LHeC-Note-2012-NNN

Referee Reports on the CDR

DRAFT version of
March 17^{th}, 2012

This note is a collection of the reports delivered by the expert referees which were invited by CERN to comment on the draft of the conceptual design report (CDR) of the Large Hadron electron Collider (LHeC). The version (1.0) of the CDR draft, to which the comments refer, is documented as LHeC-Note-2011-003 GEN. The final collection of referee reports will include a few more reports. It will also include answers from the authors to essential questions raised by the referees. The CDR is being updated correspondingly.

1 Ring Ring Design

Referees:

Kurt Huebner (CERN)
Alexander N. Skrinsky (INP Novosibirsk)
Ferdinand Willeke (BNL)

Comments on the Conceptual Design Report for A Large Hadron Electron Collider.

Ferdinand Willeke, Brookhaven National Laboratory, Upton NY, USA

Report on the Ring-Ring Collider Part

General Remarks

The team is to be congratulated for producing a substantial conceptual design report. Many technical aspects have been worked out to a fair amount of detail which corresponds well to the anticipated conceptual design level and which is sufficient to make good judgment of the feasibility of building a large hadron lepton collider.

The report is clearly written, though parts of the report would benefit from a better description and caption of the figures, from a more uniform use of symbols and abbreviations, from a more complete definition of the quantities introduced. A glossary would be very helpful to make the report more easily readable.

Comments on Ring-Ring Solution

The ring-ring solution is a straight forward path to a competitive high peak luminosity and high integrated luminosity collider with a minimum of technical risks, performance risks, and a minimum of necessary accelerator R&D. As most of the proposed technology is fairly conventional, there exist from previous experience a fairly solid base for estimating cost and schedule of the corresponding construction project.

The design of magnets and cryogenic system of the LHC did not take into account the addition of an electron ring. Therefore retrofitting the lepton ring in the LHC tunnel requires significant modification of existing accelerator hardware. Furthermore there is significant civil construction to provide bypasses around the existing experimental hall. This is associated with a large cost. Taking this cost into account it is not obvious whether the ring-ring solution can be realized at lower cost compared to other scenarios. Moreover, a large period without LHC p-p or ion-ion operation possible will have to be scheduled to implement the changes to present day LHC.

On the other hand, assuming that the LHeC physics case justifies the construction of a new large lepton accelerator system, the effort of fitting the lepton ring into the LHC tunnel and the impact on LHC operations should be put in perspective to the overall effort and should not be overemphasized.

The ring-ring solution for the LHeC will not drive new technical development and there are no strong synergies with other technologies relevant for future accelerator development such as novel methods of particle acceleration. Moreover the LHeC is based on technologies which are available or are at reach today.

Comments on the Choice of Parameters

The projected LHeC performance is based on beam parameters which for the most part have been demonstrated in LEP, HERA, and LHC or are baseline LHC parameters the achievement of which is assumed a high priority for accelerator development at CERN in the next few years. Therefore this choice of parameters may be in general considered conservative. However, attention has to be paid to details. Nevertheless the risk of falling significantly short of expected performance is thus relatively low.

The overall power consumption required for the ring-ring collider is considerable but the additional power does not increase the projected LHC power consumption by a large factor. Rough scaling results in a factor of 5-10 times the beam-power required to sustain the overall facility. The ring-ring solution is from a power consumption point of view a quite competitive solution to the LINAC-ring or ERL-Ring solutions.

In that sense the chosen parameters may be considered “conservative” and “realistic”. This allows to fairly safe estimate of integrated luminosity and offers the possibilities of further performance enhancement by more aggressive approaches.

Comments on Design Strategy

A fairly large emphasis of the design report has been placed on investigation of LHC and LHeC interferences. This emphasis is considered very adequate as the practical realization of the Ring-Ring solution with a minimum impact on the LHC physics program is one of the major technical challenges.

The general concept of bypasses of the electron ring in the horizontal plane around the existing experimental halls which provide the space for the RF system of the electron ring and which require a small radial shift of the electron radial position with respect to the proton orbit appears to be quite reasonable.

The electron lattice layout which is designed to accommodate the geometrical constraints of the LHC lattice thereby accepting a non-ideal electron optics is a reasonable compromise and appears to be feasible.

Remarks on Interaction Region Layout and Colliding Beam Considerations

The interaction region design concept is quite similar to the HERA interaction region layout with the exception of the s-shaped beam separation scheme the small crossing angle. The achievable luminosity depends strongly on the existence of non-standard superconducting magnets in the interaction region. They focus the proton beam. Holes in the flux return yoke allow the electron beam to pass at a fairly small horizontal distance from the proton beam without beam affected by the strong quadrupole fields. On should expect that especially the half-aperture superconducting quadrupoles will be very difficult to be constructed and built. The present study is limited to 2-d magnetic field calculations which show that from a magnetic point of view that such magnets are possible. The main challenge however appears to be the mechanical design. It is unclear how the structure has to look like which supports the necessary pre-stress on the superconducting coil without compromising the magnetic design. In this case a conceptual engineering study appears to be mandatory before the concept of the interaction region design and the achievable luminosity can be considered as feasible and realistic.

The synchrotron radiation absorbers which protect the crotch-area and the superconducting proton magnets have to absorb a fairly high synchrotron radiation power of several tens of kW. While power density numbers are not provided in the report, the shown graphics suggest a peak power density of > 300 W/mm^2. This density can only be handled if the absorbing surface is slanted with respect to the direction of the incoming beam. A slanting angle of 60mrad (measured from the beam axis) should not be exceeded. The absorbers thus might take more space than indicated in the report. Note that with an optimally cooled surface, a power density of only 12 W/mm^2 may be considered safe. It seems that the proposed solution exceeds this safe power density by a large factor.

Remarks on Beam-Beam Interaction

The head-on beam-beam parameters for the electron beam, $\xi_{x,\,y}$ = 0.086, has been chosen based on LEP experience with $\xi_{x,\,y}$ = 0.070. The beam-beam tune shift of the electron beam in HERA, $\xi_{x,\,y}$ = 0.025/0.045, however was limited by the diffusion rate, the emittance blow up and the tail forming in the proton beam. Based on this experience, the tune-shift value appears to be too optimistic. It is not so clear how the much higher beam energy of the proton beam in LHC on one hand and the much more critical vulnerability of the LHC to proton beam losses would change this experience. A fairly detailed and realistic simulation study would be required to be able to commit to the high tune shift value.

In order to achieve highest luminosity, the crossing angle between proton and electron beam should be as small as possible. This in turn exposes the beams to substantial long range beam-beam forces. The feasibility of the high luminosity interaction region layout depends strongly on the beam-beam effects and in particular on long range beam-beam forces. The choice of a 1mrad crossing angle appears to be a reasonable choice. At the first parasitic crossing, an electron with an amplitude of ~10 times its rms horizontal beam size passes through the center of the proton beam. Such particles are probably lost after a few turns which is compatible with acceptable beam lifetime if the transverse distribution doesn't have significant tails. A careful study of a realistic distribution of the electron beam in presence of central and parasitic collisions in order to determine the e-beam lifetime appears to be strongly desirable to validate the choice of IR parameters. The absence of such a study is a shortcoming of the CDR which should be corrected.

The presented luminosity reduction factor S of 0.75 is quite moderate and may not justify the complication of crab cavities. However this option should be discussed. The proton bunch length which determines S for given crossing angle should be presented and discussed in the report.

Comments on Ring Design

The layout of the RF system based on superconducting cavities is reasonable, although a CW gradient of 11 MV/m should not be called conservative.

Comments on the Vacuum system

Power density on the vacuum chamber wall is quite high. It exceeds the synchrotron radiation power density on the vacuum wall of HERA by more than a factor of 2 (estimated as for a 20mm half aperture as 30 W/mm^2). This needs special attention in the design of the vacuum chamber and may have an impact on the layout of the dipole and quadrupole magnets in the arc.

2 Linac Ring Design

Referees:

Reinhard Brinkmann (DESY)
Andy Wolski (Cockcroft)
Kaoru Yokoya (KEK)

Beschleuniger | Forschung mit Photonen | Teilchenphysik

Deutsches Elektronen-Synchrotron
Ein Forschungszentrum der Helmholtz-Gemeinschaft

DESY, 22603 Hamburg

Dr. Reinhard Brinkmann
Direktor Beschleunigerbereich
Tel. +49-40-89983197
Reinhard.Brinkmann@desy.de

Prof. S. Bertolucci
CERN
CH-1211 Genève 23

DESY Deutsches Elektronen-Synchrotron
Notkestraße 85
22607 Hamburg
Tel. +49 40 8998-0
Fax +49 40 8998-3282

Briefanschrift
22603 Hamburg

Standorte DESY
Hamburg
Zeuthen/Brandenburg

26. October 2011

Dear Sergio,

I am sending you my comments as a referee of the LHeC design report. We already had the opportunity to discuss these points during our meeting at CERN on Oct 18 and Oliver Brüning has produced an excellent summary of our discussions, but as we agreed I reproduce my comments here in written form as a reference.

I studied the machine layout chapters for both the R-R and L-R options. I did not find the time to study the chapters on technical components in any detail, but I believe that at this point in time these details are not decisive for the basic conclusions on how to proceed with the LHeC design.
The most important decision in order to be able to proceed with a technical design for LHeC is the choice between the two options. In my view, the R-R solution has a much higher impact on the existing LHC ring, on the operation of the LHC and logistics in general, in comparison with the R-L solution. Without being able to judge on technical boundary conditions in any detail, my feeling is that installation of an additional electron ring in the LHC tunnel would indeed be very painful, perhaps even hardly possible. Then one would conclude that the L-R solution is the preferable way to go. This can, however, only be concluded if from a science case point of view the operation with positrons is acceptable at much lower luminosity than the one with electrons. The achievable average intensity of positrons (with suitable phase space properties) will be at least one, possibly two orders of magnitude lower than the electron intensity. So, if high luminosity hadron-positron operation is a must from scientific arguments, I would view the e+ production as a show stopper of the R-L option. If the science case is compatible with lower hadron-positron luminosity, then the R-L option is the way to go. It is in my view also very attractive in a more general strategic sense: establishing the high-performance superconducting CW-linac technology (with energy recuperation) at CERN could be very beneficial for other future projects and a 20 GeV CW machine could in the long term be suitable for other applications in addition to the LHeC. This may become a crucial point in a decision process towards the possible approval of the LHeC project.

Comments on more specific machine design questions:

- There is an inconsistency in table 7.31 on page 235 regarding the electron and proton beam sizes at the parasitic IP. Since beta* is much smaller for electrons than for protons, beta at the parasitic interaction a few meters from the IP should be much larger for electrons than for protons, opposite to what is quoted in the table. I see a potential problem with a relatively strong effect on the e-beam due to the larges beta's, this would have to be studied with simulations.
- In HERA the radiation damage effect of synchrotron radiation on the super insulation in the proton ring magnets was an issue. This may not be the case in an R-R LHeC with sufficient lead shielding (HERA was not lead-shielded), but this would have to be studied carefully, given the potential disastrous effect if such a radiation damage occurs.
- Instead of a superconducting recirculating linac injector for the electron ring, a conventional (S-band) racetrack-shaped design may be the more economic solution. At DESY, recently a low-emittance recirculating linac injector was proposed by Markus Hüning as a possible future injector for an ultimate storage ring light source at 6 GeV.
- In the R-L scenario it is stated correctly in the text, that RF losses of the cavities into the liquid Helium is smaller for the lower frequency variant (720 MHz). However, this does not show up in the tables quoting the expected range of cryo losses, where the 1.3GHz version is comparable to or even slightly better than the 720MHz version. This should be corrected to be consistent. In praxis, the theoretical advantage of the lower frequency of about a factor two in dynamic losses may be somewhat compromised by a higher statistical probability of surface defects due to the about two times larger surface area per unit length of cavity.
- Concerning the difference in material cost, we can derive from the known XFEL cavity cost that the material amounts to about 15% of the total cost of about 1.5M€ per 1.3GHz complete accelerator module comprising 8 1m long cavities.
- With regard to possible collaborations on the development of the s.c. CW linac technology for the R-L LHeC, I would like to point out that this technology is under development in Germany within the Helmholtz Association (by HZ-Berlin, HZ-Dresden-Rossendirf and DESY), with HZB having launched a substantial development programme towards a 100mA ERL prototype. On the CW SRF, including the injector, there exists a good international networking with other labs like JLAB, BNL and Cornell. There is also a large scale production of 1.3GHz components ongoing in industry for the European XFEL accelerator. In view of this situation, the 1,3 GHz version may be advantageous, however there would also be opportunities for collaboration and synergies for the 720MHz approach in view of the ESS project, which is expected to start construction in 2013/14.

It has been a pleasure to discuss the LHeC design with you and your co-workers at CERN. Please don't hesitate to contact me if you have further questions regarding my comments on the LHeC design.

With my best regards,

Reinhard Brinkmann

Referee Report on LHeC CDR, Chapter 8

A significant advantage of the linac-ring option for LHeC is clearly the fact that most of the new infrastructure is decoupled (in an engineering sense) from the LHC. Thus, construction of a linac-ring LHeC would have much less impact on LHC operations than construction of a ring-ring LHeC. Unfortunately, there are many substantial drawbacks to the linac-ring option, in particular: increased construction costs (for example, associated with the additional tunnel); potentially large power requirements (which strongly motivates an energy-recovery scheme of some kind); the difficulty of producing a sufficient flux of positrons to achieve the luminosity goals. Both the ring-ring and linac-ring options have issues associated with interaction region design, and beam dynamics. There is no obvious reason why these issues should be worse for one case compared to the other, though certain specific aspects may be different.

All the important issues for the linac-ring option appear to have been investigated in appropriate detail, and are discussed in the CDR (Chapter 8). There are strong constraints on the configuration, arising from the specifications on energy and luminosity, and limits on construction and running (power) costs. The constraints have been systematically considered, with the conclusion that the energy-recovery recirculating linac seems the most appropriate (indeed, only practical) choice for the baseline configuration, up to 60 GeV beam energy. The drawback is that this option cannot realistically be upgraded to provide higher energy, because of synchrotron radiation losses in the arcs. A basic design for an energy-recovery recirculating linac for LHeC is presented in the CDR: although not entirely complete, more than sufficient work (including optics design) has been done to allow some parameter optimisation, and evaluation of such issues as synchrotron radiation energy losses, and beam instabilities from impedance and ion effects. There appear to be no show-stoppers. Where specific issues are identified, appropriate solutions are presented (for example, synchrotron radiation energy losses are compensated by booster linacs). A substantial amount of very interesting work has been done in particular on beam instabilities driven by impedance and ion effects.

The interaction region design seems reasonable. Handling the radiation power (from beamsstrahlung, and from bending of the electron beam in the IR magnets) is clearly a significant issue, and has been considered in appropriate detail. Options for γ-*p* and γ-*A* collisions are mentioned, but have received less attention so far.

The physics studies demand a high degree of beam polarisation, with electron spins oriented longitudinally at the collision point. For electrons, it is relatively straightforward to produce a beam with (at least) 90% polarisation; however, maintaining this degree of polarisation in the arcs of a recirculating linac (given the expected energy spread on the beam) would require the spins to be oriented vertically during acceleration. The particle spins must then be rotated into the required longitudinal direction after acceleration, at 60 GeV. This requires more powerful magnets than would be needed if the spin rotation could be done at low energy; however, it still looks feasible, using the design outlined in the CDR. More detailed studies are reportedly in progress.

For beam energies significantly above 60 GeV, an energy-recovery recirculating linac becomes unattractive, because of the large synchrotron radiation energy losses in the arcs. A single straight (pulsed) linac is an option for beam energies up to 140 GeV. A more elaborate alternative is to use an energy-recovery straight linac, with a series of (roughly 10 GeV) transfer beams used to carry the power from the decelerating section to the accelerating section of the linac. Both options would be expected to have a relatively high cost in infrastructure. With realistic power limits, the straight linac (without energy recovery) would appear to fall short of the luminosity goal by one or two orders of magnitude. The straight linac with energy recovery would allow the power limitations to be overcome, and would achieve (in principle) the luminosity goal; however, despite some connections with CLIC technology, there is clearly a very significant amount of R&D to be done, before this solution could be considered really practical. With 15 energy-transfer beams, the number of beamlines crossing the interaction region would be very large (comprising two hadron beams, an electron beam, and 15 energy transfer beams).

One of the most significant challenges for the linac-ring LHeC will be the production of positrons. To achieve the luminosity goal in the energy-recovery recirculating linac, a positron production rate four orders of magnitude larger than for SLC would be required. A "conventional" source (electrons impacting a solid or liquid target) is considered in the CDR, though this will not produce polarised beams; and handling the power load on the target presents a formidable challenge. A Compton source would allow the production of polarised beams of positrons, but again there is significant R&D required before such a source could be considered realistic. Because of the challenges of producing positrons at the required rates, re-using positrons after collision would have very significant benefits; however, cooling the collided beams at the necessary rate would be very difficult. The challenge of providing for positron beams looks to be one of the most significant weaknesses of the linac-ring option, compared to the ring-ring option for LHeC. I cannot comment on the physics case for positron-hadron collisions.

While there has clearly been a significant amount of work on issues expected to be significant for (in particular) the energy-recovery recirculating linac, there is naturally a concern regarding the lack of really relevant experience of this kind of machine. While a number of ERLs have by now been operated (very successfully) in different parts of the world, there is no experience of operating such a machine on the scale that would be required for LHeC. Issues such as (for example) alignment, stabilisation and synchronisation do become more difficult as the size of the machine increases. Some parameter comparisons are made in the CDR with CLIC and ILC: such comparisons are not especially encouraging, given that these machines also exist so far only on paper. It would improve confidence considerably if as many references as possible could be given to experience from facilities already operating: this would also help to identify and make clear how far the proposed facility requires technology or performance beyond what has already been demonstrated, and what is required in R&D (including prototyping, and system tests) before construction could begin.

The contributors and editors of the CDR are to be congratulated on the work that has been done for this design study. While it is still at the conceptual stage, with some very different configurations still being considered and compared, the work appears careful and systematic. The report itself is well-written and coherent – this is not to be taken for granted, given the difficulties of ensuring consistent use of key parameters at this stage of a project.

Andy Wolski,
University of Liverpool and the Cockcroft Institute.

24 February 2012.

3 Energy Recovery

Referees:

Georg Hoffstaetter (Cornell)
Ilan Ben Zvi (BNL)

Cornell Laboratory for
Accelerator-based Sciences
and Education (CLASSE)

F. R. Newman Laboratory
Garden Avenue
Ithaca, NY 14853 USA
Ph: (607) 255-4951
Fax: (607) 254-4552

Georg Hoffstaetter
Cornell University

Referee comments to "A Large Hadron Electron Collider at CERN, Report on the Physics and Design Concepts for Machine and Detector"

The following comments were presented and discussed in detail during a phone conference on February 17th, 2011 14:30-16:30am CET with the following members of the LHeC Study Group: Max Klein, Daniel Schulte, Frank Zimmermann, Alex Bogacz. The following list of topics is rather terse, for more details please refer to the notes from this phone meeting.

A lot of thought and detailed work has gone into this document. I congratulate your team for a large job well done. Here are a few comments that should be addressed.

Page 21, line 759: The goal to complete LHeC in 10 years is very challenging and will require a decision for this project within the next 2 years, which is a tight schedule for such a major decision.

Page 24, line 830: Point out that the potential for larger current is not the only and possibly not the dominant reason for considering a linac-ring collider. Important other benefits include the potential for higher electron current and thus higher luminosity and a construction time that can overlap with LHC running.

Line 833: Point out how much more power it would take to increase the electron energy of a ring-ring collider, and how much for a linac-ring solution. Also point out that for higher electron energies in a ring, the polarization strongly reduces.

Page 27:

a) The table lists ER efficiency. This quantity should be defined. One component of it will be the power need per cavity. It should be more clearly stated how this power need (apparently 17kW) has been computed.

b) The LR* mode with 140GeV would require a 40MW beam dump. This is 4 times more than an ILC dump and therefore a huge construction. This complexity should be pointed out somewhere.

c) Point out somewhere that 6.4mA with 90% polarization are not easily produced, as of today.

Page 185, line 4403: Point out that the electron current in the ring-ring option is large enough to influence the pp tune shift and may therefore influence the pp luminosity.

Page 204: Table 7.9 specifies 100mA electron current, whereas the table on page 27 specified 131mA. I believe the table on page 27 should probably be changed.

Page 220: Table 7.18 specifies 100mA electron current, whereas the table on page 27 specified 131mA. I believe the table on page 27 should probably be changed.

Page 244: Figure 7.46 shows 30% polarization at 60GeV, whereas the table on page 27 specifies 40%. I believe the table on page 27 should probably be changed.

Page 260:

a) Touschek loss rates should be studied, and the Touschek halo evaluated, particularly after deceleration.

b) line 5903 "A 60-GeV recirculating" represents the baseline scenario sounds as if other scenarios had been considered. I recommend taking this sentence out.

c) lines 5912-5914 "An advanced Energy Recovery option" boost the luminosity potentially by several orders of magnitude? Let the reader wonder what would be needed and why this option is not proposed. I recommend taking this section out. Otherwise, an extension is needed that describes how this option allows for more current, would need a much longer linac with correspondingly much larger cooling needs, and an estimate for the required operating power (probably >>100MW) should be mentioned.

Page 263, line 6016: Point out that the current limit of the JLAB FEL is 10mA because of well understood BBU (feel free to quote our papers), and that significantly larger currents would be possible with suitably designed cavities. It is therefore believed that more than 6.4mA for the LHeC ERL would be feasible.

Page 265:

a) line 6031: Pointing out progress in ILC gradients as an advantage for 1.3GHz is not fully convincing, because ILC type gradients are not needed for the ERL.

b) line 6032: I would replace ?2 to 4? by "2", because it is clear how the cavities surface area decreases with frequency.

c) line 6043: You could add a bullet with "Other projects, e.g. low emittance ERL light sources, can reduce the bunch charge by choosing a higher RF frequency. This is not so for the LHeC where the bunch distance is not determined by the RF frequency but by the distance between proton bunches."

d) line 6044-6046: It is not yet known that Nb on Cu cavities can be produced with the large Q0 needed for the ERL. These lines should therefore be taken out, or phrased in a much more uncertain way.

Page 266, Table 8.1: Recommendations to make the Table clearer are

a) 3nd row, 3rd column: change 0.72 to 1.3

b) 6th row, 1st column: change 100 Ohm to “1 Ohm in Linac def”.

c) Change 400-500 to “approx. 450”

d) Change 1200 to “approx. 1200”

e) Change “2.5” “5.0” to “4”.

e) Bring footnotes 1 and 2 from page 265 to page 266.

f) Change “8-32” to the value that corresponds to the specified Q0.

g) Change “13-37” to the value that corresponds to the specified Q0.

h) Eliminate row 10 with the total loss and mention somewhere that the static loss depends on the cryomodule design and can be made small compared to the dynamic loss.

i) lines 6050-6061: A table for the power budget would be useful. Currently the power is described in this chapter, which is less clear than a table would be.

All the best for the future of LHeC!

Best regards,

Georg Hoffstaetter

Remarks on LHCCDR1.0-1

Ilan Ben-Zvi

Trivial corrections:
On page 2, LHeC Study Group list of names, change "BenZvi" to Ben-Zvi".
On page 291, last sentence, change "his" to "its".
On page 300, line 6650, change "1200" to "positioned at 120 degrees to each other".

Linac consistency:

On page 267, line 6105, it is not clear what is the meaning of the statement "The linac cavity filling factor is 57.1%." What is included in this filling factor? The so called “active length” of a cavity is somewhat arbitrary, however a detailed design, which includes the HOM damping real-estate, FPC and robust flanges can yield the flange-to-flange length of the cavity.There is additional discussion of the linac layout on page 290. According to that, the 12.8 meter long cryomodule has 8 cavities, which allows 1.6 meters for each cavity unit. This is just enough for the cavities, but does not leave any extra space for interconnects between cavities. If so, there are implications to the design of the cavity, including some flexible element to allow flanging the cavities together.

Using the information evolved for the eRHIC BNL-3 cavity, at a frequency of 704 MHz we find:
Parameters: Geometry factor 283 Ohm, R/Q 506.3 Ohm, Epk/Eacc 2.46, Bpk/Eacc 4.26 mT/(MV/m), beam pipe radius 110 mm, length flange to flange 1620.57 mm.

These numbers match well with the information given in the CDR.

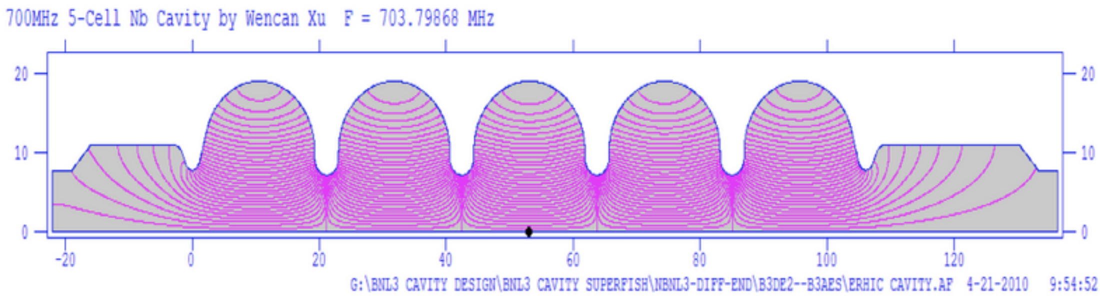


Figure: Superfish simulation of the fields in the BNL-3 cavity.

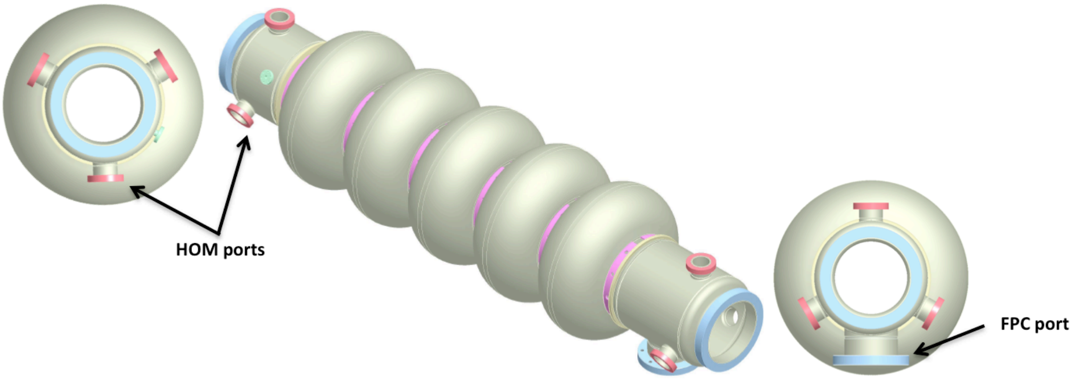


Figure: Structure of the BNL-3 cavity, showing HOM and FPC ports.

Scaling the length for the frequency ratio of 704 MHz/721 MHz, the length of the LHeC cavity would be 1582.36 mm. To this we must add 80 mm for the cavity-to-cavity connection, to make the cavity in the cryostat actual length 1662.36 mm.

Thus the length of the cavity string in an 8 cavity cryomodule would be 13.3 meters, and with transitions this fits well with the assumed 14 meter length of the cryomodule (section 9.4.2). A schematic cryomodule s shown in the figure below.

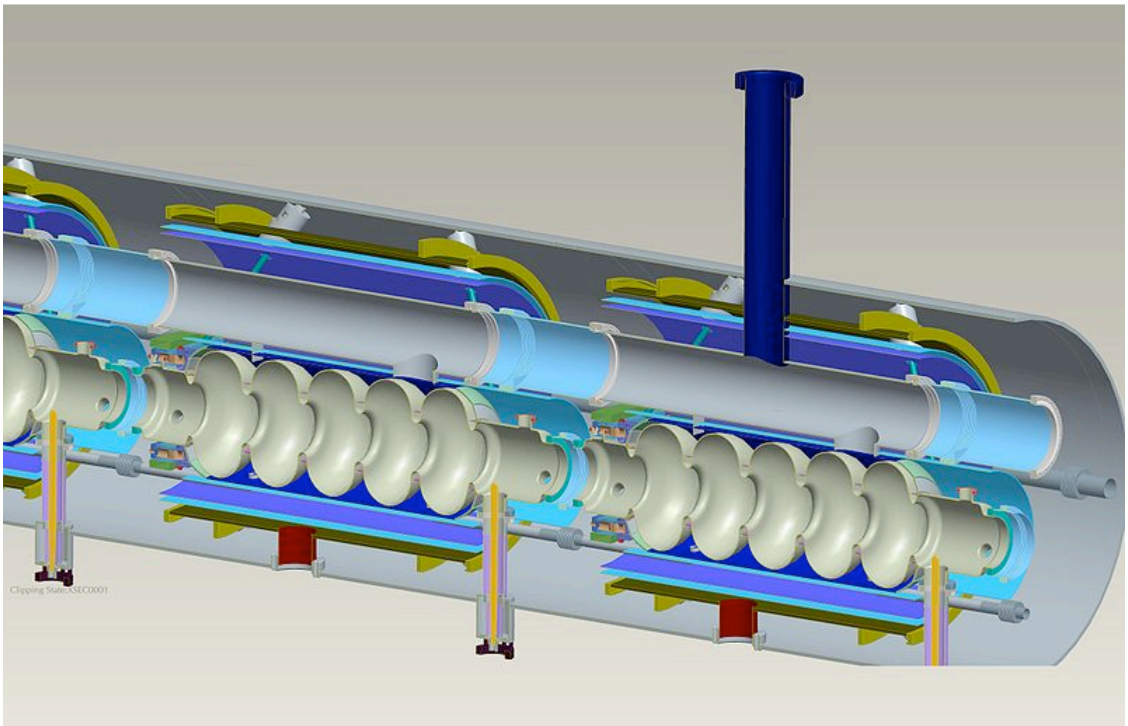


Figure: A concept of a ERL cryomodule with multiple cavities.

The damping of HOMs in the ERL cavities is a very important issue. A huge amount of power must be removed from the cavities and dumped at room temperature. The design of such strong damping in a compact ERL is still a matter of active R&D. For the BNL-3 cavity a couple of options are being investigated. The 6 HOM ports will be equipped with electric coupling antennas. To avoid dumping a lot of fundamental mode power into the HOM load, high-pass filters are being developed. One, based on lumped elements, is shown in the figure below, and its filter curve is shown further below. Another successful candidate uses a section of a ridge waveguide to cut off the fundamental mode while transmitting the HOMs.

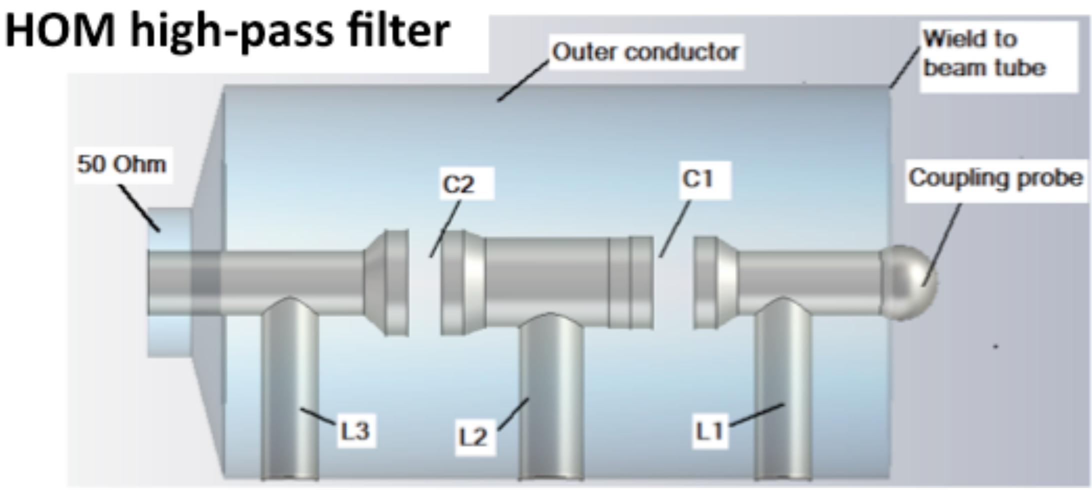


Figure: HOM probe integrated with a lumped-element high-pass filter.

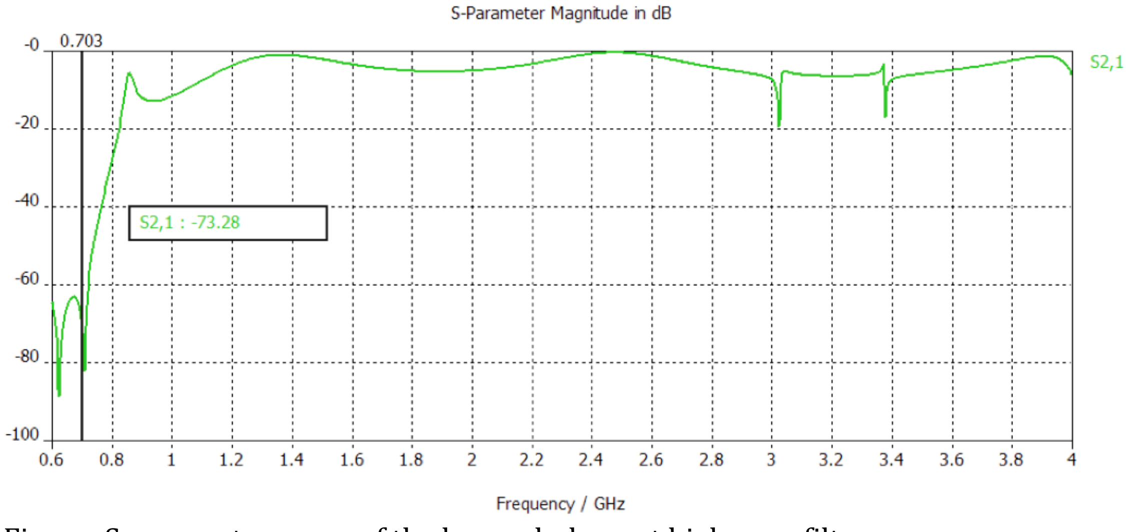


Figure: S-parameter curve of the lumped-element high-pass filter.

4 Magnets

Referees:

Neil Marks (Cockcroft)
Martin Wilson (CERN)

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
Laboratoire Européen pour la Physique des Particules
European Laboratory for Particle Physics

LHeC Conceptual Design Study.

Comments and observations on room temperature magnet designs; as presented in Draft 1.0 of the LHeC CDR.

Neil Marks 21/12/2011.

1. Introduction.

This document results from an invitation by Dr Sergio Bertolucci to study and provide a referee's report on the proposals for the design of the warm electromagnets needed for both the ring/ring and linac/ring LHeC options, as described in draft 1.0 of the conceptual design study report: 'A Large Hadron Electron Collider at CERN'. Subsequent to the distribution of this document a meeting was held at CERN on 2/12/2011, where relevant issues were discussed.

This paper records the details of the technical issues that were raised.

2. General Impression.

It should be immediately stated that, in the opinion of the referee, the proposals relating to the room-temperature magnets are sound and are based on accepted and reliable 'state-of-the-art' techniques which, in the event of moving to a full design study, would provide a firm foundation for continuing technical development. The comments recorded below therefore do not represent any criticism of the work performed at CERN or elsewhere, either in its technical contents or completeness of application, but are meant to indicate areas where it is believed that additional study in the future would be rewarding or where a firm recommendation can be made for deeper, detailed examination, as might occur in a technical design review (TDR).

The issue that are raised are identified by the numbering of the sections and sub-sections of the CDR document.

3. Ring/ring option.

3.1 Dipoles (section 9.2.1).

3.1.1 It should be stressed that the low value of flux density at injection in the lepton ring of the LHeC (0.0127 T at 10 GeV) represents a major challenge. CERN has ample experience in building and operating very low field magnets in LEP, where the injection field at 20 GeV was 0.02 T. So the field at the beam in LHeC would be nearly half the lowest LEP field. The CERN staff responsible for magnet design are well aware of this problem. It should be emphasised that CERN, because of the LEP history, is probably in the best position to judge the consequences of this challenge and to work to overcome the resulting difficulties. It may well be that the final version of the CDR should mention these advantageous circumstances, which should partially offset the technical risks imposed by the requirement for such a low field.

3.1.2 The dipole cross section design produced to provide a good quality field over the range of field ramping (see Fig 9.8 in the CDR) shows an ingenious and effective solution to the problem of the higher reluctance which the magnet steel will exhibit at low flux densities. The compensation for the shorter path length around the inside of the 'C ' core by means of an inward projection of the pole should substantially reduce (or even eliminate) the quadrupole component that is present in any asymmetric dipole.

3.1.3 For the RR option (and the LR option), it is proposed that the dipoles be excited by two turns – one single turn above and one below the vertical median beam gap (see Fig 9.8 in the CDR); the 'single solid bars, after insulation, are individually slid inside the magnet'. This results in the following conflicting technical and financial consequences:

- the magnet assembly procedure is very straight forward and rapid, hence with lower cost;
- if water cooling should be needed (probably unnecessary) the introduction of a water circuit should be easy and low cost;
- the necessary high circuit current of 1300 A will result in large terminals and high cross section inter-magnet connections;
- the dipole power supply will be rated at 1,300A, but with a rather low voltage and low impedance – not optimum from electrical engineering considerations;
- whilst the magnet power loss is almost the same as in a multi-turn coil, losses in interconnections, terminals and in the power supply will be significantly higher than for a multi-turn magnet operating at lower current and higher voltage.

The CDR could briefly mention these conflicting issues, indicating this to be an area of investigation in any future TDR, to assess whether the simpler, cheaper magnet assembly procedure outweighs the increased costs elsewhere.

3.2 BINP Model (dipoles) (section 9.2.2).

The work performed at BINP, using an assembly exclusively comprising magnet steel, is impressive and clearly indicates that the cycle to cycle repeatability of injection field in an individual magnet can be achieved using 'conventional' 0.35 mm silicon steel. However, the same comments, relating to inter magnet repeatability, that are made in section 3.3 (below) are relevant.

3.3 CERN Model (dipoles) (section 9.2.3).

This short section in the CDR belies the substantial work performed at CERN, which has been published by Tommasini *et al* as 'Dipole Magnets for the LHeC Ring-Ring Option'; this is worth citing as a reference.

3.3.1 The use of the interleaved plastic spacers follows on from the success in the LEP ring, where a more prosaic filler material was used. As stated in the CDR, this produces a very significant reduction in magnet mass and an increase in flux density in the magnet steel, which is advantageous when operating at such low minimum fields. This technique is full endorsed by the referee.

3.3.2 The paper cited above produces strong evidence of fully adequate cycle-to-cycle reproducibility of injection field in an individual magnet. However, the work to date has not addressed the similarity that can be achieved between magnets in a production run of 3080 units, probably manufactured by a number of different commercial companies. This issue is, of course, met in every production sequence of accelerator magnets; however, for LHeC the problem is compounded by the low value of injection field, where the variation in magnetic parameters will be greater. The standard solution is to 'shuffle' the magnet steel during assembly, so that every magnet contains a near equal 'representative' amount of all steel batches that have been produced at the steel manufacturer's works. This process is not usually statistically analysed in great detail. However, for the LHeC magnets, such an analysis will be vital. This should entail the examination of the statistical data (coercive force and permeability at injection field) of the steel that is proposed and then establishing a shuffling procedure that can be shown to satisfy the magnet to magnet similarity that will give an acceptable closed orbit at injection. This could be a fairly demanding exercise and is clearly best suited to a full technical design.

3.3.3 It should be noted that the same issue will arise if the BINP design is used, except that, in this case, the problem will be more severe, as the flux density in the BINP steel is but c 1/3 of that in the CERN model.

3.4 Quadrupole (section 9.2.4).

This section includes quadrupole for both the e ring and insertion and by-pass regions. The parameters for both regions are undemanding and are well within the compass of standard designs. The cross sections and other designs presented in the CDR are conventional and do not present any technical or financial risks.

4. <u>Linac/ring option.</u>

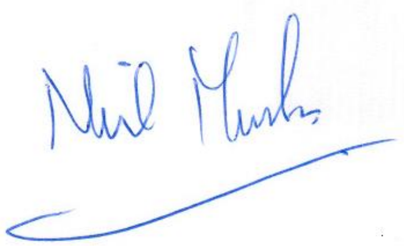
4.1 Dipoles (section 9.2.1).

Whilst the parameters for the RR and LR options are different, the proposed solutions, involving 2 turn coils and low field requirements in some magnets, are similar. The comments made in section 3.1.3 are therefore relevant to some degree. However, the magnets in the 6 arcs will run at different power levels, with the proposed maximum excitation current being 2,200 A (70% higher than the maximum excitation proposed for the RR magnets). Consequentially, the issue of a reasonable optimisation between the magnet assembly costs, power supply ratings and long-term energy costs in interconnections and power supplies are different to those for the RR magnets. There is also the issue of how the dipoles strings are to be connected and the number of independent power supplies needed. These questions will require addressing in any technical design exercise that is undertaken.

4.2 Quadrupoles (section 9.2.4).

4.2.1 The 74 quadrupoles required for the two 10 GeV linacs are slightly more demanding than the quads in the RR option, calling for 10 T/m with an inscribed radius of 70mm. However, this does not represent a major design problem. It is noted that a footnote presents the option of using super-conducting magnets by moving these quadrupoles in to the linac cryostats, for which there is an existing DESY design.

4.2.2 The 4 X 360 (1440) quadrupoles for the recirculation arcs, with a maximum gradient of 41 T/m and an inscribed radius of 20 mm, do represent a design challenge, though the tapered pole cross section shown in the CDR would appear to be adequate. More serious is the total power consumption of the whole assembly, which is currently estimated to be c 3.3 MW. This figure should be presented in table 9.9 of the CDR. Serious consideration should also be given to using permanent-magnet excited units. These would have significantly higher capital cost than electro-magnets but would save on power supply capital, the cost of interconnecting power cables and on long term energy costs. Units in which the gradient strength can be varied by mechanical methods have been described (Shepherd *et al*: 'Novel Adjustable Permanent-magnet Quadrupoles') However, in the recirculation arcs, a large variation of strength of individual quadrupoles should not be required. Hybrid permanent units appear to provide an attractive alternative to electro-magnets and would be worthwhile studying in the event of there being a detailed technical design exercise for the LHeC.



Neil Marks,
The Cockcroft Institute,
Daresbury Science and Innovation Campus,
Daresbury,
Warrington,
WA4 4AD,
UK.

neil.marks@stfc.ac.uk

A Large Hadron Electron Collider at CERN

LHeC-Note-2011-003 GEN

Comments on the Superconducting Magnets by Martin Wilson 31 December 2011

1. Ring-Ring Quadrupoles

As described in sections 7.4.1 and 9.1.2, the IR triplet for the proton ring must have produce 127T/m over an aperture radius of 22mm for the proton beam and a field free aperture of 30mm radius for the electron beam. At the point closest to the IP, the separation between proton and electron beams is just 55mm, which would seem to leave a septum of only 3mm for the field to change from ~ 3T at the edge of the proton beam aperture to ~ zero at the edge of the electron beam aperture. This requirement will be challenging (impossible?) to achieve in practice, and septum of more like 20 -30mm will probably be needed. I suggest that section 7.4 should devote a little more space to writing down exactly what the requirements are for each element of the triplet in this tightly constrained region – apertures, gaps gradients and, equally important, the maximum tolerable field in the electron beam hole. Further away from the IP, with a larger separation between beams, the gradient of 127T/m presents no difficulty and a design of the type shown in Fig 9.2 should work fine. The only complication is that the location of the electron beam hole varies along the length of the magnet but, after some more design work at CERN, I am sure that such magnets could be ordered directly from industry.

As an alternative to the half quadrupole idea, I would like to suggest the 'figure of eight' quadrupole, which used to be quite popular with iron dominated magnets. Here, as shown below, the return flux from each of the four quadrants is directed above and below the median plane. I suggest that this might have two advantages:

a) Because no flux needs to cross the median plane in the region of the electron beam, it should be easier to achieve a low field there.

b) Because there is left/right symmetry, there will be no dipole term in the proton beam hole.

Figure of eight quadrupoles worked well in a low field iron dominated regime. I have no idea how well they will work in the higher field, coil dominated regime, but CERN has probably the best computational skills in the world to find out!

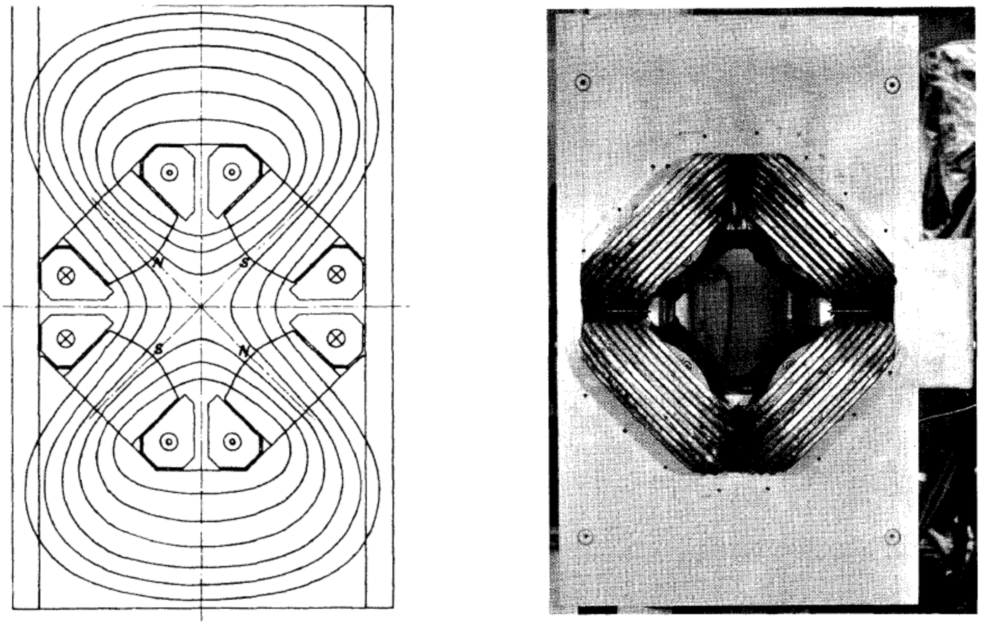


Fig 1: Figure of Eight Quadrupoles (a) Sketch of the principle [1] and (b) Practical example [2]

2. Linac Ring Collider Quadrupoles.

These are much more challenging! The first quadrupole Q1 in Table 8.3 has a gradient of 187T/m in an aperture of 22mm, ie a maximum quadrupole field of 4.1T, which in a usual coil configuration would probably give a peak field of ~ 4.8T on the superconductor. In a figure of eight quadrupole it would probably be higher and in the half quadrupole I would expect it to be considerably higher, but still within range of NbTi. The single aperture quadrupole design shown on the LHS of Fig 9.5 can easily produce the gradient, but the beam separation is 90mm, whereas section 8.2.1 calls for 70mm. The hole for the electron and other proton beams is only ~ 50mm diameter, but the layout in Fig 8.14 shows it to be about 160mm across.

The half quadrupole shown on the RHS of Fig 9.5 provides the required gradient, beam separation and hole width, but at the cost of a substantial dipole component in the electron aperture and also in the quadrupole field. Perhaps this confirms my fears about the half quadrupole, which come about for two main reasons:

a) Magnetic mirrors depend on the iron having high permeability, but here we are well into saturation

b) Magnetic mirrors work best with a semi infinite slab of iron, but here we must cut a large hole at the point where most of the flux would naturally cross the median plane

Here again, it seems to me that the figure of eight configuration could offer some useful possibilities.

The strongest quadrupole Q2 in Table 8.3 has a gradient of 308T/m in an aperture of 30mm, ie a maximum quadrupole field of 9.2T, which in a usual coil configuration would probably give a peak field of ~ 10.8T on the superconductor. Such fields are above the range of NbTi but comfortably within the range of Nb_3Sn (or HTS). For example the short and long LARP Nb_3Sn quadrupoles TQS03 [3] and LQS01 [4] have both reached peak fields above 12T at 1.9K. So it seems that the required gradient should be achievable. However, even for Q2 we still have the problem of clearance for the electron and other proton beams. From Fig 8.1.4, it appears that the other proton beam stay clear aperture starts at a distance ~ 130mm from the proton beam centre line and requires a very large hole. Fig 2 shows TQS03 with the necessary aperture sketched in. Most of the iron has gone from the median plane, which will have a strong effect on the field amplitude and quality. Perhaps the figure of eight configuration could also help here.

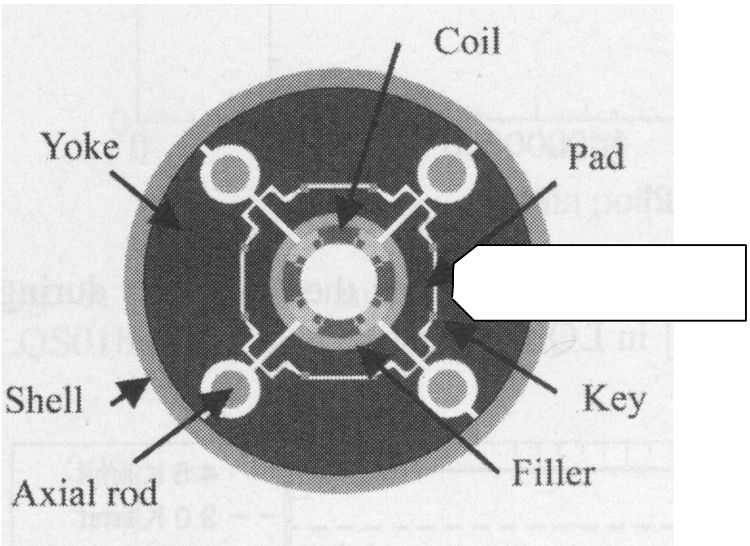


Fig 2: Cross section of TQS03 [3] with superposed hole for the electron and other proton beams

In conclusion, my opinion is that the required gradients, although high, are within reach of current technology. However the need for a field free (and in some cases very large) hole so close to the magnet will distort the field shape greatly. Some 'blue sky thinking' is needed to explore the possible configurations of coils and iron which best meet this requirement. My own inclination is to look at 'figure of eight', but there may be a better one. Having got the best magnetic design, some mechanical engineering will be needed to find the best way of supporting the electromagnetic forces without obstructing the aperture. Only when this has been done should any prototype hardware be constructed.

3. Detector Solenoids

The design presented in Section 13.2 looks OK to me and should be well within the scope of current technology. I certainly agree with the decision to put all magnets in the same cryostat because there will be strong forces between the solenoid and dipole end turns. Although the dipole has a much lower field, attention should be given to the magnetic forces here because they produce a bending stress in the support structure which may produce excessive deflections in such a thin walled cylinder.

Given some more design work at CERN or a national laboratory, I have no doubt that this system could be produced in industry.

4. General and Editing Comments on the Report

Chapter 7: Apart from a brief mention in Fig 7.1 and on page 237, I couldn't find anything on rf or acceleration in the ring.

page 205: It would be helpful to have a table of quadrupole strengths, apertures and size of field free hole to go with Fig 7.17. Quadrupoles should be numbered Q1, Q2 etc on Fig 7.17.

page 206: Does Table 2 in the text mean Table 7.10?

page 275-6: It is difficult to make the connection between Fig 8.1.4 and Table 8.3 – are there 3 blocks per quadrupole, if so why has Q3 only got one block although the Table says it is 9m long. Is Q1 nearest to the IP? Table could also define the size and location of the field free hole.

page 333: The apertures for Q1 and Q2 (linac ring) listed in Table 9.2 are quite different from those in Table 8.1.4. The ring-ring parameters here should also correspond with the new table requested above for p 205.

References

[1] Asner A. 'The CERN Slim Beam Transport Elements', Proc MT-1, p218 (1965)

[2] Bendall RG. et al: 'Beam Handling Magnets for Nimrod', Proc MT-2, p121 (1967)

[3] Felice H. et al, 'Performance of a Nb_3Sn quadrupole under high stress', IEEE Trans App Superconductivity **21,** 3 p1849 (2011)

[4] Ambrosio G. et al, 'Test results from the first 3.7m long Nb_3Sn quadrupole by LARP and future plans', IEEE Trans App Superconductivity **21,** 3 p1858 (2011)

5 Interaction Region

Referees:

Daniel Pitzl (DESY)
Mike Sullivan (SLAC)

Mike Sullivan, Feb. 13, 2012

Comments on the LHeC IR designs

In general, the designs are very well developed. There has clearly been a lot of work to get a better understanding of each design and to obtain a first round of optimization of the IR parameters and constraints. I will concentrate on the design aspects that relate to synchrotron radiation backgrounds and power issues.
The methods used to study backgrounds involve GEANT4 models and generators that are cross-checked by a simpler program IRSYN and by analytical calculations. The cross-checks show good agreement for total SR power and generated crital photon energies. Using GEANT to model the aborbers, beam pipe and other aspects of the backgrounds from SR should work reasonably well, especially for the IR design. In the LHeC, the necessity of bringing the electron beam into collision with the proton beam means that SR issues are dominated by the bending radiation from the dipoles used to steer the electron beam into and out of collision. In dipole fields, all beam particles are bent and therefore all beam particles contribute to the SR power and backgrounds. Therefore, a monte carlo sampling of the beam profile (assumed to be gaussian) will yield an accurate picture of the SR power and beam pipe surface power levels from SR.

RR
For the Ring-Ring designs, a considerable amount of thought has gone into adressing the issue of the high SR power and significant effort has been made to minimize the total amount of SR power. In these cases with an electron ring, the strong bending magnets around the IP can actually generate unwanted emittance growth if the strengths become too high and this is another reason to avoid high strength dipole fields. As mentioned in the text, initial studies have looked at absorber designs that can handle the SR power and also minimize photon backscatter rates from the absorber surface. The simulation descriptions do not mention (unless I missed it) how far out the beam particle distribution is tracked (how many beam sigmas). This is an important issue for the electron ring cases, as stored beams can (and generally do) generate non-gaussian transverse beam tail distributions. In order to maintain a reasonable beam lifetime collimators and other beam pipe features must stay away from the beam centroid by usually something like at least 7σ in x and at least this much in y. The y value can depend on the xy coupling. This being the case, SR simulations should trace beam particles out to at least 7σ and more likely out to at leaast 10σ. The power contribution from these high sigma particles is small but they generate SR photons with steep angles wrt to the beam axis (especially in quadrupole fields) and these photons can be more difficult to shield from the detector beam pipe. The beam particle density out in this high sigma region is somewhat unknown and therefore conservatism is encouraged. We suggest assuming a fairly high particle density out here (perhaps 10^{-3} to 10^{-4} of the peak of the gaussian).

LR

The interaction region for the Linac-Ring option has many similar characteristics of the RR IR options. The electron beam in this case is head-on with the proton beam and the SR power generated by the bending dipoles (48 kW) is quite comparable to the RR cases (33 kW and 51 kW). Because the LR collision is a single pass collider the electron beam transverse profile should be gaussian and there should not be any non-gaussian beam tail distributions. This being the case, the study of SR backgrounds using a MC generator is quite sound and should give an accurate representation of these backgrounds. There is still significant effort to properly model backscattering rates as there are major rate reductions from the backscattering (or forward scattering) surface as well as solid angle reduction in rates from the scattering surface to the beam pipe of interest. But here as in the RR cases, the SR background is dominated by bending radiation in which all beam particles contribute equally making the MC method quite effective.

In closing, I would like to say that the designs look reasonably advanced and mature given that this is the early stages of design work.

6 Detector Design

Referees:

Philippe Bloch (CERN)
Roland Horisberger (PSI)

ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE
EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Laboratoire Européen pour la Physique des Particules
European Laboratory for Particle Physics

GENEVE, SUISSE
GENEVA, SWITZERLAND

Mail address: CERN, PH Department
CH-1211 GENEVE 23
Switzerland

Telex / Telex : 419000 CER CHE
Téléfax/fax : +41 (22) 766 8686
Téléphone/Telephone :
Direct : +41 (22) 767 8636
Mobile : +41 76 487 3647
Secret : +41 (22) 767 2142
Central/Exchange : +41 (22) 767 6111
E-mail : Philippe.Bloch@cern.ch

Votre référence/Your reference:
Notre référence/Our reference:

Geneva, March 11, 2012

Report on the LHeC detector presented in the CDR.

The detector concept in the document is well presented and based on the strong experience of the proponents in HERA and LHC experiments.
The remarks below concentrate on the Tracker and Calorimeters of the main detector, which are the most challenging parts.

A general remark concerns the integration aspects and in particular the space needed for the services and installation. This issue is important because in the present design both the central Tracker and the ECAL have a very compact transverse dimension. A loss of space of a few centimeters due to services could have potentially a strong impact on their final performance

- For the Tracker, space will be needed to support the object, to bring the large power and to cool the detector. Furthermore, if the radiation level reaches few 10^{14} particles/cm^2, a cold operation (-15 or -20 ° C) may be needed, requiring a thermal shield around the Tracker. To set the scale the CMS outer support tube is 30mm thick, the thermal shield about 10 mm, the cables take also some centimeters.
- For the ECAL, the space left (about 40 cm) seems also shallow. For example, the *active* part of ATLAS Barrel LAr is 47cm thick for 23 X0.

Concerning the Tracker, my main question is whether a realistic assumption has been used for the material budget. The numbers in Table13.5 for the LicToy simulation can not be correct. Based on CMS studies for the upgrade, one expects *at least* 20% X0 material budget for such a Tracker and probably more. What is the impact of a realistic assumption of the material budget on the performance ?

Concerning the calorimeters, my main interrogation is whether the magnetic field configuration, i.e. the coil between ECAL and HCAL is compatible with the expected (state of the art) performance for hadron calorimetry. Inactive material after 1 interaction length will certainly strongly impact on the energy resolution. This configuration has not been used in recent collider experiments except for LEP where hadron calorimetry played a minor role. What will be the corresponding impact on the physics? Is there a way to compensate by using EFLOW algorithms “à la CMS” to recover the energy resolution of jets (by essentially using the HCAL only for neutral hadrons), despite the very small radius of the Tracker?

Furthermore, one may ask the following questions:

- In the Ring-Ring option, what is the advantage to use LAr compared to for example Pb-Sci? Have the other possibilities (coil before ECAL or coil after HCAL) been studied?
- In the Linac Ring option, the magnet configuration is driven by the need to incorporate the SC dipoles. Is there an alternative e.g. with small, non cryogenic dipoles which would allow the same possibilities mentioned above for Ring-Ring?

In the Ring-Ring option, a double configuration with either 1°or 10° acceptance has been envisaged, requiring the move of FHC3 and BHC3 for inserting low beta quadrupoles: have the installation aspects been looked and does it require a special long shutdown?

Finally, I believe that the compatibility of Figure 13.37 and figures 13.34 on pion energy resolutions should be checked.

Philippe BLOCH

7 Installation and Infrastructure

Referees:

Sylvain Weisz (CERN)

8 New Physics at Large Scales

Referees:

Cristinel Diaconu (IN2P3 Marseille)
Gian Giudice (CERN)
Michelangelo Mangano (CERN)

BSM Chapter of LHeC Physics and Design Concept

Referees: Cristinel Diaconu, Gian Giudice, Michelangelo Mangano

- General remarks
- Specific comments, section by section
- Typos etc

General remarks

- **Very good work overall**
  - Exhaustive compilation of BSM models of potential relevance for the LHeC programme, with a proper emphasis on the topics of higher priority

- **Could benefit from the following additions:**
  - a summary table with all discussed ideas, the relevant machine configuration and the reach (expressed in a specific parameter mass coupling etc.) compared to LHC. This may be part of a "conclusions" section where a few statements should be made on how the authors see the role of this machine for the new physics searches
  - a more uptodate assessment of the implications of the currently available LHC results and the 15fb^{-1} prospects (e.g. LQs limits, 4-th generation constraints)
  - a timeline of the expected LHC discoveries that would impact the decision to proceed with the approval of the LHCeC project (e.g. the LQ discovery potential as a function of integrated luminosity)
  - *Minor overall issue: for many plots there is no mention, whether in the text or in the caption, of the assumed energy or luminosity assumptions*

“Introduction”

- **Line 599 - The section 1.2 Open Questions is not well focused on the big open questions of the field, but is just a list of (more or less motivated) possibilities. For example:**

  - Line 602 - "Unexplained symmetry between quarks and leptons [42]". Meaning? The ref is a 1976 paper.
  - Line 604 - "Artificial that [quarks and leptons] share the electromagnetic and weak interactions but differ in [...] strong interaction" Is this a big open question?
  - Line 613 - "RPV SUSY in which there is no LSP". There is always an LSP.

Chapter 5

- **Title: New physics at *large scales***

  - Should be either "high energy" or "small scales". *Large scale* usually means low-energy
  - Ditto at lines 2103-2104

Section 5.1.1: Quark substructure

- Line 2135-36:
  - *"... comparable to the sensitivity that the LHC is expected to reach"*
  - More quantitative details on this comparison would be useful
    - what are the relevant observables?
    - how does this differ from the study of qqqq effective interactions, and does $<r^2>$ relate to the parameters of 4-quark operators?
    - what is the timescale for the LHC to set limits of relevance for the LHeC?

- Minor issue:
  - *colored areas vs dashed line in the fig? Sensitivity vs limit?*

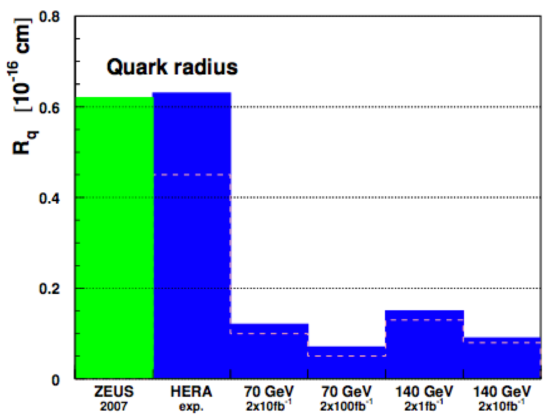


Figure 5.1: Sensitivity (95% confidence level limits) of an LHeC collider to the effective quark rad

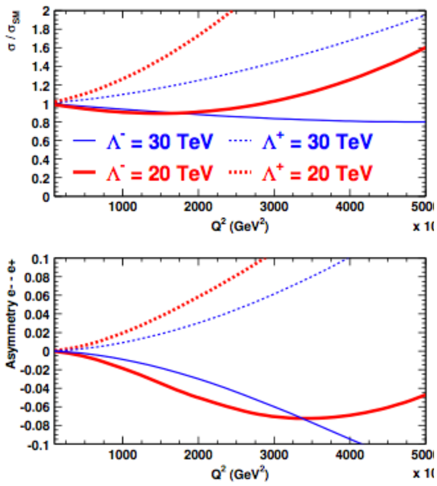
Section 5.1.2: Contact interactions

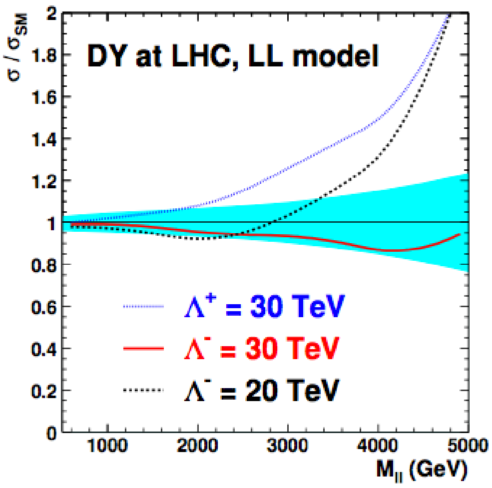
(1)

$$\eta^{q}_{ab} \equiv \epsilon \frac{g^2}{\Lambda^{q\,2}_{ab}}, \qquad (5.4)$$

What is the value of **g** used in the numerical analysis?

(2)

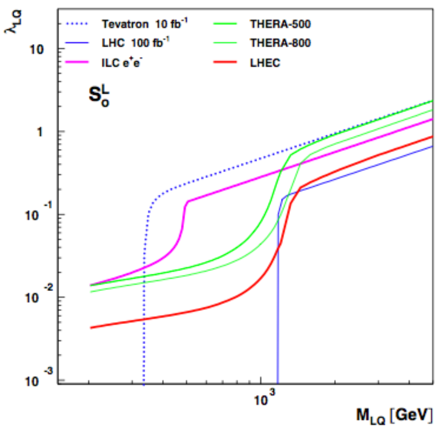


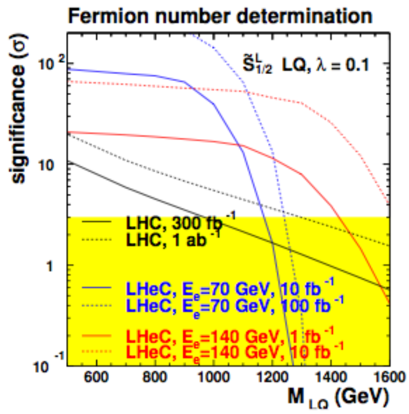


- Energy, luminosity?
- Cannot compare the two, no indication of statistical sensitivity
- Is there a discovery/measurement reach beyond the LHC discovery reach?
- Evolution of PDF systematics at the LHC
- What's the impact of angular distributions, AFB, etc at the LHC is determining couplings (sign, size, chirality, ...)?

Section 5.2: Leptoquarks (LQ)

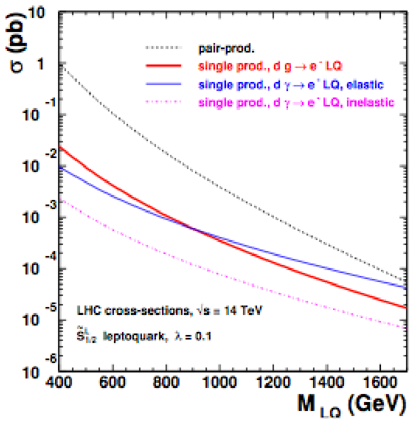
(1)

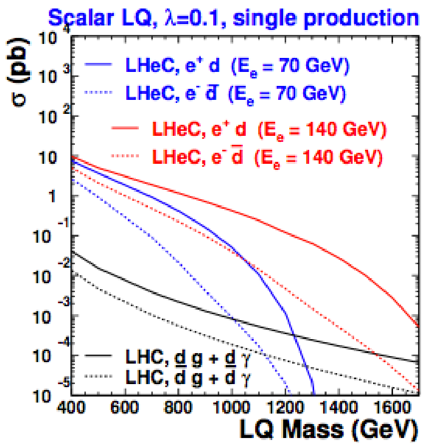




Not clear from these figs what the added value of the LHeC is. There appears a small window of opportunity only for the 140 GeV option, between 1300 and 1600 GeV.

What's the timescale to understand from the LHC whether this is relevant? 1-year at 14 TeV?





(2) What about t-channel LQ exchange procs at the LHC, possibly for large λ and large mass?

(3) Line 2344-47: the nu decay channels are already used at LHC, is a quantitative statement possible?

Section 5.3.1: Excited leptons

(1) Leptons or simply *electrons* ?

(2) Line 2435: "*The production cross sections of excited neutrinos at the LHeC is also shown in figure 5.15* " **??????**

(3) Specify f=f'=1 in the figure

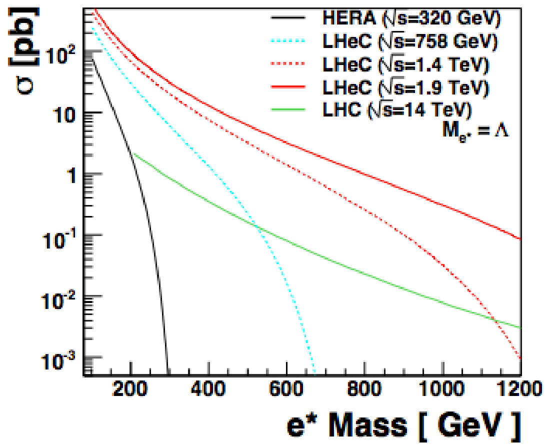


Figure 5.15: The e^* production cross section for different design scenarios of the LHeC electron-proton collider, compared to the cross sections at HERA and at the LHC.

(4) Line 2469: "*LHC ($\sqrt{s}$ = 14 TeV) could exclude e∗ masses up to 1.2 TeV for an integrated luminosity of 100 fb^{-1}*"

It appears from the plot that 1 fb^{-1} suffice for exclusion?

(5) σ_{LHC} ~ O(0.1) σ_{LHeC} ⇒ always compensated by integrated luminosity difference?

What happens beyond 1.2 TeV?

Section 5.3.3: 4th generation leptons

(1) Having a magnetic interaction in the mixing between first and fourth generation is fairly arbitrary. What is the new information beyond what discussed for the "excited fermions".

(2) Having a mixing only between 1st and 4th generation seems ad-hoc. If more mixings are allowed (e.g. 1-4 and 2-4), what are the constraints from, e.g. $(g-2)_\mu$, $\mu \to e\gamma$?

Section 5.4.2: top couplings

(1) What about the potential of the LHeC in normal running mode (no gamma-p option)?

(2) Any reach for Z u→t ?

(3) Line 2528:

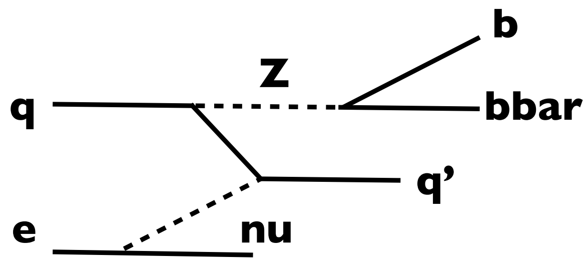
> For numerical calculations anomalous interaction vertices are implemented into the CalcHEP package [211] using the CTEQ6M [131] parton distribution functions. The Feynman diagrams for the subprocess

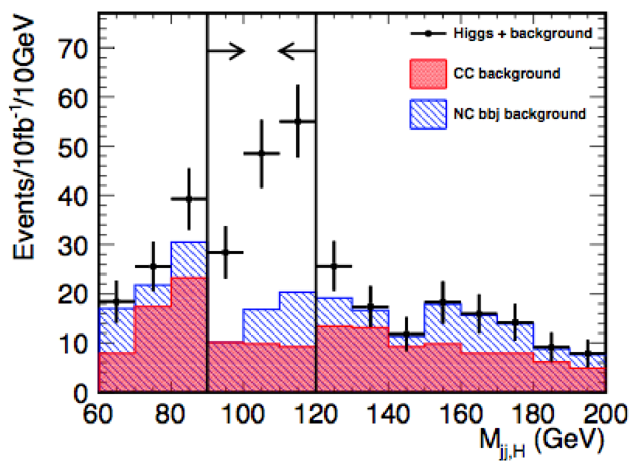
Start by introducing what's being done

(4) Line 2563: last phrase is about the same as the beginning of this section (2499) and it sounds a bit misplaced

Section 5.5: H →bb

(1) Was the eq →νq' Z →νq' bb background included?





(2) More in general (see Table 5.6 and/or line 2705): Are complementary analyses possible to determine the normalisation of the background? Why the uncertainty is expected to be negligible?

Section 5.5.4: WWH

(1) Clarify comparison with LHC reach in HWW coupling. Is the sensitivity on the HWW coupling (the normal coupling, not the anomalous one) competitive with the LHC for relatively light Higgs?

(2) a few remarks about the background and the migrations influence on the angular distributions would be useful.

(3) Line 2719 - "handle on the quartic self-coupling". Do you mean a handle on the structure of the EW breaking sector?

(4) Line 2722 and eq. (5.14) - Do you mean g_{\mu \nu} instead of lambda_{\mu \nu}?

Other

(1) Are di-leptons (same charge) also a case for LHeC (for instance doubly charged Higgs)?

Typos

- Line 2328 - assuracy
- Line 2282: should be 300 **fb–1**, not pb–1
- Figure 5.18: the legend is scrambled
- Line 2537 - reducese
- Line 2586 - at n high
- Ref. [236] - Missing author name.
- Ref. [238] - Put 2010 PDG edition

9 Precision QCD and Electroweak

Referees:

Guido Altarelli (Roma)
Vladimir Chekelian (MPI Munich)
Alan Martin (Durham)

LHeC report on Physics
Suggestions and comments on Chapter 4 (and a bit also on Chapter 6) by Guido Altarelli
25 October 2011

General Remarks: Chapter 4 gives a good and complete list of LHeC capabilities and goals in the domain of “Precision QCD and Electroweak Physics”. The positive aspect of this Chapter is the systematic, exhaustive, balanced and clear presentation and discussion. What can I suggest as possible improvements? The main defect that I see is that the Chapter looks too much as a simple collection of items organised as a direct extrapolation from HERA. The questions it raises is whether the HERA time context will still be appropriate for the LHeC time and what is the relative value of the different issues from that point of view. I suggest that at the end of each paragraph, or at least of the most important of them, there should be a discussion of their importance in themselves and for the LHC and for future hadron colliders. Similarly at the end of the whole Chapter there should be again a summary and a ranking of the highlights and why and to which extent these measurements will be important in the physics context of the 2020’s.

Personally I would interchange the order of Chapters 5 and 6. In fact small x physics is still mostly in the SM domain, while New Physics is more into the exotic (by the way New Physics at Large Scales: I find large scales is ambiguous, I would say either large energy scales or at large Q2; it is not large distances). Also I would prefer to anticipate all the small-x log resummation (that is all the leading twist improvements at small-x) in Chapter 4, because this part will be directly relevant to the PDF determination in the small-x range of the LHeC.

I now come to more detailed comments.

4.1.1

The statement:

“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.”

is perhaps too strong and it could be criticised. For hadron colliders in QCD the argument is not really definitive (see Ref. 289 for a review) and many people still advance doubts. Actually this question could be studied experimentally, in that the LHeC, with its improved precision, could put bounds on the allowed amount of possible factorisation violations (eg by measuring in DIS the gluon at large x and then comparing with jet production at large pT in hadron colliders).

4.1.2 - 4.1.3 – 4.1.5

FL (and perhaps also F2,3gammaZ) deserve to be put among the highlights. I would change " the symmetry between sea and antiquarks" (you mean between sea quarks and antiquarks?). This latter form also appears in the next subsection on charged currents but still it is not appropriate given the level of refinement aimed to at the LHeC.

FL is interesting in itself as a basic test of QCD and for reaching the gluon density. But I do not think that the statement:

"The LHeC thus will provide the first precision measurement of FL(x;Q2) 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."

is justified. Indeed the ranges of Q2 and x shown in fig. 4.7 should fully be within the domain of leading twist QCD with resummed small-x logs. Often new regimes of multi parton interactions or of gluon saturation have been invoked for explaining the available data but, from F2 singlet scaling violations such effects have not yet been clearly observed, in precisely that range of Q2 and x.
Later, at the start of sect. 4.3 it says:

"The addition of precision measurements of FL, ..., will unravel the saturating behaviour of xg."

One is not at all sure, as I said, that this promise can be maintained

4.2 PDF's

Of course the determination of the PDF's is the core business of an e-p collider. Here it would be especially useful to put at the end a list of the most important qualitative breakthroughs that would occur in this domain and their impact on hadron colliders and on other experiments (eg for valence quarks, strange quarks and antiquarks, gluons, heavy quarks,). Since the most guaranteed and important contribution of the LHeC is on this domain it is imperative to argue that this effort is really worthwhile in terms of feedback on the physics of next decades.

The top quark part looks a bit over optimistic/emphatic to me: eg the BSM probe through the top, the top mass (probably ~ 1 GeV, as obtained at hadron colliders is even too much to be theoretically controlled) etc. On the gluon again there are some not very well grounded statements, for example when it says:

“The peculiarity of the gluon density is that it is defined and observable only in the context of a theory. Moreover, a crude data base and correspondingly rough fit ansatz can screen local deviations from an otherwise preferred smooth behaviour. It has yet not been settled whether there are gluonic “hot" spots in the proton or not. An example for possible surprises is provided by the analysis [41], in which Chebyshev polynomials ......”

Rather the real good progress is because:

“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 > =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 and 4.18.”

4.4 alphas

It is true that the situation of the determination of alphas in DIS is still unsatisfactory and that the LHeC can be important in this respect. But the presentation here is still somewhat confuse. The table is already obsolete. The results from the most recent works in refs [97-99] should be brought to the forefront. Also a comparison with the other totally inclusive, lightcone dominated methods (e+e- ann., Z decay, tau decay) would be essential. But, besides the description of the present situation, the real issue is whether an improvement of the statistical error as given in Table 4.4 and detailed in the related discussion, is useful in view of the systematics and of the theoretical uncertainties. And in fact it says:

"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."

4.6 Charm and Beauty

This section is written along a good template with introduction and highlights, much as I was suggesting.

I would de-emphasize intrinsic heavy flavour because rather controversial. Accordingly, the space given to the D* meson photoproduction appears excessive to me.

4.9 Electroweak Physics

I think that this section is particularly questionable. One risks to discuss the physics of the future in terms of the context of the past. In fact, the section starts with:

"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."

But we hope that, already by next year, we will have more direct and complete information on the SM or SM-similar Higgs from the LHC. In the text it later says:

"It is unlikely that operating experiments will change significantly the above picture of electroweak precision measurements."

While from the context one can see that the author simply means that no better measurements of mtop and mW will happen in the near future, it however sounds pretty surprising because the current experiments will hopefully completely vanify or drastically change the motivations for such precision tests by settling the Higgs issue, in a sense or the other, and hopefully also produce new particles. I think, in fact, that precision EW experiments have already given their response at LEP and that now either new physics is directly found or we better quit.

Besides this general skepticism of mine on the interest of precision EW tests for the future, I also think that the discussion presented at the present draft is still rather approximative being presumably preliminary. On the light quark couplings, one does not understand what the various scenarios A, B.... are and what is included in the quoted errors. On the weak mixing angle there is no discussion of a comparison of the LHeC determination, when all ambiguities are taken into account, with the precision already obtained at LEP etc. Rather one hides this comparison behind a different definition of the mixing angle beyond leading order. It is true that this definition is better suited for the LHeC, but the fact remains that both the final precision at the LHeC, all errors included, and the comparison with the present accuracy at equal definitions, are missing.

On Chapter 6 (this is not my assigned task, but still...)

I find the introduction in sect 6.1 a bit confusing (repetitions, not a clear line of argument, questionable statements etc) and there is not a clear separation among items with different degrees of model dependence. In this respect I repeat the point that the resummation of small-x logs, which has to do with the leading twist splitting functions, should better be transferred to Chapter 4 because it will be even more relevant at the LHeC than at HERA for the extraction of PDF's from the data. In Chap.6 it is particularly evident that the text has been written in patches then put together.

In conclusion I think that the physics case for the LHeC is mainly based on the issues discussed in Chapter 4, plus a selection of the issues in Chapter 6 and a few items of new physics like leptoquarks and right handed currents (which however risk to be already severely constrained by the LHC by the time the LHeC will operate). The present TDR covers the physics programme in a clear and mostly satisfactory way. The Report could be made more convincing if the relevance of these issue would be further evaluated in the physics context of the LHeC years when most of the LHC outcome will be known.

LHeC Report, Precision QCD and Electroweak Physics: Referee Comments

Vladimir Chekelian
Max-Plank-Institut für Physik, Föhringer Ring 6, 80805 München

Chapter 4 of the LHeC Report on the Physics and Design Concepts for Machine and Detector, "Precision QCD and Electroweak Physics", is solid, well written and motivated. It demonstrates physics prospects which are related to high precision measurements with the LHeC to test and develop QCD and the electroweak theory.

The LHeC machine opens a new era in precision QCD and electroweak physics in the deep inelastic ep, eD and eA scattering. The expected kinematic reach is extended in Q^2 up to 1 TeV^2, x up to 0.8, y down to 0.001 with luminosity of 10-50 fb^{-1} and electron (positron) beam longitudinal polarization up to 80%. It is by far exceeds the first ep collider HERA with Q^2 up to 0.05 TeV^2, x up to 0.65 and y down to 0.01. The LHeC thus becomes the world's cleanest high resolution microscope, designed to continue the pass of deep inelastic lepton-hadron scattering into unknown areas of physics and kinematics.

This is quantified in a detailed simulation of the neutral (NC) and charged current (CC) processes at the LHeC. The expected systematic uncertainties are estimated and discussed in detail. The structure function F_2, F_L, xF_3, $F_2^{\gamma Z}$, $F_2^{c\bar{c}}$, $F_2^{b\bar{b}}$ will be determined with unprecedented precision. For example the uncertainty of the longitudinal structure function F_L is estimated to be 4% at $Q^2 = 3.5$ GeV^2 compared to 12% at HERA. The LHeC is the first DIS experiment which is able to completely unfold the the partonic content of the proton: g, u, d, s, c, b, t, resolving open issues related to $(s - \bar{s})$, $\bar{u}/\bar{d}$, u/d, etc. The expected gain in the precision of the PDFs in the QCD fit using the LHeC data is evaluated and compared to HERA, BCDMS and precision W charge asymmetry data from the LHC. The precision of the gluon distribution and strong coupling determinations is carefully examined. A dedicated part is written for top quark physics which becomes a new subject of research in DIS at the LHeC. Owing to the much extended range, higher cross section and dedicated silicon tracking, high precision measurements of the c and b densities will be available for the development of the QCD theory of heavy quarks and for the description of new phenomena which may be expected to be related especially to the b density. The measurements with electron-deutron scattering will allow to extend the current experimental knowledge on the structure of the neutron by nearly four orders of magnitude in Q^2 and $1/x$. The precision QCD tests at the LHeC with jets in the final state are introduced and evaluated. With the enlarged energy, new measurements of the total photoproduction cross sections can be performed. The electroweak physics which focuses on the precision measurements of the light weak NC quark couplings and on the scale dependence of the electroweak mixing angle, can be determined from polarization asymmetries in NC and the NC/CC cross section ratio.

To summarize, the physics output of LHeC related to precision QCD and electroweak physics is worked out in the document in an encouraging and convincing way.

Few suggestions from my side to Chapter 4 are listed below:

- in view of extended phase space and excellent precision, the second order QED correction to be addressed at high x and low y.

- it is desirable to introduce and discuss the measurement of the ratio F_2^n/F_2^p at the LHeC.

- discuss importance of the strong coupling determination in DIS in view of lattice calculations which provide the best precision at present.

- stress once more in the section related to the high p_t jets that the absence of the NNLO calculations is a limiting factor.

The comments to Chapter 4 were presented at the LHeC Referees meeting at CERN on 25 October 2011, more details can be found on the corresponding slides.

24 February 2012 (presented at CERN on 25 October 2011)

LHeC report on Design Concepts

Suggestions and comments on Chapter 4 (together with a couple on Chapter 6) by Alan Martin (IPPP, Durham)

24 October 2011

Overall summary: The Chapter is well-constructed, and makes a strong, persuaive physics case for the construction of the LHeC.

Page 30: Typo in eq.(4.4)

$$.... - \frac{y^2}{Y_+} F_L$$

.

Page 30: after eq.(4.5) insert $\quad ...xF_3^Z,$

see also the Review of Particle Properties [1] for a summary of the formulae used in subsections 4.1.2 and 4.1.3. (which become 4.1.3 and 4.1.4 after adding the mew subsection below)

Page 31, line 979: I was pulled up by the remark: "Assuming symmetry between sea and antiquarks,...". I had not heard this expression before. This is an area that the LHeC could illuminate for the first time. Therefore for the clarity of future discussions in this Chapter, I recommend adding the following short subsection in the middle of **Page 30**:

Subsection 4.1.2: The LHeC can probe $q \neq \bar{q}$ and $u^p \neq d^n$

For evolution at high Q^2, the transition $g \to q\bar{q}$ populates the q and $\bar{q}$ PDFs equally. Of course, in the non-perturbative region there is no reason to have $q = \bar{q}$. Until recently, the lack of appropriate data has meant that this equality is assumed to be true for $s, c, ..$ quarks, and that

$$u = u_v + u_{\rm sea}, \quad \bar{u} = u_{\rm sea},$$

and similarly for d. Recent PDF analyses have attempted to determine s and $\bar{s}$ separately, using dimuon production data, subject to the constraint

$$\int_0^1 (s(x, Q^2) - \bar{s}(x, Q^2))dx = 0$$

which follows since protons have no valence strange quarks. However the information obtained for $s - \bar{s}$ is very limited.

In this whole area the LHeC can dramatically transform our knowledge. For the first time, we will be able to explore $\bar{u} \neq u_{\rm sea},\ \bar{d} \neq d_{\rm sea},\ \bar{s} \neq s,\ \bar{c} \neq c...$ with good precision.

Moreover, by measuring the DIS processes $eN \to e\gamma X$, the LHeC has the unique opportunity to perform a precision measurement of the photon parton distributions of the proton and the neutron. Hence to quantify the amount of the corresponding isopin violations $u^p \neq d^n$ and $u^n \neq d^p$.

Page 31 line 980: better to write

$xF_3^{\gamma Z} \simeq (2u_v + d_v)/3$

Page 44, line 1183: rather than "50-100% to about 5%", I note from Fig. 4.9 that it seems to be "20% to about 2%". Perhaps I am misreading something?

Page 44: in eq.(4.25) and in lines 1193 and 1194

replace k by κ_Z

Page 48: improve the notation on Fig. 4.13: $xs\ \ 3^j$; explain ϵ_c and bgd_q in the caption.

Page 49: mention c and $\bar{c}$ in the caption to Fig. 4.14.

Page 50: I would not include [74] (except perhaps in a footnote) or Fig. 4.15. Apart from some slides at DIS2011, I could find no further information. In general, heavy quark PDFs are non-zero for $Q^2 < m_Q^2$. The partons of Fig. 4.15 will be in a non-conventional scheme.

Page 51: I recommend deleting "An example...cool spot in the proton" starting on line 1270. I guess this is just due to the oscillations of the Chebyshev polynomials. It certainly would be eliminated if jets were included in the fit.

Page 54: Section 4.4.1 Status of the DIS Measurements of α_s

add to Table 4.3

NNPDF	0.1173 ± 0.0007	[2]
CT10	0.1180	[3]

add final paragraph to this subsection:

Recent studies have found that $\alpha_s(M_Z^2)$ obtained from DIS data is closer to the world average than indicated by the large spread of values shown in Table 4.3. It is found to be necessary to perform global fits which include a careful treatment of the Tevatron jet data, since, at present, these data are the main constraint on the high x gluon PDF. Note that the value of α_s is *anticorrelated* with the low x gluon through the scaling violations of the HERA data. Thus α_s is *correlated* with the high x gluon through the momentum sum rule. As a consequence, the values of α_s found including a careful treatment of jets by MSTW08, NNPDF1.2 and CT10.1 give the most reliable determinations. Also HERAPDF gives a compatible value of α_s when jets are included, see Table 4.4. Ref. [4] gives detailed reasons why the low values of α_s in Table 4.3 are questionable. For the reasons given in Section 4.3, the LHeC will be able to considerably improve the gluon PDF at large x (as well as at low x) and hence help to obtain the dramatic improvement in the determination of α_s from DIS.

Section 4.4.2 Simulation of α_s determination

Replace the paragraph on **page 55** starting “It is obvious....” by

It is clear from Table 4.4 that the LHeC will give an enormous improvement in the experimental error on α_s from the evolution of structure functions and other processes, including jets. However, there is also the theory uncertainty to consider. It will be a great challenge to QCD theory to reduce this uncertainty, so as to make the most use of such results. We will need to study the effect of non-linear terms and additional $\ln(1/x)$ contributions in DGLAP evolution at low x, and to have an accurate knowledge of the charm quark mass (to 10 MeV, or so, for a knowledge of α_s to one per mille). Also we should include the QED corrections in the evolution (as discussed below). However, these limitations will be automatically improved by the LHeC itself. Then, to reduce the uncertainty due to the choice of renormalisation and factorisation scales, it appears to be necessary, for the expected precision, to work at higher-order than NNLO.

Page 56, Section 4.5 eD scattering, line 1399, add footnote

....tagged – footnote – (Such an eD experiment with tagged protons has been successfully carried out at the Jefferson laboratory [5], but at much lower energies and with much less statistics.)

Page 56, after line 1419, insert a new subsection:

QED corrections and photon PDFs of the proton and neutron

The LHeC offers the unique opportunity to include $\mathcal{O}(\alpha)$ corrections to parton evolution by measuring the photon parton distributions, $\gamma^{p,n}(x,Q^2)$, of the proton and the neutron. The most direct measurement is to observe wide-angle scattering of the photon by the electron beam. To be specific, the processes $eN \to e\gamma X$ where the final state electron and photon are produced with equal and opposite large transverse momentum. The subprocess is then simply QED Compton scattering, $e\gamma \to e\gamma$, and the cross sections are obtained by the convolution [6]

$$\frac{d\sigma(eN \to e\gamma X)}{dx^\gamma} \;=\; \gamma^{p,n}(x^\gamma,\mu^2)\;\hat{\sigma}(e\gamma \to e\gamma).$$

If the photon is produced with transverse energy E_T^γ and pseudorapidity η^γ in the LHeC laboratory frame, then

$$x^\gamma = \frac{E_T^\gamma E_e \exp(\eta^\gamma)}{2E_pE_e - E_T^\gamma E_p \exp(-\eta^\gamma)},$$

where E_e and E_p are the energies of the electron and proton beams respectively. At HERA only a single measuremet of the $ep \to e\gamma X$ cross section was made (for $x_\gamma \sim 0.005$), with a large uncertainty [7]. Also, a first estimate of $\gamma^{p,n}(x, Q^2)$ PDFs was performed in [6].

Such measurements at the LHeC will be considerably more precise and will allow an investigation of whether the $\mathcal{O}(\alpha)$ contributions have a sizeable effect, in comparison to the $\mathcal{O}(\alpha_s^2)$ NNLO QCD terms, in a complete QED-modified DGLAP evolution, including QED terms in the input. Even if they are found to have a small effect, they necessarily lead to a precise determination of the isopin violations $u^p \neq d^n$ and $u^n \neq d^p$. Recall that it was these isospin violations, together with $s \neq \bar{s}$, which explained away the NuTeV $\sin^2\theta_W$ anomaly. Of course, ideally, for precision physics we should anyway use QED-modified partons which include $\gamma^{p,n}(x, Q^2)$.

Page 59: replace the two sentences on lines 1476/8 by a new paragraph:

The value of the mass of the charm quark is also an important uncertainty in the predictions. In the determinations of m_c we have to distinguish between the pole mass and the running mass. Fits to the present data have been performed using both as free parameters. First, Ref. [10] used the pole mass as a free parameter and finds $m_c = 1.45$ GeV at NLO and 1.26 GeV at NNLO. Alternatively, Ref. [9] use the running mass and finds $m_c(m_c) = 1.26$ GeV at NLO and 1.01 GeV at NNLO. Typically the uncertainties quoted in these results are about $\pm 10\%$. After the conversion from the pole to the running mass these values obtained by the two analyses are quite compatible with each other. Clearly, LHeC data are required to improve the perturbative stability and to increase the precision in our knowledge of m_c.

Page 62, Fig. 4.21: define DIS, that is the range of Q^2.

Page 65, Section 4.6.4 Intrinsic Heavy Flavour

I believe this section is misleading. The $1/m_Q^2$ behaviour, that is mentioned, is obtained from the operator product expansion. It reflects just the perturbative $g \to Q\bar{Q}$ contribution and is already accounted for in the conventional PDFs, that is without an intrinsic $Q\bar{Q}$ component. The intrinsic component is of a non-perturbative nature. It arises from the exchange of many low q^2 gluons, and therefore should be suppressed by a large power: $(1/m_Q^2)^n$ where $n > 2$. It is most natural to expect an exponential suppression.

I would concentrate this section on intrinsic charm, where we are more or less close to the non-perturbative domain, and where Fig. 4.24 demonstrates the possible effect. There is a small chance of having sufficient intrinsic $b\bar{b}$ admixture to also be seen, but certainly the $t\bar{t}$ admixture is extremely small.

I would not mention the Higgs signal from a $t\bar{t}$ component (except perhaps in a footnote giving references to those who advocated, controversially, this process), since the expected rate is very, very small. To my knowledge, the best LHeC Higgs signal is to look for $H \to b\bar{b}$ plus a forward jet, which you discuss elsewhere in the report. The LHeC is not strong on the Higgs.

The claims of the second paragraph of this section (line 1636 on) are too strong:

May I suggest the word “strong” is deleted the word “may” is inserted (may have been underestimated) in the first sentence of the paragraph. Then add the sentence “See, however, the limits on intrinsic charm, discussed in Sections 4.4 and 9.2 of [8].” Then delete “Furthermore” and replace “will lead” by “may lead” in the next sentence.

Page 79, Fig. 4.35:

What are scenarios B,C,D,E? Do they refer to Table 4.2? If so, mention Table 4.2. But presumably not, as B should then give a tighter constraint on the couplings than C?

Page 83, Fig. 4.37:

It would be good to see NC/CC both taken at $Q^2 = 9500$ GeV^2, using at least NLO partons. The LHeC will enormously reduce any PDF uncertainty and so it appears that NC/CC might be the best way to probe the scale dependence of $\sin^2\theta_W$.

Page 85, after line 2089: I recommend a summary to the Chapter, something like that below. I am sure it can be improved.

Summary

This chapter has described how the LHeC can make an enormous improvement in our knowledge of the partonic structure of the proton and neutron, in precision, in kinematic scope and in the types of partons explored. The knowledge of PDFs is an essential ingredient in extracting physics from all high energy colliders involving nucleon beams. Up to now the global PDF analyses have been based on a pure DGLAP approach, which has been able to satisfactorily describe all DIS and related hard scattering data, albeit with limited precision and kinematic scope. However, the kinematic reach of the LHeC takes us into a low x domain where, for sure, the pure DGLAP approach will be insufficient and novel physics effects will be able to be explored. Our present understanding and expectations of this domain will be the subject of Chapter 6.

Chapter 6: a couple of comments. The first, rather general and not thought through, and the second a specific addition

Around page 147

I wonder if there should be more discussion introducing GPDs, which are quite fundamental? In case it helps, I attach a very brief summary of GPDs which, for the first time, will be included in the Reviews of Particle Properties, 2012 edition. GPDs can be explored at the LHeC via DVCS, $\gamma p \to Vp$ and $\gamma p \to Zp$.

Page 150: insert a new subsection in the middle of the page

Exclusive J/ψ photoproduction at NLO

Instead of using the simple ad hoc gluon introduced above eq.(6.10), we now consider how elastic J/ψ data, obtained at the LHeC, may be used to determine the gluon PDF at low scales and very low x. Recall, at leading order the cross section is proportional to the square of the gluon distribution. More recently, the collinear factorisation formalism has been extended to NLO for heavy vector meson photoproduction [11]. The result had a large, unphysical dependence on the factorisation scale. Nevertheless, the NLO framework can be used to determine the 'correct', physical scale which resums large logarithms, $\ln(1/x)$, responsible for the large scale dependence. After this, the remaining scale dependence turns out to be moderate [12].

The production amplitude at NLO depends on both the gluon and the quark GPDs. Such GPDs are currently not well constrained by data, but, fortunately for high energies (small x), can be estimated from the diagonal PDFs [13]. So measurements of J/ψ photoproduction at the LHeC (with $E_e = 50$ GeV, $E_p = 7$ TeV) will probe the gluon distribution down to $x \sim 10^{-5}$ at scales $m^2_{J/\psi}/4$. For Υ photoproduction we reach $x \sim 10^{-4}$, and for $\gamma p \to Zp$ we reach $x \sim 10^{-2}$. Such measurements at low x at the LHeC will be invaluable in constraining global PDF analyses, and, at not too low x, in probing GPDs.

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[2] NNPDF Collaboration, R.D. Ball et al., arXiv:1110.2483

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[9] [91]

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[12] S.P. Jones, A.D. Martin, M.G. Ryskin and T. Teubner, *in preparation.*

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10 Physics at High Parton Densities

Referees:

Alfred Mueller (Columbia)
Raju Venugopalan (BNL)
Michele Arneodo (INFN Torino)

LHeC Report Discussion of High Parton Densities: Referee Comments

Michele Arneodo[(1)], Al Mueller[(2)], Raju Venugopalan[(3)]

October 23, 2011

1. Università del Piemonte Orientale, I-28100 Novara, Italy
2. Physics Department, Columbia University, New York, NY 10027, USA
3. Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA

1 Overview

Experiments probing small values of Bjorken x at fixed large transverse resolution scales Q^2 provide sub-femtoscopic snapshots of the structure of protons and nuclei as quantum states containing large numbers of gluons and sea quarks. These states have universal properties and are expected, from fundamental considerations related to the stability of QCD, to exhibit maximal occupancy, a phenomenon known as "parton saturation". The parton saturation regime resolved at small x is a novel non-perturbative regime of strong non-linear color fields in QCD. Because these high parton density states are accessed at fairly large Q^2, essential features of their dynamics can be understood using weak coupling methods. Beyond intrinsic interest in the dynamics of this novel many-body regime of QCD, a careful study of its properties may provide fresh insight into the intrinsically non-perturbative dynamics of chiral symmetry breaking and confinement in QCD. The LHeC will be the ultimate machine to explore the fundamental physics of parton saturation in QCD. In addition, it represents an important future direction in studies of collective properties of QCD, as represented by two generations of experiments at the SPS, RHIC and LHC.

2 Report Summary

Chapter 6, "Physics of High Parton Densities", is well written and presents the case for the LHeC as an extremely good machine for studying high parton densities and the phenomenon of saturation in QCD.

The first part of the chapter gives a good summary of the status of small x physics, and clearly and fairly covers the results from HERA and their implications. In particular, the discussion of the NLO DGLAP fits to the HERA structure functions is well done. There are hints that fits to the inclusive F_2 data below $Q^2 = 4$ GeV^2 and fits to $F_2^{\mathrm{diff.}}$ data below $Q^2 = 8$ GeV^2 may not follow NLO DGLAP evolution. As discussed, while suggestive of saturation, these hints of tension in the data could be due to alternative sources; in particular, for the inclusive data, small x resummations could provide a more conventional explanation.

The p+A and A+A programs at the LHC have great potential for studying small-x physics and strong hints for saturation effects have already been seen in forward di-hadron production in deuterium-gold collisions at RHIC. While the LHC should have an exciting program, experience shows that e+p and e+A collisions will be an immensely cleaner and precise environment to study parton saturation. As a case in point, virtual photons provide by far the best measure of quark and gluon distributions. An ambitious, but not unrealistic, long range goal for theorists is to describe, *ab initio*, the formation of the quark-gluon plasma in A+A collisions from the initial heavy-ion parton distributions measured in e+A collisions at the LHC. We also note that even if saturation dynamics were uncovered in p+A collisions at the LHC, understanding its universal features will require a lepton probe.

The significantly extended reach in x of LHeC relative to HERA in extracting parton densities, as well as the improvements in the quality of existing fits is well presented. Of particular note is the improvement gained by adding data from F_L and heavy flavor measurement (Figs. 6.14 and 6.15). As shown in Fig. 6.17 for $F_L^{\rm proton}$, the x range in which good measurements could be made extends between $5 \cdot 10^{-6}$ and 10^{-4} for $Q^2 = 5$ GeV^2. F_L is particularly sensitive to saturation effects and this x range is the range where saturation effects must be strong.

Equally impressive is the extraction of gluon distributions in nuclei, which is currently unknown in the small x region. The authors demonstrate a significant reduction in the uncertainties of nuclear PDF fits (EPS09) by inclusion of LHeC pseudo-data. As noted, in addition to their intrinsic interest, these extractions can provide important corroboration of knowledge gained from p+A and A+A studies at the LHC. As saturation effects can be expected to be large, the leading twist nuclear gluon distribution is more meaningful at larger Q^2 than the $Q^2 = 1.69$ GeV^2 shown in Fig. 6.20. In contrast to the proton case, much of the improvement in extraction of nuclear parton distributions appears to be driven by F_2 and not by F_L and heavy flavor measurements. In particular, the ratio $R_{F_L}^{\rm Pb}$ shown in Fig. 6.18 has large errors in the interesting x range and depends strongly on the exact value of x.

The authors emphasize exclusive diffractive J/Ψ production in both e+A and e+p collisions as one of the best ways to see saturation. We agree. The spatial size of the J/Ψ is such that saturation effects should be very strong. At HERA, saturation effects in diffractive vector meson production are significant only for the most central impact parameter collisions and systematic uncertainties complicate clean interpretation of the results. Fig. 6.23 illustrates the impact of LHeC on this measurement clearly in comparison of pseudo-data to a model where non-linear saturation effects can be turned on and off. At the highest LHeC energies the authors show (Fig. 6.25) that for impact parameters less than 0.2-0.3 fm, the survival probability of a dipole of the size of the J/Ψ to go through a proton without interacting should be less than 1/4; the corresponding kinematic regime, which is accessible in experiment, sets the dynamics strongly in the saturation region. For e+A collisions, for a wide range of impact parameters, nuclei should be quite black for dipoles of the size of the J/Ψ; a model computation (Fig. 6.31) shows a reduction of $d\sigma/dt|_{t=0}$ for photo-production of J/Ψ's by a factor of three at the highest W's in going from protons to lead.

Hard diffractive final states offer the opportunity to study the nature of color singlet exchanges (responsible for final states with a rapidity gap) in a weak coupling framework. The authors clearly demonstrate the impressive reach of LHeC in performing diffractive measurements with very large mass final states (in particular, Fig. 6.37). However, the plots chosen showing the reach with β for different ranges of $x_{pom.}$ and Q^2 are not particularly informative and the presentation could be improved. For example, one might have expected that $F_{2,A}^{\text{diff.}}/F_{2,A}$ to show black disc behavior in the LHeC range, to grow strongly with energy towards a value of 1/2. Fig. 6.41 shows growth with energy, but the value of the ratio is shown for a β range where the connection to the approach of cross-sections to the black-body limit is not apparent.

Jet correlation studies offer the opportunity to perform precision tests distinguishing DGLAP versus BFKL resummation schemes in QCD. In nuclei, di-jet measurements of sufficiently high invariant mass (and in particular diffractive di-jets) can provide useful additional channels to constrain nuclear parton distributions. Extracting information on saturation from jet measurements, while perhaps feasible, is challenging on account of the difficulty in cleanly identifying low mass jets. However di-hadron measurements at small x can provide important information on saturation, in particular the QCD evolution of multi-parton distributions. These measurements will also provide an important test of the universality of this evolution because the evolution of multi-parton distributions can also in principle be extracted in p+A collisions. Studying jet quenching in e+A collisions will provide an important benchmark to studies of the same in A+A collisions at the LHC; we recommend more detailed studies on this topic.

3 Suggestions

We list here a few suggestions and comments that we hope will improve the presentation of material discussed in this chapter.

- Page 121: Some care must be exercised in the discussion of unitarity here and elsewhere. QCD is a unitary theory and the microscopic dynamics "don't lead to it"; unitarity is intrinsic to the dynamics. Various perturbative calculational schemes may, when stretched out of the regime of applicability, violate unitarity–this suggests the limits of their applicability. One might emphasize instead that non-linear QCD dynamics is essential even in weak coupling to ensure unitarity at high energies, thereby suggesting that saturation must be a fundamental feature of QCD.

- Fig. 6.2: This is a nice plot, but requires some further explanation. The shorter squiggly lines with decreasing x are meant to illustrate shorter lifetimes, but to the uninitiated reader, they may suggest excitations of shorter wavelength, contrary to what one expects at small x.

- Fig. 6.24: It is unclear that the linear-linear scale plot (b) is necessary.

- Exclusive photo-production of hard final states is being studied at the LHC (cf. Phys. Rept. 458 (2008) 1). It might be useful to discuss the relative reach and impact of these measurements on the LHeC, and conversely, of the latter on LHC diffractive measurements – e.g. in terms of the rapidity-gap survival probability.

- The potential of the LHeC for diffractive measurements goes beyond the channels discussed. It might be appropriate to elaborate on the fact that some measurements difficult or impossible at HERA become feasible at the LHeC – among them, exclusive dijet production, inclusive W and Z production (mentioned at the top of p. 167) and possibly Z photo-production. Diffraction in charged current events, barely touched at HERA, may be worth considering. Some of these reactions are being measured at the LHC.

- Fig. 6.25a is a very nice figure. It would look even more impressive if $S^2 = (1 - N)^2$ were plotted instead of N. After all, S^2 is the survival probability of a dipole to go through the proton or nucleus without interacting. A small value of S^2 is a very good measure of saturation. Also, a corresponding figure for Pb would be useful for comparison, not so much for the impact parameter dependence, but for the strength of the interaction of a dipole of size $r \leq 1\ \mathrm{GeV}^{-1}$ with the nucleus.
- page 158: A very simple estimate of break up for heavy nuclei gives $|t|_{\mathrm{breakup}} = 0.02\ \mathrm{GeV}^2$. This appears consistent with Fig. 6.30. However, the text on page 158 quotes $|t| = 0.05\ \mathrm{GeV}^2$ in one place and $\geq 0.01\ \mathrm{GeV}^2$ in another. The latter is likely closer to the right number.
- Figs. 6.39 and 6.40 could perhaps be combined into one figure because they would allow better comparison of the two models, rather than have two figures with nearly identical kinematics.
- Fig. 6.41 is an interesting figure but needs to be better motivated in the text (and perhaps caption) to convey the message.
- An interesting option to discuss is the possibility of deuterium beams which offer the possibility of studying neutron structure functions, allowing for precision flavor decomposition of the sea as well as exploring very cleanly the Gribov relation between diffraction off nucleons and nuclear shadowing. This topic has been discussed in Chapter 4 but it would be useful to refer to this discussion in Chapter 6 as well.
- The authors might wish to tailor the relative length of different sub-sections to be compatible with the physics message. For instance, the discussion of final state radiation and hadronization is less than a page, while the discussion of unintegrated pdfs is 2.5 pages. There are a few other such examples where the treatment could be better balanced and benefit from further editing.

4 Summary

The LHeC is a versatile machine for studying small x physics. Having both protons and lead beams is a great advantage. Large nuclei not only increase the value of the saturation momentum but also allow saturation phenomena to be seen over a wide range of impact parameters. The LHeC would be a truly exciting machine for studying small x physics and this comes across clearly in the text of Chapter 6.