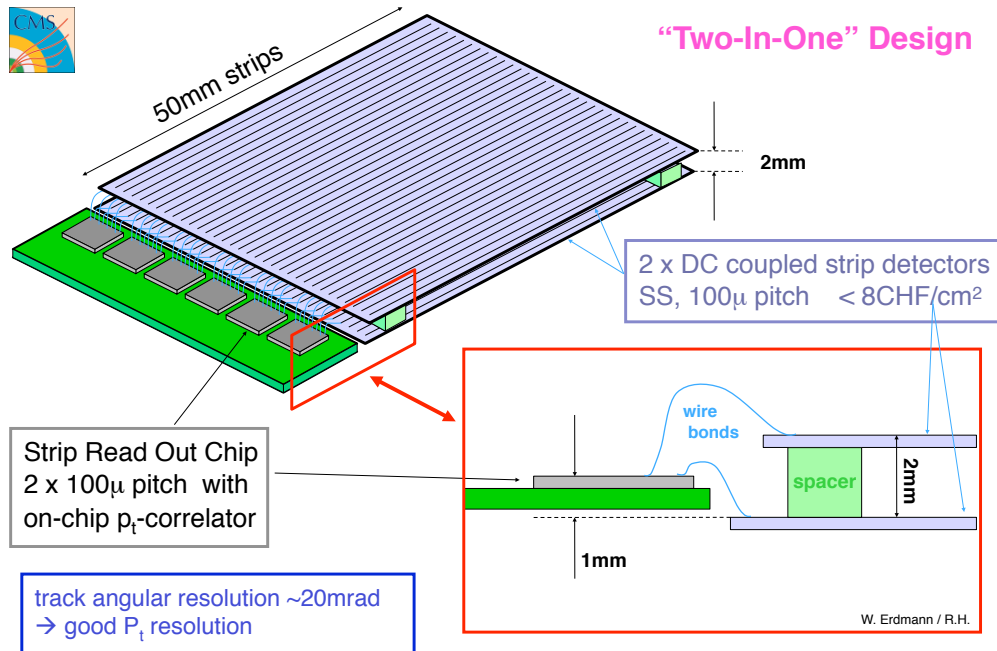


Figure 13.23: Layout of the 2_in_1 strip sensor design used as p_t -trigger setup for the CMS experiment.

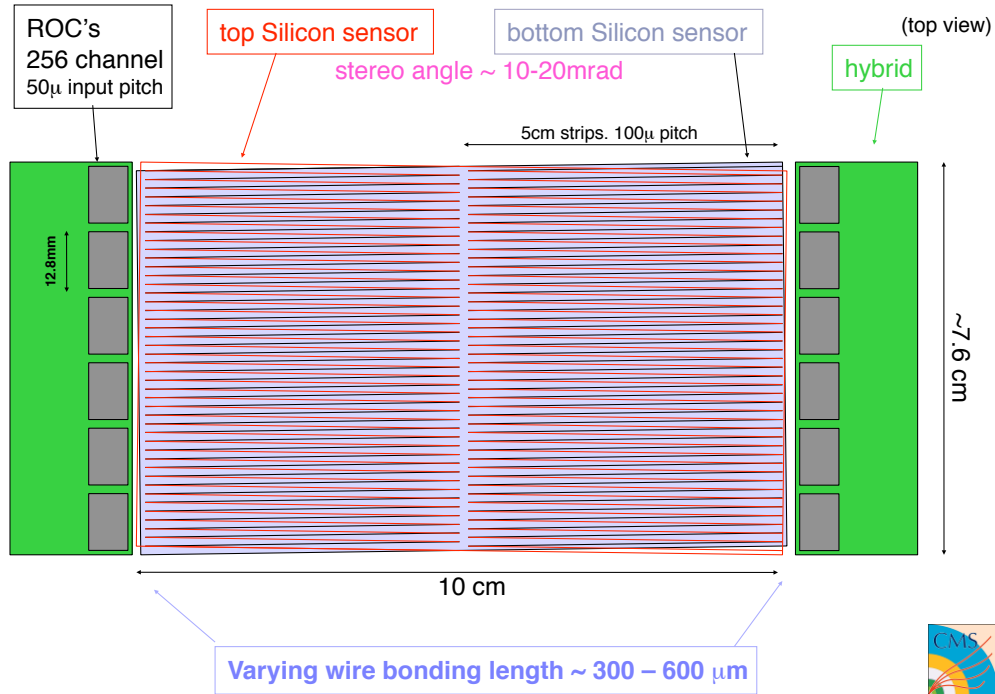


Figure 13.24: Layout of the 2_in_1 strip sensor design used as tracker module. Double use of e.g. power and cooling for the two strip wafer.

9171 **Trigger** The trigger capabilities of the tracking system is yet to be defined and will have a direct impact
 9172 on sensor choice, associated electronics and arrangement. It is possible that very recent developments of
 9173 3D integration semiconductor layers interconnected to form monolithic unities of sensor&electronic circuitry
 9174 would be available in time for installation in the 2020's, but conventional wire bonded or bump bonded
 9175 solutions may be more cost efficient and rely on components available today. For example, the 2_in_1 strip
 9176 sensor design p_t -trigger discussed by the CMS upgrade design group [752], shown in Fig. 13.23, would have
 9177 a direct impact on a muon-trigger definition. The sensor, hybrid and readout modules are available and
 9178 interconnected by wire bonds. The 2_in_1 sensor design is a very elegant way of saving resources when
 9179 designing a tracker, as shown in Fig. 13.24

9180 **Front-end** Candidates of readout chips attached to the sensors are e.g. the ATLAS FE-I4 ($50\mu m * 250\mu m$)
 9181 [748] and CMS ROC ($100\mu m * 150\mu m$) [754]). The sensor pitch has to be matched and the electronics scheme
 9182 defined beforehand.

9183 Powering and cooling

9184 The size of the largest stave structure to be installed (half z-length $\approx 94cm$) is smaller than the stave length
 9185 used e.g. by ATLAS ($\approx 120cm$). Powering and cooling per stave are therefore less demanding than for the
 9186 current LHC installations. Minimisation of cooling directly reduces the material budget; cooling is related
 9187 to power consumption issues and it may be a criterion for technology selection. A decision on the powering
 9188 concept is needed (serial, parallel powering). It will depend on the template chosen for readout and services.
 9189 An obvious solution is to re-apply the scheme used by a current LHC experiment in line with the sensor,
 9190 electronics & readout option selected.

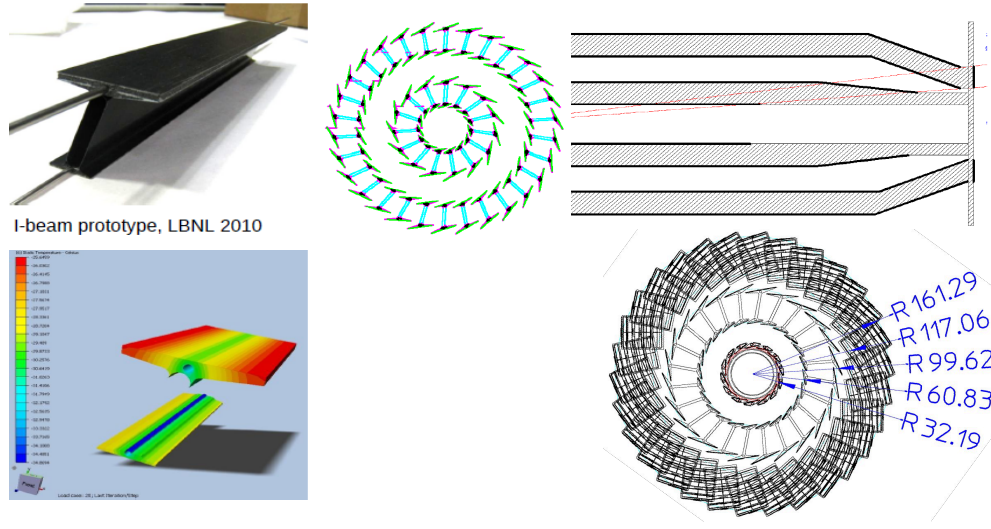


Figure 13.25: Proposed mechanics and sensor layout for the ATLAS pixel upgrade.

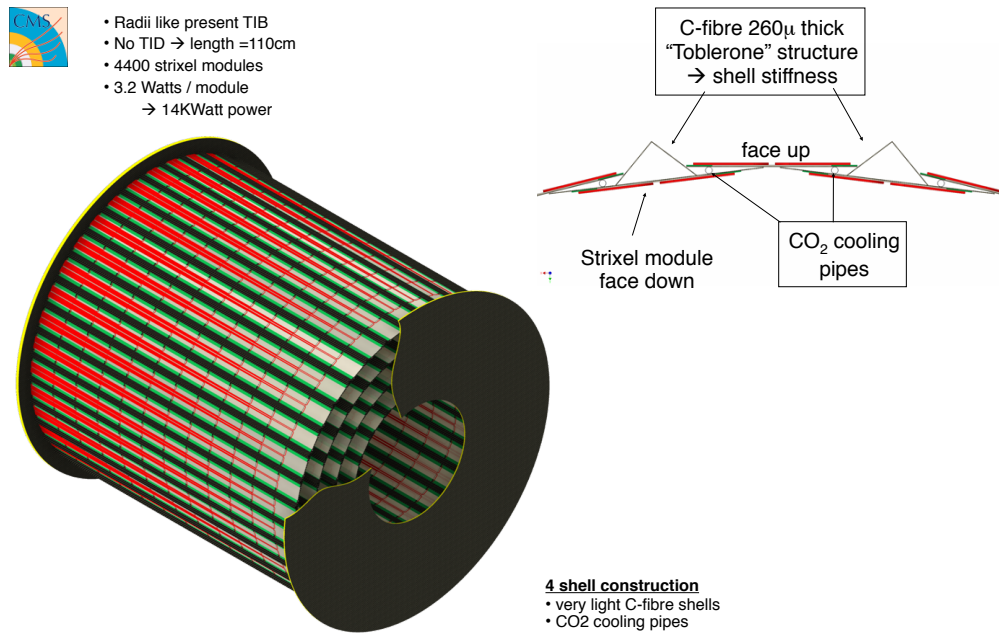


Figure 13.26: Proposed mechanics layout for the CMS inner barrel tracker upgrade.

Inner & outer ring of blades

CO₂ tubes embedded in half disk support:

- support cylinder:
 - Carbon carbon
 - Grooves for cooling tube
 - Stainless steel tube:
 - 1.8mm OD, 100 μ m wall

Blades:

- all identical
- Rotated by 20° radial
- Tilted by 12° (inner ring)
- 2 modules per blade (ϕ overlap)
- individually replaceable

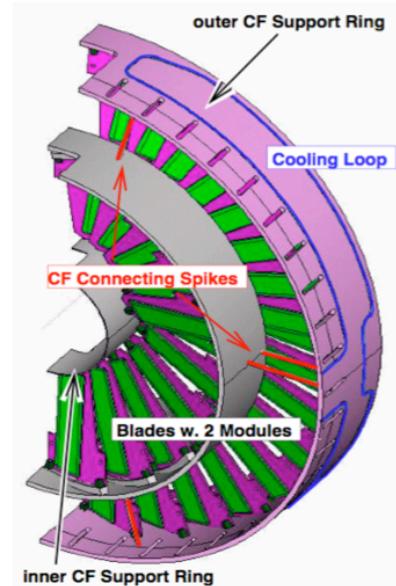
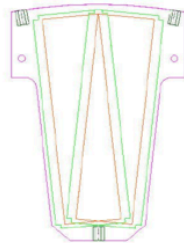


Figure 13.27: Proposed mechanics layout for the CMS tracker wheel upgrade.

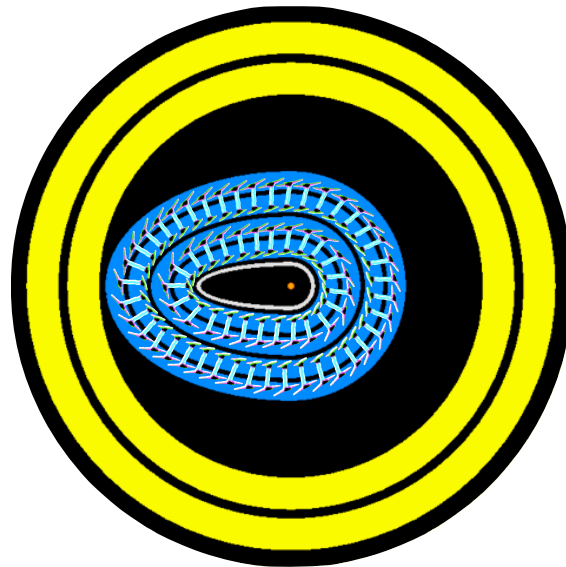


Figure 13.28: Artist view of the pixel sensor arrangement using the double-I ATLAS layout as template (Fig. 13.25).

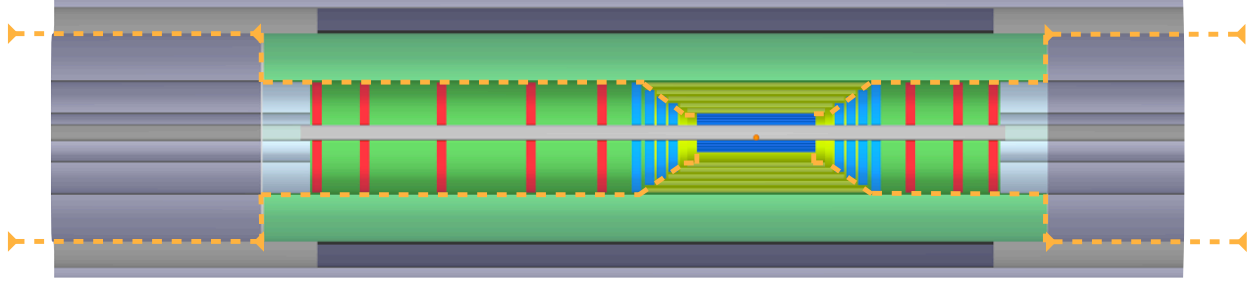


Figure 13.29: Path of services for all tracking detectors (shown in orange). The services are integrated into support structures whenever possible

9191 Mechanical support

9192 The mechanical support and cooling elements have to be chosen to minimise the material budget and hence
 9193 minimise the impact of multiple-scattering on track resolution by the tracker material. Rigid but very light
 9194 mechanics in connection with improved sensor arrangement, incorporation of cooling systems and all other
 9195 services into the support structure are the main design criteria for HL-LHC upgrade projects for e.g. ATLAS
 9196 and CMS - this is also the case for LHeC.

9197 In Figs. 13.25, 13.26 and 13.27, possible mechanical solutions for the ATLAS [748, 770] and CMS [752]
 9198 tracker upgrades in the barrel and forward/backward tracker regions are shown. These designs may serve as
 9199 templates for the LHeC detector. As an example, an artist's view in Fig. 13.28 shows an implementation of
 9200 the double-I ATLAS pixel arrangement into a 4 layer pixel structure for the LHeC detector. The goal is the
 9201 design of a tracker which is in the range $\approx 1.5 - 2\%X_0$ in terms of radiation lengths.

9202 Readout

9203 Possible paths for the IN/OUT services of the LHeC tracking detectors are sketched in Fig. 13.29. The cables
 9204 and tubes are integrated into the support structures of the sub-detectors as far as possible. Optimisation of
 9205 detector readout reduces the cost and material impact of cables. An example is discussed in detail for the
 9206 ATLAS/CMS HL-LHC opto-link upgrade in Ref. [771]. The front end electronics buffer depth will depend
 9207 on bunch crossing rate (25ns) and the trigger/readout speed capability.

9208 Radiation detectors

9209 Special Interaction Region instrumentation for tuning of the machine in order to minimise background and
 9210 optimise luminosity is needed. Radiation detectors, e.g. near mask and tight apertures, are useful for
 9211 fast identification of background sources. Fast bunch related informations are collected efficiently e.g. by
 9212 dedicated diamond detectors, e.g. for CMS [772-775].

9213 13.4 Calorimetry

9214 The LHeC calorimetry has to fulfill the requirements described in 12.1. The goal is a powerful level 1
 9215 trigger and a detector able to resolve shower development in three-dimensional space with no or minimal
 9216 punch through. High transverse and longitudinal segmentation are necessary along with a good matching to
 9217 tracking detectors for particle identification and separation of neutral and charged particles. The calorimetry
 9218 needs to be hermetic in order to provide a good measurement of the total transverse energy in the charged
 9219 current process. These considerations are summarised in Tab. 12.1.

9220 The baseline design foresees a modular structure of independent electromagnetic (EMC) and hadronic
 9221 (HAC) calorimeter components. In order to fully contain electromagnetic showers, the EMC must provide

9222 $\sim 25 - 30X_0$. The design of the EMC modules will vary when moving from the very forward region, where
 9223 energies up to $\mathcal{O}(1\text{TeV})$ are expected, to the barrel and the backward region, where an accurate and precise
 9224 measurement of the scattered electron with energy $\mathcal{O}(60\text{ GeV})$ is paramount.

9225 In the baseline design, the EMC is surrounded by the solenoid coil which provides the magnetic field for
 9226 momentum measurement in the tracking. The hadronic calorimetry comes next and has sufficient depth in
 9227 order to precisely measure jets over the full energy range, while providing the granularity in a projective
 9228 modular design such that it can faithfully separate multiple jet events. The forward part of the HAC will
 9229 need to provide up to $10\lambda_I$ to guarantee containment of energies up to a few TeV.

9230 In the next sections the baseline design for the EMC and HAC components is presented and discussed
 9231 along with a comparison of technologies and the experience from other HEP detectors e.g. [776], [777], [778],
 9232 [779], [780]. A brief summary of ongoing R&D into new technologies which could extend the precision and
 9233 scope of the detector are briefly addressed.

9234 13.4.1 The Barrel Electromagnetic Calorimeter

9235 In the barrel region ($2.8 < \eta < -2.3$), a Liquid Argon calorimeter (LAr) with *accordion-shaped* electrodes,
 9236 as is currently in use by ATLAS [781], is proposed. The principle of LAr sampling calorimetry is to arrange
 9237 many layers of passive material, in this case lead ($X_0=0.56\text{ cm}$), alternated with layers of active material,
 9238 here LAr with $X_0=14.0\text{ cm}$. The choice of Liquid Argon follows from its intrinsic properties of excellent
 9239 linearity, stability in time and radiation tolerance [782–789]. A LAr calorimeter would provide the required
 9240 energy resolution, detector granularity and projective design. The detector, with an outer diameter of 88 cm,
 9241 would share the same cryostat as the main solenoid which in the case of a Linac-Ring design would include
 9242 the bending dipoles. The performance of the LAr calorimetry system has been extensively addressed [781]
 9243 and here only specific design issues and detector simulation will be discussed.

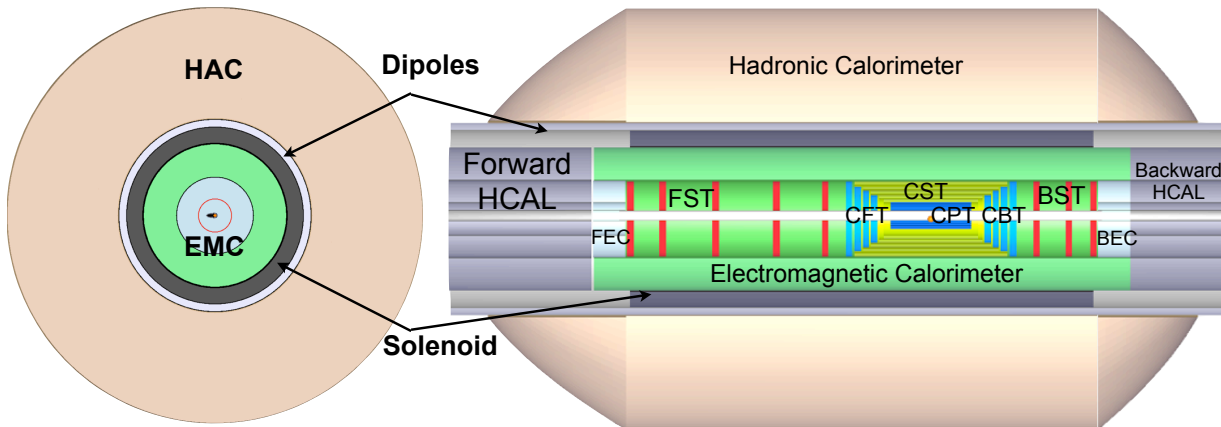


Figure 13.30: x - y and r - z view of the LHeC Barrel EM calorimeter (green).

9244 Fig. 13.30 shows a x - y and r - z view of the LHeC Barrel EM calorimeter. The layout allows the extraction
 9245 of detector signals without significantly degrading the high-frequency components which are vital for fast
 9246 shaping. The flexibility in the longitudinal and transverse segmentation, and the possibility of implementing
 9247 a section with narrow strips to measure the shower shape in its initial development, represent additional
 9248 advantages. It is worth noting that due to the asymmetric design, the projective structure is not fully
 9249 symmetric as the calorimeter and the solenoid centre are shifted forward with respect to the interaction
 9250 point.

9251 Fig. 13.31 shows a detail of the accordion-electrode structure. A basic cell consists of an absorber plate,
 9252 a liquid argon gap, a readout electrode and a second liquid argon gap. The mean thickness of the liquid
 9253 argon gap is constant along the whole barrel and along the calorimeter depth. The readout granularity

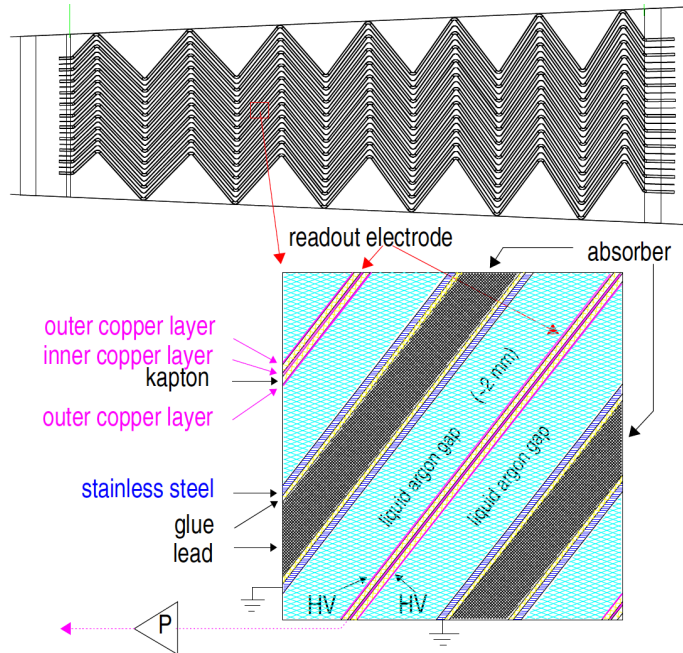


Figure 13.31: Longitudinal view of one cell of the ATLAS LAr Calorimeter, showing the accordion structure.

9254 is subdivided into 3 cylindrical sections of increasing size in $\Delta\eta \times \Delta\phi$. As shown in Fig. 13.32, the first
 9255 sampling section of the EMC would have a very fine granularity ($\Delta\eta \times \Delta\phi = 0.003 \times 0.1$), to optimize the
 9256 ability to separate photons from π^0 energy deposits. The second sampling section, mainly devoted to energy
 9257 measurement, would have a granularity of about 0.025×0.025 , and the final sampling section has a slightly
 9258 coarser granularity of $\Delta\eta \times \Delta\phi = 0.050 \times 0.025$.

9259 13.4.2 The Hadronic Barrel Calorimeter

9260 The baseline hadronic calorimeter in the barrel region is a sampling calorimeter using steel and scintillating
 9261 tiles as absorber and active material, respectively [790]. The *Tile Calorimeter* would provide the required
 9262 mechanical stability for the inner LAr and Magnet cryostat along with the iron required for the return flux
 9263 of the solenoidal field, as is also the case in ATLAS [781].

9264 The Tile calorimeter consists of a cylindrical structure with inner and outer radius of 120 and 260 cm
 9265 respectively (Tab. 13.6). The central HAC barrel part is 580 cm in length along the beam axis. Endcaps
 9266 extend the calorimetry further in the forward and backward direction in order to guarantee sufficient energy
 9267 containment. The detector cylinder would be built of several independent wedges along the azimuthal
 9268 direction while the modularity and segmentation may vary depending on the machine design.

9269 The Tile calorimeter forms the shell of the inner part of the LHeC detector. Once the barrel and the
 9270 extended barrels are assembled, all of the sub-detectors apart from the muon system will be placed inside of
 9271 it. The massive iron structure is rigid enough to support their weight, in particular the liquid argon cryostat
 9272 and the solenoid.

9273 The absorber structure is a laminate of steel plates of various dimensions, connected to a massive struc-
 9274 tural element referred to as a girder. The highly periodic structure of the system allows the construction of a
 9275 large detector by assembling smaller sub-modules together. Since the mechanical assembly is completely in-
 9276 dependent from the optical instrumentation, the design is simple and cost effective. Simplicity has also been
 9277 the guideline for the light collection scheme: the fibres are coupled radially to the tiles along the external
 9278 faces of each module. The laminated structure of the absorber allows for channels in which the fibres run.

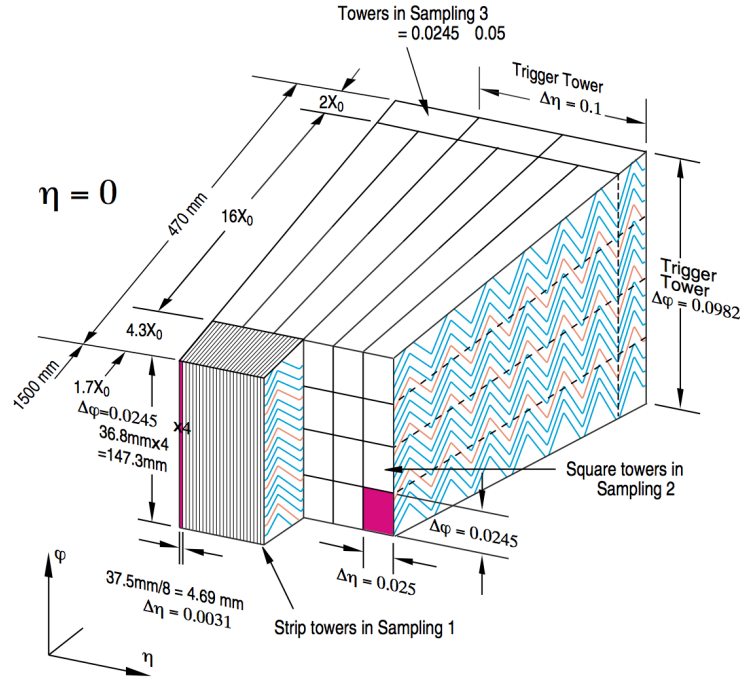


Figure 13.32: 3D view of the accordion structure of the ATLAS LAr Calorimeter

9279 The use of fibres for the readout allows a layered cell read-out to be used, creating a projective geometry
 9280 for triggering and energy reconstruction. A compact electronics read-out is housed in the girder of each
 9281 module. Finally, the scintillating tiles are read out in two separate photomultipliers, providing the required
 9282 redundancy.

9283 The granularity of the Tile Calorimeter is important to finely match the electromagnetic LAr calorimeter
 9284 in front and correct for the dead material of the magnet complex. The proposed hadronic segmentation for
 9285 the cells behind the electromagnetic section, will allow an efficient hadron leakage cut, needed for electron
 9286 and photon identification. A reasonable longitudinal segmentation, especially around the maximum depth
 9287 of the shower, favours an appropriate weighting technique to restore, at the level of 1-2%, the linearity of
 9288 the energy response to hadrons, which is intrinsically non-linear because of the non-compensating nature
 9289 of the calorimeter. At the highest energies, the resolution of the calorimetry is dominated by the constant
 9290 term, for which the largest contribution comes from the detector non-linearity and calibration. An attempt
 9291 is made to keep the constant term below the 2% level.

9292 with the same granularity

9293 13.4.3 Endcap Calorimeters

9294 Calorimetry in the forward and backward direction at the LHeC is of extreme importance: in the forward
 9295 region for the measurement of the hadronic final state, and in the backward region for the measurement
 9296 of the low energy scattered electron. Here, a good e/h separation is also important to suppress hadronic
 9297 background.

9298 As seen in Fig. 13.60, the very forward and to a lesser extent the backward parts of the calorimeter are
 9299 exposed to high levels of particle radiation and must therefore be radiation hard by design. Synchrotron
 9300 radiation and any further background radiation must also be tolerated in addition.

9301 Fig. 13.9 shows in detail the endcap calorimeters for the Ring-Ring design. The two-phase experimental
 9302 program requires the endcaps to be modular as these components will either be moved along the beam

E-Calo Parts	FEC1	FEC2		EMC		BEC2	BEC1
Min. Inner radius R [cm]	3.1	21		48		21	3.1
Min. polar angle θ [°]	0.48	3.2		6.6/168.9		174.2	179.1
Max. pseudorapidity η	5.5	3.6		2.8/-2.3		-3.	-4.8
Outer radius [cm]	20	46		88		46	20
z -length [cm]	40	40		660		40	40
Volume [m ³]	0.3			11.3		0.3	
H-Calo Parts barrel			FHC4	HAC	BHC4		
Inner radius [cm]			120	120	120		
Outer radius [cm]			260	260	260		
z -length [cm]			217	580	157		
Volume [m ³]			121.2				
H-Calo Parts Inserts	FHC1	FHC2	FHC3		BHC3	BHC2	BHC1
Min. inner radius R [cm]	11	21	48		48	21	11
Min. polar angle θ [°]	0.43	2.9	6.6		169.	175.2	179.3
Max/min pseudorapidity η	5.6	3.7	2.9		-2.4	-3.2	-5.
Outer radius [cm]	20	46	88		88	46	20
z -length [cm]	177	177	177		117	117	117
Volume [m ³]	4.2				2.8		

Table 13.6: Summary of calorimeter dimensions.

The electromagnetic barrel calorimeter is currently represented by the barrel part EMC (LAr-Pb module); the setup reaches $X_0 \approx 25$ radiation length) and the movable inserts forward FEC1, FEC2 (Si-W modules ($X_0 \approx 30$) and the backward BEC1, BEC2 (Si-Pb modules; $X_0 \approx 25$).

The hadronic barrel parts are represented by FHC4, HAC, BHC4 (forward, central and backward - Scintillator-Fe Tile modules; $\lambda_I \approx 8$ interaction length) and the movable inserts FHC1, FHC2, FHC3 (Si-W modules; $\lambda_I \approx 10$), BHC1, BHC2, BHC3 (Si-Cu modules, $\lambda_I \approx 8$) see Fig. 13.9.

9303 line or completely removed to allow the placement of the strong focussing magnets for the high luminosity
 9304 phase. The relevant dimensions and specifications are summarised in Tab. 13.6. For the Linac-Ring design,
 9305 where no additional magnets along the beam line will be required, the subcomponents FHC2/FHC3 and
 9306 BHC2/BHC3, can be combined into single modules.

9307 The restrictive geometry of the insert calorimeters requires a non-conventional and challenging design
 9308 based on previous developments [791–798]. Tungsten (W) is considered as the absorber material, in particular
 9309 for the forward inserts, because of its very short radiation length and large absorption to radiation length
 9310 ratio. About 26 cm of tungsten will absorb electromagnetic showers completely and will contain the hadronic
 9311 shower to a large extent and over a large range of energy ($\approx 30X_0 + \approx 10\lambda_I$). The electromagnetic and
 9312 hadronic sections can be combined to minimise boundary effects. An alternative to tungsten for the hadronic
 9313 absorber is copper (Cu).

9314 Simulations have been performed to compare the different absorbers. Since the backward inserts have
 9315 looser requirements, the material for the absorbers are lead (Pb) for the electromagnetic part and copper
 9316 for the hadronic. For the Ring-Ring option, where no dipole field along the beampipe is required, a more
 9317 economical choice of steel (Fe) instead of copper can be considered. The active signal sensors for both the
 9318 forward and backward calorimeters have been chosen to be silicon-strip (electromagnetic fwd/bwd parts)
 9319 and silicon-pad (hadronic fwd/bwd parts).

9320 13.5 Calorimeter Simulation

9321 In this section preliminary results on simulations of the barrel and endcap calorimeters are illustrated. The
 9322 detector components presented in 13.4.1, 13.4.2, 13.4.3 have been simulated using **GEANT4.9.2** [799] with
 9323 single and multiple particle events along with full $e-p$ events from the **QGSP-3.3** [800] physics list. The
 9324 Quark-Gluon String Precompound (**QGSP**) is based on theory-driven models and uses the quark-gluon-
 9325 string model for interactions and a pre-equilibrium decay model for fragmentation.

9326
 9327 The detector geometry, including the various layers of active, absorbing and support material were coded
 9328 and inserted in the simulation. Energy resolutions for electromagnetic and hadronic deposits were studied
 9329 along with concepts for optimal trigger and signal reconstruction. Particular attention was put into the key
 9330 features and the construction constraints of the detector, namely the beam optics and the magnets (the
 9331 solenoid and the Linac-Ring dipoles). Where a similar design from an existing or developing detector are
 9332 available, the results are presented complemented by referenced studies.

9333
 9334 The energy resolution of a calorimeter is parameterized by the following quadratic sum:

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus b \quad (13.1)$$

9335 where E is the particle energy in GeV , a is the stochastic term, which is arising from fluctuations in the
 9336 number of signal producing processes, b is the constant term, which describes imperfections in calorimeter
 9337 construction, fluctuations in longitudinal energy containment, non-uniformities in signal collection etc. A
 9338 third term c (left out here) is often also added which would represent the noise in experimental data de-
 9339 scription. The energy deposition of primary and secondary particles in the calorimeter was obtained using
 9340 **GEANT4**, and fitted to extract a and b . Effects due to the readout process were not considered at this
 9341 stage.

9342
 9343 Each energy distribution was fitted with a Gaussian, $\pm 2\sigma$ around the mean and the energy depended
 9344 resolution was calculated using those mean values fitted. An example of the energy distribution and Gaus-
 9345 sian fit applied is shown in Fig. 13.33. The a and b parameters are then calculated from the fit of σ/E .

9346

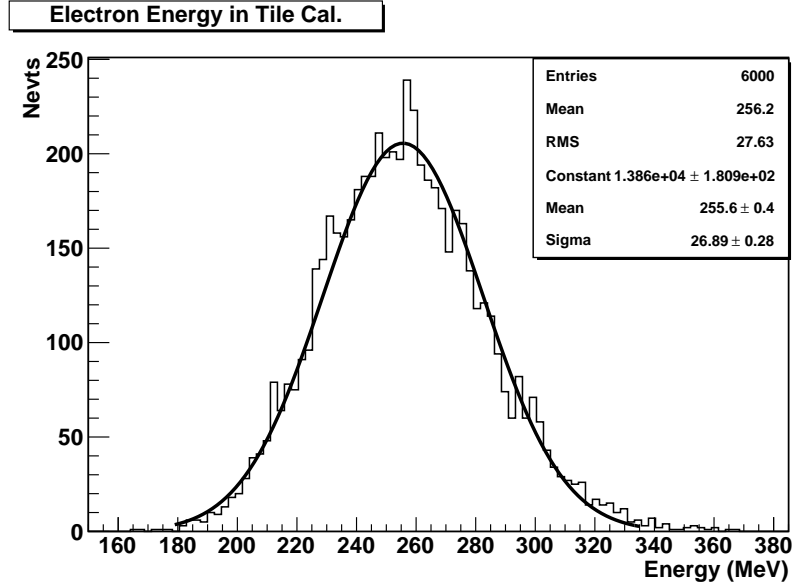


Figure 13.33: Example for a pion energy distribution and the Gaussian fit. The resulting σ and mean values are estimated for pions of an incident angle $\theta = 70^\circ$ and 10 GeV energy.

9347 13.5.1 The Barrel LAr Calorimeter Simulation

9348 A simplified layout, adapted from the ATLAS LAr calorimeter [781], has been implemented in a **GEANT4**
 9349 simulation and used to extract the main characteristics of the LHeC barrel electromagnetic calorimeter.

9350 The accordion shaped absorber sheets are 2.2 mm thick lead layers interspersed with 3.8 mm wide gaps
 9351 filled with liquid argon. In the present model the electrodes which in the case for ATLAS are 2×0.275 mm
 9352 thick, were not considered. Both absorber and the liquid argon gap have an accordion fold length of 40.1 mm
 9353 and 13 bend angles of 90° . A total of 62 absorber sheets each 250 cm wide in z -direction have been incorpo-
 9354 rated into the simulation (Fig. 13.35-left). A 20 GeV incident single electron showering in the stack is shown
 9355 in Fig. 13.35-right. The energy resolution for electrons was obtained from the ratio of the mean and the
 9356 standard deviation of the electron response, both obtained by fitting a Gaussian to the energy spectrum.
 9357 Figure 13.36 shows the energy resolution for electrons of energy between 10 and 400 GeV. These results are
 9358 in agreement with [789]. In the simulation the energy deposited in the active material is normalized to the
 9359 energy of the incident particle.

9360 13.5.2 The Barrel Tile Calorimeter Simulation

Tile Rows	Height of Tiles in Radial Direction	Scintillator Thickness
1-3	97 mm	3 mm
4-6	127 mm	3 mm
7-11	147 mm	3 mm
x -depth	1407 mm	

Table 13.7: Longitudinal (into x -direction) segmentation of the hadronic tile calorimeter (HAC).

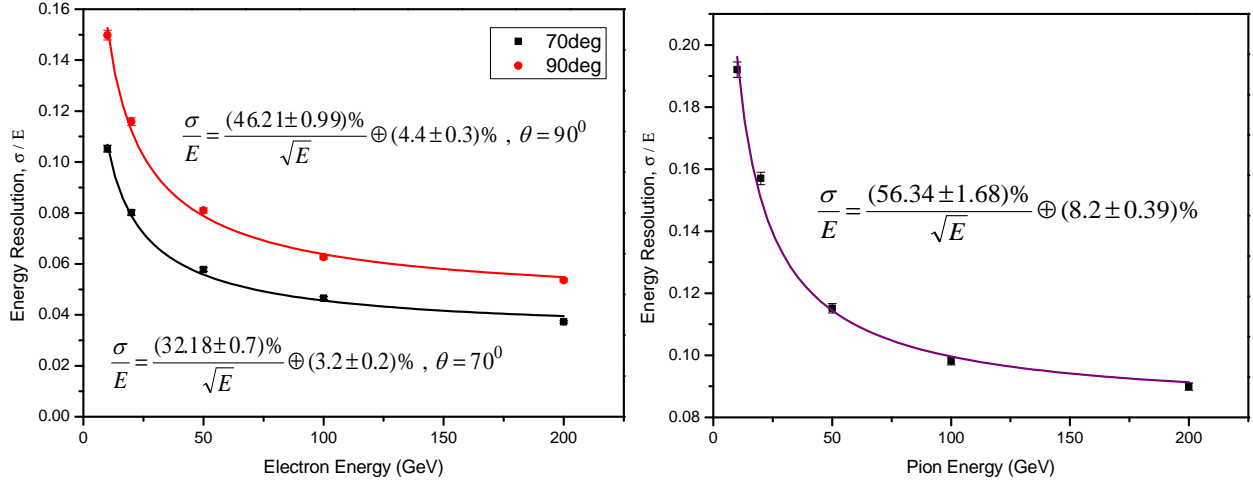


Figure 13.34: Tile Calorimeter energy resolution for electrons at $\theta = 70^\circ$ and 90° (left) and for pions at $\theta = 90^\circ$ (right).

9361 The HAC is a scintillator-steel tile calorimeter: 4 mm thick steel plates are interspaced by 3 mm thick
 9362 scintillator tiles. The tiles are placed in planes perpendicular to the z -direction. The absorber structure
 9363 consist of 262 repeated periods, each of which spans 19 mm in z and consist of 16 mm of steel and 3 mm
 9364 of scintillator tile. 11 transverse rows of tiles are used in a module. The total interaction depth of the
 9365 HAC prototype correspond to $\lambda_I = 7$. The longitudinal segmentation of the HAC module is described in
 9366 Tab. 13.7. In this section the performance of the hadron calorimeter alone has been investigated. in the
 9367 later sections the combined use of EMC and HAC parts has been studied. The energy resolution of the tile
 9368 calorimeter was simulated with electrons and pions within the energy range 3-200 GeV (Fig. 13.34). The
 9369 obtained stochastic term values are consistent with results obtained for ATLAS [789]. The response to
 9370 electrons show the general good resolution such that any leakage from the electromagnetic calorimetry in
 9371 front of HAC would be resolved safely.

9372 13.5.3 Combined Liquid Argon and Tile Calorimeter Simulation

9373 The combined system (accordion and tile calorimeter) has been studied. The effect of the dead material due
 9374 to the magnet and the cryostat between the EMC and HAC has been studied in first approximation. The
 9375 energy resolution of the combined system has been simulated. The effect of the solenoid and the cryostat
 9376 infrastructure has been simulated by adding a thick Aluminum layer (14 cm) in between EMC and HAC.
 9377 The study has been performed with particles in a wide range of energy and for different incident angle in
 9378 order to obtain information about the detector response for particles entering the calorimeters at different
 9379 z . The hadronic shower simulations have been obtained in the energy range 3 GeV-200 GeV. First results of
 9380 the energy resolutions as a function of energy for pions are shown in Fig. 13.37.

9381 13.5.4 Lead-Scintillator Electromagnetic Option

9382 Along with the baseline liquid argon calorimeter, a more conservative option, not requiring a dedicated
 9383 cryogenic system, has been considered for the barrel electromagnetic calorimetry. For this purpose a
 9384 lead-scintillator sampling calorimeter, composed of 20×0.85 cm thick Pb layers interspaced by 4 mm plas-
 9385 tic scintillator plates was setup for simulation. The radiation length of this systems correspond to $30X_0$
 9386 ($X_0(Pb) = 0.56$ cm). All dimensions of the calorimeter systems have been kept according to the default solu-
 9387 tion summarized in Tab. 13.6.

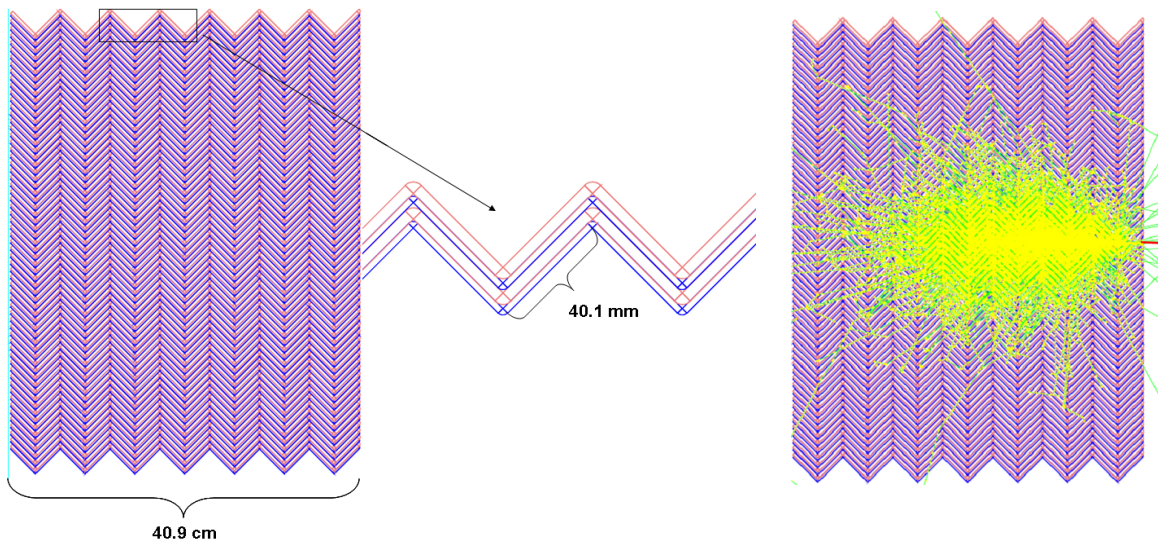


Figure 13.35: View of the parallel geometry accordion calorimeter (left) and simulation of a single electron shower with initial energy of 20 GeV (right).

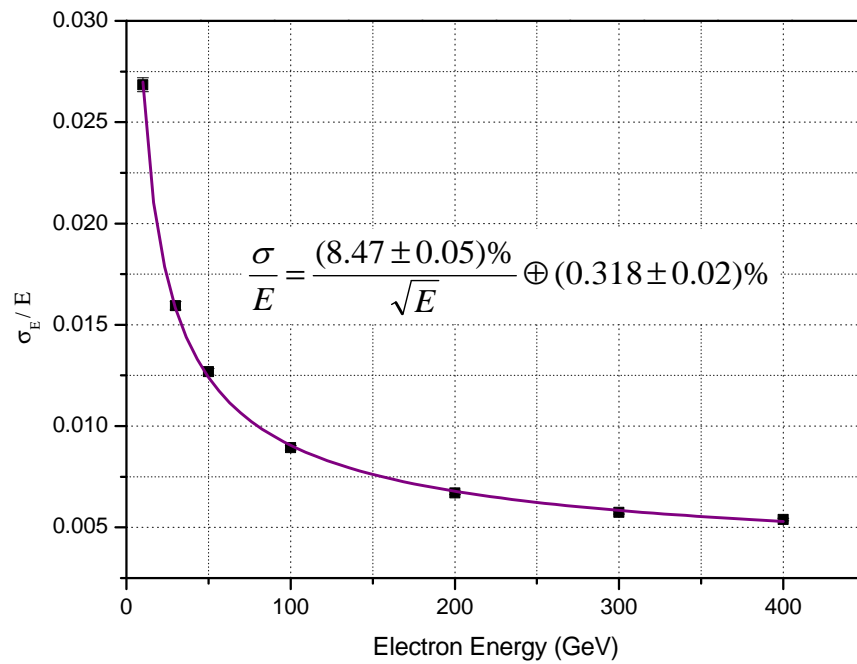


Figure 13.36: LAr accordion calorimeter energy resolution for electrons between 10 and 400 GeV.

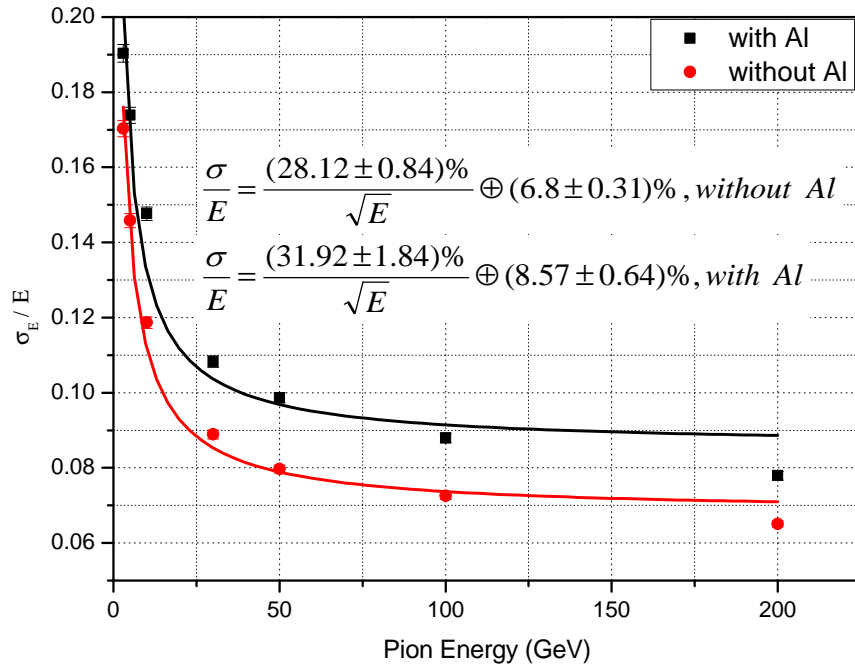


Figure 13.37: Accordion and Tile Calorimeter energy resolution for pions with and without 14cm Al block.

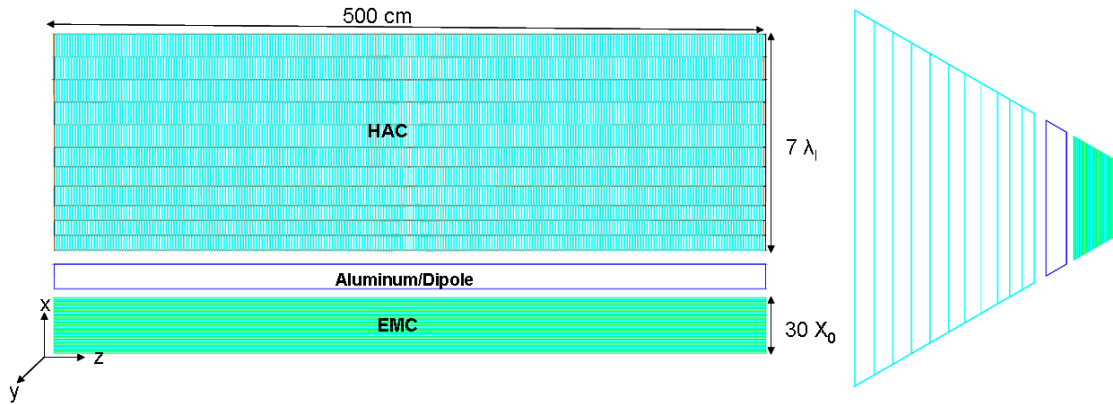


Figure 13.38: Simulation - barrel calorimeter module EMC/solenoid-dipole-system($\propto 16$ cm Al-block)/HAC.

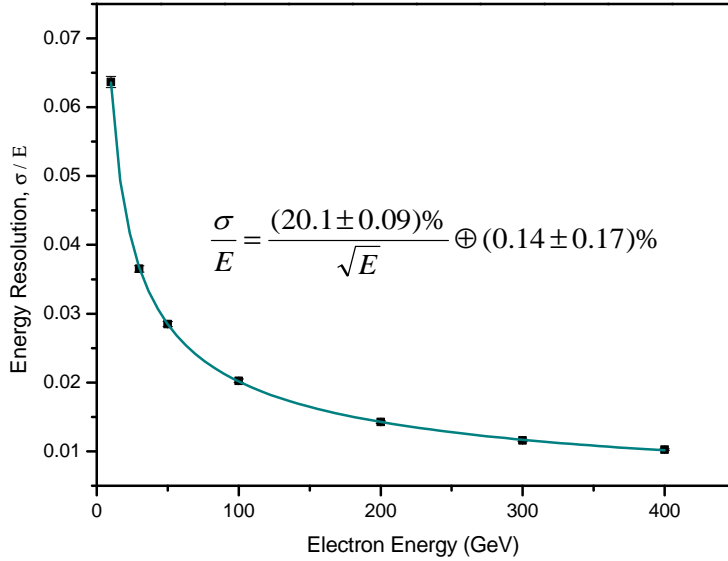


Figure 13.39: EM-Calorimeter energy resolution for electrons at $\theta = 90^\circ$.

9388 The lead-scintillator EMC stack was placed 30 cm in front of the HAC. Again an aluminum block of 16 cm
 9389 was inserted between EMC and HAC representing the magnet/cryostat system as illustrated in Fig. 13.38.
 9390 The sketched module would be one out of 6 azimuthal segments of the complete barrel EMC and HAC. The
 9391 energy resolution of the electromagnetic lead-scintillator calorimeter as obtained with electrons of 10-400 GeV
 9392 is shown in Fig. 13.39.

9393 As the energy loss for electrons and pions differs in shape, normalization and depth, it is worth looking
 9394 in more detail into their shower profiles when traversing the calorimeter. At detector level, this information,
 9395 if available, can be used to identify and discriminate particles and improve the energy resolution. High
 9396 granularity, necessary to separate jets and energy deposits coming from different products, along with a
 9397 longitudinal segmentation and software reweighting are essential.

9398 Longitudinal and transverse shower profiles have been studied with electrons and pions of different energies.
 9399 The detector structure set up here for first test only and non projective designed but the comparison of studies
 9400 with electrons and pions sent into the calorimeter system with incident angles between 30° and 90° are of
 9401 some interest for studying shower profile properties. The effective calorimeter depth is larger for particles
 9402 with $\theta \neq 90^\circ$ (37 cm for the EMC and 140 cm for the barrel HAC in case of perpendicular impact). The
 9403 longitudinal shower profiles for electrons and pions are summarized in Fig. 13.40 and Fig. 13.41. They show
 9404 the mean deposited energy as a function of the calorimeter stack depth. The longitudinal shower profile of
 9405 electrons is shorter than for pions as expected. The energy deposition of the electrons has its maximum in
 9406 the EMC (Fig. 13.40). The leakage into the hadronic part of the calorimeter system is small and sums up
 9407 to $\mathcal{O}(10)$ MeV. Pions penetrate deeper into the calorimeter and the maximum of energy deposition is seen
 9408 consistently in the HAC region (Fig. 13.41-right). Less energy deposition occurs in the region between 37
 9409 and 67 cm because of the aluminum layer which represents the cryostat-wall, the solenoid and the dipole
 9410 magnet structures. The containment of the hadronic showers is complete.

9411 Transverse profiles are usually expressed as a function of the transverse coordinates and are integrated
 9412 over the longitudinal coordinate. Fig. 13.42 shows the transverse shower profiles for electrons and pions.
 9413 Since the electromagnetic showers are compact, the electromagnetic energy is deposited relatively close to
 9414 the core of the shower. As expected the hadronic profiles show a larger transverse spread.

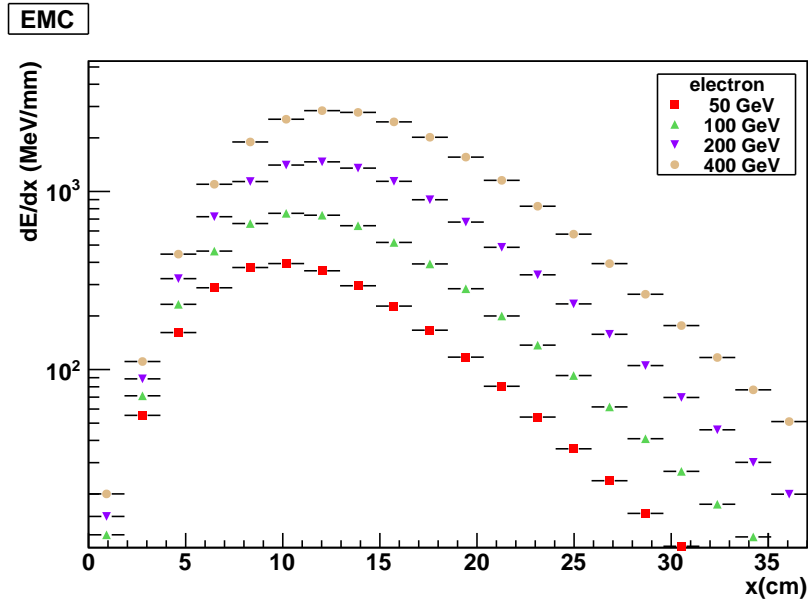


Figure 13.40: Electron longitudinal shower profile for EMC at various energies. Only the statistical uncertainties are shown.

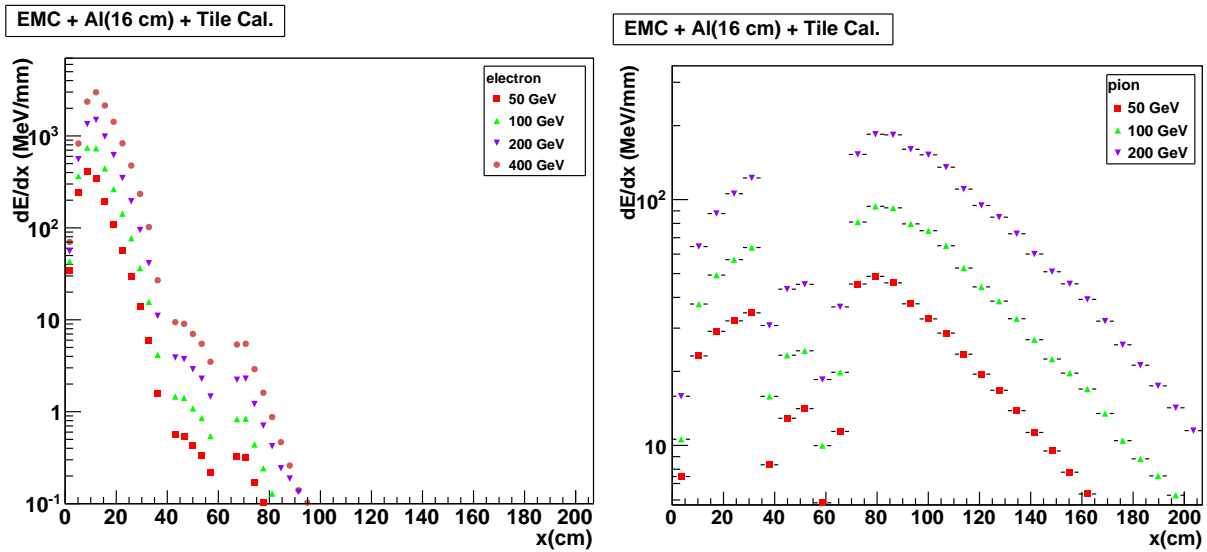


Figure 13.41: Electron (left) and Pion (right) longitudinal shower profile for the EMC/solenoid-dipole-system (Al-block)/HAC at various energies.

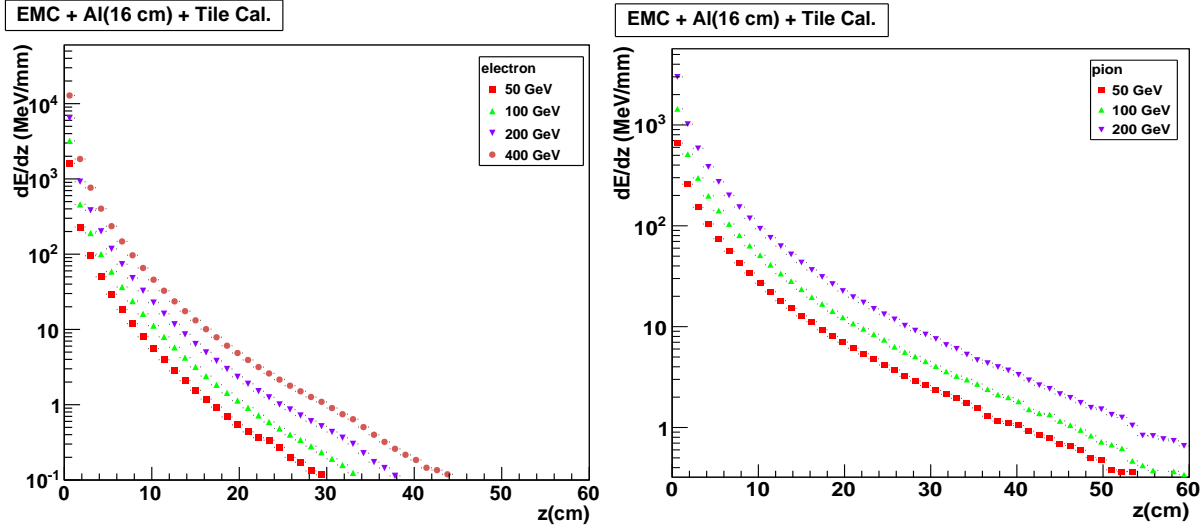


Figure 13.42: Energy deposit and transverse shower profiles for electron (left) and pion (right).

13.5.5 Forward and Backward Inserts Calorimeter Simulation

The very important forward/backward instrumentation for calorimetric measurement has been chosen such that from the point of view of performance and availability of the technology all currently known boundary conditions could be met. More detailed studies towards a technical design will clarify open issues. The details of the stack constructions are summarized in Table 13.8. The following options have been considered for the insert calorimeters:

- The forward electromagnetic calorimeter (FEC) inserts (i.e. FEC1 and FEC2) are tungsten-silicon sampling calorimeters for compact and radiation hard stack design matching the tracking system towards the interaction point with high granularity.
- The forward hadronic calorimeter (FHC) inserts (i.e. FHC1, FHC2 and FHC3) have been simulated using two different absorber materials, Copper (*Cu*) and Tungsten (*W*). Using *W* only would make the forward insert calorimeters FEC&FHC very homogenous. The electromagnetic and the hadronic part could be combined in the same compartment. On the other hand using *Cu* is probably more economical.
- The backward electromagnetic calorimeter (BEC) inserts (i.e. BEC1 and BEC2) are lead-silicon sampling calorimeters, with silicon as sensitive media because of the synchrotron radiation risk, specifically in the backward direction. The energy of particles, predominantly the "kinematical peak electrons" scattered backward, is expected to be low enough such that a smaller integrated radiation length X_0 installed and the use of *Pb* as absorber material is justified.
- The backward hadronic calorimeter (BHC) inserts (i.e. BHC1, BHC2 and BHC3) have been setup as copper-silicon sampling calorimeters.

The BEC, BHC and BEC&BHC composite calorimeter are generally structured as their forward electromagnetic and hadronic calorimeter counterparts sketched in Figure 13.43.

The lateral size of a shower is due to the multiple scattering of electrons and positrons and characterized by the Molière radius (ρ_M) of the setup. The lateral development of the electromagnetic showers initiated by electrons or photons scales with the Molière radius. The Molière radii of tungsten and lead are $\rho_M=0.9327$ cm

Calorimeter Module	Layer	Absorber	Thickness	Instrumented Gap	Total Depth
FEC _(W-Si) 30X₀	1-25	1.4 mm	16 cm	5 mm	35.5 cm
	26-50	2.8 mm	19.5 cm		
FHC _(W-Si) 10λ_I	1-15	1.2 cm	39 cm	14 mm	165 cm
	16-31	1.6 cm	48 cm		
	32-46	3.8 cm	78 cm		
FHC _(Cu-Si) 10λ_I	1-10	2.5 cm	30 cm	5 mm	165 cm
	11-20	5 cm	55 cm		
	21-30	7.5 cm	80 cm		
BEC _(Pb-Si) 25X₀	1-25	1.8 mm	17 cm	5 mm	39 cm
	26-50	3.8 mm	22 cm		
BHC _(Cu-Si) 7.9λ_I	1-15	2.0 cm	39.75 cm	6.5 mm	145.35 cm
	16-27	3.5 cm	49.8 cm		
	28-39	4.0 cm	55.8 cm		

Table 13.8: Layer material choice and dimension of electromagnetic and hadronic calorimeter modules simulated. X_0 denotes the radiation length and λ_I the interaction length for the whole stack, respectively. Additional to each absorber layer, layers are placed inside the gap describing the instrumentation (support and readout, respectively): Si-sensors (525 μ m), Si-support structures (FR4; 0.65 mm) and Kapton based circuits (1.15 mm). Constants used: $X_0(W)=0.3504$ cm, $\lambda_I(W)=9.946$ cm, $\lambda_I(Cu)=15.06$ cm and $X_0(Pb) = 0.5612$ cm.

Calorimeter Module (Composition)	Parameterized Energy Resolution
Electromagnetic Response	
FEC _(W-Si)	$\frac{\sigma_E}{E} = \frac{(14.0 \pm 0.16)\%}{\sqrt{E}} \oplus (5.3 \pm 0.049)\%$
BEC _(Pb-Si)	$\frac{\sigma_E}{E} = \frac{(11.4 \pm 0.5)\%}{\sqrt{E}} \oplus (6.3 \pm 0.1)\%$
Hadronic Response	
FEC _(W-Si) & FHC _(W-Si)	$\frac{\sigma_E}{E} = \frac{(45.4 \pm 1.7)\%}{\sqrt{E}} \oplus (4.8 \pm 0.086)\%$
FEC _(W-Si) & FHC _(Cu-Si)	$\frac{\sigma_E}{E} = \frac{(46.0 \pm 1.7)\%}{\sqrt{E}} \oplus 6.1 \pm 0.073)\%$
BEC _(Pb-Si) & BHC _(Cu-Si)	$\frac{\sigma_E}{E} = \frac{(21.6 \pm 1.9)\%}{\sqrt{E}} \oplus (9.7 \pm 0.4)\%$

Table 13.9: Energy resolution parameterization for electrons in the electromagnetic stacks (FEC/BEC) and for pions in the composite FEC&FHC and BEC&BHC stack structures, respectively. For each stack structure, the energy range used in the fits is:

- FEC_(W-Si): 1 GeV-5 TeV electrons,
- BEC_(Pb-Si): 3 GeV-100 GeV electrons,
- FEC_(W-Si) & FHC_(Cu-Si) and FEC_(W-Si) & FHC_(W-Si): 50 GeV-1 TeV pions,
- BEC_(Pb-Si) & BHC_(Cu-Si): 3 GeV-100 GeV pions.

The energy resolution spectra from the simulation are summarized in Figs. 13.44 and 13.45.

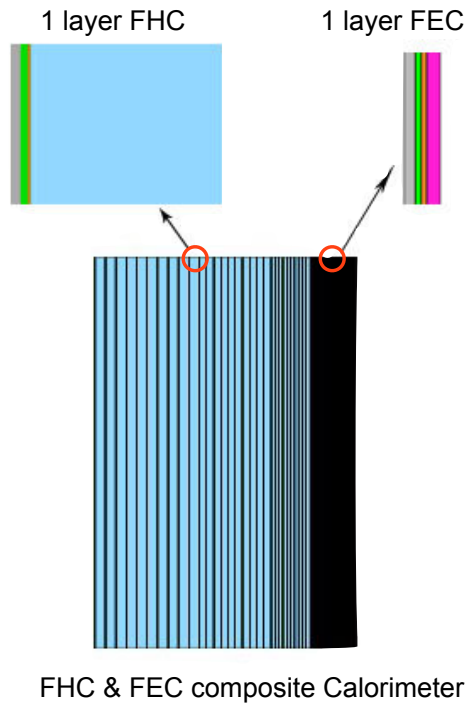


Figure 13.43: Cross section in rz of FHC+FEC. Color coding: the absorber of the FHC is in blue. The absorber of the FEC is in pink. The silicon detectors, silicon support and kapton circuits of FEC and FHC are in brown, green and gray respectively.

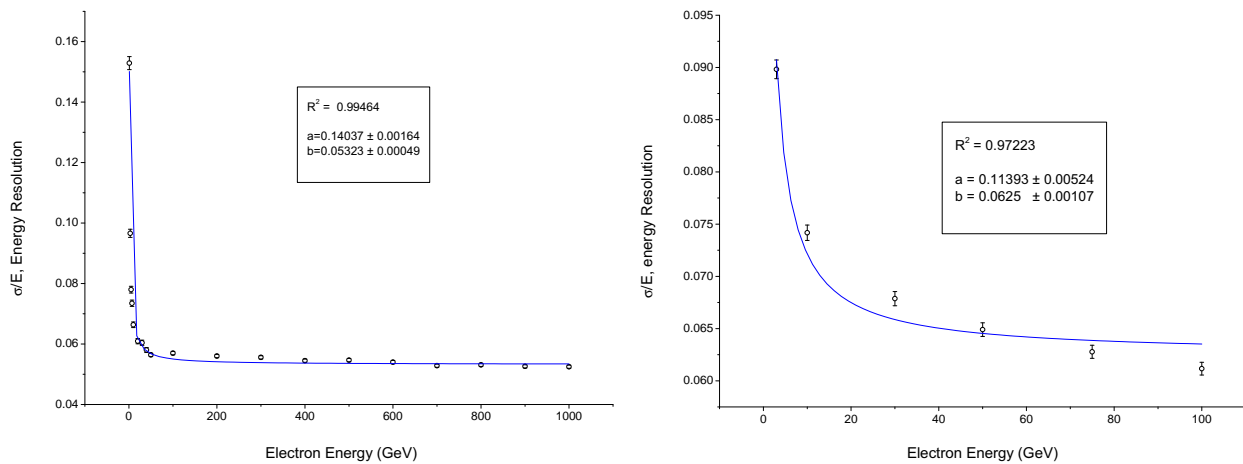


Figure 13.44: Energy resolution spectra for electrons in the energy range 1 GeV-1 TeV in the $FEC_{(w-si)}$ (left) and for electrons (energy range 3 GeV-100 GeV) in the $BEC_{(Pb-Si)}$ stacks (right).

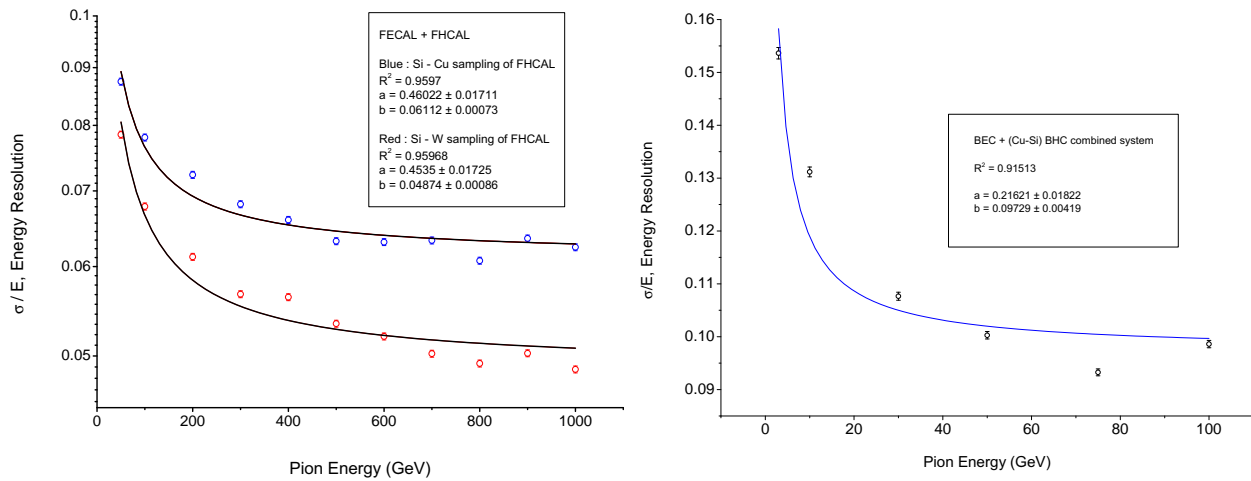


Figure 13.45: Comparison of energy resolution spectra for pions (energy range 50 GeV-1 TeV) in $FEC_{(W-Si)}$ & $FHC_{(Cu-Si)}$ and $FEC_{(W-Si)}$ & $FHC_{(W-Si)}$ composite system, respectively (left) and energy resolution spectrum for pions (energy range 3 GeV-100 GeV) in the $BEC_{(Pb-Si)}$ & $BHC_{(Cu-Si)}$ composite system (right).

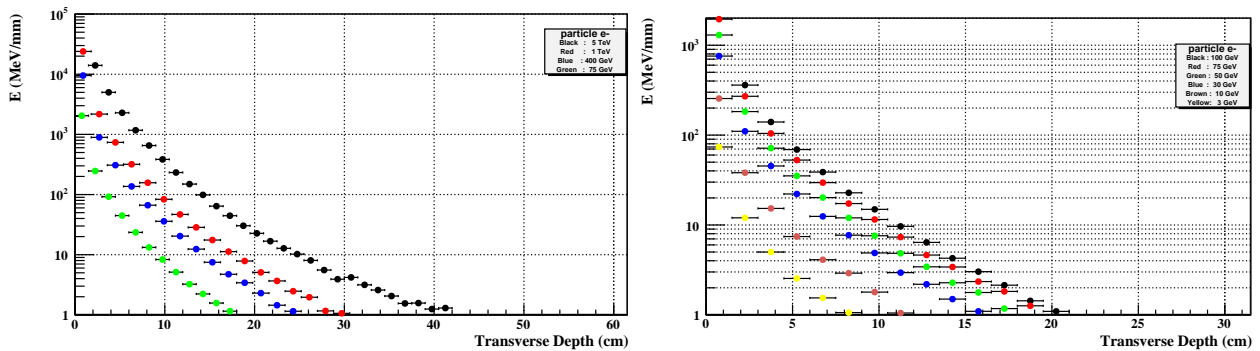


Figure 13.46: Comparison of transverse shower profiles for electrons with energies 75 GeV-5 TeV on $FEC_{(W-Si)}$ (left) and 3 GeV-100 GeV on $BEC_{(Pb-Si)}$ (right).

9441 and $\rho_M=1.602$ cm [64], respectively. ⁴ ρ_M has to be low enough to separate showers, thus that argument is
 9442 in favour of W specifically for the construction of the forward insert calorimeters (Fig. 13.46).

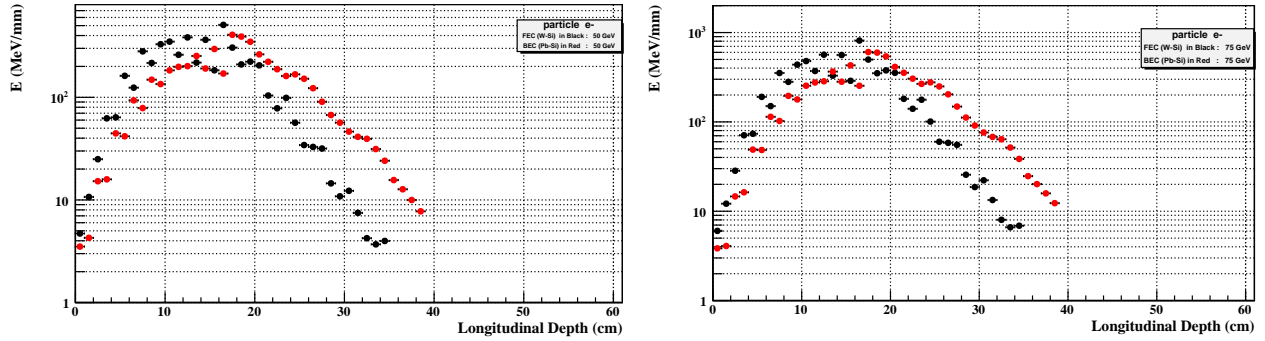


Figure 13.47: Comparison of average energy deposition as a function of longitudinal shower extension for electrons energies of 50 GeV (left) and 75 GeV (right) in $FEC_{(W-Si)}$ (black) and $BEC_{(Pb-Si)}$ (red).

9443 The simulated maximum longitudinal shower profiles for electrons in the FEC and BEC (Fig 13.47) are
 9444 in agreement with former results [801]. In average 99.4% and 98.8% of the incident energy for simulated
 9445 electron energies in the range of 1 GeV-1 TeV for $FEC_{(W-Si)}$ and 3 GeV-100 GeV for $BEC_{(Pb-Si)}$, respec-
 9446 tively, are contained in the electromagnetic calorimeters. Thus the high energy electromagnetic showers are
 9447 sufficiently well contained in the $30X_0^{FEC}$ and $25X_0^{BEC}$ stack construction, respectively, taking into account
 9448 the considerably lower energies expected in backward direction.

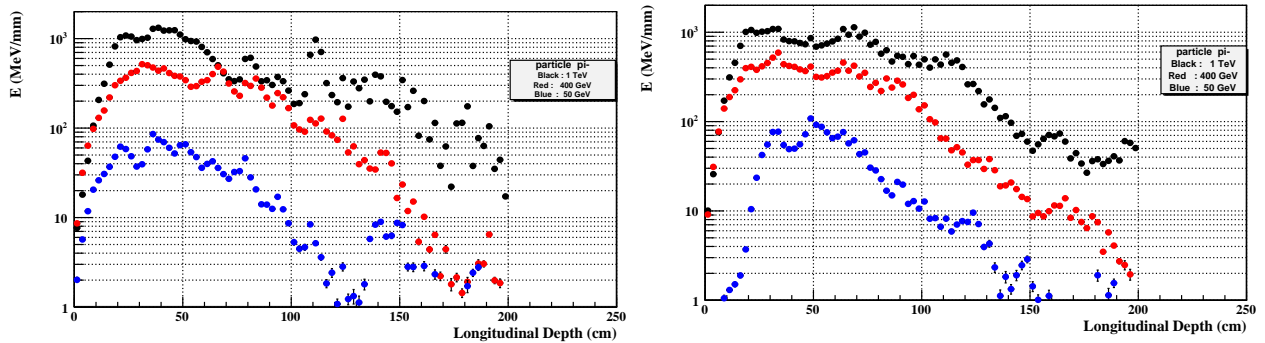


Figure 13.48: Average energy deposition as a function of depth for pions in the energy range 50 GeV-1 TeV in the $FEC_{(W-Si)}$ & $FHC_{(W-Si)}$ system (left) and in the $FEC_{(W-Si)}$ & $FHC_{(Cu-Si)}$ composite stack system (right).

9449 The longitudinal distribution of the hadronic calorimeters and shower maxima of the longitudinal dis-
 9450 tribution scales with the nuclear interaction length λ_I . For copper λ_I is by $\approx 51\%$ larger than for tungsten.
 9451 Indeed we observed that showers in the $FHC_{(W-Si)}$ stack (Fig. 13.48-left) reaches the energy deposition
 9452 maximum already earlier in the calorimeter, i.e. at smaller depth values. That effect is more pronounced for
 9453 lower energetic pions (Fig. 13.49-left). The thickness of $10\lambda_I$ provides sufficient containment of the hadronic
 9454 cascades for precision measurements both of jet properties and of E_T^{miss} . The overall containment when
 9455 using $FHC_{(W-Si)}$ instead of $FHC_{(Cu-Si)}$ for the configurations described in Tab. 13.9 seems to be better.

9456 Some leakage for the hadronic calorimetry ($BEC_{(Pb-Si)}$ & $BHC_{(Cu-Si)}$) in the backward direction has
 9457 been observed. This is not too worrisome as the main focus in the backward direction is the analysis of

⁴The Molière radius, ρ_M , is the radius of a cylinder containing on average 90% of the electromagnetic shower's energy deposition.

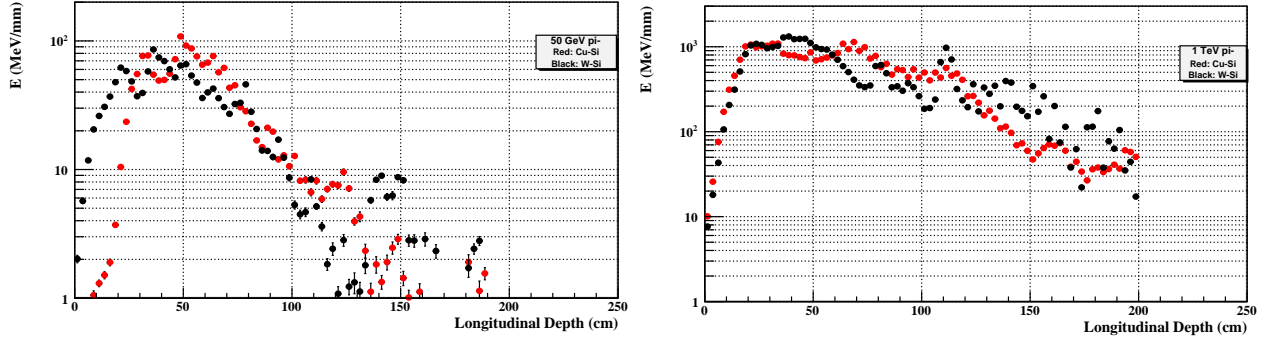


Figure 13.49: Comparison of $FEC_{(W-Si)}$ & $FHC_{(Cu-Si)}$ (red) and $FEC_{(W-Si)}$ & $FHC_{(W-Si)}$ (black) stack systems in terms of average energy depositions as a function of stack depth for pions of energy 50 GeV (left) and the same comparison for pions with energy 1 TeV (right).

9458 the electromagnetic component of the $e^\pm p/e^\pm A$ scattering. It should be mentioned that important design
 9459 details which will affect the performance of the real calorimeter are not defined yet. Two of these are the
 9460 granularity definitions which have to be optimized for shower separation, and the impact of the dead regions
 9461 coming from the cabling and the mechanical infrastructure, which is unavoidable and introducing losses in
 9462 terms of energy measurement [802], [803]. A detailed simulation will take that into account.

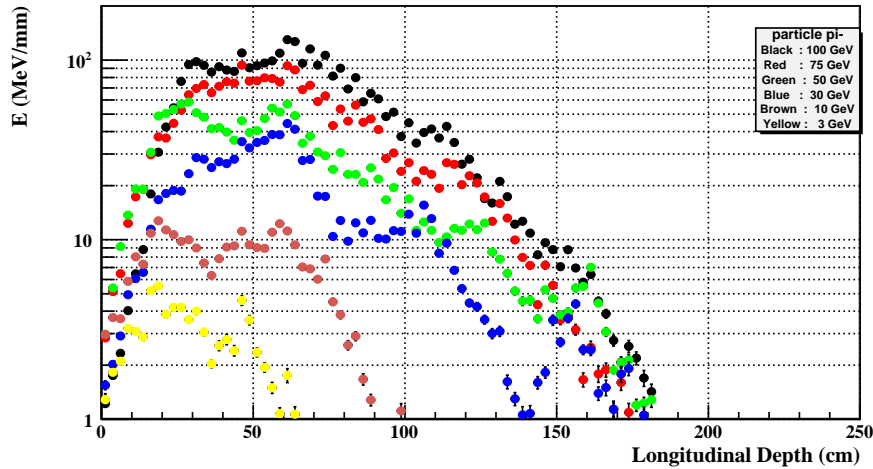


Figure 13.50: Average energy deposition as a function of depth for pions in the energy range 3 GeV-100 GeV incident on the $BEC_{(Pb-Si)}$ & $BHC_{(Cu-Si)}$ composite system.

9463 13.6 Calorimeter Summary

9464 At the LHeC different calorimeter approaches are required following the asymmetric interaction region and
 9465 energy imbalance of the interacting beams.

9466 High energy jets with energy up to few TeV are expected in the forward region requiring radiation hard
 9467 design, a high granularity and depth of up to $10 \lambda_I$ and in a very compact space. More relaxed are the
 9468 requirements in the barrel and backward region.

9469 The choice of the sampling calorimetry for all calorimeter parts is motivated by the good experience from
9470 past experiments and from the LHC along with considerations on the available technologies, their costs and
9471 the detector dimensions.

9472 In the barrel region, the need for a precise match to the tracking system and the ability to separate mul-
9473 tiple events pushes toward a solution which allows for a high energy linearity and a high readout granularity
9474 as obtainable for liquid argon. The use of a compensating calorimeter, as was for instance the uranium
9475 calorimeter of ZEUS, would allow to reduce the e/h energy fluctuations and provide an absolute energy
9476 measurement, but only hardly and at high manufacturing expense, provide the required granularity. More-
9477 over software compensation and energy-reweighting for a linear response of the electromagnetic/hadronic
9478 calorimeter is nowadays well established (H1/ATLAS).

9479 **Particle-Flow Calorimeter** [804–806] as presently being designed for the future ILC, have very specific
9480 construction requirements making at present their choice also not suitable for the LHeC. Some of these
9481 aspects are the powering scheme and the related duty cycle which follows from the large number of channels
9482 involved, the required cooling, the large dimensions and costs.

9483 As already mentioned very challenging appears the design in the forward and backward endcaps especially
9484 at small angle. In these regions the momentum measured by the tracking system is also less precise due to
9485 the almost parallel magnetic field and the higher multiple scattering due to an effective larger beampipe and
9486 infrastructure the particles have to cross. The silicon-absorber based inserts in the forward and backward
9487 directions will have to be compact and efficiently matched to the tracking devices in front. In any case the
9488 projective design of the calorimeter stack cells has to be ensured making use of signal weighting for good
9489 space resolutions (of the order of 1 mm).

9490 An alternative approach would be the implementation of the **Double Readout Calorimeter** concept [807]
9491 ⁵. The dual readout calorimeters measure each shower twice and in two different ways. The major compo-
9492 nent, dE/dx contributions of all charged particles (e^\pm, π^\pm, K^\pm , spallation p, recoil p, nuclear fragments, etc.),
9493 is measured in scintillating material and the electromagnetic part, predominantly coming from subshowers
9494 from $\pi^0 \rightarrow \gamma\gamma$ decays, is measured by the Čerenkov light generated in clear fibres/plates by the relativistic
9495 e^\pm passing through [808]. Making use of a obviously constant ratio of $(e/h)_C$ (for Čerenkov light emit-
9496 ting material) and $(e/h)_S$ (for Scintillation light emitting material), respectively, the energy response of the
9497 calorimeter to electrons e and to hadrons h at all energies can be controlled by construction with convincing
9498 results [809] [808].

9499
9500 The preliminary simulations and the results shown indicate the validity of the proposed design concepts as
9501 a baseline solution for the given dimensions of the LHeC detector. A more elaborated design will be possible
9502 as soon as general decisions on the accelerator concept and therefore magnet design have been taken.

9503 13.7 Muon Detector

9504 Muon detection is an important aspect of the physics program covered by the LHeC. In particular the muon
9505 detector can improve the scope and the spectrum of measurements, here only a few are listed:

- 9506 • Higgs decay, leptoquarks, lepton flavor violation
- 9507 • PDF fits from semileptonic decay of hadrons and heavy flavors.
- 9508 • Vector meson production

9509 The penetrative power of muons would be exploited by several layers of muon chambers ensuring good
9510 tracking resolution and hermetic coverage, in particular towards small angles in the forward and backward
9511 regions. These regions, particular challenging for central tracking detector due to the accelerator infrastruc-
9512 ture, are more accessible at larger distance from the interaction region as is done for travelling minimum
9513 ionizing particles as muons are.

⁵using plates/fibres in the double readout calorimeter stack for both signal components which are radiation hard

9514 Fig. 13.51 shows the muon polar distributions at the LHeC coming from the decay elastic $ep \rightarrow J/\psi \rightarrow$
 9515 $\mu^+\mu^-$ production. The improvement by enlarging the coverage towards small angles is evident as shown in
 9516 Fig. 13.52 where the coverage as a function of the γp system center of mass energy W is shown for the cases
 9517 of 10° and 1° detector acceptance.

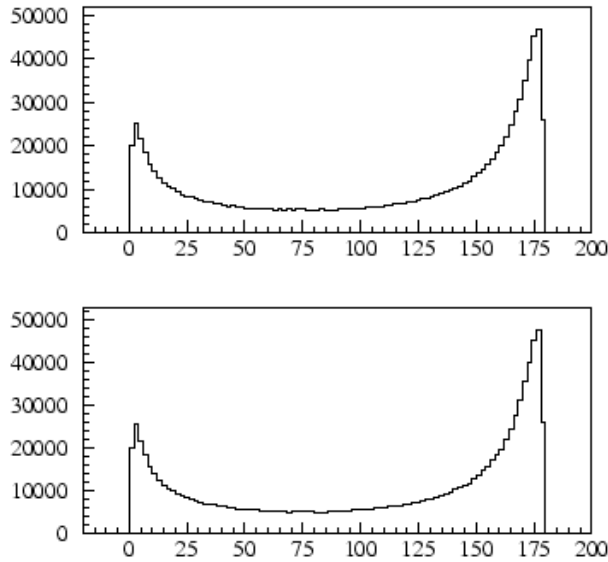


Figure 13.51: Distribution for J/ψ with $E_e = 50$ GeV. Polar angle of positive (top) and negative (bottom) muon respectively.

9518 13.7.1 Muon detector design

9519 The LHeC main detector will be surrounded by multiple layers of muon detectors. Fig. 13.53 shows a 3d
 9520 view of the baseline detector (option A). Three muon double detector layers mechanically attached to an
 9521 iron structure which could provide either the return flux of residual B field from the inner solenoid or an
 9522 additional field from warm magnets.

9523 Following the state of the art of present muon detector as implemented in the LHC experiments and
 9524 in similar high energy physics experiments, several options providing the required tracking resolution, rate
 9525 sustainability and prompt trigger and readout are available.

9526 The two LHC general purpose detectors, ATLAS and CMS, combine Drift Tubes and Cathode Strip
 9527 Chambers for precision measurements along with with Resistive Plates Chambers and Thin Gap Chambers
 9528 for Trigger and second coordinate measurements [810, 811]. A similar approach can be considered for the
 9529 LHeC muon detector with 2 or 3 superlayers each one composed of a double layer of 2d trigger detector and
 9530 a precision measurement as shown in Fig.13.54.

9531 Other technologies (as for instance micromegas [812], etc.) along with further developments of the
 9532 existing ones (thin gap RPC [813], smaller monitored drift tubes [814], thin strip TGC [815, 816]), might also
 9533 be considered for the LHeC. It is anyhow evident that the requirements from the LHC would also satisfy the
 9534 running at the LHeC where backgrounds and luminosity are expected to be lower.

9535 To provide at this stage a complete design of the muon detector is beyond the scope of this document
 9536 as too many options are available and depend on the choices to be taken in the accelerator and the main
 9537 detector design. Only a few options are discussed below with the aim to demonstrate, for the baseline design,
 9538 the feasibility and scope of a detector using available technologies. More studies and design optimization
 9539 will follow in the next steps.

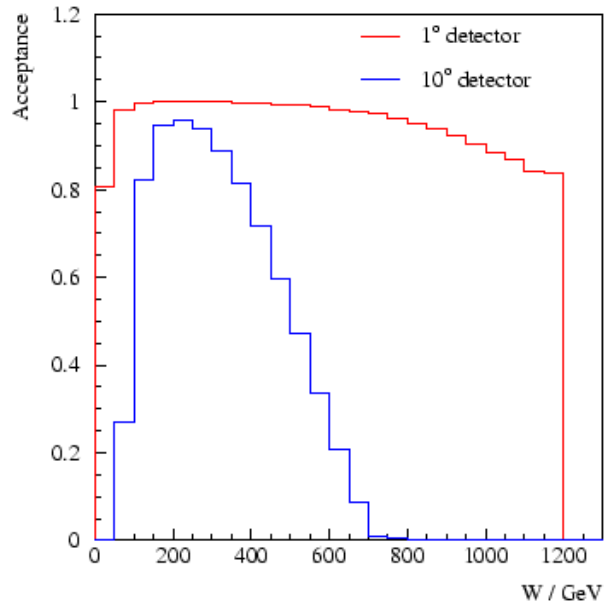


Figure 13.52: Acceptance for J/ψ with $E_e = 50$ GeV as a function of W , the center of mass energy of the γp system. A detector with larger coverage both in the forward and in the rear region allows for measurements on a much wider W range.

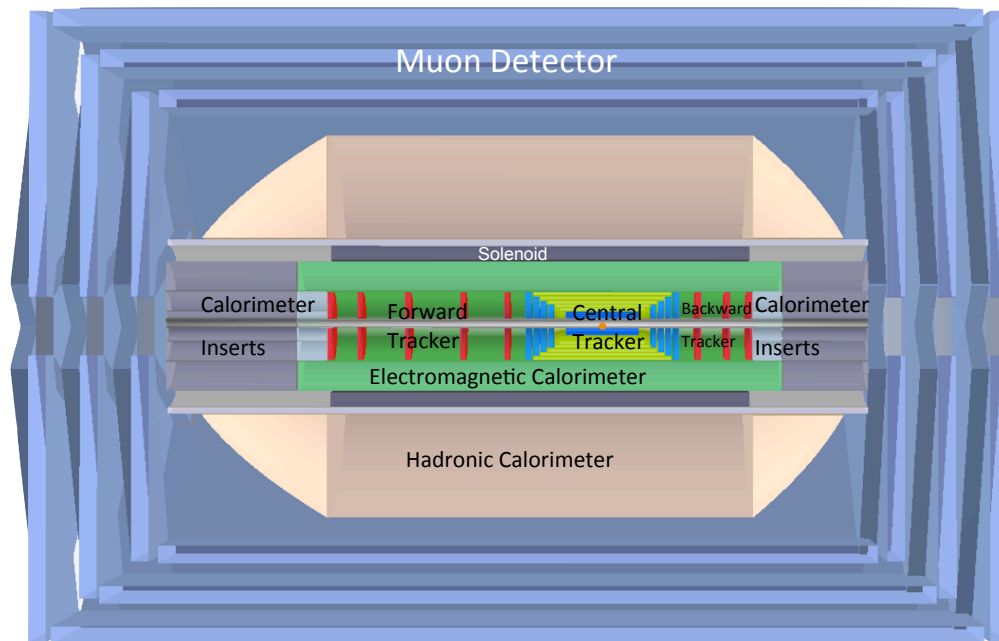


Figure 13.53: A full view of the baseline detector in the r - z plane with all components shown. The detector dimensions are ≈ 14 m in z with a diameter of ≈ 9 m.

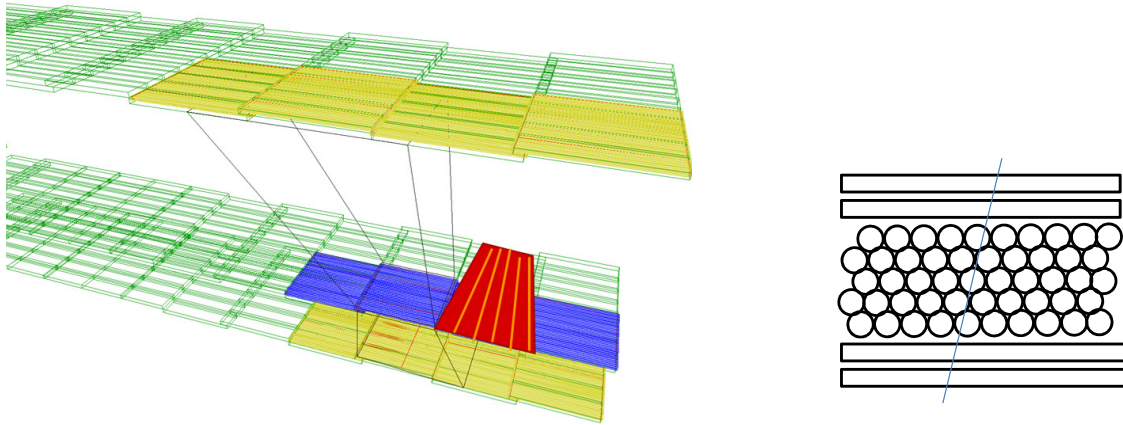


Figure 13.54: Artist 3d view of the projective arrangement of the layers barrel muon chambers (left). A schematic view of the cross section of one of the chambers which include a double layer of $\eta\phi$ trigger measurement used also for level one triggering along with the precision measurement obtained by drift tubes

13.7.2 The LHeC muon detector options

Neglecting for the moment the detector technologies to be used, depending on the experimental weight the muon detector will have within the LHeC detector, few different approaches satisfying increasing requirements can be considered.

1. Muon tagging
2. Combined muon momentum measurement
3. Standalone momentum measurement

With “muon tagging”(1) we indicate a muon detector built with at least 2 layers of muon chambers that provide $\eta\phi$ measurement and a fast coincidence for trigger purposes. No additional magnetic field would be set up and the muon detector, using only the return flux of the central solenoid would be able to provide only a very rough estimate of the particle momentum. The multiple layers and the fast detector response would allow a pointing trigger to reject non prompt particles. Muon Momentum measurements would be done using mainly the tracking detector and possibly complemented by the energy deposits in the calorimeter (that have to be compatible with those of a minimum ionizing particle) and the muon tag.

The next step (2) would be to enhance the muon momentum measurement by adding an extra magnetic field, embedding the muon chambers in an iron yoke. The amount of iron and the size of the yoke can be optimized in order maximize the resolution in the energy range required.

Both options (1) and (2) can be considered for the baseline design option A and. It is worth noticing that for low energy muons (as expected in the barrel and rear region) an instrumented yoke might not be required as the momentum resolution of the tracking system will be far superior. For muon momenta of 20 GeV and above the presence of an additional magnetic field or an instrumented iron yoke could improve especially in the forward and backward region, where the momentum resolution is worse due to the solenoidal field being parallel to the beamline.

Although the presence of an iron mass serves four good purposes, namely:

- return the magnetic flux
- serve as a hadron (π^\pm, K, p, n) particle filter so that predominantly μ^\pm emerge at a large radius

- 9566 • provide excellent mechanical support for all detector systems, especially the massive calorimeter
- 9567 • serve as a radiation shield for the area and the electronics

9568 as soon as the solenoid field and its size increase, the required shielding also increases proportionally and its
 9569 density, weight and costs pose important limitations which might be overcome by the use of a twin solenoid
 9570 system as discussed in 13.2.5.

9571 This novel approach which would guarantee a “standalone momentum measurement ” (3). The outer
 9572 solenoid allows for a very smooth and constant field in an iron free region. As shown in Fig. 13.55, the muon
 9573 detector is immersed in a strong constant field (~ 1.5 T) which would allow precise momentum measurement
 9574 of momenta up to 500 GeV with $\delta p/p \propto x$. A strong advantage of an air muon spectrometer is the significant
 9575 reduction of the uncertainty due to multiple Coulomb scattering. Additionally, the use of forward
 9576 and backward coils can improve the field quality also in the endcap regions allowing the field to line up
 9577 transversely to the beam line, for an improved longitudinal momentum measurement.

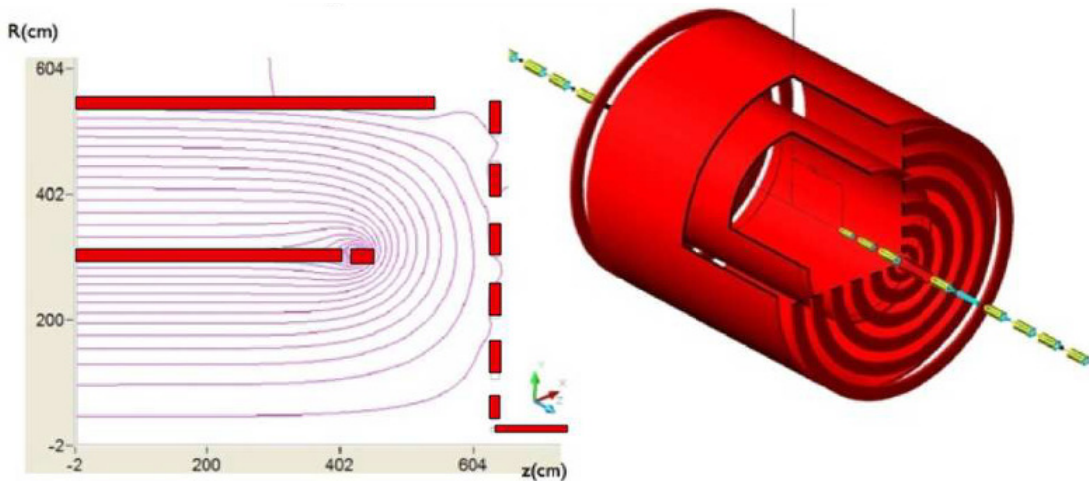


Figure 13.55: Magnetic field lines for the dual solenoid and wall of coil [817]. The whole detector is enclosed in a second return solenoid; forward and rear coils which allow for a smooth field at the detector muon encaps

9578 13.7.3 Forward Muon Extensions

9579 Detection of muons in the forward hemisphere is extremely relevant at the LHeC where the kinematics of
 9580 important physical phenomena (production of heavy flavours, high x physics, leptoquarks etc.) requires a
 9581 coverage down to the smallest possible angle with respect to the beam axis. Since the tracking momentum
 9582 resolution deteriorates at small angles an independent measurement in the forward region would provide a
 9583 completely independent tool for the measurement of the muon momentum.

9584 Given the high particle, and specifically, muons flux expected in the forward region, the use of a dedicated
 9585 forward muon toroid would allow the measurement of muon charge and momentum. In Fig.13.56 a sketch of a
 9586 possible design for a “small” forward muon toroid is given. For the baseline detector A, a more conventional,
 9587 iron based solution (as in HERA for H1 and ZEUS) could be adopted incorporated or located outside of the
 9588 the muon iron-yoke. The option of an air core forward toroid combined, either with the option A detector
 9589 inside the iron yoke system or in the larger twin solenoid option B would even more enhance the forward
 9590 muon momentum resolution especially for very small angles with respect to the beam line.

9591 The insertion of a forward air core based toroid closer to the central tracking system was also consid-
9592 ered and rejected as the bulk material of the required coils, located between the tracking planes and the
9593 calorimeters would compromise the calorimetry measurements.

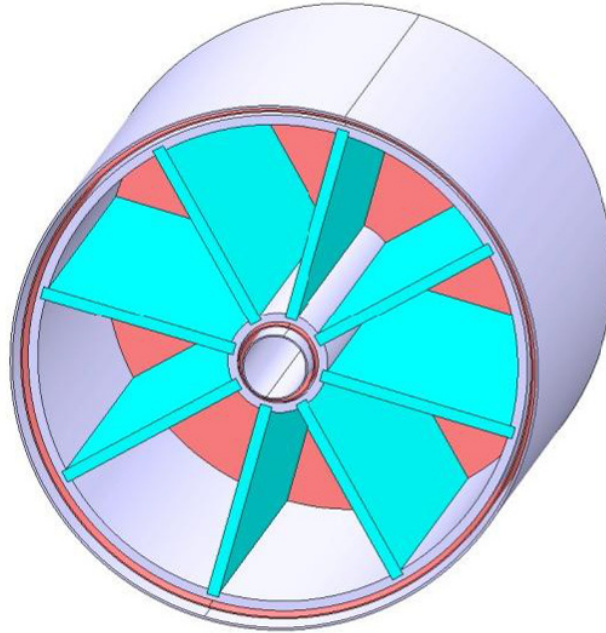


Figure 13.56: CAD drawing for a 2T air core toroid with 20 cm bore and a size about 1 m³

9594 **13.7.4 Muon Detector Summary**

9595 Several options for the LHeC muon detector are available.

9596 These range from a simple muon tagging detector which, combined with the baseline detector A would
9597 already be sufficient for a clean muon trigger, allowing to remove beam gas background and non pointing
9598 tracks. The precision of the momentum resolution would depend mostly on the main detector (tracking and
9599 calorimetry) which anyhow would degrade at small forward and backward angle.

9600 Improvements by means of a iron yoke and conventional forward muon toroids would allow improved
9601 performance especially for higher momenta and for muon spectroscopy in the forward region. The experience
9602 from HERA indicate that a solution lacking of a standalone muon trigger could be acceptable for most of
9603 the physics program.

9604 The ultimate design nevertheless appears to be the the twin solenoid option. This more challenging
9605 design, shown in Fig.13.57 naturally follows the option B of the baseline design: the larger main solenoid is
9606 located outside of the hadronic calorimeter and together with a second active shielding solenoid provides a
9607 wide material free region for precise standalone muon momentum measurement. The higher energies available
9608 in the forward region and the interesting physics channels also push for a leading edge design towards use
9609 of additional forward muon toroid. The detector acceptance for the muon channel physics could be largely
9610 extended.

9611 **13.8 Event and Detector Simulations**

9612 Minimum bias events in the LHeC Detector have been simulated using the **GEANT4** Toolkit [799]. In
9613 addition **ROOT** [818], **GDML** [819], **AIDA** [820] and **Pythia6** [130] have also been incorporated. A **ROOT**

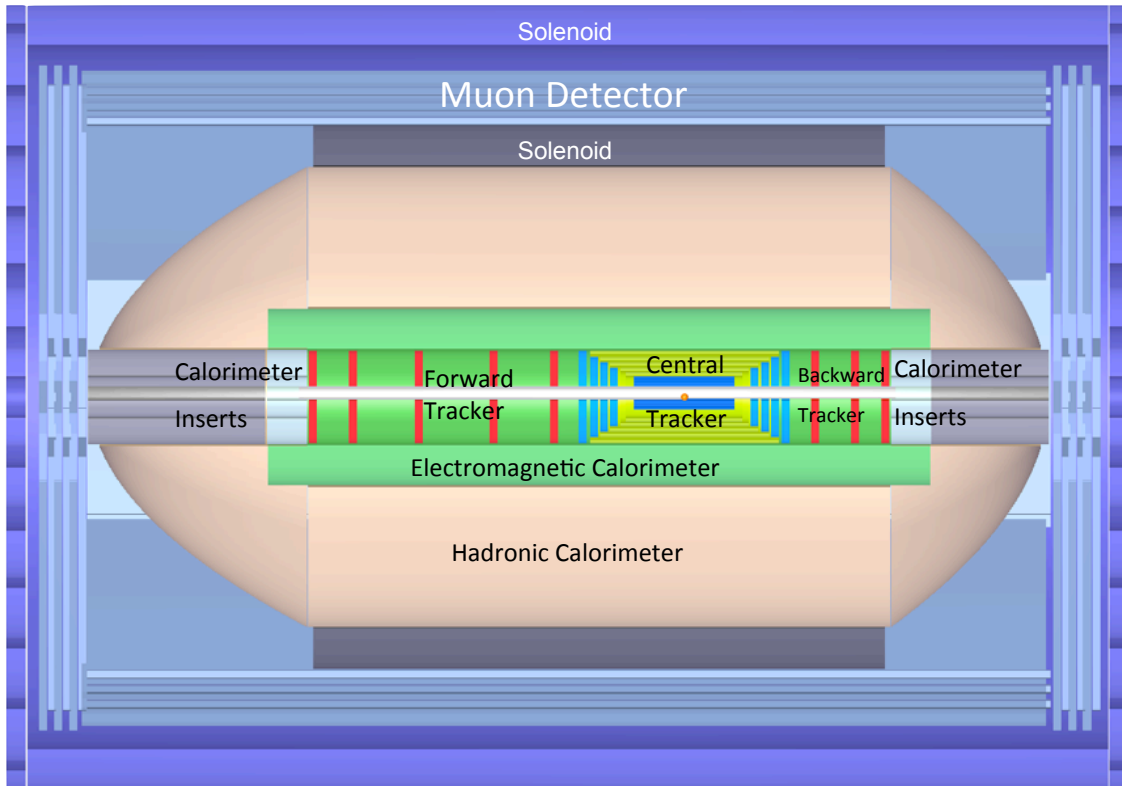


Figure 13.57: The option B of the LHeC baseline detector. The larger solenoid surrounds the hadronic calorimetry. The volume outside the solenoid is filled with an approximately uniform magnetic field of 1.5 T and is instrumented with 3 multilayers of muon chambers.

9614 macro has been written which gives a general description of the LHeC Detector geometry and materials. This
 9615 description is then transported from **ROOT** to **GEANT4** in XML format via **GDML**. A **Pythia6** program
 9616 has also been used to create minimum bias ep events. **Pythia6** outputs the events in HEPEVT format. This
 9617 is then run through a subroutine to produce a format readable by **GEANT4**. The actual simulations are
 9618 completed natively in **GEANT4** once the geometry, materials and events are loaded. The Analysis is done
 9619 with **ROOT** (and the Java Analysis Studio **JAS** [820]) which is interfaced to **GEANT4** via **AIDA**. The
 9620 flow of these simulations is outlined in Figure 13.58.

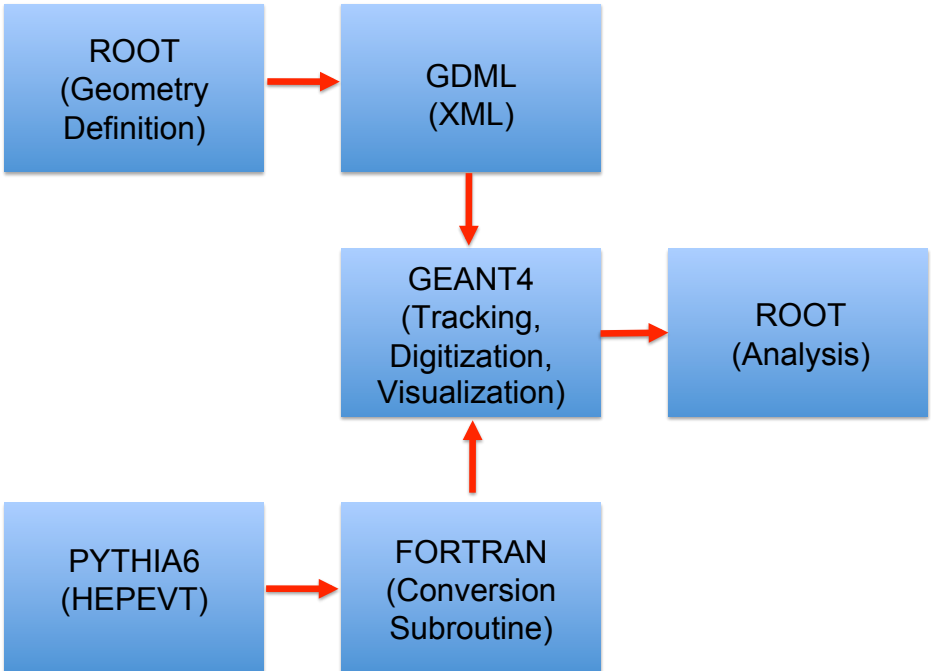


Figure 13.58: Simulation Framework Flow Chart

9621 **13.8.1 Pythia6**

9622 The **Pythia6**([130]) event used in the **GEANT4** simulations contains γ^*P interactions convoluted with the
 9623 γ/e^- flux. This setup contains non vanishing cross sections including semihard QCD, elastic scattering,
 9624 single/double diffractive among others (The listed interactions dominate σ_{tot}). In order for the events to be
 9625 minimum bias no restrictions are placed on the W or Q^2 range.

9626 Table 13.10 gives the **Pythia6** parameters used for the minimum bias events. The logarithm of the
 9627 variables W and Q^2 are given. Since these variables obey amplitudes given by $P(x) \propto \frac{1}{x^2}$ then $P(\text{Log}(x)) \propto$
 9628 e^{-x^2} showing that Log(x) produces mean and rms values following normal statistics.

9629 The tools available for ep event generation are not current. The frontier of high energy physics is focused
 9630 on hadron collisions due to the LHC. The numerous problems present in a new energy scale require developers
 9631 to focus in this area. This results in a lack of development of event generation tools for a new energy scale of
 9632 ep collisions. This is the reason we are using **Pythia6** as opposed to its C++ successor. Although it works
 9633 fine for an approximation it would be advantageous to have development here.

9634 The parameters used to scale the results of the simulation in order to find annual quantities are given in
 9635 Table 13.11.

Characteristic	Value
$Log(W)_{mean}$ [GeV]	2.09
$Log(W)_{rms}$ [GeV]	0.55
$Log(Q^2)_{mean}$ [GeV^2]	-4.98
$Log(Q^2)_{rms}$ [GeV^2]	3.15
Electron Energy [GeV]	60
Proton Energy [GeV]	7000

Table 13.10: Pythia6 Parameters

Characteristic	Value
Total Cross Section [mb]	0.0686
Luminosity [$mb^{-1}s^{-1}$]	10^6
$\frac{dN}{dt}$ [int/yr]	2.57×10^{12}

Table 13.11: Scaling Parameters

13.8.2 1 MeV Neutron Equivalent

In order to find the 1 MeV Neutron Equivalent one must find the appropriate displacement damage functions [D(E)] for the particles. By scaling the damage functions by the reciprocal of D(n, 1 MeV) one arrives at a weight which will turn a fluence of random particles into the 1 MeV Neutron Equivalent fluence. D(E) is not only dependent on particle type but also on the material in which the particles are traversing. The D(E) functions used in the simulations can be found in Figure 13.59 [821].

In order to find the 1 MeV Neutron Equivalent fluence through the tracking portion of the detector scoring was incorporated into the **GEANT4** simulations. A user defined scorer was used that would calculate the number of hits on the surface of a detector component, weight the hits according to the appropriate damage functions and finally divide the sum of these weighted hits by the inner surface area of the detector component. The flux was then scaled by the number of events per year using the mentioned scaling parameters given in Table 13.11. The total 1 MeV Neutron Equivalent fluences are given in Table 13.12.

A different approach was used in order to find the 1 MeV Neutron Equivalent fluence distribution in R_{polar} and Z . In order to retain data generated on the event level instead of the run level a set up of Sensitive Detectors [SD] must be initialized that will measure user defined quantities for traversing particles. The entire tracking region was set as one SD, with each hit containing the position information, and the current $D(E)$ value of the given track. A 2D histogram is generated for the variables R_{polar} and Z . The intensity (each hit weighted by its $D(E)$ value) is then scaled by the number of events in the run, the number of events per year, and a fluence weighting function. This function divides the number of entries in each bin by the average surface area the bin represents (i.e. $2\pi R_{mean}\Delta Z$ where R_{mean} is the mean R value which the bin spans and ΔZ is the width of the Z bins). By this weighting process the resulting 2D histogram (Figure 13.60) displays the 1 MeV Neutron Equivalent Fluence in $\frac{cm^{-2}}{year}$.

13.8.3 Nearest Neighbor

The **Geant4** simulations were also used to find the resolution required in the forward tracking. Firstly, the flux through the surface of CFT1, CFT4, FST1, and FST5 was found. A minimization algorithm is then used to find the nearest neighboring hit at the $Z = constant$ surface for each hit. This distance scale is characteristic of the resolution required for the tracking component in question. The nearest neighboring hit distribution is calculated on the event level. This implies that only the hits from the same event are compared. This will have to be studied further to take pileup into account, however information on the event

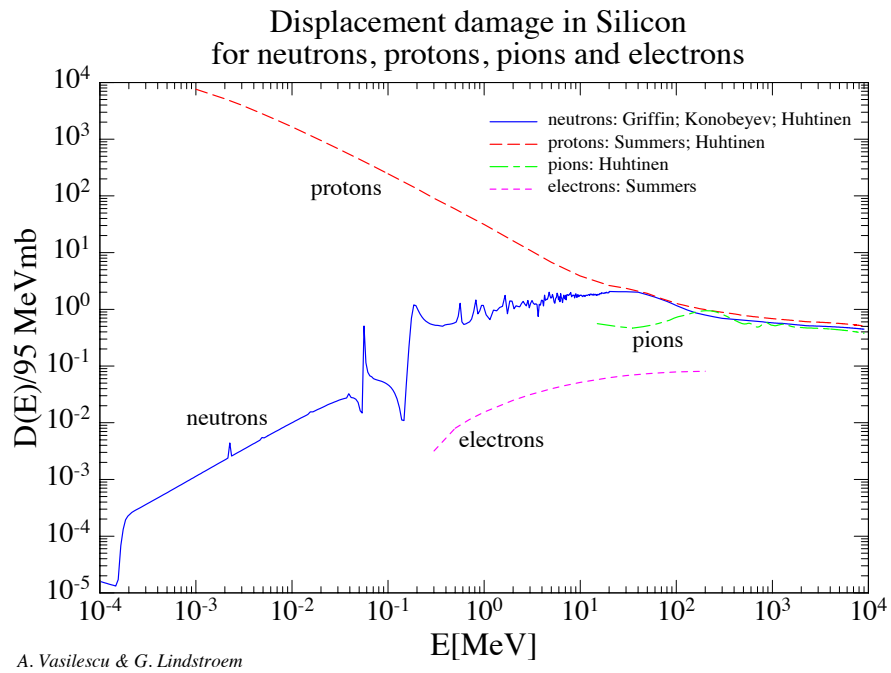


Figure 13.59: Displacement Damage for various particles in Silicon

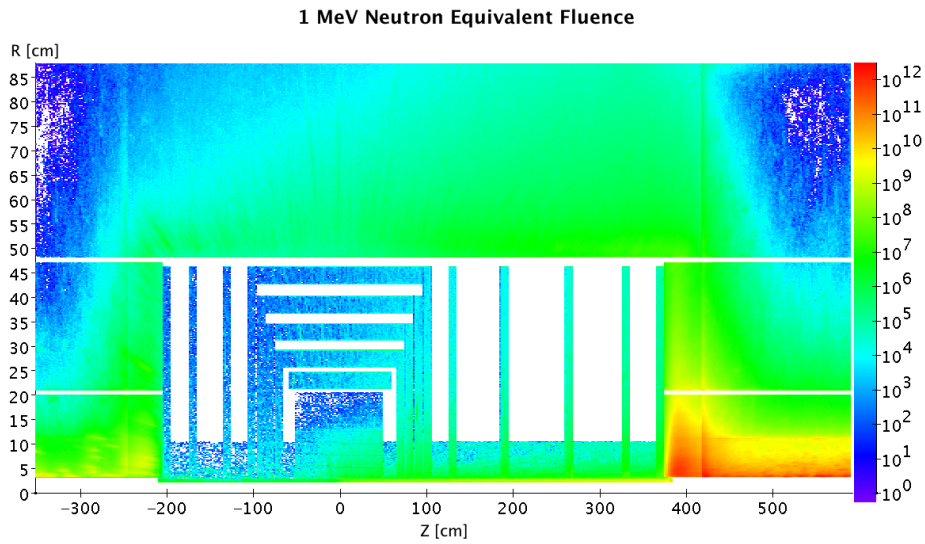


Figure 13.60: 1 MeV Neutron Equivalent Fluence [$\text{cm}^{-2}/\text{year}^{-1}$].

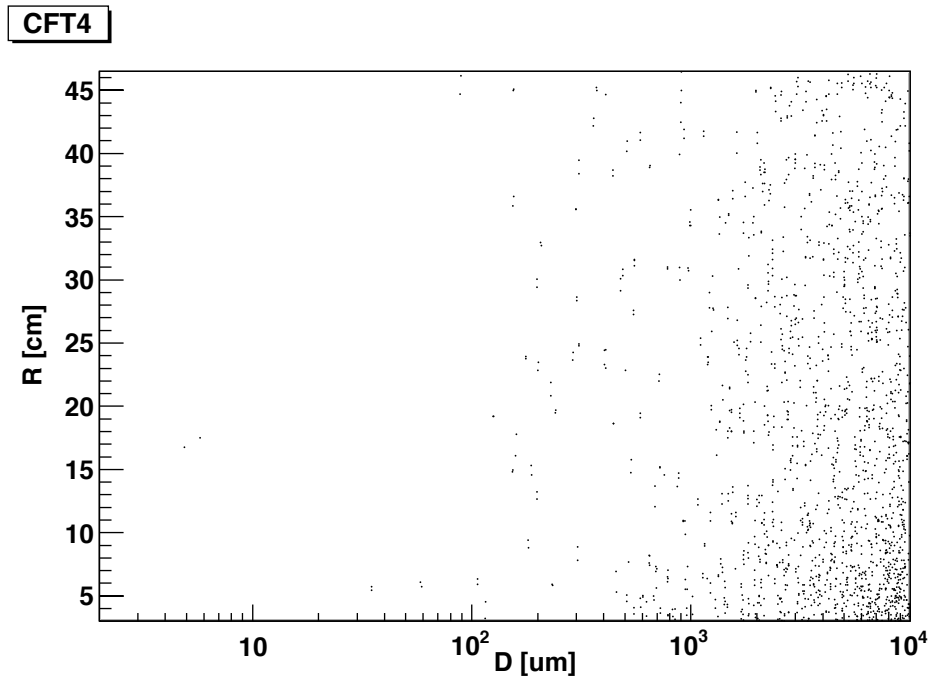


Figure 13.61: Nearest Neighbor distribution for CFT4

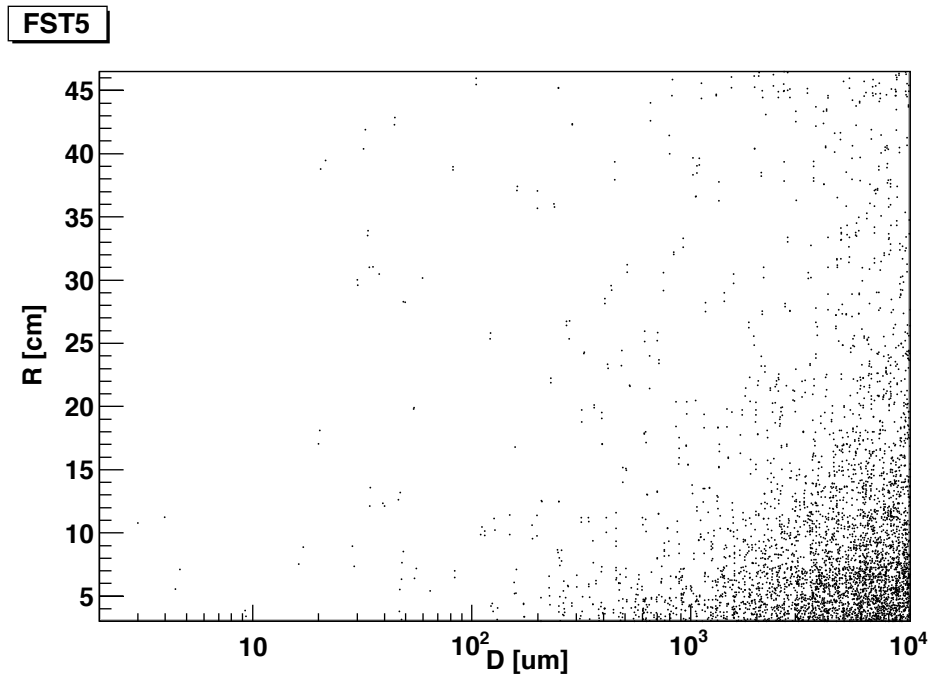


Figure 13.62: Nearest Neighbor distribution for FST5

Central Barrel			
Region	ΔZ [cm]	R_{min} [cm]	Fluence [$\frac{N}{cm^2 yr}$]
CPT1	100	3.1	1.38×10^{10}
CPT2	100	5.6	9.99×10^9
CPT3	100	8.1	8.26×10^9
CPT4	100	10.6	7.25×10^9
CST1	116	21.2	6×10^9
CST2	128	25.6	5.66×10^9
CST3	148	31.2	5.38×10^9
CST4	168	36.7	5.25×10^9
CST5	188	42.7	5.16×10^9
Central Endcaps			
Region	Z [cm]	ΔR [cm]	Fluence [$\frac{N}{cm^2 yr}$]
CFT1	70	26	8×10^9
CFT2	80	31.6	7.42×10^9
CFT3	90	37.1	7.08×10^9
CFT4	101	43.1	6.93×10^9
CBT1	-70	26	2.77×10^9
CBT2	-80	31.6	2.48×10^9
CBT3	-90	37.1	2.26×10^9
CBT4	-101	43.1	2.09×10^9
Fwd/Bwd Planes			
Region	Z [cm]	ΔR [cm]	Fluence [$\frac{N}{cm^2 yr}$]
FST1	130	43.1	8.2×10^9
FST2	190	43.1	1.14×10^{10}
FST3	265	43.1	1.63×10^{10}
FST4	330	43.1	2.29×10^{10}
FST5	370	43.1	2.75×10^{10}
BST1	-130	43.1	1.96×10^9
BST2	-170	43.1	1.91×10^9
BST3	-200	43.1	1.99×10^9

Table 13.12: 1 MeV Neutron Equivalent Fluence

9665 level is a nice approximation. The nearest neighbor distribution for CFT4 is shown in Figure 13.61 and for
9666 FST5 in Figure 13.62. The x axis contains the value of the nearest neighbor for each hit in terms of μm while
9667 the y axis contains R in terms of cm. A required resolution of 10 or less μm would require pixel detectors
9668 instead of strip detectors. The CFT4 and FST5 Figures display a very low hit density in this area. The
9669 percentage of hits with $D < 10 \mu m$ for the four tracking components in question are given in Table 13.13.

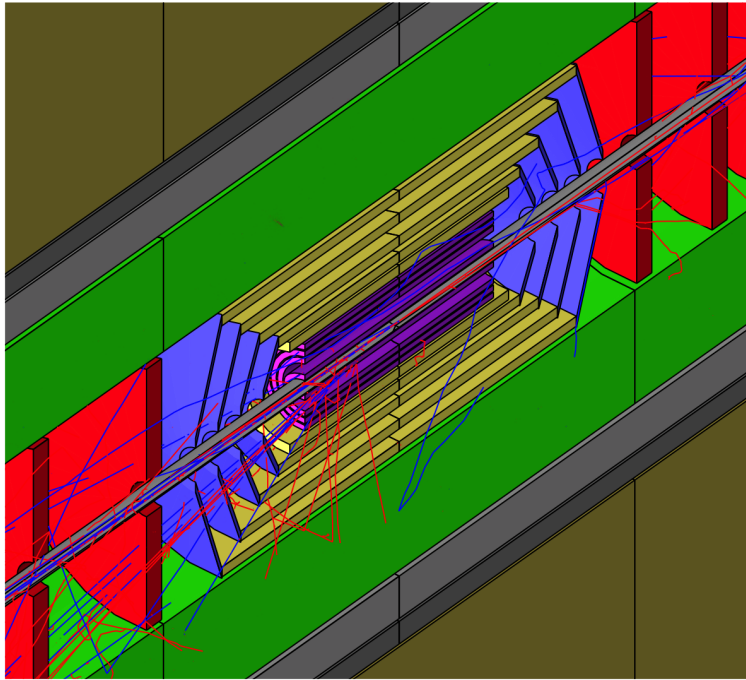


Figure 13.63: G4 Event

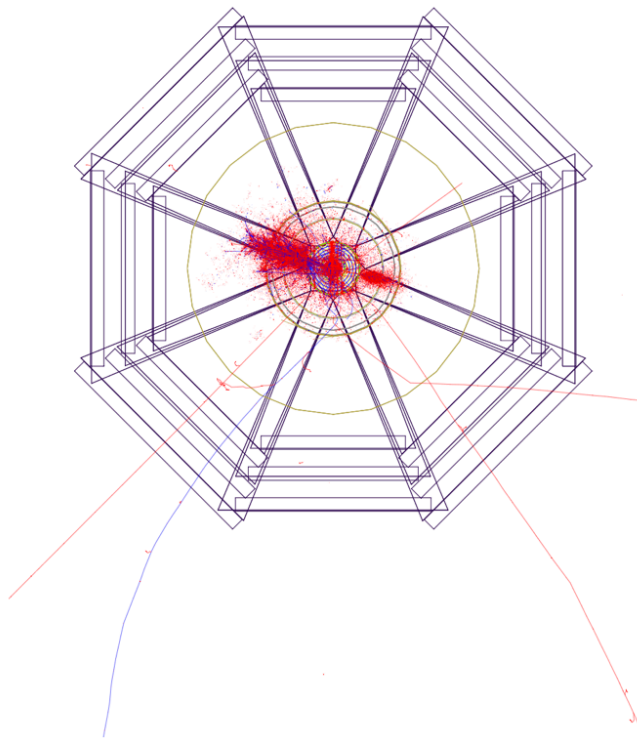


Figure 13.64: Leptoquark Event XY

Tracking Component	Hits under 10 μm [%]
CFT1	0.18
CFT4	0.23
FST1	0
FST5	0.1

Table 13.13: Nearest Neighbor under 10 μm

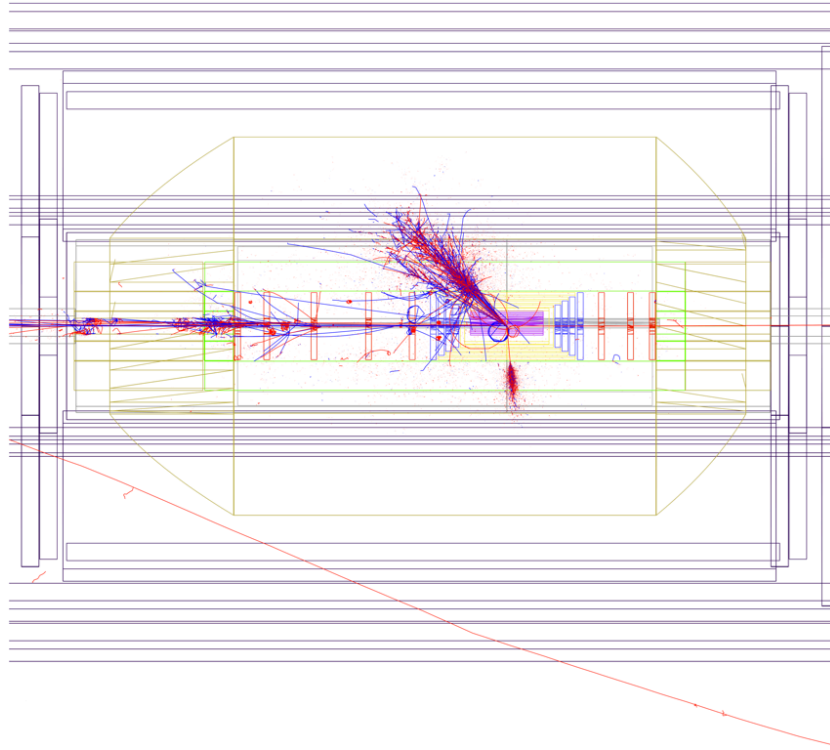


Figure 13.65: Leptoquark Event RZ

9670 13.8.4 Cross Checking

9671 DAWN was used for visualization of the detector. This was able to produce clear pictures which was one
 9672 way to make sure the translation of geometry from **ROOT** to **GEANT4** went as expected. An event in the
 9673 central tracking region is presented in Figure 13.63.

9674 In addition to the minimum bias events, **Pythia6** was also used to create some Leptoquark events. This
 9675 was one method of checking the **Pythia6** input (i.e. that the events produced describe the given kinematic
 9676 range and cross sections available). However it was also utilized to determine the detector response at various
 9677 kinematic ranges. Since $\sigma_{EM} \propto \frac{1}{Q^4}$ The minimum bias events have very low Q^2 and therefore very forward
 9678 jets, which leaves almost no activity in the barrel HCAL. By looking at some high Q^2 events it is possible
 9679 to see the response of the hadronic calorimetry in the barrel region, making sure it is showering correctly.
 9680 Some pictures of the Leptoquark events are given in Figure 13.64 and Figure 13.65.

9681 13.8.5 Future Goals

9682 There are many goals still to be accomplished by the LHeC Detector Simulations. The set up needs to be
9683 modified to include a detailed calorimeter description. Currently e.g. the forward/backward calorimeter
9684 volumes contain a mixture of FR4, Kapton, Active and Passive material which is weighted according to a
9685 realistic set up. This design must be replaced with a realistic setup of the calorimeters. This also needs
9686 to be done for the tracking which is currently composed of single silicon pieces instead of smaller modules.
9687 The majority of the work in making these changes comes from the required read out geometry and sensitive
9688 detector set up that would be required for analysis of a complicated geometrical structure. This also might
9689 require a restructuring of the simulation package. Since the detector description was done first in **ROOT**,
9690 **GDML** was an option to allow utilizing **GEANT4** without recoding the geometry. However if the geometry
9691 will significantly change then this might benefit from being done natively in **GEANT4**. Of course the
9692 Geometry needs to be iterated until it actually describes the exact detector (service pipes, read out, etc...).
9693 However this will come with the TDR.

9694 Finally the stability of the simulations needs to be assessed. Eventually a complex multifunctional
9695 detector simulation package needs to be produced. This is best done by wrapping numerous simulation
9696 toolkits into a single package utilizing **ROOT**, such as **AliROOT** [822], [823], [824] or **ILCROOT** [825].
9697 The LHeC simulations at some point need to make a shift towards creating a package like this, in order to
9698 promote greater functionality and greater accessibility.

Chapter 14

Forward and Backward Detectors

In this chapter forward and backwards detector are presented. These detector are located from few tens of meters from the interaction point up to several hundreds in order to provide specific information not accessible to the main detector. Main focus are the measurements of

- the instantaneous luminosity (Section 14.1)
- the electron or positron beam polarization (Section 14.2)
- very forward diffractive nucleons (Section 14.3,14.4)

The placement of dedicated taggers both forward and backwards along the beampipe, as discussed in Section 14.1 will provide also additional means to trigger and select data for specific analyses.

14.1 Luminosity Measurement and Electron Tagging

Luminosity measurement is an important issue for any collider experiment. At the LHeC, where precision measurements constitute a significant part of the physics programme, the design requirement is $\delta\mathcal{L} = 1\%$.

In addition to an accurate determination of integrated luminosity, \mathcal{L} , for the normalisation of physics cross sections, the luminosity system should allow for fast beam monitoring with a typical statistical precision of 1%/sec for tuning and optimisation of ep -collisions and to provide good control of the mid-term variations of instantaneous luminosity, L .

Rich experience gained by H1 [826,827] and ZEUS [828,829] Collaborations at HERA was used in the design studies of the luminosity system for the LHeC. In particular, one important lesson to be learnt from HERA is to prepare several alternative methods for luminosity determination.

For the LHeC we consider both Linac-Ring (LR) and Ring-Ring (RR) options as well as high Q^2 ($10^\circ - 170^\circ$ acceptance) and low Q^2 ($1^\circ - 179^\circ$ acceptance) detector setups. This spans over a wide range of instantaneous luminosity¹ $L = (10^{32} - 2 \cdot 10^{33})\text{cm}^{-2}\text{s}^{-1}$. Hence suitable processes for the three tasks outlined above should have the following minimal visible cross sections²:

- fast monitoring ($\delta\mathcal{L} = 1\%/sec \Rightarrow 10\text{ kHz}$) - $\sigma_{\text{vis}} \gtrsim 100\mu\text{b}$,
- mid-term control ($\delta\mathcal{L} = 0.5\%/hour \Rightarrow 10\text{ Hz}$) - $\sigma_{\text{vis}} \gtrsim 100\text{nb}$,
- physics sample normalisation ($\delta\mathcal{L} = 0.5\%/week \Rightarrow 0.1\text{ Hz}$) - $\sigma_{\text{vis}} \gtrsim 1\text{nb}$.

¹This also takes into account exponential reduction of L during the data taking in every luminosity fill.

²Statistical error has to be small in comparison with total error δL_{tot} in order not to spoil overall accuracy.

9726 The best candidate for luminosity determination is the purely electromagnetic *bremstrahlung reaction* $ep \rightarrow$
 9727 $e\gamma + p$ shown in Figure 14.1a, which has a large and precisely known cross section. Depending on the photon
 9728 emission angle it is called either Bethe-Heitler process (collinear emission) or QED Compton scattering (wide
 9729 angle bremsstrahlung). In addition, Neutral Current DIS events in a well understood (x, Q^2) range can be
 9730 used for the *relative* normalisation and mid-term yield control.

9731 While QED Compton and NC DIS processes can be measured in the main detector dedicated ‘tunnel
 9732 detectors’ are required to register Bethe-Heitler events. For the latter, additional challenges as compared
 9733 to HERA are related to the LHeC specifics: non-zero beam crossing angle in IP for RR option, and severe
 9734 aperture limitation for LR option. Finally, for the high luminosity LHeC running one should not forget
 9735 about significant pileup (L/bunch is $\sim 2 - 3$ times bigger as compared to HERA-II running).

9736 14.1.1 Options

9737 The huge rate of ‘zero angle’ electrons and photons from Bethe-Heitler reaction³ makes a dedicated luminosity
 9738 system in the tunnel ideal for fast monitoring purposes. However, it is usually very sensitive to the details
 9739 of the beam optics at the IP, may suffer from synchrotron radiation (SR) and requires, for accurate absolute
 9740 normalisation, a large and precisely known geometrical acceptance which is often difficult to ensure. On
 9741 the contrary, the main detector has stable and well known acceptance and is safely shielded against SR.
 9742 Therefore, although QED Compton events in the detector acceptance have significantly smaller rates they
 9743 may be better suited for overall global normalisation of the physics samples. Thus the two methods are
 9744 complementary, having very different systematics and providing useful redundancy and cross check for the
 9745 luminosity determination.

9746 To evaluate the main LHeC detector acceptance for NC DIS events and for the elastic QED Compton
 9747 process DJANGO [830] and COMPTON [831] event generators were used respectively. Different options for
 9748 dedicated luminosity detectors in the LHC tunnel have been studied with help of the special H1LUMI program
 9749 package [832], which contains Monte Carlo generation of the ‘collinear’ photons and electrons from various
 9750 processes (Bethe-Heitler reaction, quasi-real photoproduction, e-beam scattering on the rest gas) as well as
 9751 a simple tracking through the beamline.⁴

9752 14.1.2 Use of the Main LHeC Detector

9753 To estimate visible cross sections for NC DIS and elastic QED Compton events a typical HERA analysis
 9754 strategy was used. That is: safe fiducial cuts against energy leakage over the backward calorimeter boundaries
 9755 at small radii, safe (Q^2, y) cuts for NC DIS events to restrict measurement to the phase space where F_2 is
 9756 known to good precision of $1 - 2\%$ and the F_L contribution is negligible, and elasticity cuts for QEDC events
 9757 to reject the less precisely known inelastic contribution. In addition basic cuts against major backgrounds
 9758 were applied (photoproduction in case of NC DIS and DVCS, elastic VM production and low mass diffraction
 9759 in case of QED Compton).

9760 The visible NC DIS cross section, $\sigma_{\text{vis}}^{\text{DIS}}(Q^2 > 10\text{GeV}^2, 0.05 < y < 0.6) \simeq 10$ nb for 10° setup and $\simeq 150$
 9761 nb for 1° setup. This corresponds to a $10 - 15$ Hz rate which is comfortable enough for mid-term yield
 9762 control.

9763 For elastic QED Compton events, the visible cross section, $\sigma_{\text{vis}}^{\text{QEDC}} \simeq 0.03$ nb for 10° setup and $\simeq 3.5$ nb
 9764 for 1° setup. Hence while for the latter sufficiently high rate is possible even for $L = 10^{32}\text{cm}^{-2}\text{s}^{-1}$, in case
 9765 of ‘high Q^2 ’ setup the QEDC event rate is $4 - 5$ times smaller, thus only providing acceptable statistical
 9766 precision for large samples, of the order 0.5% /month.

9767 In order to improve this a special small dedicated calorimeter could eventually be added after the strong
 9768 focusing quadrupole, at $z = -6\text{m}$. Such ‘QEDC tagger’ should consist of two movable stations approaching
 9769 the beam-pipe from the top and the bottom in the vertical direction, as sketched in Figure 14.1b. This way
 9770 detector sections will be safe with respect to SR fan confined in the median plane. The visible elastic QED

³Total cross section, $\sigma_{BH} \simeq 870$ mb for 60×7000 GeV² ep collisions at the LHeC.

⁴The tracking has been performed by interfacing H1LUMI to GEANT3 [833] having LHeC beamline implemented up to $\sim 110\text{m}$ from the IP.

9771 Compton cross section for such a device is 4.3 ± 0.2 nb which significantly improves statistics for the luminosity
9772 measurement. The angular acceptance of the ‘QEDC tagger’ corresponds to the range $\theta = 0.5^\circ - 1^\circ$ which
9773 lies outside the tracking acceptance. Therefore calorimeter sections should be supplemented by small silicon
9774 detectors in order to make it possible to reconstruct the event vertex from the final state containing only
9775 one electron and one photon. These silicon trackers are also useful for e/γ separation and rejection of the
9776 potential background. Actual dimensions and parameters of this optional ‘QEDC tagger’ requires extra
9777 design studies.

9778 14.1.3 Dedicated Luminosity Detectors in the tunnel

9779 In case of the RR-option which implies non-zero crossing angle for early e/p beam separation, the dominant
9780 part of the Bethe-Heitler photons will end up at $z \simeq -22$ m, between electron and proton beam-pipes (see
9781 Figure 14.1c). This is the hottest place where also a powerful SR flux must be absorbed. On the first glance
9782 this makes luminosity monitoring based upon the bremsstrahlung photons impossible.

9783 There is however an interesting possibility. SR absorber needs good cooling system. The most natural
9784 cooling utilises circulating water. This cooling water can be used at the same time as an active media for
9785 Čerenkov radiation from electromagnetic showers initiated by the energetic Bethe-Heitler photons. The idea
9786 is based on two facts:

- 9787 1. The dominant part of the SR spectrum lies below the Čerenkov threshold for water, $E_{\text{thr}} = 260$ keV,
9788 and hence will not produce light signal. Low intensity tail of the energetic synchrotron photons can be
9789 further suppressed by few radiation lengths of the absorber material in front of the water volume.
- 9790 2. Water is absolutely radiation resistant media and hence such simple Čerenkov counter can stand any
9791 dose without performance deterioration.

9792 The Čerenkov light can be collected and read out by two photo-multipliers as sketched on Figure 14.1d.
9793 The geometric acceptance depends on the details of the e -beam optics. For the actual RR design with the
9794 crossing angle ~ 1 mrad the acceptance to the Bethe-Heitler photons is up to 90%, thus allowing fast and
9795 reliable luminosity monitoring with 3 – 5% systematic uncertainty.

9796 Of course, such an active SR absorber is not a calorimeter with good energy resolution, but just a simple
9797 counter. It is worth noting, that similar water Čerenkov detector has been successfully used in the H1
9798 Luminosity System during HERA-I operation.

9799 In case of LR-option, electrons collide with protons head-on, with zero crossing angle. This makes
9800 the situation very similar to HERA, where Bethe-Heitler photons travel along the proton beam direction
9801 and can be caught at around $z = -120$ m, after the first proton bending dipole. Essential difference is
9802 that unlike HERA, LHC protons are deflected horizontally at this place rather than vertically. Thus the
9803 luminosity detector should be placed in the median plane next to the interacting proton beam, p_1 , as shown
9804 on Figure 14.1e. In this case energy measurement with good resolution is not a problem, so major uncertainty
9805 will come from the knowledge of the limited geometric acceptance. This limitation is defined by the proton
9806 beam-line aperture, in particular by the aperture of the quadrupoles Q1-Q3 of the low-beta proton triplet.
9807 Moreover, it might be necessary to split D1 dipole into two parts in order to provide escape path for the
9808 photons with sufficient aperture. First estimates show that the geometric acceptance of the Photon Detector
9809 up to 95% is possible at the nominal beam conditions. HERA experience tells, that the uncertainty can be
9810 estimated as $\delta A = 0.1 \cdot (1 - A)$ leading to the total luminosity error of $\delta L = 1\%$ in this case.

9811 14.1.4 Small angle Electron Tagger

9812 The Bethe-Heitler reaction can be tagged not only by detecting a final state photon, but also by detecting the
9813 outgoing electron. Since all other competing processes have much smaller cross sections measuring inclusive
9814 rate of the scattered electrons under zero angle will provide a clean enough sample for luminosity monitoring.
9815 The remaining small background (mainly due to off-momentum electrons from e -beam scattering on the rest
9816 gas) can be precisely controlled and statistically subtracted using non-colliding (*pilot*) electron bunches.

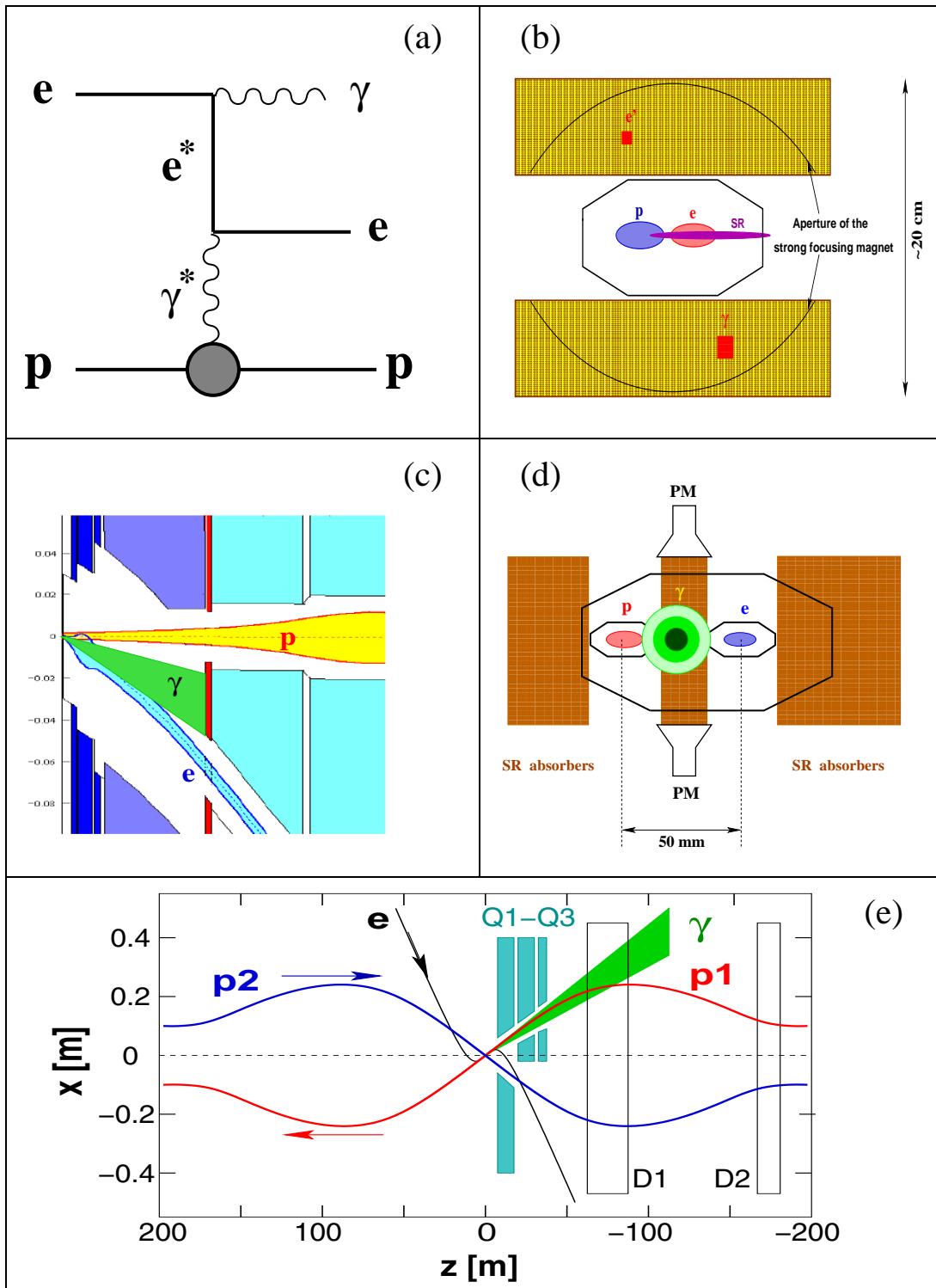


Figure 14.1: Options for the luminosity monitoring at the LHeC. (a) Feynman diagram for QEDC (γ^* pole) or BH (γ^* , e^* poles) processes; (b) QEDC tagger at $z = -6\text{m}$; (c,d) active SR absorber at $z = -22\text{m}$ for RR-option (circles show 1-, 2- and 3- σ contours for BH photons); (e) schematic view for the LR-option with $3\text{-}\sigma$ fan of BH photons.

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In order to determine the best positions for the Electron taggers the LHeC beamline simulation has been performed in the vicinity of the Interaction Region for the RR-option. Several positions for the e -tagger stations were tried:⁵ $z = -14\text{m}$, -22m and -62m . As one can see on the top part of Figure 14.2 all places provide reasonable acceptances, reaching approximately (20 – 25)% at the maximum. However, $z = -14\text{m}$ and $z = -22\text{m}$ most likely will suffer from SR flux, making e -tagger operation problematic at those positions.

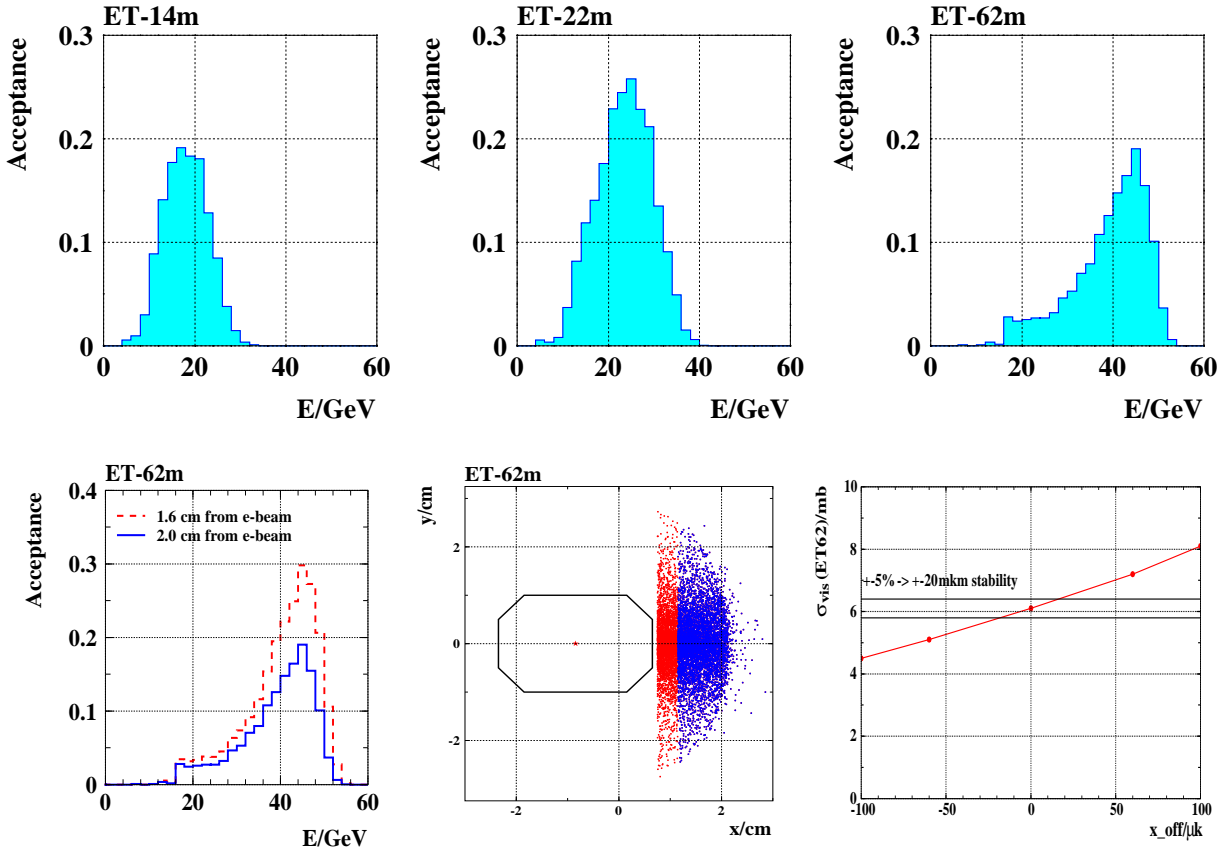


Figure 14.2: Top: acceptances of the e -taggers for Bethe-Heitler events at different z -positions from IP (RR-option). Bottom: variations in the acceptance of the e -tagger at $z = -62\text{m}$ as a function of its position with respect to the e -beam axis and on the horizontal offset of the beam orbit at the IP.

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The most promising position for the Electron tagger is at $z = -62\text{m}$. The actual acceptance strongly depends both on the distance of the sensitive detector volume from the e -beam axis and on the details of the electron optics at the IP, such as beam tilt or small trajectory offset, as illustrated on the bottom part of Figure 14.2. Therefore a precise independent monitoring of beam optics and accurate position measurement of the e -tagger are required in order to control geometrical acceptance to a sufficient precision. For example, instability in the horizontal trajectory offset at IP, x_{off} , of $\pm 20\mu\text{m}$ leads to the systematic uncertainty of 5% in the visible cross section, $\sigma_{\text{vis}}(ET62)$.

It is fair to note, that the magnetic field of the main LHeC detector was not taken into account in the simulation. The influence of this field is expected to be very small and will not alter basic conclusions of this section. Also, for the LR-option a similar acceptance is expected, although it may differ in shape somewhat.

⁵For the station at $z = -14\text{m}$ the electron dipole magnet should be split into two parts, while the region around $z = -62\text{m}$ has sufficiently comfortable place for the Electron tagger, before the e -beam is bended vertically.

9832 In order to demonstrate that the ideas described in Sec. 14.1.3 and 14.1.4 are realistic a typical example
 9833 of the online rates variations for the H1 Luminosity System at HERA is shown on Figure 14.3. The system
 9834 utilised all three types of the detectors discussed above: a total absorption electromagnetic calorimeter for
 9835 the Bethe-Heitler photons (PD), a water Čerenkov counter (VC) and the Electron tagger (ET6). One can
 9836 see, that online luminosity estimate by every of those detectors is well within 5% in spite of significant
 9837 changes in the acceptance due to electron beam tilt jumps and adjustments at the IP.

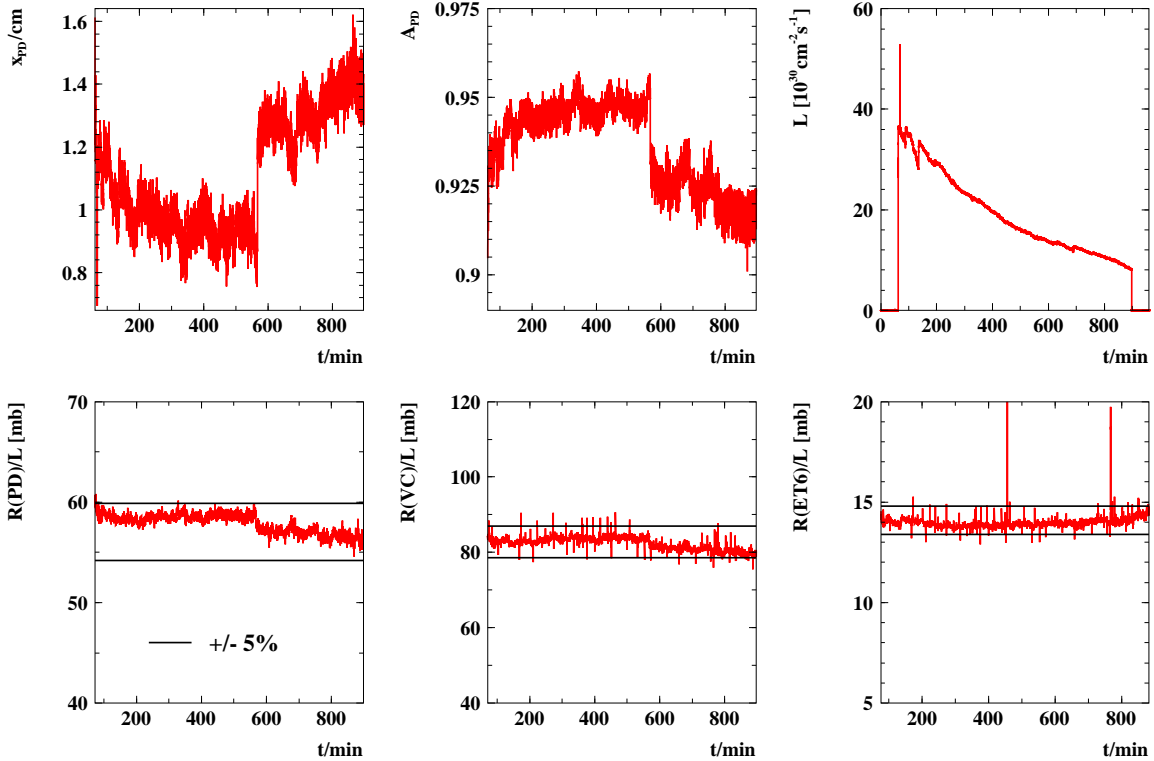


Figure 14.3: Online H1 Lumi System acceptance and rates variations in a typical HERA luminosity fill.

9838 14.1.5 Summary and Open Questions

9839 Accurate luminosity measurement at the LHeC is highly non-trivial task. As follows from HERA experience
 9840 unexpected surprises are possible, hence it is important to consider several scenarios from the beginning and
 9841 to prepare alternative methods for luminosity determination.

9842 Statistical precision and systematic uncertainties for different methods of luminosity measurement are
 9843 summarised in Table 14.1.

9844 Precise determination of integrated luminosity, \mathcal{L} , is possible with the main detector utilising the QEDC
 9845 process. $\delta\mathcal{L} = 1.5 - 2\%$ is within reach. Further improvement requires in particular more accurate theoretical
 9846 calculation of the elastic QED Compton cross section, with $\delta\sigma_{\text{el}}^{\text{QEDC}} \lesssim 0.5\%$. To enhance statistical precision
 9847 a dedicated QEDC tagger at $z = -6\text{m}$ might be useful. This device could also be used to access very low
 9848 Q^2 region, interpolating between DIS and photoproduction regimes.

9849 Fast instantaneous luminosity monitoring is challenging, but several options do exist which are based
 9850 upon detection of the photons and/or electrons from the Bethe-Heitler process.

Method	Stat. error	Syst.error	Systematic error components		Application
BH (γ)	0.05%/sec	1–5%	$\sigma(E \gtrsim 10\text{GeV})$ acceptance, A E -scale, pileup	0.5% 10%(1– A) 0.5 – 4%	Monitoring, tuning, short term variations
BH (e)	0.2%/sec	3–6%	$\sigma(E \gtrsim 10\text{GeV})$ acceptance background E -scale	0.5% 2.5 – 5% 1% 1%	Monitoring, tuning, short term variations
QEDC	0.5%/week	1.5%	σ (el/inel) acceptance vertex eff. E -scale	1% 1% 0.5% 0.3%	Absolute \mathcal{L} , global normalisation
NC DIS	0.5%/h	2.5%	σ ($y < 0.6$) acceptance vertex eff. E -scale	2% 1% 1% 0.3%	Relative \mathcal{L} , mid-term variations

Table 14.1: Dominant systematics for various methods of luminosity measurement.

- 9851 • Photon Detector at $z = 110\text{m}$ for LR option requires properly shaped proton beam-pipe at $z =$
9852 $-68 - 120\text{m}$ from IP2.
 - 9853 • In case of RR option Bethe-Heitler photons can be detected using a water Čerenkov counter integrated
9854 with SR absorber at $z = -22\text{m}$.
 - 9855 • Electron tagger at $z = -62\text{m}$ is very promising for both LR and RR schemes. It can be used not only
9856 for luminosity monitoring, but also to enhance photoproduction physics capabilities and to provide
9857 extra control of the γp background to DIS, by tagging quasi-real photoproduction events.
- 9858 Good monitoring of the e -optics at the IP is required to control acceptances of the tunnel detectors to a
9859 level of 2 – 5%.

9860 14.2 Polarimeter

The most powerful technique to measure the polarisation of the electrons and positrons of LHeC is Compton polarimetry. At high electron beam energies, this technique has been successfully used in the past at SLC [834] and at HERA [835] for example. The experimental setup consists of a laser beam which provides the electron/positron beam, and a calorimeter to measure the scattered gamma ray. At SLC, the scattered electron was also measured in a dedicated spectrometer. From the kinematics of Compton scattering one can get the expression for the maximum scattered photon energy:

$$E_{\gamma,max} \approx E_0 \frac{x}{1+x}$$

and the minimum scattered electron energy

$$E_{e,min} \approx E_0 \frac{1}{1+x},$$

9861 where E_0 is the electron/positron beam energy and $x = 4kE_0/m_e^2$ with k being the laser photon beam
9862 energy. At LHeC and for a $\approx 1\mu\text{m}$ laser beam wavelength, one gets $E_{\gamma,max} \approx 29\text{GeV}$ and $E_{e,min} \approx 31\text{GeV}$.

9863 Providing that the laser beam is circularly polarised, the electron/positron beam longitudinal polarisation is
9864 obtained from a fit to the scattered photon and/or to the electron energy spectrum. From an experimental
9865 point of view, both measurements can be complementary since the high energy region of the scattered
9866 photon energy spectrum is sensitive to the electron/positron beam longitudinal polarisation, whereas it is
9867 the opposite for the scattered electron/positron energy spectrum. Indeed, the high measurement precision of
9868 SLC was achieved thanks to the measurement of the scattered electrons. The measurement of both scattered
9869 photon and electron/positron spectra was therefore foreseen for a very high precision polarimetry at future
9870 electron-positron high energy colliders [262, 836].

9871 For LHeC, we may follow the work done for the future linear colliders [836]. In order to reach the per
9872 mille level on the longitudinal polarisation measurement, one may measure both the scattered photon and
9873 electron energy spectrum.

9874 14.2.1 Polarisation from the scattered photons

9875 The photons are scattered within a very narrow cone of half aperture $\approx 1/\gamma$. It is therefore impossible
9876 to distinguish the photons reaching the calorimeter. As for the extraction of the longitudinal polarisation
9877 from the scattered photon beam energy, one may then distinguish three dynamical regimes [837]. The
9878 single and few scattered photons regimes, where one can extract the polarisation from a first principle fit
9879 to the scattered photon energy spectrum; the multi-photon regime where the central limit theorem holds
9880 for the energy spectra and where the longitudinal polarisation is extracted from an asymmetry between the
9881 average scattered energies corresponding to a circularly left and right laser beam polarisation [838]. Both
9882 regimes have positive and negative experimental features. In the single and few photon regimes the energy
9883 spectra exhibits kinematical edges which allow an in situ calibration of the detector energy response but
9884 the physical accelerator photon background which is difficult to model precisely, e.g. synchrotron radiation,
9885 limits the final precision on the polarisation measurement [837]. In the multi-photon regime, the background
9886 is negligible since it is located at low energy but one cannot measure the energy calibration of the detector
9887 in situ and one must rely on some high energy extrapolation of calibrations obtained at low energy [838]
9888 (e.g. for 100 scattered photon/bunch the deposited energy in the calorimeter would be more than 1TeV at
9889 LHeC). However, the laser technology has improved in the last ten years and one can consider at present
9890 a very stable pulsed laser beam with adjustable pulse energy allowing to operate in single, few and multi
9891 photon regimes. In this way, one can calibrate the calorimeter in situ and optimise the dynamical regime, a
9892 multi-photon regime as close as possible to the few photon regime, in order to minimise the final uncertainty
9893 on the polarisation measurement.

9894 14.2.2 Polarisation from the scattered electrons

9895 The nice feature of the scattered electron/positron is that one can use a magnetic spectrometer to distinguish
9896 them from each other. Following [836] one may carefully design a Compton interaction region in order to
9897 implement a dedicated electron spectrometer followed by a segmented electron detector in order to measure
9898 the scattered electron angular spectrum, itself related to the electron energy spectrum. A precise particle
9899 tracking is needed but this experimental method also allows a precise control of the systematic uncertainties
9900 [834].

9901 Common to both techniques is the control and measurement of the laser beam polarisation. it was shown
9902 in [839] that a few per mille precision can be achieved in an accelerator environment. Therefore, with a
9903 redundancy in measuring the electron/positron beam longitudinal polarisation from both the electron and
9904 photon scattered energy spectra, a final precision at the per mille level will be reachable at LHeC.

9905 14.3 Zero Degree Calorimeter

9906 The goal of Zero Degree Calorimeter (ZDC) is to measure the energy and angles of very forward particles. At
9907 HERA experiments, H1 and ZEUS, the forward neutral particles scattered at polar angles below 0.75 mrad

9908 have been measured in the dedicated Forward Neutron Calorimeters (FNC) [498,840]. The LHC experiments,
9909 CMS, ATLAS, ALICE and LHCf, have the ZDC calorimeters for detection of forward neutral particles,
9910 ALICE has also the ZDC calorimeter for the measurements of spectator protons [841–845].

9911 The ZDC calorimeter will be an important addition to the future LHeC experiment as many physics
9912 measurements in ep , ed and eA collisions can be made possible with the installation of ZDC.

9913 14.3.1 ZDC detector design

9914 The position of the Zero Degree Calorimeter in the tunnel and the overall dimensions depend mainly on the
9915 space available for the installation. At the LHC the beams are deflected by two separating dipoles. These
9916 dipoles also deflect the spectator protons, separating them from the neutrons and photons, which scatter at
9917 $\sim 0^\circ$.

9918 The ZDC detector will be made of two calorimeters: one for the measurement of neutral particles at 0°
9919 and another one positioned externally to the outgoing proton beam for the measurement of spectator protons
9920 from eD and eA scattering. The geometry, technical specifications and proposed design of ZDC detectors
9921 are to large extent similar to the ZDCs of the LHC experiments. There the ZDC calorimeter for detection
9922 of neutral particles are placed at $z = 115 - 140$ m in a 90 mm narrow space between two beam pipes. (The
9923 photo of neutron calorimeter of ALICE experiment [841, 842] is shown in Figure 14.4). In the case of the
9924 LHeC, the ZDC calorimeter can be placed in the space available at about 90 – 100 m next to the interacting
9925 proton beam pipe, as indicated in Figure 14.5.

9926 Below the general considerations for the design are presented. In order to finalise the study of the
9927 geometry of detectors, a detailed simulation of the LHeC interaction region and the beamline must be
9928 performed.

9929 14.3.2 Neutron Calorimeter

9930 The design of ZDC has to satisfy various technical issues. Detector has to be capable of detecting neutrons
9931 and photons produced with scattering angles up to 0.3 mrad or more and energies between some hundreds
9932 GeV to the proton beam energy (7 TeV) with a reasonable resolution of few percents. It should be able
9933 to distinguish hadronic and electromagnetic showers (i.e. separate neutrons from photons) and to separate
9934 showers from two or more particle entering the detector (i.e. needs position resolution of $\mathcal{O}(1\text{mm})$ or better).

9935 The condition, that at least 95% of hadronic shower of $\mathcal{O}(\text{TeV})$ is contained within the calorimeter,
9936 requires 9.5–10 nuclear interaction lengths of absorber. The neutron ZDC will be made of two sections.
9937 The front part of calorimeter (electromagnetic section) with $1.5\text{--}2 \lambda$ length and fine granularity is needed for
9938 precise determination of the position of impact point, discrimination of electromagnetic and hadronic showers
9939 and separation of showers from two or more particles entering the detector. The hadronic section of the ZDC
9940 can be built with coarser sampling, which gives an increase of average density and, consequently, the increase
9941 of effective nuclear interaction length. The ZDC will be operating in a very hard radiation environment,
9942 therefore it has to be made of radiation resistant materials. Since the different parts of calorimeter undergo
9943 different intensity of radiation (higher for front part), it is advantageous to have longitudinal segmentation
9944 of 4-5 identical sections, which will allow to control the change of energy response due to radiation damage.
9945 Comparison of the energy spectrum from the showers which start in different sections can be used for
9946 correction of changes in energy response.

9947 A possible solution to build a compact device with good radiation resistance is to use spaghetti calorimeter
9948 with tungsten absorbers and quartz fibres. The principle of operation is based on the detection of Cherenkov
9949 light produced by the shower's charged particles in the fibres. These detectors are proven to be fast (\sim few
9950 ns), radiation hard and have good energy resolution. Using tungsten as a passive material allows the
9951 construction of compact devices. One can also consider option to use thick gaseous electron multipliers
9952 (THGEM) [846, 847] as active media.

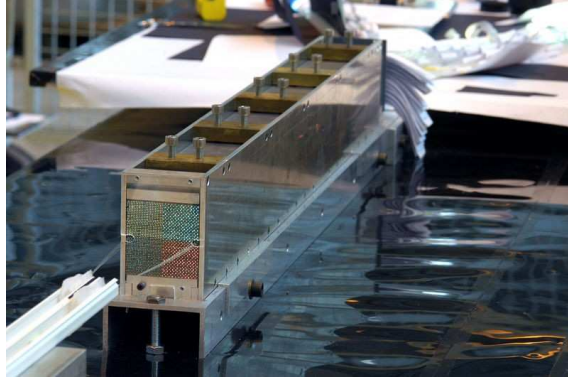


Figure 14.4: Photo of the Zero Degree Neutron Calorimeter (ZN) of ALICE experiment.

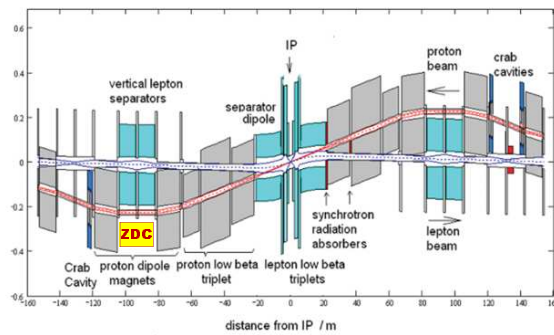


Figure 14.5: Schematic layout of the LHeC interaction region. The possible position of the ZDC is indicated.

9953 14.3.3 Proton Calorimeter

9954 In analogy to ALICE experiment, the second ZDC for detection of spectator protons can be positioned at
 9955 about a same distance from IP as neutron ZDC [841, 842]. The size of proton ZDC has to be small, due to
 9956 the few cm small size of spectator proton spot, but sufficient to obtain shower containment. This calorimeter
 9957 will be made with same technique as the neutron ZDC.

9958 14.3.4 Calibration and monitoring

9959 After initial calibration of the ZDCs with test-beams, it is essential to have regular online and offline control
 9960 of the stability of the response, in particular due to hard radiation and temperature environment. The
 9961 stability of the gain of the PMTs and the radiation damage in fibres can be monitored using the laser or
 9962 LED light pulses. The stability of absolute calibration can be monitored using the interactions of the proton
 9963 beam and residual gas molecules in the beam-pipe and comparison with the results of Monte Carlo simulation
 9964 based on pion exchange, as used at HERA [498, 840]. A useful tool for absolute energy calibration will be the
 9965 reconstruction of invariant masses, e.g. $\pi^0 \rightarrow 2\gamma$ or $\Lambda, \Delta \rightarrow n\pi^0$, with decay particles produced at very small
 9966 opening angles and reconstructed in ZDC. This will however require the possibility to reconstruct several
 9967 particles in the ZDC within one event.

14.4 Forward Proton Detection

In diffractive interactions between protons or between an electron and a proton, the proton may survive a hard collision and be scattered at a low angle θ along the beam line while losing a small fraction ξ ($\sim 1\%$) of its energy. The ATLAS and CMS collaborations have investigated the feasibility to install detectors along the LHC beam line to measure the energy and momentum of such diffractively scattered protons [848]. Since the proton beam optics is primarily determined by the shape of the accelerator - which will not change for proton arm of the LHeC - the conclusions reached in this R&D study are still relevant for an LHeC detector.

In such a setup, diffractively scattered protons are separated from the nominal beam when traveling through dipole magnets with a slightly lower momentum. This spectroscopic behavior of the accelerator is described by the energy dispersion function, D_x , which, when multiplied with the actual energy loss, ξ , gives the additional offset of the trajectory followed by the off-momentum proton:

$$x_{\text{offset}} = D_x \times \xi.$$

The acceptance window in ξ is therefore determined by the closest possible approach of the proton detectors to the beam for low ξ and by the distance of the beam pipe walls from the nominal proton trajectory for high ξ . The closest possible approach is often taken to be equal to 12σ with σ equal to the beam width at a specific point. At the point of interest, 420m from the interaction point, the beam width is approximately equal to $250 \mu\text{m}$. On the other hand, the typical LHC beam pipe radius at large distances from the interaction point is approximately 2 cm. Even protons that have lost no energy, will eventually hit the beam pipe wall if they are scattered at large angles. This therefore fixes the maximally allowed fourmomentum-transfer squared t , which is approximately equal to the square of the transverse momentum p_T of the scattered proton at the interaction point.

At 420 m from the interaction point, the dispersion function at the LHC reaches 1.5 m, which results in an optimal acceptance window for diffractively scattered protons (roughly $0.002 < \xi < 0.013$). The acceptance as function of ξ and t is shown in Fig. 14.6, using the LHC proton beam optics [849]. The small corrections to be applied for the LHeC proton beam optics are not considered to be relevant for the description of the acceptance.

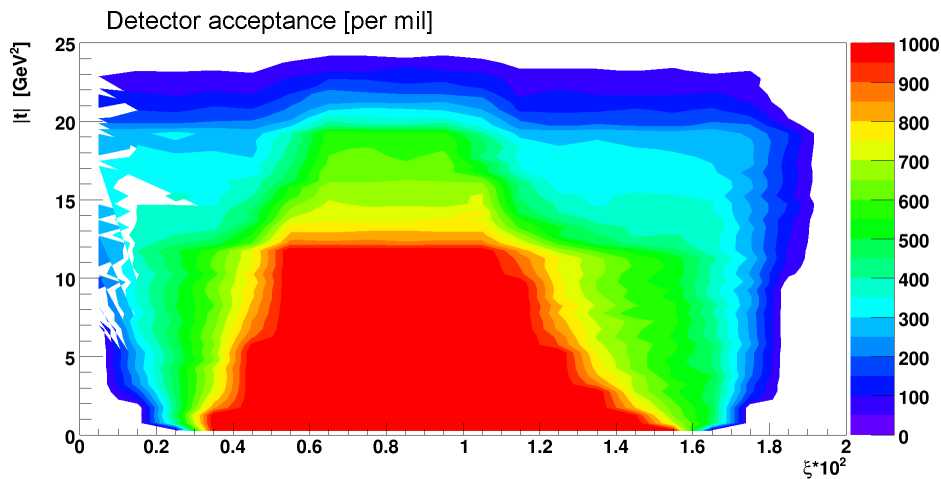


Figure 14.6: The acceptance for a proton detector placed at 420m from the interaction point is shown as function of the momentum loss ξ and the fourmomentum-transfer squared t . The color legend runs from 0% (no acceptance) to 1000% (full acceptance).

When the proton's position and angle w.r.t. the nominal beam can be accurately measured by the detectors, it is in principle possible to reconstruct the initial scattering angles and momentum loss of the

9991 proton at the interaction point. Even with an infinitesimally small detector resolution, the intrinsic beam
 9992 width and divergence will still imply a lower limit on the resolution of the reconstructed kinematics. As the
 9993 beam is typically maximally focussed at the interaction point in order to obtain a good luminosity, it will
 9994 be the beam divergence that dominates the resolution on reconstructed variables.

9995 Figure 14.7 show the relation of position and angle w.r.t. the nominal beam and the proton scattering
 9996 angle and momentum loss in both the horizontal and vertical plane as obtained from the LHC proton beam
 9997 optics [849]. Clearly, in order to distinguish angles and momentum losses indicated by the curves in Fig. 14.7,
 9998 the detector must have a resolution better than the distance between the curves.

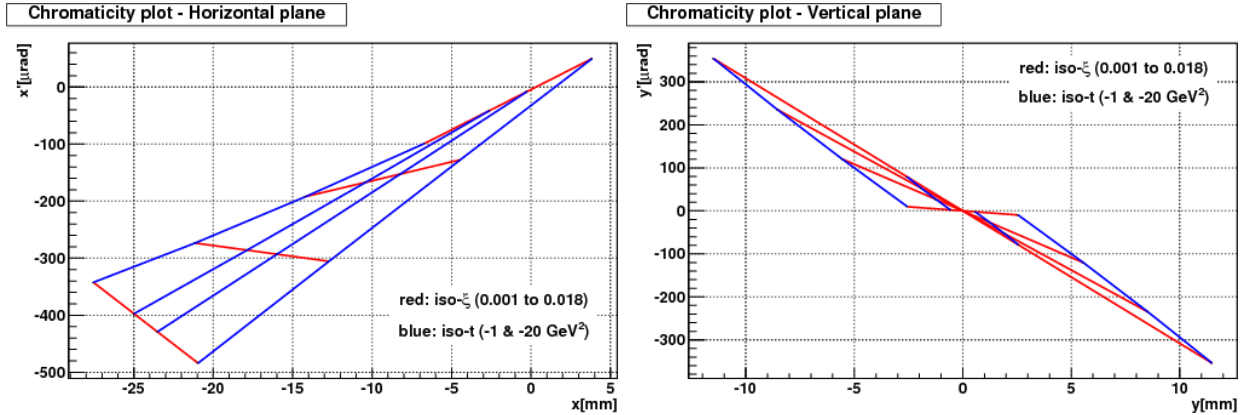


Figure 14.7: Lines of constant ξ and $t \approx (1 - \xi)E_{\text{beam}}\theta^2$ are shown in the plane of proton position and angle w.r.t. the nominal proton beam in the horizontal (left) and vertical (right) plane.

9999 As stated above, protons with the same momentum loss and scattering angles will still end up at different
 10000 positions and angles due to the intrinsic width and divergence of the beam. Lower limits on the resolution
 10001 of reconstructed kinematics can therefore be determined. These are typically of the order of 0.5‰ for ξ and
 10002 0.2 μrad for the scattering angle θ . Figure 14.8 show the main dependences of the resolution on ξ , t and the
 10003 azimuthal scattering angle ϕ .

10004 A crucial issue in the operation of near-beam detectors is the alignment of the detectors w.r.t. the nominal
 10005 beam. Typically, such detectors are retracted when beams are injected and moved close to the beam only
 10006 when the accelerator conditions are declared to be stable. Also the beam itself, may not always be reinjected
 10007 at the same position. It is therefore important to realign the detectors at for each accelerator run and to
 10008 monitor any drifts during the run. At HERA, a kinematic peak method section was used for alignment:
 10009 as the reconstructed scattering angles depend on the misalignment, one may extract alignment constants
 10010 by required that the observed cross section is maximal for forward scattering. In addition, this alignment
 10011 procedure may be cross-checked by using a physics process with a exclusive system produced in the central
 10012 detector such that the proton kinematics is fixed by applying energy-momentum conservation to the full set
 10013 of final state particles. The feasibility of various alignment methods at the LHeC remains to be studied.

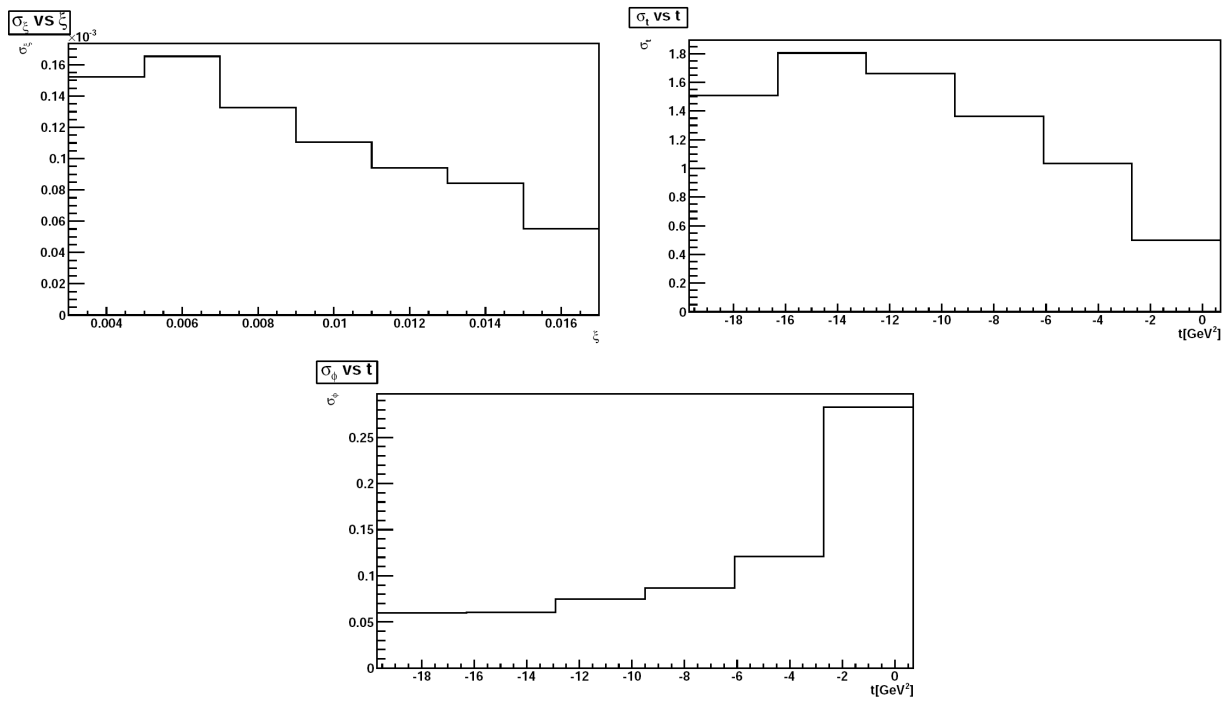


Figure 14.8: The lower limit due to the intrinsic beam width and divergence on the resolution of kinematic variables is shown for ξ as function ξ (top left), t as function t (top right) and ϕ as function of t (bottom).

10014

Part V

10015

Summary

The summary will be added when the referee process is completed.

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11507 Chapter 15

11508 Appendix

11509 15.1 Scientific Advisory Committee

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- 11599 **Detector Design**
- 11600 Philippe Bloch (CERN)
- 11601 Roland Horisberger (PSI)
- 11602 **Installation and Infrastructure**
- 11603 Sylvain Weisz (CERN)
- 11604 **New Physics at Large Scales**
- 11605 Cristinel Diaconu (IN2P3 Marseille)
- 11606 Gian Giudice (CERN)
- 11607 Michelangelo Mangano (CERN)
- 11608 **Precision QCD and Electroweak**
- 11609 Guido Altarelli (Roma)
- 11610 Vladimir Chekelian (MPI Munich)
- 11611 Alan Martin (Durham)
- 11612 **Physics at High Parton Densities**
- 11613 Alfred Mueller (Columbia)
- 11614 Raju Venugopalan (BNL)
- 11615 Michele Arneodo (INFN Torino)