INTERACTION REGION OPTICS FOR THE NON-INTERACTING LHC PROTON BEAM AT THE LHeC

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Abstract

The Large Hadron Electron Collider project is a proposal to study e-p and e-A interactions at the LHC. Two electron accelerator designs are being studied; a linac and a synchrotron. In the synchrotron option, a 60GeV electron beam is collided with one of the LHC proton beams to provide high luminosity TeV-scale interactions. The interaction region for this scheme is complex and introduces a series of challenges due to the integration of the two machines. One of these is the optics of the second non-interacting proton beam. The second proton beam must not interfere with the LHeC experiment, but simultaneous running of the remaining LHC experiments requires that this beam must still circulate relatively undisturbed. This paper discusses methods to solve these challenges for the electron synchrotron design.

INTRODUCTION

The LHeC shares with HERA the challenge of colliding electrons and protons at high intensity and energy. LHeC however introduces an additional unique factor of dealing with two proton beams, as the baseline LHC is a proton-proton collider not designed for lepton-hadron operation. To avoid disruption of the LHeC experiment, and minimise impact on the other LHC experiments, the two proton beams must not collide or exhibit significant beam-beam interaction. Furthermore the second proton beam must not interfere with the electron beam.

The LHeC has two interaction region (IR) designs, one for higher luminosity (HL) and one for higher acceptance (HA) [1]. In both IRs, a solution must be found for dealing with the second proton beam. Detector designs strongly prefer a single central beam pipe for all beams. A second pipe would complicate detector design and reduce efficiency, as space would have to be made through inner calorimetry to accommodate it. As such, the non-colliding (NC) beam must be guided through the IR along with the two other beams.

DESIGN ELEMENTS

To avoid collisions and beam-beam effects, the bunches of the NC proton beam are offset in time. Using the LHC ultimate parameters, bunch spacing is 25 ns. The second proton beam bunches would therefore be offset by 12.5 ns locally to the LHeC experiment. This prevents proton-proton collisions at the IP, and allows the NC beam to overlap with the co-rotating electron beam. Thus the NC beam can use the same aperture as the electron beam.

Proton-proton parasitic interactions and beam-beam effects can still occur; to minimise these, the NC beam is left unsqueezed, and a proton-proton crossing angle is implemented. The unsqueezed beam and crossing angle minimise effective luminosity at parasitic crossings, and the crossing angle also generates separation. For unsqueezed optics, LHC alignment optics [2] are modified and used on the NC beam only. The alignment optics scheme deactivates the final triplet and repurposes the matching section to control beta growth through the long drift space, allowing the beam trajectory to be used as a reference for alignment of the triplet. The optics used in this paper is that developed for the linac-ring design presented in the LHeC CDR [3], and is show in Figure 1 for the IP and matching section.

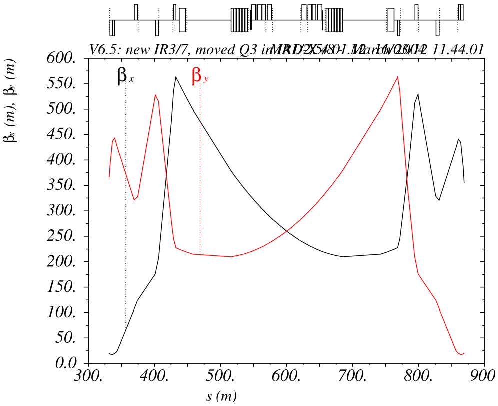

Figure 1: Optics for the NC proton beam, adapted from LHC alignment optics [2]. IP2 is at the centre of the *s* axis.

A crossing angle is generated by using the LHC separator dipoles D1 and D2, at roughly 60 m and 120 m from the IP respectively. Figure 2 shows the trajectories of the three beams for the HA design. The proton final triplet is rotated about the IP to match the new trajectory of the colliding beam. D1 and D2 in nominal LHC operation bring the beams to collision from the ∼190 mm separation in the arc. D2 brings the beams together after the arc and D1 reverses this bending before collision. D1 is not designed for the large separation between beams seen in Figure 2 and will need to be replaced.

The electron trajectory is rotated to match the colliding proton beam, such that the electron-proton crossing angle

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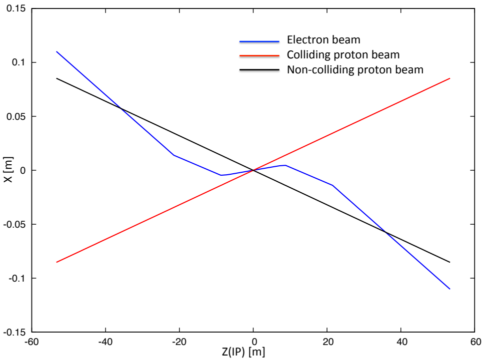

Figure 2: Trajectories of the three beams in the HA IR design. Proton-proton crossing angle generated by D1, situated at ∼60 m either side of the IP. Electron-proton crossing angle remains 1mrad. Proton triplet begins at 23 m, where the electron and NC proton beams enter shared pipe.

is still 1 mrad. This requires a change to the LSS geometry and optics solution which is not included in the CDR, but has been implemented in the most recent design, presented elsewhere in these proceedings [1, 4]. This has not introduced any additional issues to the design of the LSS, and in fact the increased crossing angle with respect to the nominal LHC LSS aids horizontal separation. Note also that the electron IR itself is unchanged in both the HL and HA designs, so synchrotron radiation calculations and detector designs do not require updates.

SOLUTION

For unsqueezed optics, zero triplet strength is required for the NC beam. The triplet quadrupoles each have a single proton aperture and as such the proton beams cannot be focused differently if both pass through the main aperture. Therefore the NC beam is guided through the same aperture as the electron beam, and experiences effectively no focusing. The proton LSS matching quadrupoles, which are separately powered for each beam, are then used to implement the NC beam optics.

Q1 will be a half-quadrupole, shown in Figure 3 [3]. A large field-free aperture accomodates the electron beam and the NC proton beam. Q2 and Q3 have standard designs which incorporate low-field pockets. These holes will be used for the shared electron and NC proton apertures. Note that the current LHC Q2 is in fact composed of two separate identical magnets, referred to here as Q2A (nearer to the IP) and Q2B (further from the IP).

Aperture calculations are based on 15σ proton envelopes and 20σ electron envelopes. In both IRs, aperture is driven by horizontal requirements, since the horizontal envelopes and horizontal separation dominate over the vertical electron envelope. Q2 and Q3 electron apertures are circular; aperture radius is thus determined by the larger dimension.

The crossing angle is tailored such that the NC beam trajectory is similar to that of the electron beam, with the

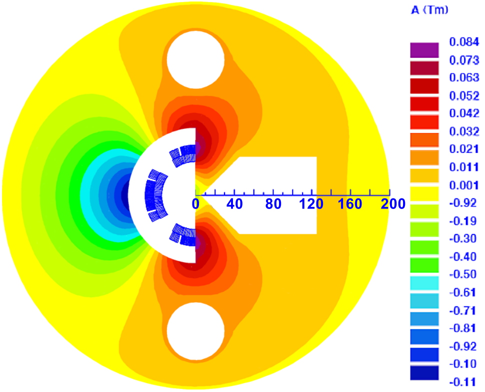

Figure 3: Design of proton Q1 half-quadrupole [3]. Note the arrow-shaped aperture on the right through which the electron and NC proton beams will pass.

electron and proton bunches interleaved due to the proton bunch offset. The proton-proton crossing angle differs in the HL and HA solutions since the separation schemes in the two IRs are dissimilar, resulting in different electron trajectories. The solutions below are thus presented separately for the HL and HA IR designs.

High Luminosity

The proton-proton crossing angle is optimised to 3 mrad to minimise aperture requirements, by making the NC beam follow the electron beam closely. The electron trajectory is determined by the IR separation scheme. It is impossible to have the proton beam exactly follow the electron beam due to the offset between the two generated by the separation scheme. The electron beam, having larger emittance, dominates aperture requirements. Figure 4 shows the beam trajectories and envelopes, with the positions of the proton quadrupoles and required aperture. Table 1 quantifies the aperture requirements.

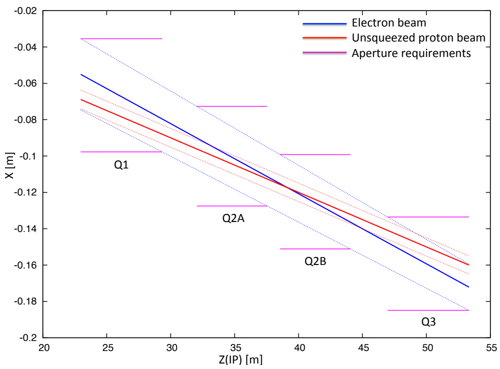

Figure 4: Proton triplet aperture requirements with trajectories and envelopes of the electron beam and NC proton beam for the HL layout.

There is a small amount of freedom in choosing the proton-proton crossing angle here since the aperture requirements are clearly dominated by the electron envelope.

Table 1: Proton Triplet Aperture Requirements for the HL Layout. Aperture centre is relative to centre of yoke and main proton aperture.

Element	Aperture Radius	Aperture Centre
Q1	0.0311 m	-0.0666 m
Q2A	0.0274 m	-0.1001 m
Q2B	0.0259 m	-0.1251 m
Q3	0.0257 m	-0.1592 m

A value near the centre of this range is chosen for flexibility and allows more space for transverse proton bunch tails.

High Acceptance

The proton-proton crossing angle is optimised to 3.4 mrad to minimise aperture requirements, by making the NC beam follow the electron beam closely. The electron trajectory is determined by the IR separation scheme. The electron beam, having larger emittance, dominates aperture requirements. The separation between the electron beam and the NC proton beam is larger in the HA layout than in the HL layout, due to the later bending in the HA separation scheme. This increases aperture requirements. Table 2 and Figure 5 show the required apertures.

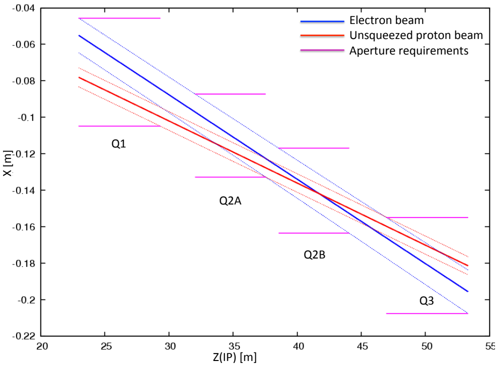

Figure 5: Proton triplet aperture requirements with trajectories and envelopes of the electron beam and NC proton beam for the HA layout.

Table 2: Proton Triplet Aperture Requirements for the HA Layout. Aperture centre is relative to centre of yoke and main proton aperture.

Element	Aperture Radius	Aperture Centre
Q1	0.0296 m	-0.0752 m
Q2A	0.0227 m	-0.1100 m
Q2B	0.0233 m	-0.1402 m
Q3	0.0264 m	-0.1811 m

Decreasing crossing angle is of no benefit since the Q1 aperture is somewhat fixed by the half-quadrupole design, and is already far in excess of the requirement shown here. Q3 aperture would also be detrimentally increased; the Q3 aperture is already far from the centre of the yoke, and increasing aperture radius increases yoke radius. Increasing crossing angle is also of no benefit, since it does not decrease Q3 aperture requirements, and increases others.

SUMMARY

In this paper, a solution has been presented to permit the second LHC proton beam to pass through the LHeC IR with minimal disruption to either the LHC or LHeC. The second proton beam occupies the same beam pipe as the electron beam in the proton IR, bored through the proton IR quadrupoles, and is offset in time to allow interleaved proton and electron bunches. This solution appears feasible and no issues are foreseen for future development.

Aperture requirements for the HL layout are somewhat less demanding than for the HA layout, but neither set presents difficulties in magnet design using existing technology. Larger apertures, and apertures further from the centre, may require larger yokes. Currently LHC magnets all have yokes less than 270mm in radius, and manufacturing processes used at CERN are limited to creating yokes of this size. To maximise feasibility of the LHeC magnet requirements cannot exceed this constraint without significant justification. The planned Q1 half-quadrupole design does not require modification. To simplify manufacturing and adhere as closely as possible to LHC standards, Q2A and Q2B would ideally be two copies of the same yoke. This requires a significantly larger hole which would consequently require a larger yoke than the existing 200 mm radius design. Q2B is likely to require a larger yoke in either case. Q3 also requires a larger yoke, but in all cases the tooling limit of 270 mm should be sufficient.

In both designs, the crossing angle may be increased if desired for beam-beam reasons. The existing Q1 design supports a crossing angle up to 4 mrad, but this would require significantly larger apertures in the other magnets. It is not foreseen that larger crossing angles will be required however, and those stated here appear optimal.

REFERENCES

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[2] A. Verdier, Alignment optics for LHC, LHC Project Note 325 (2003).

[3] LHeC Study Group. A Large Hadron Electron Collider at CERN. In progress, 2012.

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