PROCEEDINGS OF SCIENCE

Proton Beam Dynamics for Concurrent Operation of the LHeC and HL-LHC

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The Large Hadron electron Collider (LHeC) project is studying a new LHC interaction region for deep inelastic scattering collisions between electrons and hadrons in the TeV energy scale. An intense 50 GeV lepton beam is brought into collision with one 7 TeV hadron beam from CERN's Large Hadron Collider in parallel to the hadron-hadron operation. A flexible proton beam optics has been found for matched e-p beam conditions, fully compatible with the HL-LHC upgrade project for highest e-p luminosity.

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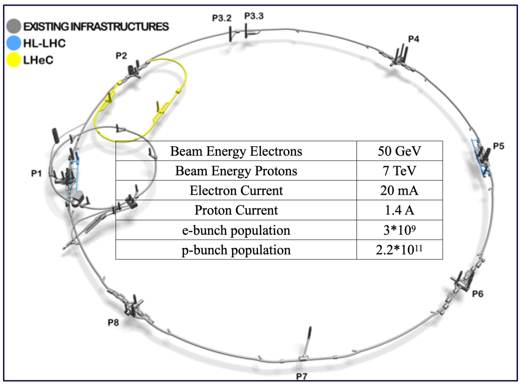
1. Overview of the LHeC

The Large Hadron electron Collider (LHeC) is a feasibility study that investigates high luminosity electron-proton collisions in one of the four interaction points (IP) of the High Luminosity Large Hadron Collider (HL-LHC) [1]. The general layout is shown in Fig. 1. Two operation modes are possible. Standard p-p collisions in the four IPs or, in truly concurrent operation mode, e-p collisions in one of the IPs simultaneous to p-p collisions in the remaining three. In order to achieve highest luminosity in the e-p operation, a new beam optics has been established, with "relaxed" β-functions for the non-colliding proton beam, thus providing maximum aperture space for the strong focused colliding beam.



Beam Energy Electrons	50 GeV
Beam Energy Protons	7 TeV
Electron Current	20 mA
Proton Current	1.4 A
e-bunch population	$3*10^9$
p-bunch population	$2.2*10^{11}$

Figure 1: Layout of the LHeC and main parameters: an energy recovery linac (ERL) provides the 50 GeV electron beam (yellow) to collide at a LHC interaction point with one of the 7 TeV proton beams. While e-p collisions will take place, the non-colliding proton beam still is available for collisions at the remaining IPs.

2. Flexible Proton Beam Optics

The two proton beams have asymmetric optics in the LHeC Interaction region, [2]. The colliding proton beam (B1) optics is focused to low β^* values for high luminosity collisions. The spectator proton beam (B2) optics is kept relaxed to establish high β^* values at the e-p interaction point and thus to limit the β-function inside the mini-β quadrupoles. As a direct consequence the aperture need is reduced and a maximum inter beam distance in the shared beam pipe is achieved. Such a special asymmetric optics configuration is possible due to the in-built flexibility of the proton lattices in the LHC. In Figure 2 the two operation scenarios are compared.

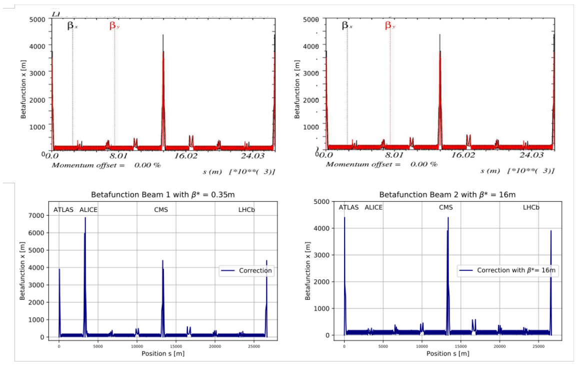


Figure 2: Optics of the two proton beams in the LHC. Upper part: β-function of proton beam 1 and 2 for standard LHC p-p collisions. Lower part: the colliding proton beam is focused to smallest possible β^* values to push the luminosity for e-p collisions (left). The non-colliding p-beam is kept on a relaxed optics to minimise the aperture need (right).

3. Luminosity Reach and Machine Performance

Different modular proton beam optics for concurrent e-p and p-p collisions in the HL-LHC have been designed and optimised. For the LHC configuration the achievable luminosity is a direct consequence of the aperture limit in the *NbTi* quadrupoles. In a second step the situation has been studied for a possible replacement of the *NbTi* quadrupoles by Nb_3Sn magnets, as foreseen for the HL-LHC. The higher critical field of the Nb_3Sn coils will allow for a considerable increase in free aperture and thus for an even more distinct focusing scheme, leading to even smaller β^* values. With this new design the proton beams can be separated by at least 24 σ in the critical shared beam pipe aperture. The situation is visualised in Fig. 3: The colliding proton beam in red reaches small beta values at the IP, leading to an increased aperture need in the mini-β quadrupoles. The non-colliding proton beam (blue) is optimised for smallest aperture need, which corresponds to values of $\beta^* = 23m$ at the IP. The figure shows the two well separated beams in the horizontal plane. An equivalent separation at the parasitic encounters (that will appear every 3.75m) is obtained via a vertical crossing angle bump. Following this concept the spectator proton beam (B2) is guided through the same beam pipe but spatially distanced from the e-p collision. It will reach the remaining three LHC IPs to collide with B1 for truly concurrent operation.

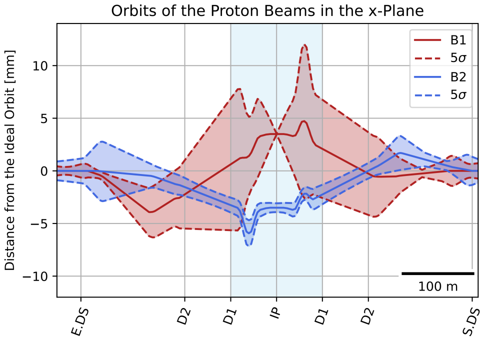


Figure 3: Horizontal beam separation of the two proton beams. While the two proton beams, B1 and B2, are guided in the shared beam pipe, proton beam (B1) is brought into collision with the electrons. Sufficient beam separation and distance to the beam pipe aperture is achieved by an optimised combination of the β^* values of the two proton beams, see [4].

A further increase of the e-p luminosity is possible if an advanced focusing technique, ATS, is applied: like in IP1 and IP5 of the HL-LHC, a β-wave is created in front and after the interaction region [5]. It has been introduced in the new e-p interaction point to allow for even stronger focusing and higher luminosity. Figure 4 shows the new optics, applied for the colliding beam and well embedded into the overall upgrade optics of the storage ring.

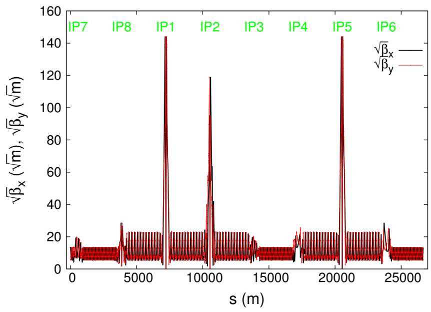


Figure 4: An advanced beam optics, based on the HL-LHC uprade optics, ATS, to allow for higher luminosity in e-p collisions. The dedicated β-wave to increase the chromatic correction capabilities and allow for stronger focusing is clearly visible in the figure [6].

Beam optics for the colliding protons in the range of $\beta^* = 15 \ldots 35cm$ have been established, see Table 1. The resulting luminosity is calculated based on the HL-LHC [3] and LHeC [1] design parameters, namely for bunch intensities as mentioned in the table. The required magnet technology for the super-conducting LHC triplet magnets is included. In the most advanced case of stand alone operation and Nb_3Sn magnet technology, even values of $\beta^* = 10cm$ are in reach, leading to a luminosity of $L = 6.6 \cdot 10^{33} cm^{-2} s^{-1}$.

Table 1: Luminosity reach for e-p collisions at the LHeC as function of the β^* value at the interaction point. The table includes the required magnet technology for the triplet magnets, that defines the free aperture for the two proton beams and their inter beam distance.

Colliding beam, $\beta_1\,[m]$	0.15	0.20	0.25	0.30	0.35
Non-colliding beam, $\beta_2\,[m]$	18-24	18-24	18-24	18-24	18-24
Proton bunch intensity	$2.2 \cdot 10^{11}$				
Electron bunch intensity	$3.1 \cdot 10^{9}$				
Luminosity $[10^{33} cm^{-2} s^{-1}]$	4.4	3.3	2.6	2.2	1.9
Magnet technology	Nb_3Sn	Nb_3Sn	Nb_3Sn	NbTi	NbTi
Operation mode	stand alone	concurrent	concurrent	stand alone	concurrent

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[4] T. v. Witzleben et al.,Beam Dynamics for Concurrent Operation of te LHeC and the HL-LHC, proc. IPAC 2023, Venice.

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