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BEAM DYNAMICS FOR CONCURRENT OPERATION OF THE LHeC AND THE HL-LHC

T .von Witzleben*[1,2], K. D. J. André[1], R. De Maria[1], B. Holzer[1], M. Klein[3], J. Pretz[2,4], M. Smith[3]
[1]CERN, Meyrin, Switzerland
[2]RWTH Aachen University, Aachen, Germany
[3]University of Liverpool, Liverpool, UK
[4]Forschungszentrum Jülich GmbH, Jülich, Germany

Abstract

The Large Hadron Electron Collider (LHeC) is a study at CERN to construct an energy recovery linear accelerator (ERL) tangentially to the High Luminosity Large Hadron Collider (HL-LHC). This would enable deep inelastic scattering collisions between electrons and protons in the ALICE interaction region (IR2). In this design, one of the two proton beams of the HL-LHC collides with the electron beam in IR2, while the second proton beam avoids this collision. This way, the e-p collisions can take place concurrently with p-p collisions in ATLAS, CMS and LHCb. The LHeC/ALICE interaction region is laid out for alternate e-p and p-p data, using a common detector, suitable for this novel way of interaction. It therefore requires a highly precise beam optics and orbit for the three beams: the two proton beams of the HL-LHC, as well as the electron beam from the ERL. The highly asymmetric optics and orbits of the two proton beams, allowing concurrent operation of the HL-LHC experiments and e-p collisions, have been investigated with MAD-X. The impact of an optimized electron mini-beta insertion, focusing and bending the electrons, on the proton beam dynamics has been considered.

THE LHeC DESIGN STUDY

The LHeC design study investigates the option of colliding an electron beam with one of the 7 TeV proton beams of the LHC and thereby creating world's cleanest high precision microscope for the inner structure of hadrons.

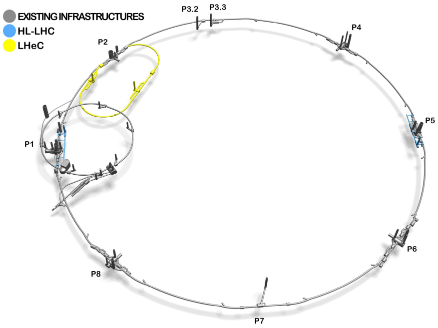

Figure 1: Schematic of a possible LHeC layout. It displays the energy recovery linac (yellow), the super proton synchrotron with the LHC (grey) and the high luminosity upgrade (blue) [1].

An energy recovery linac (ERL) is used to accelerate the electrons to their final energy of 50 GeV, as to realize e-p collisions with a center of mass energy of $\sqrt{s}$=1.2 TeV. This center of mass energy is four times greater than that of its predecessor, HERA. A schematic of the LHeC is shown in Fig. 1 and a detailed description of the LHeC design can be found at Ref. [1].

DESIGN OF THE ELECTRON INTERACTION REGION

The ERL consists of two opposite superconducting linear accelerators, which are connected by three return arcs. The electrons are accelerated and decelerated over three turns in the same radio frequency (RF) cavities. This technology aims to recover 96.7 % of the electron energy [2] and will be tested in the facility PERLE (Powerful ERL for Experiment) in Orsay [3]. A schematic of the ERL is shown in Fig. 2 with the main parameters of the ERL displayed in Table 1.

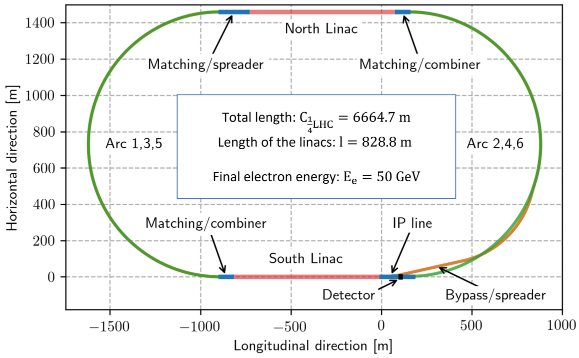

Figure 2: Schematic of the energy recovery linac used to accelerate the electrons. It shows the two linacs connected by three return archs [4].

Table 1: Parameter List of the Energy Recovery Linac

Parameter	Value	Unit
Beam Energy	50	GeV
Bunch Charge	499	pC
Bunch Spacing	24.95	ns
Electron Current	20	mA
Trans. norm. Emittance	30	µm
RF Frequency	801.58	MHz
Acceleration Gradient	20.06	MV m^{-1}

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* tiziana.von.witzleben@cern.ch

After three turns the electrons collide head-on with the protons. The electron interaction region features a dipole magnet embedded in the particle detector, which separates the electron beam from the protons after the collision. It also features a doublet of quadrupoles to focus the electrons. The protons pass through the electron magnets, while the electrons do not see the proton triplet, as the electron beam is bent away before. After passing through the interaction region, the remaining electrons are directed back into their RF cavities to recover their energy. This electron interaction region has been optimized to minimize the synchrotron radiation power and the critical energy of the photons [4].

DESIGN OF THE PROTON INTERACTION REGION

During operation of the HL-LHC, the two proton beams will collide in four interaction points (IPs). Namely, in ATLAS (IP1), ALICE (IP2), CMS (IP5) and LHCb (IP8). The electron beam is meant to collide in IP2 with one of the two proton beams from the HL-LHC. Therefore, the e-p data acquisition would alternate with the data acquisition of the ALICE experiment in a common multipurpose detector, but still operate concurrently with the p-p collisions in ATLAS, CMS and LHCb. The colliding proton beam will be referred to as beam 1 in this paper. The second proton beam (beam 2) needs to be guided through the same magnet aperture around IP2. It needs to be spatially separated from the colliding proton beam, as to minimize long range beam-beam effects. In the horizontal plane, the two proton beams are separated using a horizontal separation orbit bump, acting on both of them. In the vertical plane, the two proton beams are separated using a vertical crossing bump on the non-colliding beam, while the colliding beam is kept on its original collision orbit. In order to further maximise the distance between the two proton beams, asymmetric optics are used on the two beams and they are focused down to different $\beta*$ values. Beam 1 is focused down as far as possible, while beam 2 is kept at a higher $\beta*$ value. This way the smallest aperture is obtained in the triplet region, where the beams will get the closest to each other. In Figs. 3 and 4, the orbits and optics of the two beams around IP2 are shown. All beam modellings have been performed with MAD-X [5].

Parameter Optimization in IR2

In order to maximise the distance between the two proton beams in the shared aperture, a parameter scan has been performed. The orbit parameters that were investigated were the size of the symmetric horizontal separation bump (sep) of the two proton beams and the vertical crossing bump of the non-colliding beam (x). The parameters for the performed scans are shown in Table 2.

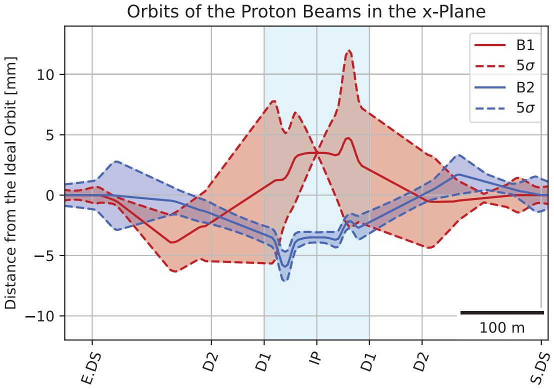

Figure 3: Orbits of the two proton beams around the IP in the x-plane with 5σ envelopes. The colliding beam is shown in red and the non-colliding beam in blue.

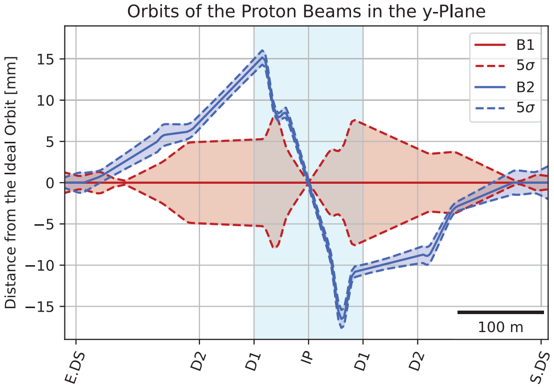

Figure 4: Orbits of the two proton beams around the IP in the y-plane with 5σ envelopes. The magnets D1 mark the dipoles which guide the beams into separate apertures. In the light blue area, the beams share the same aperture.

Table 2: Parameter list for the optics and orbit scans. All possible orbit and optics combinations were tested.

Parameter	Value	Unit
β^*_{B1}	0.35	m
β^*_{B2}	10 to 70	m
x	-300, -325, -350	µrad
sep	3.0, 3.25, 3.5	mm

During the scans, the colliding beam was focused down to a $\beta*$ value of 0.35 m and kept at this value, while the non-colliding beam was matched to $\beta*$ values between 10 m and 70 m in steps of 1 m. According to Ref. [6], the β value at the beginning and at the end of a drift space of length l, before and after a symmetry point $\beta*$, can be determined using:

$$\beta(l) = \beta^* + \frac{l^2}{\beta^*}\,. \tag{1}$$

The minimal value of the β function at a distance l from the symmetry point can be determined by deriving this equation and setting it equal to zero. The smallest value for $\beta(l)$ is therefore achieved with: $\beta^* = l$. In case of the LHeC, the length of the drift space is 23 m [7], and therefore an optimal $\beta*$ value around 23 m is expected. To determine the optimal $\beta*$ value for the non-colliding beam and the best settings for the orbits of the two proton beams, in every scan, the minimal distance between the two beams in the shared aperture was recorded. The minimal distance between the two proton beams in the shared aperture, measured in σ of the non-colliding beam is shown in Fig. 5.

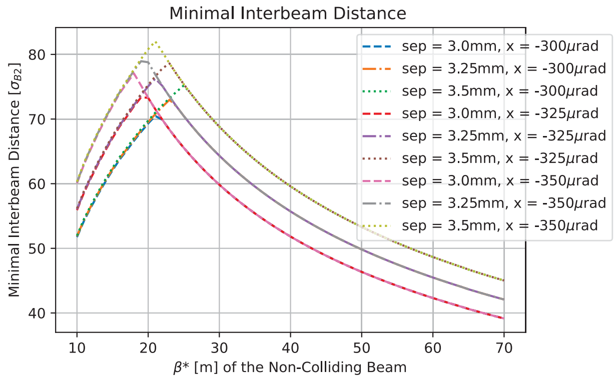

Figure 5: Minimal distance between the two proton beams in σ of the non-colliding beam for different orbit and optics settings.

During the parameter optimization, it was assured, that a minimal distance of 12σ was kept to the aperture limit for both beams. After the parameter scans, it was decided to use a non-colliding beam with a β^* of 21 m, a separation bump of 3.5 mm and a crossing angle of 350 μrad, since this maximised the space between the beams. A zoom of the total distance between the beams in the shared aperture is displayed in Fig. 6. The value at the IP is not shown in the graph, as with a beam size of 11 μm, it reaches a value of 646 σ.

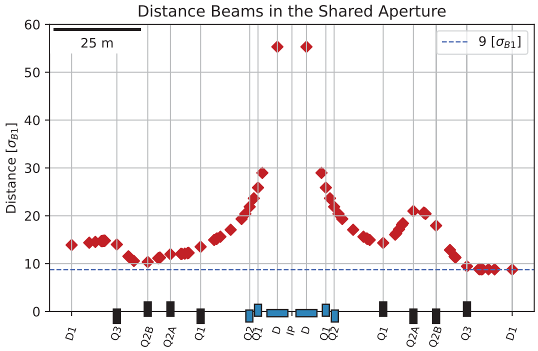

Figure 6: Distance between the two proton beams in σ of the colliding beam in the shared magnet aperture. The blue line marks the minimal distance of 9σ. The labels show the positions of the proton triplet (black) and the electron doublet and dipoles (blue).

Low β^* Optics

With 3×10^9 electrons per bunch and a proton β^* value of 0.35 m, a luminosity of $1.4 \times 10^{33} \mathrm{cm}^2\,\mathrm{s}^{-1}$ can be reached. The optics in the HL-LHC is designed in the achromatic telescope squeeze (ATS) scheme[8]. Hence, the matching quadrupoles in IR2 are used to further focus down the β^* in IR1. Additionally, a beta-wave in the optics assures, that the betafunction reaches a maximum at every other sextupole and thus, increases the sextupoles' efficiancy to control the chromaticity. This was considered, while focusing down the colliding beam at IP2. The matching quadrupoles in IP2 were not strong enough to match down to a β^* value of 0.35 m. This problem occurred already in a previous study of the LHeC [9]. It could be resolved by replacing a matching quadrupole on each side of IP2. Two 3.4 m long MQM magnets were replaced by two 4.8 m long MQML magnets, which otherwise share the same characteristics [10]. Now, the colliding beam could be focused down to 0.35 m, while the non-colliding beam was relaxed to 21 m at the IP. The optics was rematched, considering the phase advance and the dispersion. In this way the chromaticity could be controlled with the ATS optics and the magnets used could stay within their hardware limits for their normalized gradients.

Impact of the Electron Magnets on the Proton Beam Dynamics

The electron doublet consists of two dipole magnets, partially embedded in the particle detector, and two focusing quadrupoles on each side. The electron dipoles are used to bend the electrons towards the collision and subsequently to separate them from the protons. Their placement implies, that the protons also pass through these magnets. In Fig. 4 the impact on the proton orbit from these dipoles can be seen as a slight deflection outwards for both proton trajectories in the separation bump. The focusing electron quadrupoles induce a beta-beat of about ±8 % on both proton beams. Both effects have been corrected for both beams.

SUMMARY AND OUTLOOK

A concept for the proton beam dynamics for concurrent operation of the e-p and p-p collisions in the HL-LHC has been designed and optimized. With slight modifications to the LHC lattice, the proton beams can be separated by at least 9σ in the e-p interaction region, where they share the same magnet aperture. A β^* of 0.35 m of the colliding proton beam assures a luminosity of $1.4 \times 10^{33} \mathrm{cm}^2\,\mathrm{s}^{-1}$. The new and optimised electron interaction region [4] has been inserted in this proton lattice and the effect on the proton beam dynamics has been corrected. This design enables concurrent operation of the high luminosity experiments with the LHeC or the ALICE experiment. As a next step, the beam-beam effects from the non-colliding proton beam on the colliding one will be investigated in tracking simulations. Meanwhile, further efforts will be taken to get closer to the design goal reported in the LHeC design report of a β^* of 10 cm [1] for the colliding proton beam.

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