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LHeC IR OPTICS DESIGN INTEGRATED INTO THE HL-LHC LATTICE

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Abstract

The two main drivers for the CDR LHeC IR design were chromaticity and synchrotron radiation. Recently it has been proposed that the LHeC IR proton optics could make use of the Achromatic Telescopic Squeeze (ATS) [1] scheme, which benefits from higher arc beta functions for the correction of chromaticity. In this scenario the distance between the IP and the proton triplet can be increased allowing for a reduction of the IR dipole field and the synchrotron radiation. First feasibility considerations and more in-depth studies of the synchrotron radiation effects are presented in this paper.

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INTRODUCTION

A first conceptual design of the LHeC linac-ring Interaction Region (IR) is presented in the LHeC Conceptual Design Report [2]. The merits of the design are a very low β^* of 0.1 m with proton triplets as close as possible to the IP to minimize chromaticity. Head-on proton-electron collisions are achieved by means of dipoles around the Interaction Point (IP). A crossing angle of 6 mrad between the non-colliding proton beams allows enough separation to place the proton triplets. Only the proton beam colliding with the electrons is focused. In the IR2 configuration the electrons are injected parallel to the LHC Beam 1 and collide head-on with Beam 2, see Fig. 1.

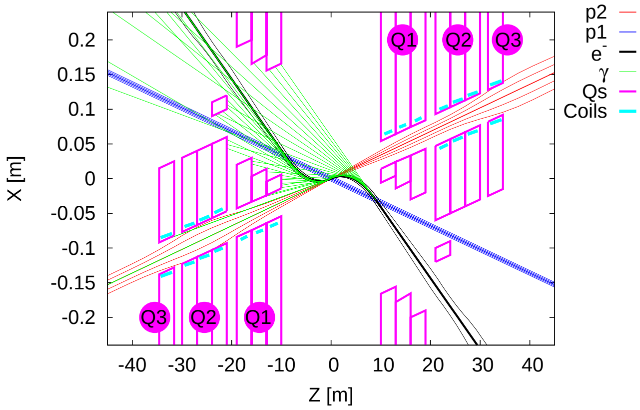

Figure 1: LHeC interaction region with a schematic view of synchrotron radiation. Beam trajectories with 5σ and 10σ envelopes are shown.

Bending dipoles around the IP are used to make the electrons collide head-on with Beam 2 and to safely extract the disrupted electron beam. The required field of these dipoles is determined by the L^* and the minimum separation of the electron and the focused beam at the first quadrupole (Q1). A 0.3 T field extending over 9 m allows for a beam separation of 0.07 m at the entrance of Q1. This separation distance is compatible with mirror quadrupole designs using Nb_3Sn technology. A transverse section of the Q1 quadrupole is shown in Fig. 2. The electron beam radiates 48 kW in the IR dipoles. The impact of the back-scattered synchrotron radiation in the detector needs to be carefully evaluated, while reducing the total SR power is highly recommended.

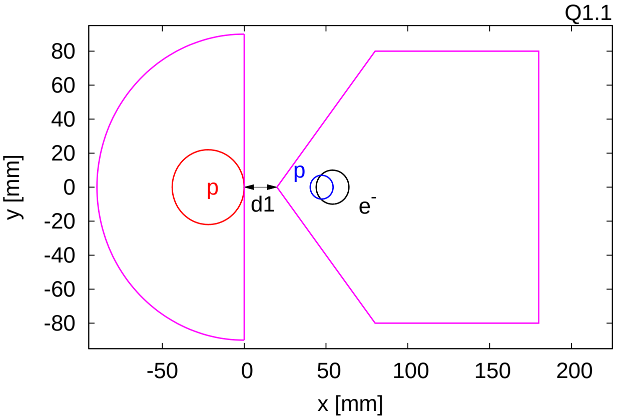

Figure 2: Transverse section of the first Q1 block showing the face closest to the IP.

After matching this triplet to the LHC and correcting linear chromaticity the chromatic β-beating at dp/p=0.001 is about 100% [2]. This is intolerable regarding collimation and machine protection issues. Therefore an appropriate chromatic correction scheme is required. The HL-LHC optics uses beta-beating waves in the arcs in order to accomplish achromatic β^* squeeze by increasing the beta-function in the sextupoles at the same time as reducing the β^*. In [3] it was proposed to extend the ATS beta-beating wave to the arc 2-3 in order to provide enough chromatic correction for the LHeC IP. A realization of this optics is shown in the next section.

EXTENDED ATS SCHEME

The HL-LHC injection, pre-squeeze and collision optics [1, 4] remain unchanged from the end of IR4 to the beginning of IR6 and from the end of IR7 to the beginning of IR2. However, IR2 has to be significantly modified for the aims of the LHeC experiments.

Instead of the original LHC triplets, IR2 should be equipped with two special septum triplets at L^* of 10 m as shown in Fig. 1. The triplet has the same layout, parameters and field gradients as specified in the LHeC CDR [2]. The strengths of dipoles D2 and D1 on both sides of IP2 have to be stronger than the nominal by factors of 1.21 and 3.43 respectively, to provide the required crossing angle. The field in each dipole will be about 6 T: this means a hardware upgrade will be required. The polarity of the dipoles is reversed, compared to their present polarity.

In order to arrange the ATS optics in IR2, the arc cells in sector 2-3 are exactly adjusted to the phase advance of $\pi/2$ in both planes. Then new matching conditions for both proton beams are imposed for the left and right phase advance of IR2 (with respect to IP2). This extends the so-called ATS pre-squeeze optics (no beta-beating in the arcs) up to the beginning of IR3 providing β^* of 30 cm at IP2 for beam 2. Beam 1 by-passes the triplets through their field-free apertures and does not experience any focusing from the triplets.

The phase advance in sectors 3-4 and 6-7 is slightly changed to restore the betatron tunes of the machine to the nominal values of 62.31/60.32 (horizontal/vertical) specified for the present HL-LHC optics design. With equal field gradients in the two apertures of the arc quadrupoles, the integer part of the betatron tunes of beam 1 is one unit less than the nominal values because beam 1 has no strong focusing in IR2. Introducing a small field imbalance in the quadrupoles of sectors 3-4 and 6-7 can give equal integer parts for the betatron tunes for both beams.

During transition from the pre-squeeze to the collision optics, the ATS is applied. There is no variation of quadrupole strengths in the low-beta insertions IR1, IR2 and IR5 at this stage. Adjusting the quadrupole strengths in the neighbouring straight sections i.e. IR8/IR3 and IR4 /IR6, β-beating waves in sectors 4-5, 5-6, 8-1, 1-2, and 2-3 start to build up producing further reductions in β^* from 30 cm to 10 cm at IP2 and from 44 cm to 15 cm at IP1 and IP5 as shown in Fig. 3. At the same time, the β-beating waves reach a maximum at every second sextupole, which significantly enhances the efficiency of the chromatic correction. This makes it possible to compensate the chromaticity contributed from the low-beta insertions while remaining within the limit (600 A) of the existing LHC sextupoles.

In spite of the fact that beam 1 does not collide with electrons, ATS optics for beam 1 have been implemented in IR2 in order to avoid an unacceptable field imbalance in the two apertures of the IR2 quadrupoles during the transition. Figure 4 shows ATS collision optics for both proton beams.

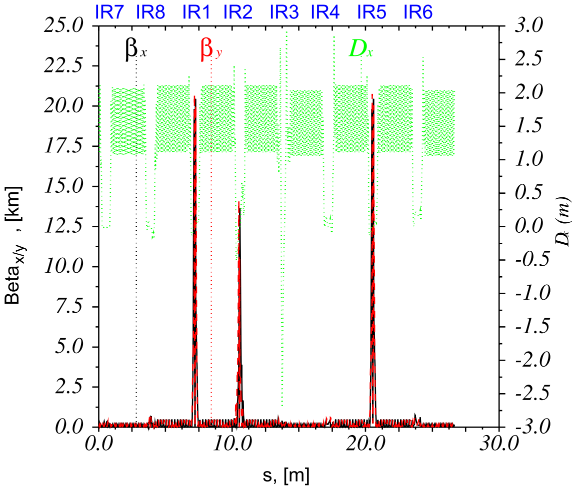

Figure 3: LHeC ATS collision optics for beam 2 with $\beta^* = 10$ cm at IP2 and $\beta^* = 15$ cm at IP1 and IP5.

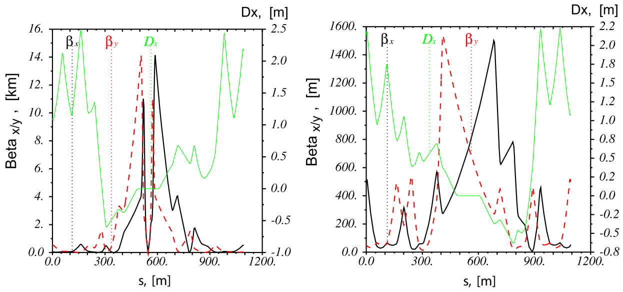

Figure 4: ATS collision optics in IR2 for beam 2 with $\beta^* = 10$ cm (left) and beam 1 (right).

The insertion IR3 is kept strictly unchanged from the injection to collision in the HL-LHC optics design. In our case, good flexibility in tuning of IR3 is required to absorb β-beating waves and at the same time to meet optics matching conditions specified for the momentum cleaning systems located in IR3. Tuning flexibility can be significantly improved if the warm dual-bore Q5 quadrupoles powered in series are involved in the variation process, maintaining identical field in both apertures. More details can be found in Ref. [5].

INCREASING L*

The motivation to increase L^* is twofold:

- reduce total synchrotron radiation power in the IR;
- avoid the need for any cantilever or new support for Q1 as the tunnel starts 23 m from the IP.

Increasing L^* will in turn increase the chromaticity of the IR and chromatic aberrations might put a limit in the minimum β^*. To reduce the synchrotron radiation power it is assumed that the IR dipole field is reduced. This reduces the separation of the long-range beam-beam encounters between the proton and the electron beam. Figure 5 shows the long-range separation at the first encounter between the proton and the electron beams versus β^* and for the two possible bunch spacings 50 ns and 25 ns. For the longest L^* and for 25 ns a 16σ separation is expected which seems unlikely to be of major concern, although beam-beam simulations should be performed.

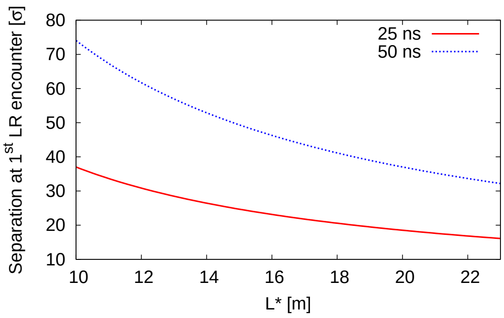

Figure 5: Separation between the proton and the electron beams at the first long-range encounter versus L^* assuming a linear increase of the separation at the first triplet quadrupole.

Figure 6 shows the radiation power in the IR dipoles as a function of L^* and the beam separation at the first quadrupole. It is assumed that the entire L^* region is used for the bending dipoles. A green line is used to show the results of scaling from the LHeC CDR design, showing a linear reduction of SR power with L^*. A star marks the location of a possible IR design using current HL-LHC triplet designs. This assumes the use of an HL-LHC quadrupole with e$^-$ beam pipe at the position indicated in Fig. 7. This implies a larger separation between the electron and the proton beam as the two LHC proton beams share the same aperture. The radiated power would be about 20% larger than for the CDR design.

CONCLUSIONS

A first integration of the LHeC IR within the HL-LHC optics has been accomplished by extending the ATS scheme. This allows designs to be considered with larger L^* and consequently more chromaticity, but lower synchrotron radiation power. Placing the first quadrupole at 23 m has the advantages of not needing any cantilever system and reducing the radiated power by a factor two. Consideration has also been given to using the HL-LHC quadrupole design; this would lead to about 20% higher synchrotron radiation power in the IR dipoles.

ACKNOWLEDGMENTS

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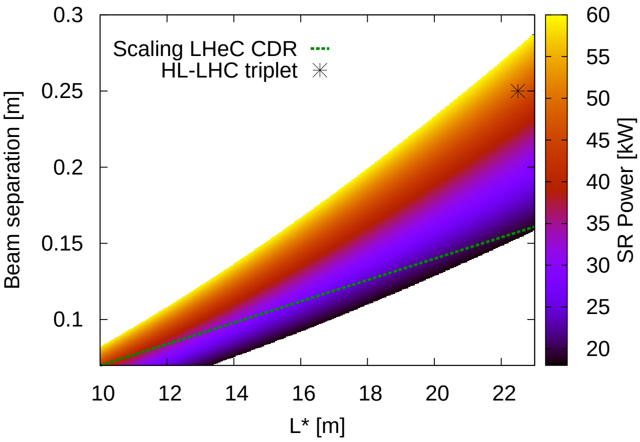

Figure 6: Synchrotron radiation power in the IR dipoles as function of the L^* and the beam separation at the first quadrupole.

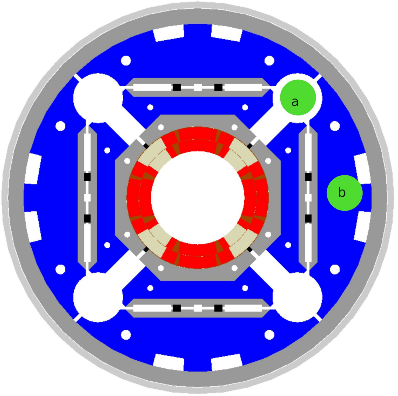

Figure 7: HL-LHC triplet quadrupole design with 2 possible positions for the e$^-$ beam pipe (marked with a and b).

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