LHeC IR OPTICS DESIGN INTEGRATED INTO THE HL-LHC LATTICE

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Abstract

The Large Hadron Electron Collider (LHeC) [1] is a proposed upgrade to the LHC to provide electron-proton collisions and explore the new regime of energy and intensity for lepton-nucleon scattering. The work presented here investigates optics and layout solutions allowing simultaneous nucleon-nucleon and lepton-nucleon collisions at separate interaction points compatible with the proposed High Luminosity Large Hadron Collider (HL-LHC) lattice. A first lattice design has been proposed that collides proton beam 2 with the electron beam. The nominal design calls for a β^* (β function in the interaction point) of 10 cm using an extended version of the Achromatic Telescopic Squeezing (ATS) scheme, and a L^* (distance to the inner triplet) of 10 m. Modifying these two parameters, β^* and L^*, can provide benefits to the current design since the values of these parameters have direct effects on the luminosity, the natural chromaticity and the synchrotron radiation of the electron beam. This work aims to explore the range over which these parameters can be varied in order to achieve the desired goal.

INTRODUCTION

An interaction region design for the LHeC was proposed in the CDR [1]. The aim of this design was to achieve head-on electron-proton (e-p) collisions in the interaction region 2 (IR2) at a luminosity of $10^{33}\text{cm}^{-2}\text{s}^{-1}$ which requires a low $\beta^* = 10$ cm (β function in the interaction point). This low β was achieved by implementing a new set of quadrupoles closer to the interaction point (IP), called the inner triplet (IT), at a distance L^* from the IP. These magnets have a normal hole to focus the proton beam 2 and a field free hole for the proton beam 1 to go through unfocussed, along with the electron beam and the synchrotron radiation (SR) it produces. An illustration of the new IT design is shown in Fig. 1.

In order to change the trajectory of the proton beams, the polarity of the two dipoles close to the IP (D1 and D2) must be reversed, compared to the present polarity, and the strength of D2 should be 1.21 stronger and the one of D1 3.43 stronger, giving a crossing angle of $\theta = 6.8$ mrad between the proton beams. Head-on collisions are achieved by means of dipoles around the IP. A schematic view of this design is shown in Fig. 2.

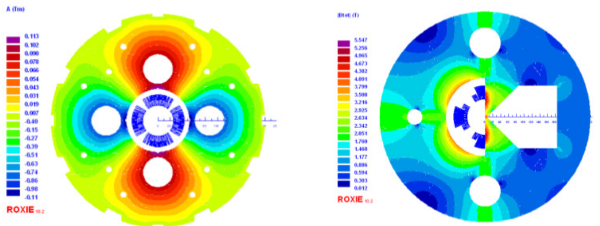

Figure 1: Design of the half quadrupole for Q1 (right) and the normal quadrupole for Q2 (left).

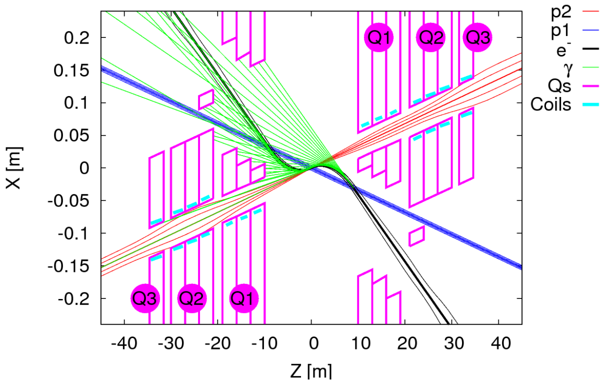

Figure 2: Schematic view of the LHeC interaction region. The proton and electron beam trajectories are shown with 5σ and 10 σ envelopes [2].

The minimization of β^* is limited by the quadrupole strengths and the huge chromatic aberrations caused by the new IT. In order to overcome these limitations a technique called the Achromatic Telescopic Squeezing (ATS) Scheme [3] has been proposed. This technique consists of creating and absorbing a β wave in the arcs adjacent to the IP. This β wave is carefully constructed in a way that will minimize the value of β^* and, at the same time, maximize the efficiency of the sextupoles.

A first integration of the LHeC into the HL-LHC lattice is described in [4], achieving a value of $\beta^* = 10$ cm for IP2 and β^*=15 cm in IP1 and IP5.

The aim of this work is to explore the flexibility of this design by minimizing β^* and increasing L^*, not only because of the benefits that they give in terms of luminosity and SR, but also because the HL-LHC lattice imposes limitations on the proton beam, which encourages us to be as flexible as possible with the parameters that can be changed.

CHANGING PARAMETERS

The luminosity of the e-p collisions is inversely proportional to the β^* (Eq. 1) [5].

$$L = \frac{1}{4\pi e}\frac{N_{b,p}}{\epsilon_p}\frac{1}{\beta_p^*} I_e H_{hg} H_D \qquad (1)$$

In the drift space next to the IP the β function increases as:

$$\beta(s) = \beta^* + s^2/\beta^* \tag{2}$$

where s is the distance to the IP.

In consequence, minimizing β^* (to increase the luminosity) and increasing L^* (to reduce the SR) results in a large β function in the location of the IT that could lead to a loss of aperture and an increase in the natural chromaticity produced by the quadrupoles.

The values of the Courant-Snyder parameters at the ends of the IR2 create the beta wave necessary to minimize the β^* in the IP2 and are fixed by the HL-LHC lattice. Keeping these values at the ends of the IR2, the strengths of the quadrupoles in the IR2 can be used as parameters to find solutions for different values of L^* and β^*. For L^*, solutions for the cases $L^* = 10 - 20$ m with $\beta^* = 10$ cm have been found as well as solutions for the cases $\beta^* = 5 - 10$ cm and $\beta^* = 20$ with $L^* = 10$ m. The natural chromaticity of all these cases is shown in Fig. 3.

As expected, the natural chromaticity increases in both cases, but it does so linearly as we increase L^*, whereas minimizing β^*causes the natural chromaticity to increase more rapidly.

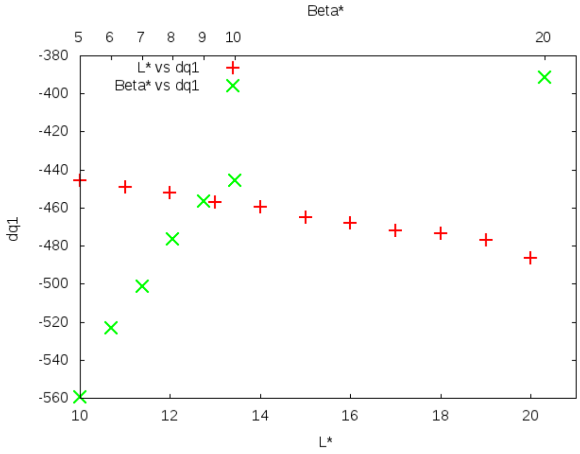

Figure 3: Natural chromaticity plotted as a function of L^* with β^*= 10 cm (red), and as a function of β^* with L^*=10 m.

The cases $L^* > 14$ m are of particular interest, not only because they generate less SR, but also because of the benefits they give in quadrupole design. For $L^* > 14$ m the separation between the proton beams is enough (≥ 87 mm) to be able to use a normal quadrupole (left side of Fig. 1) as opposed to the half quad design (right side of Fig. 1), where stray fields are found in the free field regions that increase the difficulty to match the electron beam lattice.

CHROMATICITY CORRECTION LIMITS

Different solutions of L^* and β^* have been found that provide the desired luminosity. But it is necessary to see whether the sextupole efficiency has been increased enough to perform the chromatic correction.

Using a MADX matching procedure, the 32 sextupole families of the LHC were used as variables to reduce the horizontal (dq1) and vertical (dq2) chromaticity to a positive value of 2, and to reduce as well the value of the chromatic amplitude function (W_x and W_y) to a value of 200 in the collimation insertions in interaction region 3 (IR3) and interaction region 7 (IR7). These values are set by the LHC machine to ensure stability.

This matching procedure was successfully performed for the nominal design of $L^* = 10$ m and $\beta^* = 10$ cm. In this case the values of the horizontal and vertical chromaticity diminished from dq1=-445.83 and dq2=-446.77 to a value of dq1=dq2=2. The values of W_x and W_y were also matched to 200 in IR3 and IR7 as is illustrated in Fig. 4.

The tune spread over a momentum $\delta_p = \pm 0.001$ was also studied on a frequency map. The comparison between the tune spread before and after the correction is shown in Fig. 5.

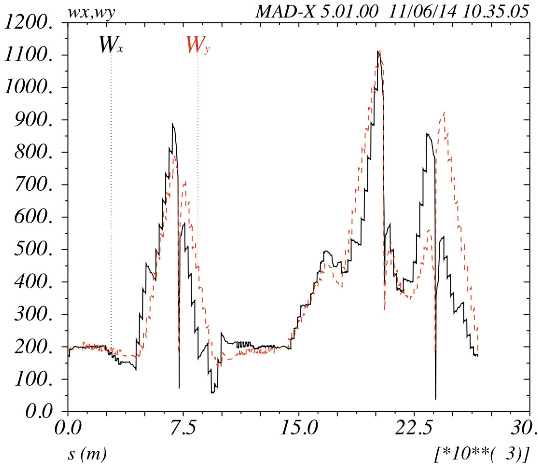

Figure 4: The horizontal (W_x) and vertical (W_y) chromatic amplitude functions. The value of this function in IR3 ($\sim$ 12.5 km) and IR7 ($\sim$ 0 km) is 200.

The same procedure was performed to search the limits of this chromatic correction. For the lower β^* cases, this limit was found to be β^*= 8 cm where the matching procedure was performed successfully and the tune spread diagram avoids resonances up to order 9.

For the different L^* cases, solutions for the matching procedure were found for a maximum of $L^* = 19$ m, however the corresponding tune spread crossed resonances of order 2 because of high order chromaticities. The complete chromatic correction including a tune spread avoiding resonances up to order 9 was found only up to a value of $L^* = 18$ m.

Considering the natural chromaticity shown in Fig. 3 we can draw the limit of the chromaticity correction by this method for cases with natural chromaticity of dq ~ -470 .

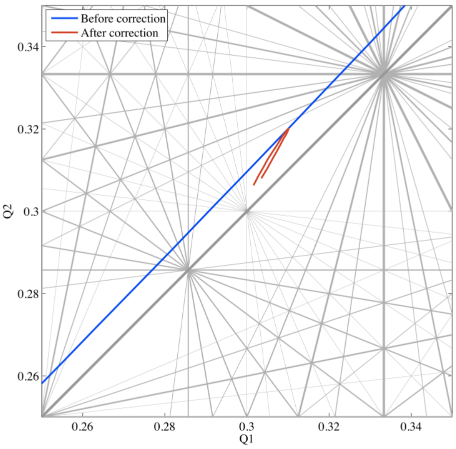

Figure 5: Tune spread over a frequency map showing resonances up to order 10, for a δp=$\pm$0.001 before correcting the chromaticity (blue) and after the correction (red).

SYNCHROTRON RADIATION

The SR produced by the electron beam while transporting it to and from the IP is a problem that has to be treated with great care in order to minimize the damage in the quadrupoles and the pipes.

The power in the SR as a function of L^* for the LHeC was reported in [4]. A possible way to reduce this power further for $L^* > 10$ m would be to reduce the separation of the beams at the entrance of the Q1, since this would reduce in consequence the necessary bending of the electron beam.

In order to minimize this separation the following constraints were considered:

- The distance between the beams has to be greater than 65 mm for $L^* < 14$ m (separation in half quadrupole design) and greater than 87 mm for $L^* > 14$ m (separation in normal quadrupole design).
- The separation at the first long-range encounter, corresponding to 3.75 m for a 25 ns bunch spacing and 7.5 m for a 50 ns bunch spacing, has to be of at least 12 σ.
- The size of the electron beam must physically fit inside the field-free hole.

Taking these constraints into consideration, the minimum beam separation (d(L)) and the aperture in σ that could be fitted in the field-free hole were calculated and are shown in Table 1.

Figure 6 shows the radiation power as a function of L^* and the beam separation. Three different lines are shown, the first one illustrates the results of scaling the LHeC CDR reported in [4], the other ones illustrate the cases with the minimum distance for the 25 ns and 50 ns bunch spacings. The reduction of the SR for the cases $L^* > 10$ m is clearly observed.

Table 1: Minimum separation between beams for each L^* and for two different bunch spacings (25 and 50 ns) with the aperture size in sigmas.

L^*	$d(L)_{25}$ (m)	$d(L)_{50}$ (m)	Aperture size (σ)
10	0.068	0.068	46
11	0.068	0.068	42
12	0.068	0.068	38
13	0.068	0.068	35
14	0.087	0.087	25
15	0.087	0.087	23
16	0.087	0.087	22
17	0.087	0.087	20
18	0.098	0.087	19
19	0.109	0.087	18
20	0.121	0.087	17

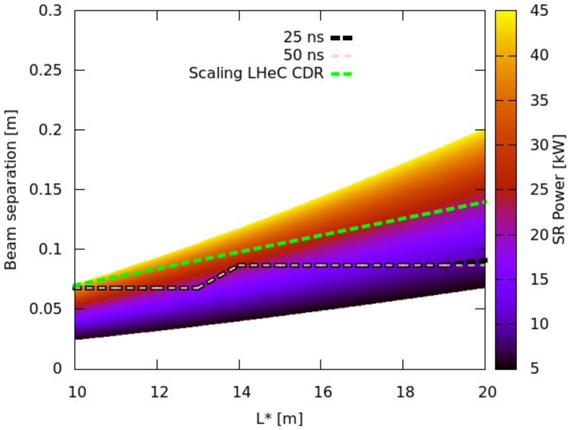

Figure 6: Synchrotron radiation power given as a function of L^* and the beam separation in Q1. The green line show the cases for scaling the LHeC CDR, the black and pink lines show the minimum beam separation for bunch spacings 25 ns and 50 ns respectively.

CONCLUSIONS

The flexibility of the integration of the LHeC into the HL-LHC lattice has been explored in terms of minimizing β^* to increase the luminosity and increasing L^* to reduce the synchrotron radiation. The results show that it is recommended to keep the β^* at 10 cm, where luminosity is still achievable, but increase L^* to $\sim$ 14-18 m which will allow the chromaticity to be corrected and also give important benefits in terms of the quadrupole design and the reduction of SR.

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