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Overview of the LHeC and FCC-eh Accelerator Concepts

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The Large Hadron–Electron Collider is designed to move the field of deep inelastic scattering to the energy and intensity frontier of particle physics. Exploiting energy-recovery technology, it collides a novel, intense electron beam with a proton or ion beam from the High-Luminosity Large Hadron Collider. The accelerator and interaction regions are designed for concurrent electron–proton and proton–proton operations. This paper represents the concepts of an updated design study and discusses the design challenges of the project.

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1. Introduction

The field of deep inelastic lepton–hadron scattering (DIS) was born at SLAC about 50 years ago and led to the discovery of partons, which in the end are the basis of the Standard Model. In the quest for higher resolution of these deep inelastic collisions it is only natural to utilise the high energies available in the proton beams of the Large Hadron Collider (LHC), in order to provide collisions with a high energetic electron beam and pave the way to an unprecedented kinematic range in DIS physics. This opportunity arises by a modification of one of the LHC interaction regions where the lattice of the accelerator is re-arranged to establish electron-proton collisions in concurrent operation to the LHC standard p-p experiments. The layout of the Large Hadron Electron Collider (LHeC) is schematically shown in Fig. 1. The intense electron beam of 50 GeV, accelerated in a racetrack shaped ERL for most compact design, will be brought into collision with the 7 TeV protons of the LHC (details in [1]).

Figure 1: Aerial view of the proposed LHeC: A racetrack electron accelerator, operated in ERL mode, is connected to the LHC in the Geneva lake valley.

The main parameters are associated with the HL-LHC design, i.e. the luminosity upgrade of LHC, [2] and are summarized in table 1 leading to a luminosity at the e-p interaction point in the order of $L = 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.

Parameter	Unit	Electrons	Protons
beam energy	GeV	50	7000
beam current	mA	20	1400
bunches per beam	-	1188	2808
bunch population	10^{10}	0.3	22
bunch charge	nC	0.5	35.24
norm. emittance (at IP)	mm · mrad	30	2.5
beta function at IP	cm	10.9	10
luminosity	$\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	$0.7 \cdot 10^{34}$	

Table 1: Parameter list of the LHeC.

2. Layout of the ERL

The design of the Energy Recovery Linac consists of a number of key modules, typical for an ERL, that are combined with the special request for particle collisions: two superconducting (s.c.)

linacs operated in continuous-wave mode are connected by three return arcs on both sides to allow three accelerating and three decelerating passes. Each of the two linacs provides an accelerating voltage of 8.25 GV. After three acceleration turns the electrons have reached a kinetic energy of E_{final} = 50 GeV and will be brought into collision with the LHC proton beam. Superconducting cavities with a high quality factor are the prerequisite for a successful energy recovery performance: the accelerating bunches, gaining their energy from the resonant cavity field, are interleaved with the decelerating bunches that - shifted in time by half an RF wavelength - restore their energy in the resonant cavity field. Special beam optics for highest emittance preservation and a dispersion free spreader / re-combiner section between each linac and the arcs are essential parts of the machine. They are described in detail in the proceedings of the last ICHEP, 2020 [3].

3. Design Challenges

While the LHeC concept will allow concurrent operation of e-p and p-p collisions, there are a number of challenges that require a careful design and optimisation of the new lattice. Among them and most prominent is the design of a combined mini-beta scheme for the electron and the proton beam, the beam separation and along with it the control of the unavoidable emission of synchrotron radiation. Finally, the influence of the electron magnets on the orbit and optics of the protons has to be compensated to guarantee independent collisions at the e-p and p-p interaction regions.

4. Interaction Region

The Interaction Region (IR) of the ERL is one of the most challenging parts of the machine: while seeking for the highest luminosity in e-p collisions, the electron and proton bunches have to be separated after the interaction and guided to their lattice structures, to avoid parasitic bunch encounters. In addition, beam-beam effects between the electron and the colliding proton beam have to be limited to a tolerable level and beam-beam effects of the second, non-colliding, proton beam have to be avoided. In order to meet these requirements, the design of the IR has been based on a compact magnet structure for an effective beam separation and smallest synchrotron radiation effects in the IR [4]. As seen in Fig. 2, the mini beta focusing structure of the electrons is embedded in the LHC proton interaction region. It combines the requirements of focusing and separation of the electrons in one compact lattice structure: due to the different rigidity of the beams, a separation is possible by applying a series of magnets, acting as a quasi-constant deflecting field, which has been optimised for lowest critical energy and radiation power of the emitted synchrotron light. As an unavoidable side effect of the design, a certain influence of the electron mini beta quadrupoles on the proton orbit and beam optics is obtained, which needs compensation.

4.1 A Three Beam Problem

A truly concurrent operation of e-p and p-p collisions requires dedicated correction of orbit and optics of the proton beams to leave the optics parameters at the other LHC interaction points untouched. An additional requirement arises from the fact that the foreseen e-p collisions will be alternated by p-p or ion-ion collisions at the same experiment (e.g. in IP2). As a direct consequence for possible e-p operation mode, the second "non-colliding" proton beam has to be guided inside the

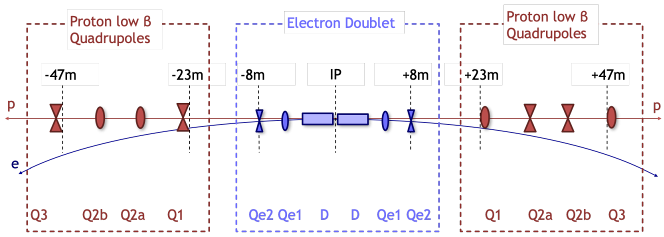

Figure 2: Schematic view of the LHeC interaction region: The electron mini-beta magnets and the separation dipole are embedded in the LHC final focus structure.

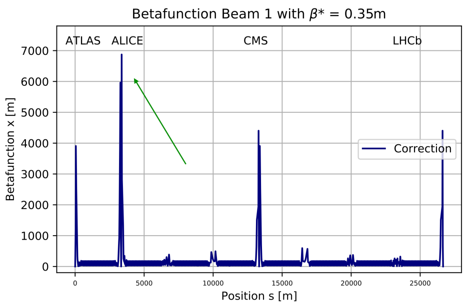

Figure 3: Optics of the colliding protons: Strong focusing in IR2 (arrow) for max. luminosity.

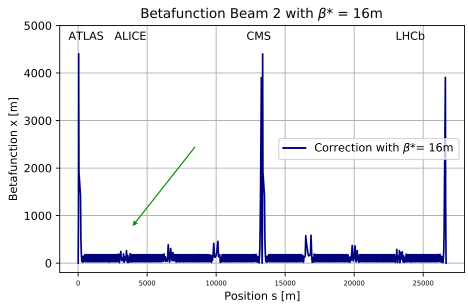

Figure 4: Relaxed beam optics for the non-colliding protons for sufficient aperture (arrow).

same magnet lattice, separated sufficiently to avoid beam-beam interactions with either the proton or electron beam. A "relaxed" beam optics has been established, with reduced $\beta-$function to allow for sufficient aperture inside the mini-beta proton quadrupoles. Figs. 3 and 4 show the two beam optics that have been optimised for this purpose: due to the flexibility of the LHC matching quadrupoles of the two beams, the colliding proton beam can be focused strongly (here down to $\beta^* = 35\,\text{cm}$) and brought into collision with the counter-rotating electron beam, while the non-colliding protons follow a beam optics that has been established for maximum aperture. With $\beta^* = 16\,\text{m}$ at the IP, the beam dimensions in the mini-beta section are considerably reduced. The underlying concept is the well known relation between the β-function at the collision point and its value at the location of the first focusing element, namely the mini-beta quadrupole, $\beta(s) = \beta^* + \frac{s^2}{\beta^*}$.

In the quest for compactness and minimised synchrotron load in the IR, special magnet designs are needed for the proton mini-β quadrupoles. A normal conducting half quadrupole as the first focusing element reduces the separation need of the electron beam. It is followed by a s.c. quadrupole with a field free aperture for the outgoing electrons to allow for smallest synchrotron light power during beam separation. Fig. 5 and 6 show the design principles of the two magnets.

Following a general rule of the LHC design, the layout of the new interaction region is built in a fully modular manner, i.e. the optics parameters as well as the orbit of the two proton beams are re-matched after the mini-beta insertion to the periodic solution of the neighbouring arcs, without any influence on the adjacent interaction points (IP1 and IP8). While this request is straightforward for the LHC standard operation, the influence of the electron mini-β quadrupoles on the two proton beams has to be compensated. This is provided by a re-optimisation of the optics, as shown in

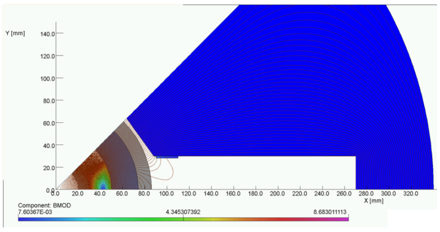

Figure 5: S.c. quadrupole with field free region for the outgoing electrons.

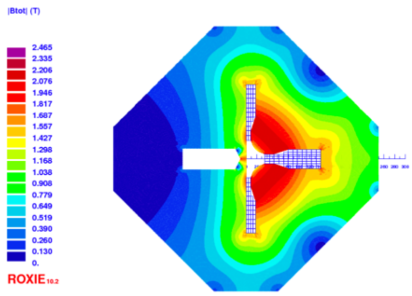

Figure 6: Normal conducting half quadrupole as first focusing element.

Fig. 7. The uncorrected influence of the electron magnets creates a mismatch of the proton optics, that is corrected perfectly by a local re-matching of the structure.

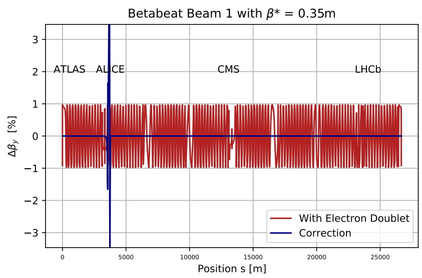

Figure 7: Distortion of the proton optics by the electron mini-β quadrupoles (red), re-matched to the ideal periodic beam parameters (blue).

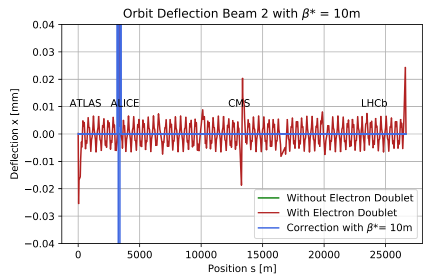

Figure 8: Orbit effect of the electron separation scheme on the protons (red). Orbit corrector dipoles are used to compensate this closed orbit locally (blue).

In a second step, the proton orbit has to be re-optimised for a fully modular insertion of the e-p interaction region: the beam separation scheme that guides the electron beam towards its ERL lattice and avoids parasitic bunch encounters, has a side effect on the design orbit of the protons. Both proton beams will be deflected (in opposite directions) and the resulting effect has to be compensated for by a combination of orbit corrector dipoles. A slight deflection of the orbit, between the off-centre quadrupoles of the e-lattice and the location of the proton corrector dipoles is well within the aperture limits of the magnets (see Fig. 8).

5. The FCC-eh

The interaction region described in this paper refers to electron-proton collisions in the LHC. However, due to the modular concept of the design, it can be easily adapted to the lattice of the Future Circular Collider (FCC). The electron beam optics and the ERL design remain unchanged. The optics of the two proton beams on the other hand will be re-matched to the given arc structure of the FCC in the same manner as described for the LHeC case and a concurrent operation of e-p and p-p collisions in the FCC-eh will be as straight forward as in the case of the LHeC. In Fig. 9

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the location of the ERL in the lattice geometry of the FCC-hh is shown schematically. The main parameters are summarised in table 2. Due to an increased circumference of the ERL and thus reduced synchrotron light power, an electron beam energy of 60 GeV is foreseen. At the same time, the higher proton energy allows not only for a better resolution of the DIS physics, but also - due to the smaller beam emittance $\varepsilon \propto 1/\gamma$ - to a comfortably enhanced luminosity of the e-p collisions.

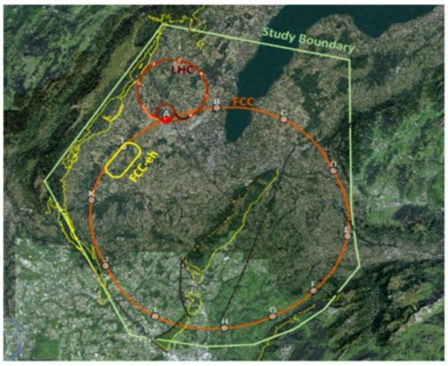

Figure 9: Proposed scenario for electron-proton collisions at the FCC. The general layout of the IR corresponds to the optimised scheme described above, adapted to the beam parameters of the FCC-hh.

Parameter	Unit	
beam energy (e)	GeV	60
beam energy (p)	GeV	50000
beam current I_e	mA	20
bunch population N_e	10^9	3.1
bunch population N_p	10^{11}	1
norm. emittance (ε_p)	μ rad	2.2
proton β-function at IP	cm	15
luminosity	$cm^{-2}\,s^{-1}$	$1.5 \cdot 10^{34}$

Table 2: Parameter list of the FCC-eh

References

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