INTEGRATION WITH THE LHC OF ELECTRON INTERACTION REGION OPTICS FOR A RING-RING LHeC

L. Thompson*, R.B. Appleby†, The University of Manchester, Cockcroft Institute, UK
H. Burkhardt, B.J. Holzer, CERN, Geneva, Switzerland
M. Fitterer, CERN, Geneva, Switzerland and KIT, Karlsruhe, Germany
M. Klein, CERN, Geneva, Switzerland and The University of Liverpool, UK
P. Kostka, DESY, Zeuthen, Germany
N.R. Bernard, ETH, Zurich, Switzerland

Abstract

The Large Hadron Electron Collider (LHeC) project is a proposal to study e-p and e-A interactions at the LHC. One design uses an electron synchrotron to collide a 60 GeV $e^{\pm}$ beam with the 7 TeV proton beam. Designing a new accelerator around the existing LHC machine poses unique challenges, particularly in the interaction region (IR). The electron beam must be quickly separated from the proton beam after the interaction point (IP) to avoid beam-beam effects, while not significantly reducing luminosity or producing large amounts of synchrotron radiation. The proton beam must pass through the electron optics, while the electron beam must avoid the proton optics. The long straight section requires bending in both planes to counteract the IP crossing angle and to displace the beam vertically from the electron machine to the proton IP. An achromatic bending scheme is used in the vertical plane to eliminate dispersion at the IP and provide an optics which is well matched to the LHeC ring lattice. The interaction region and long straight section design is presented and detailed, and the design process and principles discussed.

INTERACTION REGION

To satisfy the luminosity and detector coverage/machine acceptance constraints of the LHeC, two electron interaction region (IR) designs have been studied. A high luminosity (HL) option, uses final focusing elements embedded in the detector to minimise l^*. A high acceptance (HA) design uses focusing quadrupoles placed outside the detector. This gives greater detector coverage, for low Q and x^2 physics. Both must deliver luminosity around 10^{33} cm^{-2}s^{-1}, separate the electron and proton beams efficiently to avoid parasitic beam-beam interactions, and minimise synchrotron radiation emission. The interaction regions are those presented in the LHeC CDR [1] and are included here primarily as context for the long straight section (LSS) design. Table 1 presents the key parameters of the two designs, and Figure 1 shows an example of the electron orbit in the HA IR, relative to the proton beam orbit. For further information see the CDR when published, or papers from previous IPAC proceedings [2] [3].

* luke.thompson@hep.manchester.ac.uk
† robert.appleby@manchester.ac.uk

Table 1: Interaction Region Parameters for the High Luminosity and High Acceptance Layouts

Parameter	HL IR	HA IR
$L(0)$ [cm^{-2}s^{-1}]	1.8×10^{33}	8.5×10^{32}
θ_{IP} [radians]	1×10^{-3}	1×10^{-3}
$L(\theta)$ [cm^{-2}s^{-1}]	1.34×10^{33}	7.3×10^{32}
$l*$ [m]	1.2	6.2
β_x^* [m]	1.8	4.0
β_y^* [m]	1.0	2.0
σ_x^* [m]	3.0×10^{-5}	4.5×10^{-5}
σ_y^* [m]	1.6×10^{-5}	2.2×10^{-5}

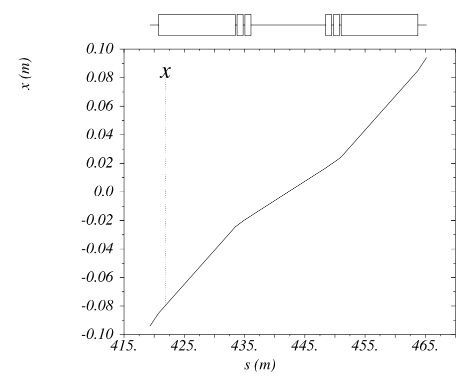

Figure 1: Electron beam orbit in the High Acceptance IR, designed for beam separation. Separation is generated by a crossing angle, dipoles, and offset final quadrupoles.

LONG STRAIGHT SECTION

The LSS geometrically and optically matches the IR to the rest of the LHeC ring lattice. For the purposes of this paper, the LSS is defined from the start of the left dispersion suppressor (DS) to the end of the right DS, a total length of ∼880 m. This is due to the need to alter the DS's optically and geometrically from the nominal design.

The LSS geometry uses a complex bending scheme in the horizontal and vertical planes to transport the beam around the LHC and satisfy the various constraints. Included amongst these is a 0.6 m radial shift between the LHeC ring and the LHC IP. The LHeC has a radius which, on average, is 0.6 m less than that of the LHC [1]. The LHeC lattice design includes bypasses which transport the beam around IP1 and IP5, to avoid interference with AT-

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LAS and CMS. To compensate for the path length difference generated by these long bypasses, the radius of the ring is decreased. As such the LSS must transport the beam 0.6 m horizontally to the IP, and then back again to the ring. The IR separation scheme must fit into the design orbit. Furthermore the LHeC is displaced ∼1 m vertically above the LHC, which must also be accounted for. The resulting complex scheme has a small path length difference which must be compensated elsewhere in the ring, nominally in the bypasses. Due to the large amount of bending required, synchrotron radiation (SR) generation is also a constraint. SR studies for this solution are presented in these proceedings in [4]. The LSS design has been iterated multiple times, each time refining the design and better respecting various constraints. The LSS presented here is an update of that in the LHeC CDR. The solution presented here is for the HA IR layout. Adapting a solution for the HL layout presents no additional challenges.

DISPERSION

A key constraint coupled to optics and geometry is dispersion. Since dispersion is an optical quantity generated by bends which define the orbit, this is challenging for the LHeC LSS. The DSs are designed to match horizontal dispersion from the LSS to the arc but there is no equivalent scheme in the lattice to deal with large vertical dispersion. Therefore an achromatic vertical separation scheme is used, utilising a double bend achromat (DBA) design [3]. Two vertical DBA sections on either side of the IR form doglegs while generating no vertical dispersion. This complicates optical matching due to limited optical flexibility of the DBA scheme. Figure 2 details the geometry of the DBA sections used in the LSS. The beam trajectory smoothly achieves vertical separation in an s-shape with space between the two modules for separation to increase, and for placement of matching quadrupoles. Only the quadrupole triplets between the dipoles are part of the DBAs; other quadrupoles are used for matching. Figure 3 shows the optics solution for one of the DBAs. DBAs use two identical dipoles with quadrupoles at the midpoint, which create a turning point in the dispersion function and cause the second bend to cancel dispersion.

GEOMETRY

Figure 4 shows the geometry of the LSS solution. Figure 5 breaks down the components of the right side of the LSS. In this design the vertical doglegs are placed between the two horizontal dipole sets. The left DS dipoles have nominal bend strength, while the right DS dipoles are weakened to accommodate the 1.2 m horizontal separation. An extra dipole is used before the right DS, to compensate the resulting difference in angle at the entrance to the arc.

Compared to the LSS in the LHeC CDR, this iteration includes modifications made to accommodate the second, non-colliding (NC) proton beam, as presented elsewhere

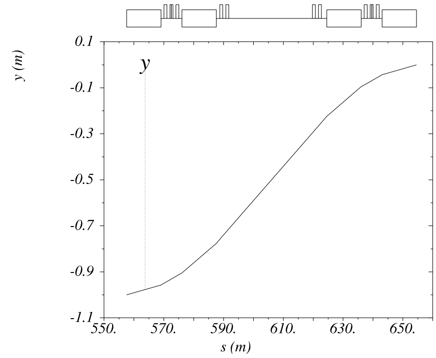

Figure 2: Orbit plot for a DBA dogleg pair in the HA LSS design. The first DBA achromatically bends the beam upwards, while the second reverses this deflection. The scheme displaces the beam vertically without changing angle or vertical dispersion.

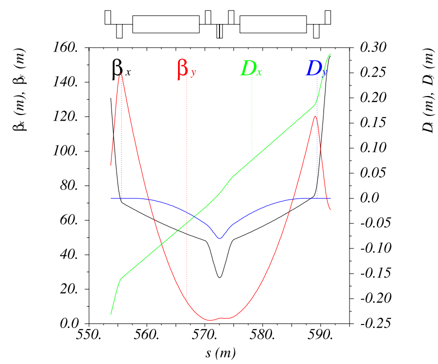

Figure 3: β and dispersion functions in both transverse planes for a single DBA module in the HA LSS design. The cancellation of vertical dispersion, in blue, is clear.

in these proceedings [5]. The NC beam solution is in fact beneficial to the LSS design, generating horizontal separation faster due to the increased proton-proton crossing angle. This allows this LSS design to start vertical separation later compared to previous designs. A primary goal of the

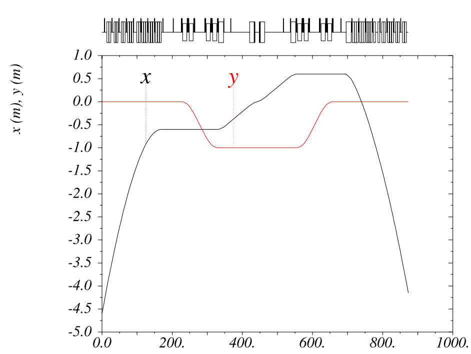

Figure 4: Geometry of the LSS design. For these small angles, the s axis approximates the z axis well, and is used to allow MADX to display lattice elements.

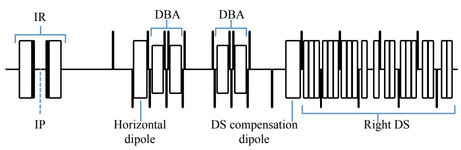

Figure 5: Components of the right side of the LSS. The DS compensation dipole, not used on left side, corrects angle from the weakened DS dipoles.

LSS is to remove the electron beam from the LHC machine as soon as possible. In previous iterations the design could not rely on horizontal separation alone to accomplish this as it was too gradual. Thus, vertical separation had to be started early, and this caused space conflicts with LHC elements. In this design, vertical separation is performed after the beam reaches 0.6 m horizontal separation; since this horizontal angle is generated entirely within the IR, and electron matching quadrupoles do not start until well outside the proton final triplet, space conflicts are avoidable.

OPTICS

Placement of quadrupole elements is constrained by LSS geometry requirements, and by LHC element placement. While the LSS horizontal dipoles alone do not significantly constrain space, the vertical DBAs are long and cannot be interrupted with extra quadrupoles since quadrupoles are used to satisfy the achromatic condition.

Quadrupole triplets are used in the centre of the DBAs to allow some matching flexibility. A single quadrupole would have a fixed strength to cancel dispersion. This does not allow any flexibility for matching, and the quadrupole strength tends to be high. As such this is unsuited to this design. The triplet DBA still requires relatively high strength quadrupole fields, and generates a characteristic beta function shape, resulting in peaks and waists which make matching more challenging. Figures 6 and 7 show the beta and dispersion functions of the LSS optics. Experience with previous iterations of the LSS has aided the design of this optics solution, and this version presents greater flexibility and a smoother, albeit complex match.

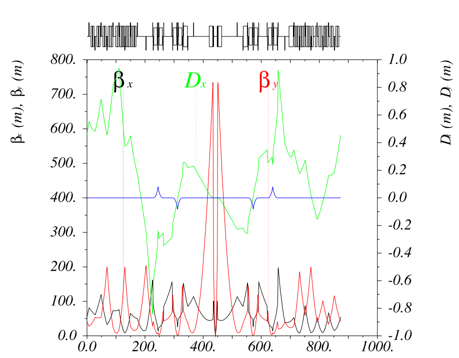

Figure 6: Optics plot for the HA LSS design.

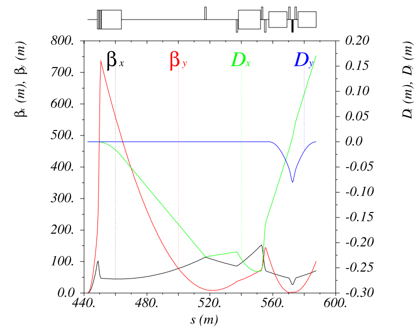

Figure 7: Zoomed optics plot for the HA LSS design.

The DS quadrupoles are rematched from nominal strengths, where dispersion is zero between the DS's, but the elements are not moved. The vertical separation solution is long and adds many constraints to the optical match while also creating peaks, and there is insufficient freedom to match all parameters without using the DSs.

Between the DS's the LSS is roughly symmetric in β and antisymmetric in D. The DS's, themselves slightly asymmetric due to LHC constraints, are matched asymmetrically as the dispersion function must be positive both exiting and entering the arcs. The DS compensator dipole does not significantly complicate dispersion matching.

SUMMARY

In this paper the latest designs and solutions of the electron IR and LSS for a ring-ring LHeC have been presented and discussed. This iteration of the LSS incorporates the non-colliding second proton beam solution presented elsewhere [5], and is also the first design to show that integration with the LHC LSS and IR is indeed feasible, though not without challenges. Optical matching is also more flexible. Further work will be necessary to ensure compatibility and technical feasibility into the engineering stage, but these designs are sufficient to show that this region of the LHeC electron ring design faces no significant issues.

REFERENCES

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

[2] R.B. Appleby *et al*, Interaction Region Design for a Ring Ring Version of the LHeC Study. IPAC'10 Proceedings, 2010.

[3] L. Thompson *et al*, Interaction Region Design for a Ring-Ring LHeC. IPAC'11 Proceedings, 2011.

[4] L. Thompson *et al*, Synchrotron Radiation Studies for a Ring-Ring LHeC Interaction Region and Long Straight Section. IPAC'12 Proceedings, 2012.

[5] L. Thompson *et al*, Interaction Region Optics for the Non-Interacting LHC Proton Beam at the LHeC. IPAC'12 Proceedings, 2012.