

## 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 two different design options: a Ring-Ring and a Linac-Ring option and outlines the next developments for the project.

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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 two different design options: a Ring-Ring and a Linac-Ring option and outlines the next developments for the project.

## 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. 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 last 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) so that a decision on the project could be taken when the LHC starts its second run period at full energy.

\*On behalf of the LHeC study team and collaboration.

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.

## RING-RING OPTION

The Ring-Ring (R-R) configuration features the installation of a new electron synchrotron storage ring inside the LHC tunnel, on top of the existing LHC ring. The R-R option is technically rather straightforward (in between the technologies of the LEP-I and LEP-II projects). It's main challenge lies in the integration of the machine inside a tunnel with an already operational accelerator and its entire infrastructure. Furthermore, aiming at a simultaneous exploitation of the LHeC with the HL-LHC, the new lepton ring needs to bypass at least the two high luminosity experiments of the LHC. Each bypass has an approximate length of 1.5 km and has been designed with additional galleries for the RF infrastructure installations of the new Lepton ring.

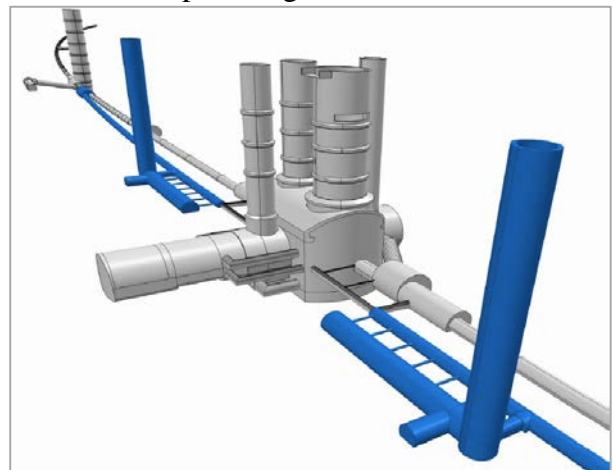


Figure 1: LHeC bypass tunnel and RF Galleries at ATLAS (in blue).

Fig. 1 shows the schematic bypass layout around the ATLAS experiment in the LHC Interaction Region [IR] 1. The ATLAS bypass concept exploits the existing survey gallery in order to minimize the size of the bypass

extension around the large ATLAS cavern. It thus consists of two separate parts left and right to the experiment, of about 500m each. Figure 2 illustrates a typical cross section of the LHC tunnel with the LHC equipment and the space required for the additional components of the lepton storage ring for the LHeC. The position of the lepton synchrotron magnets is shifted inwards with respect to the LHC magnets in order to compensate for the path length increase due to the bypasses and to generate a circumference for the LHeC lepton beam equal to that for the proton beams of the LHC machine. First short prototype dipole magnets were built at BINP Novosibirsk and at CERN.

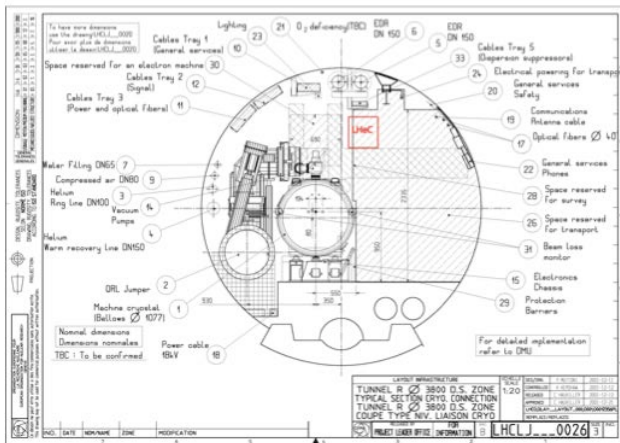


Figure 2: Typical LHC tunnel cross section with indication of the position for the LHeC magnets.

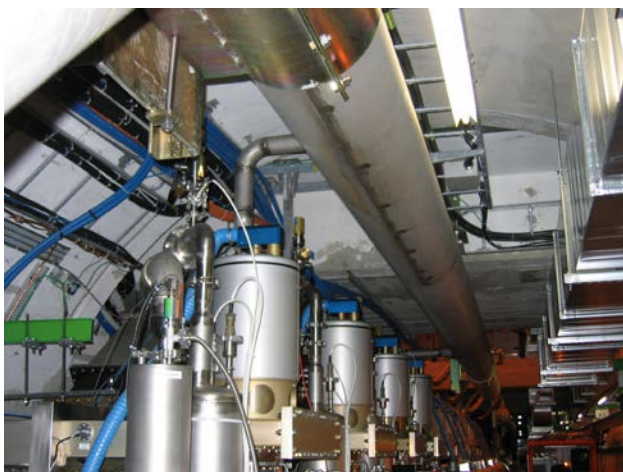


Figure 3: LHC infrastructure in IR4 that interferes with the LHeC R-R installation.

Figure 3 shows as an example of space limitations for the installation of a new lepton storage ring inside the existing LHC tunnel the

LHC RF installation in IR4. However, lattice and beam optics could be designed in spite of such space constraints exploiting asymmetric FODO cells [1]. The interference with the existing LHC installations is large but as discussed in [1] not insurmountable.

The current 10-year plan for the LHC operation at CERN foresees three long shut downs of 1.5 to 2 years length. The first two shutdowns, LS1 in 2013 and LS2 in 2018, are too early as to be of significant use for the RR LHeC installation. This leaves essentially only the third long shutdown LS3, currently foreseen for 2022, for the whole installation of the LHeC machine and its detector. The main challenge for the R-R solution is the time and scheduling for its installation.

## 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, is based on a modest civil engineering effort and directly compares with the LHeC Ring-Ring option. 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 R-R option. First considerations have been made as to possibly reach a luminosity level of  $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ , 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 linac 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 4 shows a schematic layout of the 60 GeV ERL option and Figure 5 shows a schematic view of the resulting underground installation. The overall LHeC complex would have approximately the same size as the existing SPS machine.

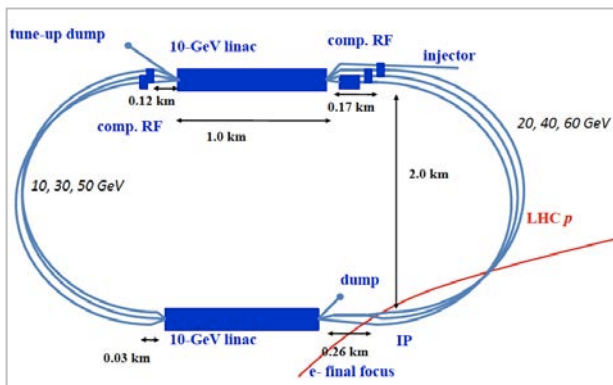


Figure 4: Schematic layout of the 60 GeV ERL option.

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 [3], 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  $L = 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$  is given in [3].

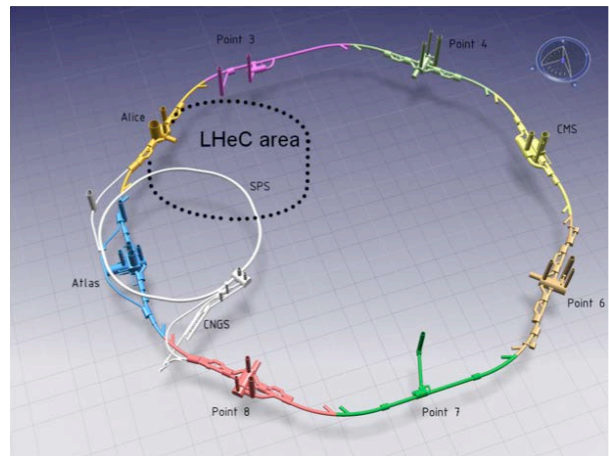


Figure 5: Civil engineering layout of the 60 GeV ERL option [13].

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 [ $\text{cm}^{-2} \text{ s}^{-1}$ ]	$10^{33}$	$4 \cdot 10^{31}$
Cavity gradient [MV/m]	20	32
RF Power Loss [W/cavity]	13-37	11
W per W (1.8K to RT)	700	700
Cavity $Q_0$	$2.5 \cdot 10^{10}$	$2.5 \cdot 10^{10}$
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

## 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.

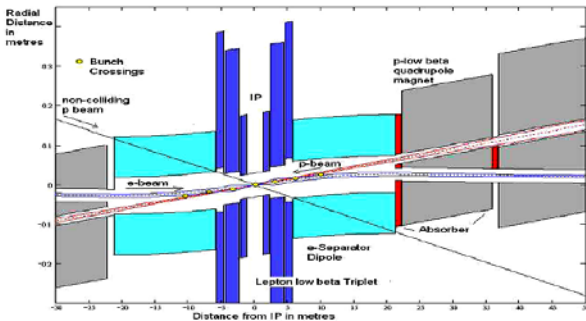


Figure 6: Schematic layout of the Interaction Region of the Ring-Ring option.

Figure 7 shows the conceptual design of a superconducting mirror quadrupole magnet that features 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.

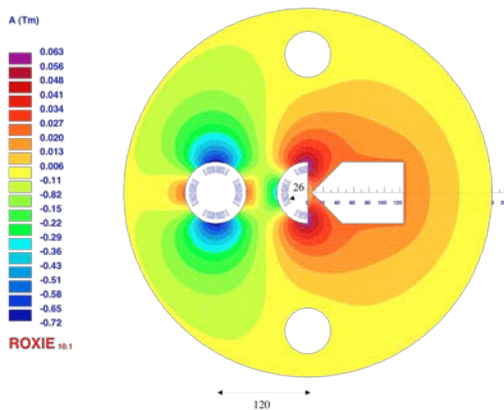


Figure 7: Conceptual design of a superconducting mirror quadrupole magnet with two high field apertures and one low field aperture for the lepton beam.

## LHEC PLANNING AND TIMELINE

Figure 9 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.

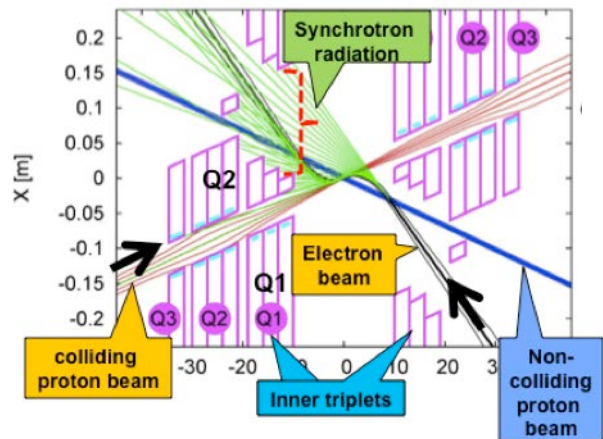


Figure 8: Schematic layout of the Interaction Region of the Linac-Ring option with the Synchrotron radiation fan.

## POST CDR STUDIES

Following the LHeC workshop in 2012 [4] 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 [4] 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.

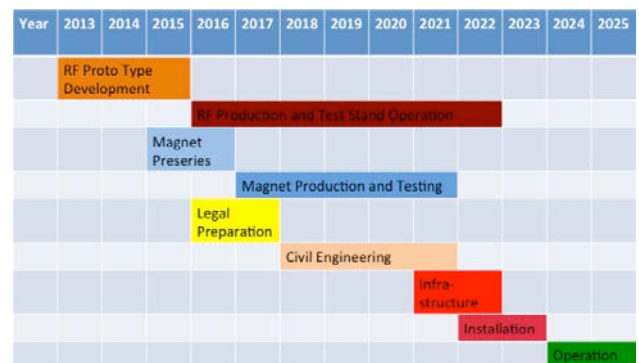


Figure 9: Tentative schedule for the LHeC project.

The first post CDR activities have been focused on:

- Choice of the LHeC RF frequency: a dedicated collaboration workshop identified in 2013 [5] 801.58MHz as the optimum choice for the LHeC based on RF power considerations and offering synergies with the HL-LHC project [7].
- Beam dynamic studies in the ERL for different bunch filling patterns and including wakefields and beam-beam interactions [9].
- Design studies for a dedicated LHeC test facility at CERN with ERL operation mode [10][11].
- Re-Optimization of the LHeC IR and it's integration into the HL-LHC lattice [12].
- Detailed civil engineering studies for the LHeC installation [13].
- 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  $L = 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ [3].

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 10 shows a schematic layout for an LHeC-TF at CERN as presented in [10][11].

### 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.

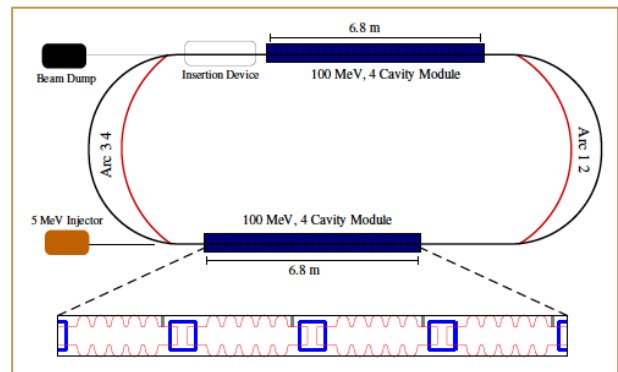


Figure 10: Schematic layout of an ERLTF at CERN [10].

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