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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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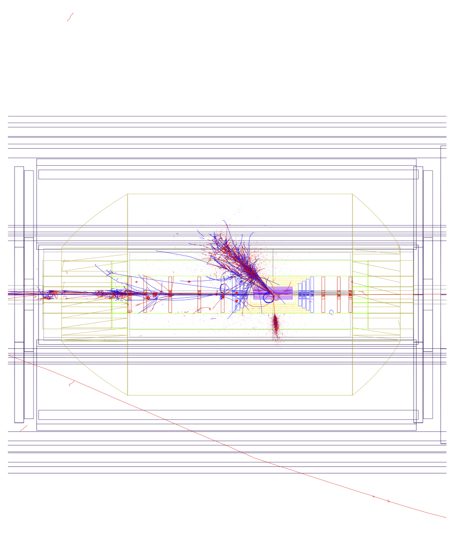

View of a (draft) leptoquark event in the LHeC Detector modelled in GEANT4

Abstract

The physics programme and the design are described of a new electron-hadron collider, the LHeC, in which electrons of 60 to possibly 140 GeV collide with LHC protons of 7000 GeV. The Large Hadron Electron Collider extends the kinematic range of HERA by nearly two orders of magnitude in four-momentum squared, Q^2, and in $1/x$, using a design luminosity of $\mathrm{O}(10^{33})\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The physis programme is devoted to an exploration of the energy frontier complementing the LHC with high precision DIS measurements which are projected to solve a number of fundamental questions in strong and electroweak interactions. The LHeC thus becomes the world's cleanest high resolution microscope, designed to continue the path of deep inelastic lepton-hadron scattering into unknown areas of physics and kinematics. This includes electron-ion (eA) scattering into a range extended by four orders of magnitude as compared to previous lepton-nucleus experiments. The LHeC may be realised as a ring-ring or linac-ring collider. For both options the optics and beam dynamics studies are presented, along with technical design considerations on the interaction region, magnets, cryo, rf, civil engineering and further components. A design study is also presented of a detector suitable to perform high precision DIS measurements in a wide range of acceptance using state-of-the art detector technology, which is modular and of limited size enabling its fast installation. The detector includes tagging devices for electron, photon, proton and neutron detection near to the beampipe. The LHeC may be built and is designed to be operated while the LHC runs. It so represents a major opportunity for particle physics to progress and for the LHC to be further exploited.

LHeC Study Group

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Contents

Part I

Introduction

Chapter 1

Lepton-Hadron Scattering

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 [1] and its interpretation by Rutherford [2] 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 [3]. Later, through inelastic electron proton scattering at Stanford [4,5], proton structure was understood in terms of quarks, still the smallest known constituents of matter. With the discovery of the scaling with Q^2 of the proton structure function $F_2(x, Q^2)$ for the originally accessed values around $x \simeq 0.2$ and its quark model interpretation in terms asymptotic freedom [6, 7], deep inelastic scattering (DIS) became a field of fundamental theoretical importance [8] 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) [9] as the appropriate theory of the strong interaction.

QCD is a Yang-Mills Lagrangian gauge field theory, in which the interaction between confined quarks proceeds via coloured gluons. 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. The development of QCD beyond leading order is one of the most remarkable recent achievements of particle physics theory and experiment. It leads to a consistent description of all perturbatively accessible strong interaction observables, including the complex violations of the scaling of F_2 away from $x \sim 0.2$, as has recently been precisely measured over a wide kinematic range at HERA [10].

As discussed in detail in Section II, several fundamental properties of nature could be explored more deeply than hitherto through a continued programme of scattering electrons from protons and nuclei at a Large Hadron electron Collider (LHeC), as is proposed in sections III and IV. A few of the most pressing questions are outlined briefly below.

- The Standard Model of particle physics contains a remarkable, but unexplained, symmetry between quarks and leptons [11], with three generations, in each of which two quarks and two leptons are embedded. It was pointed out long ago [12] that it appears somewhat artificial that the basic building blocks of matter share the electromagnetic and the weak interactions but differ in their sensitivity to the strong interaction. Many theories which unify the quark and lepton sectors, such as E6 [13], R-parity violating supersymmetry [14] and left-right symmetric extensions of the Standard Model [15], predict new resonant states with both lepton and baryon numbers, usually referred to as leptoquarks. Although some of the specific theories have not been supported by experiment, the search for leptoquarks has been a prime motivation for high energy scattering experiments. An LHeC, in combination with the existing LHC programme, can extend this search into a previously unexplored mass region, with the prospect of deciphering the leptoquark quantum numbers.

- The mass of baryons is almost entirely due to strong interaction field energy, generated through the self-interaction of gluons in a manner which is not yet well understood, but which may be accessible through a more detailed mapping of QCD dynamics, particularly in the low x region of proton structure, where gluon densities become very large and $g \rightarrow gg$ splittings dominate. The search for the Higgs boson, which explains the masses of the electroweak bosons, is currently the central focus of particle physics and is expected to be resolved within the next year by the ATLAS and CMS experiments. The question of hadronic mass deserves similar exploration.

- No analytic proof yet exists that QCD should exhibit the property of colour confinement, though it is reasonable to assume that it is a consequence of gluon dynamics, as reflected for example in popular hadronisation models [16]. Studying the behaviour of gluons under new extreme conditions and contrasting the conditions under which the proton stays intact with those in which it is destroyed may help to shed light on the precise mechanism at work.

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

- After quarks were discovered, a distinction was soon made between valence and sea quarks [17]. However, it was not until the high energy colliding beam configuration of HERA became available that the richn partonic structure of the proton was fully realised. Despite the resulting fast development of our knowledge of the parton momentum distribution functions (PDFs) in the proton, there are still many outstanding important questions concerning quark-gluon interactions in hadronic matter, which cannot be answered with currently available data.

  - Modern determinations of PDFs assume that sea quarks and anti-quarks have the same momentum distributions. Experimental constraints are required to test this assumption.

  - Similarly, the strange-quark density is often assumed to be a fixed fraction of the down-quark density, for which there is no experimental verification.
  - With no high energy DIS data available from deuteron scattering, the low x quark content of the neutron is unresolved. It is important to test the assumption of isospin symmetry, which relates for example the neutron down quark distribution to the proton up-quark distribution.
  - The gluon density is still not precisely determined, particularly at small and large x values. This has implications for example to our knowledge of the Higgs boson cross section at the LHC, since the dominant production mechanism is through gluon-gluon fusion.
  - With no data on the scattering of leptons from heavy ions with colliding beam kinematics, our knowledge of the modifications to nucleon parton densities when they are bound inside nuclei, rather than free, is restricted to high x values. This is reflected in a lack of detailed understanding of shadowing phenomena, particularly for the gluon density and a corresponding lack of knowledge of the initial state of heavy ion collisions at LHC energies.
  - The emission of partons is assumed in PDF fits to be governed by the linear DGLAP evolution equations, an approximation to a full solution to QCD in which parton cascades are ordererd in transverse momentum. There are good reasons to believe that the DGLAP approximation is insufficient to describe the Q^2 evolution of low x partons, even within the x range to which the LHC rapidity plateau corresponds. Inclusive DIS and jet data in an extended low x kinematic regime are required to resolve this situation.
  - The understanding of the role of heavy quarks in QCD is still at its infancy. Charm may exist in an intrinsic state [18]. The b density, which plays an important role in the production mechanisms for new particles in many LHC scenarios, is measured to only about 20 % accuracy and the role of top quarks in DIS is completely unknown due to the limited energy and luminosity of HERA.
  - While ordinary quark distributions correspond to an incoherent sum of squared amplitudes, a new approach has been developed, which uses quark amplitudes and Generalised Parton Distributions (GPDs) to understand proton structure in a new, three-dimensional way [19,20]. Our understanding of GPDs is limited by the relative paucity of experimental data on exclusive DIS channels.

- The rapid rise of the proton gluon density as x decreases cannot continue indefinitely. At x values within the reach of LHeC ep and eA scattering, a transition takes place from the currently known DIS regime in which the proton behaves as a dilute system to a new low x domain in which parton densities saturate and the proton approaches a 'black disk' limit [21]. This latter region represents a fundamentally new regime of strong interaction dynamics, for which a rich phenomenology has developed, but where the detailed mechanisms and the full consequences are not yet known. Experimental data at sufficiently low x with scales which are large enough to allow a partonic interpretation are urgently required in order to test the models and fully understand the behaviour of partons at high densities.

Despite its huge success in describing existing high energy data, the Standard Model is known to be incomplete, not only due to the absence of an experimentally established mechanism for electroweak symmetry breaking. As the exploitation of the TeV energy regime and the high luminosities of the LHC era develops further, a full understanding can only be obtained by challenging the existing theory through new precision measurements, as broad in scope as possible, with initial states involving leptons as well as quarks and gluons. Furthermore, many of the remaining open fundamental questions in our field are associated with the strong interaction sector of the Standard Model, to which a future facility such as the LHeC provides unique experimental sensitivity.

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 tera 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 LHeC has to be built in the coming about 10 years.

- The design has to be adapted for synchronous pp and ep (or e.g. pA and eA) operation - for example 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 and makes the most efficient use of both the proton beams and the electron beam installation too.

It can not realistically be assumed today, that the ep physics would commence only when the pp programme was finished: because of the finite LHC lifetime, which nowadays is estimated to be about 20 years.

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

2.3 Choice of Electron Beam Energy

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

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

The LHeC can use an up to 7 TeV energy proton beam. For this design study the electron beam energy 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 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 luminosity even the highest Q^2 values and x close to 1 become accessible then. The kinematic range of the LHeC as compared to HERA at low x and at high Q^2 is illustrated in Fig. 2.1.

The choice of a default $E_e = 60\,\text{GeV}$ for this design report is dictated by physics and by practical considerations:

- New physics has been assumed to appear at the TeV energy scale. At the time of completion of this report, the LHC has excluded much of the sub-TeV physics beyond the Standard Model (SM) but leaves the possibility open of resonant lepton-parton states with masses of larger than about 500 GeV, for which the LHeC would be a particularly suitable machine with a range of up to $M \lesssim \sqrt{s}$.

- High precision QCD and electroweak physics require a maximum range in $\ln Q^2$ and highest Q^2, respectively. The unification of electromagnetic and weak forces takes place at $Q^2 \simeq M_Z^2$ which is much exceeded by the LHeC energies. Part of the electroweak physics requires lepton beam polarisation which as is shown below may reach values (for the ring) as at HERA at 60 GeV but much less at significantly larger E_e.

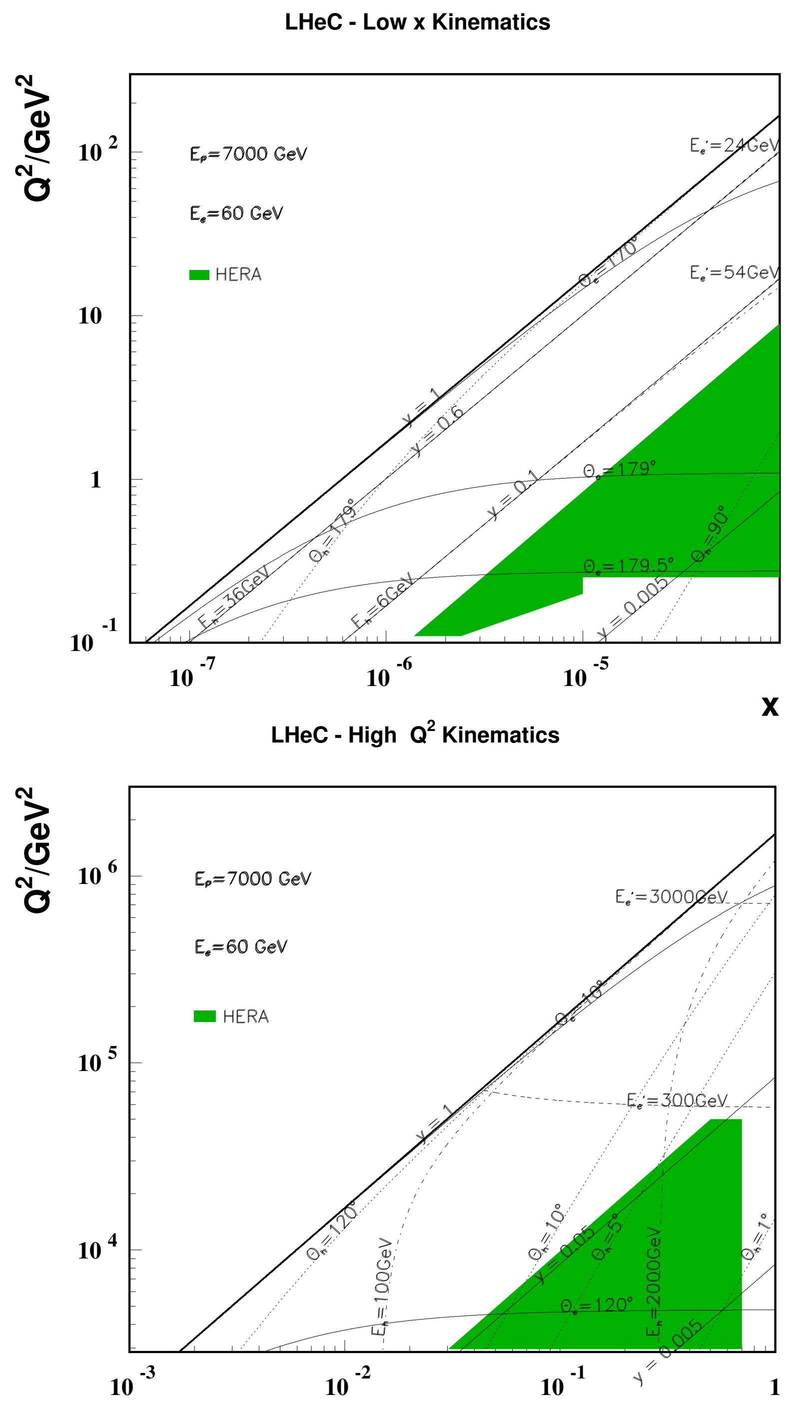


Figure 2.1: Kinematics of ep scattering at the LHeC at low x (top) and high Q^2 (bottom). Solid (dotted) curves correspond to constant polar angles θ_e (θ_h) of the scattered electron (hadronic final state). The polar angle is defined with respect to the proton beam direction. Dashed (dashed-dotted) curves correspond to constant energies E'_e (E_h) of the scattered electron (hadronic final state). The shaded 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.

- The discovery of gluon saturation requires to measure at typical values of small $x \simeq 10^{-5}$ with $Q^2 >> M_p^2$, where M_p is the mass of the proton. The choice of energies ensures this discovery in *ep* collisions in the DIS region.

- Energy losses by synchrotron radiation, $\propto E_e^4$, both in the ring and the return arcs for the linac, can be kept at reasonable levels, in terms of the power, P, needed to achieve high luminosity and the radius of the racetrack return arcs for the linac too.

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

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 $1° - 179°$, at reduced luminosity and a high luminosity phase, of acceptance limited to $8° - 172°$. 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. This does not imply that any decision was taken about which experiment one would favour to stop in ten years.

2.5 Two Electron Beam Options

It was shown a few years ago [?] that an electron beam in the LHC tunnel would allow to achieve an outstanding luminosity of about $10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ 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

[1] Such 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.

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 decision 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

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

with $\gamma = E_p/M_p$. The design luminosity assumes the so-called ultimate proton beam parameters for $E_p = 7$ TeV with 1.7 10^{11} protons per bunch and $\epsilon_p = 3.8\,\mu$m. Eq. 2.1 then corresponds to

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

where the electron beam current is given by

$$I_e = 0.35mA \cdot P[MW] \cdot (\frac{100}{E_e[GeV]})^4 \tag{2.3}$$

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

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

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

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

which scales as

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

where the electron beam current is given by

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

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

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

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

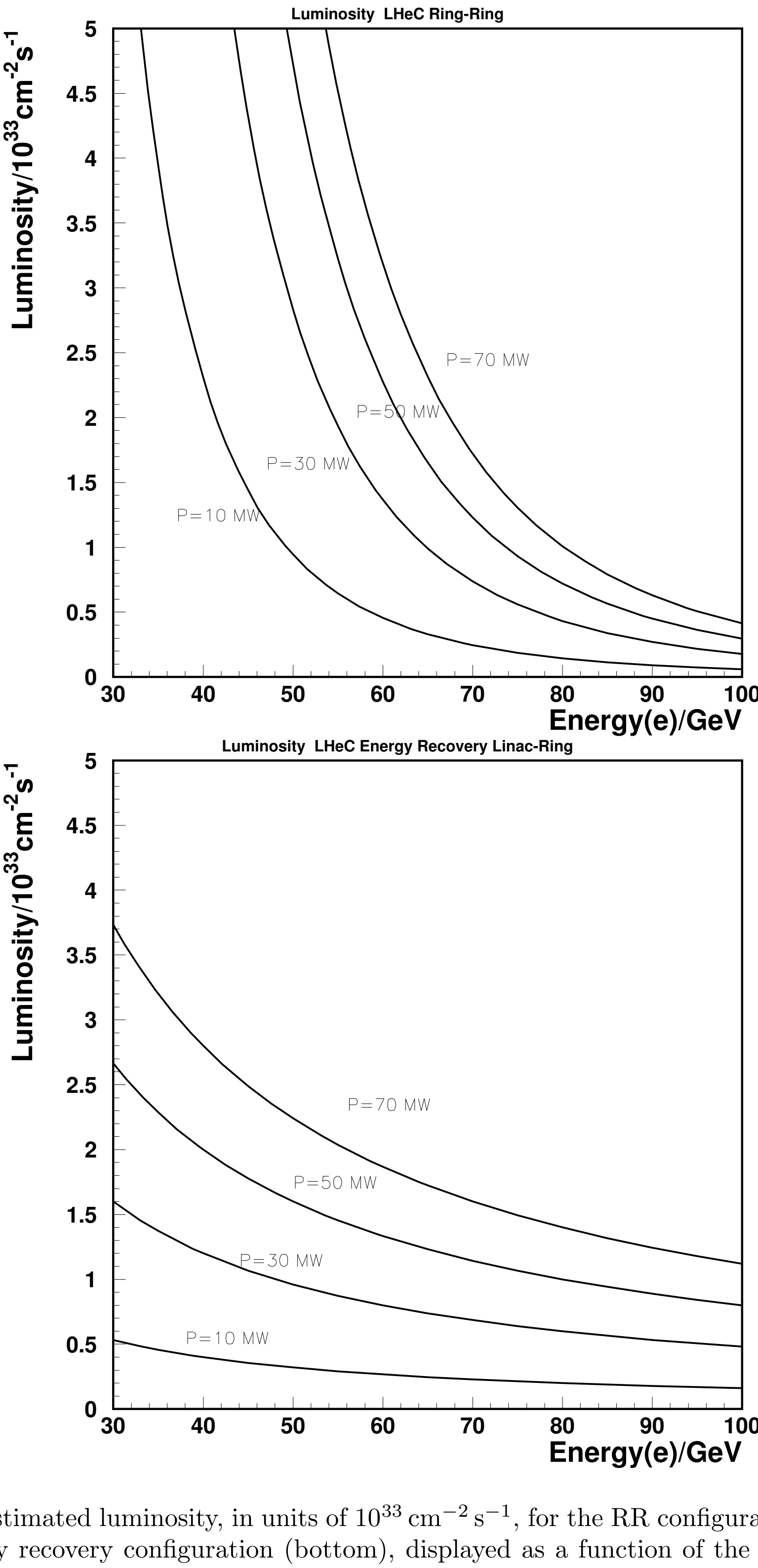


Figure 2.2: Estimated luminosity, in units of $10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, for the RR configuration (top) and the LR energy recovery configuration (bottom), displayed as a function of the electron beam energy with the beam power as a parameter, see text.

Chapter 3

Executive Summary

The excutive summary will be added after the completion of the referee process.

Part II

Physics

Chapter 4

Precision QCD and Electroweak Physics

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 tensors,

$$\frac{d^2\sigma}{dxdQ^2} = \frac{2\pi\alpha^2}{Q^4 x}\sum_j \eta_j L_j^{\mu\nu} W_j^{\mu\nu}, \tag{4.1}$$

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

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

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

4.1.2 Neutral Current

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

$$\frac{d^2\sigma_{NC}}{dxdQ^2} = \frac{2\pi\alpha^2 Y_+}{Q^4 x} \cdot \sigma_{r,NC} \tag{4.3}$$

$$\sigma_{r,NC} = \mathbf{F_2} + \frac{Y_-}{Y_+}\mathbf{xF_3} - \frac{y^2}{Y_-}\mathbf{F_L}, \tag{4.4}$$

where the electromagnetic coupling constant α, the photon propagator and a helicity factor are absorbed in 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 the lepton beam charge and polarisation (P) and on the electroweak parameters as [22]

$$\begin{aligned} \mathbf{F_2^\pm} &= F_2 + \kappa_Z(-v_e \mp Pa_e) \cdot F_2^{\gamma Z} + \kappa_Z^2(v_e^2 + a_e^2 \pm 2Pv_ea_e) \cdot F_2^Z \\ \mathbf{xF_3^\pm} &= \kappa_Z(\pm a_e + Pv_e) \cdot xF_3^{\gamma Z} + \kappa_Z^2(\mp 2v_ea_e - P(v_e^2 + a_e^2)) \cdot xF_3^Z. \end{aligned} \tag{4.5}$$

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

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

with the weak mixing angle $\sin^2\Theta = 1 - M_W^2/M_Z^2$. In the hadronic tensor decomposition [23] the structure functions are well defined quantities. In the Quark Parton Model (QPM) the longitudinal structure function is zero [24] and the two other functions are given by the sums and differences of quark (q) and anti-quark ($\overline{q}$) distributions as

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

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

$$v_f = i_f - e_f 2\sin^2\Theta \qquad a_f = i_f \tag{4.8}$$

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, respectively. Thus the vector coupling of the electron, for example, is very small, $v_e = -1/2 + 2\sin^2\Theta \simeq 0$, since the weak mixing angle is roughly equal to 1/4.

At low Q^2 and low y the reduced NC cross section, Eq. 4.3, to a very good approximation is given by $\sigma_r = F_2(x, Q^2)$. At $y > 0.5$, F_L makes a sizeable contribution to $\sigma_{r,NC}$. In the DGLAP approximation of perturbative QCD, to lowest order, the longitudinal structure function is given by [25]

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

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

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

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

neglecting terms $\propto v_e$ which can be easily obtained from Eq. 4.5. If data are taken with opposite polarisation and charge, the asymmetry represents a measurement of the difference of quark and anti-quark distributions in NC, see Eq. 4.7. In contrast to what is often stated, the charge asymmetry is a parity conserving quantity $\propto a_e a_q$. Assuming symmetry between sea and antiquarks, it is a direct measure of the valence quarks, $xF_3^{\gamma Z} = 2u_v + d_v$ in ep. This function was measured for the first time in $\mu^\pm$ Carbon scattering by the BCDMS Collaboration [26] at large $x > 0.2$ and for Q^2 of about $50\,\mathrm{GeV}^2$. With the LHeC, for the first time, high precision measurements of xF_3 in NC become possible as is demonstrated in Sect. 4.2.2. These will access the valence quarks at low $x \lesssim 0.001$ for the first time in direct measurements.

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

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

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 measure of parity violation at very small distances.

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

The polarisation asymmetry also permits a high precision measurement of the weak mixing angle at different Q^2 values, below and to much higher values than M_Z^2, at which $\sin^2\Theta$ was precisely measured at LEP and the SLC, see Sect. 4.6.1.

4.1.3 Charged Current

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

$$\frac{\mathrm{d}^2\sigma^\pm_{CC}}{\mathrm{d}x\mathrm{d}Q^2} = \frac{1 \pm P}{2} \cdot \frac{G_F^2}{2\pi x} \cdot \left[\frac{M_W^2}{M_W^2 + Q^2}\right]^2 Y_+ \cdot \sigma_{r,CC}. \tag{4.12}$$

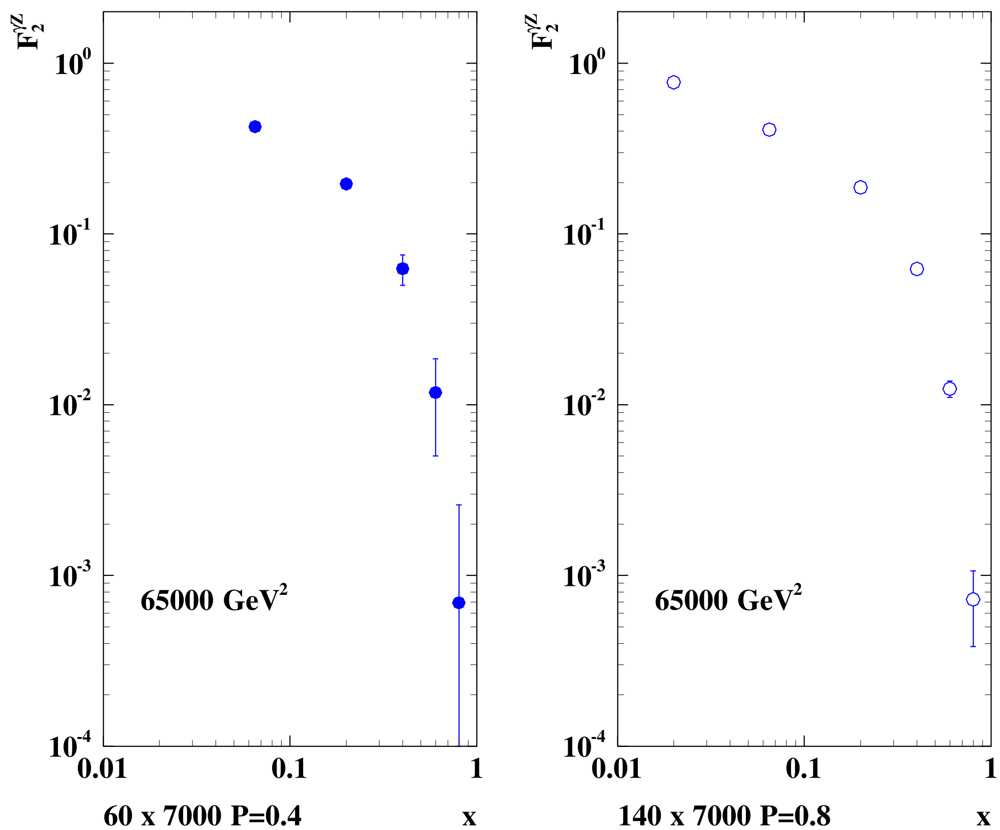


Figure 4.1: Simulation of the measurement of the γZ interference structure function $F_2^{\gamma Z}$, shown as a function of x for a typical high Q^2 value, for two LHeC configurations ($E_e = 60\,\mathrm{GeV}$ and $P = \pm 0.4$, left) and ($E_e = 140\,\mathrm{GeV}$ and $P = \pm 0.9$, right). The proton beam energy is $7\,\mathrm{TeV}$ and the luminosity assumed is $10\,\mathrm{fb}^{-1}$ 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.

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

$$\sigma^{\pm}_{r,CC} = W_2^{\pm} \mp \frac{Y_-}{Y_+} x W_3^{\pm} - \frac{y^2}{Y_+} W_L^{\pm} \,. \tag{4.13}$$

In the on-mass shell scheme, the Fermi constant G_F is defined, see for example [27], using the weak boson masses as

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

with $\sin^2\theta = 1 - M_W^2/M_Z^2$ as above. The higher order correction term Δr can be approximated [28] as $\Delta r = 1 - \alpha/\alpha(M_Z) - 0.0094 (m_t/173GeV)^2/\tan^2\theta$, and thus introduces a dependence of the DIS cross section on the mass of the top quark. The choice of G above allows the CC cross section, Eq. 4.12, to be rewritten as

$$\frac{\mathrm{d}^2\sigma^{\pm}_{CC}}{\mathrm{d}x \mathrm{d}Q^2} = \frac{1 \pm P}{2} \cdot \frac{2\pi\alpha^2 Y_+}{Q^4 x} \cdot \kappa_W^2 \cdot \sigma_{r,CC}, \tag{4.15}$$

with

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

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

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

$$W_2^+ = x(\overline{U} + D)\,,\; xW_3^+ = x(D - \overline{U})\,,\; W_2^- = x(U + \overline{D})\,,\; xW_3^- = x(U - \overline{D})\,. \tag{4.17}$$

Using these equations one finds

$$\sigma^+_{r,CC} \sim x\overline{U} + (1-y)^2 xD, \tag{4.18}$$

$$\sigma^-_{r,CC} \sim xU + (1-y)^2 x\overline{D}. \tag{4.19}$$

Combined with Equation 4.5, which approximately reduces to

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

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

$$U = u + c \qquad \overline{U} = \overline{u} + \overline{c} \qquad D = d + s \qquad \overline{D} = \overline{d} + \overline{s}\,. \tag{4.21}$$

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

$$u_v = U - \overline{U} \qquad\qquad d_v = D - \overline{D}. \tag{4.22}$$

4.1.4 Cross Section Simulation and Uncertainties

The LHeC extends the kinematic range as compared to HERA in the negative momentum transfer squared Q^2 from a maximum of about 0.03 to $1\,\mathrm{TeV}^2$ and towards low x, e.g. for $Q^2 = 3\,\mathrm{GeV}^2$, from about $4 \cdot 10^{-5}$ to $2 \cdot 10^{-6}$. The projected increase of integrated luminosity by a factor of 100 allows to also extend the kinematic range at large x, in charged currents, from practically about 0.4 to 0.8. Due to the enlarged electron beam energy E_e the range of high inelasticity $y \simeq 1 - E'_e/E_e$ should extend closer to 1. A reduced noise in the calorimeters may allow to reach lower values of y than at HERA, also because the hadronic y is determined as the sum over $E - p_z$ divided by twice the with the LHeC enhanced electron beam energy. While these extensions of kinematic coverage and improvements of statistical precision are impressive, an estimate of the impact of LHeC NC and CC cross section measurements on derived quantities such as structure functions and parton distributions requires to also estimate the expected systematic measurement accuracy as may be achieved with the detector described in Chapter 12 below. In the following the assumptions and simulation results are presented for the NC and the CC cross sections, which are subsequently used in QCD fit and other analyses throughout this report.

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

In the absence of a detailed detector simulation at this stage, the systematic NC cross uncertainties due to E'_e, θ_e and E_h are calculated, following [29], from the derivatives of the NC cross section in the chosen bins taking into account the Jacobians where needed. The results have been compared, for the HERA kinematics, with the H1 MC simulation of systematic errors [30] and found to be in very good agreement for all three sources. The resulting error depends much on the kinematics. At low Q^2, for example, the systematic cross 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 Q^2 it is negligible. Low Q^2 is the backward region, of large electron scattering angles with respect to the proton beam direction.

A particular challenge is the measurement at large x because the cross section varies as

[1] Basically 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^2_e, y_e at large y and Q^2_e, 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.

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 $Q^2 = 100\,\mathrm{GeV}^2$, is about 1.2, 0.7 and 2.0 % for $y = 0.84,\ 0.1,\ 0.004$.

$(1 - x)^c$, with $c \simeq 3$, and thus the relative error is amplified $\propto 1/(1 - x)$ as x approaches 1. At high x the hadronic final state is scattered into the forward detector region where the energy calibration becomes challenging. The calculated correlated NC cross section errors are illustrated in Figs. 4.2 and 4.3 for $Q^2 = 2$ and $20000\,\mathrm{GeV}^2$, respectively. In the detector chapter these calculations have been taken to define approximate requirements on the scale calibrations in the different detector regions. An example for the resulting cross section measurement is displayed in Fig. 4.4.

For the CC case, a similar simulation was done, albeit with less numeric effort. An illustration of the high precision and large range of the inclusive CC cross section measurements is presented in Fig. 4.5. The systematic cross section error, based on the H1 experience, was set to 2 % and for larger $x > 0.3$ a term was added to allow the error to rise linearly to 10 % at $x = 0.9$. For both NC and CC cross sections the statistical error is given by the number of events but limited to 0.1 % from below. With these error assumptions a number of data sets was simulated, both for NC and CC, which is summarised in Table 4.2. The energies of these sets had been chosen prior to the final baseline energy choice. For the simulation of the F_L measurement, described below, a separate set of beam energies is considered.

4.1.5 Longitudinal Structure Function $\mathbf{F_L}$

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

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

is defined by two proton structure functions, F_2 and F_L with $y = Q^2/sx$, $Y_+ = 1 + (1 - y)^2$ and $f(y) = y^2/Y_+$. The two functions reflect the transverse and the longitudinal polarisation state of the virtual photon probing the proton structure, i.e. $F_T = F_2 - F_L$ and F_L, respectively. The positivity of the transverse and longitudinal cross sections requires $0 \le F_L \le F_2$. Since for most of the kinematic range the y dependent factor $f(y)$ is very small, there follows that

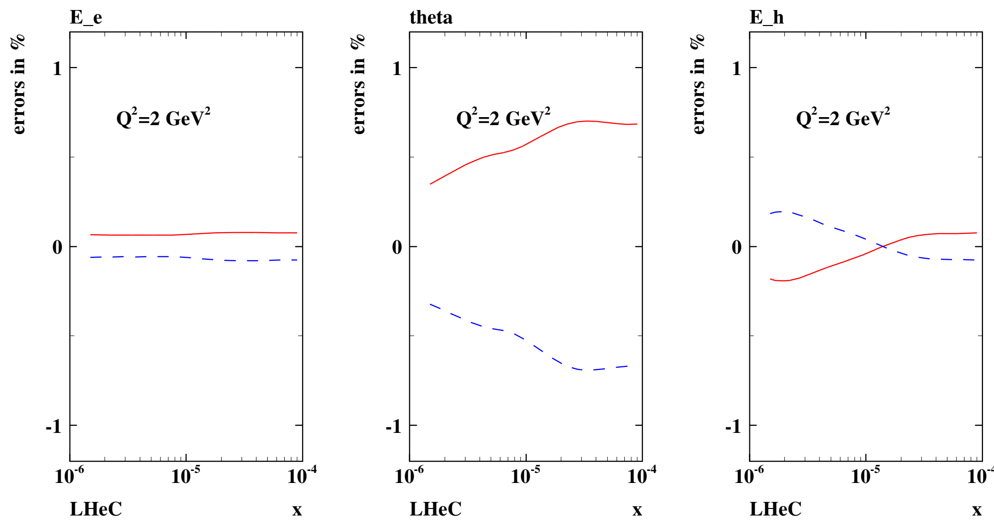


Figure 4.2: Neutral current cross section errors, calculated for $60 \times 7000\,\mathrm{GeV}^2$, as result from scale uncertainties of the scattered electron energy $\delta E'_e/E'_e = 0.1\,\%$, of its polar angle $\delta\theta_e = 0.1\,\mathrm{mrad}$ and the hadronic final state energy $\delta E_h/E_h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

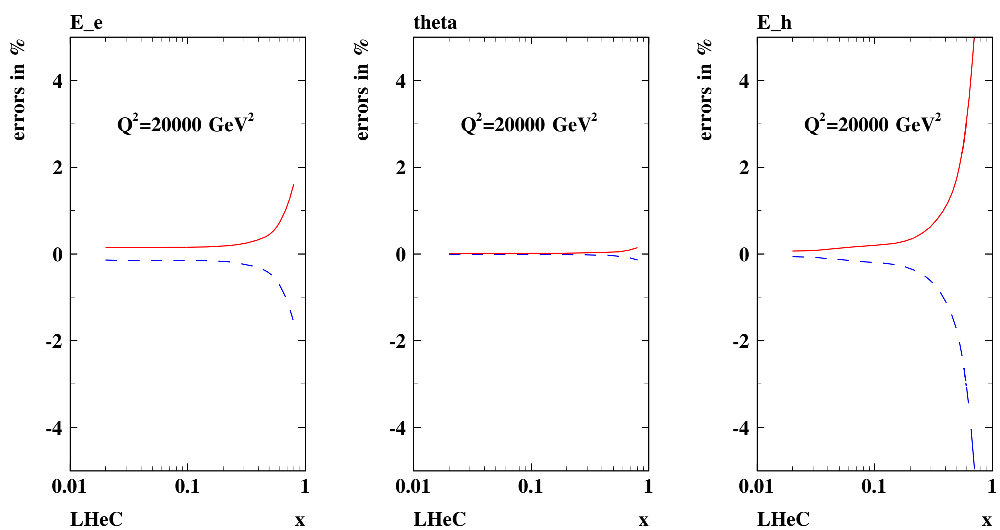


Figure 4.3: Neutral current cross section errors, calculated for $60 \times 7000\,\mathrm{GeV}^2$ unpolarised e^-p scattering, as result from scale uncertainties of the scattered electron energy $\delta E'_e/E'_e = 0.1\,\%$, of its polar angle $\delta\theta_e = 0.1\,\mathrm{mrad}$ and the hadronic final state energy $\delta E_h/E_h = 0.5\,\%$, at large $Q^2 = 20000\,\mathrm{GeV}^2$ 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 $Q^2 = 200000\,\mathrm{GeV}^2$ for example too.

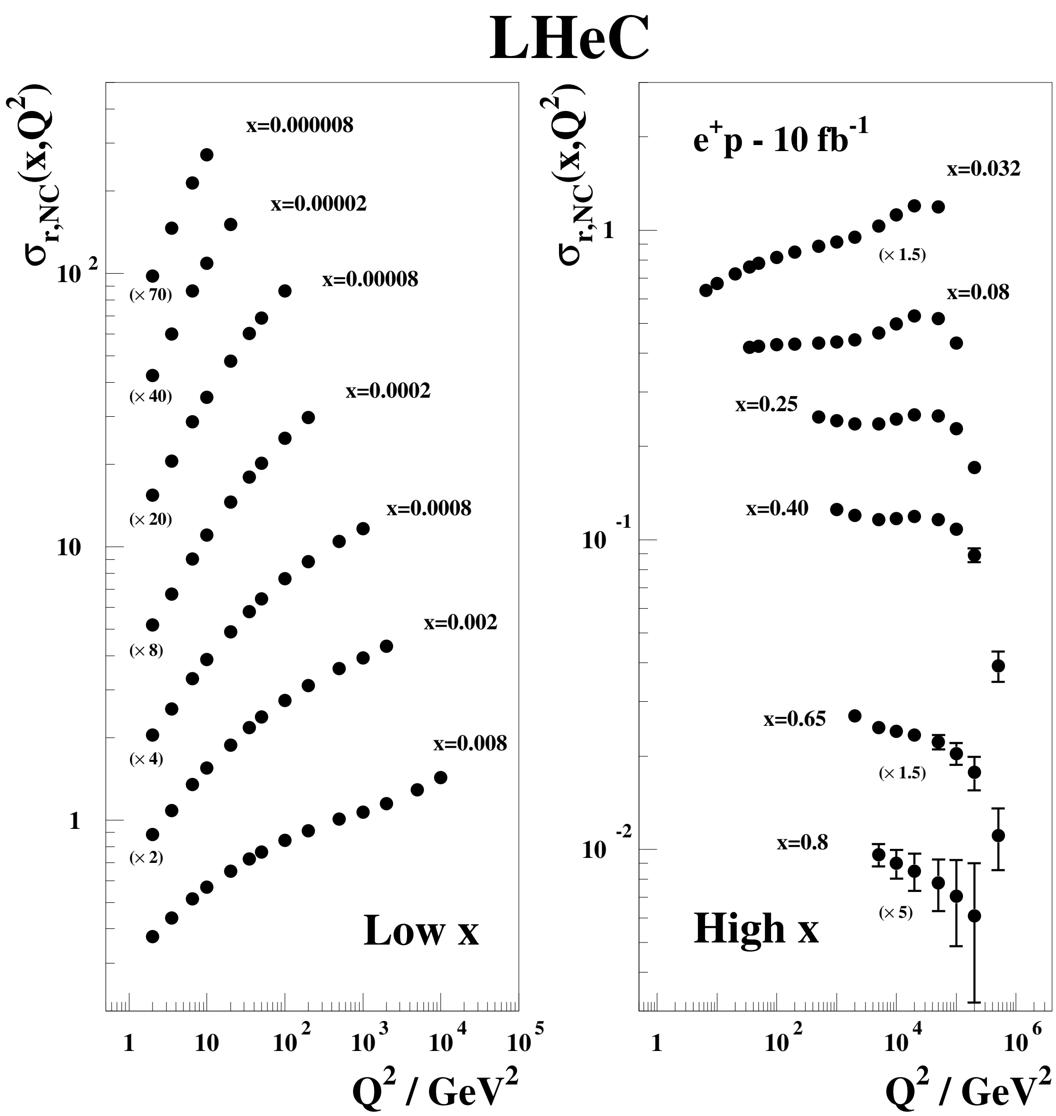


Figure 4.4: Simulated neutral current cross section measurement for an integrated luminosity of $10\,\mathrm{fb}^{-1}$ in unpolarised e^-p scattering at $E_e = 60$ and $E_p = 7000\,\mathrm{GeV}$. The reduced NC cross section is measured at unprecedented precision and range. Plotted is the total uncertainty 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 $Q^2 \geq 100\,\mathrm{GeV}^2$. 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. 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.

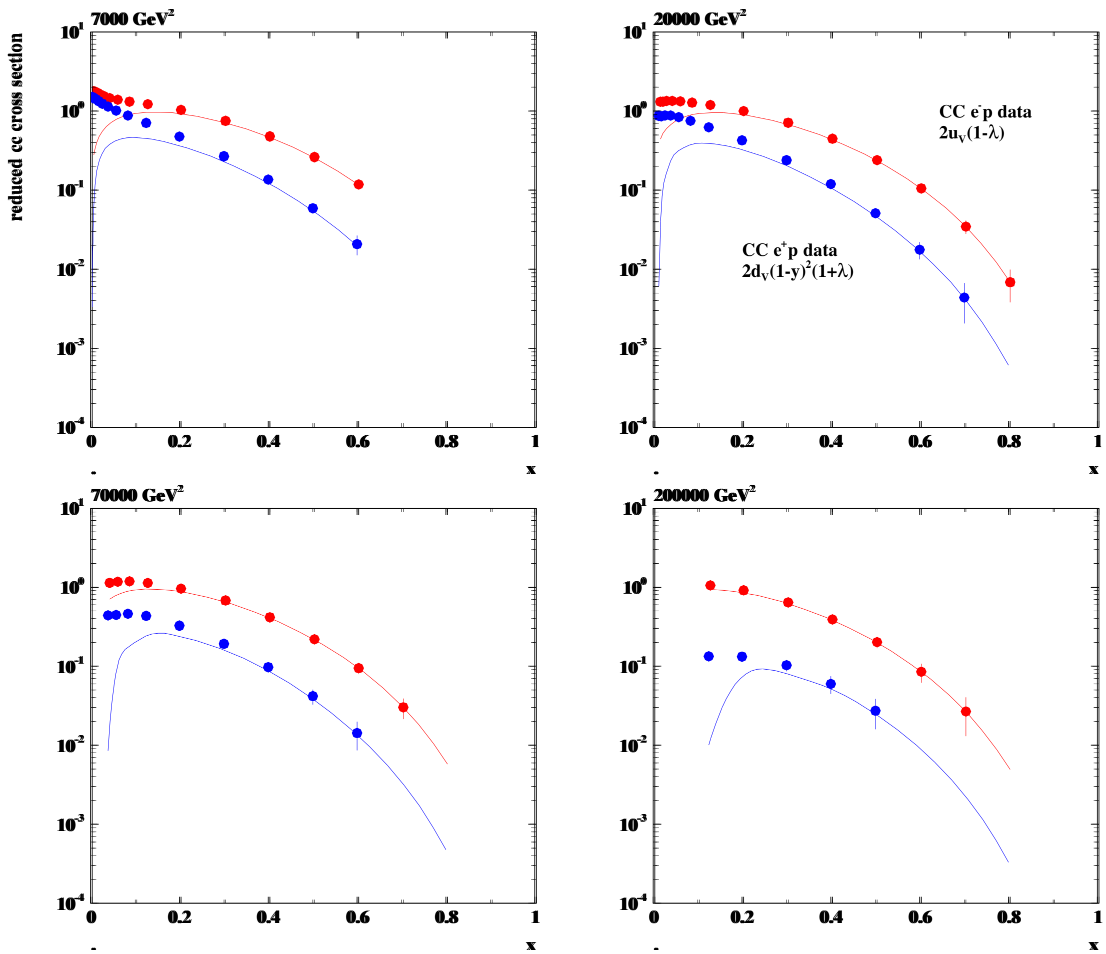


Figure 4.5: Reduced charged current cross sections with statistical uncertainties corresponding to $1\,\mathrm{fb}^{-1}$ electron (top data points, red) and positron (lower data points, blue) proton scattering at the LHeC, The curves are determined by the dominant valence quark distributions, u_v for 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^2_{min} 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 $0.5\,\text{fb}^{-1}$, 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.

F_L causes in most of the kinematic range only a small correction to the reduced cross section, which is governed by F_2, apart from the regio of maximum y. At small x, the inelasticity is given as $y \simeq 1 - E'_e/E_e$. Therefore, in order to extract F_L, DIS has to be measured extremely accurately at small scattered lepton energies, which is a question of how large E_e is, how to trigger and how to control the background from particle production at low energies. A variation of the beam energies is required to separate the two functions measured at the same x and Q^2 by variation of $y = Q^2/sx$.

A first measurement of F_L at low x at HERA has recently been performed by the ZEUS Collaboration [31] and by the H1 Collaboration [32]. For the study of the gluon distribution at lowest x, the H1 data are crucial as only H1 has measured F_L below Q^2 of about $10\,\text{GeV}^2$ owing to their backward detector constellation upgraded in the nineties. The F_L measurement at HERA was performed towards the end of the accelerator operation and could only extend over a period of three months with about $10\,\text{pb}^{-1}$ of integrated luminosity spent at two reduced proton beam energies, 450 and 565 GeV, besides the nominal 920 GeV. The H1 result is consistent with pQCD predictions. The ratio $R = F_L/(F_2 - F_L)$ has been found to be independent of x and Q^2 at 20 % accuracy, i.e. $R = 0.26 \pm 0.05$ [32]. This interesting relation deserves a more precise investigation and may break when the region of saturation is entered at lower x than HERA could access.

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

In the low x studies below a similar simulation was used for which the luminosity assumptions were similar but a set of reduced proton beam energies was considered. The advantage of lowering E_p is that the 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 instead, one has to accept a lower y_{max} as below a few GeV of energy the background is too high for a reliable measurement to be performed. The results of both F_L simulations, with reduced E_e or E_p, come out to be very similar.

The result of the simulation study is shown in Fig. 4.6. The technique applied is the conventional separation of F_2 and F_L by fitting a straight line to the various reduced cross section data points at fixed Q^2 and x with $f(y)$ as the parameter and separating the uncorrelated from the correlated systematic uncertainties which partially cancel in such an analysis. The expected accuracy on F_L is typically 4 % at Q^2 of $3.5\,\text{GeV}^2$ or 7 % at Q^2 of $25\,\text{GeV}^2$ at a number of points in x, with mainly similar contributions from the calculated correlated and the assumed uncorrelated systematic uncertainties, and less due to statistics which yet starts to become important for $Q^2 \geq 100\,\text{GeV}^2$. The LHeC thus will provide the first precision measurement of $F_L(x, Q^2)$ ever, in a region where the behaviour of the gluon density ought to change significantly and new, non-linear laws for parton evolution should emerge.

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

4.2 Determination of Parton Distributions

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

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

The striking potential of the determination of the quark and gluon distributions will be discussed and illustrated below. For the various PDFs, the current knowledge is illustrated with

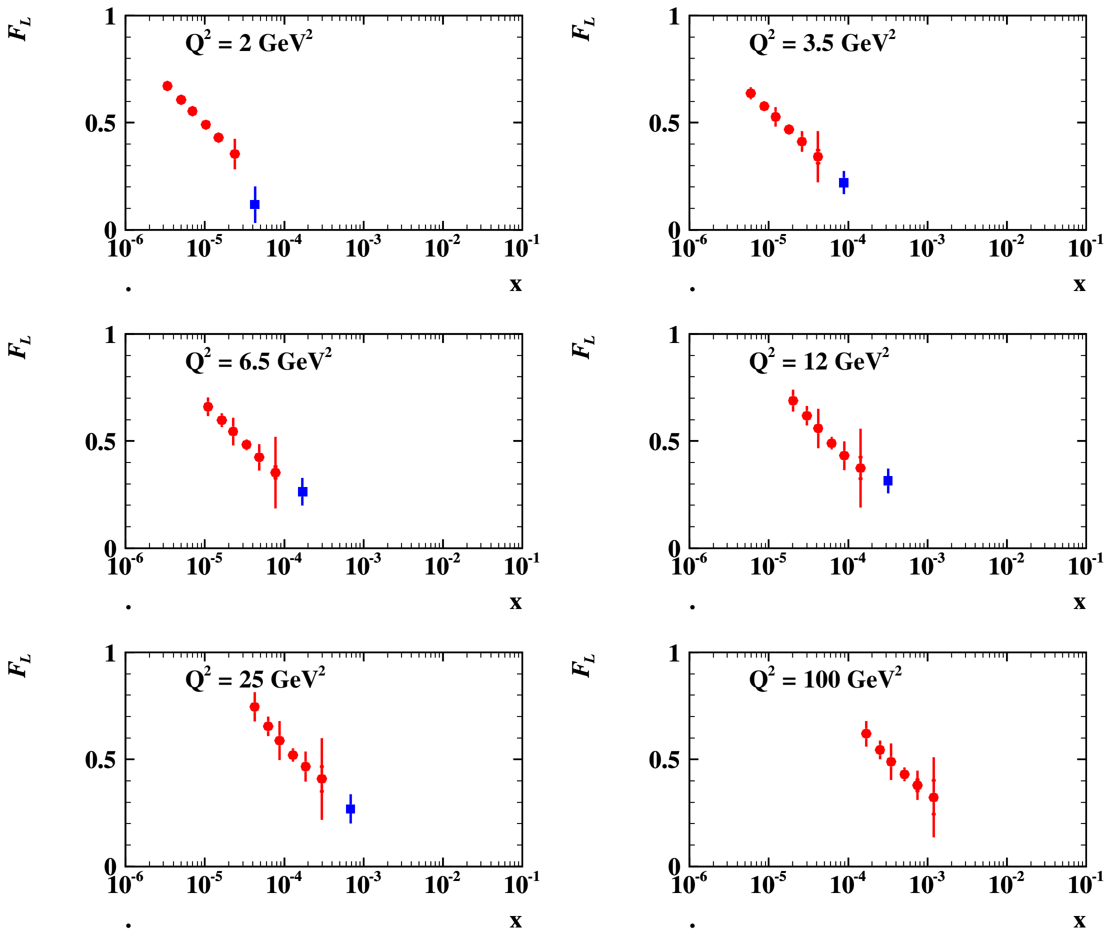


Figure 4.6: Simulated measurement of the longitudinal structure function $F_L(x, Q^2)$ at the LHeC (red closed circles) from a series of runs with reduced electron beam energy, see text. The inner error bars denote the statistical uncertainty, the outer error bars are the total errors with the additional 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 [32]. The LHeC extends the measurement towards low x and high Q^2 (not fully illustrated here) with much improved precision.

a series of plots based on the world's best PDF determinations available today. Simulations of direct quark distribution measurements will be shown. Moreover, a consistent set of standard QCD fits has been performed using the simulated LHeC and further data which is first described in what follows. This is used to illustrate the effect the inclusive NC and CC data are expected to have on the PDF uncertainties.

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

4.2.1 QCD Fit Ansatz

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

The procedure used here is adopted from the HERA QCD fit analysis [10]. The QCD fit analysis to extract the proton's PDFs is performed imposing a $Q^2_{min} = 3.5$ GeV^2 to restrain to the region where perturbative QCD can be assumed to be valid. The fits are extended to lowest x for systematic uncertainty studies, even when at such low x values non-linear effects are expected to appear.

The fit procedure consists first in parametrising PDFs at a starting scale $Q^2_0 = 1.9$ GeV^2, chosen to be below the charm mass threshold. The parametrised PDFs are the valence distributions xu_v and xd_v, the gluon distribution xg, and the $x\bar{U}$ and $x\bar{D}$ distributions, where $x\bar{U} = x\bar{u}$, $x\bar{D} = x\bar{d} + x\bar{s}$. The following standard functional form is used to parameterise them

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

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

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 the sea distributions, an assumption the validity of which will be settled with the LHeC. The strange quark 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 $f_s = 0.31$. In addition, to ensure that $x\bar{u} \to x\bar{d}$ as $x \to 0$, $A_{\bar{U}} = A_{\bar{D}}(1 - f_s)$. The D and E are introduced one by one until no further improvement in χ^2 is found. The best fit resulted in a total of 10 free parameters [10]. As discussed above this will change considerably when the LHeC data become available and more flexible parameterisations and methods can be tested. This has been studied to some extent in the simulation for α_s presented below.

The PDFs are then evolved using DGLAP evolution equations [33] at NLO in the $\overline{MS}$ scheme with the renormalisation and factorisation scales set to Q^2 using standard sets of parameters as for $\alpha_s(M_Z)$. These, as well as the exact treatment of the heavy quark thresholds, are of no significant influence for the estimates of the PDF uncertainties to which the subsequent analysis is only directed. The experimental uncertainties on the PDFs are determined using the $\Delta\chi^2 = 1$ criterion.

4.2.2 Valence Quarks

The knowledge of the valence quark distributions, both at large and at low Bjorken x, as derived in the current world data QCD fit analyses is amazingly limited, as is illustrated in Fig. 4.7 from a comparison of the leading determinations of PDF sets. This has to do, at high x, with the limited luminosity, challenging 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 LHeC is demonstrated in

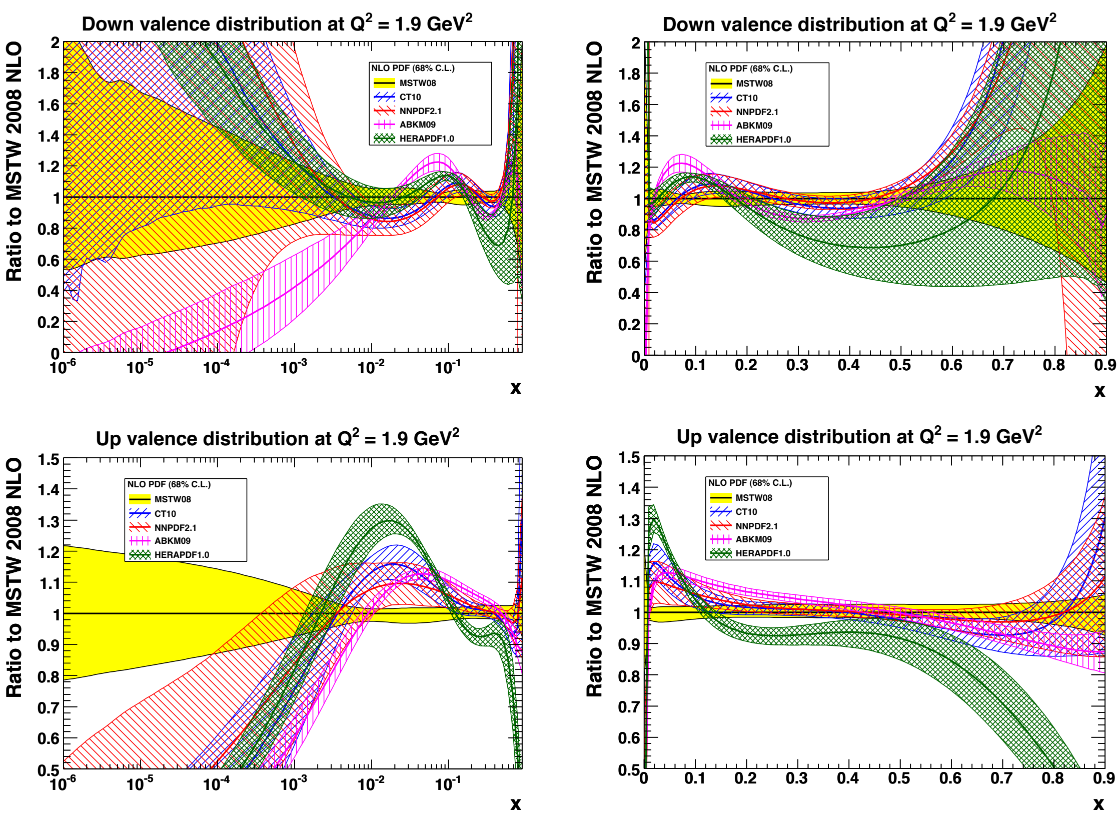


Figure 4.7: Ratios (to MSTW08) and uncertainty bands of valence quark distributions, at $Q^2 = 1.9\,\mathrm{GeV}^2$, for most of the available recent PDF determinations. Top: up valence quark; down: down valence quark; left: logarithmic x, right: linear x.

Fig. 4.8. As can be seen, the uncertainty of the down valence quark distribution at, for example, $x = 0.7$ is reduced from a level of $50 - 100\,\%$ to about $5\,\%$. The up valence quark distribution is better known than d_v, because it enters with a four-fold weight in F_2, due to the electric quark charge ratio squared, a big improvement yet is also visible. These huge improvement effects at large x are a consequence of the high precision measurements of the NC and the CC inclusive cross sections, which at high x tend to $4u_v + d_v$ and u_v (d_v) for electron (positron) scattering, respectively. At HERA the luminosity and range had not been high enough to allow a similar measurement as will be possible for the first time with the LHeC. This is illustrated in Fig. 4.9 which compares the HERA II result of the ZEUS Collaboration, H1's still to be released, on the CC cross section with the LHeC simulation.

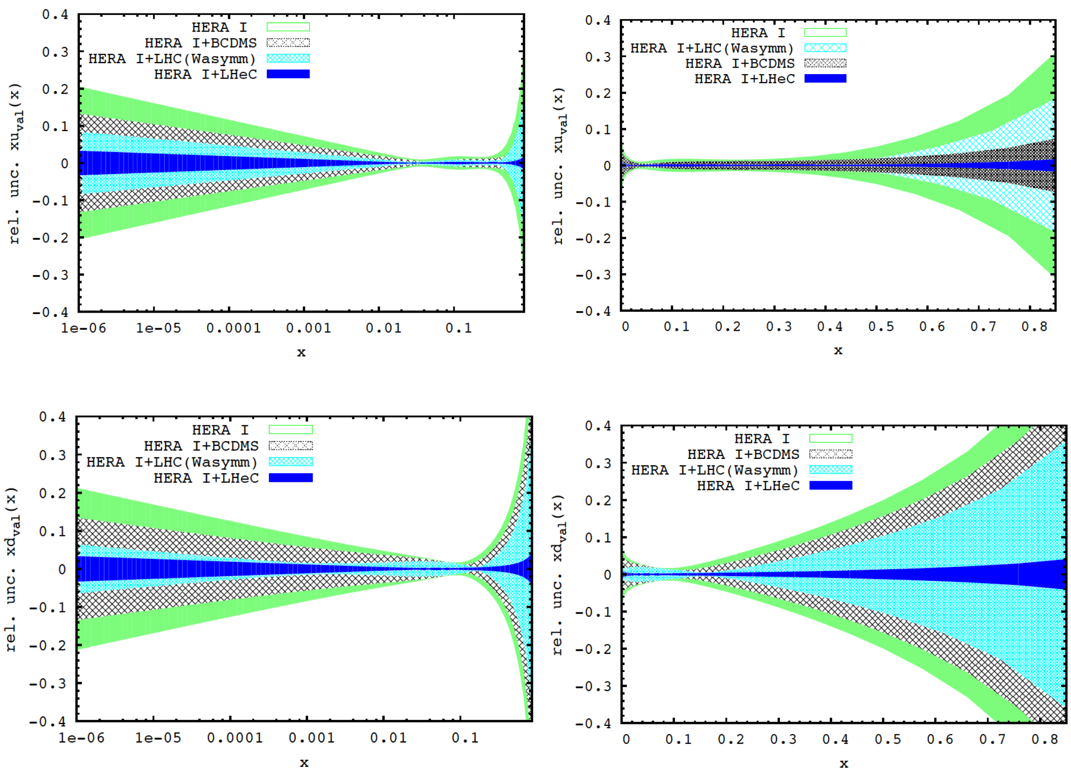


Figure 4.8: Uncertainty of valence quark distributions, at $Q^2 = 1.9\,\mathrm{GeV}^2$, as resulting from an NLO QCD fit to HERA (I) alone (green, outer), HERA and BCDMS (crossed), HERA and LHC (light blue, crossed) and the LHeC added (blue, dark). Top: up valence quark; down: down valence quark; left: logarithmic x, right: linear x.

Access to valence quarks at low x can be obtained from the $e^{\pm}p$ cross section difference as

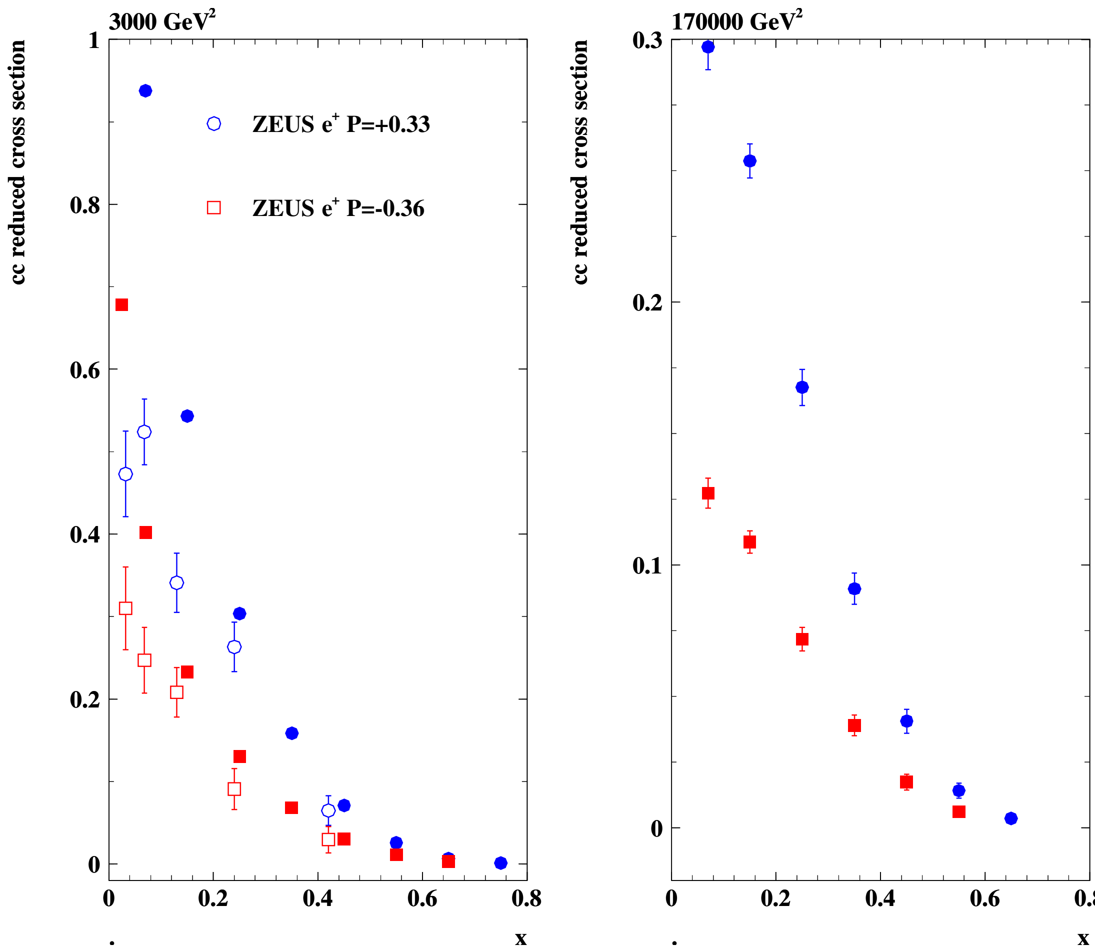


Figure 4.9: Reduced charged current e^+p scattering cross section versus Bjorken x for different polarisations $\pm P$ and values of Q^2. Closed points: LHeC simulations for $10\,\text{fb}^{-1}$; open points: ZEUS measurements based on the full HERA statistics of about $0.15\,\text{fb}^{-1}$ per polarisation 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 dependend factors Y_-/Y_+, which is at the origin of the simulated and measured cross section differences apparent at lower x.

introduced above:

$$\sigma^{-}_{r,NC} - \sigma^{+}_{r,NC} = 2\frac{Y_-}{Y_+}(-a_e \cdot kxF_3^{\gamma Z} + 2v_e a_e \cdot k^2 xF_3^Z). \tag{4.25}$$

Since the electron vector coupling, v_e, is small and k not much exceeding 1, to a very good approximation the cross section difference is equal to $-2kY_- a_e xF_3^{\gamma Z}/Y_+$. In leading order pQCD this "interference structure function" can be written as

$$xF_3^{\gamma Z} = 2x[e_u a_u(U - \overline{U}) + e_d a_d(D - \overline{D})], \tag{4.26}$$

with $U = u + c$ and $D = d + s$ for four flavours. The $xF_3^{\gamma Z}$ structure function thus provides information about the light-quark axial vector couplings (a_u, a_d) and the sign of the electric quark charges (e_u, e_d). Equivalently one can write

$$xF_3^{\gamma Z} = 2x[e_u a_u(u_v + \Delta_u) + e_d a_d(d_v + \Delta_d)]. \tag{4.27}$$

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

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

with $\Delta = 2\Delta_u + \Delta_d$. Neglect of Δ leads to a sum rule [34], which in leading order is

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

The $xF_3^{\gamma Z}$ structure function thus is determined by the valence quark distributions and predicted to be only very weakly depending on Q^2. Fig. 4.10 shows a simulation of $xF_3^{\gamma Z}$ and its comparison with the so far most accurate measurement from HERA. With such a high precision interesting tests are possible of the relation of $xF_3^{\gamma Z}$ to xW_3, which should only differ by the weak couplings involved in NC and CC.

4.2.3 Strange Quarks

The strange quark distribution $s(x, Q^2)$ has been very difficult to measure. In DIS some information is obtained from di-muon production in neutrino-nucleon scattering. Often s is linked to the behaviour of the sea quarks. Recently the HERMES Collaboration, from kaon multiplicities, derived an unusual behaviour of the strange quark density as compared to previous analyses [35]. Some hints for a difference between the s and $\overline{s}$ distributions have been discussed. The existing information on the sum of the strange and anti-strange quark distributions is plotted in Fig. 4.11. Obviously there is no real understanding of the strange quark distribution in the proton available. This will change with the LHeC. Here s and $\overline{s}$ may be very well measured as a function of x and Q^2 from the $W^+s \to c$ and $W^-\overline{s} \to \overline{c}$ processes, i.e. with charmed quark tagging in CC DIS using electron and positron beams, respectively. The precision for s which may be obtained is illustrated in Fig. 4.12. Accurate measurements may be obtained for the first time ever. The simulation of $\overline{s}$ obviously leads to the same picture such that over a wide kinematic range possible differences between s and $\overline{s}$ may be established.

[2] However, 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.

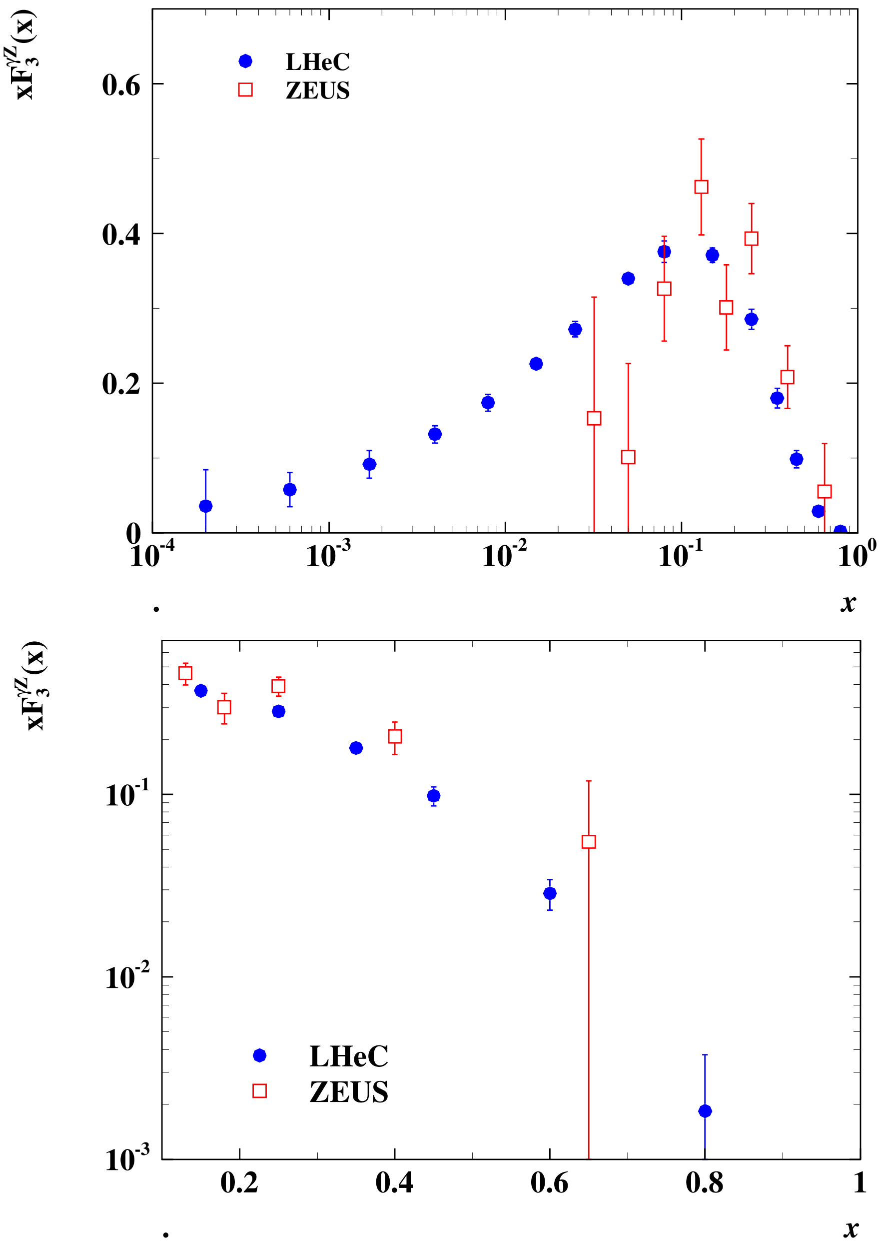


Figure 4.10: Simulation (top) of the LHeC measurement of the interference structure function $xF_3^{\gamma Z}$ from unpolarised $e^{\pm}p$ scattering with $10\,\mathrm{fb}^{-1}$ luminosity per beam (blue, closed points) compared with the HERA II data as obtained by the ZEUS Collaboration with about $0.15\,\mathrm{fb}^{-1}$ luminosity per beam charge. This measurement at HERA is limited by its statistical accuracy mainly and therefore with the forthcoming H1 data added, only an about $1/\sqrt{2}$ improvement of the precision at HERA can be expected. 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 $1500\,\mathrm{GeV}^2$ exploiting the fact that the valence quarks are approximately independent of Q^2. The lower plot is a zoom into the high x region.

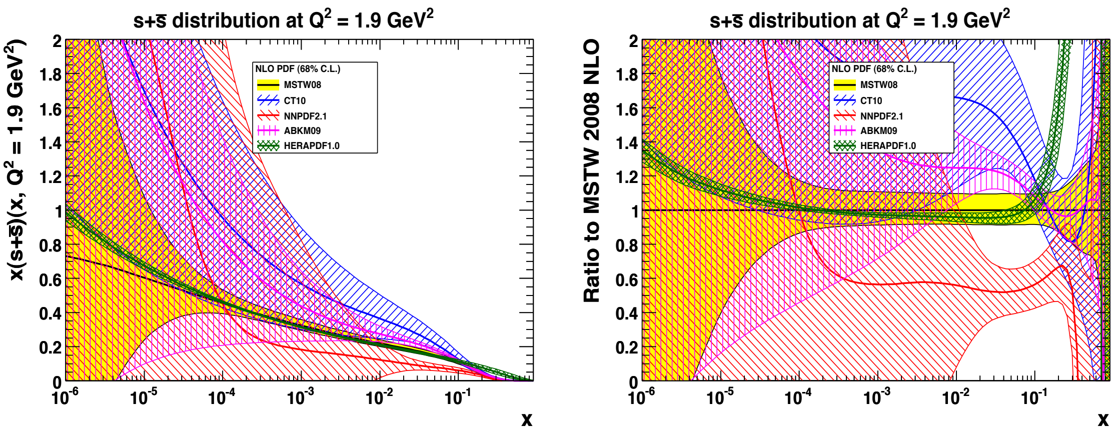


Figure 4.11: Sum of the strange and anti-strange quark distribution as embedded in the NLO QCD fit sets as noted in the legend. Left: $s+\bar{s}$ versus Bjorken x at $Q^2 = 1.9\,\mathrm{GeV}^2$; right: ratio of $s+\bar{s}$ of various PDF determinations to MSTW08. In the HERAPDF1.0 analysis (green) the 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 $s+\bar{s}$.

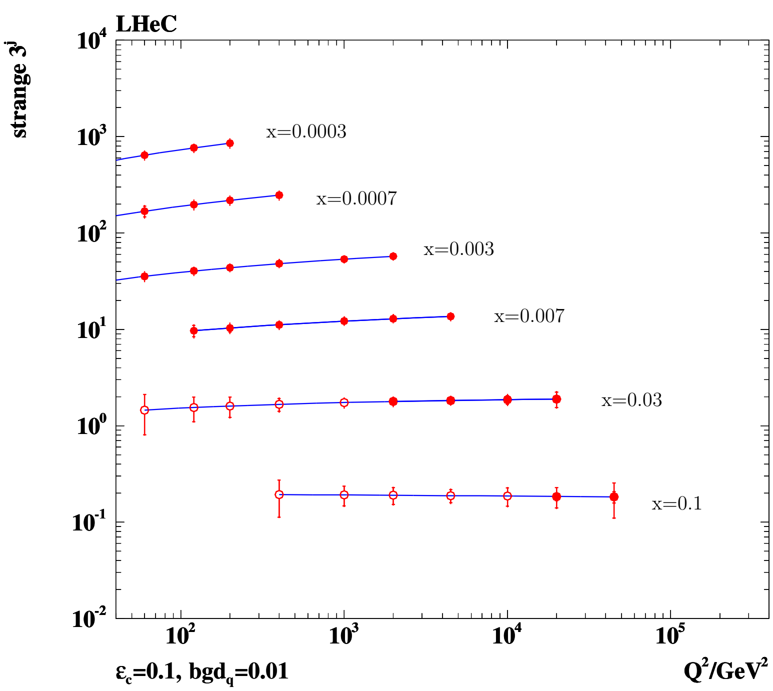


Figure 4.12: Simulated measurement of the strange quark density with the LHeC. Closed (open) points: tagging acceptance down to 10 (1°).

4.2.4 Top Quarks

The top is the heaviest of the quarks. It decays before hadrons are formed. It has not been explored in DIS yet because the cross sections at HERA have been to small [36]. This is different at the LHeC where top in charged currents is produced with a cross section of order 5 pb^{-1} as can easily be estimated from the LO calculation of Wb scattering. At the LHeC therefore, for the first time, one can study top quarks in deep inelastic scattering. Positron (electron) proton charged current scattering provides a clear distinction between top (anti-top) quark production in Wb to t fusion. The rates of this process are very high, as is illustrated as a function of Q^2 in Fig. 4.13. Besides the rates and the charge tag it is noteable that the absence of pile-up and

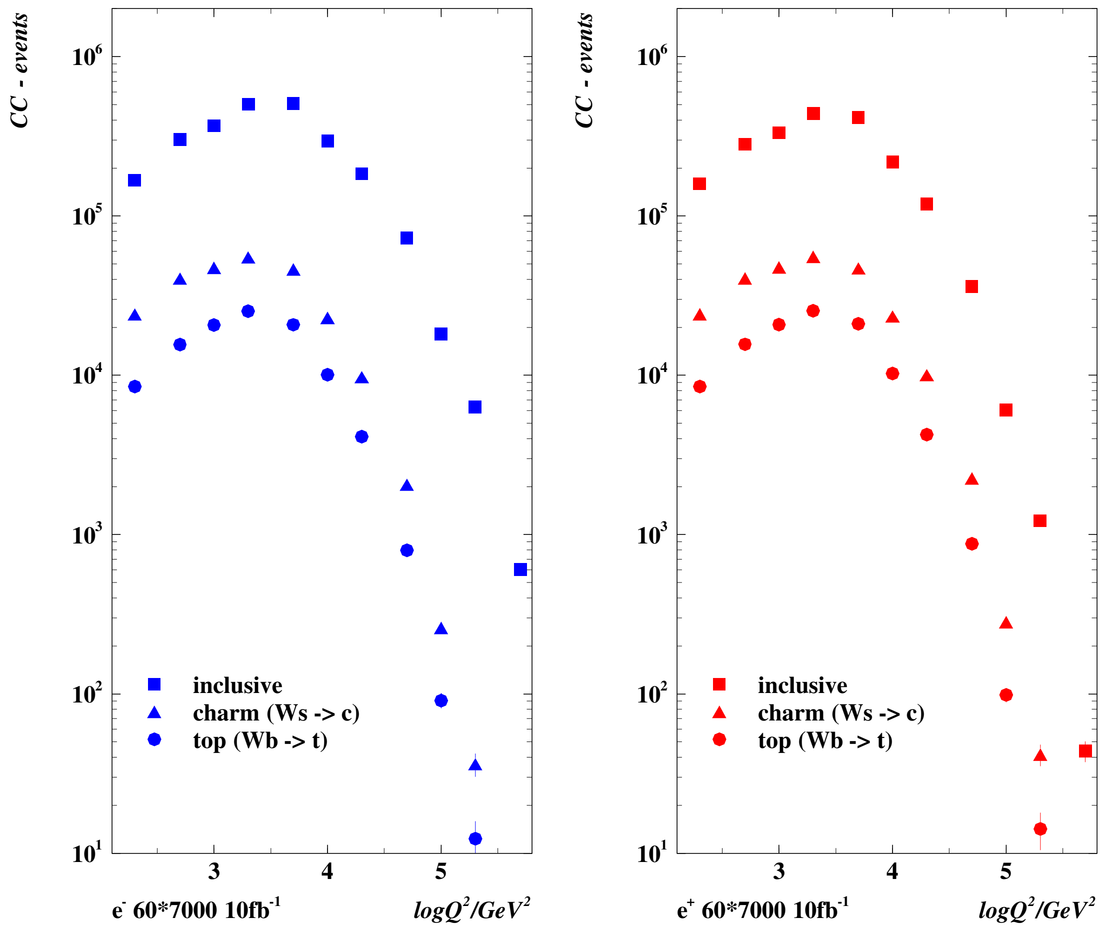


Figure 4.13: Charged current event rates for unpolarised e^-p (left) and e^+p (right) scattering in which $\bar{t}$ and t is produced, respectively. Squares: inclusive CC rate vs. Q^2; triangles: charm production from Ws fusion; closed cirles: top production from Wb fusion, estimated in a massless heavy flavour treatment. The rates are calculated for the default beam energies for 10 fb^{-1} of integrated luminosity. The errors are only statistical.

underlying event effects, characteristic for LHC measurements, provide comfortable conditions for top quark physics at the LHeC.

Due to its large mass, the top quark may very well play a role in the mechanism of electroweak symmetry breaking (EWSB) both in the Standard Model as well as BSM physics. In the Standard Model, a precise measurement of single top production in DIS (see for example [37]) is sensitive to the b quark content of the proton. In a BSM EWSB scenario, the top quark will couple to the new physics sector and give rise to anomalous production modes. The LHeC is expected to provide competitive sensitivity to flavor changing neutral currents (FCNC) especially anomalous $tu\gamma$ and tuZ couplings.

In the SM, top is produced dominantly in gluon-boson fusion at $x \lesssim 0.1$. In CC this leads to a top-beauty final state while in NC this gives rise to pair produced top-antitop quarks, with a cross section of order 10 times lower than in CC [36]. The electron beam charge distinguishes top and anti-top quark production in CC. Thus a unique SM top physics program can be performed at the LHeC. This includes the consideration of a top-quark density which at very high scales may be considered "light". Recently a six-flavour variable number scheme has been proposed [38], limited so far to leading order, in which it is predicted that the top contribution to proton structure has an on-set much below the threshold of its production in a massless scheme. This is illustrated in Fig. 4.14. Due to the very high Q^2 and statistics, the LHeC opens top quark PDF physics as a new field of research.

Top, including anomalous couplings, has been considered for the CDR initially [39], based on some ANOTOP and PYTHIA studies at generation level. With a detector now simulated in GEANT4 and in the light of the first top results provided by the LHC experiments [40], as well as further prospects, the CC and NC top physics at the LHeC deserves a more detailed study. This shall include an analysis about the possible precision measurement of the top (and anti) top quark mass, which at the LHC may be determined with an accuracy of 1 GeV and possibly be better in ep. Independently of whether one soon finds the SM 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 approriate 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 meaurements 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

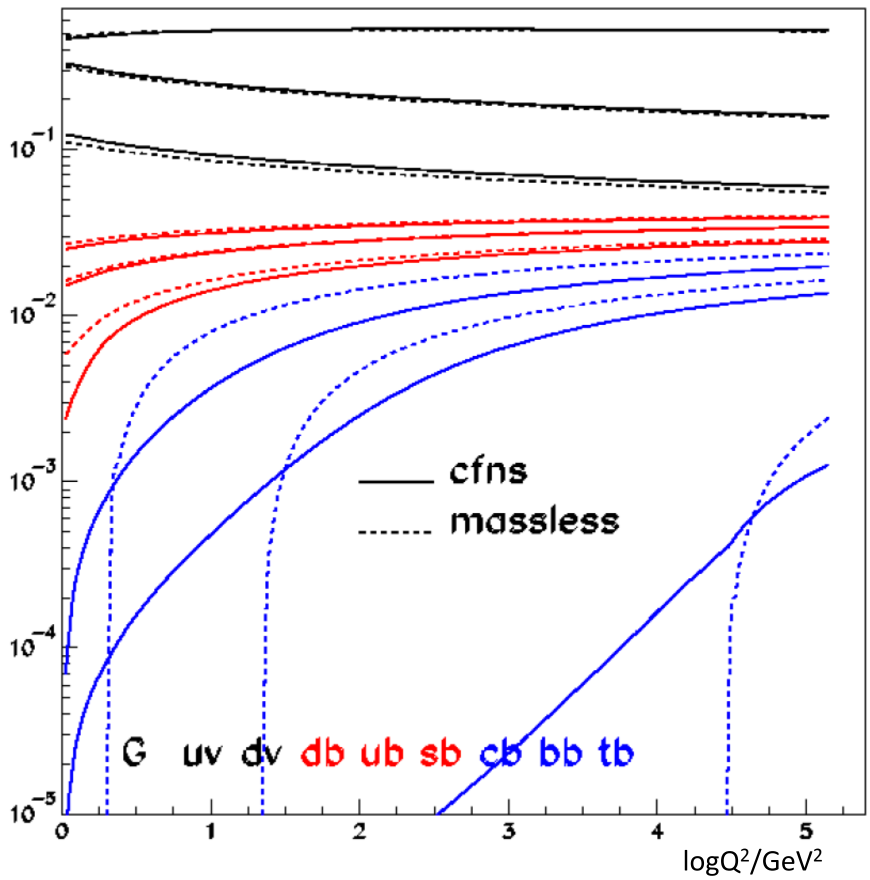


Figure 4.14: Parton momentum fractions as a function of Q^2 in a novel six-flavour variable number scheme (CFNS), solid curves, and in the massless scheme, dashed curves. At HERA one has observed beauty and charm production already below the conventional threshold of $\sqrt{Q^2} = m_Q$. The scheme of [38] suggests that there is a very early onset of top with measurable rates already at Q^2 values of only about one tenth of $m_t^2 \simeq 3\ 10^4\,\mathrm{GeV}^2$. With the LHeC the 'PDF' top physics is expected to commence.

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 [41], 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. 4.15 showing the world determinations, and their uncertainties, of $xg(x, Q^2)$ at a typical initial, low scale, and from Fig. 4.16 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. 4.15, as compared to the other determinations, albeit with large uncertainties.

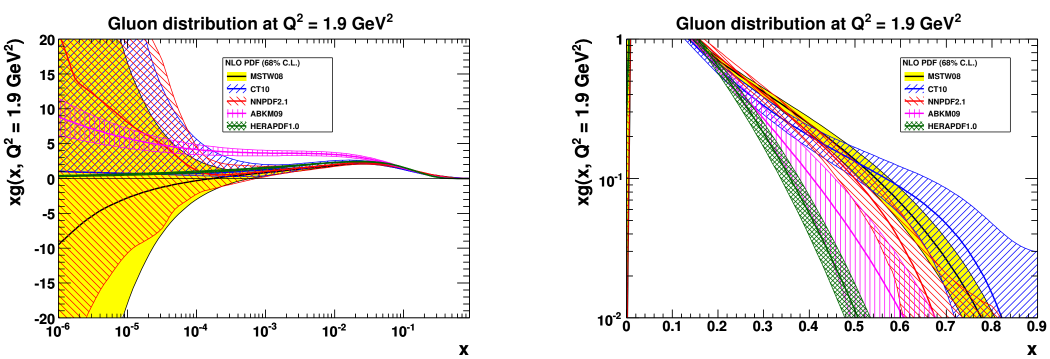


Figure 4.15: Gluon distribution and uncertainty bands, at $Q^2 = 1.9\,\mathrm{GeV}^2$, for most of the available recent PDF determinations. Left: logarithmic x, right: linear x.

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. 4.17. 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 [10], related to the difficulty of parameterising the PDFs and choosing the optimum solution

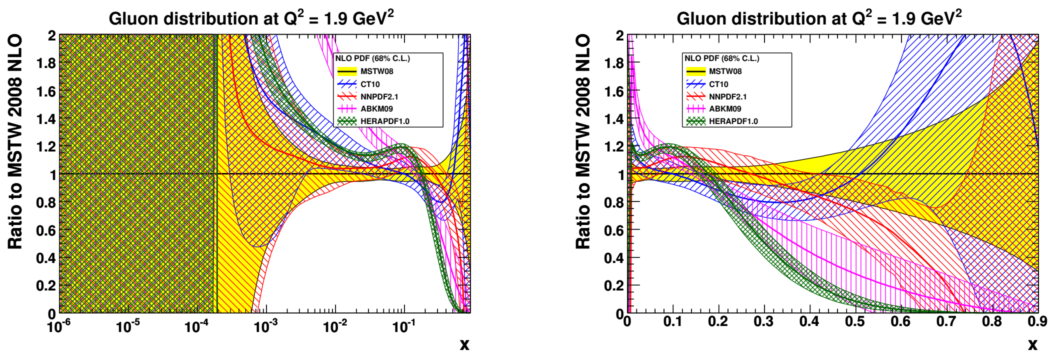


Figure 4.16: Ratios to MSTW08 of gluon distribution and uncertainty bands, at $Q^2 = 1.9\,\mathrm{GeV}^2$, for most of the available recent PDF determinations. Left: logarithmic x, right: linear x.

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.

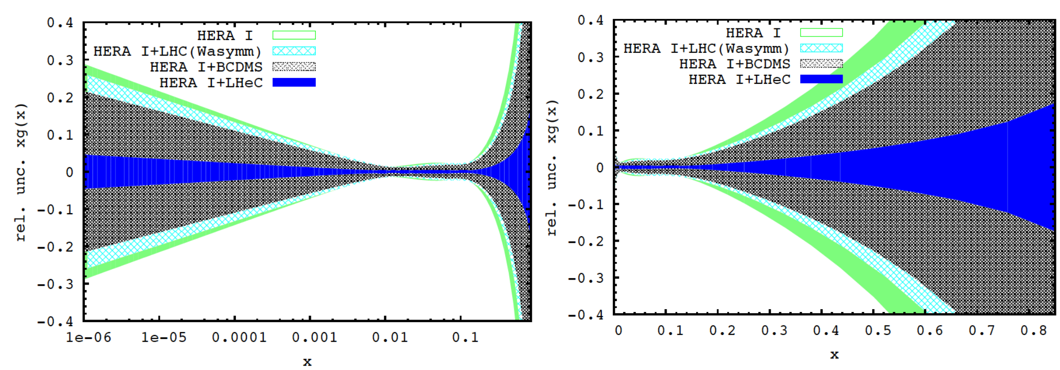


Figure 4.17: Relative uncertainty of the gluon distribution at $Q^2 = 1.9\,\mathrm{GeV}^2$, as resulting from an NLO QCD fit to HERA (I) alone (green, outer), HERA and BCDMS (crossed), HERA and LHC (light blue, crossed) and the LHeC added (blue, dark). Left: logarithmic x, right: linear x.

4.4 Prospects to Measure the Strong Coupling Constant

The precise knowledge of $\alpha_s(M_Z^2)$ is of instrumental importance for the correct prediction of the electro-weak gauge boson production cross sections and the Higgs boson cross section at Tevatron and the LHC [42]. Indepently of such applications, the accurate determination of the coupling constants of the known fundamental forces is of importance in the search for their possible unification within a more fundamental theory. Among the coupling constants of the forces in the Standard Model, the strong coupling α_s exhibits the largest uncertainty, which is currently of the size of $\sim 1\%$. Any future improvement of this accuracy, along with the consolidation of the genuine central value, is one of the central issues of contemporary elementary particle physics. It demands deep experimental and theoretical efforts to obtain the required precision and especially to handle all essential systematic effects.

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

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

4.4.1 Status of the DIS Measurements of α_s

During the last 35 years the strong coupling constant has been measured with increasing accuracy in lepton-nucleon scattering in various experiments at CERN, FERMILAB and DESY. The precision, which has been reached currently, requires the description of the deep-inelastic scattering structure functions at $O(\alpha_s^3)$ [43–45].

[3] These are presented below but have not been used in this document for a determination of the strongh coupling constant. One knows of course that the use of jet data in DIS helps resoving 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 [46]
GRS	0.112	valence analysis, NNLO [47]
ABKM	0.1135 ± 0.0014	HQ: FFNS $N_f = 3$ [48]
ABKM	0.1129 ± 0.0014	HQ: BSMN-approach [48]
JR	0.1124 ± 0.0020	dynamical approach [49]
JR	0.1158 ± 0.0035	standard fit [49]
MSTW	0.1171 ± 0.0014	[50]
ABM	0.1147 ± 0.0012	FFNS, incl. combined H1/ZEUS data [51]
BBG	$0.1141\ ^{+0.0020}_{-0.0022}$	valence analysis, N^{3}LO [46]
world average	0.1184 ± 0.0007	[52]

Table 4.3: Recent NNLO and N^{3}LO determinations of the strong coupling $\alpha_s(M_Z)$ in DIS world data analyses.

As is well known [53], though also questioned [54], 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 [46, 47]. The analysis [46] 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 $\overline{d} - \overline{u}$ distributions and the $O(\alpha_s^2)$ heavy flavor corrections were accounted for. The analysis could be extended to N^{3}LO effectively due to the dominance of the Wilson coefficient in this order [44] if compared to the anomalous dimension, cf. [**?**, 46]. 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 [48]. In the fixed flavor number scheme (FFNS) the value of $\alpha_s(M_Z^2)$ is the same as in the non-singlet case [46]. The comparison between the FFNS and the BMSN scheme [55] 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 [49] are statistically compatible with the results of [46–48], while those of [50] yield a higher value.

In [51] 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 [56] and the account of recent F_L data reduce this value again to the NNLO value given in [48]. 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 [57, 58], 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 [52] based on NLO, NNLO and N^{3}LO 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 $\alpha_s(M_Z) \simeq 0.113$ [59] and exhibit some peculiar systematic error effects, when compared to the SLAC data and in the pQCD analyses as are discussed in [60, 61]. 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 on wants to unambigously determine the strong coupling constant in DIS. These problems have been discussed in detail above, and recently also in presentations by MSTW [62] and in a phenomenological study of the NNPDF group [63].

The question, of how large α_s is, remains puzzling, as has been discussed at a recent workshop [64] 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 uncertainy, 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 $10\,\mathrm{GeV}^2$ 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 neccessary. However, as mentioned above there already exist first N^3LO 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 precison and unprecented 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 [65] are in good agreement with the numbers presented here.

case	cut [Q^2 in GeV^2]	α_S	$\pm$uncertainty	relative accuray 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 mimimum parameter set used in [10] and the other one with four extra parameters added as has been described VOICAWHERE. 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.

4.5 Electron-Deuteron Scattering

The structure of the deuteron and of the neutron are experimental unknowns over most of the kinematic region of deep inelastic scattering. The last time lepton-deuteron scattering was measured occured in the fixed target μD experiments at CERN [66–68], while it had only been considered at HERA [69–71]. The LHeC so extends the range of these measurements by nearly four orders of magnitude in Q^2 and $1/x$, which gives rise to a most exciting programme in QCD and in experimental physics.

DIS and Partons

Electron-deuteron scattering complements ep scattering in that it makes possible accurate measurements of neutron structure in the new kinematic range accessed by the LHeC. In a collider configuration, in which the hadron "target" has momentum much larger than the lepton probe, the spectator proton can be tagged and its momentum measured with high resolution [69]. The resulting neutron structure function data are then free of nuclear corrections which have plagued the interpretation of deuteron data, especially at larger x, until now [72]. At low x, for the first time, since diffraction is related to shadowing, one will be able to control the shadowing corrections at the per cent level of accuracy as is also discussed below.

Accurate en cross section measurements will resolve the quark flavour decomposition of the sea, i.e. via 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 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 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 since it disentangles the evolution of the non-singlet and the singlet contributions. Down to x of about 10^{-3} the W^+/W^- LHC data will also provide important information on the up-down quark distributions, albeit at high Q^2.

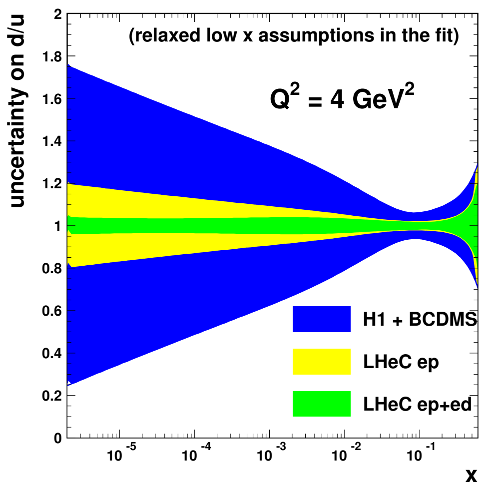


Figure 4.18: Uncertainty of the d/u ratio as a function of x from a QCD fit to H1 and BCDMS data (outer band, blue), to the LHeC proton data (middle band, yellow) and the combined simulated proton and deuteron data from the LHeC (inner band, green). In these fits the constraint of u and d to be the same at low x has been relaxed.

With ep, eD and W^+/W^- data, the low x sea will be resolved for the first time, as all the low x light quark information from HERA has been restricted to F_2^p only.

A special interest in high precision neutron data at high Q^2 arises from the question of whether there holds charge symmetry at the parton level. This, as has been discussed recently [73]. It may be studied in the charged current ep and eD reactions, using both electrons and positrons, by measuring the asymmetry ratio

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

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

Hidden Colour

In nuclear physics nuclei are simply the composites of nucleons. However, QCD provides a new perspective [74, 75]. Six quarks in the fundamental 3_C representation of $SU(3)$ color can combine into five different color-singlet combinations, only one of which corresponds to a proton and neutron. The deuteron wavefunction is a proton-neutron bound state at large distances, but as the quark separation becomes smaller, QCD evolution due to gluon exchange introduces four other “hidden color” states into the deuteron wavefunction [76]. The normalization of the deuteron form factor observed at large Q^2 [77], as well as the presence of two mass scales in the scaling behavior of the reduced deuteron form factor [74], suggest sizable hidden-color Fock state contributions in the deuteron wavefunction [78]. The hidden-color states of the deuteron can be materialized at the hadron level as $\Delta^{++}(uuu)\Delta^{-}(ddd)$ and other novel quantum fluctuations of the deuteron. These dual hadronic components become important as one probes the deuteron at short distances, such as in exclusive reactions at large momentum transfer. For example, the ratio $d\sigma/dt(\gamma d \to \Delta^{++}\Delta^{-})/d\sigma/dt(\gamma d \to np)$ is predicted to increase to a fixed ratio 2 : 5 with increasing transverse momentum p_T. Similarly, the Coulomb dissociation of the deuteron into various exclusive channels $ed \to e' + pn, pp\pi^{-}, \Delta\Delta, \cdots$ will have a changing composition as the final-state hadrons are probed at high transverse momentum, reflecting the onset of hidden-color degrees of freedom. The hidden color of the deuteron can be probed at the LHeC in electron deuteron collisions by studying reactions such as $\gamma^* d \to npX$ where the proton and neutron emerge in the target fragmentation region at high and opposite p_T. In principle, one can also study DIS reactions $ed \to e'X$ at very high Q^2 where $x > 1$. The production of high p_T anti-nuclei at the LHeC is also sensitive to hidden color-nuclear components.

4.6 Electroweak physics

Precision electroweak measurements at low energy have played a central role in establishing the Standard Model (SM) as the theory of fundamental interactions. More recently, measurements at LEP, SLD, and the Tevatron have confirmed the SM at the quantum level, verifying the existence of its higher-order loop contributions. The sensitivity of these contributions to virtual heavy particles has allowed for an estimate of the mass of the top quark prior to its actual discovery in 1995 by the CDF and DØ Collaborations. Now that the determination of the top mass at the Tevatron has become quite accurate, reaching the 1% level, electroweak precision measurements imply significant constraints on the mass of the last missing piece of the SM, the Higgs boson. The current situation is illustrated in fig.4.6, where the Higgs mass sensitivity of a global fit to electroweak precision observables in the SM is shown [79] (a similar analysis has been performed in [80]). The left panel shows the $\Delta\chi^2$ of a fit to all relevant electroweak observables, while the right panel also include information from direct searches for the Higgs boson at LEP-2 and the Tevatron. Indeed, direct searches exclude a Higgs boson with mass lower than 114GeV or in a narrow window around 160GeV. An important implication (at 95% CL) is that if the SM is correct, the Higgs boson must soon be found with mass below 155GeV either at the Tevatron or at LHC.

Electroweak precision measurements are also very effective in constraining the possible extensions of the SM. In general, the observed good quality of the SM fit disfavors new physics at an energy scale of O(100GeV) that modifies the Higgs mechanism in a drastic way. On the other hand, the fit does present a few interesting deviations at the level of 2-3σ. An important one is related to the tension between the FB asymmetry of $Z \to b\bar{b}$ measured at LEP, which favors a heavy Higgs, and the LR asymmetry in $Z \to \ell\bar{\ell}$ and the W mass, which both favors a very light Higgs. Unfortunately, the present determination of M_H depends largely on these conflicting information, whose origin could be either statistical or rooted in new physics around the corner [81]. Another plausible $\sim 3\sigma$ hint of physics beyond the SM, without Higgs implications, is the discrepancy between the measured magnetic anomalous moment of the muon and its SM prediction [82].

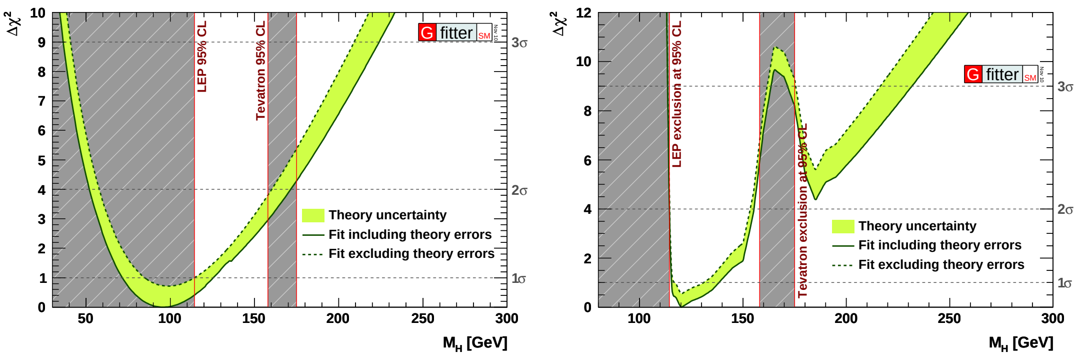


Figure 4.19: Higgs mass sensitivity of a current fit to precision electroweak observables [79]. The right panel includes the information from direct searches.

It is unlikely that operating experiments will change significantly the above picture of electroweak precision measurements. The Tevatron and LHC will marginally improve the current precision on the top mass and reach a combined 15 MeV uncertainty on M_W, while LHCb might be able to achieve an interesting accuracy in the measurement of $\sin^2\theta_W$, perhaps at the level of LEP [83,84]. Two experiments at Jefferson Lab, Q-weak [85] and (later) MOLLER [86], will measure the weak mixing angle from parity violation in $e-p$ and $e^- - e^-$ scattering at low energy: these are interesting measurements complementary to the existing ones; MOLLER, in particular, will reach an accuracy similar to that of LEP. On the other hand, it is widely expected that either the Higgs boson or new physics will be discovered at the LHC, if not both. This is the context in which precision electroweak measurements at LHeC have to be set: rather than improving bounds on the SM parameters they might help understand new physics, if that is discovered at LHC.

The electroweak measurements possible at LHeC are in essence the same that have already been performed at HERA (see [87, 88] for an overview), but they will greatly benefit from the higher energy and larger luminosity. A first class of measurements involves polarized charged currents (CC) only.

They include a verification of the left-handedness of CC from the polarization dependence of the CC cross-section. At HERA this has led to a bound on possible right-handed currents, expressed in terms of the mass of a right-handed W_R boson that couples to quarks with the same strength as the SM one. While HERA-I result, $M_{W_R} > 210$GeV at 95% CL, can be significantly improved at the LHeC, low-energy flavour bounds are much stronger. It is otherwise difficult to learn from CC alone. For instance, the Q^2-dependence of the CC cross sections, proportional to $G_F^2 (M_W^2/(M_W^2+Q^2))^2 \phi(x,Q^2)$, allows in principle to extract the propagator mass M_W, but the residual dependence on the structure of the nucleon requires a simultaneous fit to the pdfs, which necessarily includes NC cross sections as well. In fact, the sensitivity to M_W that can be achieved in this way is rather low: at LHeC, assuming SM NC couplings, the experimental error is about 150MeV (scenario D), far from being competitive. Higher sensitivity to M_W can in principle be obtained by trading G_F for the appropriate combination of $\alpha(M_Z), M_W, M_Z$ but then the precision in luminosity and other systematics become a bottleneck and one cannot achieve an M_W determination much better than above.

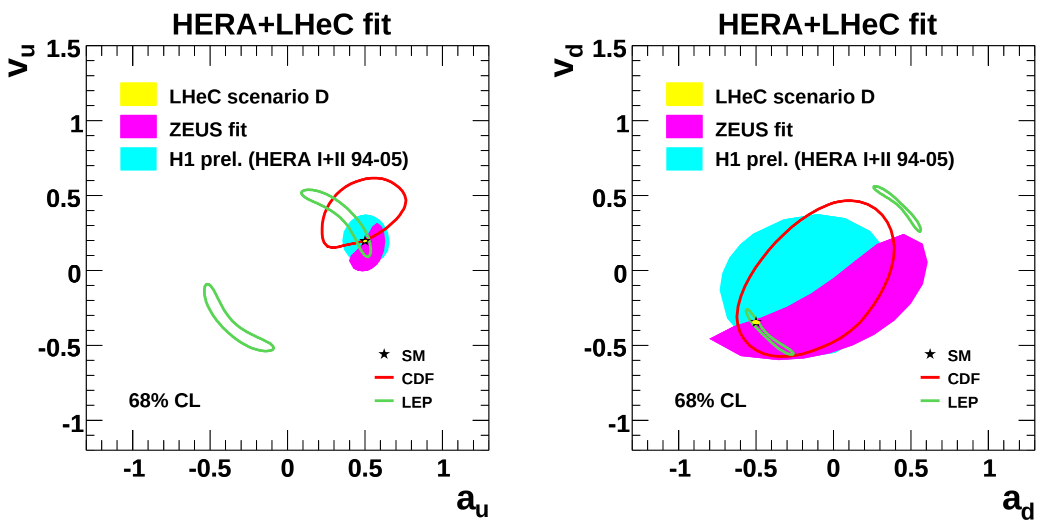


Figure 4.20: Determination of the vector and axial NC couplings of the light quarks at LEP, CDF, HERA and LHeC.

Paolo: this statement has to be checked. Using only HERA-I data H1 find an experimental uncertainty of about 200MeV if data are analyzed in this way. How much can this be improved at LHeC? I see a clear bottleneck: the precision in luminosity (most of the M_W sensitivity comes from the overall normalization) and the model error which in H1 paper is 40MeV. All other theoretical uncertainties can be brought significantly down.

On the other hand, LHeC will be able to measure at the percent level the neutral current couplings of the light quarks. As can be seen in Fig. 4.20, LEP has been able to constrain well only a combination of them. On the other hand, DIS experiments with polarized electron and positron beams can completely disentangle the vector and axial couplings of up and down type light quarks. Of course this requires a simultaneous fit to pdfs and electroweak couplings, keeping fixed the leptonic couplings, which have been very precisely measured at LEP and SLD. As illustrated in Fig.4.20, the preliminary results by ZEUS and H1 have improved on the LEP determination in the case of the up quarks [88–90]. The expected resolution for scenario D of LHeC is hardly visible on the scale of Fig. 4.20: the results for the various LHeC scenarios (and combination thereof) are shown in Table **??** *(still to be made, see later. It should be something like slide 43 of Claire's LHeC talk)*. The accuracy on the vector and axial vector couplings of the $u, d = s$ quarks ranges, in the best possible scenario, ranges between 1 and 4%, with an improvement wrt HERA by a factor 10 to 40. A comparison among the various LHeC scenarios can be found in Fig. 4.21: the most interesting scenarios are B and D. *(Assuming Voica's results for scenario B)* A high degree of polarization (scenario D) can be compensated by much higher luminosity (scenario B).

A better determination of the light quark NC couplings will particularly constrain New Physics models that modify significantly the light quark NC couplings, without affecting the well-measured lepton and heavy quark couplings. It is not easy to realize such an exotic scenario

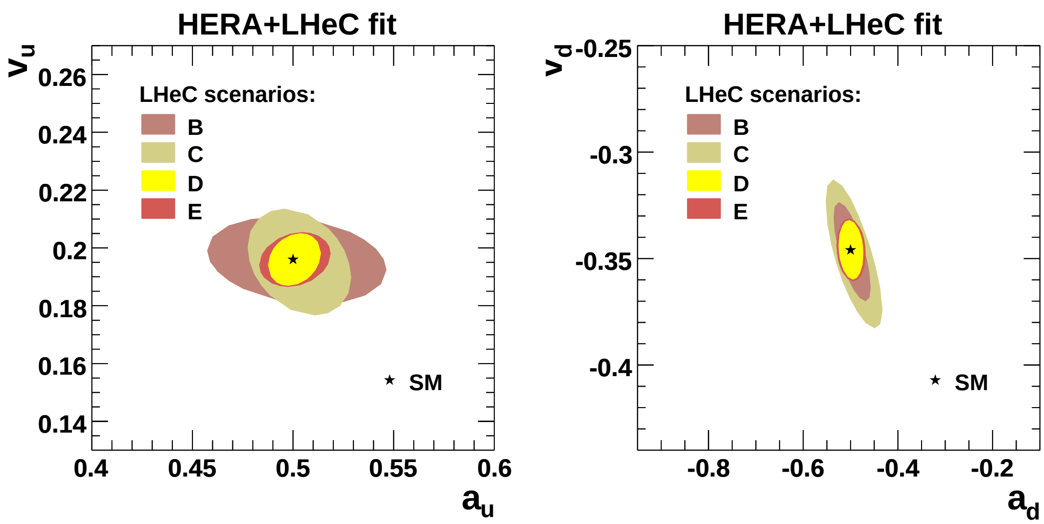


Figure 4.21: Determination of the vector and axial NC couplings of the light quarks at LHeC, comparison different scenarios. (TO BE UPDATED??)

in a natural way, although family non-universal (leptophobic) Z' models (see for instance [91,92] and refs. therein), R-parity violating supersymmetry (see [93] for a review) and leptoquarks [94] can in principle succeed. LHeC could therefore accurately test a spectrum of interesting new physics models. A specific linear combination of the light quark NC vector couplings (v_u and v_d) will be soon be measured at the % level by the QWeak Collaboration [85]. Their results, combined with existing precise measurement of Atomic Parity Violation and DIS, will provide a percent determination of v_u and v_d [95] and test the same kind of models, but it will not probe the axial couplings.

Additional issues concerning this fit:

- *Voica has shown that high precision can be obtained also in scenario B. Claire's results for B are less precise, likely because of lower angular coverage (down to 10 degrees, only for B). However, there are a few strange features in Voica's numbers (see my dec 10 email)*
- *what is the effect of combining scenarios B+H and other similar combinations of scenarios?*
- *what is the effect on electroweak couplings of relaxing the assumptions on the sea quarks (as Voica discusses on p.13 of her Chavannes slides)?*
- *I think somebody in Chavannes asked a question on the importance of polarized positrons for electroweak physics. Can we answer?*

If there is time, two easy, complementary analyses that might give a feeling of the constraining power in more general new physics models are the following

1. *we express all the NC quark and lepton couplings in terms of* $\sin^2\theta_W$*, and fit for it. NC and CC couplings are all normalized to* G_F*.*

2. *we express the lepton and quark couplings in terms of* $G_F, sin^2\theta_W$ *and* ρ *(a renormalization factor in front of the NC coupling), and fit for them, see PDG.*

A fit to oblique parameters S, T, U *is also possible but requires more work. Not important.*

4.6.1 Determination of the Weak Mixing Angle

Cross Section Asymmetries and Ratios

The LHeC is a unique facility for electroweak physics because of the very high luminosity, high measurement precision and the extreme range of momentum transfer Q^2. Fig. 4.22 illustrates the reach and the size of the electroweak effects in NC scattering. Depending on the charge and polarisation of the electron beam, the contributions from γZ interference and pure Z exchange become comparable to or even exceed the photon exchange contribution, i.e. of F_2, which has dominated hitherto all NC DIS measurements. With the availability of two charge and two polarisation states, of neutral and charged current measurements, proton and isoscalar targets, a unique menu becomes available for testing the electroweak theory, by measuring for example the light weak neutral current couplings, discussed subsequently, extracting the heavy quark contributions from γZ interference or measuring the energy dependence of the weak mixing angle, considered here.

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

In NC scattering, the polarisation asymmetry

$$A^{\pm} = \frac{1}{P_R - P_L} \cdot \frac{\sigma^{\pm}_{NC}(P_R) - \sigma^{\pm}_{NC}(P_L)}{\sigma^{\pm}_{NC}(P_R) + \sigma^{\pm}_{NC}(P_L)} \tag{4.31}$$

served for the decisive confirmation of the left handed weak neutral current doublet structure as was predicted by the GWS theory in 1979 [96]. The size of the electroweak asymmetries is given by the relative amount of Z to photon exchange $\mathrm{O}(10^{-4}Q^2/\mathrm{GeV}^2)$, i.e. it becomes of order 1 at high Q^2 at the LHeC.

To a good approximation the asymmetry measures the structure function ratio

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

Thus A^+ is expected to be about equal to $-A^-$ and to be only weakly dependent on the parton distributions. The product of the axial coupling of the electron and the vector coupling of the quarks, inherent in $F_2^{\gamma Z}$, determines the polarisation asymmetry to be parity violating. A measurement of $A^{\pm}$ provides a unique and precise measurement of the scale dependence of the weak mixing angle, as is discussed below (Sect. 4.6.1). At large x the polarisation asymmetry provides an NC measurement of the d/u ratio of the valence quark distributions, according to

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

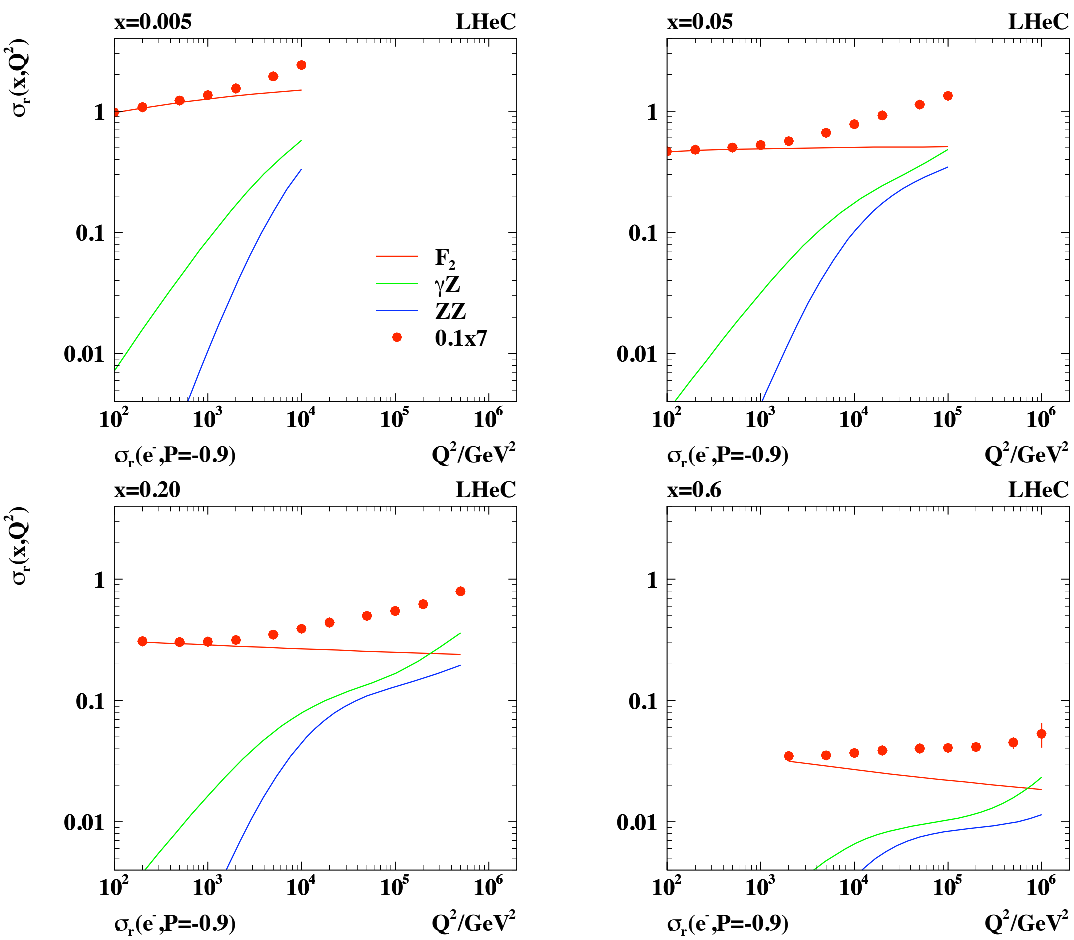


Figure 4.22: Simulated measurement of the neutral current DIS cross section (closed points) with statistical errors for $10\,\mathrm{fb}^{-1}$ shown as a function of Q^2 for different values of Bjorken x. The different curves represent the contributions of pure photon exchange (red), γZ interference (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.

Further asymmetries of NC cross sections have been discussed in [22].

The neutral-to-charged current cross-section ratio

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

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

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

which reveals the striking similarity of the neutral and charged weak interactions at high energies. One may further consider, for example, a quantity which is the eN analogon to the Paschos-Wolfenstein relation [97] in νN scattering

$$A_{NCC} = \frac{\sigma^{+}_{NC} - \sigma^{-}_{NC}}{\sigma^{+}_{CC} - \sigma^{-}_{CC}}. \tag{4.36}$$

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

Measurement of the Weak Mixing Angle

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

The accuracy estimated for $\sin^2\theta$ depends on its definition. The electroweak theory has three independent parameters. In the on-mass shell scheme, these are chosen to be the fine structure constant α and the weak boson masses, M_W and M_Z. For the subsequent study, as in a similar study of H1 [89], the values of α and M_Z are fixed, which are best known, M_Z to 0.002 %. For the estimate of the sensitivity to electroweak effects as the third parameter here $\sin^2\theta$ is chosen, which is used, together with α and M_Z to calculate G and M_W and also occurs in the weak neutral current couplings. This way both the NC and the CC cross sections are sensitive to $\sin^2\theta$. Equivalently one could have expressed all parameters using α, M_Z and M_W, and determine M_W. 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

$$\Delta M_W = \frac{M_W \delta \sin^2\theta}{2\sin^2\theta}, \tag{4.37}$$

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

A simulation is done of the NC and CC cross sections depending on the lepton beam charges and polarisations based on the formulae presented above. This allows to build a variety of asymmetries and cross section ratios and derive their sensitivity to the weak mixing angle. An example is illustrated in Fig. 4.23. Here the polarisation asymmetry (left) and the NC/CC ratio (right) are calculated for different values of $\sin^2\Theta$ using two recent sets of leading order parton distributions, CTEQ6LL and MSTW08. The measurement accuracy of $\sin^2\Theta$ has a statistical, a polarisation, a systematic and a pdf uncertainty. One derives that the statistical precision is about 0.1 % for the NC asymmetry A^- and even 0.05 % for the NC/CC ratio R^- for e^-p scattering with an assumed polarisation of -0.8 and a luminosity of $10\,\text{fb}^{-1}$ for default beam energies.

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

The requirements for A^- and R^- are different. The asymmetry A^- requires frequent changes of the polarisation to control the time dependence of the measurement. It measures essentially a ratio of the structure functions $F_2^{\gamma Z}/F_2$ and therefore it is rather insensitive to uncertainties related to the parton distributions. In fact, one observes in Fig. 4.23 that the predictions of the two PDF sets considered differ by less than the statistical uncertainty for A^-. The NC/CC ratio R is less sensitive to time drifts as the NC and CC data are taken simultaneoulsy. Its statistical power is highest, as had already been noticed for HERA [98]. It yet is sensitive to the PDFs. For the two sets of PDFs considered here, an about two per cent difference is calculated of the R^- ratios. This would spoil the extraction of $\sin^2\Theta$. The high sensitivity of R to the mixing angle can only be employed when the PDFs are much better known than so far. This, however, is one of the major goals of the LHeC physics programme and large improvements are to be expected as is discussed in Sec. 4.2. The potential of measuring $\sin^2\Theta$ from NC/CC ratios is observed to be particular striking. However, for the evaluation of the scale dependence of $\sin^2\Theta$ below, the results derived from A^- are used due to its much smaller PDF sensitivity.

The mixing angle, similar to α_s, is predicted to vary strongly as a function of the scale μ, which in DIS is precisely known and given as $\sqrt{Q^2}$. This dependence results from higher order loop effects as calculated in [99]. Precise measurements to per mille uncertainty were performed at the Z pole by SLC and LEP experiments. Recent low energy experiments have provided measurements of $\sin^2\Theta$ at very low Q^2 as from the parity violation asymmetry due to polarisation conjugation in Moeller scattering at $Q^2 = 0.026\,\text{GeV}^2$ by the E158 experiment. At scale values of about 5 GeV the NuTeV Collaboration has determined the mixing angle which for some time created a substantial epxerimental and theoretical effort when it appeared to be above the theoretical expectation by a few standard deviations. Explanations of this "anomaly" included variations of the strange quark density, effects from QED or nuclear corrections. An ultraprecise measurement of $\sin^2\Theta$ is envisaged, yet still at $\mu = M_Z$, if a new Z_0 factory was built.

The current measurements are summarised in Fig. 4.24. The plot also contains projected $\sin^2\Theta$ uncertainty values from the LHeC, as listed in Table 4.5, which result from simulations of the parity violation asymmetry A^- in polarised e^-p scattering, for scales between about 10 and 400 GeV. Due to the high statistics nature of the DIS NC process, the variation of $\sin^2\Theta$ as

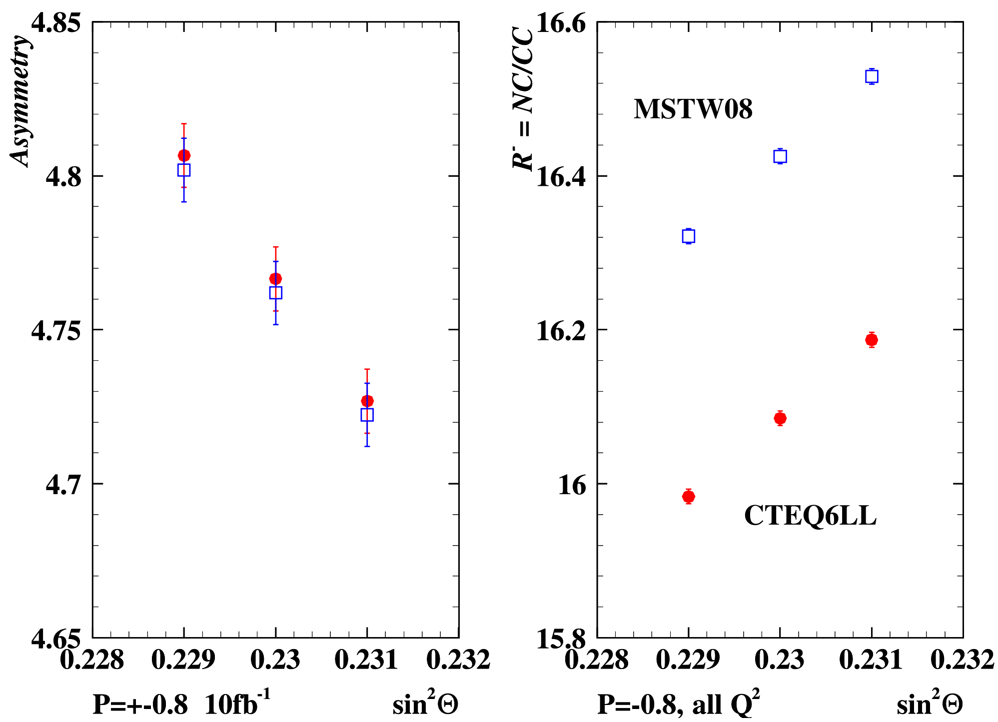


Figure 4.23: Simulated measurement of the polarisation NC cross section asymmetry A^- (left), in per cent for $P = \pm 0.8$, and the ratio of neutral-to-charged current cross sections, $R = NC/CC$ (right), for $P = -0.8$, for different values of $\sin^2\theta$ defined in the on-mass shell scheme. The errors are statistical for luminosities of $10\,\text{fb}^{-1}$ per beam for polarised electron scattering for $E_e = 60\,\text{GeV}$ and the nominal $7\,\text{TeV}$ proton beam. The closed (open) symbols show the simulation for the CTEQ6LL (MSTW08) leading order parametersisations of the parton distributions. The average Q^2 is $1300\,\text{GeV}^2$ for the NC asymmetry A^-, while for the ratio R the average CC Q^2 is about $9500\,\text{GeV}^2$. 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.

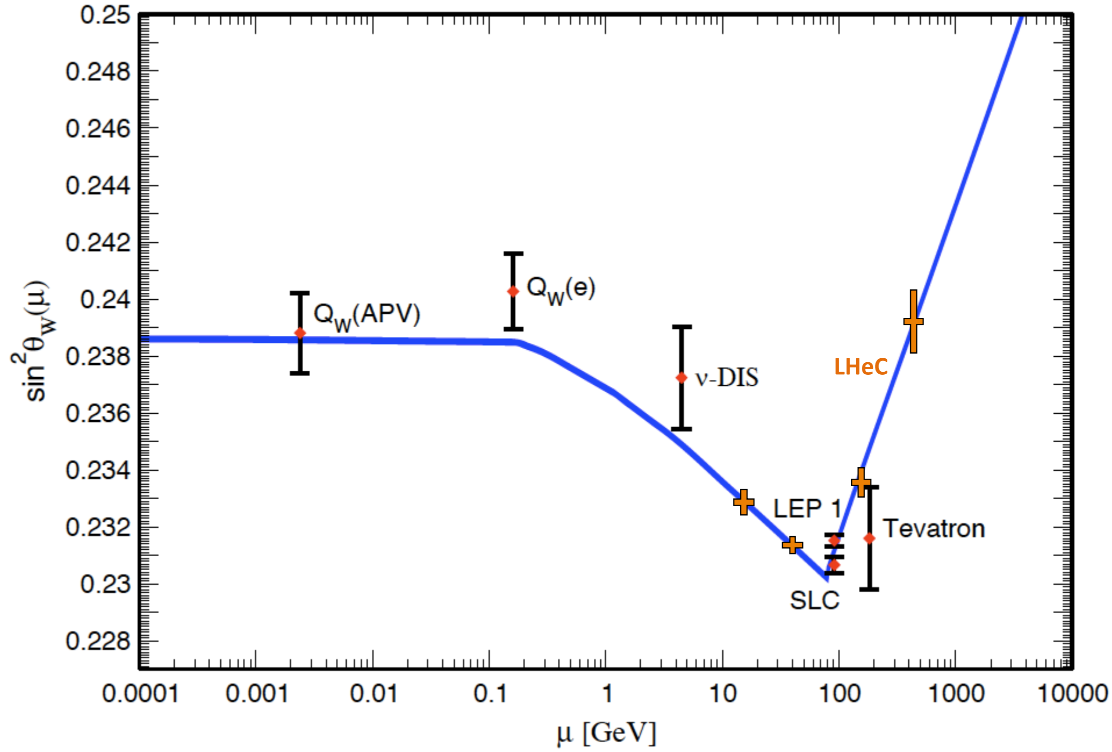


Figure 4.24: Dependence of the weak mixing angle in the on-mass shell scheme on the energy scale μ, taken from [28]. Four simulated points have been added based on the estimated measurement accuracy using the polarisation asymmetry A^- binned in intervals of $\sqrt{Q^2}$, see text.

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 $Q^2 \sim 300\,\mathrm{GeV}^2$	-1.	-0.8	-1.	0.8	0.00068	0.00029	0.00083
e^- PC Med $Q^2 \sim 1500\,\mathrm{GeV}^2$	-1.	-0.8	-1.	0.8	0.00027	0.00012	0.00029
e^- PC High $Q^2 \sim 22000\,\mathrm{GeV}^2$	-1.	-0.8	-1.	0.8	0.00044	0.00071	0.00055
e^- PC vHigh $Q^2 \sim 130000\,\mathrm{GeV}^2$	-1.	-0.8	-1.	0.8	0.00170	0.00460	0.00200

Table 4.5: Estimated accuracies of the weak mixing angle, $\delta \sin^2 \Theta$, in the on-mass shell scheme, from simulated measurements of the NC asymmetry and the NC/CC cross section ratio for different beam charge and polarisation conditions.

a function of $\sqrt{Q^2}$ can be measured for a large range of $\sqrt{Q^2}$. At low scales the range limited by the sensitivity to the Z exchange effects and at high scales by the kinematic limit and luminosity. It may deserve a study to understand to how low values of Q^2 the asymmetry A^- can be determined in a meaningful measurement, which is related to time drifts, polarisation flip times etc. and likely can only be answered with real data. It is to be noted that previous and planned fixed target experiments measure this asymmetry at extremely small values of Q^2 as compared to the range of the LHeC.

From the range considered here, with $Q^2 > 300\,\mathrm{GeV}^2$, it can be concluded, see Fig. 4.24, that the expected measurement accuracy would lead to a decisive test of the scale dependence of $\sin^2 \Theta$.

4.7 Charm and Beauty production

4.7.1 Charm and Beauty production at LHeC

Introduction and overview of expected highlights

In this section it is shown that the measurements of charm and beauty production at LHeC provide high precision pQCD tests and are crucial to improve the knowledge of the proton structure. Historically the HERA charm and beauty studies extended by large amount results from previous fixed target experiments. This allowed a great advancement in the understanding of the dynamics of heavy quark production. The LHeC is the ideal machine for a further extension of similar historic importance because a higher centre of mass energy and a much larger integrated luminosity compared to HERA are available. On top of this the heavy flavour measurements will greatly benefit from the advanced detector design at LHeC with high precision (Silicon or similar) trackers all over the place. At HERA the tagging was restricted to central rapidities and effective efficiencies[4] of only 0.1% (1%) for charm (beauty) were reached. At LHeC efficiencies of 10% (50%) should be possible for charm (beauty) and a large rapidity range can be covered from the very backward to the very forward regions. Before further elucidating the great measurement prospects the next paragraph introduces the main heavy quark production processes, the relevant pQCD theoretical schemes and some related open questions.

In leading order, heavy quarks are produced in ep collisions via the Boson Gluon Fusion (BGF) process shown in Figure 4.25 on the left. This process provides direct access to the

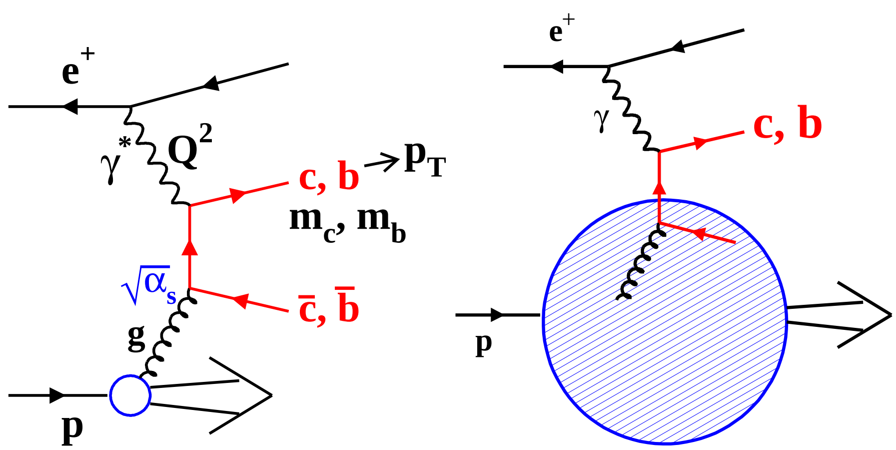


Figure 4.25: Left: Leading order Boson Gluon Fusion (BGF) diagram for charm and beauty production in ep-collisions. Right: Sketch of the leading order process in the massless approach where charm and beauty quarks are treated as massless sea quarks in the proton.

gluon density in the proton. BGF type processes dominate DIS scattering towards lower x, due to the large gluon density. In the high Q^2 limit, the events with charm and beauty quarks are expected to account for $\sim 36\%$ and $\sim 9\%$ of the BGF processes and hence contribute significantly to inclusive DIS. On the theoretical side, the description of heavy quark production in the framework of perturbative QCD is complicated due to the presence of several large scales like the heavy quark masses, the transverse momentum p_T of the produced quarks and the momentum transfer Q^2. Different calculation schemes have been developed to obtain predictions from pQCD. At low scales p_T (or Q^2) the fixed-flavour number scheme (FFNS) [100–102] is expected to be most appropriate where the quark masses are fully accounted for. At very high scales the NLO FFNS scheme predictions are expected to break down since large logarithms $\ln(p_T^2/m^2)$ are neglected that represent collinear gluon radiations from the heavy quark lines. These logarithms can be resummed to all orders in the alternative zero-mass variable flavour number (ZM-VFNS) [103–106] schemes. Here the charm and beauty quarks are treated above kinematic threshold as massless and appear also as active sea quarks in the proton, as depicted in figure 4.25 in the sketch on the right. Most widespreadly used are nowadays the so-called generalised variable flavour number schemes (GM-VFNS) [107, 108]. These mixed schemes converge to the massive and massless schemes at low and high kinematical scales, respectively, and apply a suitable interpolation in the intermediate region. However, the exact modelling

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

of the interpolation and in general the treatment of mass dependent terms in the perturbation series are still a highly controversial issue among the various theory groups. The different treatments have profound implications for global PDF fits and influence the fitted densities of gluons and other quark flavours in the proton. This has direct consequences for many important cross section predictions at LHC, for instance for Z and W production. The value of the charm quark mass is also an important uncertainty in the calculations. Recently the running charm mass has been fitted [56] to fixed target and HERA charm data obtaining a value $m_c(m_c) = 1.01 \pm 0.09(\mathrm{exp}) \pm 0.03(th)$ GeV.

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

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

- *Gluon density determination:* At HERA the recorded charm data provide already some interesting sensitivity to the gluon density in the proton. However due to the small tagging efficiencies the precisions are far below those obtained from the scaling violations of F_2 or those from jet data. At LHeC this situation will highly improve and it will be possible to probe the gluon density via the BGF process down to proton momentum fractions $x_g \leq 10^{-5}$, where it is currently not well known. At such low values of x_g the gluon density has risen so high that non-linear effects have to occur in order to damp the rise of the cross section to be compliant with unitarity constraints. Since the gluon density is not directly measurable it is of particular importance that the new theory of non-linear gluon interactions is constrained with high precision measurements of the scaling violations of F_2, of F_L and of the BGF process in charm and in beauty production in DIS. In this context it is also interesting to note that in the BGF process one can reach for charm production much smaller x_g values than with flavour inclusive jets since experimentally one can tag charm quarks with small transverse momenta. The studies of heavy flavour production sensitive to the gluon density can be done both in DIS and in the photoproduction kinematic regimes.

- *Charm and beauty densities in the proton:* In general the measurements of the structure functions F_2^{cc} and F_2^{bb} are of highest interest for theoretical analyses of heavy flavour production in ep collisions. These structure functions are describing the parts of F_2 which are due to events with charm or beauty quarks in the final state. At sufficiently high $Q^2 \gg m_c^2, m_b^2$, the two structure functions can be directly related to effective densities of charm and beauty quarks in the proton, This can be used for predictions of many interesting processes at LHC with charm or beauty quarks in the initial state. For instance, as discussed in [109], in the minimal supersymmetric extension of the standard model the production of the neutral Higgs boson A is driven by $b\bar{b} \to A$ and for the calculation of this process the PDF uncertainties dominate over the theoretical uncertainties of the perturbative calculation. At HERA the measurements of F_2^{bb} barely reached the necessary high Q^2 regime and only with modest precision. Huge phase space extensions and precision improvements will be possible at LHeC.

- *Intrinsic charm component:* Since long it has been suggested [18, 110–112] that the proton wave function might contain an intrinsic charm component $uudc\bar{c}$. This would show up mainly at large $x > 0.1$ Unfortunately at HERA this large x region could not be studied mainly due to the limited detector acceptance in the forward region. Due to the even larger boost in the forward direction at LHeC the situation is also not easy there. However, with a forward tracking acceptance down to small polar angles there could be a chance to study this effect, in particular with the planned proton low energy runs.

- *Strange/antistrange densities:* Events with charm quarks in the final state can be also used as a tool for other purposes. The strange and antistrange quark densities in the proton can be analysed via the charge current process $sW \to c$, where the charm quark is tagged in the event. At HERA this was impossible due to the small cross sections, but at LHeC the cross sections for CC reactions are much higher and as noted before the other experimental conditions (luminosities, detector) will greatly improve. This leads to the first and precise measurement of both the strange and the anti-strange quark densities as is demonstrated in Sect. 4.2.

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

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

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

Total production cross sections for charm, beauty and top quarks

This section presents total cross sections for various heavy quark processes at LHeC (with 7 TeV proton beam energy) as a function of the lepton beam energy. Predictions are obtained for:

charm and beauty production in photoproduction and DIS, the charged current processes $sW \rightarrow c$ and $bW \rightarrow t$ and top quark pair production in photoproduction and DIS. For comparison the flavour inclusive charged current total cross section is also shown. Table 4.6 lists the generated processes, the used Monte Carlo generators and the selected parton distribution functions. The

Process	Monte Carlo	PDF
Charm γp	PYTHIA6.4 [113]	CTEQ6L [114]
Beauty γp		
tt γp		
Charm DIS	RAPGAP3.1 [115]	CTEQ5L [116]
Beauty DIS		
tt DIS		
CC e^+p	LEPTO6.5 [117]	CTEQ5L
CC e^-p		
$sW \rightarrow c$		
$\bar{s}W \rightarrow \bar{c}$		
$bW \rightarrow t$		
$\bar{b}W \rightarrow \bar{t}$		
tt DIS	RAPGAP 3.1	CTEQ5L

Table 4.6: Used generator programmes for the predictions of total cross sections at LHeC, shown in Figure 4.26. 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.

resulting cross sections are shown in Figure 4.26. For comparison also the predicted cross sections for the HERA collider (with 920 GeV proton energy) are presented. The cross sections at LHeC are typically about one order of magnitude larger compared to HERA. Attached to the right of the plot are the number of events that are produced per 10 fb^{-1} of integrated luminosity. For instance for charm more than 10 billion events are expected in photoproduction and for beauty more than 100 million events. In DIS the numbers are typically a factor of five smaller. The strange and antistrange densities can be probed with some hundred thousands of charged current events with charm in the final state. The top quark production is dominated by the single production in the charged current reaction with beauty in the initial state and about one hundred thousands tops and a similar number of antitops are expected. In summary the LHeC will be the first *ep* collider which provides access to all quark flavours and with high statistics.

Charm and Beauty production in DIS

This section presents predictions for charm and beauty production in neutral current DIS, for Q^2 values 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 the contributions from charm and beauty events to F_2. As explained in section 4.7.1 the two structure functions are of large interest for theoretical analyses. Experimentally they are obtained by determining the total charm and beauty cross sections in

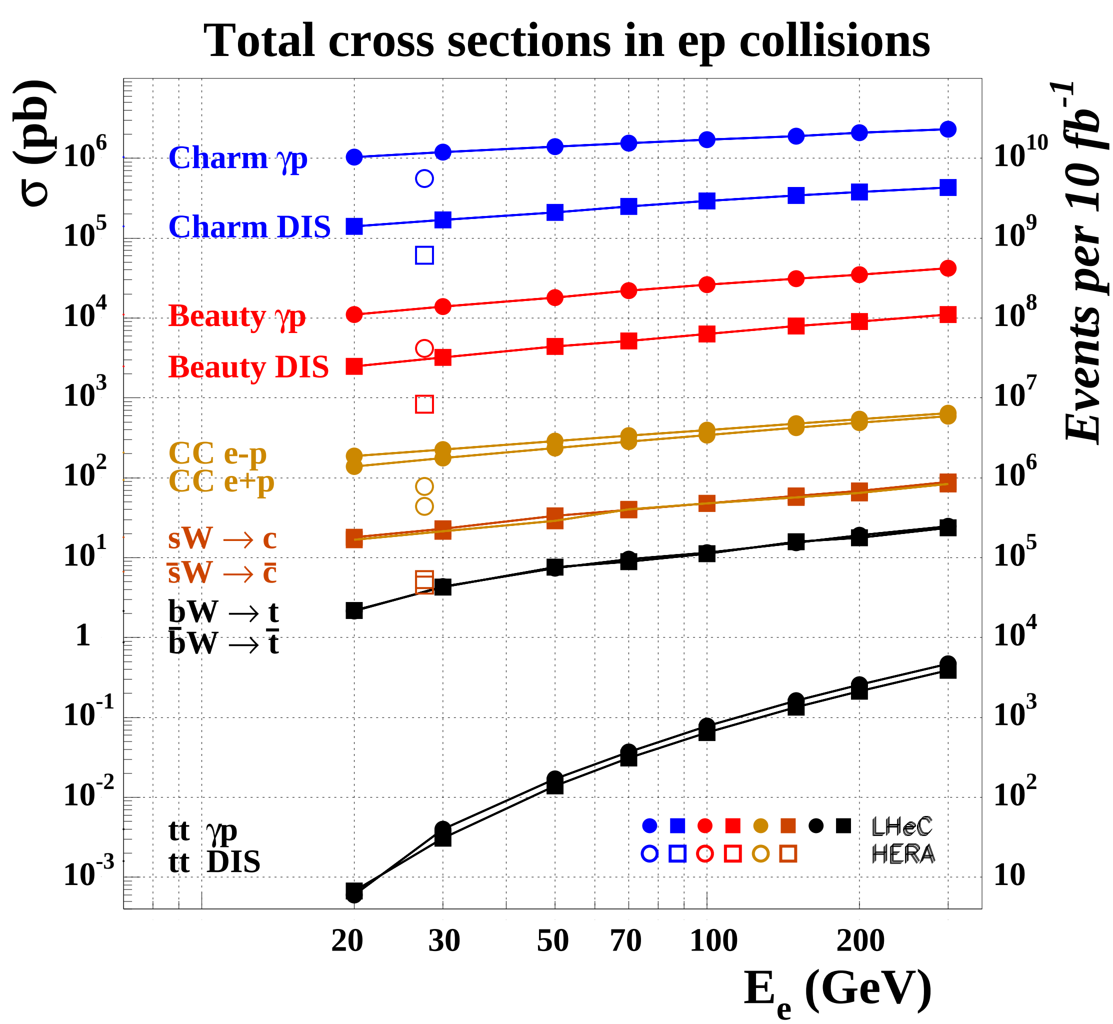


Figure 4.26: Total production cross section predictions for various heavy quark processes at the LHeC (with 7 TeV proton energy), as a function of the lepton beam energy. The following processes are covered: charm and beauty production in photoproduction and DIS, the charged current processes $sW \to c$ and $bW \to t$ 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 4.6. For comparison also the predicted cross sections at HERA (with 920 GeV proton energy) are shown.

two-dimensional bins of x and Q^2. The LHeC projections shown here were obtained with the Monte Carlo programme RAPGAP [115] which generates charm and beauty production with massive leading order matrix elements supplemented by parton showers. The proton Parton Distribution Function set CTEQ5L [116] were used and the heavy-quark masses were set to $m_c = 1.5$ GeV and $m_b = 4.75$ GeV, respectively. In general at HERA the RAPGAP predictions are known to provide a reasonable description of the measured charm and beauty DIS production data. The RAPGAP data were generated for an LHeC collider scenario with 100 GeV electrons colliding with 7 TeV protons. The statistical uncertainties have been evaluated such that they correspond to an integrated data luminosity of 10 fb^{-1}. All studies were done at the parton level, hadronisation effects were not taken into account. Tagging efficiencies of 10% for charm quarks and 50% for beauty quarks have been assumed, respectively. These efficiencies are about a factor 100 larger compared to the effective efficiencies (including the dilution due to background pollution) at HERA which may look surprisingly but is explainable. At HERA the charm quarks were tagged either with full charm meson reconstruction or with inclusive secondary vertexing of charm hadron decays. The first method suffered from very small branching ratios of suitable decay channels. The second technique which was also used for the beauty tagging was affected by a large pollution from light quark background events due to the limited detector capabilities to separate secondary from primary vertices. At LHeC one can expect a much better secondary vertex identification and thus a very strong background reduction. It is difficult to predict exactly how much background pollution will remain at LHeC, so for the purpose of this simulation study it was completely neglected. Systematic uncertainties were also neglected for the studies presented here. From the experiences at HERA the total systematic uncertainties for charm and beauty cross sections in the visible ranges can be expected to be of similar size as the statistical ones.

Figures 4.27 and 4.28 show the resulting RAPGAP predictions at LHeC for the structure functions F_2^{cc} and F_2^{bb}, respectively, compared to recent measurements [118] from HERA. The data are shown as a function of x for various Q^2 values. The Q^2 values were chosen such that they cover a large fraction of the specific values for which HERA results are available. Some further values demonstrate the phase space extensions at LHeC. The projected LHeC data are presented as points with error bars which (where visible) indicate the estimated statistical uncertainties. 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. The selected results from HERA are shown as triangles with error bars indicating the total uncertainty. The HERA F_2^{cc} results in Figure 4.27 are those of a recent weighted average [118] of almost all available measurements from H1 and ZEUS. In a large part of the covered phase space these results are already rather accurate, with precisions between 5% and 10%. The overlayed LHeC projections show a vast phase space increase to lower and larger x and also to much higher Q^2 values. In the kinematic overlap region the expected statistical precisions at LHeC are typically a factor $\sim$ 40 better than at HERA which can be easily explained by the 20 times larger integrated luminosity and the $\sim$ 100 times better tagging efficiency. For the smaller x not covered by HERA the precision even improves at LHeC due to the growing cross sections driven by the rise of the gluon density. 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 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 4.28 show the RAPGAP predictions at LHeC for F_2^{bb}. Also shown are the results from the H1 analysis [119] based on inclusive secondary vertex tagging. Clearly these results

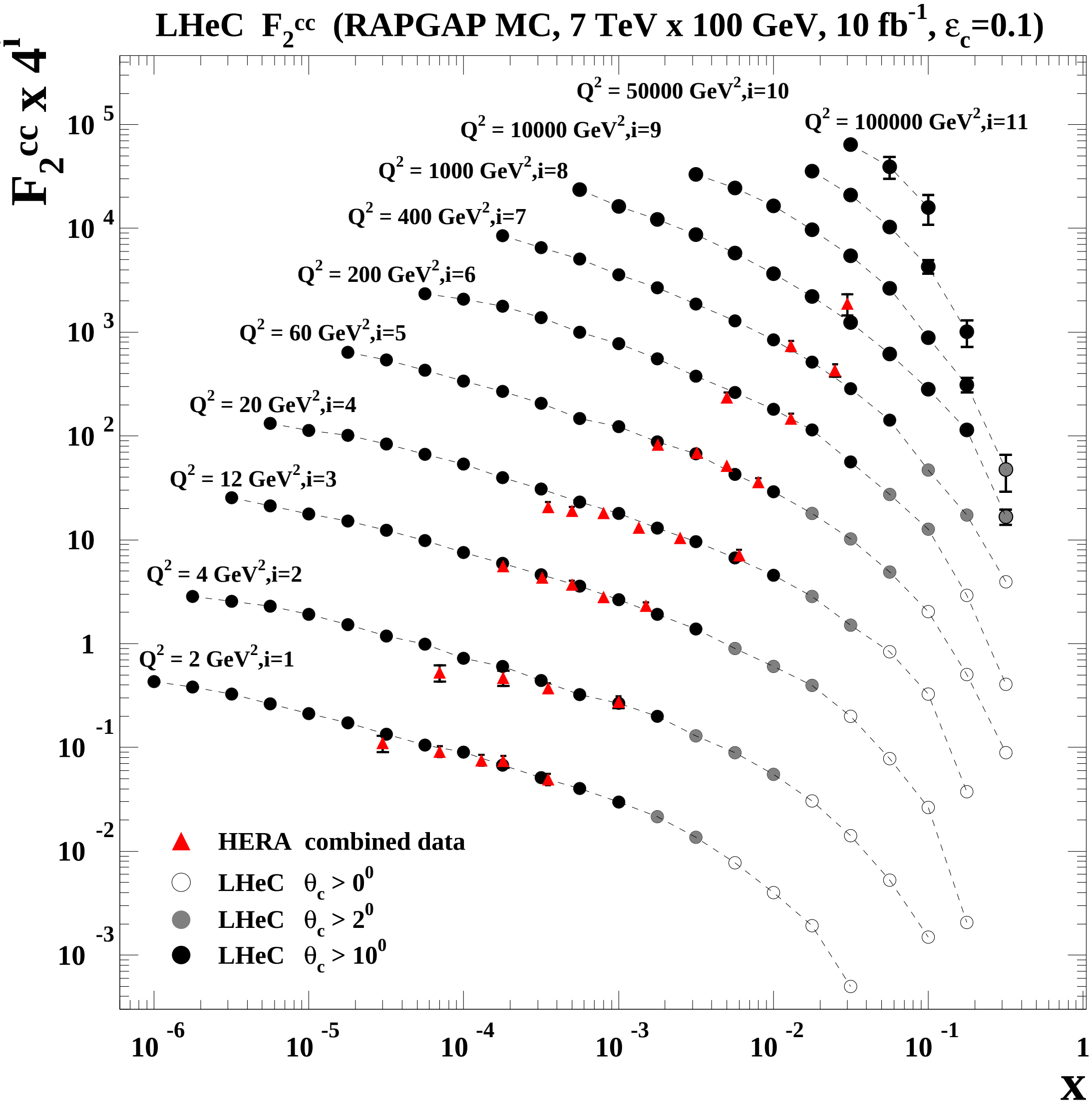


Figure 4.27: F_2^{cc} projections for LHeC compared to HERA data [118], shown as a function of x for various Q^2 values. The expected LHeC results obtained with the RAPGAP MC simulation are shown as points with error bars representing the statistical uncertainties. The dashed lines are interpolating 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.

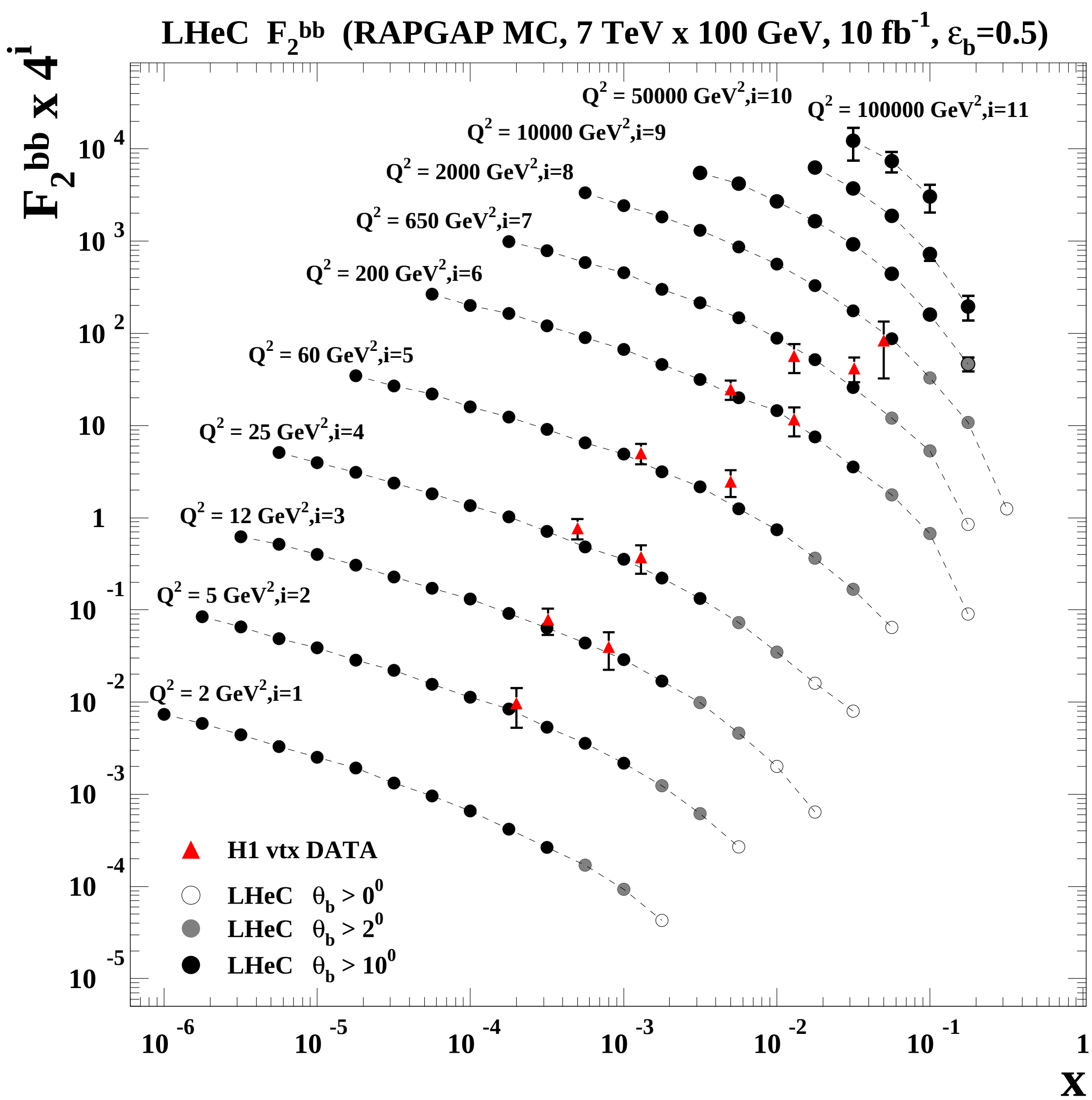


Figure 4.28: F_2^{bb} projections for LHeC compared to HERA data [119] from H1, shown as a function of x for various Q^2 values. The expected LHeC results obtained with the RAPGAP MC simulation are shown as points with error bars representing the statistical uncertainties. The dashed lines are interpolating 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 $\theta_b > 2^0$ and $\theta_b > 10^0$, 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.

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 4.7.1, 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.

Intrinsic Heavy Flavour

It is conventional to assume that the charm and bottom quarks in the proton structure function only arise from gluon splitting $g \to Q\bar{Q}$. In fact, the proton light-front wavefunction contains *ab initio* intrinsic heavy quark Fock state components such as $|uudc\bar{c}>$ [18,110–112]. 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 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 [110, 112]. 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 [120], 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 $p\bar{p} \to \gamma c X$ inclusive cross section observed by the D0 collaboration [121] at the Tevatron indicates that the charm distribution has been underestimated at $x > 0.1$.

In [122] a novel mechanism for inclusive and diffractive Higgs production $pp \to pHp$ is proposed, in which the Higgs boson carries a significant fraction of the projectile proton momentum. The production mechanism is based on the subprocess $(Q\bar{Q})g \to H$ where the $Q\bar{Q}$ in the $|uudQ\bar{Q}>$ 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 $\gamma p \to HX$ at the LHeC based on the mechanism $\gamma(Q\bar{Q}) \to H$ 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 $|uudQ\bar{Q}>$ 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 $\gamma p \to cX$ where the charm jet is produced at high p_T in the reaction $\gamma c \to cg$.

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. Approximately, as may be derived from Eq. 11.8, the small hadronic scattering angle, θ_h, is obtained from 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 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 attempt to access maximum x thus requires to find an optimum of high luminosity, to reach high Q^2, and low proton beam energy, to access large x. Fig. 4.29 shows a simulated measurement of the charm structure function for $E_p = 1$ TeV and a luminosity of $1\,\mathrm{fb}^{-1}$. The two curves illustrate the difference between CTEQ66 PDF sets with and without an intrinsic charm component, based on [120]. The actual amount of intrinsic charm may be larger than in the CTEQ attempt, it may also be smaller. One so finds that a reliable detection of an intrinsic heavy charm component at the LHeC may be possible, but will be a challenge for forward charm detection and requires high luminosity. The result yet may be rewarding as it would have quite some theoretical consequences as sketched above. It would be obtained in a region of high enough Q^2 to be able to safely neglect any higher twist effects which may mimic such an observation at low energy experiments.

D^* meson photoproduction study

A study is presented of D^* meson photoproduction at LHeC compared to HERA. It is based on NLO predictions in the so-called general-mass variable-flavour-number scheme (GM-VFNS) [107,108] for 1-particle inclusive heavy-meson production. Both direct and resolved photon contributions are taken into account. The cross section for direct photoproduction is a convolution of the proton PDFs, the cross section for the hard scattering process and the fragmentation functions FF for the transition of a parton to the observed heavy meson. For the resolved contribution, an additional convolution with the photon PDFs has to be performed. For the photoproduction predictions at the ep-colliders HERA and LHeC, the calculated photon proton cross sections are convoluted with the photon flux using the Weizsaecker-Williams approximation.

In the GM-VFNS approach the large logarithms $\ln(p_T^2/m^2)$, which appear due to the collinear mass singularities in the initial and final state, are factorized into the PDFs and the FFs and summed by the well known DGLAP evolution equations. The factorization is performed following the usual $\overline{\mathrm{MS}}$ prescription which guarantees the universality of both PDFs and FFs. At the same time, mass-dependent power corrections are retained in the hard-scattering cross sections, as in the FFNS. For the photon PDF the parametrization of Ref. [123] with the standard set of parameter values is used and for the proton PDF the parametrization CTEQ6.5 [124] of the CTEQ group. For the FFs the set Belle/CLEO-GM of Ref. [125] is chosen. Various combinations of beam energies are studied. To compare with the situation at HERA, as a reference, the values $E^p = 920$ GeV and $E^e = 27.5$ GeV for proton and electron energies, respectively, are also included. For the LHeC the proton energy is taken to be always $E^p = 7$ TeV and the options $E^e = 50$, 100 and 150 GeV are considered. The exchanged photons are restricted to inelasticities y in the range $0.1 < y < 0.9$. The transverse momentum p_T and the rapidity η of the D^*-meson are varied in the kinematic ranges $5 < p_T < 20$ GeV or $20 < p_T < 100$ and $|\eta| < 2.5$. Numerical results are shown in Fig. 4.30 for the differential cross section $d\sigma/dp_T$ integrated over the rapidity $|\eta| \leq 2.5$ and in Fig. 4.31 for $d\sigma/d\eta$, integrated

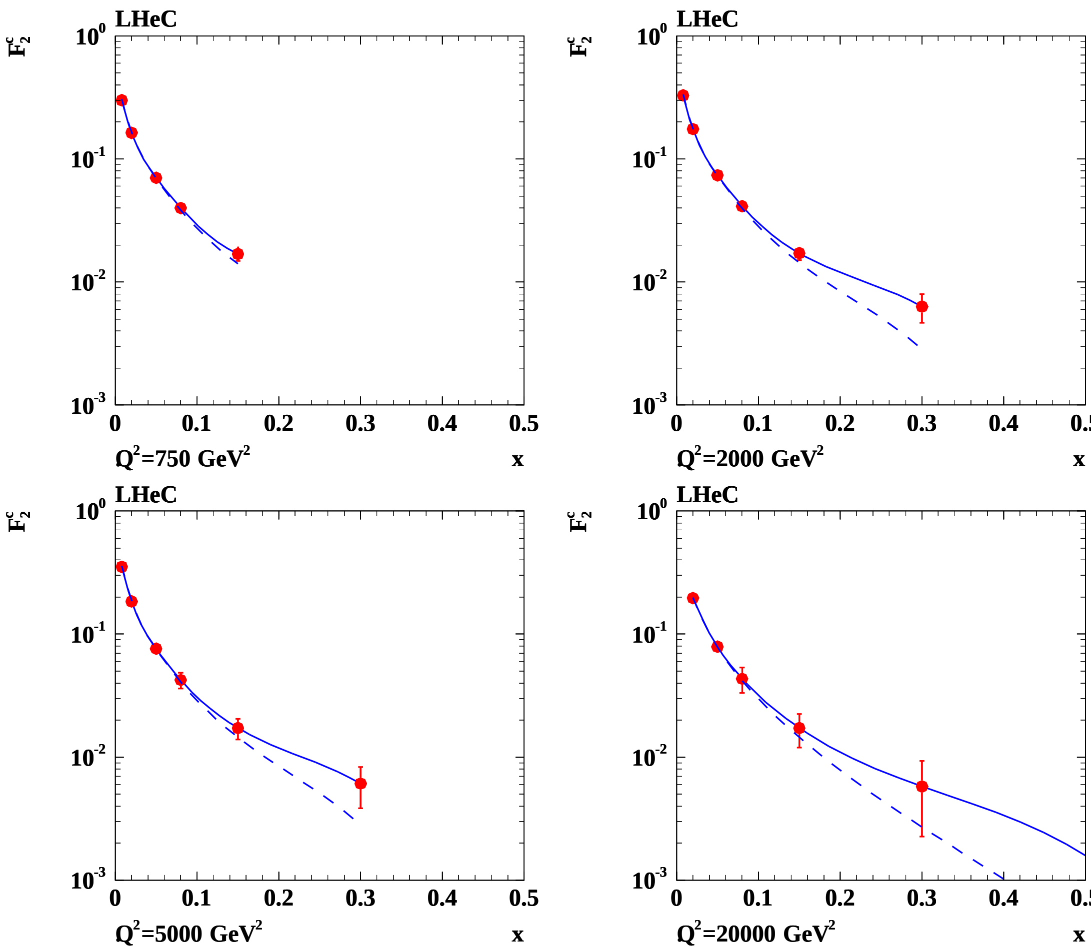


Figure 4.29: Simulation of measurement of the charm structure function at large x, see text. The errors are statistical, taking tagging and background efficiencies into account. The tagging efficiency for charm quarks was assumed to be 10% and the amount of background was estimated to be $0.01 \cdot N_{ev}$, 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 CTEQ6m.

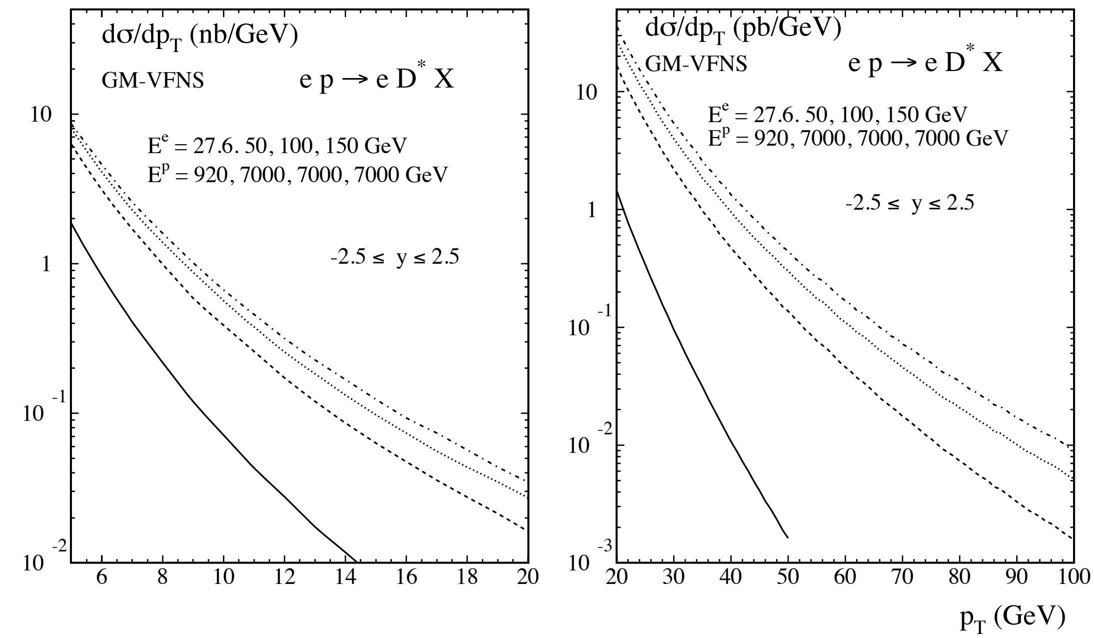


Figure 4.30: The p_T-differential cross section for the production of D^* mesons at LHeC for different beam energies integrated over rapidities $|\eta| \leq 2.5$, for the low-p_T range 5 GeV$\leq p_T \leq$ 20 GeV (left) and for the high-p_T range 20 GeV$\leq p_T \leq$ 50 GeV (right). The curves from bottom to top correspond to the combinations of beam energies as indicated in the figure.

over the p_T-ranges $5 \leq p_T \leq 20$ GeV and $20 \leq p_T \leq 100$ GeV.

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

4.8 High p_t jets

4.8.1 Jets in ep

The study of the jet final states in lepton-proton collisions allows the determination of aspects of the nucleon structure which are not accessible in inclusive scattering. Moreover, jet production allows for probing predictions of QCD to a high accuracy. Depending on the virtuality of the exchanged photon, one distinguishes processes in photoproduction (quasi-real photon) and deep inelastic scattering.

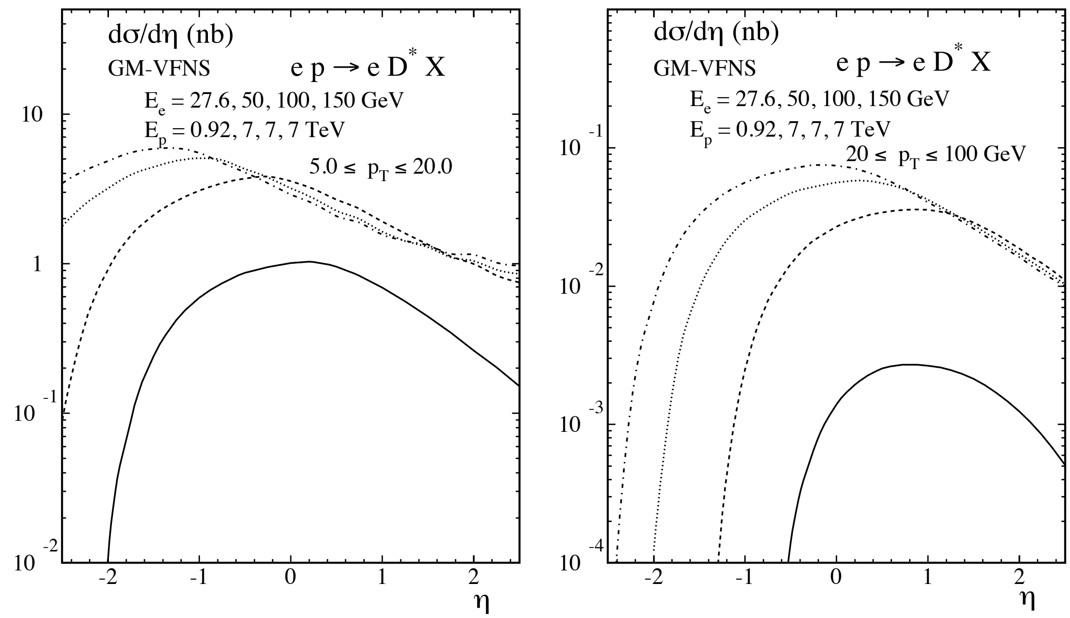


Figure 4.31: Rapidity distribution of the cross section for the production of D^* mesons at LHeC for different beam energies integrated over the low-p_T range 5 GeV$\leq p_T \leq$ 20 GeV (left) and the high-p_T range 20 GeV$\leq p_T \leq$ 50 GeV (right). The curves from bottom to top correspond to the combinations of beam energies as indicated in the figure.

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

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

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

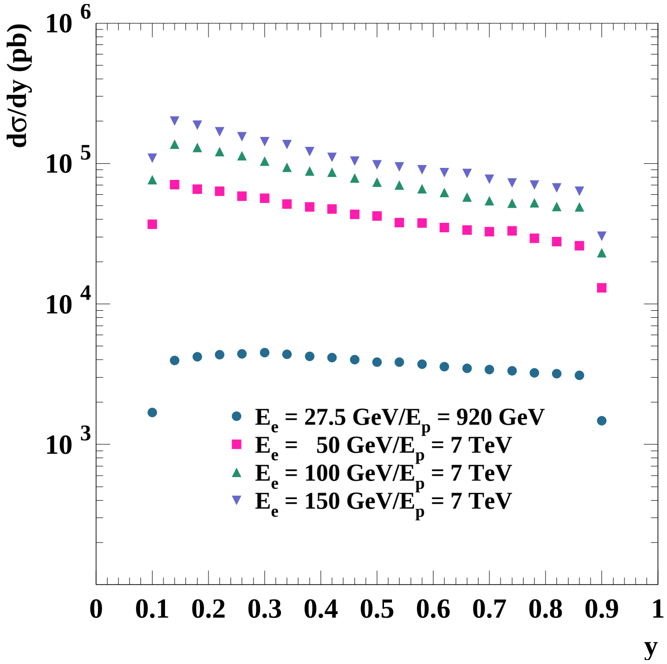


Figure 4.32: PYTHIA predictions for photoproduction cross section at HERA and for three LHeC scenarios.

Another motivation for making new photoproduction experiments is to improve the knowledge of the parton content of the photon. At present, most information on the photon structure is inferred from the colliison of quasi-real photons with electrons at e^+e^- colliders, resulting in a decent determination of the total (charge weighted) quark content of the quasi-real photon. Its gluonic content, and the quark flavour decomposition are on the other hand only loosely constrained. Improvements to the photon structure are of crucial importance to physics studies at a future linear e^+e^- collider like the ILC or CLIC. Such a collider, operating far above the Z-boson resonance, will face a huge background from photon-photon collisions. This background can be suppressed only to a certain extent by kinematical cuts. Consequently, accurate predictions of it (which require an improved knowledge of the photon's parton content) are mandatory for the reliable interpretation of hadronic final states at the ILC or CLIC. Several parametriza-

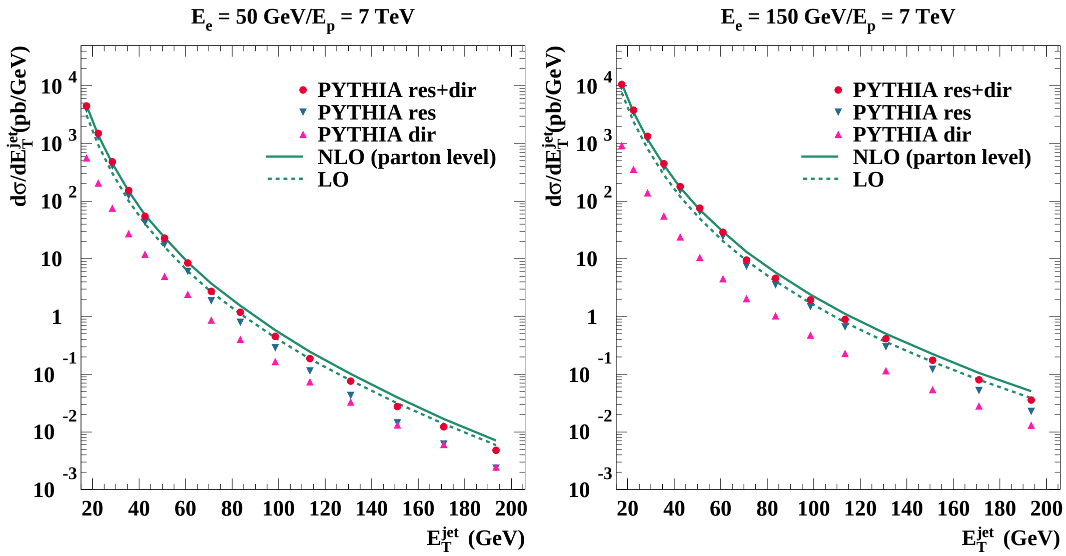


Figure 4.33: Parton level predictions for the inclusive transverse energy distribution in photoproduction.

tions of the parton distributions in the photon are available. They differ especially in the gluon content of the photon. For the studies presented here, the GRV-HO parametrization [126] is used as default.

The photoproduction studies performed at LHeC were done for three different electron energy scenarios: E_e=50, 100 and 150 GeV. In all cases, the proton energy was set to 7 TeV. PYTHIA MC samples of resolved and direct processes were generated for these three scenarios. Jets were searched using the k_t-cluster algorithm in the kinematic region of $0.1 < y < 0.9$ and $Q^2 < 1$ GeV^2. Inclusive jet cross sections were done for jets of $E_t^{\rm jet} > 15$ GeV and $3 < \eta^{\rm jet} < 3$. Figure 4.32 shows the PYTHIA MC cross sections as functions of y for the three scenarios plus the corresponding cross section for the HERA regime. It can be seen that the LHeC cross sections are one to two orders of magnitude larger than the cross section at HERA.

The full study was complemented with fixed-order QCD calculations at order α_s and α_s^2 using the program by Klasen et al. [127] with the CTEQ6.1 sets for the proton PDFs, GRV-HO sets for the photon PDFs, $\alpha_s(M_Z) = 0.119$ and the renormalisation and factorisation scales were set to the transverse energy of each jet.

Figure 4.33 shows the inclusive jet cross sections at parton level as functions of $E_t^{\rm jet}$ for the three energy scenarios for the PYTHIA res+dir (red dots), PYTHIA resolved (blue triangles) and PYTHIA direct (pink triangles) together with the predictions from the NLO (solid curves) and LO (dashed curves) QCD calculations. The calculations predict a sizeable rate for Etjet of at least up to 200 GeV. Resolved processes dominate at low $E_t^{\rm jet}$, but the direct processes become increasingly more important as $E_t^{\rm jet}$ increases. The PYTHIA cross sections (which have been normalised to the NLO integrated cross section) agree well in shape with the NLO calculations. Investigating the $\eta^{\rm jet}$ distribution, we find that resolved processes dominate in the forward region, while direct processes produce more central jets.

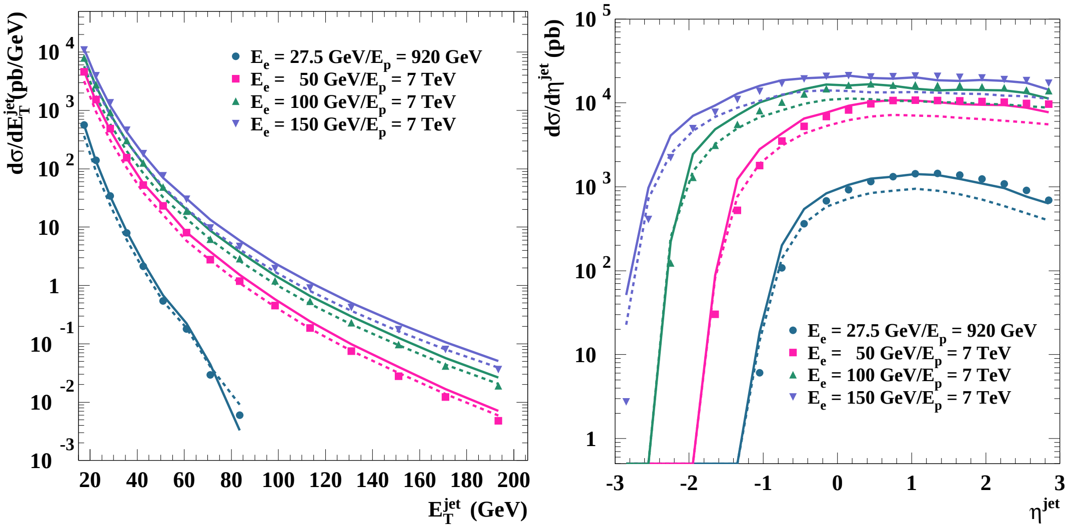


Figure 4.34: Dijet distributions in photoproduction as function of the jet transverse energy (left) and of the jet rapidity (right) for different LHeC energies compared to the HERA kinematic range.

Figure 4.34 show the inclusive jet cross sections at parton level as functions of $E_t^{\rm jet}$ (on the left) and $\eta^{\rm jet}$ (on the right) for the PYTHIA resolved+direct (symbols) and the predictions from the NLO (solid curves) and LO (dashed curves) QCD calculations together for the three energy scenarios. For comparison, the calculations for the HERA regime are also included. It is seen that the cross sections at fixed $E_t^{\rm jet}$ increase and that the jets tend to go more backward as the collision energy increases. The much larger photon-proton centre-of-mass energies that could be available at LHeC provide a much wider reach in $E_t^{\rm jet}$ and $\eta^{\rm jet}$ compared to HERA.

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

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

An especially interesting region for such studies has been the regime of large (for HERA) Q^2 values of, for example, $Q^2 > 125$ GeV^2. In this regime, the theoretical uncertainties, especially those due to the unknown effects of missing higher orders in the perturbative expansion, are found to be small. Recently, both the H1 and ZEUS collaborations have published measurements of inclusive-jet and dijet events in this kinematic regime.

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

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

For inclusive-jet production we study cross sections in the indicated kinematic regime as functions of Q^2, x_{Bj}, $E_{T,jet}^{Breit}$ and η_{jet}^{lab}, the jet pseudorapidity in the laboratory frame. For dijet production, studies are presented as functions of Q^2, the logarithm of the proton momentum fraction ξ, $\log_{10}\xi$, the invariant dijet 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 difference of the two jet pseudorapidities in the laboratory frame, η'.

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

The theoretical calculations where performed with the DISENT program [128] using the CTEQ6.1 proton PDFs [114,129]. The central default squared renormalisation and factorisation scales were set to Q^2. The theory calculations for the LHeC scenario were corrected for the effects of hadronisation and Z^0 exchange using Monte Carlo data samples simulated with the LEPTO program [117].

Theoretical uncertainties were assessed by varying the renormalization scale up and down by a factor 2 (to estimate the potential effect of contributions beyond NLO QCD), by using the 40 error sets of the CTEQ6.1 parton distribution functions, and by varying α_s using the CTEQ6AB PDF [130]. The dominant theory uncertainty turned out to be due to the scale variations, resulting in effects of a few to up to 20% or more, for example for low values of Q^2 or, for the case of the dijet measurement, for low values of the invariant dijet mass, M_{jj}, or the logarithm of momentum fraction carried into the hard scattering, $\log_{10}\xi$.

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

Figure 4.35 shows the inclusive jet cross section as function of Q^2 and of the jet transverse energy in the Breit frame, while Figure 4.36 shows the dijet cross section as funtion of Q^2 and of $\xi = x_{Bj}(1+M_{jj}^2/Q^2)$. The top parts of the figures show the predicted cross sections together with the expected statistical and (uncorrelated) experimental systematic uncertainties as errors

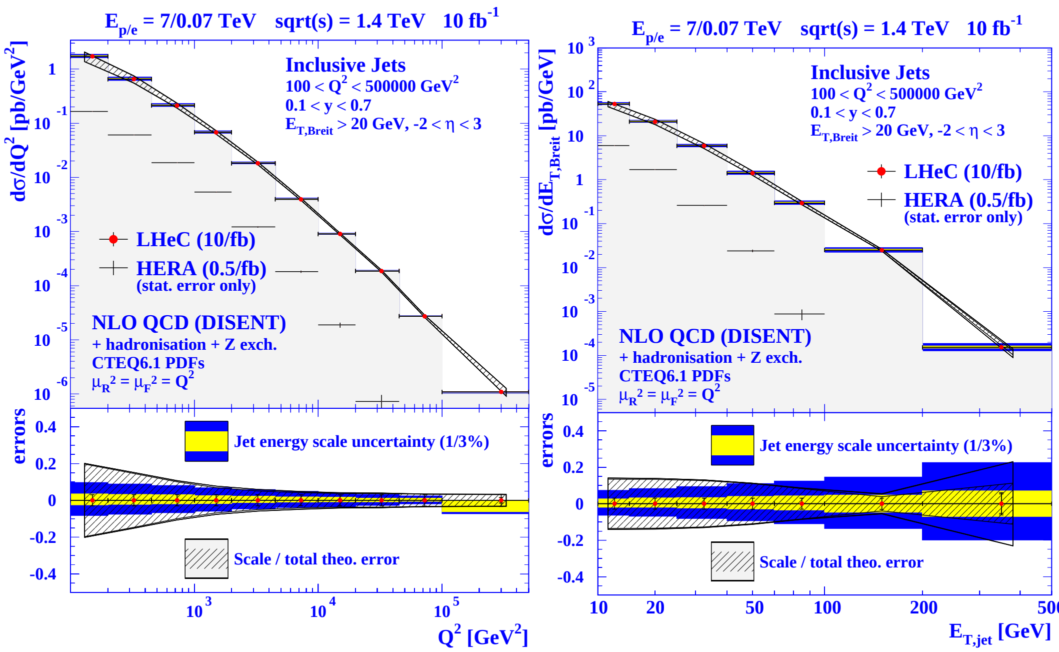


Figure 4.35: Predicted LHeC results for inclusive jet production as function of Q^2 and of E_T in the Breit frame. Predictions for HERA results are also shown.

bars. The correlated jet energy scale uncertainty is indicated as a coloured band; the inner, yellow band assumes an uncertainty of 1%, the outer, blue band one of 3%. Also shown as a thin hashed area are the theoretical uncertainties; the width of the band indicates the size of the combined theoretical uncertainty. In case of inclusive-jet production, also the predictions for HERA are indicated as a thin line.

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

The inclusive-jet cross section as function of Q^2 shows a typical picture: In most region of the phase space, the uncertainties are dominated by the theory uncertainties, and here mainly by the renormalisation scale uncertainty. The typical size of experimental uncertainties is of the order of 10%, with larger values in regions with low relevant scales — i.e. low invariant dijet masses, low jet transverse energies or low Q^2 values. The theoretical uncertainties are typically between 5 and 20%, with partially strong variations over the typical range of the observable in question.

A comparison with the HERA predictions for inclusive-jet production shows that the LHeC cross sections is typically larger by 1 to 3 orders of magnitude. The dijet final state allows for a full reconstruction of the partonic kinematics, and can thus be used to probe the parton distribution functions in Q^2 and ξ. It can be seen that a measurement at LHeC covers a

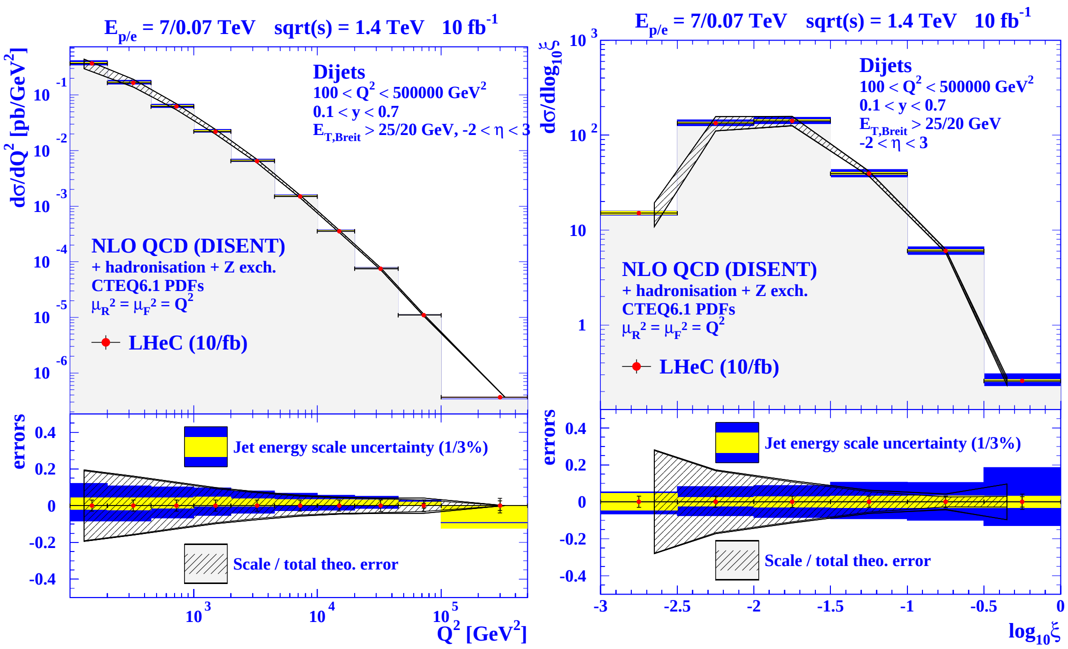


Figure 4.36: Predicted LHeC results for dijet production as function of Q^2 and of ξ.

large kinematical range ranging down to $\xi \approx 10^{-3}$ and up to $Q^2 = 10^5$ GeV^2. Potentially limiting factors in an extraction of parton distribution functions are especially the jet energy scale uncertainty on the experimental side and missing higher order (NNLO) corrections on the theory side. The jet energy scale uncertainty can be addressed by the detector design and by the experimental setup of the measurement. NNLO corrections to dijet production in deep inelastic scattering are already very much demanded by the precision of the HERA data, their calculation is currently in progress [131, 132].

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

4.8.2 Jets in γA

For photoproduction in eA collisions, jets provide an abundant yield of high-energy probes of the nuclear medium. The expected cross sections have been computed using the calculations in [133, 134], for an electron beam of 50 GeV colliding with the LHC beams. For the nuclear case the same integrated luminosity (2 fb^{-1}) was assumed per nucleon as for ep. Only jets with $E_{Tjet} > 20$ GeV are considered, and for the distribution in E_{Tjet} the pseudorapidity acceptance is $|\eta_{jet}| < 3.1$, corresponding to $5^{\circ} < \theta_{jet} < 175^{\circ}$ in polar angle. The simulations use the Weizsäcker-Williams photon flux from the electron with the standard option in [133, 134]. The chosen photon, proton and nuclear modified PDFs are taken from GRV-HO [135], CTEQ6.1M [129] and EPS09 [136], respectively - see Subsec. 6.1.4 for explanations on the nuclear modifications of PDFs. The renormalization and factorization scales are taken to be $\mu_R = \mu_F = \sum_{jets} E_{Tjet}/2$ and the inclusive k_T jet algorithm [137] is used with $D = 1$. The statistical uncertainty in the computation (i.e. in the Monte Carlo integration) is smaller than 10 % for all results shown. This large statistical uncertainty is reached only for the largest E_{Tjet}, with much smaller uncertainties at lower values of E_T. No attempt has been made to estimate the uncertainties due to the choices of photons flux, photon or proton parton densities, scales or jet algorithms (see [138, 139] for such considerations at HERA). The issues of background subtraction, experimental efficiencies in the jet reconstruction or energy calibration have also yet to be addressed. The only uncertainty studied thus far is that due to the nuclear parton densities, which is extracted in the EPS09 framework [136] using the Hessian method.

The results are shown in Fig. 4.37. One observes that yields of around 10^3 jets per GeV are expected with $E_{Tjet} \sim 95$ (80) GeV in ep (ePb), for $|\eta_{jet}| < 3.1$ and the considered integrated luminosity of 2 fb^{-1} per nucleon. The effects of the nuclear modification of parton densities and their uncertainties are smaller than 10 %. The two-peak structure in the η_{jet}-plot results from the sum of the direct plus resolved contributions, 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 photons.

4.9 Total photoproduction cross section

Due to the $1/Q^4$ propagator term, the LHeC ep cross section is dominated by very low Q^2 quasi-real photons. With a knowledge of the effective photon flux [140], measurements in this kinematic region can be used to obtain real photoproduction (γp) cross sections. The real photon has a dual nature, sometimes interacting in a point-like manner and sometimes interacting through its effective partonic structure, resulting from $\gamma \to q\bar{q}$ and higher multiplicity splittings well in advance of the target [141, 142], the details of which are fundamental to the understanding of QCD evolution.

The behaviour of the total photoproduction cross section at high energy is a topic of a major interest. It is now firmly established experimentally that all hadronic cross sections rise with centre of mass energy for large energies. The Froissart-Martin bound has been derived for hadronic probes. It therefore remains to be seen whether this bound is applicable to γp scattering. For example in Refs. [143, 144] it has been argued that the bound for real photon-hadron interactions should be of a different functional form, namely $\ln^3 s$. This would imply that the universality of the asymptotic behaviour of hadronic cross sections does not hold. Therefore the measurement of the total photoproduction cross section at high energies will bring an important insight into the problems of universality of hadronic cross sections, unitarity constraints, the role of diffraction and the interface between hard and soft physics.

In Fig. 4.38, available data on the total cross section are shown [28, 145–147][5], together with a variety of models. More specifically, the dot-dashed black line labelled 'FF model GRS' is a minijet model [149], the yellow band labelled 'Godbole et al.' is an eikonalized minijet model

[5] The recent results by ZEUS [148] refer only to the energy behavior of the cross section in the range 194 $< W <$ 296 GeV, but do not provide absolute values.

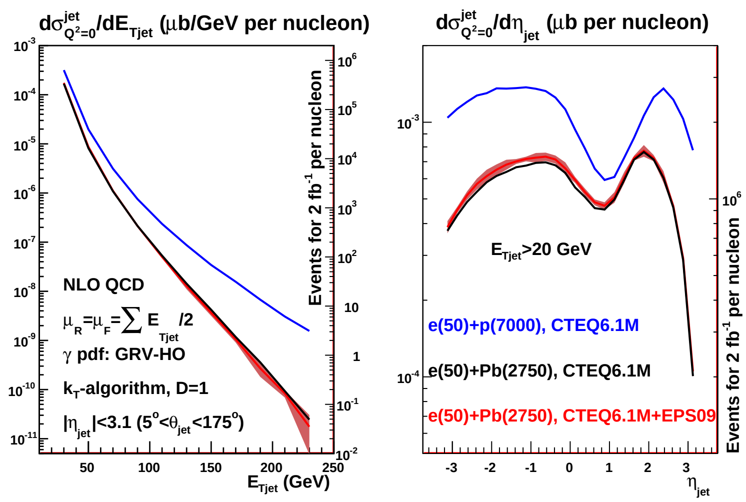


Figure 4.37: Predictions for the inclusive jet distribution in photoproduction, differential in E_{Tjet} (plot on the left) and η_{jet} (plot on the right) for $e(50)$+$p(7000)$ (blue lines), $e(50)$+Pb(2750) without nuclear modification of the parton densities (black lines), and $e(50)$+Pb(2750) with 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).

with soft gluon resummation [149] with the band defined by different choices of the parameters in the model, the red solid line labelled 'Block & Halzen' is based on a low energy parametrization of resonances joined with Finite Energy Sum Rules and asymptotic $\ln^2 s$-behaviour [150, 151], and the dashed blue line labelled 'Aspen model' is a QCD inspired model [152].

The theoretical predictions diverge at energies beyond those constrained by HERA data, where cross sections were obtained by tagging and measuring the energies of electrons scattered through very small angles in dedicated calorimeters located well down the beampipe in the outgoing electron direction [145, 146]. As discussed in Chapter 13, the most promising location for similar small angle electron detectors at the LHeC is in the region around 62 m from the interaction point, which could be used to tag scattered electrons in events with $Q^2 < 0.01$ GeV^2 and $y \sim 0.3$. This naturally leads to measurements of the total photoproduction cross section at γp center-of-mass energies $W \sim 0.5\sqrt{s}$. The measurements would be strongly limited by systematics. In the absence of a detailed simulation of an LHeC detector these uncertainties are hard to estimate. For the simulated data in Fig. 4.38, uncertainties of 7% have been assumed, matching the precision of the H1 and ZEUS data. This would clearly be more than adequate to distinguish between many of the available models. The HERA uncertainties were dominated by the invisible contributions from diffractive channels in which the diffractive masses were too small to leave visible traces in the main detector. If detector acceptances to 1° are achieved at the LHeC, better precision is expected to be possible.

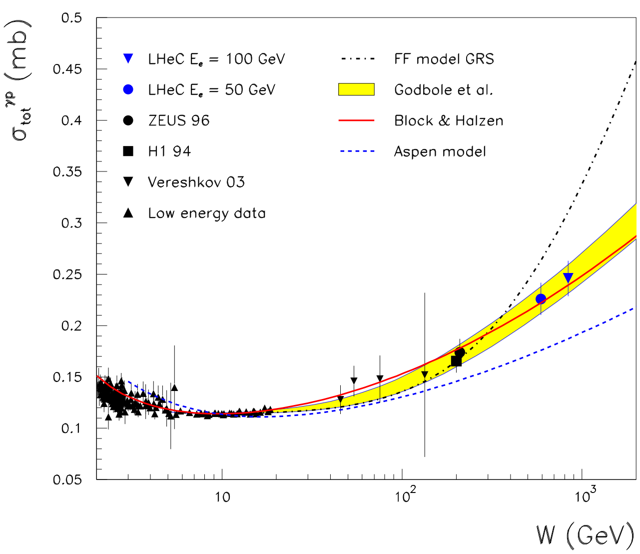


Figure 4.38: Simulated LHeC measurements of the total photoproduction cross section with $E_e = 50$ GeV or $E_e = 100$ GeV, compared with previous data and a variety of models (see text for details). This is derived from a similar figure in [149].

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 [153–156] 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 $\mathrm{d}\sigma/\mathrm{d}Q^2$. An alternative way to parameterize the effects of fermion substructure makes use of form factors, which would also lead to deviations of $\mathrm{d}\sigma/\mathrm{d}Q^2$ 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 $\mathrm{d}\sigma/\mathrm{d}Q^2$ 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.

A possible method to investigate fermion substructures is to assign a finite size of radius R to the electroweak charges of leptons and/or quarks while treating the gauge bosons γ and Z still as pointlike particles [157]. A convenient parametrisation is to introduce 'classical' form factors $f(Q^2)$ at the gauge boson–fermion vertices, which are expected to diminish the Standard Model cross section at high momentum transfer

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

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

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

Figure.5.1 shows the sensitivity that an LHeC collider could reach on the "quark radius" [158]. Two 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 be reached, which is one order of magnitude better than the current constraints, and comparable to the sensitivity that the LHC is expected to reach.

5.1.2 Contact Interactions

New currents or heavy bosons may produce indirect effects through the exchange of a virtual particle interfering with the γ and Z fields of the Standard Model. For particle masses and scales well above the available energy, $\Lambda \gg \sqrt{s}$, such indirect signatures may be investigated by searching for a four-fermion pointlike $(\bar{e}\,e)(\bar{q}\,q)$ contact interaction. The most general chiral invariant Lagrangian for neutral current vector-like contact interactions can be written in the form [159–161]

$$\begin{aligned}\mathcal{L}_V = \sum_{q=u,\,d} \{ & \eta^q_{LL}\,(\bar{e}_L\gamma_\mu e_L)(\bar{q}_L\gamma^\mu q_L) + \eta^q_{LR}\,(\bar{e}_L\gamma_\mu e_L)(\bar{q}_R\gamma^\mu q_R) \\ & + \eta^q_{RL}\,(\bar{e}_R\gamma_\mu e_R)(\bar{q}_L\gamma^\mu q_L) + \eta^q_{RR}\,(\bar{e}_R\gamma_\mu e_R)(\bar{q}_R\gamma^\mu q_R)\} \,,\end{aligned} \tag{5.3}$$

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

$$\eta^q_{ab} \equiv \epsilon \frac{g^2}{{\Lambda^q_{ab}}^2} \,, \tag{5.4}$$

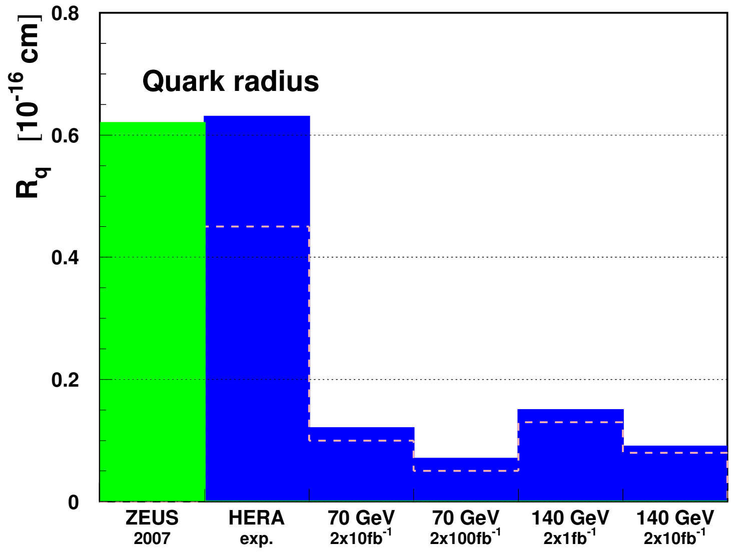


Figure 5.1: Sensitivity (95% confidence level limits) of an LHeC collider to the effective quark radius.

where a and b indicate the L, R helicities, g is the overall coupling strength, Λ^q_{ab} is a scale parameter and ϵ is a prefactor, often set to $\epsilon = \pm 1$, which determines the interference sign with the Standard Model currents. The ansatz eq. (5.3) can be easily applied to any new phenomenon, *e.g.* (eq) compositeness, leptoquarks or new gauge bosons, by an appropriate choice of the coefficients η_{ab}. Scalar and tensor interactions of dimension 6 operators involving helicity flip couplings are strongly suppressed at HERA [161] and therefore not considered.

Figure 5.2 shows the sensitivity that an LHeC could reach on the scale Λ, for two example cases of contact interactions [158]. In general, with 10 fb^{-1} of data, LHeC would probe scales between 25 TeV and 45 TeV, depending on the model. The sensitivity of LHC to such $eeqq$ interactions, which would affect the di-electron Drell-Yan (DY) spectrum at high masses, is similar.

Figure 5.3 shows how the DY cross-section at LHC would deviate from the SM value, for three examples of $eeqq$ contact interactions. In the "LL" model considered here, the sum in eq. (5.3) only involves left-handed fermions and all amplitudes have the same phase ϵ. With only pp data, it will be difficult to determine simultaneously the size of the contact interaction scale Λ and the sign of the interference of the new amplitudes with respect to the SM ones: for example, for $\Lambda = 20$ TeV and $\epsilon = -1$, the decrease of the cross-section with respect to the SM prediction for di-electron masses below ~ 3 TeV, which is characteristic of a negative interference, is too small to be firmly established when uncertainties due to parton distribution functions are taken into account.

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

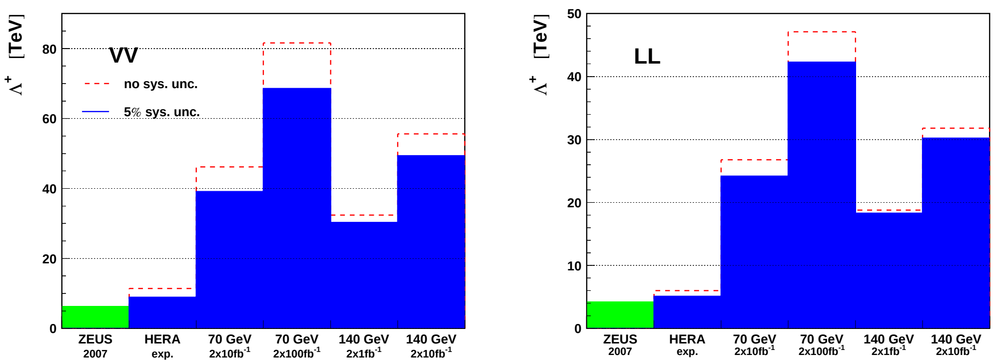


Figure 5.2: Sensitivity (95% confidence level limits) on the scale Λ for two example contact interactions.

Moreover, with a polarised lepton beam, ep collisions would help determine the chiral structure of the new interaction. More generally, it is very likely that both pp and ep data would be necessary to underpin the structure of new physics which would manifest itself as an $eeqq$ contact interaction. Such a complementarity of pp, ep (and also ee) data was studied in [162] in the context of the Tevatron, HERA and LEP colliders.

5.1.3 Kaluza-Klein gravitons in extra-dimensions

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

5.2 Leptoquarks and leptogluons

The high energy of the LHeC extends the kinematic range of DIS physics to much higher values of electron-quark mass $M = \sqrt{sx}$, beyond those of present ep colliders. By providing both baryonic and leptonic quantum numbers in the initial state, it is ideally suited to a study of the properties of new bosons possessing couplings to an electron-quark pair in this new mass range. Such particles can be squarks in supersymmetric models with R-parity violation ($\not R_p$), or first-generation leptoquark (LQ) bosons which appear naturally in various unifying theories beyond

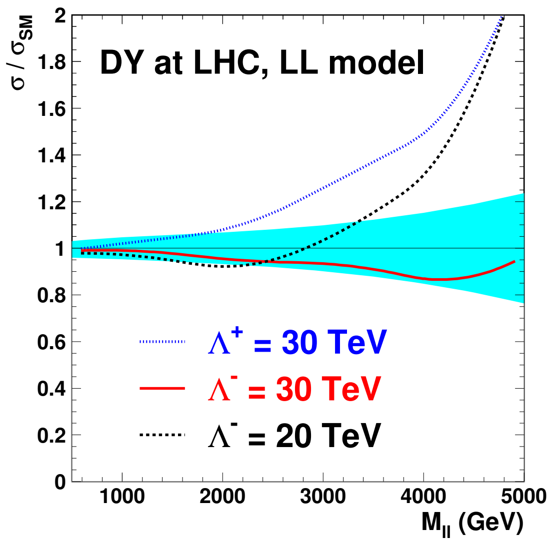


Figure 5.3: Example deviations, from its SM value, of the Drell-Yan cross-section at LHC as a function of the dilepton mass, in the presence of an *eeqq* contact interaction. The blue band shows the relative uncertainty of the predicted SM cross-sections due to the current uncertainties of the parton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

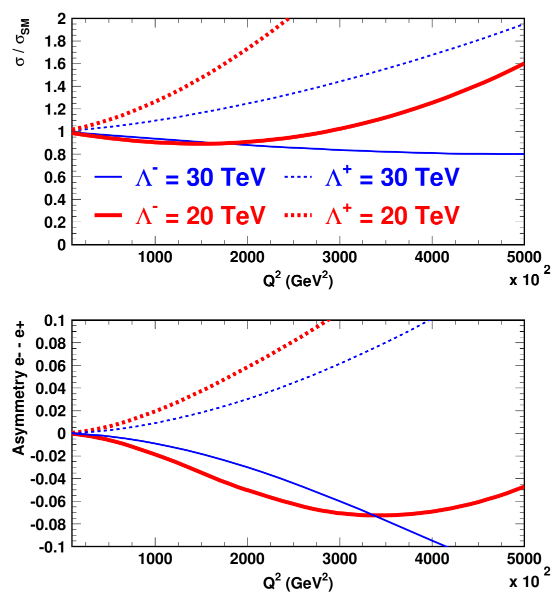


Figure 5.4: (top) Example deviations of the e^-p DIS cross-section at LHeC, in the presence of an *eeqq* CI. The ratio of the "measured" to the SM cross-sections, $r = \sigma/\sigma_{SM}$, is shown. (bottom) Asymmetry $\frac{r(e^+)-r(e^-)}{r(e^+)+r(e^-)}$ between e^+p and e^-p measurements of σ/σ_{SM}.

the Standard Model (SM) such as: E_6 [163], where new fields can mediate interactions between leptons and quarks; extended technicolor [164,165], where leptoquarks result from bound states of technifermions; the Pati-Salam model [15], where the leptonic quantum number is a fourth color of the quarks or in lepton-quark compositeness models. They are produced as single $s-$channel resonances via the fusion of incoming electrons with quarks in the proton. They are generically referred to as "leptoquarks" in what follows. The case of "leptogluons", which could be produced in *ep* collisions as a fusion between the electron and a gluon, is also addressed at the end of this section.

5.2.1 Phenomenology of leptoquarks in *ep* collisions

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

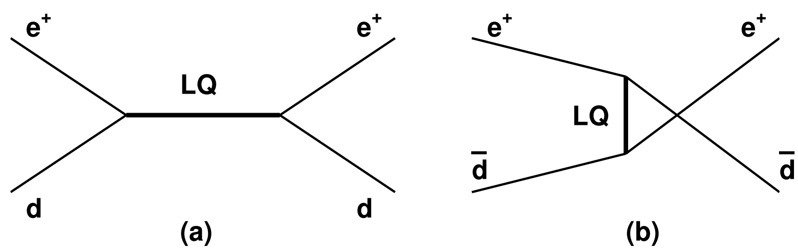


Figure 5.5: Example diagrams for resonant production in the s-channel (a) and exchange in the u-channel (b) of a LQ with fermion number $F = 0$. The corresponding diagrams for $|F| = 2$ LQs are obtained from those depicted by exchanging the quark and antiquark.

parameter of the model.

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

The resonant production or t-channel exchange of a leptoquark gives $e + q$ or $\nu + q'$ final states leading to individual events indistinguishable from SM NC and CC DIS respectively. For the process $eq \rightarrow LQ \rightarrow eq$, the distribution of the transverse energy $E_{T,e}$ of the final state lepton shows a Jacobian peak at $M_{LQ}/2$, M_{LQ} being the LQ mass. Hence the strategy to search for a LQ signal in *ep* collisions is to look, among 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. Moreover, the significance of the LQ signal over the SM DIS background can be enhanced by exploiting the specific angular distribution of the LQ decay products (see spin determination, below).

5.2.2 The Buchmüller-Rückl-Wyler Model

A reasonable phenomenological framework to study first generation LQs is provided by the BRW model [166]. This model is based on the most general Lagrangian that is invariant under $SU(3) \times SU(2) \times U(1)$, respects lepton and baryon number conservation, and incorporates dimensionless family diagonal couplings of LQs to left- and/or right-handed fermions. Under these assumptions LQs can be classified according to their quantum numbers into 10 different LQ isospin multiplets (5 scalar and 5 vector), half of which carry a 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					
${}^{1/3}S_0$	$e^+_R \bar{u}_R \to e^+ \bar{u}$	1/2	${}^{5/3}S_{1/2}$	$e^+_R u_R \to e^+ u$	1
	$e^+_L \bar{u}_L \to e^+ \bar{u}$	1		$e^+_L u_L \to e^+ u$	1
${}^{4/3}\tilde{S}_0$	$e^+_L \bar{d}_L \to e^+ \bar{d}$	1	${}^{2/3}S_{1/2}$	$e^+_L d_L \to e^+ d$	1
${}^{4/3}S_1$	$e^+_R \bar{d}_R \to e^+ \bar{d}$	1	${}^{2/3}\tilde{S}_{1/2}$	$e^+_R d_R \to e^+ d$	1
${}^{1/3}S_1$	$e^+_R \bar{u}_R \to e^+ \bar{u}$	1/2			
Vector Leptoquarks					
${}^{4/3}V_{1/2}$	$e^+_L \bar{d}_R \to e^+ \bar{d}$	1	${}^{2/3}V_0$	$e^+_L d_R \to e^+ d$	1
	$e^+_R \bar{d}_L \to e^+ \bar{d}$	1		$e^+_R d_L \to e^+ d$	1/2
${}^{1/3}V_{1/2}$	$e^+_L \bar{u}_R \to e^+ \bar{u}$	1	${}^{5/3}\tilde{V}_0$	$e^+_L u_R \to e^+ u$	1
${}^{1/3}\tilde{V}_{1/2}$	$e^+_R \bar{u}_L \to e^+ \bar{u}$	1	${}^{5/3}V_1$	$e^+_R u_L \to e^+ u$	1
			${}^{2/3}V_1$	$e^+_R d_L \to e^+ d$	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 $e + q$.

We use the nomenclature of [167] to label the different LQ states. In addition to the underlying hypotheses of BRW, we restrict LQs couplings to only one chirality state of the lepton, given that deviations from lepton universality in helicity suppressed pseudoscalar meson decays have not been observed [168, 169].

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

5.2.3 Phenomenology of leptoquarks in pp collisions

Pair production In pp collisions leptoquarks would be mainly pair-produced via gg or qq interactions. As 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 than that of the electromagnetic coupling, $\sqrt{4\pi\alpha_{em}}$), the production cross-section is essentially independent of λ. At the LHC, LQ masses up to about 1.5 to 2 TeV will be probed [170], independently of the coupling λ. However, the determination of the quantum numbers of a first generation LQ in the pair-production mode is not possible (e.g. for the fermion number) or ambiguous and model-dependent (e.g. for the spin). Single LQ production is much better suited for such studies.

Single production Single LQ production at the LHC is also possible. So far, only the production mode $gq \to e + LQ$ (see example diagrams in Fig. 5.6a and b) has been considered

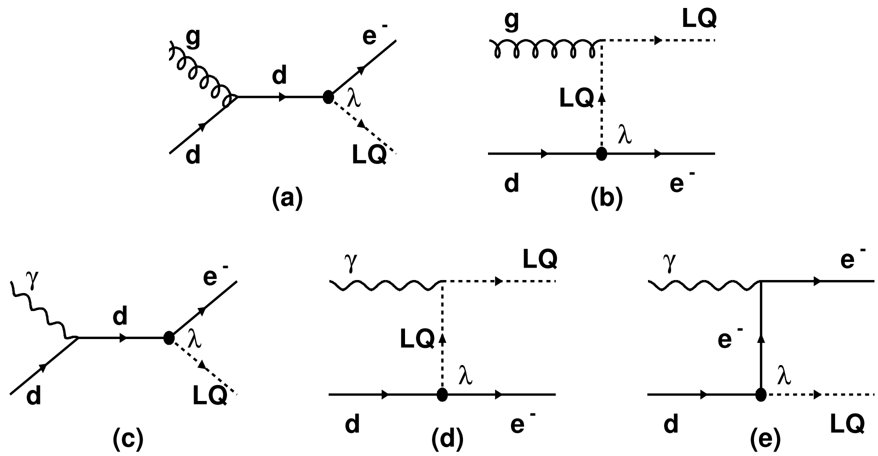


Figure 5.6: Diagrams for single LQ production in pp collisions, shown for the example case of the $\tilde{S}^L_{1/2}$ scalar leptoquark. The production may occur via qg interactions (a and b), or via $q\gamma$ interactions (c, d and e). In the latter case, the photon can be emitted by the proton (elastic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

in the literature (see e.g. [170]). In the context of this study, the additional production mode $\gamma q \to e + LQ$ has been considered as well (see example diagrams in Fig. 5.6c, d and e). This cross-section has been calculated by taking into account:

- the inelastic regime, where the photon virtuality q^2 is large enough and the proton breaks up in a hadronic system with a mass well above the proton mass. In that case, the photon is emitted by a parton in the proton, and the process $qq' \to q + e + LQ$ is calculated.

- the elastic regime, in which the proton emitting the photon remains intact. This calculation involves the elastic form factors of the proton.

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

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

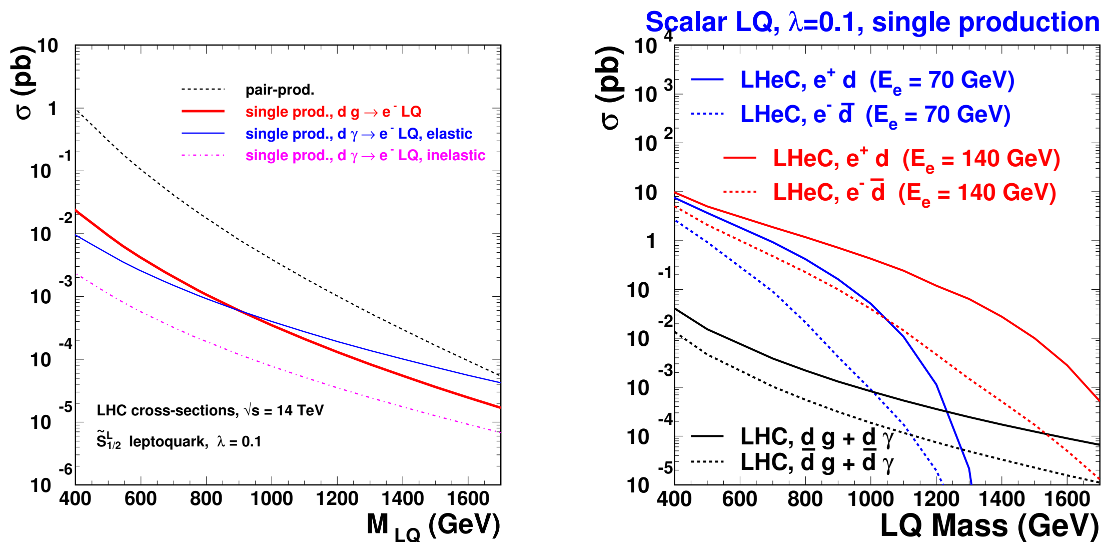


Figure 5.7: left: Single LQ production cross-section at the LHC. right: comparison of the cross-section for single LQ production, at LHC and at LHeC.

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

5.2.4 Current status of leptoquark searches

The H1 and ZEUS experiments at the HERA ep collider have constrained the coupling λ to be smaller than the electromagnetic coupling ($\lambda < \sqrt{4\pi\alpha_{em}} \sim 0.3$) for first generation LQs lighter than 300 GeV. The D0 and CDF experiments at the Tevatron pp collider set constraints on first-generation LQs that are independent of the coupling λ, by looking for pair-produced LQs that decay into eq (νq) with a branching ratio β $(1-\beta)$. For a branching fraction $\beta = 1$, masses below 299 GeV are excluded by the D0 experiment [171]. The CMS and ATLAS experiments have recently set tighter constraints [172,173]. Fig. 5.8 shows the bounds obtained by the CMS experiment with ~ 32 pb^{-1} collected in 2010, in the β versus M_{LQ} plane. For $\beta = 1$ ($\beta = 0.5$), masses below 384 GeV (340 GeV) are ruled out.

5.2.5 Sensitivity on leptoquarks at LHC and at LHeC

Mass - coupling reach Fig. 5.9 shows the expected sensitivity [158] 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.

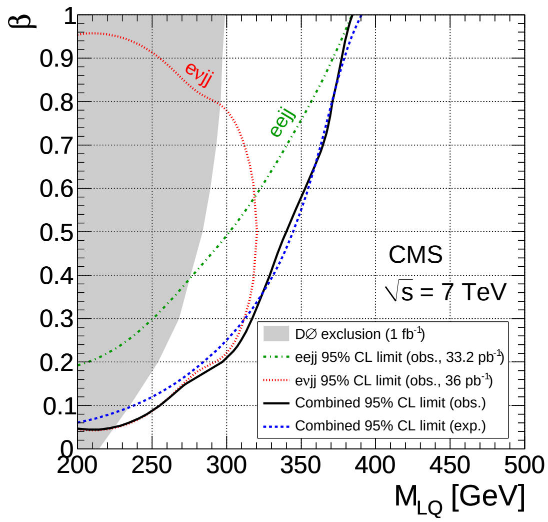


Figure 5.8: *Constraints on first generation leptoquarks obtained by the CMS experiment.*

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,

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

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

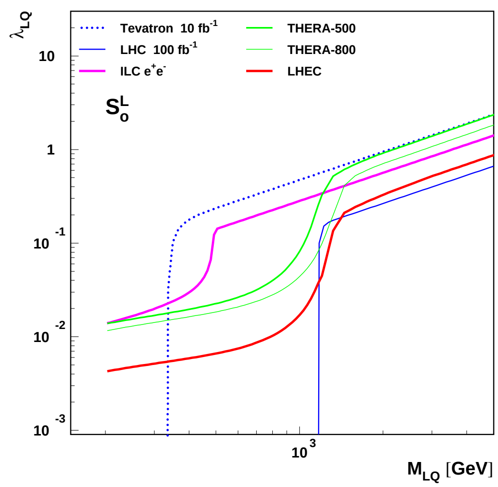


Figure 5.9: *Mass-dependent upper bounds on the LQ coupling* λ *as expected at LHeC for a luminosity of* $10\ \mathrm{fb}^{-1}$ *(full red curve) and at the LHC for* $100\ \mathrm{fb}^{-1}$ *(full blue curve). These are shown for an example scalar LQ coupling to* e^-u*.*

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

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

should thus provide a determination of the LQ fermion number. However, the single LQ pro-

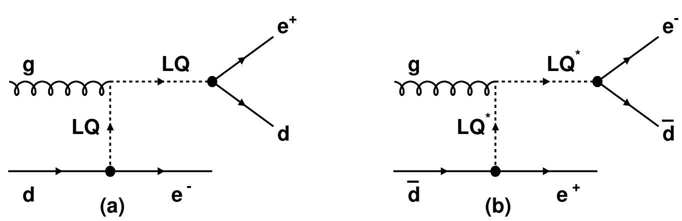


Figure 5.10: *Single production of a* $F = 0$ *leptoquark decaying (a) into a positron and a jet and (b) into an electron and a jet. In (a) (resp. (b)), the jet comes from a quark (an antiquark); conservation of the baryon number implies that the parton involved in the initial state is a quark (an antiquark).*

duction cross section at the LHC is two orders of magnitude lower than at the LHeC (Fig. 5.7), so that the asymmetry $\mathcal{A}_{pp}$ measured at the LHC may suffer from statistics in a large part of the parameter space. For a LQ coupling 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 ~ 1 TeV, while the LHeC can determine F for LQ masses up to 1.5 TeV (Fig. 5.11 and Fig. 5.12). Details of the determination of $\mathcal{A}_{pp}$ at the LHC are given in the next paragraph.

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 [174] implemented in CalcHep [175], 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. 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-handed coupling was allowed. The $^{1/3}S_0$ leptoquark was also assumed to couple only to the first generation. Masses of 500 GeV, 750 GeV and 1 TeV were considered. The renormalization and factorization scales were set at $Q^2 = m^2_{LQ}$ and the coupling parameter $\lambda = 0.1$. A center of mass energy of 14 TeV was assumed at the LHC.

High statistics background samples, corresponding to 150 fb^{-1} were also produced by generating the same processes $pp \rightarrow e^+e^- + \text{jet}$, including all diagrams except those involving the exchange of leptoquarks. Kinematic preconditions were applied at the generation level to both signals and background: (i)$p_T(\text{j}et) > 50$ GeV, (ii) $p_T(e^{\pm}) > 20$ GeV, (iii) invariant mass of jet-$e^+ - e^-$ system > 200 GeV. The cross sections for 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, 750 GeV and 1 TeV respectively, and 1780 fb for the background. These events were subsequently passed to Pythia [113] to perform parton showering and hadronization, then processed through Delphes [176] for a fast simulation of the ATLAS detector. Finally, considering events with two reconstructed electrons of opposite sign and, assuming that the leptoquark has already been discovered (at the LHC), the combination of the highest p_T jet with the reconstructed e^- or e^+ with a mass closest to the known leptoquark mass is chosen as the LQ candidate. The following cuts for $m_{LQ} = 500$, 750 and 1000 GeV, respectively, are applied:

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

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

LQ mass	$^{1/3}S_1 \rightarrow e^+\bar{u}$		$^{1/3}\bar{S}_1 \rightarrow e^-u$		Charge Asymmetry
(GeV)	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 aymmetry measurement with 300 fb^{-1} at the LHC, for $\lambda = 0.1$.

Flavour structure of the LQ coupling More generally, using the same charge asymmetry observable, the LHeC will be sensitive to the flavour structure of the leptoquark, through the dependence on the parton 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 assuracy 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 $\mathrm{d}\sigma\,/\,\mathrm{d}y$ 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 $\mathrm{d}\sigma\,/\,\mathrm{d}y \propto (1-y)^2$. These y spectra from scalar or vector LQ production are markedly different from the $\mathrm{d}\sigma\,/\,\mathrm{d}y \propto y^{-2}$ distribution expected at fixed M for the dominant t-channel photon exchange in neutral current DIS events [1]. 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 $g\,LQ\,\overline{LQ}$ 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.

[1] At 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.

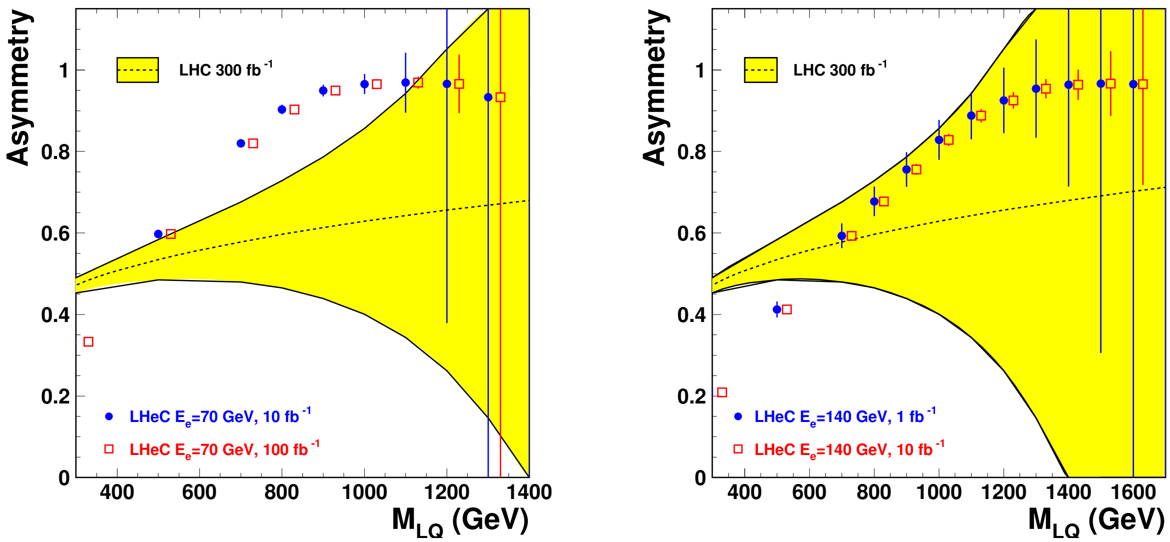


Figure 5.11: *Asymmetries which would determine the fermion number of a LQ, the sign of the asymmetry being the relevant quantity. The dashed curve shows the asymmetry that could be measured at the LHC; the yellow band shows the statistical uncertainty of this quantity, assuming an integrated luminosity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

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 :

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

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

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

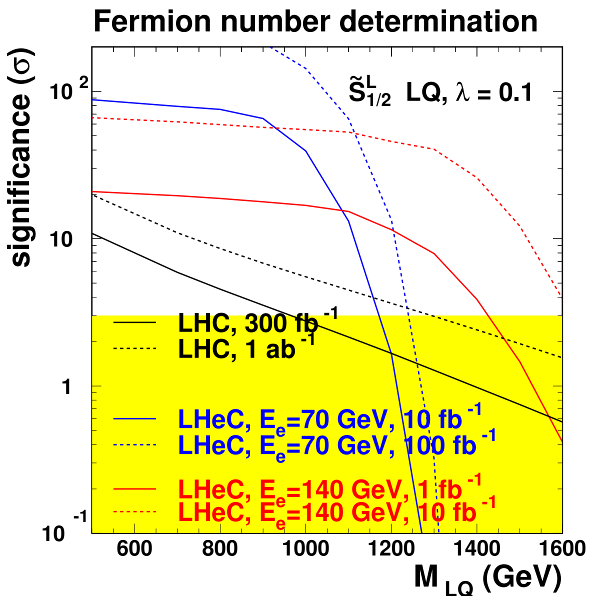


Figure 5.12: Significance of the determination of the fermion number of a LQ, at the LHC (black curve) and at the LHeC (blue and red curves). This corresponds to a $\tilde{S}^{L}_{1/2}$ leptoquark, assuming a coupling of $\lambda = 0.1$.

Chiral structure of the LQ coupling Chirality is central to the SM Lagrangian. Polarised electron and positron beams[2] at the LHeC will shed light on the chiral structure of the LQ-e-q couplings. Measurements of a similar nature at LHC are impossible.

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

5.2.7 Leptogluons

While leptoquarks and excited fermions are widely discussed in the literature, leptogluons have not received the same attention. However, they are predicted in all models with colored preons [177–182]. For example, in the framework of fermion-scalar models, leptons would be bound states of a fermionic preon and a scalar 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 octet partner [182].

A study of leptogluons production at LHeC is presented in [183]. It is based on the following

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

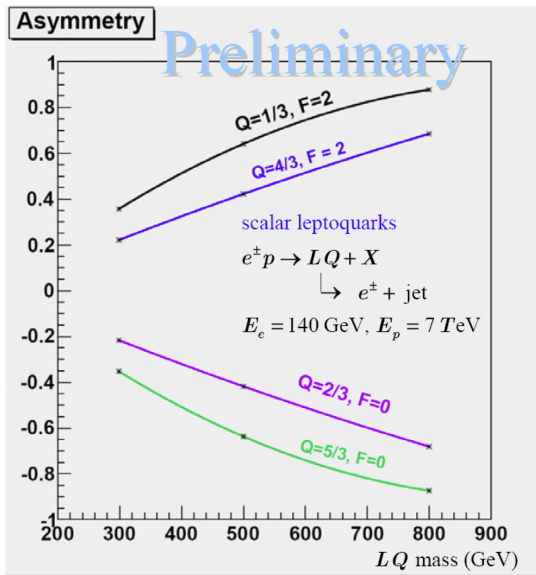


Figure 5.13: Charge asymmetry vs LQ mass for different types of scalar LQ's.

Lagrangian:

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

where $G_{\mu\nu}^{\alpha}$ is the field strength tensor for gluon, index $\alpha = 1, 2, ..., 8$ denotes the color, g_s is gauge coupling, 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 anti-symmetric tensor and Λ is the compositeness scale. The leptonic chiral invariance implies $\eta_L \eta_R = 0$.

The phenomenology of leptogluons at LHC and LHeC is very similar to that of leptoquarks, despite their different spin (leptogluons are fermions while leptoquarks are bosons) and their different interactions. Figure 5.14 shows typical cross-sections for single leptogluon production at the LHeC, assuming Λ is equal to the leptogluon mass. It is estimated that, for example, a sensitivity of to a compositeness scale of 200 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} is 1.1 TeV for $\Lambda = 10$ TeV.

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

5.3 Excited leptons and other new heavy leptons

The three-family structure and mass hierarchy of the known fermions is one of the most puzzling characteristics of the Standard Model (SM) of particle physics. Attractive explanations are provided by models assuming composite quarks and leptons [184]. The existence of excited states of fermions (F^*) is a natural consequence of compositeness models. More generally, various models predict the existence of fundamental new heavy leptons, which can have similar experimental characteristics as excited leptons. They could, for example, be part of a fourth

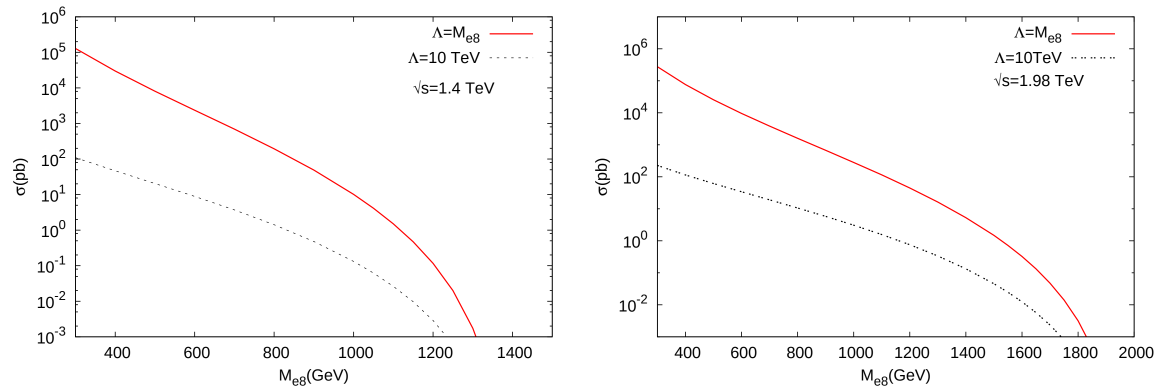


Figure 5.14: Resonant e_8 production at the LHeC, for two values of the center-of-mass energy.

Standard model family. They arise also in Grand Unified Theories, and appear as colorless fermions in technicolor models.

New heavy leptons could be pair-produced at the LHC up to masses of $\mathcal{O}(300)$ GeV. As for the case of leptoquarks, pp data from pair-production of new leptons may not allow for a detailed study of their properties and couplings. Single production of new leptons is also possible at the LHC, but is expected to have a larger cross-section at LHeC, via $e\gamma$ or eW interactions. The case of excited electrons is considered in the following, with more details being given in [185].

Single production of excited leptons at the LHC ($\sqrt{s}$ up to 14 TeV) may happen via the reactions $pp \rightarrow e^{\pm}e^{*} \rightarrow e^{+}e^{-}V$ and $pp \rightarrow \nu e^{*} + \nu^{*}e^{\pm} \rightarrow e^{\pm}\nu V$. The LHC should be able to tighten considerably the current constraints on these possible new states and to probe excited lepton masses of up to 1 TeV [186]. A sensitivity similar to the LHC could be reached at the ILC [187], with different $e^{+}e^{-}$, $e\gamma$ and $\gamma\gamma$ collisions modes and a centre of mass energy of $\sqrt{s} \geq 500$ GeV.

Recent results of searches for excited fermions [188–190] at HERA using all data collected by the H1 detector have demonstrated that ep colliders are very competitive to pp or $e^{+}e^{-}$ colliders. Indeed limits set by HERA extend at high mass beyond the kinematic reach of LEP searches [191,192] and to higher compositeness scales than those obtained at the Tevatron [193] using 1 fb^{-1} of data. Therefore a future LHeC machine, with a centre of mass energy of $1-2$ TeV, much higher than at the HERA ep collider, would be ideal to search for and study excited fermions. This has motivated us to examine excited electron production at a future LHeC collider and compare it to the potential of other types of colliders at the TeV scale, the LHC and the ILC.

5.3.1 Excited Fermion Models

Compositeness models attempt to explain the hierarchy of masses in the SM by the existence of a substructure within the fermions. Several of these models [194–196] predict excited states of the known fermions, in which excited fermions are assumed to have spin 1/2 and isospin 1/2 in order to limit the number of parameters of the phenomenological study. They are expected to be grouped into both left- and right-handed weak isodoublets with vector couplings. The existence of the right-handed doublets is required to protect the ordinary light fermions from radiatively acquiring a large anomalous magnetic moment via F^*FV interaction (where V is a γ, Z or W).

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

$$\mathcal{L}_{GM} = \frac{1}{2\Lambda}\bar{F_R^*}\,\sigma^{\mu\nu}\left[g\,f\,\frac{\vec{\tau}}{2}\,\vec{W_{\mu\nu}} + g'\,f'\,\frac{Y}{2}\,B_{\mu\nu} + g_s\,f_s\,\frac{\vec{\lambda}}{2}\,\vec{G_{\mu\nu}}\right]F_L \;+\; h.c., \tag{5.6}$$

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

In addition to gauge mediated (GM) interactions, novel composite dynamics may be visible as contact interactions (CI) between excited fermions and ordinary fermions. Such interactions can be described by an effective four-fermion Lagrangian [196]:

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

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

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

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

5.3.2 Simulation and Results

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

Considering pure gauge interactions, excited electrons could be produced in ep collisions at the LHeC via a t-channel γ or Z bosons exchange. The Monte Carlo (MC) event generator COMPOS [197] is used for the calculation of the e^* production cross section and the simulation of signal events. The production cross sections of excited neutrinos at the LHeC is also shown in figure 5.15. These results are obtained with the assumption $f = +f'$ and $M_{e^*} = \Lambda$ and are compared to production cross section at HERA and also at the LHC [186]. In the mass range accessible by the LHeC, the e^* production cross section is clearly much higher than at the LHC.

Considering gauge and contact interactions together, formulae for the e^* production cross section via CI and of the interference term between contact and gauge interactions have been incorporated into COMPOS [188,198]. For simplicity, the relative strength of gauge and contact interactions are fixed by setting the parameters f and f' of the gauge interaction to one.

Comparisons of the e^* production cross section via only gauge interactions and via GM and CI together, as a function of the e^* mass, are presented in figure 5.16(a) for $M_{e^*} = \Lambda$ and figure 5.16(b) for $\Lambda = 10$ TeV, respectively. These results for the LHeC at $\sqrt{s} = 1.4$ TeV are compared to the cross section at an LHC operating at $\sqrt{s} = 14$ TeV. These plots demonstrate that at the LHeC the ratio of the contact and gauge cross sections (proportional to $\hat{s}/\Lambda^4$ and $1/\Lambda^2$ respectively) decreases as Λ and M_{e^*} increase differently than for the LHC where contact interactions may be an important source of production of excited electrons. In the mass range accessed at the LHeC, e^* decays are dominated by gauge decays, provided that Λ is large enough. Therefore, only gauge decays are looked for in the present study.

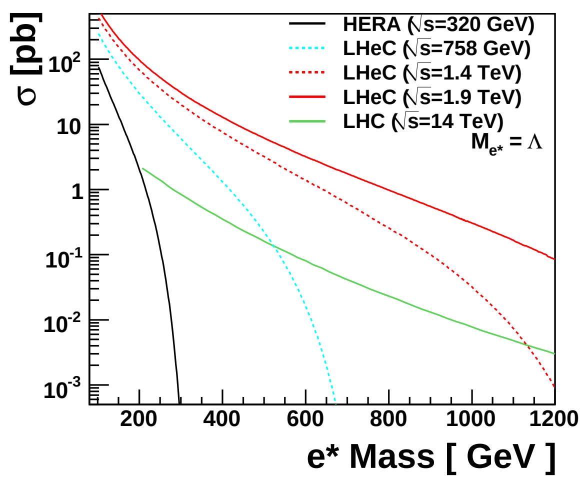


Figure 5.15: The e^* production cross section for different design scenarios of the LHeC electron-proton collider, compared to the cross sections at HERA and at the LHC.

In order to estimate the sensitivity of excited electron searches at the LHeC, the e^* production followed by its decay in the channel $e^* \rightarrow e\gamma$ is considered. This is the key channel for excited electron searches in *ep* collisions as it provides a very clear signature and has a large branching ratio. Only the main sources of backgrounds from SM processes are considered here, namely neutral currents (NC DIS) and QED-Compton ($e\gamma$) events. Other possible SM backgrounds are negligible. The MC event generator WABGEN [199] is used to generate these background events. Figure 5.17 compares the e^* production cross section to the total cross section of SM backgrounds. Background events dominate in the low e^* mass region. Hence to enhance the signal, candidate events are selected with two isolated electromagnetic clusters with a polar angle between 5° and 145° and transverse energies greater than 15 GeV and 10 GeV, respectively.

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

In case of gauge interaction, the attainable limits at the LHeC on the ratio f/Λ are shown in figure 5.18 for excited electrons, for the hypothesis $f = +f'$ and different integrated luminosities $L = 10$ fb^{-1} for $\sqrt{s}$ up to 1.4 TeV and $L = 1$ fb^{-1} for $\sqrt{s}$ up to 2 TeV. They are compared to the upper limits obtained at LEP [191,192], HERA [188] and also to the expected sensitivity of

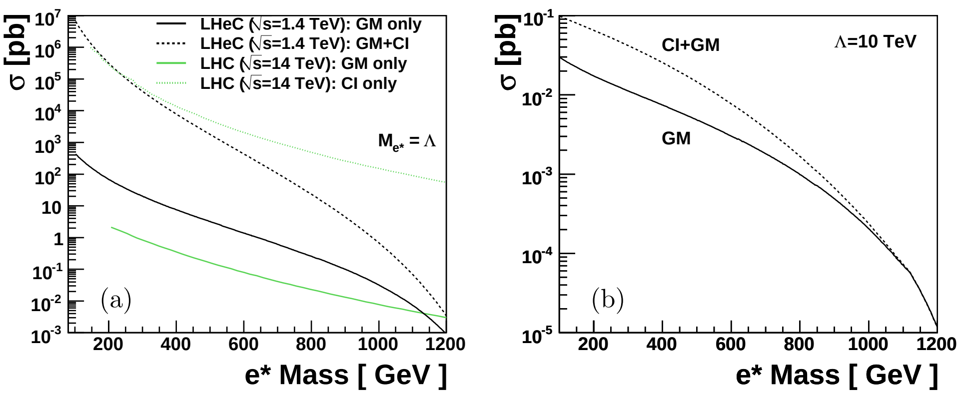


Figure 5.16: Comparison of the e^* production cross section via gauge and contact interactions. In figure (a), the results for the LHeC ($\sqrt{s}$ = 1.4 TeV) and for the LHC ($\sqrt{s}$ = 14 TeV) are compared. Production cross sections for a fixed Λ value of 10 TeV are shown in figure (b) for the LHeC.

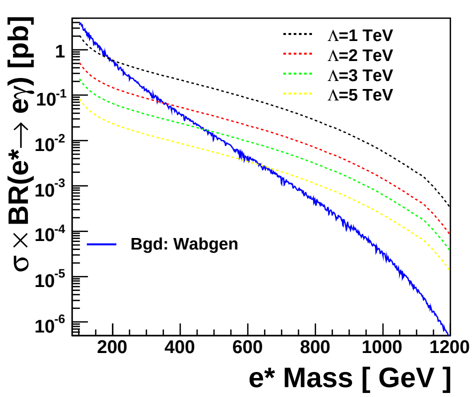


Figure 5.17: Electromagnetic production cross section for e^* ($e^* \to e\gamma$) for different values of Λ.

the LHC [186]. Considering the assumption $f/\Lambda = 1/M_{e^*}$ and $f = +f'$, excited electrons with masses up to 1.2(1.5) TeV, corresponding to centre of mass energies of $\sqrt{s} = 1.4(1.9)$ TeV of the LHeC, are excluded. Under the same assumptions, LHC ($\sqrt{s} = 14$ TeV) could exclude e^* masses up to 1.2 TeV for an integrated luminosity of 100 fb^{-1}. In the accessible mass range of LHeC, the LHeC would be able to probe smaller values of the coupling f/Λ than the LHC. Similarly to leptoquarks (see section 5.2), if an excited electron is observed at the LHC with a mass of $\mathcal{O}(1$ TeV), the LHeC would be better suited to study the properties of this particle, thanks to the larger single production cross-section (see Fig. 5.15).

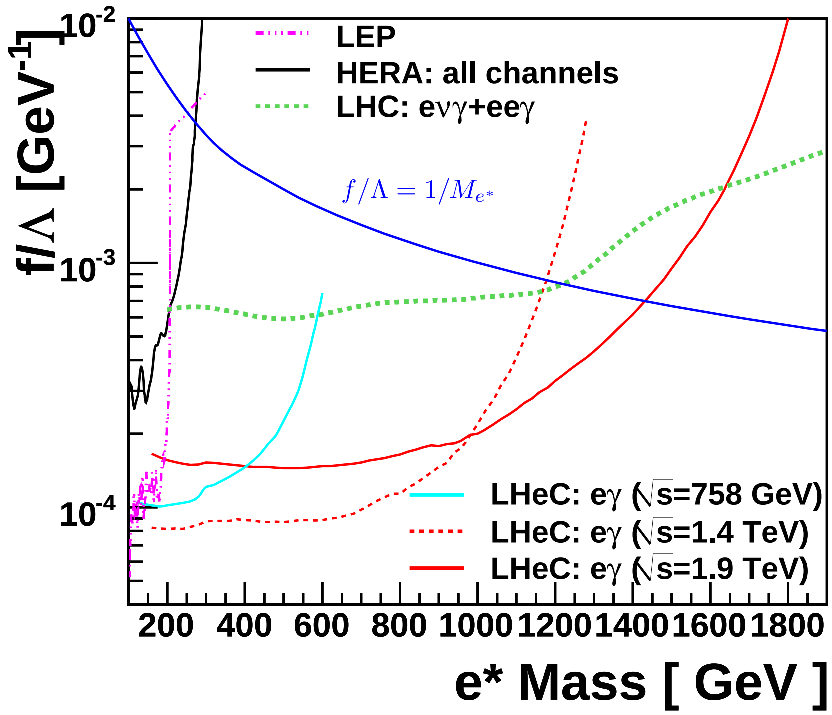


Figure 5.18: Sensitivity to excited electron searches for different design scenarios of the LHeC electron-proton collider, compared to the expected sensitivity of the LHC ($\sqrt{s} = 14$ TeV, $L = 100$ fb^{-1}). Different integrated luminosities at the LHeC ($L = 10$ fb^{-1} for $\sqrt{s}$ up to 1.4 TeV and $L = 1$ fb^{-1} for $\sqrt{s}$ up to 2 TeV) are assummed. 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.

5.3.3 New leptons from a fourth generation

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

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

In that case, the single production of l_4 and ν_4 would be similar to that of excited electrons and neutrinos. For a study of the properties and couplings of such a new lepton, an ep machine would offer the same advantages as presented above in the case of excited electrons. A study of the processes $ep \to l_4 X \to Ze(\gamma\mu)X$ and $ep \to \nu_4 X \to W(e,\mu)X$ at the LHeC is presented in [200]. For example, for an anomalous coupling $\kappa/\Lambda = 1$ TeV^{-1}, LHeC would be able to cover l_4 masses up to ~ 900 GeV.

5.4 New physics in boson-quark interactions

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

5.4.1 An LHeC-based γp collider

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

5.4.2 Anomalous Single Top Production at the LHeC Based γp Collider

The top quark is expected to be most sensitive to physics beyond the Standard Model (BSM) because it is the heaviest available particle of the Standard Model (SM). A precise measurement of the couplings between SM bosons and fermions provides a powerful tool for the search of BSM physics allowing a possible detection of deviations from SM predictions [201]. Anomalous tqV ($V = g, \gamma, Z$ and $q = u, c$) couplings can be generated through dynamical mass generation [37],sensitive to the mechanism of dynamical symmetry breaking. They have a similar chiral structure as the mass terms, and the presence of these couplings would be interpreted as signals of new interactions. This motivates the study of top quark flavour changing neutral current (FCNC) couplings at present and future colliders.

Current experimental constraints at 95% C.L. on the anomalous top quark couplings are [202]: $BR(t \to \gamma u) < 0.0132$ and $BR(t \to \gamma u) < 0.0059$ from HERA; $BR(t \to \gamma q) < 0.041$ from LEP and $BR(t \to \gamma q) < 0.032$ from CDF. The HERA has much higher sensitivity to $u\gamma t$ than $c\gamma t$ due to more favorable parton density: the best limit is obtained from the ZEUS experiment.

The top quarks will be produced in large numbers at the Large Hadron Collider (LHC), allowing great precision measurement of the coupling. For a luminosity of 1 fb^{-1} (100 fb^{-1}) the expected ATLAS sensitivity to the top quark FCNC decay is $BR(t \to q\gamma) \sim 10^{-3}(10^{-4})$ [203, 204]. The production of top quarks by FCNC interactions at hadron colliders has been studied in [205–217], e^+e^-colliders in [37, 218–221] and lepton-hadron collider in [37, 222–224]. LHC will give an opportunity to probe $BR(t \to ug)$ down to 5×10^{-3} [225]; ILC/CLIC has the potential to probe $BR(t \to q\gamma)$ down to 10^{-5} [226].

A linac-ring type collider presents the sole realistic way to TeV scale in γp collisions [227–232]. Recently this opportunity has been widely discussed in the framework of the LHeC project [233]. Two stages of the LHeC were considered: QCD Explorer ($E_e = 50 - 100$ GeV) and Energy Frontier ($E_e > 250$ GeV). The potential of the LHeC as a γp collider to search for anomalous top quark interactions has been investigated [234]. The effective Lagrangian involving anomalous $t\gamma q$ ($q = u, c$) interactions is given by [225].

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

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 h_q are complex numbers, g_e is the electromagnetic coupling constant, κ_q is a real and positive anomalous FCNC coupling constant and Λ is the new physics scale. The neutral current magnitudes in the Lagrangian satisfy $|(f_q)^2 + (h_q)^2| = 1$ for each term. The anomalous decay width can be calculated as

$$\Gamma(t \to q\gamma) = (\frac{\kappa_q}{\Lambda})^2 \frac{2}{9} \alpha_{em} m_t^3 \tag{5.10}$$

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

For numerical calculations anomalous interaction vertices are implemented into the CalcHEP package [175] using the CTEQ6M [114] parton distribution functions. The Feynman diagrams for the subprocess $\gamma q \to W^+ b$, where $q = u, c$ are shown in Fig. 5.19. The first three diagrams correspond to irreducible backgrounds and the last one to the signal. The main background comes from associated production of W boson and the light jets.

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

Here, b-tagging efficiency is assumed to be 60% and the mistagging factors for light (u, d, s) and c quarks are taken as 0.01 and 0.1, respectively. A p_T cut reducese the signal (by $\sim 30\%$

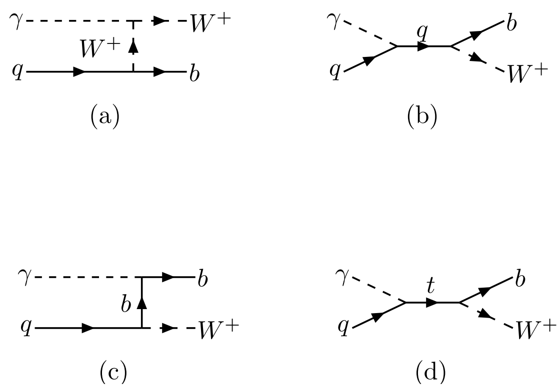


Figure 5.19: Feynman diagrams for $\gamma q \to W^+ b$, where $q = u, c$.

for $p_T > 50$ GeV), whereas the background is essentially suppressed (by a factor 4-6) . In order to improve the signal to background ratio further, one can apply a cut on the invariant mass of $W + jet$ around top mass. In Table 5.3, the cross sections for signal and background processes are given after having applied both a p_T and an invariant mass cuts ($M_{Wb} = 150 - 200$ GeV).

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.

$\kappa/\Lambda = 0.01$ 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}

In order to calculate the statistical significance (SS) we use following formula [235] :

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

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

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

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

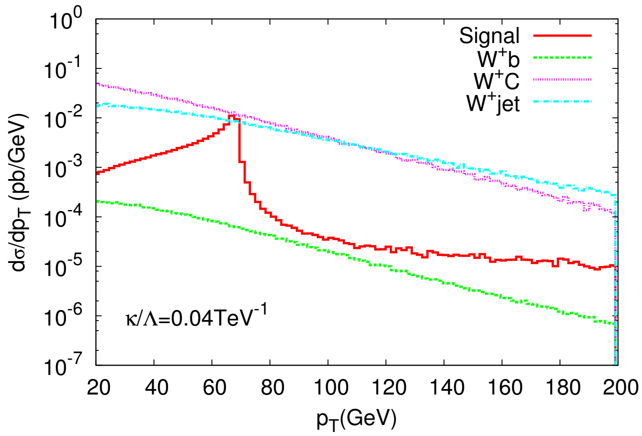


Figure 5.20: The transverse momentum distribution of the final state jet for the signal and background processes. The differential cross section includes the b-tagging efficiency and the rejection factors for the light jets. The center of mass energy $\sqrt{s_{ep}} = 1.4$ TeV and κ/Λ =0.04 TeV $^{-1}$.

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

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

where σ^i_B is the cross-section for the SM background in the i^{th} bin, including both b-jet and light-jet contributions with their corresponding efficiency factors. In the σ_{S+B} calculations, we take into account the different values for κ_u and κ_c as well as the signal-background interference. Figs. 5.20-5.21 show that the sensitivity is enhanced by a factor of 1.5 when the luminosity changes from 2 fb^{-1} to 10 fb^{-1}. Concerning the energy upgrade, increasing electron energy from 70 GeV to 140 GeV results in 20% improvement for κ_c [234]. Increasing the electron energy further (energy frontier ep collider) does not give an essential improvement in the sensitivity to anomalous couplings [236].

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

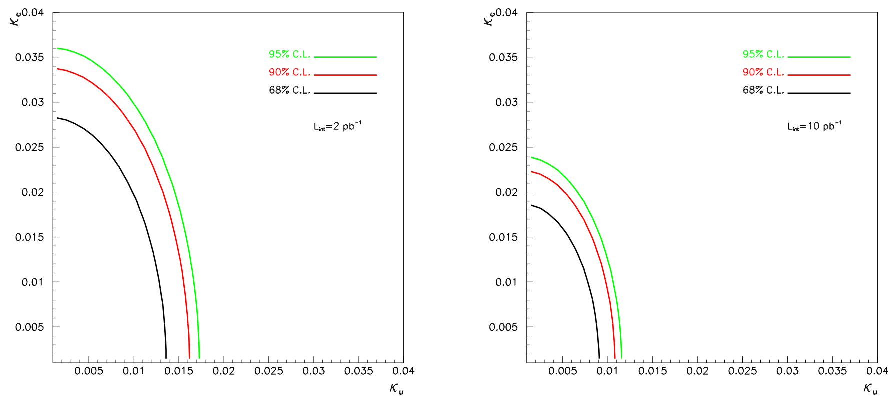


Figure 5.21: Contour plot for the anomalous couplings reachable at the LHeC based γp collider with the ep center of mass energy $\sqrt{s_{ep}} = 1.4$ TeV and integrated luminosity of $L_{int} = 2$ fb^{-1} (left) or $L_{int} = 10$ fb^{-1} (right)

5.4.3 Excited quarks in γp collisions at LHeC

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

A sizeable f_s coupling would allow for resonant q^* production at the LHC via quark-gluon fusion. In that case, the LHC would offer a large discovery potential for excited quarks and would be well suited to study the properties and couplings of these new quarks. However, if the coupling of excited quarks to gq happens to be suppressed, the LHC would mainly produce q^* via pair-production and would have little sensitivity to couplings f/Λ or f'/Λ. Such couplings would be better studied, or probed down to much lower values, via single-production of q^* at the LHeC. A study of the LHeC potential for excited quarks is presented in [237]. 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 $q^* \to q\gamma$ and $q^* \to qg$ have been considered here.

5.4.4 Quarks from a fourth generation at LHeC

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

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

is very similar to that of excited quarks. A γp collider based on LHeC would have a better sensitivity than LHC to anomalous couplings κ_γ and κ_Z. A detailed study is presented in [200] and example results are shown in Fig. 5.23. These figures also show the clear advantage of a γp collider compared to an ep collider, for the study of new physics in γq interactions.

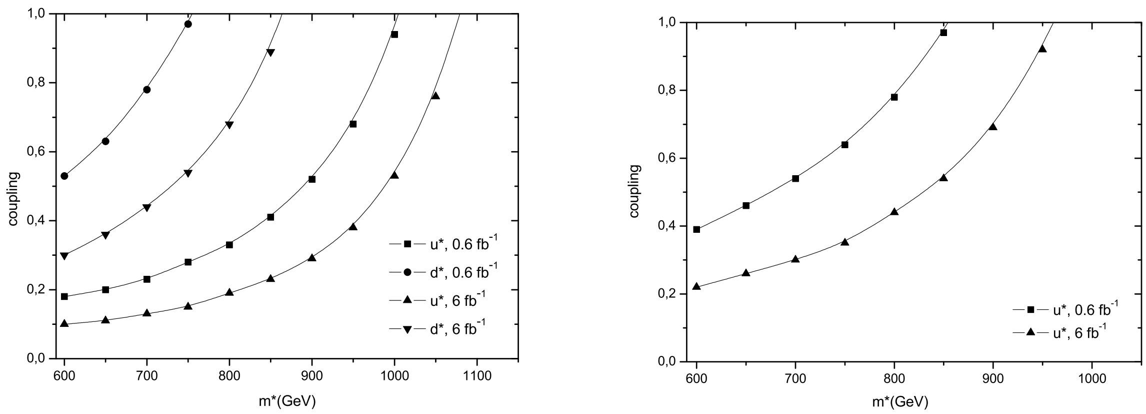


Figure 5.22: Observation reach at 3σ for coupling and excited quark mass at a γp collider with $\sqrt{s} = 1.27$ TeV from an analysis of (left) the jj channel and (right) the γj channel.

5.4.5 Diquarks at LHeC

The case of diquark production at LHeC has been studied in [238]. The production cross-section can be sizeable at n high energy ep machine, especially when operated as a γp collider. The measurement of the $\gamma p \to DQ + X$ cross-section, for a diquark DQ of known mass and known coupling to the diquark pair[3] would provide a measurement of the electric charge of the diquark. It would thus be complementary to the pp data, which offer no simple way to access the DQ electric charge. However, the diquark masses and couplings that could be accessible at LHeC appear to be already excluded by the recent search for dijet resonances at the LHC [239].

5.4.6 Quarks from a fourth generation in Wq interactions

In case fourth generation quarks do not have anomalous interactions as in Eq. 5.13, they (or vector-like quarks coupling to light generations [240, 241]) could be produced in ep collisions by Wq interactions provided that the V_{Qq} elements of the extended CKM matrix are not too small, via the usual vector WqQ interactions. An example of the sensitivity that could be reached at LHeC is presented in [242], assuming some values for the V_{Qq} parameters. Measurements of single Q production at LHeC would provide complementary information to the LHC data, that could help in determining the extended CKM matrix.

5.5 Sensitivity to a Higgs boson

Understanding the mechanism of electroweak symmetry breaking is a key goal of the LHC physics programme. In the SM, the symmetry breaking is realized via a scalar field (the Higgs

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

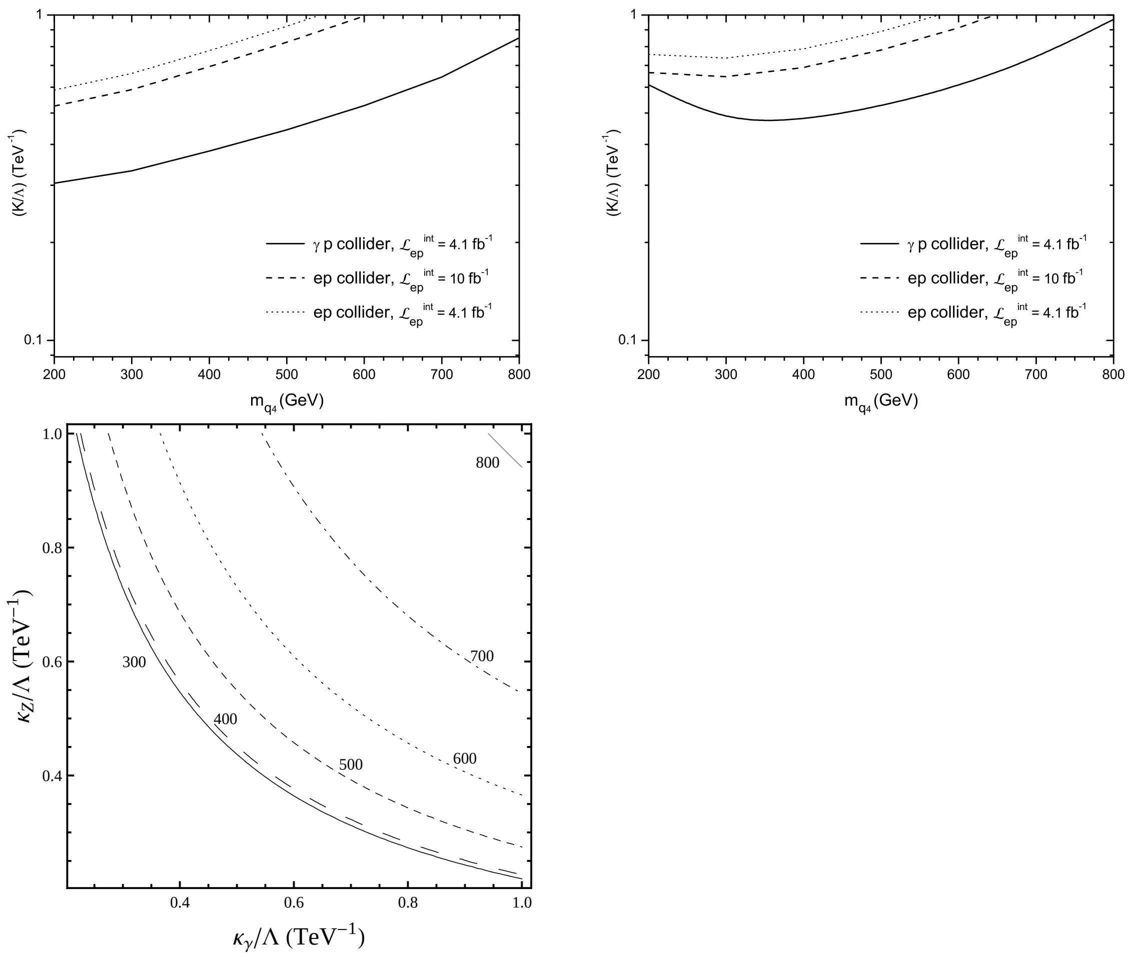


Figure 5.23: The achievable values of the anomalous coupling strength at ep and γp colliders for a) $q_4 \to \gamma q$ anomalous process and (b) $q_4 \to Zq$ anomalous process as a function of the q_4 mass; (c) the reachable values of anomalous photon and Z couplings with $L_{int} = 4.1$ fb^{-1}.

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

- establish that the Higgs field is indeed accounting for the fermion masses, via Yukawa couplings $y_f H \bar{f} f$;

- disentangle between the SM and (some of) its extensions. For example, despite the richer content of the Higgs sector in the Minimal Supersymmetric Standard Model, only the light SUSY Higgs boson h would be observable at the LHC in certain regions of parameter space. Its properties are very similar to those of the SM Higgs H, and precise measurements of ratios $BR(\Phi \to VV)/BR(\Phi \to f\bar{f})$ will be essential in determining whether or not the observed boson, Φ, is the SM higgs scalar.

Electroweak precision measurements strongly suggest that the SM Higgs boson should be light, in which 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 will be very challenging at the LHC [203, 235, 243]. Indeed, the observation of $H \to b\bar{b}$ in the inclusive production mode is made very difficult by the huge QCD background, although a possible search channel would be associated WH and ZH production, with highly boosted Higgs, leading to a high mass jet with substructure [244]. The observability of the signal in the $t\bar{t}H$ production mode also suffers from a large background, including background of combinatorics origin, and from experimental systematic uncertainties.

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

At the LHeC, a light Higgs boson could be produced via WW or ZZ fusion with a sizeable cross-section. This section focusses on the observability of the signal $ep \to H + X \to b\bar{b} + X$ at LHeC, which may be the first observation of the $H \to b\bar{b}$ decay.

5.5.1 Higgs production at LHeC

In ep collisions, the Higgs boson could be produced in neutral current (NC) interactions via the ZZH coupling, and in charged current (CC) interactions via the WWH coupling. The corresponding diagrams are shown in Fig. 5.24, and the production cross-sections, as a function of the Higgs mass, is displayed in Fig. 5.25. The WWH production largely dominates the total cross-section. As is the case for the inclusive CC DIS interactions, the cross-section is much larger in e^-p collisions than in e^+p collisions, due to the more favorable density of the valence quark that is involved (u in e^-p, d in e^+p), and to the more favorable helicity factors. Table 5.5 shows the Higgs production cross-section (at leading order) via CC interactions in e^-p collisions, for various values of the Higgs mass and three example values of the electron beam energy. The scale dependency of these leading order estimate is of $\mathcal{O}(10\%)$. Next-to-leading order corrections were calculated in [245, 246]. They are small, but can affect within $\mathcal{O}(20\%)$ the shape of some 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.

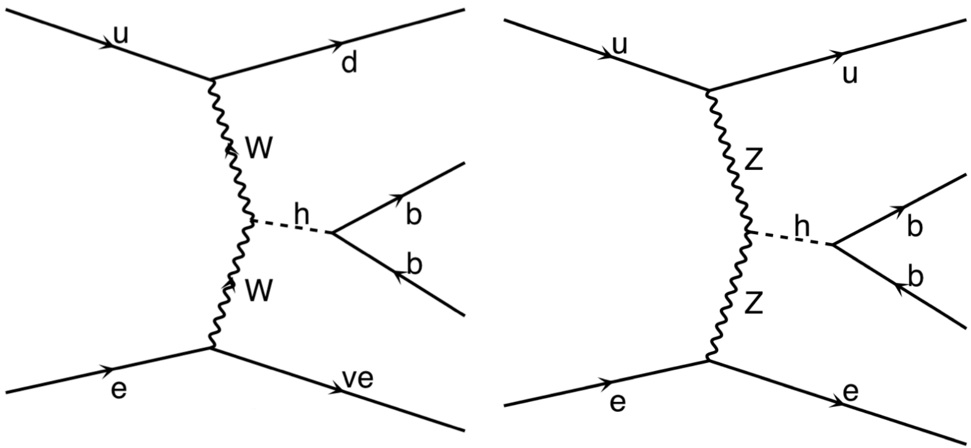


Figure 5.24: Feynman diagrams for CC(left) and NC(right) Higgs production at the LHeC.

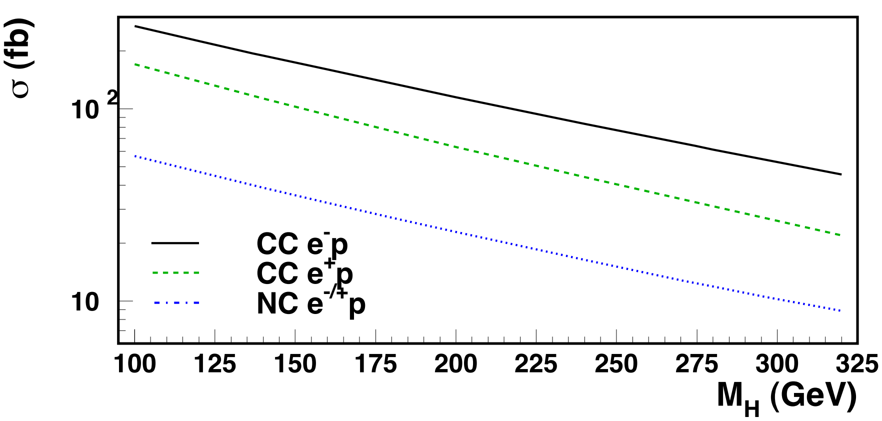


Figure 5.25: Production cross-section of a SM Higgs boson in ep collision with E_e=150 GeV and E_p=7 TeV, as a function of the Higgs mass.

5.5.2 Signal and background Monte-Carlo samples

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

MadGraph [247] has been used to generate SM Higgs production, CC and NC DIS background events. Calculations of cross-sections and generation of final states of outgoing particles are performed by MadGraph, given the beam parameters, considering all possible tree-level Feynman diagrams in the SM. In the case of NC, since the cross section is very high, diverging at low scattering angle, only processes producing two or more b quarks were generated in order to have sufficient MC statistics. By artificially increasing the mistag probability, it was possible to verify that, after the selection, essentially all the remaining NC background is indeed due to events with two truly b-quark jets in the final state. Fragmentation and hadronization processes were simulated by PYTHIA [113] with custom modifications to apply for ep collisions. Finally, particles were passed through a generic detector using the PGS [248] fast detector simulation tool. We assumed tracking coverage of $|\eta| < 3$ and calorimeter coverage of $|\eta| < 5$ with electromagnetic calorimeter resolution of $5\,\%/\sqrt{E(\mathrm{GeV})}$ (plus 1% of constant term) and hadronic calorimeter resolution of $60\,\%/\sqrt{E(\mathrm{GeV})}$. Jets were reconstructed by a cone algorithm with a cone size of $\Delta R = 0.7$. The efficiency of b-flavor tagging was assumed to be 60 % and flat within the calorimeter coverage, whereas mistagging probabilities of 10 % and 1 % for charm-quark jets and for light-quark jets, respectively, were taken into account.

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

5.5.3 Observability of the signal

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

- **cut (1): Primary cuts**
  - Exclude electron-tagged events
  - $E_{T,miss} > 20\,\mathrm{GeV}$
  - $N_{jet}(P_{T,jet} > 20\,\mathrm{GeV}) \geq 3$
  - $E_{T,total} > 100\,\mathrm{GeV}$
  - $y_{JB} < 0.9$, where $y_{JB} = \Sigma(E - p_z)/2E_e$
  - $Q^2_{JB} > 400\,\mathrm{GeV}$, where $Q^2_{JB} = E^2_{T,miss}/(1 - y_{JB})$
- **cut (2): b-tag requirement**
  - $N_{b\text{-}jet}(P_{T,jet} > 20\,\mathrm{GeV}) \geq 2$, where b-jet means a b-tagged jet
- **cut (3): Higgs invariant mass cut**

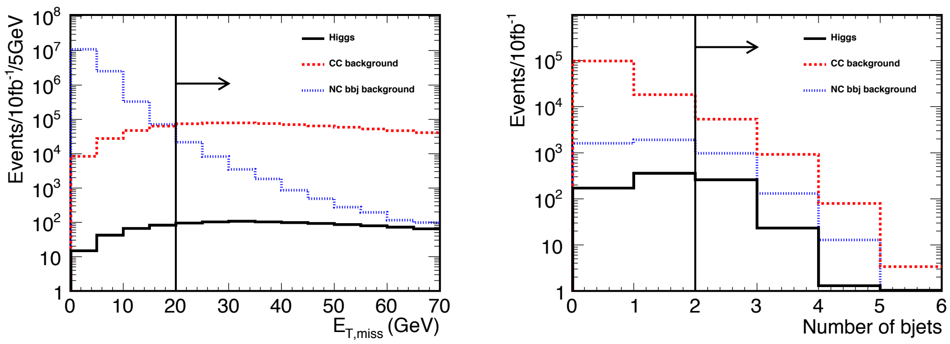


Figure 5.26: Missing E_T (left) and number of b-tagged jets (right). Solid (black), dashed (red) and dotted (blue) histograms show $H \to b\bar{b}$, CC and NC DIS background, respectively. The right plot is for events passing cut (1) in the text.

  - $90 < M_H < 120$ GeV; due to the energy carried by the neutrino from b decays, the mass peaks are slightly lower than the true Higgs mass

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

- **cut (4): rejection of single top production** Single top events result in a final state with two b-jets and a W decaying into two light-quark jets. The following cuts were found to be efficient in suppressing this background.
  - $M_{jjj,top} > 250$ GeV, where the three-jet invariant mass ($M_{jjj,top}$) was reconstructed from two b-jets with the lowest η and any third jet with the lowest η regardless of b-tag
  - $M_{jj,W} > 130$ GeV, where di-jet invariant mass ($M_{jj,W}$) was reconstructed from one b-jet with the lowest η and any second jet with the lowest η regardless of b-tag but excluding the second lowest η b-jet
- **cut (5): forward jet tagging**
  - $\eta_{jet} > 2$ for the lowest-η jet excluding the two b-jets

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

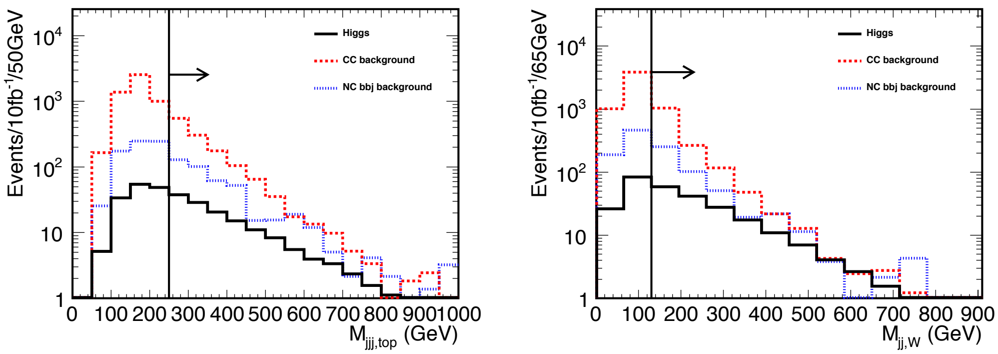


Figure 5.27: Three-jet (left) and di-jet (right) invariant masses. Solid (black), dashed (red) and dotted (blue) histograms show $H \to b\bar{b}$, CC and NC DIS background, respectively.

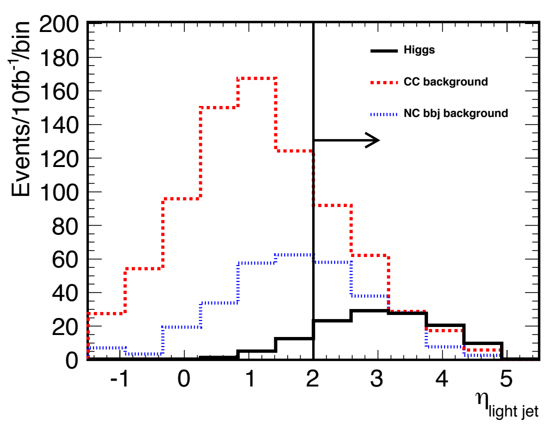


Figure 5.28: η_{jet} distribution for the lowest-η jet excluding the two b-tagged jets. Solid (black), dashed (red) and dotted (blue) histograms show $H \to b\bar{b}$, CC and NC DIS background, respectively.

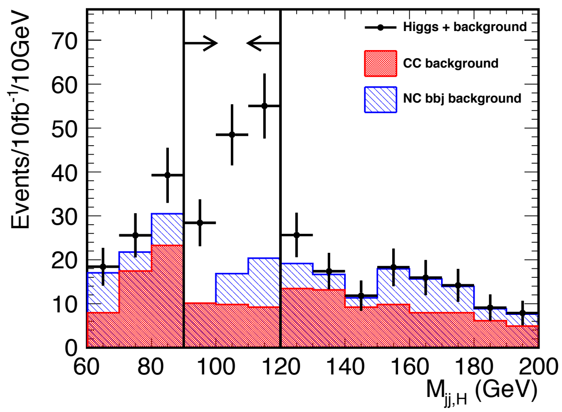


Figure 5.29: Reconstructed invariant Higgs mass after all selection criteria, except for the Higgs mass cut, have been applied. Points with error bars (black) show the $H \to b\bar{b}$ signal added to the CC (red histogram) and NC (hatched blue histogram) DIS background for an integrated luminosity of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

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

The results shown here are subject to large uncertainties. First, as mentioned above, the very large NC background cross section at forward scattering angles makes it impossible to simulate a sufficient number of events to limit the Monte Carlo statistical uncertainty. It is estimated that the background evaluation, with the above method where only events with at least two b quarks were simulated, has an uncertainty of about a factor 3. With a full simulation, it can be expected to be negligible when the true measurement is realized. Neglecting, therefore, this source of uncertainty, the systematic errors which will dominate are expected to be the theoretical estimates of signals and backgrounds and instrumental effects: efficiency and acceptance of lepton and jet reconstruction, b-tagging and mistagging probabilities. They are difficult to estimate without real data and a real detector. The statistical uncertainty on the cross section can, however, be estimated: 15% for the reference case of 150 GeV $\times$ 7 TeV beams and a Higgs of mass 120 GeV. This represents a direct measure of the statistical uncertainty on the product of the squares of couplings Hbb and HWW.

Chapter 6

Physics at High Parton Densities

6.1 Physics at small x

6.1.1 Unitarity and QCD

Introduction

QCD [9] 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 [249–251] 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 [252] 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 [253–255], 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 factorizaton 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 [256]. 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 [257–260] 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 [261, 262]

$$\sigma_{\rm tot} \le {\rm const.} \ln^2 s/s_0 \;, \tag{6.1}$$

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 [263, 264]. 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 $\sigma_{\rm tot}$ for the scattering of a virtual photon on a hadron h, $\gamma^* h \to X$. The growth of F_2 at small x translates into the rise of $\sigma_{\rm tot}$ 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

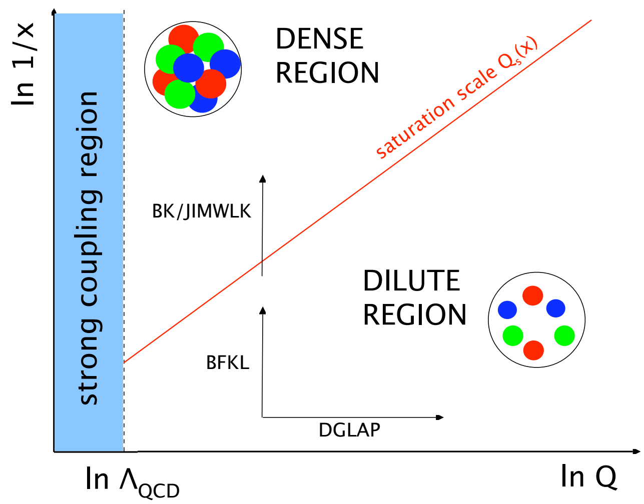


Figure 6.1: Schematic view of the different regions for the parton densities in the $\ln Q^2 - \ln 1/x$ plane. See the text for comments.

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 [21, 250, 265]. Though they are quite successful in describing existing data on inclusive and diffractive ep and eA scattering (see e.g. [266, 267] 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 recombination[1] in perturbative QCD in order to describe its high-energy

[1] Note 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.

behaviour. In the pioneering work in [256, 268], 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 [269], 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.

Later on these ideas were developed to include all corrections enhanced by the local density, to constitute what is called the Color Glass Condensate (CGC) [257–260, 270–277] (see also the most recent developments in [278–281]). The CGC provides a non-perturbative, but weak-coupling, realization of the parton saturation ideas within QCD. The linear limit of the basic CGC equation is the BFKL equation, which is the generally accepted linear evolution equation for the high-energy limit. As illustrated in Fig. 6.1, the evolution in the $\ln Q^2 - \ln 1/x$ plane is driven by both linear equations: along $\ln Q^2$ for DGLAP and along $\ln 1/x$ for BFKL.

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

The mean field version of the CGC, the Balitsky-Kovchegov (BK) equation [259, 260], provides a non-linear evolution equation for unintegrated gluon densities. It turns out that the BK approach results in a gluon density which, for a fixed resolution of the probe, is saturated for small longitudinal momentum fractions x, whereas at large values of x, the non-linear term is negligible. The separation between these two limits is given by a dynamically generated saturation momentum $Q_s(x)$ which increases with decreasing x (c.f. figure 6.1), and therefore saturation is determined by the condition $Q_s(x) > Q$. Then, for large energies or small x, the system is in a dense regime of high gluon fields (thus non-perturbative) but the typical gluon momentum, $\sim Q_s$, is large (thus the coupling constant which determines gluon interactions is weak). The qualitative behavior of the saturation scale with energy and nuclear size can be argued as follows. The transition from a dilute to a dense regime is marked by the packing factor (in this case, the product of the density of gluons per unit transverse area times the gluon-gluon cross section) becoming of the order unity i.e.

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

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

The BK equation was derived under several simplifying assumptions such as the scattering of a dilute projectile on a dense target, a large number of QCD colours and the absence of

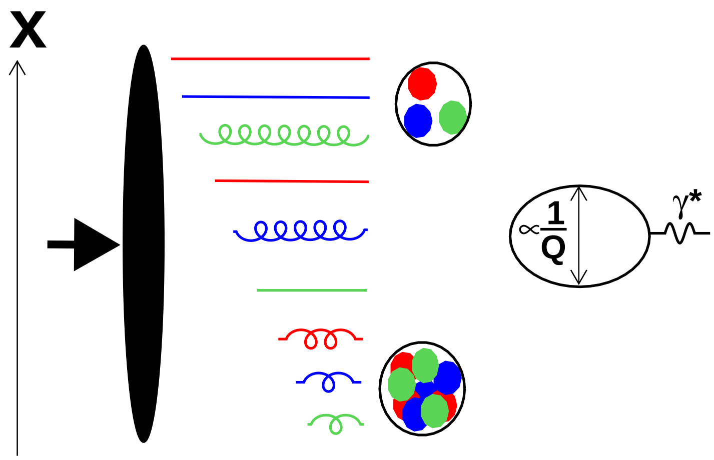


Figure 6.2: Illustration of saturation ideas. The hadron is moving very fast to the right, and its wave function contains many partonic components. Specifically, it includes partons with both large and small fractions of its longitudinal momentum x. The former are in a dilute regime, while the latter 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 $1/Q$.

correlations in the target. At present, the discussion is concentrated on how to overcome these difficulties [278, 282, 283]. Possible phenomenological implications [284–286], are being considered. Also, the proposed relation between high-energy QCD and Statistical Mechanics [282, 287] is under investigation.

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

Resummation at low x

The generic challenges that the small-x region bears in QCD are inherently related to the divergence of the gluon number density with decreasing values of x. As is well known, deep-inelastic partonic cross sections and parton splitting functions receive large corrections in the small-x limit due to the presence of powers of $[\alpha_s \log x]$ to all orders in the perturbative expansion [253, 263, 264, 288, 289]. It thus suggests dramatic effects from logarithmically enhanced corrections, so the success of fixed order NLO perturbation theory at HERA has been very hard to explain in regions where x becomes small. Recently, hints have been found that indeed the DGLAP fits tend to deteriorate systematically in the region of small x and Q^2 [10, 290]. Direct calculations at next-to-leading logarithmic accuracy in the BFKL framework were performed [291, 292], and showed a slow convergence of the perturbative series in the high-energy, or small-x regime. Therefore, generically one expects deviations from fixed-order DGLAP evolution in the small-x and small-Q regime which call for resummation of higher orders in perturbation theory.

Extensive analyses have been performed in the last few years [293–298], which indeed point to the importance of resummation to all orders. Resummation should embody important constraints like kinematic effects, momentum sum rules and running coupling effects.

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

The importance of diffraction

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

Diffraction has been extensively analyzed at HERA, with a variety of measurements in bins of x and Q^2, as well as more differential analyses which include the dependence on the momentum transfer t. Physically, for the diffractive event to occur, there must be an exchange of a coherent, color neutral cluster of partons (a quasiparticle) which leaves the interacting proton intact. This color neutral cluster is often called the *pomeron*, and it can be characterised via a factorisation theorem [299] by a set of partonic densities analogous to those for the proton or nucleus. At lowest order, the QCD realisation of the pomeron is a pair of gluons [300, 301], which leads to enhanced sensitivity to saturation phenomena compared to the single gluon exchange in hte bulk of non-diffractive processes.

There are strong theoretical indications that diffraction is closely linked with the phenomenon of partonic saturation. From a wide range of calculations, mostly based on the so-called dipole model, see for example [302,303], it is known that diffractive DIS events involve softer effective scales than non-diffractive events at the same Q^2. Thus, the exploration of diffractive phenomena offers a unique window to analyze the transition between perturbative and non-perturbative dynamics in QCD.

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

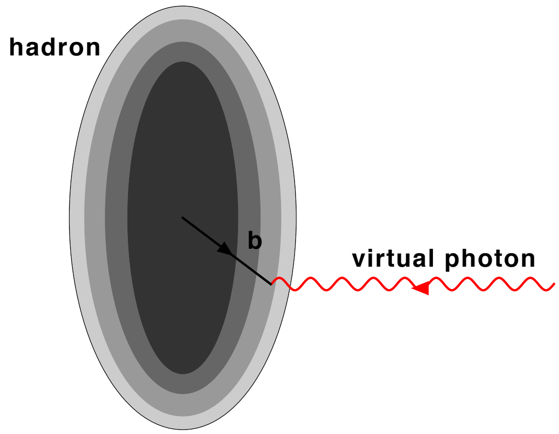


Figure 6.3: Illustration of the transverse profile of the hadron as explored by a virtual photon at impact parameter b.

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

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

The importance of nuclei

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

- 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 [304] 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

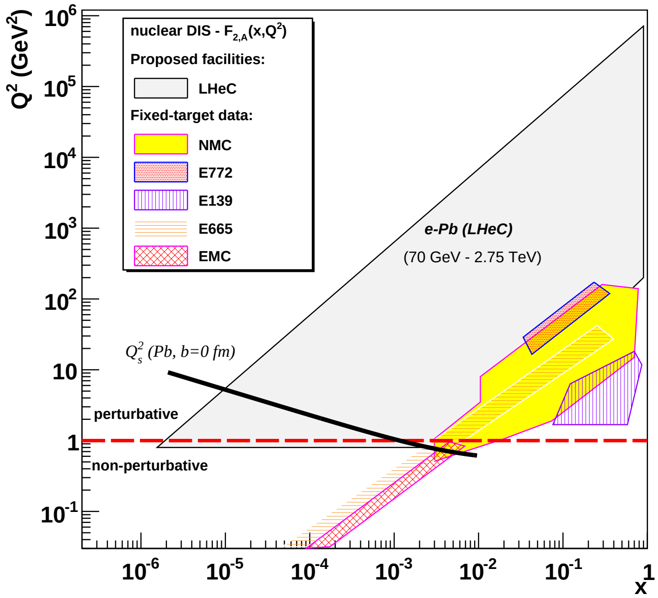


Figure 6.4: Kinematical coverage of the LHeC in the $\ln Q^2 - \ln 1/x$ plane for nuclear beams, compared with existing nuclear DIS and Drell-Yan experiments.

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 [265], in which the cross section reaches the geometrical bound given by the transverse proton or nucleus size. When α_s is small enough for

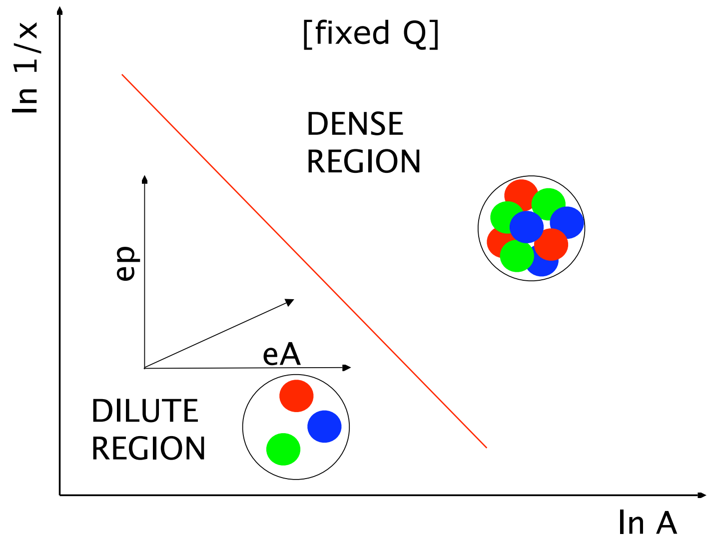


Figure 6.5: Schematic view of the different regions for the parton densities in the $\ln 1/x - \ln A$ plane, for fixed Q^2. See the text for comments.

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 [305]. 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.

Although no conclusive saturation signals have been observed in parton density fits to existing HERA data, various hints have been obtained, for example, by studying the change in fit quality as low-x and Q^2 data are progressively omitted, in the NNPDF [290] and HERAPDF [10] analyses (see Subsec. 6.1.2).

A more common approach is to fit the data to dipole models [302, 303, 306, 307], which are applicable at very low Q^2 values beyond the range in which quarks and gluons can be considered to be good degrees of freedom. The typical conclusion [307] is that HERA data in the perturbative regime exhibit at best weak evidence for saturation. However, when data in the $Q^2 < 1$ GeV^2 region are included, models which include saturation effects are quite successful in the description of the wide variety of experimental data.

The 'geometric scaling' [308] feature of the HERA data (Fig. 6.6a) reveals that, to a good approximation, 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 the saturation scale, see Eq. (6.2). This parameterisation works well for scattering off both protons and ions, as shown in Fig. 6.6b [308, 309]. Geometric

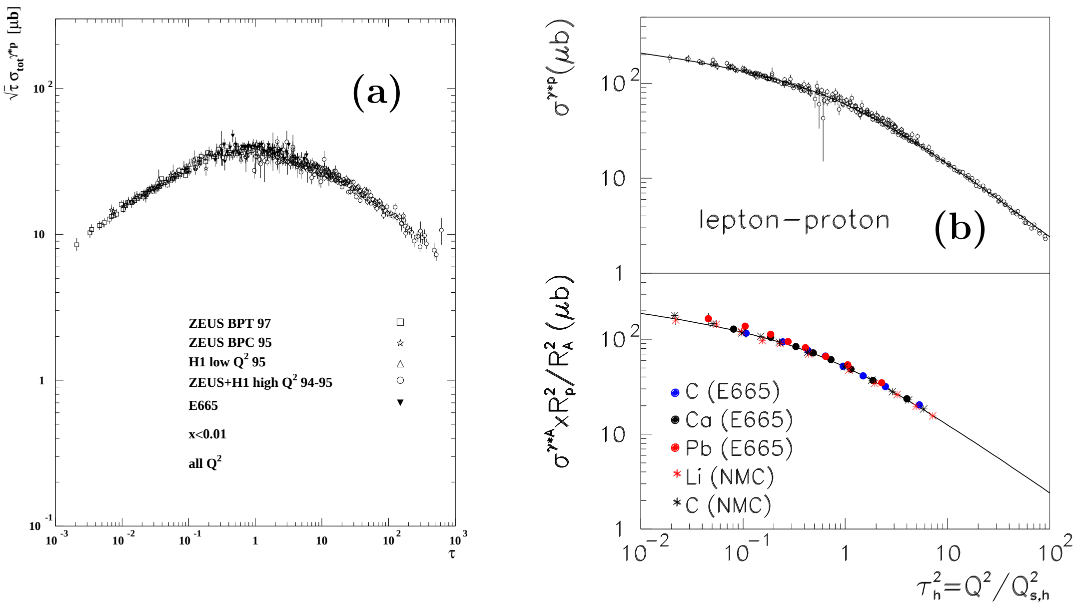


Figure 6.6: (a) Geometric scaling plot [308], in which low x data on the $\gamma^* p$ cross section from HERA and E665 are plotted as a function of the dimensionless variable τ (see text). The cross sections are scaled by $\sqrt{\tau}$ for visibility. (b) Geometric scaling plot showing cross sections for electron scattering off nuclei as well as off protons [309].

scaling is observed not only for the total $\gamma^* p$ cross section, but also for other, more exclusive observables in $\gamma^* p$ collisions [310,311] and even in hadron production in proton-proton collisions at the LHC [312] and nucleus-nucleus collisions at RHIC [309]. This feature supports the view (Subsec. 6.1.1) of the cross section as being invariant along lines of constant 'gluon occupancy'. When viewed in detail (Fig. 6.6), there is a change in behaviour in the geometric scaling plot near $\tau = 1$, which has been interpreted as a transition to the saturation region shown in Fig. 6.1. However, data with $\tau < 1$ exist only at very low, non-perturbative, Q^2 values to date, precluding a partonic interpretation. Also, the fact that the scaling extends to large values of τ which characterize the dilute regime, has prompted theoretical explanations of this phenomenon which do not invoke the physics of saturation [313].

Dipole models

As mentioned previously, one of the interesting observations at HERA is the success of the description of many aspects of the experimental data within the framework of the so-called dipole picture [257, 314, 315] with models that include unitarisation or saturation effects [316, 317]. These models are based on the assumption that the relevant degrees of freedom at high energy are colour dipoles. Dipole models in DIS are closely related to the Good-Walker picture [318] previously developed for soft processes in hadron-hadron collisions. In DIS, dipoles are shown to be the eigenstates of high-energy scattering in QCD, and the photon wave function can be expanded onto the dipole basis.

The dipole factorization for the inclusive cross section in DIS is illustrated in Fig. 6.7. It differs from the usual picture of the virtual photon probing the parton density of the target

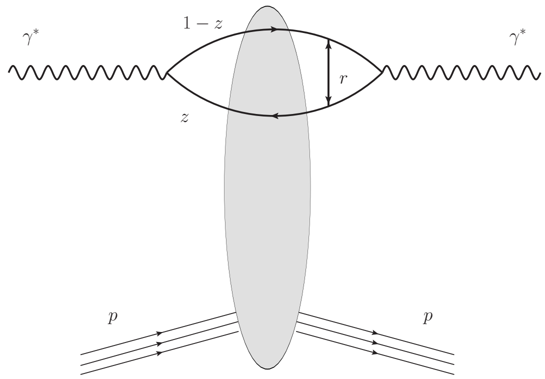


Figure 6.7: Schematic representation of dipole factorisation at small x in DIS. The virtual photon fluctuates into a quark-antiquark pair and subsequently interacts with the target. All the details of the dynamics of the interaction are encoded in the dipole scattering amplitude.

in that here the partonic structure of the probed hadron is not evident. Instead, one chooses a particular Lorentz frame where the photon fluctuates into a quark-antiquark pair with a transverse separation r and at impact parameter b with 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 or nuclear radius, the lifetime of the $q\bar{q}$ fluctuation is much longer than the typical time for interaction with the target. The interaction of the $q\bar{q}$ dipole with the hadron or nucleus is then described by a scattering matrix $S(r, b; x)$ such that $|S(r, b; x)| < 1$. The unitarity constraints can be incorporated naturally in this picture [319] by the requirement that $|S(r, b; x)| \geq 0$, with $S(r, b; x) = 0$ corresponding to the black disk limit. Integrating $1 - S(r, b; x)$ over the impact parameter b one obtains the dipole cross section $\sigma^{q\bar{q}}(r, x)$, which depends on the dipole size and the energy (through the dependence on $x = x_{\mathrm{Bj}}$). The transverse size of the partons probed in this process is roughly proportional to the inverse of the virtuality of the photon Q^2. This statement is most accurate in the case of a longitudinally polarized photon, while in the case of a transversely polarized one, the distribution of the probed transverse sizes of dipoles is broadened due to the so-called aligned jet configurations.

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

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

where C is a constant. In this regime, where r is small, the dipole cross section is small and consequently 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 [302, 306, 320] 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 [303], and exclusive diffraction of vector mesons in [321, 322]. 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 [303]. 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.

Deviations from fixed order linear DGLAP evolution in inclusive HERA data

HERA provided extremely valuable information about the proton structure functions based on measurements of the total virtual photon-proton cross section. As discussed in previous sections, the experimental data on the inclusive structure function F_2 have been successfully described by fits which use linear fixed-order DGLAP evolution, see [114, 116, 323–329]. The current status of the calculations is fixed order at next-to-next-to-leading accuracy.

There are several theoretical indications that at small x and/or at small Q^2 the fixed-order DGLAP framework needs to be extended, since in these regimes perturbative QCD predicts other relevant phenomena: linear small-x resummation, non-linear evolution and parton saturation or other higher-twist effects. Even if it is unclear in which kinematic regime these effects should become relevant, it is evident that at some point they will lead to deviations from fixed-order DGLAP evolution. Therefore, the important question is whether these deviations are already present in HERA data. Several analyses have been performed which aimed to address this question.

In one analysis [307], the inclusive structure function $F_2(x, Q^2)$ is subjected to fits in which the dipole cross section either does not contain saturation properties, or saturates as expected in two rather different models [306, 307]. All three dipole fits are able to describe the HERA data adequately in the perturbative region $Q^2 \geq 2$ GeV^2, whereas a clear preference for the models containing saturation effects becomes evident when data in the range $0.045 < Q^2 < 1$ GeV^2 are added [307]. Due to the non-perturbative nature of this kinematic region, there is no clear interpretation in terms of parton recombination effects. Similar conclusions are drawn when the same dipole cross sections are applied to various less inclusive observables at HERA [330].

In another analysis [290], possible indications of deviations from linear DGLAP evolution were discussed. It was based on an unbiased PDF analysis of the inclusive HERA data. Below, we discuss briefly the updated version of this study which uses the most precise inclusive DIS data to date, the combined HERA–I dataset [10] in the framework of the global NNPDF2.0 fitting framework.

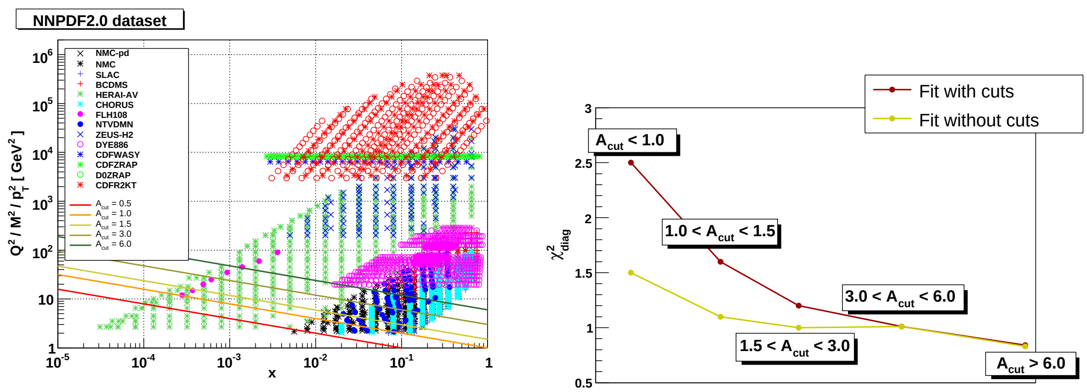


Figure 6.8: Left plot: the kinematic coverage of the data used in the NNPDF2.0 analysis, indicating the different choices of $A_{\rm cut}$ used to probe deviations from DGLAP. Right plot: the diagonal $\chi^2_{\rm diag}$ evaluated in kinematic slices corresponding to the different $A_{\rm cut}$ cuts,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

Deviations from DGLAP evolution can be investigated by exploiting the discriminating and sensitive framework of global PDF fits. The key idea is to perform global fits only in the large-x, large-Q^2 region, where NLO DGLAP is expected to be reliable. This way one can determine *safe* parton distributions which are not contaminated by possible non-DGLAP effects. These PDFs are then evolved backwards into the potentially *unsafe* low-x and low-Q^2 kinematic region, and are used to compute physical observables, which are compared with data. A deviation between the predicted and observed behavior in this region can then provide a signal for effects beyond NLO DGLAP.

The PDFs were determined within the *safe* kinematic region in which

$$Q^2 \geq A_{\rm cut} \cdot x^{-\lambda}, \tag{6.4}$$

where $\lambda = 0.3$ and $A_{\rm cut}$ is a variable parameter. To be precise, only data were fitted which passed the cut Eq. (6.4) (see the left plot in Fig. 6.8). The above definition is theoretically appealing, since it has the effective form of a saturation scale, and is also very practical, since it does not remove moderate-Q^2, large-x data, which are expected to be fully consistent with DGLAP and which are very important to constrain the safe PDFs.

The NNPDF2.0 analysis [329] was repeated for different choices of the kinematic cuts, one for each choice of $A_{\rm cut}$, and the results were compared with experimental data. As shown in Fig. 6.9, at high $Q^2 = 15$ GeV^2, one does not see any significant deviation from NLO DGLAP. In this region all PDF sets agree with data and with one another. The only difference between the different sets is that as $A_{\rm cut}$ increases the PDFs errors grow, as is statistically expected due to the experimental information removed by the cuts. The situation is different at a lower $Q^2 = 3.5$ GeV^2: the prediction obtained from the backwards evolution of the data above the cut exhibits a systematic downward trend, becoming more evident with increasing $A_{\rm cut}$. It is thus apparent that, at low-x, low-Q^2, NLO DGLAP evolution fails to provide an accurate description of the data. More precisely, one observes that NLO DGLAP evolves faster with Q^2 than actual data.

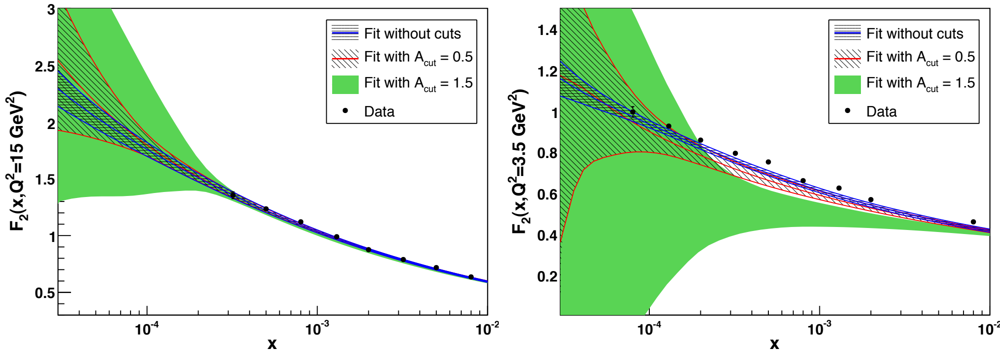


Figure 6.9: Left: the proton structure function $F_2(x, Q^2 = 15\ \text{GeV}^2)$ at small-x, computed from PDFs obtained from the NNPDF2.0 fits with different values of A_{cut}. Right: the same but at a lower $Q^2 = 3.5\ \text{GeV}^2$ scale.

To be sure that one is observing a genuine small-x effect, one needs to check that it becomes less and less relevant as x and Q^2 increase. To this aim the diagonal χ^2_{diag} was computed in different kinematic slices, both from the fit without cuts and from that with the maximum cut $A_{\text{cut}} = 1.5$. The expectation is that at larger x and Q^2 the difference between the two fits becomes smaller, as deviations from NLO DGLAP should become negligible. This is exactly what happens, as one can see from the right plot in Fig. 6.8: starting from $A_{\text{cut}} \gtrsim 4$ the statistical features of the two fits are comparable.

In summary, there is mounting evidence that the low-Q^2–low-x region covered by HERA is incompatible with fixed-order linear evolution. In particular, deviations from fixed order NLO DGLAP have been found in the combined HERA–I dataset from an unbiased global PDF analysis [331]. Similar conclusions have been reached in other independent studies like, for example, the HERAPDF analysis [10]. Also, the fit quality to the small-Q^2 data at NNLO is actually worse than at NLO [327] in agreement with the claims in [290] that these deviations are consistent with either expectations from small-x resummations or saturation models, though not from NNLO. Still, it should be noted that there is no general consensus [332]. In any case, it is clear that this method should be used to analyse LHeC inclusive structure function data, and would allow a detailed characterization of the new high-energy QCD dynamics unveiled by the LHeC. The novel phenomena should be established cleanly in the high Q^2 perturbative region where it can be understood in terms of parton degrees of freedom. This can only be achieved by analysing DIS at lower x values than are accessible at HERA.

Linear resummation schemes

The deviations from DGLAP evolution could be caused by higher order effects at small x and small Q which need to be resummed to all orders of perturbation theory. As mentioned previously, the problem of resummation at small x has been extensively studied in recent years, see for example [293–298]. It has been demonstrated that the small-x resummation framework accounts for running coupling effects, kinematic constraints, gluon exchange symmetry and other physical constraints. The results were shown to be very robust with respect to scale changes and different resummation schemes. As a result, the effect of the resummation of terms which are enhanced at small x is perceptible but moderate - comparable in size to typical NNLO fixed order corrections in the HERA region.

A major development for high–energy resummation was presented in [295], where the full small-x resummation of deep-inelastic scattering (DIS) anomalous dimensions and coefficient functions was obtained including the quark contribution. This allowed for the first time a consistent small-x resummation of DIS structure functions. These results are summarized in Fig. 6.10, taken from Ref. [295], where the K-factors for F_2 and F_L for the resummed results are compared. As is evident from this figure, resummation is quite important in the region of low x for a wide range of Q^2 values. One observes, for example, that the fixed order NNLO contribution leads to an enhancement of F_2 with respect to NLO, whereas the resummed calculation leads to a suppression. This means that a truncation at any fixed order is very likely to be insufficient for the description of the LHeC data and therefore the fixed-order perturbative expansion becomes unreliable in the low-x region, which calls for the resummation. Furthermore, the resummation of hard partonic cross sections has been performed for several LHC processes such as heavy quark production [333], Higgs production [334, 335], Drell-Yan [336, 337] and prompt photon production [338,339]. The LHC is thus likely to provide a testing ground in the near future.

We refer to the recent review in Ref. [340] as well as to the HERA-LHC workshop proceedings [341] for a more detailed summary of recent theoretical developments in high-energy resummation.

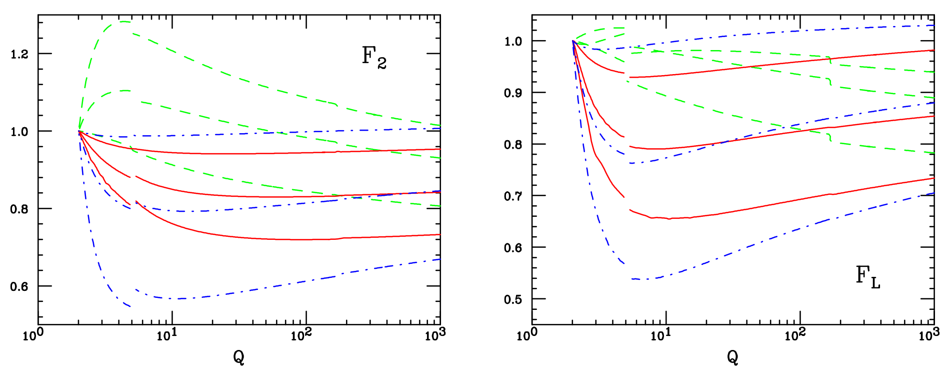


Figure 6.10: The K-factors, defined as the ratio of the fixed-order NNLO or resummed calculation to the NLO fixed-order results for the singlet F_2 and F_L structure functions, with F_2 and F_L kept fixed for all x at $Q_0 = 2$ GeV. Results are shown at fixed $x = 10^{-2}$, 10^{-4} or 10^{-6} as a function 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 $\mathrm{Q_0\overline{MS}}$ scheme (red, solid), resummed NLO in the $\overline{\mathrm{MS}}$ 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.

To summarise, small-x resummation is becoming a very important component for precision LHC physics, and will become a crucial ingredient of the LHeC small-x physics program [342, 343]. The LHeC extended kinematic range will enhance the differences between the resummed predictions with respect to fixed-order DGLAP calculations.

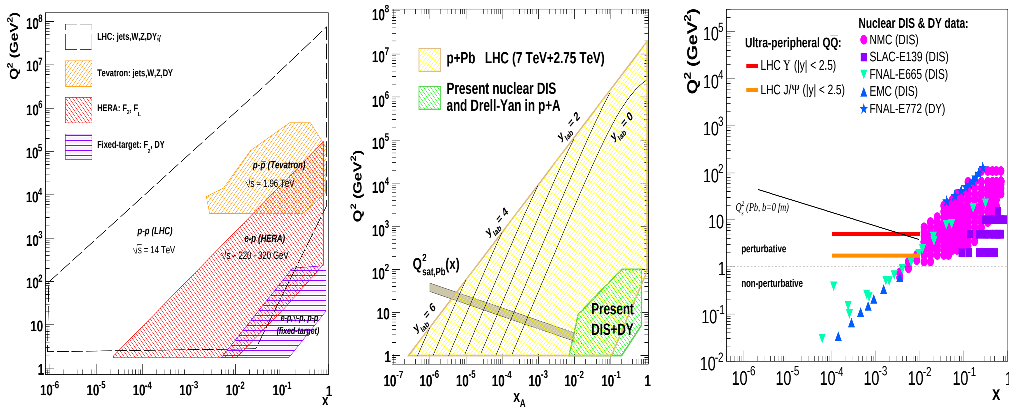


Figure 6.11: Kinematic reaches in the (x, Q^2) plane covered in proton-proton (left), proton-nucleus (center) [344] and ultraperipheral nucleus-nucleus (right) [345] collisions at the LHC. Also shown are the regions studied so far in collider and fixed-target experiments. Estimates of the saturation 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 $Q_s^2 \approx 1$ GeV^2 for proton and $Q_s^2 \approx 5$ 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 $x \approx 10^{-2}$ [136]. 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 $2 \to 2$ process with a particle of momentum p_T produced at pseudo-rapidity η is

$$x_{min} = \frac{x_T\, e^{-\eta}}{2 - x_T\, e^{\eta}} \quad , \qquad \text{where} \quad x_T = 2p_T/\sqrt{s}\,, \tag{6.5}$$

i.e. x_{min} decreases by a factor $\sim$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. (6.5) it follows that the measurement at the LHC of particles with transverse momentum $p_T = 10$ 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 [346]; and forward isolated photons [347] and Drell-Yan (DY) [348] in LHCb.

Low-x studies in proton-nucleus collisions

Until an electron-ion collider becomes available, proton-nucleus collisions will be the best available tool to study small-x physics in a nuclear environment without the strong influence of the final-state medium, as expected in the AA case. Though proton-nucleus collisions are not yet scheduled at the LHC, detailed feasibility studies exist [349] and strategies to define the accessible physics programme are being developed [344]. The pA programme at the LHC serves a dual purpose [344]: to provide "cold QCD matter" benchmark measurements for the physics measurements of the AA programme without significant final-state effects, and to study the nuclear wavefunction in the small-x region. In Fig. 6.11 (center) we show how dramatically the LHC will extend the region of phase space in the (x, Q^2) plane[2] by orders of magnitude compared with those studied at present. The same figure also shows the scarcity of nuclear DIS and DY measurements and, correspondingly, the lack of knowledge of nuclear PDFs in the regions needed to constrain the initial state for the AA programme - there is almost no information at present in the region $x \lesssim 10^{-2}$ [136].

Nuclear PDF constraints, checks of factorization (universality of PDFs) and searches for saturation of partonic densities will be performed in pA collisions at the LHC by studying different production cross sections for e.g. inclusive light hadrons [350], heavy flavour particles [351], isolated photons [352], electroweak bosons [353] and jets. Additional opportunities also appear in the so-called ultra-peripheral collisions in which the coherent electromagnetic field created by the proton or the large nucleus effectively acts as one of the colliding particles with photon-induced collisions at centre of mass energies higher than those reached in photoproduction at the HERA collider [354] (see next subsection).

At this point it is worth mentioning that particle production in the forward (proton) rapidity region in dAu collisions at RHIC shows features suggestive of saturation effects, although no consensus has been reached so far, see [355–360] and references therein. The measurements at RHIC suffer from the limitation of working at the edge of the available phase space in order to study the small-x region in the nuclear wave function. This limitation will be overcome by the much larger available phase space at the LHC.

Low-x studies in nucleus-nucleus collisions

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

[2] Asymmetric 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.

A possible means of obtaining direct information on the nuclear parton distribution functions is through the study of final state particles which do not interact strongly with the surrounding medium, such as photons [361] or electroweak bosons [353]. Beyond this, global properties of the collision such as the total multiplicities or the existence of long-range rapidity structures (seen in AuAu collisions at RHIC [362] and in *pp* and PbPb collisions at the LHC [363,364]) are sensitive to the saturation momentum which at the LHC is expected to be well within the weak coupling regime [365], $Q^2_{\rm sat,Pb} \approx 5 - 10$ GeV^2. CGC predictions for charged hadron multiplicities in central Pb-Pb collisions at 5.5 TeV per nucleon are $dN_{ch}/d\eta|_{\eta=0} \approx 1500$–2000 [366]. (Note that the predictions done before the start of RHIC in 2000 were 3 times higher). Recent data from ALICE [367] give $dN_{ch}/d\eta|_{\eta=0} \approx 1600$ in central Pb-Pb at 2.76 TeV per nucleon, in rough agreement with CGC expectations.

As already noted for the pA case, one of the cleanest ways to study the low-x structure of the Pb nucleus at the LHC may be via ultra-peripheral collisions (UPCs) [354] in which the strong electromagnetic fields (the equivalent flux of quasi-real photons) generated by the colliding nuclei can be used for photoproduction studies at maximum energies $\sqrt{s_{\gamma N}} \approx 1$ TeV, that is 3–4 times larger than at HERA. In particular, exclusive quarkonium photoproduction offers an attractive opportunity to constrain the low-x gluon density at moderate virtualities, since in such processes the gluon couples *directly* to the c or b quarks and the cross section is proportional to the gluon density *squared*. The vector meson mass M_V introduces a relatively large scale, amenable to a perturbative QCD treatment. In $\gamma {\rm A} \to J/\psi\,(\Upsilon)\,{\rm A}^{(*)}$ processes at the LHC, the gluon distribution can be probed at values as low as $x = M_V^2/W_{\gamma {\rm A}}^2 e^y \approx 10^{-4}$, where $W_{\gamma {\rm A}}$ is the γA centre of mass energy (Fig. 6.11 right). Full simulation studies [345, 368] of quarkonium photoproduction tagged with very-forward neutrons, show that ALICE and CMS can carry out detailed p_T,η measurements in the dielectron and dimuon decay channels.

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

6.1.4 Nuclear targets

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

Additionally, nuclear effects have to be better understood in order to improve the constraints on nucleon PDF in analyses which include DIS data with neutrino beams (e.g. [327,329]). Due to the smallness of the cross section, such neutrino experiments use nuclear targets, so corrections for nuclear effects are a significant source of uncertainty in the extraction of parton densities even for the proton.

Comparing nuclear parton density functions

The nuclear modification of structure functions has been extensively studied since the early 70's [369, 370]. It is usually characterized through the so-called nuclear modification factor which, for a given structure function or parton density f, reads

$$R_f^A(x,Q^2) = \frac{f^A(x,Q^2)}{A \times f^N(x,Q^2)} \ . \tag{6.6}$$

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

The nuclear modification factor for F_2 shows a rich structure: an enhancement ($R > 1$) at large $x > 0.8$, a suppression ($R < 1$) for $0.3 < x < 0.8$, an enhancement for $0.1 < x < 0.3$, and a suppression for $x < 0.1$ where isospin effects can be neglected. The latter effect is called shadowing [304], and is the dominant phenomenon at high energies (the kinematical region $x < 0.1$ will determine particle production at the LHC, see Sec. 6.1.3 and [371]).

The modifications in each region are believed to be of different dynamical origin. In the case of shadowing, the explanation is usually given in terms of a coherent interaction involving several nucleons, which reduces the nuclear cross section from the totally incoherent situation, $R = 1$, towards a region of total coherence. In the region of very small x, small-to-moderate Q^2 and for large nuclei, the unitarity limit of the nuclear 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 [136, 372, 373]. 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 [21, 265] can in principle be employed to constrain the initial conditions for DGLAP evolution, as has been explored previously at both LO [267] and NLO [374][3] accuracy, see Subsec. 6.2.4. All nuclear PDF analyses [136, 372, 373] include data from NC DIS and DY experiments, and [136] also uses particle production data at mid-rapidity in deuterium-nucleus

[3] In the approach in [374] predictions are provided only for sea quarks and gluons, with the valence taken from the analysis in [375].

collisions at RHIC. Error sets obtained through the Hessian method are provided in [136]. CC DIS data have been considered only recently [376, 377][4] 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 [136]. 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 $Q^2 > 2$ GeV^2 and x smaller than a few times 10^{-2}. The constraints on the small x gluon are particurly 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 [136], 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 [344, 361, 371, 378, 379]) regarding the correct interpretation of the findings of the heavy-ion programme at RHIC (see e.g. [380, 381] 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:

The knowledge of parton densities inside nuclei is an essential piece of information for the analysis of the medium created in ultra-relativistic heavy-ion collisions using hard probes, i.e. those observables whose yield in nucleon-nucleon collisions can be predicted in pQCD (see [361, 371, 378, 379]). The comparison between the expectation from an incoherent superposition of nucleon-nucleon collisions and the measurement in nucleus-nucleus collision characterises the nuclear effects. However, we need to disentangle those effects which originate from the creation of a hot medium in nucleus-nucleus collisions, from effects arising only from differences in the partonic content between nucleons and nuclei.

Our present knowledge of parton densities inside nuclei is clearly insufficient in the kinematic regions of interest for RHIC and, above all, for the LHC (see [371] and Subsection

[4] The analysis in [377] shows the compatibility of the nuclear corrections as extracted in [136] with CC DIS data on nuclear targets, while in [376] some tension is found between NC and CC DIS data.

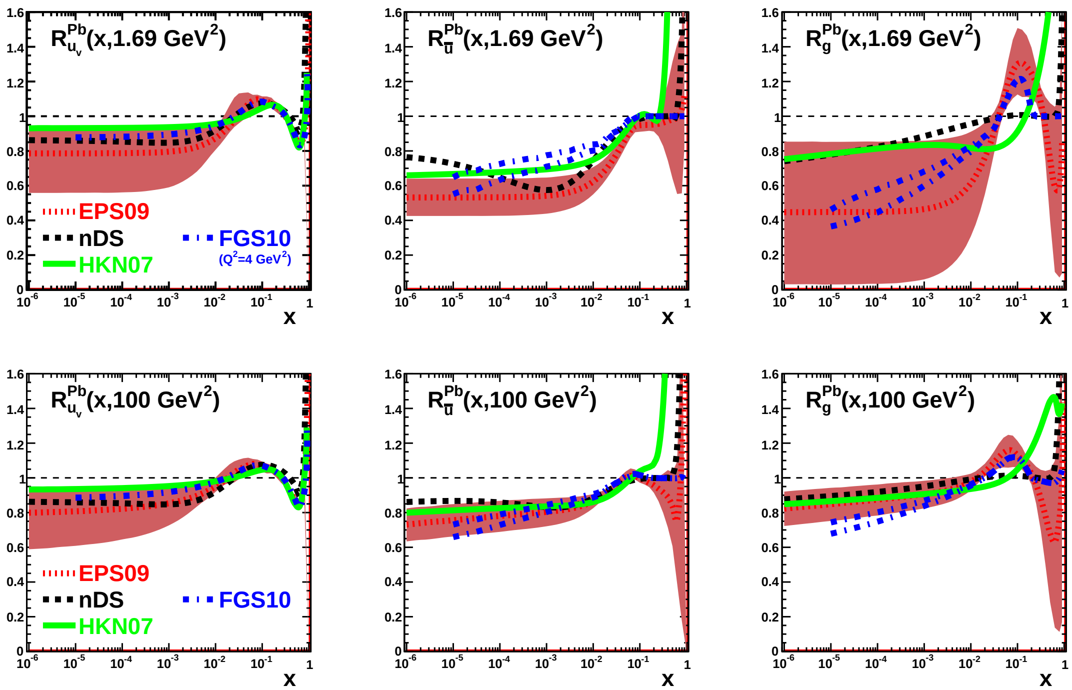


Figure 6.12: Ratio of parton densities in a bound proton in Pb to those in a free proton scaled by $A = 207$, for valence u (left), $\bar{u}$ (middle) and g (right), at $Q^2 = 1.69$ (top) and 100 (bottom) GeV^2. Results are shown from [372] (nDS, black dashed), [373] (HKN07, green solid), [136] (EPS09, red dotted) and [374] (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 [136].

6.1.3). Such ignorance reflects in uncertainties larger than a factor $3-4$ for the calculation of different cross sections in nucleus-nucleus collisions at the LHC (see Fig. 6.12 and [350]), thus weakening strongly the possibility of extracting quantitative characteristics of the produced hot medium. While the pA program at the LHC will offer new constraints on the nuclear parton densities (e.g. [344, 350]), measurements at the LHeC would be far more constraining and would reduce the uncertainties in nucleus-nucleus cross sections to less than a factor two.

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

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

The CGC offers a well-defined framework in which the initial condition and thermalization mechanism can be computed from QCD, see Subsection 6.1.1 and e.g. [382] and refs. therein. Although our theoretical knowledge is still incomplete, electron-nucleus collisions are considerably less complex than the nucleus-nucleus collisions in which these CGC-based calculations already exist and can be tested. In this way, electron-ion collisions offer a testing ground for ideas on parton production in a dense environment, which is required for a first principles calculation of the initial conditions for the collective behavior in ultra-relativistic heavy-ion collisions. The LHeC offers the possibility of studying particle production in the kinematic region relevant for experiments at RHIC and the LHC.

c. Parton fragmentation and hadronization inside the nuclear medium:

The mechanism through which a highly virtual parton evolves from an off-shell coloured state to a final state consisting of colourless hadrons, is still subject to great uncertainties. Electron-ion experiments offer a testing ground for our ideas and understanding of such phenomena, see [383] and refs. therein, with the nucleus being a medium of controllable extent and density which modifies the radiation and hadronization processes.

The LHeC will have capabilities for particle identification and jet reconstruction for both nucleon and nuclear targets. Its kinematic reach will allow the study of partons traveling through the nucleus from low energies, for which hadronization is expected to occur inside the nucleus, to high energies with hadronization outside the nucleus. Therefore the modification of the yields of energetic hadrons, observed at RHIC[5] and usually attributed to in-medium energy loss - the so-called jet quenching phenomenon - will be investigated. With jet quenching playing a key role in the present discussions on the production and characterisation of the hot medium produced in ultra-relativistic heavy-ion collisions, the LHeC will offer most valuable information on effects in cold nuclear matter of great importance for clarifying and reducing the existing uncertainties.

[5] LHC experiments have already observed the jet quenching phenomenon both at the level of single-particle spectra [384] and through the study of jets [385, 386], which will play a central role in heavy-ion physics at these energies.

6.2 Prospects at the LHeC

6.2.1 Strategy: decreasing x and increasing A

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

The LHeC will offer a huge lever arm in x and also a possibility of changing the matter density at fixed values of x. This will allow us to pin down and compare the small x and saturation phenomena both in protons and nuclei and will offer an excellent testing ground for theoretical predictions. Thus, in the following, LHeC simulations of electron-proton collisions are paralleled by those in electron-lead wherever possible. For a complementary perspective on the opportunities for novel QCD studies offered by the LHeC, see [54].

6.2.2 Inclusive measurements

Predictions for the proton

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

In Fig. 6.13 we show several predictions for the proton structure functions, F_2 and F_L, in ep collisions at $Q^2 = 10$ 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 extrapolation of models that reproduce correctly the available HERA data for the same observables in the small-x region. They are classified into two categories: those based on linear evolution approaches and those that include non-linear small-x dynamics. Among the linear approaches we include extrapolation from the NLO DGLAP fit as performed by the NNPDF collaboration [387] (solid yellow bands) and the results from a combined DGLAP/BFKL approach, which includes resummation of small-x effects [388] (black-dotted-dotted lines). The non-linear calculations shown here are all formulated within the dipole model. We distinguish two categories: those based on the eikonalization of multiple scatterings together with DGLAP evolution of the gluon distributions [320, 321] (blue dashed-dotted lines) and those relying in the Color Glass Condensate effective theory of high-energy QCD scattering (red dashed lines). The latter include calculations based on solutions of the running coupling Balitsky-Kovchegov equation [389] and other more phenomenological models of the dipole amplitude without [306], or with [322] impact parameter dependence. Finally, we also include a hybrid approach, where initial conditions based on Regge theory and including non-linearities are evolved in Q^2 according to linear DGLAP evolution [266] (green dotted line). In all cases the error bands are generated by allowing variations of the free parameters in each subset of models. The green filled squares correspond to the subset of the simulated LHeC pseudodata at $Q^2 = 10$ GeV^2 (see subsection 4.1.4).

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

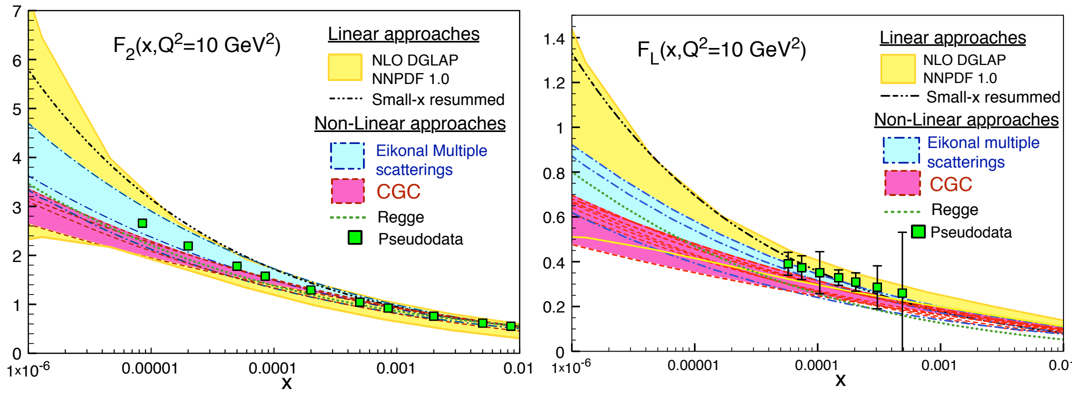


Figure 6.13: Predictions from different models for $F_2(x, Q^2 = 10\ \mathrm{GeV}^2)$ (plot on the left) and $F_L(x, Q^2 = 10\ \mathrm{GeV}^2)$ (plot on the right) versus x, together with the corresponding pseudodata. See the text for explanations.

Constraining small-x dynamics

The potential impact of the LHeC on low x parton densities within the framework of an NLO DGLAP analysis is assessed by adding the pseudodata introduced in subsection 4.1.4 into the NNPDF fitting analysis. The pseudodata are first generated at the extrapolated central values according to the existing NNPDF fits.

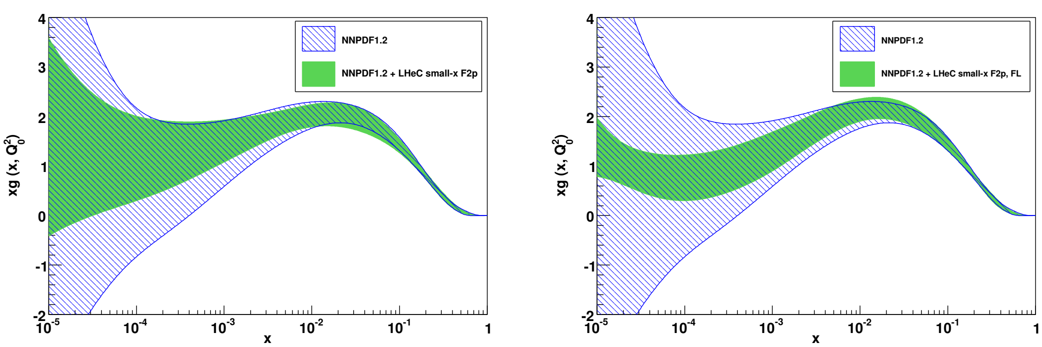


Figure 6.14: The results for the gluon distribution in the standard NNPDF1.2 DGLAP fit [387], together with the results when additionally including LHeC pseudodata for F_2 (left) and for both F_2 and F_L (right). The results are shown at the starting scale for DGLAP evolution, $Q_0^2 = 2\ \mathrm{GeV}^2$.

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

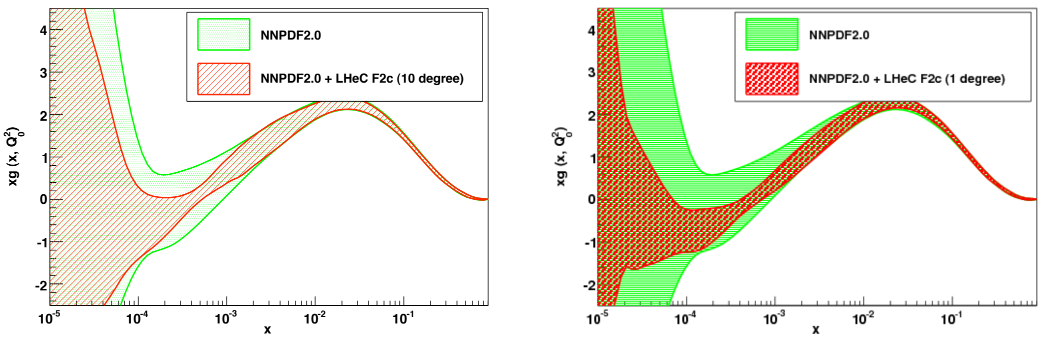


Figure 6.15: The effect on the extracted gluon distribution function of the inclusion of the LHeC pseudodata on the charmed structure function in the NNPDF global analysis. Left plot: scattered electron acceptance extending to within 10° of the beampipe. Right plot: 1° acceptance. The results are shown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

As is well known from experience at HERA, the measurement of the longitudinal structure function presents many experimental challenges and involves possibly undesirable modifications to the beam energies. An alternative constraint on the gluon density from the charmed structure function F_2^c has therefore also been investigated. As discussed in detail in Subsec. 4.7.1, the LHeC will offer unique precision in the 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 [390]. 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 $E_e = 70$ GeV and electron acceptance for $\theta_e \leq 179°$, for an integrated luminosity of 1 fb^{-1}. The study is carried out in the framework of the NNPDF1.0 analysis [391] 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 $\sim 8\%$.

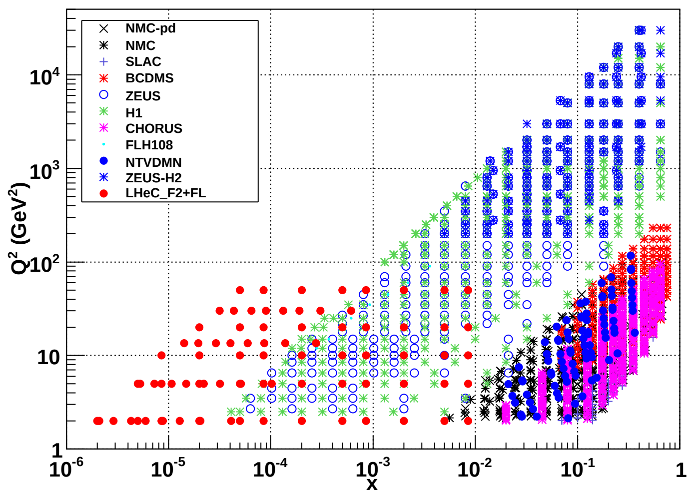


Figure 6.16: The kinematic coverage of the LHeC pseudodata used in the present studies, together with the data already included in the reference NNPDF1.0 dataset.

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 [389], which is based on non-linear Balitsky-Kovchegov evolution with a running coupling, and the FS04 dipole model [307]. 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 DGLAP analysis yields an acceptable fit when only the $F_2(x, Q^2)$ LHeC pseudodata are included. This implies that although the underlying physical theories are different, the small-x extrapolations of AAMS09 and FS04 for F_2 are sufficiently similar to DGLAP-based extrapolations for the differences to be absorbed as modifications to the shapes of the non-perturbative initial conditions for the PDFs at the starting scale Q_0^2 for DGLAP evolution. More sophisticated analyses, based for example on sequential kinematical cuts and backwards DGLAP evolution, as presented in Subsec. 6.1.2, could still be applied. However, it seems likely that it will not be possible unambiguously to establish non-linear effects using LHeC data on F_2 alone.

The situation is very different when data on the longitudinal structure function $F_L(x, Q^2)$

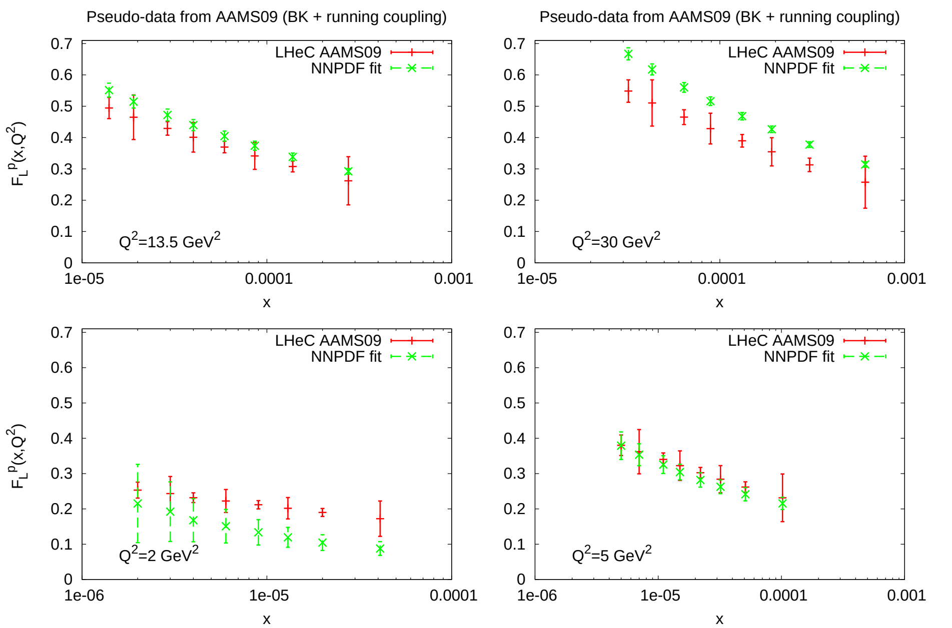


Figure 6.17: The results for F_L obtained from the best NLO DGLAP fit to the standard NNPDF1.2 data set, together with the LHeC pseudodata for $F_2(x, Q^2)$ and $F_L(x, Q^2)$ generated with the (saturating) AAMS09 model. The fit results are compared with the input AAMS09 F_L pseudodata.

are included in the NNPDF fit, provided the lever-arm in Q^2 is large enough for the gluon sensitivty through the Q^2 evolution of F_2 to conflict with that through F_L. The analysis based on linear DGLAP evolution fails to 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 illustrated in Fig. 6.17, where the best fits from the NNPDF DGLAP analysis are compared with the LHeC F_L pseudodata generated from the AAMS09 model. This is a clear signal for a departure from fixed-order DGLAP of the simulated pseudodata. This analysis shows that the combined use of F_2 and F_L data is a very sensitive probe of novel small-x QCD dynamics, and that their measurement would be very likely to discriminate between different theoretical scenarios. Using F_2^c data in place of F_L may offer a similarly powerful means of establishing deviations from fixed-order linear DGLAP evolution at small x.

Predictions for nuclei: impact on nuclear parton distribution functions

The LHeC, as an electron-ion collider in the TeV regime, will have an enormous potential for measuring the nuclear parton distribution functions at small x. Let us start by a brief explanation of how the pseudodata for inclusive observables in ePb collisions are obtained: To simulate an LHeC measurement of F_2 in electron-nucleus collisions, the points (x, Q^2), generated for $e(50) + p(7000)$ collisions for a high acceptance, low luminosity scenario, as explained in subsection 4.1.4, are considered. Among them, we keep only those points at small $x \leq 0.01$

and not too large $Q^2 < 1000$ GeV^2 with $Q^2 \leq sx$, for a Pb beam energy of 2750 GeV per nucleon. Under the assumption that the instantaneous luminosity per nucleon is the same in ep and eA [392], 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 [302, 393] 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 [393] 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 targets[6]. 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 [393]. The relative uncertainties are taken to be exactly the same as in the ep simulation, as explained above.

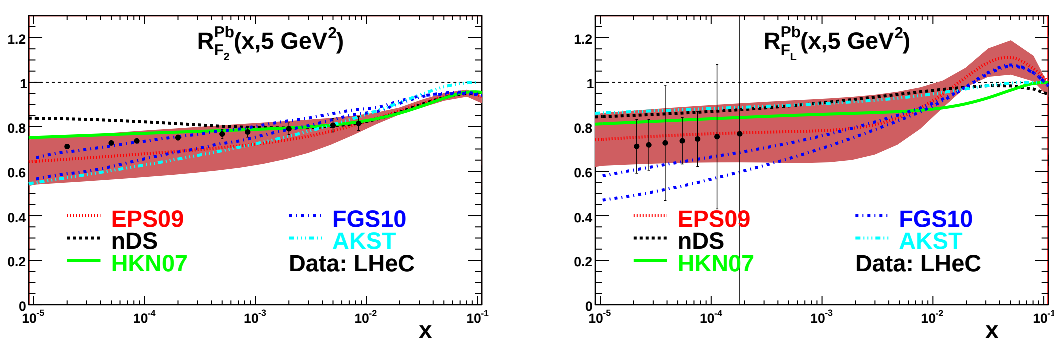


Figure 6.18: Predictions from different models for the nuclear modification factor, Eq. (6.6) for Pb with respect to the proton, for $F_2(x, Q^2 = 5\,\text{GeV}^2)$ (plot on the left) and $F_L(x, Q^2 = 5\,\text{GeV}^2)$ (plot on the right) versus x, together with the corrresponding LHeC pseudodata. Dotted lines correspond to the nuclear PDF set EPS09 [136], dashed ones to nDS [372], solid ones to HKN07 [373], dashed-dotted ones to FGS10 [374] and dashed-dotted-dotted ones to AKST [267]. The band corresponds to the uncertainty in the Hessian analysis in EPS09 [136].

In Fig. 6.18 we show several predictions for the nuclear suppression factor, Eq. (6.6), with respect to the proton, for the total and longitudinal structure functions, F_2 and F_L respectively, in ePb collisions at an example $Q^2 = 5$ GeV^2 and for $10^{-5} < x < 0.1$. Predictions based on global DGLAP analyses of existing data at NLO: nDS, HKN07 and EPS09 [136, 372, 373], plus those from models using the relation between diffraction and nuclear shadowing, AKST and

[6] A 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.

FGS10 [267, 374], are shown together with the LHeC pseudodata. Brief explanations on the different models can be found in Subsec. 6.1.4. Clearly, the accuracy of the data at the LHeC will offer huge possibilities for discriminating between different models and for constraining the dynamics underlying nuclear shadowing at small x.

In order to better quantify how the LHeC would improve the present situation concerning nuclear PDFs in global DGLAP analyses (see the uncertainty band in Fig. 6.12), nuclear LHeC pseudodata have been included in the global EPS09 analysis [136]. The DGLAP evolution was carried out at NLO accuracy, in the variable-flavor-number scheme (SACOT prescription) with the CTEQ6.6 [325] set for free proton PDFs as a baseline. See [136] and references therein for further details. The only difference compared with the original EPS09 setup is that one additional gluon parameter, x_a, has been varied (this parameter was originally frozen in EPS09), and the only additionally weighted data set was the PHENIX data on π^0 production at mid-rapidity [394] in dAu collisions at RHIC.

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

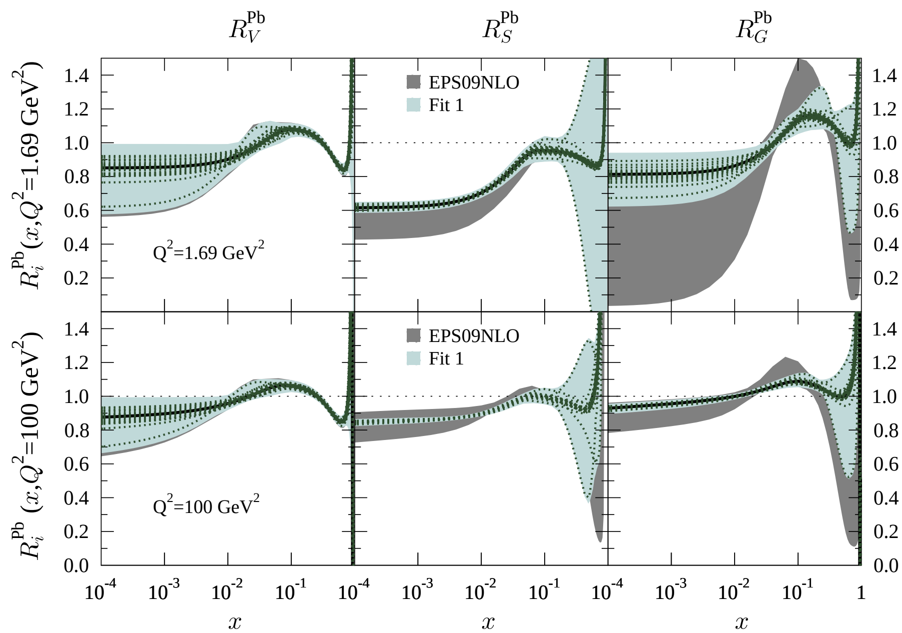


Figure 6.19: Ratio of parton densities for protons bound in Pb to those in a free proton, for valence u (left), $\bar{u}$ (middle) and g (right), at $Q^2 = 1.69$ (top) and 100 (bottom) GeV^2. The dark grey band corresponds to the uncertainty band using the Hessian method in the original EPS09 analysis [136], 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 [136].

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

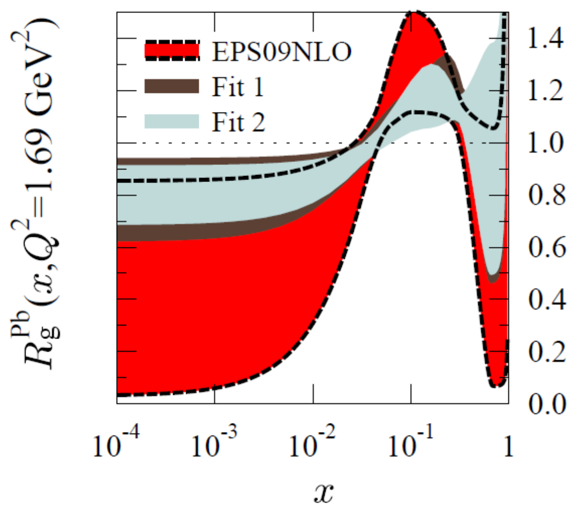


Figure 6.20: Ratio of the gluon density for protons bound in Pb to that of a free proton at $Q^2 = 1.69$ GeV^2. The red band corresponds to the uncertainty using the Hessian method in the original EPS09 analysis [136], while the dark brown band corresponds to the uncertainty obtained after including 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).

In both Figs. 6.19 and 6.20 a sizable reduction of the uncertainties in the sea quark and gluon nuclear parton distributions at large $x > 0.1$ can also be observed. This improvement is basically due to the constraints imposed by sum rules and to the fact that DGLAP evolution links large and small x. Although the study of parton distributions at large x is not the subject of this chapter, it is worth commenting that F_2 could be measured in eA collisions at the LHeC with a statistical accuracy better than a few percent up to $x \sim 0.6$ but for large $Q^2 > 1000$ GeV^2. On the other hand, flavor decomposition will only be accessible for $x < 0.1$. Therefore, the LHeC will provide additional information on the antishadowing ($R > 1$, $0.1 < x < 0.3$) and - with less precision - on the EMC-effect ($R < 1$, $0.3 < x < 0.8$) regions. The latter is valence-dominated and there exist data from fixed target experiments, though at much smaller Q^2, so at the LHeC the validity of leading-twist DGLAP evolution will be tested.

Furthermore, the large lever-arm in Q^2 opens the possibility of measuring CC events in

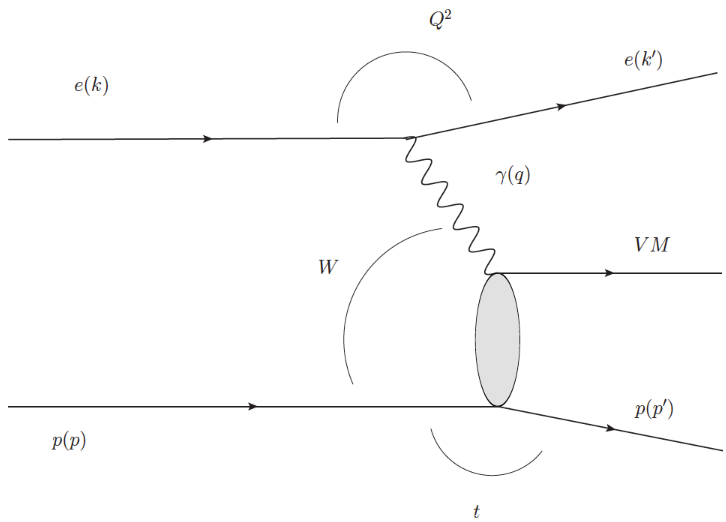


Figure 6.21: Schematic illustration of the exclusive vector meson production process and the kinematic variables used to describe it in photoproduction ($Q^2 \to 0$) and DIS (large Q^2). The outgoing particle labelled 'VM', may be either a vector meson with $J^{PC} = 1^{--}$ or a photon.

electron scattering on nuclear targets, thus helping to improve the loose contraints on the flavour decomposition of the nuclear parton densities coming from existing DIS and DY data. In this respect (see the comments in Subsec. 6.1.4) the LHeC may help to clarify the issue of the compatibility of the nuclear corrections extracted in neutrino-nucleus collisions with those coming from electron- or muon-nucleus collisions[7].

In conclusion, the precision and large lever-arm in x and Q^2 of the nuclear data at the LHeC will offer huge possibilities for discriminating different models and for constraining the parton densities in global DGLAP analyses. Besides measurements of the reduced cross section, data on its charm and bottom components and on F_L will help to constrain the nuclear effects on PDFs, see e.g. the recent work in [396, 397].

6.2.3 Exclusive Production

Introduction

Exclusive processes such as the electroproduction of vector mesons and photons, $\gamma^* N \to VN (V = \rho^0, \phi, \gamma)$, or photoproduction of heavy quarkonia, $\gamma N \to VN (V = J/\psi, \Upsilon)$ - see Fig. 6.21 - provide information on nucleon structure and small-x dynamics which is complementary to that obtained in inclusive measurements [305]. The exclusive production of J/ψ and ρ mesons in ep collisions and Deeply-Virtual Compton Scattering (DVCS, $ep \to e\gamma p$), have been particularly prominent in the development of our understanding of HERA physics [398].

[7]Note 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 [395].

Diffractive channels such as these are favourable, since the underlying exchange crudely equates to a pair of gluons, making the process sensitive to the square of the gluon density [399], in place of the linear dependence for F_2 or F_L. With a sufficiently good theoretical understanding of the exclusive production mechanism, this may enhance substantially the sensitivity to non-linear evolution and saturation phenomena. As already shown at HERA, J/Ψ production in particular is a potentially very clean probe of the gluonic structure of the hadron [322, 399]. The same exclusive processes can be measured in deep inelastic scattering off nuclei, where the gluon density is modified by nuclear effects [400]. In addition, exclusive processes give access to the spatial distribution of the gluon density, parametrized by the impact parameter [401] of the collision. The correlations between the gluons coupling to the proton contain information on the three-dimensional structure of the nucleon or nucleus, which is encoded in the Generalised Parton Densities (GPDs). The GPDs combine aspects of parton densities and elastic form factors and have emerged as a key concept for describing nucleon structure in QCD (see [20, 402, 403] for a review).

Exclusive processes can be treated conveniently within the dipole picture described in Subsec. 6.1.2. In this framework, the cross section can be represented as a product of three factorisable terms: the splitting 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 proton and, in the case of vector mesons, a wave function term for the projection of the dipole onto the meson. As discussed in Subsec. 6.1.2 the dipole formalism is particularly convenient since saturation effects can be easily incorporated.

Generalised Parton Densities and Spatial Structure

At sufficiently large Q^2 the exclusively produced meson or photon is in a configuration of transverse size much smaller than the typical hadronic size, $r_\perp \ll R_{\mathrm{hadron}}$. As a result its interaction with the target can be described using perturbative QCD [404]. A QCD factorisation theorem [405] states that the exclusive amplitudes in this regime can be factorised into a perturbative QCD scattering process and certain universal process-independent functions describing the emission and absorption of the active partons by the target, the generalized parton distributions (GPDs).

The Fourier transform of the GPDs with respect to the transverse momentum transferred to the nucleon describes the transverse spatial distribution of partons (illustrated in Fig. 6.3) with a given longitudinal momentum fraction x [406]. The transverse spatial distributions of quarks and gluons are fundamental characteristics of the nucleon, which reveal the size of the configurations in its partonic wave function and allow the study of the non-perturbative dynamics governing their change with x, such as Gribov diffusion, chiral dynamics, and other phenomena. The nucleon transverse gluonic size is also an essential input in studies of saturation at small x. It determines the initial conditions of the non-linear QCD evolution equations and thus directly influences the impact parameter dependence of the saturation scale for the nucleon [321, 407], which in turn predicates its nuclear enhancement [408]. Information on the nucleon transverse quark and gluon distributions is further required in the phenomenology of high-energy pp collisions with hard processes, including those with new particle production, where it determines the underlying event structure (centrality dependence) in inclusive scattering [409] and the rapidity gap survival probability in hard single diffraction [410] and central exclusive diffraction [411, 412]. 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 $1\,\mathrm{GeV}^2$. 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 [413, 414] 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 [305]. Measurements of DVCS at HERA [415,416] 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 ssytematic 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 $Q^2 \sim \text{few} \times 10\,\mathrm{GeV}^2$ 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 [400, 417–419]. 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 exlcusive 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, $\gamma^* N \to V + Y$ (Y = 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 [420]. 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.

Exclusive Production Formalism in the Dipole Approach

For the exclusive production of vector mesons, a QCD factorization theorem has been demonstrated (for σ_L) in [404]. The dipole model follows from this QCD factorization theorem in the LO approximation. Within the dipole model, see Subsec. 6.1.2, the amplitude for the exclusive diffractive production of a particle E, $\gamma^* p \to Ep$, shown in Fig. 6.22(a), can be expressed as

$$\mathcal{A}_{T,L}^{\gamma^* p\to E+p}(x,Q,\Delta) = \mathrm{i}\int \mathrm{d}^2\boldsymbol{r}\int_0^1 \frac{\mathrm{d}z}{4\pi}\int \mathrm{d}^2\boldsymbol{b}\;(\Psi_E^*\Psi)_{T,L}\;\mathrm{e}^{-\mathrm{i}[\boldsymbol{b}-(1-z)\boldsymbol{r}]\cdot\boldsymbol{\Delta}}\;\frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}^2\boldsymbol{b}}\;. \tag{6.7}$$

Here $E = V$ for vector meson production, or $E = \gamma$ for deeply virtual Compton scattering (DVCS). In Eq. (6.7), z is the fraction of the photon's light-cone momentum carried by the quark, $r = |\boldsymbol{r}|$ is the transverse size of the $q\bar{q}$ dipole, while $\boldsymbol{b}$ is the impact parameter, that is, $b = |\boldsymbol{b}|$ is the transverse distance from the centre 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 outgoing proton, $\boldsymbol{\Delta}$, is the Fourier conjugate variable to the impact parameter $\boldsymbol{b}$, and $t \equiv (p-p')^2 = -\Delta^2$. The forward overlap function between the initial-state photon wave function and the final-state vector meson or photon wave function in Eq. (6.7) is denoted $(\Psi_E^*\Psi)_{T,L}$, while the factor $\exp[\mathrm{i}(1-z)\boldsymbol{r}\cdot\boldsymbol{\Delta}]$ originates from the non-forward wave function [421]. The differential cross section for an exclusive diffractive process is obtained from the amplitude, Eq. (6.7), by

$$\frac{\mathrm{d}\sigma_{T,L}^{\gamma^* p\to E+p}}{\mathrm{d}t} = \frac{1}{16\pi}\left|\mathcal{A}_{T,L}^{\gamma^* p\to E+p}\right|^2, \tag{6.8}$$

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

$$\sigma_{T,L}^{\gamma^* p}(x,Q) = \mathrm{Im}\,\mathcal{A}_{T,L}^{\gamma^* p\to\gamma^* p}(x,Q,\Delta=0) = \sum_f \int \mathrm{d}^2\boldsymbol{r}\int_0^1 \frac{\mathrm{d}z}{4\pi}(\Psi^*\Psi)_{T,L}^f \int \mathrm{d}^2\boldsymbol{b}\;\frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}^2\boldsymbol{b}}\;. \tag{6.9}$$

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

The unknown quantity common to Eqs. (6.7) and (6.9) is the b-dependent dipole–proton cross section,

$$\frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}^2\boldsymbol{b}} = 2\,\mathcal{N}(x,r,b)\;, \tag{6.10}$$

where $\mathcal{N}$ is the imaginary part of the dipole–proton scattering amplitude, which can vary between zero and one, with $\mathcal{N} = 1$ corresponding to the unitarity ("black disk") limit. The scattering amplitude $\mathcal{N}$ encodes the information about the details of the strong interaction between the dipole and the target (proton or nucleus). It is generally parameterised according to some theoretically-motivated functional form, with the parameters fitted to data. Most dipole models assume a factorised b dependence, $\mathcal{N}(x,r,b) = T(b)\,\mathcal{N}(x,r)$, with $\mathcal{N}(x,r) \in [0,1]$ 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, the "saturation scale" is strongly dependent on impact parameter and the chosen of b-dependence

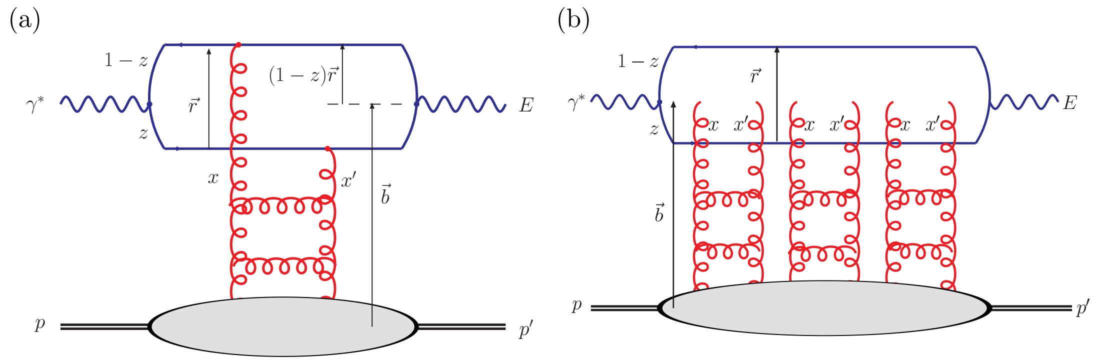


Figure 6.22: Parton level diagrams representing the $\gamma^* p$ scattering amplitude proceeding via (a) single-Pomeron and (b) multi-Pomeron exchange, where the perturbative QCD Pomeron is represented by a gluon ladder. For exclusive diffractive processes, such as vector meson production ($E = V$) or 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 $p' = p$.

must be made consistent with the t-dependence of exclusive diffraction at HERA. This matching is complicated by the the non-zero effective "Pomeron slope" $\alpha'_{\mathbb{P}}$ measured at HERA, which implies a correlation between the x- and b- dependences of $\mathcal{N}(x, r, b)$. Therefore, for accurate results, $\mathcal{N}(x, r, b)$ should be determined from the simultaneous description of inclusive DIS and exclusive diffractive processes.

An impact-parameter-dependent saturation ("b-sat") model [321, 322] has been shown to describe very successfully a broad range of HERA data on exclusive diffractive vector meson (J/ψ, ϕ, ρ) production and DVCS (see also the rather different approach in [422]), including almost all aspects of the Q^2, W and t dependence with the exception of $\alpha'_{\mathbb{P}}$, together with the inclusive structure functions F_2, $F_2^{c\bar{c}}$, $F_2^{b\bar{b}}$ and F_L. The "b-Sat" parameterisation is based on LO DGLAP evolution of an initial gluon density, $xg(x, \mu_0^2) = A_g\, x^{-\lambda_g}\,(1-x)^{5.6}$, with a Gaussian impact parameter dependence, $T(b) \propto \exp(-b^2/2B_G)$. The dipole scattering amplitude is parametrized as

$$\mathcal{N}(x, r, b) = 1 - \exp\left(-\frac{\pi^2}{2N_c} r^2 \alpha_S(\mu^2)\, xg(x, \mu^2)\, T(b)\right), \tag{6.11}$$

where the scale $\mu^2 = 4/r^2 + \mu_0^2$, $B_G = 4$ GeV^{-2} was fixed from the t-slope of exclusive J/ψ photoproduction at HERA, and the other three parameters ($\mu_0^2 = 1.17$ GeV^2, $A_g = 2.55$, $\lambda_g = 0.020$) were fitted to ZEUS F_2 data with $x_{\rm Bj} \leq 0.01$ and $Q^2 \in [0.25, 650]$ GeV^2 [322]. The eikonalised dipole scattering amplitude of Eq. (6.11) can be expanded as

$$\mathcal{N}(x, r, b) = \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n!} \left[\frac{\pi^2}{2N_c} r^2 \alpha_S(\mu^2)\, xg(x, \mu^2)\, T(b)\right]^n, \tag{6.12}$$

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

Simulations of LHeC Elastic J/ψ and Υ Production

Due to the extremely clean final states produced, the relatively low effective x-values ($x_{\rm eff} \sim (Q^2+m_V^2)/(Q^2+W^2)$) and scales ($Q^2_{\rm eff} \sim (Q^2+m_V^2)/4$) accessed [399,423], and the experimental possibility of varying both W and t over wide ranges, J/ψ photoproduction ($Q^2 \to 0$) may offer the cleanest available signatureto study the transition between the dilute and dense regimes of small-x partons. It should be possible to detect the muons from J/ψ or Υ decays with acceptances extending to within 1° of the beampipe with dedicated muon chambers on the outside of the experiment. Depending on the electron beam energy, this makes invariant photon-proton masses W of well beyond 1 TeV accessible.

For the analysis presented here we concentrate on the photoproduction limit, where the HERA data are most precise due to the large cross sections and where unitarity effects are most important. Studies have also been made at larger Q^2 [424], where the extra hard scale additionally allows a perturbative treatment of exclusive light vector meson (e.g. ρ, ω, ϕ) production. Again, perturbative unitarity effects are expected to be important for light vector meson production when $Q^2 \gtrsim 1$ GeV^2 is not too large.

LHeC pseudodata for elastic J/ψ and Υ photoproduction and electroproduction have been generated using the DIFFVM Monte Carlo generator [425] under the assumption of 1° acceptance and a variety of luminosity scenarios. The DIFFVM generator involves a simple Regge-based parameterization of the dynamics and a full treatment of decay angular distributions. Statistical uncertainties are estimated for each data point. Systematic uncertaintes are hard to estimate without a detailed simulation of the muon identification and reconstruction capabilities of the detector, but are likely to be at least as good as the 10% measurements typically achieved for the elastic J/ψ at HERA.

The plots in Fig. 6.23 show t-integrated predictions for exclusive J/ψ photoproduction ($Q^2 = 0$) obtained from Eqs. (6.7) and (6.8), using the eikonalised "b-Sat" dipole scattering amplitude given in Eq. (6.11) together with a "boosted Gaussian" vector meson wave function [322, 426]. Also shown is the single-Pomeron exchange contribution obtained by keeping just the first ($n = 1$) term in the expansion of Eq. (6.12), such that the scattering amplitude is linearly dependent on the gluon density, without refitting any of the input parameters. The difference between the "eikonalised" and "1-Pomeron" predictions therefore indicates the importance of unitarity corrections, which increase significantly with rising γp centre-of-mass energy W. The maximum kinematic limit accessible at the LHeC, $W = \sqrt{s}$, is indicated with different options for electron beam energies (E_e) and not accounting for the angular acceptance of the detector. The most precise HERA data [414, 427] are overlaid, together with sample LHeC pseudodata points, assuming 1° muon acceptance, with the errors (statistical only) given by an LHeC simulation with $E_e = 150$ GeV. The central values of the LHeC pseudodata points were obtained from a Gaussian distribution with the mean given by extrapolating a power-law fit to the HERA data [414, 427] and the standard deviation given by the statistical errors from the LHeC simulation. The plots in Fig. 6.23 show that the errors on the LHeC pseudodata are much smaller than the difference between the "eikonalised" and "1-Pomeron" predictions. Therefore, exclusive J/ψ photoproduction at the LHeC may be an ideal observable for investigating unitarity corrections at a perturbative scale provided by the charm-quark mass.

Similar plots for exclusive Υ photoproduction are shown in Fig. 6.24. Here, the unitarity corrections are smaller than for J/ψ production due to the larger scale provided by the bottom-quark mass and therefore the smaller typical dipole sizes r being probed. The simulated LHeC pseudodata points also have larger statistical errors than for J/ψ production due

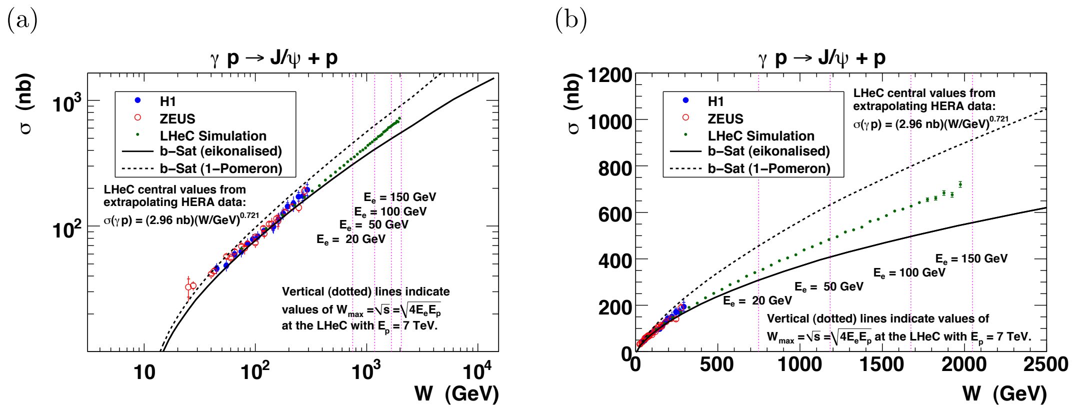


Figure 6.23: LHeC exclusive J/ψ photoproduction pseudodata, as a function of the γp centre-of-mass energy W, plotted on a (a) log–log scale and (b) linear–linear scale. The difference between the solid and dashed curves indicates the size of unitarity corrections according to the b-Sat dipole model.

to the much smaller cross sections. Nonetheless, the simulations indicate that a huge improvement in kinematic range and precision is possible compared with the very sparse Υ data from HERA [428–430].

In order to achieve a satisfactory description of the experimental data on exclusive Υ photoproduction, an additional normalization factor of ~ 2 has to be included in the dipole calculation (a similar factor is required for other calculations using the dipole model, see for example Ref. [431]). This normalization factor does not arise from any theoretical considerations. Therefore, the dipole model prediction for the Υ in diffractive exclusive processes in DIS still poses significant theoretical questions which cannot be resolved without LHeC data.

The cross sections shown in Figs. 6.23 and 6.24 are integrated over $t \equiv (p - p')^2 = -\Delta^2$, where $\boldsymbol{\Delta}$ is the Fourier conjugate variable to the impact parameter $\boldsymbol{b}$. One expects that at high center-of-mass energies (small x), saturation effects are most important close to the centre of the proton (small b), where the interaction region is densest. This is illustrated in Fig. 6.25(a) where the b-Sat model dipole scattering amplitude is shown as a function of b for various x values. By measuring exclusive diffraction in bins of $|t|$ one can extract the impact parameter profile of the interaction region. This is illustrated in Fig. 6.25(b) where the integrand of Eq. (6.7) is shown for different values of t as a function of impact parameter. Clearly for large values of $|t|$, small values of b are probed in the impact parameter profile., corresponding to the most densely populated region, where saturation effects should be most clearly visible. Indeed, the eikonalised dipole model of Eq. (6.11) leads to "diffractive dips" in the t-distribution of exclusive J/ψ photoproduction at large $|t|$ (reminiscent of the dips seen in the t-distribution of the proton-proton elastic cross section), departing from the exponential fall-off in the t-distribution seen with single-Pomeron exchange [321]. The HERA experiments have only been able to make precise measurements of exclusive J/ψ photoproduction at relatively small $|t| \lesssim 1$ GeV^2, and no significant departure from the exponential fall-off, $\mathrm{d}\sigma/\mathrm{d}t \sim \exp(-B_D|t|)$, has been observed.

In Fig. 6.26, LHeC pseudodata on the differential cross section $\mathrm{d}\sigma/\mathrm{d}t$ is shown as a function of the energy W in different bins of t for the case of exclusive J/Ψ production. Again two different b-Sat model scenarios are shown, with unitarisation effects and with single Pomeron

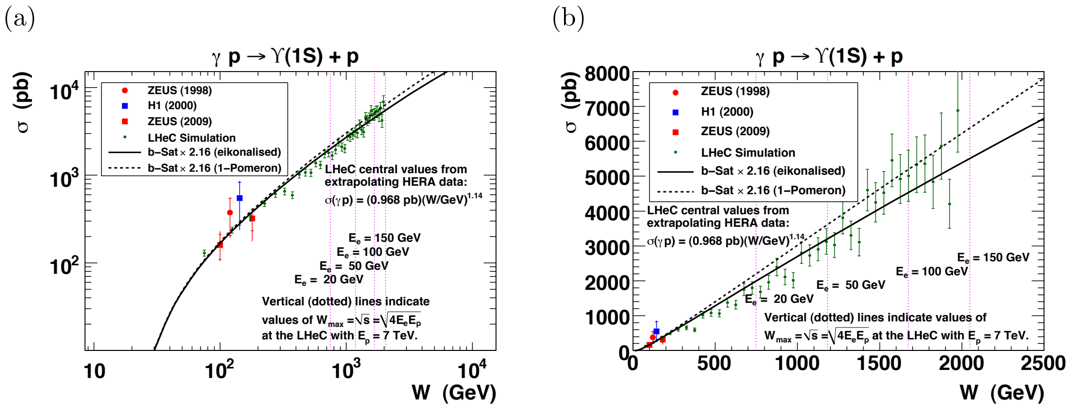


Figure 6.24: LHeC exclusive Υ photoproduction pseudodata, as a function of the γp centre-of-mass energy W, plotted on a (a) log–log scale and (b) linear–linear scale. The difference between the solid and dashed curves indicates the size of unitarity corrections according to the b-Sat model. The b-Sat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

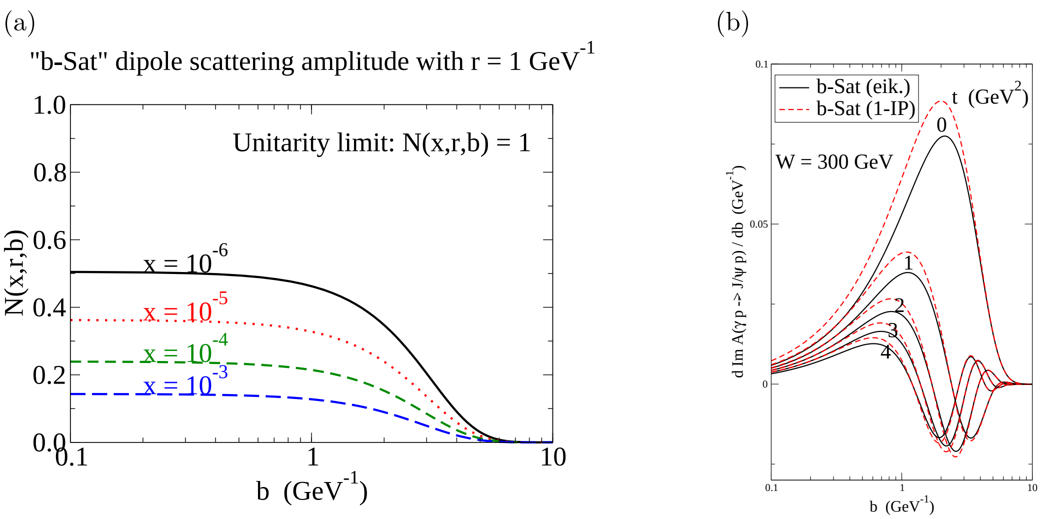


Figure 6.25: (a) The imaginary part of the dipole scattering amplitude, $\mathcal{N}(x, r, b)$, as a function of the impact parameter b, for fixed values of dipole size $r = 1$ GeV^{-1} (typical for exclusive J/ψ photoproduction) and different x values. (b) The (r-integrated) amplitude - the integrand of Eq. (6.7) - for exclusive J/ψ photoproduction as a function of b, for $W = 300$ GeV and $|t| = 0, 1, 2, 3, 4$ GeV^2.

exchange. Already for small values of $|t| \sim 0.2$ GeV^2 and low values of electron energies there is a large discrepancy between the models. The LHeC simulated data still have very small errors in this regime, and can clearly distinguish between the different models. The differences are of course amplified for large t and large electron beam energies. However the precision of the data deteriorates at large t.

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

Simulations of Deeply Virtual Compton Scattering at the LHeC

Simulations of the DVCS measurement possibilities with the LHeC have been made using the Monte Carlo generator MILOU [432], in the 'FFS option', for which the DVCS cross section is estimated using the model of Frankfurt, Freund and Strikman [433]. A t-slope of $B = 6$ GeV^{-2} is assumed.

The $ep \rightarrow e\gamma p$ DVCS cross section is estimated in various scenarios for the electron beam energy and the statistical precision of the measurement is estimated for different integrated luminosity and detector acceptance choices. Detector acceptance cuts at either 1° or 10° are placed on the polar angle of the final state electron and photon. Based on experience with controlling backgrounds in HERA DVCS measurements [415, 416, 434], an additional cut is placed on the transverse momentum P_T^γ of the final state photon.

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

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

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

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

Further studies of this process will require a better understanding of the detector in order to estimate systematic uncertainties. A particularly interesting extension would be to investigate possible beam charge [415, 434] and polarisation asymmetry measurements at lower x or larger Q^2 than was possible at HERA. With the addition of such information, a full study of the

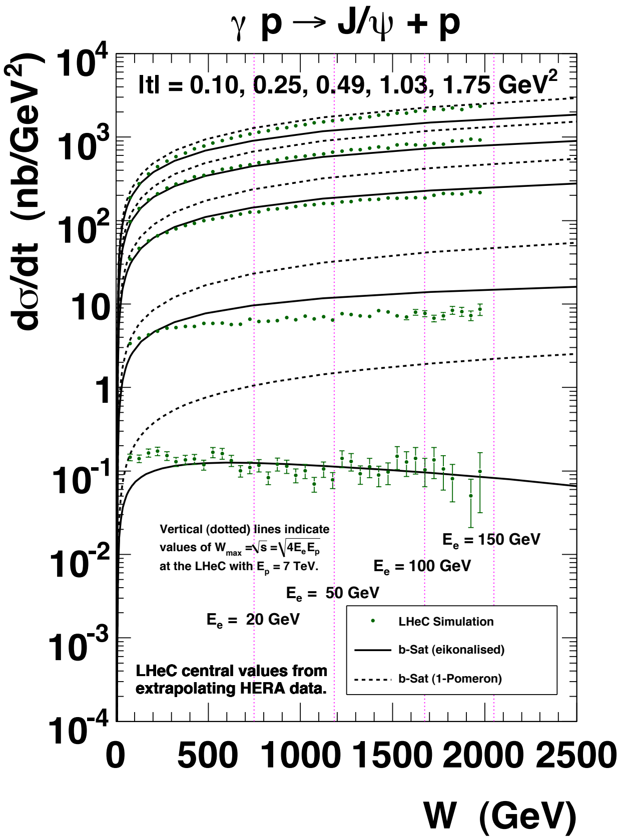


Figure 6.26: Simulated LHeC measurements of the W-dependence of exclusive J/ψ photoproduction at the LHeC, differentially in bins of $|t| = 0.10, 0.20, 0.49, 1.03, 1.75$ GeV^2. The difference between the solid and dashed curves indicates the size of unitarity corrections according to the b-Sat dipole 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 [427] and H1 [414], then the t-distribution was assumed to behave as $\mathrm{d}\sigma/\mathrm{d}t = \sigma \cdot B_D \exp(-B_D|t|)$, 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 [427] and H1 [414].

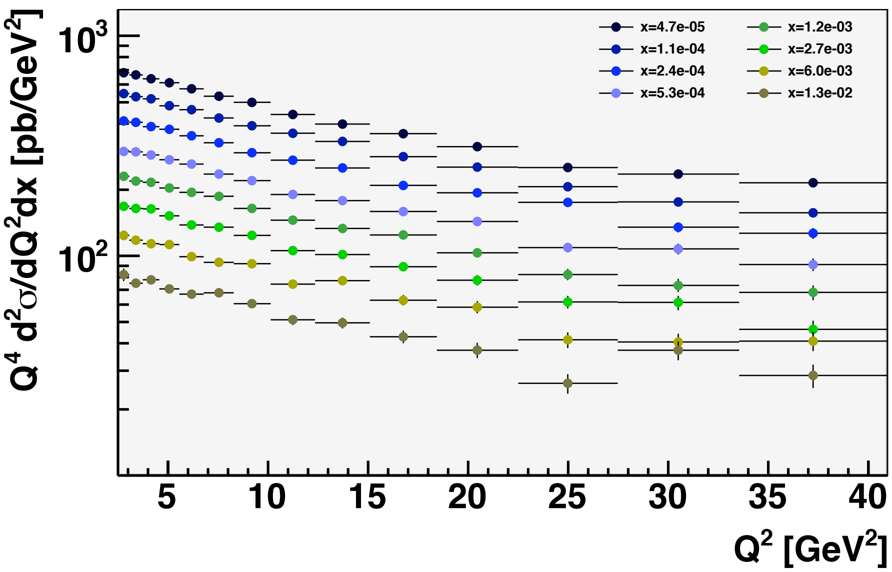


Figure 6.27: Simulated LHeC measurement of the DVCS cross section multiplied by Q^4 for different x values for a luminosity of 1 fb^{-1}, with $E_e = 50$ GeV, and electron and photon acceptance extending to within 1° of the beampipe with a cut at $P_T^\gamma = 2$ GeV. Only statistical uncertainties are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

potential of the LHeC to constrain GPDs could be performed.

Diffractive Vector Meson Production off Nuclei

Exclusive diffractive processes are similarly promising as a source of information on the gluon density in the nucleus [400]. Quasi-elastic scattering of photons from nuclei at small x can be treated within the same dipole model framework as for ep scattering, making the comparisons with the proton case relatively 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 [321, 400]. Previous experimental data on exclusive production from nuclei exist [435, 436], 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 ($e\text{A}\to eXY$) 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

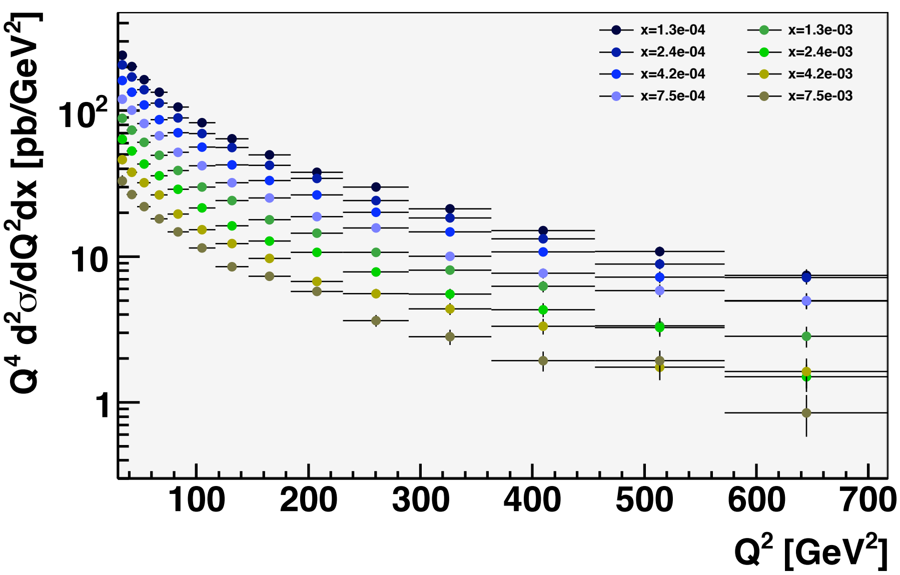


Figure 6.28: Simulated LHeC measurement of the DVCS cross section multiplied by Q^4 for different x values for a luminosity of 100 fb^{-1}, with $E_e = 50$ GeV, and electron and photon acceptance extending to within 10° of the beampipe with a cut at $P_T^{\gamma} = 5$ GeV. Only statistical uncertainties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

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 $|t| = 0.7$ 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 $|t| \gtrsim 0.01$ 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 13.3) 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

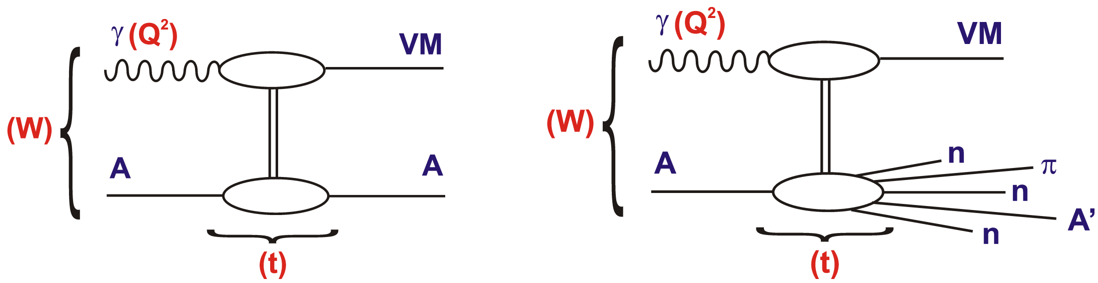


Figure 6.29: Diagrams illustrating the different types of exclusive diffraction in the nuclear case: coherent (plot on the left) and incoherent (plot on the right). While the diagrams have been drawn for the case of exclusive vector meson production, they equally apply to an arbitrary diffractively produced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

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 $\Delta t < 0.01\ \mathrm{GeV}^2$ throughout the range shown in Fig. 6.30 assuming $\Delta p_T(J/\psi) < 10$ 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 wave function is not important, in contrast to what happens at larger $|t|$ where the distribution reflects the functional form of the nuclear density.

Saturation effects can be studied in a very clean way using the t-averaged gluon density obtained in this way from the forward coherent cross section. Fig. 6.31 shows this cross section for J/Ψ production as a function of W for different nuclei. The cross section varies substantially as a function of the $\gamma^* p$ centre of mass energy W and the nuclear mass number A. It is also very sensitive to shadowing or saturation effects due to the fact that the differential cross section at $t = 0$ has a quadratic dependence on the gluon density and A. Due to this fact, the ratios of the cross sections for nuclei and protons are roughly proportional to the ratios of the gluon densities squared. This has been exploited in the calculation [437] presented in Fig. 6.32, where the nuclear modification factor R for the square of the gluon density is shown. The predictions are consistent with those obtained from the b-Sat model (Fig. 6.31). Therefore, a precise measurement of the J/ψ cross section around $t = 0$ is an invaluable source of information on the gluon density and in particular on non-linear effects.

Another region of interest is the measurement at larger $|t|$, $|t| \gtrsim 0.15\ \mathrm{GeV}^2$. Here the reaction is fully dominated by the incoherent processes in which the nucleus breaks up. The shadowing or saturation effects should be stronger in this region than in the coherent case [408] and the shape of the diffractive cross section should be only weakly sensitive to nuclear effects [400]. Finally, the intermediate region between $|t| \sim 0.01\ \mathrm{GeV}^2$ and $|t| \sim 0.1\ \mathrm{GeV}^2$ is also very interesting because here the barely known gluonic nuclear effects can be studied.

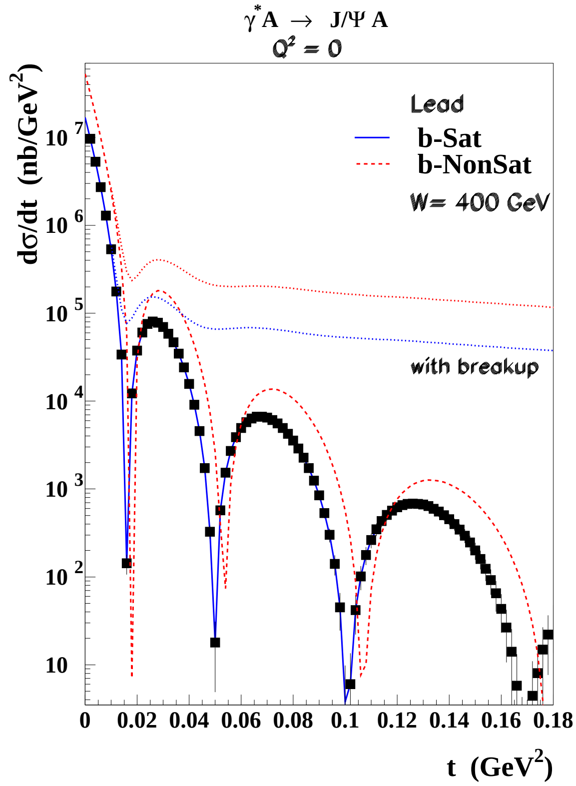


Figure 6.30: Differential cross section for the diffractive production of J/Ψ on a lead nucleus, as a function of the momentum transfer $|t|$. The dashed-red and solid-blue lines correspond to the b-Sat model predictions for coherent production without and with saturation effects, respectively. The dotted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

Searching for the Odderon

Exclusive processes in photoproduction and DIS offer unique sensitivity to rare exchanges in QCD. One prominent example is that of exclusive pseudoscalar meson production, which could proceed via the exchange of the Odderon. The Odderon is the postulated Reggeon which is the C-odd partner of the Pomeron. The exchange of an Odderon should contribute with different signs to particle-particle and particle-antiparticle scattering. Therefore, in the case of hadron-hadron collisions it could lead, via the optical theorem, to a finite difference between proton-proton and proton-antiproton total cross sections at high energies, provided the intercept of the Odderon is close to unity. Despite many searches, no evidence for Odderon exchange has been found so far, see for example [438]. Nevertheless, the existence of the Odderon is a firm prediction of high-energy QCD, for a comprehensive review see [439]. At lowest order in perturbation theory it can be described as a system of three non-interacting gluons. In the

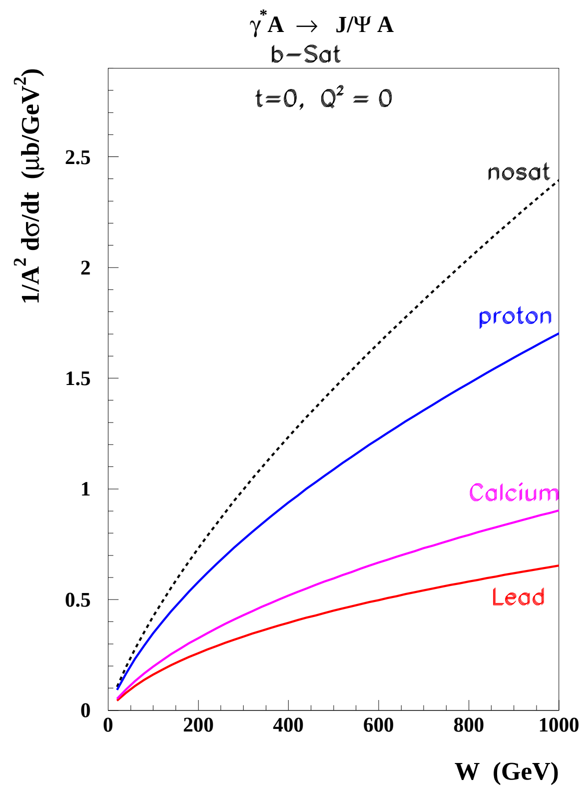


Figure 6.31: Energy dependence of the coherent photoproduction of the J/Ψ on a proton and different nuclei in the forward case $t = 0$ according to the b-Sat model. The cross sections are normalized by a factor $1/A^2$, corresponding to the dependence on the gluon density squared if no nuclear effects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

leading logarithmic approximation in x its evolution is governed by the Bartels-Kwieciński-Praszałowicz (BKP) equations [440–442]. Up to now, two solutions to the BKP equations are known, one with intercept slightly below one [443] and the other with intercept exactly equal to one [444].

Several channels involving Odderon exchange are possible at the LHeC, leading to the exclusive production of pseudoscalar mesons, $\gamma^{(\star)}p \to Cp$, where $C = \pi^0, \eta, \eta', \eta_c \ldots$ Searches for the Odderon in the reaction $ep \to e\pi^0 N^*$ were performed by the H1 collaboration at HERA [445] at an average γp c.m.s energy $\langle W \rangle = 215$ GeV. No signal was found and an upper limit on the cross section was derived, $\sigma(ep \to e\pi^0 N^*,\ 0.02 < |t| < 0.3\ \text{GeV}^2) < 49$ nb at the 95 % confidence level. Although the predicted cross sections for processes governed by Odderon exchange are rather small, they are not suppressed with increasing centre-of-mass energy and the large luminosities offered by the LHeC may be exactly what is required for a discovery. In addition to π^0 production, Odderon searches at the LHeC could be based on other exclusive channels, for example with heavier mesons η_c, η_b [446]. An even more sensitive test, ideal for

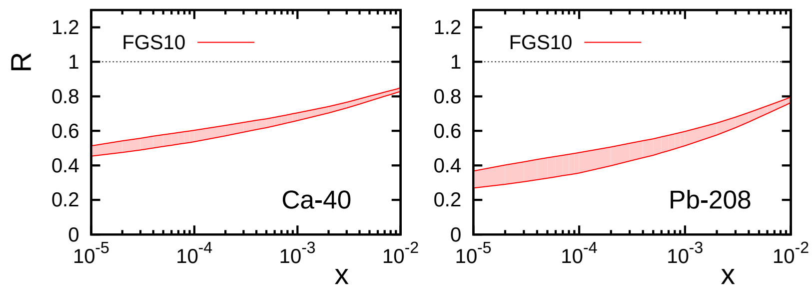


Figure 6.32: The x dependence of the nuclear modification ratio for the gluon density squared, from nuclei to protons (rescaled by A^2), for the scale corresponding to the exclusive production of the J/Ψ. Calculations obtained from the model described in [437].

study at the LHeC, is the measurement of the difference between charm and anti-charm angular or energy distributions in $\gamma^* p \to c\bar{c}N^*$. An asymmetry arises from the interference of pomeron and Odderon exchange amplitudes [447].

6.2.4 Inclusive diffraction

Introduction to Diffractive Deep Inelastic Scattering

Approximately 10% of low-x DIS events are of the diffractive type, $ep \to eXp$, with the proton surviving the collision intact despite the large momentum transfer from the electron (Fig. 6.33). This process is usually interpreted as the diffractive dissociation of the exchanged virtual photon to produce any hadronic final state system X with mass much smaller than W and the same net quantum numbers as the exchanged photon ($J^{PC} = 1^{--}$). Due to the lack of colour flow, diffractive DIS events are characterised by a large gap in the rapidity distribution of final state hadrons between the scattered proton and the diffractive final state X.

As discussed in section 6.2.3, similar processes exist in electron-ion scattering, where they can be sub-divided into fully coherent diffraction, where the nucleus stays intact ($eA \to eXA$) and incoherent diffraction, where the nucleons within the nucleus are resolved and the nucleus breaks up ($eA \to eXY$, Y being a system produced via nuclear or nucleon excitation, with the same quantum numbers as A).

Theoretically, rapidity gap production is usually described in terms of the exchange of a net colourless object in the t-channel, which is often referred to as a pomeron [448, 449]. In the simplest models [450, 451], this pomeron has a universal structure and its vertex couplings factorise, such that it is applicable for example to proton-(anti)proton scattering as well as DIS. One of the main achievements at HERA has been the development of an understanding of diffractive DIS in terms of parton dynamics and QCD [452]. Events are selected using the experimental signatures of either a leading proton [453–455] or the presence of a large rapidity gap [454, 456]. The factorisable pomeron picture has proved remarkably successful for the description of most of these data.

The kinematic variables used to describe diffractive DIS are illustrated in Fig. 6.33. In addition to x, Q^2 and the squared four-momentum transfer t, the mass M_X of the diffractively produced final state provides a further degree of freedom. In practice, the variable M_X is often

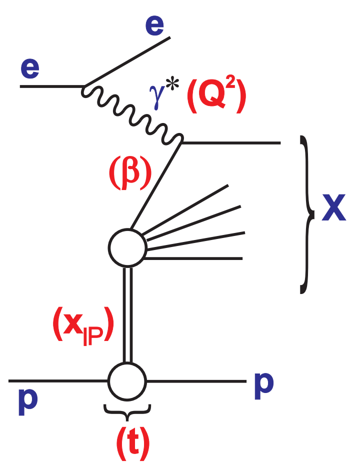


Figure 6.33: Illustration of the kinematic variables used to describe the inclusive diffractive DIS process $ep \to eXp$.

replaced by

$$\beta \;=\; \frac{Q^2}{Q^2 + M_X^2 - t} \;. \tag{6.13}$$

Small values of β refer to events with diffractive masses much bigger than the photon virtuality, while values of β close to unity are associated with small M_X values. In models based on a factorisable pomeron, β may be interpreted as the fraction of the pomeron longitudinal momentum which is carried by the struck parton. The variable

$$x_{\mathbb{P}} = \frac{x}{\beta} = \frac{Q^2 + M_X^2 - t}{Q^2 + W^2 - M^2} \;, \tag{6.14}$$

with M the nucleon mass, is then interpreted as the longitudinal momentum fraction of the Pomeron with respect to the incoming proton or ion. It also characterises the size of the rapidity gap as $\Delta\eta \simeq \ln(1/x_{\mathbb{P}})$.

Measuring Diffractive Deep Inelastic Scattering at the LHeC

Diffractive DIS (DDIS) can be studied in a substantially increased kinematic range at the LHeC, which will allow a whole new level of investigations of the factorisation properties of inclusive diffraction, will lead to new insights into low-x dynamics and will provide a subset of final states with known quantum numbers for use in searches for new physics and elsewhere.

As shown in [299], collinear QCD factorisation holds in the leading-twist approximation in diffractive 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 [457] 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

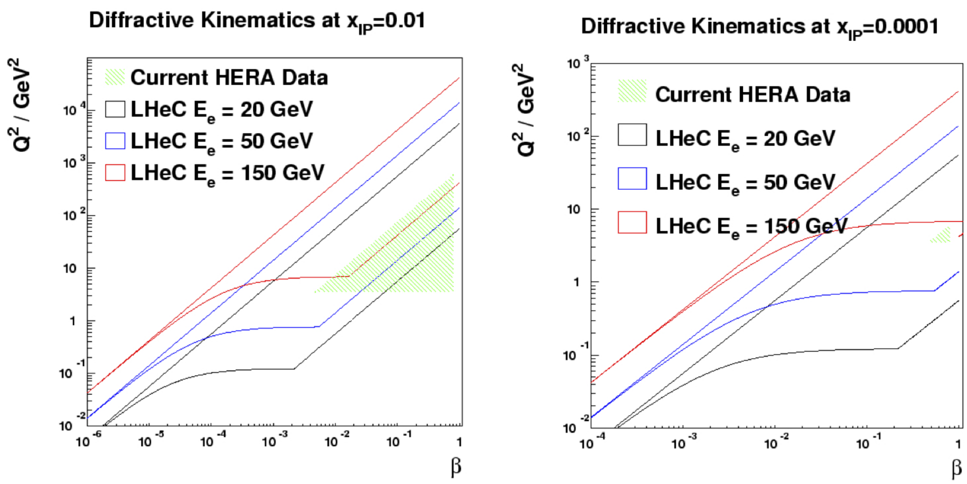


Figure 6.34: Diffractive DIS kinematic ranges in Q^2 and β of HERA and of the LHeC for different electron energies $E_e = 20, 50, 150$ GeV at $x_{\mathbb{P}} = 0.01$ (left plot), and $x_{\mathbb{P}} = 0.0001$ (right plot). In both cases, 1° acceptance is assumed for the scattered electron and the typical experimental restriction $y > 0.01$ is imposed. No rapidity gap restrictions are applied.

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 DDIS data [456, 458–460] 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 [449].

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 13). 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 [456], 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.

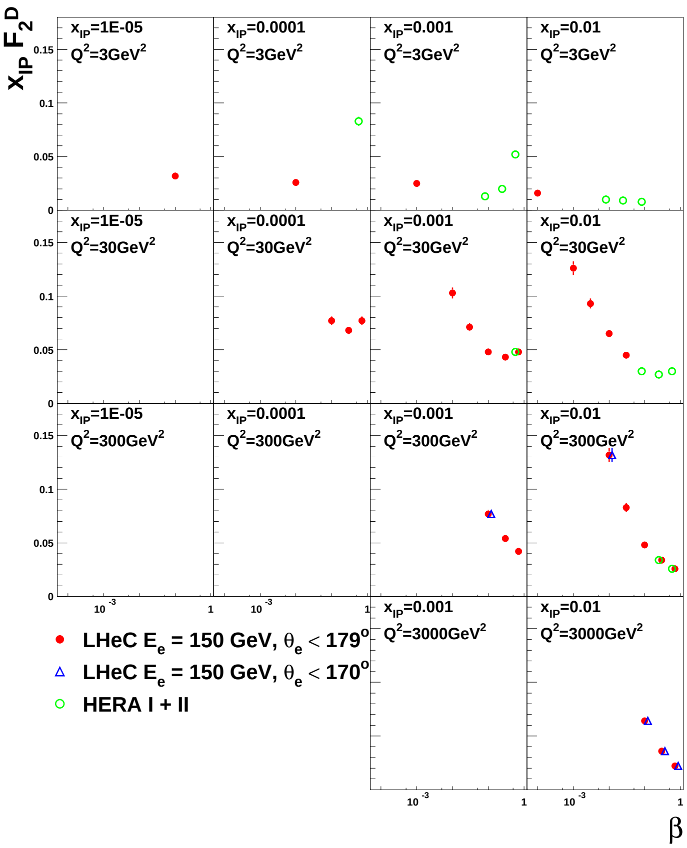


Figure 6.35: Simulation of a possible LHeC measurement of the diffractive structure function, F_2^D using a 2 fb^{-1} sample, compared with an estimate of the optimum results achievable at HERA using the full luminosity for a single experiment (500 pb^{-1}). The loss of kinematic region if the LHeC scattered electron acceptance extends to within 10° of the beam-pipe, rather than 1° is also illustrated.

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 $\eta_{\max}$ 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 [115]. This correlation depends only on the proton beam energy and is thus the same for all LHeC running scenarios. At HERA, a cut at $\eta_{\max} \sim 3.2$ has been used to select diffractive events. Assuming LHeC forward instrumentation extending to around $\theta = 1^\circ$, a cut at $\eta_{\max} = 5$ 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 13). 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.

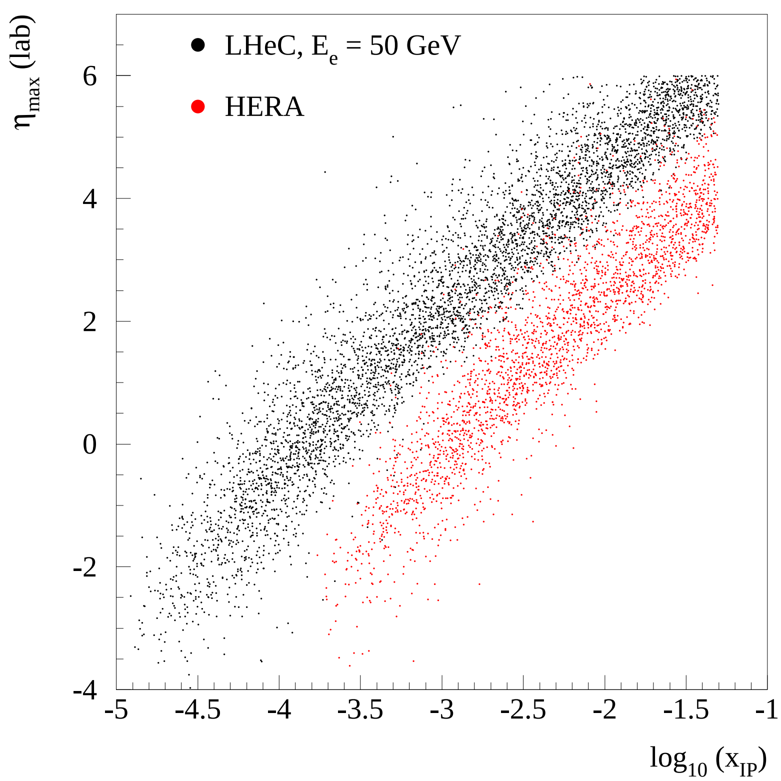


Figure 6.36: Comparison of the correlation between the rapidity gap selection variable, $\eta_{\max}$ and $x_{\mathbb{P}}$ at HERA and at the LHeC, using events simulated with the RAPGAP Monte Carlo generator.

Diffractive Parton Densities and Final States

The previously unexplored diffractive DIS region of very low β is of particular interest. Here, diffractively produced systems will be created with unprecedented invariant masses. Figure 6.37a shows a comparison between HERA and the LHeC in terms of the M_X distribution which could be produced in diffractive processes with $x_{I\!P} < 0.05$ (using the RAPGAP Monte Carlo model [115]). Figure 6.37a compares the expected M_X distributions for one year of running at three LHeC electron beam energy choices. Diffractive masses up to several hundred GeV are accessible with reasonable rates, such that diffractive final states involving beauty quarks

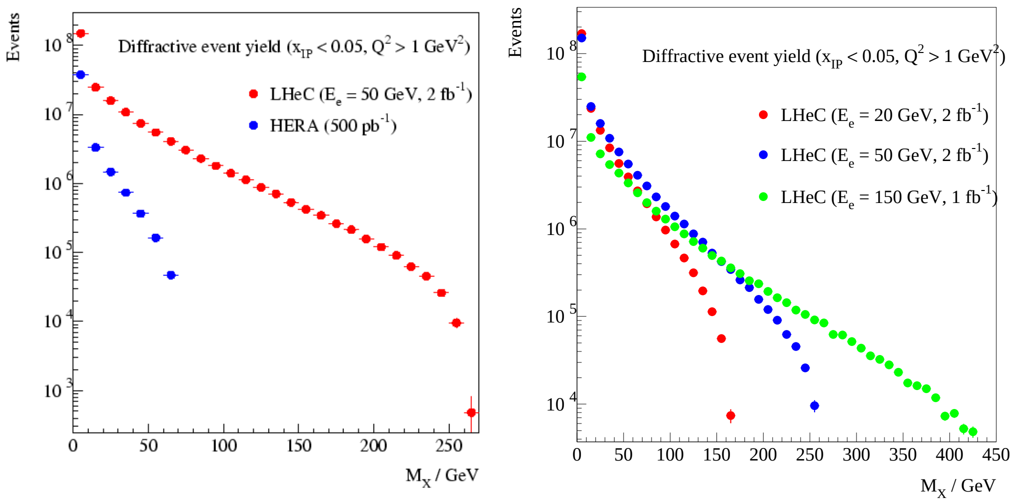


Figure 6.37: Simulated distributions in the invariant mass M_X according to the RAPGAP Monte Carlo model for samples of events obtainable with $x_{\mathbb{P}} < 0.05$ (a) One year of high acceptance LHeC running at $E_e = 50$ GeV compared with HERA (full luminosity for a single experiment). (b) Comparison between three different high acceptance LHeC luminosity and E_e scenarios.

and W and Z bosons, or even exotic states with 1^- quantum numbers, could be produced.

Large improvements in DPDFs are likely to be possible from NLO DGLAP fits to LHeC diffractive structure function data. In addition to the extended phase space in β, the extension of the kinematic range towards larger Q^2 increases the lever-arm for extracting the diffractive gluon density and opens the possibility of significant weak gauge boson exchange, which would allow a quark flavour decomposition for the first time.

Proton vertex factorisation can be tested precisely by comparing the LHeC β and Q^2 dependences at different small $x_{\mathbb{P}}$ values in their considerable regions of overlap. The production of dijets or heavy quarks as components of the diffractive system X will provide a means of testing QCD collinear factorisation. These processes are driven by boson-gluon fusion ($\gamma^* g \to q\bar{q}$) and thus provide complementary sensitivity to the diffractive gluon density to be compared with that from the scaling violations of the inclusive cross section. Factorisation tests of this sort have been carried out on many occasions at HERA, with NLO calculations based on DPDFs predicting jet and heavy flavour cross sections which are in good agreement with data at large Q^2 [461,462]. However, due to the relatively small accessible jet transverse momenta at HERA, the precision is limited by scale uncertainties on the theoretical predictions. At the LHeC, much larger diffractive jet transverse momenta are measurable ($p_T \lesssim M_X/2$), which should lead to much more precise tests [463].

The simulated measurement of the longitudinal proton structure function, F_L described in subsection 4.1.5, could also be extended to extract the diffractive analogue, F_L^D. At small β, where the cross section for longitudinally polarised photons is expected to be dominated by a leading twist contribution, an F_L^D measurement provides further complementary constraints on the role of gluons in the diffractive PDFs. As $\beta \to 1$, a higher twist contribution from longitudinally polarised photons, closely related to that driving vector meson electroproduction, dominates the diffractive cross section in many models [464] and a measurement to even modest precision would give considerable insight. A first measurement of this quantity has recently been reported by the H1 Collaboration [465], though the precision is strongly limited by statistical uncertainties. The LHeC provides the opportunity to explore it in much finer detail.

In contrast to leading proton production, the production of leading neutrons in DIS ($ep \to eXn$) requires the exchange of a net isovector system. Data from HERA have supported the view that this process is driven dominantly by charged pion exchange over a wide range of neutron energies [466]. With the planned emphasis on zero degree calorimetry for leading neutron measurements (see Chapter 13), LHeC data will thus constrain the structure of the pion at much lower x and larger Q^2 values than has been possible hitherto. Note also that the combination of rapidity gap detection and zero degree calorimetry offers the possibility of disentangling coherent from incoherent nuclear diffraction.

Diffractive DIS, Dipole Models and Sensitivity to Non-linear Effects

Diffractive DIS at the LHeC will give us an opportunity to test the predictions of collinear factorisation and the possible onset of non-linear or higher-twist effects in the evolution. Of particular importance is the semi-hard regime $Q^2 < 10$ GeV^2 and x as small as possible. It is possible that the non-linear saturation regime will be easier to reach with diffractive than with inclusive measurements, since diffractive processes are mostly sensitive to quantum fluctuations in the proton wave function that have a virtuality of order of the saturation scale Q_s^2, instead of Q^2. As a result, power corrections (not the generic Λ_{QCD}^2/Q^2 corrections, but rather the sub-class of them of order Q_s^2/Q^2) are expected to come into play starting from a higher value of Q^2 in diffractive than in inclusive DIS. Indeed, there is already a hint of this at HERA: collinear factorization starts to fail below about 3 GeV^2 in the case of F_2 [10], while it breaks down already around 8 GeV^2 in the case of F_2^D [456]. This fact can alternatively be observed in the feature that models which in principle should only work for small Q^2, can in practice be used up to larger Q^2 for diffractive than for inclusive observables (see e.g. [266]).

With the sort of measurement precision for F_2^D possible at the LHeC, it ought to be possible to distinguish between different models, as illustrated in Fig. 6.38. For the simulated data shown here, a conservative situation is assumed, in which the electron beam energy is 50 GeV and only the rapidity gap selection method is used, such that the highest $x_{\mathbb{P}}$ bin is at 0.001. H1 Fit B [456] extrapolations (as in Fig. 6.35) are compared with the "b-sat" [321, 322] and bCGC [467] dipole models. As has been found to be necessary to describe HERA data, photon fluctuations to $q\bar{q}g$ states are included in addition to the usual $q\bar{q}$ dipoles used to describe inclusive and vector meson cross sections. Both dipole models differ substantially from the H1 Fit B extrapolation. The LHeC simulated precision and kinematic range are sufficient to distinguish between a range of models with and without saturation effects, and also between different models which incorporate saturation.

Predicting nuclear shadowing from inclusive diffraction in ep

The connection between nuclear shadowing and diffraction was established a long time ago by Gribov [265]. Its key approximation is that the nucleus can be described as a dilute system of nucleons in the nucleus rest frame. The accuracy of this approximation for hadron-nucleus in-

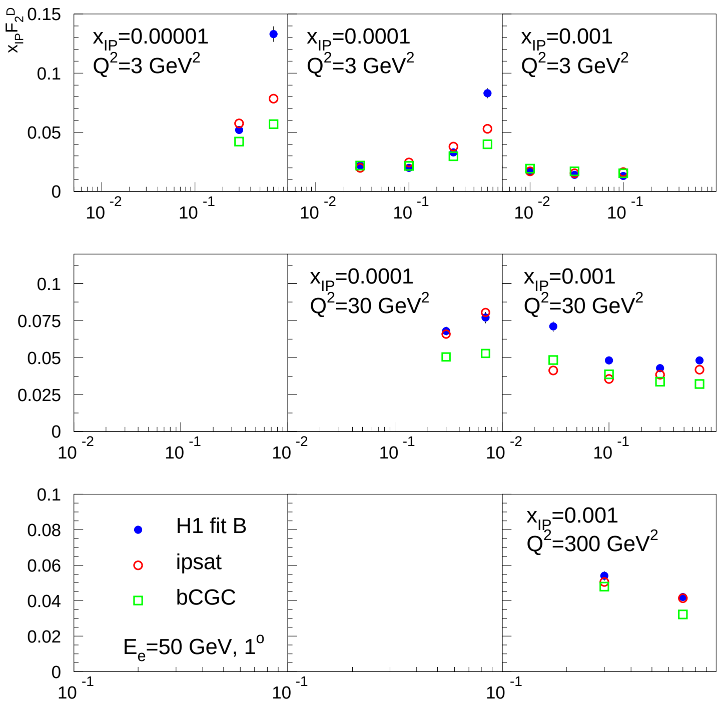


Figure 6.38: Simulated F_2^D measurements in selected $x_{\mathbb{P}}$, β and Q^2 bins. An extrapolation of the H1 Fit B DPDF fit to HERA data is compared with two different implementations of the dipole model, both of which contain saturation effects and include $q\bar{q}g$ photon fluctuations in addition to $q\bar{q}$ ones.

teractions is on the level of a few %, which reflects the small admixture of non-nucleonic degrees of freedom in nuclei and the small off-shellness of the nucleons in nuclei as compared to the soft strong interaction scale. Gribov's result can be derived using the AGK cutting rules [468] and hence it is a manifestation of unitarity [469, 470]. The formalism can be used to calculate directly cross sections of $\gamma(\gamma^*)$-nucleus scattering for the interaction with $N = 2$ nucleons, but has to be supplemented by additional considerations to account for the contribution of the interactions with $N \geq 3$ nucleons.

In this context, nuclear PDFs at small x can be calculated [469, 470] combining unitarity relations for different cuts of the shadowing diagrams corresponding to diffractive and inelastic final states, with the QCD factorisation theorem for hard diffraction [299]. A *model-independent* expression for the nuclear PDF at fixed impact parameter b, valid for the case $N = 2$ [469], reads:

$$\begin{aligned}
\Delta \left[xf_{j/A}(x, Q^2, b)\right] &= xf_{j/N}(x, Q^2, b) - xf_{j/A}(x, Q^2, b) \\
&= 8\pi A(A-1)\Re e \left[\frac{(1-i\eta)^2}{1+\eta^2} \int_x^{0.1} dx_{\mathbb{P}} \beta f_j^{D(4)}(\beta, Q^2, x_{\mathbb{P}}, t_{\min}) \right. \\
&\times \left. \int_{-\infty}^{\infty} dz_1 \int_{z_1}^{\infty} dz_2 \, \rho_A(\vec{b}, z_1) \rho_A(\vec{b}, z_2) e^{i(z_1 - z_2) x_{\mathbb{P}} m_N} \right], \qquad (6.15)
\end{aligned}$$

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 nucleon PDFs, $\eta = \Re e\, A^{diff}/\Im m\, A^{diff} \approx 0.17$, $\rho_A(r)$ is the nuclear matter density, and $t_{\min} = -m_N^2 x_{\mathbb{P}}^2$ with m_N the nucleon mass. Eq. (6.15) satisfies the QCD evolution equations to all orders in α_s. Numerical studies indicate that the dominant contribution to the shadowing probed by present experiments - corresponding to not very small x - comes from the region of relatively large β, for which small-x approximations which involve resummation of $\ln x$ terms are not important.

In Eq. (6.15), 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 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 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 [471], 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 [374, 437]. 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 [267,469,472,473] (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 [437, 469, 474]. 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

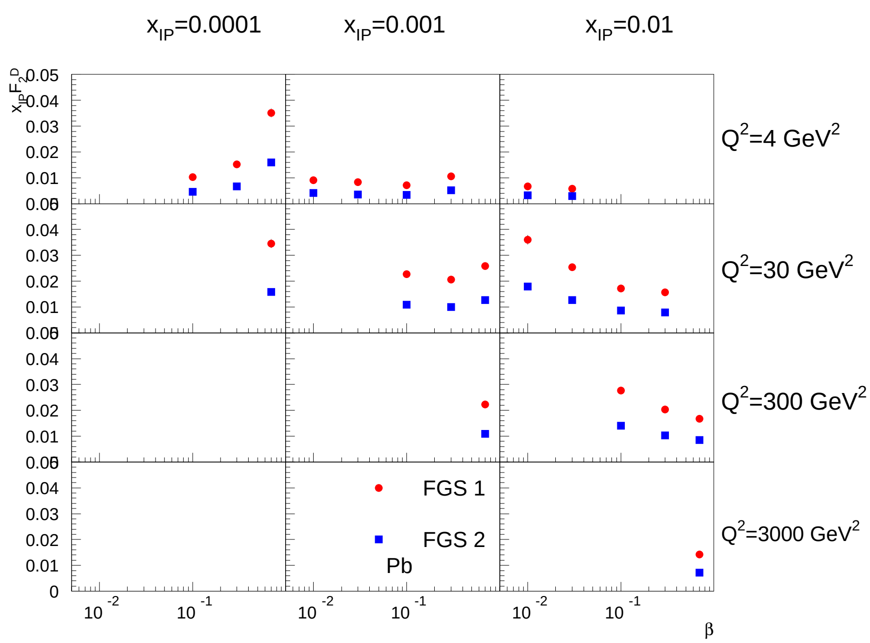


Figure 6.39: Diffractive structure function $x_{\mathbb{P}} F_2^D$ for Pb in bins of Q^2 and $x_{\mathbb{P}}$ as a function of β. Model calculations are taken from [437].

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 [437] and KLMV [475,476]. 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 [303] that the constancy with energy of this ratio for the proton can be naturally explained in the models which include saturation

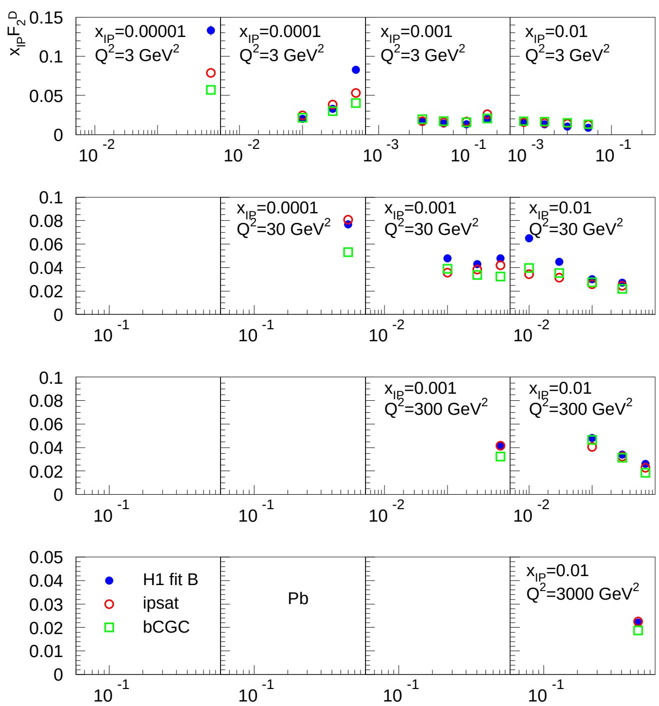


Figure 6.40: Diffractive structure function $x_{\mathbb{P}} F_2^D$ for Pb in bins of Q^2 and $x_{\mathbb{P}}$ as a function of β. Model calculations are based on the dipole framework [475, 476].

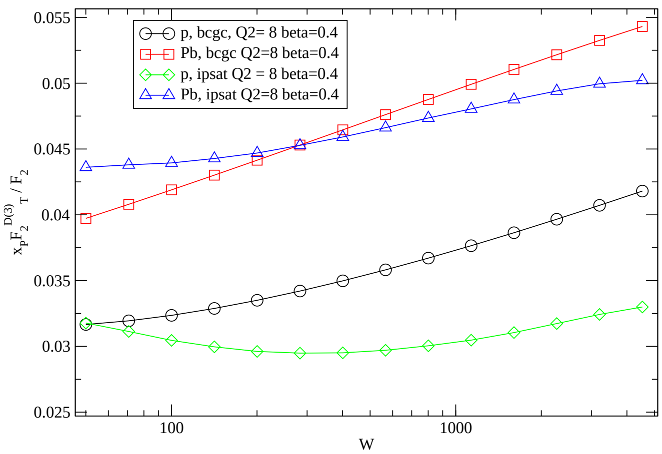


Figure 6.41: Ratio of the transversely polarised photon contribution to the diffractive structure function $x_{\mathbb{P}}F_2^D$ to the inclusive structure function in p and Pb for fixed values of Q^2 and β as a function of the energy W. The model calculations are based on the dipole framework [475, 476].

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 data showed approximate energy independence of this ratio, which could be easily obtained within the GBW saturating dipole model [303]. Within the given energy range the models shown in figure 6.41 predict a slight variation with energy. Note however the rather substantial difference between predictions coming from the different models. The uncertainty in modelling the impact parameter is one of its main sources. LHeC data are required for clarification.

6.2.5 Jet and multi-jet observables, parton dynamics and fragmentation

Introduction

Inclusive measurements provide essential information about the integrated distributions of partons in a proton. However, as was discussed in previous sections, more exclusive measurements are needed to pin down the essential details of the small-x dynamics. For example, a central prediction of the BFKL framework at small x is the diffusion of the transverse momenta of the emitted partons between the photon and the proton. In the standard collinear approach with integrated parton densities the information about the transverse momentum is not accessible. However, it can be recovered within a different framework which utilizes unintegrated parton distribution functions, dependent on parton transverse momentum as well as x and Q^2. Unintegrated PDFs are natural in the BFKL approach to small-x physics. A general, fundamental expectation is that as x decreases, the distribution in transverse momentum of the emitted partons broadens, resulting in diffusion.

The specific parton dynamics can be tested by a number of exclusive measurements. These in turn can provide valuable information about the distribution of transverse momentum in the proton. As discussed in [477], for many inclusive observables the collinear approximation with integrated PDFs is completely insufficient, and even just including parton transverse momentum effects by hand may not be sufficient to describe many observables. In DIS, for example, processes needing unintegrated distributions include the transverse momentum distribution of heavy quarks. Similar problems are encountered in hadron collisions when studying heavy quark and Higgs production. The natural framework using unintegrated PDFs gives a much more reliable description. Furthermore, lowest-order calculations in the framework with unintegrated PDFs provide a much more realistic description of cross sections concerning kinematics. This may well lead to NLO and higher corrections being much smaller numerically than they typically are at present in standard collinear factorization, since the LO description is better.

This approach, however, calls for precise measurements of a variety of relatively exclusive processes in a wide kinematic range. As discussed below, measurements of dijets, forward jets and particles, as well as transverse energy flow, are required to constrain the unintegrated PDFs and will give valuable information about parton dynamics at small x. While we will discuss the case of DIS on a proton, all conclusions can be paralleled for DIS on nuclei.

Unintegrated PDFs

The standard integrated parton densities are functions of the longitudinal momentum fraction of a parton relative to its parent hadron, with an integral over the parton transverse momentum. In contrast, unintegrated, or transverse-momentum-dependent (TMD), parton densities depend on both parton longitudinal momentum fraction and parton transverse momentum. Processes for which unintegrated densities are natural include the Drell-Yan process (and its generalization to Higgs production), and semi-inclusive DIS (SIDIS). In SIDIS, we need TMD fragmentation functions as well as TMD parton densities.

In the literature there are several apparently different approaches to TMD parton densities, with varying degrees of explicitness in the definitions and derivations.

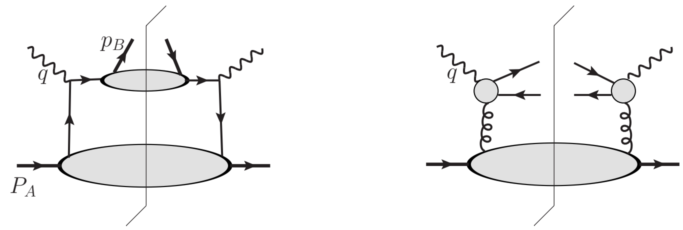
- The CSS approach [478–481] and some further developments [482].
- The CCFM approach [483–486] for small x.
- Related BFKL associated works [281, 487].

Central to this subject is the concrete definition of TMD densities, and complications arise because QCD is a gauge theory. A natural initial definition uses light-front quantization: the unintegrated density of parton j in hadron h would be

$$f_{j/h}(x, \boldsymbol{k}_\perp) \stackrel{?}{=} \frac{1}{2x(2\pi)^3} \sum_\lambda \frac{\langle P, h | b^\dagger_{k,\lambda,j} b_{k,\lambda,j} | P, h \rangle_{\rm c}}{\langle P, h | P, h \rangle} , \tag{6.16}$$

where $b_{k,\lambda,j}$ and $b^\dagger_{k,\lambda,j}$ are light-front annihilation and creation operators, j and λ label parton flavor and helicity, while $k = (k^+, \boldsymbol{k}_\perp)$ is its momentum, and only connected graphs 'c' are considered. The '?' over the equality sign warns that the formula does not apply literally in QCD. Expressing $b_{k,\lambda,j}$ and $b^\dagger_{k,\lambda,j}$ in terms of fields gives the TMD density as the Fourier transform of a light-front parton correlator. For example, for a quark

$$f_j(x, \boldsymbol{k}_\perp) \stackrel{?}{=} \int \frac{{\rm d}w^- \, {\rm d}^2\boldsymbol{w}_\perp}{(2\pi)^3} \, e^{-ixP^+w^- + i\boldsymbol{k}_\perp \cdot \boldsymbol{w}_\perp} \, \langle P | \, \overline{\psi}_j(0, w^-, \boldsymbol{w}_\perp) \, \frac{\gamma^+}{2} \, \psi_j(0) \, | P \rangle_{\rm c} \, . \tag{6.17}$$



(a) (b)

Figure 6.42: (a) Parton model factorisation for a SIDIS cross section. (b) Factorization for high-energy $q\bar{q}$ photoproduction.

One can similarly define a TMD fragmentation function [479] $d_{h/j}(z, \boldsymbol{p}_\perp)$, for the probability density of final-state hadron h in an outgoing parton j.

The corresponding factorization formula for SIDIS $e + A(P_A) \to e + B(p_B) + X$ is [482]

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x\,\mathrm{d}Q^2\,\mathrm{d}z\,\mathrm{d}^2\boldsymbol{P}_{B\,\perp}} = \sum_j \int \mathrm{d}^2\boldsymbol{k}_\perp\, H_j f_{j/A}(x, \boldsymbol{k}_\perp) d_{B/j}(z, \boldsymbol{p}_{B\,\perp} + z\boldsymbol{k}_\perp), \tag{6.18}$$

where z and $\boldsymbol{P}_{B\,\perp}$ are the fractional longitudinal momentum and the transverse momentum of the detected hadron relative to the simplest parton-model calculation of the outgoing jet, while H_j is the hard-scattering factor for electron-quark elastic scattering; see Fig. 6.42(a). In the fragmentation function $d_{B/j}$ in Eq. (6.18), the use of $z\boldsymbol{k}_\perp$ with its factor of z is because the transverse-momentum argument of the fragmentation function is a transverse momentum of the outgoing hadron relative to the parton initiating the jet, whereas $\boldsymbol{k}_\perp$ is the transverse momentum of a parton relative to a hadron.

The most obvious way of applying (6.17) in QCD is to define the operators in light-cone gauge $A^+ = 0$, or, equivalently, to attach Wilson lines to the quark fields with a light-like direction for the Wilson lines. One minor problem in QCD is that, because the wave function is infinite (see below), the exact probability interpretation of parton densities cannot be maintained.

A much harder problem occurs because QCD is a gauge theory. Evaluating TMD densities defined by (6.17) in light-cone gauge gives divergences where internal gluons have infinite negative rapidity [478]. These cancel only in the integrated density. The physical problem is that any coloured parton entering (or leaving) the hard scattering is accompanied by a cloud of soft gluons, and the soft gluons of a given transverse momentum are distributed uniformly in rapidity. A parton density defined in light-cone gauge corresponds to the asymptotic situation of infinite available rapidity.

A quark in a realisable hard scattering can be considered as having a transverse recoil against the soft gluons, but with a physically restricted range of rapidity. So a proper definition of a TMD density must implement a rapidity cut-off in the gluon momenta. Evolution equations must take into account the rapidity cut-off. The CSS formalism [478] has an explicit form of the rapidity cut-off and an equation for the dependence of TMD functions on the cut-off. But in any alternative formalism the need in the definitions for a cut-off to avoid rapidity divergences is non-negotiable.

Parton densities and fragmentation functions are only useful because they appear in factorisation theorems, so a useful definition must allow useful factorisation theorems to be formulated and derived. An improved definition involving Wilson line operators has recently been given in [488]; see also [489].

A second train of argument leads to a related kind of factorisation (the so-called $k_\perp$-factorisation) for processes at small x [288]. A classic process is photo- or electro-production of charm pairs $\gamma(p_1) + h(p_2) \to Q(p_3) + \bar{Q}(p_4) + X$, for which $k_\perp$-factorisation has the form

$$4M^2 \sigma_{\gamma g}(\rho, M^2/Q_0^2) = \int \mathrm{d}^2\boldsymbol{k}_\perp \int_0^1 \frac{\mathrm{d}z}{z} \hat{\sigma}(\rho/z, \boldsymbol{k}_\perp^2/M^2) f_{g/h}(x, \boldsymbol{k}_\perp), \tag{6.19}$$

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 definition of the TMD gluon density [483] is said to use light-cone gauge, but there is in fact a hidden rapidity cut-off resulting from the use of the BFKL formalism.

Although both (6.18) and (6.19) use $k_\perp$-dependent parton densities, there are important differences. In (6.19), the hard scattering cross section $\hat{\sigma}$ has the incoming gluon *off*-shell, whereas in (6.18), the hard scattering H_j uses on-shell partons. This is associated with a substantial difference in the kinematics. In (6.18) for SIDIS, the transverse momenta of the partons relative to their hadrons are less than Q, which allows the neglect of parton virtuality in the hard scattering. This approximation fails at large partonic transverse momentum, $\boldsymbol{k}_\perp \sim Q$, but ordinary collinear factorisation is valid in that region. So the factorisation formula is readily corrected, by adding a suitable matching term [478].

In contrast, in the small-x formula (6.19), the gluon transverse momentum is comparable with the hard scale M. So it is not appropriate to neglect $\boldsymbol{k}_\perp$ with respect to M, and the hard scattering is computed with an off-shell gluon. Factorisation is actually obtained from BFKL physics, where the gluons in Fig. 6.42(b) couple the charm quark subgraph to a subgraph where the lines have much larger rapidity.

The evolution equation of the CS-style TMD functions used in (6.18) gives the dependence of the TMD functions on the rapidity difference between the hadron and the virtual photon momenta. The results for TMD functions and for the cross sections can finally be obtained [482] in terms of (a) ordinary integrated parton densities and fragmentation functions, (b) perturbatively calculable quantities, and (c) a restricted set of non-perturbative quantities. The most important of these non-perturbative quantities is the distribution in recoil transverse momentum per unit rapidity against the emission of the soft interacting gluons, which is exponentiated after evolution. Importantly, it is independent of x and z, and it is universal between processes [490], and different only between gluons (color octet) and quarks (color triplet). There is also what can be characterised as a non-perturbative intrinsic transverse momentum distribution in both parton densities and fragmentation functions. In the quark sector, all but the fragmentation function are well measured in Drell-Yan processes [491].

On the other hand, evolution for the small-x formalism in (6.19) is given by the BFKL method.

The avenues for further improvement on this subject are both theoretical and experimental. On the theory side, these concern the relation between different formalisms for evolution [281, 478, 482, 487, 492], the extension of factorisation theorems to a larger number of particles in the final state, and the matching to Monte Carlo generators. On the experimental side, the sensitivity to TMD functions is linked to a sensitivity to parton transverse momentum. This is the case of SIDIS at low transverse momentum. Another interesting process which would enable the TMD gluon functions to be probed is $ep \to e\pi\pi X$, with the pions being in different directions (different jets), but such that they are close to back-to-back in the (q, p_i) (the so-called brick wall) frame.

Finally, measuring SIDIS and dijet production off protons or nuclei at the LHeC will allow detailed investigations of non-linear parton evolution in QCD. In this respect, the SIDIS cross section [493] and dihadron production [494] have been studied in the CGC framework. It turns out that, for small x, one is sensitive to the saturation regime of the target (proton or nucleus) wave function if the transverse momentum of the produced hadron is of the order of the saturation momentum.

Dijet production and angular decorrelation

Dijet production in high energy deep inelastic electron-proton scattering is a very valuable process for the study of small-x behavior in QCD. The dominant process is illustrated in Fig. 6.43, which is that of the $\gamma^* g \to q\bar{q} \to$ dijet production. The incoming gluon can have sizeable transverse momentum accumulated from diffusion in k_T along the gluon chain. As Bjorken-x becomes smaller, and therefore the longitudinal momentum of the gluon also decreases, larger values of the transverse momentum k_T can be sampled. This will lead to an azimuthal decorrelation between the jets which increases with decreasing x. The definition of $\Delta\phi$ is indicated in Fig. 6.43. That is, the jets are no longer back-to-back since they must balance the sizable transverse momentum k_T of the incoming virtual gluon.

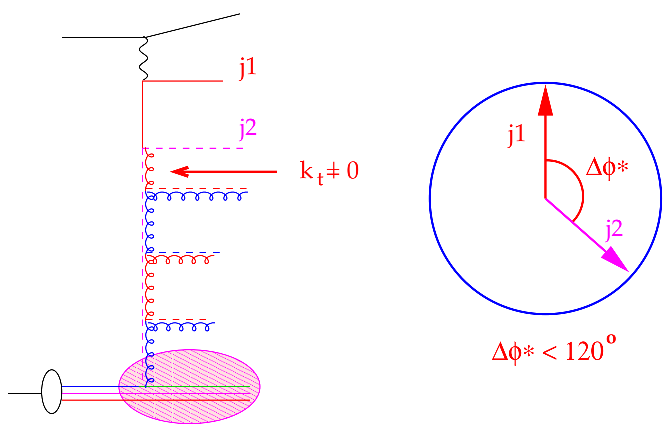


Figure 6.43: Schematic representation of the production of a system of two jets in the process of virtual photon-gluon fusion. The incoming gluon has non-vanishing transverse momentum $k_T \neq 0$ which leads to the decorrelation of the jets. $\Delta\phi$ is the angle between two jets.

This picture of dijet production is to be contrasted with the conventional picture which uses integrated parton distributions, and typically leads to a narrow distribution about the back-to-back jet configuration. Higher orders usually broaden the distribution. However, as shown by direct measurements of DIS dijet data [495], NLO DGLAP calculations are not able to accommodate the pronounced effect of the decorrelation.

Explicit calculations for HERA kinematics show that the models which include the resummation of powers of $\log 1/x$ compare favourably with the experimental data [496–500]. The proposal and calculations to extend such studies to diffractive DIS also exist [501, 502].

In Fig. 6.44 we show the differential cross section as a function of $\Delta\phi$ for jets in the region $-1 < \eta_{jet} < 2.5$ with $E_{\mathrm{T,jet1}} > 7$ GeV and $E_{\mathrm{T,jet2}} > 5$ GeV found with the k_t jet algorithm in the kinematic range $Q^2 > 5$ GeV, $0.1 < y < 0.6$ for different regions in x. The 'MEPS' prediction comes from a Monte Carlo generator [115] using $\mathcal{O}(\alpha_s)$ matrix elements with a DGLAP-type parton shower. The 'CDM prediction uses the same generator [115], but with higher order parton radiation simulated with the Colour Dipole Model [503], thus effectively including some k_t diffusion. Finally, the CASCADE Monte Carlo prediction [504], uses off-shell matrix elements convoluted with an unintegrated gluon distribution (CCFM set A), with subsequent parton showering according to the CCFM evolution equation.

At large x all predictions agree reasonably well, in both shape and normalisation. At smaller x the $\Delta\phi$-distribution becomes flatter for CDM and CASCADE, indicating higher order effects leading to a larger decorrelation of the produced jets. Whereas a decorrelation is observed, its size depends on the details of the 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.

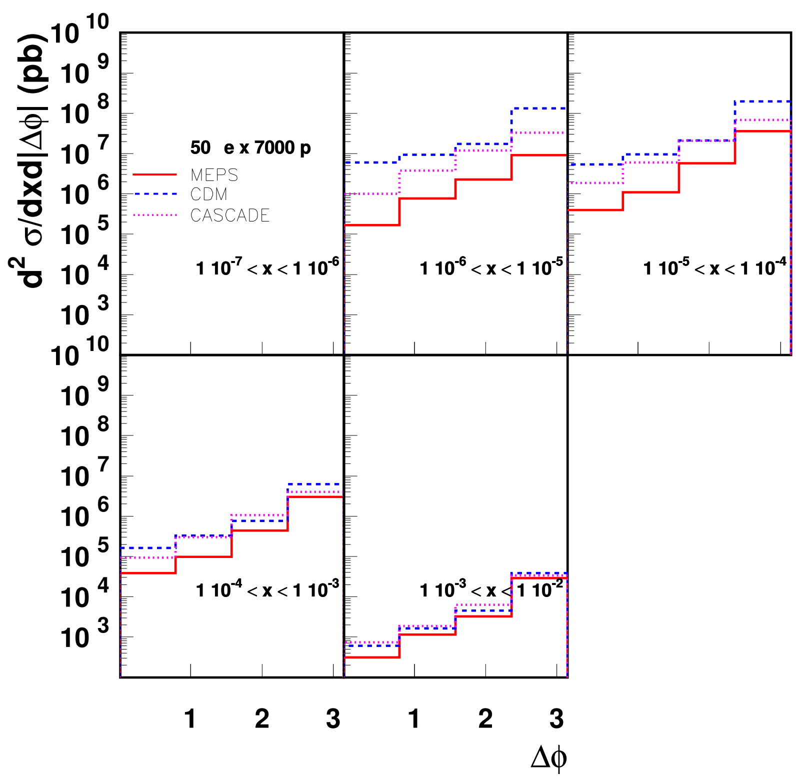


Figure 6.44: Differential cross section for dijet production as a function of the azimuthal separation $\Delta\phi$ for dijets with $E_{\mathrm{T,jet1}} > 7$ GeV and $E_{\mathrm{T,jet2}} > 5$ GeV.

Thus, in principle, a measurement of the azimuthal dijet distribution offers a direct de-

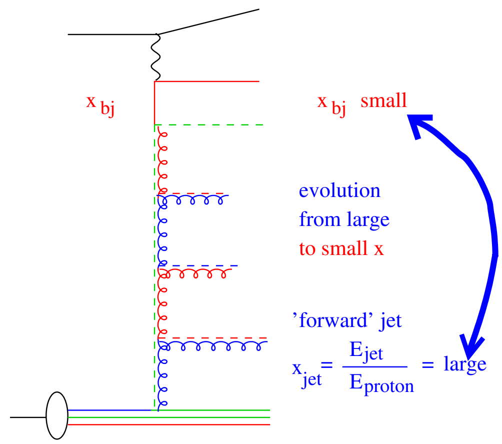


Figure 6.45: Schematic representation of the production of a high transverse momentum forward jet in DIS.

termination of the k_T-dependence of the unintegrated gluon distribution. When additionally supplemented by inclusive measurements, it can serve as an important constraint for the precise determination of the fully unintegrated parton distribution, with the transverse momentum dynamics in the proton completely unfolded.

Forward observables

It was proposed some time ago [505, 506] that a process which would be very sensitive to the parton dynamics and the transverse momentum distribution was the production of forward jets in DIS. According to [505, 506], DIS events containing identified forward jets provide a particularly clean window on small-x dynamics. The schematic view of the process is illustrated in Fig. 6.45. The forward jet transverse momentum provides the second hard scale p_T. Hence one has a process with two hard scales: the photon virtuality Q and the transverse momentum of the forward jet p_T. As a result the collinear (DGLAP) configurations (with no diffusion and strongly ordered transverse momenta) can be eliminated by choosing the scales to be of comparable size, $Q^2 \simeq p_T^2$. Additionally, the jet is required to be produced in the forward direction by demanding that x_J, the longitudinal momentum fraction of the produced jet, is as large as possible, and x/x_J is as small as possible. This requirement selects events with a large sub-energy between the jet and the virtual photon, such that the BFKL framework should be applicable. There have been dedicated measurements of forward jets at HERA [507–512], which demonstrated that DGLAP dynamics at NLO are indeed incompatible with the experimental measurements. On the other hand, calculations based on resummations of powers of $\log 1/x$ (BFKL and others) [513–519] are consistent with the data. The azimuthal dependence of forward jet production has also been studied [520, 521] as a sensitive probe of the small-x dynamics.

Another observable that provides a valuable insight into the features of small-x physics is the transverse energy (E_T-flow) accompanying DIS events at small x. The diffusion of the transverse momenta in this region leads to a strongly enhanced distribution of E_T at small x. As shown in [522, 523], small-x evolution results in a broad Gaussian E_T-distribution as a function of rapidity. This should be contrasted with the much smaller E_T-flow obtained assuming strong k_T-ordering as in DGLAP-based approaches, which give an E_T-distribution that narrows with decreasing x, for fixed Q^2.

The first experimental measurements of the E_T-flow in small-x DIS events indicate that there is significantly more E_T than is given by conventional QCD cascade models based on DGLAP evolution. Instead we find that they are in much better agreement with estimates which incorporate dynamics beyond fixed-order DGLAP [503,518,524] such as BFKL evolution. The latter dynamics are characterized by an increase of the E_T-flow in the central region with decreasing x.

However, the experimental data from HERA do not enable a detailed analysis due to their constrained kinematics. At the LHeC one could perform measurements with large separations in rapidity and for different selections of the scales (Q, p_T). In particular, there is a possibility of varying scales to test systematically the parton dynamics from the collinear (strongly ordered) regime $Q^2 \gg p_T^2$ to the BFKL (equal scale, Regge kinematics) regime $Q^2 \simeq p_T^2$. Measurements of the energy flow in different x-intervals, in the small-x regime, should therefore allow a definitive check of the applicability of BFKL dynamics and of the eventual presence of more involved, non-linear effects.

A simulation of forward jet production at the LHeC is shown in Figs. 6.46 and 6.47. The jets are required to have $E_T > 10$ GeV with a polar angle $\Theta_{jet} > 1°$ or $3°$ in the laboratory frame. Jets are found with the SISCone jet-algorithm [525]. The DIS phase space is defined by $Q^2 > 5$ GeV, $0.05 < y < 0.85$.

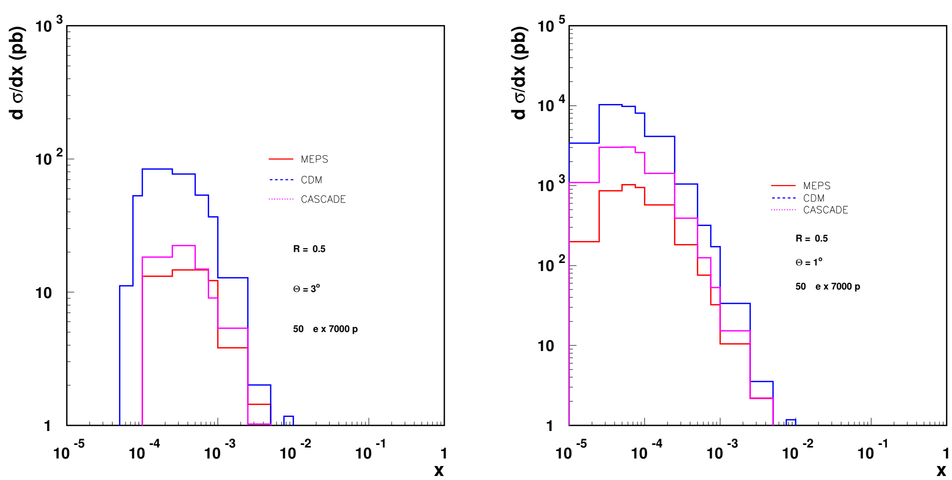


Figure 6.46: Cross section for forward jets with $\Theta_{jet} > 3°$ (left) and $\Theta_{jet} > 1°$ (right). Predictions from MEPS, CDM and CASCADE are shown. Jets are found with the SISCone algorithm using $R = 0.5$.

In Fig. 6.46 the differential cross section is shown as a function of Bjorken x for an electron energy of $E_e = 50$ GeV. The calculations are obtained from the MEPS [115], CDM [503] and CASCADE [518] Monte Carlo models, as described in the previous section. Predictions for $\Theta_{jet} > 3°$ and $\Theta_{jet} > 1°$ are shown. One can clearly see that the small-x range is explored

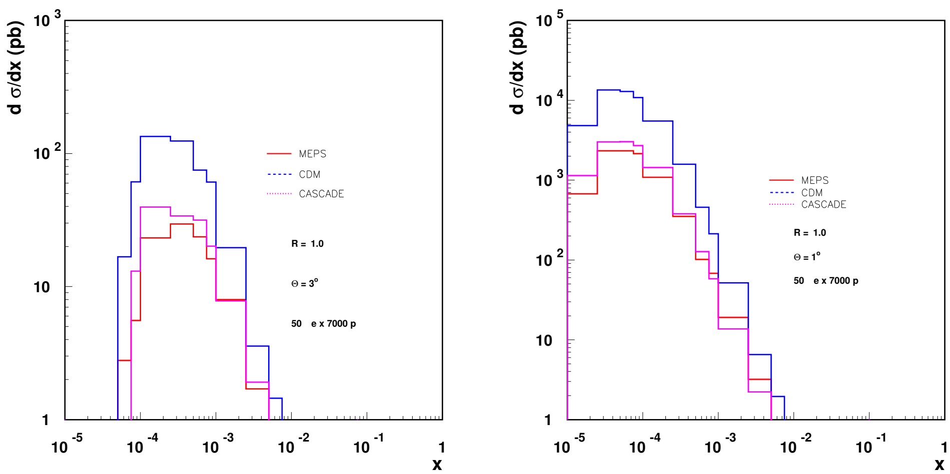


Figure 6.47: Cross section for forward jets with $\Theta_{jet} > 3^\circ$ (left) and $\Theta_{jet} > 1^\circ$ (right). Predictions from MEPS, CDM and CASCADE are shown. Jets are found with the SISCone algorithm using $R = 1.0$.

in detail with the small angle scenario. In Fig. 6.47 the forward jet cross section is shown when using $R = 1$ instead of $R = 0.5$ (Fig. 6.46). It is important to note that good forward acceptance of the detector is crucial for the measurement of forward jets. The dependence of the cross section on the acceptance angle is very strong as is evident from comparisons between the cross sections for different Θ_{jet} cuts Figs. 6.46 and 6.47.

A complementary reaction to that of forward jets is the production of forward π^0 mesons in DIS. Despite having a lower rate, this process offers some advantages over forward jet production. By looking onto single particle production the dependencies on the jet finding algorithms can be eliminated. Also, the non-perturbative hadronisation effects can be effectively encompassed into fragmentation functions [514].

Perturbative and non-perturbative aspects of final state radiation and hadronization

The mechanism through which a highly virtual parton produced in a hard scattering gets rid of its virtuality and colour and finally projects onto an observable final state hadron, is unknown to a great extent (see [383] and references therein). The different postulated stages of the process are illustrated in Fig. 6.48. The coloured parton undergoes QCD radiation before forming first a coloured excited bound state (pre-hadron), then a colourless pre-hadron and ultimately a final state hadron. These sub-processes are characterised by different time scales. While the first stage can be described in perturbative QCD [526], subsequent ones require models (e.g. the QCD dipole model for the pre-hadron stages) and non-perturbative information.

The LHeC offers great opportunities to study these aspects and improve our understanding of all of them. The energy of the parton which is struck by the virtual photon implies a Lorentz dilation of the time scales for each stage of the radiation and hadronisation processes. All of

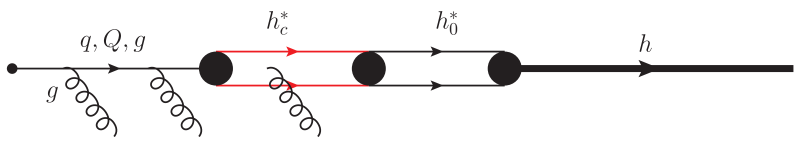


Figure 6.48: Sketch of the different postulated stages in the hadronisation of a highly virtual parton. From left to right: radiating parton; radiating coloured pre-hadron, colourless pre-hadron and final state hadron.

them are influenced by the fact that they do not take place in the vacuum, but within the QCD field created by the other components of the hadron or nucleus. While at fixed target SIDIS or DY experiments, the lever arm in energy is relatively small (energy transfer to the struck parton in its rest frame, $\nu < 100$ GeV), at the LHeC this lever arm will be huge ($\nu < 10^5$ GeV; see also in Subsec. 4.8.2 the abundant yield of expected high transverse momentum jets in photoproduction), implying that the different stages can be considered to happen in or out of the hadron field depending on the parton energy. Furthermore, the fact that we can introduce a piece of coloured matter of known length and density - a nucleus - by doing ePb collisions at different centralities, allows a controllable variation of the influence of the different processes. The induced differences in the final distributions of hadrons, both in terms of their momenta and of their relative abundance, will provide important information about the time scales and the detailed physical mechanisms at work in each stage. Dramatic effects are predicted in some models [143], with a significant suppression of the forward hadron spectra due to the creation of the dense partonic system. Note that SIDIS experiments already provide information for the determination of standard fragmentation functions (see [527, 528] for a recent analysis). The other pieces of information, coming mainly from e^+e^- experiments, will not be improved until next-generation linear colliders become available.

Furthermore, these studies will shed light on two aspects already discussed in Subsec. 6.1.4, related to the study of ultrarelativistic heavy-ion collisions: the characterization of the medium created in such collisions through hard probes, and the details of particle production in a dense situation which will define the initial conditions for the collective behavior of this medium. Concerning the latter, our theoretical tools for computing particle production in eA collisions are more advanced e.g. within the CGC framework, and on a safer ground than in nucleus-nucleus collisions (see Subsec. 6.1.1 and e.g. [382] and refs. therein). The possibility of disentangling the different mechanisms through which the factorisation that is used in dilute systems - collinear factorisation [252] - becomes broken by density effects (e.g. initial and final state energy loss or final state absorption) will be possible at the LHeC and will complement existing studies done at much smaller energies in fixed target SIDIS and DY experiments [383].

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 [529, 530]. 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

$$\mathcal{L}^{\nu}_{int} \sim 250 \times 10^{9}\ \mathrm{g/cm^2}\ , \qquad\qquad \mathcal{L}^{\gamma}_{int} \sim 100\ \mathrm{g/cm^2}\ .$$

Thus, very energetic photons with energy bigger than ~ 10 TeV cannot reach the Earth from the very distant corners of our Universe without being rescattered. In contrast, neutrinos can travel very long distances without interacting. They are also not deflected by galactic magnetic fields, and therefore at ultra-high energies the angular distortion of the neutrino trajectory is very small. As a result, highly energetic neutrinos reliably point back to their sources. The interest in the neutrinos at these high energies has led to the development of several neutrino observatories, see [530] and references therein.

For reliable observations based on neutrino detection, precise knowledge about their production rates and interactions is essential to estimate the background, the expected fluxes and the detection probabilities. Even though neutrinos interact only weakly with other particles, strong interactions play an essential role in the calculations of their production rates and interaction cross sections. This is due to the fact that neutrinos are produced in the decays of various mesons such as π, K, D and even B, which are produced in high-energy proton-proton (or proton-nucleus or nucleus-nucleus) collisions. These hadronic processes occur mainly in the atmosphere though possibly also in the accretion discs of remote Active Galactic Nuclei. Further, the interactions of highly energetic neutrinos with matter are dominated by the deep inelastic cross section with nucleons or nuclei. Hence, low x information from high-energy collider experiments such as HERA, Tevatron, LHC and, most importantly, the future LHeC, is invaluable.

One of the main uncertainties (if not the dominant one) in the current limits on high-energy neutrino production is due to the neutrino-nucleon (nucleus) cross section. In fact, event rates are proportional to the neutrino cross section in many experiments. This cross section involves the gluon distribution probed at very small values of Bjorken x, down to even $\sim 10^{-9}$, which corresponds to a very high centre of mass energy.

To visualize the kinematic regime probed in ultra-high energy neutrino-nucleon interactions, contour 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 contours enclose regions with different contributions to the total cross section $\sigma(E_\nu)$. For very high energy $E_\nu = 10^{11}$ GeV the dominant contribution comes from the domain $Q^2 \simeq M_W^2$ and $x_{\min} \simeq M_W^2/(2M_N E) \sim 10^{-8} - 10^{-7}$ where M_N is the nucleon mass, inaccessible to any current or proposed accelerators. However, at lower neutrino energy $E_\nu = 10^7$ GeV the relevant domain of (x, Q^2) could be very well covered by the LHeC, thus providing important new constraints on the neutrino-nucleon cross section.

On the other hand, another process which has been proposed for neutrino detection comes from the discovery of neutrino flavor oscillations, which makes it possible that high rates of

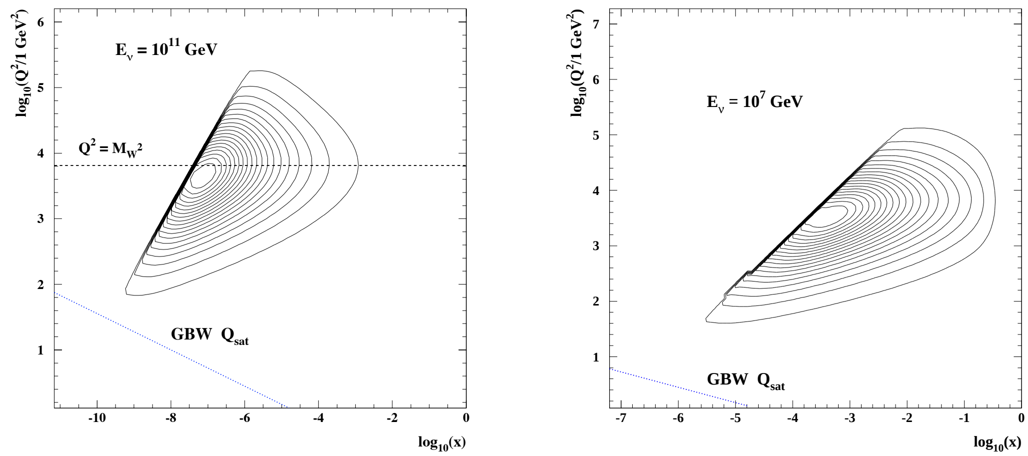


Figure 6.49: Contour plot showing the x, Q^2 domain of the dominant contribution to the differential cross section $\mathrm{d}\sigma/\mathrm{d}\ln(1/x) d\log Q^2$ for the total ν-nucleon interaction at neutrino laboratory energies of $E_\nu = 10^{11}$ GeV (left plot) and $E_\nu = 10^7$ GeV (right plot). The 20 contours enclose contributions of 5, 10, 15 $\cdots$ 100 % of the cross section. The saturation scale according to the model in [302] is shown as a dashed line. See the text for further explanation.

τ neutrinos reach the Earth, despite being heavily suppressed in most postulated production mechanisms. The possibility to search for ν_τ's by looking for τ leptons that exit the Earth, Earth-skimming neutrinos, has been shown to be particularly advantageous to detect neutrinos of energies in the EeV (10^{18} eV) range [531]. The short lifetime of a τ lepton originating a neutrino charged current interaction allows the τ to decay in flight while still close to the Earth's surface, producing an outgoing air shower, detectable in principle by various techniques. This channel suffers from negligible contamination for other neutrino flavors. The sensitivity to ν_τ's through the Earth-skimming channel directly depends both on the neutrino charged current cross section and on the τ range (the energy loss) which is determined by the amount of matter with which the neutrino has to interact to produce an emerging τ. It turns out that the τ energy loss is also determined by the behavior of the proton and nucleus structure functions at very small values of x, see e.g. [532]. The average energy loss per unit depth, X, is conveniently represented by:

$$-\left\langle \frac{dE}{dX} \right\rangle = a(E) + b(E)E, \quad b(E) = \frac{N_A}{A} \int dy\, y \int dQ^2 \frac{d\sigma^{lA}}{dQ^2 dy} \ , \tag{6.20}$$

where the $a(E)$ term is due to ionization, $b(E)$ is the sum of fractional losses due to e^+e^- pair production, Bremsstrahlung and photonuclear interactions, N_A is Avogadro's number and A is the mass number. The parameter $a(E)$ is nearly constant and the term $b(E)E$ dominates the energy loss above a critical energy that for τ leptons is a few TeV, with the photonuclear interaction being dominant for τ energies exceeding $E = 10^7$ GeV (as already assumed in Eq. (6.20)). In Fig. 6.50 the relative contribution to $b(E)$ of different x and Q^2 regions is shown. It can be observed that the energy loss is dominated by very small x and, in contrast to the case of the neutrino cross section, by small and moderate $Q^2 \lesssim m_\tau^2$.

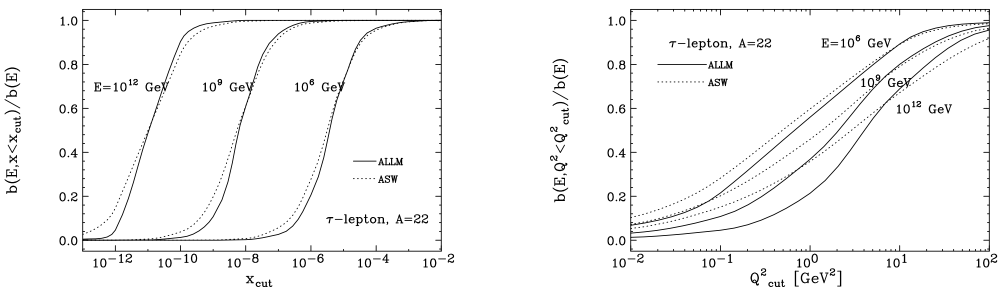


Figure 6.50: The relative contribution of $x < x_{cut}$ (plot on the left) and of $Q^2 < Q^2_{cut}$ (plot on the right) to the photonuclear energy loss rate, $b(E)$, for different neutrino energies $E = 10^6$, 10^9 and 10^{12} GeV, in two different models for the extrapolation of structure functions to very small x. See the text and [532] - from which these plots were taken - for explanations.

As the LHeC will be able to explore a new regime of low x and high Q^2 and constrain the parton distributions, the measurements performed at this collider will be invaluable for the precise evaluation of the neutrino-nucleon (or nucleus) scattering cross sections and τ energy loss necessary for ultra-high energy neutrino astronomy.

Part III

Accelerator

Chapter 7

Ring-Ring Collider

7.1 Baseline Parameters and Configuration

7.2 Geometry

All lattice descriptions in this chapter are based on the LHeC lattice Version 1.1.

7.2.1 General Layout

The general layout of the LHeC consists of eight arcs, six straight sections and two bypasses. The e-p collision experiment is located in Point 2, which is also the only interaction point of the beams. All straight sections except the straight sections in the bypasses have the same length as the LHC straight sections: 538.8 m at even points and 537.8 m at odd points.

The insertions shared with the LHC are already used for the experiments or for LHC equipement. Therefore the RF for the electron ring is installed in the straight sections of the bypasses [?]. Out of the same reason the beam is injected in the bypass around Point 1. Point 1 is preferred over Point 5 out of geological and infrastructural reasons. The overall layout of the LHeC is shown in Fig. 7.1.

7.2.2 Electron Ring Circumference

The LHeC electron beam collides only in one point (Point 2) with the protons of the LHC. This leaves the options to either exactly match the circumferences of the proton and electron rings or to allow a difference of a multiple of the LHC bunch spacing. In the case of different circumferences the proton beam could become unstable due to beam-beam interactions with the electrons [533]. To avoid this possible effect in the LHeC, the electron ring circumference is matched exactly to the proton ring circumference.

The adjustment of the circumference can principally be achieved in two different ways:

1. Different bypass designs, e.g. inner and outer bypass, which compensate each other in length.

2. Radial displacement of the electron ring to the inside or outside of the LHC in the places where the two rings share the same tunnel to compensate for the path length difference caused by the bypasses.

The different design possibilities for the bypasses are discussed in Sec. 7.2.4. Considering the different bypass options and their characteristics, the best choice seems to be outer bypasses around both experiments.

7.2.3 Idealized Ring

In the following the average between LHC beam 1 and beam 2 is taken as reference for the LHC.

General Layout

To compensate the path length difference from the bypasses, the electron ring is placed in average 61 cm to the inside of the LHC in the sections where both rings share the tunnel. For this a complete ring with an ideally constant radial offset of 61 cm to the LHC was designed. In the following we refer to this ring as the *Idealized Ring*.

In addition to the horizontal displacement, the electron ring is set 1 m above the LHC in order to minimize the interference with the LHC elements. The main remaining conflict in the arc are then the service modules as shown in Fig. 7.11.1 and the DFBs in the insertions [**?**]. A representative cross section of the LHC tunnel is shown in Fig. 7.2.

In the main arcs the service modules have a length of 6.62 m and are installed at the beginning of each LHC arc cell. The insertions host a different number of DFBs with a varying placement and length. The idealized ring lattice is optimized in a way to avoid all service modules in the main arcs. In order to show that it is possible to design an optics with no e-ring elements at all DFB positions in the insertions, the dispersion suppressor of the even respectively odd insertions was adapted to the DFB positions and lengths in IR2 respectively IR3. For simplicity all straight sections are filled with a regular FODO cell structure.

Geometry

To adjust the beam optics to the regular reappearance of the service modules at the beginning of each LHC arc cell it is suggested to use a multiple or $1/n$th, $n \in \mathbb{N}$, of the LHC arc cell length as LHeC FODO cell length. Beside the integration constraints, the cell has to provide the right emittance. Taking half the LHC arc cell length as LHeC FODO cell length already fulfils this second criterion (Sec. 7.3.1).

As the LHC arc cell is symmetric, the best geometrical agreement with the LHC main arc would be achieved, if the LHeC cell had as well a symmetrical layout. Because of the service modules, no elements can be placed in the first approx. 6.9 m of two consecutive cells. If all cells would have the same layout, another 6.9 m would be lost in the second FODO cell. This would result in additional and therefore unwanted synchrotron radiation losses as the energy loss in a dipole magnet is proportional to the inverse length of the dipole

$$U_{\text{dipole}} = \frac{C_\gamma}{2\pi} E_0^4 \frac{\theta^2}{l} \ , \ C_\gamma = \frac{4\pi}{3} \frac{r_e}{(m_e c^2)^3} \tag{7.1}$$

where θ is the bending angle, l the length of the dipole and E_0 the beam energy. In order to avoid this, the LHeC arc cell is a double FODO cell, symmetric in the positioning of the quadrupoles but asymmetric in the placement of the dipoles (Fig. 7.3).

The bending angle in the arc cells and also in the DS is determined by the LHC geometry. In the following we refer to the LHC DS as the section from the end of the arc to the beginning of the LSS. With this definition the LHC DS consists of two cells. Keeping the same converting rule as in the arc (one LHC FODO cell corresponds to two LHeC FODO cells), the LHeC DS would then ideally consist of 4 equal cells. Consistently the ratio between the LHeC DS and arc cell is the same as between the LHC DS and arc cell. For the LHC this ratio is 2/3. This leaves the following choices for the number of dipoles in the arc and DS cell:

$$N_{\text{Dipole, arc cell}} = \frac{3}{2} N_{\text{Dipole, DS cell}} = 3, 6, 9, 12, 15 \ \ldots \tag{7.2}$$

A good compromise between a reasonable dipole length and an optimal usage of the available space for the bending are 15 dipoles per arc cell. The dipoles are then split up in packages of $3+4+4+4$ in one arc cell and $2+3$ in one DS cell.

Beside the bending angle also the module length of the electron ring has to be matched to the LHC geometry. As the electron ring is radially displaced to the inside of the proton ring all e-ring modules are shorter 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

The above considerations already fix the bending angle of the dipoles, which leaves only position and length as free parameters. Ideally the dipole length would be chosen as long as possible, but due to the asymmetry of the arc cell, the dipoles have to be shortened and moved to the right in order to fit the LHC geometry.

The LHeC DS layout would ideally be similar to the LHC DS layout (Fig. 7.4), but has to be modified in order to leave space for the DFBs in the DS region. In the final design the dipoles are placed as symmetrically as possible between the regular arrangement of the quadrupoles (Fig. 7.5, 7.6). The difference between the LHC proton ring and the idealized LHeC electron ring is shown in Fig. 7.7 and 7.8.

7.2.4 Different Bypass Options

In the design of the e-ring geometry it is foreseen to bypass the LHC experiments at Point 1 and Point 5. The main requirements for both bypasses are, that all integration constraints are respected, synchrotron radiation losses are not considerably increased and that the change in circumference can be compensated by the reduction or increase of the radius of the ring.

Three different options are considered as basic bypass designs:

Vertical Bypass: A vertical bypass would have to be a vertically upward bypass as downward would imply to cross the LHC magnets and other elements. For this a separation of about 20 to 25 m is required [534]. This can only be achieved by strong additional vertical bending. In general a vertical bypass would therefore be rather long, increase the synchrotron radiation due to the additional vertical bends and decrease the polarization compared to a horizontal bypass. A vertical bypasses is therefore only considered as an option, if horizontal bypasses are not possible.

Horizontal Inner Bypass: A horizontal inner bypass can be constructed by simply decreasing the bending radius of the main bends. Consequently the synchrotron radiation losses for an inner bypass are larger than for a comparable outer bypass. The advantage of an inner bypass is, if used in combination with an outer one, that it reduces the circumference and the two bypasses could compensate each others path length differences.

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.

7.2.5 Bypass Point 1

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 Fig. 7.9.

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 Fig. 7.10.

7.2.6 Bypasses Point 5

Due to the compact design of the cavern in Point 5 a separation of only approx. 20 m is needed to completely bypass the experiment on the outside (Fig. 7.11). 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 center straight section parallel to the proton ring.

7.2.7 Matching Proton and Electron Ring Circumference

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 idealized ring (Sec. 7.2.3) in front of the last two arc cells. The separation Δ_{BP}, the remaining angel θ_{BP} and the inserted straight section s_{BP} are related by (Fig. 7.12):

$$\Delta_{\mathrm{BP}} = s_{\mathrm{BP}} \sin\theta_{\mathrm{BP}} \tag{7.3}$$

As indicated in Fig. 7.12 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.

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:

$$\Delta s_{\mathrm{BP}} = s_{\mathrm{BP}} - x_{\mathrm{BP}} = 2\Delta_{\mathrm{BP}} \tan\left(\frac{\theta_{\mathrm{BP}}}{2}\right) \tag{7.4}$$

This change can be compensated by a change of radius of the idealized ring by:

$$\Delta s_{\mathrm{BP}} = 2\pi\Delta R \tag{7.5}$$

Taking the change in radius into account, the separation Δ_{BP} has to be substituted by $\Delta_{\mathrm{BP}} + \Delta R =: \Delta_{\mathrm{BP,tot}}$. The radius change and the total separation are then related by:

$$\Delta R = \frac{\Delta_{\mathrm{BP}}}{\pi \cot\left(\frac{\theta_{\mathrm{BP}}}{2}\right) - 2}\ , \quad \text{with } \Delta_{\mathrm{BP}} = \Delta_{\mathrm{BP1}} + \Delta_{\mathrm{BP5}} \tag{7.6}$$

As the bypass in Point 1 passes through the existing survey gallery, the geometry and with it the separation in Point 1 can not be changed. The bypass in Point 5 however is fully decoupled from the existing LHC cavern and tunnel and is therfore used for the fine adjustment of the circumference. The design values of both bypasses are summarized 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 idealized ring	61 cm	

Table 7.2: Bypass Figures

7.3 Layout and Optics

Throughout the whole electron ring lattice, the choice of the optics is strongly influenced by the geometrical constraints and shortage of space in the LHC tunnel. The main interference with the LHC beside Point 1 and Point 5, which have to be bypassed, are the service modules and DFBs in the tunnel, where no electron ring elements can be placed.

7.3.1 Arc Cell Layout and Optics

The LHC service modules are placed at the beginning of each LHC main arc cell. In order to obtain a periodic solution of the lattice, the electron ring arc cell length can only be a multiple or $1/n$th, $n \in \mathsf{N}$, of the LHC FODO cell length. In general the emittance increases with increasing cell length L in a FODO cell assuming the same phase advance and bending radius. In the case of the LHeC electron ring a FODO cell length corresponding to half the LHC FODO cell length delivers an emittance close to the design value. The emittance of a cell with the full LHC FODO cell length is at least by approx. a factor of 4 too large. Choosing half the LHC FODO cell length divides the arc into 23 equal double FODO cells with a symmetric configuration of the quadrupoles and an asymmetric distribution of the dipoles, precisely 8 dipoles in the first FODO cell and 7 in the second. The dipole configuration is asymmetric in order to use all available space for the bending of the e-beam and consequently minimize the synchrotron radiation losses. With a phase advance of 180° horizontally and 120° vertically over the complete double FODO cell, which corresponds to a phase advance of 90°/60° per FODO cell, the horizontal emittance lies with 4.70 nm well below the design value of 5 nm. Because of the asymmetry of the dipole configuration, the phase advance in the horizontal plane is also not equally distributed. In the first half it is with 90.6°/60° slightly larger than in the second half with 89.4°/60°. The optics of one arc cell is shown in Fig. 7.3 and the parameters listed in Table 7.3.

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°.

7.3.2 Insertion Layout and Optics

For simplicity all even and all odd insertions of the electron ring have the same layout as described in Sec. 7.2.1. Each insertion is divided in three parts: the dispersion suppressor on the left side (DSL), the straight section and the dispersion suppressor on the right side (DSR).

Dispersion Suppressor

Different well known standard DS designs like the missing bend or half bend scheme exist, but they are all based on specific placement of the dipoles. In the case of the LHeC the position of the dipoles is strongly determined by the LHC geometry and does not match any of the standard schemes. Therefore the matching has to be done with individual quadrupoles slightly supported by the position of the dipoles. Each DS contains 8 matching quadrupoles. The DS on the left side is split into two DS sections, reaching from the first DFB to the second and from the second to the beginning of the straight section. In the DSL the quadrupoles are distributed equally in each section. In the DSR they are placed with equal distances from each other throughout the complete DS. This layout turned out to be better for the right side due to the different arrangement of the DFBs. The DS of the even and odd points differ slightly in their length but have in general the same layout. The length of the DS is listed in Table 7.1. The DS optics are shown in Fig. 7.5 and 7.6.

Straight Section

For simplicity the straight sections consist of a regular FODO lattice with a phase advance of 90°/60°. In a later stage the lattice and optics of the straight sections will have to be adjusted to the different insertions.

7.3.3 Bypass Layout and Optics

The general layout and nomenclature of the bypasses is illustrated in Fig. 7.13. The straight sections LSSL, LSSR and IR are dispersion free sections reserved for the installation of RF, wiggler(s), injection etc. Two normal arc cells (4 FODO cells) with 8 individual quadrupoles are used as dispersion suppressor before the fist straight section LSSL and after the last straight section LSSR. In the sections TLIR and TRIR the same configuration of dipoles is kept as in the idealized lattice due to geomteric reasons. Between this fixed arrangement of dipoles 14 matching quadrupoles per side are placed as equally as possible.

The straight sections consist of a regular FODO lattice with a phase advance of 90°/60°.

The complete bypass optics in Point 1 and Point 5 are shown in Fig. 7.14 and 7.15.

7.3.4 Chromaticity Correction

The phase advance of one LHeC FODO cell is approximately 90°/60°. The traditional choice would be to correct the chromaticity with two interleaved families in the horizontal and three in the vertical plane, but this scheme leads to one strong and one weak sextupole in the horizontal plane, which is undesirable for the suppression of resonances. An interleaved scheme with 6 sextupoles yields to approximately similar strength for all sextupoles and shall therefore lead to more stability. More detailed studies have to be carried out to find the best correction scheme, but in general chromaticity correction will most probable not be a problem in this machine.

7.3.5 Working Point

Due to the bypasses and the single interaction region, the LHeC lattice has a symmetry of one. As 50% coupling are assumed also coupling resonances can be excited and must be taken into account for the choice of the working point. In addition the beam will suffer a maximal beam-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 in the horizontal and 0.090 in the vertical plane in the case of the 10° option. Taking all this into account, a possible working point could be $Q_x = 122.1/Q_y = 83.13$ for the 1° optics and $Q_x = 122.1011/Q_y = 83.1283$ for the 10° optics. The working point diagrams for both cases are shown in Fig. 7.16 and 7.17.

7.3.6 Aperture

The current LHeC e-ring magnet apertures [?] are based on the experience from LEP [?] applied 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 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. in the insertion quadrupoles. In the estimate all insertions were included except the interaction region. All values are summarized in Table 7.4, 7.5, 7.6, 7.7. The hor. aperture in the insertion dipoles could be slightly to tight, but can be probably extended without problems over the current 20 mm half aperture. In all calculations a gaussian profile in all three dimensions was assumed and the maximum beam size is consequently given by:

$$\sigma_{x,y} = \sqrt{\beta_{x,y}\epsilon_{x,y} + D_{x,y}^2\sigma_E^2} \tag{7.7}$$

where $\epsilon_{x,y}$ are the design emittances of 5 respectively 2.5 nm.

Hor. Half Apert. Dip.	30 mm
Ver. Half Apert. Dip.	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

7.3.7 Complete Lattice and Optics

Combining all the lattice parts discussed in section 7.3.1 to 7.3.3 one obtains a lattice with the parameters listed in Table 7.8

Beam Energy	60 GeV
Numb. of Part. per Bunch	1.98×10^{10}
Numb. 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

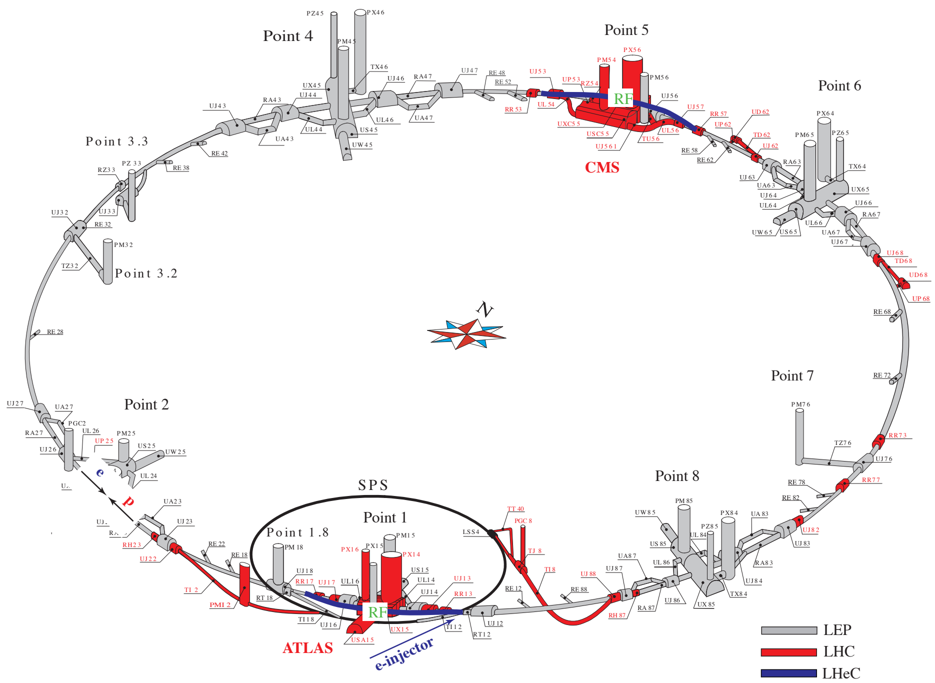


Figure 7.1: Schematic Layout of the LHeC: In grey the LEP tunnel now used for the LHC, in red the LHC extensions. The two LHeC bypasses are shown in blue. The RF is installed in the central straight section of the two bypasses. The bypass around Point 1 hosts in addition the injection.

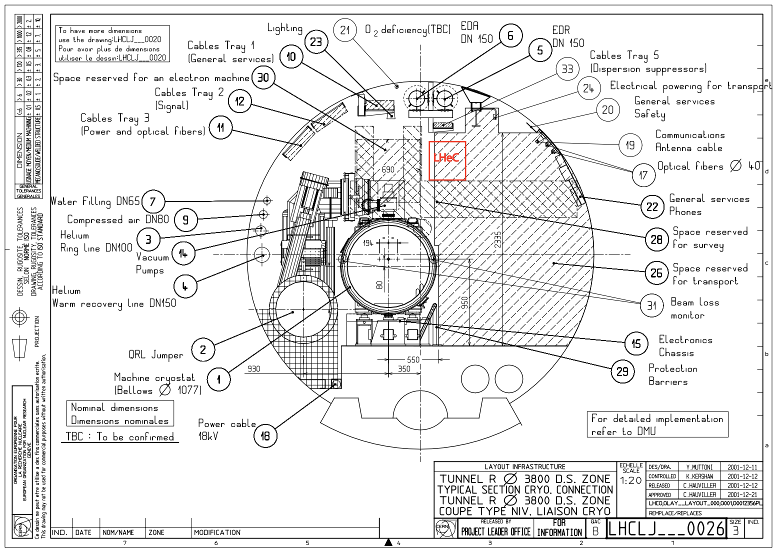


Figure 7.2: Representative cross section of the LHC tunnel. The location of the electron ring is indicated in red.

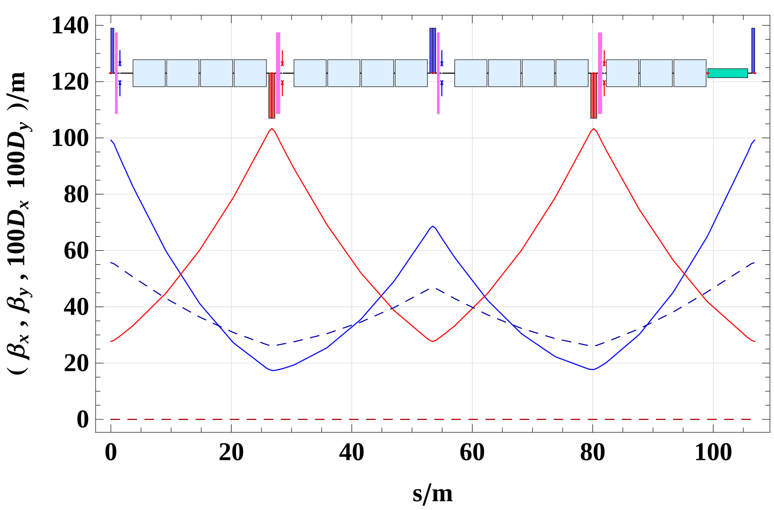


Figure 7.3: Electron ring arc cell optics. One arc cell consists of two FODO cells symmetric in the placement of the quadrupoles and asymmetric for the dipoles.

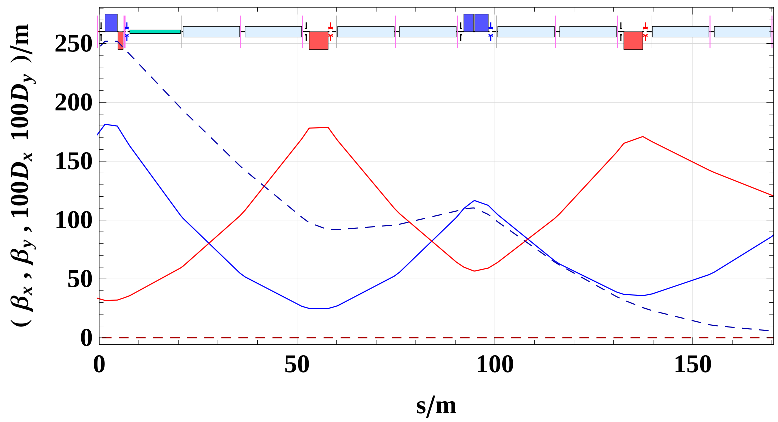


Figure 7.4: LHC DS on the left side of IP2.

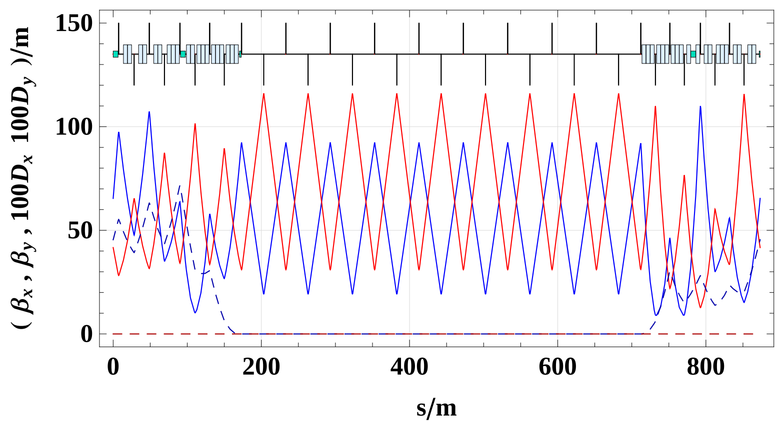


Figure 7.5: LHeC IR for even IRs, based on the DFB configuration in Point 2.

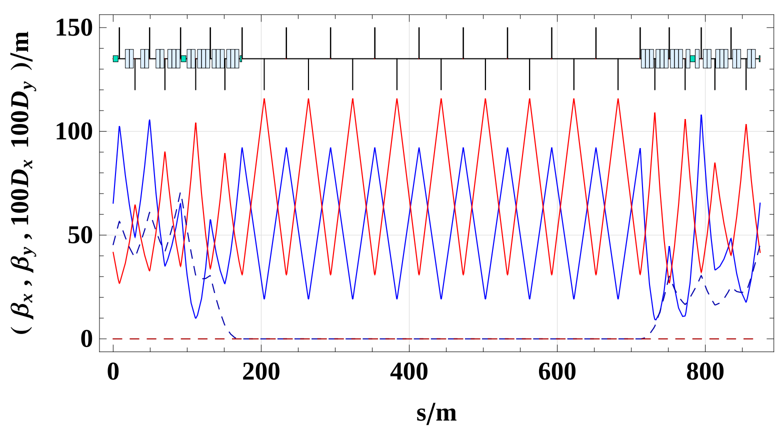


Figure 7.6: LHeC IR for odd IRs, based on the DFB configuration in Point 3.

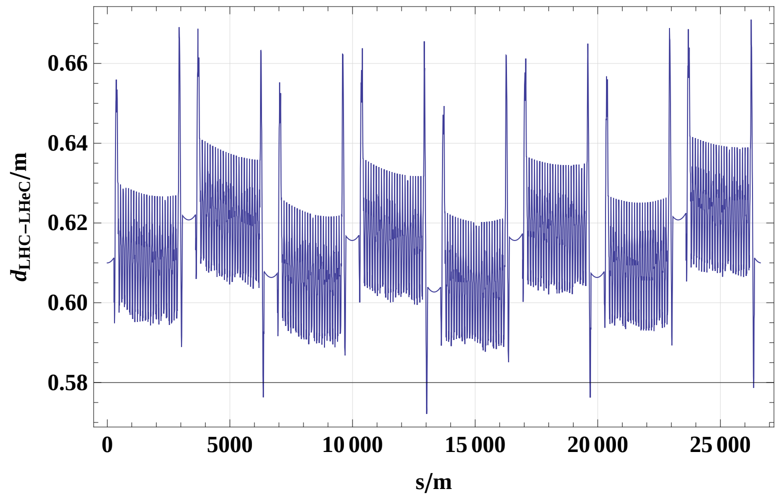


Figure 7.7: Radial distance between the idealized electron ring and the proton ring

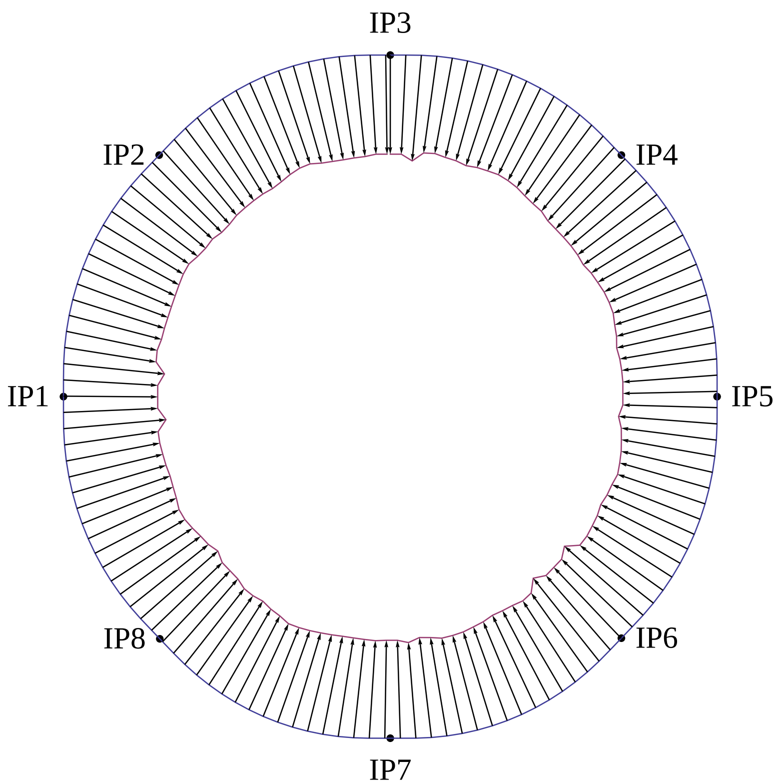


Figure 7.8: LHC and LHeC. The distance between the two rings is exaggerated by a factor 2000.

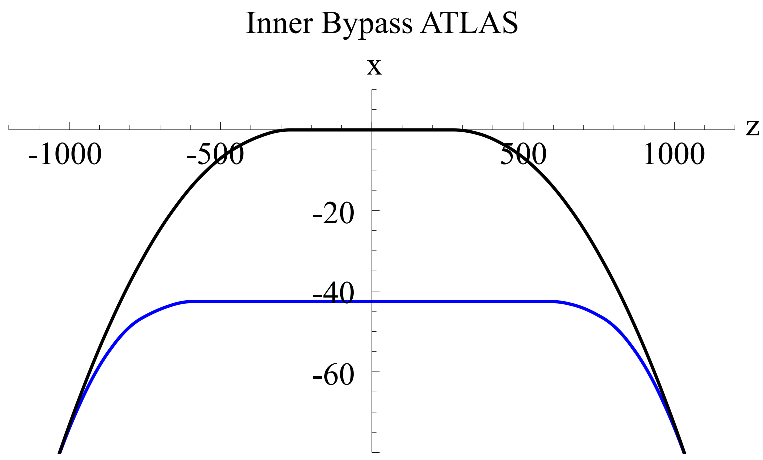


Figure 7.9: Example of an inner Bypass around Point 1. The Bypass is shown in blue, The LHC proton ring in black.

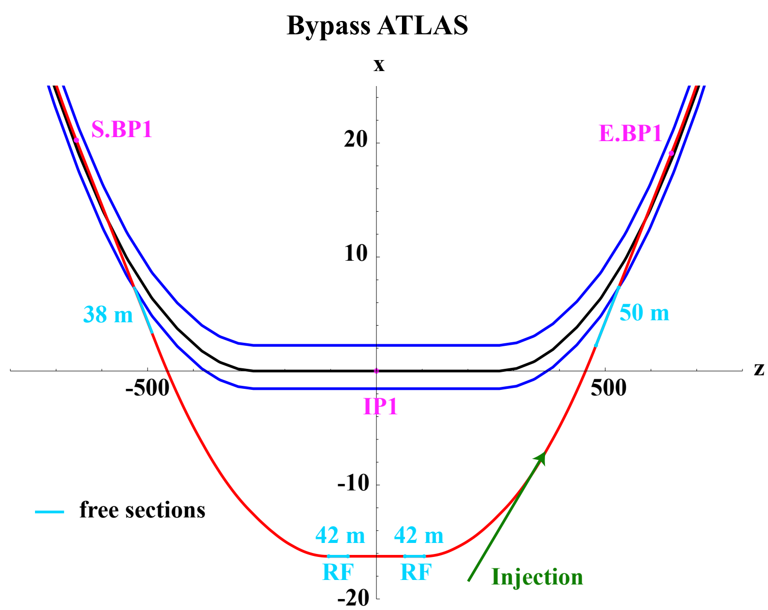


Figure 7.10: Final bypass design using the survey gallery in Point 1. The LHC proton ring is shown in black, the electron ring in red and the tunnel walls in blue. Dispersion free sections reserved for the installation of RF, wiggler(s), injection and other equipment are marked in light blue. The injection 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

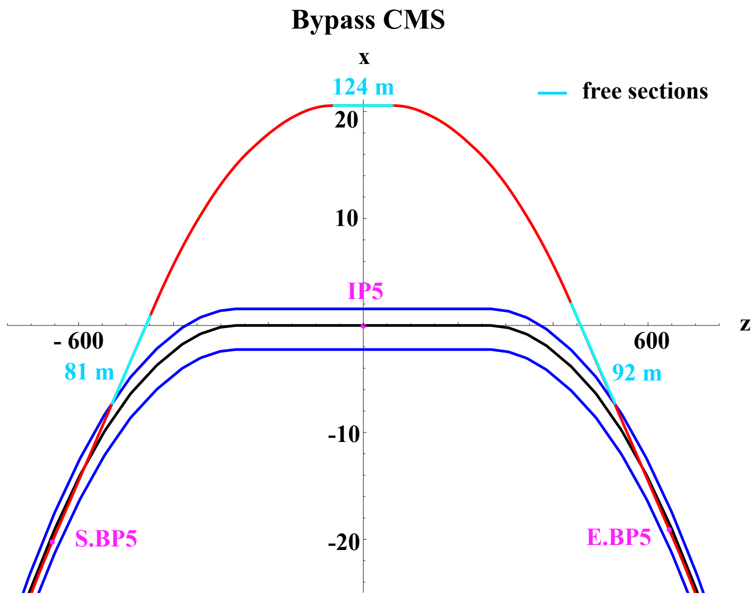


Figure 7.11: Horizontal outer bypass in Point 5. The LHC proton ring is shown in black, the electron ring in red and the tunnel walls in blue. Dispersion free sections reserved for the installation of RF, wiggler(s), injection and other equipment are marked in light blue. Beginning and end of the bypass are marked with S.BP5 and E.BP5

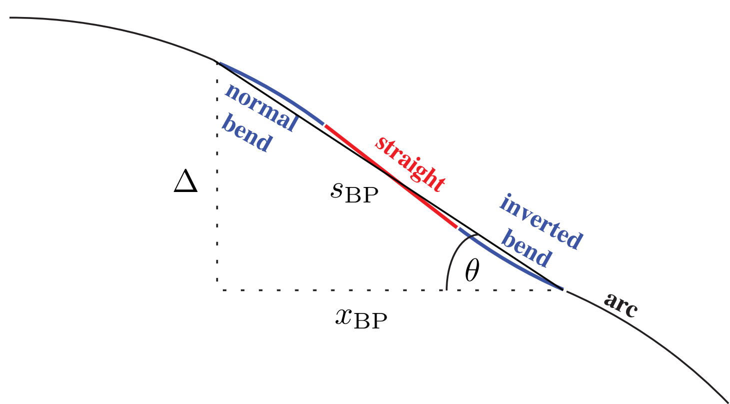


Figure 7.12: Outer bypass: a straight section is inserted to obtain the required separation. A larger separation could be achieved by inserting inverted bends.

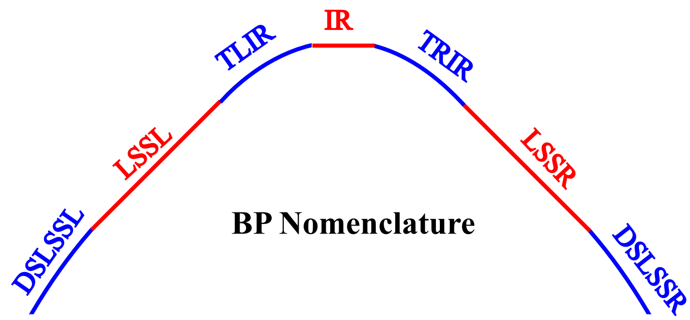


Figure 7.13: Bypass layout and nomenclature.

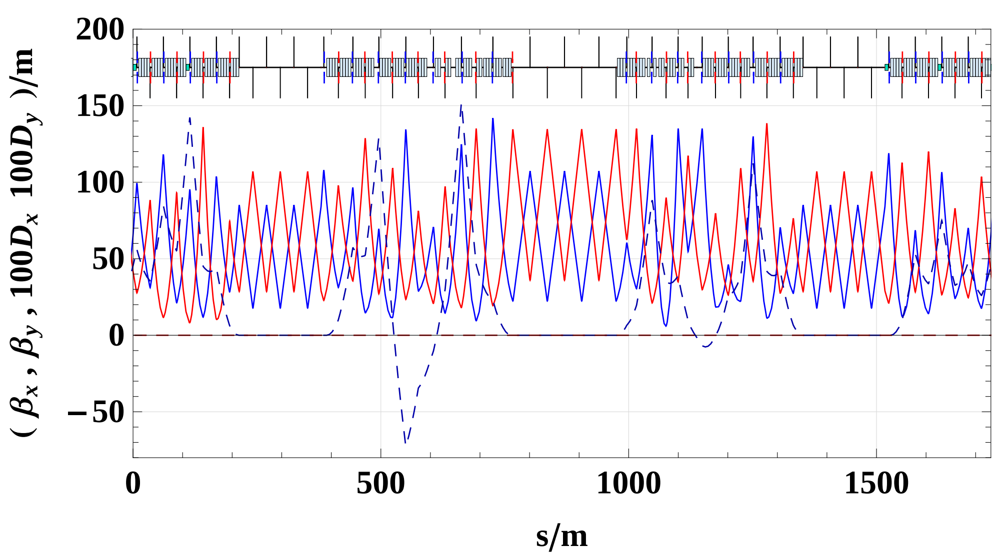


Figure 7.14: Bypass optics Point 1.

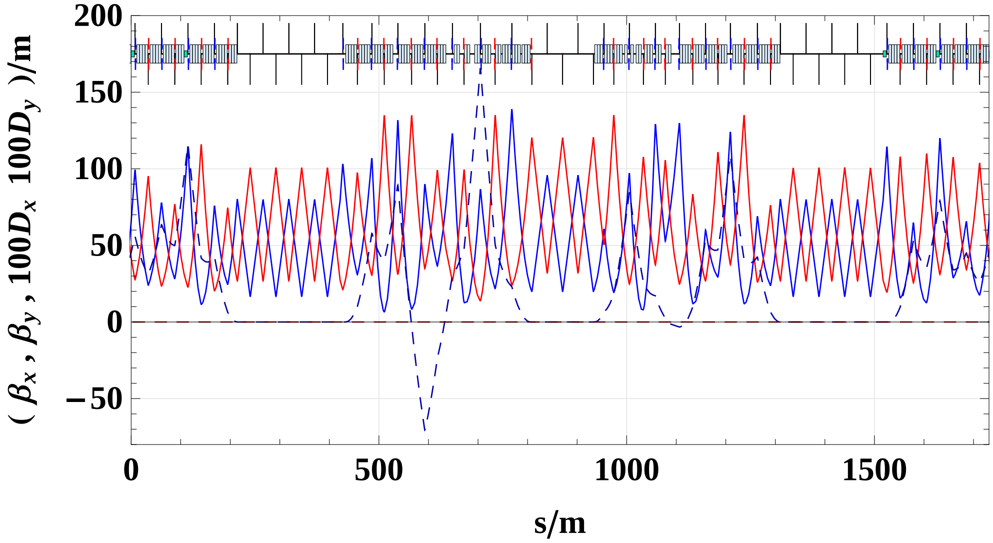


Figure 7.15: Bypass Optics Point 5.

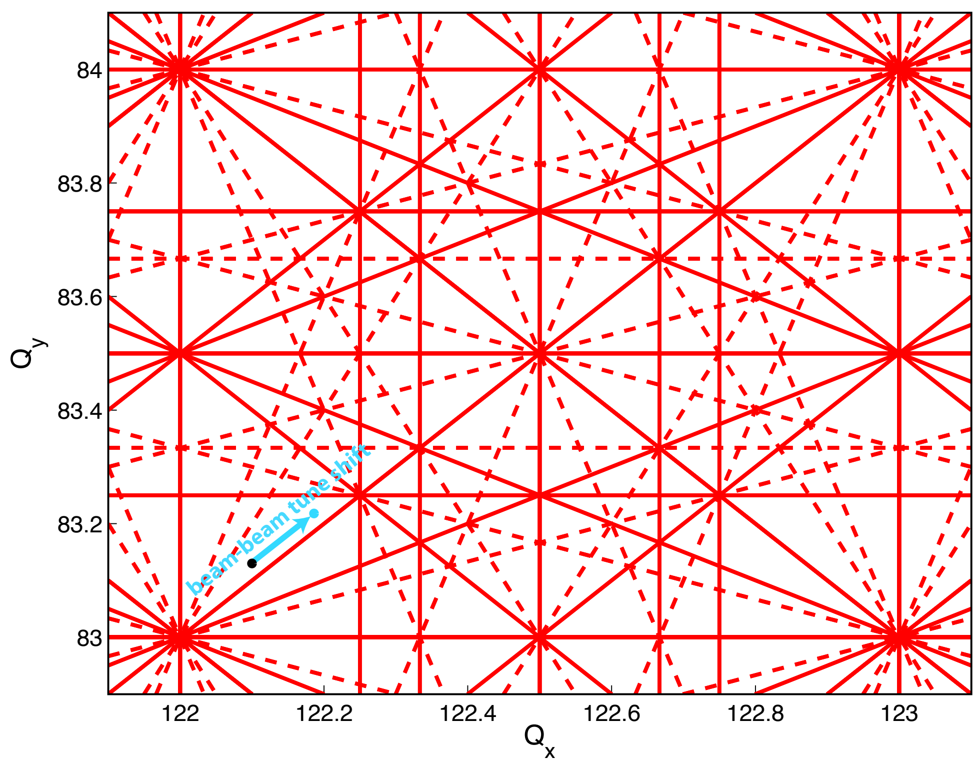


Figure 7.16: Working Point for the 1° optics. The dashed lines are the coupling resonances up to 4th order, the solid lines the constructive resonances up to 4th order. The black dot indicates the working point without beam-beam tune shift and the blue one with beam-beam tune shift.

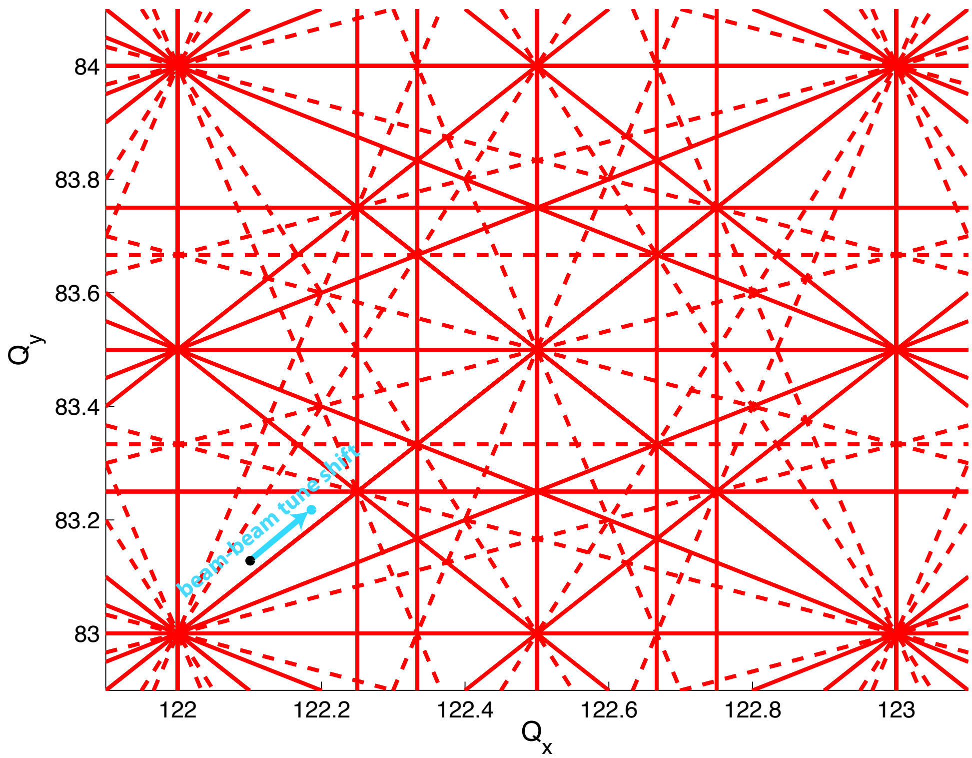


Figure 7.17: Working Point for the 10° optics. The dashed lines are the coupling resonances up to 4th order, the solid lines the constructive resonances up to 4th order. The black dot indicates the working point without beam-beam tune shift and the blue one with beam-beam tune shift.

7.4 Layout

The design of the Interaction Region (IR) of the LHeC is particularly challenging as it has to consider boundary conditions from

- The lattice design and beam optics of the electron and proton beam
- The geometry of the LHC experimental cavern and the tunnel
- The beam separation scheme which is determined by the bunch pattern of the LHC standard proton operation and related to this the optimisation of the synchrotron light emission and collimation
- The technical feasibility of the hardware.

Therefore the IR has to be optimised with respect to a well matched beam optics that adapts the optical parameters from the new electron-proton interaction point to the standard LHC proton beam optics in the arc and to the newly established beam optics of the electron ring. At the same time the two colliding beams as well as the non-colliding proton beam of LHC have to be separated efficiently and guided into their corresponding magnet lattices. As a general rule that has been established in the context of this study any modification in the standard LHC lattice and any impact on the LHC proton beam parameters had to be chosen moderately to avoid detrimental effects on the performance of the LHC proton-proton operation.

The layout and parameters of the new e/p interaction point are defined by the particle physics reqirements. At present the physics programme that has been proposed for the LHeC [?] follows two themes - a high luminosity, high Q^2 programme requiring a forward and backward detector acceptance of around 10° and a low x, low Q^2 programme, which requires an increased detector acceptance in forward and backward direction of at least 1° and could proceed with reduced luminosity. Accordingly two machine scenarios have been studied for the interaction region design. Firstly, a design that has been optimised for high luminosity with an acceptance of 10° and secondly, a high acceptance design that allows for a smaller opening angle of the detector. In both cases the goal for the machine luminosity is in the range of $10^{33}\,\mathrm{cm}^{-1}\,\mathrm{s}^{-1}$ but the layouts differs in the magnet lattice, the achievable absolute luminosity and mainly the synchrotron radiation that is emitted during the beam separation process. Both options will be presented here in detail and the corresponding design luminosity, the technical requirements and the synchrotron radiation load will be compared. In both cases however, a well matched spot size of the electron and proton beam had to be established at the collision point: Experience in SPS and HERA [?], [?] showed that matched beam cross sections have to be established between the two colliding beams to guarantee stable beam conditions. Considering the different nature of the beams, namely the emittances of the electron beam in the two transverse planes, the interaction region design has to consider this boundary condition and the beam optics has to be established to achieve equal beam sizes $\sigma_x(p) = \sigma_x(e)$, $\sigma_y(p) = \sigma_y(e)$ at the IP.

The basic beam parameters however like energy, particle intensity and beam emittances are identical for both designs, determined by the electron and proton ring lattices and the pre-accelerators. They are summarised in Table 7.9.

Colliding two beams of different characteristics, the luminosity obtained is given by the equation

$$L = \sum_{i=1}^{n_b} (I_e * I_p) \frac{1}{e^2 f_0 2\pi \sqrt{\sigma_{xp}^2 + \sigma_{xe}^2}\sqrt{\sigma_{yp}^2 + \sigma_{ye}^2}}, \tag{7.8}$$

Table 7.9: Main parameters for e/p collisions.

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	

where $\sigma_{x,y}$ denotes the beam size of the electron and proton beam in the horizontal and vertical plane and I_e, I_p the electron and proton single bunch currents. In all IR layouts the electron beam size at the IP is matched to the proton beam size in order to optimise the delivered luminosity and minimise detrimental beam beam effects.

The main difference of the IR design for the electron proton collisions with respect to the existing LHC interaction regions is the fact that the two beams of LHeC cannot be focussed and / or guided at the same time: The different nature of the two beams, the fact that the electrons emit synchrotron radiation 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 7.18 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 combind in a very compact lattice structure, which is the prerequisite to achieve luminosity values in the range of 10^{33} cm $^{-2}$ 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 = 22m 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 = 3.75m, as the

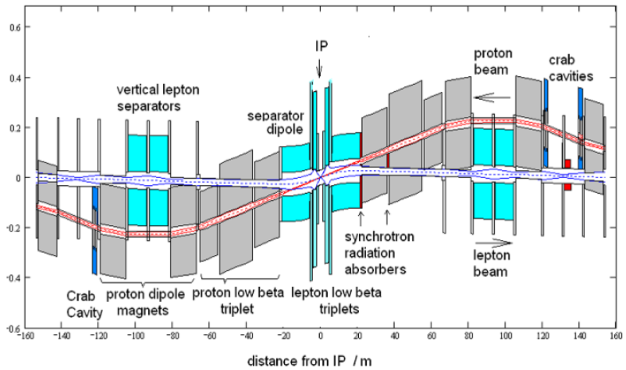


Figure 7.18: Schematic layout of the LHeC interaction region

nominal bunch distance in LHC corresponds to $\Delta t = 25ns$. 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 m) a minimum separation of $\Delta x = 55$mm is needed to guide the electron beam along the mirror plate of a sc. proton half quadrupole [?]. A first layout of this magnet is sketched in figure 7.19

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 $\rho = 6757m$ for the 10 degree option. In the case of the 1 degree option the quadrupole lenses of the electron lattice cannot be included inside the detector design as the opening angle of the detector does not provide enough space for the hardware of the electron ring lattice. Therefore a much larger distance between the IP and the location of the first electron lens had to be chosen (Δ s =6.2m instead of Δ s =1.2m). As a consequence - in order to achieve the same overall beam separation - stronger magnetic separation fields have to be applied resulting in a bending radius of $\rho = 4057m$ in this case. In both cases the position of the electron quadrupoles is following the design orbit of the electron beam to avoid local strong bending fields and keep the synchrotron radiation power to a minimum. This technique has already been succesfuly applied at the layout of the HERA electron-proton collider [?].

Still the separation at the location of the first proton magnet is small and a half quadrupole design for this super conducting magnet has been chosen at this point. The resulting beam

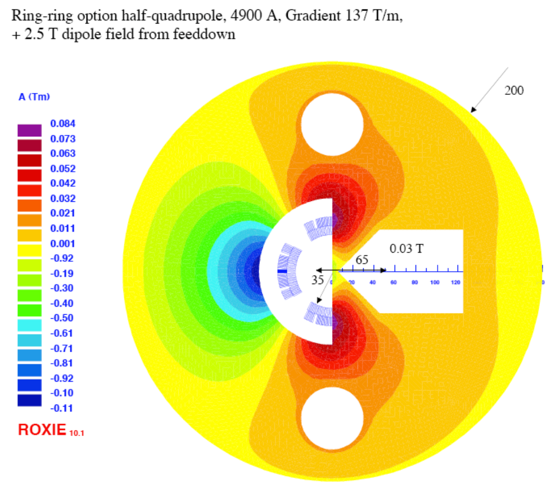


Figure 7.19: Super conducting half quadrupole in the proton lattice: The electron beam will pass on the right hand side of the mirror plate in a quasi field free region [?].

parameters - including the expected luminosity for this ring ring option - are summarised in Table 2.

It has to be pointed out in this context that the arrangement of the off centre quadrupoles as well as the strength of the separator dipole depend on the beam optics of the electron beam. The beam size at the parasitic crossings and at the proton quadrupole will determine the required horizontal distance between the electron and proton bunches. The strength and position of these magnets however will determine the optical parameters, including the dispersion function that is created during the separation process itself. Therefore a self-consistent layout concerning optics, beam separation and geometry of the synchrotron light absorbers has to be found.

It is obvious that these boundary conditions have to be fulfilled not only during luminosity operation of the e/p rings. During injection and the complete acceleration procedure of the electron ring the influence of the electron quadrupoles on the proton beam has to be compensated with respect to the proton beam orbit (as a result of the separation fields) as well as to the proton beam optics: The changing deflecting fields and gradients of the electron magnets will require correction procedures in the proton lattice that will compensate this influence at any moment.

7.4.2 Crossing Angle

A central aspect of the LHeC IR design is the beam-beam interaction of the colliding elecron 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 Δt =25 ns or Δ s=7.5 m. The counter rotating bunches therefore meet after the

Table 7.10: Parameters of the mini beta optics for the 1° and 10° options of the LHeC Interaction Region.

Detector Option		1°		10°	
Quantity	unit	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	22
Crossing angle	mrad	1.0		1.0	
Synch. Rad. in IR	kW	51		33	
absolute Luminosity	m^{-2} s^{-1}	$8.54 * 10^{32}$		$1.8 * 10^{33}$	
Loss-Factor S		0.86		0.75	
effective Luminosity	m^{-2} s^{-1}	$7.33 * 10^{32}$		$1.34 * 10^{33}$	

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 7.20 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,

$$\beta(s) = \beta^* + \frac{s^2}{\beta^*}, \tag{7.9}$$

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 the required strength in the separation magnets and minimise the synchrotron radiation power that is created inside the interaction region.

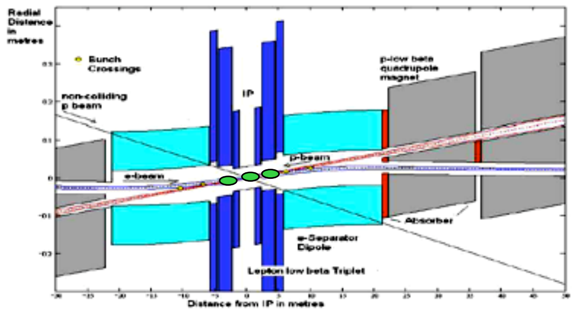


Figure 7.20: LHeC interaction region including the location of the first parasitic bunch encounters where a sufficient beam separation is achieved by a crossing angle of 1 mrad. The location of the parasitic encounters is indicated by green ovals.

As a draw back however the luminosity is reduced due to the fact that the bunches will not collide anymore head on. This reduction is expressed in a geometric luminosity reduction factor "S", that depends on the crossing angle θ, the length of the electron and proton bunches σ_{ze} and σ_{zp} and the transverse beam size in the plane of the bunch crossing σ_x^*:

$$S(\theta) = \left[1 + \left(\frac{\sigma_{sp}^2 + \sigma_{se}^2}{2\sigma_x^{*2}}\right) \tan^2 \frac{\theta}{2}\right]^{-\frac{1}{2}} \quad . \tag{7.10}$$

Accordingly, the effective luminosity that can be expected for a given IR layout is obtained by

$$L = S(\theta) * L_0 \tag{7.11}$$

For the two beam optics that have been chosen for this design study (the 1° and the 10° option) and a crossing angle of $\theta = 1$mrad the loss factor amounts to $S = 74\%$ and $S = 85\%$ respectively.

7.4.3 Beam Optics and Luminosity

A special boundary condition had to be observed in the design of the proton beam optics of the LHeC: For the layout of the four present proton-proton interaction regions in the LHC machine an anti-symmetric option had been chosen: A solution that is appropriate for a round beam optics ($\sigma_x{}^* = \sigma_y{}^*$). An optimised design for collisions with the flat $e^\pm$ beams however requires unequal β -functions for the hadron beam at the IP and the existing LHC optics can no longer be maintained. Therefore the optical layout of the existing triplet structure in the LHC had to be modified to match the required beta functions ($\beta_x = 1.8$m, $\beta_y = 0.5$m) at the IP to the regular optics of the FODO structure in the arc (Figure 7.21).

In the case of the electron beam optics, two different layouts of the interaction region are considered: One optical concept for highest achievable luminosity and a solution for maximum

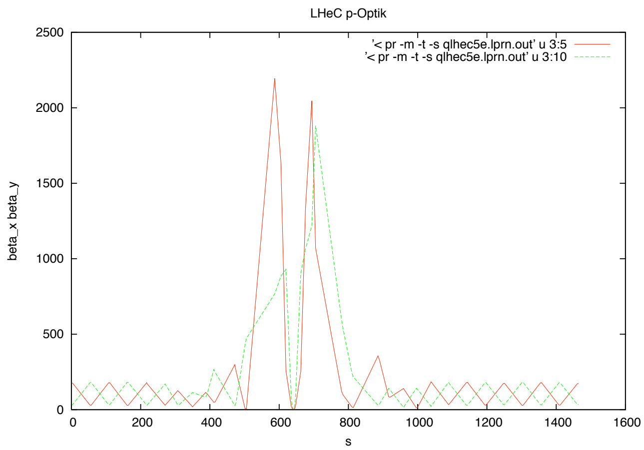


Figure 7.21: Proton optics for the LHeC interaction region. The gradients of the antisymmetric triplet lattice in the standard LHC have been modified to adopt for the requirements of the LHeC flat beam parameters.

detector acceptance. In the first case an opening angle of 10° is available inside the detector geometry and allows to install an embedded magnet structure where the first electron quadrupole lenses can be placed as close as s= 1.2m from the IP. This early focusing scheme leads to moderate values of the β function inside the mini beta quadrupoles and therefore allows for a smaller spot size at the IP and larger luminosity values can be achieved. Still however the quadrupoles require a compact design: While the gradients required by the optical solution are small (for a super conducting magnet design) the outer radius of the first electron quadrupole has been limited to $r_{max} = 210$mm.

In the case of the 1° option the detector design is optimised for largest detector acceptance. Accodingly the opening angle of the detector hardware is too small to deliver space for accelerator magnets. The mini beta quadrupoles therefore have to be located outside the detector, and a distance $s = 6$m from the IP had to be chosen in this case. Even if the magnet dimensions are not limited by the detector design in this case, the achievable luminosity is about a factor of two smaller than in the 10° case.

The two beam optics that are based on these considerations are discused in detail in the next chapter of this report. In the case of the 10° option a triplet structure has been chosen to allow for moderate values of the beta functions inside the mini beta quadrupoles. As a special feature of the optics that is shown in Figure 7.22 the focusing effect of the first quadrupole magnet is moderate: Its gradient has been limited as it has to deliver mainly the first beam separation. Table 7.10 includes as well the overall synchrotron radiation power that is produced inside the IR. Due to the larger bending radius (i.e. smaller bending forces) in the case of the 10° option the produced synchrotron radiation power is limited to about 30 kW, while the alternative - high acceptance - option has to handle 50kW of synchrotron light.

The details of the synchrotron light characteristics are covered in the next chapters of this

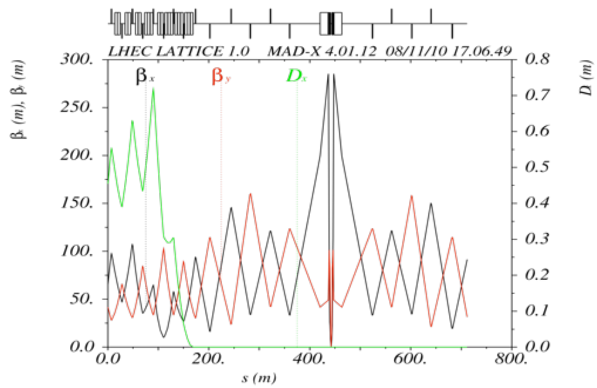


Figure 7.22: Electron optics for the LHeC interaction region. The plot corresponds to the 10 degree option where a triplet structure combined with a separation dipole has been chosen to separate the two beams.

report for both cases, including the critical energies and the design of the required absorbers.

For the 1° option the mini beta focusing is based on a quadrupole doublet as the space limitations in the transverse plane are much more relaxed compared to the alternative option and the main issue here was to find a compact design in the longitudinal coordinate: Due to the larger distcance of the focusing and separating magnets from the IP the magnet structure has to be more compact and the separating field stronger to obtain the required horizontal beam distance at the location s=22m of the first proton quadrupole. The corresponding beam optics for both options are explained in full detail below.

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7.5 Design Requirements of the Electron Beam Optics

7.5.1 Optics Matching and IR Geometry

Once the beams are separated into independent beam pipes, the electron beam must be transported into the ring lattice. Quadrupoles are used in the electron machine LSS to transport the beam from the IP to the dispersion suppressor and match twiss parameters at either end. This matching must be smooth and not require infeasible apertures. In addition the first electron quadrupoles will be located inside the detector hardware and therefore a compact design is required within the limited space available.

The complete design of the long straight section "LSS", that includes the mini beta insertion, the matching section and the dispersion suppressor must be designed around a number of further constraints. As well as beam separation, the electron beam must be steered from the electron ring into the IR and back out again. The colliding proton beam must be largely undisturbed by the electron beam. The non-colliding proton beam must be guided through the

IR without interacting with either of the other beams.

7.6 High Luminosity IR Layout

7.6.1 Parameters

Table 7.11 details the interaction point parameters and other parameters for this design. To optimise for luminosity, a small $l*$ is desired. An acceptance angle of 10° is therefore chosen, which gives an $l*$ of 1.2m 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.

SR calculations are detailed in section [NATHAN]. The total power emitted in the IR is similar to that in the HERA-2 IR [reference] and as such appears to be reasonable, given enough space for absorbers.

7.6.2 Layout

Due to the relatively round beam spot aspect ratio of 1.8:1, a final quadrupole triplet layout has been chosen for this design. The relatively weak horizontal focussing quadrupole used as first magnet lens is mainly needed for beam separation, followed by two strong, nearly doublet like quadrupoles. The focusing strength Figure 7.23 and table 7.12 detail the layout.

The $l*$ of 1.2 m allows both strong focusing of the beam, and constant bending of the beam from 1.2 m to 21.5 m. This is achieved with offset quadrupoles and a separation dipole.

Figure 7.24 shows the β functions of the beam in both planes from the IP to the face of the final proton quadrupole at s = 23 m.

7.6.3 Separation Scheme

As described above a quadrupole triplet configuration is used for the first focusing of the electron beam. This has the effect of generating a larger peak in β_x, between parasitic crossings but leads to smaller horizontal beam sizes at these locations and therefore reduces the necessary

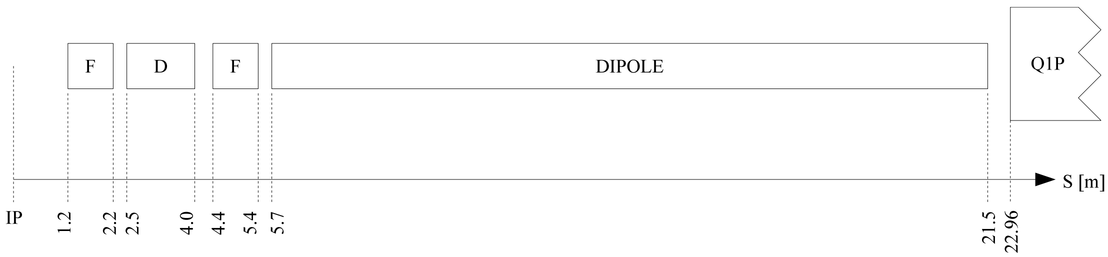

Figure 7.23: Layout of machine elements in the High Luminosity IR. Note that the left side of the IR is symmetric.

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	89.09228878	-0.0296	-3.32240×10^{-4}
Q2E.L	-4	1.5	-102.2013150	-0.0296	2.89624×10^{-4}
Q1E.L	-2.2	1.0	54.34070578	-0.0296	-5.44711×10^{-4}
IP	0.0	-	-	-	-
Q1E.R	1.2	1.0	54.34070578	0.0296	5.44711×10^{-4}
Q2E.R	2.5	1.5	-102.2013150	0.0296	-2.89624×10^{-4}
Q3E.R	4.4	1.0	89.09228878	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.

beam separation. The first F quadrupole reduces β_x at s = 3.75 m compared to an initial D quadrupole. The third F quadrupole then brings β_x down from the peak sufficiently to avoid large beam-beam interactions at the second parasitic crossing, s = 7.5 m.

This is provided by the bending effect of the offset quadrupoles, and also the IP crossing angle of 1 mrad. These elements ensure that the separation between the beams, normalised to beam size, increases at each parasitic crossing. Note that 1 mrad is not a minimum crossing angle required by beam-beam interaction separation criteria; it is however a chosen balance between luminosity loss and minimising bend strength. In theory, this layout could support an IP with no crossing angle; however the bend strength required to achieve this would generate an undesirable level of SR power.

7.6.4 Optics Matching and IR Geometry

The IR is matched into the ring arc lattice by means of matching quads in the LSS. The quads are roughly evenly placed, with sufficient space left after the IR section to accommodate the proton optics and the remaining electron ring geometry, which has yet to be designed fully. The solution is nearly symmetric about the IP; however due to the geometry of the LHC lattice,

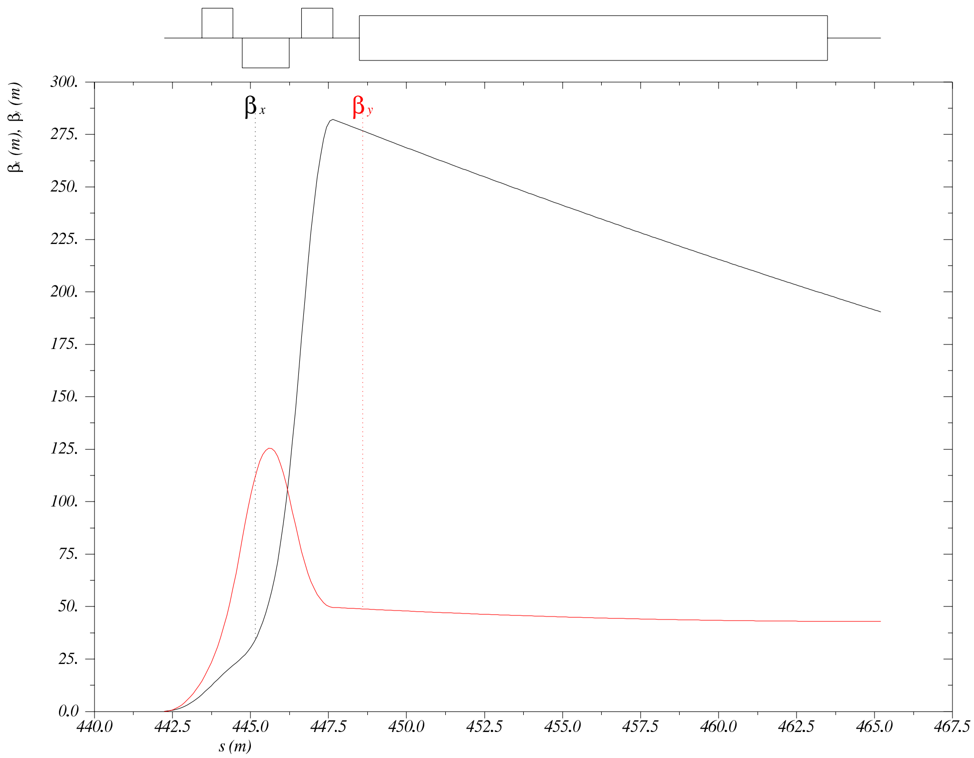

Figure 7.24: β functions in both planes for the High Luminosity IR layout, from the IP to the face of the final proton quadrupole at s = 23 m. Note that s is relative to the ring, which begins at the left side of the left dispersion suppressor of IP2.

the electron ring itself is not exactly symmetric. As such the solution differs slightly on either side of the LSS. Table 7.13 details the layout of machine elements in the LSS. Five matching quadrupoles are used on either side of the IP. A sixth quadrupole is used on the left side, next to the dispersion suppressor. Due to the asymmetric design of the dispersion suppressors, a quadrupole (MQDSF.L2) is included at the same distance from the IP on the right side as part of the dispersion suppressor. MQDSF.L2 is required to match the optics, but is more constrained than the other matching quadrupoles. Figure 7.25 shows the β functions of the matching from the IP to the dispersion suppressor, on both sides of the IP (Figure 7.26)

A smooth matching is obtained, where the maximum beta functions are well controlled and continuously reduced to the values of the arc structure. The beam envelopes in the LSS are of

Element	S_{entry} [m]	L [m]	Gradient [T/m]
MQDSF.L2	-268.8944	1.0	9.611358758
MQDM5.L2	-240.5	1.0	-7.435432612
MQFM4.L2	-198.5	1.0	7.148957108
MQDM3.L2	-160.5	1.0	-6.493088294
MQFM2.L2	-120.5	1.0	6.057685328
MQDM1.L2	-82.5	1.0	-4.962254798
MQDM1.R2	81.5	1.0	-4.977379112
MQFM2.R2	119.5	1.0	6.030944724
MQDM3.R2	159.5	1.0	-6.63145508
MQFM4.R2	197.5	1.0	6.884472924
MQDM5.R2	239.5	1.0	-7.439587356

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.

reasonable size and do not require excessive aperture.

Note that this solution is not yet matched for dispersion as the rest of the ring geometry in the LSS and IR areas is yet to be designed.
Plans for the remaining IR geometry include a second horizontal dipole, and quadrupoles, on either side to turn each separation dipole into a dispersion-free S-shaped bend. This will be used to extract the beam into the electron machine.

7.7 High Acceptance IR Layout

7.7.1 Parameters

Table 7.14 details the design parameters for this option. The chosen detector opening angle for this layout is 1°. All elements, especially the mini beta quadrupoles of the electron ring, therefore have to be placed outside the limits of the detector, at $z = \pm 6.2$m, where z the is longitudinal axis of the detector. As such, the actual acceptance of the layout is limited by the beam pipe rather than the size of machine elements. This also gives further flexibility in the strengths and designs of the final focusing quadrupoles, although this flexibility is not exploited in the design.

SR calculations are discussed in detail in section [NATHAN]. The total power emitted in the IR is similar to that in the HERA-2 IR [reference] and as such appears to be reasonable, given enough space for absorbers. However it is significantly higher than that in the high luminosity layout. As discussed in section [NATHAN], an option exists to reduce the total SR power by including a dipole field in the detector, thus mitigating the limitation imposed on dipole length by the larger $l*$.

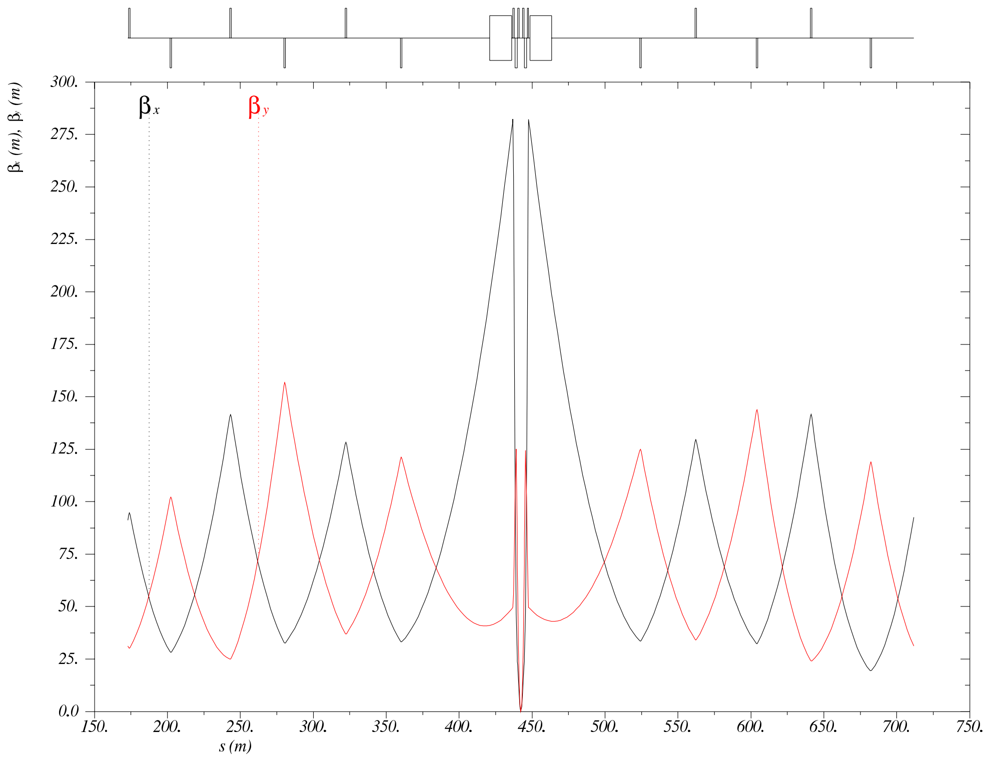

Figure 7.25: β functions in both planes for the High Luminosity IR layout, from the end of the left dispersion suppressor to the start of the right dispersion suppressor. Note that s is relative to the ring, which begins at the left side of the left dispersion suppressor of IP2.

7.7.2 Layout and separation scheme

A symmetric final quadrupole doublet layout has been chosen for this design. The beam spot aspect ratio of 2:1 is marginally flatter than the High Luminosity layout, and as such a triplet is less suitable. Figure 7.28 and table 7.15 detail the layout.

The l^* of 6.2m imposes limitations on focusing and bending in this layout. Focusing is limited by quadratic β growth through a drift space, which is increased for smaller β^*. As such, lower instantaneous luminosity is attainable.

As in the high luminosity option the beam separation will be achieved by a combination of a adequate crossing angle and the separation fields of off-centre quadrupole magnets. However,

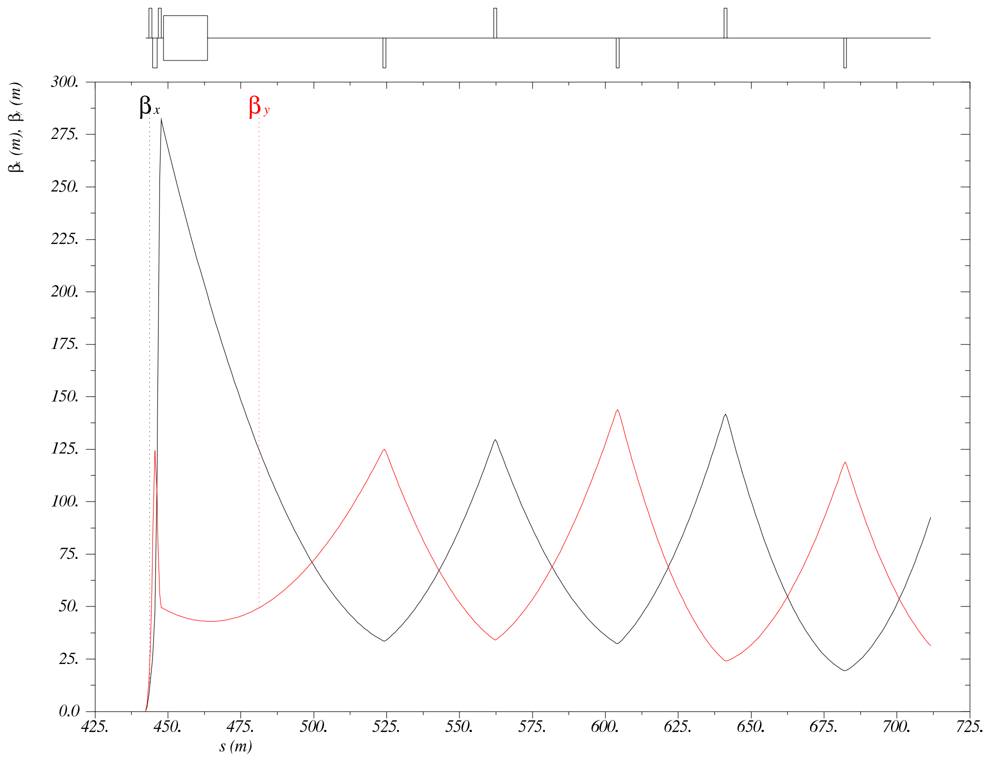

Figure 7.26: β functions in both planes for the High Luminosity IR layout, from the IP to the start of the right dispersion suppressor. Note that s is relative to the ring, which begins at the left side of the left dispersion suppressor of IP2.

due to the large free space of z=6m to the IP, stronger fields have to be applied to obtain the same geometric separation at the first proton quadrupole.
Figure 7.29 shows the β functions of the beam in both planes from the IP to the face of the final proton quadrupole at s = 23 m.

7.7.3 Optics Matching and IR Geometry

The lattice that is used to match the IR optics to the periodic arc structure corresponds to a large extent to the one presented for the high luminosity option. Figure 7.30 shows the β functions of the matching from the IP to the dispersion suppressor, on both sides of the IP (Figure 7.31).

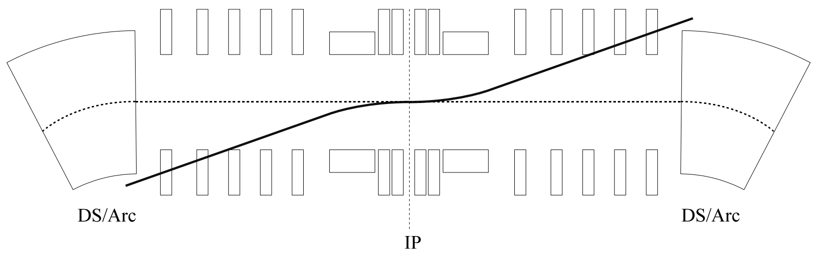

Figure 7.27: Graphical representation of misaligned LSS/IR geometry. With beam steering in the IR and no compensation in the LSS, the electron beam no longer lines up with the ring lattice reference orbit. Diagram is not to scale and does not represent the correct optical layout of the IR nor the LSS.

$L(0)$	$8.54{\times}10^{32}$
θ	$1{\times}10^{-3}$
$S(\theta)$	0.858
$L(\theta)$	$7.33{\times}10^{32}$
β_x*	0.4 m
β_y*	0.2 m
σ_x*	$4.47{\times}10^{-5}$ m
σ_y*	$2.24{\times}10^{-5}$ m
SR Power	51 kW
E_c	163 keV

Table 7.14: Parameters for the High Acceptance IR.

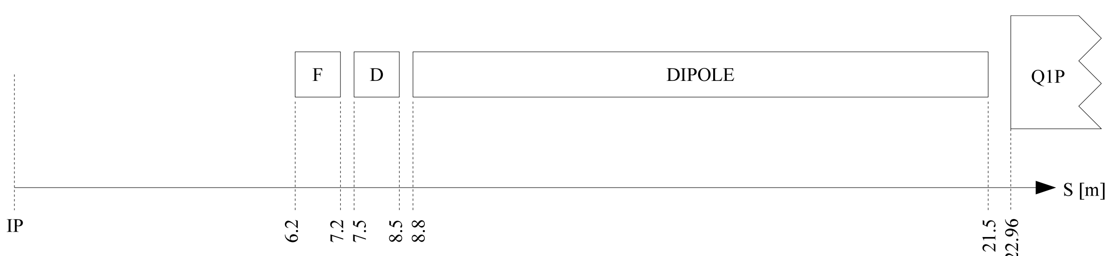

Figure 7.28: Layout of machine elements in the High Acceptance IR. Note that the left side of the IR is symmetric.

As with the High Luminosity layout, a smooth matching is obtained, with the IR β peaks being brought down and controlled before being matched into the arc solution. The beam envelopes in the LSS are of reasonable size and do not require excessive aperture.

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	-77.31019000	-0.0493	6.37691×10^{-4}
Q1E.L	-7.2	1.0	90.40354154	-0.0493	-5.45333×10^{-4}
IP	0.0	-	-	-	-
Q1E.R	6.2	1.0	90.40354154	0.0493	5.45333×10^{-4}
Q2E.R	7.5	1.0	-77.31019000	0.0493	-6.37691×10^{-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.

Other geometric issues must again be addressed, which are briefly discussed in section 7.6.4.

7.7.4 Comparison of Layouts

Table 7.17 shows a direct comparison of various parameters of the two layouts.

The difference in luminosity after considering the loss factor S due to the crossing angle, is a factor of 1.8. However it should be noted that this design strives for technical feasibility and both layouts could be squeezed further to decrease β^* in both planes. The High Luminosity layout could likely be squeezed further than the High Acceptance layout due to the large difference in l^*, as shown in figure 7.32 which compares the two IR layouts. At this stage both designs deliver their required IP parameters of luminosity and acceptance and appear to be feasible.

The High Acceptance design generates a higher level of SR power. This still appears to be within reasonable limits and is discussed in section [NATHAN]. Furthermore, an option is discussed to install a dipole magnet in the detector. This early separation would reduce the required strength of the dipole fields in the IR, significantly reducing total SR power.

Synchrotron radiation and absorbers

The synchrotron radiation (SR) in the interaction region has been analyzed in three ways. The SR was simulated in depth using a program made with the Geant4 (G4) toolkit. In addition a cross check of the total power and average critical energy was done in IRSYN, a Monte Carlo simulation package written by R. Appleby. [535] A final cross check has been made for the radiated power per element using an analytic method. These other methods confirmed the results seen using G4. The G4 program uses Monte Carlo methods to create gaussian spatial and angular distributions for the electron beam. The electron beam is then guided through vacuum volumes that contain the magnetic fields for the separator dipoles and electron final focusing quadrupoles.

The SR is generated in these volumes using the appropriate G4 process classes. The G4 SR class was written for a uniform magnetic field, and therefore the quadrupole volumes were divided such that the field remained approximately constant in each volume. This created

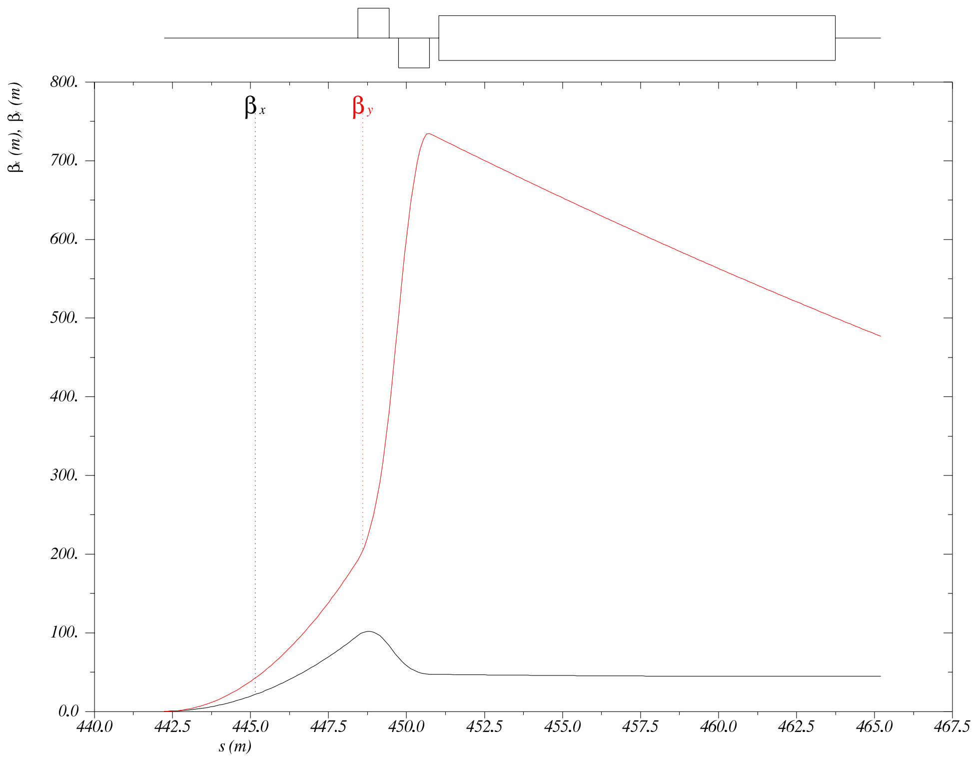

Figure 7.29: β functions in both planes for the High Acceptance IR layout, from the IP to the face of the final proton quadrupole at s = 23 m. Note that s is relative to the ring, which begins at the left side of the left dispersion suppressor of IP2.

agreement between upstream and downstream quadrupoles since for a downstream quadrupole the beta function at the entrance and exit are reversed from its upstream counterpart. This agreement confirms that the field was approximately constant in each volume.

The position, direction, and energy of each photon created is written as ntuples at user defined Z values. These ntuples are then used to analyze the SR fan as it evolves in Z. The analysis was done primarily through the use of MATLAB scripts. It was necessary to make two versions of this program. One for the high luminosity design and one for the high detector acceptance design.

Before going further I will explain some conventions used for this section. I will refer to the electron beam as *the beam* and the proton beams will be referred to as either the interacting or non interacting proton beams. The beam propagates in the -Z direction and the interacting

Element	S_{entry} [m]	L [m]	Gradient [T/m]
MQDSF.L2	-268.8944	1.0	9.643324144
MQFM6.L2	-237.5	1.0	-7.513288936
MQDM5.L2	-205.5	1.0	7.74537173
MQFM4.L2	-174.5	1.0	-6.18152704
MQDM3.L2	-143.5	1.0	6.475404012
MQFM2.L2	-111.5	1.0	-9.254556824
MQDM1.L2	-80.5	1.0	5.843405232
MQDM1.R2	79.5	1.0	5.843405232
MQFM2.R2	110.5	1.0	-9.254556824
MQDM3.R2	142.5	1.0	6.475404012
MQFM4.R2	173.5	1.0	-6.048380018
MQDM5.R2	204.5	1.0	7.360488416
MQFM6.R2	236.5	1.0	-7.225547436

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.

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.

proton beam propagates in the +Z direction, I will use a right handed coordinate system where the X axis is horizontal and the Y axis is vertical. The beam centroid always remains in the Y = 0 plane. The *angle of the beam* will be used to refer to the angle between the beam centroid's velocity vector and the Z axis, in the Y = 0 plane. This angle is set such that the beam propagates in the -X direction as it traverses Z.

The SR fans extension in the horizontal direction is driven by the angle of the beam at the entrance of the upstream separator dipole. Because the direction of emitted photons is parallel to the direction of the electron that emitted it, the angle of the beam and the distance to the absorber are both greatest at the entrance of the upstream separator dipole and therefore this

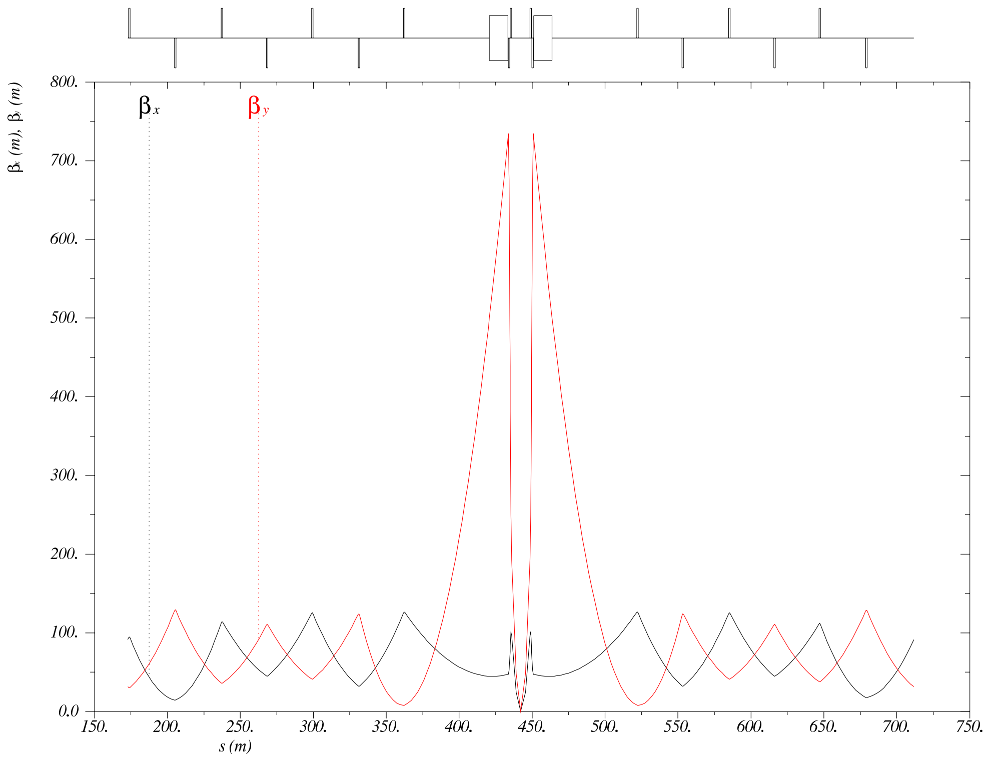

Figure 7.30: β functions in both planes for the High Acceptance IR layout, from the end of the left dispersion suppressor to the start of the right dispersion suppressor. Note that s is relative to the ring, which begins at the left side of the left dispersion suppressor of IP2.

defines one of the edges of the synchrotron fan on the absorber. The other edge is defined by the crossing angle and the distance from the IP to the absorber. The S shaped trajectory of the beam means that the smallest angle of the beam will be reached at the IP. Therefore the photons emitted at this point will have the lowest angle and for this given angle the smallest distance to the absorber. This defines the other edge of the fan in the horizontal direction.

The SR fans extension in the vertical direction is driven by the beta function and angular spread of the beam. The beta function along with the emittance defines the r.m.s. spot size of the beam. The vertical spot size defines the Y position at which photons are emitted. On top of this the vertical angular spread defines the angle between the velocity vector of these photons and the Z axis. Both of these values produce complicated effects as they are functions of Z. These effects also affect the horizontal extension of the fan however are of second order

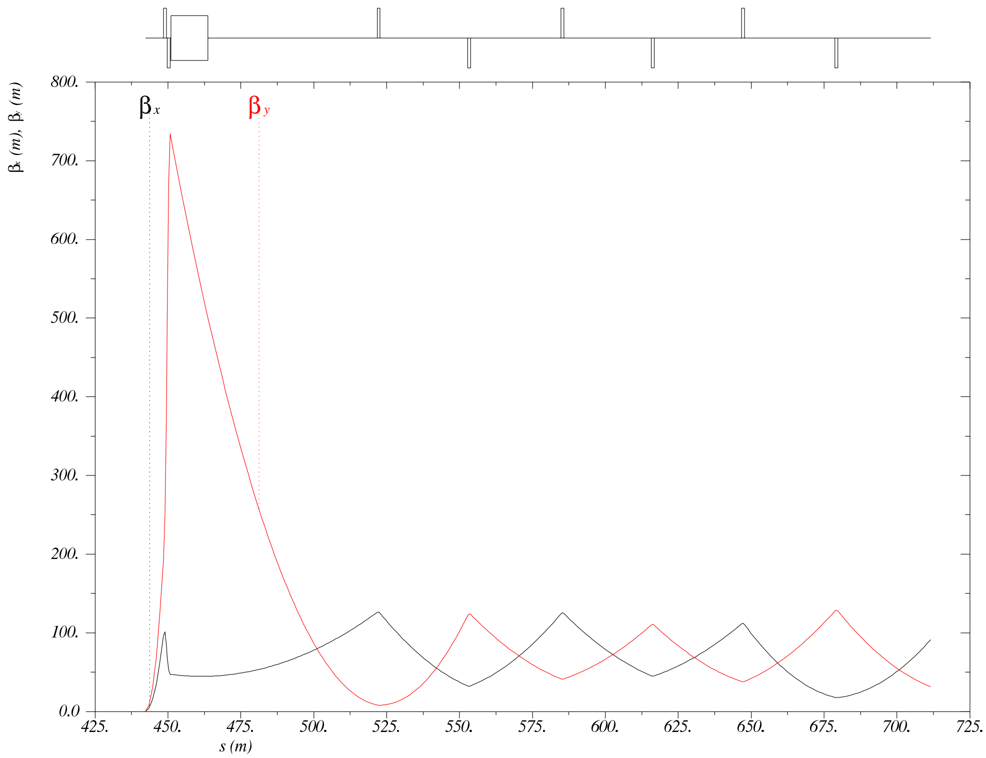

Figure 7.31: β functions in both planes for the High Luminosity IR layout, from the IP to the start of the right dispersion suppressor. Note that s is relative to the ring, which begins at the left side of the left dispersion suppressor of IP2.

when compared to the angle of the beam. Since the beam moves in the Y = 0 plane these effects dominate the vertical extension of the beam.

The number density distribution of the fan is a complicated issue. The number density at the absorber is highest between the interacting beams. The reason for this is that although the separator dipoles create significantly more photons the number of photons generated per unit length in Z is much lower for the dipoles as opposed to the quadrupoles due to the high fields experienced in the quadrupoles. The position of the quadrupole magnets then causes the light radiated from them to hit the absorber in the area between the two interacting beams.

Figure 7.32: Scale comparison of the layouts for the High Luminosity and High Acceptance designs. Note the large difference in l^*.

High Luminosity

Parameters: The parameters for the high luminosity option are listed in Table 7.18. The separation refers 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

The energy, current, and crossing angle (θ_c) are common values used in all RR calculations. The dipole field value refers to the constant dipole field created throughout all dipole elements in the IR. The direction of this field is opposite on either side of the IP. The quadrupole elements have an effective dipole field created by placing the quadrupole off axis, which is the same as this constant dipole field. The field is chosen such that 55 mm of separation is reached by the face of the proton triplet. This separation was chosen based on S. Russenschuck's SC quadrupole design for the proton final focusing triplet. [536] The separation between the interacting beams can be increased by raising the constant dipole field. However, for a dipole magnet $P_{SR} \propto |B^2|$, [537] therefore an optimization of the design will need to be discussed. The chosen parameters give a flux of 5.39×10^{18} photons per second at Z = -21.5 m.

Power and Critical Energy: Table 7.19 shows the power of the SR produced by each element along with the average critical energy produced per element. This is followed by the total power produced in the IR and the average critical energy. Since the G4 simulations utilize Monte Carlo, multiple runs should be made with various seeds to get an estimate for the standard error.

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 [Geant4]

The power from the dipoles is greater than any one quadrupole however the critical energies of the quadrupoles are significantly higher than in the dipoles. It is expected that the dipole and quadrupole elements can create power on the same order however have very different critical energies. This is because the dipole is an order of magnitude longer than the quadrupole elements. Since the SR power created for both the quadrupole and dipoles are linearly dependent on length [537] one needs to have a much higher average critical energy to create comparable amounts of power.

Comparison: The IRSYN cross check of the power and critical energies is shown in Table 7.20. This comparison was done for the total power and the average critical energy.

	Power [kW]		Critical Energy [keV]	
	Geant4	IRSYN	Geant4	IRSYN
Total/Avg	33.2	X	126	X

Table 7.20: High Luminosity: Geant4 and IRSYN comparison

A third cross check to the G4 simulations was made for the power as shown in Table 7.21. This was done using an analytic method for calculating power in dipole and quadrupole magnets. [537] This was done for every element which provides confidence in the distribution of this power throughout the IR.

	Power [kW]	
Element	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

Number Density and Envelopes: The number density of photons as a function of Z is shown in Figure 7.33. Each graph displays the density of photons in the $Z = Z_o$ plane for various values of Z_o. The first three figures give the growth of the SR fan inside the detector area. This is crucial for determining the dimensions of the beam pipe. Since the fan grows asymmetrically in the -Z direction an asymmetric elliptical cone geometry 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 high luminosity case is the minimum for the two Ring Ring options as well as the Linac Ring option, which is most important inside the detector region. This is due to the lower value of l^*. Because the quadrupoles are closer to the IP and contain effective dipole fields the angle of the beam at the entrance of the upstream dipole can be lower as the angle of the beam doesnt need to equal the crossing angle until $Z = l^*$. The number density of this fan appears as expected. There exists the highest density between the two beams at the absorber.

In Figure 7.33 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 7.34, where the beam and fan envelopes are shown in the Y = 0 plane. This makes it clear that the fan is antisymmetric which comes from the S shape of the electron beam as previously mentioned.

Critical Energy Distribution: The Critical Energy is dependent upon the element in which the SR is generated, and for the quadrupole magnets it is also dependent upon Z. This is a result of the fact that the critical energy is proportional to the magnetic field component that is perpendicular to the particle direction. i.e. $E_c \propto B_\perp$. [538] Since the magnitude of the magnetic field is dependent upon x and y, then for a gaussian beam in position particles will experience different magnetic fields and therefore have a spectrum of critical energies. In a dipole the field is constant and therefore regardless of the position of the particles as long as they are in the uniform field area of the magnet they have a constant critical energy. Since the magnetic field

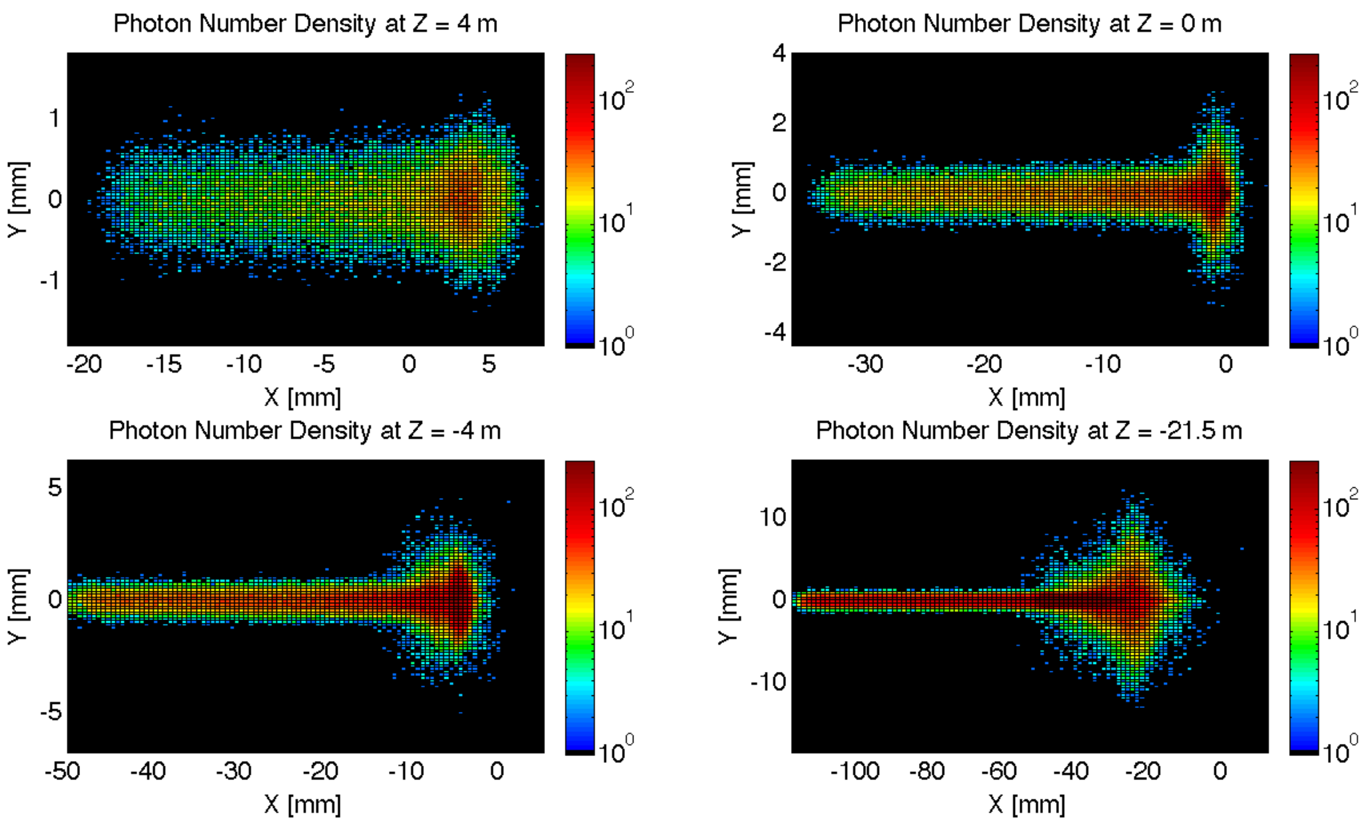

Figure 7.33: High Luminosity: Number Density Growth in Z

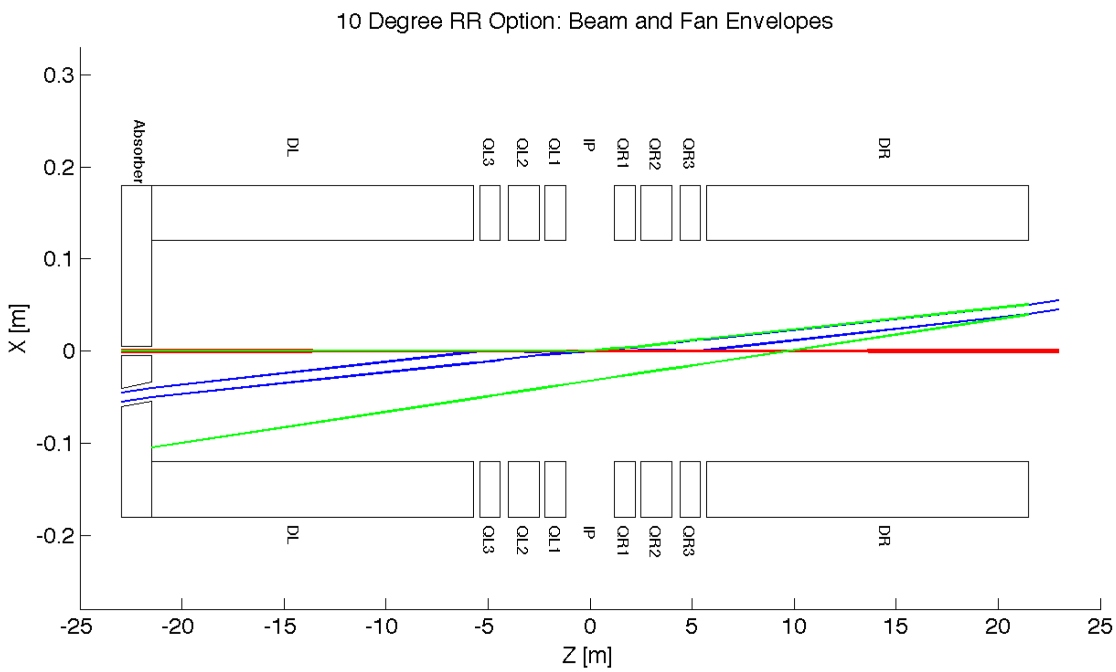

Figure 7.34: High Luminosity: Beam Envelopes in Z

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 decrease in critical energies. The opposite will occur for an increasing spot size. This is evident from Figure 7.35.

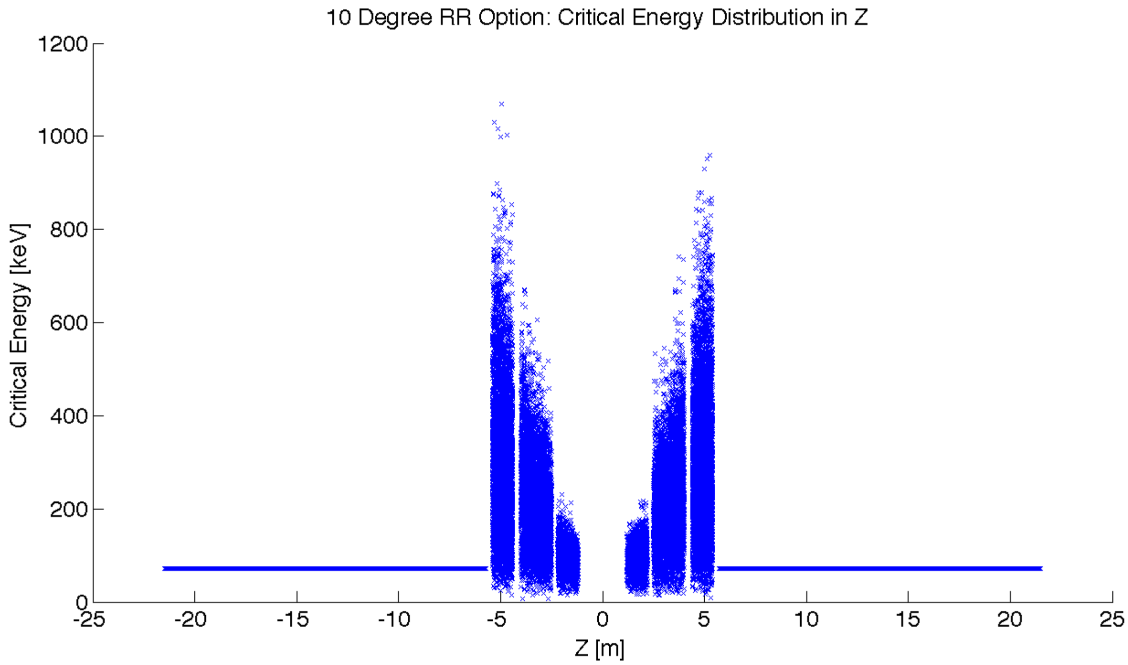

Figure 7.35: High Luminosity: Critical Energy Distribution in Z

Absorber: The Photon distribution on the absorber surface is crucial. The distribution decides how the absorber must be shaped. The shape of the absorber in addition to the distribution on the surface then decides how much SR is backscattered into the detector region. In HERA backscattered SR was a significant source of background that required careful attention. [539] Looking at Figure 7.36 it is shown that for the high luminosity option 19.2 kW of power from the SR light will fall on the face of the absorber which is 58% of the total power. This gives a general idea of the amount of power that will be absorbed. However, backscattering and IR photons will lower the percent that is actually absorbed.

Proton Triplet: The super conducting final focusing triplet for the protons needs to be protected from radiation by the absorber. Some of the radiation produced upstream of the absorber however will either pass through the absorber or pass through the apertures for the two interacting beams. This is most concerning for the interacting proton beam aperture which will have the superconducting coils. A rough upper bound for the amount of power the coils can absorb before quenching is 100 W. [540] There is approximately 217 W entering into the interacting proton beam aperture as is shown in Figure 7.36. This doesnt mean that all this power will hit the coils but simulations need to be made to determine how much of this will hit

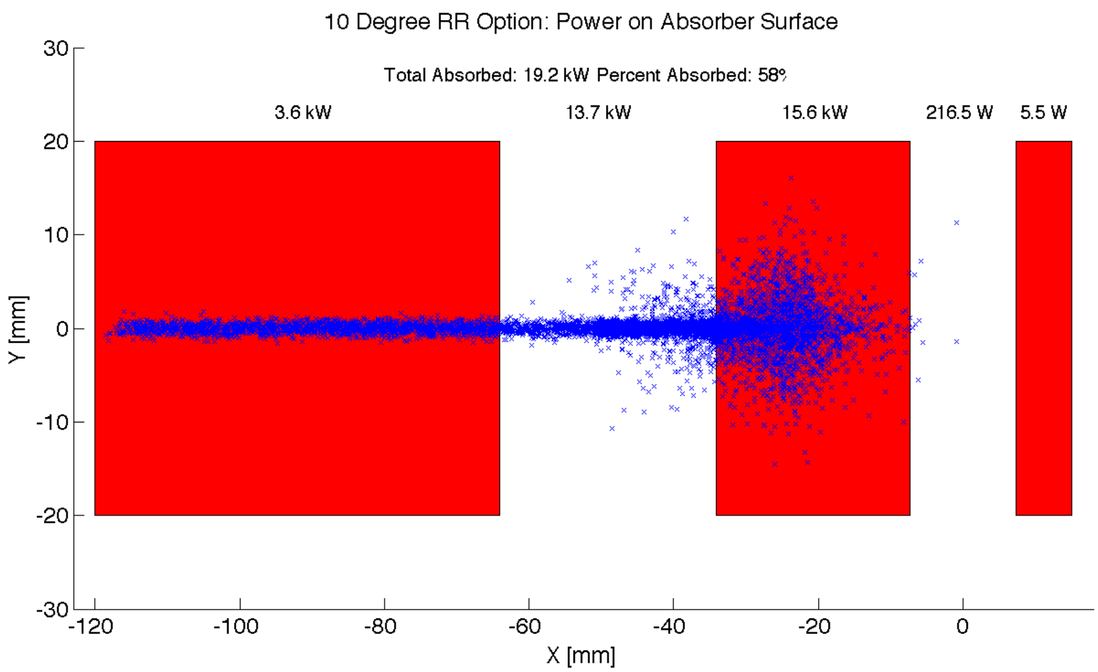

Figure 7.36: High Luminosity: Photon distribution on Absorber Surface

the coils. The amount of power that will pass through the absorber can be disregarded as it is not enough to cause any effects. The main source of power moving downstream of the absorber will be the photons passing through the beams aperture. This was approximately 13.7 kW as can be seen from Figure 7.36. Most of this radiation can be absorbed in a secondary absorber placed after the first downstream proton quadrupole. Overall protecting the proton triplet is important and although the absorber will minimize the radiation continuing downstream this needs to be studied in depth.

Backscattering: Another Geant4 program was written to simulate the backscattering of photons into the detector region. The ntuple with the photon information written at the absorber surface is used as the input for this program. An absorber geometry made of copper is described, and general physics processes are set up. A detector volume is then described and set to record the information of all the photons which enter in an ntuple. The first step in minimizing the backscattering was to optimize the absorber shape. Although the simulation didnt include a beam pipe the backscattering for different absorber geometries was compared against one another to find a minimum. The most basic shape was a block of copper that had cylinders removed for the interacting beams. This was used as a benchmark to see the maximum possible backscattering. In HERA a wedge shape was used for heat dissipation and minimizing backscattering. [539] The profile of two possible wedge shapes in the YZ plane is shown in Figure 7.37. It was found that this is the optimum shape for the absorber. The reason for this is that a backscattered electron would have to have its velocity vector be almost parallel to the wedge surface to escape from the wedge and therefore it works as a trap. As can be seen from Table 7.22 utilizing the wedge shaped absorber did not reduce the power by much. This appears to be a statistical limitation. This needs to be redone with higher statistics to get a better opinion on the difference between the two geometries.

After the absorber was optimized it was possible to set up a beam pipe geometry. An asymmetric elliptical cone beam pipe geometry made of beryllium was used since it would minimize the necessary size of the beam pipe as previously mentioned. The next step was to place the lead shield and masks inside this beam pipe. To determine placement a simulation was run with just the beam pipe. Then it was recorded where each backscattered photon would hit the beam pipe in Z. A histogram of this data was made. This determined that the shield should be placed in the Z region ranging from -20 m until the absorber (-21.5 m). The shields were then placed at -21.2 m and -20.5 m. This decreased the backscattered power to zero as can be seen from Table 7.22. Although this is promising this number should be checked again with higher 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

Cross sections of the beam pipe in the Y = 0 and X = 0 planes with the shields and masks included can be seen in Figure 7.38.

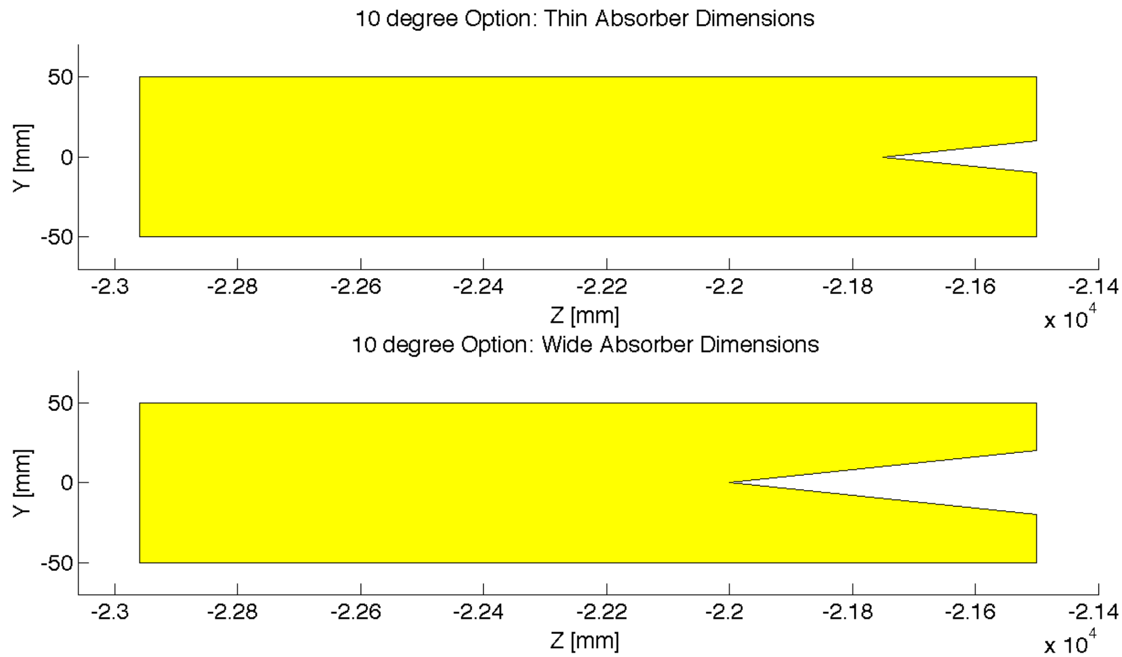

Figure 7.37: 10 deg: Absorber Dimensions

High Detector Acceptance

Parameters: For the Ring Ring high acceptance option the basic parameters are listed in Table 7.23. The separation refers 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]	0.0493
Separation [mm]	55.16
γ/s	6.41×10^{18}

Table 7.23: High Acceptance: Parameters

The energy, current, and crossing angle (θ_c) are common values used in all RR calculations. The dipole field value refers to the constant dipole field created throughout all dipole elements in the IR. The separation is the same as in the high luminosity case and can be altered for

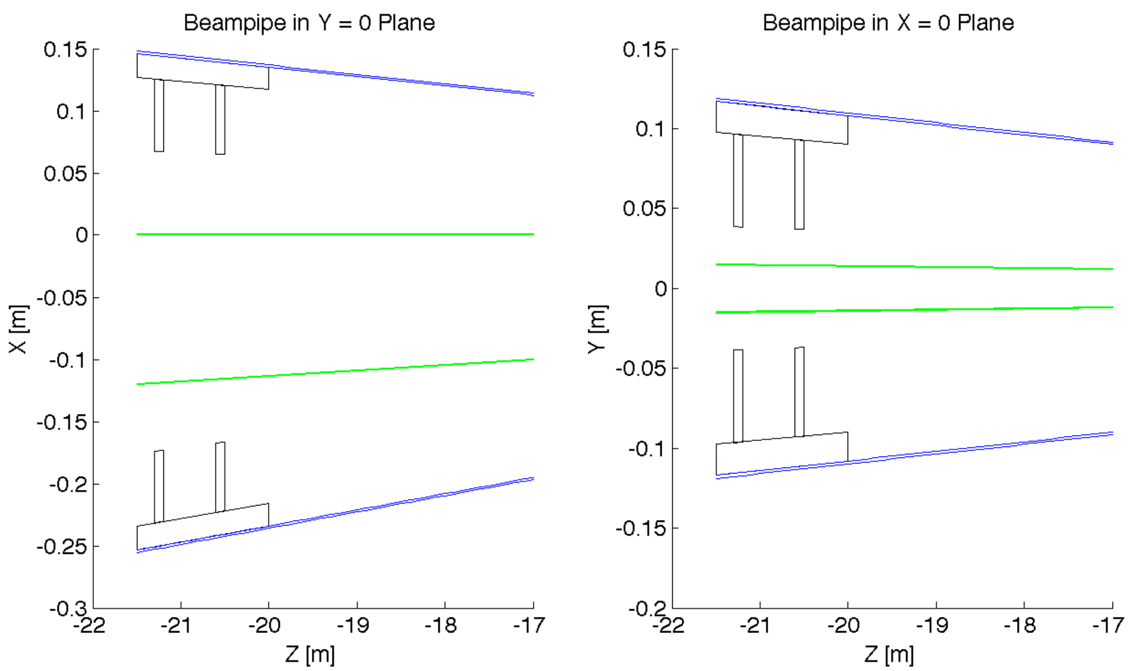

Figure 7.38: High Luminosity: Beampipe Cross Sections

the same reasons with the same ramifications.The chosen parameters give a flux of 6.41×10^{18} photons per second at Z = -21.5 m, which is slightly higher than in the high luminosity case. This is expected as the fields experienced in the high acceptance case are higher.

Power and Critical Energy: Table 7.24 shows the power of the SR produced by each element along with the average critical energy produced per element. This is followed by the total power produced in the IR and the average critical energy. Since the G4 simulations utilize Monte Carlo, multiple runs should be made with various seeds to get an estimate for the standard error.

The distribution of power and critical energy over the IR elements is similar to that of the high acceptance option with the exception of the upstream and downstream separator dipole magnets. The power and critical energies are significantly higher than before. This is due to the higher dipole field and the quadratic dependence of power on magnetic field and linear dependence of critical energy on magnetic field. [538]

Comparison: The IRSYN cross check of the power and critical energies is shown in Table 7.25. This comparison was done for the total power and the critical energy.

A third cross check to the G4 simulations was also made for the power as shown in Table 7.26. This was done using an analytic method for calculating power in dipole and quadrupole magnets. [537] This comparison provides confidence in the distribution of the power throughout the IR.

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

	Power [kW]	
Element	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

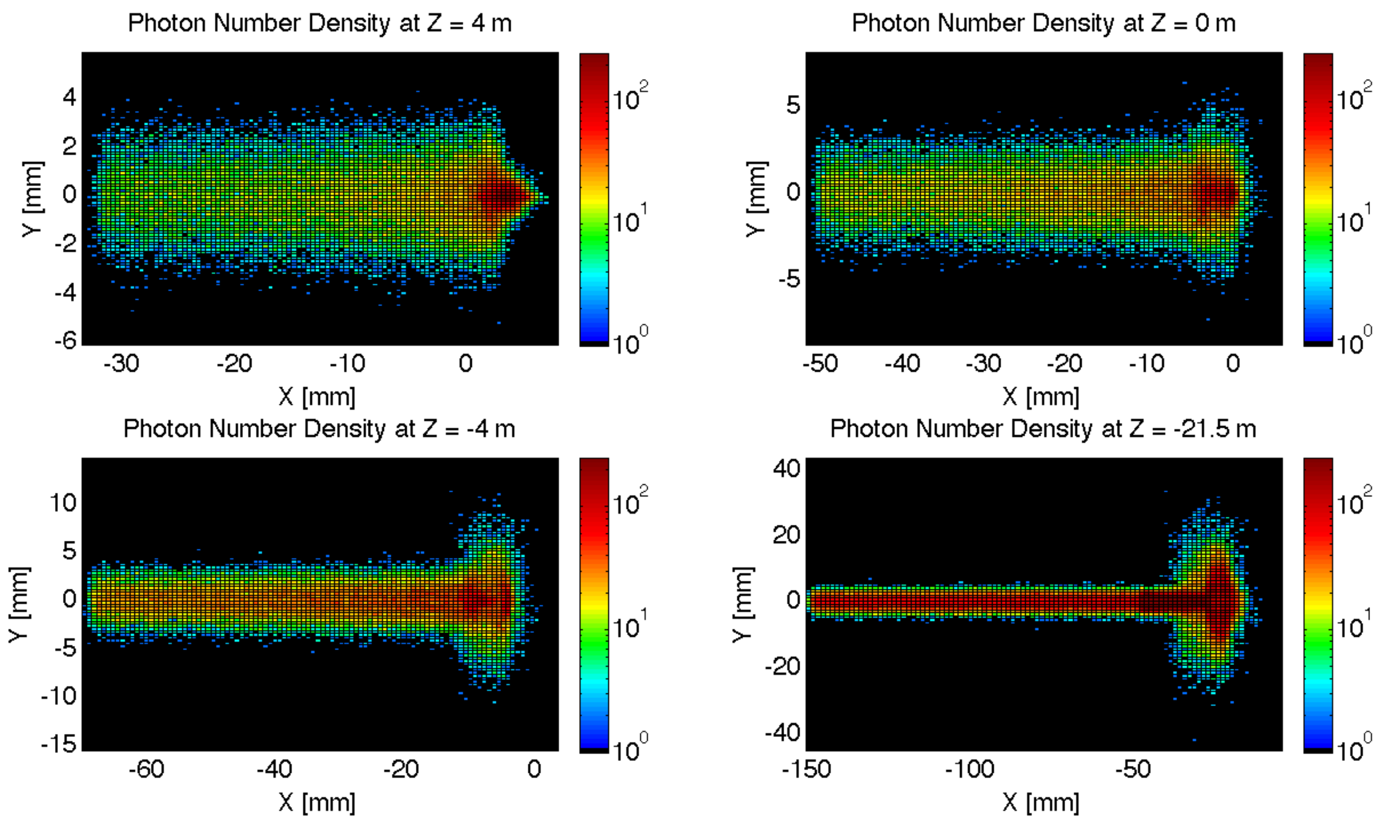

Figure 7.39: High Acceptance: Number Density Growth in Z

Number Density and Envelopes: The number density of photons as a function of Z is shown in Figure 7.39. The horizontal extension of the fan in the high acceptance case is larger than in the high luminosity case however still lower than in the LR option. Since the beam stays at a constant angle for the first 6.2 m after the IP it requires larger fields to bend in order to reach the desired separation. This means that an overall larger angle is reached near the absorber, and since the S shaped trajectory is symmetric in Z the angle of the beam at the entrance of the upstream quadrupoles is also larger and therefore the fan extends further in X.

The envelope of the SR fan can be seen in Figure 7.40, where the XZ plane is shown at the value $Y = 0$. Once again the fan is antisymmetric due to the S shape of the electron beam.

Critical Energy Distribution: The critical energy distribution in Z is similar to that of the high luminosity case. This is due to the focusing of the beam in the IR. This is evident from Figure 7.41.

Absorber: Looking at Figure 7.42 it is shown that for the high acceptance option 38.5 kW of power from the SR light will fall on the face of the absorber which is 75% of the total power.

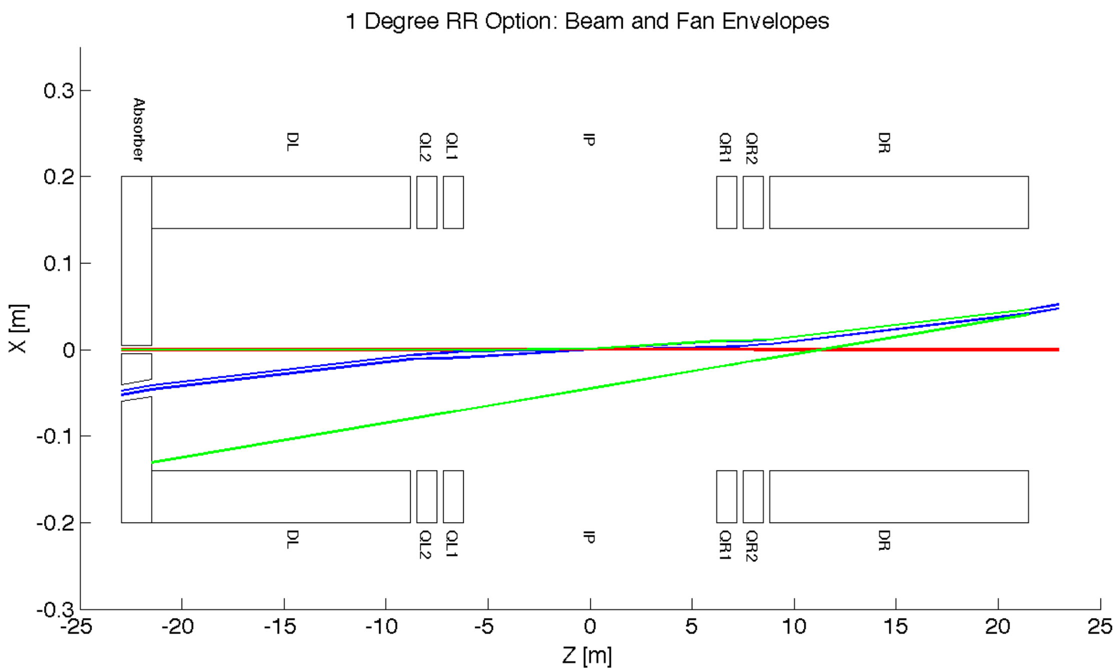

Figure 7.40: High Acceptance: Beam Envelopes in Z

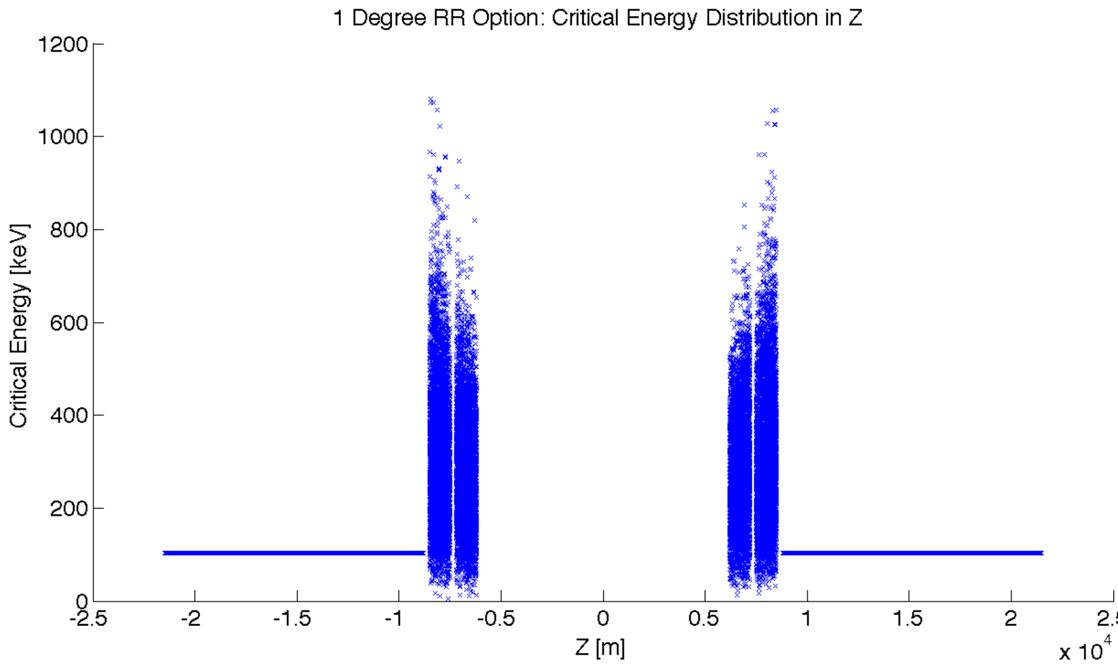

Figure 7.41: High Acceptance: Critical Energy Distribution in Z

This gives a general idea of the amount of power that will be absorbed. However, backscattering and IR photons will lower the percent that is actually absorbed.

Proton Triplet: The super conducting final focusing triplet for the protons needs to be protected from radiation by the absorber. Some of the radiation produced upstream of the absorber however will either pass through the absorber or pass through the apertures for the two interacting beams. This is most concerning for the interacting proton beam aperture which will have the superconducting coils. A rough upper bound for the amount of power the coils can absorb before quenching is 100 W. [540] In the high acceptance option there is approximately 0.4 W entering into the interacting proton beam aperture as is shown in Figure 7.42. Therefore for the high acceptance option this is not an issue. The amount of power that will pass through the absorber can be disregarded as it is not enough to cause any significant effects. The main source of power moving downstream of the absorber will be the photons passing through the beams aperture. This was approximately 12.7 kW as can be seen from Figure 7.42. Most of this radiation can be absorbed in a secondary absorber placed after the first downstream proton quadrupole. Overall protecting the proton triplet is important and although the absorber will minimize the radiation continuing downstream this needs to be studied in depth.

Backscattering: Another Geant4 program was written to simulate the backscattering of photons into the detector region. The ntuple with the photon information written at the absorber surface is used as the input for this program. An absorber geometry made of copper

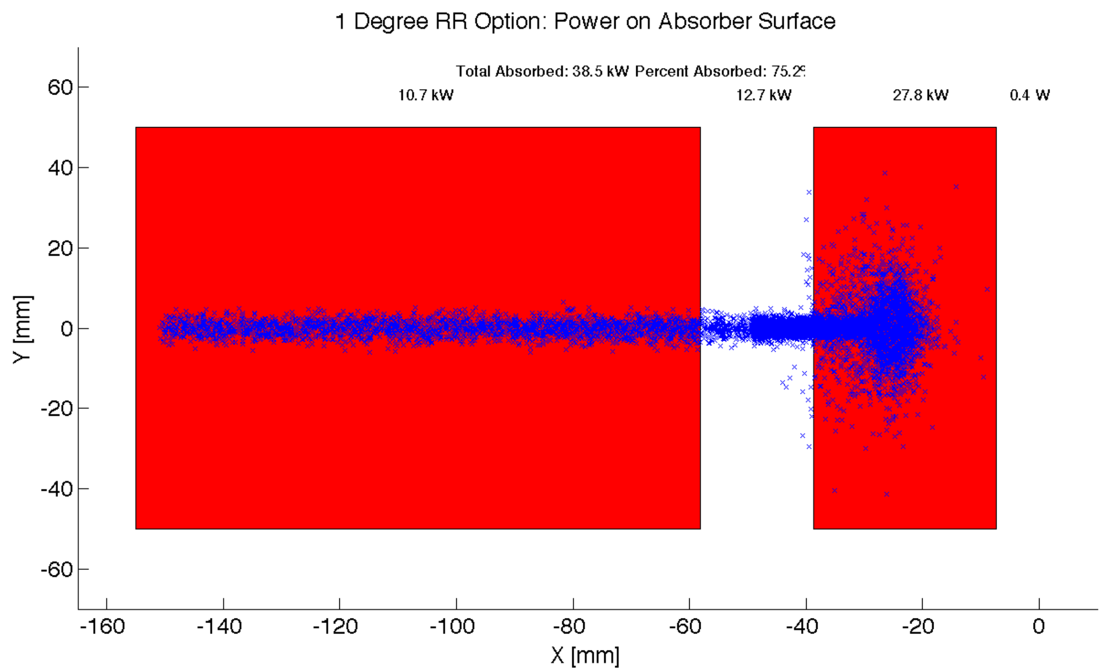

Figure 7.42: High Acceptance: Photon distribution on Absorber Surface

is described, and general physics processes are set up. A detector volume is then described and set to record the information of all the photons which enter in an ntuple. The first step in minimizing the backscattering was to optimize the absorber shape. Although the simulation didnt include a beam pipe the backscattering for different absorber geometries was compared against one another to find a minimum. The most basic shape was a block of copper that had cylinders removed for the interacting beams. This was used as a benchmark to see the maximum possible backscattering. In HERA a wedge shape was used for heat dissipation and minimizing backscattering. [539] The profile of two possible wedge shapes in the YZ plane is shown in Figure 7.43. It was found that this is the optimum shape for the absorber. The reason for this is that a backscattered electron would have to have its velocity vector be almost parallel to the wedge surface to escape from the wedge and therefore it works as a trap. As can be seen from Table 7.27 utilizing the wedge shaped absorber decreased the backscattered power by a factor of 9.

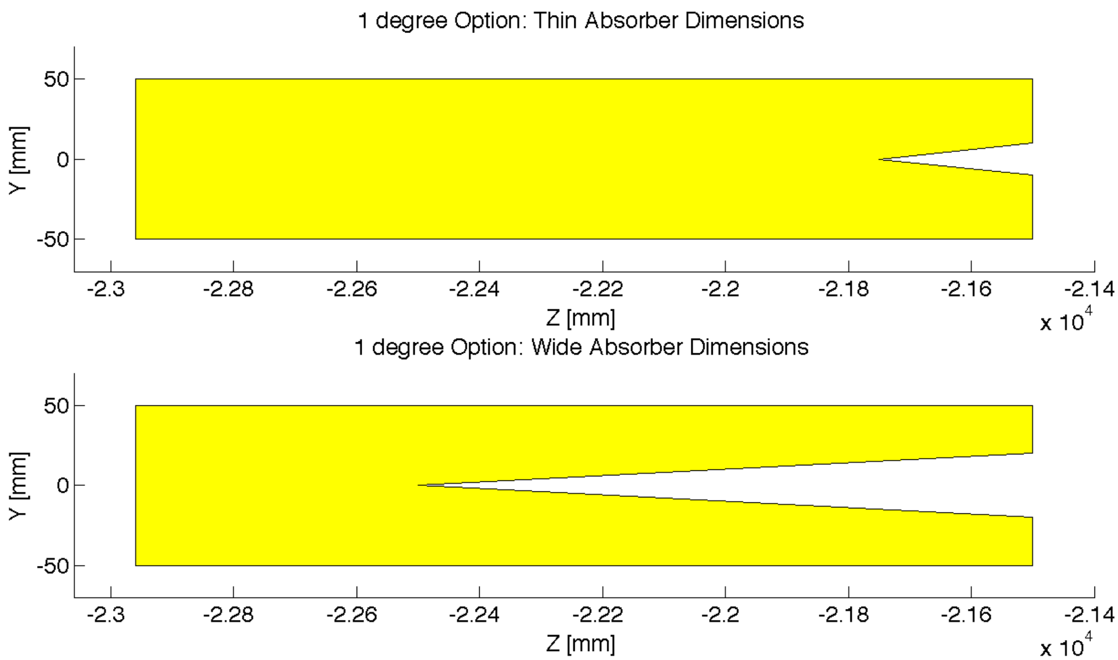

Figure 7.43: 1 deg: Absorber Dimensions

After the absorber was optimized it was possible to set up a beam pipe geometry. An asymmetric elliptical cone beam pipe geometry made of beryllium was used since it would minimize the necessary size of the beam pipe as previously mentioned. The next step was to place the lead shield and masks inside this beam pipe. To determine placement a simulation was run with just the beam pipe. Then it was recorded where each backscattered photon would hit the beam pipe in Z. This determined that the shield should be placed in the Z region ranging from -20 m until the absorber (-21.5 m). The shields were then placed at -21.2 m and -20.6 m. This decreased the backscattered power to zero as can be seen from Table 7.27. Although this is promising this number should be checked again with higher statistics to judge its accuracy. Overall 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

Cross sections of the beam pipe in the Y = 0 and X = 0 planes with the shields and masks included can be seen in Figure 7.44.

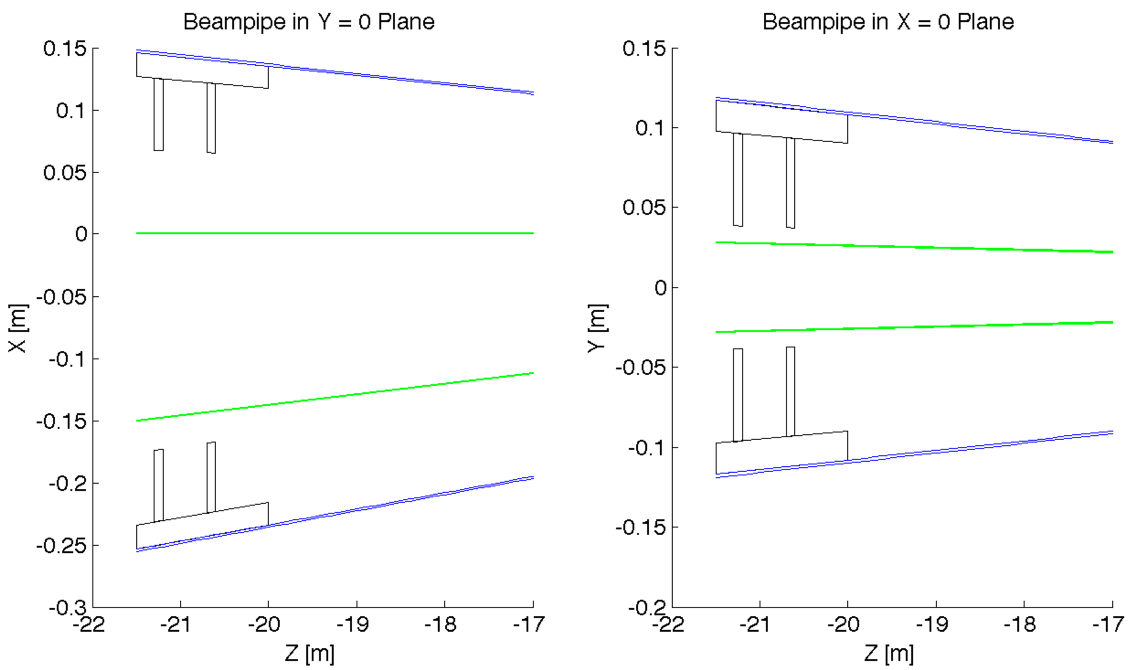

Figure 7.44: High Acceptance: Beampipe Cross Sections

7.8 Beam-beam effects in the LHeC

In the framework of the Large Hadron electron Collider a ring-ring option is considered where protons of one beam collide with the protons of the second proton beam as well as with leptons from the second ring. To deduce possible limitations the present knowledge of the LHC beam-beam effects from proton-proton collisions are fundamental to define parameters of an interaction point with electron-proton collisions. From past experience it is known that the maximum achievable luminosity in a collider is limited by beam-beam effects. These are often quantified by the maximum beam-beam tune shifts in each of the two beams. An important aspect in electron-proton collisions is that the proton beam, more sensitive to transverse noise, could be perturbed by a higher level of noise in the electron beam. In this section we will assess some limits to the possible tune shift achievable in collision based on experience from past colliders as CESR [?] and LEP [?] and more recent ones like the LHC [?].

7.8.1 Head-on beam-beam effects

A first important performance issue in beam-beam interaction comes from the restricted choice of the β-function at the interaction point to keep the transverse beam sizes equal for the two beam since proton and electron emittances are different. The choice of beta functions at the interaction point has to be different 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 [?]. In a mismatched collision the larger bunch may suffer more because a large part of the particle distribution will experience the non-linear beam-beam force of the other bunch. With this in mind it is preferable to keep the electron beam slightly larger than the proton beam since the electron beam may be less sensitive due to strong radiation damping. This matching implies that the electron emittances must be controlled during operation and kept as constant as possible (i.e. H/V coupling). For the proton beam the beam-beam effects from the electron beam will be different for the two planes. Optical matching of the beam sizes at the IP is the first constraint for any interaction region layout proposed.

Another important issue is the achievable tune shift and how this relates to the linear beam-beam parameter which is normally the parameter used to evaluate the strength of the beam-beam interaction.

The linear beam-beam parameter is defined as ξ_{bb} and is expressed for the case of round beams like in proton-proton collision at the LHC as:

$$\xi_{bb} = \frac{N r_p \beta^*}{4\pi\gamma\sigma^2} \tag{7.12}$$

where r_p is the proton classical radius, β^* is the optical amplitude function (β-function) at the interaction point, $\sigma = \sigma_{x,y}$ is the transverse beam size in meters at the interaction point, N_p is the bunch intensity and γ is the relativistic factor. For proton-proton collisions where ξ_{bb} does not reach too large values and the operational tune is far enough away from linear resonances, this parameter is about equal to the linear tune shift ΔQ expected from the head-on beam-beam interaction. This is the case for the LHC proton-proton collisions at IP1 and IP5 where the linear tune shift per IP is of the order of 0.0034/0.0037 for nominal beam parameters as summarized in Table 7.28 and corresponds to the linear beam-beam parameter ξ_{bb}. This is in general not true for lepton colliders where the operational scenario differs from hadron colliders and other effects become dominant and have to be taken into account.
In the case of electron beams the transverse shape of the beams is normally elliptical with $\sigma_x > \sigma_y$. In this configuration one can generalize the linear beam-beam parameter calculation with the following formula [?]:

$$\xi_{x,y} = \frac{N r_e \beta^*_{x,y}}{2\pi\gamma\sigma_{x,y}(\sigma_x + \sigma_y)} \tag{7.13}$$

Parameter	LEP	LHC (nominal)
Beam sizes	160μm $\cdot$ 4μm ?	16.6μm $\cdot$ 16.6μm
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.

with r_e is the electron classical radius.

In the case of electron-proton collisions one has to also take into account the different species during collision and the beam-beam parameters become:

$$\xi_{(x,y),b_1} = \frac{N_{b_2} r_{b_1} \beta^*_{(x,y),b_1}}{2\pi\gamma_{b_1}\sigma_{(x,y),b_2}(\sigma_{x,b_2}+\sigma_{y,b_2})} \tag{7.14}$$

Here b_1 and b_2 refer to beam 1 and beam 2 respectively. The linear beam-beam parameter ξ is often used to quantify the strength of the beam-beam interaction, however it does not reflect the non-linear nature of the electromagnetic interaction. Nevertheless, it can be used for comparison and as a scaling parameter. Since a general beam-beam limit cannot be found and will be different from one collider to the next, the interpretation should be conservative.

In Table 7.28 we compare LEP and LHC beam parameters and achieved linear beam-beam parameters. Some of the differences are striking: while the beams in the LHC are round at the interaction point, they are very flat in LEP. This is due to the excitation of the beam in the horizontal plane by the strong synchrotron radiation and damping in the vertical plane. Another observation is the much larger beam-beam parameter in LEP.

One reason for the larger achievable beam-beam parameter in lepton colliders is due to a significant dynamic beta effect when operating at a working point close to integer tune. This is considered more difficult with proton beams. In Equation 7.15 the perturbed β^* is expressed as a function of the beam-beam parameter and the phase advance between two interaction points $2\pi Q^i$. The tune shift becomes a function of the tune which can be chosen to keep the actual shift small.

$$\beta^*(Q) = \frac{\beta}{\sqrt{1+4\pi\xi(cot(2\pi Q^i)) - 4\pi^2\xi^2}} \tag{7.15}$$

From experience it is known that electrons have a bigger range for the linear head-on beam-beam parameter: LEP II has proved a beam-beam parameter of 0.07 corresponding to a measured ΔQ of 0.03 as also confirmed in other lepton colliders. CESR demonstrated the possibility to achieve tune shifts of the order of 0.09. A second and most important reason for a higher acceptable tune shift in lepton colliders is the synchrotron radiation damping. Furthermore, while for lepton colliders a clear indication for a "beam-beam limit" exists, not such criteria can be easily defined for hadron machines [?]. With these brief resume on the head-on linear beam-beam parameters reached so far it is clear that the beam which will have some limits on the choice of parameters ξ_{bb} is the proton beam.

IR Option	1 degree		10 degree	
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	45μm		30μm	
σ_y	22μm		15.8μm	
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	$7.33 \cdot 10^{32}$ $cm^{-2}s^{-1}$		$1.34 \cdot 10^{33}$ $cm^{-2}s^{-1}$	

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.

The LHC as a proton-proton collider has confirmed previous experience from SppS and Tevatron that a total linear tune shift of 0.018 (0.006 per IP) is tolerable with neither important losses nor reduction of beam lifetime during normal operation. It is generally admitted that ξ_{bb} could reach a value of 0.01 per interaction point. Recent experiments at the LHC with very high intensity beams beyond ultimate and reduced beam transverse sizes demonstrated the possibility of reaching head-on tune shifts well beyond the nominal values [?]. At the LHC tune shifts per IP close to 0.02 have been achieved. Total tune shift exceeding 0.034 have also been achieved with stable beams for two symmetric crossings at IP1 and IP5. These latest experiments demonstrate the possibility to operate with larger than nominal beam-beam parameters.

The calculated beam-beam parameters for the electron and proton beams due to an electron-proton collision in the LHeC are summarized in Table 7.29 for the two interaction region options (1 Degree Option and 10 Degree Option).

The two proposed interaction region options will give for the proton beams a maximum beam-beam parameter in the horizontal plane of about $8 \cdot 10^{-4}$. This effect is in the shadow of

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.

the proton-proton collision at IP1 and IP5 which will give a beam-beam parameter of $5.5 \cdot 10^{-3}$ per single IP for nominal 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.

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.

7.8.2 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:

$$d(s)_{x,y} \; = \; \alpha \frac{s}{\sqrt{\epsilon_{x,y}\beta(s)_{x,y}}} \tag{7.16}$$

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 6 σ separation may be acceptable since it is shown experimentally that few encounters also at smaller separation do not affect the beams dramatically [**?**]. 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 6 σ 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.
For any reliable study of the LHeC project one has to address other possible beam-beam issues with extensive numerical simulations of the operational scenario of the LHeC. This is fundamental since there is no other possible simplification which can be adopted in evaluating the non-linear parts of the beam-beam forces. For this reason a detailed and full interaction layout with crossing schemes matched in thin lens version is needed. With the complete optic layout beam-beam effects which still need further studies by means of numerical simulation campaign are the following:

- Long-range tune shifts and orbit effects.
- Self-consistent study of the proton-proton and electron-proton beam dynamics interplay.
- Dynamic aperture tracking studies.
- Multi-bunch effects.

The evaluation of the non-linear effects of the beam-beam interactions with self-consistent calculations will define a set of parameters for operation [**?**].

7.9 Performance as an electron-ion collider

With the first collisions of lead nuclei ($^{208}Pb^{82+}$) in 2010, the LHC has already demonstrated its capability as a heavy-ion collider and this naturally opens up the possibility of electron-nucleus (e-A) collisions in the LHeC.

This mode of operation would obviously require an interruption of p-p collisions in the LHC. In principle, the CERN complex could provide A-A (or even p-A) collisions to the LHC experiments while the LHeC operates with e-A collisions. The lifetime of the nuclear beam would depend mainly on whether it was exposed to the losses from A-A luminosity in the LHC (in this case it would be at least a few hours).

In the first decade or so of LHC operation, the ion injector chain is expected to provide mainly $^{208}Pb^{82+}$, but also other species such as $^{40}Ar^{18+}$ or $^{129}Xe^{54+}$, either to the LHC or from the SPS to fixed target experiments in the North Area. These beams could also be collided with electrons in the LHeC but solid intensity estimates are not yet available for the lighter ions. For simplicity, we shall estimate LHeC performance in e-Pb collisions with the design performance values of the ion injector chain as r described in [**?**] and the assumption of a single nuclear beam in one ring of the LHC with parameters as recalled from [541] in Table 7.32. It is assumed that present uncertainties about the Pb intensity limits at full energy in the

LHC will have been resolved, if necessary, by installation of new collimators in the dispersion suppressors of the collimation insertions in the LHC. This simplifies the discussion because the design emittances of Pb and proton beams in the LHC are such that both species have the same geometric beam sizes and considerations of optics and aperture can be taken over directly. The required parameters of the Pb beam are given in .

Energy	E_{Pb}	574. TeV
Energy per nucleon	E_N	2.76 TeV
No. of bunches	n_b	592
Ions per bunch	N_{Pb}	$7. \times 10^7$
Normalised emittance	ε_n	$1.5\,\mu$m

Table 7.32: Parameters for the $^{208}\mathrm{Pb}^{82+}$ beam according to Chapter 21 of [541].

Take electron beam parameters can be taken from Table 7.8.

Assume that the injection system can create an electron bunch train matching the 592-bunch train of Pb nuclei in the LHC so that every Pb bunch finds a collision partner in the electron beam. Assuming further that the hadron optics can be adjusted to match the sizes of the electron and Pb beams the luminosity can be expressed in terms of the interaction point optical functions and emittances of the electron beam. Since the e-A physics is focused on low-x these are taken from Table 7.14 describing the High Acceptance optics, which reduces the luminosity by a factor 2 as compared with the High-Luminosity optics. Thus

$$L_{eA} = \frac{n_b f_0 N_{\mathrm{e}} N_{\mathrm{Pb}}}{4\pi\sqrt{\beta^*_{xe}\varepsilon_x}\sqrt{\beta^*_{ye}\varepsilon_y}} = 2.66 \times 10^{28}\,\mathrm{cm}^{-2}\mathrm{s}^{-1} \tag{7.17}$$

corresponding to an electron-nucleon luminosity of

$$L_{eN} = AL_{eA} = 5.5 \times 10^{30}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}. \tag{7.18}$$

It should be noted that Pb single-bunch intensities have already exceeded the design values by 70-80 %, albeit only in the simplified “Early” injection mode. Moreover, by the time the LHeC comes into operation, it is not unreasonable to hope that ways to increase the number of Pb bunches and perhaps to reduce their emittance (by cooling) may be implemented. Therefore, on an optimistic view, the luminosity could be a few times higher than the value quoted here.

In addition, the 592 electron bunches only use 21 % of the power installed for 2808 bunch operation. Increasing the single bunch intensity as far as possible to exploit this would provide a further gain in luminosity. Present experience with beam-beam effects in the LHC suggests that the additional intensity would not present any problem. Indeed the optimum may be to exploit the full RF power with a smaller number of Pb bunches.

Therefore 7.18 should be considered a very conservative estimate with a further order of magnitude in e-A luminosity probably well within reach of the LHeC.

7.10 Spin polarisation – an overview

Before describing concepts for attaining electron and positron spin polarisation for the ring-ring option of the LHeC we present a brief overview of the theory and phenomenology. We can then draw on this later as required. This overview is necessarily brief but more details can be found in [542, 543].

7.10.1 Self polarisation

The spin polarisation of an ensemble of spin–1/2 fermions with the same energies travelling in the same direction is defined as

$$\vec{P} = \langle \frac{2}{\hbar}\vec{\sigma} \rangle \tag{7.19}$$

where $\vec{\sigma}$ is the spin operator in the rest frame and $\langle\ \rangle$ denotes the expectation value for the mixed spin 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". The polarisation is then the average of $\vec{S}$ over an ensemble of particles such as that of a bunch of particles.

Relativistic $e^{\pm}$ circulating in the (vertical) guide field of a storage ring emit synchrotron radiation and a tiny fraction of the photons can cause spin flip from up to down and vice versa. However, the up–to–down and down–to–up rates differ, with the result that in ideal circumstances the electron (positron) beam can become spin polarised anti-parallel (parallel) to the field, reaching a maximum polarisation, P_{st}, 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 dynamical phenomena occurring in storage rings, and the inverse time constant for the exponential build up is [544]:

$$\tau_{\mathrm{st}}^{-1} = \frac{5\sqrt{3}}{8}\frac{r_{\mathrm{e}}\gamma^5\hbar}{m_{\mathrm{e}}|\rho|^3} \tag{7.20}$$

where r_{e} is the classical electron radius, γ is the Lorentz factor, ρ is the radius of curvature in the magnets and the other symbols have their usual meanings. The time constant is usually in the range of a few minutes to a few hours.

However, even without radiative spin flip, the spins are not stationary but precess in the external fields. In particular, the motion of $\vec{S}$ for a relativistic charged particle travelling in electric and magnetic fields is governed by the Thomas-BMT equation $d\vec{S}/ds = \vec{\Omega}\times\vec{S}$ where s is the distance around the ring [543, 545]. The vector $\vec{\Omega}$ depends on the electric ($\vec{E}$) and magnetic ($\vec{B}$) fields, the energy and the velocity ($\vec{v}$) which evolves according to the Lorentz equation:

$$\vec{\Omega} = \frac{e}{m_{\mathrm{e}}c}\left[-\left(\frac{1}{\gamma}+a\right)\vec{B} + \frac{a\gamma}{1+\gamma}\frac{1}{c^2}(\vec{v}\cdot\vec{B})\vec{v} + \frac{1}{c^2}\left(a+\frac{1}{1+\gamma}\right)(\vec{v}\times\vec{E})\right] \tag{7.21}$$

$$= \frac{e}{m_{\mathrm{e}}c}\left[-\left(\frac{1}{\gamma}+a\right)\vec{B}_{\perp} - \frac{g}{2\gamma}\vec{B}_{\parallel} + \frac{1}{c^2}\left(a+\frac{1}{1+\gamma}\right)(\vec{v}\times\vec{E})\right]. \tag{7.22}$$

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 the motion. The coordinate δ is the fractional deviation of the energy from the energy of a synchronous particle ("the beam energy") and l is the distance from the centre of the bunch. The coordinates x and y are the horizontal and vertical positions of the particle relative to the reference trajectory and $p_x = x', p_y = y'$ (except in solenoids) are their conjugate momenta. The quantity g is the appropriate gyromagnetic factor 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 parallel and perpendicular to the velocity.

In a simplified picture, the majority of the photons in the synchrotron radiation do not cause spin flip but tend instead to randomise the $e^{\pm}$ orbital motion in the (inhomogeneous) magnetic fields. Then, if the ring is insufficiently-well geometrically aligned and/or if it contains special magnet systems like the "spin rotators" needed to produce longitudinal polarisation at a detector (see below), the spin-orbit coupling embodied in the Thomas-BMT equation can cause spin diffusion, i.e. depolarisation. Compared to the S-T polarising effect the depolarisation tends to rise very strongly with beam energy. The equilibrium polarisation is then less than 92.4% and will depend on the relative strengths of the polarisation and depolarisation processes. As we shall see later, even without depolarisation certain dipole layouts can reduce the equilibrium polarisation to below 92.4 %.

Analytical estimates of the attainable equilibrium polarisation are best based on the Derbenev-Kondratenko (D-K) formalism [546, 547]. This implicitly asserts that the value of the equilibrium polarisation in an $e^{\pm}$ storage ring is the same at all points in phase space and is given by

$$P_{\mathrm{dk}} \quad = \quad \mp \frac{8}{5\sqrt{3}} \frac{\oint ds \left\langle \frac{1}{|\rho(s)|^3} \hat{b} \cdot (\hat{n} - \frac{\partial \hat{n}}{\partial \delta}) \right\rangle_s}{\oint ds \left\langle \frac{1}{|\rho(s)|^3} (1 - \frac{2}{9} (\hat{n} \cdot \hat{s})^2 + \frac{11}{18} |\frac{\partial \hat{n}}{\partial \delta}|^2) \right\rangle_s} \tag{7.23}$$

where $< >_s$ denotes an average over phase space at azimuth s, $\hat{s}$ is the direction of motion and $\hat{b} = (\hat{s} \times \dot{\hat{s}})/|\dot{\hat{s}}|$. $\hat{b}$ is the magnetic field direction if the electric field vanishes and the motion is perpendicular to the magnetic field. $\hat{n}(u;s)$ is a unit 3-vector field over the phase space satisfying the Thomas-BMT equation along particle 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 C is the circumference of the ring.

The field $\hat{n}(u;s)$ is a key object for systematising spin dynamics in storage rings. It provides a reference direction for spin at each point in phase space and it is now called the *"invariant spin field"* [543, 548, 549]. 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 and away from spin-orbit resonances (see below), $\hat{n}$ is normally at most a few milliradians away from $\hat{n}_0$.

A central ingredient of the D-K formalism is the implicit assumption that the $e^{\pm}$ polarisation at each point in phase space is parallel to $\hat{n}$ at that point. In the approximation that the particles have the same energies and are travelling in the same direction, the polarisation of a bunch measured in a polarimeter at s is then the ensemble average

$$\vec{P}_{\mathrm{ens,dk}}(s) \;=\; P_{\mathrm{dk}} \; \langle \hat{n} \rangle_s \; . \tag{7.24}$$

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 average, $P_{\mathrm{ens,dk}}(s)$, is essentially independent of s.

Equation 7.23 can be viewed as having three components. The piece

$$P_{\mathrm{bk}} \quad = \quad \mp \frac{8}{5\sqrt{3}} \frac{\oint ds \left\langle \frac{1}{|\rho(s)|^3} \hat{b} \cdot \hat{n} \right\rangle_s}{\oint ds \left\langle \frac{1}{|\rho(s)|^3} (1 - \frac{2}{9} (\hat{n} \cdot \hat{s})^2) \right\rangle_s} \approx \mp \frac{8}{5\sqrt{3}} \frac{\oint ds \frac{1}{|\rho(s)|^3} \hat{b} \cdot \hat{n}_0}{\oint ds \frac{1}{|\rho(s)|^3} (1 - \frac{2}{9} n_{0s}^2)} \; . \tag{7.25}$$

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 [550, 551] 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. 7.20 must be replaced by

$$\tau_{\mathrm{dk}}^{-1} \;=\; \frac{5\sqrt{3}}{8}\frac{r_{\mathrm{e}}\gamma^5\hbar}{m_{\mathrm{e}}}\frac{1}{C}\oint ds \left\langle \frac{1-\frac{2}{9}(\hat{n}\cdot\hat{s})^2+\frac{11}{18}|\frac{\partial \hat{n}}{\partial \delta}|^2}{|\rho(s)|^3} \right\rangle_s \;. \tag{7.26}$$

This can be written in terms of the spin-flip polarisation rate, τ_{bk}^{-1}, and the depolarisation rate, τ_{dep}^{-1}, as:

$$\frac{1}{\tau_{\mathrm{dk}}} \;=\; \frac{1}{\tau_{\mathrm{bk}}}+\frac{1}{\tau_{\mathrm{dep}}}\;, \tag{7.27}$$

where

$$\tau_{\mathrm{dep}}^{-1} \;=\; \frac{5\sqrt{3}}{8}\frac{r_{\mathrm{e}}\gamma^5\hbar}{m_{\mathrm{e}}}\frac{1}{C}\oint ds \left\langle \frac{\frac{11}{18}|\frac{\partial \hat{n}}{\partial \delta}|^2}{|\rho(s)|^3} \right\rangle_s \tag{7.28}$$

and

$$\tau_{\mathrm{bk}}^{-1} \;=\; \frac{5\sqrt{3}}{8}\frac{r_{\mathrm{e}}\gamma^5\hbar}{m_{\mathrm{e}}}\frac{1}{C}\oint ds \left\langle \frac{1-\frac{2}{9}(\hat{n}\cdot\hat{s})^2}{|\rho(s)|^3} \right\rangle_s \;. \tag{7.29}$$

The time dependence for build-up from an initial polarisation P_0 to equilibrium is

$$P(t) \;=\; P_{\mathrm{ens,dk}}\left[1-e^{-t/\tau_{\mathrm{dk}}}\right]+P_0 e^{-t/\tau_{\mathrm{dk}}}\;. \tag{7.30}$$

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

$$\nu_0 \;=\; k_0+k_I Q_I+k_{II}Q_{II}+k_{III}Q_{III}\;. \tag{7.31}$$

Here $k_0, k_I, k_{II}, k_{III}$ are integers, Q_I, Q_{II}, Q_{III} are the three tunes of the synchrobetatron 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 the closed orbit [1]. In the special case, or in the approximation, of no synchrobetatron coupling one can make the associations: $I \rightarrow x$, $II \rightarrow y$ and $III \rightarrow s$, where, here, the subscript s labels the synchrotron mode. In a simple flat ring with no closed-orbit distortion, $\nu_0 = a\gamma$ where γ is the Lorentz factor for the nominal beam energy. For $e^{\pm}$, $a\gamma$ increments by 1 for every 441 MeV increase in beam energy. In the presence of misalignments and special elements like rotators, ν_0 is usually still approximately proportional to the beam energy. Thus an energy scan will show peaks in $\tau_{\rm dep}^{-1}$ and dips in $P_{\rm ens,dk}(s)$, namely at around the resonances. Examples can be seen in figures 7.45 and 7.46 below. The resonance condition expresses the fact that the disturbance to spins is greatest when the $|\vec{\Omega}(u;s) - \vec{\Omega}(0;s)|$ along a trajectory is coherent ("in step") with the natural spin precession. The quantity $(|k_{_I}| + |k_{_{II}}| + |k_{_{III}}|)$ is called the order of the resonance. Usually, the strongest resonances are those for which $|k_{_I}| + |k_{_{II}}| + |k_{_{III}}| = 1$, i.e. the first-order resonances. The next strongest are usually the so-called *"synchrotron sideband resonances"* of parent first-order resonances, i.e. 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 synchrotron motion. All resonances are due to the non-commutation of successive spin rotations in 3-D and they therefore occur even with purely linear orbital motion.

We now list some keys points.

- The approximation on the r.h.s. of Eq. 7.25 makes it clear that if there are dipole magnets with fields not parallel to $\hat{n}_0$, as is the case, for example, when spin rotators are used, then $P_{\rm bk}$ can be lower than the 92.4% achievable in the case of a simple ring with no solenoids and where all dipole fields and $\hat{n}_0(s)$ are vertical.

- If, as is usual, the kinetic polarisation term makes just a small contribution, the above formulae can be combined to give

$$P_{\rm ens,dk} \quad \approx \quad P_{\rm bk} \frac{\tau_{\rm dk}}{\tau_{\rm bk}} \ . \tag{7.32}$$

  ¿From Eq. 7.27 it is clear that $\tau_{\rm dk} \leq \tau_{\rm bk}$.

- The underlying rate of polarisation due to the S-T effect, $\tau_{\rm bk}^{-1}$, increases with the fifth power of the energy and decreases with the third power of the bending radii.

- It can be shown that as a general rule the "normalised" strength of the depolarisation, $\tau_{\rm dep}^{-1}/\tau_{\rm bk}^{-1}$, increases with beam energy according to a tune-dependent polynomial in even powers of the beam energy. So we expect that the attainable equilibrium polarisation decreases as the energy increases. This was confirmed LEP, where with the tools available, little polarisation could be obtained at 60 GeV [552].

7.10.2 Suppression of depolarisation – spin matching

Although the S-T effect offers a convenient way to obtain stored high energy $e^{\pm}$ beams, it is only useful in practice if there is not too much depolarisation. Depolarisation can be significant if the ring is misaligned, if it contains spin rotators or if it contains uncompensated solenoids or skew quadrupoles. Then if $P_{\rm ens,dk}$ and/or $\tau_{\rm dk}$ are too small, the layout and the optic must

[1] In fact the resonance condition should be more precisely expressed in terms of the so-called amplitude dependent spin tune [543, 548, 549]. But for typical $e^{\pm}$ rings, the amplitude dependent spin tune differs only insignificantly from ν_0.

be adjusted so that $(|\frac{\partial \hat{n}}{\partial \delta}|)^2$ is small where $1/|\rho(s)|^3$ is large. So far it is only possible to do this within the linear approximation for spin motion. This technique is called *"linear spin matching"* and when successful, as for example at HERA [553], it immediately reduces the strengths of the first-order spin-orbit resonances. Spin matching requires two steps: *"strong synchrobeta spin matching"* is applied to the optics and layout of the perfectly aligned ring and then *"harmonic closed-orbit spin matching"* is applied to soften the effects of misalignments. This latter technique aims to adjust the closed orbit so as to reduce the tilt of $\hat{n}_0$ from the vertical in the arcs. Since the misalignments can vary in time and are usually not sufficiently well known, the adjustments are applied empirically while the polarisation is being measured.

Spin matching must be approached on a case–by–case basis. An overview can be found in [542].

7.10.3 Higher order resonances

Even if the beam energy is chosen so that first-order resonances are avoided and in linear approximation $P_{\rm ens,dk}$ and/or $\tau_{\rm dk}$ 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 $\tau^{-1}_{\rm dep}$ in the form

$$\tau^{-1}_{\rm dep} \propto \frac{A_y}{(\nu_0 - k_0 \pm Q_y)^2} \ . \tag{7.33}$$

This becomes

$$\tau^{-1}_{\rm dep} \propto \sum_{\tilde{k}_s=-\infty}^{\infty} \frac{A_y\, B_y(\zeta; \tilde{k}_s)}{\left(\nu_0 - k_0 \pm Q_y \pm \tilde{k}_s\, Q_s\right)^2}$$

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 [554, 555].

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 $\tau^{-1}_{\rm dep}/\tau^{-1}_{\rm bk}$ with energy.

7.10.4 Spin rotators

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. 7.25, $\hat{n}_0$ must be close to vertical in most of the dipoles. We have seen at Eq. 7.24 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: $\delta\theta_{\rm spin} = (a\gamma + 1)\delta\theta_{\rm orb}$ in obvious notation. Thus for the high-energy ring considered here, spin rotators should be based on dipoles as in HERA [553]. 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. 7.25 shows that $P_{\rm bk}$ 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 $P_{\rm bk}$ 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.

7.10.5 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 which agrees well with the on-momentum emittance calculated by MadX. 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, $\tau_{\rm bk} \approx 60$ minutes.

For the simple flat ring these values can be obtained by hand from Eq. 7.25 and Eq. 7.29. 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 [556]. 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 [557]) of the SLIM algorithm [542].

The equilibrium polarisation is then obtained from Eq. 7.23. 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. 7.28 beyond first order represents a difficult computational problem. Therefore a pragmatic approach is adopted, whereby the rate of depolarisation 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. 7.32.

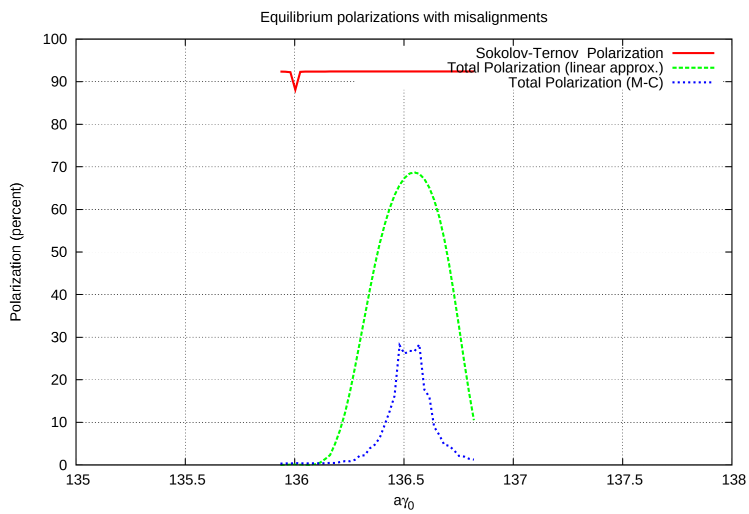

Figure 7.45: Estimated polarisation for the LHeC without spin rotators, $Q_s = 0.06$.

Some basic features of the polarisation for the misaligned flat ring are shown in figures 7.45 and 7.46 where polarisations are plotted against $a\gamma$ around 60 GeV. In both cases the r.m.s. vertical closed-orbit deviation is about 75μm. This is obtained after giving the quadrupoles r.m.s. vertical misalignments of 150μm 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 7.45 the synchrotron tune, Q_s, is 0.06 so that $\xi \approx 5$. For figure 7.46, $Q_s = 0.1$ so that $\xi \approx 1.9$.

The red curves depict the polarisation due to the Sokolov-Ternov effect alone. The dip to below 92.4 % at $a\gamma = 136$ is due to the characteristic very large tilt of $\hat{n}_0$ from the vertical at an integer value of $a\gamma$. See [542].

The green curves depict the equilibrium polarisation after taking into account the depolarisation associated with the misalignments and the consequent tilt of $\hat{n}_0$. The polarisation is calculated with the linearised spin motion as in item 3 above. In these examples the polarisation reaches about 68 %. The strong fall off 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 small these curves are similar for the two values of Q_s.

The blue curves show the polarisation obtained as in item 4 above. Now, by going beyond the linearisation of the spin motion, the peak polarisation is about 27 %. The fall from 68 %

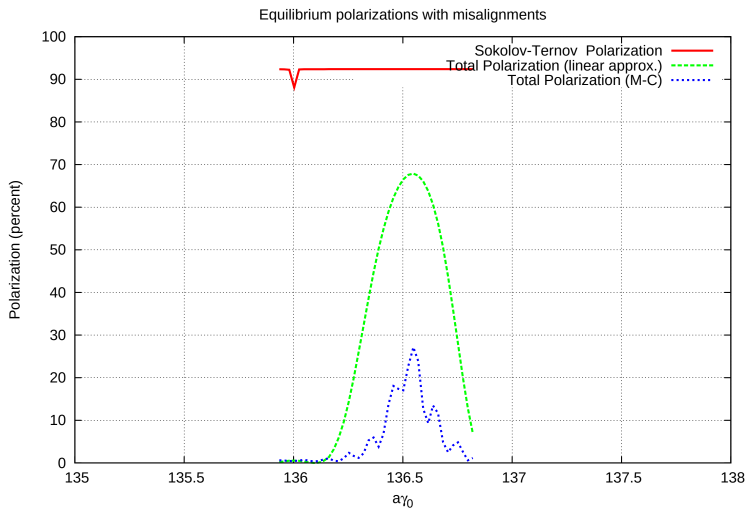

Figure 7.46: Estimated polarisation for the LHeC without spin rotators, $Q_s = 0.1$.

is mainly due to synchrotron sideband resonances. With $Q_s = 0.06$ (Fig. 7.45) the resonances are overlapping. With $Q_s = 0.1$, (Fig. 7.46) the sidebands begin to separate. In any case these curves demonstrate the extreme sensitivity of the attainable polarisation to small tilts of $\hat{n}_0$ at high energy. Simulations for $Q_s = 0.1$ with a series of differently misaligned rings, all with r.m.s. vertical closed-orbit distortions of about 75μm, exhibit peak equilibrium polarisations ranging from about about 10 % to about 40 %. Experience at HERA suggests that harmonic closed-orbit spin matching can eliminate the cases of very low polarisation.

Figure 7.47 shows a typical energy dependence of the peak equilibrium polarisation for a fixed rf voltage and for one of the misaligned rings. The synchrotron tune varies from $Q_s = 0.093$ at 40 GeV to $Q_s = 0.053$ at 65 GeV due to the change in energy loss per turn. As expected the attainable polarisation falls steeply as the energy increases. However, although with this good alignment, a high polarisation is predicted at 45 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.

As mentioned above it was difficult to get polarisation at 60 GeV at LEP. However, these calculations suggest that by adopting the levels of alignment that are now standard for synchrotron-radiation sources and by applying harmonic closed-orbit spin matching, there is reason to hope that high polarisation in a flat ring can still be obtained.

7.10.6 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.

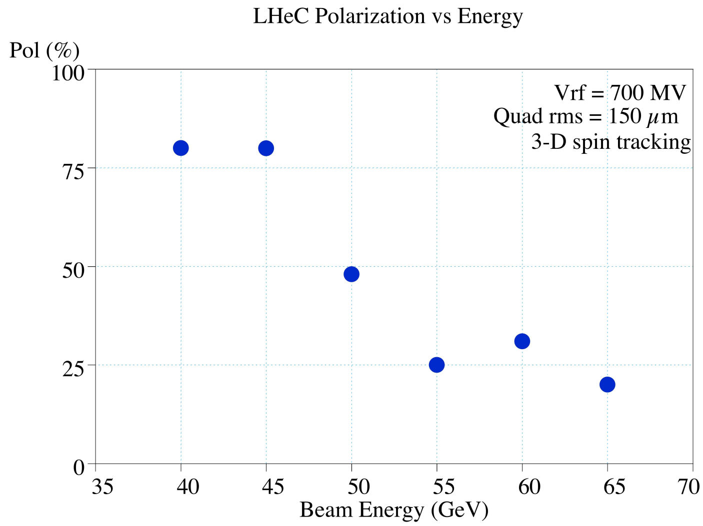

Figure 7.47: Equilibrium polarisation *vs* ring energy, full 3-D spin tracking results

(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.

(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 [558] 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. 7.25 shows that $P_{\rm bk}$ vanishes. In principle, this problem can be overcome for two snakes by again appealing to Eq. 7.25 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. 7.25 shows that the pure Sokolov-Ternov polarisation would be much less than 92.4%. One version of this concept [559] 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 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.

7.10.7 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 150μm 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 synchrotron sideband resonances is being investigated. At present, this appears to potentially yield a similar degree of polarisation, at the expense of increased energy dissipation in the arcs arising from the required differences of the bending radii in the two halves of the machine.

7.11 Integration and machine protection issues

7.11.1 Space requirements

The integration of an additional electron accelerator into the LHC is a difficult task. For once,the LEP tunnel was designed for LEP and not for the LHC, which is now using up almost all space in the tunnel. It is not evident, how to place another accelerator into the limited space. Secondly, the LHC will run for several years, before the installation of a second machine can start. Meanwhile the tunnel will be irradiated and all installation work must proceed as fast as possible to limit the collective and individual doses. The activation after the planned high-luminosity-run of the LHC and after one month of cool-down is expected to be around 0.5...1$\mu Sv/h$ [**?**] on the proton magnets and many times more at exposed positions. Moreover the time windows for installation will be short and other work for the LHC will be going on, maybe with higher priority. Nevertheless, with careful preparation and advanced installation schemes an electron accelerator can be fitted in.

So far all heavy equipment had to pass the UJ2, while entering the tunnel. There the equipment has to be moved from TI2, which comes in from the outside, to the transport zone of LHC, which is on the inner side of the ring. Clearly, everything above the cold dipoles has to be removed. The new access shafts and the smaller size of the equipment for the electron ring may render this operation unnecessary.

General The new electron accelerator will be partially in the existing tunnel and partially in specially excavated tunnel sections and behind the experiments in existing underground areas. The excavation work will need special access shafts in the neighborhood of the experiments from where the stub-tunnels can be driven. The connection to the existing LEP tunnels will be very difficult. The new tunnel enters with a very small grazing angle, which means over a considerable length. Very likely the proton installation will have to be removed while the last meters of the new tunnel is bored.

Figure 7.48 [?] shows a typical cross section of the LHC tunnel, where the two machines are together. The LHC dipole dominates the picture. The transport zone is indicated at the right (inside of the ring). The cryogenic installations (QRL) and various pipes and cable trays are on the left. The dipole cross section shows two concentric circles. The larger circle corresponds to the largest extension at the re-enforcement rings and marks a very localized space restriction on a very long object. The inner circle is relevant for items shorter than about 10 m longitudinally. A hatched square above the dipole labeled *30* indicates the area, which was kept free in the beginning for an electron machine. Unfortunately, the center of this space is right above the proton beam. Any additional machine will, however, have to avoid the interaction points 1 and 5. In doing so additional length will be necessary, which can only be compensated for by shifting the electron machine in the arc about 60 cm to the inside (right). The limited space for compensation puts a constraint on the extra length created by the bypasses. The transport zone will, however, be affected. This requires an unconventional way to mount the electron machine. Nevertheless, there is clearly space to place an electron ring into the LHC, for most of the arc. Figure 7.49 gives the impression that the tunnel for most of its length is not too occupied.

In the arc In Fig. 7.49 one sees the chain of superconducting magnets and in the far distances the *QRL Service Module* with its jumper, the cryogenic connection between the superconducting machine and the cryogenic distribution line. The service modules come always at the position of every second quadrupole and have a substantial length. The optics of the LHeC foresees no e-ring magnet at these positions. A photo of service modules in the workshop is shown in figure 7.50 (courtesy CERN). The picture 7.49, taken in sector 3, shows also the critical tunnel condition in this part of the machine. Clearly, heavy loads cannot be suspended from the tunnel ceiling. The limit is set to 100 kg per meter along the tunnel. The e-ring components have to rest on stands from the floor wherever possible. See **??** on page **??**. Normally there is enough space between the LHC dipoles and the QRL to place a vertical 10 cm quadratic or rectangular support. Alternatively a steel arch bolted to the tunnel walls and resting on the floor can support the components from above. This construction is required wherever the space for a stand is not available.

The electron machine, though partially in the transport zone, will be high up in the tunnel, high enough not to interfere with the transport of a proton magnet or alike. The transport of cryogenic equipment may need the full hight. Transports of that kind will only happen, when part of the LHC are warmed up. This gives enough time to shift the electron ring to the outside by 30 cm, if the stands are prepared for this operation. The outside movement causes also a small elongation of the inter-magnet connections. This effect is locally so small that the expansion joints, required anyway, can accommodate it. One could even think of moving large sections of the e-machine outwards in a semi-automatic way. Thus the time to clear the transport path can be kept in the shadow of the warm-up and cool-down times.

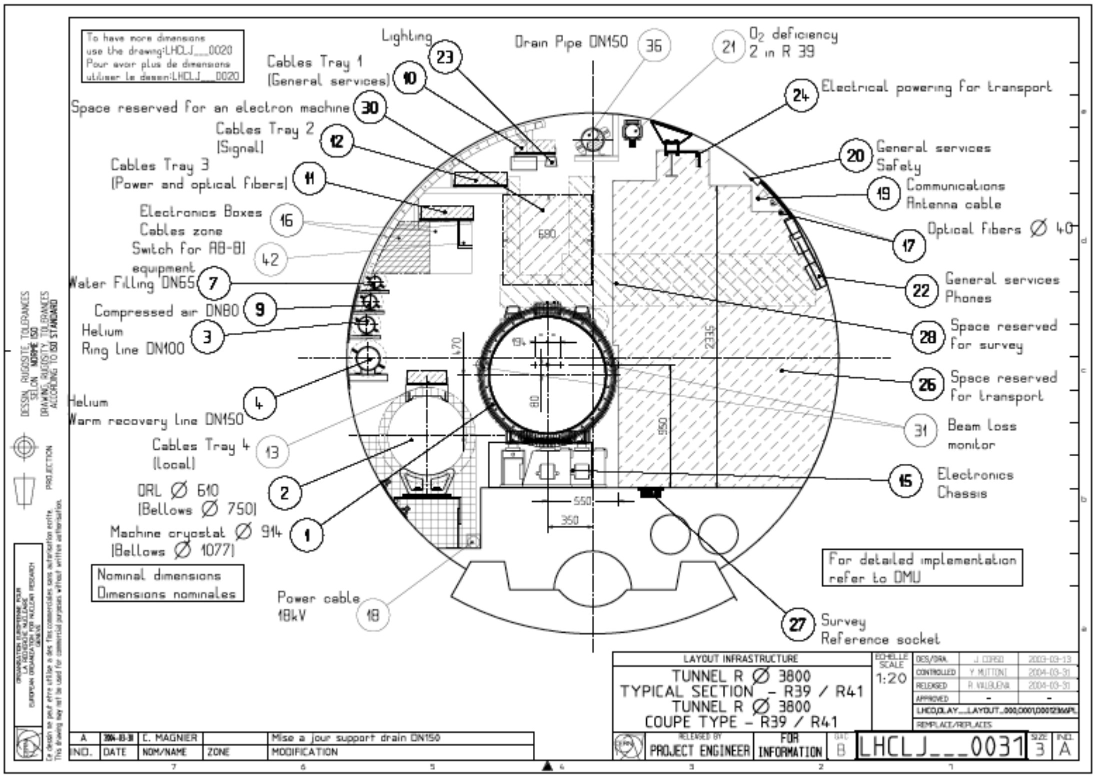

Figure 7.48: Cross-section of the LHC tunnel [?]

Dump area The most important space constraints for the electron machine are in the proton dump area, the proton RF cavities, point 3, and in particular the collimator sections.

Figure 7.51 [**?**] shows the situation at the dump kicker. The same area is also shown in a photo in Figure 7.52, while Figure 7.53 shows one of the outgoing dump-lines. The installation of the e-machine requires the proper rerouting of cables (which might be damaged by radiation and in need of exchange anyhow), eventually turning of pumps by 90 degrees or straight sections in the electron optics to bridge particularly difficult stretches with a beam pipe only.

Point 4, proton RF The Figures 7.54 [**?**] and 7.55 illustrate the situation at the point 4, where the LHC RF is installed. Fortunately, the area is not very long. A short straight section could be created for the electron ring. This would allow to pass the area with just a shielded beam pipe.

Cryolink in point 3 The geography around point 3 did not permit to place there a cryoplant. The cryogenic cooling for the feedboxes is provided by a cryolink, as is shown in the figures 7.56 and 7.57. In particular above the Q6 proton quadrupole changes have to be made. There are other interferences with the cryogenics, as for example at the DFBAs (main feedboxes). An example is shown in figure 7.58. Eventually the electron optics has to be adapted to allow the

Figure 7.49: View of sector 4.

Figure 7.50: Sideview of a QRL service module with the jumper

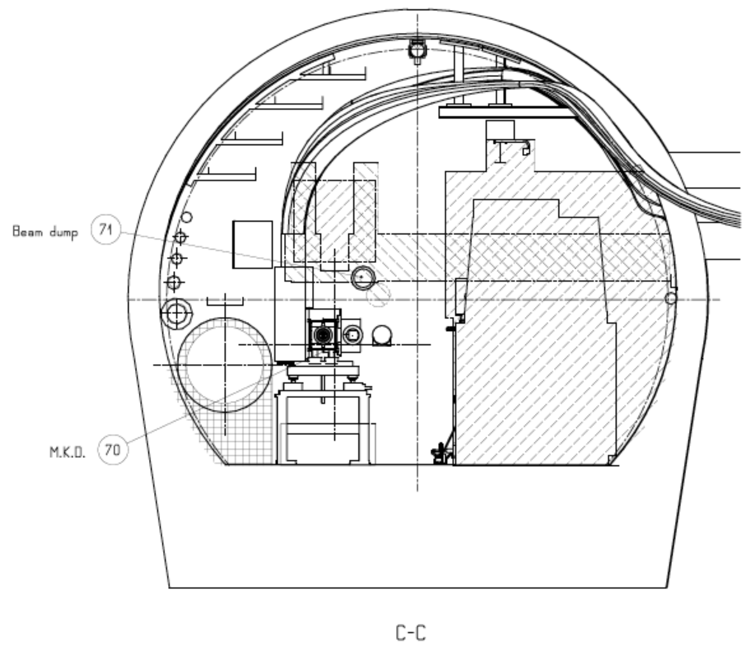

Figure 7.51: Dump kicker [?]

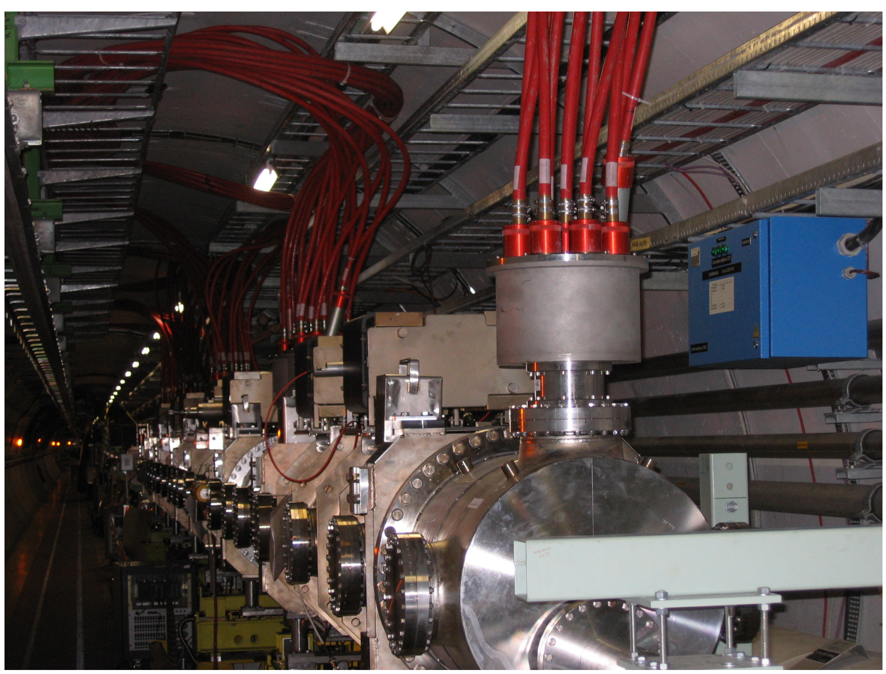

Figure 7.52: Dump kicker

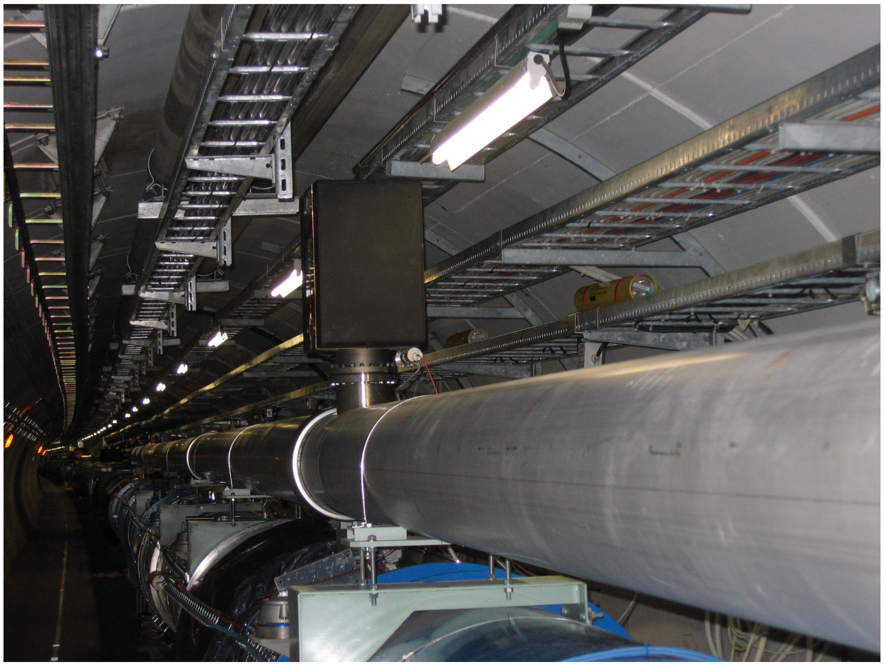

Figure 7.53: Dump line

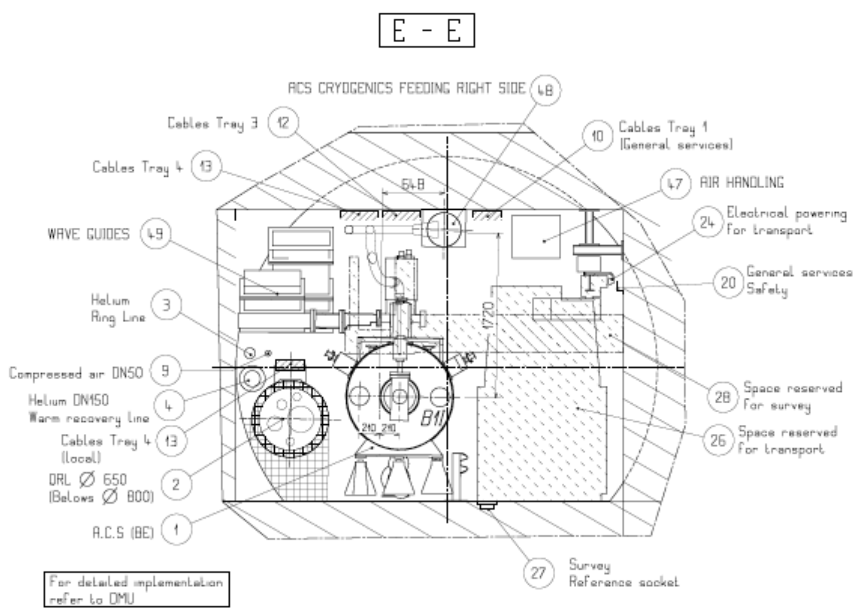

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Figure 7.54: Proton RF in point 4 [?]

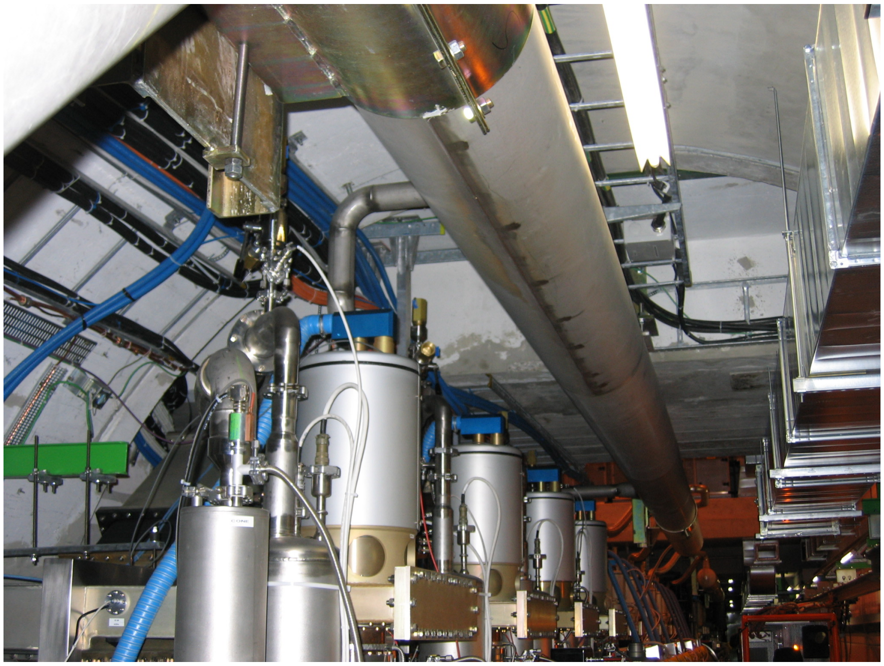


Figure 7.55: Point 4

beampipe to pass the cables, which may have to be moved a bit.

Long straight section 7 An extra air duct is mounted in the long straight section 7 (LSS7) as is indicated in Fig. 7.59 avoiding the air pollution of the area above point 7. The duct occupies the space planned for the electron machine. The air duct has to be replaced by a slightly different construction mounted further outside (to the right in the figure). There are also air ducts at points 1 and 5, but they are not an issue. The electron ring is passing behind the experiments in these points

Proton collimation The areas around point 3 (-62...+177m) and point 7 (-149...+205m) [**?**] are heavily used for the collimation of the proton beam. The high dose rate in the neighborhood of a collimator makes special precautions for the installation of new components or the exchange of a collimator necessary. Moreover, the collimator installation needs the full hight of the tunnel. Hence, the e-installation has to be suspended from the re-enforced tunnel roof. The e-machine components must be removable and installable, easy and fast. The re-alignment must be well prepared and fast, possibly in a remote fashion. It is uncommon to identify fast mounting and demounting as a major issue. However, with sufficient emphasis during the R&D phase of the project, this problem can be solved.

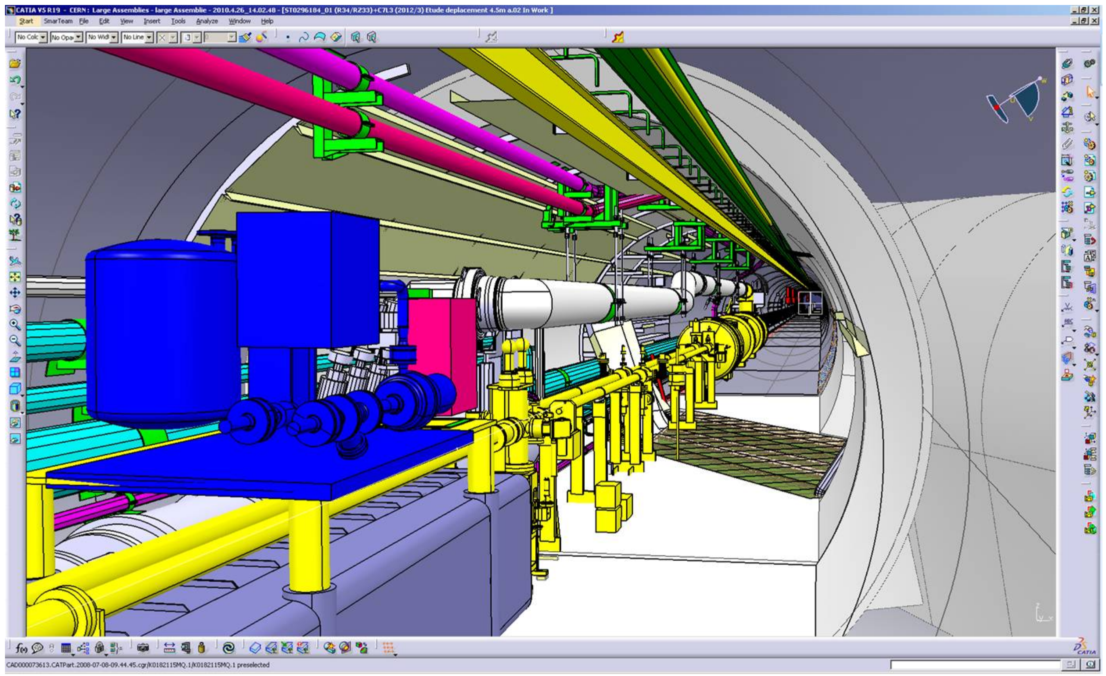


Figure 7.56: The cryogenic connection in point 3

7.11.2 Impact of the synchrotron radiation on tunnel electronics

It is assumed that the main power converters of the LHC will have been moved out of the RRs because of the single event upsets, caused by proton losses.

The synchrotron radiation has to be intercepted at the source, as in all other electron accelerators. A few millimeter of lead are sufficient for the relatively low (critical) energies around 100 to 200 keV. The K-edge of lead is at 88 keV, the absorption coefficient is above 80/cm at this energy [**?**]. One centimeter of lead is sufficient to suppress 300 keV photons by a factor of 100. Detailed calculations of the optics will determine the amount of lead needed in the various places. The primary shielding needs an effective water cooling to avoid partial melting of the lead.

The electronics is placed below the proton magnets. Only backscattered photons with correspondingly lower energy will reach the electronics. If necessary, a few millimeter of extra shielding could be added here.

The risk for additional single event upsets due to synchrotron radiation is negligible.

7.11.3 Compatibility with the proton beam loss system

The proton beam loss monitoring system works very satisfactory. It has been designed to detect proton losses by observing secondaries at the outside of the LHC magnets. The sensors are ionization chambers. Excessive synchrotron radiation (SR) background will presumably trigger the system and dump the proton beam. The SR background at the monitors has to be reduced by careful shielding of either the monitors or the electron ring. Alternatively, the

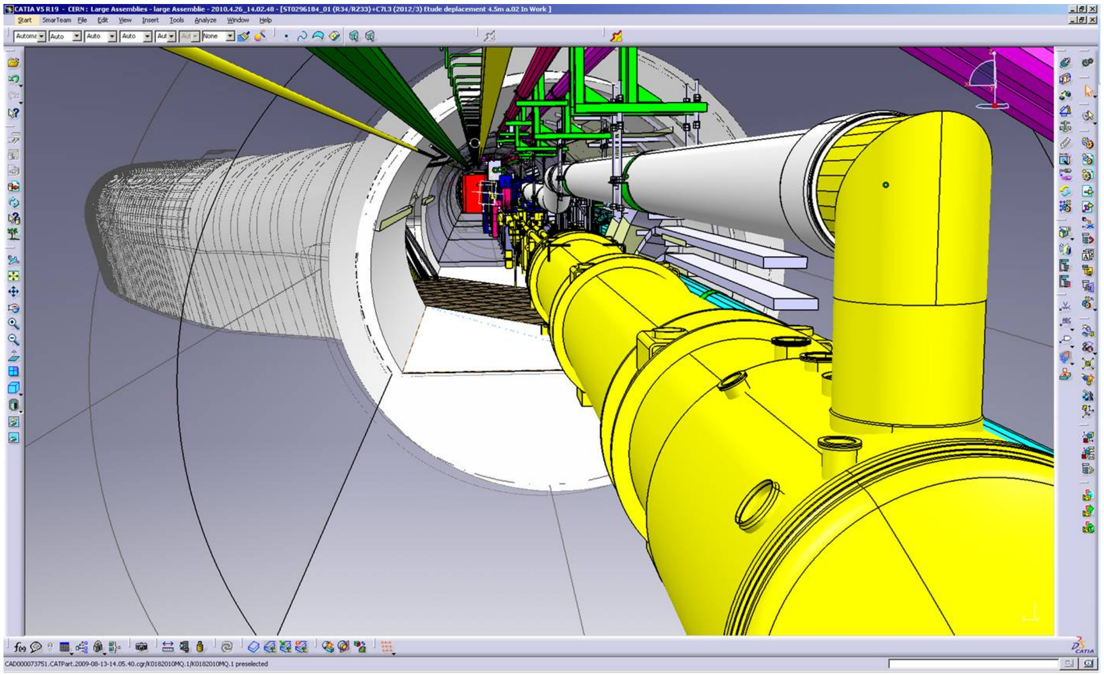


Figure 7.57: The cryogenic connection in point 3

impact of the photon background can be reduced by using a new loss monitoring system which is based on coincidences (as was done elsewhere [**?**]).

7.11.4 Space requirements for the electron dump

7.11.5 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. [?], 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.

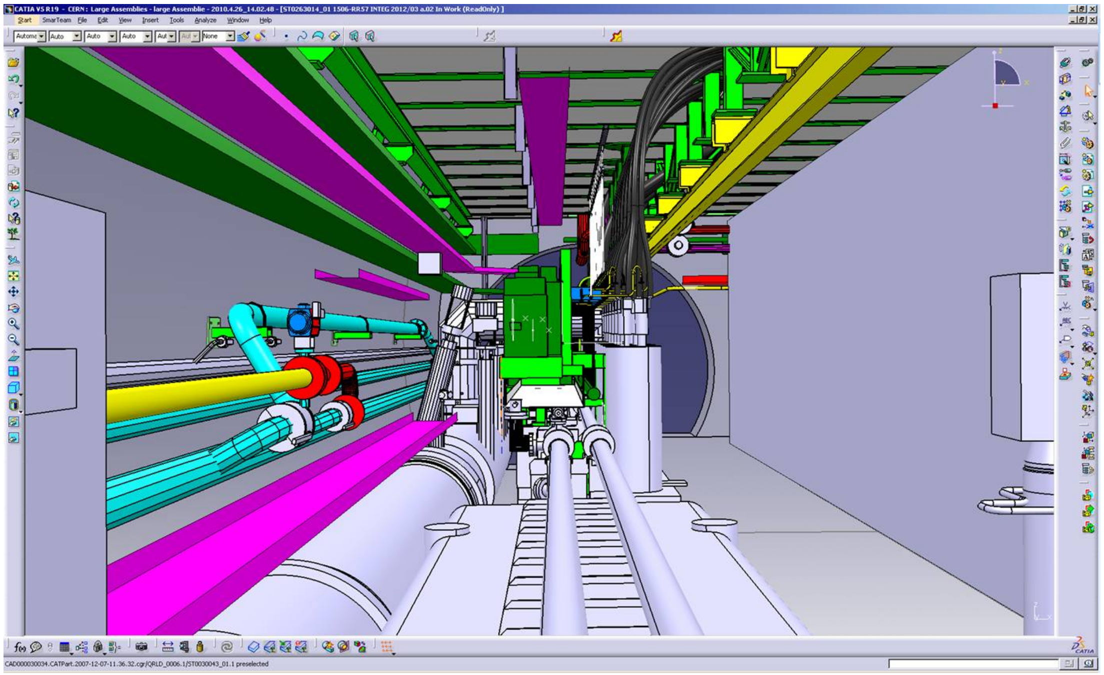


Figure 7.58: A typical big current feedbox (DFBA)

7.11.6 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 situation. This requirement lead to a very modular architecture, which could be expanded to include the electron accelerator.

7.12 LHeC Injector for the Ring-Ring option

Figure 10.27 shows the layout of the LPI (LEP Pre-Injector) as it was working in 2000.

LPI was composed of the LIL (LEP Injector Linac) and the EPA (Electron Positron Accumulator).

Table 10.18 gives the beam characteristics at the end of LIL.

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 7.33: LIL beam parameters.

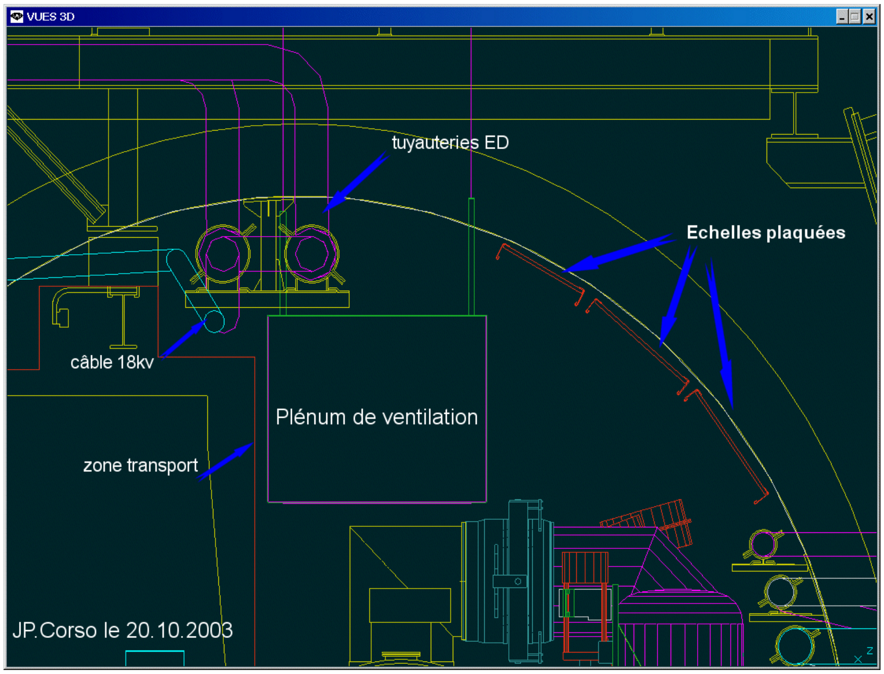


Figure 7.59: Air-duct in LSS7 [?]

Figure 10.28 shows an electron beam profile at the end of LIL (500 MeV).
Table 10.19 gives the electron and positron beam parameters at the exit of EPA.

Energy	200 to 600 MeV
Charge	up to $4.5 \times 10^{11} e\pm$
Intensity	up to 0.172 A
Number of buckets	1 to 8
Emittance	0.1 mm.mrad
Tune	$Q_x = 4.537, Q_y = 4.298$

Table 7.34: The electron and positron beam parameters at the exit of EPA.

In summary, the LPI characteristics fulfils completely the requested performance for the LHeC injector based on Ring-Ring option.

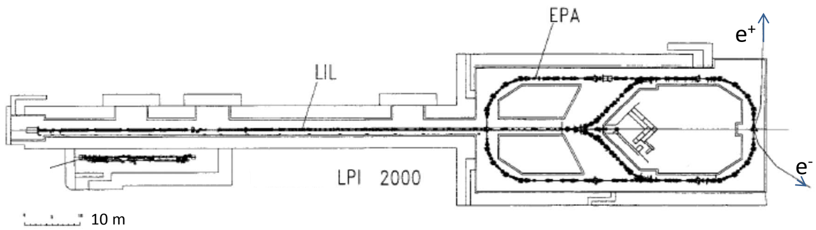


Figure 7.60: Layout of the LPI in 2000.

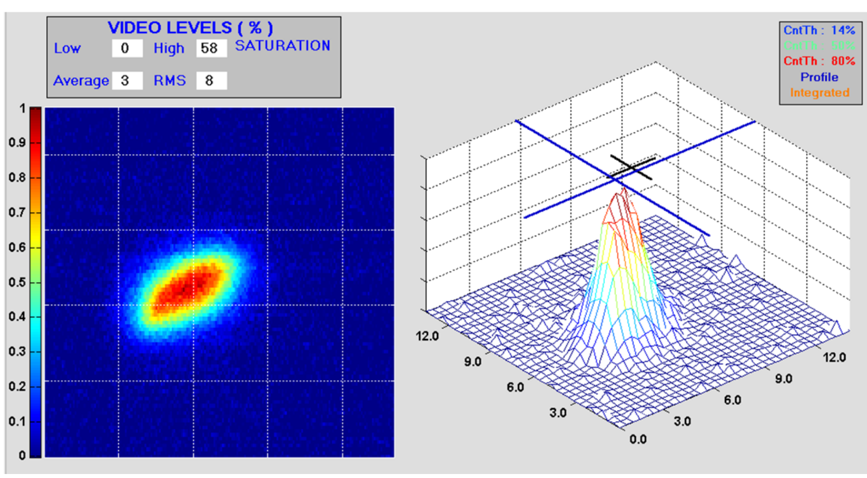


Figure 7.61: Electron beam profile at 500 MeV.

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) radiofrequency (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 DESY XFEL, 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 [560]. 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.

The development of a CW SC recirculating energy-recovery linac (ERL) for LHeC would prepare the ground, the technology and the infrastructure for many possible future projects, e.g., for an International Linear Collider, for a Muon Collider[1], for a neutrino factory, or for a proton-driven plasma wake field accelerator. A ring-linac LHeC would, therefore, promote any conceivable future high-energy physics project, while pursuing an attractive forefront high-energy physics programme in its own right.

8.1.2 ERL Performance and Layout

Particle physics imposes the following performance requirements. The lepton beam energy should be 60 GeV or higher and the electron-proton luminosity of order 10^{33} cm^{-2}s^{-1}. Positron-proton collisions are also required, with at least a few percent of the electron-proton luminosity. Since the LHeC should operate simultaneously with LHC *pp* physics, it should not degrade the *pp* luminosity. Both electron and positron beams should be polarized. Lastly, the detector acceptance should extend down to 1° or less. In addition, the total electrical power for the lepton branch of the LHeC collider should stay below 100 MW.

For round-beam collisions, the luminosity of the linac-ring collider [561] is written as

$$L = \frac{1}{4\pi e} \frac{N_{b,p}}{\epsilon_p} \frac{1}{\beta_p^*} I_e H_{hg} H_D \ , \tag{8.1}$$

where e denotes the electron charge, $N_{b,p}$ the proton bunch population, β_p^* the proton IP beta function, I_e the average electron beam current, H_{hg} the geometric loss factor arising from crossing angle and hourglass effect, and H_D the disruption enhancement factor due to the electron pinch in collision, or luminosity reduction factor from the anti-pinch in the case of positrons. In the above formula, it is assumed that the electron bunch spacing is a multiple of the proton beam bunch spacing. The latter could be equal to 25, 50 or 75 ns, without changing the luminosity value.

The ratio $N_{b,p}/\epsilon_p$ is also called the proton beam brightness. Among other constraints, the LHC beam brightness is limited by the proton-proton beam-beam limit. For the LHeC design we assume the brightness value obtained for the ultimate bunch intensity, $N_{p,p} = 1.7 \times 10^{11}$, and the nominal proton beam emittance, $\epsilon_p = 0.5$ nm ($\gamma\epsilon_p = 3.75$ μm). This corresponds to a total *pp* beam-beam tune shift of 0.01. More than two times higher values have already been demonstrated, with good *pp* luminosity lifetime, during initial LHC beam commissioning, indicating a potential for higher *ep* luminosity.

To maximize the luminosity the proton IP beta function is chosen as 0.1 m. This is considerable smaller than the 0.55 m for the *pp* collisions of the nominal LHC. The reduced beta function can be achieved by reducing the free length between the IP and the first proton quadrupole (10

[1]The proposed Muon Collider heavily relies on SC recirculating linacs for muon acceleration as well as on a SC-linac proton driver.

m instead of 23 m), and by squeezing only one of the two proton beams, namely the one colliding with the leptons, which increases the aperture available for this beam in the last quadrupoles. In addition, we assume that the final quadrupoles could be based on Nb_3Sn superconductor technology instead of Nb-Ti. The critical field for Nb_3Sn is almost two times higher than for Nb-Ti, at the same temperature and current density, allowing for correspondingly larger aperture and higher quadrupole gradient. Nb_3Sn quadrupoles are presently under development for the High-Luminosity LHC upgrade (HL-LHC).

The geometric loss factor H_{hg} needs to be optimized as well. For round beams with $\sigma_{z,p} \gg \sigma_{z,e}$ (well fulfilled for $\sigma_{z,p} \approx 7.55$ cm, $\sigma_{z,e} \approx 300$ μm) and $\theta_c \ll 1$, it can be expressed as[2]

$$H_{hg} = \frac{\sqrt{\pi} z e^{z^2} \mathrm{erfc}(z)}{S} \,, \tag{8.2}$$

where

$$z \quad \equiv \quad 2 \frac{(\beta_e^*/\sigma_{z,p})(\epsilon_e/\epsilon_p)}{\sqrt{1+(\epsilon_e/\epsilon_p)^2}} S$$

and

$$S \quad \equiv \quad \sqrt{1 + \frac{\sigma_{x,p}^2 \theta_c^2}{8 \sigma_p^{*\,2}}} \,.$$

Luminosity loss from a crossing angle is avoided by head-on collisions. The luminosity loss from the hourglass effect, due to the long proton bunches and potentially small electron beta functions, is kept small, thanks to a “small” linac electron beam emittance of 0.43 nm ($\gamma\epsilon_e =$ 50 μm). We note that the assumed electron-beam emittance, though small when compared with a storage ring of comparable energy, is still very large by linear-collider standards.

The disruption enhancement factor for electron-proton collisions is about $H_D \approx 1.35$, according to Guinea-Pig simulations [564] and a simple estimate based on the fact that the average rms size of the electron beam during the collision approaches a value equal to $1/\sqrt{2}$ of the proton beam size. This additional luminosity increase from disruption is not taken into account in the numbers given below. On the other hand, for positron-proton collisions the disruption of the positrons leads to a significant luminosity reduction, by roughly a factor $H_D \approx 0.3$, similar to the case of electron-electron collisions [565].

The final parameter determining the luminosity is the average electron (or positron) beam current I_e. It is closely tied to the total electrical power available (taken to be 100 MW).

Crossing Angle and IR Layout

The colliding electron and proton beams need to be separated by 7 cm at a distance of 10 m from the IP in order to enter through separate holes in the first proton quadrupole magnet. This separation could be achieved with a crossing angle of 7 mrad and crab cavities. The required crab voltage would, however, need to be of order 200 MV, which is 20–30 times the voltage needed for *pp* crab crossing at the HL-LHC. Therefore, crab crossing is not considered

[2] The derivation of this formula is similar to the one for the LHC in Ref. [562], 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 [563].

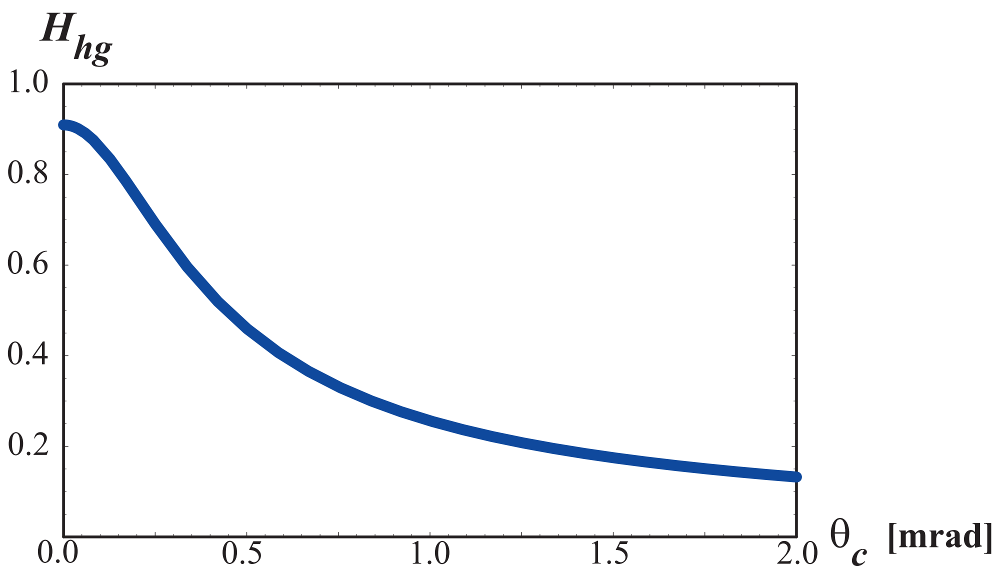


Figure 8.1: Geometric luminosity loss factor H_{hg}, (8.2), as a function of the total crossing angle

an option for the L-R LHeC. Without crab cavities, any crossing angle should be smaller than 0.3 mrad, as is illustrated in Fig. 8.1. Such small a crossing angle is not useful, compared with the 7 mrad angle required for the separation. The R-L interaction region (IR), therefore, uses detector-integrated dipole fields around the collision point, to provide head-on *ep* collisions ($\theta_c = 0$ mrad) and to separate the beams by the required amount. A dipole field of about 0.3 T over a length of ± 9 m accomplishes these goals.

The IR layout with separation dipoles and crossing angle is sketched in Fig. 8.2. Significant synchrotron radiation, with 48 kW average power, and a critical photon energy of 0.7 MeV, is emitted in the dipole fields. A large portion of this radiation is extracted through the electron and proton beam pipes. The SC proton magnets can be protected against the radiation heat load by an absorber placed in front of the first quadrupole and by a liner inside the beam pipe. Backscattering of synchrotron radiation into the detector is minimized by shaping the surface of absorbers and by additional masking.

The separation dipole fields modify, and enhance, the geometric acceptance of the detector. Figure 8.3 illustrates that scattered electrons with energies of 10–50 GeV might be detected at scattering angles down to zero degrees.

Electron Beam and the Case for Energy Recovery

The electron-beam emittance and the electron IP beta function are not critical, since the proton beam size is large by electron-beam standards (namely about 7 μm rms compared with nm beam-sizes for linear colliders). The most important parameter for high luminosity is the average beam current, I_e, which linearly enters into the luminosity formula (8.1). In addition to the electron beam curent, also the bunch spacing (which should be a multiple of the LHC 25-ns proton spacing) and polarization (80–90% for the electrons) need to be considered. Having pushed all other parameters in (8.1), Fig. 8.4 illustrates that an average electron current of

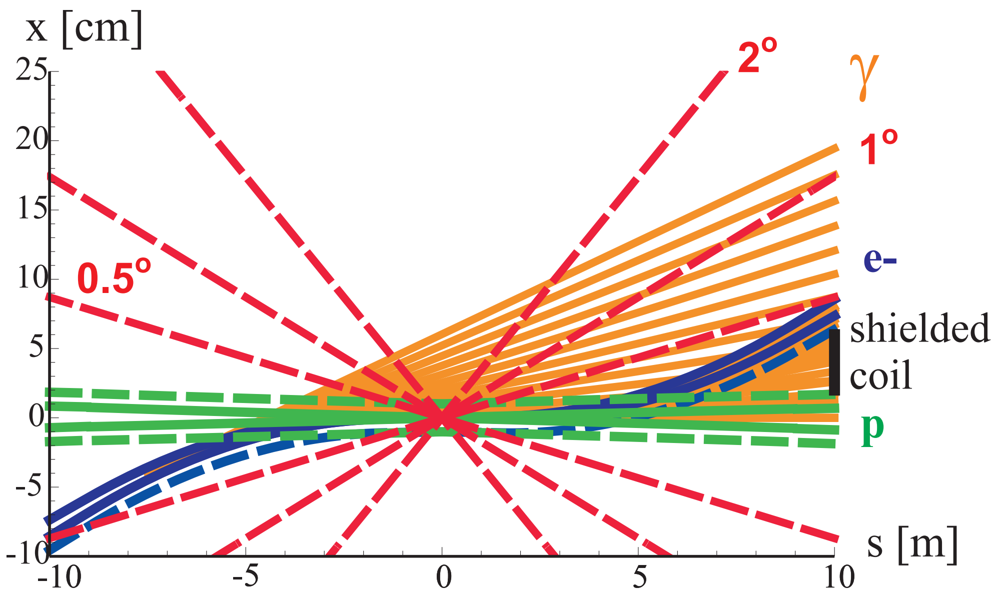


Figure 8.2: Linac-ring interaction-region layout. Shown are the beam enevelopes of 10σ (electrons) [solid blue] or 11σ (protons) [solid green], the same envelopes with an additional constant margin of 10 mm [dashed], the synchroton-radiation fan [orange], the approximate location of the magnet coil between incoming protons and outpgoing electron beam [black], and a "1 degree" line.

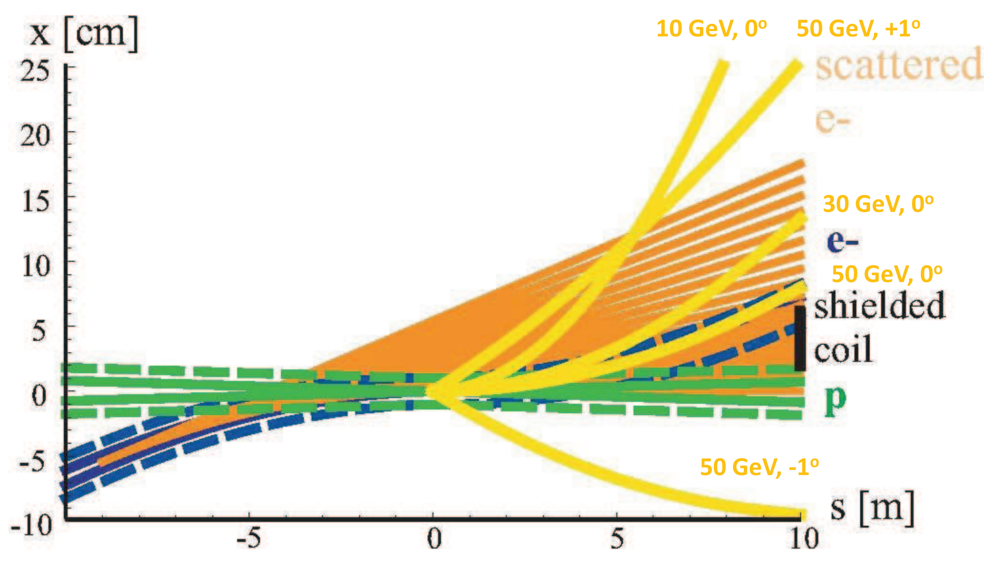


Figure 8.3: Example trajectories in the detector dipole fields for electrons of different energies and scattering angles, demonstrating an enhancement of the detector acceptance by the dipoles.

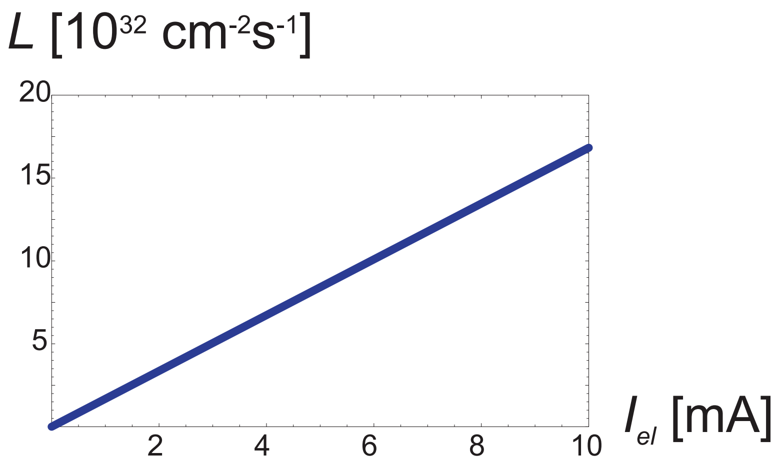


Figure 8.4: Linac-ring luminosity versus average electron beam current, according to (8.1).

about 6.4 mA is required to reach the target luminosity of 10^{33} cm^{-2}s^{-1}.

For comparison, the CLIC main beam has a design average current of 0.01 mA [566], so that it falls short by a factor 600 from the LHeC requirement. For other applications it has been proposed to raise the CLIC beam power by lowering the accelerating gradient, raising the bunch charge by a factor of two, and increasing the repetition rate up to three times, which raises the average beam current by a factor 6 to about 0.06 mA (this type of CLIC upgrade is described in [232]). This ultimate CLIC main beam current is still a factor 100 below the LHeC target. On the other hand, the CLIC drive beam would have a sufficiently high current, namely 30 mA, but at the low energy 2.37 GeV, which would not be useful for high-energy *ep* physics. Due to this low an energy, also the drive beam power is still a factor of 5 smaller than the one required by LHeC. Finally, the ILC design current is about 0.04 mA [567], which also falls more than a factor 100 short of the goal.

Fortunately, SC linacs can provide higher average current, e.g. by increasing the linac duty factor 10–100 times, or even running in continuous wave (CW) mode, at lower accelerating gradient. Example average currents for a few proposed designs illustrate this point: The CERN High-Power Superconducitng Proton Linac aims at about 1.5 mA average curent (with 50 Hz pulse rate) [568], the Cornell ERL design at 100 mA (cw) [569], and the eRHIC ERL at about 50 mA average current at 20 GeV beam energy (cw) [**?**]. All these designs are close to, or exceed, the LHeC requirements for average beam current and average beam power (6.4 mA at 60 GeV). It is worth noting that the JLAB UV/IR 4th Generation Light Source FEL is routinely operating with 10 mA average current (135 pC pulses at 75 MHz) [570].

The target LHeC IP electron-beam power is 384 MW. With a standard wall-plug-power to RF conversion efficiency around 50%, this would imply about 800 MW electrical power, far more than available. This highlights the need for energy recovery where the energy of the spent beam, after collision, is recuperated by returning the beam 180° out of phase through the same RF structure that had earlier been used for its acceleration, again with several recirculations. An energy recovery efficiency $\eta_{\rm ER}$ reduces the electrical power required for RF power generation at a given beam current by a factor $(1 - \eta_{\rm ER})$. We need an efficiency $\eta_{\rm ER}$ above 90% or higher to reach the beam-current goal of 6.4 mA with less than 100 MW total electrical power.

The above arguments have given birth to the LHeC Energy Recovery Linac high-luminosity baseline design, which is being presented in this chapter.

Choice of RF Frequency

Two candidate RF frequencies exist for the SC linac. One possibility is operating at the ILC and XFEL RF frequency around 1.3 GHz, the other choosing a frequency of about 720 MHz, close to the RF frequencies of the CERN High-Power SPL, eRHIC, and the European Spallation Source (ESS).

The ILC frequency would have the advantage of synergy with the XFEL infrastructure, of profiting from the high gradients reached with ILC accelerating cavities, and of smaller structure size, which could reduce the amount of high-purity niobium needed by a factor 2 to 4.

Despite these advantages, the present LHeC baseline frequency is 720 MHz, or, more precisely, 721 MHz to be compatible with the LHC bunch spacing. The arguments in favor of this lower frequency are the following:

- A frequency of 721 MHz requires less cryo-power (about two times less than at 1.3 GHz according to BCS theory; the exact difference will depend on the residual resistance [571]).
- The lower frequency will facilitate the design and operation of high-power couplers [572], though the couplers might not be critical [573].
- The smaller number of cells per module (of similar length) at lower RF frequency is preferred with regard to trapped modes [574].
- The lower-frequency structures reduce beam-loading effects and transverse wake fields.
- The project can benefit from synergy with SPL, eRHIC and ESS.

In case the cavity material costs at 721 MHz would turn out to be a major concern, they could be reduced by applying niobium as a thin film on a copper substrate, rather than using bulk niobium. The thin film technology may also enhance the intrinsic cavity properties, e.g. increase the Q value.

Linac RF parameters for both 720 MHz and 1.3 GHz in CW mode as well as for a pulsed 1.3-GHz option are compared in Table 8.1. The 721 MHz parameters are derived from eRHIC [575]. Pulsed-linac applications for LHeC are discussed in subsections 8.1.4 and 8.1.6.

ERL Electrical Site Power

The cryopower for two 10-GeV accelerating SC linacs is 28.9 MW, assuming pessimistically 37 W/m heat load at 1.8 K and 18 MV/m cavity gradient (this is a pessimistic estimate since the heat load could be up to 3 times smaller; see Table 8.1), and 700 "W per W" cryo efficiency as for the ILC. The RF power needed to control microphonics for the accelerating RF is estimated at 22.2 MW, considering that 10 kW/m RF power may be required, as for eRHIC, with 50% RF generation efficiency. The electrical power for the additional RF compensating the synchrotron-radiation energy loss is 24.1 MW, with an RF generation efficiency of 50%. The cryo power for

[1] The 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 [576].

[2] The 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 [567]).

Table 8.1: Linac RF parameters for two different RF frequencies and two modes of operation.

	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

the compensating RF is 2.1 MW, provided in additional 1,44 GeV linacs, and the microphonics control for the compensating RF requires another 1.6 MW. In addition, with an injection energy of 50 MeV, 6.4 mA beam current, and as usual 50% efficiency, the electron injector consumes about 6.4 MW. A further 3 MW is budgeted for the recirculation-arc magnets [577]. Together this gives a grand total of 88.3 MW electrical power, some 10%.below the 100 MW limit.

ERL Configuration

The ERL configuration is depicted in Fig. 8.5. The shape, arc radius and number of passes have been optimized with respect to construction cost and with respect to synchrotron-radiation effects [578].

The ERL is of racetrack shape. A 500-MeV electron bunch coming from the injector is accelerated in each of the two 10-GeV SC linacs during three revolutions, after which it has obtained an energy of 60 GeV. The 60-GeV beam is focused and collided with the proton beam. It is then bent by 180° in the highest-energy arc beam line before it is sent back through the first linac, at a decelerating RF phase. After three revolutions with deceleration, re-converting the energy stored in the beam to RF energy, the beam energy is back at its original value of 500 MeV, and the beam is now disposed in a low-power 3.2-MW beam dump. A second, smaller (tune-up) dump could be installed behind the first linac.

Strictly speaking, with an injection energy into the first linac of 0.5 GeV, the energy gain in the two accelerating linacs need not be 10 GeV each, but about 9.92 GeV, in order to reach 60 GeV after three passages through each linac. Considering a rough value of 10 GeV means that we overestimate the electrical power required by about 1%.

Each arc contains three separate beam lines at energies of 10, 30 and 50 GeV on one side, and 20, 40 and 60 GeV on the other. Except for the highest energy level of 60 GeV, at which there is only one beam, in each of the other arc beam lines there always co-exist a decelerating

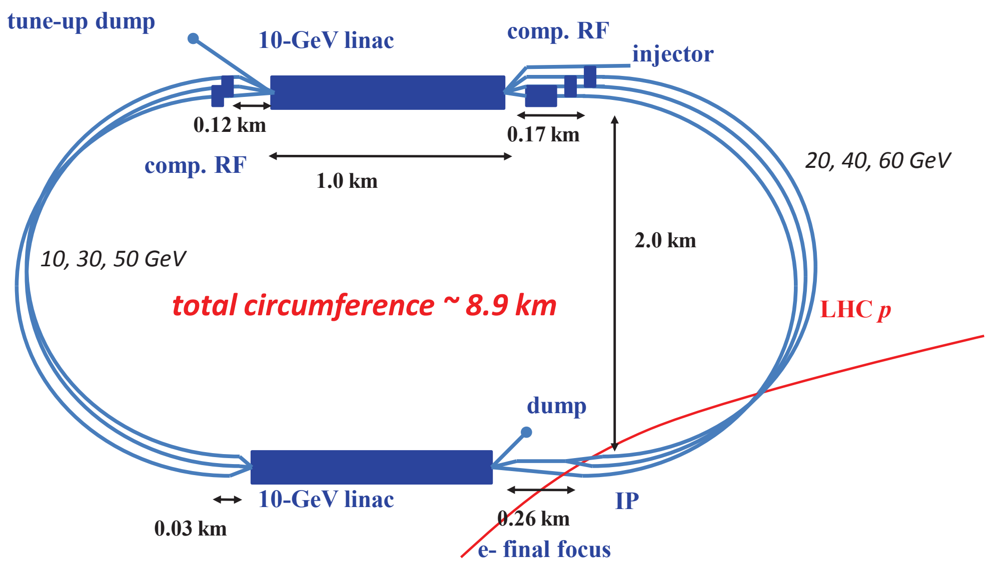


Figure 8.5: LHeC ERL layout including dimensions.

and an accelerating beam. The effective arc radius of curvature is 1 km, with a dipole bending radius of 764 m [579].

The two straight sections accommodate the 1-km long SC accelerating linacs. There is another 290 m section in each straight. In one straight of the racetrack 260 m of this additional length is allocated for the electron final focus (plus matching and splitting), the residual 30 m on the other side of the same straight allows for combining the beam and matching the optis into the arc. In the second straight section the additional RF compensating for 1.44 GeV energy loss is installed [580]. For the highest energy, 60 GeV, there is a single beam and the compensating RF (750 MV) can have the same frequency, 721 MHz, as in the main linac [580]. For the other energies, a higher harmonic RF system, e.g. at 1.442 GHz, can compensate the energy loss for both decelerating and accelerating beams, which are 180° out of phase at 721 MHz. On one side of the second straight one must compensate a total of about 907 MV (=750+148+9 MW, corresponding to the energy loss at 60, 40 and 20 GeV, repectively), which should easily fit within a length of 170 m. On the other side one has to compensate 409 MV (=362+47 MV), corresponding to SR energy losses at 50 and 30 GeV), for which a length of 120 m is available.

The total circumference of the ERL racetrack is chosen as 8.9 km, equal to one third of the LHC circumference. This choice has the advantage that one could introduce ion-clearing gaps in the electron beam which would match each other on successive revolutions (e.g. for efficient ion clearing in the linacs that are shared by six different parts of the beam) and which would also always coincide with the same proton bunch locations in the LHC, so that in the latter a given proton beam would either always collide or never collide with the electrons [581]. Ion clearing may be necessary to suppress ion-driven beam instabilities. The proposed implementation scheme would remove ions while minimizing the proton emittance growth which could otherwise arise when encountering collisions only on some of the turns. In addition, this arrangement can be useful for comparing the emittance growth of proton bunches which are colliding with the electrons and those which are not.

The length of individual components is as follows. The exact length of the 10-GeV linac is 1008 m. The individual cavity length is taken to be 1 m. The optics consists of 56-m long FODO cells with 32 cavities. The number of cavities per linac is 576. The linac cavity filling factor is 57.1%. The effective arc bending radius is set to be 1000 m. The bending radius of the dipole magnets is 764 m, corresponding to a dipole filling factor of 76.4% in the arcs. The longest SR compensation linac has a length of 84 m (replacing the energy lost by SR at 60 GeV). Combiners and splitters between straights and arcs require about 20–30 m space each. The electron final focus may have a length of 200–230 m.

IP Parameters and Beam-Beam Effects

Table 8.2 presents interaction-point (IP) parameters for the electron and proton beams.

Table 8.2: IP beam parameters

	protons	electrons
beam energy [GeV]	7000	60
Lorentz factor γ	7460	117400
normalizwed 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]	$\geq$430	6.4
bunch spacing [ns]	25 or 50	(25 or) 50
bunch population [ns]	1.7×10^{11}	(1 or) 2×10^9

Due to the low charge of the electron bunch, the proton head-on beam-beam tune shift is tiny, namely $\Delta Q_p = +0.0001$, which amounts to only about 1% of the LHC *pp* design tune shift (and is of opposite sign). Therefore, the proton-beam tune spread induced by the *ep* collisions is negligible. In fact, the electron beam acts like an electron lens and could conceivable increase the *pp* tune shift and luminosity, but only by about 1%. Long-range beam-beam effects are equally insignificant for both electrons and protons, since the detector-integrated dipoles separate the electron and proton bunches by about $36\sigma_p$ at the first parasitic encounter, 3.75 m away from the IP.

One further item to be looked at is the proton beam emittance growth. Past attempts at directly simulating the emittance growth from *ep* collisions were dominated by numerical noise from the finite number of macroparticles and could only set an upper bound [582], nevertheless indicating that the proton emittance growth due to the pinching electron beam might be acceptable for centered collisions. Proton emittance growth due to electron-beam position jitter and simultaneous *pp* collisions is another potential concern. For a 1σ offset between the electron and proton orbit at the IP, the proton bunch receives a deflection of about 10 nrad (approximately $10^{-4}\sigma^*_{x',y'}$). Beam-beam simulations for LHC *pp* collisions have determined the acceptable level for random white-noise dipole excitation as $\Delta x/\sigma_x \leq 0.1\%$ [583]. This translates into a very relaxed electron-beam random orbit jitter tolerance of more than 1σ. The tolerance on the orbit jitter will then not be set by beam-beam effects, but by the luminosity loss resulting from off-center collisions, which, without disruption, scales as $\exp(-(\Delta x)^2/(4\sigma_{x,y}^{*\,2}))$. The random orbit jitter observed at the SLAC SLC had been of order 0.3–0.5σ [584, 585]. A 0.1σ offset at LHeC would reduce the luminosity by at most 0.3%, a 0.3σ offset by 2.2%. Disruption further relaxes the tolerance.

The strongest beam-beam effect is encountered by the electron beam, which is heavily disrupted. The 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" $\theta_0 \equiv D\sigma^*/\sigma_{z,p} = N_{b,p} r_e/(\gamma_e \sigma^*)$ [586] is about 600 μrad (roughly $10\sigma^*_{x',y'}$), which is huge. Simulations show that the actual maximum angle of the disrupted electrons is less than half θ_0.

Figure 8.6 illustrates the emittance growth and optics-parameter change for the electron beam due to head-on collision with a "strong" proton bunch. The intrinsic emittance grows by only 15%, but there is a 180% growth in the mismatch parameter "$B_{\rm mag}$" (defined as $B_{\rm mag} = (\beta\gamma_0 - 2\alpha\alpha_0 + \beta_0\gamma)/2$, where quantities with and without subindex "0" refer to the optics without and with collision, respectively. Without adjusting the extraction line optics to the parameters of the mismatched beam the emittance growth will be about 200%. This would be acceptable since the arc and linac physical apertures have been determined assuming up to 300% emittance growth for the decelerating beam [579]. However, if the optics of the extraction line is rematched for the colliding electron beam (corresponding to an effective β^* of about 3 cm rather than the nominal 12 cm; see Fig.8.6 bottom left), the net emittance growth can be much reduced, to only about 20%. The various optics parameters shown in Fig. 8.6 vary by no more than 10–20% for beam-beam orbit offsets up to 1σ.

Figure 8.7 presents the average electron deflection angle as a function of the beam-beam offset. The extraction channel for the electron beam must have sufficient aperture to accommodate both the larger emittance due to disruption and the average trajectory change due to off-center collisions.

8.1.3 Polarization

The electron beam can be produced from a polarized DC gun with about 90% polarization, and with, conservatively, 10–50 μm normalized emittance [587]. Spin-manipulation tools and measures for preserving polarization, like Wien filter and/or spin rotators, and polarimeters should be included in the optics design of the injector, the final focus, and the extraction line.

As for the positrons, up to about 60% polarization can be achieved either with an undulator [588] or with a Compton-based e^+ source [589, 590][3].

8.1.4 Pulsed Linacs

For beam energies above about 140 GeV, due to the growing impact of synchrotron radiation, the construction of a single straight linac is cheaper than that of a recirculating linac [578]. Figure 8.8 shows the schematic of an LHeC collider based on a pulsed straight 140-GeV linac, including injector, final focus, and beam dump. The linac could be either of ILC type (1.3 GHz RF frequency) or operate at 721 MHz as the preferred ERL version. In both cases, ILC

[3] The primary challenge for positrons is to produce them in sufficient number and with a small enough emittance.

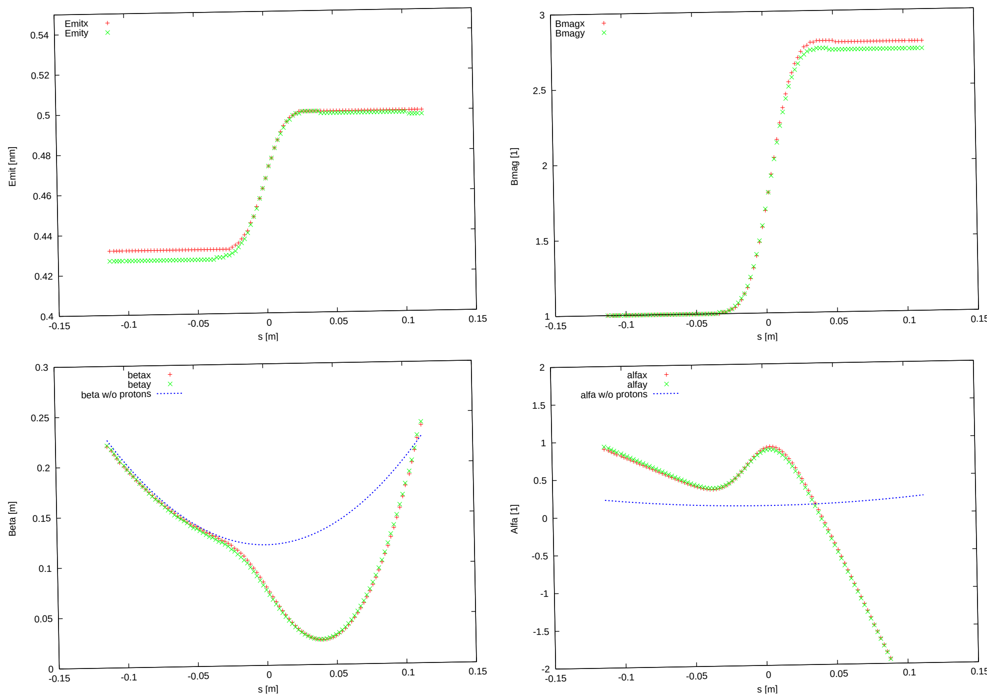


Figure 8.6: Simulated evolution of the electron beam emittance (top left), mismatch factor B_{mag} (top right) beta dfunction (bottom left) and alpha function (bottom right) during the collision with a proton bunch, as a function of distance from the IP.

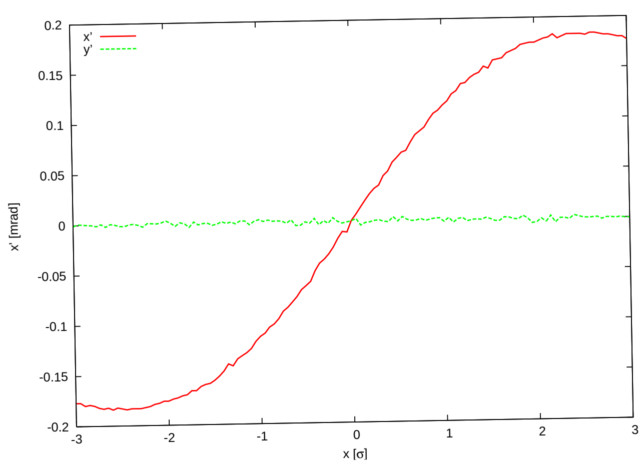


Figure 8.7: Simulated electron horizontal center-of-mass deflection angle as a function of the horizontal beam-beam offset.

Figure 8.8: Pulsed single straight 140-GeV linac for highest energy ep collisions.

values are assumed for the cavity gradient (31.5 MV/m) and for the cavity unloaded Q value ($Q_0 = 10^{10}$). This type of linac would be extendable to ever higher beam energies and could conceivably later become part of a linear collider. In its basic, simplest and conventional version no energy recovery is possible for this configuration, since it is impossible to bend the 140-GeV beam around. The lack of energy recovery leads to significantly lower luminosity. For example, with 10 Hz repetition rate, 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, the average electron current would be 0.27 mA and the luminosity 4×10^{31} cm^{-2}s^{-1}.

The construction of the 140-GeV pulsed straight linac could be staged, e.g. so as to first feature a pulsed linac at 60 GeV, which could also be used for γ-p/A collisions (see subsection 8.1.6). The linac length decreases directly in proportion to the beam energy. For example, at 140-GeV the pulsed linac measures 7.9 km, while at 60 GeV its length would be 3.4 km. For a given constant wall-plug power, of 100 MW, both the average electron current and the luminosity scale roughly inversely with the beam energy. At 60 GeV the average electron current becomes 0.63 mA and the pulsed-linac luminosity, without any energy recovery, would be more than 9×10^{31} cm^{-2}s^{-1}.

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 [591]. 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 is realized without bending the spent beam. With two straight linacs facing each other this configuratiom 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} cm^{-2}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 $\sigma_\gamma \approx 10\mu$m.

With a laser wavelength around $\lambda_\gamma \approx 250$ nm ($E_{\gamma,0} \approx 5$ eV), obtained e.g. from a Nd:YAG

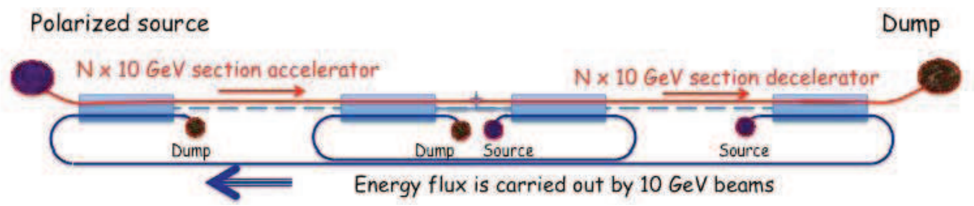


Figure 8.9: Highest-energy high-luminosity ERL option based on two straight linacs and multiple 10-GeV energy-transfer beams [591].

laser with frequency quadrupling, the Compton-scattering parameter x [592, 593],

$$x \approx 15.3 \left[\frac{E_{e,0}}{\text{TeV}}\right] \left[\frac{E_{\gamma,0}}{\text{eV}}\right] , \tag{8.3}$$

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 $E_{\gamma,\max} = x/(x+1)E_0$, 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 $E_{\gamma.\max}$.

The probability of scattering per individual electron is [594]

$$n_\gamma = 1 - \exp(-q) \tag{8.4}$$

with

$$q = \frac{\sigma_c A}{E_{\gamma,0} 2\pi\sigma_\gamma^2} , \tag{8.5}$$

where σ_c denotes the (polarized) Compton cross section and A the laser pulse energy. Using the formulae in [?], the Compton cross section for $x = 4.8$ and $2\lambda_e P_c = -1$ is computed to be $\sigma_c = 3.28 \times 10^{-25}$ cm^2. The pulse energy corresponding to $q = 1$, i.e. to a conversion efficiency of 65%, is estimated as $A \approx E_{\gamma,0} 2\pi\sigma_\gamma^2/\sigma_c \approx 16$ J. To set this into perspective, for a $\gamma\gamma$ collider at the ILC, Ref. [595] considered a pulse energy of 9 J at a four times longer wavelength of $\lambda \approx 1\ \mu$m.

The energies of the leftover electrons after conversion extend from about 10 to 60 GeV. This spent electron beam, with its enormous energy spread, must be safely extracted from the interaction region. The detector-integrated dipole magnets will assist in this process. They will also move the scattered electrons away from the interaction point. A beam dump for the neutral photons should also be installed, behind the downstream quadrupole channel.

Figure 8.11 presents an example photon energy spectrum after the conversion and a luminosity spectrum [596], obtained from a simulation with the Monte-Carlo code CAIN [597].

Differently from $\gamma\gamma$ collisions at a linear collider, thanks to the much larger IP spot size and smaller beam energy, the conversion point can be a much larger distance $\Delta s \approx \beta^* \sim 0.1$ m away from the interaction point, which could simplify the integration in the detector, and is also necessary as otherwise, with e.g. a mm-distance between CP and IP, the conversion would take place inside the proton bunch.

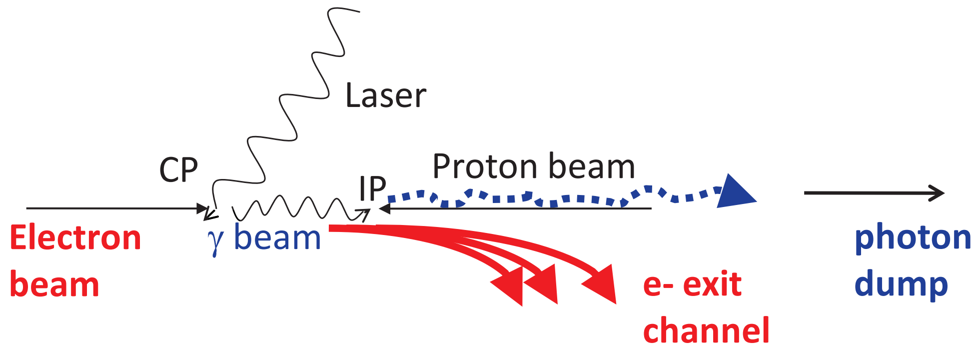


Figure 8.10: Schematic of γ-p/A collision; prior to the photon-hadron interaction point (IP), the electron beam is scattered off a several-J laser pulse at the conversion point (CP).

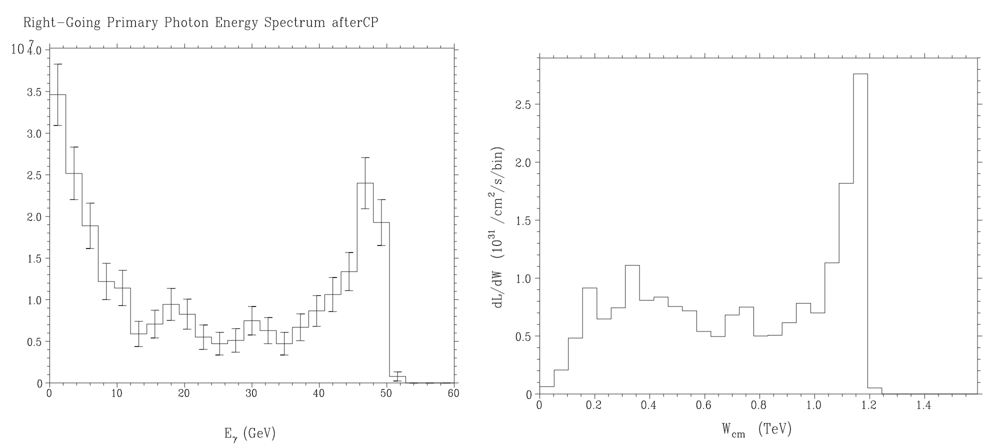


Figure 8.11: Simulated example photon spectrum after the conversion point (left) and γ-p luminosity spectrum [596].

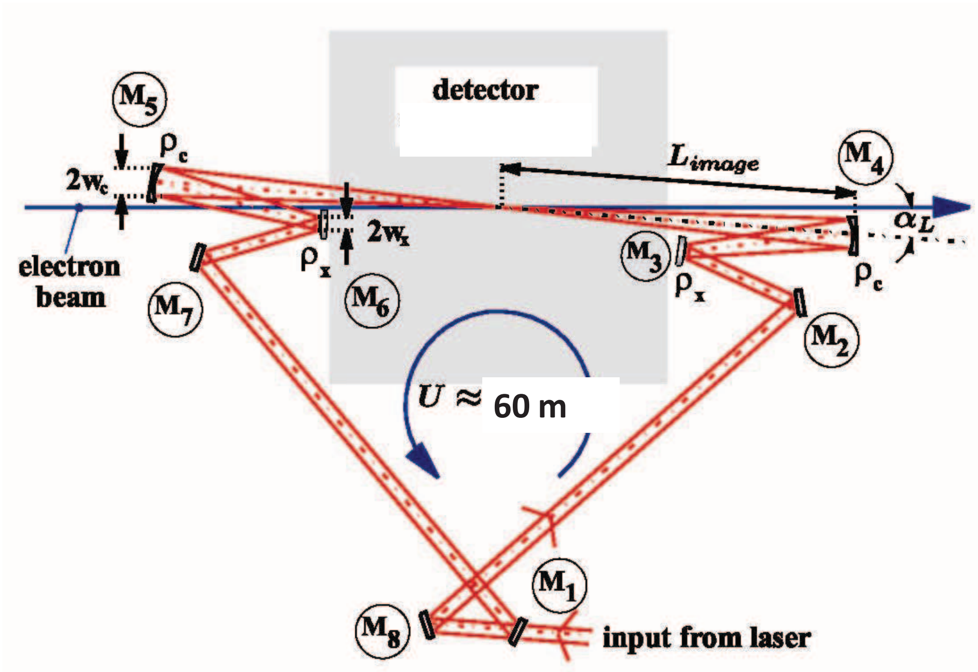


Figure 8.12: Recirculating mirror arrangement providing a laser-pulse path length of 60 m for pulse stacking synchronously with the arriving electron bunches (adapted from [595]).

To achieve the required laser pulse energy, external pulses can be stacked in a recirculating optical cavity. For an electron bunch spacing of e.g. 200 ns, the path length of the recirculation could be 60. A schematic of a possible mirror system is sketched in Fig. 8.12 (adapted from [595]).

8.1.7 Summary of Basic Parameters and Configurations

The baseline 60-GeV ERL option presented here can provide a *pe* luminosity of 10^{33} cm^{-2}s^{-1}, at less than 100 MW total electrical power for the electron branch of the collider, and with less than 9 km circumference. Its main hardware component is about 21 GV of SC-RF.

A pulsed 140-GeV linac, without energy recovery, could achieve a luminosity of 1.4×10^{31} cm^{-2}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 decelating linac, and multiple 10-GeV "energy-transfer beams". This type of collider could potentially reach luminosities of 10^{35} cm^{-2}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 beam 1 and collide them head-on with beam 2, 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 a 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 beam 2 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 10.1. 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.

8.2.2 Optics

Colliding proton optics

The colliding beam triplet starts at L^*=10m from the IP. It consists of 3 quadrupoles with main parameters given in Table 8.3. The quadrupole aperture is computed as 11max(σ_x,σ_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 Nb_3Sn design described in Section 10.1. 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

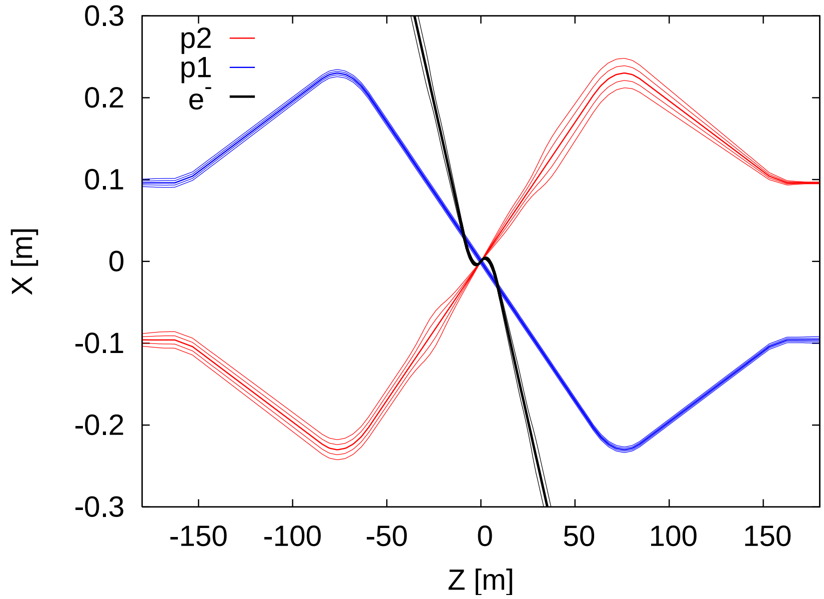


Figure 8.13: LHeC interaction region displaying the two proton beams and the electron beam trajectories with 5σ and 10σ envelopes.

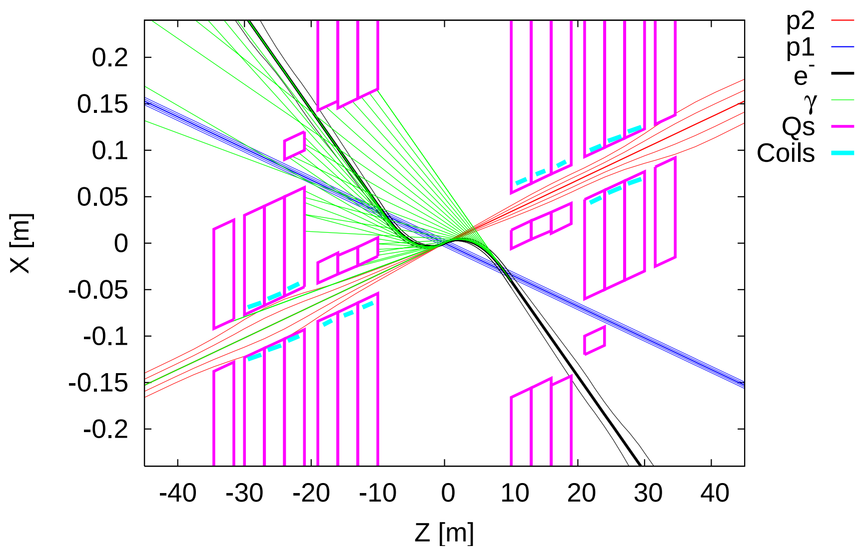


Figure 8.14: LHeC interaction region with a schematic view of synchrotron radiation. Beam trajectories with 5σ and 10σ envelopes are shown. The parameters of the Q1 and Q2 quadrupole segments correspond to the Nb_3Sn half-aperture and single-aperture (with holes) quadrupole of Fig. 10.6.

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 11max(σ_x,σ_y)+5 mm.

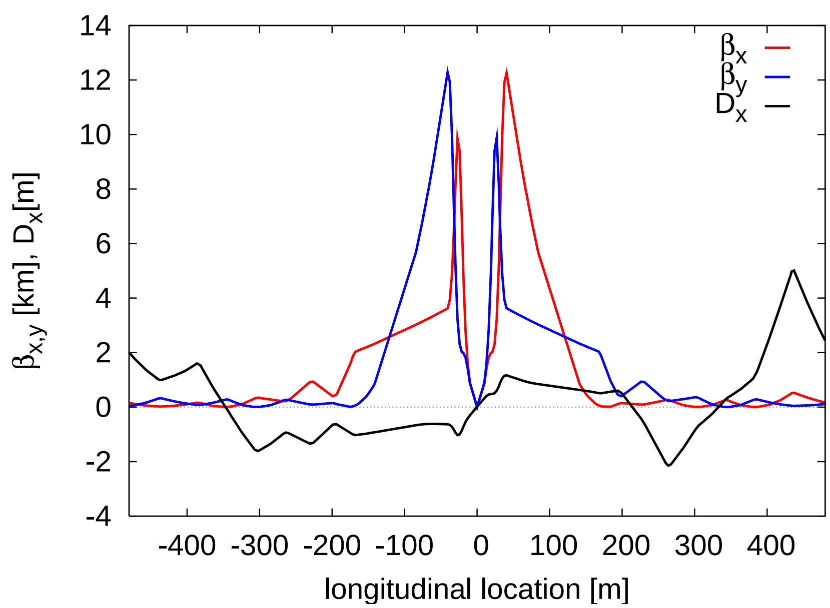


Figure 8.15: Optics functions for main proton beam.

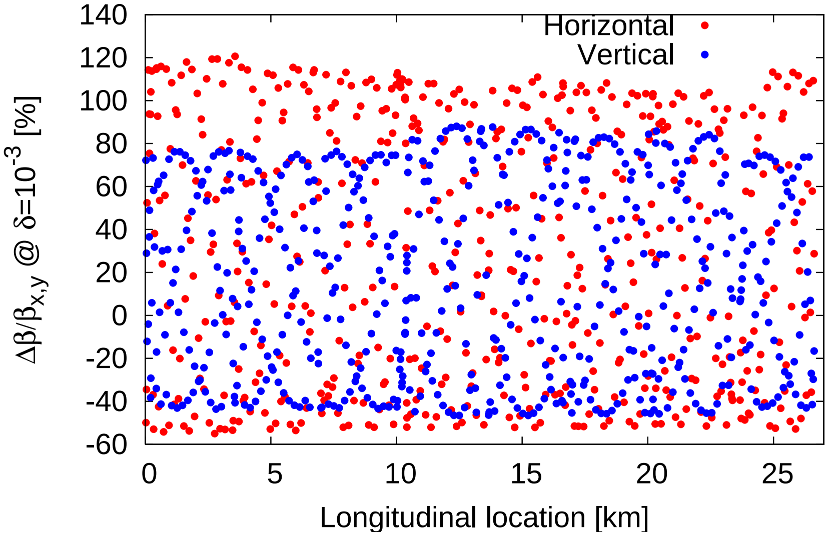


Figure 8.16: Chromatic beta-beating at dp/p=0.001.

It was initially hoped that a compact Nb_3Sn triplet with L^*=10m 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. **??**). 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 [598–600]. Other local chromatic correction approaches as [601], where quadrupole doublets are used to provide the strong focusing, could also be considered for the LHeC.

Since LHeC anyhow requires a new dedicated chromaticity correction scheme, current NbTi technology could be pursued instead of Nb_3Sn and the L^* could also be slightly increased. The same conceptual three-beam crossing scheme as in Fig. 8.13 could be kept.

To achieve L^* below 23 m requires a cantilever supported on a large mass as proposed for the CLIC QD0 [602] to provide sub-nanometer stability at the IP. The LHeC vibration tolerances are much more relaxed, being on the sub-micrometer level.

Non-colliding proton optics

The non-colliding beam has no triplet quadrupoles since it does not need to be focused. The LHC "alignment optics" [603] was used as a starting point. Figure 8.17 shows the optics functions around the IP. The LHeC IP longitudinal location can be chosen so as to completely avoid unwanted proton-proton collisions.

The non-colliding proton beam travels through dedicated holes in the proton triplet quadrupoles, in Q1 together with the electron beam. The Q1 hole dimensions are determined by the electron beam, see below. By contrast, the non-colliding proton beam travels alone through the first module of the Q2, requiring about 30 mm full aperture. No fields are assumed in these apertures but the possible residual fields could easily be taken into account for the proton optics.

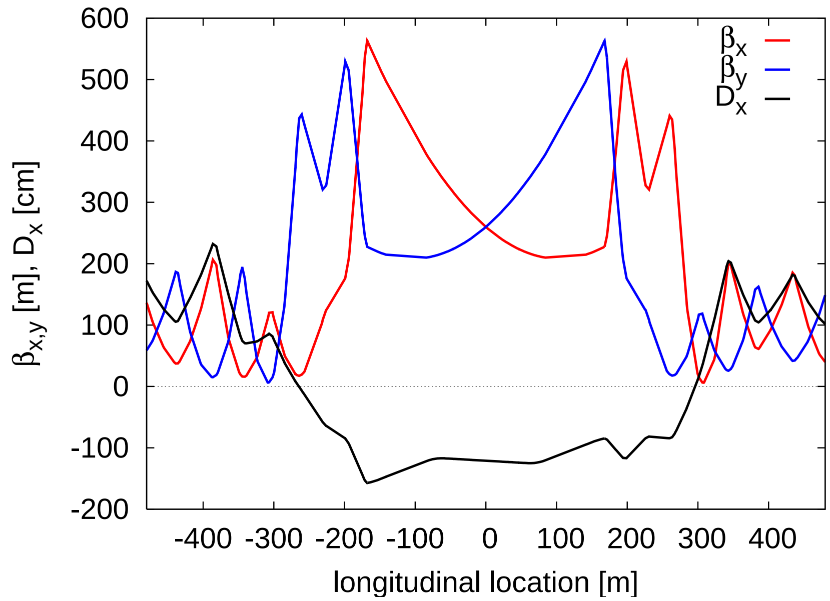


Figure 8.17: Optics functions for the non-colliding proton beam without triplets.

Electron optics

The electron L*=30 m has been chosen to allow for enough separation between the proton and the electron final focusing quadrupoles. A first design of the optics already matched to the exit of the linac is shown in Fig. 8.18. The electron focusing quadrupoles feature moderately low gradients as shown in Table 8.4. The IP beam size aberration versus the relative rms energy spread of the beam is shown in Fig. 8.19. Chromatic correction is mandatory for relative energy spreads above 3×10^{-4}. It is recommended to design a chromatic correction section. About 200 m are available between the exit of the linac and the IP while the current electron final focus is using only 90 m, leaving space for collimation and beam diagnostics.

The electrons shares a hole with the non-colliding proton beam in the first half-quadrupole,

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 11max(σ_x,σ_y)+5 mm.

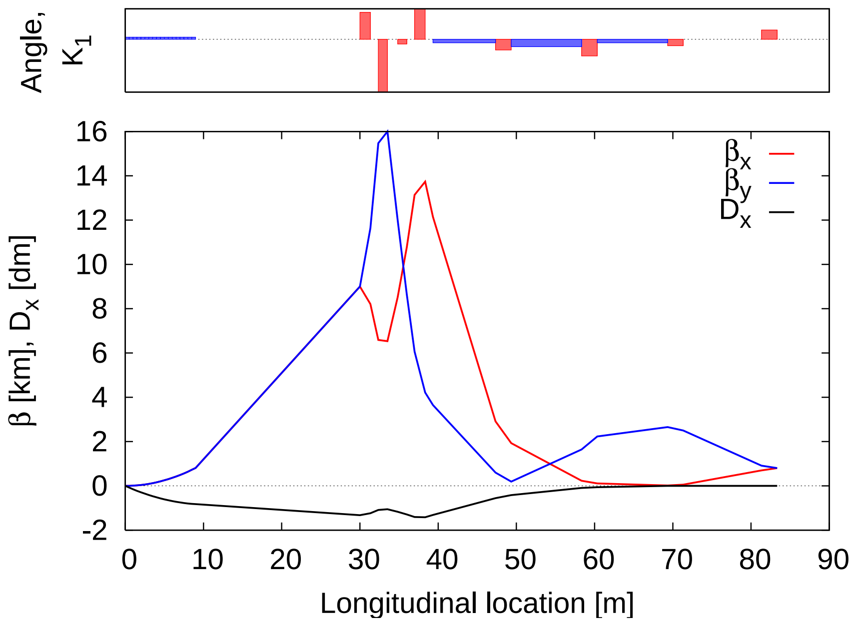


Figure 8.18: Optics of the electron beam.

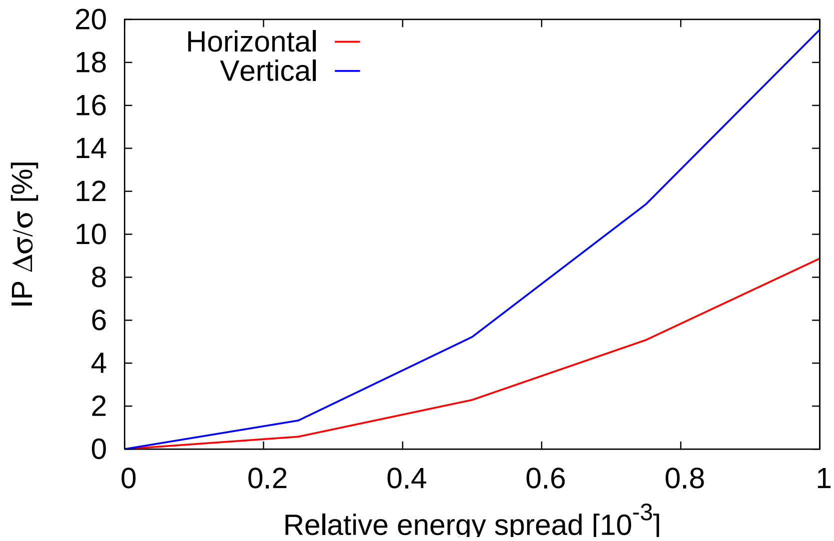


Figure 8.19: IP electron beam size versus relative energy spread of the beam.

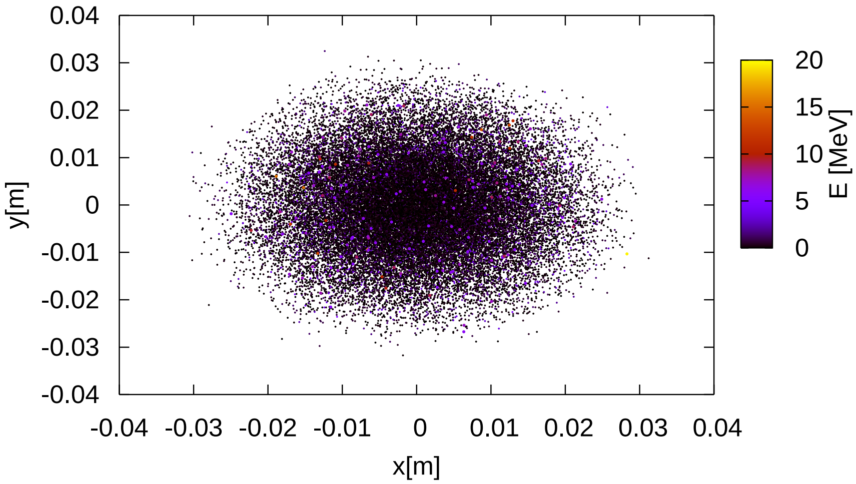


Figure 8.20: Distribution of the spent electron beam at 10 m from the IP. The Gaussian and rms sigmas are shown on the plot.

Q1, and then travels through a dedicated hole in the cryostat of Q2. The common hole in the proton Q1 must have about 160 mm full horizontal aperture to allow for the varying separation between the electron and non-colliding proton orbit (120 mm) with the usual electron-beam aperture assumptions (±20 mm). First design of mirror magnets for Q1 feature a field of 0.5 T in the electron beam pipe. This value is considered too large when compared to the IR dipole of 0.3 T, but new designs with active isolation or dedicated coils could considerably reduce this field. Migrating to NbTi technology would automatically reduce this field too.

Spent electron beam

The proton electromagnetic field provides extra focusing to the electron beam. This increases the divergence of the electron. Figure 8.20 shows the horizontal distribution of the electrons at 10 m from the IP (entry of Q1) as computed by Guineapig [604]. The contribution of dispersion and energy spread to the transverse size of the exiting collided beam can be neglected. Therefore, it is possible to linearly scale the sigmas at 10 m to estimate both the horizontal and vertical sigmas at any other longitudinal location. The simulation used 10^5 particles. No particles are observed beyond 4.5 mm from the beam centroid at 10 m from the IP and beyond 9 mm at 20 m. A radial aperture of 10 mm has been reserved for the beam size at the incoming electron Q1 hole. The same value of 10 mm seem to be enough to also host the spent electron beams, although it might be worth to allocate more aperture margin in the last block of Q1.

8.2.3 Modifications for γp or γ-A

The electron beam can be converted into photons by Compon scattering off a high-power laser pulse, as discussed Section 8.1.6. For this option a laser path and high-finesse optical cavities must be integrated into the interaction region. A multiple mirror arrangement has been sketched in Fig. 8.12. The 0.3-T dipole field after the (now) γ-p interaction point will help to separate the Compton-scattered spent electron beam from the high-energy photons. The high-energy photons propagate straight into the direction of the incoming proton beam through the main openings of Q1 and Q2, while the spent electrons will be extracted through the low-field exit holes shared with the non-colliding proton beam, as for electron-proton collisions.

8.2.4 Synchrotron radiation and absorbers

Introduction

The synchrotron radiation (SR) in the linac-ring interaction region has been analyzed by three different approaches. The SR was simulated using a program made with the Geant4 (G4) toolkit. In addition, a cross check of the total power and average critical energy was done in IRSYN, a Monte Carlo simulation package written by R. Appleby [535]. A final cross check of the radiated power has been performed using an analytic method. The latter two checks confirmed the results obtained from G4. The G4 program uses Monte Carlo methods to create the desired Gaussian spatial and angular distributions of an electron beam. This electron beam distribution is then transported through a "vacuum system," including the magnetic fields for the separator dipoles. In a non-zero magnetic field SR is generated using the appropriate G4 process classes. The position, direction, and energy of each photon emitted is written as ntuples at user defined longitudinal positions (Z values). These ntuples are then used to analyze the SR fan as it evolves in Z. The latter analysis was done primarily through MATLAB scripts.

This section uses the following conventions. The electron beam is being referred to as *the beam* and the proton beams will be called either the interacting or non interacting proton beams. The (electron) beam propagates in the $-Z$ direction and the interacting proton beam propagates in the $+Z$ direction. At the collision point both beams propagate ub the straight Z (or $-Z$) direction. A right-handed coordinate system is used where the X axis is horizontal and the Y axis vertical. The beam centroid always remains in the $Y = 0$ plane. The *angle of the beam* will be used to refer to the angle between the beam centroid's direction and the Z axis, in the $Y = 0$ plane. This angle is defined such that the beam propagates in the $-X$ direction when it passes through the dipole field as it moves along Z.

The SR fans extension in the horizontal direction is determined by the angle of the beam at the entrance of the upstream separator dipole. Because the direction of the photons is parallel to the direction of the electron from which it is emitted, the angle of the beam and the X-distance to the interacting proton beam at the Z location of the last proton quadrupole are both greatest for photons generated at the entrance of the upstream separator dipole and, therefore, this angle defines one of the edges of the synchrotron fan on the absorber in front of the proton quadrupole. The other edge is defined by the crossing angle, which is zero for the linac-ring option. The S shaped trajectory of the beam means that the smallest angle of the beam will be reached at the IP. Therefore, the photons emitted at this point will move exactly along the Z axis. This defines the other edge of the fan in the horizontal direction.

The SR fans extent in the vertical direction is determined by the beta function and angular spread of the beam. The beta function along with the emittance defines the local rms beam size. The vertical rms beam size characterizes the range of Y positions at which photons are emitted. Possibly more importantly, the vertical angular spread defines the angle between the velocity vector of these photons and the Z axis. Both of these dependencies are functions of Z. Similar effects also affect the horizontal extension of the SR fan, however, in the horizontal plane they are of second order when compared to the horizontal deflection angle in the strong dipole field.

The number density distribution of the SR fan is inferred from the simulations. The number density at the location of the absorber is highest in the region between the two interacting beams. This is due to the S shaped trajectory of the beam.

Parameters

The parameters for the Linac Ring option are listed in Table 8.5. The separation refers to the displacement between the two interacting beams at the face of the proton triplet.

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

The energy, current, and crossing angle (θ_c) are the common values used in all LR calculations. The B value refers to the constant dipole field created throughout the two dipole magnets in the IR. The direction of this field is opposite on either side of the IP. The field is chosen such that 75 mm of separation is reached by the face of the proton triplet. This separation was chosen based on S. Russenschuck's SC quadrupole design. [536] The separation between the interacting beams can be increased by raising the constant dipole field however for a dipole magnet $P_{SR} \propto |B^2|$, [537] therefore an optimization of the design will need to be discussed. The chosen parameters give a flux of 1.37×10^{18} photons per second at Z = -9 m.

Power and Critical Energy

Table 8.6 shows the power of the SR produced in the IR along with the critical energy. This is followed by the total power produced in the IR and the critical energy. Since the G4 simulations utilize Monte Carlo, multiple runs were used to provide a standard error. This only caused fluctuations in the power since the critical energy is static for a constant field and constant energy.

These magnets have strong fields and therefore produce high critical energies and a substantial amount of power. Although the power is similar to that of the RR design the critical energy is much larger. This comes from the linear dependence of critical energy on magnetic field (*i.e.* $E_c \propto B$). [538] With the dipole field in the LR case being an order of magnitude

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 [Geant4]

larger than the dipole fields in the RR case the critical energies from the dipole magnets are also an order of magnitude larger in the LR case.

Comparison

The IRSYN cross check of the power and critical energies is shown in Table 8.7. This comparison was done for the total power and the critical energy.

	Power [kW]		Critical Energy [keV]	
	Geant4	IRSYN	Geant4	IRSYN
Total	48.8 +/- 0.1	X	718	718

Table 8.7: LR: Geant4 and IRSYN comparison

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. [537]

	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

Number Density and Envelopes

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

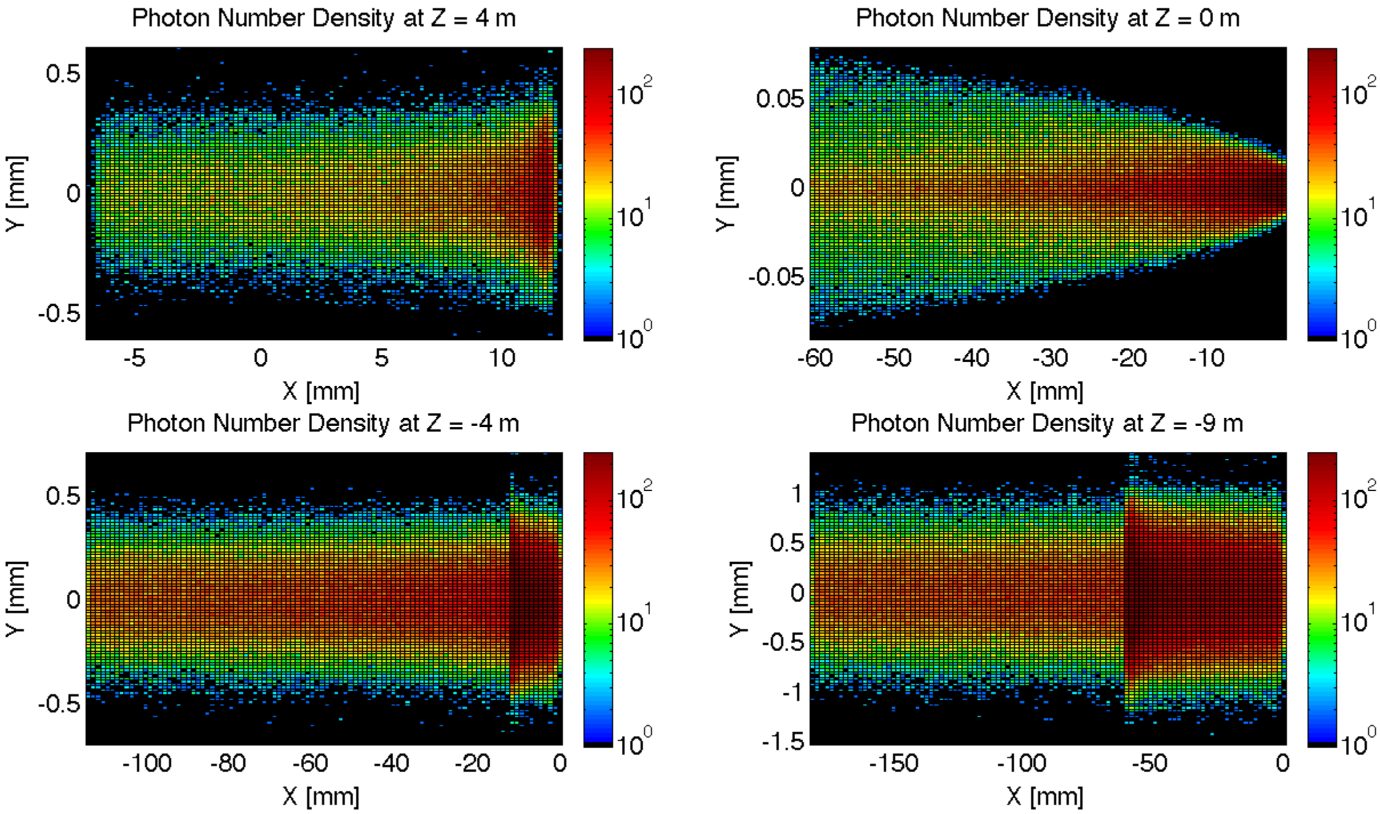


Figure 8.21: LR: Number Density Growth in Z

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 are shown in the Y = 0 plane. This makes it clear that the fan is antisymmetric which comes from the S shape of the electron beam as previously mentioned.

Absorber

The Photon distribution on the absorber surface is crucial. The distribution decides how the absorber must be shaped. The shape of the absorber in addition to the distribution on the surface then decides how much SR is backscattered into the detector region. In HERA backscattered SR was a significant source of background that required careful attention. [539] Looking at Figure 8.23 it is shown that for the LR option 35.15 kW of power from the SR light will fall on the face of the absorber which is 73% of the total power. This gives a general idea of the amount of power that will be absorbed. However, backscattering and IR photons will

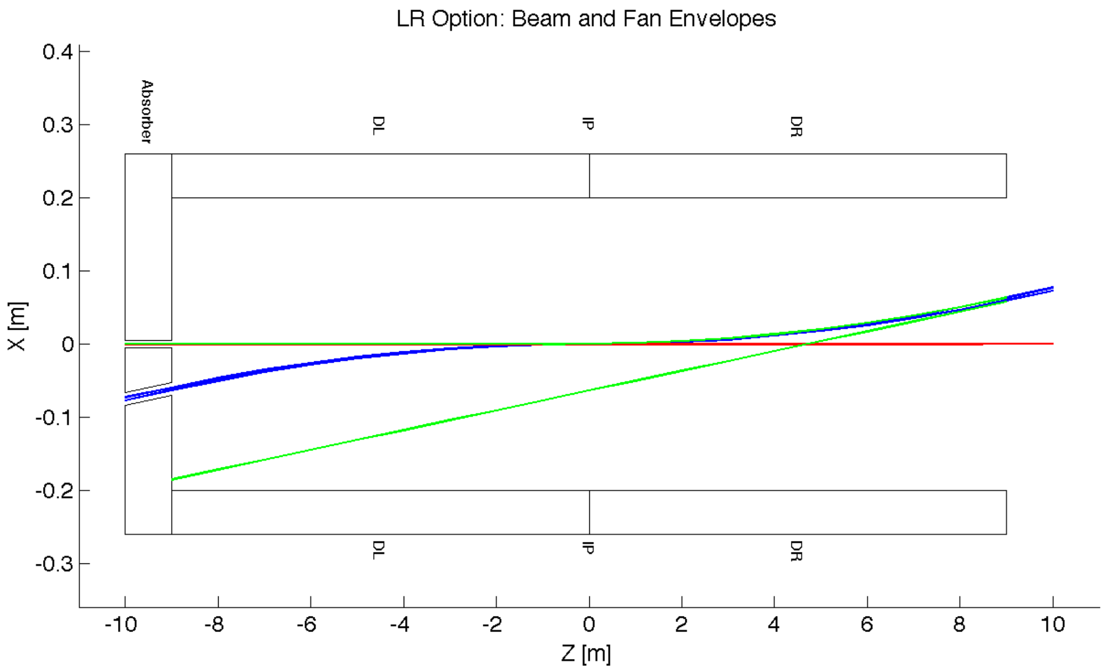


Figure 8.22: LR: Beam Envelopes in Z

lower the percent that is actually absorbed.

Proton Triplet: The super conducting final focusing triplet for the protons needs to be protected from radiation by the absorber. Some of the radiation produced upstream of the absorber however will either pass through the absorber or pass through the apertures for the two interacting beams. This is most concerning for the interacting proton beam aperture which will have the superconducting coils. A rough upper bound for the amount of power the coils can absorb before quenching is 100 W. [540] There is approximately 2 kW entering into the interacting proton beam aperture as is shown in Figure 8.23. This doesnt mean that all this power will hit the coils but simulations need to be made to determine how much of this will hit the coils. The amount of power that will pass through the absorber (0.25 W) can be disregarded as it is not enough to cause any significant effects. The main source of power moving downstream of the absorber will be the photons passing through the beams aperture. This was approximately 11 kW as can be seen from Figure 8.23. Most of this radiation can be absorbed in a secondary absorber placed after the first downstream proton quadrupole. Overall protecting the proton triplet is important and although the absorber will minimize the radiation continuing downstream this needs to be studied in depth.

Beamstrahlung The beamstrahlung photons travel parallel to the proton beam until the entrance of D1 without impacting the triplets. Figure 8.24 shows the transverse and energy distributions of the beamstralung photons at the entry of D1 as computed with Guineapig [604].

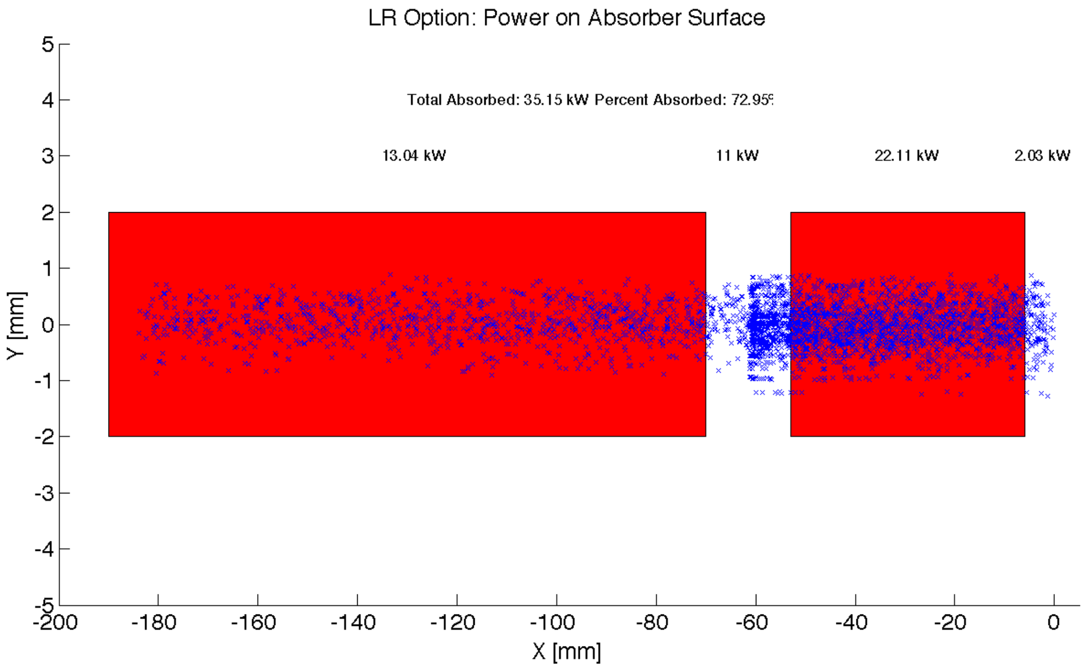


Figure 8.23: LR: Photon distribution on Absorber Surface

The maximum photon energy is about 20 MeV the average photon energy is 0.4 MeV. The beamstrahlung power is 980 W. D1 has to be designed to properly dispose the neutral debris from the IP. Splitting D1 into two parts could allow an escape line for the neutral particles.

Backscattering Another G4 program was written to simulate the backscattering of photons into the detector region. The ntuple with the photon information written at the absorber surface is used as the input for this program. An absorber geometry made of copper is described, and general physics processes are set up. A detector volume is then described and set to record the information of all the photons which enter in an ntuple. The first step in minimizing the backscattering was to optimize the absorber shape. Although the simulation didnt include a beampipe the backscattering for different absorber geometries was compared against one another to find a minimum. The most basic shape was a block of copper that had cylinders removed for the interacting beams. This was used as a benchmark to see the maximum possible backscattering. In HERA a wedge shape was used for heat dissipation and minimizing backscattering. [539] The profile of this geometry in the YZ plane is shown in Figure 8.25. It was found that this is the optimum shape for the absorber. The reason for this is that a backscattered electron would have to have to have its velocity vector be almost parallel to the wedge surface to escape from the wedge and therefore it works as a trap. One can be seen from Table 8.9 utilizing the wedge shaped absorber decreased the backscattered power by a factor of 4. The energy distribution for the backscattered photons can be seen in Figure 8.26.

After the absorber was optimized it was possible to set up a beam pipe geometry. An

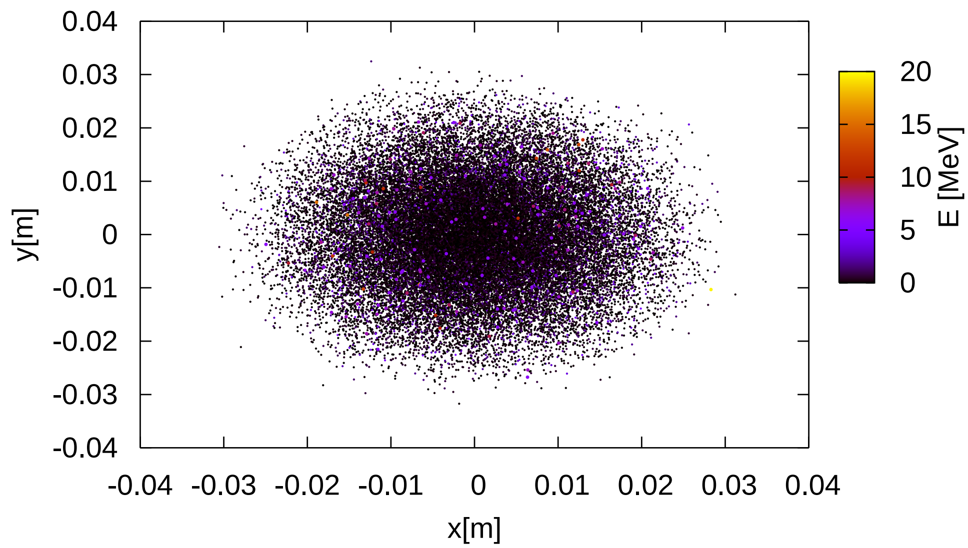


Figure 8.24: Beamstrahlung photons at the entrance of D1.

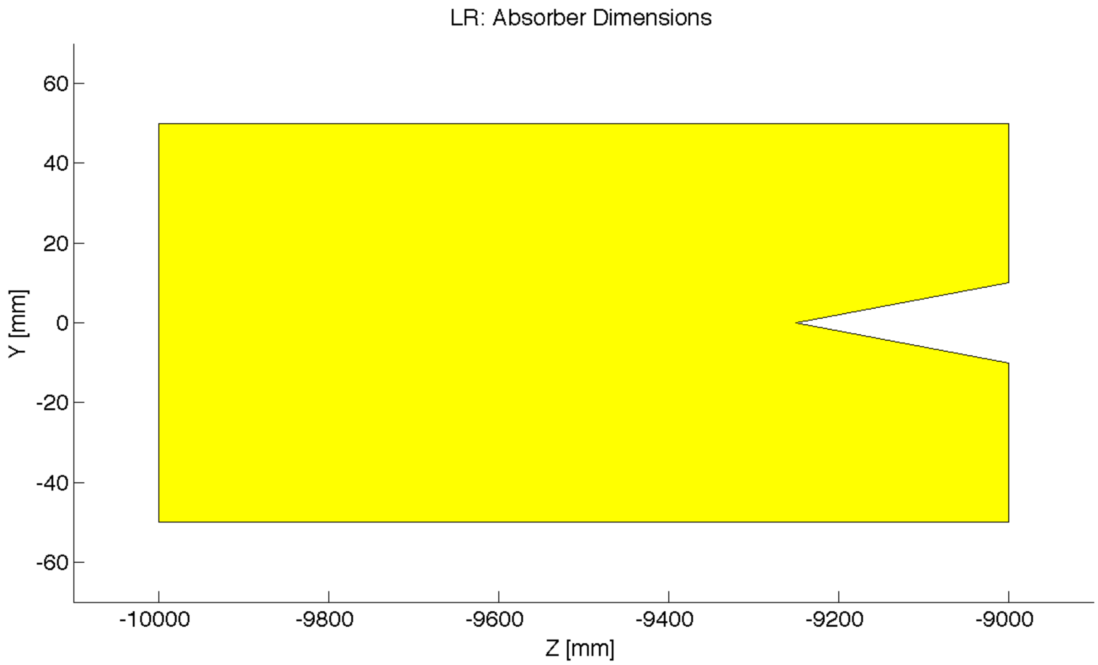


Figure 8.25: LR: Absorber Dimensions

asymmetric elliptical cone beam pipe geometry made of beryllium was used since it would minimize the necessary size of the beam pipe as previously mentioned. The next step was to place the lead shield and masks inside this beam pipe. To determine placement a simulation was run with just the beam pipe. Then it was recorded where each backscattered photon would hit the beam pipe in Z. A histogram of this data was made as shown in Figure 8.27. This determined that the shield should be placed in the Z region ranging from -8 m until the absorber (-9 m). The masks were then placed at -8.9 m and -8.3 m. This decreased the backscattered power by a factor of 40 as can be seen from Table 8.9. Overall there is still more optimization that can occur with this placement.

Absorber Type	Power [W]
Flat	645.9
Wedge	159.1
Wedge & Mask/Shield	4.3

Table 8.9: LR: Backscattering/Mask

Cross sections of the beampipe in the Y = 0 and X = 0 planes with the shields and masks included can be seen in Figure 8.28.

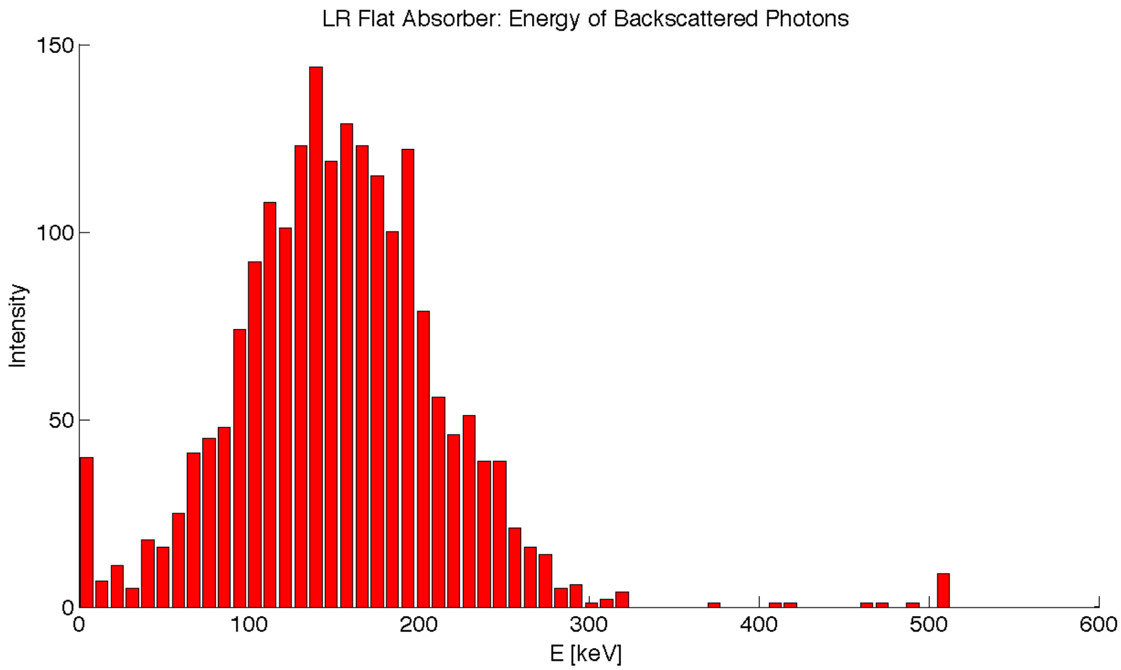


Figure 8.26: LR: Backscattered Energy Distribution

8.3 Linac Lattice and Impedance

8.3.1 Overall Layout

The proposed layout of the recirculating linear accelerator complex (RLA) is illustrated schematically in Fig. 8.29. It consists of the following components:

- A 0.5 GeV injector with an injection chicane.
- A pair of 721.44MHz SCRF linacs. Each linac is one kilometer long with an energy gain 10GeV per pass.
- Six 180° arcs. Each arc has a radius of one kilometer.
- For each arc one re-accelerating station that compensates the synchrotron radiation emitted in this arc.
- A switching station at the beginning and end of each linac to combine the beams from different arcs and to distribute them over different arcs.
- An extraction dump at 0.5 GeV.

After injection, the beam makes three passes through the linacs before it collides with the LHC beam. The beam will then perform three additional turns in which the beam energy is almost completely extracted. The size of the complex is chosen such that each turn has the same

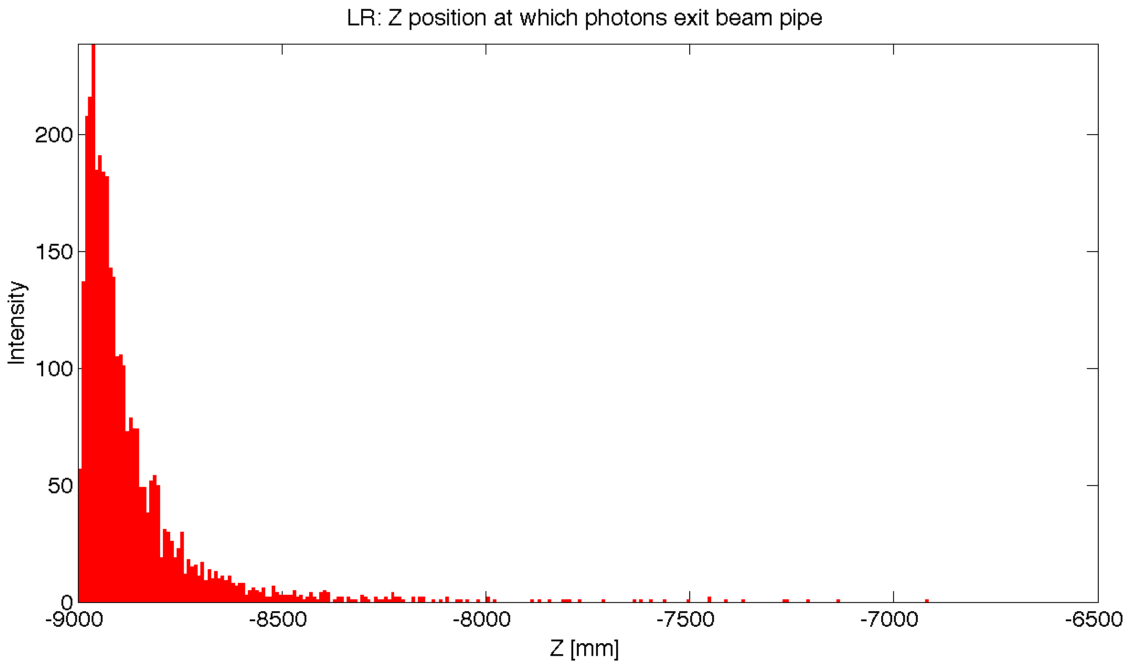


Figure 8.27: LR: Backscattered Photons Exiting the Beam Pipe

length and that three turns correspond to the LHC circumference. This choice is motivated by the following considerations:

- To avoid the build-up of a significant ion density in the accelerator complex, clearing gaps may be required in the beam.
- 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

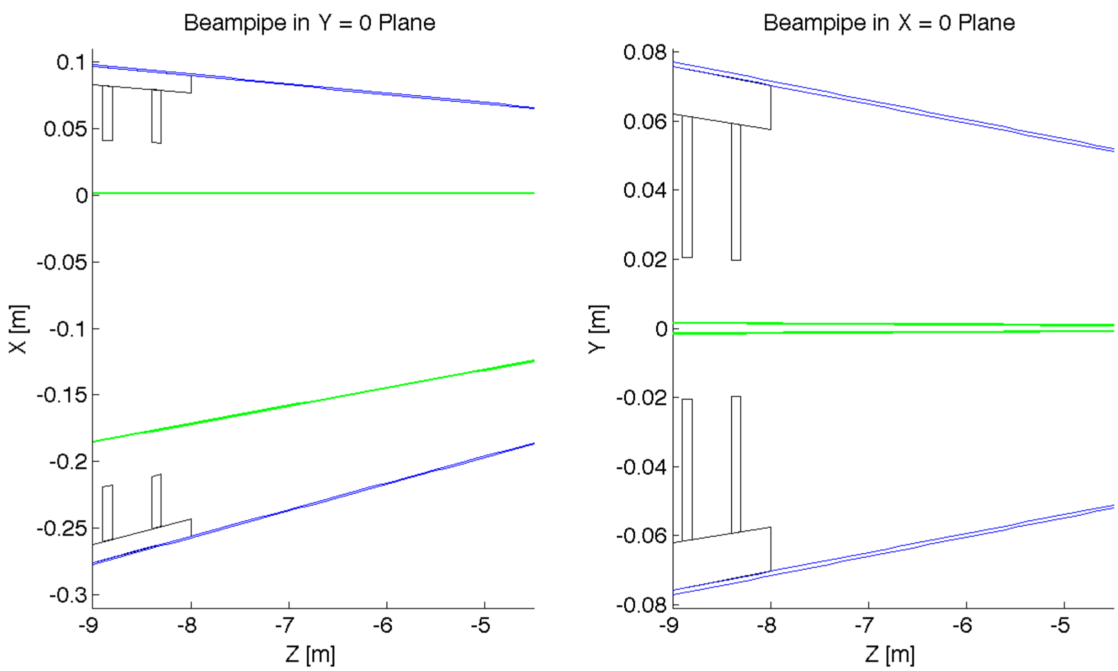


Figure 8.28: LR: Beampipe Cross Sections

advance of 130° for the beam that passes with the lowest energy and a quadrupole spacing of 28m [605]. Alternative choices are possible. An example is an optics that avoids any quadrupole in the linacs [606].

Linac Module Layout

The linac consists of a series of units, each consisting of two cryomodules and one quadrupole pack. See Fig. 8.30 for the layout. Each cryomodule is 12.8m and contains eight 1m-long accelerating cavities. The interconnect between two adjacent cryomodules is 0.8m long. The quadrupole pack is 1.6m long, including the interconnects to the adjacent cryomodules. The whole unit is 28m long.

Each quadrupole pack contains a quadrupole, a beam position monitor and a vertical and

Parameter	Symbol	Value
Particles per bunch	N	$2 \cdot 10^9$
Initial normalised transverse emittance	ϵ_x, ϵ_y	30μm
Normalised transverse emittance at IP	ϵ_x, ϵ_y	50μm
Bunch length	σ_z	600μm

Table 8.10: Key beam parameters.

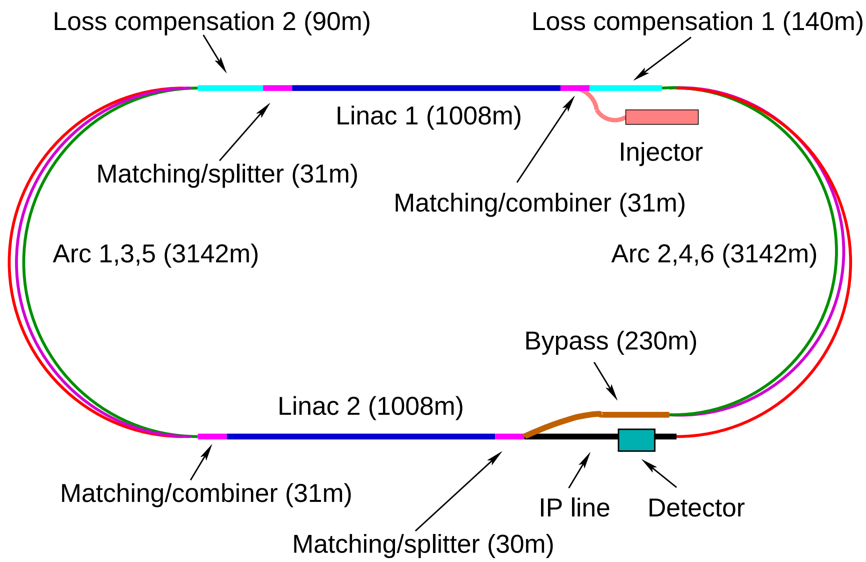


Figure 8.29: The schematic layout of the recirculating linear accelerator complex.

Figure 8.30: The schematic layout of a linac unit.

horizontal dipole corrector, see section 2.9.

Linac Optics

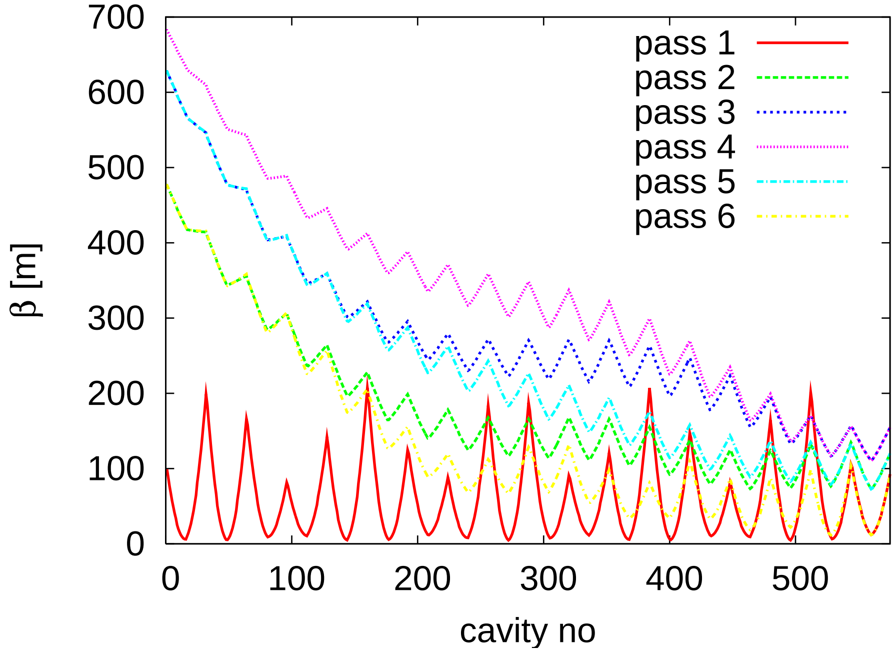
The linac consists of 36 units with a total length of 1008m. In the first linac, the strength of the quadrupoles has been chosen to provide a phase advance per cell of 130° for the beam in its first turn. In the second linac, the strength has been set to provide a phase advance of 130° for the last turn of the beam. The initial Twiss parameters of the beam and the return arcs are optimised to minimise the beta-functions of the beams in the following passages. The critrium used has been to minimise the integral

$$\int_0^L \frac{\beta}{E} ds \tag{8.6}$$

Single bunch transverse wakefield effects and multi-bunch effects between bunches that have been injected shortly after each other are proportional to this integral [607]. The final solution is shown in Fig. 8.31. A significant beta-beating can be observed due to the weak focusing for the higher energy beams.

Return Arc Optics

At the ends of each linac the beams need to be directed into the appropriate energy-dependent arcs for recirculation. Each bunch will pass each arc twice, once when it is accelerated before the collision and once when it is decelerated after the collision. The only exception is the arc at



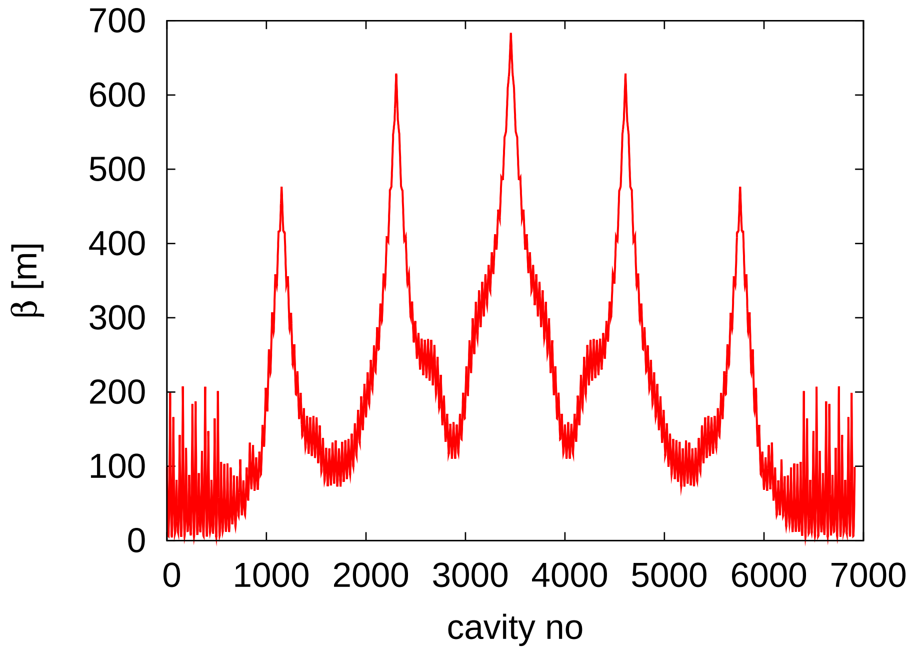


Figure 8.31: Beta-functions in the first linac. On the top, the beta-functions of the six different beam passages in the first linac are shown. On the bottom, the beta-function as seen by the beam during his stay in the linacs are shown.

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.

highest energy that is passed only once. For practical reasons, horizontal rather than vertical beam separation was chosen. Rather than suppressing the horizontal dispersion created by the spreader, the horizontal dispersion can been smoothly matched to that of the arc, which results in a very compact, single dipole, spreader/recombiner system.

The initial choice of large arc radius (1 km) was dictated by limiting energy loss due to synchrotron radiation at top energy (60.5 GeV) to less than 1%. However other adverse effects of synchrotron radiation on beam phase-space such as cumulative emittance and momentum growth due to quantum excitations are of paramount importance for a high luminosity collider that requires normalized emittance of 50 mm mrad.

Three different arc designs have been developed [605]. In the design for the lowest energy turns, the beta-functions are kept small in order to limit the required vacuum chamber size and consequently the magnet aperture. At the higest energy, the lattice is optimised to keep the emittance growth limited, while the beta-functions are allowed to be larger. A cell of the lowest and one of the highest energy arc is shown in Fig. 8.32 All turns have a bending radius of 764m. The beam pipe diameter is 25mm, which corresponds to more than 12σ aperture.

An interesting alternative optics, which pushes towards a smaller beam pipe, has also been developed [606].

Synchrotron Radiation in Return Arcs

Synchrotron radiation in the arcs leads to a significant beam energy loss. This loss is compensated by the small linacs that are incorporated before or after each arc when the beams are already or still separated according to their energy, see Fig. 8.29. The energy loss at the 60GeV turn-round can be compensated by a linac with an RF frequency of 721.44MHz. The compensation at the other arcs is performed with an RF frequency of 1442.88MHz. In this way the bunches that are on their way to the collision point and the ones that already collided can

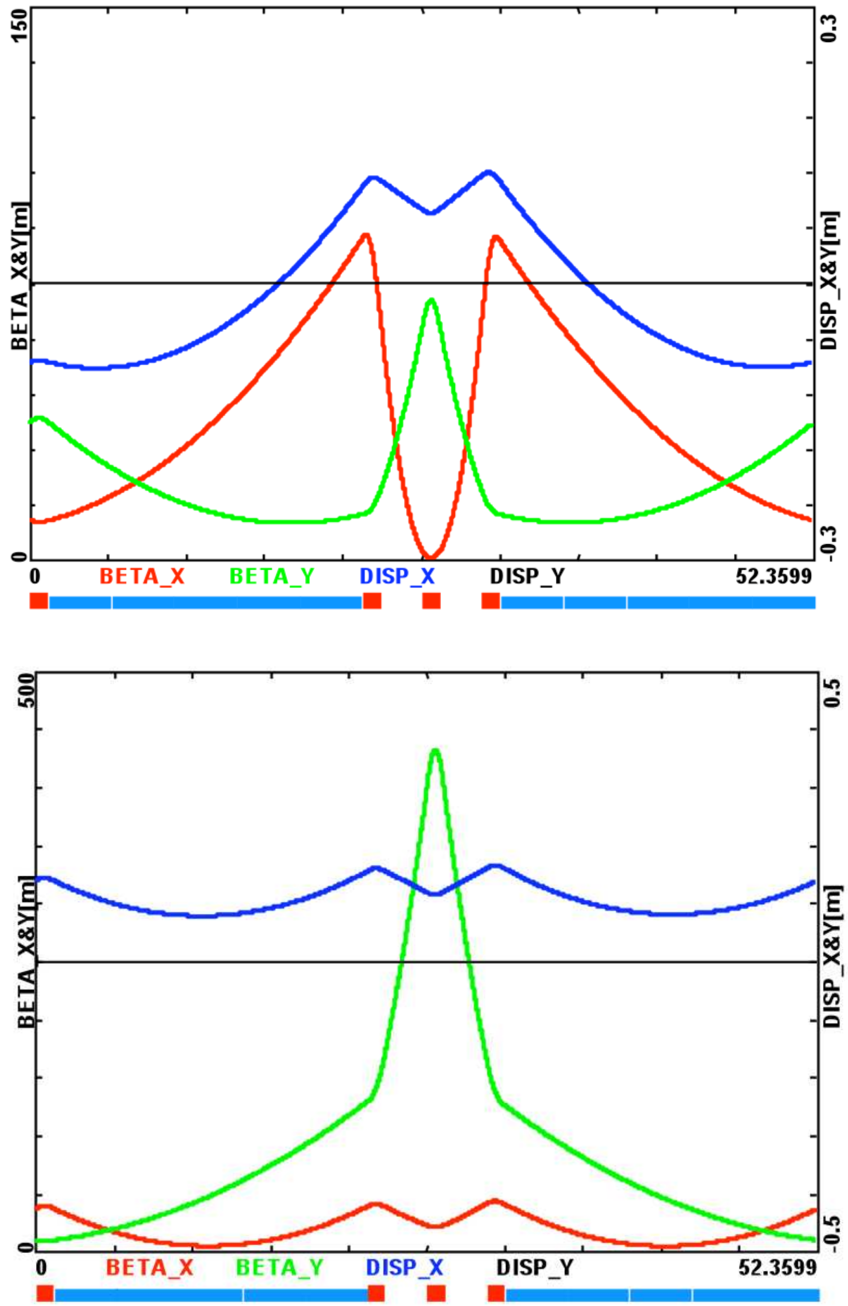


Figure 8.32: The optics of the lowest (top) and the highest (bottom) energy return arcs.

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.

both be accelerated. This ensures that the energy of these bunches are the same on the way to and from the interaction point, which simplifies the optics design. If the energy loss were not compensated the beams would have a different energy at each turn, so that the number of return arcs would need to be doubled.

The synchrotron radiation is also generating an energy spread of the beam. In Tab. 8.11 the relative energy spread is shown as a function of the arc number that the beam has seen. At the interaction point, the synchrotron radiation induced RMS energy spread is only 2×10^{-4}, which adds to the energy spread of the wakefields. At the final arc the energy spread reaches about 0.22%, while at the beam dump it grows to a full 4.5%.

The growth of the normalised emittance is given by

$$\Delta\epsilon = \frac{55}{48\sqrt{3}} \frac{\hbar c}{mc^2} r_e \gamma^6 I_5 \tag{8.7}$$

Here, r_e is the classical electron radius, and I_5 is given by

$$I_5 = \int_0^L \frac{H}{|\rho|^3} ds = \frac{\langle H \rangle \theta}{\rho^2} \quad H = \gamma D^2 + 2\alpha D D' + \beta D'^2 \tag{8.8}$$

For a return arc with a total bend angle $\theta = 180°$ one finds

$$\Delta\epsilon = \frac{55}{48\sqrt{3}} \frac{\hbar c}{mc^2} r_e \gamma^6 \pi \frac{\langle H \rangle \theta}{\rho^2} \tag{8.9}$$

The synchrotron radiation induced emittance growth is shown in table 8.12. Before the interaction point a total growth of about 7μm is accumulated. The final value is 26μm. While this growth is significant compared to the target emittance of 50μm at the collision point, it seems acceptable.

Matching Sections and Energy Compensation

Currently we do not have a design of the matching sections. However, we expect these sections to be straightforward. For the case of the linac optics without quadrupoles and the alternative return arc lattice design matching sections designs exist and exhibit no issues [606]. 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 [608]. 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 [609]. 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

$$W_{\perp}(s) \approx \frac{1}{(70/39)^3} W_{\perp,ILC}(s/(70/39)) \quad W_L(s) \approx \frac{1}{(70/39)^2} W_{L,ILC}(s/(70/39)) \tag{8.10}$$

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. 300μm, 600μm and 900μm. This longest value yields the smallest final energy spread. The energy spread along during the beam life-time can be seen in Fig. 8.33. The wakefield induced energy spread is between 1×10^{-4} and 2×10^{-4} at the interaction point, 1–2×10^{-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. 8.34.

Multi-Bunch Transverse Wakefield Effects

For a single pass through a linac the multi-bunch effects can easily be estimated analytically [607]. Another approach exists in case of two passes through one cavity [610]. 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 [611]. It assumes point-like bunches and takes a number of dipole wake field modes into account. A cavity-to-cavity frequency spread of the wakefield modes can also be modeled. The arcs are replaced with simple transfer matrices. In the simulation, we offset a single bunch of a long train by one unit and determine the final position in phase space of all other bunches.

We evaluated the beam stability using the wakefield modes that have been calculated for the SPL cavity design [612]. The level of the Q-values of the transverse modes is not yet known. We assume $Q = 10^5$ for all modes, which is comparable to the larger of the Q-values found in the TESLA cavities. A random variation of the transverse mode frequencies of 0.1% has been

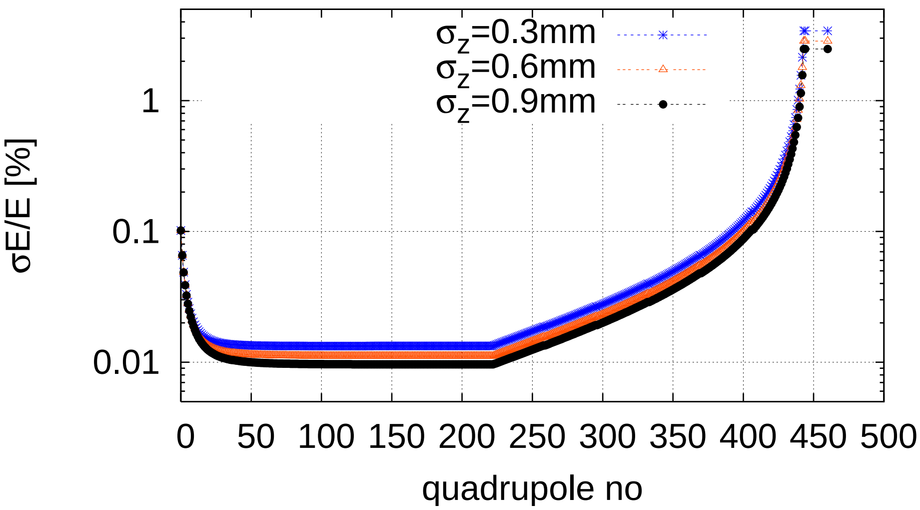


Figure 8.33: The RMS energy spread due to single bunch wakefields along the linacs. The bunch has been cut longitudinally at $\pm 3\sigma_z$ and at $\pm 3\sigma_E$ in the initial uncorrelated energy spread.

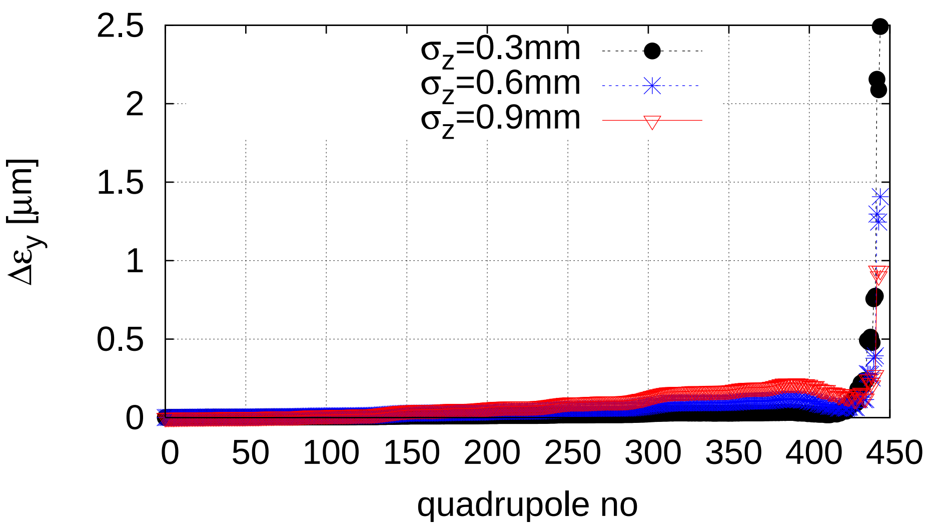


Figure 8.34: The single-bunch emittance growth along the LHeC linacs for a bunch with an initial offset of $\Delta x = \sigma_x$. The arcs have been represented by a simple transfer matrix.

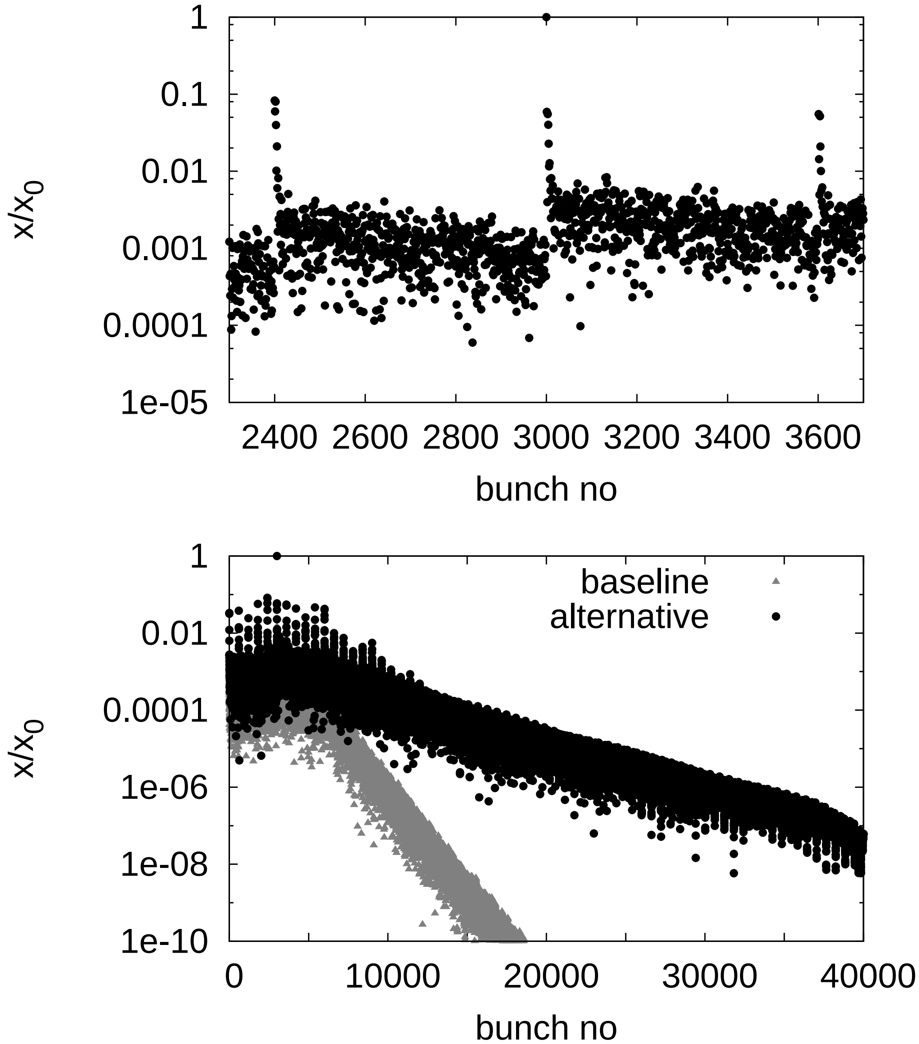


Figure 8.35: Multi-bunch beam break-up assuming the SPL cavity wakefields. One bunch has been offset at the beginning of the machine and the normalised amplitudes of the bunch oscillations are shown along the train at the end of the last turn. The upper plot shows a small number of bunches before and 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.

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.

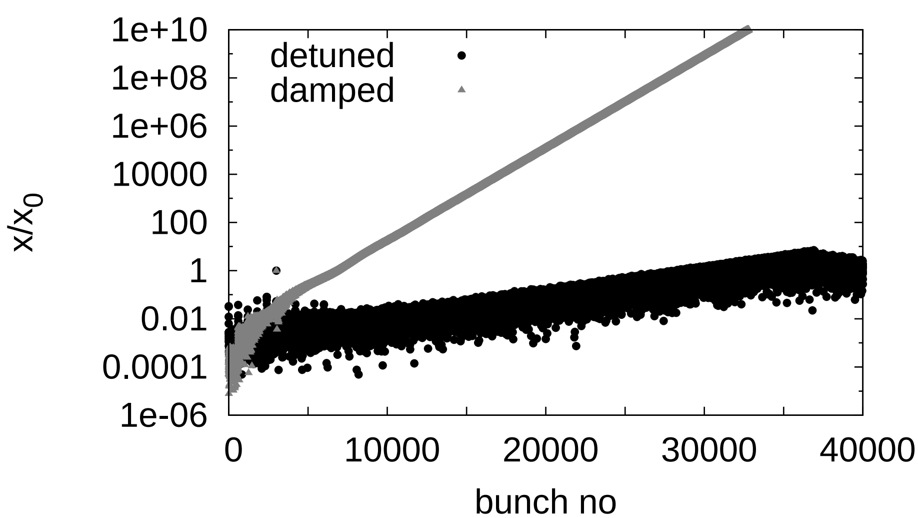


Figure 8.36: Multi-bunch beam break-up for the SPL cavities. In one case only damping, in the other case only cavity-to-cavity mode detuning is present.

assumed, which corresponds to the target for ILC [609]. The results in Fig. 8.35 indicate that the beam remains stable in our baseline design. Even in the alternative lattice with no focusing in the linacs, the beam would remain stable but with significantly less margin.

We also performed simulations, assuming that either only damping or detuning were present, see Fig. 8.36. The beam is unstable in both cases. Based on our results we conclude

- One has to ensure that transverse higher order cavity modes are detuned from one cavity to the next. While this detuning can naturally occur due to production tolerances, one has to find a method to ensure its presence. This problem exists similarly for the ILC.
- Damping of the transverse modes is required.

Further studies can give more precise limits on the maximum required Q and minimum mode detuning.

Fast Beam-Ion Instability

Collision of beam particles with the residual gas in the beam pipe will lead to the production of positive ions. These ions can be trapped in the beam. There presence modifies the betatron function of the beam since the ions focus the beam. They can also lead to beam break-up, since bunches with an offset will induce a coherent motion in the ions. This can in turn lead to a kick of the ions on following bunches.

Trapping Condition in the beam pulse In order to estimate whether ions are trapped or not, one can replace each beam with a thin focusing lens, with the strength determined by the charge and transverse dimension of the beam. In this case the force is assumed to be linear with the ion offset, which is a good approximation for small offsets.

The coherent frequency f_i of the ions in the field of a beam of with bunches of similar size is given by [613]:

$$f_i = \frac{c}{\pi}\sqrt{\frac{Q_i N r_e \frac{m_e}{A m_p}}{3\sigma_y(\sigma_x+\sigma_y)\Delta L}} \quad (8.11)$$

Here, N is the number of electrons per bunch, ΔL the bunch spacing, r_e the classical electron radius, m_e 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 mass. The beam transverse beam size is given by σ_x and σ_y. The ions will be trapped in the beam if

$$f_i \leq f_{limit} = \frac{c}{4\Delta L} \quad (8.12)$$

In the following we will use $\Delta L \approx 2.5$m, i.e. assume that the bunches from the different turns are almost evenly spaced longitudinally.

In the linacs, the transverse size of the beam changes from one passage to the next while in each of the return arcs the beams have (approximately) the same size at both passages. But the variation from one turn to the next is not huge, so we use the average focusing strength of the six turns. The calculation shows that ions will be trapped for a continuous beam in the linacs. Since we are far from the limit of the trapping condition, the simplification in our model should not matter. As can be seen in Fig. 8.37 CO_2^+ ions are trapped all along the linacs. Even hydrogen ions H_2^+ would be trapped everywhere. If one places the bunches from the six turns very close to each other longitudinally, the limit freqeuncy f_{limit} is reduced. However, the ratio

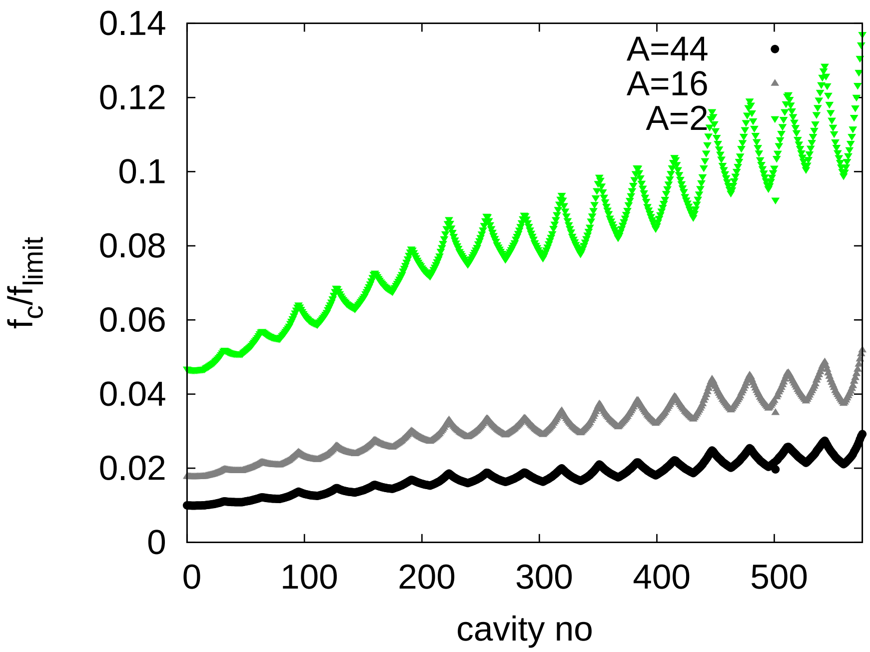


Figure 8.37: The oscillation frequency f_c of ions of different mass number A in the linacs using the average focusing strength of the bunches at different energy. The frequency is normalised to the limit frequency f_{limit} above which the ions would not be trapped any more.

f_c/f_{limit} is not increased by more than a factor 6, which is not fully sufficient to remove the H_2^+.

Impact and Mitigation of Ion Effects Without any methods to remove ions, a continous beam would collect ions until they neutralise the beam current. This will render the beam unstable. Hence one needs to find methods to remove the ions. We will first quickly describe the mitigation techniques and then give a rough estimate of the expected ion effect.

A number of techniques can be used to reduce the fast beam-ion instability:

- An excellent vacuum quality will slow down the build-up of a significant ion density.
- Clearing gaps can be incorporated in the electron beam. During these gaps the ions can drift away from the beam orbit.
- Clearing electrodes can be used to extract the ions. They would apply a bias voltage that lets the ions slowly drift out of the beam.

Clearing Gaps In order to provide the gap for ion cleaning, the beam has to consist at injection of short trains of bunches with duration τ_{beam} separated by gaps τ_{gap}. If each turn of the beam in the machine takes τ_{cycle}, the beam parameters have to be adjusted such that $n(\tau_{beam} + \tau_{gap}) = \tau_{cycle}$. In this case the gaps of the different turns fall into the same location of the machine. This scheme will avoid beam loading during the gap and ensure that the gaps a fully empty. By chosing the time for one round trip in the electron machine to be an integer fraction of the LHC roundtrip time $\tau_{LHC} = m\tau_{cycle}$, one ensures that each bunch in the LHC will either always collide with an electron bunch or never. We chose to use $\tau_{cycle} = 1/3\tau_{LHC}$ and to use a single gap with $\tau_{gap} = 1/3\tau_{cycle} \approx 10\ \mu$s.

In order to evaluate the impact of a clearing gap in the beam, we model the beam as a thick focusing lens and the gap as a drift. The treatment follows [614], except that we use a thick lens approach and correct a factor two in the force. The focusing strength of the lens can be calculated as

$$k = \frac{2Nr_e m_e}{A_{ion} m_p \sigma_y(\sigma_x + \sigma_y)\Delta L} \tag{8.13}$$

The ions will not be collected if the following equation is fulfilled

$$\left|2\cos(\sqrt{k}(L_{erl} - L_g)) - \sqrt{k}L_g \sin(\sqrt{k}(L_{erl} - L_g))\right| \geq 2 \tag{8.14}$$

Since the beam size will vary as a function of the number of turns that the beam has performed, we replace the above defined k with the average value over the six turns using the average bunch spacing ΔL,

$$k = \frac{1}{n}\sum_{i=1}^{n} \frac{2Nr_e m_e}{A_{ion} m_p \sigma_{y,i}(\sigma_{x,i} + \sigma_{y,i})\Delta L}. \tag{8.15}$$

The results of the calculation can be found in Fig. 8.38. As can be seen, in most locations the ions are not trapped. But small regions exist where ions will accumulate. More study is needed to understand which ion density is reached in these areas. Longitudinal motion of the ions will slowly move them into other regions where they are no longer trapped.

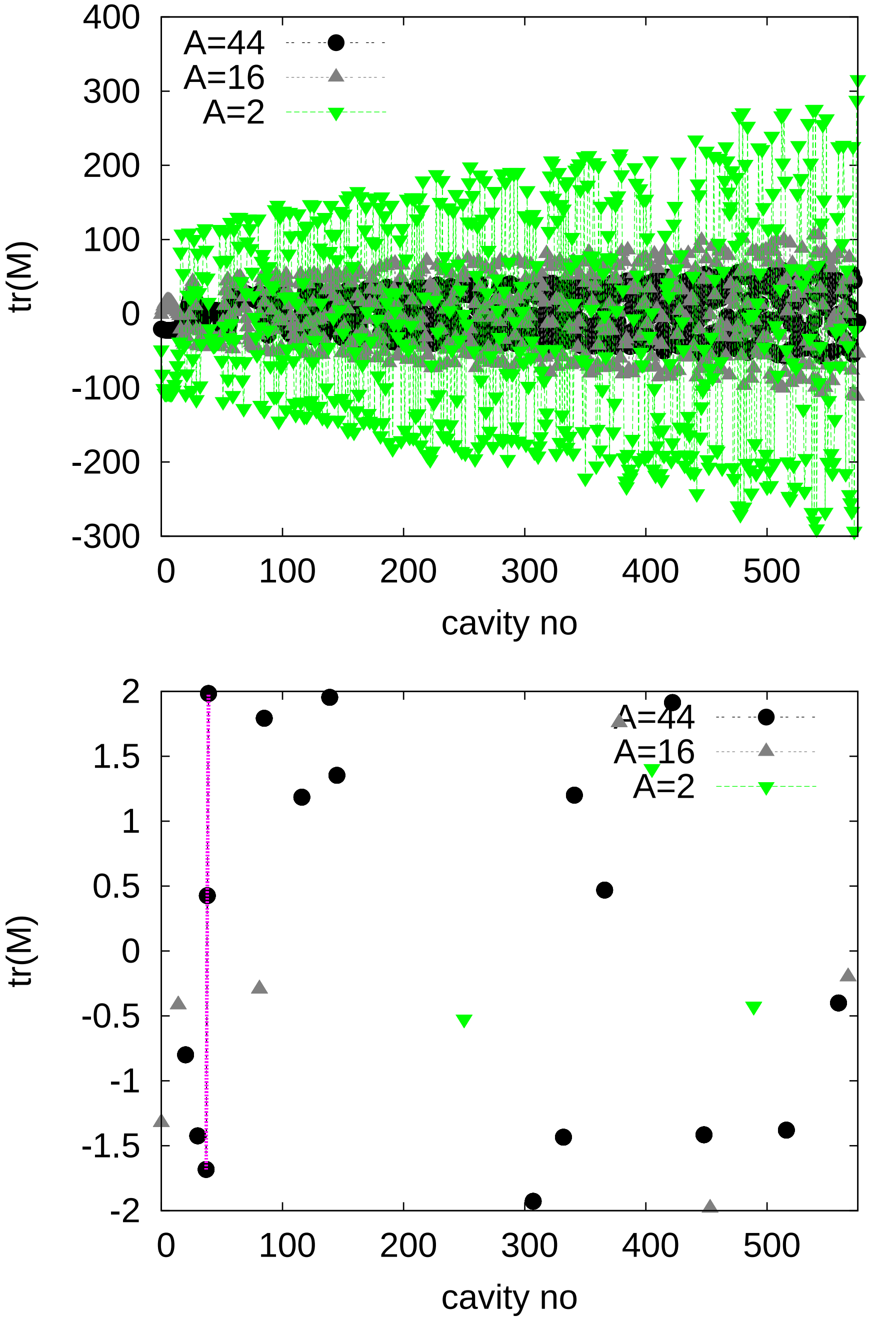


Figure 8.38: The trace of the transfer matrix for H_2^+, CH_4^+ and CO_2^+ ions in presence of a clearing gap. Values above 2 or below -2 indicate that the ions will not be trapped.

Ion Instability While the gap ensures that ions will be lost in the long run, they will still be trapped at least during the full train length of 20μs. We therefore evaluate the impact of ions on the beam during this time. This optmistically ignores that ions will not be completely removed from one turn to the next. However, the stability criteria we employ will be pessimistic. Clearly detailed simulations will be needed in the future to improve the predictive power of the estimates.

Different theoretical models exist for the rise time of a beam instability in the presence of ions. A pessimistic estimate is used in the following. The typical rise time of the beam-ion instability for the nth bunch can be estimated to be [613]

$$\tau_c = \frac{\sqrt{27}}{4}\left(\frac{\sigma_y(\sigma_x+\sigma_y)}{Nr_e}\right)^{\frac{3}{2}}\sqrt{\frac{A_{ion}m_p}{m}}\frac{kT}{p\sigma_{ion}}\frac{\gamma}{\beta_y cn^2\sqrt{L_{sep}}} \tag{8.16}$$

This estimate does not take into account that the ion frequency varies with transverse positon within the bunch and along the beam line.

We calculate the local instability rise length $c\tau_c$ for a pressure of $p = 10^{-11}$hPa at the position of the beam. As can be seen in Fig. 8.39 this instability rise length ranges from a few kilometers to several hundred. One can estimate the overall rise time of the ion instability by averaging over the local ion instability rates:

$$\langle\frac{1}{\tau_c}\rangle = \frac{\int \frac{1}{\tau_c(s)}ds}{\int ds} \tag{8.17}$$

For the worst case in the figure, i.e. CH_4^+, ones finds $c\tau_c \approx 14$ km and for H_2^+ $c\tau_c \approx 25$km. The beam will travel a total of 12km during the six passes through each of the two linacs. So the typical time scale of the rise of the instability is longer than the life time of the beam and we expect no issue. This estimate is conservative since it does not take into account that ion frequency varies within the beam and along the machine. Both effects will stabilise the beam. Hence we conclude that a partial pressure below 10^{-11} hPa is required for the LHeC linacs.

In the cold part of LEP a vacuum level of 0.5×10^{-9}hPa has been measured at room temperature, which corresponds to 0.6×10^{-10}hPa in the cold [615]. This is higher than required but this value "represents more the outgassing of warm adjacent parts of the vacuum system" [615] and can be considered a pessimistic upper limit. Measurements in the cold at HERA showed vacuum levels of 10^{-11}hPa [616], which would be sufficient but potentially marginal. Recent measurements at LHC show a hydrogen pressure of 5×10^{-12}hPa measured at room temperature, which corresponds to about 5×10^{-13}hPa in the cold [617]. For all other gasses a pressure of less than 10^{-13}hPa is expected measured in the warm [617], corresponding to 10^{-14}hPa in the cold. These levels are significantly better than the requirements. The shortest instability rise length 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 expect a problem with the fast beam-ion instability in the linacs provided the vacuum system is designed accordingly.

The effect of the fast beam-ion instability in the arcs has been calculated in a similar way, taking into account the reduced beam current and the baseline lattice for each arc. Even H_2^+ will be trapped in the arcs. We calculate the instability rise length $c\tau_c$ for a partial pressure of $10^{-9\ \mathrm{hPa}}$ for each ion mass and find $c\tau_c \approx 70$km for H_2^+, $c\tau_c \approx 50$km for N_2^+ and CO^+ and $c\tau_c \approx 60$km forCO_2^+. The total distance the beam travels in the arcs is 15km. Hence we conclude that a partial pressure below 10^{-9} hPa should be sufficient for the arcs. More detailed

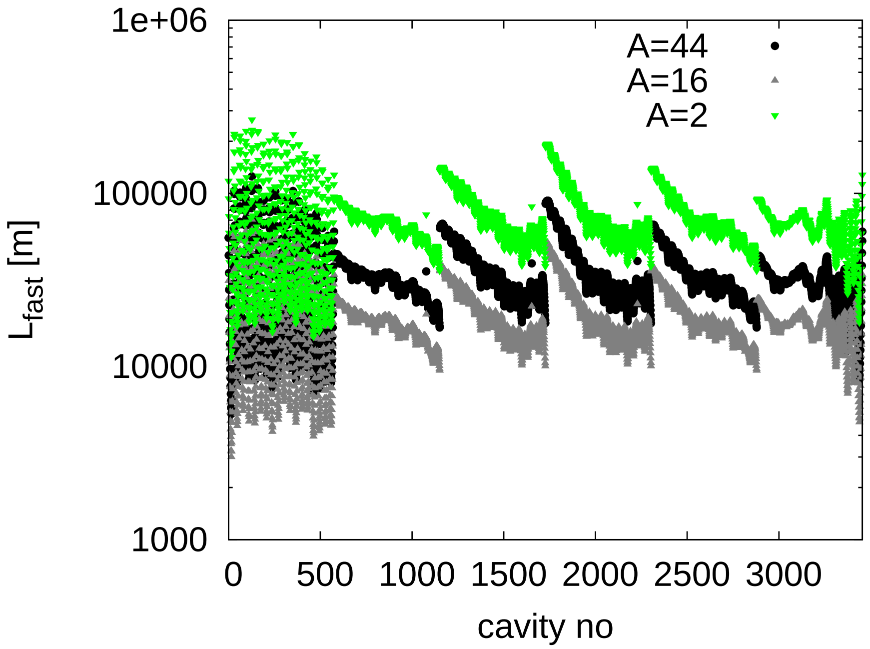


Figure 8.39: The instability length of the beam-ion instability assuming a very conservative partial pressure of 10^{-11}hPa for each gas.

work will be needed in the future to fully assess the ion effects in LHeC but we 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 [614] for a round beam:

$$\frac{\Delta\phi}{\phi} = \frac{1}{2}\frac{Nr_e}{\Delta L\epsilon_y}\frac{\theta}{\langle\beta_y^{-1}\rangle}$$

Here θ is the neutralisation of the beam by the ions. We use the maximum beta-function in the linac to make a conservative approximation $\langle\beta^{-1}\rangle = 1/700$m. At the end of the train we find $\rho \approx 3.3\times10^{-5}$ for $p = 10^{-11}$hPa in the cold and $p = 10^{-9}$hPa in the warm parts of the machine. This yields $\Delta\Phi/\Phi \approx 7\times10^{-4}$. Hence the phase advance error can be neglected.

Impact of the Gap on Beam Loading It should be notet that the gaps may create some beam-loading variation in the injector complex. We can estimate the associated gradient variation assuming that the same cavities and gradients are used in the injector as in the linacs. We use

$$\frac{\Delta G}{G} \approx \frac{1}{2}\frac{R}{Q}\omega\frac{\tau_{gap}\tau_{beam}I}{\tau_{gap}+\tau_{beam}}\frac{1}{G} \tag{8.18}$$

In this case the 10μs gaps in the bunch train correspond to a gradient variation of about 0.6%. This seems very acceptable.

8.3.4 Imperfections

Static imperfections can lead to emittance growth in the LHeC linacs and arcs. However, one can afford an emittance budget that is significantly larger than the one for the ILC, i.e. 10μm vs. 20nm. If the LHeC components are aligned with the accuracy of the ILC components, one would not expect emittance growth to be a serious issue. In particular in the linacs dispersion free steering can be used and should be very effective, since the energies of the different probe beams are much larger than they would be in ILC.

Gradient Jitter and Cavity Tilt

Since the cavities have titlts with respect to the beam line axis, dynamic variations of the gradient will lead to transverse beamdeflections. This effect can be easily calculated using the following expression:

$$\frac{\langle y^2 \rangle}{\sigma_y^2} = \frac{\langle (y')^2 \rangle}{\sigma_{y'}^2} = \frac{1}{2}\frac{1}{\epsilon}\int \frac{\beta}{E} ds \frac{L_{cav}\langle \Delta G^2 \rangle \langle\langle (y'_{cav})^2 \rangle}{mc^2}$$

For an RMS cavity tilt of 300μradian, an RMS gradient jitter of 1% and an emittance of 50μm we find

$$\frac{\langle y^2 \rangle}{\sigma_y^2} = \frac{\langle (y')^2 \rangle}{\sigma_{y'}^2} \approx 0.0125$$

i.e. an RMS beam jitter of $\approx 0.07\sigma_y$. At the interaction point the beam jitter would be $\approx 0.05\sigma_{y'}$.

8.4 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 **??**.

The Linac-Ring option is based on an ERL machine where the beam pattern, at IP, is shown in Figure 8.40.

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 x 0.33 nC/b = 6.6 mA.

Figure 8.41 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 down 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 8.14 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.

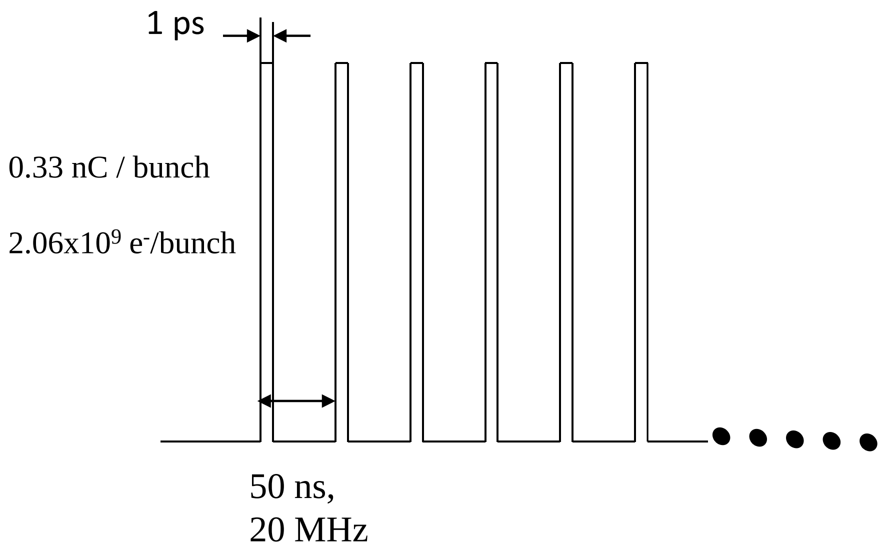


Figure 8.40: Beam pattern at IP

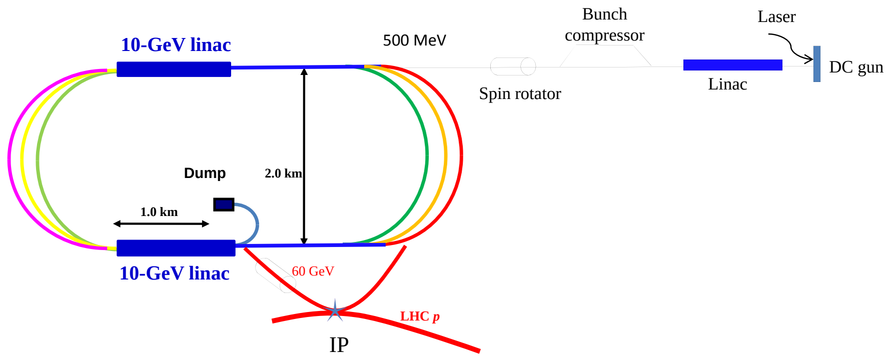


Figure 8.41: Layout of the injector (not to scale).

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 8.14: Beam parameters at the source.

- 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).
- the laser parameters (300 nJ/pulse on the photocathode, 20 MHz repetition rate) will need some R&D according to what is existing today on the market.
- the space charge could increase the transverse beam emittances.

In conclusion, a tradeoff between the photocathode, the gun and the laser seems reachable to get acceptable parameters at the gun exit. A classical Pre-Injector Linac accelerates electron beam to the requested ERL energy. Different stages of bunch compressor are used to compensate the initial laser pulse and the space charge effects inducing bunch lengthening. A classical spin rotator system rotates the spin before injection into the ERL.

8.5 Spin Rotator

The LHeC physics requires polarized electrons with spin aligned longitudinally at the collision point [618]. In the electron accelerator of LHeC, consisting of two 10-GeV superconducting linear accelerators linked with six 180° arc paths, the depolarization due to the arcs is negligible if the spin is aligned vertically in the arcs.

The motion of the spin vector S is governed by Thomas-BMT equation [**?**, 619] shown in Eq. 8.19

$$\frac{d\vec{S}}{dt} = \frac{e}{m\gamma}\vec{S} \times [(1 + G\gamma)\vec{B}_\perp + (1 + G)\vec{B}_\parallel] \qquad (8.19)$$

where e, m and γ are the electric charge, mass and Lorentz factor of the particle. G is the anomalous g-factor. For protons, $G = 1.7928474$ and for electrons, $G = 0.00115$. $\vec{B}_{\perp}$ and $\vec{B}_{\parallel}$ are the magnetic field perpendicular and parallel to the particle velocity direction, respectively. In Eq. 8.19, magnetic field is in the laboratory frame while the spin vector $\vec{S}$ is in the particle's rest frame. In a bending dipole, a spin vector precesses $G\gamma$ times of the particle's orbital rotation in the particle's moving frame. It is also evident that solenoid field is less effective to manipulate spin motion at high energies.

For the LHeC physics program, the polarization of 60 GeV electron beam needs to be aligned longitudinally at the collision point which is after the last arc and the acceleration. The most economical way to control the spin direction at the collision point is to control the spin direction of the low energy electron beam at the early stage of injector using a Wien Filter, a traditional low energy spin rotator. Since spin vector rotates $G\gamma\pi$ each time it passes through a 180° arc, the goal of the Wien Filter is to put the spin vector in the horizontal plane with an angle to the direction of the particle's velocity to compensate the amount of spin rotations before collision.

For the layout of LHeC, i.e. two linear accelerators linked with two arcs, spin vector rotates

$$\phi_{arc} = G\pi[\gamma_i(2n-1) + \Delta\gamma n(2n-1)] \tag{8.20}$$

after its nth path. Here, γ_i is the initial Lorentz factor of the beam and $\Delta\gamma$ is the energy gain of each linear accelerator. In addition, LHeC also employs two horizontal bending dipoles on either side of the collision point to separate the electrons from the protons. Each of this bending dipole is 0.3 T and spans 9 m from the collision point. For 60 GeV electron beam, it rotates the spin vector by $\phi_{IP} = 104.4°$. For initial energy of 10 GeV and each linear accelerator energy gain of 10 GeV, Table 8.15 lists the amount of spin 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 spin rotations in the

Table 8.15: total spin rotation from arcs and final bending dipole at collision point

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

range of 2π. Since the spin rotation is proportional to beam energy, for a beam of particles with non-zero momentum spread, different amount of spin rotation then generates a spread of spin vector directions. This results in an effective polarization loss due to the spread of the spin vector. Fig. 8.42 shows the angle spread of the spin vector for an off-momentum particle at 20GeV, 40GeV and 60GeV. The calculation assumes the initial energy before the electron beam enters the arc is 10 GeV and energy gain of each linear accelerator is 10 GeV. It shows that for 60 GeV electron beam, a momentum spread of 3×10^{-4} can cause about 10% polarization loss effectively due to the spread of the spin vectors. This may not be able to satisfy the requirement on high polarization.

In order to provide the desirable polarization direction without sacrificing polarization, one can take the traditional approach of high energy polarized beams at HERA and RHIC, i.e. to

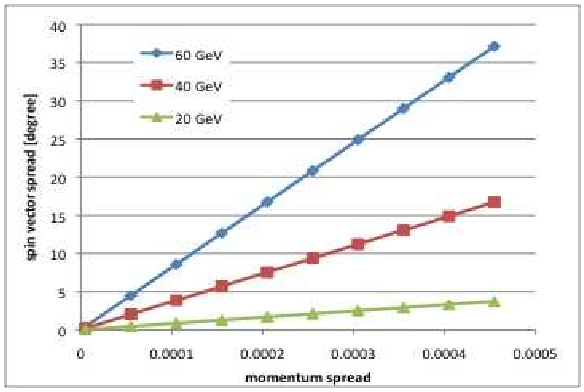


Figure 8.42: Calculated spin vector spread as function of momentum spread. The effective polarization loss is the cosine of spin vector spread angle, i.e. for an angle of 30 degrees, the effective polarization is 86% of initial beam polarization

rotate the spin vector to vertical direction before it gets accelerated to high energy. Since the spin vector aligns with the main bending magnetic fields' direction, this prevents the spread of the spin vector due to the momentum spread. After the last arc and acceleration, at 60 GeV beam energy, the spin vector must be rotated back so as to be longitudinally aligned at the collision point. To this end, for the current compact LHeC design, we propose to use a RHIC type spin rotator [**?**, 620] at the LHeC. Besides saving space of being compact, this approach also provides the advantage of independent control of the spin vector orientation, as well as nearly energy independent spin rotation for the same magnetic field. The four helical dipoles are arranged in a similar fashion as the RHIC spin rotator, i.e. with alternating helicity. Fig. 8.43 shows the schematic layout. Each helical dipole is 3.3 m long and the helicity alternates between right hand to left hand between each helical dipole. The two inner helical dipoles have the same magnetic field but opposite helicity. Same applies to the two outer helical dipoles.

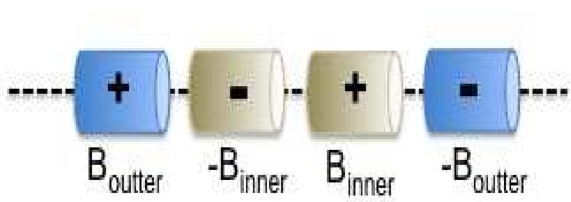


Figure 8.43: Schematic layout of LHeC spin rotator. A total of four helical dipoles with alternating helicity marked as + and -. The polarity of two outer helical dipole fields are also opposite. And so is the polarity of the two inner helical dipoles.

For each helical dipole, the magnetic field is given by

$$B_x = Bcoskz; B_y = Bsinkz; B_z = 0.0 \tag{8.21}$$

where, $B_{x,y,x}$ are the horizontal, vertical and longitudinal component of the magnetic field, respectively. Z is the longitudinal distance along the helical dipole axis. $|k| = \frac{2\pi}{\lambda}$ and λ are wave number and wave length of the helical field, respectively.

For spin roator, all helical dipoles are chosen to be one period, i.e. $\lambda = L$, where L is the length of each helical dipole. Depending on the direction of the helicity, $\frac{k}{|k|} = \pm 1$. Fig. 8.44 shows the correlation of the magnetic field for the inner and outer helical magnets of a spin rotator which brings the spin vector from vertical direction to be in the horizontal plane. Fig. 8.45 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.

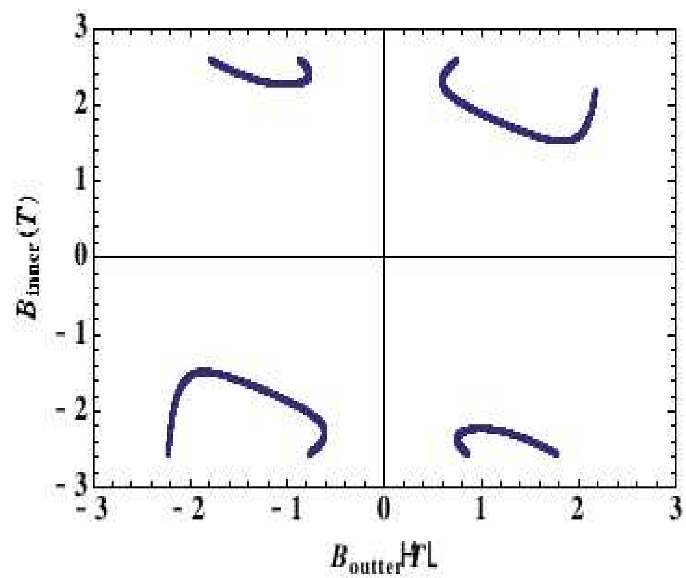


Figure 8.44: correlation of the outter and inner helical dipole magnetic field strength for a spin rotator which is designed to bring a vertically aligned spin vector to the horizontal plane.

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.

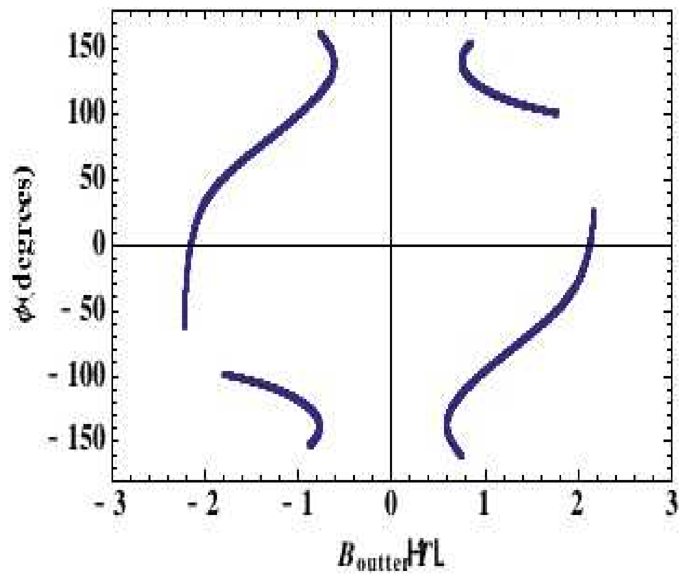


Figure 8.45: spin vector direction in the horizontal plane as function of outer helical magnet field strength

8.6 Positron Options for the Linac-Ring LHeC

8.6.1 Motivation

To accomplish the full particle physics programme of the LHeC it is important to provide both positron-proton (nucleon) and electron-proton (nucleon) collisions. In case of the Linac-Ring LHeC this implies that a challenging rate of positrons must be maintained at the interaction point.

8.6.2 LHeC Linac-Ring e^+ Requirements

Table 8.16 compares the e^+ beam flux foreseen for LHeC with those obtained at the SLC, and targeted for CLIC and the ILC.

The SLC (Stanford Linear Collider) was the only linear-collider type machine which has produced e^+ for a high-energy particle physics experiment. The flux for the CLIC project (a factor 20 compared to SLC) is already considered challenging and possible options with hybrid targets are under investigation on paper. Even more positrons would be required for the ILC. The requested LHeC flux for pulsed operation at 140 GeV (a factor 300 compared to SLC) could be obtained, in a first approximation, with 10 e^+ target stations working in parallel. Several more advanced solutions are proposed to meet the requested LHeC flux for the CW option (a factor 7300 compared to SLC).

	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)	0.66 (H)	10 (H)	100	50
	2 (V)	0.02 (V)	0.04 (V)		
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 8.16: Comparison of the e^+ flux.

8.6.3 Mitigation Schemes

Two main approaches can be considered to reduce the rate of positrons that needs to be produced at the source, namely

- Recycling the positrons after the collision, with implied considerations on e^+ emittance after collision, emittance growth in the 60-GeV return arc due to synchrotron radiation, and the possible introduction of a cooling scheme, e.g. laser cooling à la Telnov at lower beam energy, introducing a tri-ring recovery scheme with fast laser cooling in central ring. (see below), or a using a large damping ring. If 90% of the positrons are recycled the requirement for the source drops by an order of magnitude.

- Repeated collisions on multiple turns, e.g. using a (pulsed) 180-degree phase-shift chicane in order to recover 60 GeV in the second return arc after the collision.

Reuse and Cooling of Positrons

One of the most challenging problems associated with the continuous production of positrons is cooling (damping) of the positron beam emerging from a source or recycled after the collision. The cooling process in a storage ring requires many synchrotron and betatron oscillation periods as well as the emission of many photons. The direct connection of the ERL's output and input aiming at a reuse of the positron beam does not solve the problem of beam cooling, since the electron suffers from noticeable disruption.

Beam cooling, that is at least an e-fold reduction of energy spread and transverse emittances, usually requires at least thousand turns of beam in a damping ring. The employment of a novel idea of fast cooling [?] 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 present consideration 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

$$\tau_{x,y} = \frac{2EC}{cJ_{x,y}U} \quad , \tag{8.22}$$

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:

$$U = \frac{C_\gamma E^4}{\rho}(1 + F_w) \quad , \tag{8.23}$$

with $\rho = E/(eB)$ the bending radius and F_w the wiggler damping factor:

$$F_w = \frac{L_w B_w^2}{4\pi B^2 \rho} \quad , \tag{8.24}$$

with L_w and B_w the wiggler length and field respectively. The transverse damping time can be rewritten as

$$\tau = \frac{8\pi C}{ceC_\gamma E(eB_w^2 L_w + 4\pi BE)} \quad , \tag{8.25}$$

[4] A 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.

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, the total wiggler length and the damping time. Figure 8.46 shows the dependence of the damping ring energy on the total wiggler length for a damping time of 2 ms (red curve). Without wigglers, the ring has to run at 22 GeV, whereas for around 10 GeV, wigglers with a total length of 800 m are needed. The blue curve represents the same dependence when the low repetition rate is considered which indeed increases the damping time by an order of magnitude. In that case, the ring energy without any wigglers can be reduced to 7 GeV and it can be dropped to less than 4 GeV for a total wiggler length of 200 m.

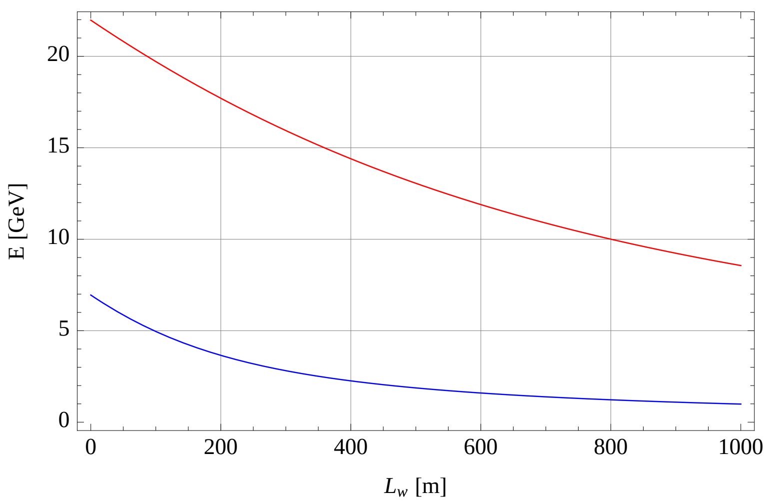


Figure 8.46: Dependence of the damping ring energy on the total wiggler length for a transverse damping time of 2 ms (red curve) and 20 ms (blue curve).

A tentative parameter list for the low and high repetition rate option can be found in table 8.6.3. This example considers for both cases, 234 bending magnets of 0.5m-long dipoles with 1.8T bending field. The wiggler field of 1.9 T and a period of 5 cm is within the reach of modern hybrid wiggler technology. A big challenge is the longitudinal parameters driven from the high energy loss per-turn, especially in the high repetition rate case, where around 300 MV of total RF voltage is needed to restore the high-energy loss/turn. In addition, the bunch has to to be kept short (around 5 mm) in order to achieve the longitudinal emittance target of 10 keV-m, which necessitates a quasi-isochronous ring, with momentum compaction factor, close to 10^{-6}. This may be a challenge for lattice design as low momentum compaction factors are achieved for strong focusing conditions, which increase chromaticity, and necessitate strong sextupoles with detrimental effects for the dynamic aperture of the ring. The average beam power of 25 MW indicates that the wall-plug power would be quite high and may necessitate the use of super-conducting RF system to increase efficiency. In the low repetition case, the RF voltage and power are an order of magnitude more relaxed.

Tri-Ring Scheme

A possible solution to cool down a continuous positron beam, both the recycled beam and/or a new beam from a source, is the tri–ring scheme illustrated in Fig. 8.47.

The operation cycle of the system is as follows:

- The basic cycle lasts N turns
  - N–turn injection from ERL into the accumulating ring (bottom)
  - N–turn cooling in the cooling ring (middle); fast laser cooling may be employed here
  - N–turn slow extraction from the extracting ring (top) into rgw ERL
- One–turn transfer from the cooling ring into the extracting ring
- One–turn transfer from the accumulating ring into the cooling ring

The average current in the cooling ring is $N\times$average ERL current. The number of turns of the main cycle is limited by the efficiency of multiturn injection and the maximum current wgiuch can be stored (and cooled) in the cooling ring.

Laser cooling may generate a new low-emittance positron beams to compensate for losses.and emittance growth of the recycled beam.

Reusing and/or cooling of positrons relaxes the requirements for all types of positron source discussed in the following. The cooling period is limited by the maximal stored current in the

Table 8.17: CLIC versus NLC parameters driving the DRs design.

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

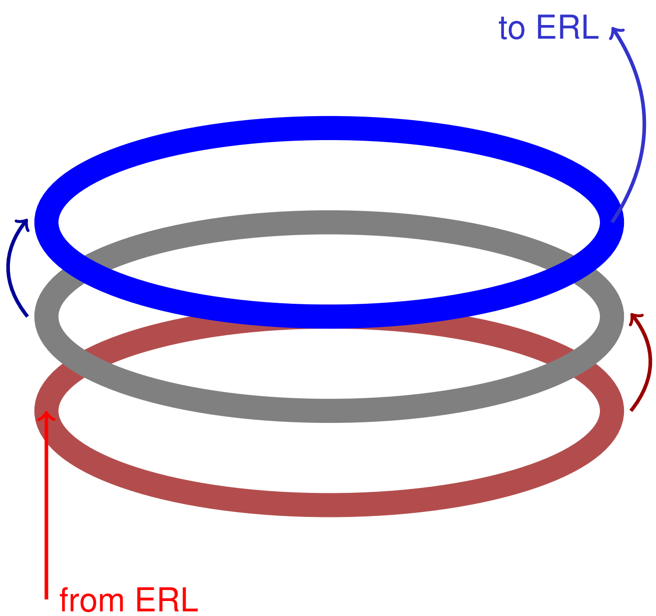


Figure 8.47: Tri-ring scheme

ring and by the multiturn injection. Fast laser cooling may be employed for compensating positron emittance growth when reusing positrons or to compensate losses (without a dedicated high-current positron source). The slow extraction process is also able to further reduce the energy spread (chromatic extraction) or, alternatively, the transverse emittance (resonant extraction).

8.6.4 Positron Production Schemes

Positrons can be produced by pair creation when high-energy electrons or photons hit a target. Conventional sources, as used at the SLC, sent a high-energy electron beam on a conversion target. Alternatively, a high-energy electron beam can first be used to create high-energy photons, and these photons are then sent onto a target. The prior conversion into photons reduces the heat load of the target, for a given output intensity, and it may also improve the emittance of the generated positrons.

There exist a number of schemes that can accomplish the conversion of electrons into photons. Several of them employ Compton scattering off a high-power laser pulse stacked in an optical cavity. According to the electron-beam accelerator employed, one distinguishes Compton rings, Compton linacs, and Compton ERLs. An alternative scheme uses the photons emitted by an electron beam of very high energy (of order 100 GeV) when passing through a short-period undulator.

Finally, there even exists a simpler scheme where a high-power laser pulse itself serves as the target for (coherent) pair creation.

Applications of the various possible schemes to the LHeC are discussed in the following sections.

8.6.5 Targets

For the positron flux considered the heating and possible destruction of the target are important concerns. Different target schemes and types can address these challenges:

- Multiple targets operating in parallel (Section 8.6.6).
- He-cooled granular W-sphere targets (Secgtion 8.6.6).
- Rotating-wheel targets (Section 8.6.6).
- Sliced-rod W tungsten conversion targets (Section 8.6.7);
- Liquid mercury targeta (Section 8.6.7).
- Running tape with annealing process (Section 8.6.7).

8.6.6 Conventional Scheme based on e^- Beam Hitting Target

The LHeC ERL option requires a positron current of 6 mA or 4×10^{16} e^+/s, with normalized emittance of $\leq$50 μm and longitudinal emittance $\leq$5 MeV-mm.

For a conversion target with optimized length the power of the primary beam is converted as follows $P_{primary}(100\%) = P_{thermal}(30\%) + P_\gamma(50\%) + P_{e^-}(12\%) + P_{e^+}(8\%)$. The average kinetic energy of the newly generated positrons is $< T_{e^+} > \approx 5$ MeV, which allows estimating the total power incident omn the target as $P_{target} = 5$ MV $\times 6$ mA / 0.08 = 375 kW. Assuming an electron linac efficiency of $\eta_{acc} \approx 20\%$ we find $P_{wall} = P_{target}/0.2 = 1.9$ MW. This wall-plug power level looks feasible and affordable.

Figure 8.48 illustrates a possible option, which alone would already meet the requirements for the 140-GeV single-linac case, where the repetition rate is 10 Hz. The idea is to use 10 e^+ target stations in parallel. This implies installing 2 RF deflectors upstream and the same downstream. Experience exists for RF deflectors at 3 GHz and with operating 2 lines in parallel. Assuming that this configuration is acceptable from the beam-optics point-of-view, it would be necessary to implement a fast damping scheme because the bare emittances from the target will be too high for the injection into the ERL.

Table 8.18 shows the beam characteristics at the end of the 10 GeV Primary beam Linac for electrons, before splitting the beam.

Table 8.19 shows the beam parameters at each e^+ target. Energy of 5.6 kW is deposited in each target and the Peak Energy Deposition Density (PEDD) is around 30 J/g. This value has been chosen, in order to be below the breakdown limit for tungsten (W) target. It is based on recent simulations [**?**] with conventional W targets. A new study has been done [**?**], assuming a target made out of an assembly of densely packed W spheres (density about 75% of solid

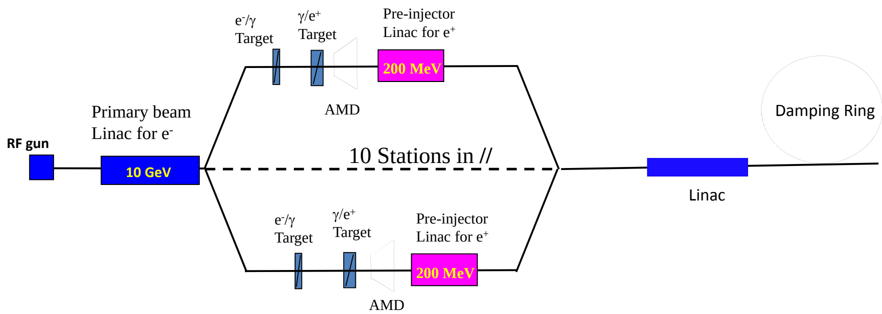


Figure 8.48: Possible layout with unpolarised e^+ for the LHeC injector (p-140 GeV).

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 8.18: Electron beam parameters before splitting.

tungsten) with diameters of 1–2 mm. The cooling is provided by blowing He-gas through the voids between the spheres. Such He-cooled granular targets have been considered for neutrino factories and recently for the European Spallation Source ESSS.

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 8.19: Beam parameters at each e^+ target.

To achieve the required cooling and the corresponding mass flow of the cooling fluid, we consider pressurized 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 for each target. From this a convection coefficient of about $\alpha = 1$ W/cm^2/K can be expected and a cooling time constant τ (exponential decay time after an adiabatic temperature rise of a sphere) of 185 ms will result. Clearly, not much cooling during a pulse of 5 ms duration will occur, but cooling will set in during the off-beam time of

95 ms between the pulses. The peak temperature after each pulse will stabilize at about 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 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 containedin a structure, similar to a care tyre, as is illustrated in Fig. 8.49. The container is possibly made of ligh 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.

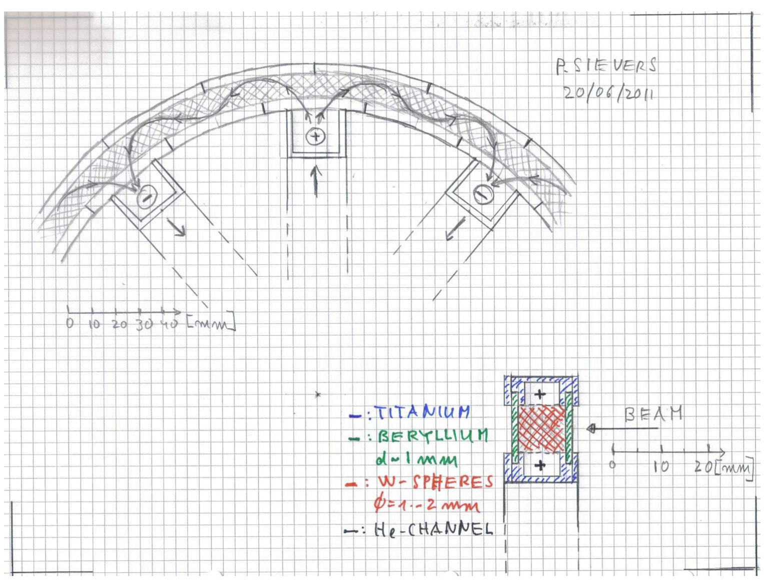


Figure 8.49: Artist's view of rotating wheel containing W spheres with He cooling.

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 to 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.

This last approach is focused on e^+ targets. Presently with conventional targets, the transverse normalized rms beam emittances, in both planes, are in the range of 6000 to 10 000 mm.mrad. With the new type of target, we do not know yet by how much the transverse emittances will be changed. In any case, a strong reduction of emittances is mandatory for the requested LHeC performance.

Assuming that large or small emittances could be recombined, Table 8.20 shows a possible e+ flux after recombination.

Finally, if a solution is found for the emittances, it will be necessary to design and implement a linac 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 8.20: Positron beam parameters after recombination.

8.6.7 Compton Sources

In Compton sources, (polarized) positrons are produced as a result of the following processes:

1. Electron beam (current I_{e-}) scatters off polarized laser photons (energy in pulse W).
2. Gamma flux, $\sim I_{e-} \times W$, is first collimated and then impinging on a conversion target.

3. Produced positrons lose a fraction of energy while traversing the target.

4. Postselection: low-energy positrons are discarded to attain the required polarization.

Three principal factors limit the performance of polarized positron sources based on Compton scattering. They are:

1. Limited average current of electrons scattering off laser photons (world record $I_{e-} = 5\,\mathrm{A}$ – PEP ring).

2. Limited energy of pulses stored in optical resonators (fast progress, an array of resonators may be employed, 1. . . 5 J assumed maximal accepted: higher energy of pulses violates electron dynamics).

3. Limited power density of gammas, to which the conversion target is tolerable (sliced–rod convertor reduces positron losses and increases the current).

The polarization degree of positrons is determined by the cut-off energy of positrons exiting from the target: the higher the polarization required the higher the energy threshold for discarding low-energy positrons (and the lower the yield). The optimal target thickness that maximizes the yield also decreases with the increase of the polarization requested, along with a decrease in the yield of positrons (but with an improved quality of the positron beam: a smaller energy spread, and a smaller transverse emittance).

For a CLIC source of polarized positrons [**?**] (1 GeV electron energy, 1 μm YAG laser system, and, correspondingly, 20 MeV maximal energy of the Compton spectrum) “envelopes” describing the limiting number of positrons from the conversion target per scattered gamma and the associated polarization are presented in Fig. 8.50.

Compton Ring

A typical Compton-ring gamma source (the CLIC ring) with the parameters listed in [?], and modified to accommodate an entire array of optical resonators, namely 10 units with 50 mJ of laser energy stored in each, installed in the dispersive section, is capable of producing 0.01 gammas per electron-turn. This scheme cam be enhanced by increasing the laser energy by a factor of 10, up to 5 J, and by halving the collision angle, to 4 degrees, which increases the yield by an order of magnitude, up to 0.1 gammas per electron-turn.

A typical tungsten convertor optimized for Compton gammas with a maximal energy of 20 MeV can delivered 0.01 positrons with 60% polarization per incident scattered gamma. The convcerter can be enhanced as well: a sliced-rod convertor target produces 0.07/0.13 positrons per gammas for a 1 m or 3 m long rod, respectively [**?**].

Including a 50 % overhead, for either the standard scheme and with teh two types of enhancements, various projects require the minimal circulating currents in Compton rings listed in Table 8.21.

Table 8.21 illustrates that a Compton-ring source equipped with an array of optical resonators yielding a total laser-pulse energy of 5 Joule, together with a sliced-rod conversion raget, will produce the desired flux of polarized positrons even for the LHeC ERL option.

In conclusion, according to the present understandiung and simulations, a Compton positron source may produce sufficient average positron beam current for all LHeC options. The conversion of gammas to positrons is a bottleneck, which requires a study and optimization of effective convertor targets such as the sliced-rod converter.

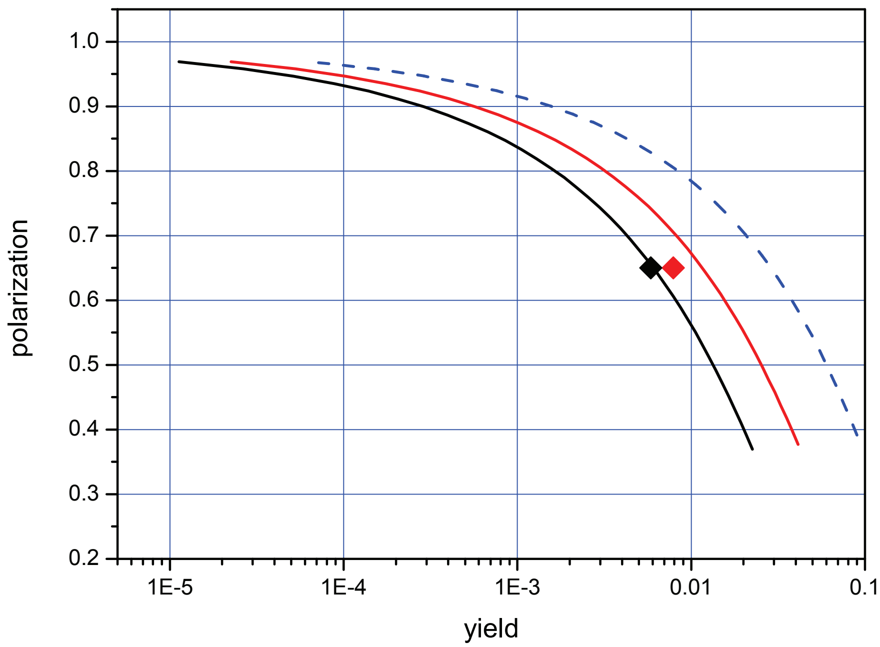


Figure 8.50: Limits for Ti (black) and W (red) conversion targets. Diamonds: simulations (A.Schalicke, S.Riemann). Blue Dashed curve: a sliced–rod conversion target.

Table 8.21: IP positron current and the implied mininum electron beam current in a Compton Ring

	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

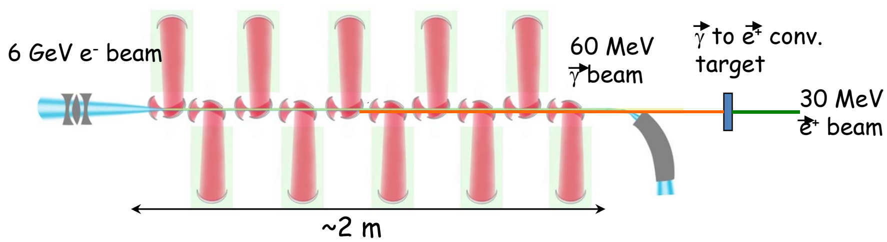


Figure 8.51: Layout based on Compton Linac.

Compton Linac

Positrons, even polarized, can be generated by the Compton scattering process of high-power laser pulses stacked in optical cavities with a high-energy electron beam from a linac. Figure 8.51 present a possible layout for such configuration.

At BNL, a ratio photon/electron close to 1 has been demonstrated. Assuming that a ratio photon/positron close to 2% is achievable, then 50 photons are required to produce 1 e^+. For LHeC, one needs 0.35 nC/bunch (for the e^+ to be produced). Based on above estimations, it implies ∼18 nC/bunch (for the e^- beam). Then with 10 optical cavities, the requested e^- charge is about 1.8 nC / bunch which is a reasonable value.

Power Analysis for Compton Schemes and Compton ERL

A number of pertinent technologies have been investigated, but are not yet established:

1. 1.3 Ampere ERL (R&D at BNL)
2. Mercury target or annealing target (Muon collider collaboration)
3. High finesse optical stacking cavities with factor 1000 enhancement, 1 kW pump (France, KEK, . . .)

This section considers different Compton-based options for an LHeC positron source including power considerations. The following source requirements were taken into account:

- 6mA average current or 4×10^{16} e$^+$/sec
- 2×10^7 bunches with 2×10^9 e$^+$/bunch
- Normalized rms emittance of 50 microns
- Longitudinal emittance 5 MeV-mm or 10 mm normalized.

The **power analysis** for the different schemes can be done backwards:

1. power of the captured positron beam
2. → power of the gamma beam entering the conversion target and generating electron positron pairs

3. → drive electron beam generating gamma beam
4. → klystron generating drive electron beam
5. → wall plug power

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.

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.

To summarize:

- 6 mA × 30 MeV → 180 kW e^+ beam (Output of conversion target)
- $\gamma \rightarrow e^+$ efficiency about 2% → 9 MW γ beam (conversion efficiency)
- $e^- \rightarrow \gamma$ about 10%, 90 MW e^- beam
- Wall → e− about 50% or 180 MW wall power

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:

- 6 mA x 30MeV =¿ 180kW e+ beam (Output of conversion target)
- $\gamma \rightarrow e^+$ about 1% → 18 MW γ beam (Conversion efficiency)
- $e^- \rightarrow \gamma$ about 0.5% 4 GW e^- beam (99.9% efficient ERL)
- Wall → e^- about 50% of 0.001×4 GW + 18 MW
- Total ≈50 MW wall power

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.

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:

- Normalized positron beam emittance, expressed through its energy, RMS beam size and angular divergence at the target exit: $\epsilon_N \approx \gamma_{e^+}\sigma\sigma'$.
- Acquired angular spread in the length target (typically selected at 0.4 radiation length) can be estimated as
$$\sigma_{e^+} \approx \frac{1}{\sqrt{2}}\frac{14\text{MeV}}{E_{e^+}}\sqrt{\frac{L_{target}}{X_0}} \approx \frac{10}{\gamma_{e^+}} \ .$$
- Three components contribute to the beam size:

  1. Scattering in the target:
  $$\sigma_{e^+,sc} \approx \frac{\sqrt{2}}{3}\sigma'_{e^+}L_{\text{target}} \approx \frac{\sqrt{2}}{3}\ 0.3\ 1.2\ \text{mm} \approx 150\ \mu\text{m} \ .$$
  2. Beam size due to gamma beam divergence:
  $$\sigma_{\gamma,div} \approx \frac{1}{2\gamma_{e^-}}\frac{L_{IR}}{\sqrt{2}} \approx \frac{1}{2\times 4000}\frac{0.1\ \text{m}}{\sqrt{2}} \approx 15\ \mu\text{m} \ .$$
  3. and e- beam size on target:
  $$\sigma_{\gamma e^-} \approx \sqrt{\frac{\epsilon_{Ne^-}}{\gamma_{e^-}}\beta_{e^-}} \approx \sqrt{\frac{10\ \mu\text{m}}{4000}1\ \text{m}} \approx 50\ \mu\text{m} \ .$$

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:
$$\epsilon_{||,N} \approx \Delta\gamma_{e^+}\sigma_{\tau e^-} \approx \frac{60-30}{4}\ 60\ \mu\text{m} \approx 450\ \mu\text{m} \ .$$

Compton-ERL Target: Charged particle beams exiting the conversion target generate most of the heat. The deposited power can be estimated (roughly) as 6 mA $\times$ 5 MeV $\times$ 2 $\times$ 2, or 120 kW. 5 MeV is estimated for the energy loss and factors of 2 are attributed to equal parts of captured and non-captured low energy positrons, and to the equal number of electrons and positrons. This suggests that a liquid mercury target may be an important candidate.

Compton ERL Summary: High current ERL seems the most promising approach, e.g. a 3-GeV 1.3-A ERL with 2-micron wavelength optical enhancement cavities.

Target is going to be a very difficult consideration (candidates would be a liquid mercury target or running tape with annealing process). The desired emittances are not reached from any Compton scheme source, even if the target is immersed in a strong magnetic field. Therefore, cooling or scraping would be required.

Laser Pulses and Optical Cavities

Different experimental programs presently underway aim at achieving a very important photon pulse intensity by direct production in a laser system and stacking in a passive optical resonator. This laser-stacking scheme allows increasing the available average power in the optical cavity without requiring impossible performances to the drive laser system. As far as Compton-source developments are concerned, depending on the purpose of the application, the stored pulse length ranges from a few hundreds of femtoseconds to a few picoseconds, the repetition frequency (which determines the cavity length) from 20 to 200 MHz, and the wavelength from 0.5 to 1.1 μm.

When trying to achieve storing a very high power in a Fabry-Perot optical resonator the state of the art of the present technology has to be taken into account. As far as the laser is concerned, in the last years an impressive increase in the available average power has been provided by the development of the fiber amplifiers. The best performances have been obtained by combining the development of large core single mode photonic crystal fibers with the chirped-pulse amplification (CPA) technique. For example, a 200-fs, 1048-nm wavelength, 78-MHz oscillator pulse after a first stretching to 800 ps, has been amplified in a system composed of a two-stage double-clad photonic crystal fiber preamplifier (30 μm mode field and 170 μm pump cladding diameter) pumped at 976-nm wavelength, and a main-amplifier double-clad water cooled fibre (27-μm mode field and 500 μm air clad). After this phase a recompression of the pulse to 640 fs has yielded an "incredible" average power of 830 W and about 10 μJ per puls [**?**].

To stack many short laser pulses in a Fabry Perot resonator, and obtain an important pulse enhancement, it is necessary to lock the cavity characteristic comb with the laser one. This implies to act on two degrees 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 [**?**]. 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 [**?**]. 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/cm^2 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) [**?**]. 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.

8.6.8 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 Nb_3Sn 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.

8.6.9 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 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 Log(100)∼5 damping times, with an implied RF power of $P_{RF} = 1$ GeV $\times$ 5 mA $\times$ 5/0.6 = 60 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 [**?**, ?, **?**]. It should be reconsidered with 2011 state of the art TiSa lasers and X-ray FELs [**?**].

8.6.10 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 if they can be cooled. The compact tri-ring scheme is an attractive proposal for recooling the spent and recycled positrons. A conventional damping ring in the SPS tunnel would be an alternative.

Assuming some of the aforementioned measures are taken to reduce the required positron intensity, which needs to be generated, by at least an order of magnitude, and also assuming that an advanced target, e.g. W-granules, rotating wheel, sliced-rod converter, or liquid metal jet, can be used, several of the proposed source and cooling concepts could provide the intensity and the beam quality required by the LHeC ERL.

For example, the Compton-ring source and the Compton ERL are viable candidates for the Linac-Ring LHeC positron source. Coherent pair production and an advanced undulator represent other possible schemes, still to be explored for LHeC in greater detail. The coherent pair production would have the appealing feature of generating positrons with an inherently small emittance.

In conclusion, it does seem technically possible to meet the very demanding requirements for the LHeC positron source by a combination of approaches. A serious and concerted R&D effort will be required to determine the optimum linac-ring positron configuration.

Chapter 9

Civil Engineering and Services

9.1 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.

9.2 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.

9.2.1 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

Figure 9.1: Tram stop outside CERN Meyrin Site.

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 9.1, 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.

9.2.2 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

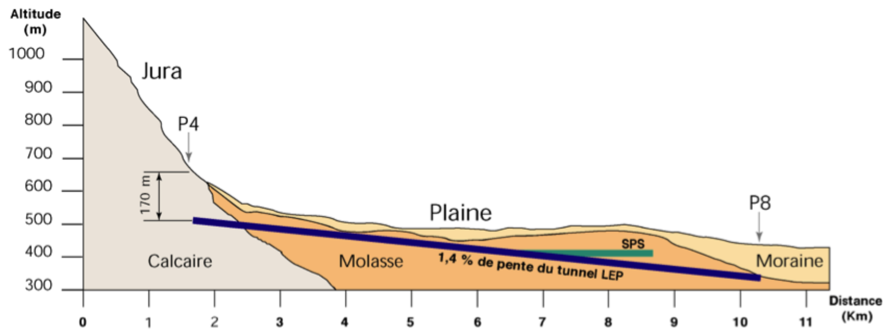


Figure 9.2: Simplified cross section of the LHC housed mostly in Molasse Rock

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.

9.2.3 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 Wurmien and Rissien glaciations. Figure 9.2 shows a simplified layout of the LHC.

9.2.4 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 fenceline, 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

All temporary facilities needed for the construction works have also been included in the cost estimate.

Figure 9.3: TBM Gripper type machine used for Neutrino tunnel at CERN (left) and roadheader type machine (right).

9.2.5 Construction Methods

It is envisaged that Tunnel Boring Machines (TBMs) will be utilised for the main tunnel excavation greater than approximately 2km in length. In the Molasse rock, a shielded TBM will be utilised, with single pass pre-cast segmental lining, followed by injection grouting behind the lining. For planning and costing exercises, an average TBM advancement of 25m per day, or 150m per week is predicted.

The second phase excavation will be executed using a roadheader type machine. Both machines types are shown in figure 9.3. Any new shafts that have to pass through substantial layers of water bearing moraines (for example at CMS) will have to utilize the ground freezing technique. This involves freezing the ground with a primary cooling circuit using ammonia and a secondary circuit using brine at -23C, circulating in vertical tubes in pre-drilled holes at 1.5 metre intervals. This frozen wall allows excavation of the shafts in dry ground conditions and also acts as a retaining wall. Figure 9.4 shows this method being utilized for LHC shaft excavation at CMS.

9.3 Civil Engineering Layouts for Ring-Ring

The Ring-Ring solution will require new bypass tunnels at both Point 1 (currently housing the LHC Atlas detector) and Point 5 (CMS). Both of the bypass tunnels are on the outside of the LHC ring. Figure 9.5 shows the bypass tunnel in blue needed around Point 1. This tunnel is 730m long and has an internal diameter of 4.5m. Two new 12m diameter shafts are required to allow access to construct the underground areas with minimum disruption to LHC operations. Underground areas are made available for RF/Cryogenic and general services. Two junction caverns will be excavated to create a liaison with the LHC tunnel.

Waveguides ducts (0.9m diameter) will connect the LHeC Bypass tunnel to the RF cavern, as shown in Figure 9.6. In order to position the bypass as close as possible to the LHC ring, it has been assumed that the LHeC beampipe can be accommodated within the existing survey gallery, and pass through the ATLAS experimental hall.

The Bypass around CMS Point 5 is 1km long with an internal tunnel diameter of 4.5m.

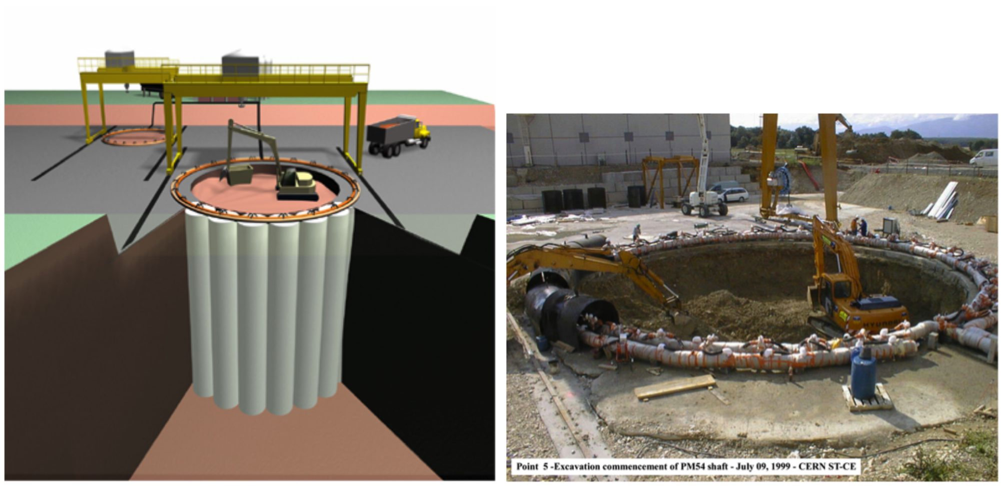


Figure 9.4: LHC Shaft PM54, linking up cylinders of ice to construct a temporary wall.

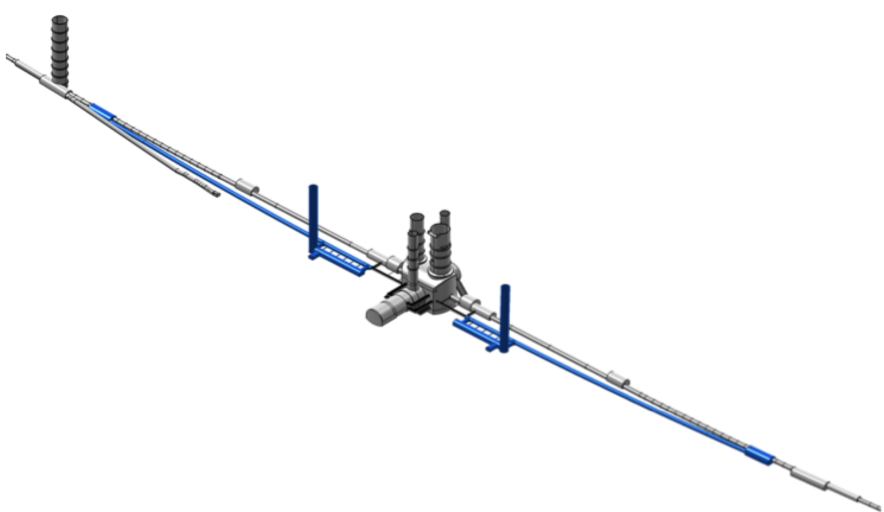


Figure 9.5: Ring-Ring Bypass around ATLAS Point 1.

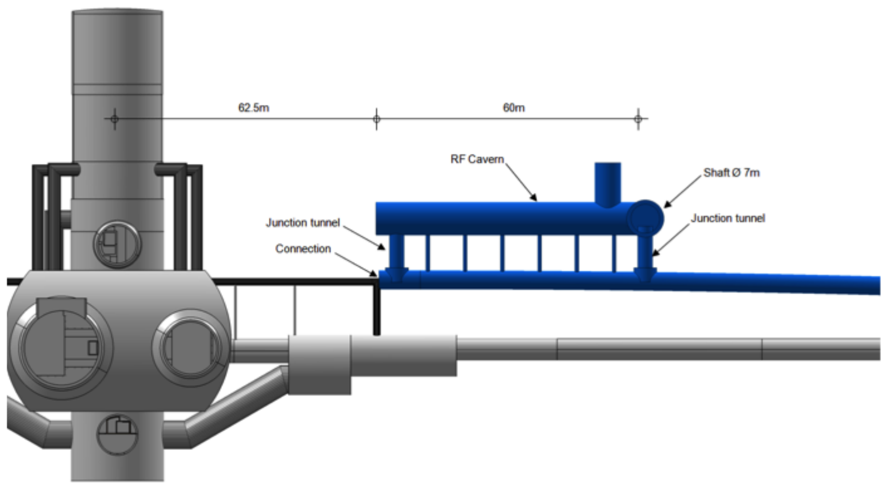


Figure 9.6: Cryo and RF Caverns at Point 1.

Only one new shaft is required for excavation works. A roadheader type machine will be used for excavation, with the new tunnel position as close as possible to the LHC tunnel as not to induce movements or create operational problems to the existing facilities. Figure 9.7 shows the new bypass tunnel and service cavern required around CMS.

Figure 9.8 shows a 3d model of the bypass around the CMS Point 5. The new excavations will have a minimum of 7m of Molasse rock separating the new works from existing LHC structures. This is to avoid any unwanted deformation or vibration problems on the existing LHC structures.

9.4 Civil Engineering Layouts for Linac-Ring

For the CDR it has been assumed that the 60 GeV Energy Recovery Linac (ERL) will be located around the St.Genis area of France, injecting directly into the LHC ALICE Cavern at point 2. Approximately 10km of new tunnels (5m and 6m diameter), 2 shafts and 9 caverns will be required. The majority of civil engineering works can be completed while LHC is operational. Figure 9.9 highlights the area on the LHC where the new ERL will be situated.

The ERL will be positioned inside the LHC Ring, in order to ensure that new surface facilities are located, as much as possible, on existing CERN land. Secondary tunnels running alongside the long straight sections will house RF, Cryogenic and Services for the machine. One of the long straight sections is shown in Figure 9.10. The entire ERL will be tilted in order to follow a suitable layer of Molasse rock. On average the ERL will be tilted approximately 1.4%, dipping towards Lake Geneva, as per LHC.

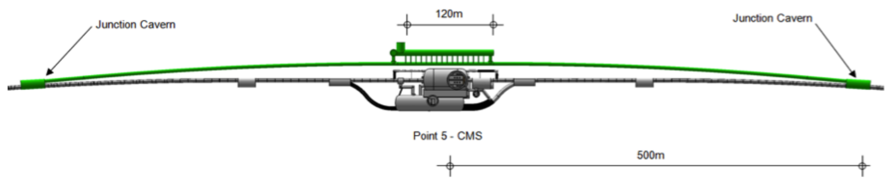


Figure 9.7: Ring-Ring Bypass around CMS Point 5.

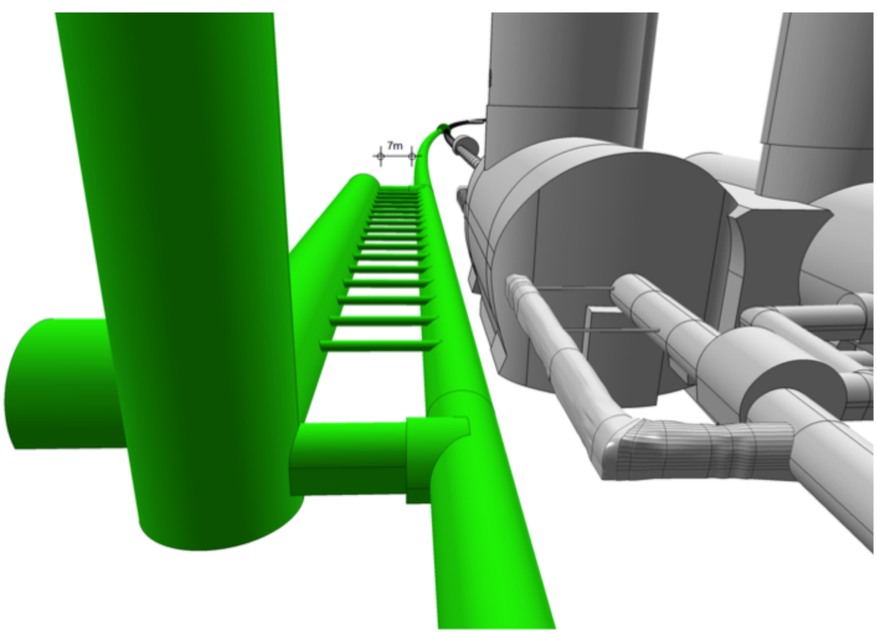


Figure 9.8: 3d model of Ring-Ring Bypass around CMS Point 5 The civil engineering for the e- injection complex for the Ring-Ring option has not been studied for the CDR.

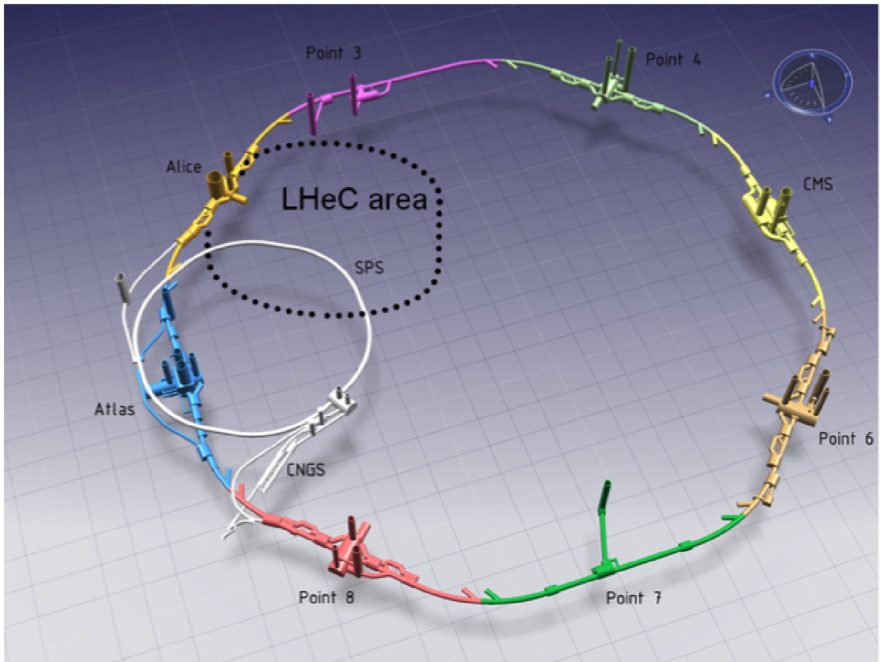


Figure 9.9: Schematic model of ERL position injecting into ALICE.

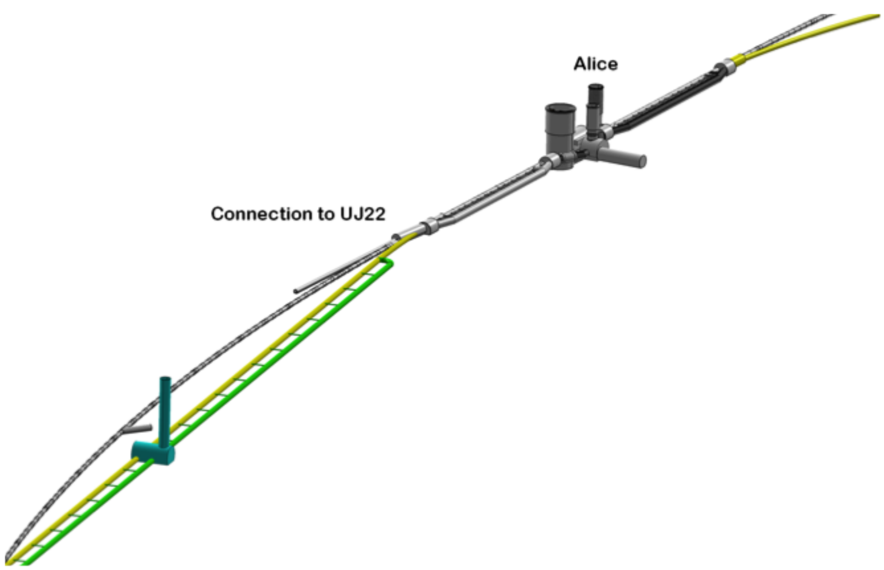


Figure 9.10: ERL Injection area into ALICE and RF/Cryo/Services Cavern (yellow & green).

9.5 Summary

From a civil engineering point of view, both the Ring-Ring and Linac-Ring options are feasible. The Ring-Ring option will provide a cheaper solution, however, with a marginally increased risk to LHC activity, due to the fact that most of the excavation works being in close proximity to the existing installations. The Linac-Ring option is the cleaner solution from a civil engineering point of view, with much less risk to LHC, but with substantial extra cost and greater time needed for environmental and building permit procedures.

Chapter 10

System Design

10.1 Magnets for the Interaction Region

10.1.1 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 [?] magnet built for the LHC [?].

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 Nb_3Sn superconducting technology. Here we limit ourselves to the two most promising conceptual designs.

10.1.2 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 Section xx; the schematic layout is shown in Fig. 10.1.

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. 10.2 shows a superferric magnet as built for the KEKb facility [?]. 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.

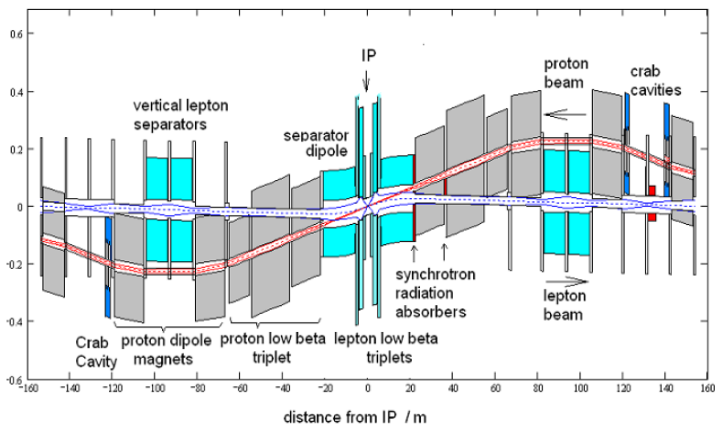


Figure 10.1: Layout of the LHeC interaction region (ring-ring option).

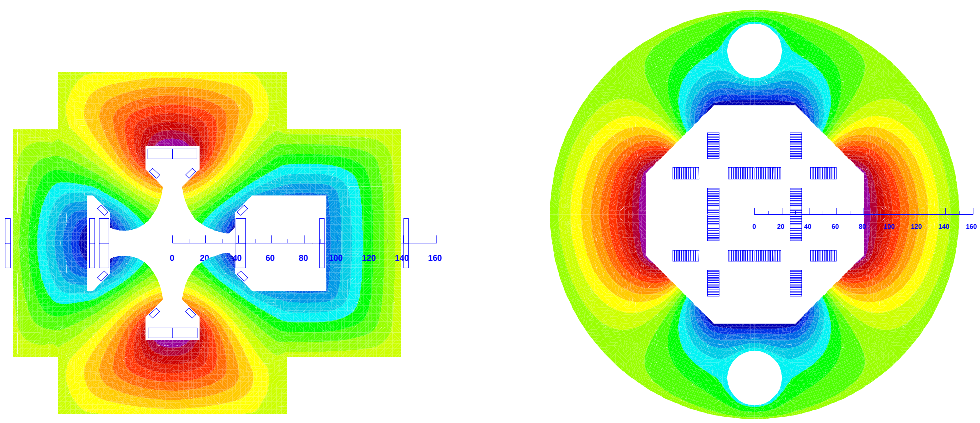


Figure 10.2: Cross-sections of insertion quadrupole magnets with iso-surfaces of the magnetic vector potential (field-lines). Left: Super-ferric, similar to the design presented in [?]. Right: Superconducting block-coil magnet as proposed in [?] for a coil-test facility.

The magnetic flux density in the low-field region of the design shown in Fig. 10.2 (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. 10.3.

Fig. 10.3 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 diameter, in the single aperture version the beam pipe 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

Table 10.1: Characteristic data for the superconducting cables ands 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
$J_{\text{c}}(B_{\text{ref}}, T_{\text{ref}})$ ($\text{A}\,\text{mm}^{-2}$)	2872	2810
$-\text{d}J_{\text{c}}/\text{d}B$ ($\text{A}\,\text{mm}^{-2}\,\text{T}$)	600	606
ρ(293 K)/ρ(4.2 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 thickn. narrow side (mm)	0.08	0.08
Insulation thickn. 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

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 Table 10.1. The outer radii of the magnet coldmasses do not exceed the size of the triplet magnets installed in the LHC (diameter of 495 mm). The fringe field in the aperture of the electron beam is in all cases below 0.05 T.

Fig. 10.4 shows half-aperture quadrupoles (single and double-aperture versions for the proton beams) in a similar design as proposed in [**?**]. The reduced aperture requirement in the double-aperture version makes it possible to use a single layer coil and thus to reduce the beam-separation distance between the proton and the electron beams. The field-free regions is large enough to also accommodate the counter rotating proton beam. The version shown in Fig. 10.4 (left) employs a double-layer coil. In all cases the outer diameter of the coldmasses do not exceed the size of the triplet magnets currently installed in the LHC tunnel.

For this CDR we retain only the single aperture version for the Q2 (shown in Fig. 10.3, left) and the half-aperture quadrupole for the Q1 (shown in Fig. 10.4, top left). The separation distance between the electron and proton beams in Q1 requires the half-aperture quadrupole design to limit the overall synchrotron radiation power emitted by bending of the 60 GeV electron beam. The single aperture version for Q2 is retained in the present layout, because the counter rotating proton beam can guided outside the Q2 triplet magnet. The design of Q3 follows closely that of Q2, except for the size of the septum between the proton and the electron

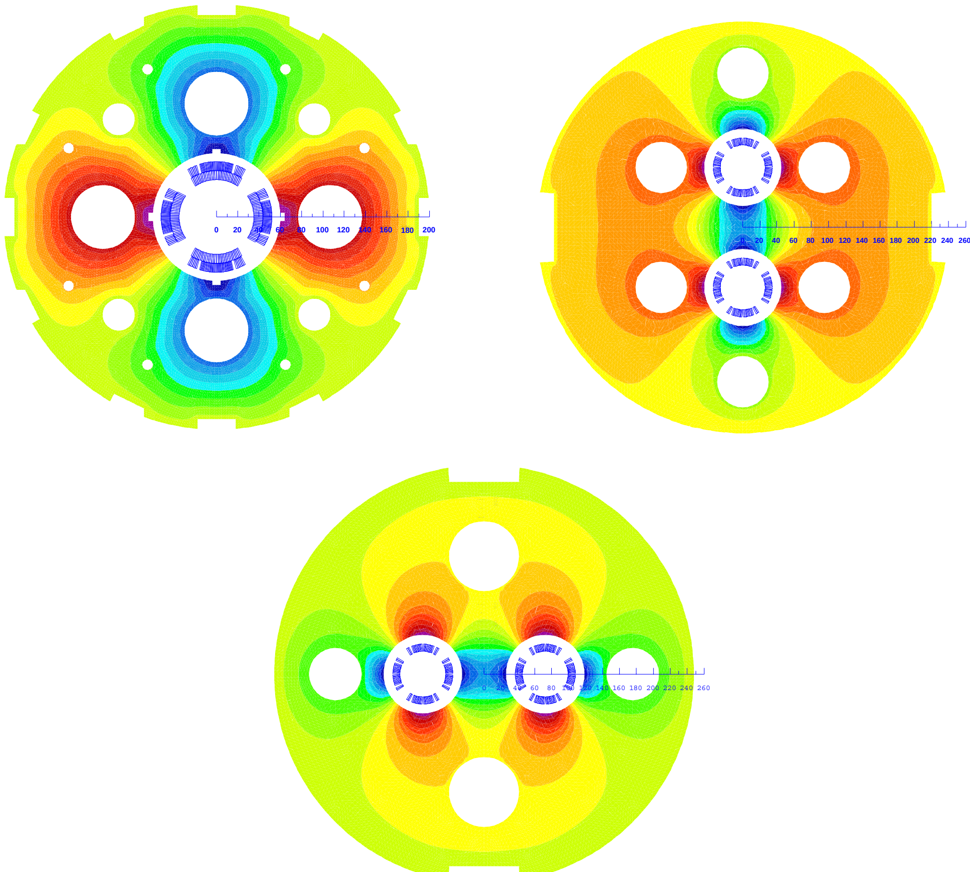


Figure 10.3: Cross-sections with field-lines of insertion quadrupole magnets. Classical designs similar to the LHC magnet technology. Top left: Single aperture with a double layer coil employing both cables listed in Table 10.1. Design chosen for Q2. Top right: Double aperture vertical. Bottom: Double 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 10.1.

beams.

The coils in all three triplet magnets are made from two layers, using both Nb-Ti composite cables as specified in Table 10.1. The layers are individually optimized for field quality. This reduces the sensitivity to manufacturing tolerances and the effect of superconductor magnetization [**?**]. The mechanical design will be similar to the MQXA magnet where two kinds of interleaved yoke laminations are assembled under a hydraulic press and locked with keys in order to obtain the required pre-stress of the coil/collar structure. The main parameters of the magnets are given in Table 10.2.

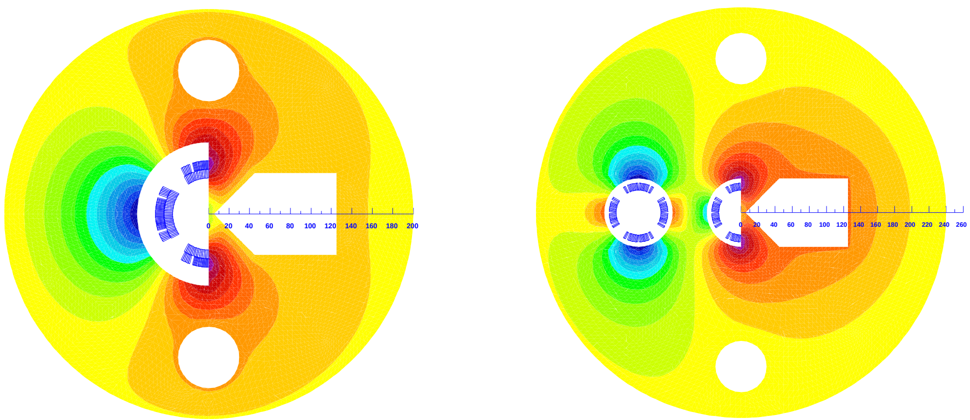


Figure 10.4: Cross-sections of insertion quadrupole magnets with field-lines. Left: Single half-aperture quadrupole with field-free domain [?]; design selected for Q1. Right: Double-aperture magnet composed of a quadrupole and half quadrupole.

10.1.3 Magnets for the linac-ring option

The requirements in terms of aperture and field gradient are more difficult to obtain for the linac-ring option. Consequently we present the limitations for the field gradient and septum size achievable with both Nb-Ti and Nb_3Sn superconducting technologies. We limit ourselves to the two conceptual designs already chosen for the ring-ring option. For the half quadrupole, shown in Fig. 10.6 (right), the working points on the load-line are given for both superconducting technologies in Fig. 10.5.

However, the conductor size must be increased and in case of the half quadrupole, a four layer coil must be used; see Fig. 10.6. The thickness of the coil is limited by the flexural rigidity of the cable, which will make the coil-end design difficult. Moreover, a thicker coil will also increase the beam separation between the proton and the electron beams. The results of the field computation are given in Table 10.2, column 3 and 4. Because of the higher iron saturation, the fringe fields in the electron beam channel are considerably higher than in the magnets for the ring-ring option.

For the Nb_3Sn option we assume composite wire produced with the internal Sn process (Nb rod extrusions), [**?**]. The non-Cu critical current density is 2900 A/mm^2 at 12 T and 4.2 K. The filament size of 46 μm in Nb_3Sn strands give rise to higher persistent current effects in the magnet. The choice of Nb_3Sn would impose a considerable R&D and engineering design effort, which is however, not more challenging than other accelerator magnet projects employing this technology [**?**].

Fig. 10.7 shows the conceptual design of the mechanical structure of these magnets. The necessary prestress in the coil-collar structure, which must be high enough to avoid unloading at full excitation, cannot be exerted with the stainless-steel collars alone. For the single aperture magnet as shown in Fig. 10.7 left, two interleaved sets of yoke laminations (a large one comprising the area of the yoke keys and a smaller, floating lamination with no structural function) provide the necessary mechanical stability of the magnet during cooldown and excitation.

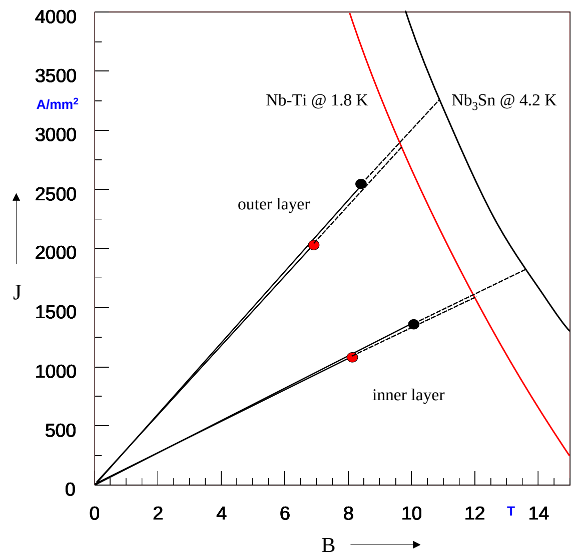


Figure 10.5: Working points on the load-line for both Nb-Ti and Nb_3Sn variants of the half quadrupole for Q1.

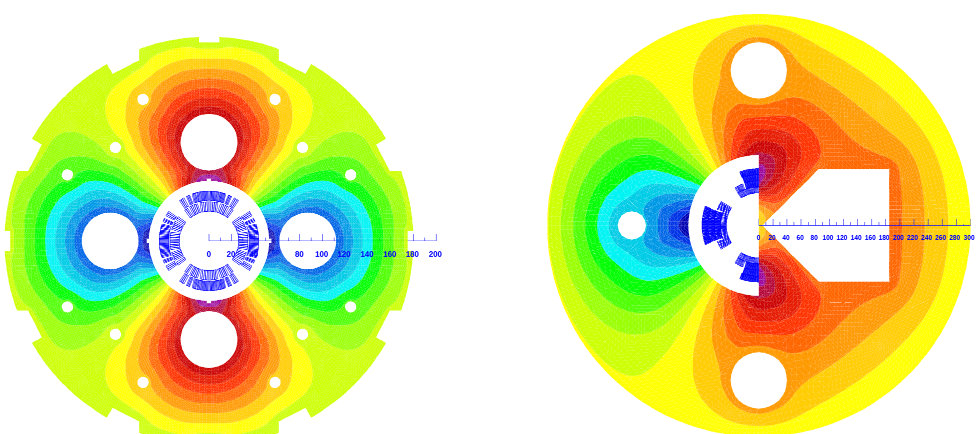


Figure 10.6: Cross-sections of the insertion quadrupole magnets for the linac-ring option. Left: Single aperture quadrupole. Right: Half quadrupole with field-free region.

Preassembled yoke packs are mounted around the collars and put under a hydraulic press, so that the keys can be inserted. The sizing of these keys and the amount of prestress before the cooldown will have to be calculated using mechanical FEM programs. This also depends on the elastic modulus of the coil, which has to be measured with a short-model equipped with

Table 10.2: 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_3Sn 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

pressure gauges. Special care must be taken to avoid nonallowed multipole harmonics because the four-fold symmetry of the quadrupole will not entirely be maintained.

The mechanical structure of the half-quadrupole magnet is somewhat similar, however, because of the left/right asymmetry four different yoke laminations must be produced. The minimum thickness of the septum will also have to be calculated with structural FEM programs.

10.1.4 Dipole Magnets

Two different types of bending magnets are considered in this document: the ones for the LR Option, used in the arcs of the recirculator, and the ones for the RR Option, to be installed in the LHC ring.

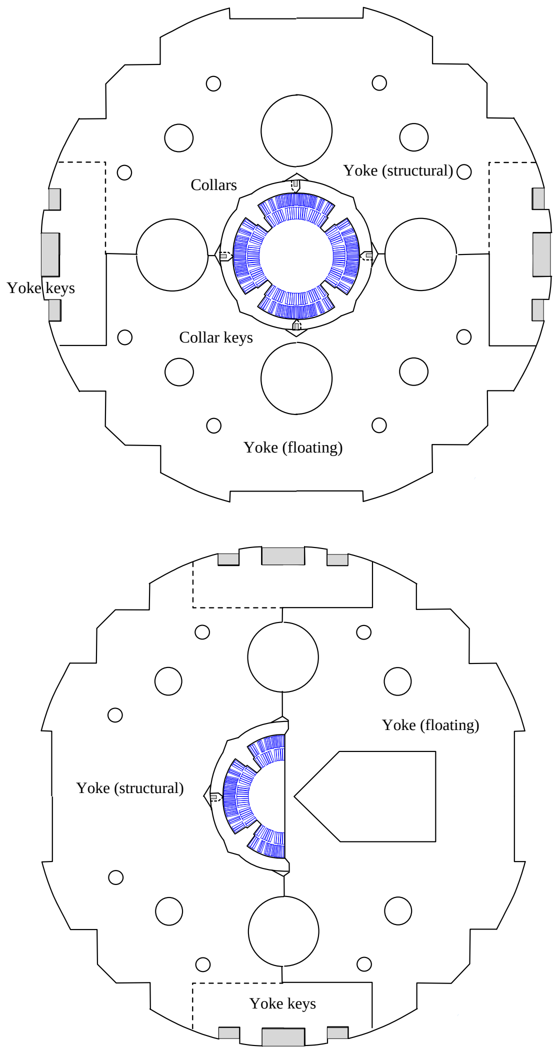


Figure 10.7: Sketch of the mechanical structure. Left: Single aperture magnet. Right: Half quadrupole with field-free region.

Dipole Magnets for the LR Option

Each of the 6 arcs of the recirculator needs 600 four-meter-long bending magnets, providing a magnetic field from 0.046 T to 0.264 T depending on the arc energy from 10.5 GeV to 60.5 GeV.

Considering the relatively low field strength required even for the highest energy arc, and the small required physical aperture of 25 mm only, it is proposed here to adopt the same cross section for all magnets, possibly with smaller conductors for the lowest energies.

This allows the design of very compact and relatively cheap magnets, running at low current densities to minimize the power consumption.

Table 10.3 summarizes the main parameters of the proposed magnet design illustrated in Figure 10.8.

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 10.3: 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.

Dipole Magnets for the RR Option

3040 bending magnets, 5.35-meter-long each, are needed in the LHC tunnel for the RR option. They shall provide a magnetic field ranging from 0.0127 T at 10 GeV to 0.0763 T at 60 GeV. Additionnally, about 40 magnets will be needed in the Interaction Regions totalling about 3080 magnets. The main issues in the design of these magnets are:

- the field range, situated in low field region, and in particular the very low injection field constitute a challenge for achieving a satisfactory field reproducibility from cycle to cycle and for making field quality relatively constant during the field ramp. These specific issues will be discussed further in the paragraphs dealing with the experimental work carried out at BINP and at CERN
- compactness, to fit in the present LHC

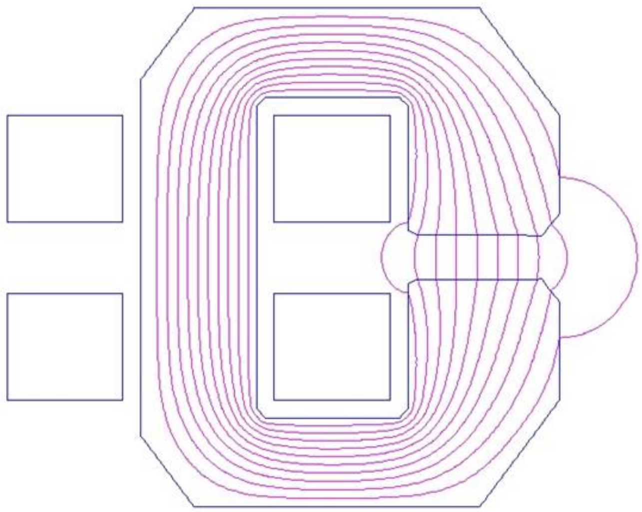


Figure 10.8: Bending magnets for the LR recirculator

- compatibility with synchrotron radiation power

The proposed design is constituted by compact C-Type dipoles, with the C-aperture on the external side of the ring to possibly allow the use of a vacuum pre-chamber and in any case to avoid the magnet intercepts the synchrotron radiation. The unusual poles shape allows minimizing the difference of flux lines length over the horizontal aperture, making magnetic field quality less dependent on the iron characteristics than in a C-type dipole of conventional shape. The coils are constituted by solid single bars of conductor, which after insulation are individually slit inside the magnet. The conductor can be in aluminium or in copper depending from economical reasons coming from a correct balance between investment cost and operation. The present design is based on an aluminium conductor, which among other has the advantage of making the magnet lighter than with a copper conductor. The conductor size is sufficiently large to reduce the dissipated power within levels which can be dealt by ventilation in the LHC tunnel: this is a considerable advantage in terms of simplicity of magnet manufacture, connections, reliability and of course of avoiding the installation of a water cooling circuit in the LHC arcs.

Table 10.4 summarizes the main parameters of the proposed magnet design illustrated in Figure 10.9.

10.1.5 BINP Model

Two different types of models have been manufactured, both aiming at demonstrating that a cycle-to-cycle reproducibility of the relatively low injection field (only 127 Gauss at an injection energy of 10 GeV) better than 0.1 Gauss can be achieved. Both models, pictured in Figure 10.10, showed a magnetic field reproducibility at injection field within +/- 0.075 Gauss when cycled between injection and maximum field. To achieve such results both models make use of the same iron laminations, which are 3408 type silicon steel grain oriented 0.35 mm thick.

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 10.4: Main parameters of bending magnets for the RR Option.

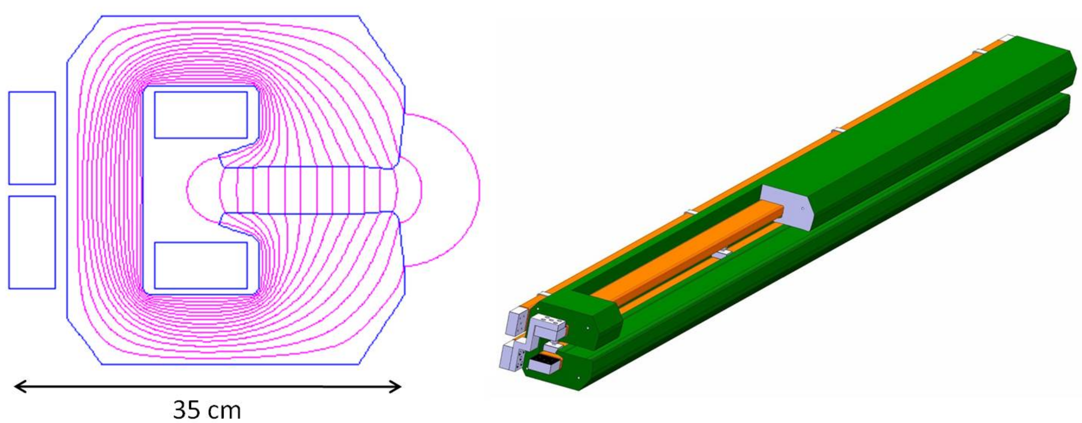


Figure 10.9: Bending magnets for the RR Option

Their coercive force in the direction of the orientation is about 6 A/m, and perpendicular to the direction of the orientation remains relatively low at about 22 A/m. The C-type model has been assembled in two variants, with the central iron part with grains oriented vertically and with grain oriented horizontally (both blocks are as shown in the picture). The relevant magnetic measurements did not show differences between the two versions.

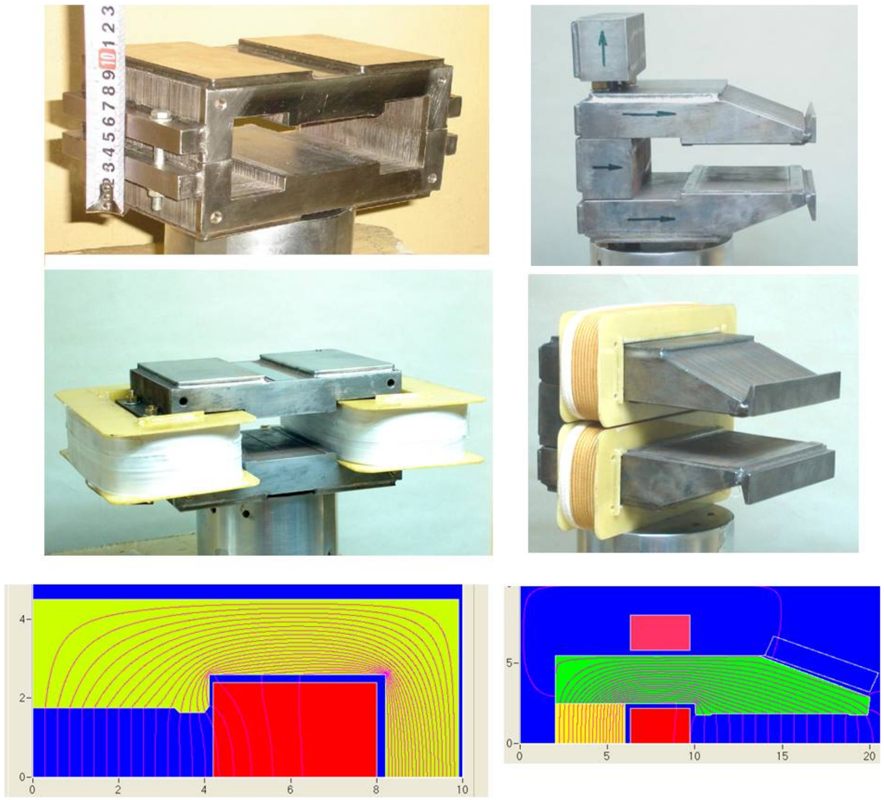


Figure 10.10: H and C-Type model magnets made by BINP

10.1.6 CERN Model

As a complementary study to the one made by BINP, the CERN model explores the manufacture of lighter magnets, with the yoke made by interleaved iron and plastic laminations. The magnetic flux produced in the magnet aperture is concentrated in the iron only, with a thickness ratio between plastic and iron of about 2:1 the magnetic field in the iron is about 3 times that in the magnet gap. In addition to a lighter assembly, this solution has the advantage of increasing the magnetic working point of the iron at injection fields, thus being less sensitive to the quality of the iron and in particular to the coercive force. To explore the whole potential of this solution three different lamination materials have been explored: an expensive NiFe 50 steel (Hc 3A/m) which will act as reference, a conventional grain oriented steel with similar characteristics as the one used by BINP, and a conventional low carbon steel with Hc 70 A/m. The model cross section reproduces the refence one described for the RR dipoles.

10.1.7 Quadrupole and Corrector Magnets

In case of the RR option we need, in the LHC tunnel:

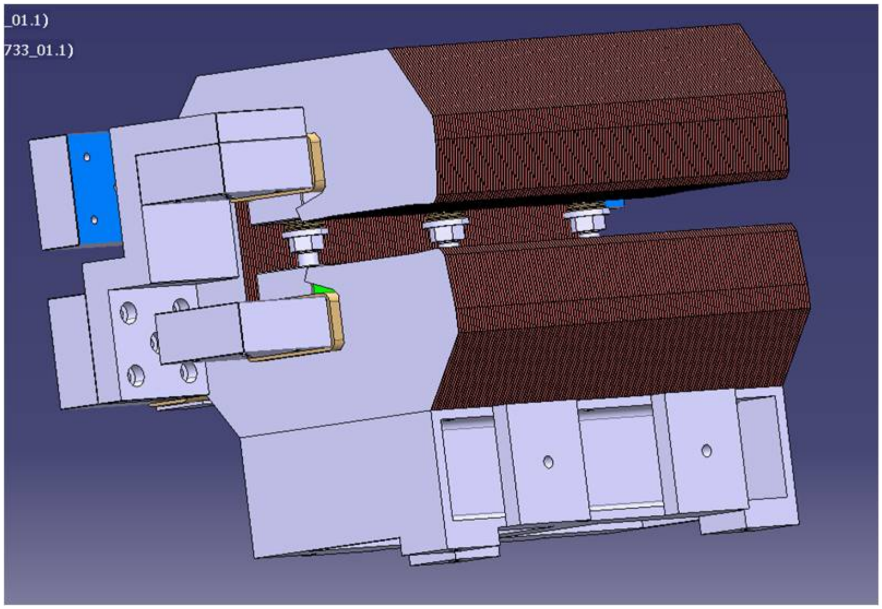


Figure 10.11: 400 mm long RR dipole model with interleaved laminations

- in the arcs, 336 QF each providing 10.28T integrated strength, and 336 QD each providing 8.40T integrated strength
- in the insertion and by-pass, 97 QF each providing 18T integrated strength, and 97 QD each providing 12.6T integrated strength

In case of the LR option we need:

- in the two 10 GeV linacs, 37+37 quadrupoles each providing 2.5T integrated strength
- again in the two 10 GeV linacs, 37+37 correctors each providing 10mTm integrated strength in both vertical and horizontal direction
- in the recirculator arcs 4 different quadrupole types, the Q0, Q1 and Q3 each providing about 35 T integrated strength, and the Q2 each providing about 50T integrated strength

RR: 336+336 quadrupoles in the arcs

Considering the integrated strength of QD and QF are not much different, we propose having the same type of magnets: the relevant parameters are summarized in Table 10.5 and the cross section is illustrated in Figure 10.12.

RR: 148 + 148 quadrupoles in the insertion and by-pass

In total 148 QF and 148 QD quadrupoles are needed in the insertion and by-pass. The required integrated strength is 18T for the QF and 13T for the QD. We propose having the same magnet cross section with two different length, 1.0 m the QF and 0.7 m the QD, capable of producing a

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/mm2
Magnet inductance 3	milli-Henry	
Magnet resistance	16	milli-Ohm
Power @ 60 GeV	2500	Watt
Cooling	water	

Table 10.5: Main parameters of arc quadrupole magnets for the RR Option.

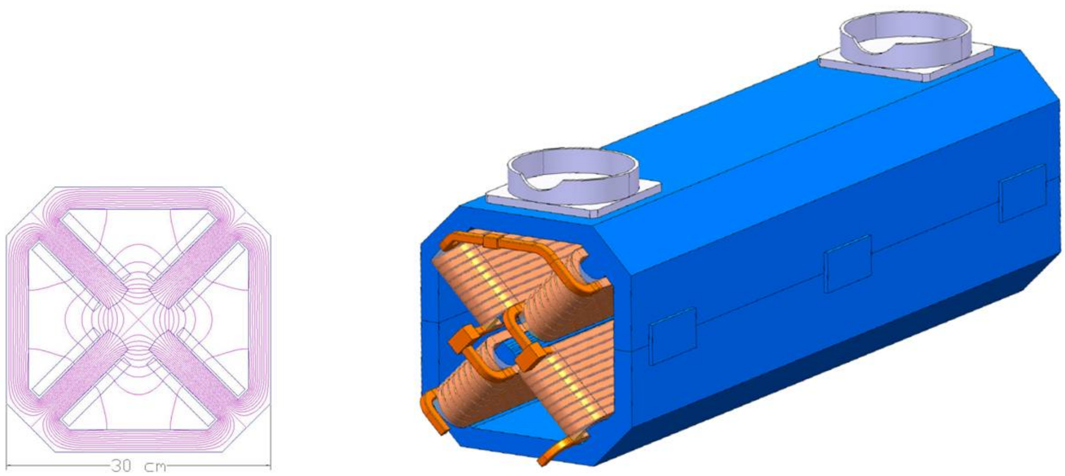


Figure 10.12: Arc quadrupole magnets for the RR Option

gradient of up to 19 T/m. The relevant parameters are summarized in table 10.9 and the cross section is illustrated in Figure 10.13.

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/mm2
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 10.6: Main parameters of insertion and by-pass quadrupole magnets for the RR Option.

LR: 37 + 37 quadrupoles for the two 10 GeV Linacs

The present design solution considers 70 mm aperture radius magnets to be compatible with any possible aperture requirement. The relevant parameters are summarized in table **??** and the cross section is illustrated in Figure 10.14.

LR: 37 + 37 correctors for the two 10 GeV Linacs

The combined function correctors shall provide an integrated field of 10 mTm in an aperture of 140 mm. The relevant parameters are summarized in table 10.8 and the cross section is illustrated in Figure 10.15.

LR: 360 Q0 + 360 Q1+ 360 Q2 + 360 Q3 quadrupoles for the recirculator arcs

In each of the 6 arcs there are 4 types of quadrupoles, each type in 60 units, making 240 quadrupoles per arc. The required integrated strength can be met with one type of quadrupole manufactured in two different length: 1200 mm the Q2 and 900 mm the Q0-Q1-Q3. The quadrupoles of the low energy arcs may use a smaller conductor or less turns or the same conductor as the higher energy quadrupoles showing then ecological friendly power consumption. The relevant parameters are summarized in table **??** and the cross section is illustrated in Figure 10.16.

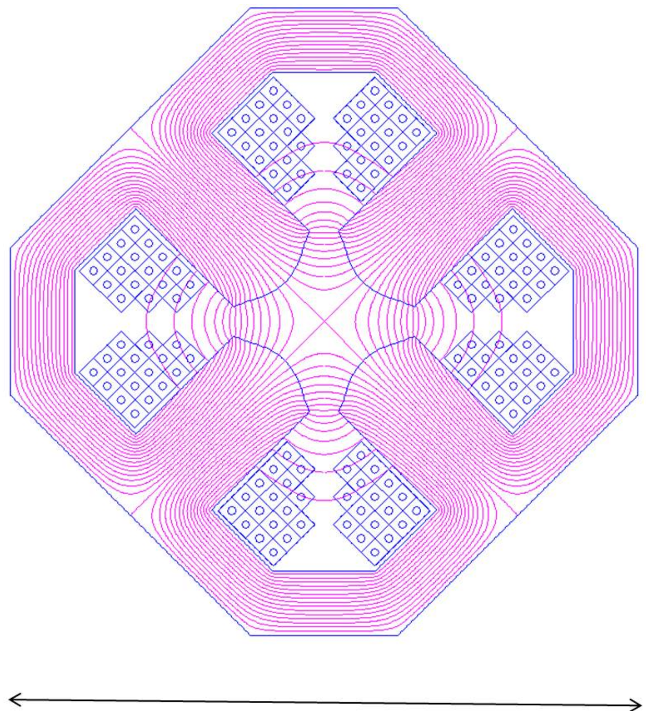


Figure 10.13: Insertion and by-pass quadrupole magnets for the RR Option

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/mm2
Magnet inductance	12	milli-Henry
Magnet resistance	24	milli-Ohm
Power @ 500 A	6	kWatt
Cooling	water	

Table 10.7: Main parameters of quadrupoles for the 10 GeV linacs of the LR option

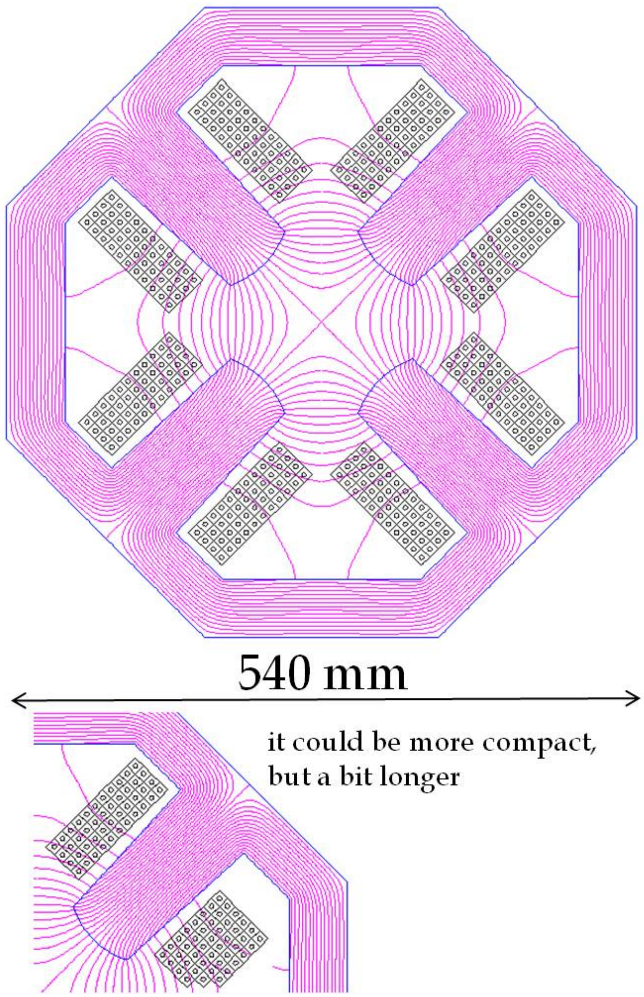


Figure 10.14: Quadrupoles for the 10 GeV linacs of the LR option

10.2 Ring-Ring RF Design

10.2.1 Design Parameters

The RF system parameters for the e-ring are listed in Table 10.10. 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 power of 47.3 MW is lost due to synchrotron radiation. For the voltages needed superconducting RF is the only choice.

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/mm2
Magnet inductance per circuit	10	milli-Henry
Magnet resistance per circuit	0.1	Ohm
Power per circuit	160	Watt
Cooling	air	

Table 10.8: Main parameters of combined function corrector magnets for the LR Option.

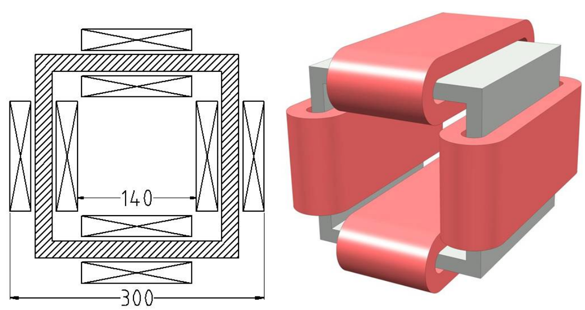


Figure 10.15: Combined function corrector magnets for the LR Option

10.2.2 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) [?] [?] [?]. The same frequency is also used at BNL for ERL cavities for the RHIC upgrade project [?]. Both cavities are 5-cell and can

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/mm2
Magnet inductance	15/20	milli-Henry
Magnet resistance	30/40	milli-Ohm
Power @ 410 A	5/7	kWatt
Cooling	water	

Table 10.9: Main parameters of quadrupoles for the recirculators of the LR option

achieve gradients greater than 20 MV/m. For the present study we take an RF frequency of 721.42 MHz, which is compatible with LHCÕs minimum 25 ns bunch spacing. 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 transfered 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.

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 10.10: RF system parameters for the electron ring.

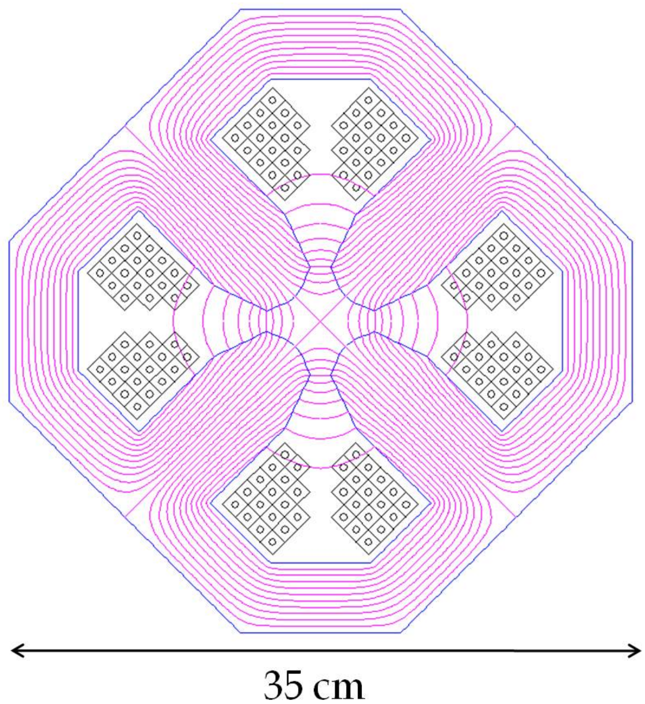


Figure 10.16: Quadrupoles for the recirculators of the LR option

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 10.17.

RF Power System

The configuration for powering of one eight cavity cryomodule is shown in figure 10.18. 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 of klystrons is 56, delivering an average total RF power of 49 MW. Taking 65 % klystron efficiency and 95 % efficiency in the power converters gives roughly 79 MW grid power needed for the RF power system.

RF Power System Layout

The klystrons are installed in the additional tunnels parallel to the by-passes. An estimated surface area of 100m2 is needed for the two klystrons, circulators, HV equipment and Low Level RF and controls racks for each 8 cavity module in adjacent RF gallery. This defines the tunnel

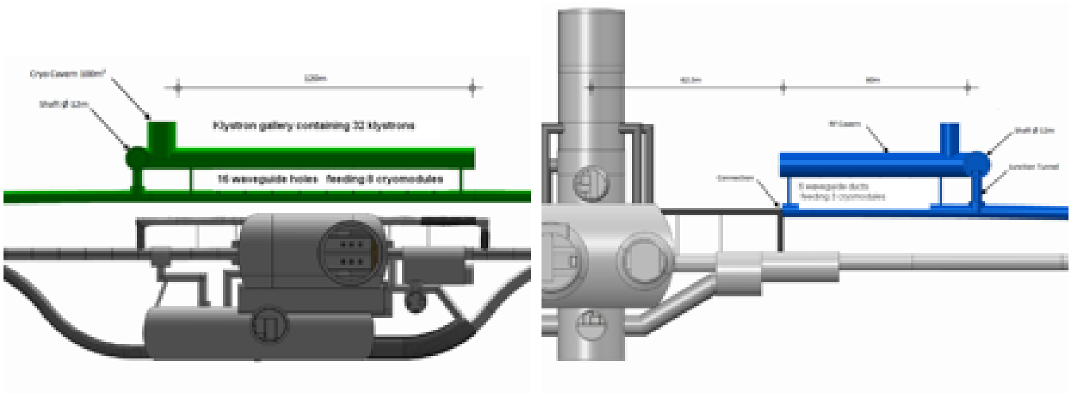


Figure 10.17: RF tunnel Layouts at CMS and ATLAS bypasses. Note only the right hand side at ATLAS shown.

width over the 13 m module interval (length + spacing) to be 8 m. Waveguide ducts are needed between the by-passes and the RF tunnels. With one waveguide per klystron into the tunnel, and two waveguides per duct, there are 16 ducts in the CMS tunnels, spaced roughly 6.5 m apart. At ATLAS there would be six ducts on either side with the same spacing. The required diameter of the duct tunnel is 90cm.

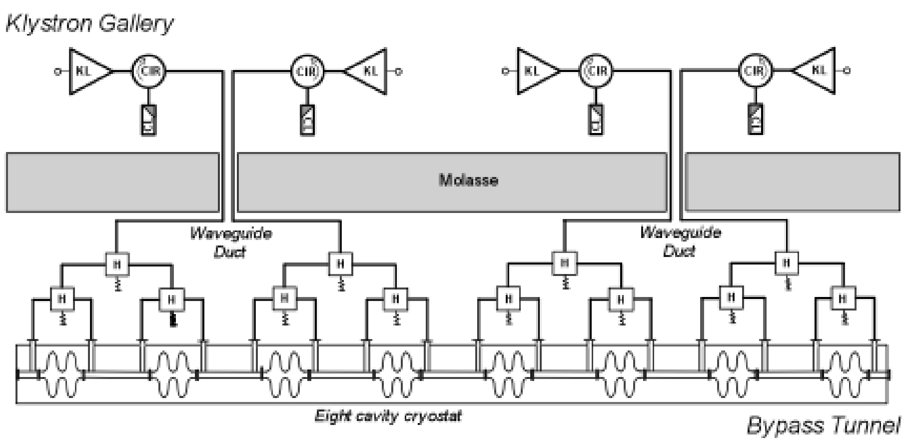


Figure 10.18: Layouts of RF power equipment in bypass and in RF gallery for one cryomodule.

Surface Installations

One HV Power Converter rated at 6 MVA is needed per 4 klystrons. These are housed in surface buildings: eight converters at CMS, and six at ATLAS.

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 10.11: Energy losses in the arcs on a half circle of 1 km radius

Conclusions

721.4 MHz RF systems can be just fitted in the two bypasses nearest ATLAS and CMS. Detailed studies need to be done on the optimization of the cavity geometry for the high beam current and ensuring acceptable transverse impedance. The RF power system is large. Further work is needed on integration to exactly define tunnel and cavity cavern layouts and quantify the space requirements. Phased installation with gradual energy build-up, as was done for LEP, is an interesting possibility. The power needed for RF is 79 MW. To this must be added power for RF controls, for power converters, cryogenics and all other machine equipment.

10.3 Linac-Ring RF Design

10.3.1 Design Parameters

The ERL design [?] [?] [?] is based on two 10 GeV linacs, with 0.3 GeV injection and 6 linac passes to reach 60 GeV. This is shown in Figure **??**.

The overall parameters are given in table [Frank]. 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 though the arcs due to synchrotron radiation as shown in Table 10.11.

The energy loss in the arcs can be compensated by independent RF systems operating at twice the normal RF frequency. As proposed by [?] 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 $1 \cdot 10^{10}$. 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 10.12, 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.

10.3.2 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 10.13.

RF power system

Assuming optimum coupling the forward power per cavity is approximately 17.9 kW and 28.7 kW for Cases 1 and 2 respectively. The available power per cavity must be somewhat higher to allow margin for operation of RF the feedback systems; i.e. 21 kW and 33 kW per cavity. These levels can certainly be achieved with solid state amplifiers, avoiding the need for high voltage power supplies and associated protection equipment. The grid to RF conversion efficiency is also somewhat higher; 70 % can be taken. The total supplied average RF powers are approximately 17 MW and 27 MW for the two cases and the grid power required for powering of the linacs is 24 MW and 39 MW respectively.

RF Power system layout

The RF amplifiers and RF feedback and controls racks are housed in a separate parallel powering gallery. There is one RF amplifier per cavity, the power being fed by WR1150 standard waveguides, each 11.5 inches by 5.75 inches (30 cm by 15 cm). The number of holes between the powering and linac tunnels can be limited to one per four cavities, i.e. two per cryomodule, spaced 8 m apart giving 118 holes per linac. The diameter is 90cm. The diameters could be reduced if half height waveguides or coax lines are used.

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 10.12: 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 10.13: ERL cryomodule numbers, length and spacing.

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 10.14: Arc RF systems overall parameters.

10.3.3 Arc RF systems

Table 10.11 shows the synchrotron radiation losses in the arcs; they are negligible in the 10 GeV arc. In the 20, 30, 40 and 50 GeV arc both the accelerated and decelerated beams pass the same arc RF system with 180^0 phase shift at the basic frequency of 721.42 MHz; hence to accelerate both beams, the arc RF system is operated at twice the frequency, i.e. at 1442.82 MHz. The 60 GeV arc carries only the decelerated beam and there one can use the linac RF cavities at 721.42 MHz. However, since here the required power per cavity is much larger the solid state amplifiers of the main linac cannot be used but a klystron or IOT must be applied. Overall parameters for these RF systems are given in Table 10.14.

The arc systems provide very different voltages. Parameters for the individual systems are given in table 10.15. Use of cavities and cryostats scaled to those in the linacs is assumed; however short cryostats containing four cavities could be used in the 20 and 40 GeV arc systems. Powering would be by klystrons, a total of 36 rated at a maximum of 360 kW, with one klystron supplying up to four cavities.

It can be noted that the overall grid power is less if the arc energy recovery is supplied by the main linacs. (39 MW compared to 24 plus 18 = 42 MW). This is partly due to the assumed higher efficiency of the solid state amplifiers in the linacs compared to the klystrons in the arc RF systems.

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 10.15: Parameters of the individual arc RF systems.

10.4 Crab crossing for the LHeC

Due to the very high electron beam energies for the LHeC, the required RF power and the interaction region design due to synchrotron radiation 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 accomodate 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. The complex interaction region in the LHeC and the issues associated with the sychrotron radiation can be relaxed with an implementation of crab crossing. In addition to the luminosity gain, the issues associated with the synchrotron radiation can be relaxed with an implementation of crab crossing near the IR. It is also a natural knob to regulate the beam-beam parameter if desired. Although the linac-ring option plans to employ separation dipoles and mirrors for sychrotron radiation, crab crossing can prove to be a simpler option if the technology is viable.

10.4.1 Luminosity Reduction

In the nominal LHC with proton-proton collision, the two beams share a common vaccum 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

$$R = \frac{1}{\sqrt{1 - \Phi^2}} \tag{10.1}$$

where $\Phi = \sqrt{\theta\sigma_z/2\sigma_x}$ is the Piwinski parameter, which is proprotional to ratio of the longitudinal and transverse beam sizes in the plane of the crossing.

With reducing β^* for the upgrade and a constant beam-to-beam separation in the IRs ($\sim 10\sigma$), the luminosity reduction factor becomes significant. To compensate this crossing angle, a crab crossing scheme is proposed and R&D is moving rapidly to realize the technology [?, ?]. In addition to crossing angle compensation, it allows a natural knob to regulate the beam-beam parameter which can valuable while operating close to the beam-beam limit.

For the electron-proton collisons, the Piwinski parameter can be redefined as

$$\Phi_p = \frac{\theta_c}{2\sqrt{2}\sigma_x^*}\sqrt{\sigma_{z,p}^2 + \sigma_{z,e}^2} \tag{10.2}$$

where $\sigma_{z,p}$ and $\sigma_{z,e}$ are the proton and electron bunch lengths. Table 10.16 lists the relevant parameters of the crossing schemes in the LHeC as compared to some other machines.

10.4.2 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. 10.19) were simulated to determine the luminosity gain in the different cases with crab cavities and comparing it to the nominal case (see Table 10.17).

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-negligable.

Table 10.16: Relevant parameters of the crossing schemes in the LHeC compared to LHC, KEK-B and eRHIC. Note † corresponds to electrons and * corresponds vertical plane.

	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)

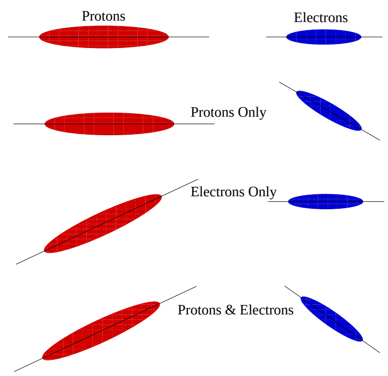


Figure 10.19: Schematic of different crossing schemes using crab cavities on either proton or electron beams as compared to the head-on collision.

10.4.3 RF Technology

The cavity voltage required for can be calculated using

$$V_{crab} = \frac{2cE_0 \tan(\theta_c/2) \sin(\mu_x/2)}{\omega_{RF}\sqrt{\beta_{crab}\beta^*} \cos(\psi^x_{cc\to ip} - \mu_x/2)} \tag{10.3}$$

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, $\psi^x_{cc\to ip}$ 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 the both the proton and the electron beams.

To accomodate 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 interection region constraints. The effort to compress the cavity footprint recently resulted in several TEM type deflecting mode geometries [?]. Apart

Table 10.17: Luminosity gains computed for different crossing schemes with crab cavities and a crossing angle of 1 mrad.

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

from being significantly smaller than its elliptical counterpart, the deflecting mode is the primary mode thus giving paving way to a new class of cavities at lower frequencies (400 MHz) which is preferred from the RF curvature point of view

Demontration of novel RF concepts providing high kick gradients and robust operation within the LHC constraints are mandatory to realize the benefits of crab crossing. R&D on novel concepts are 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.

10.5 Vacuum

10.5.1 Vacuum requirements

In particle accelerators, beams are travelling 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 therefore depends on partial pressure, weight of the gas species and radiation length [g/cm2]. In presence of a photon-stimulated desorption, the residual gas is dominated by hydrogen (75%) followed by CO/CO_2 (24%) and 1% CH_4. Argon normally represents less than 1% of the residual gas if welding best practice for UHV applications is applied. To be noted that Argon is 67 times more harmful than hydrogen (H_2), CO_2, CO and N_2 are about 30 times worst and is 10 times worst.

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 (ionisation) and for positive beams only, electron (ionisation) induced instabilities (beam blow up). The heat load induced by scatted 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 ionisation cross-sections. In the case of the LHeC, this limitation exists only in the experimental areas where the two beams travel in the same beampipe. 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 later 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.

10.5.2 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 enhanced the electron cloud build-up and mitigation solutions shall be included at the design stage.

Synchrotron radiation power

The synchrotron radiation power is an issue for the heat load deposited on the beampipes and for its evacuation and will be the driving factor for the mechanical engineering of the beampipes. Indeed, the heated surfaces will have a higher outgassing rates, the increase being exponentially dependent with the surface temperature (factor 10 for a $\Delta T = 50°\text{C}$ increase). The synchrotron radiation power can be calculated with equation 10.4. Since scaling linearly with the beam intensity, I, with the power of 4 for energy, E, and inversely to power of 2 of the bending radius, the synchrotron radiation power in the Ring-Ring option is expected to be 45 times higher than LEP and locally at the by-passes, the power can be about 180 times higher. To be compared with the factor 10 expected in the bending and injection sections of the Linac-Ring option.

$$P[W/m] = 1.24 \times 10^3 \frac{E^4 I}{\rho^2} \tag{10.4}$$

Photon-induced desorption

The desorption rate depends on critical energy of the synchrotron light, ϵ_c, the energy which divides in two the emitted power. For most materials, the desorption rates vary quasi linearly with the critical energy (equation 10.5).

$$\epsilon_c(eV) = \frac{3 \cdot 10^{-7}}{R} \left(\frac{E_B}{E0}\right)^3 \tag{10.5}$$

$E_0 = 5.10^{-4}$ GeV for electrons, E_B is the energy of the beam and R the bending radius.

For the LHeC, the beam energies will be equivalent to the LEP at start. Then, a similar value of the critical energy can be assumed allowing the comparison with LEP pressure observations. Figure 10.20 shows typical photo-desorption yields measured on copper and stainless steel samples. But the beam intensities being by far larger, the linear photon flux which scales linearly (equation 3) with energy and intensity and inversely with bending radius will increase significantly.

$$\Gamma[photons/s/m] = 7 \times 10^{19} \frac{EI}{\rho} \tag{10.6}$$

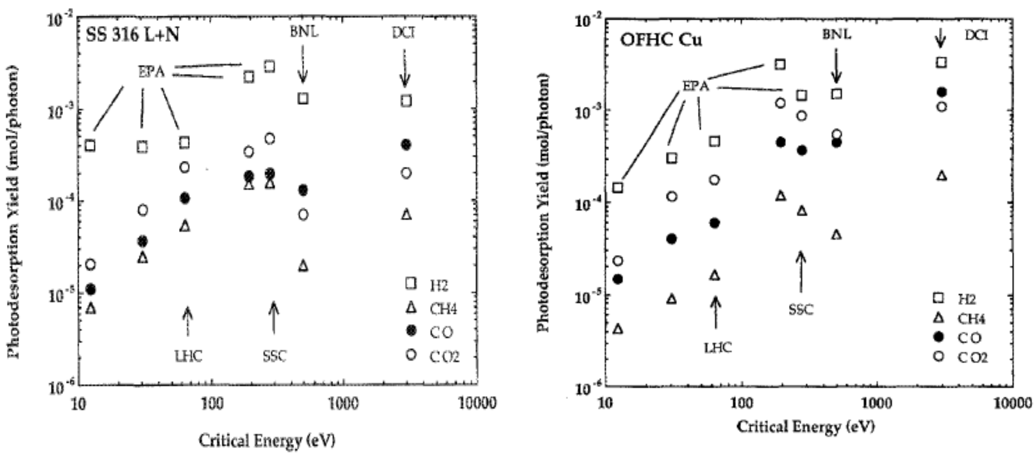


Figure 10.20: Photodesorption yields measured on copper and stainless steel surfaces. To be noted that the desorption yields of methane, η_{CH_4}, is 50 times lower than η_{H_2}.

For the Ring-Ring option (bending sections and by-passes), the linear photon flux is expected to be 45 times larger than in LEP, to be compared to the factor 5 expected for the Linac-Ring option.

The photon stimulated pressure rise, ΔP, depends linearly on the critical energy, on the beam energy and beam intensity as shown by equation 10.7. The temperature affecting the dependence of the desorption yield (equation 10.8 and 10.9), η, to the critical energy, ϵ_c the pressure rises will differ between surfaces at ambient temperature (equation 10.8) and at cryogenic temperature (equation 10.9).

$$\Delta P \propto \eta(\epsilon_c) EI \tag{10.7}$$

$$\text{at room temperature : } \quad \eta \propto \epsilon_c \ \text{ and } \ \mathrm{\epsilon_c \propto E^3} \ \text{ such that } \ \mathrm{\Delta P \propto E^4 I} \tag{10.8}$$

$$\text{at cryogenic temperature : } \quad \eta \propto \epsilon_c^{2/3} \ \text{ and } \ \mathrm{\epsilon_c \propto E^3} \ \text{ such that } \ \mathrm{\Delta P \propto E^3 I} \tag{10.9}$$

Therefore, the photon stimulated pressure rise is expected to be 45 times higher than LEP for the Ring-Ring option, to be compared with the factor 30 for the Linac-Ring option.

Vacuum cleaning and beam scrubbing

The dynamic pressure i.e. the pressure while operating the accelerator with beams will be dominated by the beam-induced dynamic effects like stimulated desorption due to beam losses or synchrotron radiations or by electron stimulated desorption in case an electron cloud is building-up.

In presence of synchrotron radiation, the vacuum cleaning process which characterises the reduction of the desorption yields (η) of a surface resulting from the bombardment of the surface by electrons, photons or ions, significantly decreases the induced gas loads ($3-4$ orders of magnitude observed in LEP) improving the dynamic pressure at constant pumping speed. This results in a progressive increase of the beam lifetime.

In presence of an electron cloud, the beam scrubbing which characterises the reduction of the secondary electron yield (SEY, δ) of a surface resulting from the bombardment of the surface by electrons, photons or ions, significantly decreases the induced gas loads ($2-3$ orders of magnitude observed in SPS) improving the dynamic pressure at constant pumping speed. Similarly to what happens with the vacuum cleaning, this results also in a progressive increase of the beam lifetime.

By default and mainly driven by costs and integration issues, the vacuum system of an accelerator dominated by beam-induced dynamic effects is never designed to provide the nominal performances as from "day 1". Indeed, vacuum cleaning and beam scrubbing are assumed to improve the beampipe surface characteristics while the beam intensity and beam energy are progressively increased during the first years of operation.

This implies accepting a shorter beam lifetime or reduced beam current during the initial phase; about 500 h of operation with beams were required for LEP to achieve the nominal performances. New technical developments such as Non-Evaporable Coatings (NEG) shall be considered since significantly decreasing the time required to achieve the nominal performances (Figures 10.21 and 10.22).

10.5.3 Vacuum engineering issues

The engineering of the vacuum system has to be integrated right from the beginning of the project. This becomes imperative for the Ring-Ring option since it has to take into account the constraints of the LHC and allow for future consolidations and upgrades. For the Linac-Ring option, the tangential injection and dump lines will be in common with the LHC beam vacuum over long distances. The experience has shown that the vacuum engineering shall proceed in parallel on the following topics: expertise provided to beam-related components (magnets, beam instrumentation, radio-frequency systems, etc.), engineering of vacuum related components (beampipes, bellows, pumping ports, etc.) and machine integration including the cabling and the integration of the services.

Basically, the vacuum system is designed to interconnect the beam related equipments installed on the beam line (magnets, kickers, RF cavities, beam absorbers, beam instrumentation, etc.) and to provide the adequate pumping speed and vacuum instrumentation. The vacuum components are often composed by vacuum pipes, interconnection bellows, diagnostics, pumping ports and sector valves. The number of pumps, vacuum diagnostics, bellows and ports will differ significantly between the two options discussed in this CDR and also between vacuum sectors of the same accelerator.

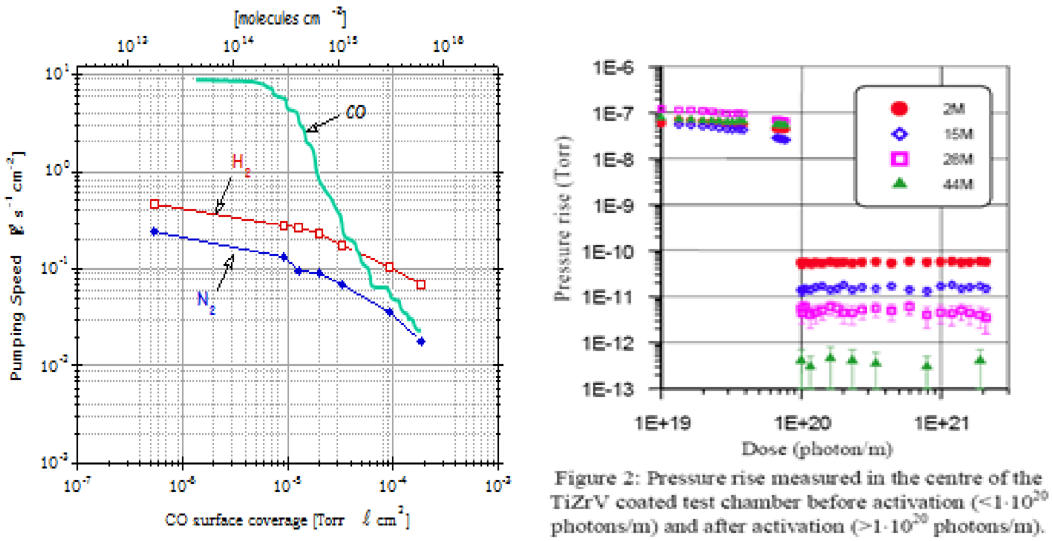
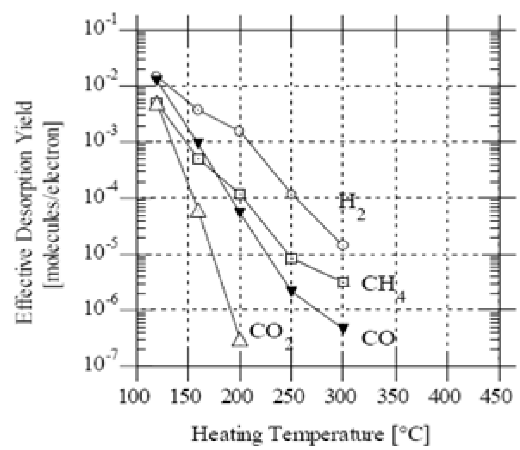


Figure 10.21: NEG pumping speed for different gas species and pressure rises measured in presence of a photon flux before and after NEG activation.

Table 2: Summary of results from the activated test chamber

Gas	Sticking probability	Photodesorption yield (molecules/photon)
H_2	~0.007	~$1.5\cdot10^{-5}$
CH_4	0	$2\cdot10^{-7}$
CO (28)	0.5	<$1\cdot10^{-5}$
C_xH_y(28)	0	<$3\cdot10^{-8}$
CO_2	0.5	<$2\cdot10^{-6}$



*C. Benvenuti *et al.* J.Vac.Sci.Technol A 16(1) 1998

Figure 10.22: Photon (left) and Electron (right) desorption yields.

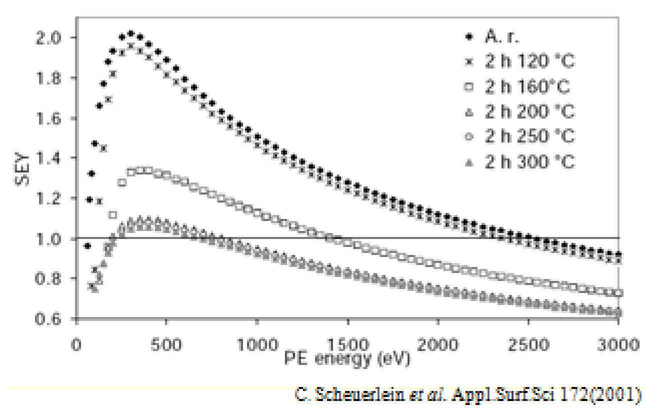


Figure 10.23: Reduction of the secondary electron yield (SEY, δ) by Photons a) and Electron b) desorption yields.

Vacuum pumping

The vacuum system of the LHeC will be mainly operated at ambient temperature. These systems rely more and more on NEG coatings since they provide a distributed pumping and huge pumping speed (Fig.2) and capacity and reduce the outgassing and desorption yields (Fig.3-4). These coatings are compatible with copper, aluminium and stainless steel beampipes. An alternative could be to use the LEP configuration with NEG strips. This alternative solution has only the advantage of avoiding the bake out constraints for the activation of the NEG coatings. A configuration of a distributed ion pumps is not considered since less performing and only applicable in dipole magnets i.e. bending sections. In any case, ion pumps are required as a complement of the NEG coatings to pump the noble gasses and methane to avoid the ion beam-induced instability. Sublimation pumps are not excluded in case of local huge outgassing rates, NEG cartridges being an interesting alternative since recent developments made by manufacturers include an ion pump and a NEG cartridge in the same body.

The roughing from atmosphere down to the UHV range will be obtained using mobile turbomolecular pumping stations. These pumps are dismounted prior to beam circulations.

The part of the vacuum system operated at cryogenic temperature, if any, could rely on gas condensation if the operating temperatures are below 2 K. Additional cryosorbing material could be required if an important hydrogen gas load is expected. This issue still needs to be addressed. As made for the LHC, the parts at cryogenic temperature must be isolated from the NEG coated part by sector valves when not at their operating temperature to avoid the premature saturation of the NEG coatings.

The pumping layout will be simpler for the Ring-Ring option since more space is available around the beampipes. The tighter tolerances for the Linac-Ring option make the integration and pumping layout more delicate. However, the vacuum stability will be easier to ensure in the Linac-Ring option since only the bending sections are exposed to the synchrotron radiation.

Vacuum Diagnostics

For both options, the radiation level expected will be too high to use pressure sensors with onboard electronics. Therefore, passive gauges shall be used, inducing additional cabling costs and need for gauge controllers.

Vacuum Sectorisation

The sectorisation of the beam vacuum system results from the integration of various constraints, the major being: venting and bake-out requirements, conditioning requirements (RF and HV devices), protection of fragile and complex systems (experimental areas and ceramic chambers), decoupling of vacuum parts at room temperature from upstream and downstream parts at cryogenic temperature thus non-baked, radiation issues, etc.

For UHV beam vacuum systems, all-metal gate valves shall be preferred in order to allow for bake-out at temperature above 250°C. VITON-sealed valves even though the VITON has been submitted to a special treatment are not recommended nearby NEG coatings or NEG pumps since minor outgassing of Fluor will degrade the pump characteristics.

In the injection and extraction regions, the installation of the sector valves will lead to integration issues since the space left between the beampipes with a tangential injection/extraction and the circulating beams is often limited. This could result in a long common beam vacuum which implies that the LHC beam vacuum requirements will apply to the LHeC part shared with LHC.

Vacuum protection

The distribution of the vacuum sector valves will be made in order to provide the maximum protection to the beam vacuum in case of failure (leak provoked or not). Interlocking the sector valves is not an obvious task. Indeed, increasing the number of sensors will provide more pressure indications but often results in a degradation of the overall reliability. The protection at closure (pressure rise, leaks) is treated differently from the protection while recovering from a technical stop with parts of the accelerator beampipe vented or being pumped down.

The vacuum protections of the common beampipes between LHeC and LHC shall fulfill the strong LHC requirements. Indeed, any failure in the LHeC propagating to the LHC could lead to long machine downtime (several months) in case of an accidental venting of an LHC beam vacuum sector.

HOM and Impedance implications

The generation and trapping of higher order mode (HOM) resulting from the changes in beampipe cross-sections are severe issues for high intensity electron machines. Thus, the engineering design of LHeC must be inspired on new generation of synchrotron radiation light sources instead of the simple LEP design. All bellows and gaps shall be equipped with optimised RF fingers, designed to avoid sparking resulting from bad electrical continuity. Indeed, these effects could induce pressure rises and machine performance limitations.

Bake-out of vacuum system

An operating pressure in the UHV range (10^{-10} Pa) will be required for both options. This implies the use of a fully baked-out beam vacuum system.Two options are possible: permanent and dismountable bake out. The permanent solution could be an option for the Linac-Ring but has to be excluded for the Ring-Ring option for cost reasons. As done for the dipole chambers (bending sections) of LEP, hot pressurised water can be used but the limit at 150°C is a constraint for the activation of NEG coatings. Developments are being carried on at CERN to lower the activation temperature from 180°C down to 150°C but this technology is not yet available.

Shielding issues

The synchrotron radiation power is an engineering challenge for the beampipes. Indeed, 50% of the radiation power hitting the vacuum chamber is absorbed in the beampipe chamber (case of LEP aluminum chamber). The remainder 50%, mainly the high-energy part of the spectrum, escapes into the tunnel and creates severe problems like degradation of organic material and electronics due to high dose rates and formation of ozone and nitric acid could lead to severe corrosion problems in particular with aluminum and copper materials.

In this respect, the Ring-Ring option is less favorable since the synchrotron radiation will be localised at the plane of the existing LHC cable trays and electrical distribution boxes in the tunnel. Similar constraints exist also for the Linac-Ring option but these zones are localised at the bending sections of the LHeC.

Detailed calculations are still to be carried on but based on LEP design, a lead shielding of 3 to 8 mm soldered directly on the vacuum chamber would be required for 70 GeV beams. Higher energies could require more thickness. The evacuation of the synchrotron radiation induced heat load on the beampipe wall and on lead shielding is a critical issue which needs to be studied. In case of insufficient heat propagation and cooling, the lead will get melted as observed in LEP in the injection areas. The material fatigue shall also be investigated since running at much higher beam current as compared to LEP, will increase the induced stress to the material and welds of the beampipes.

As made in LEP, the best compromise to fulfill the above mentioned constraints is the use of aluminum beampipes, covered by a lead shielding layer. The complex beampipe cross-section required to optimise the water cooling of the beampipe and shielding is feasible by extrusion of aluminum billets and the costs are acceptable for large productions. The large heat conductivity helps also the heat exchange. However, extruded aluminum beampipes induce limitations for the maximum bake out temperature and therefore for the NEG coatings activation. Special grades of aluminum shall be used. The reliability of vacuum interconnections based on aluminum flanges is a concern at high temperature (>150°C) and corrosion issues shall be addressed. The stainless steel beampipes do not have these limitations but they have poorer heat conductivity and they are more difficult and costly to machine and shape.

The LEP 110 GeV operation has shown the criticality of unexpected synchrotron radiations heating vacuum components and in particular the vacuum connections between pipes or equipments. Indeed, the flanges, by "offering" a thick path, are behaving as photon absorbers and heat up very quickly. Hence, at cool down and due to the differential dilatation, leaks are opening. In LEP, these unexpected SR induced heat loads resulted from orbit displacement in quadrupoles during the ramp in energy and of the use of the wigglers also during the ramp. In LHeC, resulting from the much higher beam current, these issues shall be carefully studied.

Corrosion issues

In vacuum systems, feedthroughs and bellows are particularly exposed to corrosion. The feedthroughs, particularly those of the ion pumps where high voltage is permanently present, are critical parts. A demonstrated and cheep solution to prevent the risk of corrosion consists in heating directly the protective cover to reduce the relative humidity around the feedthrough.

The bellows are critical due to their thickness, often between $0.1 - 0.15$ mm. PVC material must be prohibited in the tunnel. Indeed, in presence of radiations, it can generate hydrochloric acid (HCl) which corrodes stainless steel materials. This corrosion has the particularity to be strongly penetrating, once seen at the surface, it is often too late to mitigate the effects. Aluminum bellows are exposed to corrosion by nitric acid (HNO_3) which is generated by the combination of O_3 and NO.

Humidity is the driving factor and shall be kept 50%. However, in the long term, accidental spillage can compromise locally the conditions and therefore, corrosion-resistant design are strongly recommended.

10.6 Beam Pipe Design

10.6.1 Requirements

The vacuum system inside the experimental sector has a number of different and sometimes conflicting requirements. Firstly, it must allow normal operation of the LHC with two circulating beams in the chamber. This implies conformity with aperture, impedance, RF, machine protection as well as dynamic vacuum requirements. The addition of the incoming electron beam adds constraints in terms of geometry for the associated synchrotron radiation (SR) fan and the addition of SR masks in the vacuum. Finally, optimization of the surrounding detector for high acceptance running means that all materials for chambers, instrumentation and supports must be optimized for transparency to particles and the central chamber must be as small and well aligned as possible to allow detectors to approach the beam aperture limit at the interaction point.

10.6.2 Choice of Materials for beampipes

LHC machine requirements imply an inner beampipe wall that has low impedance (good electrical conductivity) along with low desorption yields for beam stimulated emissions and resistance to radiation damage.

Ideal materials for transparency to particles have low radiation length (Z) and hence low atomic mass. These materials either have poor (i.e. high) desorption yields (eg. aluminium, beryllium) or are not vacuum and impedance compatible (eg. carbon). Solutions to this problem typically include thin film coatings to improve desorption yields and composite structures to combine good mechanical properties with vacuum and electrical properties.

The LHC experimental vacuum systems, along with most other colliders currently use metallic beryllium vacuum chambers around the interaction points due to a very favourable combination of Z, electrical conductivity, vacuum tightness, radiation resistance, plus mechanical stiffness and strength. High desorption yields are suppressed by a thin film TiNiV non-evaporable getter (NEG) coating. This coating also gives a high distributed vacuum pumping speed, allowing long, small aperture vacuum chambers to be used that would otherwise be conductance-limited. Activation of this coating requires periodic heating of the chamber to $180 - 220°C$ under vacuum for a few hours. This means that the chamber and environment must be designed for these temperatures. This activation is scheduled in annual LHC shutdowns. Long-term development is in progress for low desorption yield coatings that do not require high temperature activation [621]. These may have applications for LHeC.

Production technology developed for the LHC uses beryllium sections machined from hot-pressed blocks and electron beam welded to produce chambers. This has the advantage that a wide range of vacuum chamber forms can be manufactured. Cylindrical and conical chamber sections are installed in the LHC experiments.

Disadvantages of beryllium include high cost, fragility and toxicity in the powder form, as well as limited availability. For this reason, long-term development of other technologies for experimental beampipes is under way at CERN which may yield applications for LHeC.

Composite beampipe structures made from carbon and other low-Z materials have been developed for colliders. These typically use a thin inner membrane to comply with vacuum and impedance requirements. Composite structure pipes were eventually rejected for LHC application for reasons of temperature and radiation resistance and the risk of delamination due to mismatch of thermal expansion coefficients. Lower luminosity in LHeC experiments combined with new low temperature coatings may allow these materials to be re-evaluated.

10.6.3 Beampipe Geometries

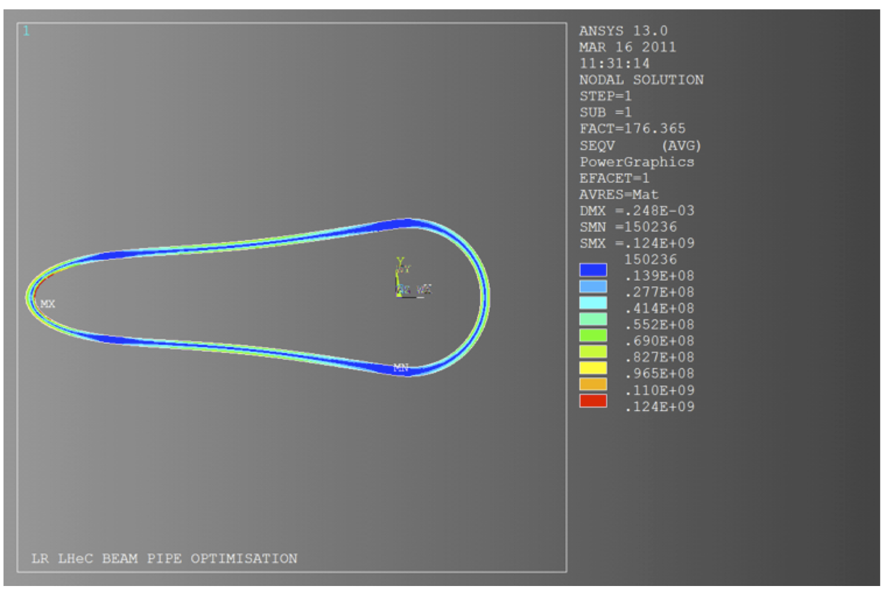


Figure 10.24: Section through the LR geometry showing contours of Von Mises equivalent stress (Pa).

The proposed geometry has a cross section composed of a half-circle intersecting with a half-ellipse. Cylindrical cross-sections under external pressure fail by elastic instability (buckling) whereas elliptical sections can (depending on the geometry) fail by plastic collapse (yielding).

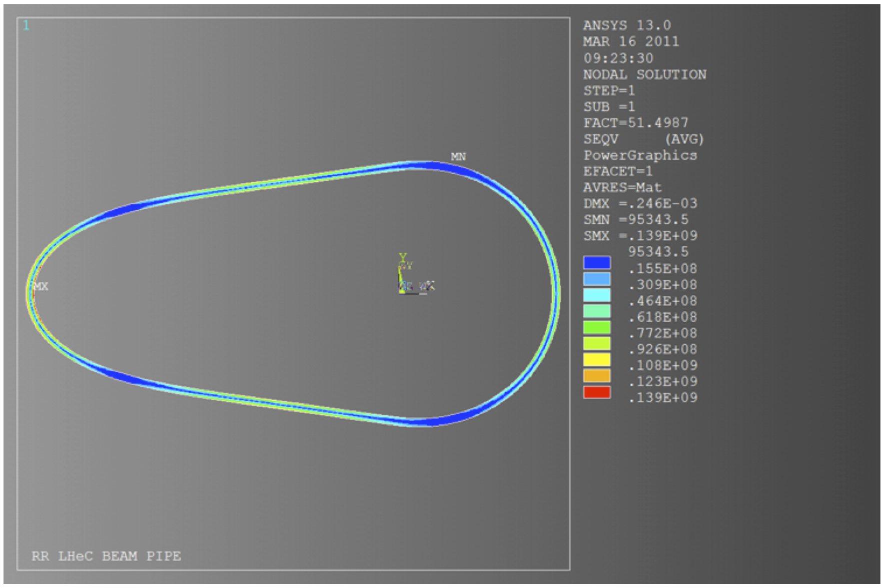


Figure 10.25: Section through the RR geometry showing contours of Von Mises equivalent stress (Pa).

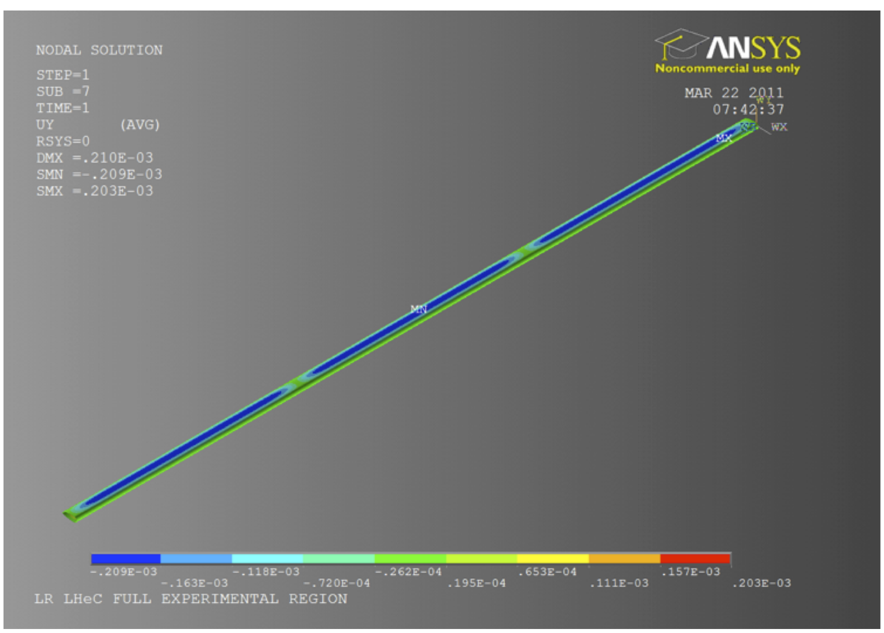


Figure 10.26: 3-D view of the LR geometry showing contours of bending displacement [m].

Figure 10.24 and 10.25 show optimizations of the proposed geometries for the LINAC-Ring (LR) and Ring-Ring (RR) beampipes assuming a long chamber of constant cross section made from beryllium metal. Preliminary analyses have been performed using the ANSYS finite element code. The wall thickness was minimized for the criteria of yield strength and buckling load multiplier. The LR geometry considered has a circular section radius of 22 mm and elliptical major radius of 100 mm. The RR geometry has a circular section radius of 22 mm and elliptical major radius of 55 mm. This preliminary analysis suggests that a constant wall thickness of $2.5 - 3\,mm$ for the LR and 1.3 to $1.5\,mm$ for the RR would be sufficient to resist the external pressure. Failure for both of these sections would be expected to occur by plastic collapse.

At this stage of the project, these geometries represent the most optimized forms that fulfill the LHC machine requirements. However, for 1 degree tracks this corresponds to X/X0 $\approx$ 21-25% for the LR and $\approx$ 41-49% for the RR designs. This suggests that additional effort must be put into beampipe geometries optimized for low angles. Composite beampipe concepts suggested for machines such as the LEP [622] should be re-considered in the light of advances in lightweight materials and production techniques.

The optimized section of the experimental chamber is 6.1 m in length. This length will require a number of optimized supports. These supports function to reduce bending deflection and stresses to within acceptable limits and to control the natural frequency of chamber vibration. The non-symmetric geometry will lead to a torsional stress component between supports which must be considered in their design. Figure 10.26 shows a preliminary analysis of bending displacement for the LR chamber geometry. With 2 intermediate supports the maximum calculated displacement (without bakeout equipment) is 0.21 mm.

10.6.4 Vacuum Instrumentation

If, as assumed, this chamber is coated with a NEG film on the inner surfaces, then a high pumping speed of chemically active gasses will be available. Additional lumped pumps will be required for non-gettered gasses such as CH_4 and noble gasses; however, outgassing rates for these gasses are typically very low.

The vacuum sector containing the experiment will be delimited from the adjacent machine by sector valves. These will be used to allow independent commissioning of machine and experiment vacuum. The experimental vacuum sector will require pressure gauges covering the whole range from atmospheric to UHV, these are used both for monitoring the pressure in the experimental chamber and as interlocks for the machine control system.

10.6.5 Synchrotron Radiation Masks

LHeC experimental sector will require a moveable SR mask upstream of the interaction. From the vacuum perspective, this implies a system for motion separated from atmosphere by UHV bellows. The SR flux on the mask will generate a gas load that should be removed by a local pumping system dedicated to the mask. As the load due to thermally stimulated desorption increases exponentially with the temperature, cooling may be required. However, cooling the mask would significantly complicate the vacuum system design. The generation of photo-electrons must also be avoided since these photo-electrons can interact with the proton beam and lead to an electron cloud build-up.

10.6.6 Installation and Integration

The installation of the vacuum system is closely linked to the detector closure sequence. Therefore, the design has to be validated in advance to prevent integration issues which would lead to significant delay and increase of costs. Temporary supports and protections are required at each stage of the installation. Indeed, as compared to the size of the detectors, the beam pipe are small, fragile and need to be permanently supported and protected while moving the detector components. Leak tightness and bake-out testing are compulsory at each step of the installation since all vacuum systems are subsequently enclosed in the detector, preventing any access or repair. Their reliability is therefore critical. Precise survey procedures must also be developed and incorporated in the beampipe design to minimize the mechanical component of the beam aperture requirement. Engineering solutions for bakeout also has to be studied in details since the equipment (heaters, probes and cables) must fit within the limited space available between beampipes and the detector components.

10.7 Cryogenics

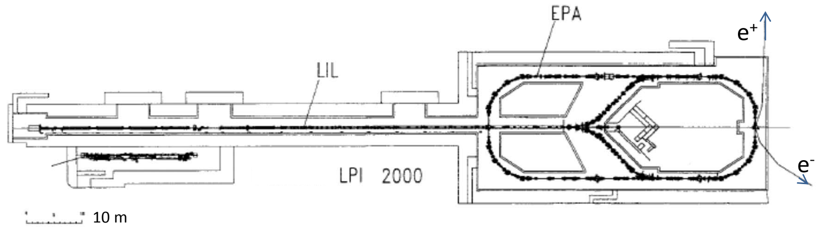


Figure 10.27: Layout of the LPI in 2000.

10.8 Positron P for the Linac-Ring option

Figure 10.27 shows the layout of the LPI (LEP Pre-Injector) as it was working in 2000.

LPI was composed of the LIL (LEP Injector Linac) and the EPA (Electron Positron Accumulator).

Table 10.18 gives the beam characteristics at the end of LIL.

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 10.18: LIL beam parameters.

Figure 10.28 shows an electron beam profile at the end of LIL (500 MeV).

Table 10.19 gives the electron and positron beam parameters at the exit of EPA.

Energy	200 to 600 MeV
Charge	up to $4.5 \times 10^{11} e\pm$
Intensity	up to 0.172 A
Number of buckets	1 to 8
Emittance	0.1 mm.mrad
Tune	$Q_x = 4.537, Q_y = 4.298$

Table 10.19: The electron and positron beam parameters at the exit of EPA.

In summary, the LPI characteristics fulfils completely the requested performance for the LHeC injector based on Ring-Ring option.

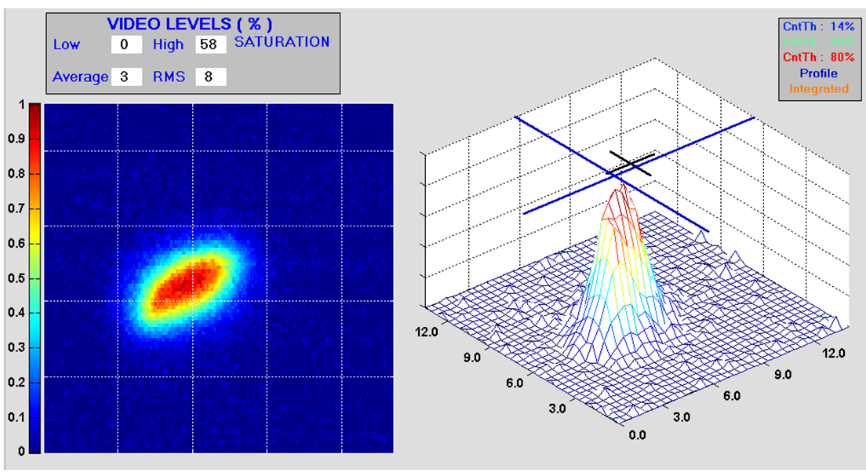


Figure 10.28: Electron beam profile at 500 MeV.

10.9 Beam dumps

Beam Dump

10.10 Post collision line for 140 GeV option

The post collision line for the 140 GeV Linac option has to be designed taking care of minimising beam losses and irradiation. The production of beamsstrhalung 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.

10.11 Absorber for 140 GeV 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 [623]. Cold pressurized water (18 m^3 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 m^3 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 undisrupted 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.

10.11.1 Energy deposition studies

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 [624]. 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/cm^3 deposited on the window have been calculated. This corresponds to a maximum temperature of 77° for the minimum ionisation particle (dE/dx = 2 MeV × cm^2/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 undisrupted 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:

$$\sigma_{Ti} = 0.49 \times \Delta P \frac{R^2}{d^2} \tag{10.10}$$

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.

10.12 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. 10.29). 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. 10.30). The beam dump will be 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. 10.30) for beam setup purposes at intermediate energy. The same design as for the nominal dump and extraction line would be applied.

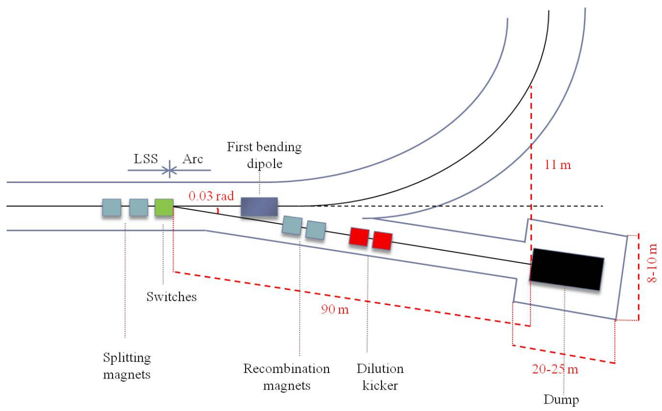


Figure 10.29: Scheme of the transfer line from end of long straight section of the linac and beam dump.

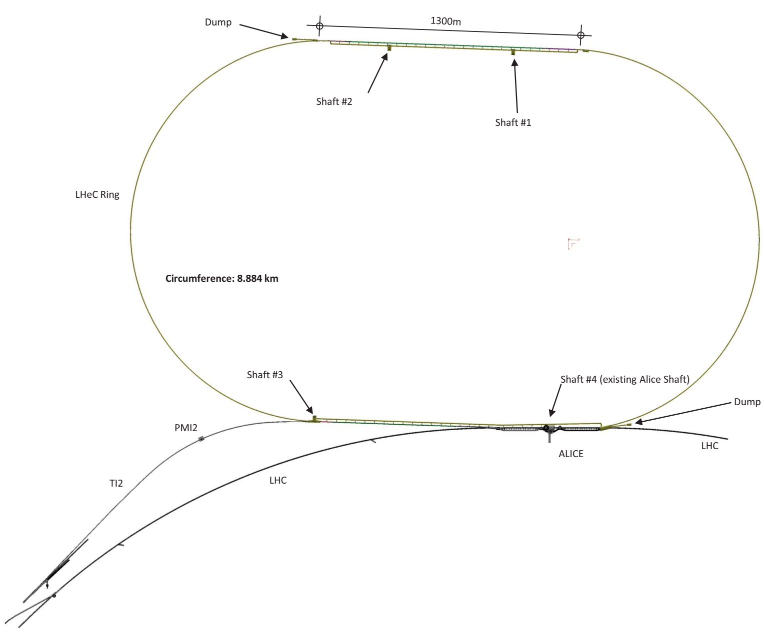


Figure 10.30: Two beam dumps are installed 90 m downstream the end of the long straight section of each linac for nominal operation and beam setup.

10.13 Absorber for ERL Linac-Ring option

During nominal operation a 0.5 GeV beam has to be dumped with a current of 6.6 mA. The setup beam will have a maximum current of 0.05 mA and an energy varying from 10 GeV to 60 GeV (10 GeV step size). Globally, a maximum beam power of 3 MW has to be dumped. The same design as for the 140 GeV option can be used by scaling linearly. In this case, a 3 m^3 water dump (0.5 m diameter and 8 m length) with a 3 m $\times$ 3 m $\times$ 10 m long shielding has to be implemented. No show stopper has been identified for the 18 MW ILC dump, same considerations are valid in this less critical case.

10.14 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.

10.14.1 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. 10.31). 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 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 10.20.

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 the kicker strength of about 1 mrad.

The septum strength should be about 33 mrad to provide enough clearance for the injected beam at the upstream lattice quadrupole, the yoke of which is assumed to have a full width of 0.6 m. This requires about 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 vertical gap of 40 mm and a current of 12 kA.

The RF frequency of the linac is 1.3 GHz and a bunch spacing of 25 ns is considered, as the LHeC electron beam bunch structure is assumed to match with the LHC proton beam structure. Optimally a train of 72 bunches would be injected, which would require a 1.8 μs flattop for the kickers and a very relaxed 0.9 μs rise time (as for the LHC injection kickers [625]). However, this train length is too long for the recirculating linac to produce, and so the kicker rise time and fall time requirements are therefore assumed to be about 23 ns, to allow for the bunch length and some jitter.

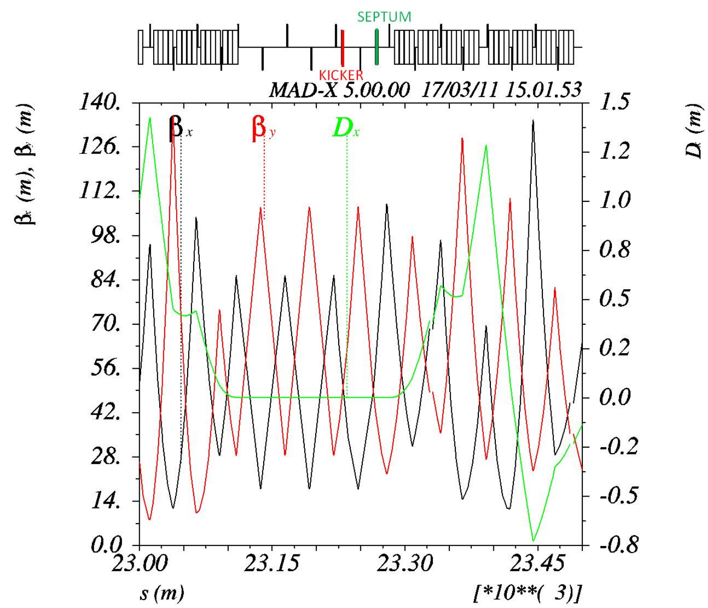


Figure 10.31: Injection optics is shown. The sequence starts (s=0) at the beginning of the dispersion suppressor at the left side of IP2 and proceeds clockwise, while the electron beam rotates counterclockwise (from right to left in the figure). The injection kicker and septum are installed in the dispersion free region of the bypass at the right side of ATLAS.

For a rise time $t_m = 23$ ns, a system impedance Z of 25 Ω is assumed, and a rather conservative system voltage U of 60 kV.

Assuming a full vertical opening h of 40 mm, and a full horizontal opening w of 60 mm (which allow $\pm 6\ \sigma$ beam envelopes with pessimistic assumptions on various tolerances and orbit), the magnetic length l_m of the individual magnets is:

$$l_m = h t_m Z / \mu_0 w = 0.31\ m$$

For a terminated system the gap field B is simply:

$$B = \frac{\mu_0 U}{2hZ} = 0.037\ T$$

As 0.03 Tm are required, the magnetic length should be 0.8 m, which requires 3 magnets. Assuming each magnet is 0.5 m long, including flanges and transitions the total installed kicker length is therefore about 1.5 m.

10.14.2 Mismatched injection

A mismatched injection is also possible, Figure 10.32 with a closed orbit bump used to bring the circulating beam orbit close to the septum, and then switched off before the next circulating bunch arrives.

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 10.20: Assumptions for beam parameters used to define the septum and kicker apertures

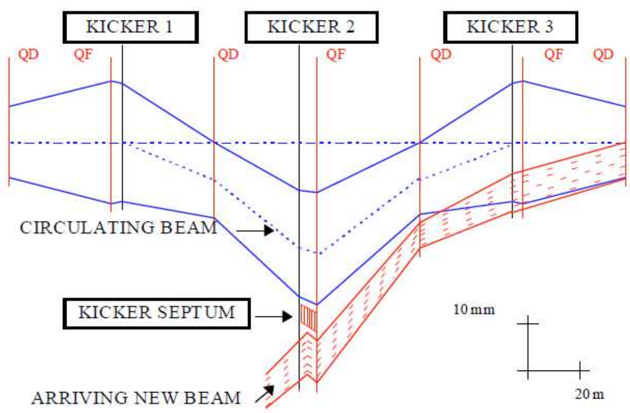


Figure 10.32: layout of mismatched injection system. To minimise kicker strengths the magnets are located near focusing quadrupoles.

The injected beam then performs damped betatron or synchrotron oscillations, depending on the type of mismatch used. In LHeC the damping time is about 3 seconds, so that to achieve the suggested 0.2 s period between injections, a damping wiggler would certainly be needed - the design of such a wiggler needs to be investigated.

Three kickers (KICKER 1, KICKER 2 and KICKER 3 in Fig. 10.32) are used to generate a closed orbit bump of 20 mm at the injection point. The kicker parameters are summarized in table 10.21. In case of betatron mismatch, the bumpers can be installed in the dispersion free region considered for the injection onto the closed orbit case discussed in the previous section (see Fig. 10.33). The installed magnet lengths of the kickers should be 2 m, 3.5 m and 1 m respectively, for the kickers size,Z and U parameters given above. Overall the kicker system is not very different to the system needed to inject onto the orbit.

To allow for the possibility of synchrotron injection, the injection kicker-septum would need to be located where the horizontal dispersion D_x is large. The beam is then injected with a

Magnet	θ_x [mrad]	B dl [Tm]
KICKER1	1.35	0.04
KICKER2	2.37	0.08
KICKER3	0.55	0.02

Table 10.21: Kickers strength and integrated magnetic field needed to generate an orbit bump of 20 mm at the injection point.

position offset x and a momentum offset δp, such that:

$$x = D_x \delta p$$

The beam then performs damped synchrotron oscillations around the ring, which can have an advantage in terms of faster damping time and also smaller orbit excursions in the long straight sections, particularly experimental ones, where the dispersion functions are small.

As an alternative to the fast (23 ns rise time) kicker for both types of mismatched injection, the kicker rise- and fall-time could be increased to almost a full turn, so that the bump is off when the mismatched bunch arrives back at the septum. This relaxes considerably the requirements on the injection kicker in terms of fall time. However, this does introduce extra complexity in terms of synchronizing the individual kicker pulse lengths and waveform shapes, since for the faster kicker once the synchronization is reasonably well corrected only the strengths need to be adjusted to close the injection bump for the single bunch.

10.14.3 Injection transfer line

The injection transfer line from the 10 GeV injection recirculating linac is expected to be straightforward. A transfer line of about 900 m, constituted by 15 FODO cells, has been considered. The phase advance of each cell corresponds to about 100°.

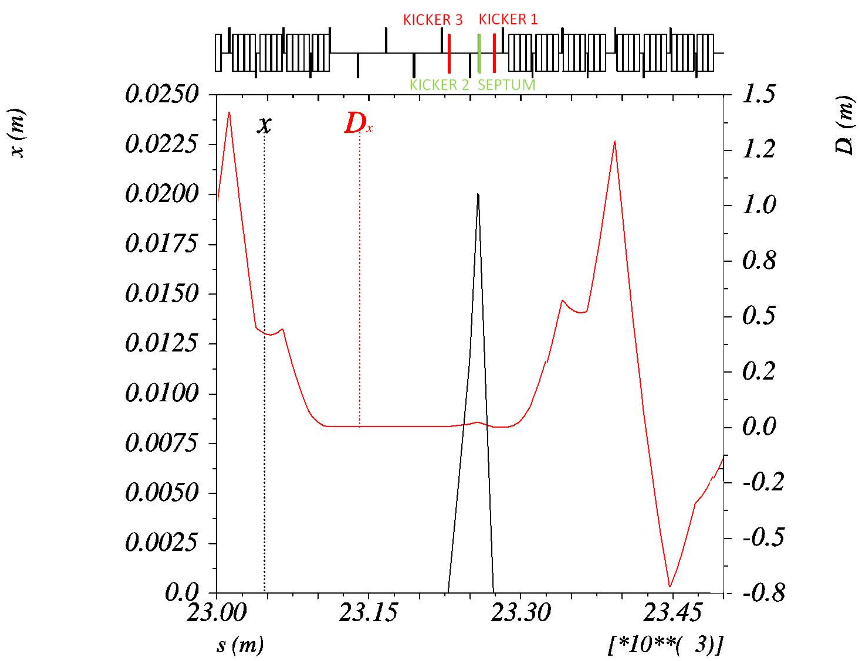


Figure 10.33: A closed orbit bump of 20 mm is generated by three kickers installed in the dispersion free region located at the right side of the bypass around ATLAS (electron beam moves from right to left in the Figure).

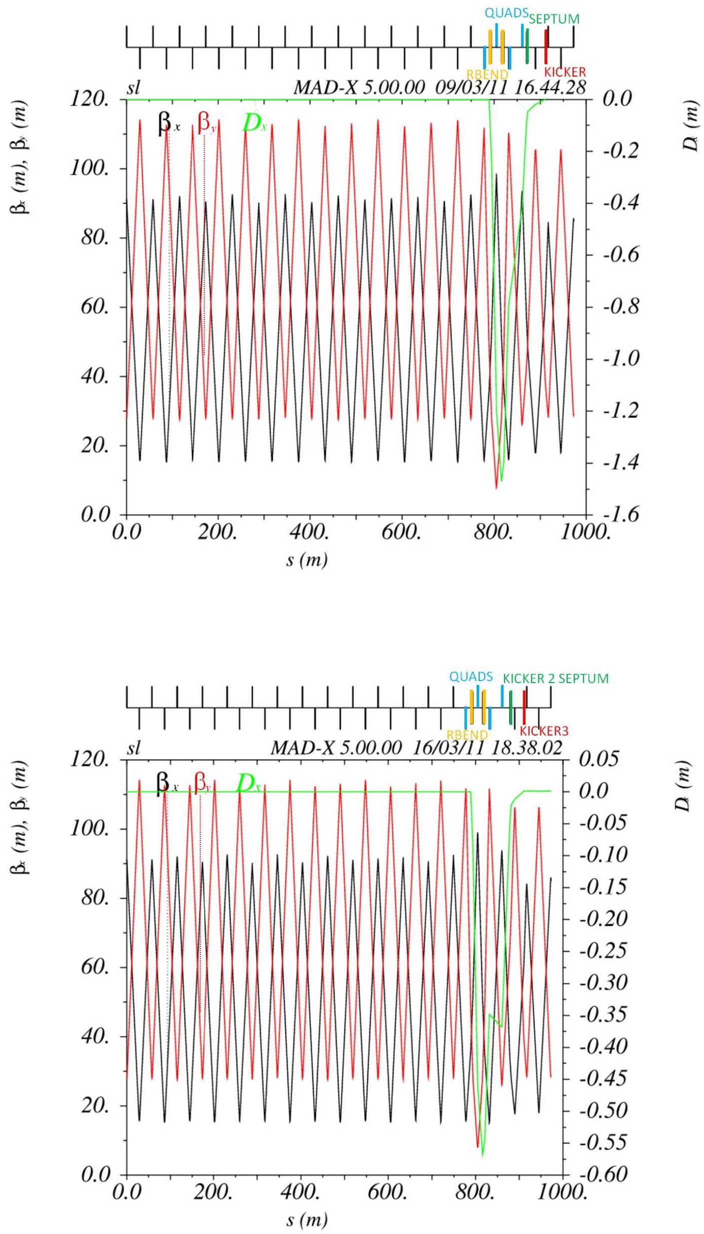


Figure 10.34: Transfer line optics for the injection onto orbit case (top) and mismatched injection case (bottom).

The last two cells are used for optics matching. In particular, four quadrupoles, 1 m long each, are used for β_x and β_y matching, while two rectangular bending magnets, 5 m long each, are used for matching the horizontal dispersion D_x to 0 (maximum D_x = -1.48 m for the injection onto closed orbit case and maximum D_x = -0.57 m for the mismatched injection case). The "good field region" for a 6σ beam envelope requires a minimum half-aperture, in the matching insertion, of 15 mm and 10 mm for the focusing and defocusing quadrupoles respectively, corresponding to a pole tip field of about 0.02 T. The maximum strength of the bending magnets, which are used for dispersion matching, corresponds to about 39 mrad. This requires 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 used.

10.15 60 GeV internal dump

An internal dump will be needed for electron beam abort. The design for LEP [626] consisted of a boron carbide spoiler and an Aluminum alloy (6% copper, low magnesium) absorbing block (0.4 m $\times$ 0.4 m $\times$ 2.1 m long). A fast kicker was used to sweep eight bunches, of 8.3×10^{11} electrons at 100 GeV, onto the absorber. The first bunch was deflected by 65 mm and the last by 45 mm, inducing a temperature increase ΔT of 165°.

The bunch intensity for the LHeC is about a factor of 20 lower than for LEP and beam size is double ($\sigma = 0.5$ mm in LEP and $\sigma = 1$ mm in LHeC).

The lower energy (60 GeV) and energy density permit to dump 160 bunches in 20 mm to obtain the same ΔT as for LEP. However, in total LHeC will be filled with 2808 bunches, which means that significant additional dilution will be required. A combination of a horizontal and a vertical kicker magnet can be used, as an active dilution system, to paint the beam on the absorber block and increase the effective sweep length. The kickers and the dump can be located in the bypass around CMS, in a dispersion free region (see fig. 10.35).

It is envisaged to use Carbon-composite for the absorber block, since this has much better thermal and mechanical properties than aluminum. The required sweep length is then assumed to be about 100 mm, from scaling of the LEP design. The minimum sweep speed in this case is about 0.6 mm per μs, which means about 54 bunches per mm. Taking into account the energy and the beam size, this represents less than a factor 2 higher energy density on the dump block, compared to the average determined by the simple scaling, that should be feasible using carbon. More detailed studies are required to optimise the diluter and block designs. Vacuum containment, shielding and a water cooling system has to be incorporated. A beam profile monitor can be implemented in front of each absorber to observe the correct functioning of the beam dump system.

The vertical kicker would provide a nominal deflection of about 55 mm (see fig. 10.36), modulated by $\pm$13% for three periods during the 100 μs abort (see fig. 10.37), while the horizontal kicker strength would increase linearly from zero to give a maximum deflection at the dump of about 55 mm (see Fig. 10.36and Fig. 10.37). This corresponds to system kicks of 2.7 and 1.6 mrad respectively.

Parameters characterizing the kicker magnets are presented in Table 10.22.

In the present lattice the dump is placed ~30 m downstream of the kickers, corresponding to a phase advance of about 63° in the horizontal plane and 35° in the vertical plane. The minimum horizontal and vertical aperture at the dump are 26 mm and 22 mm respectively (at the dump: β_x = 37 m and β_y = 55 m, using the same beam and machine parameter

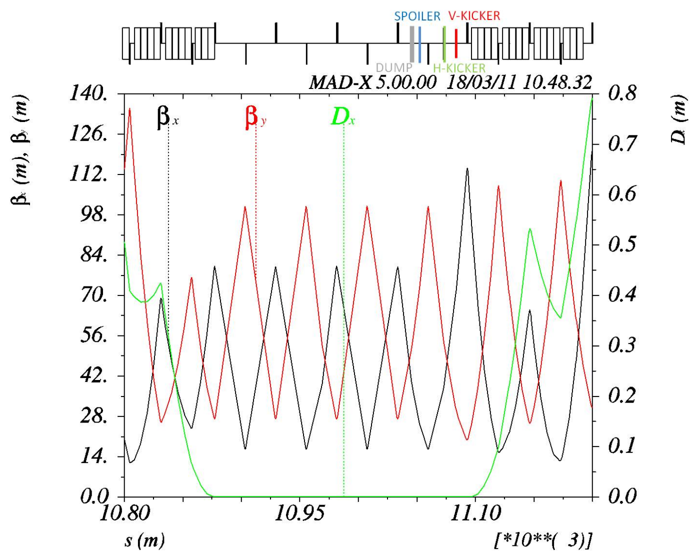


Figure 10.35: The optics in the region of the CMS bypass where the beam dump system could be installed is shown. The system consists of two kickers, one spoiler and a Carbon-composite absorber which are installed in the dispersion free region of the bypass at the right side of CMS (beam proceeds from right to left in the Figure).

assumptions, as presented in Table 10.20). The kicker system 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 LHC proton beam. Same design as for the LHC dump kicker magnets MKD can be used: a steel yoke with a one-turn HV winding. These magnets can provide a magnetic field in the gap of 0.34 T. For a magnetic length of 0.31 m (Z= 25 Ω and U = 60 kV), a total installed kicker length of 1.5 m for the horizontal system and 2.5 m for the vertical system has to be considered.

	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 [μs]	90	90

Table 10.22: Parameters characterising vertical and horizontal kicker magnets of the extraction system.

A spoiler (one-side single graphite block: 0.3 m × 0.10 m × 0.5 m long) can be installed 5 m upstream of the dump at the extraction side to provide further dilution.

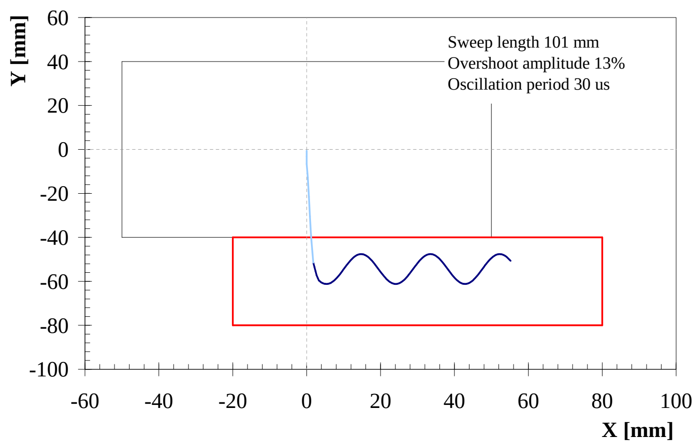


Figure 10.36: A vertical and a horizontal kicker are used to dilute the beam on the dump absorbing block.

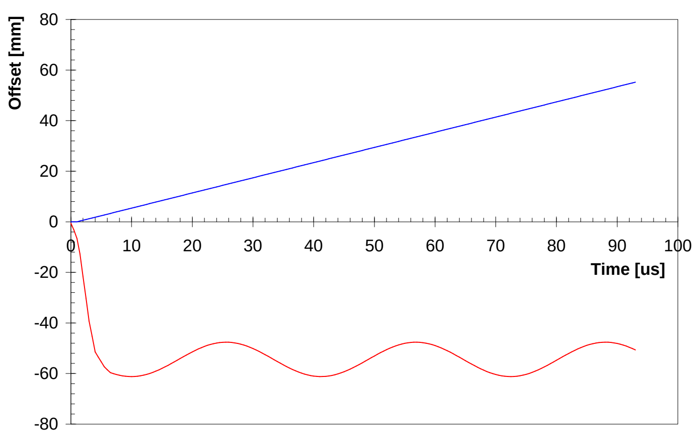


Figure 10.37: The strength of the vertical kicker oscillates in time by $\pm$ 13% around its nominal value.The deflection provided by the horizontal kicker increases almost linearly in time.

Part IV

Detector

Chapter 11

Detector Requirements

11.1 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 coverage [1], 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.

11.1.1 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 of the design study has been considered to be the ALICE cavern

[1] This 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.

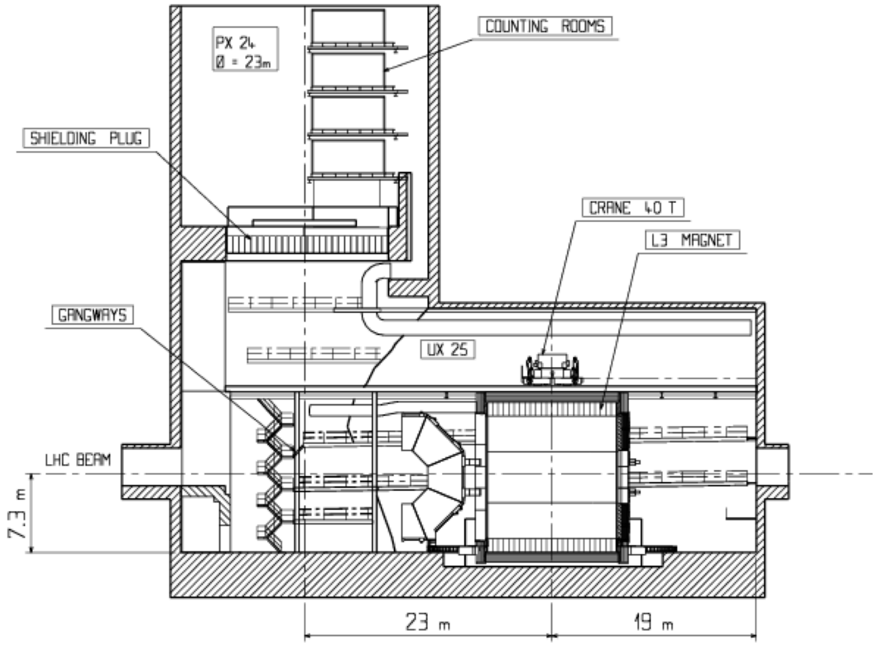


Figure 11.1: Cross section of the IP2 cavern with the ALICE detector inside the L3 magnet. Round access shaft of 23m diameter, cavern about 50m along the beam-line.

in IP2, see Fig. 11.1. The installation of the detector has to proceed as fast as possible in order not to introduce large extra delays to the LHC program. High modularity and pre-assembly above ground are therefore inevitable demands for the design.

The cost has to be limited in order for the project to be fundable in parallel to when the large upgrade investments are presumably made for the ATLAS and CMS detectors in the high luminosity phase of the LHC. The cost is related to technology choices, the detector granularity and its size. Crucial parameters of the detector are the beam pipe dimensions, when combined with the small angle acceptance constraint, see below, and the parameters of the solenoid. The cost C of a solenoid can be represented as a function of the energy density, ρ_E, $C \simeq 0.5(\rho_E/MJ)^{0.66}$ [28], which is determined as

$$\rho_E = \frac{1}{2\mu_0} \cdot \int B^2 dV \simeq \frac{1}{2\mu_0} \cdot \pi r^2 \cdot l \cdot B^2. \tag{11.1}$$

From these relations one derives roughly that the solenoid cost scales linearly with the radius r and field strength B and with the length l to the power 0.66. The solenoid radius influences the track length in the transverse plane, which determines $\propto r^{-2}$ the transverse momentum resolution whereas field strength enters linearly $\propto B^{-1}$.

The Linac-Ring version of the LHeC requires to put an extended dipole field of 0.3 T into the detector for ensuring head-on ep collisions and for separating the beams.

A balance between a strong magnetic field for optimal tracking resolution and an affordable sized magnet has to be found, knowing that the magnets themselves represent one source of inactive material and that the energy stored in the magnets and their return flux require an outer shielding proportional to the field and to the square of the solenoid radius.

In the current design the solenoid is placed in between the electromagnetic and the hadron calorimeter[2] at a radius of about 1 m. The field strength is set to 3.5 T in order to compensate the small radial extension of the tracker, the focus of which in the LHeC environment is on the forward direction. The chosen design position with dipoles and solenoid placed outside the electromagnetic calorimeter ensures good electromagnetic calorimetry and high dipole field quality near to the beam line. Fig. 11.2 shows such the magnet arrangement inside the detector volume schematically. The total material budget of the solenoid and the dipole, at perpendicular

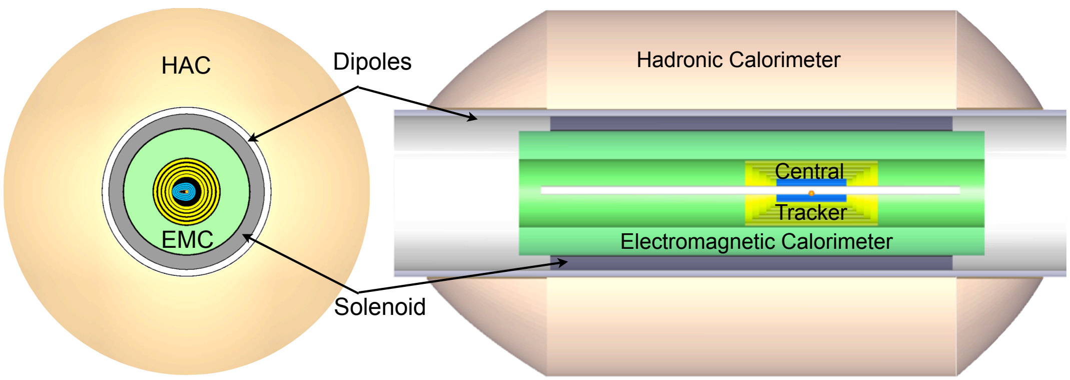


Figure 11.2: Schematic xy and rz views of the magnets and barrel calorimeter arrangement for the baseline layout.

crossing, may be represented by about $\mathcal{O}(\infty\prime)$ cm of Aluminum, corresponding to about one quarter of an interaction length (λ_I) and about 1 radiation length (X_0). This further supports the choice of the magnets located outside of the electromagnetic calorimeter, yet placed before the hadronic calorimeter in order to limit the radial dimensions. More details on the design study of the detector magnets are addressed in Sect.12.3.

11.1.2 Kinematic reconstruction

The inclusive ep DIS kinematics are defined by the negative four-momentum transfer squared, Q^2, and Bjorken x. Both are related to the cms energy squared s via the inelasticity y through the relation $Q^2 = sxy$, which implies $Q^2 \leq s$. The energy squared s is determined by the product of the beam energies, $s = 4E_pE_e$, for head-on collisions and large energies compared to the proton mass.

The kinematics are determined from the scattered electron with energy E_e' and polar angle θ_e and from the hadronic final state of energy E_h and scattering angle θ_h. The variables Q^2

[2] An 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 [627].

and y can be calculated from the scattered electron kinematics as

$$\begin{aligned} Q_e^2 &= 4E_eE_e'\cos^2(\frac{\theta_e}{2}) \\ y_e &= 1-\frac{E_e'}{E_e}\sin^2(\frac{\theta_e}{2}) \end{aligned} \tag{11.2}$$

and from the hadronic final state kinematics as

$$\begin{aligned} Q_h^2 &= \frac{1}{1-y_h}\cdot E_h^2\sin^2(\theta_h) \\ y_h &= \frac{E_h}{E_e}\sin^2(\frac{\theta_h}{2}) \end{aligned} \tag{11.3}$$

and x is given as Q^2/sy. The kinematic reconstruction in neutral current scattering therefore is redundant, which is one reason why DIS experiments at ep colliders are precise. An important example is the calibration of the electromagnetic energy scale from the measurements of the electron and the hadron scattering angles. At HERA, this led to energy calibration accuracies for E_e' at the per mil level. In a large part of the phase space, around $x = E_e/E_p$, the scattered electron energy is approximately equal to the beam energy, $E_e' \simeq E_e$, which causes a large "kinematic peak" in the scattered electron energy distribution. The hadronic energy scale can be obtained from the transverse momentum balance in neutral current scattering, $p_t^e \simeq p_t^h$. It is determined to about 1% at HERA.

Following Eq.11.3, the kinematics in charged current scattering is reconstructed from the transverse and longitudinal momenta and energy of the final state particles according to

$$\begin{aligned} Q_h^2 &= \frac{1}{1-y_h}\sum p_t^2 \\ y_h &= \frac{1}{2E_e}\sum(E-p_z). \end{aligned} \tag{11.4}$$

There have been many refinements used in the reconstruction of the kinematics, as discussed e.g. in [628], which for the principle design considerations, however, are of less importance.

11.1.3 Acceptance regions - scattered electron

The positions of isolines of constant energy and angle of the scattered electron in the (Q^2, x) plane are given by the relations:

$$\begin{aligned} Q^2(x, E_e') &= sx\cdot\frac{E_e-E_e'}{E_e-xE_p} \\ Q^2\ (x, \theta_e) &= sx\cdot\frac{E_e}{E_e+xE_p\tan^2(\theta_e/2)}. \end{aligned} \tag{11.5}$$

Following these relations, an acceptance limitation of the scattered electron angle, as due to the beam pipe or focussing magnets, to a maximum value θ_e^{max} defines a constant minimum Q^2 which independently of E_p is given as

$$Q^2_{min}(x, \theta_e^{max}) \simeq [2E_e\cot(\theta_e^{max}/2)]^2. \tag{11.6}$$

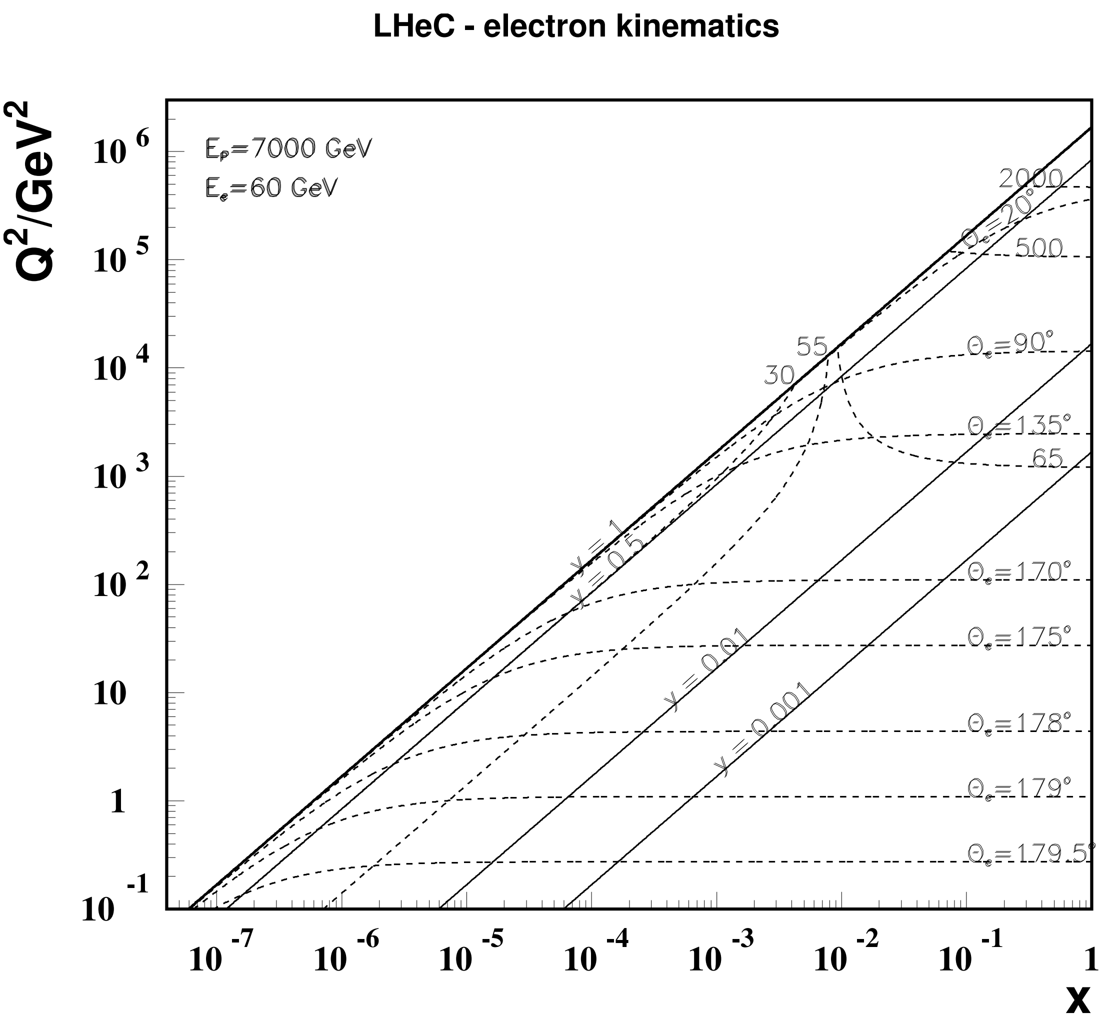


Figure 11.3: Kinematics of electron detection at the LHeC. Lines of constant scattering angle θ_e and energy, in GeV, are drawn. The region of low $Q^2 \lesssim 10^2\,\mathrm{GeV}^2$, comprising the lowest x region, requires to measure electrons scattered backwards with energies not exceeding E_e. At 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 $90 \pm 45°$, 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.

apart from the smallest x. This is illustrated in Fig. 11.3. There follows that a 179°(170°) angular cut corresponds to a minimum Q^2 of about 1 (100) GeV^2 at nominal electron beam energy. One easily recognizes in Fig. 11.3 that the physics at low x and Q^2 requires to measure electrons scattered backwards from about 135° up to 179°. Their energy in this θ_e region does not exceed E_e significantly. At lower x to very good approximation $y = E'_e/E_e$ (as can be seen from the lines $y = 0.5$ and $E'_e = 30$ GeV in Fig. 11.3).

Following Eq. 11.6, Q^2_{min} varies $\propto E_e^2$. It thus is as small as 0.03 GeV^2 for $E_e = 10$ GeV, the injection energy of the ring accelerator but increases to 6.0 GeV^2 for $E_e = 140$ GeV, the maximum electron beam energy considered in this design report, apart from smallest x, if $\theta_e^{max} = 179°$. While Q^2_{min} decreases $\propto E_e^2$, the acceptance loss towards small x is only $\propto E_e$. The measurement of the transition region from hadronic to partonic behavior, from 0.1 to 10 GeV^2, therefore requires to take data at lower electron beam energies[3]. These variations are illustrated in Fig. 11.4 for an electron beam energy of 10 GeV, the injection energy for the ring and a one-pass linac energy, and for the highest E_e of 140 GeV considered in this report.

Electrons scattered forward correspond to scattering at large $Q^2 \geq 10^4$ GeV^2, as is illustrated in the zoomed kinematic region plot Fig. 11.5. The energies in the very forward region, $\theta_e \lesssim 10°$, exceed 1000 GeV. For large E_e and x, Eq. 11.5 simplifies to $Q^2 \simeq 4E_eE'_e$, 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 $Q^2_{max} = s$.

11.1.4 Acceptance regions - hadronic final state

The positions of isolines in the (Q^2, x) plane of constant energy and angle of the hadronic final state, approximated here by the current jet or struck quark direction, are given by the relations:

$$
\begin{aligned}
Q^2(x, E_h) &= sx \cdot \frac{xE_p - E_h}{xE_p - E_e} \\
Q^2\ (x, \theta_h) &= sx \cdot \frac{xE_p}{xE_p + E_e \cot^2(\theta_h/2)}
\end{aligned}
\tag{11.7}
$$

and are illustrated in Fig. 11.6. At low $x \lesssim 10^{-4}$, the hadronic final state is emitted backwards, $\theta_h > 135°$, with energies of a few GeV to a maximum of E_e. Lines at constant y at low x are approximately at $y = 1 - E'_e/E_e$ 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 to the backward region within a few degrees of the beam pipe (Fig. 11.6). This is the high y region in which the longitudinal structure function is measured.

[3]The 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. 11.6 one derives that $E_e = 30$ GeV and 178° is leading to the same Q^2_{min} of about 1.1 GeV^2, at not extremely small x, as is $E_e = 60$ 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 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 looses 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.

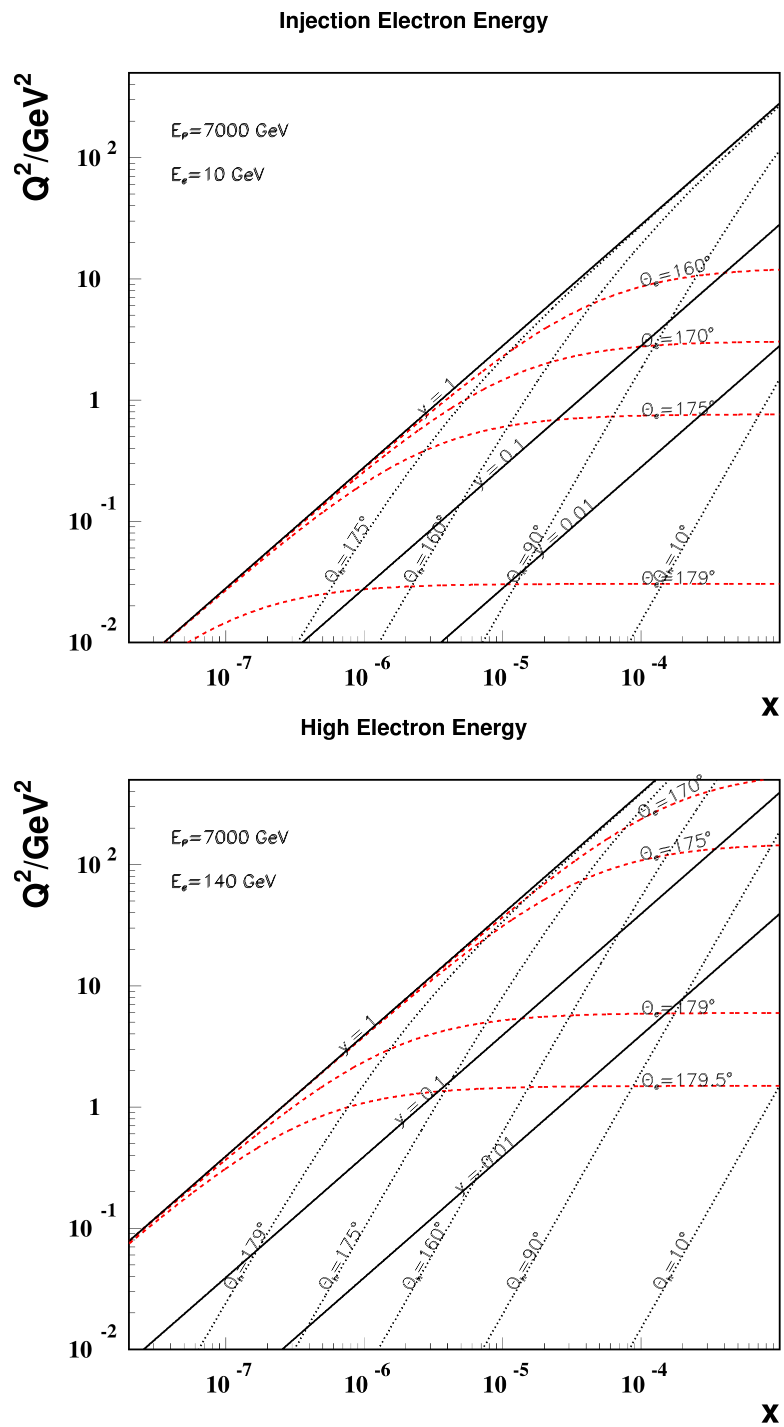


Figure 11.4: Kinematics at low x and Q^2 of electron and hadronic final state detection at the LHeC with an electron beam energy of 10 GeV (top) as compared to 140 GeV (bottom). At larger x, the iso-θ_e lines are at about constant $Q^2 \propto E_e^2$. At low x, the scattered energies, not drawn here, 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.

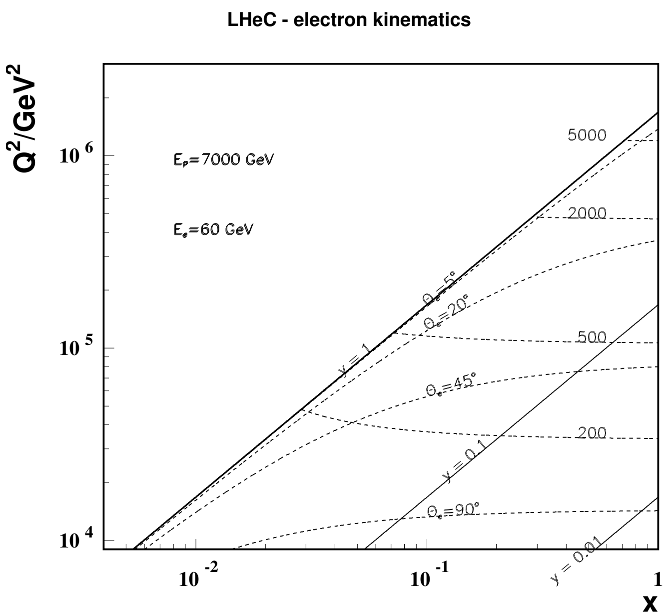


Figure 11.5: Kinematics of electron detection in the forward detector region corresponding to large $Q^2 \geq 10^4\,\text{GeV}^2$. The energy values are given in GeV. At very high Q^2 the iso-E'_e lines are rather independent of x, i.e. $Q^2(x, E'_e) \simeq 4E_eE'_e$.

The x range accessed with the barrel calorimeter region, of θ_h between 135° and 45°, is typically around 10^{-4} and smaller than a decade for each Q^2, as can be seen in Fig. 11.6. The hadronic energies in this part do not exceed typically 200 GeV. The detector part which covers this region is quite large but the requirements are modest. One might even be tempted to consider a two-arm spectrometer only. However, the measurement of missing transverse energy and the importance of using the longitudinal momentum conservation for background and radiative correction reductions, with the $E - p_z$ criterion, demand the detector to be hermetic and complete.

For the measurement of the hadronic final state the forward detector is most demanding. Due to the high luminosity, the large x region will be populated and a unique physics program at large x and high Q^2 may be pursued. In this region the relative systematic error increases like $1/(1-x)$ towards large x, see below. 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 can be derived from Eq. 11.7 and be seen in Fig. 11.6. High x coverage thus demands the registration of up to a few TeV of energy close to the beam pipe, i.e. a dedicated high resolution calorimeter is mandatory for the region below about $5 - 10°$ extending to as small angles as possible. A minimum angle cut $\theta_{h,min}$ in the forward region, the direction of the proton beam, would exclude the large x region from the hadronic final state acceptance (Fig. 11.6), along a line

$$Q^2\ (x, \theta_{h,min}) \simeq [2E_px\tan^2(\theta_{h,min}/2)]^2, \tag{11.8}$$

which is linear in the $\log Q^2$, $\log x$ plot and depends on E_p only. Thus at $E_p = 7\,\text{TeV}$ the minimum Q^2 is roughly $(1000[100]x)^2$ at a minimum angle of 10[1]°. Since the dependence in

LHeC - hadronic final state kinematics

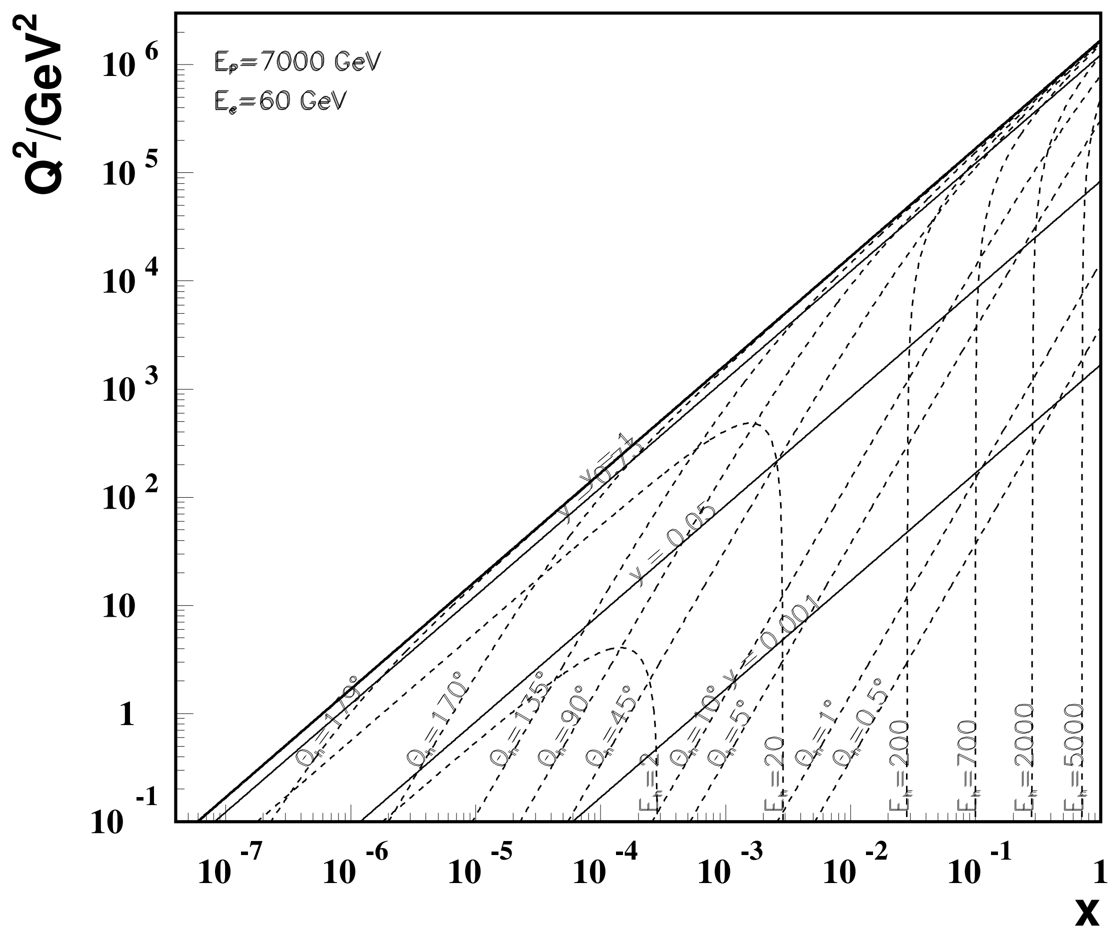


Figure 11.6: Kinematics of hadronic final state detection at the LHeC. Lines of constant energy and angle of the hadronic final state are drawn, as represented by simple kinematics of the struck quark. One easily recognizes that the most demanding region is the large x domain, where very high energetic final state particles are scattered close to the (forward) direction of the proton beam. The barrel region, of about $90 \pm 45°$, 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.

Eq. 11.8 is quadratic with E_p, lowering the proton beam energy is of considerable interest for reaching the highest possible x and overlapping with the large x data of previous experiments or searches for specific phenomena as intrinsic heavy flavour.

11.1.5 Acceptance at the High Energy LHC

Presently one considers to build a high energy (HE) LHC in the thirtees with proton beam energies of 16 TeV [629]. Such an accelerator would better be combined with an electron beam of energy exceeding the 60 GeV, considered as default here, in order to profit from the doubled proton beam energy and to limit the asymmetry of the two beam energies. Choosing the 140 GeV beam mentioned above as an example, Figure 11.7 displays the kinematics and acceptance regions for given scattering angles and energies of the electron (dashed green and red) and of the hadronic final state (black, dotted and dashed dotted). The cms energy in this case is enhanced by about a factor of five. The maximum Q^2 reaches 10 TeV^2, which is 10^6 times higher than the typical momentum transfer squared covered by the pioneering DIS experiment at SLAC. The kinematic constraints in terms of angular acceptance would be similar to the present detector 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 be doubled. With care in the present design, one would probably be able to use the main LHeC detector components also in the HE phase of the LHC.

11.1.6 Energy Resolution and Calibration

The LHeC detector is dedicated to most accurate measurements of the strong and electroweak interaction and to the investigation of new phenomena. The calorimetry therefore requires:

- Optimum scale calibrations, as for the measurement of the strong coupling constant. This is much helped by the redundant kinematic reconstruction and kinematic relations, as $E'_e \simeq E_e$ at low Q^2, $E'_e + E_h \simeq E_e$ at small x, the double angle reconstruction [630] of E'_e and the transverse momentum balance of p_T^e and p_T^h. From the experience with H1 and the much increased statistics it is assumed that E'_e may be calibrated to $0.1 - 0.5\,\%$ and E_h to $1 - 2\,\%$ accuracy. The latter precision will be most crucial in the foward, high x part of the calorimeter because the uncertainties diverge $\propto 1/(1-x)$ towards large x.

- High resolution, for the reconstruction of multi-jet final states as from the $H \to b\bar{b}$ decay. This is a particular challenge for the forward calorimeter. While detailed simulations are still ongoing one may assume that $(10-15)/\sqrt{E/GeV}\,\%$ resolutions for E'_e and $(40-50)/\sqrt{E/GeV}\,\%$ for E_h are appropriate, with small linear terms. These requirements are very similar to the ATLAS detector which quotes electromagnetic resolutions of $10/\sqrt{E/GeV} \oplus 0.007\,\%$ and hadronic energy resolutions of $50/\sqrt{E/GeV} \oplus 0.03\,\%$. The basic electromagnetic calorimeter choice for the LHeC can be for Liquid Argon (LAr) [4]. The hadronic calorimeter is outside the magnets and serving also for the magnetic flux return may be built as a tile calorimeter with the additional advantage of supporting the whole detector. The first year of operating the ATLAS combined LAr/TileCal calorimeter has been encouraging. Some special calorimeters are needed in the small angle forward

[4] In 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. 11.4.

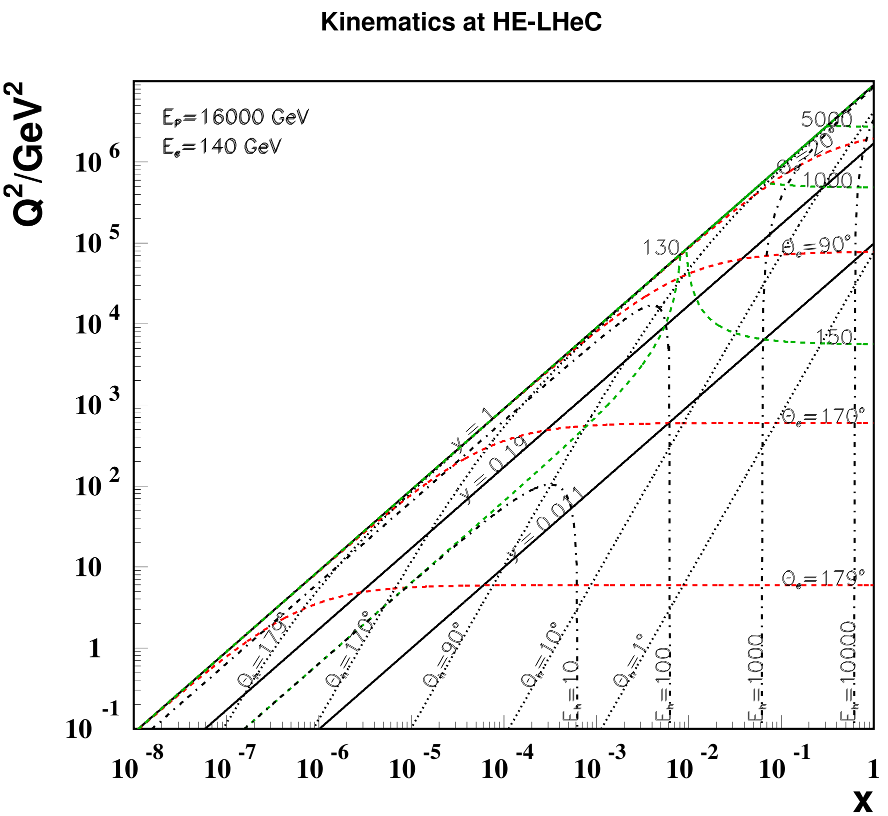


Figure 11.7: Scattered electron and hadronic final state kinematics for the HE-LHC at $E_p = 16\,\text{TeV}$ coupled with a 140 GeV electron beam. Lines of constant scattering angles and energies are plotted. The line $y = 0.011$ defines the edge of the HERA kinematics and $y = 0.19$ defines the edge of the default machine considered in this report ($E_e = 60\,\text{GeV}$ and $E_p = 7\,\text{TeV}$).

region ($\theta \lesssim 5°$) where the deposited energies are extremely large, and also in the backward region ($\theta \geq 135°$) where the electron detection of modest energy is a special task.

- 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.

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. 11.1.

11.1.7 Tracking Requirements

The tracking detector has to enable

region of detector	backward	barrel	forward
approximate angular range / degrees	179 - 135	135 -45	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 11.1: Summary of calorimeter kinematics and requirements for the default design energies of $60 \times 7000\,\mathrm{GeV}^2$, see text. The forward (backward) calorimetry has to extend to $1^\circ (179^\circ)$.

- 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

The transverse momentum resolution in a solenoidal field can be approximated by

$$\frac{\delta p_T}{p_T^2} = \frac{\Delta}{0.3BL^2} \cdot \sqrt{\frac{720}{N+4}} \tag{11.9}$$

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 [631]. As an example, for $B = 3.5\,\mathrm{T}$, $\Delta = 10\,\mu\mathrm{m}$, $N = 4 + 5$ and $L = 0.42\,\mathrm{m}$ one obtains a transverse momentum measurement accuracy of about $3 \cdot 10^{-4}$. A simulation, using the LICTOY program [632], of the transverse momentum, transverse impact parameter and polar angle resolutions is shown in Fig. 11.8. One can see that the estimate following Eq. 11.9 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 HERA and the goal of high precision vertex tagging. One finds that the impact parameter resolution, for high momenta, is a factor of eight improved over the H1 or ZEUS result.

In backward direction, a main tracking task is to determine the charge of the scattered electron or 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 spot as accurate as about $10 \times 30\,\mu\mathrm{m}^2$ and the beam pipe radius

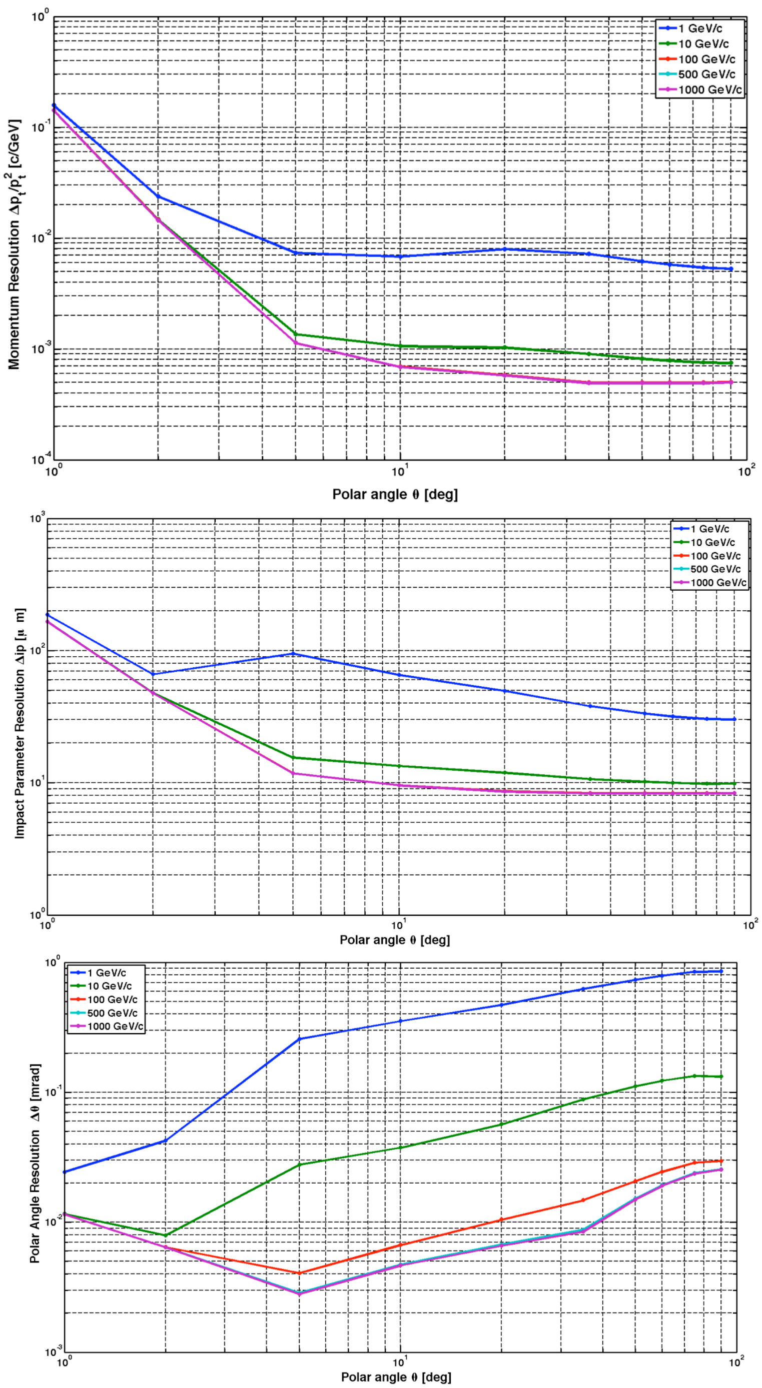


Figure 11.8: Transverse momentum (top), impact parameter (middle) and polar angle (bottom) measurement resolutions as function of the polar angle for the default detector design for four values of track transverse momentum.

of a few cm only, the backward Silicon strip tracker will allow a precise E/p determination when combined with the backward calorimeter, even better than has been achieved with the H1 backward silicon detector [32].

In the forward region, $\theta < 5^{\circ}$, as may be deduced from Figs. 11.5, 11.6, the hadronic final state, for all Q^2, and the scattered electron, when scattered "back" at high Q^2, are very energetic. This requires a dedicated calorimeter. Depending on the track path and momentum, the track sagitta becomes very small, for example about $10\,\mu$m for a 1 TeV track momentum and a 1 m track length. In such extreme cases of high momenta, the functionality of the tracker will be difficult to achieve: the sagitta becoming small means that there will be limits to the transverse momentum measurement while the ability to distinguish photons and electrons will be compromised by the high probability of showering and conversion when the pipe is passed under very small angles. A forward tracker yet is considered to be useful down to small angles for the reconstruction of the event structure, the rejection of beam induced background and the reconstruction of forward going muons. This region requires detailed simulation studies in a next phase of the project.

11.1.8 Particle Identification Requirements

The requirements on the identification of particles focus on the identification of the scattered electron, a reliable missing energy measurement and precision tracking for measuring the decay of charm and beauty particles, the latter rather on a statistical basis than individually. Classic measurements as the identification of the D meson from the $K\pi\pi$ decay with a slow pion or the identification of B production from high p_T leptons require a very precise track detector. The tracker should determine some dE/dX properties but there is no attempt to distinguish strange particles, as kaons from pions, as the measurement of the strange quark distribution is traced back to charm tagging in CC events. The identification of muons, apart from some focus on the forward and backward direction, is similar to that of pp detectors. In addition a number of taggers is foreseen to tag

- electrons scattered near the beam pipe in backward direction to access low Q^2 events and control the photoproduction background;
- photons scattered near the beam pipe in backward direction to measure the luminosity from Bethe Heitler scattering;
- protons scattered in forward direction to measure diffractive DIS in ep scattering and to tag the spectator proton in en scattering in electron-deuteron runs;
- neutrons scattered in forward direction to measure pion exchange in ep scattering and to tag the spectator neutron in ep scattering in electron-deuteron runs;
- deuterons scattered in forward direction in order to discover diffraction in lepton-nucleus scattering.

From the perspective of particle identification therefore no unusual requirements are derived. One needs a state of the art tracker with a very challenging forward part and a tagger system with the deuteron as a new component in forward direction.

11.1.9 Summary of the Requirements on the LHeC Detector

The above considerations along with the constraints from machine operation and the physics program can be summarized in the following detector requirements.

1. The LHeC experiment has to be operated in parallel to the other LHC experiments and has to be set up in accordance to CERN regulations.

2. The detector realization requires a modular design and construction with the assembly process done in parallel partly at surface level and partly in the experimental area following the LHC machine running and maintenance periods.

3. The beam pipe will host the electron beam along with the two LHC counter rotating proton beams. The non interacting proton/ion beam has to bypass the IP region guided through the same beam pipe housing the electron and interacting proton/ion beam (see chapter **??**).

4. The detector should be modular and flexible to accommodate the high acceptance as well as the high luminosity running foreseen for the two main physics programs. The flexibility should accommodate reducing/enhancing the energy asymmetry of the beams - chapter 12.4.

5. The detector design can profit from the experience at HERA and the LHC and will be based on the recent detector developments in order to meet the ambitious physics requirements, summarized in previous chapter, using settled technology, avoiding extended R&D programs and being of comparatively reasonable cost.

6. Mechanics/services have to be optimized minimizing the amount of material in sensitive regions of the experimental setup.

7. The detector has to be operated in a high luminosity environment L. High $\bar{L}$ is anticipated with small 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 the other hand β^* has to be chosen to eliminate effects of parasitic bunch crossings. The machine and detector requirements near the IP is an optimization problem.

8. The detector must experience acceptable backgrounds. The design has to be background insensitive as far as possible and the machine has to incorporate masks, shielding's and an appropriate optics design that minimizes background sources and a vacuum profile that reduces backgrounds.

9. It might be necessary to have insertable/removable shielding protecting the detector against injection and poor machine performance.

10. Special Interaction Region (IR) instrumentation for tuning of the machine with respect to background and luminosity is needed. Radiation detectors e.g. near mask and tight apertures are useful for fast identification of background sources. Fast bunch related informations are useful for beam optimization in that context.

11. Good vertex resolution for decay particle secondary vertex tagging is required, which implies a small radius and thin beam pipe optimized in view of synchrotron radiation and background production - see section 10.6.

12. The detector will have one solenoid in its default version building a homogenous field in the tracking area of 3.5 T extending over $z = +370cm, -200cm$. Solenoid options are described in section 12.3.

13. The tracking and calorimetry in the forward and backward direction has to be set up such that the extreme asymmetry of the production kinematics are taken into account by layout and choice of technology for the detector design and ensure high efficiency measurements. The detectors have to be radiation hard.

14. Very forward/backward detectors have to be set up to access the diffractive produced events and measuring the luminosity with high precision, respectively - section **??**.

Chapter 12

Central Detector

12.1 Basic Detector Description

Following the considerations of the physics requirements and the technical and operational constraints outlined above, 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 noteable 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].

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. 12.1, or not, in the Ring-Ring case, Fig. 12.2. The hadron calorimeter is enclosed in a muon tracker system, not shown here but discussed below. 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

[1] The very recent optics design results suggest that there is only a factor of two difference between the luminosity achieveable with and without the quadrupoles. That is not enough to justify considering two measurement phases, in particular having in mind that such a transisition, 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.

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, approximately with its radius which in absolute allows some ten millions CHF to be economised, with the solenoid placed inside the hadronic calorimeter [2]. 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 comparing the Linac-Ring Fig. 12.1 with the Ring-Ring Fig. 12.2.

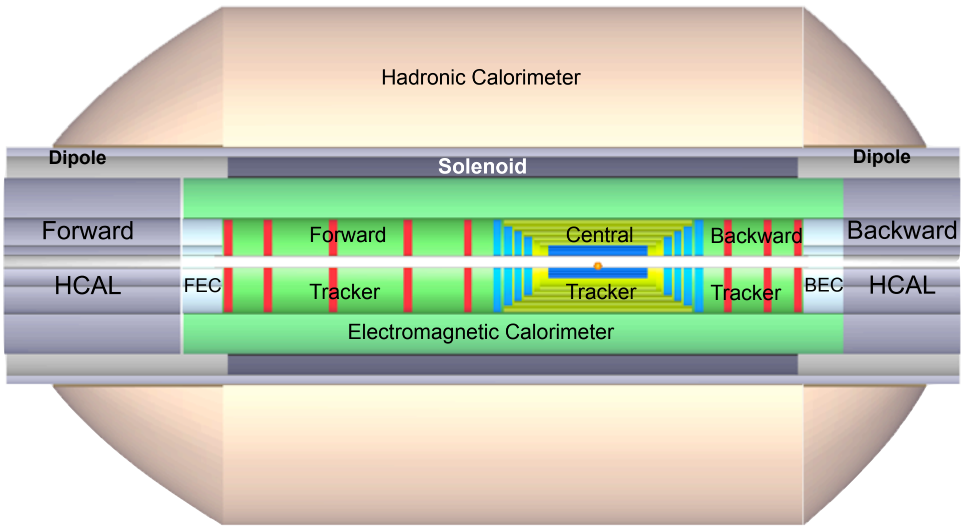


Figure 12.1: Schematic rz view of the detector design for the Linear-Ring machine option showing the characteristic dipole and solenoid placement between the electromagnetic and the hadronic calorimeters. The proton beam, from the right, collides with the electron beam, from the left, at the IP which 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.

The Ring-Ring configuration possibly requires separate data taking phases with maximum polar angle acceptance, for physics at low and high x, and with ultimate luminosity, for electroweak physics and the search for rare phenomena. Correspondingly, the LHeC inner detector is designed here with a modular structure as is illustrated in Figs. 12.3 and 12.4 which show the detector without and with the low β quadrupoles inserted to accomodate for either configuration, respectively. This requires the removal of the forward/backward tracking setup (shown in red in Fig. 12.3) and the subsequent reinstallation of the external forward/backward electromagnetic and hadronic calorimeter plugins near to the vertex. The high luminosity apparatus would have a polar angle acceptance coverage of about 8°-172° for an estimated gain in lumi-

[2] Since for the physics performance it is evidently advantageous to place the solenoid outside the hadronic calorimeter, this option, termed B, has also been studied and is discussed below. The radius of the large coil would be about 2.5 m which still compares well with for example the H1 and the CMS coils.

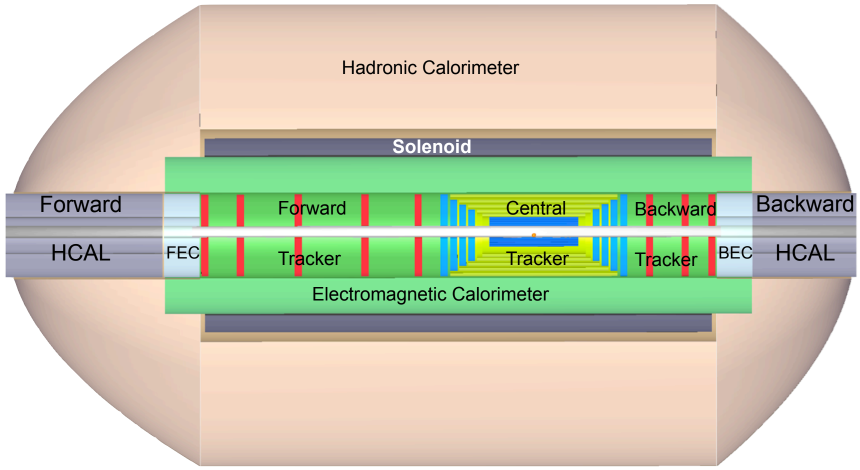


Figure 12.2: Schematic rz view of the detector design for the Ring-Ring machine option. Note that the outer part of the forward and backward calorimeters ends at smaller radii, as compared to the Linac-Ring case, since there are no dipole magnets foreseen.

nosity of slightly higher than a factor of two with respect to the large acceptance configuration.

The Ring-Ring and Linac-Ring detectors also differ due to the different optics and the beam pipe geometry.

In the Ring-Ring design the e and p/A beams collide with a small non-zero crossing angle, large enough to avoid parasitic crossings, which for a 25 ns bunch crossing occur at ± 3.75 m from the IP. Additional masks are used to shield the inner part of the detector from synchrotron radiation generated upstream of the detector.

For the Linac-Ring design, the dipole field in the detector area which allow for head-on collisions and provide the required separation, produces additional synchrotron radiation which has to pass through the interaction region requiring a larger beampipe. This difference results in a factor of two wider extension of the horizontal beam pipe in the outer region in the Linac-Ring case, which in this regard is the unfavourable solution. The radius of the circular part has been chosen according to tentative choices of the LHC upgrade beam pipe dimensions.

According to a first estimate of the synchrotron radiation and an initial placement of masks, shielding the Ring-Ring detector from direct and backscattered photons, the beam pipe geometries have been chosen as shown in Fig. 12.5 for the Ring-Ring case and in Fig. 12.6 for the Linac-Ring case.

As already mentioned, the necessity to register particle production down to 1 and 179° poses severe constraints on the material and the thickness of the pipe. In the design as shown here, a beryllum pipe would have 3.0 (1.5) mm thickness in the Linac-Ring (Ring-Ring) case. An extensive R&D program is needed aiming for higher stability of the beam pipe at given dimensions and for thinner/lighter beam wall construction resulting in higher transparency for all final state particles. This R&D program is necessary regardless of which machine option for the LHeC facility is selected. It may also turn out to be advantageous to use a trumpet shaped beampipe when this problem gets revisited in a more advanced phase of the LHeC design when

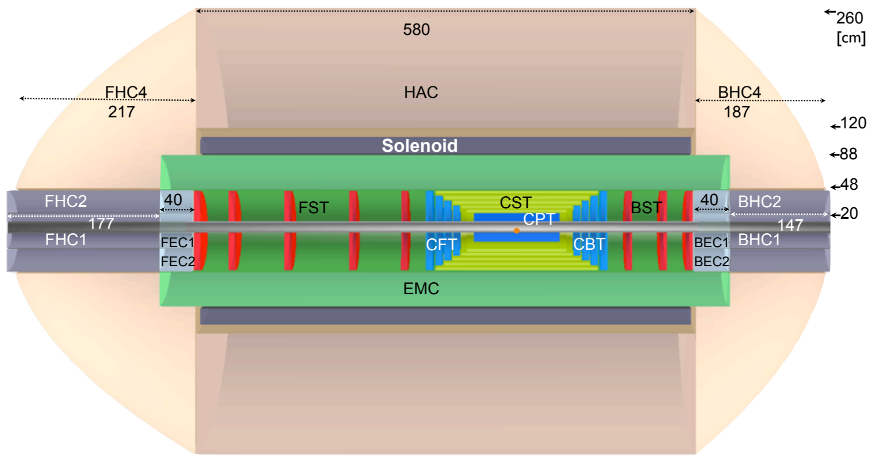


Figure 12.3: An rz cross section and dimensions of the main detector (muon detector not shown) for the Ring-Ring detector version (no dipoles) extending the polar angle acceptance to about 1° in forward and 179° in backward direction.

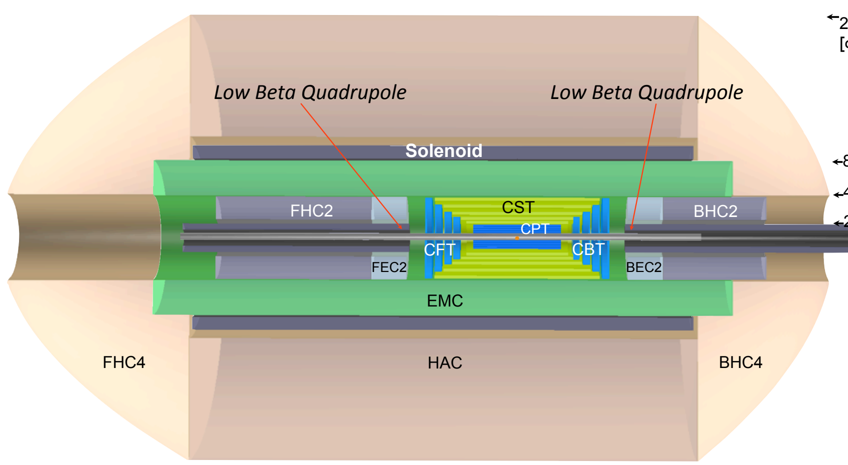


Figure 12.4: An rz cross section and dimensions of the main detector (muon detector not shown) for the Ring-Ring detector version (no dipoles) in which the luminosity is maximised by replacing the forward and backward tracker telescopes by focusing, low β quadrupole magnets at $\pm$ 1.2 m away from the nominal interaction point. The polar angle acceptance is thus reduced to about $8 - 172^\circ$. As compared to the high acceptance detector (Fig. 12.3), the outer foward/backward calorimeter inserts have been moved nearer to the interaction point.

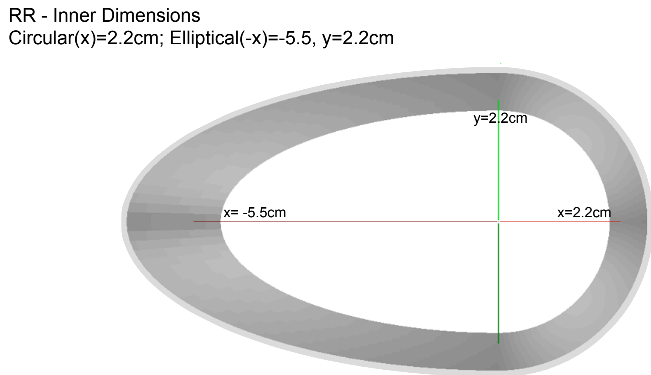


Figure 12.5: Perspective drawing of the beam pipe and its dimensions in the ring-ring configuration. The dimensions consider a 1 cm safety margin around the synchrotron radiation envelope with masks (not shown) for primary synchrotron radiation suppression placed at $z = 6,\ 5,\ 4\,\mathrm{m}$.

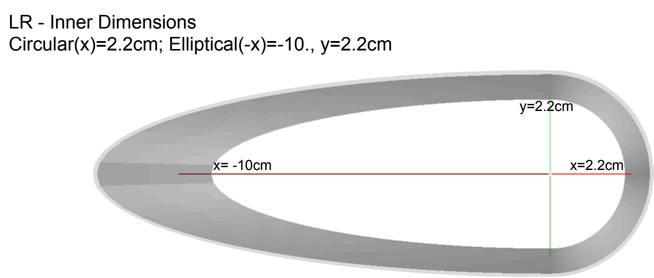


Figure 12.6: Perspective drawing of the beam pipe and its dimensions in the linac-ring configuration. The dimensions consider a 1 cm safety margin around the synchrotron radiation envelope.

more detailed simulations will be available and results of pipe material developments become known.

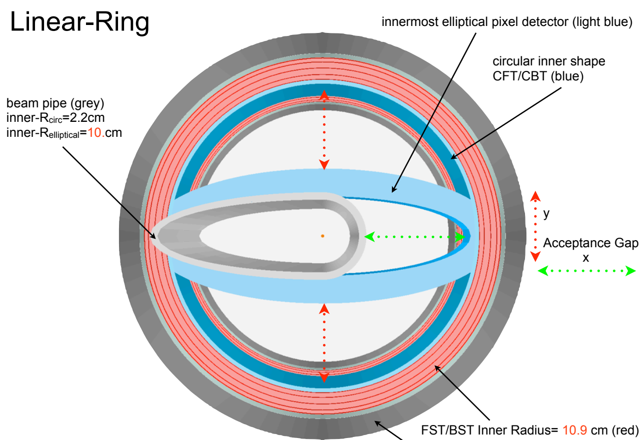


Figure 12.7: Linac-Ring beam pipe design and acceptance gap's due to deviations of inner shapes of the forward/backward tracking detectors FST/BST (circular) and the innermost central pixel detector layer (elliptical) from the pipe shape.

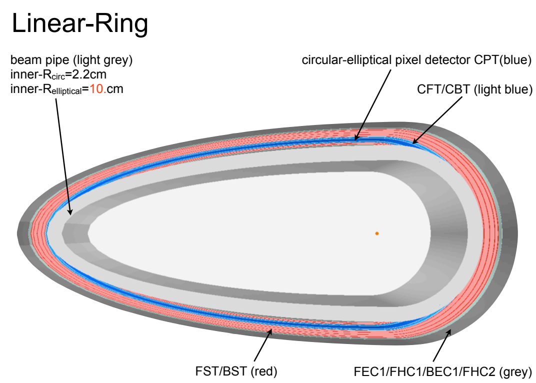


Figure 12.8: Beam pipe design for Linac-Ring and optimized circular-elliptical shape following the beam pipe for all adjacent detector parts.

In order to ensure optimal polar angle acceptance coverage, the innermost subdetector dimensions have to be adapted to the beam pipe shape. Fig. 12.7 illustrates the disposition that a circular silicon tracker would imply and the corresponding acceptance losses. These can be reduced as is shown in Fig. 12.8 if the detector acceptance follows as close as possible the elliptic-circular shape of the pipe. Electrons scattered at high polar angle, corresponding to small $Q^2 \sim 1\,\mathrm{GeV}^2$, will only be registered in the inner part of the azimuthal angle region for the nominal electron beam energy. As had been shown above, the lowering of the electron beam energy effectively reduces the strong requirement of measuring up to about 179°, at the expense however, of a somehwat reduced acceptance towards lowest Bjorken x.

The optimum configuration of the inner detector will be revisited when the choice between the Linac-Ring and the Ring-Ring option is made. It represents in any case one of the most challenging problems to be solved for the LHeC.

12.2 Baseline Detector Layout

The baseline configuration (A) of the main detector has the solenoid in between the two calorimeters, combined with a dipole field in the Linac-Ring case. It is subdivided into a central barrel and the forward and backward end-cap regions, which differ in their design because the forward region sees the remnant and the highly energetic ($E_h \lesssim E_p$) jet from the struck quark while the backward region sees the scattered electron of energy $E_e' \leq E_e$. The detector configuration is sketched in Fig. 12.9 with component abbreviations and some dimensions given. More detailed dimensions are given in Fig. 12.10.

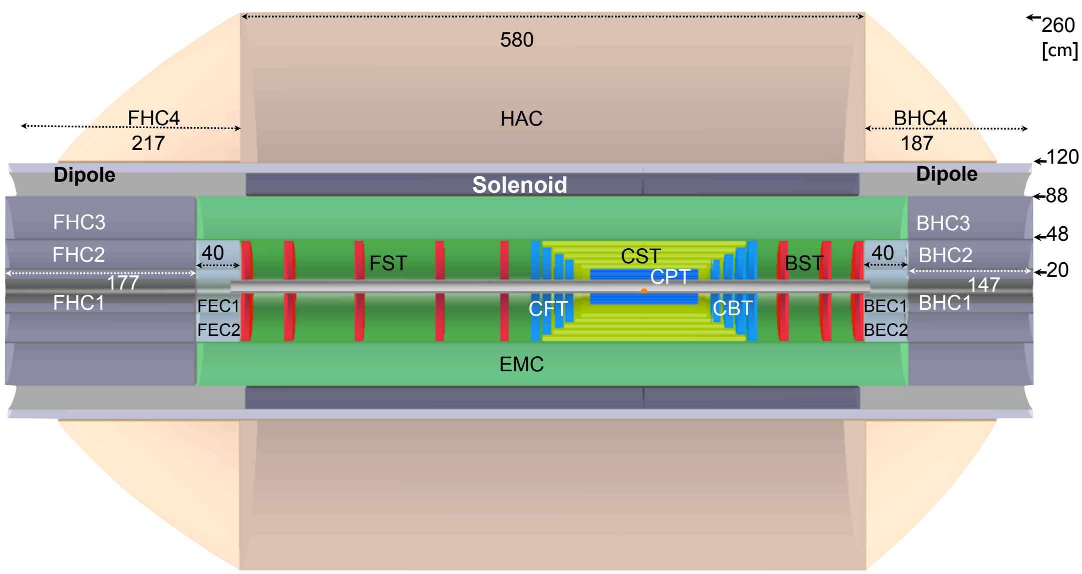


Figure 12.9: An rz cross section of the LHeC detector, in its baseline configuration (A). In the central barrel, the following components are considered: a central Silicon pixel detector (CPT); silicon tracking detectors (CST,CFT/CBT) of different technology; an electromagnetic calorimeter (EMC) surrounded 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).

For the purpose of this design, technologies had to be chosen in line with the detector requirements, see Sect. **??**, and based on an evaluation of the technologies available or under development for the LHC experiments or foreseen for a linear collider detector. The complete inner tracker is considered to be made of Silicon. This enables to keep the radius of the

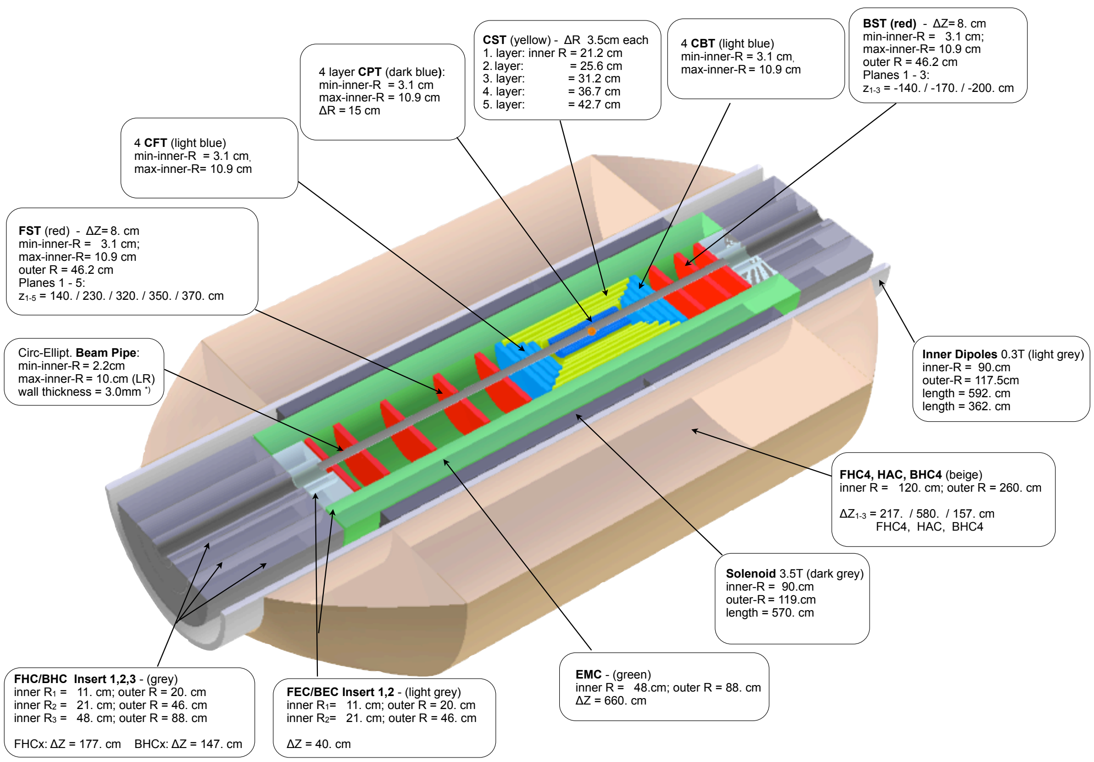


Figure 12.10: View of the baseline detector configuration (A) with some dimensions for each of the main detector components.

magnets small, at about 1 m. Based on experience with H1 and ATLAS the EMC is chosen to be a Liquid Argon (LAr) Calorimeter. The super conducting dipoles (light grey in Fig. 12.9) are placed in a common cryostat with the detector solenoid (dark grey) and the LAr EMC (green). The common cryostat is optimum for reducing the amount of material present in front of the hadronic barrel calorimeter. The HAC is an iron-scintillator tile calorimeter, which also guides the return flux of the magnetic field , as in ATLAS [633, 634]. In the baseline design (A) the muon detectors are placed outside of the magnetic field with the function of tagging muons, the momentum of which is determined by the inner tracker.

For the Ring-Ring machine, in order to maximize the luminosity, extra focusing magnets must be placed near to the interaction point [3]. This would mean replacing the FST and the BST tracking detectors by the low-β quadrupoles (see Fig. 12.4), at the expense of losing about 8° of polar angle acceptance. The modular design of the forward and backward trackers and the corresponding calorimeter modules allow the trackers to be mounted/unmounted and the calorimeter inserts to be moved in and out of position as required. The inner electromagnetic and hadronic endcap inserts, FEC1/BEC1 and FHC1/BHC1, respectively, will be removed allowing the insertion of the low β-magnets and only partially put back in. Particular attention is needed for the mechanical support structures of the quadrupoles. The structure must ensure the stability of reproducible beam steering, while interfering as little as possible with the detector. The presence of strong focussing magnets close to the interaction point was one issue experienced during HERA2 running [635].

12.2.1 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 [HERMANN??], 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. 12.11. A two solenoid configuration is the 4^{th} Concept for an ILC Detector [627]. The second outer solenoid keeps the overall dimensions of the detector limited. A detailed consideration of option B has not been intended

[3] See above for an evaluation of that possibility.

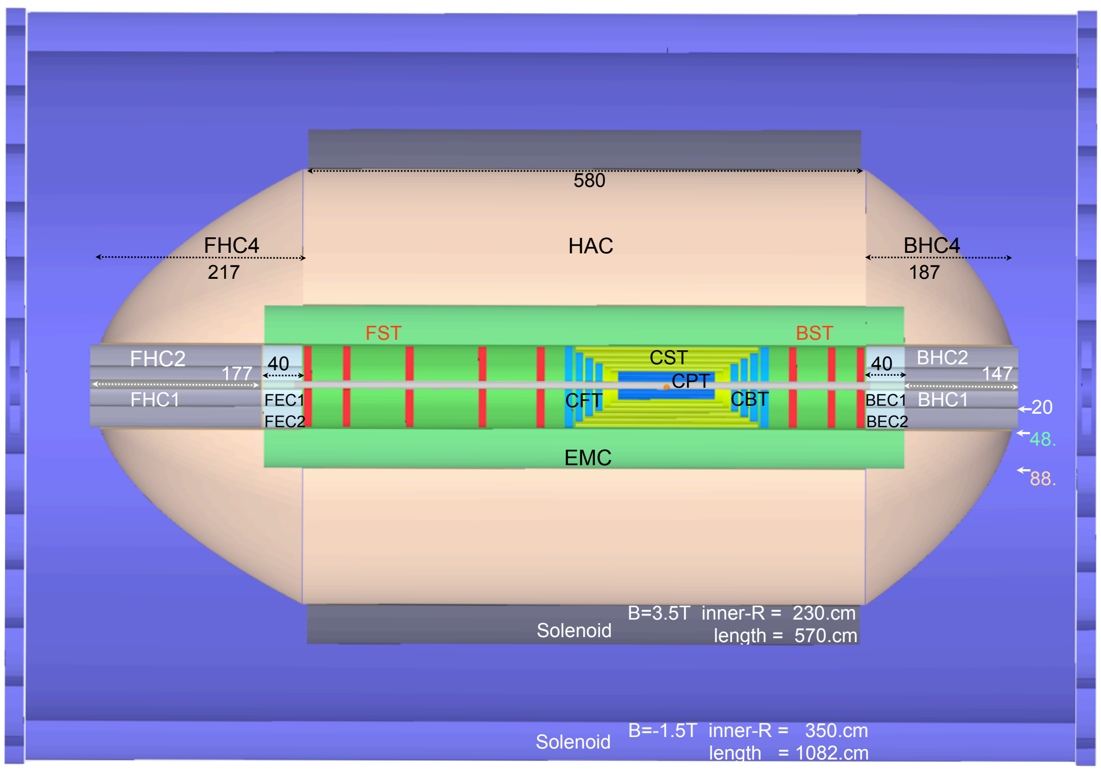


Figure 12.11: An rz cross section of the LHeC detector, option B, in which the solenoid is placed outside the HAC. A compensating larger solenoid is considered, see text. The muon detector is not shown but would be placed inside the second solenoid. The overall dimensions of this detector configuration are about 10 m length and 8 m diameter.

at this stage of the project.

12.3 Magnet Design

Option	Solenoid	Dipole	Cryostat(s)
	$B =$ $3.5T$	$B =$ $0.3T$	
	Length $= 570cm$	$L_{+z} = 600cm$, $L_{-z} = 370cm$	Length = 1020 cm
A	$R_{min} =$ $90cm$	R_{min} $=$ $90cm$ $R_{out_{Cryostat}}$ $=$ $117.5cm$	EMC, Solenoid, Dipoles $R_{in} = 48cm$, $R_{out} = 117.5cm$
B	$R^1_{min} =$ $230cm$	$\Delta R_{Cryo-Sol_{out}} -$ not defined	1^{st}-Solenoid 2^{nd}-Solenoid

Table 12.1: Magnet dimensions and characteristics of the two options A and B (no dipoles in case of Ring-Ring machine and in case B).

The main properties of the different magnet designs are summarized in Tabl. 12.1. Text beeing written by H.T.Kate, A.Dudarev - describing design properties etc.

12.4 Tracking Detector

12.4.1 Tracking Detectors Layout - Baseline Detector

The tracking detectors (Fig. 12.13) inside the electromagnetic calorimeter are Si-sensor only devices. The tracker system has to provide precise tracking, momentum determination as far as possible, vertex reconstruction and pattern recognition. It covers the pseudorapidity range $-4.8 < \eta < 5.5$ and is located inside the solenoidal field of 3.5T. Additionally a dipole field of 0.3T is superposed resulting from the beam steering dipoles housed inside the same cryostat as the solenoid. For 1° tracks the bending solenoidal field component (0.36T) is of the same order as the dipole field and the resulting track Sagitta reaches the [mm] range when particles of momentum $< 100GeV$ pass 250cm (track length measured) Fig. 12.13. The tracker described here (FST) measure 1° tracks over a distance of ≈180cm (forward direction). Therefore a momentum determination for $\approx 1^\circ$ and high momentum tracks is unlikely but with precision tracking the analysis will rely on the tagged energy measurement. The backward measurement is characterised by even shorter track length's. There the analysis will rely on the energy measurement in calorimeters combined with a well defined track definition. That approach is supported by the fact that the particle flux in backward compared to forward direction is lower due to kinematics. The well separated charged tracks in backward direction are usually easier to measure and will allow the precision tagging of corresponding calorimeter signals. Very low Q^2/low x processes will be better accessible by reducing the electron beam energy thus

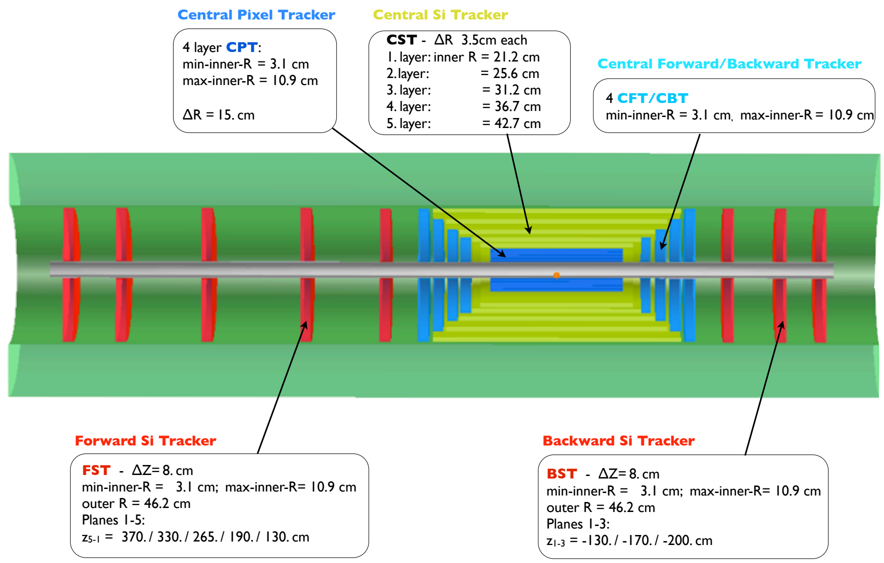


Figure 12.12: Tracker and barrel Electromagnetic-Calorimeter rz view of the baseline detector (Linac-Ring case).

measured at larger angles in backward direction (see Fig. 11.3 and Fig. 11.4 and discussion in chapter **??**).

The tracker is subdivided into central (CPT, CST, CFT/CBT) and forward/backward parts (FST, BST). Fig. 12.13 shows the tracker configuration for the high acceptance running of solution (A) of the detector design. More details are summarized in Tab. 12.2 [4] .

Acceptance coverage down to 1°and 179°, respectively, and the tagging of secondary vertices originating from the decay of heavy particles over a wide range of $|\eta|$ are requirements vital for the physics program for the LHeC experiment. Measuring close to the beam line for maximal polar angle coverage and to the vertex are major requests. The shape of the CPT and the inner dimensions of all near-beam detectors have been chosen accordingly (Fig. 12.14 show the xy view of the circular-elliptical CPT and the cylindrical CST detectors).

The *All-Silicon* based tracking devices allow high resolution track space points measurement and hence sufficient pattern recognition even at both angle acceptance limits in forward and in backward direction, respectively. The expected jet angular and energy distribution for some selected physics processes simulated using *RAPGAP* (Ref. [115]) is shown in Fig. 12.15. That figures illustrate once again the importance of the forward acceptance down to 1°.

Some results of preliminary tracker performance simulations using the LicToy-2.0 program [632] for the tracker setup (see table 12.2 and Fig. 12.16), are summarized in Fig. 12.17. The geometrical arrangement of the tracking detectors together with the pre-defined resolution

[4]The item *project area* in table 12.2 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. [636], [637], [638])

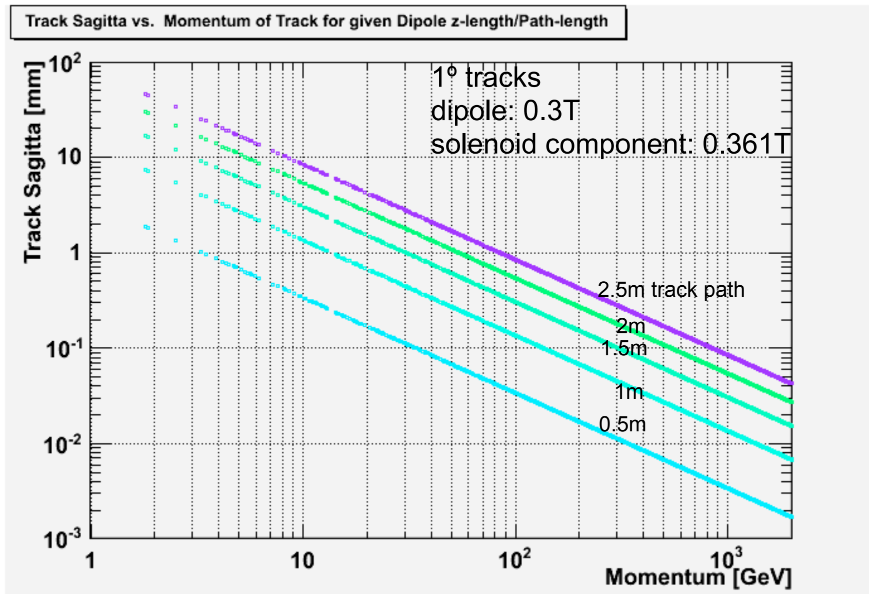


Figure 12.13: Track Sagitta vs. Momentum of 1°tracks in a superposed dipole/solenoidal field.

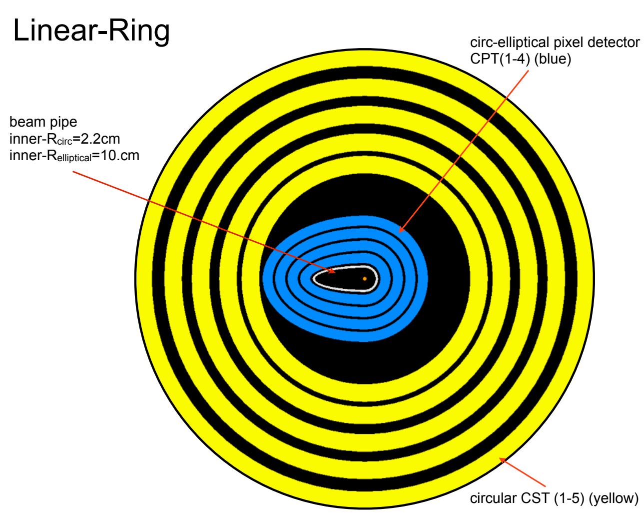


Figure 12.14: XY cut away view of the Central Pixel (CPT) and Central Strixel Tracker (CST) (Linac-Ring layout).

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 $\theta[^\circ]$	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 $\theta[^\circ]$	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 $\theta[^\circ]$	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 12.2: Summary of tracker dimensions.
The 4 Si-Pixel-Layers CPT1-CPT4 (resolution of $\sigma_{\text{pix}} \approx 8\mu m$) positioned as close to the beam pipe as possible.
Si-strixel (CST1-CST5) (resolution of $\sigma_{\text{strixel}} \approx 12\mu m$) forming the central barrel layers. An alternative is the of 2_in_1 single sided Si-strip solution for these barrel cylinders ($\sigma_{\text{strip}} \approx 15\mu m$) (Ref. [639]).
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 ($\sigma_{\text{strip}} \approx 15\mu m$). They have to be removed in case of high luminosity running for the Ring-Ring option of the accelerator configuration see Fig. 12.4.

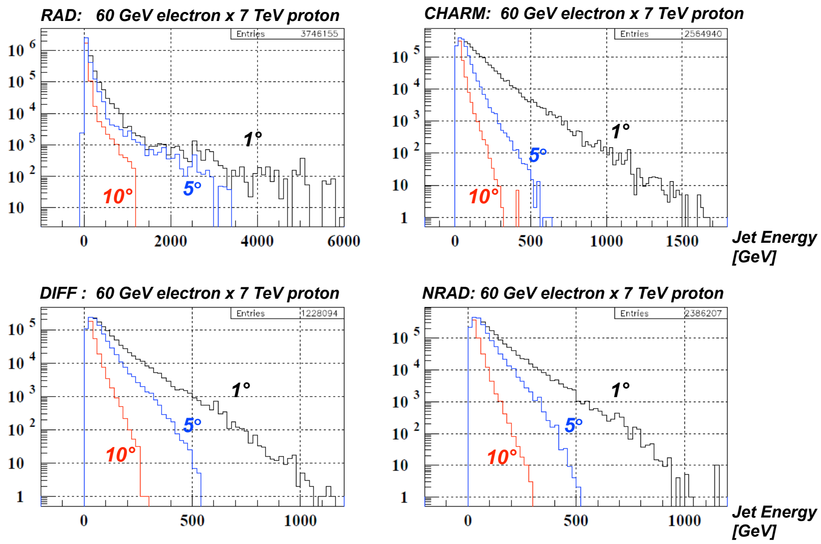


Figure 12.15: Radiative, diffractive, charm and non-radiative Jet production for polar angle $\theta = 1°$, $5°$ and $10°$.

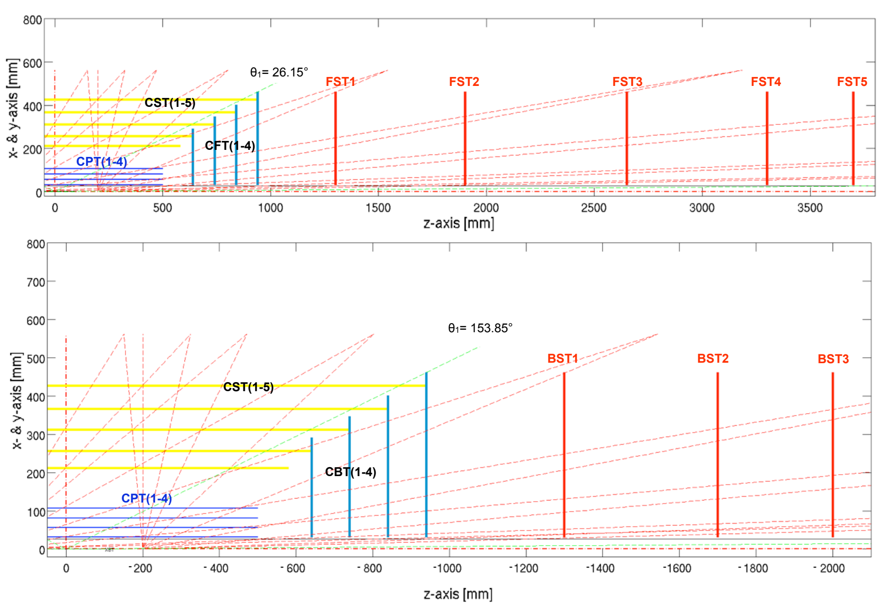


Figure 12.16: LicToy2.0 tracker design of the central/forward FST(top) and central/backward direction BST(bottom).

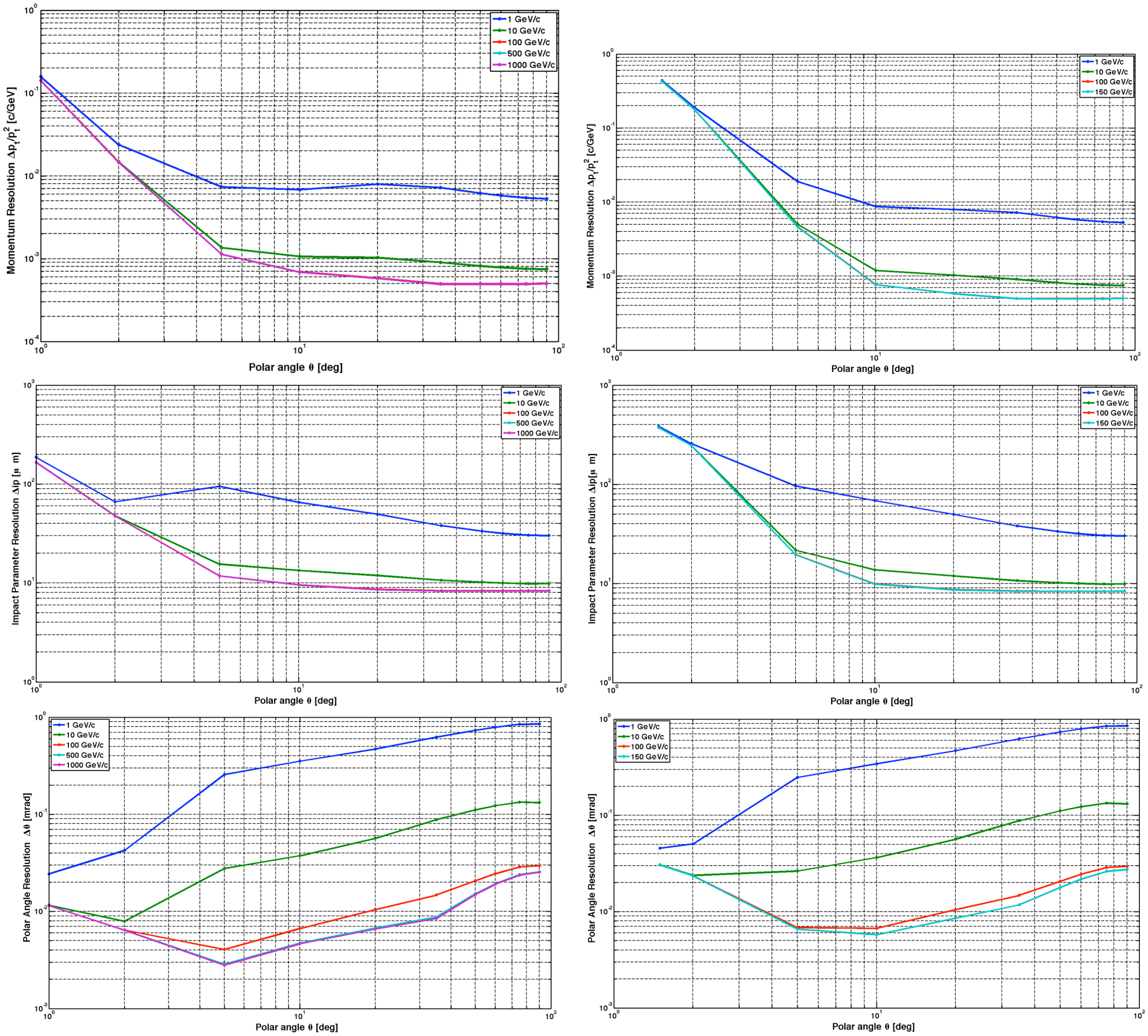


Figure 12.17: Scaled momentum, impact parameter and polar angle resolution as function of polar angle θ resulting from tracker design simulation using LiCToy2 for the FST(left) and BST(right) side. Tracker setup used as shown in Fig. 12.16,
Basic parameters:
B=3.5T, $X/X_0^{\text{beampipe}} = 0.002$, $X/X_0^{\text{det-parts}} = 0.005$, efficiency=0.99%, Resolutions(σ): $\sigma_{\text{CPT}} = 8\mu m$, $\sigma_{\text{CST,CFT,CBT}} = 12\mu m$, $\sigma_{\text{FST,BST}} = 15\mu m$, minimal inner radius $R_{\text{min}}^{\text{CPT,CFT,CBT,FST,BST}} = 3.15cm$.

settings for those parts, perform as expected at least within that simplified framework.

12.4.2 Tracking Detector Design Criteria and possible Solutions

The experience of former attempts for an optimal detector setup suggest that some criteria should be discussed as early as possible.
Some arguments for the design will predominantly be (see Ref. [640], [641]):

- Optimizing of cost for all components. Making use of technology developments for HL-LHC/ILC experiments (Ref. [642], [643], [644], [645], [646], [647], [648], [649], [650], [651], [652], [653], [654], [655]) but rely on technologies available today because of time constraints. Todays accessible sensors, integrated electronics , readout/trigger circuitry, mechanics, cooling etc. have to be used to meet the goal: installation in the 2020's.

- The default tracker setup is based on the silicon microstrip detector technology developed for the big experiments at LHC, ILC, TEVATRON, b-factories, etc. within the last 20 years. The decisions for sensor types (pixel, strixel, strip) operation depend on many factors and will be taken according to its functionality finally:

  The expected radiation load is defined and influenced by the interaction rate (25ns), luminosity ($\approx 10^{33} cm^{-2} s^{-1}$), particle rate per angle intervall, fluence n_{eq} and ionisation dose over 1 years running. Some data will be better defined after evaluation of more detailed simulations. Specifically the radiation impact on tracker wheels, calorimeter inserts and inner pixel-barrel layer has to be studied. The tools for those simulations are being prepared. Very first estimates will be discussed in section 12.5 in more detail, but no indication for extremely high radiation load into the detectors adjacent to the beam pipe have been obtained so far. The expected levels are far below what the LHC experiments have to sustain.

  A side remark is related to the active parts of the forward/backward calorimeter. For safety reasons those calorimeter inserts should be equipped with radiation hard Si-based sensors according to LHC/HL-LHC standards. Relatively small in volume but still large in terms of layer area (m^2), the equipment of calo-inserts Si-strip/Si-pad based is a sizeable investment but might be needed for safety reasons. A final decision will be possible after more cross checks (some FLUKA simulations are pending). [5]

  Decisions have to define the trigger capabilities/options, here in the context of tracking only, which have a direct impact on sensor choice, arrangement and attached electronics. It might be that very recent developments of 3D integration semiconductor layers interconnected to form monolithic unities of sensor&electronic circuitry are in time for the installation in the 2020's but conventional wire bonded or bump bonded solutions may be more cost efficient and rely on components available today. E.g. using the 2_in_1 strip sensor design as p_t-trigger discussed by the CMS upgrade design group Fig. 12.18, Refs. [639] will have, e.g., direct impact on a muon-trigger definition. The sensor, hybrid and readout modules are available and interconnected by wire bonds. On the other hand the 2_in_1 sensor design is a very elegant way saving resources when setting up a tracker (CMS design Fig. 12.19, Refs. [639]).

[5] On physics event generation level appropriate instruments are missing or of limited use; e.g. ep interactions are not incorporated into PYTHIA8 currently

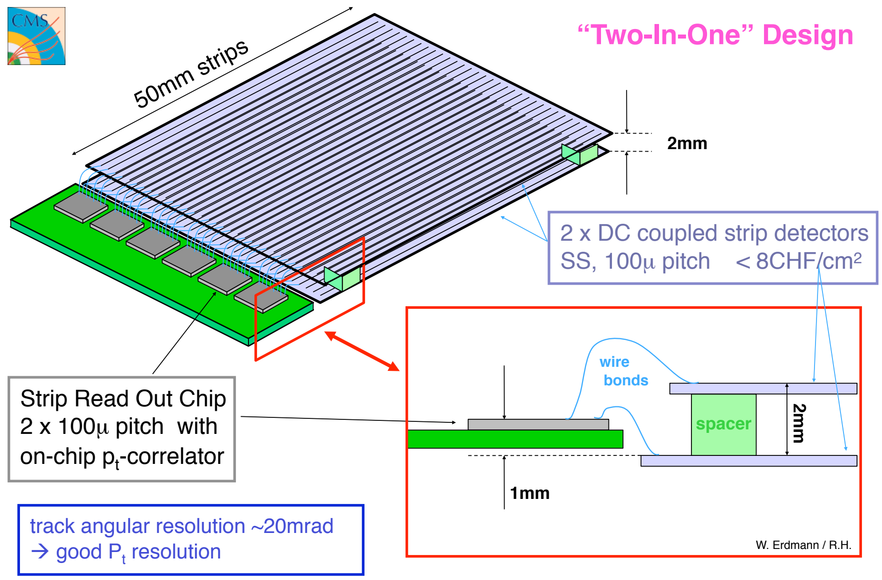


Figure 12.18: Layout of the 2_in_1 strip sensor design used as p_t-trigger setup for the CMS experiment.

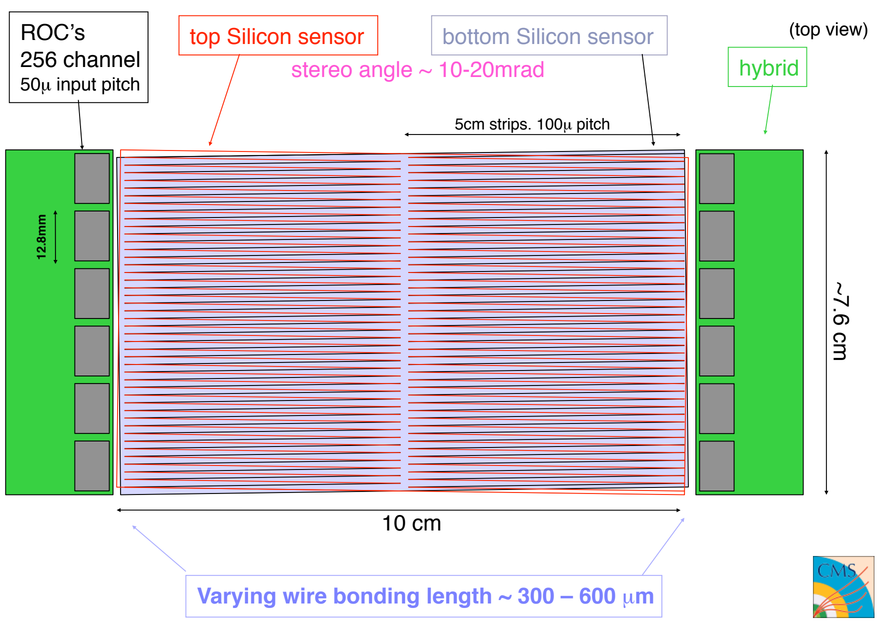


Figure 12.19: Layout of the 2_in_1 strip sensor design used as tracker module. Double use of e.g. power and cooling.

Candidates of readout chips attached to the sensors are e.g. the ATLAS FE-I4 ($50\mu m * 250\mu m$) and CMS ROC ($100\mu m * 150\mu m$) (see Refs. [641], [642]). The sensor pitch has to be matched and the electronics scheme defined before.

- The size of the largest stave structure to be installed (half z-length $\approx 94cm$) is smaller then the stave length used e.g. by ATLAS ($\approx 120cm$). Powering and in that respect cooling per stave are therefore less demanding then for the current LHC installations. Minimization of cooling effort reduces the material budget directly; cooling is related to power consumption issues and it might be a criterion for technology selection. A decision on powering concept is needed (seriell, parallel powering). It will depend on the template chosen for readout and services. The obvious suggestion is to re-apply one scheme used by a current LHC experiment inline with the sensor & electronic & readout option selected.

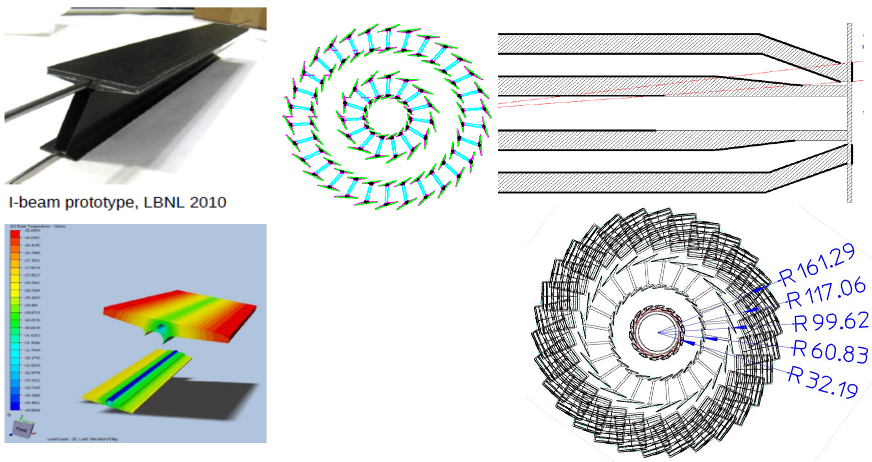


Figure 12.20: Proposed mechanics and sensor layout for the ATLAS pixel upgrade.

- The mechanical support and cooling elements have to be chosen to minimize the material budget of the setup and hence to diminish the impact of Coulomb multiple-scattering on track resolution by the tracker material. The HL-LHC upgrade developments of e.g. ATLAS and CMS show the relevance of that topic for the future physics program at the second phase of LHC. Rigid but very light mechanics in connection with improved sensor arrangement, incorporation of cooling systems and all other services into the support structure are the main design criteria for HL-LHC and should be for LHeC as well. In Figs. 12.20, 12.21 and 12.22 are possible mechanical solution for the ATLAS and CMS tracker upgrade in the barrel as well as in the forward/backward tracker region shown (Refs. [656], [639], [641]). Those designs may well serve as templates for the LHeC experiment. An artist view in Fig. 12.23 shows the implementation of the double-I ATLAS pixel arrangement into the 4 layer pixel structure of the LHeC experiment. That could be an installation template. The goal is the design of a tracker which is transparent enough and reaches in terms of radiation length thickness the range $\approx 1.5 - 2\% X_0$. Possible pathes (orange) for the IN/OUT services of the tracking detectors are sketched in Fig. 12.24. The cables and tubes are as far as possible integrated into the support structures of the

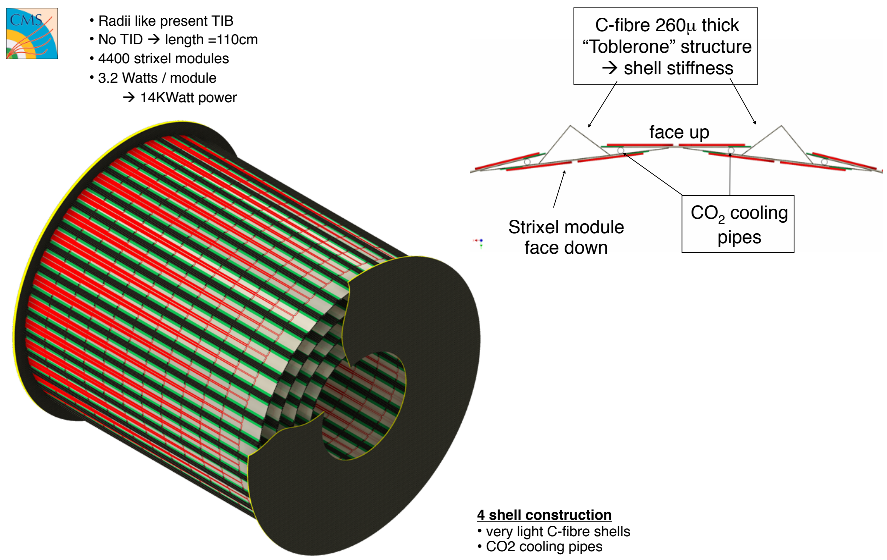


Figure 12.21: Proposed mechanics layout for the CMS inner barrel tracker upgrade.

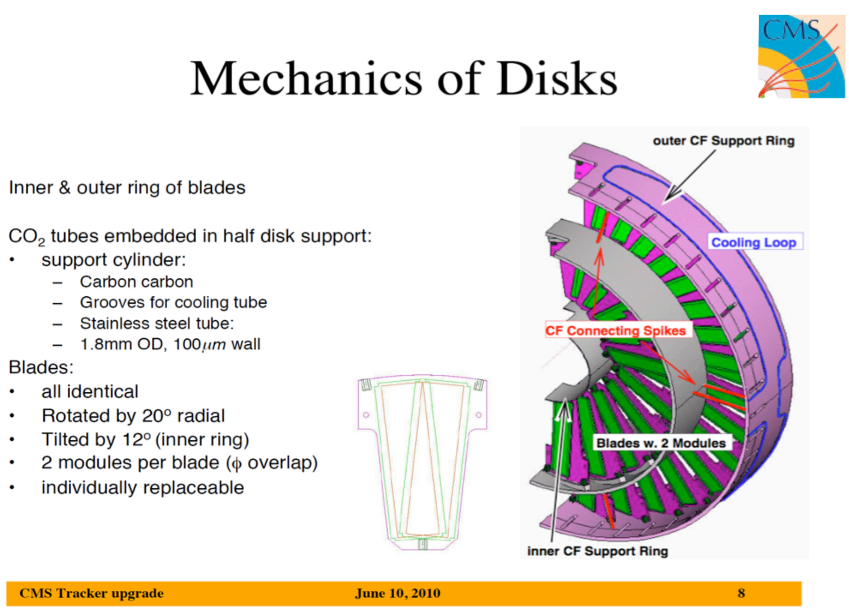


Figure 12.22: Proposed mechanics layout for the CMS tracker wheel upgrade.

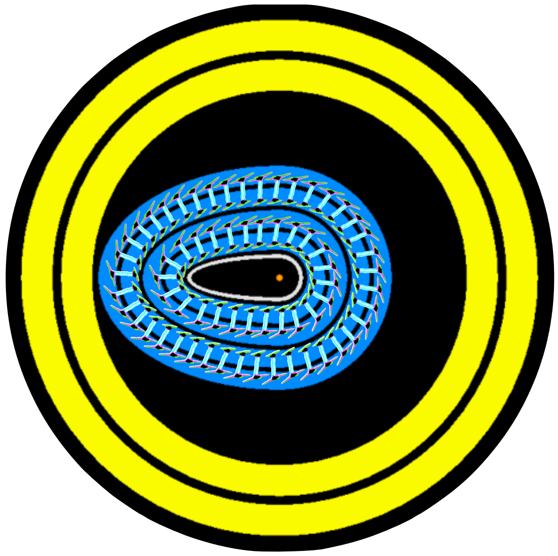


Figure 12.23: Artist view of the pixel sensor arrangement using the double-I ATLAS layout as template (Fig. 12.20).

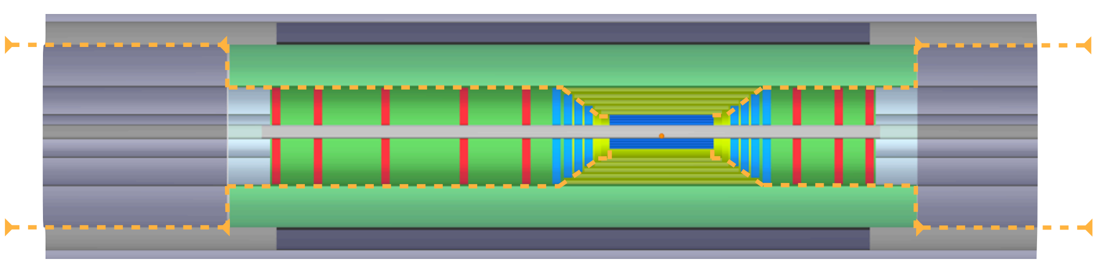


Figure 12.24: Path of services for all tracking detectors (orange). The services are integrated into support structures whenever possible

sub-detectors.

- Optimization of detector Read-Out reducing the cost and material impact of cables. An example is discussed in detail for the ATLAS/CMS HL-LHC opto-link upgrade in Ref. [657]. The front end electronics buffer depth will depend on bunch crossing rate (25ns) and trigger/readout speed capability.

- Special Interaction Region instrumentation for tuning of the machine minimizing the background and optimizing the luminosity is needed. Radiation detectors e.g. near mask and tight apertures are useful for fast identification of background sources. Fast bunch related informations are collected efficiently e.g. by dedicated diamond detectors (like for CMS: [658], [659], [660], [661]).

First and preliminary **GEANT4** studies using minimum bias events generated with **Pythia6** (Ref. [113]) will be discussed in the following section. The simulation of detector responds is important because it may have impact on technology decisions and will be evaluated further. A more refined simulation will provide, a more differential picture of the detector responds. Of course the performance of the detector in line with the software algorithms used define how accurate the particle flow tracking in jets, the reseed after interactions and conversions can be solved. That implies that the software solutions play a major role to come up with the optimized detector finally.

12.5 Geant4 Event Simulations - General Detector Description

12.5.1 Introduction

Minimum bias events in the LHeC Detector have been simulated using the **GEANT4** Toolkit [662]. In addition **ROOT** [663], **GDML** [664], **AIDA** [665] and **Pythia6** [113] have also been incorporated. A **ROOT** macro has been written which gives a general description of the LHeC Detector geometry and materials. This description is then transported from **ROOT** to **GEANT4** in XML format via **GDML**. A **Pythia6** program has also been used to create minimum bias ep events. **Pythia6** outputs the events in HEPEVT format. This is then run through a subroutine to produce a format readable by **GEANT4**. The actual simulations are completed natively in **GEANT4** once the geometry, materials and events are loaded. The Analysis is done with **ROOT** (and the Java Analysis Studio **JAS** [665]) which is interfaced to **GEANT4** via **AIDA**. The flow of these simulations is outlined in Figure 12.25.

12.5.2 Pythia6

The **Pythia6** event used in the **GEANT4** simulations contains $\gamma^* P$ interactions convoluted with the $\gamma/e-$ flux. This setup contains non vanishing cross sections including semihard QCD, elastic scattering, single/double diffractive among others (The listed interactions dominate σ_{tot}). In order for the events to be minimum bias no restrictions are placed on the W or Q^2 range.

Table 12.3 gives the **Pythia6** parameters used for the minimum bias events. The logarithm of the variables W and Q^2 are given. Since these variables obey amplitudes given by $P(x) \propto \frac{1}{x^2}$

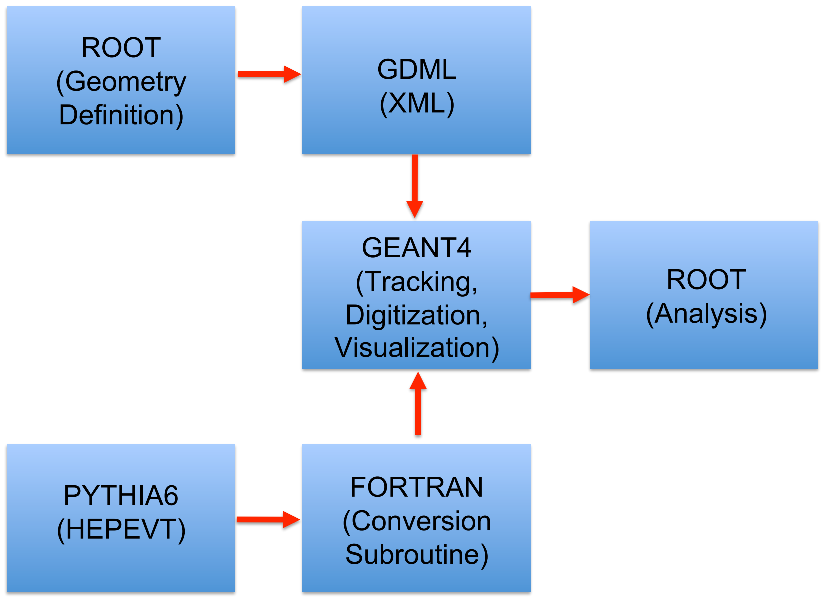


Figure 12.25: Simulation Framework Flow Chart

then $P(Log(x)) \propto e^{-x^2}$ showing that Log(x) produces mean and rms values following normal statistics.

The tools available for ep event generation are not current. The frontier of high energy physics is focused on hadron collisions due to the LHC. The numerous problems present in a new energy scale require developers to focus in this area. This results in a lack of development of event generation tools for a new energy scale of ep collisions. This is the reason we are using **Pythia6** as opposed to its C++ successor. Although it works fine for an approximation it would be advantageous to have development here.

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 12.3: Pythia6 Parameters

The parameters used to scale the results of the simulation in order to find annual quantities are given in Table 12.4.

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 12.4: Scaling Parameters

12.5.3 1 MeV Neutron Equivalent

NEIL Scaling

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 12.26 [666].

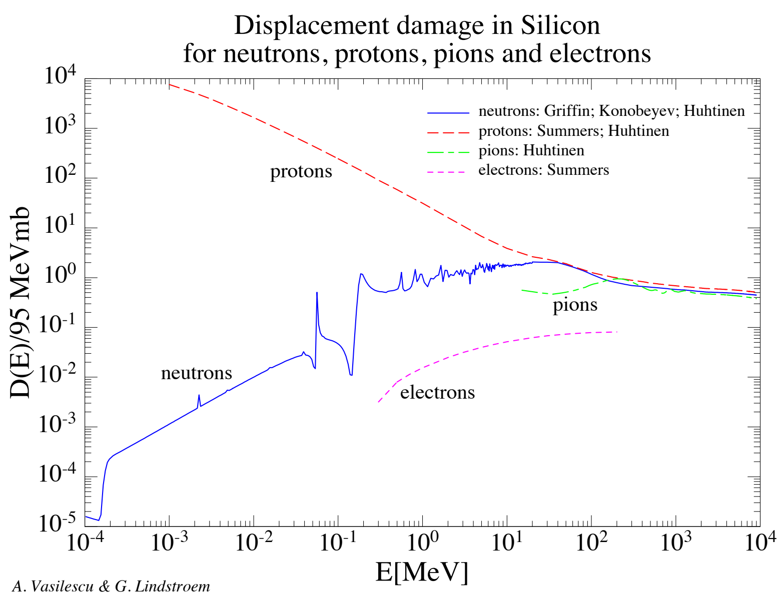


Figure 12.26: Displacement Damage for various particles in Silicon

Scoring

In order to find the 1 MeV Neturon 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 12.4. The total 1 MeV Neutron Equivalent fluences are given in Table 12.5.

Central Barrel			
Region	$\Delta Z[cm]$	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 12.5: 1 MeV Neutron Equivalent Fluence

Histogramming

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 12.27) displays the 1 MeV Neutron Equivalent Fluence in $\frac{cm^{-2}}{year}$.

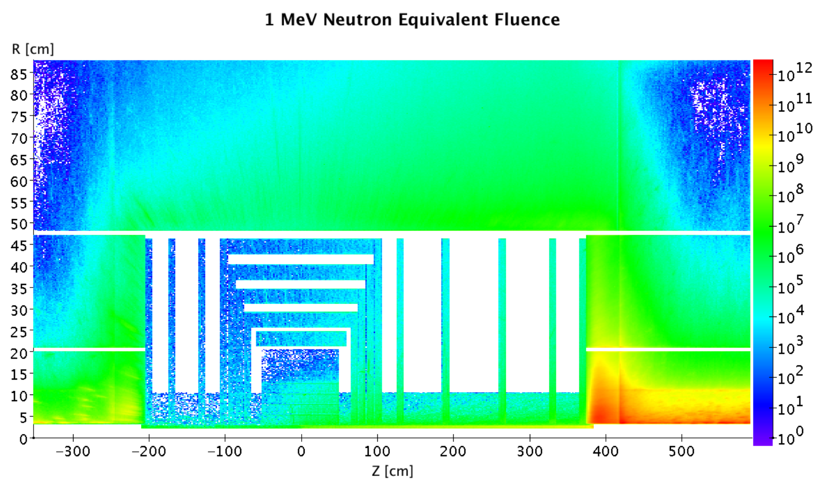


Figure 12.27: 1 MeV Neutron Equivalent Fluence [$cm^{-2}/year^{-1}$].

12.5.4 Nearest Neighbor

Tracking Componenet	Hits under 10 μm [%]
CFT1	0.18
CFT4	0.23
FST1	0
FST5	0.1

Table 12.6: Nearest Neighbor under 10 μm

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

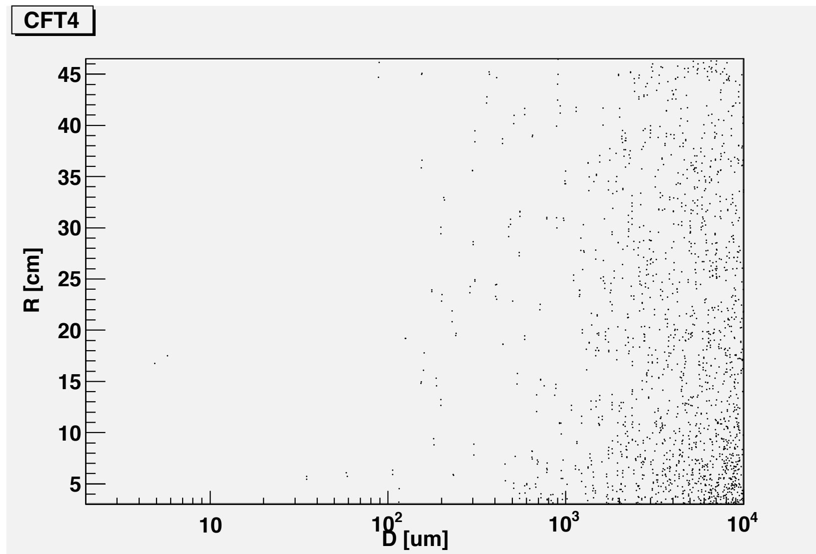


Figure 12.28: Nearest Neighbor distribution for CFT4

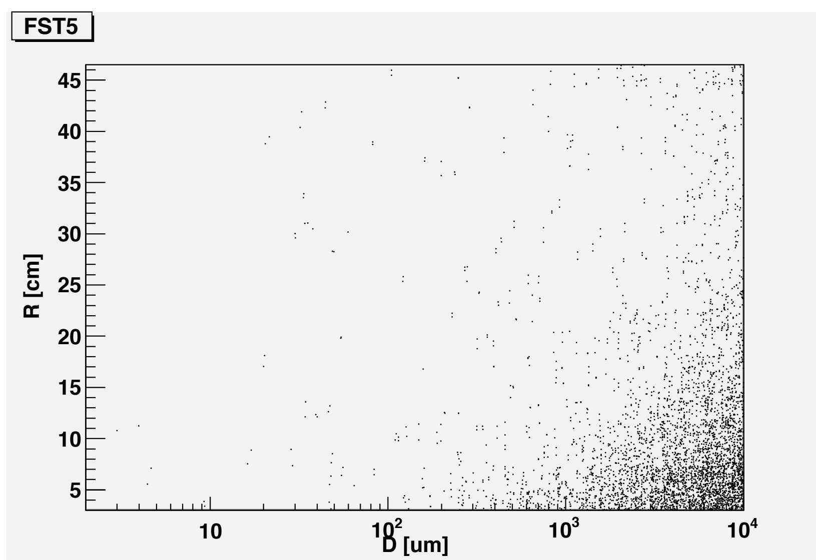


Figure 12.29: Nearest Neighbor distribution for FST5

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 level is a nice approximation. The nearest neighbor distribution for CFT4 is shown in Figure 12.28 and for FST5 in Figure 12.29. The x axis contains the value of the nearest neighbor for each hit in terms of μm while the y axis contains R in terms of cm. A required resolution of 10 or less μm would require pixel detectors instead of strip detectors. The CFT4 and FST5 Figures display a very low hit density in this area. The percentage of hits with $D < 10\,\mu m$ for the four tracking components in question are given in Table 12.6.

12.5.5 Cross Checking

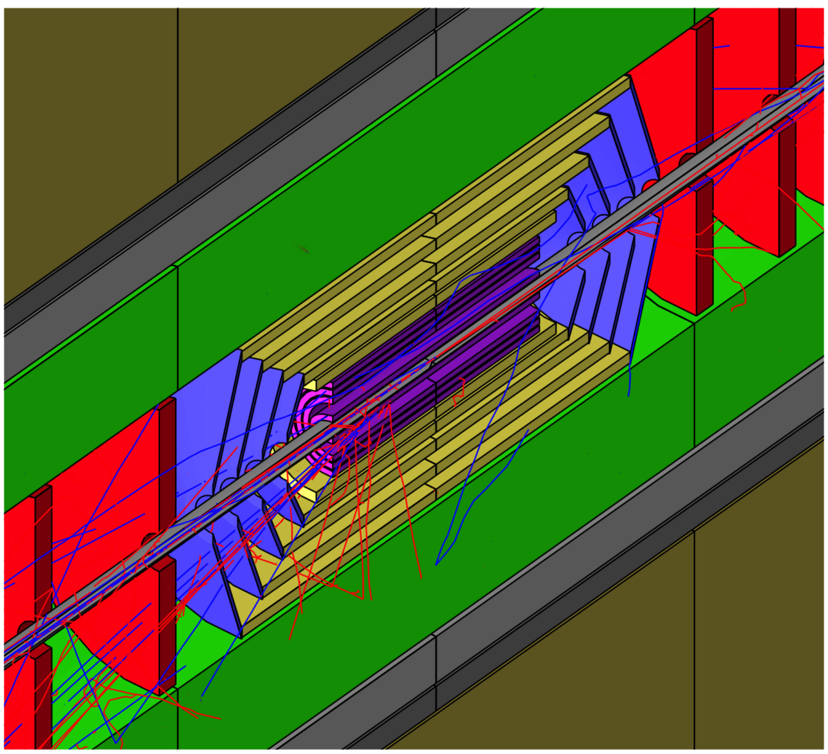


Figure 12.30: G4 Event

DAWN was used for visualization of the detector. This was able to produce clear pictures which was one way to make sure the translation of geometry from **ROOT** to **GEANT4** went as expected. An event in the central tracking region is presented in Figure 12.30.

In addition to the minimum bias events, **Pythia6** was also used to create some Leptoquark events. This was one method of checking the **Pythia6** input (i.e. that the events produced describe the given kinematic range and cross sections available). However it was also utilized to

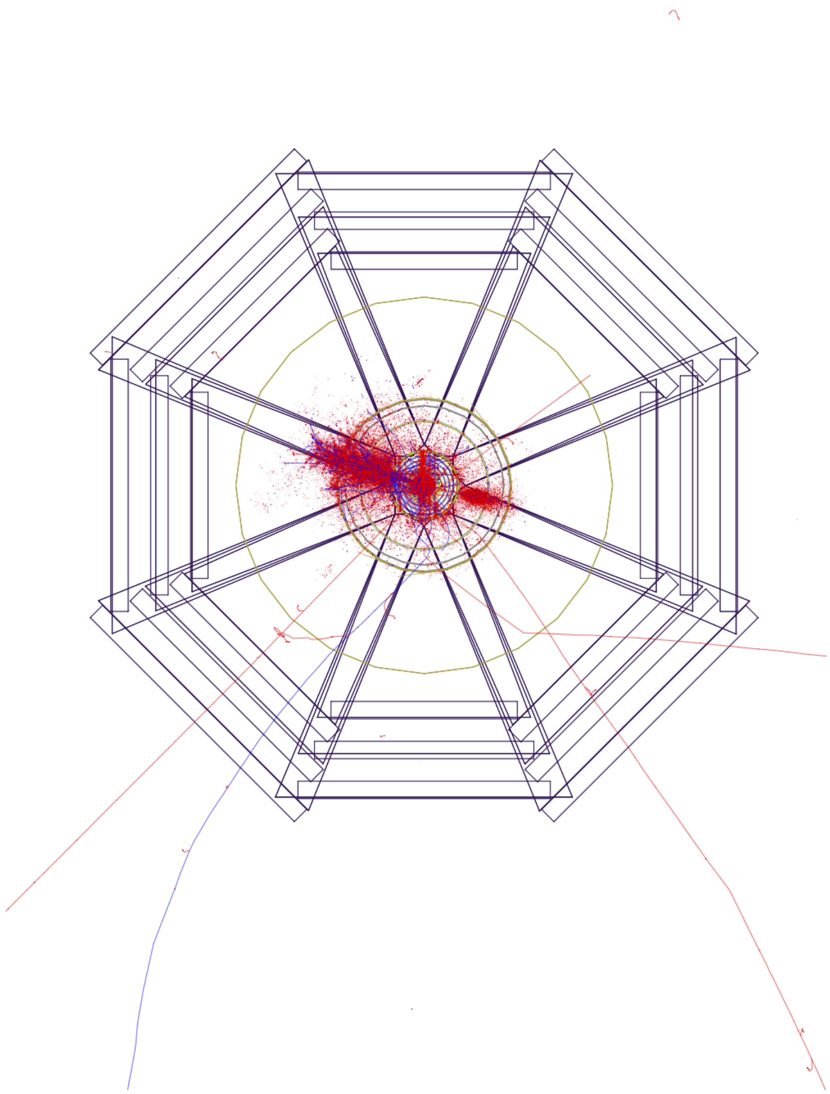


Figure 12.31: Leptoquark Event XY

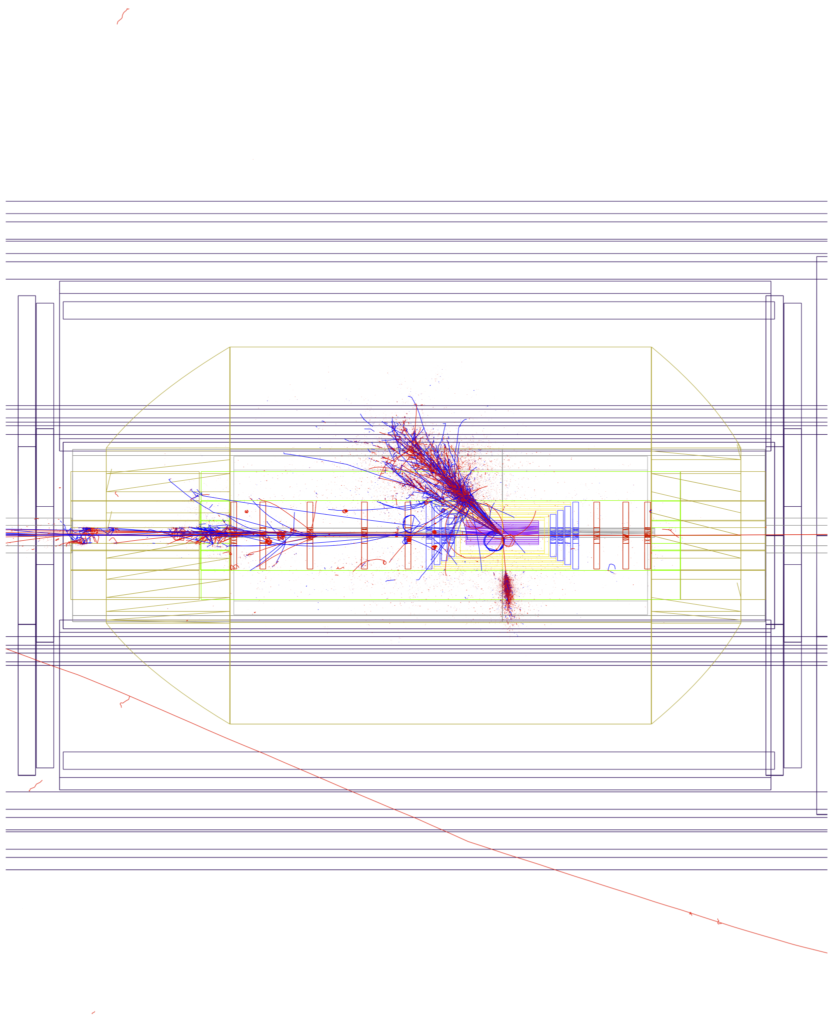


Figure 12.32: Leptoquark Event RZ

determine the detector response at various kinematic ranges. Since $\sigma_{EM} \propto \frac{1}{Q^4}$ The minimum bias events have very low Q^2 and therefore very forward jets, which leaves almost no activity in the barrel HCAL. By looking at some high Q^2 events it is possible to see the response of the hadronic calorimetry in the barrel region, making sure it is showering correctly. Some pictures of the Leptoquark events are given in Figure 12.31 and Figure 12.32.

12.5.6 Future Goals

There are many goals still to be accomplished by the LHeC Detector Simulations. The set up needs to be modified to include a detailed calorimeter description. Currently the calorimeter volumes contain a mixture of FR4, Krypton, Active and Passive material which is weighted according to a realistic set up. This design must be replaced with a realistic setup of the calorimeters. This also needs to be done for the tracking which is currently composed of single silicon pieces instead of smaller modules. The majority of the work in making these changes comes from the required read out geometry and sensitive detector set up that would be required for analysis of a complicated geometrical structure. This also might require a restructuring of the simulation package. Since the detector description was done first in **ROOT**, **GDML** was an option to allow utilizing **GEANT4** without recoding the geometry. However if the geometry will significantly change then this might benefit from being done natively in **GEANT4**. Of course the Geometry needs to be iterated until it actually describes the exact detector (service pipes, read out, etc...). However this will come with the TDR.

Finally the stability of the simulations needs to be assessed. Eventually a complex multi-functional detector simulation package needs to be produced. This is best done by wrapping numerous simulation toolkits into a single package utilizing **ROOT**, such as **AliROOT** [667], [668], [669] or **ILCROOT** [670]. The LHeC simulations at some point need to make a shift towards creating a package like this, in order to promote greater functionality and greater accessibility.

12.6 Calorimetry

The LHeC calorimetry has to fulfill the requirements described in **??**. The goal is a powerful level 1 trigger and detector able to resolve shower development in 3D space with no or minimal punch through. High transverse and longitudinal segmentation are necessary along with a good matching to tracking devices for particle identification and separation of neutral and charged particles. The calorimetry needs to be hermetic for the identification of the charged current process and good measurement of E_T^{miss}. These considerations are summarized in Tab. 11.1.

The baseline design foresees a modular structure of independent electromagnetic and hadronic calorimeter components. A high segmentation and minimal dead material between the tracking and the calorimetry will allow a precise energy measurement and identification or separation of charged and neutral particles. In order to fully contain electromagnetic showers a thickness of about $25 \sim 30X_0$ is required. The design of the EMC modules will vary when moving from the very forward region, where energies up to $\mathcal{O}(1\text{TeV})$ are expected to the barrel and the rear region where the detection of the scattered low energy electron has to be precisely tagged and measured.

Following the option A of baseline design, the EMC is surrounded by the coil providing the magnetic field for momentum measurement in the tracking.

The hadronic calorimetry, naturally surrounding the EMC is also foreseen to have a sufficient depth and a projective modular design to precisely measure over the full energy range high energetic jets and provide a granularity such to faithfully separate multiple jet events. Given the energies available at the LHeC, the forward part will be much more extended (up to $10\lambda_I$) for full containment of energies up to few TeV.

In the next sections the baseline design for the EMC and HAC components is presented and discussed along with a comparison of technologies and the experience from other HEP detectors. A brief outlook towards ongoing and new technologies R&D which would even extend the precision and the scope of the detector are briefly addressed.

12.6.1 The Barrel Electromagnetic Calorimeter

Due to the very asymmetric energy and particle multiplicity distribution over the azimuthal angle, the detector baseline design foresees a composite electromagnetic calorimeter which includes a Liquid Argon Calorimeter in the barrel region. For the endcaps very diverse requirements are pushing the design toward different technical choices.

Liquid argon (LAr) based calorimetry is a well established technology in HEP. LAr sampling calorimeter technique with "accordion-shaped" electrodes is used in ATLAS for all electromagnetic calorimetry covering the pseudorapidity interval $2.8 < \eta < -2.4$. The choice of liquid Argon calorimetry follows from its intrinsic excellent linearity, stability in time and radiation tolerance ([671], [672], [673], [674], [675], [676], [677], [678]).

At the LHeC, LAr would provide the required energy resolution, detector granularity and projective design. The detector with an outer diameter of 88 cm would share the same cryostat of the main solenoid which in case of a Linac-Ring design would include the bending dipoles. Size and construction details of the cryogenics are described in **??**. At larger radii, where most of the calorimeter weight is located and where the radiation levels are low, a less expensive technology based on absorber-scintillator hadronic calorimeter can be used. The performance of the LAr calorimetry system has been extensively addressed [679] and here only specific design issues and detector simulation will be discussed.

Fig. 12.33 shows a x-y and r-z view of the LHeC Barrel EM calorimeter. As for the ATLAS LAr Calorimeter, the detector volume is filled with a projective accordeon structure based on lead absorber. This layout allows for the extraction of the detector signals without significantly degrading the high-frequency components which are vital for fast shaping. The flexibility in the longitudinal and transverse segmentation, and the possibility of implementing a section with narrow strips to measure the shower shape in its initial part, represent additional advantages. It is worth noticing that due to the asymmetric design, the projective structure is not fully symmetric as the calorimeter and the solenoid center are shifted forward with respect to the interation point. Fig. 12.34 shows a detail of the accordeon-electrode structure. The layout, adapted from the ATLAS LAr Calorimeter [679], has been faithfully implemented in a **GEANT4** simulation. Several aspects considerations and design choices were inherited and adapted to the LHeC design. Their merits were then compared for several critical performance issues, such as energy resolution, accuracy in position and angular measurements and particle identification, and balanced against arguments of reliability and cost.

The readout granularity has been subdivided in 3 cylindrical sections of increasing size in $\Delta\eta \times \Delta\phi$. As seen in Fig. 12.35, the first sampling section of the electromagnetic calorimeter has a very fine granularity ($\Delta\eta \times \Delta\phi = 0.003 \times 0.1$), to optimize the ability to separate photons from π^0 energy deposits. The second sampling section, mainly devoted to energy measurement,

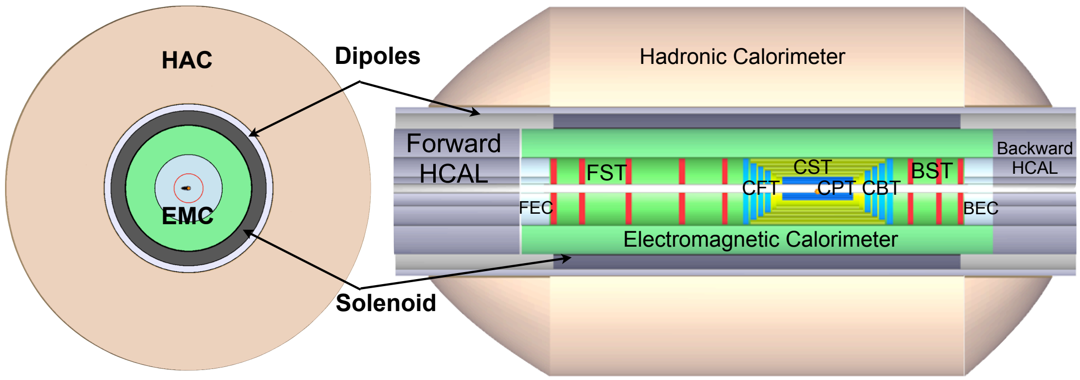


Figure 12.33: x-y and r-z view of the LHeC Barrel EM calorimeter (green).

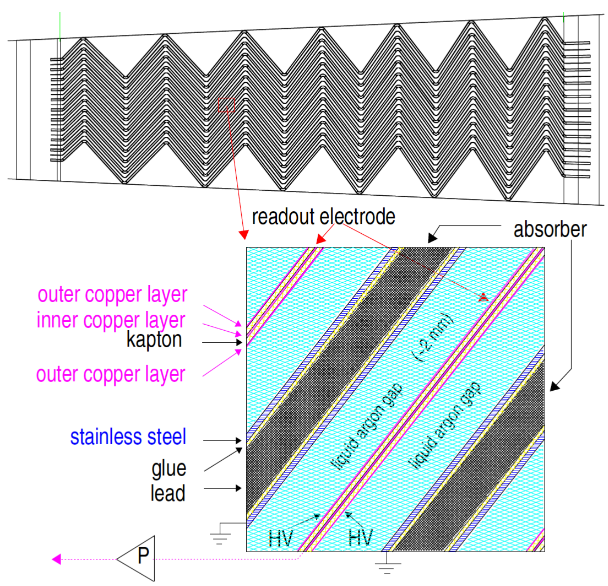


Figure 12.34: Longitudinal view of the accordeon structure of the ATLAS LAr Calorimeter

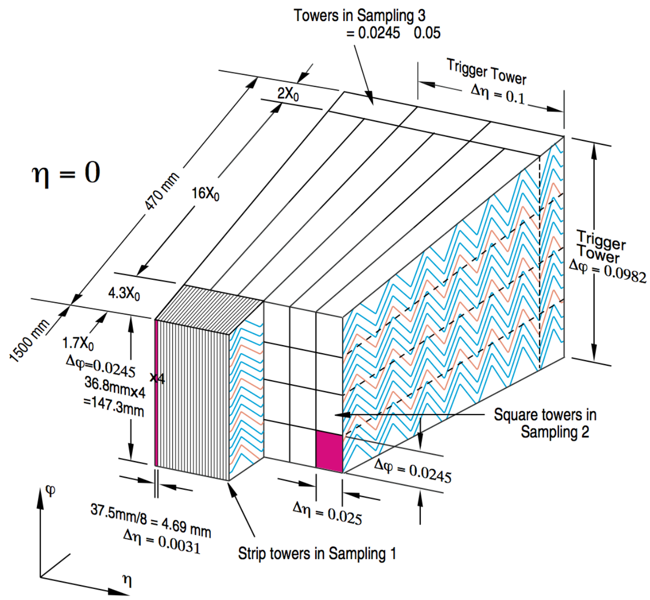


Figure 12.35: 3D view of the accordeon structure of the ATLAS LAr Calorimeter

has a granularity of 0.025×0.025, and the back sampling has a slightly coarser granularity of $\Delta\eta \times \Delta\phi = 0.050 \times 0.025$.

A basic cell consists of an absorber plate, a liquid argon gap, a readout electrode and a second liquid argon gap. The mean thickness of the liquid argon gap is constant (2.1mm) along the whole barrel and along the calorimeter depth (more details see [679]).

12.6.2 The Hadronic Barrel Calorimeter

In the barrel region a sampling device made out of steel and scintillating tiles, as absorber and active material is foreseen as baseline design. The detector would provide the required mechanical stability for the inner LAr and Magnet cryostat along with the iron required for the return flux of the solenoidal field.

The simple and very well proven idea of calorimetry is particularly suited for the LHeC environment since also in use in ATLAS [679]. The absorber structure is a laminate of steel plates of various dimensions, connected to a massive structural element referred to as a girder. The highly periodic structure of the system allows the construction of a large detector by assembling smaller sub-modules together. Since the mechanical assembly is completely independent from the optical instrumentation, the design becomes simple and cost effective. Simplicity has been the guideline for the light collection scheme used as well: the fibers are coupled radially to the tiles along the outside faces of each module. The laminated structure of the absorber allows for channels in which the fibers run. The use of fibers for the readout allows to define a tridimensional cell read-out, creating a projective geometry for triggering and energy reconstruction. A compact electronics read-out is housed in the girder of each module. Finally, the read-out of the two sides of each of the scintillating tiles into two separate photomultipliers provides the redundancy needed during the expected period of operation.

IE-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 12.7: 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. 12.9.

In the baseline design the calorimeter consists of a cylindrical structure with inner and outer radius of 120 and 260 cm respectively (Tab. 12.7). The central HAC barrel part is 580 cm in length along the beam axis. Endcaps extend the calorimetry further in the forward and backward direction in order to guarantee full energy containment. The detector cylinder would be likely built of several independent wedges along the azimuthal direction while the modularity and segmentation might vary depending on the adopted machine design (Ring-Ring or Linac-Ring). The Tile Calorimeter forms the shell of the inner part of the LHeC detector. Within its volume, once the barrel and the extended barrels are assembled, all the sub-detectors, except the muon system, will be placed. The massive iron structure is rigid enough to support their weight, with the such important components being the full Liquid Argon cryostat and the solenoid.

The main function of the Tile Calorimeter is to contribute to the energy reconstruction of the jets produced in e-p interactions and, with the addition of the end-cap and forward calorimeters, to provide a good p_T^{miss} measurement. Achieving this at the LHeC is not so straightforward as the large proton beam energy and the electron proton energy imbalance center requires good performance over an extremely large dynamic range extending from a few GeV up to several TeV.

The guidelines for the design of this device are derived from the required overall physics performance which call for an intrinsic resolution for jets in the barrel region of $50\% \cdot \sqrt{E/GeV}$ with a segmentation of $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ (11.1).

The granularity of the Tile Calorimeter is important to finely match the electromagnetic LAr calorimeter in front and correct for the dead material of the magnet complex. The proposed hadronic segmentation for the cells behind the electromagnetic section, will allow an efficient hadron leakage cut, needed for electron and photon identification. A reasonable longitudinal segmentation, especially around the maximum depth of the shower, favours an appropriate weighting technique to restore, at the level of 1-2%, the linearity of the energy response to hadrons, which is intrinsically non-linear because of the non-compensating nature of the calorimeter. At the highest energies expected, the resolution of the calorimetry is dominated by the constant term, for which the largest contribution comes from the detector non-linearity and from the calibration. An attempt is made to keep the constant term below the 2% level. For the measurement P_T^{miss} a large contribution comes from the overall acceptance of the detector.

To improve the energy measurement in the barrel/end-cap region, it will be evaluated in detail where a presampler system with the same granularity as the corresponding calorimeter region has to be implemented in front of the barrel/end-cap systems. Such presampler has a limited active thickness ($\approx 5\,\mathrm{mm}$) and does not really matter in terms of material impact and space requirements.

12.6.3 Endcap Calorimeters

Calorimetry in the forward and backward direction at the LHeC is of extreme importance: in the forward region highest energy deposits require high granularity and very good scale calibration, in the backward region high sensitivity to low energy electrons and a good e/h separation is important to suppress hadronic background.

As seen from Fig. 12.27 the very forward and to less extend also the backward parts of the calorimeter are specifically exposed to dense particle radiation and have to be radiation hard by design. Synchrotron radiation and any further background radiation has to be tolerated additionally.

Fig. 12.9 shows in detail the encap calorimters for the Ring-Ring design. The two-phase experimental program requires the endcaps to be modular as these components will be either moved along the beam line or removed to allow the placement of the strong focussing magnets for the high energy run. Relevant dimensions and specifications are summarised in Tab. 12.7

For the Linac-Ring design, where no additional magnets along the beampipe will be required, the subcomponents FHC2/FHC3 and BHC2/BHC3, can be unified in single modules for the forward and backward direction, respectively.

We envisage excellent performance regarding:

- electron identification in jets (tagging and e from heavy quark production); precision measurement of showers,
- identifying heavy flavour production by partial reconstruction,
- good γ separation by identified impact, thus discriminating γ/π^0
- hadronic and electromagnetic signatures, also in case of $e^{\pm}$-*Ion* interactions
- jet finding, jet energy and impact position measurements
- Level one triggering

The tight geometry of the insert calorimeters require a non conventional and challenging design based on former developments [680], [681], [682], [683], [684], [685], [686], [687]. The choice of a tungsten absorber specifically for the forward inserts is driven by its very short radiation length and a large absorption to radiation length ratio. About 26 cm of tungsten will absorb the electromagnetic showers completely and will contain the hadronic shower to a large extent and over a large range of energy ($\approx 30\mathrm{X}_0 + \approx 10\lambda_I$). The electromagnetic as the hadronic part can be combined even in the same compartment to minimize boundary effects.

An alternative to the tungsten hadronic absorber is copper (Cu). Simulations have been performed to compare the different absorbers. Since the backward inserts have more relaxed requirements, the absorber chosen are lead *Pb* for the electromagnetic part and *Cu* for the hadronic one. For the Ring-Ring option, where no dipole field along the beampipe is required a further and more economical choice instead of *Cu* could be steel *Fe*. The active signal sensors for both the forward as the backward calorimeter arrangements have been chosen to be Si-strip (electromagnetic fwd/bwd parts) and Si-pad (hadronic fwd/bwd parts), respectively.

12.7 Calorimeter Simulation

This sections summarizes some first simulations describing the barrel calorimeters, endcap calorimeters default setups as well as some alternative sampling arrangements. The calorimeter components presented have been simulated using **GEANT4.9.2** [662] with single and multiple particle events along with full *e-p* events from the **QGSP-3.3** [688] physics list. The Quark-Gluon String Precompound (**QGSP**) is based on theory-driven models and uses the quark-gluon-string model for interactions and a pre-equilibrium decay model for fragmentation.

The detector raw structure, including the various layers of active, absorbing and support material were coded and inserted in the simulation. Energy resolutions for electromagnetic and hadronic deposits were studied along with concepts for optimal trigger and signal reconstruction. Particular attention was put into the key features and the construction constraints of the detector, namely the beam optics and the magnets (solenoid and the Linac-Ring dipoles). Where a similar design from an existing or developing detector was available, the results are presented complemented by referenced studies.

The energy resolution of a calorimeter is parameterized by the following quadratic sum:

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus b \tag{12.1}$$

where E is the particle energy in GeV, a is the stochastic term, which is arising from fluctuations in the number of signal producing processes, b is the constant term, which includes imperfections in calorimeter construction, fluctuations in longitudinal energy containment, non-uniformities in signal collection etc. A third term c is often also added which would represent the noise in experimental data description. The energy deposition of primary and secondary particles in the calorimeter was obtained using **GEANT4**, and fitted to extract a and b. Effects including the readout process were not considered at this stage.

12.7.1 Liquid Argon Barrel Calorimeter Simulation

The parallel geometry accordion calorimeter was simulated with accordion shapes absorbers and LAr. Absorber sheets are 2.2mm thick lead and LAr gaps are 3.8mm. Both absorber and LAr gap have accordion fold length of 40.1mm and 13 bend angles of 90^0. A total of 62 absorber sheets each 250 cm wide in the z-direction were simulated (Fig. 12.36). An example of a 20 GeV incident single electron is shown in Fig. 12.37. The energy resolution for electrons was obtained from ratio of the mean and the standart deviation of the electron response, both obtained by fitting a gaussian to the energy spectrum. Figure 12.38 shows the energy resolution for electrons of energy between 10 and 400 GeV. These results are in agreement with [678]. In the simulation the energy deposited in the active material is normalized to the energy of the incident particle.

The simulation has also been performed to see the energy resolution variations of combined system (accordion and tile calorimeter) with and without a thick Aluminium layer in between simulating the effect of the magnet complex. The study has been performed with particles in a wide range of energy and incident angle in order to simulate the detector behaviour at for particle entering the calorimeters at different z. The Aluminium layer of 16cm represent the solenoid/dipole/cryostat system between the EMC and HAC calorimeters.

Hadronic shower simulations have been obtained for the energies from 3 to 200 GeV. The obtained energy resolutions as a function of energy for pions are shown in Fig. 12.39 and Fig. 12.39.

12.7.2 Electromagnetic (warm) and Hadronic Barrel (tile) Calorimeter Simulation

Beside the default LAr calorimeter setup comprising the magnet system and the electromagnetic calorimeter in one cryostat a warm EMC calorimeter has been considered and simulation performed which are summarized in the following. The barrel part of the warm electromagnetic (EMC) calorimeter module consist of a lead-scintillator sampling calorimeter, with 20 layers of 0.85 cm Pb sheets interspaced by 4 mm plastic scintillator plates. Thus the radiation length of the EMC test module correspond to $30X_0$ (X_0(Pb)=0.56cm). All dimensions of the calorimeter has been kept according to the default solution summarized in Tab. 12.7. For the simulation the Pb-scintillator EMC was placed 30 cm in front of the Hadronic Calorimeter (HAC). An aluminum block of 16 cm was placed between EMC and HAC as illustrated in Fig. 12.40. The sketched module would be one out of 6 azimuthal segments of the complete barrel EMC and HAC.

The HAC is an ATLAS type scintillator-steel tile calorimeter and made out of 4 mm thick steel plates sandwiched by 3 mm thick scintillator tiles. The tiles are placed in planes perpendicular to the z-direction. The absorber structure consist of 262 repeated period, each of which

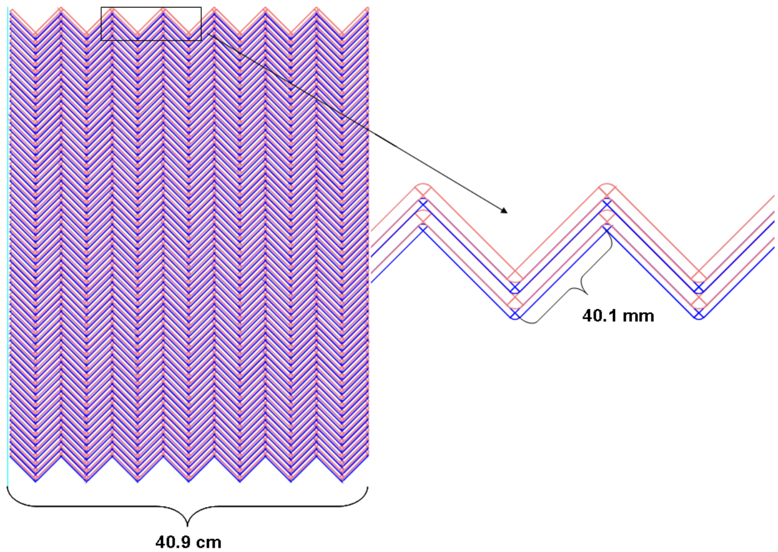


Figure 12.36: View of the parallel geometry accordion calorimeter.

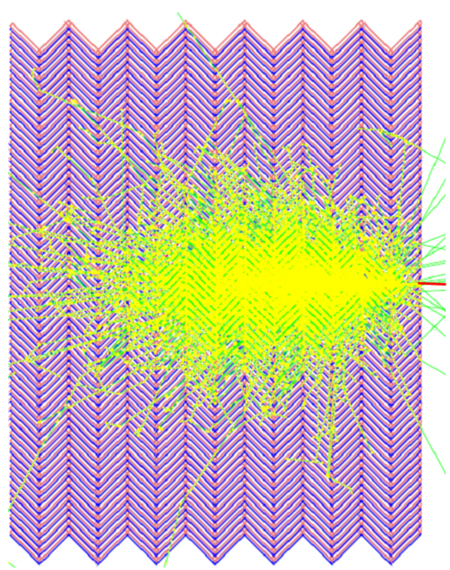


Figure 12.37: Simulation of the single electron energy with 20 GeV.

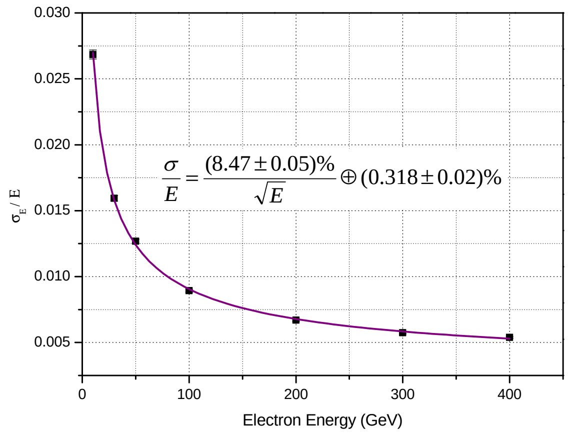


Figure 12.38: Accordion Calorimeter energy resolution for electrons between 10 and 400 GeV.

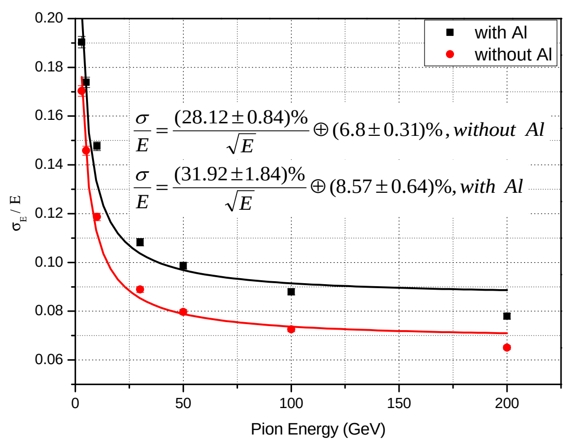


Figure 12.39: Accordion and Tile Calorimeter energy resolution for pions with and without 16cm Al block.

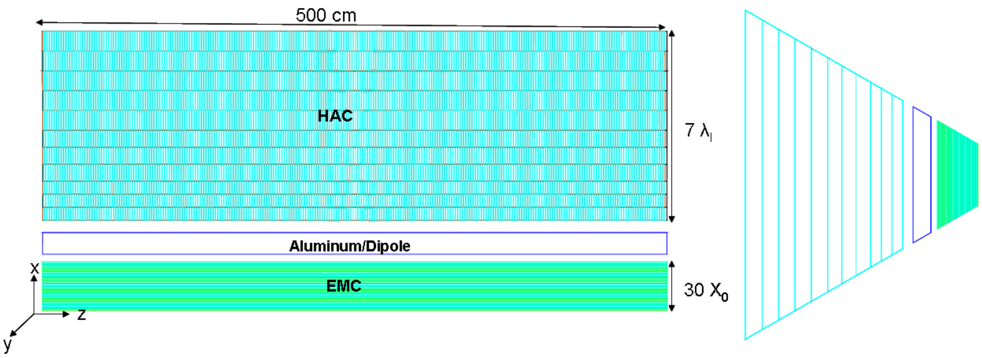


Figure 12.40: Simulation - barrel calorimeter module EMC/solenoid-dipole-system(16cm Al-block)/HAC.

spans 19 mm in z and consist of 16 mm of steel and 3 mm of scintillator tile. 11 transverse rows of tiles are used in a module. The tile rows are numbered from inner to outer radius. The total interaction depth of the HAC prototype correspond to $\lambda_I = 7$. The longitudinal segmentation of the HAC module is described in Tab. 12.8.

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

Table 12.8: Longitudinal (into x-direction) segmentation of the hadronic tile calorimeter HAC.

GEANT4-4.9.2 [662] was used with the **QGSP-3.3** [688] physics list for the simulations. The **QGSP** physics list is based on theory-driven models: it uses the quark-gluon-string model for interactions and a pre-equilibrium decay model for fragmentation. The energy distribution was fitted with a Gaussian, $\pm 2\sigma$ from the mean, and the resolution was calculated for each point. An example of the energy distribution and Gaussian fit is shown in Fig. 12.41. The a and b parameters are calculated from the fit of σ/E.

The energy resolution of the Pb-scintillator sampling EM-Calorimeter has been calculated for electrons within the energy range 10-400 GeV (Fig. 12.42). In **GEANT4** the energy deposited in the active material is normalized to the energy of the incident simulated particle. The performance of the Hadron Calorimeter in a standalone mode has been investigated. The energy resolution of the tile Calorimeter was simulated for electrons and pions within the energy range 3-200 GeV (Fig. 12.43 and 12.44). The obtained stochastic term values are consistent with [678]. The response to electrons has been studied to understand the properties of the tile calorimeter.

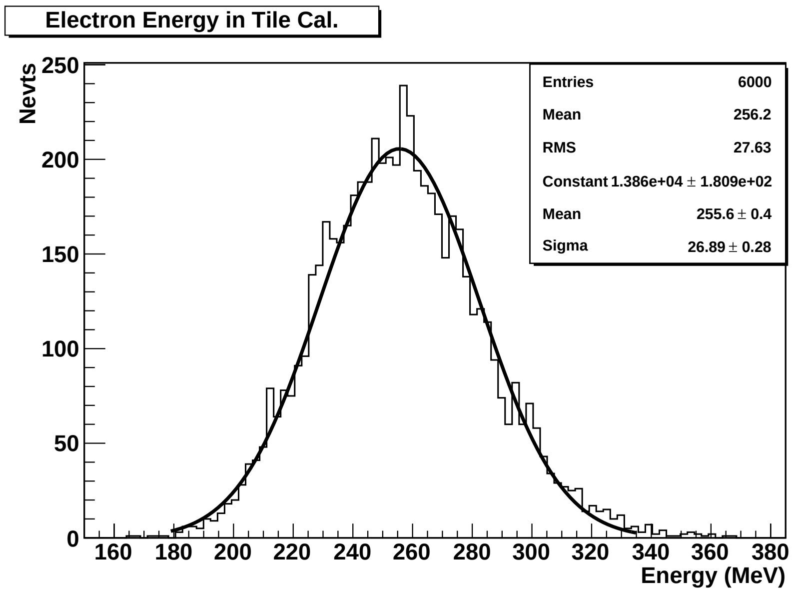


Figure 12.41: Example of the pion energy distribution and the Gaussian fit to obtain σ and mean values (Run taken at $\theta = 70°$and 10 GeV).

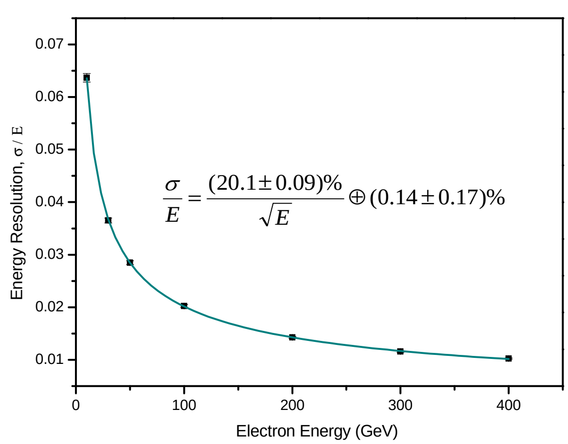


Figure 12.42: EM-Calorimeter energy resolution for electrons at θ =90°.

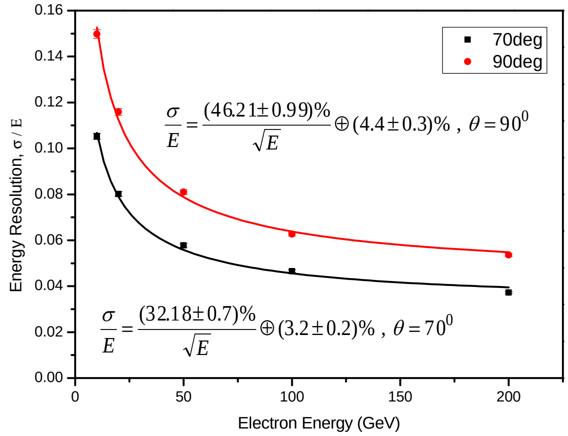


Figure 12.43: Tile Calorimeter energy resolution for electrons at $\theta = 70°$and 90°.

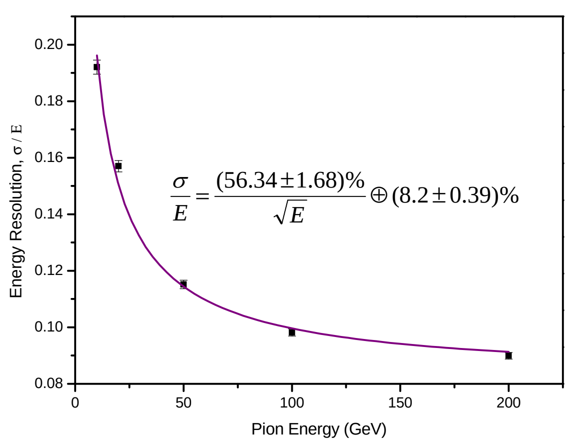


Figure 12.44: Tile Calorimeter energy resolution for pions at $\theta = 90°$.

12.7.3 Energy Resolution of the Combined Calorimeter System

The simulation has also been performed to see the energy resolution variations of the combined system as a function of incident particle angles. Fig. 12.45 shows the simulated calorimeter geometry for incident particles at the different θ angles. Hadronic shower simulations have been obtained for the incident pion angles ranged from 30°to 90°and the energies from 3 to 200 GeV. As an example, the **GEANT4** simulation for the 50 GeV incident single pion at θ =90°can be seen in Fig. 12.46. The obtained energy resolutions as a function of energy for pions at different θ angles are shown in Fig. 12.47. The calculated a and b parameters at the different angles are given in Tabl. 12.9.

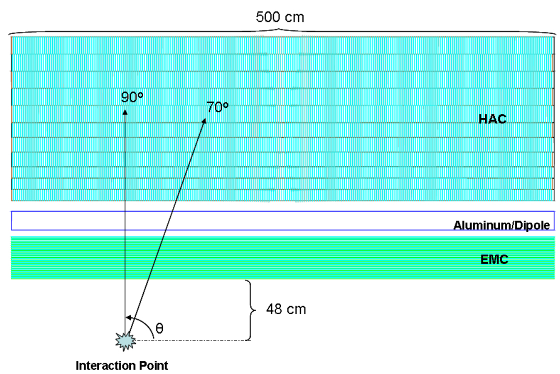


Figure 12.45: The simulated calorimeter geometry for different incident particle angle.

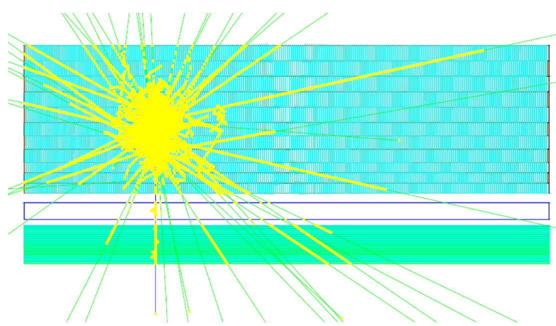


Figure 12.46: Simulation of the single pion energy with 50 GeV at θ =90°.

As the incident particle angle decreases, the total deposited energy and sigma will decrease and the energy resolution improves.

12.7.4 Longitudinal Shower Profiles

Electrons and pions develop showers at very different depth on average. In order to derive longitudinal shower development information from calorimeter system, incident particles send to the calorimeter perpendicular to beam axis. The longitudinal length of the EMC is 37 cm and

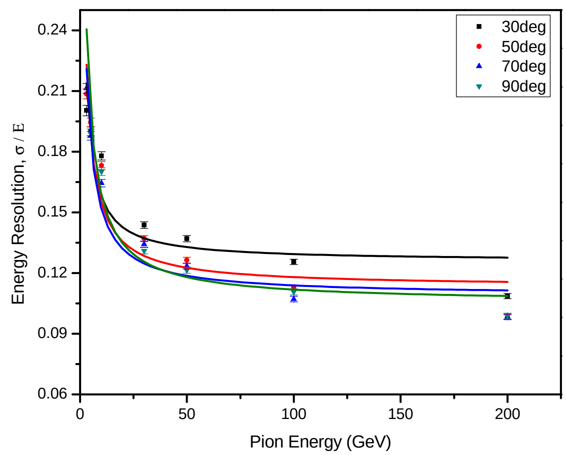


Figure 12.47: EMC+HAC energy resolution for different incident angles of pions.

	30°	50°	70°	90°
a(stoch.)%	29.93±2.96	33.28±2.62	33.28±1.98	37.44±2.5
b(const.)%	12.59±0.79	11.32±0.80	10.89±0.62	10.54±0.58

Table 12.9: Stochastic and constant terms of the pion energy resolution for different incident angles.

HAC varies from 67 cm to 207 cm. The simulated longitudinal shower profiles for electrons and pions are presented in Fig. 12.48, Fig. 12.49 and Fig. 12.50. They represent the mean deposited energy as a function of the depth. The longitudinal shower profile of electrons is shorter as of pions. The energy deposition of the electrons has its maximum in the EMC (Fig. 12.48). Pions, normally, penetrate deeper into the calorimeter. So the maximum of energy deposition of the pions are seen in the HAC (Fig. 12.50). Less energy deposition occurs between 37 and 67 cm because of the Al block representing the cryostat-wall, solenoid and dipole magnet structures.

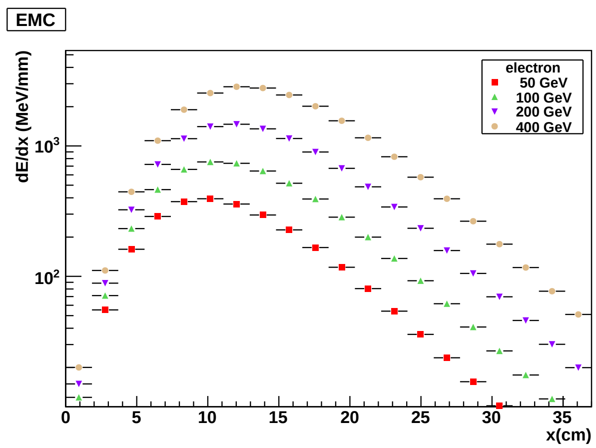


Figure 12.48: Electron longitudinal shower profile for EMC at various energies. Only statistical uncertainties are shown.

12.7.5 Transverse Shower Profiles

Transverse profiles are usually expressed as a function of the transverse coordinates, not the radius, and are integrated over the other coordinate. Figs. 12.51 and 12.52 show the transverse shower profiles for electrons and pions. Since the electromagnetic showers are compact, the electromagnetic energy is deposited relatively close to the core of the shower. As expected the hadronic transversal shower spreads are much larger than for the electromagnetic showers.

12.8 Electromagnetic and Hadronic Forward/Backward Insert Calorimeter Simulation for the LHeC Detector

12.8.1 The Forward and Backward Calorimeter Construction

The forward electromagnetic calorimeter (FEC) inserts (i.e. FEC1 and FEC2) are tungsten-silicon sampling calorimeters. The simulated FEC consists of consecutive layers of Tungsten (W) absorber, a Silicon (Si) active layer, a silicon support circuit (FR4), and circuit kapton in the listed order. The depth of each layer is given by the thickness of the W plate used in the

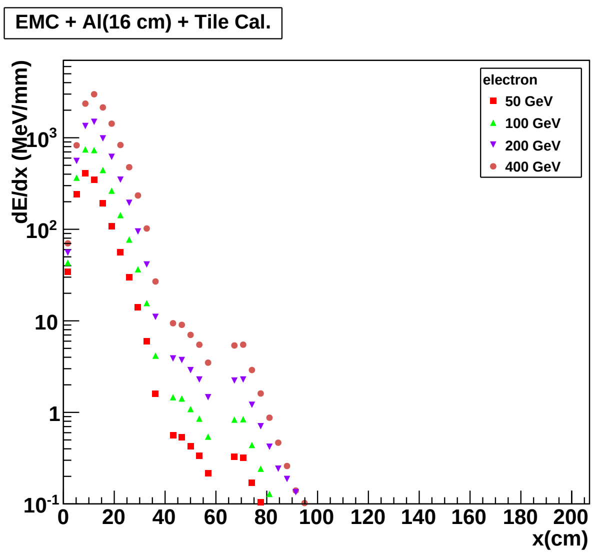


Figure 12.49: Electron longitudinal shower profile for EMC/solenoid-dipole-system (Al-block)/HAC at various energies.

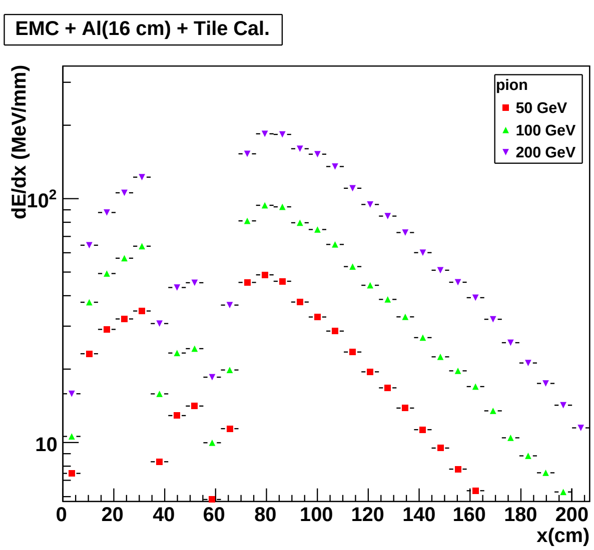


Figure 12.50: Pion longitudinal shower profile for EMC/solenoid-dipole-system (Al-block)/HAC at various energies.

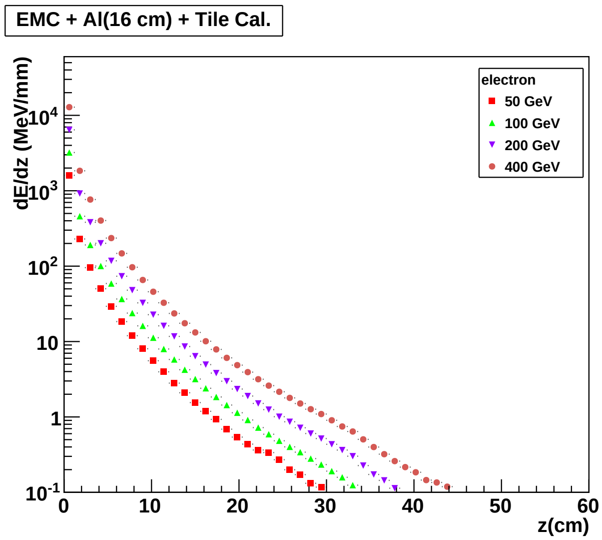


Figure 12.51: Transverse shower profiles for electron induced interactions.

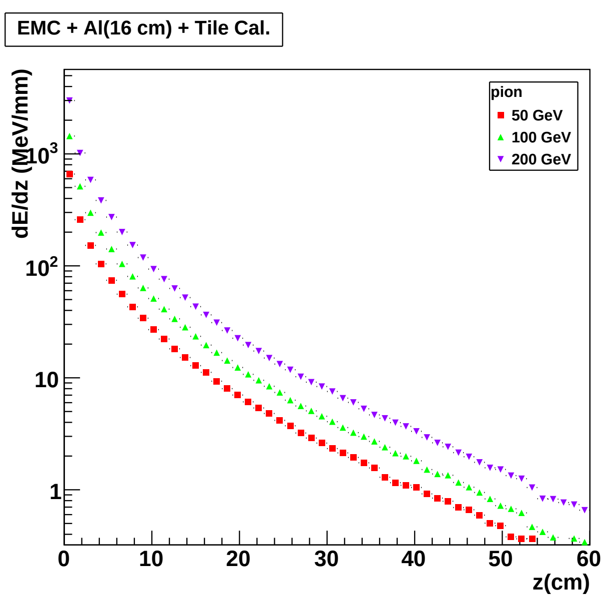


Figure 12.52: Transverse shower profiles for pion induced interactions.

layer plus 5 mm for the other components. The aborber length of the FEC prototype is 10.5 cm, which corresponds to a radiation length of $\approx 30X_0(X_0(W) = 0.3504\,\text{cm})$. The total depth of the FEC is 35.5 cm. The thickness of all FEC layers is given in Table 12.10.

	Nb of Layers	Absorber	Silicon	Silicon support circuit (FR4)	Circuit kapton
	FEC 1-25	1.4 mm	525μm	0.65 mm	1.15 mm
	FEC 26-50	2.8 mm	525μm	0.65 mm	1.15 mm

Table 12.10: Longitudinal segmentation of $\text{FEC}_{(W-Si)}$.

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). The active layers, FR4, and circuit kapton follow the same dimensions as given by the FEC. In the Cu-Si case, the nuclear interaction length of the FHC prototype corresponds to $\approx 10\lambda_I$ (λ_I(Cu)=15.06 cm). The total depth of $\text{FHC}_{(Cu-Si)}$ is 165 cm.The thickness of all $\text{FHC}_{(Cu-Si)}$ layers are given in Table 12.11.

	Nb of Layers	Absorber	Silicon	Silicon support circuit (FR4)	Circuit kapton
	FHC 1-10	2.5 cm	525μm	0.65 mm	1.15 mm
	FHC 11-20	5 cm	525μm	0.65 mm	1.15 mm
	FHC 21-30	7.5 cm	525μm	0.65 mm	1.15 mm

Table 12.11: Longitudinal segmentation of $\text{FHC}_{(Cu-Si)}$.

In the W-Si case, the nuclear interaction length of FHC prototype corresponds to $\approx 10\lambda_I$ (λ_I(W)=9.946 cm). Also in the W-Si case the space between absorber plates is 14 mm unlike the $\text{FHC}_{(Cu-Si)}$ or FEC. Total depth of $\text{FHC}_{(W-Si)}$ is 165 cm. The thickness of all $\text{FHC}_{(W-Si)}$ layers are given in Table 12.12.

	Nb of Layers	Absorber	Silicon	Silicon support circuit (FR4)	Circuit kapton
	FHC 1-15	1.2 cm	525μm	0.65 mm	1.15 mm
	FHC 16-31	1.6 cm	525μm	0.65 mm	1.15 mm
	FHC 32-46	3.8 cm	525μm	0.65 mm	1.15 mm

Table 12.12: Longitudinal segmentation of $\text{FHC}_{(W-Si)}$.

The longitudinal segmentation of the FHC and FEC is given in Figure 12.53. The absorber of the FHC is in blue. The absorber of the FEC is in pink. Finally the silicon detectors, silicon support circuits and circuit kapton of FEC and FHC are in brown, green and gray respectively.

The backward electromagnetic calorimeter (BEC) inserts (i.e. BEC1 and BEC2) are lead-silicon sampling calorimeters. The simulated BEC consists of consecutive layers of Lead (Pb) absorber, a Silicon (Si) active layer, a silicon support circuit (FR4), and circuit kapton in the listed order. The depth of each layer is given by the thickness of the Pb plate used in the layer plus 5 mm for the other components. The absorber length of the BEC prototype is 14 cm,

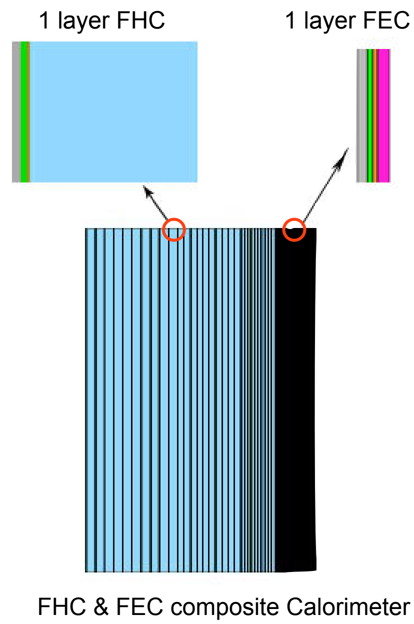


Figure 12.53: Cross section in rz of FHC+FEC.

which corresponds to a radiation length of $\approx 25X_0$ (X_0(Pb) = 0.5612 cm). The total depth of the BEC is 39 cm. The thickness of all BEC layers is given in Table 12.13.

	Nb of Layers	Absorber	Silicon	Silicon support circuit (FR4)	Circuit kapton
	BEC 1-25	1.8 mm	525μm	0.65 mm	1.15 mm
	BEC 26-50	3.8 mm	525μm	0.65 mm	1.15 mm

Table 12.13: Longitudinal segmentation of (Pb-Si) BEC.

the backward hadronic calorimeter (BHC) inserts (i.e. BHC1, BHC2 and BHC3) are iron-silicon sampling calorimeters. The active layers, FR4, and circuit kapton follow the same dimensions as given by the BEC. The Absorber length of the BHC prototype is 132.5 cm, which corresponds to the nuclear interaction length of the $7.9\lambda_I$ (λ_I(Fe)=16.77 cm) The total depth of the BHC is 145 cm.The thickness of all BHC layers are given in Table 12.14.

The overall structure of the BEC, BHC and BEC+BHC composite calorimeter are like their forward electromagnetic and hadronic calorimeter counterparts shown in Figure 12.53.

FEC Simulation Results

All of the FEC simulations were done with a radiation length of $\approx 30X_0$(W).

	Nb of Layers	Absorber	Silicon	Silicon support circuit (FR4)	Circuit kapton
	BHC 1-7	2.5 cm	525μm	0.65 mm	1.15 mm
	BHC 8-15	5 cm	525μm	0.65 mm	1.15 mm
	BHC 16-25	7.5 cm	525μm	0.65 mm	1.15 mm

Table 12.14: Longitudinal segmentation of (Fe-Si) BHC.

$$\frac{\sigma_E}{E} = \frac{(14.0 \pm 0.16)\%}{\sqrt{E}} \oplus (5.3 \pm 0.049)\% \qquad (12.2)$$

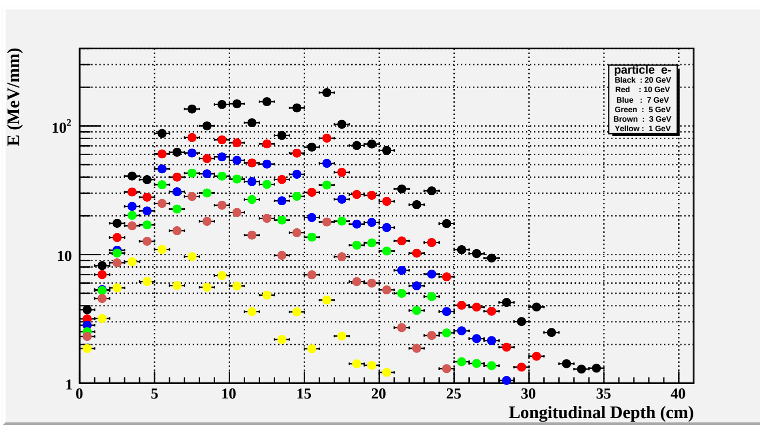


Figure 12.54: Average energy deposition as a function of depth for electrons with energy in range 1 GeV-20 GeV incident on the FEC.

FEC+FHC Composite Calorimeter Simulation Results

GEANT4 simulations were performed in order to determine the shower development profiles and the energy resolutions of the FEC+FHC$_{(Cu-Si)}$ and FEC+FHC$_{(W-Si)}$ combined systems for 50 GeV-1 TeV pions. All the simulations of the FEC + FHC composite system were done for the radiation length of ≈30X$_0$(W) for the FEC and the nuclear interaction length of ≈10λ_I for the FHC.

Cu-Si case of FHC:

$$\frac{\sigma_E}{E} = \frac{(46.0 \pm 1.7)\%}{\sqrt{E}} \oplus 6.1 \pm 0.073)\% \qquad (12.3)$$

W-Si case of FHC:

$$\frac{\sigma_E}{E} = \frac{(45.4 \pm 1.7)\%}{\sqrt{E}} \oplus (4.8 \pm 0.086)\% \qquad (12.4)$$

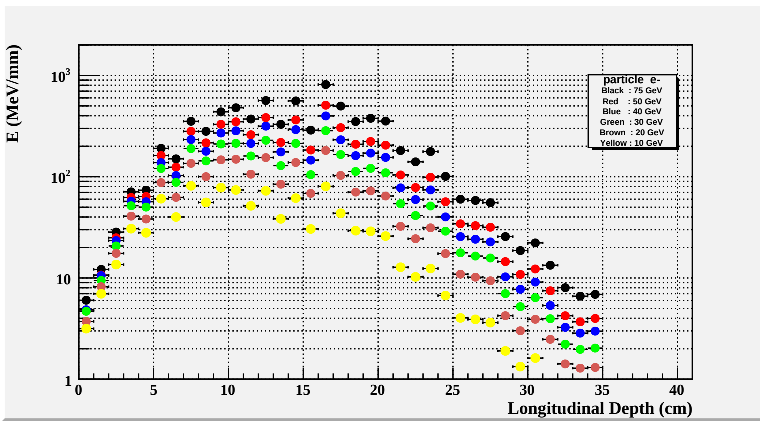


Figure 12.55: Average energy deposition as a function of depth for electrons with energy in range 10 GeV-75 GeV incident on the FEC.

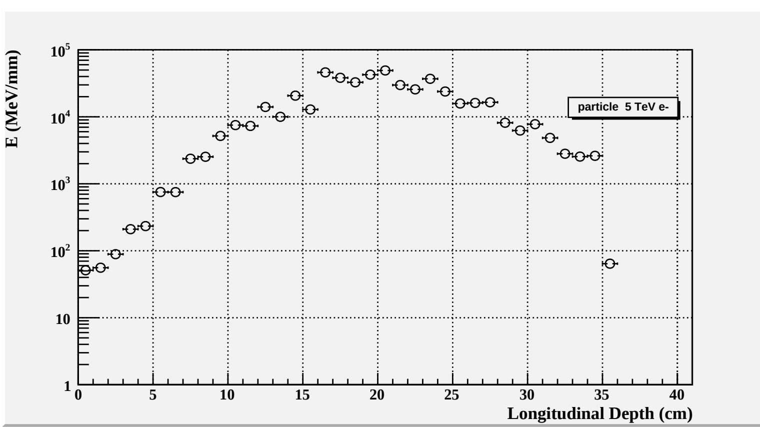


Figure 12.56: Average energy deposition as a function of depth for electrons with energy 5 TeV incident on the FEC

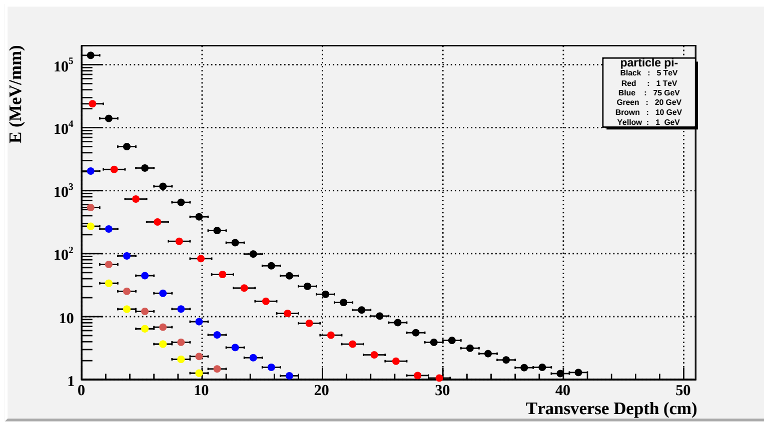


Figure 12.57: Transverse shower profiles for electrons with energy in range 1 GeV-5 TeV in the FEC.

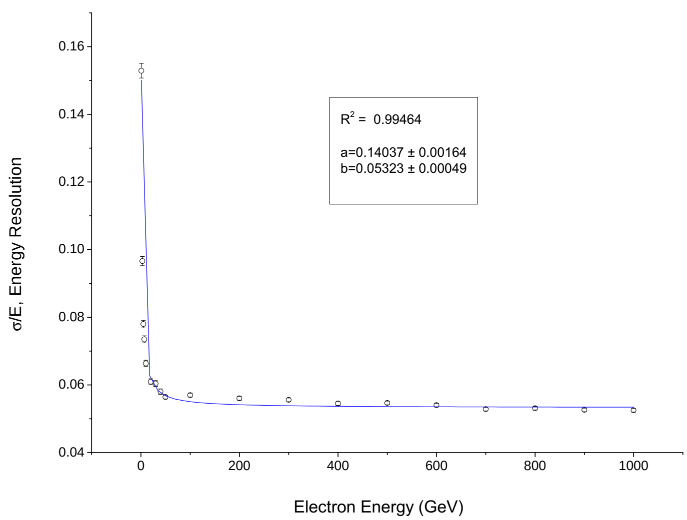


Figure 12.58: Energy Resolution spectra for electrons with energy in range 1 GeV-1 TeV in the FEC.

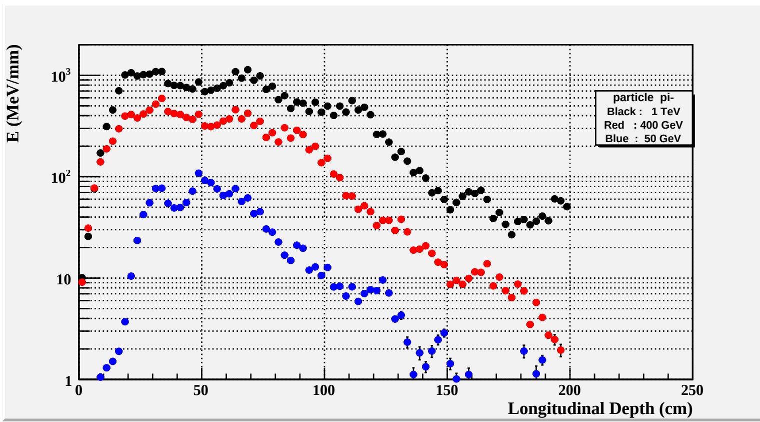


Figure 12.59: Average energy deposition as a function of depth for pions with energy in range $50\,GeV$ - $1\,TeV$ in the FEC1+FEC2 + (copper-silicon) FHC1+FHC2+FHC3 composite system.

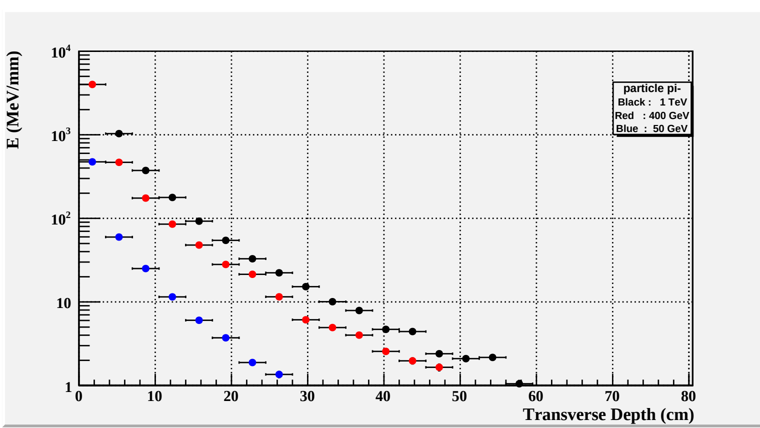


Figure 12.60: Transverse shower profiles for pions with energy in range $50\,GeV$ - $1\,TeV$ in the FEC1+FEC2 + (copper-silicon) FHC1+FHC2+FHC3 composite system.

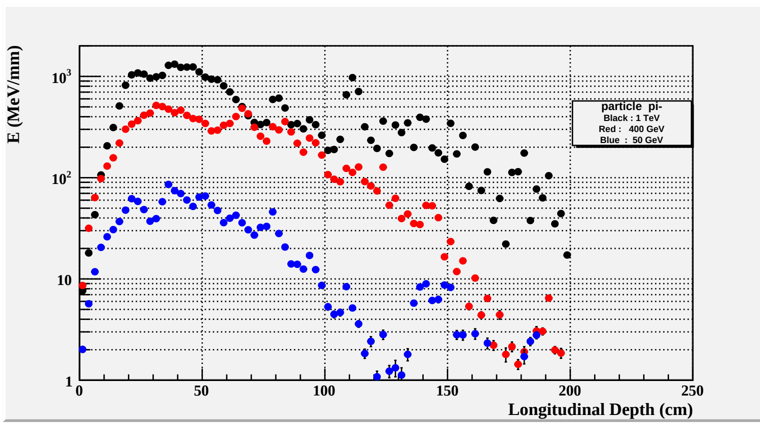


Figure 12.61: Average energy deposition as a function of depth for pions with energy in range $50\,GeV$ - $1\,TeV$ in the FEC1+FEC2 + (tungsten-silicon) FHC1+FHC2+FHC3 composite system.

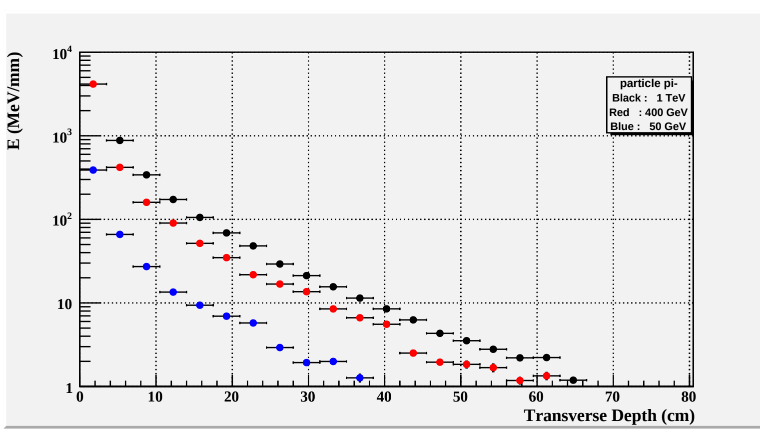


Figure 12.62: Transverse shower profiles for pions with energy in range $50\,GeV$ - $1\,TeV$ in the FEC1+FEC2 + (tungsten-silicon) FHC1+FHC2+FHC3 composite system.

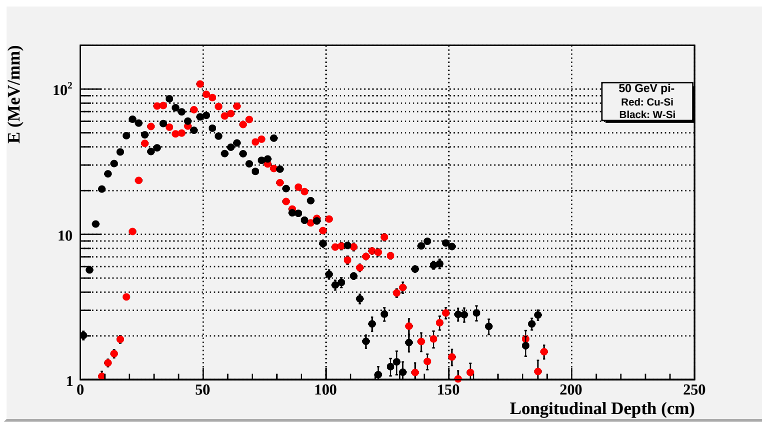


Figure 12.63: Comparision of average energy deposition as a function of depth for pions with energy $50\,GeV$ in cases of the (copper-silicon) and (tungsten-silicon) of the FHC in FEC+FHC composite system.

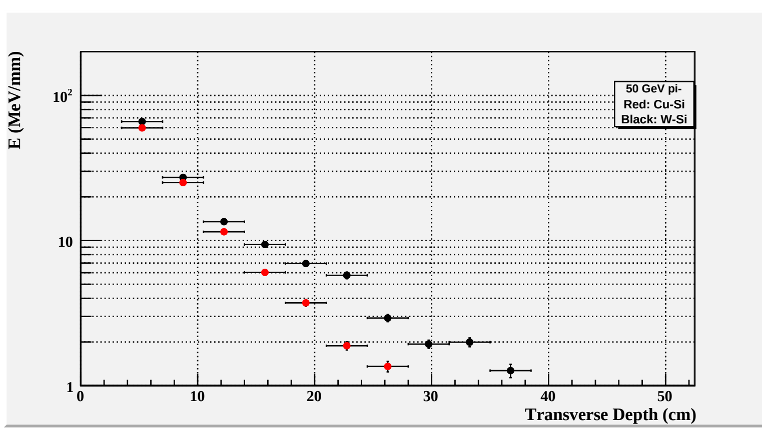


Figure 12.64: Comparision of transverse shower profiles for pions with energy $50\,GeV$ in cases of the (copper-silicon) and (tungsten-silicon) of the FHC in the FEC+FHC composite system.

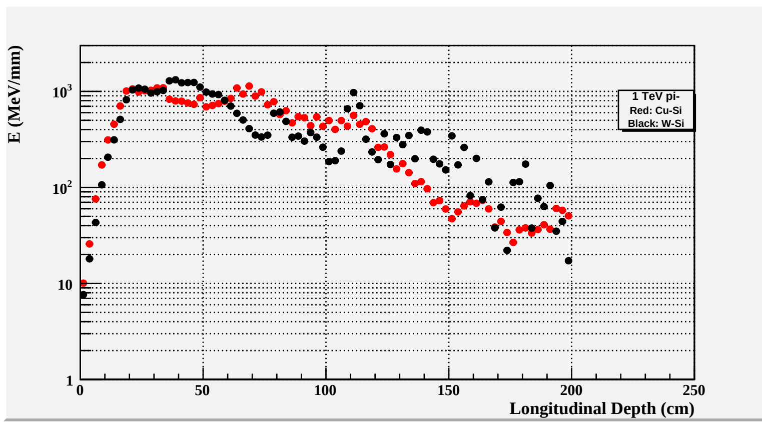


Figure 12.65: Comparision of average energy deposition as a function of depth for pions with energy $1\,TeV$ in cases of the (copper-silicon) and (tungsten-silicon) of the FHC in FEC+FHC composite system.

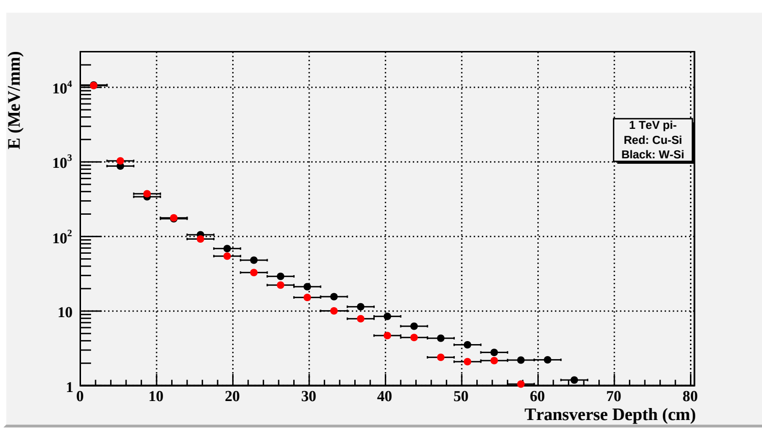


Figure 12.66: Comparision of transverse shower profiles for pions with energy $1\,TeV$ in cases of the (copper-silicon) and (tungsten-silicon) of the FHC in FEC+FHC composite system.

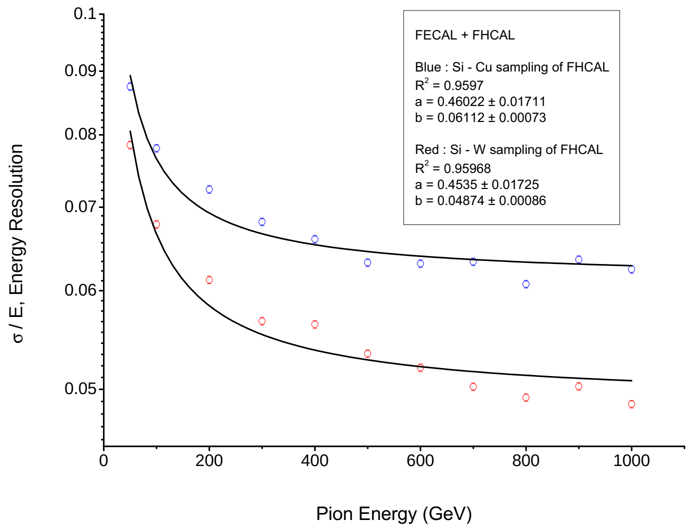


Figure 12.67: Comparision of energy resolution spectrums for pions with energy in range 50 GeV - 1 TeV in cases of the (copper-silicon) and (tungsten-silicon) of the FHC in FEC+FHC composite system.

BEC Simulation Results

All of the BEC simulations were done for a radiation length of $\approx 25X_0$(Pb), and incident electrons.

Pb-Si case of BEC:

$$\frac{\sigma_E}{E} = \frac{(11.4 \pm 0.5)\%}{\sqrt{E}} \oplus (6.3 \pm 0.1)\% \tag{12.5}$$

BEC+BHC Composite Calorimeter Simulation Results

All the simulations for the BEC (radiation length of $\approx 25X_0$(Pb)) and BHC (nuclear interaction length of $\approx 8\lambda_I$), were done for incident pions.

Energy resolution for the BEC+BHC composite system:

$$\frac{\sigma_E}{E} = \frac{(21.6 \pm 1.9)\%}{\sqrt{E}} \oplus (9.6 \pm 0.4)\% \tag{12.6}$$

12.8.2 Calorimeter Simulation Conclusion

Lateral development of the electromagnetic showers initiated by electrons or photons scales with the Moliere radius. The Moliere Radii of tungsten and lead are 0.9327 cm and 1.602 cm [28], respectively. The surface area of the calorimeters (Forward and Backward) is 300 cm×300 cm,

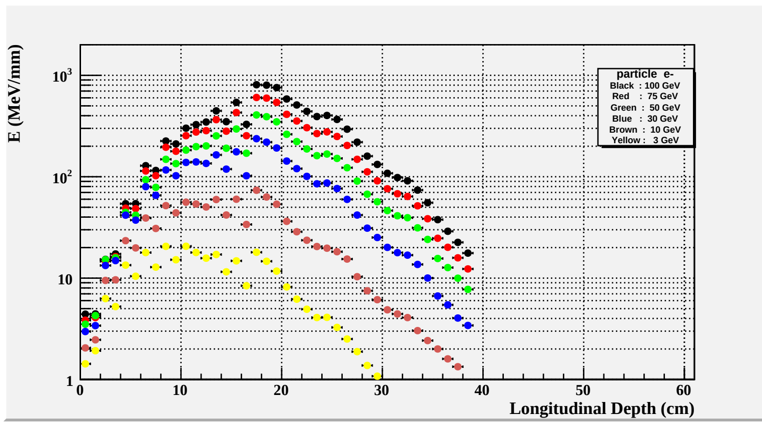


Figure 12.68: Average energy deposition as a function of depth for electrons with energy in range $3\,GeV$ - $100\,GeV$ incident on the BEC.

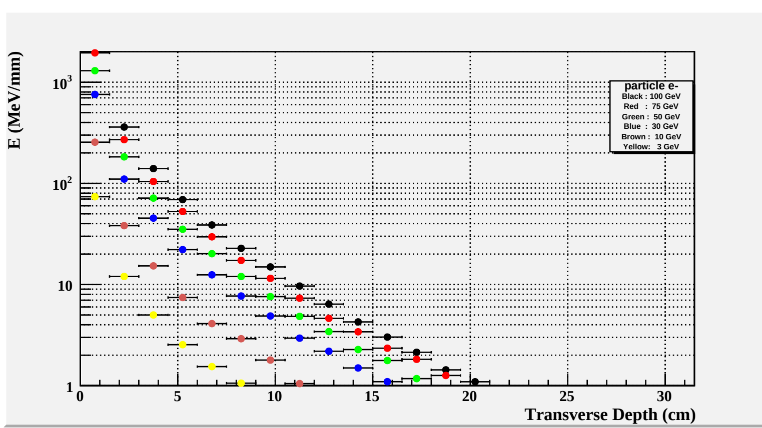


Figure 12.69: Transverse shower profiles for electrons with energy in range $3\,GeV$ - $100\,GeV$ incident on the BEC.

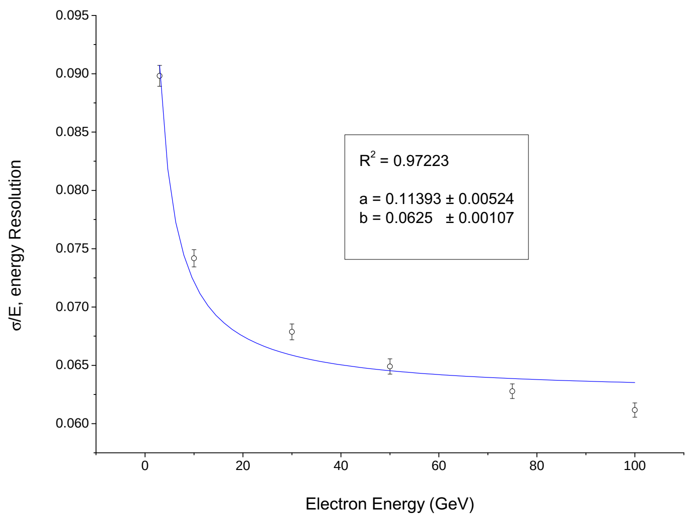


Figure 12.70: Energy resolution spectrum for electrons with energy in range 3 GeV - 100 GeV in the BEC.

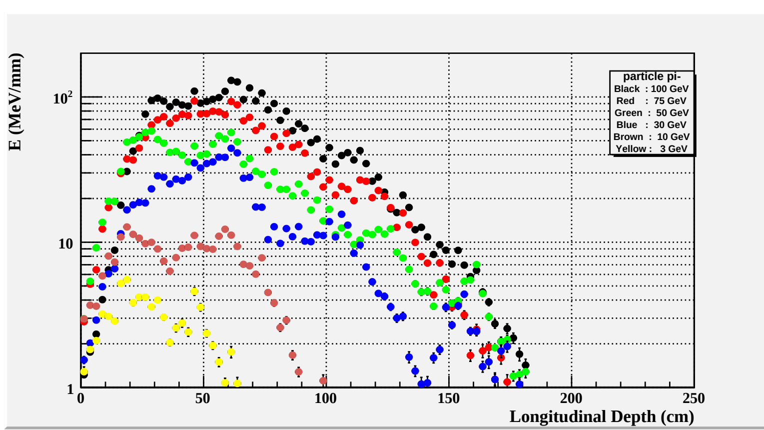


Figure 12.71: Average energy deposition as a function of depth for pions with energy in range 3 GeV - 100 GeV incident on the BEC+BHC composite system.

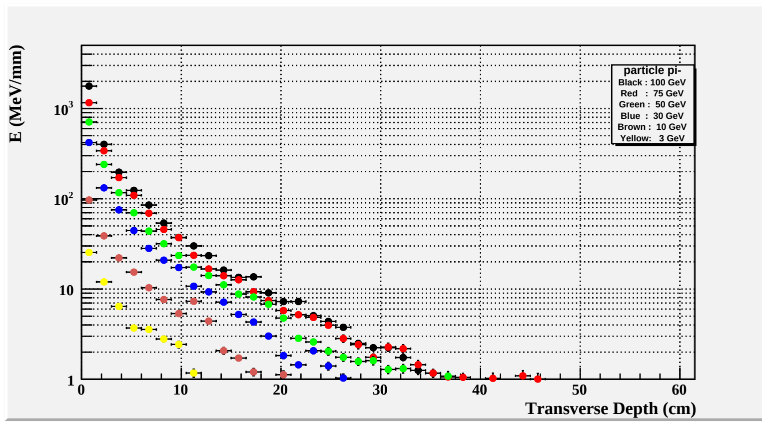


Figure 12.72: Transverse shower profiles for pions with energy in range 3 GeV-100 GeV incident on the BEC+BHC composite system.

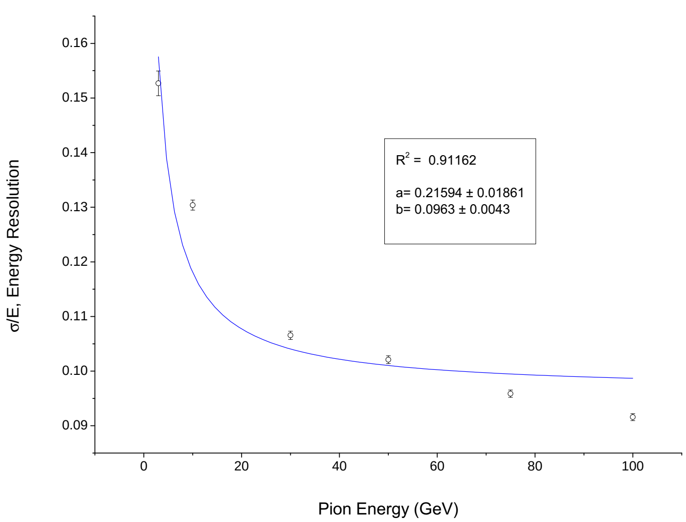


Figure 12.73: Energy resolution spectrum for pions with energy in range 3 GeV-100 GeV in the BEC+BHC composite system.

which is larger than Moliere radii, so that the whole shower is contained in the FEC or BEC transversely. The simulated maximum longitudinal shower profile for electrons in the FEC and BEC is in agreement with literature [689]. Avaraged 99.4 and 98.8 percent of the incident energy for electron energies in ranges of 1 GeV-1 TeV for FEC and 3 GeV-100 GeV for BEC are deposited in the electromagnetic calorimeter in the simulation, respectively. The relation between the depth of the shower maximum and amount of the deposited energy in the FEC or BEC is acceptable in the simulation. Also,we observed that the FEC and BEC show a linearity with 72% and 100% respectively. But, as can be seen from Fig 12.54, Fig 12.55 and Fig 12.56 for the FEC and from Fig 12.68 for BEC ,it is obvious that there will be the problem of shower leakage for these incident electron energies and higher electron energies in case of the radiation lengths of $\approx 30X_0$(W) and $\approx 25X_0$(Pb) for the FEC and BEC, respectively. Incoming electron energy to the front surface of FEC or BEC increases, an increase in the shower leakages were observed. The FEC and BEC have the stochastic terms of (14.0±0.16%) and (11.4±0.5%) and the constant terms of (5.3±0.049%) and (6.3±0.1%), respectively. If the variations in the energy leakage from the FEC or BEC via back surfaces can be prevented, the constant terms will be smaller than these values.

Longitudinal distribution of the hadronic calorimeters and shower maximum of the longitudinal distrubition are scaled with λ_I. Nuclear interaction length of the copper is bigger ≈51% than tungsten one. Accordingly, we observed that the shower maximum of the $\mathrm{FHC}_{(W-Si)}$ is in the smaller depth. Avaraged 82.6% and 85.5% of pion's energy is deposited in the $\mathrm{FEC+FHC}_{(Cu-Si)}$ and the $\mathrm{FEC+FHC}_{(W-Si)}$ combined systems and the combined systems have linearities with percentages 83.5% and 84%, respectively. Both of the combined systems have some leakages as can see in Fig 12.59 and Fig 12.61 in the higher pion's energies. In case of (W-Si) sampling, the leakage from FEC+FHC combined system is smaller 3% than (Cu-Si) sampling (see Fig 12.63). In the simulation, stochastic terms of the energy resolutions in both cases have the similar values, but the constant value of the $\mathrm{FEC+FHC}_{(W-Si)}$ are smaller by 21.3% than $\mathrm{FEC+FHC}_{(Cu-Si)}$ one. This means that if the $\mathrm{FEC+FHC}_{(W-Si)}$ combined calorimeter is used, the leakges will be smaler.

We observed that avaraged deposited pion's energy is 77.5% of the incident pion's energy in the BEC+BHC combined system and the linearity of the combined system has a percentage 72.8%. It is obvious that there are some leakages for the backward combined system according to the simulation.

12.9 Further Option

- detector design B. - No solenoid within the calorimetry.

12.10 Calorimeter Summary

- Validation of present simulation
- Alternative Calorimeter Design toward New Technologies
- Discussion : what makes sense, what not. A word on PFA etc.
- Technologies and timescale: a dual readout fully active calorimetry.

- RPC based Digital readout, integrated calorimeter and muon detector.

12.11 Muon Detector

Fig. 12.74.

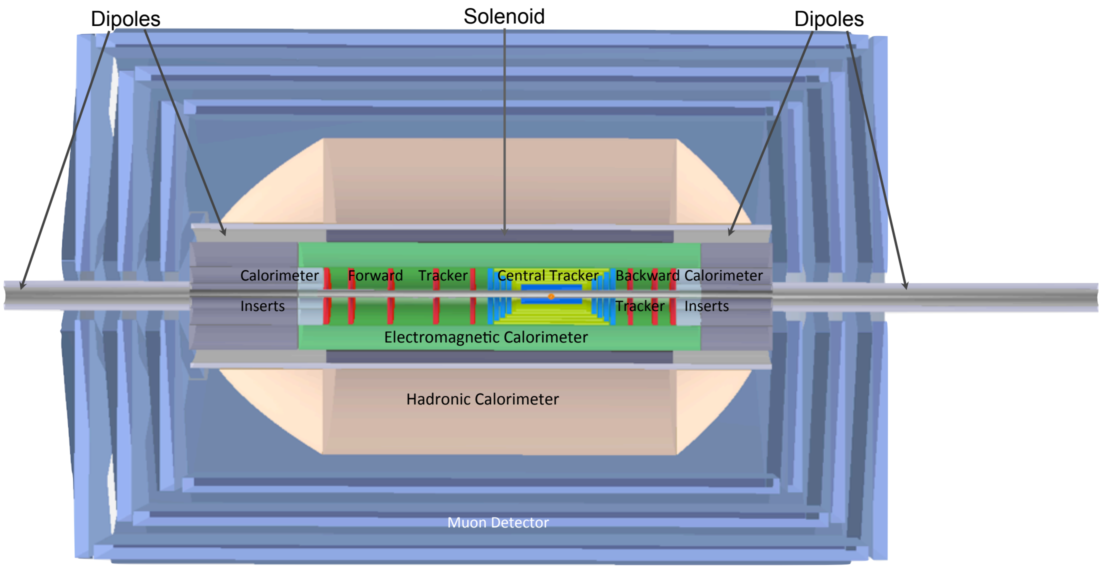


Figure 12.74: A full view of the baseline detector in the r-z plane with all components shown. The detector dimensions are $\approx 14\,\text{m}$ in z with a diameter of $\approx 9\,\text{m}$.

Chapter 13

Forward and Backward Detectors

13.1 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 [690, 691] and ZEUS [692, 693] 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 luminosity[1] $L = (10^{32} - 2 \cdot 10^{33})\text{cm}^{-2}\text{s}^{-1}$. Hence suitable processes for the three tasks outlined above should have the following minimal visible cross sections[2]:

- fast monitoring ($\delta\mathcal{L} = 1\%$/sec $\Rightarrow$10 kHz) – $\sigma_{\text{vis}} \gtrsim 100\mu\text{b}$,
- mid-term control ($\delta\mathcal{L} = 0.5\%$/hour $\Rightarrow$10 Hz) – $\sigma_{\text{vis}} \gtrsim 100\text{nb}$,
- physics sample normalisation ($\delta\mathcal{L} = 0.5\%$/week $\Rightarrow$0.1 Hz) – $\sigma_{\text{vis}} \gtrsim 1\text{nb}$.

The best candidate for luminosity determination is the purely electromagnetic *bremsstrahlung reaction* $ep \to e\gamma + p$ shown in Figure 13.1a, which has a large and precisely known cross section. Depending on the photon emission angle it is called either Bethe-Heitler process (collinear emission) or QED Compton scattering (wide angle bremsstrahlung). In addition, Neutral Current DIS events in a well understood (x, Q^2) range can be used for the *relative* normalisation and mid-term yield control.

[1] This also takes into account exponential reduction of L during the data taking in every luminosity fill.
[2] Statistical error has to be small in comparison with total error δL_{tot} in order not to spoil overall accuracy.

While QED Compton and NC DIS processes can be measured in the main detector dedicated 'tunnel detectors' are required to register Bethe-Heitler events. For the latter, additional challenges as compared to HERA are related to the LHeC specifics: non-zero beam crossing angle in IP for RR option, and severe aperture limitation for LR option. Finally, for the high luminosity LHeC running one should not forget about significant pileup (L/bunch is $\sim 2-3$ times bigger as compared to HERA-II running).

13.1.1 Options

The huge rate of 'zero angle' electrons and photons from Bethe-Heitler reaction[3] makes a dedicated luminosity system in the tunnel ideal for fast monitoring purposes. However, it is usually very sensitive to the details of the beam optics at the IP, may suffer from synchrotron radiation (SR) and requires, for accurate absolute normalisation, a large and precisely known geometrical acceptance which is often difficult to ensure. On the contrary, the main detector has stable and well known acceptance and is safely shielded against SR. Therefore, although QED Compton events in the detector acceptance have significantly smaller rates they may be better suited for overall global normalisation of the physics samples. Thus the two methods are complementary, having very different systematics and providing useful redundancy and cross check for the luminosity determination.

To evaluate the main LHeC detector acceptance for NC DIS events and for the elastic QED Compton process `DJANGOH` [694] and `COMPTON` [695] event generators were used respectively. Different options for dedicated luminosity detectors in the LHC tunnel have been studied with help of the special `H1LUMI` program package [696], which contains Monte Carlo generation of the 'collinear' photons and electrons from various processes (Bethe-Heitler reaction, quasi-real photoproduction, e-beam scattering on the rest gas) as well as a simple tracking through the beamline.[4]

13.1.2 Use of the Main LHeC Detector

To estimate visible cross sections for NC DIS and elastic QED Compton events a typical HERA analysis strategy was used. That is: safe fiducial cuts against energy leakage over the backward calorimeter boundaries at small radii, safe (Q^2, y) cuts for NC DIS events to restrict measurement to the phase space where F_2 is known to good precision of $1-2\%$ and the F_L contribution is negligible, and elasticity cuts for QEDC events to reject the less precisely known inelastic contribution. In addition basic cuts against major backgrounds were applied (photoproduction in case of NC DIS and DVCS, elastic VM production and low mass diffraction in case of QED Compton).

The visible NC DIS cross section, $\sigma_{\rm vis}^{DIS}(Q^2 > 10{\rm GeV}^2, 0.05 < y < 0.6) \simeq 10$ nb for 10° setup and $\simeq 150$ nb for 1° setup. This corresponds to a $10-15$ Hz rate which is comfortable enough for mid-term yield control.

For elastic QED Compton events, the visible cross section, $\sigma_{\rm vis}^{QEDC} \simeq 0.03$ nb for 10° setup and $\simeq 3.5$ nb for 1° setup. Hence while for the latter sufficiently high rate is possible even for $L = 10^{32}{\rm cm}^{-2}{\rm s}^{-1}$, in case of 'high Q^2' setup the QEDC event rate is $4-5$ times smaller, thus only providing acceptable statistical precision for large samples, of the order 0.5%/month.

[3] Total cross section, $\sigma_{BH} \simeq 870$ mb for 60×7000 GeV^2 ep collisions at the LHeC.

[4] The tracking has been performed by interfacing H1LUMI to GEANT3 [697] having LHeC beamline implemented up to ~ 110m from the IP.

In order to improve this a special small dedicated calorimeter could eventually be added after the strong focusing quadrupole, at $z = -6$m. Such 'QEDC tagger' should consist of two movable stations approaching the beam-pipe from the top and the bottom in the vertical direction, as sketched in Figure 13.1b. This way detector sections will be safe with respect to SR fan confined in the median plane. The visible elastic QED Compton cross section for such a device is 4.3 ± 0.2 nb which significantly improves statistics for the luminosity measurement. The angular acceptance of the 'QEDC tagger' corresponds to the range $\theta = 0.5^\circ - 1^\circ$ which lies outside the tracking acceptance. Therefore calorimeter sections should be supplemented by small silicon detectors in order to make it possible to reconstruct the event vertex from the final state containing only one electron and one photon. These silicon trackers are also useful for e/γ separation and rejection of the potential background. Actual dimensions and parameters of this optional 'QEDC tagger' requires extra design studies.

13.1.3 Dedicated Luminosity Detectors in the tunnel

In case of the RR-option which implies non-zero crossing angle for early e/p beam separation, the dominant part of the Bethe-Heitler photons will end up at $z \simeq -22$m, between electron and proton beam-pipes (see Figure 13.1c). This is the hottest place where also a powerful SR flux must be absorbed. On the first glance this makes luminosity monitoring based upon the bremsstrahlung photons impossible.

There is however an interesting possibility. SR absorber needs good cooling system. The most natural cooling utilises circulating water. This cooling water can be used at the same time as an active media for Čerenkov radiation from electromagnetic showers initiated by the energetic Bethe-Heitler photons. The idea is based on two facts:

1. The dominant part of the SR spectrum lies below the Čerenkov threshold for water, $E_{\rm thr} = 260$ keV, and hence will not produce light signal. Low intensity tail of the energetic synchrotron photons can be further suppressed by few radiation lengths of the absorber material in front of the water volume.

2. Water is absolutely radiation resistant media and hence such simple Čerenkov counter can stand any dose without performance deterioration.

The Čerenkov light can be collected and read out by two photo-multipliers as sketched on Figure 13.1d. The geometric acceptance depends on the details of the e-beam optics. For the actual RR design with the crossing angle ~ 1 mrad the acceptance to the Bethe-Heitler photons is up to 90%, thus allowing fast and reliable luminosity monitoring with $3 - 5\%$ systematic uncertainty.

Of course, such an active SR absorber is not a calorimeter with good energy resolution, but just a simple counter. It is worth noting, that similar water Čerenkov detector has been successfully used in the H1 Luminosity System during HERA-I operation.

In case of LR-option, electrons collide with protons head-on, with zero crossing angle. This makes the situation very similar to HERA, where Bethe-Heitler photons travel along the proton beam direction and can be caught at around $z = -120$m, after the first proton bending dipole. Essential difference is that unlike HERA, LHC protons are deflected horizontally at this place rather than vertically. Thus the luminosity detector should be placed in the median plane next to the interacting proton beam, p_1, as shown on Figure 13.1e. In this case energy measurement with good resolution is not a problem, so major uncertainty will come from the knowledge of the limited geometric acceptance. This limitation is defined by the proton beam-line aperture, in particular by the aperture of the quadrupoles Q1-Q3 of the low-beta proton triplet. Moreover, it might be necessary to split D1 dipole into two parts in order to provide escape path for the photons with sufficient aperture. First estimates show that the geometric acceptance of the Photon Detector up to 95% is possible at the nominal beam conditions. HERA experience tells, that the uncertainty can be estimated as $\delta A = 0.1 \cdot (1 - A)$ leading to the total luminosity error of $\delta L = 1\%$ in this case.

13.1.4 Small angle Electron Tagger

The Bethe-Heitler reaction can be tagged not only by detecting a final state photon, but also by detecting the outgoing electron. Since all other competing processes have much smaller cross sections measuring inclusive rate of the scattered electrons under zero angle will provide a clean enough sample for luminosity monitoring. The remaining small background (mainly due to off-momentum electrons from e-beam scattering on the rest gas) can be precisely controlled and statistically subtracted using non-colliding (*pilot*) electron bunches.

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] $z = -14$m, -22m and -62m. As one can see on the top part of Figure 13.2 all places provide reasonable acceptances, reaching approximately $(20 - 25)\%$ at the maximum. However, $z = -14$m and $z = -22$m most likely will suffer from SR flux, making e-tagger operation problematic at those positions.

The most promising position for the Electron tagger is at $z = -62$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 13.2. 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, $x_{\rm off}$, of $\pm 20\mu$m leads to the systematic uncertainty of 5% in the visible cross section, $\sigma_{\rm vis}(ET62)$.

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.

In order to demonstrate that the ideas described in Sec. 13.1.3 and 13.1.4 are realistic a typical example of the online rates variations for the H1 Luminosity System at HERA is shown on Figure 13.3. The system utilised all three types of the detectors discussed above: a total absorption electromagnetic calorimeter for the Bethe-Heitler photons (PD), a water Čerenkov counter (VC) and the Electron tagger (ET6). One can see, that online luminosity estimate by every of those detectors is well within 5% in spite of significant changes in the acceptance due to electron beam tilt jumps and adjustments at the IP.

[5] For the station at $z = -14$m the electron dipole magnet should be split into two parts, while the region around $z = -62$m has sufficiently comfortable place for the Electron tagger, before the e-beam is bended vertically.

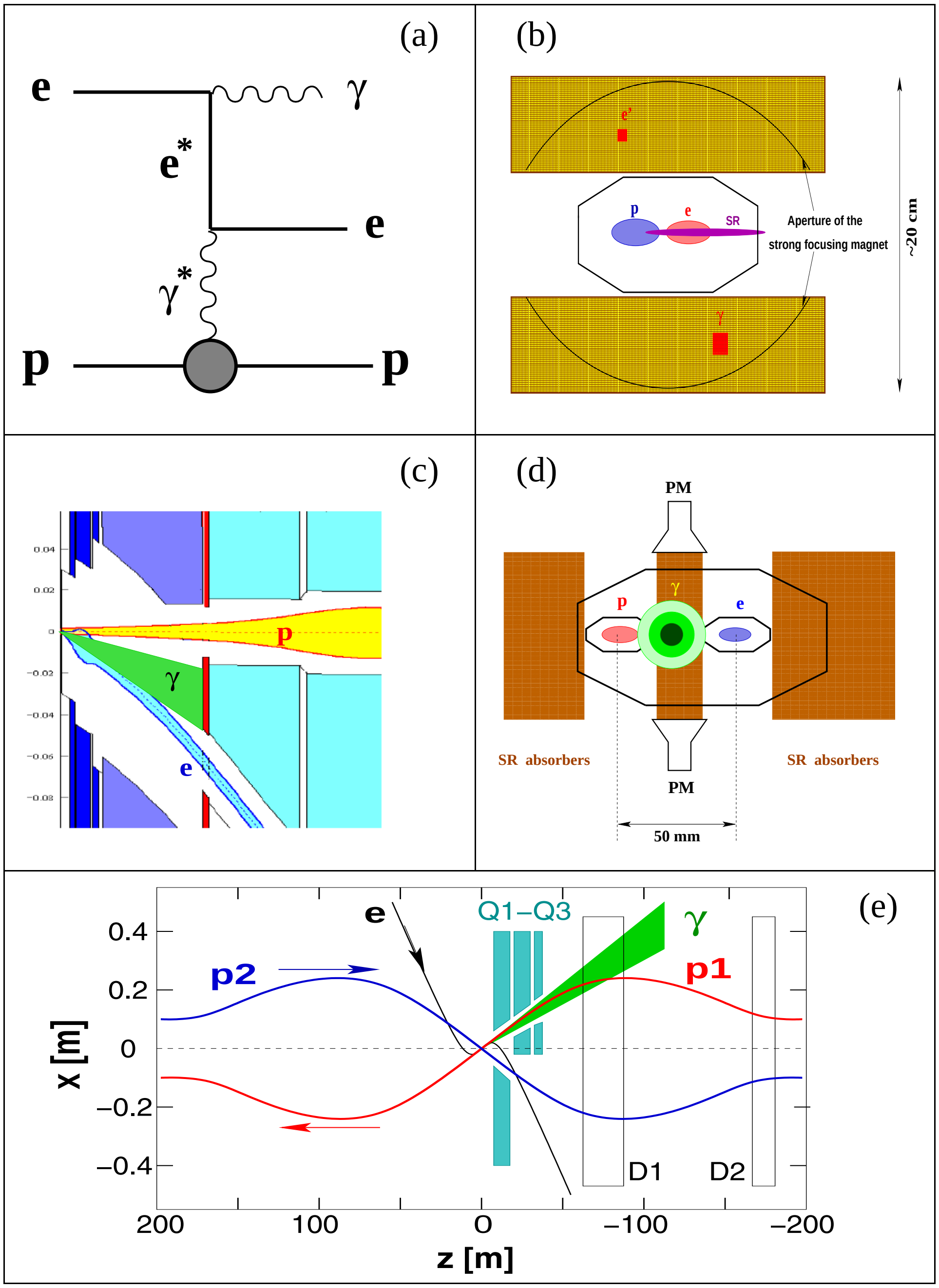


Figure 13.1: Options for the luminosity monitoring at the LHeC. (a) Feynman diagram for QEDC (γ^* pole) or BH (γ^*, e^* poles) processes; (b) QEDC tagger at $z = -6$m; (c,d) active SR absorber at $z = -22$m for RR-option (circles show 1-, 2- and 3-σ contours for BH photons); (e) schematic view for the LR-option with 3-σ fan of BH photons.

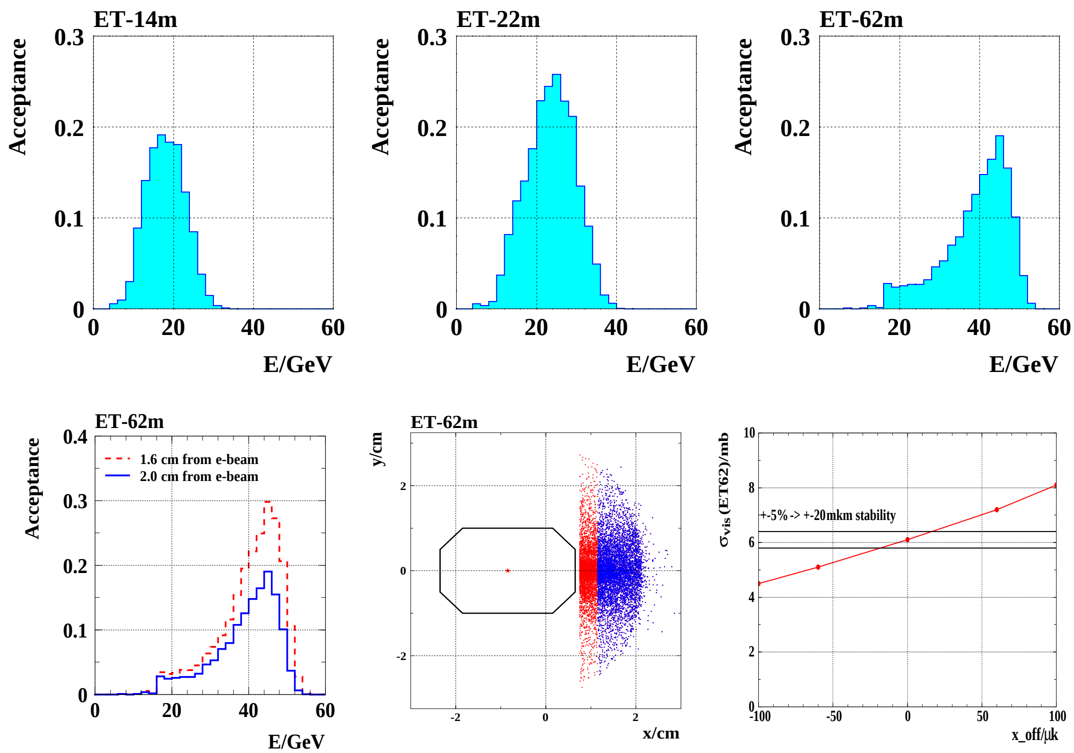


Figure 13.2: Top: acceptances of the e-taggers for Bethe-Heitler events at different z-positions from IP (RR-option). Bottom: variations in the acceptance of the e-tagger at $z = -62$m as a function of its position with respect to the e-beam axis and on the horizontal offset of the beam orbit at the IP.

13.1.5 Summary and Open Questions

Accurate luminosity measurement at the LHeC is highly non-trivial task. As follows from HERA experience unexpected surprises are possible, hence it is important to consider several scenarios from the beginning and to prepare alternative methods for luminosity determination.

Statistical precision and systematic uncertainties for different methods of luminosity measurement are summarised in Table 13.1.

Precise determination of integrated luminosity, $\mathcal{L}$, is possible with the main detector utilising the QEDC process. $\delta\mathcal{L} = 1.5 - 2\%$ is within reach. Further improvement requires in particular more accurate theoretical calculation of the elastic QED Compton cross section, with $\delta\sigma_{\rm el}^{\rm QEDC} \lesssim 0.5\%$. To enhance statistical precision a dedicated QEDC tagger at $z = -6$m might be useful. This device could also be used to access very low Q^2 region, interpolating between DIS and photoproduction regimes.

Fast instantaneous luminosity monitoring is challenging, but several options do exist which are based upon detection of the photons and/or electrons from the Bethe-Heitler process.

- Photon Detector at $z = 110$m for LR option requires properly shaped proton beam-pipe

Method	Stat. error	Syst.error	Systematic error components		Application
BH (γ)	0.05%/sec	1−5%	$\sigma(E \gtrsim 10\text{GeV})$	0.5%	Monitoring, tuning,
			acceptance, A	10%(1−A)	short term variations
			E-scale, pileup	0.5 − 4%	
BH (e)	0.2%/sec	3−6%	$\sigma(E \gtrsim 10\text{GeV})$	0.5%	Monitoring, tuning,
			acceptance	2.5 − 5%	short term variations
			background	1%	
			E-scale	1%	
QEDC	0.5%/week	1.5%	σ (el/inel)	1%	Absolute $\mathcal{L}$,
			acceptance	1%	global normalisation
			vertex eff.	0.5%	
			E-scale	0.3%	
NC DIS	0.5%/h	2.5%	σ ($y < 0.6$)	2%	Relative $\mathcal{L}$,
			acceptance	1%	mid-term variations
			vertex eff.	1%	
			E-scale	0.3%	

Table 13.1: Dominant systematics for various methods of luminosity measurement.

at $z = -68 - 120$m from IP2.

- In case of RR option Bethe-Heitler photons can be detected using a water Čerenkov counter integrated with SR absorber at $z = -22$m.

- Electron tagger at $z = -62$m is very promising for both LR and RR schemes. It can be used not only for luminosity monitoring, but also to enhance photoproduction physics capabilities and to provide extra control of the γp background to DIS, by tagging quasi-real photoproduction events.

Good monitoring of the e-optics at the IP is required to control acceptances of the tunnel detectors to a level of $2 - 5\%$.

13.2 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 [?] and at HERA [?] 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

$$E_{e,min} \approx E_0 \frac{1}{1+x},$$

where E_0 is the electron/positron beam energy and $x = 4kE_0/m_e^2$ with k being the laser photon beam energy. At LHeC and for a $\approx 1\mu$m laser beam wavelength, one gets $E_{\gamma,max} \approx 29$GeV and $E_{e,min} \approx 31$GeV. Providing that the laser beam is circularly polarised, the electron/positron beam longitudinal polarisation is obtained from a fit to the scattered photon and/or to the electron energy spectrum. From an experimental point of view, both measurements can be complementary since the high energy region of the scattered photon energy spectrum is sensitive to the electron/positron beam longitudinal polarisation, whereas it is the opposite for the scattered electron/positron energy spectrum. Indeed, the high measurement precision of SLC was achieved thanks to the measurement of the scattered electrons. The measurement of both scattered photon and electron/positron spectra was therefore foreseen for a very high precision polarimetry at future electron-positron high energy colliders [**?**, **?**].

For LHeC, we may follow the work done for the future linear colliders [?]. In order to reach the per mille level on the longitudinal polarisation measurement, one may measure both the scattered photon and electron energy spectrum.

13.2.1 Polarisation from the scattered photons

The photons are scattered within a very narrow cone of half aperture $\approx 1/\gamma$. It is therefore impossible to distinguish the photons reaching the calorimeter. As for the extraction of the longitudinal polarisation from the scattered photon beam energy, one may then distinguishes three dynamical regimes [**?**]. The single and few scattered photons regimes, where one can extract the polarisation from a first principle fit to the scattered photon energy spectrum; the multi-photon regime where the central limit theorem holds for the energy spectra and where the longitudinal polarisation is extracted from an asymmetry between the average scattered energies corresponding to a circularly left and right laser beam polarisation [**?**]. Both regimes have positive and negative experimental features. In the single and few photon regimes the energy spectra exhibits kinematical edges which allow an in situ calibration of the detector energy response but the physical accelerator photon background which is difficult to model precisely, e.g. synchrotron radiation, limits the final precision on the polarisation measurement [?]. In the multi-photon regime, the background is negligible since it is located at low energy but one cannot measure the energy calibration of the detector in situ and one must rely on some high energy extrapolation of calibrations obtained at low energy [?] (e.g. for 100 scattered photon/bunch the deposited energy in the calorimeter would be more than 1TeV at LHeC). However, the laser technology has improved in the last ten years and one can consider at present a very stable pulsed laser beam with adjustable pulse energy allowing to operate in single, few and multi photon regimes. In this way, one can calibrate the calorimeter in situ and optimise the dynamical regime, a multi-photon regime as close as possible to the few photon regime, in order to minimise the final uncertainty on the polarisation measurement.

13.2.2 Polarisation from the scattered electrons

The nice feature of the scattered electron/positron is that one can use a magnetic spectrometer to distinguish them from each other. Following [?] one may carefully design a Compton interaction region in order to implement a dedicated electron spectrometer followed by a segmented electron detector in order to measure the scattered electron angular spectrum, itself related to the electron energy spectrum. A precise particle tracking is needed but this experimental method also allows a precise control of the systematic uncertainties [?].

Common to both techniques is the control and measurement of the laser beam polarisation. it was shown in [**?**] that a few per mille precision can be achieved in an accelerator environment. Therefore, with a redundancy in measuring the electron/positron beam longitudinal polarisation from both the electron and photon scattered energy spectra, a final precision at the per mille level will be reachable at LHeC.

13.3 Zero Degree Calorimeter

The goal of Zero Degree Calorimeter (ZDC) is to measure the energy and angles of very forward particles. At HERA experiments, H1 and ZEUS, the forward neutral particles scattered at polar angles below 0.75 mrad have been measured in the dedicated Forward Neutron Calorimeters (FNC) [466, 698]. The LHC experiments, CMS, ATLAS, ALICE and LHCf, have the ZDC calorimeters for detection of forward neutral particles, ALICE has also the ZDC calorimeter for the measurements of spectator protons [699–703].

The ZDC calorimeter will be an important addition to the future LHeC experiment as many physics measurements in ep, ed and eA collisions can be made possible with the installation of ZDC.

13.3.1 ZDC detector design

The position of the Zero Degree Calorimeter in the tunnel and the overall dimensions depend mainly on the space available for the installation. At the LHC the beams are deflected by two separating dipoles. These dipoles also deflect the spectator protons, separating them from the neutrons and photons, which scatter at $\sim 0^\circ$.

The ZDC detector will be made of two calorimeters: one for the measurement of neutral particles at 0° and another one positioned externally to the outgoing proton beam for the measurement of spectator protons from eD and eA scattering. The geometry, technical specifications and proposed design of ZDC detectors are to large extent similar to the ZDCs of the LHC experiments. There the ZDC calorimeter for detection of neutral particles are placed at $z = 115 - 140$ m in a 90 mm narrow space between two beam pipes. (The photo of neutron calorimeter of ALICE experiment [699, 700] is shown in Figure 13.4). In the case of the LHeC, the ZDC calorimeter can be placed in the space available at about $90 - 100$ m next to the interacting proton beam pipe, as indicated in Figure 13.5.

Below the general considerations for the design are presented. In order to finalise the study of the geometry of detectors, a detailed simulation of the LHeC interaction region and the beamline must be performed.

13.3.2 Neutron Calorimeter

The design of ZDC has to satisfy various technical issues. Detector has to be capable of detecting neutrons and photons produced with scattering angles up to 0.3 mrad or more and energies between some hundreds GeV to the proton beam energy (7 TeV) with a reasonable resolution of few percents. It should be able to distinguish hadronic and electromagnetic showers (i.e. separate neutrons from photons) and to separate showers from two or more particle entering the detector (i.e. needs position resolution of $\mathcal{O}$(1mm) or better).

The condition, that at least 95% of hadronic shower of $\mathcal{O}$(TeV) is contained within the calorimeter, requires 9.5–10 nuclear interaction lengths of absorber. The neutron ZDC will be made of two sections. The front part of calorimeter (electromagnetic section) with 1.5-2 λ length and fine granularity is needed for precise determination of the position of impact point, discrimination of electromagnetic and hadronic showers and separation of showers from two or more particles entering the detector. The hadronic section of the ZDC can be built with coarser sampling, which gives an increase of average density and, consequently, the increase of effective nuclear interaction length. The ZDC will be operating in a very hard radiation environment, therefore it has to be made of radiation resistant materials. Since the different parts of calorimeter undergo different intensity of radiation (higher for front part), it is advantageous to have longitudinal segmentation of 4-5 identical sections, which will allow to control the change of energy response due to radiation damage. Comparison of the energy spectrum from the showers which start in different sections can be used for correction of changes in energy response.

A possible solution to build a compact device with good radiation resistance is to use spaghetti calorimeter with tungsten absorbers and quartz fibres. The principle of operation is based on the detection of Cherenkov light produced by the shower's charged particles in the fibres. These detectors are proven to be fast ($\sim$few ns), radiation hard and have good energy resolution. Using tungsten as a passive material allows the construction of compact devices. One can also consider option to use thick gaseous electron multipliers (THGEM) [704, 705] as active media.

13.3.3 Proton Calorimeter

In analogy to ALICE experiment, the second ZDC for detection of spectator protons can be positioned at about a same distance from IP as neutron ZDC [699, 700]. The size of proton ZDC has to be small, due to the few cm small size of spectator proton spot, but sifficient to obtain shower containment. This calorimeter will be made with same technique as the neutron ZDC.

13.3.4 Calibration and monitoring

After initial calibration of the ZDCs with test-beams, it is essential to have regular online and offline control of the stability of the response, in particular due to hard radiation and temperature environment. The stability of the gain of the PMTs and the radiation damage in fibres can be monitored using the laser or LED light pulses. The stability of absolute calibration can be monitored using the interactions of the proton beam and residual gas molecules in the beam-pipe and comparison with the results of Monte Carlo simulation based on pion exchange, as used at HERA [466, 698]. A useful tool for absolute energy calibration will be the reconstruction of invariant masses, e.g. $\pi^0 \to 2\gamma$ or $\Lambda, \Delta \to n\pi^0$, with decay particles produced at very small opening angles and reconstructed in ZDC. This will however require the possibility to reconstruct several particles in the ZDC within one event.

13.4 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 loosing 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 [**?**]. 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 interation point, the beam width is approximatel equal to 250 μm. 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. 13.6, using the LHC proton beam optics [**?**]. The small corrections to be applied for the LHeC proton beam optics are not considered to be relevant for the description of the 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 reconstructed the initial scattering angles and momentum loss of the proton at the interaction point. Even with an infinitesimally small detector resolution, the intrinsic beam width and divergence will still imply a lower limit on the resolution of the reconstructed kinematics. As the beam is typically maximally focussed at the interaction point in order to obtain a good luminosity, it will be the beam divergence that dominates the resolution on reconstructed variables.

Figure 13.7 show the relation of position and angle w.r.t. the nominal beam and the proton scattering angle and momentum loss in both the horizontal and vertical plane as obtained from the LHC proton beam optics [?]. Clearly, in order to distinguish angles and momentum losses indicated by the curves in Fig. 13.7, the detector must have a resolution better than the distance between the curves.

As stated above, protons with the same momentum loss and scattering angles will still end up at different positions and angles due to the intrinsic width and divergence of the beam. Lower limits on the resolution of reconstructed kinematics can therefore be determined. These are typically of the order of 0.5‰ for ξ and 0.2 μrad for the scattering angle θ. Figure 13.8 show the main dependences of the resolution on ξ, t and the azimuthal scattering angle ϕ.

A crucial issue in the operation of near-beam detectors is the alignment of the detectors w.r.t. the nonimal beam. Typically, such detectors are retracted when beams are injected and moved close to the beam only when the accelerator conditions are declared to be stable. Also the beam itself, may not always be reinjected at the same position. It is therefore important to realign the detectors at for each accelerator run and to monitor any drifts during the run. At HERA, a kinematic peak method section was used for alignment: as the reconstructed scattering angles depend on the misalignment, one may extract alignment constants by required that the observed cross section is maximal for forward scattering. In addition, this alignment procedure may be cross-checked by using a physics process with a exclusive system produced in the central detector such that the proton kinematics is fixed by applying energy-momentum conservation to the full set of final state particles. The feasibility of various alignment methods at the LHeC remains to be studied.

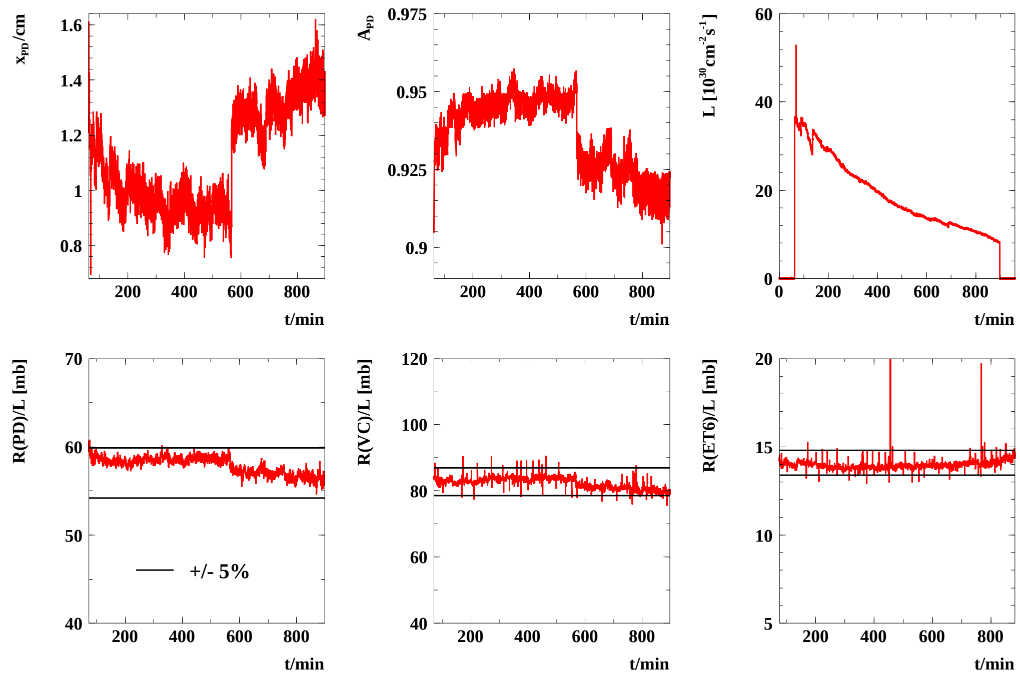


Figure 13.3: Online H1 Lumi System acceptance and rates variations in a typical HERA luminosity fill.

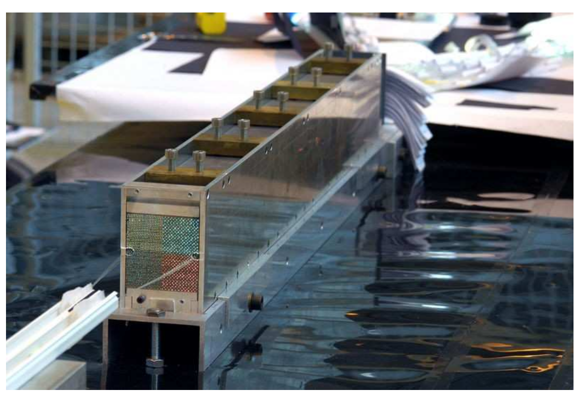


Figure 13.4: Photo of the Zero Degree Neutron Calorimeter (ZN) of ALICE experiment.

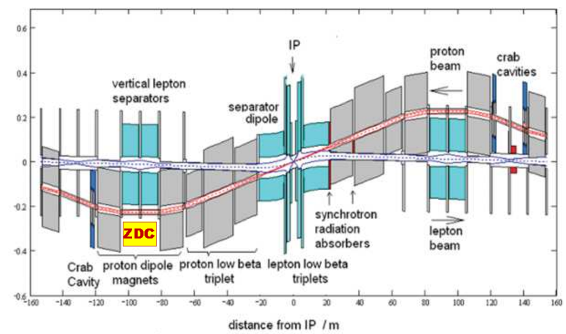


Figure 13.5: Schematic layout of the LHeC interaction region. The possible position of the ZDC is indicated.

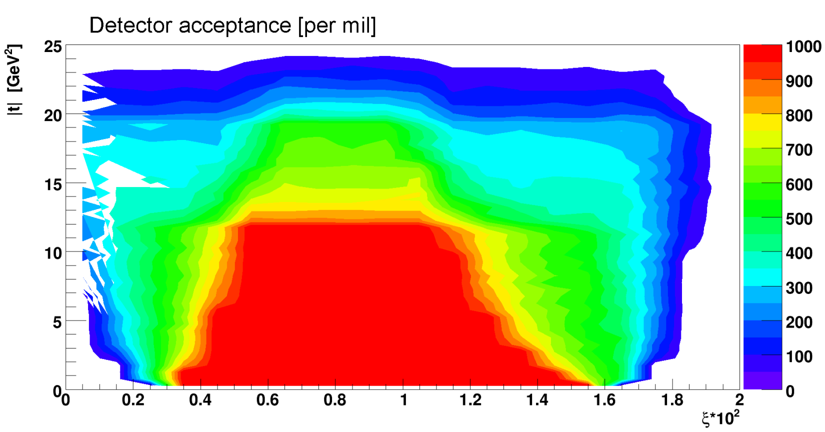


Figure 13.6: The acceptance for a proton detector placed at 420m from the interaction point is shown as function of the momentum loss ξ and the fourmomentum-transfer squared t. The color legend runs from 0‰(no acceptance) to 1000‰(full acceptance).

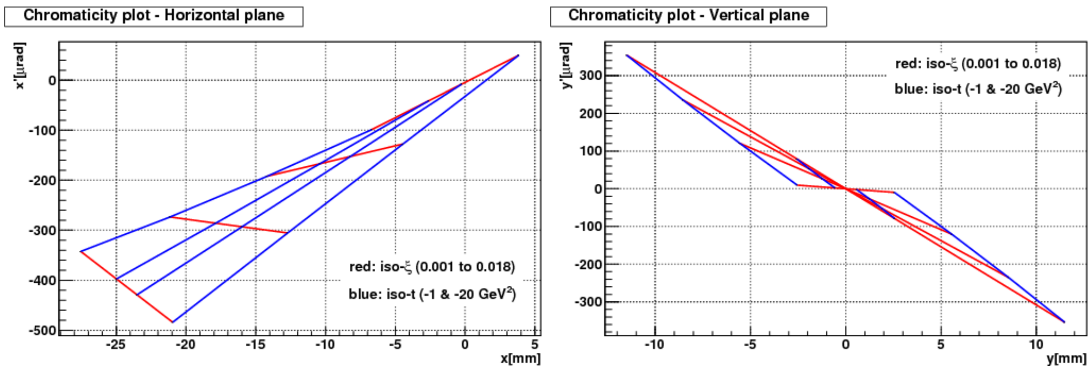


Figure 13.7: Lines of constant ξ and $t \approx (1-\xi)E_{\rm beam}\theta^2$ are shown in the plane of proton position and angle w.r.t. the nominal proton beam in the horizontal (left) and vertical (right) plane.

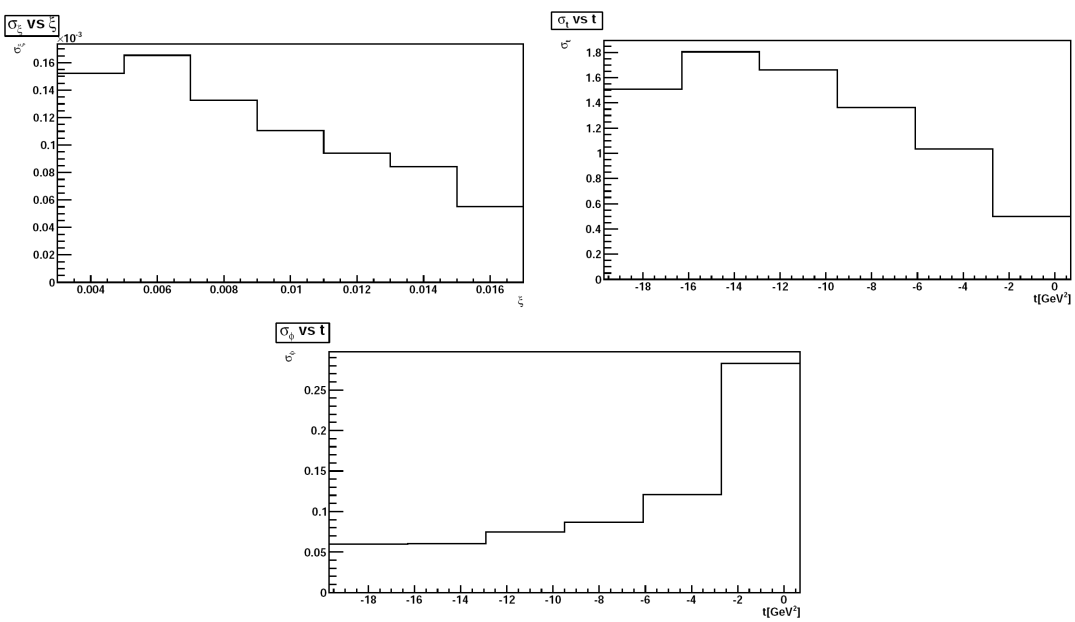


Figure 13.8: The lower limit due to the intrinsic beam width and divergence on the resolution of kinematic variables is shown for ξ as function ξ (top left), t as function t (top right) and ϕ as function of t (bottom).

Part V

Summary

Acknowledgement

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Appendix 1

Tasks for a Technical Design Report

Building and Operating the LHeC

Appendix 2

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Accelerator Design - Energy Recovery

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