OVERVIEW OF THE LHEC DESIGN STUDY AT CERN

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Abstract

The Large Hadron electron Collider (LHeC) offers the unique possibility of exploring lepton-proton collisions in the TeV Center of Mass (CM) range by further utilizing the existing LHC infrastructure. This paper summarizes the Linac-Ring option for the LHeC project and outlines the next developments for the study.

INTRODUCTION

Lepton-proton collisions in the TeV CM energy range provide a unique tool for studying new phenomena in the partonic structure of protons and nuclei, for precision Higgs physics and the search for physics beyond the Standard Model of particle physics [1,2]. The LHeC may become the first electron-ion collider ever built. The LHeC is designed to use one of the hadron beams of the LHC in a synchronous operation mode in parallel with the HL-LHC exploitation. It therefore represents an important opportunity for a further exploitation of the existing LHC infrastructure and its massive infrastructure investment already taken and to come. Achieving ep CM collision energies in the TeV range with a 7 TeV energy proton beam demands lepton beam energies above about 50 GeV. The LHeC Conceptual Design Report (CDR) [1] is based on a lepton beam energy of 60 GeV. But it also addresses the option of a much higher lepton energy (140 GeV) for exploring the high energy CM regime. The CDR was developed under the auspices of CERN, ECFA and NuPECC who sponsored around four dedicated LHeC workshops between 2008 and 2012.

The CDR explored two distinctly different design approaches for the LHeC collider: one design for a Ring-Ring option and one for a Linac-Ring option with Energy Recovery operation. Beam transfer aspects for both options are given in [3]. The last LHeC workshop in 2012 focused on the presentation of the CDR and concluded with a CERN mandate to develop the required technical R&D work over the next 4 years (2013 to 2016), focusing on the technologies required for the ERL option of the LHeC project, so that a decision on the project could be taken when the LHC starts its second run period at full energy.

LINAC-RING OPTION

The Linac-Ring [L-R] option requires a new linear accelerator for the electron beam that intersects in one location with the existing LHC machine. Several options have been considered for the linear accelerator (pulsed, re-circulating and Energy Recovery Linac configurations). These provide a range of energy and luminosity combinations. The baseline option for the LHeC CDR is a recirculating 60 GeV Energy Recovery Linac (ERL) which allows for high luminosity operation. A pulsed linac option provides still an interesting option for maximizing the energy reach of the LHeC (at the cost of a reduced peak luminosity performance) as could be demanded by findings at the LHC. Table 1 summarizes key parameters for both options. The 60 GeV ERL version is capable of reaching a luminosity as high as the Ring-Ring option (O(10^{33} cm^{-2}s^{-1})). First considerations have been made as to further increase the luminosity reach of the LHeC Linac-Ring (L-R) option and to possibly reach a luminosity level of 10^{34} cm^{-2}s^{-1}, which would enhance the potential of the LHeC for precision Higgs measurements [2].

The 60 GeV ERL version features two 1km long superconducting RF sections and two return arcs that house magnets for three passages at different energies. Each linac section provides an energy gain of 10 GeV and the machine requires in total three recirculations through the two SC linacs to reach an energy of 60 GeV. The minimum acceptable bending radius of the return arcs is determined by the maximum acceptable energy loss through synchrotron radiation and the requirement of having a total circumference that is an integer fraction of the LHC circumference. For the 60 GeV ERL option these considerations lead to a radius of curvature of 1km for the two return arcs and a total machine circumference of ca. 9km (1/3 of the LHC circumference). Figure 1 shows a schematic layout of the 60 GeV ERL option and Figure 2 shows a schematic view of the resulting underground installation. The overall LHeC complex would have approximately the same size as the existing SPS machine.

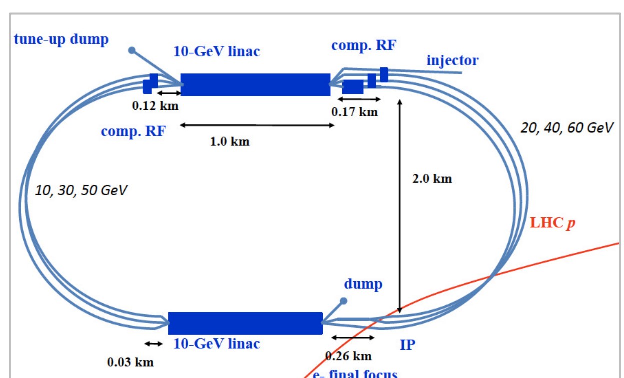

Figure 1: Schematic layout of the 60 GeV ERL option.

The L-R option has the advantage over the R-R option that all civil engineering and installation work can be done parallel to the LHC operation and thus independently of the LHC shutdown schedule. Furthermore, it is notable, as was recently pointed out [5],

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that essentially the same machine in a 4-pass regime and going to 80 GeV has an interesting application as a cost effective photon-photon collider for the study of the newly observed boson at 125 GeV. Table 1 shows the baseline parameters for the 60 GeV ERL and 140 GeV pulsed linac options of the CDR. A pushed parameter set with luminosities well around $L = 10^{34} cm^{-2}s^{-1}$ is given in [5].

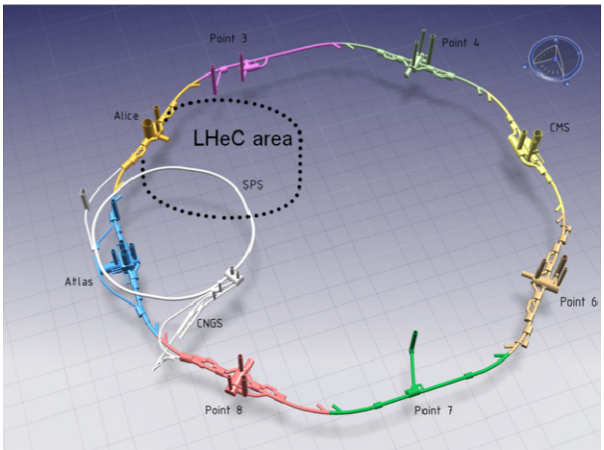

Figure 2: Civil engineering layout of the 60 GeV ERL option [4].

Table 1: LHeC baseline linac parameters for the 60 GeV ERL and 140 GeV pulsed option.

LINAC Parameters for the Linac-Ring Option		
Operation mode	**CW**	**Pulsed**
Beam Energy [GeV]	60	140
Peak Luminosity [$cm^{-2}s^{-1}$]	10^{33}	4 10^{31}
Cavity gradient [MV/m]	20	32
RF Power Loss [W/cavity]	13-37	11
W per W (1.8K to RT)	700	700
Cavity Q_0	2.5 10^{10}	2.5 10^{10}
Power loss/GeV	0.51-1.44	0.24
RF length [km]	2	7.9
Total length [km]	9	7.9
Beam current [mA]	6.4	0.27
Repetition rate	-	10 Hz
Pulse length	-	5ms

MAGNET DESIGN

A first magnet prototype development had been launched in collaboration with the Budker institute BINP in Russia and then further developed at CERN. Figure 3 shows first conceptual normal conducting magnet prototypes from BINP and Figure 4 a CERN prototype demonstrating that the required field quality and reproducibility (better than 10^{-4} relative field error and low magnetic field) can indeed be achieved.

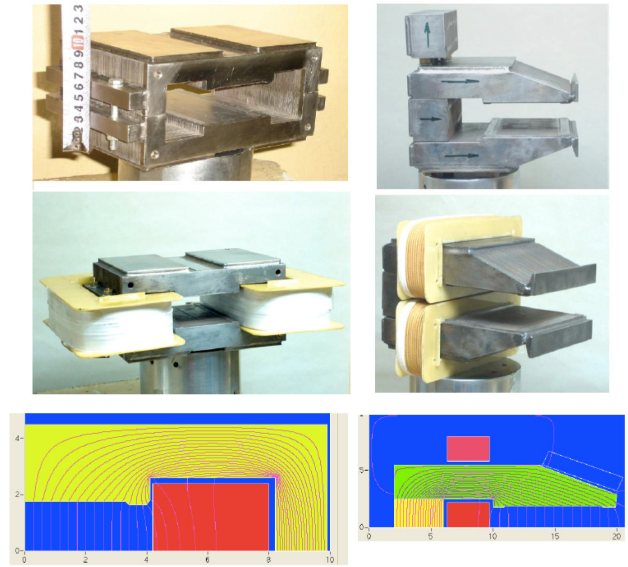

Figure 3: BINP prototype for a normal conducting LHeC dipole magnet.

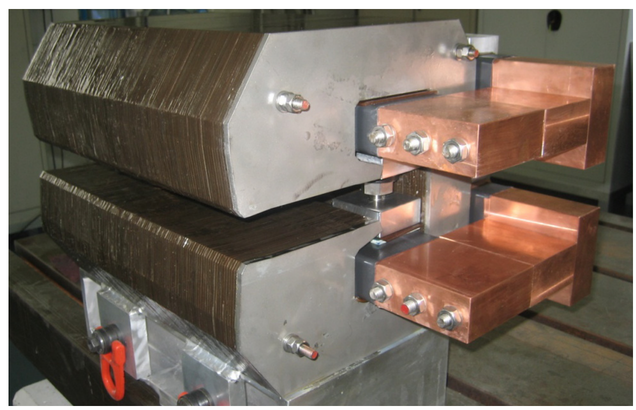

Figure 4: CERN prototype for a normal conducting LHeC dipole magnet.

Figure 5 shows a conceptual further development of the normal conducting dipole magnets for the ERL facility housing the coil windings of the three passages through the ERL return arcs within one common iron yoke. Figure 5 shows simulations for the mechanical stress within the 3-in-1 magnet cross-section.

IR DESIGN

The interaction region for the LHeC, running synchronously with the LHC, has the novel feature of accommodating three beams: the colliding proton and lepton beams and the non-colliding second proton beam of the LHC. Figure 6 shows a schematic view of the interaction region layout for the R-R option of the LHeC. The low-beta electron beam quadrupoles are placed close to the detector. They are followed by additional dipole separation magnets for the electron beam and then by low-beta quadrupole magnets for the proton beam.

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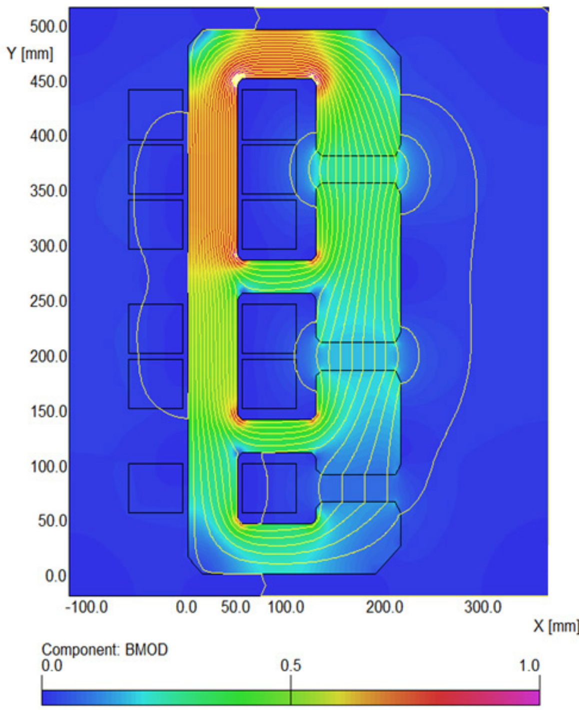

Figure 5: Conceptual design for a normal conducting 3-in-1 LHeC dipole magnet for the ERL return arcs showing simulations for the mechanical stress within the magnet cross section.

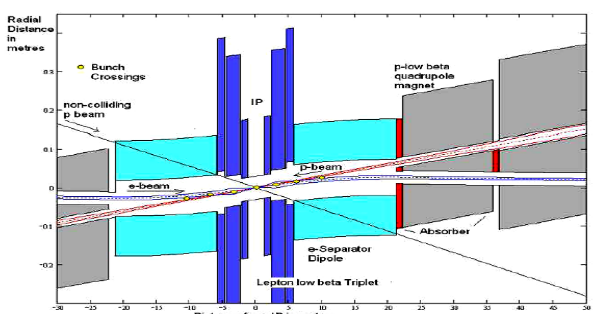

Figure 6: Schematic layout of the Interaction Region [example of the Ring-Ring option].

Figure 7 shows the conceptual design of a superconducting mirror quadrupole magnet featuring three beam apertures: two high field apertures for the two proton beams and one low field aperture for the lepton beam. Figure 8 shows the schematic IR layout together with the synchrotron radiation fan from the electron beam. The synchrotron radiation power reaches peak values of up to 30kW on the absorber blocks inside the LHeC detector. The total synchrotron radiation power inside the experimental area can be further optimized by a variation of the focusing element locations for the lepton beam (L^*) [13]. Figure 9 shows the expected total synchrotron radiation power as a function o the location of the first focusing element for the lepton beam next to the experiment (L^*).

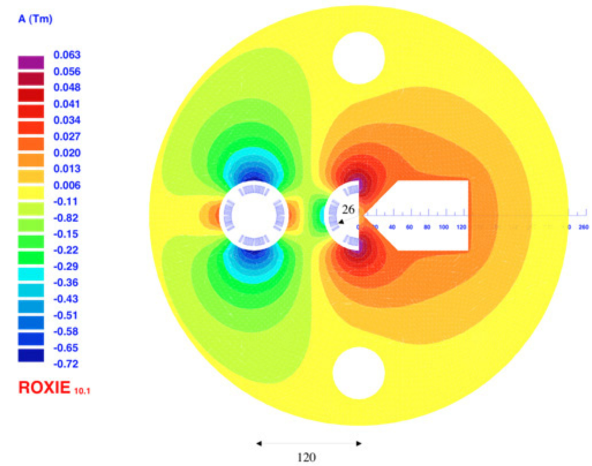

Figure 7: Conceptual design of a superconducting mirror quadrupole magnet with two high field apertures and one low field aperture for the lepton beam.

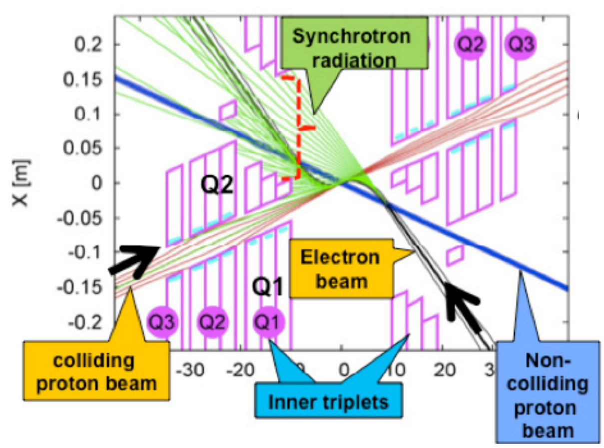

Figure 8: Schematic layout of the Interaction Region of the Linac-Ring option with the Synchrotron radiation fan.

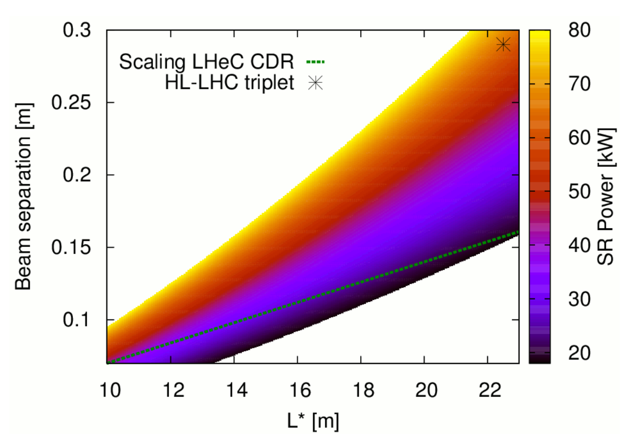

Figure 9: Expected total synchrotron radiation power as a function o the location of the first focusing element for the lepton beam next to the experiment (L^*).

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BEAM DYNAMICS STUDIES

First beam dynamics studies focused on an evaluation of ion trapping in the electron beam of the ERL and the transverse beam stability with Wakefields and beam-beam encounters [14]. Figure 10 shows the simulation of the damping of transverse oscillations in the presence of cavity Wakefields and a linearized transverse kick from the beam-beam force at the collision point. The simulations are done for a bunch population of 3 10^9 ppb and two RF systems: one based on 720MHz cavities and one based on 1.3GHz cavities. One can clearly observe that the damping of the transverse oscillations is faster for the lower frequency RF system and that the oscillations are at the stability threshold for the 1.3 GHz system.

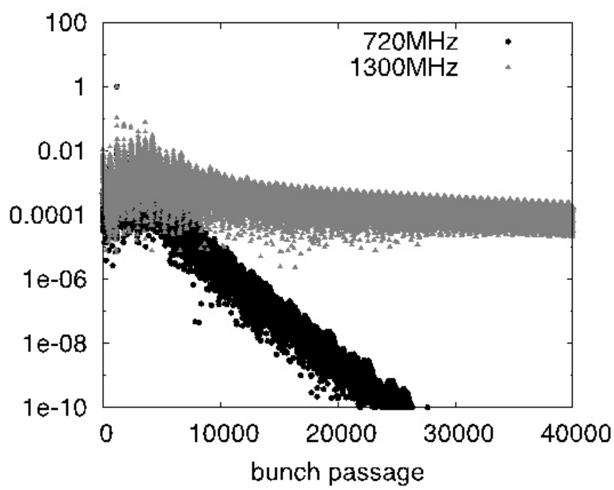

Figure 10: Simulation studies for the damping of transverse beam oscillations in the presence of cavity Wakefields and a linearized beam-beam force at the interaction point.

Further studies on RF power considerations from F. Marhauser showed that the optimum frequency choice for Nb cavities lies somewhere between 700MHz and 1GHz for small grain Nb cavities and 300MHz and 800Mhz for large grain Nb [7][8]. Observing further that the currently existing RF systems on the market (1.3 GHz for the ILC project and 704.42MHz for the SPL and ESS proton driver projects) are not really fitting the requirements for the LHeC (RF frequency is not an integer multiple of the LHC bunch spacing of 40.079MHz) led to the decision of adopting an entirely different RF frequency for the LHeC project. The choice of an RF frequency of 801.58MHz satisfies the harmonic criterion with the LHC bunch spacing (harmonic number of 20 wrt the LHC bunch spacing), satisfies the preference for lower RF frequencies from the stability point of view, lies in the overlap region of the optimum frequency intervals for small and large grain Nb cavities and provides a synergy with the HL-LHC upgrade project as the superconducting 801.58MHz cavities could also be used as a higher harmonic RF system for the HL-LHC.

Another focus of the beam dynamic studies is the evaluation of the electron beam disruption after the Interaction Point and the total beam-beam tune spread coming from the collisions with the disrupted electron beam. These studies are still in their early phases, but Figure 11 shows first simulation results [Ref Daniel 2] of the electron beam disruption indicating that careful attention has to be given to the matching of the spend beam into the return circulations of the ERL.

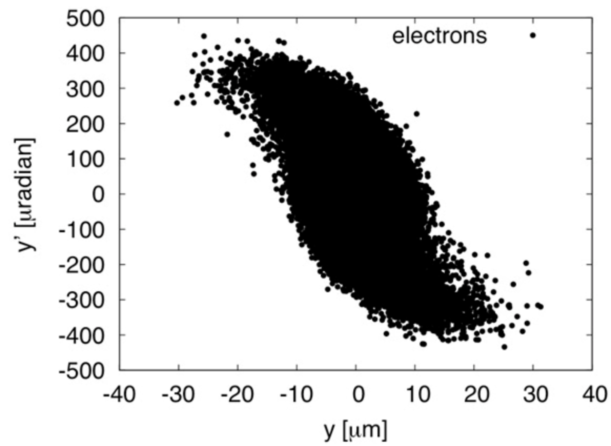

Figure 11: Simulation studies for the damping of transverse beam oscillations in the presence of cavity Wakefields and a linearized beam-beam force at the interaction point.

LHEC PLANNING AND TIMELINE

Figure 12 shows the tentative schedule for the LHeC project with the goal of a simultaneous operation start with the HL-LHC upgrade in mid 2020ies following the third long shutdown of the LHC complex.

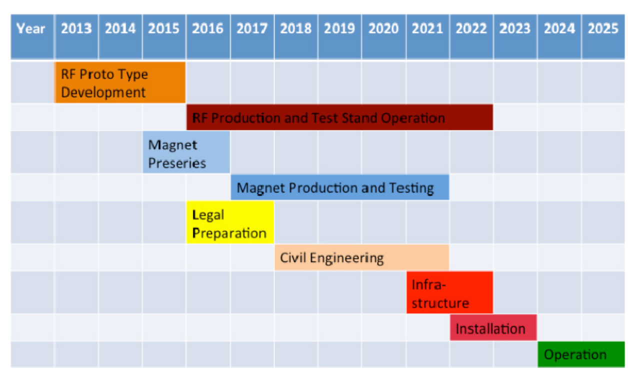

Figure 12: Tentative schedule for the LHeC project.

POST CDR STUDIES

Following the LHeC workshop in 2012 [6] it was decided to adopt the L-R option as baseline and to keep the R-R option as a backup for the LHeC project. The CERN management has given a mandate [6] to pursue the required R&D activities and studies for key components of the L-R LHeC option, e.g. SC RF, and to launch beam dynamics and design studies in the framework of international collaborations.

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The first post CDR activities have been focused on:

- Choice of the LHeC RF frequency: a dedicated collaboration workshop identified in 2013 [7] 801.58MHz as the optimum choice for the LHeC based on RF power considerations [8] and offering synergies with the HL-LHC project [9].
- Beam dynamic studies in the ERL for different bunch filling patterns and including wake-fields and beam-beam interactions [10].
- Design studies for a dedicated LHeC test facility at CERN with ERL operation mode [11][12].
- Re-Optimization of the LHeC IR and it's integration into the HL-LHC lattice [13].
- Detailed civil engineering studies for the LHeC installation [4].
- Re-Optimization of the LHeC beam parameters based on the operations experience of the first LHC running period. The LHC operation in 2012 demonstrated the feasibility of beam brightness beyond 'ultimate' LHC parameters that open the door for a performance reach of up to $L = 10^{34}$ $cm^{-2}s^{-1}$ [5].

The primary next goals of the LHeC study are the development of prototypes of the 801.58 MHz cavities together with their cryostats and the design of an LHeC Energy Recovery Linac Test Facility [LHeC-TF] at CERN. The development of the cavities provides a strong synergy with the HL-LHC upgrade program at CERN where these cavities could function as Higher Harmonic RF cavities for bunch lengthening and reduction of the IBS and geometric luminosity reduction factor. Figure 13 shows a schematic layout for an LHeC-TF at CERN as presented in [11][12].

SUMMARY

The LHeC offers the unique possibility for deep inelastic scattering physics in the TeV CM region and Higgs studies. Key technical R&D studies have been launched in 2013, in time for a project realization by 2025 and exploitation in parallel with the HL-LHC operation.

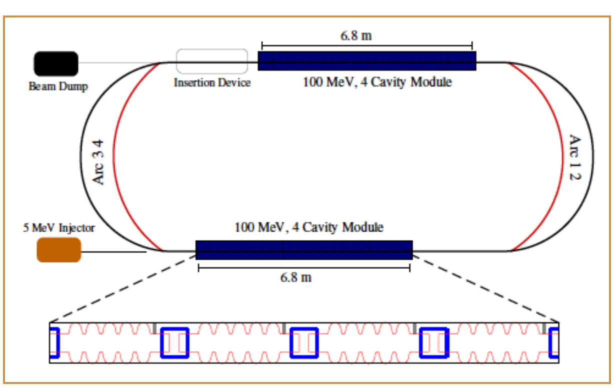

Figure 13: Schematic layout of an ERLTF at CERN [11].

REFERENCES

[1] LHeC Study Group, 'A Large Hadron Electron Collider at CERN', J.Phys.G: Nucl.Part.Phys 39(2012)075001 [arXiv:1206.2913(2012)].
[2] LHeC Study Group, 'On the Relation of the LHeC and LHC', [arXiv:1211.5102(2012)].
[3] C. Bracco and B. Goddard; 'Studies for the LHeC Beam Transfer System'; Conference Proceedings IPAC13.
[4] J. Osborne et al.; 'Civil Engineering Studies for Future Ring Colliders at CERN'; Conference Proceedings IPAC13.
[5] F. Zimmermann et al.; 'The LHeC as a Higgs Boson Factory'; Conference Proceedings IPAC13.
[6] 2012 LHeC Workshop, Chavannes de Bogies, Switzerland;
[7] https://eventbooking.stfc.ac.uk/news-events/lhec-meeting
[8] Frank Marhauser private communication.
[9] L. Rossi, O. Brüning; 'High Luminosity Large Hadron Collider A description for the European Strategy Preparatory Group'; CERN-ATS-2012-236
[10] D. Schulte, Conference proceedings, DIS2012; March 2012; University Bonn.
[11] R. Calaga et al.; 'A Proposal for an ERL Test Facility at CERN'; Conference Proceedings IPAC13.
[12] A. Valloni et al.; 'Strawman Optics Design for the LHeC ERL Test Facility'; Conference Proceedings IPAC13.
[13] M. Korostelev et al.; 'LHeC IR optics design with integration into the HL-LHC lattice', Conference Proceedings IPAC13.
[14] Daniel Schulte, EPS HEP conference 2013, Stockholm, Sweden; proceedings.

ISBN 978-3-95450-144-1