INTERACTION REGION DESIGN FOR A RING-RING 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. Using one of the LHC's proton beams, an electron beam of relatively low energy and moderately high intensity provides high luminosity TeV-scale e-p collisions at one of the LHC interaction points, running simultaneously with existing experiments. Two designs are studied; an electron ring situated in the LHC tunnel, and an electron linac. The focus of this paper is on the ring design. Designing an e-p machine presents interesting accelerator physics and design challenges, particularly when considering the interaction region. These include coupled optics, beam separation and unconventional mini-β focusing schemes. Designs are constrained by an array of interdependent factors, including beam-beam interaction, detector dimensions and acceptance, luminosity and synchrotron radiation. Methods of addressing these complex issues are discussed. The current designs for the LHeC Ring-Ring interaction region and long straight section are presented and discussed, in the context of the project goals and design challenges encountered. Future developments and work are also discussed.

DESIGN CONSTRAINTS

The LHeC aims to provide a luminosity on the order of 10^{33} cm^{-2}s^{-1}. Two different ring-ring IR schemes are considered [1]. Firstly, a high luminosity (HL) option with mini-β quadrupoles embedded inside the detector. This restricts detector coverage with a machine acceptance of 10°, so a second, high acceptance (HA) scheme proposes a lower luminosity IR with all electron optics outside the detector. Luminosity is also affected by a horizontal IP crossing angle used to minimise parasitic interactions [2].

In both cases, a feasible design for the LHeC IR requires a well-matched LSS scheme which transports the beam from the ring to the IR. Geometric constraints must be satisfied simultaneously with dispersion and twiss matching. The geometric constraints are many and non-trivial. The IR design incorporates a dipole scheme to maximise beam separation at parasitic crossings while minimising the IP horizontal crossing angle [2], and the deflection produced by this must be corrected in the LSS to re-align with the electron ring. The electron ring is positioned above the proton ring by $\sim$1 m [1], so the beam must be displaced vertically to arrive at the IP. To minimise modification of LHC optics, electron element positions are also constrained to drift spaces.

Schemes using strong vertical bending to deflect the electron beam before the proton optics are infeasible as strong bends produce extremely high SR power from the 60 GeV beam. To satisfy the constraints and reduce SR power, schemes are considered where electron elements are interleaved with proton elements, using drift spaces in the proton optics.

While providing sufficient bending in both planes, the LSS must also minimise dispersion at the IP. Optimising this in both planes is a unique challenge for a high energy, high luminosity machine. The dispersion suppressor (DS) integrated into the ring lattice, at either end of the LSS, is designed to suppress horizontal dispersion [3]. The baseline DS parameters eliminate dispersion at the start of the LSS. To design a dispersion-free horizontal deflection scheme in the LSS would be inefficient, compared to rematching the DS to match the dispersion generated in the LSS into the ring parameters. However the DS will not easily match vertical dispersion, and so a different solution is required. Dispersion in the vertical plane must be minimised within the LSS. These criteria must be satisfied alongside the geometric constraints imposed by the LHC optics. It is advantageous to remove some constraints and iteratively design schemes until all criteria are met.

IR DESIGNS

The HL option currently uses a final triplet design, while the HA scheme uses a doublet, as shown in Figure 1. The parameters for the two schemes are given in Table 1.

Table 1: Parameters for the HL and HA IP Designs

Parameter	HL	HA
$L(0)$	1.8×10^{33}	8.54×10^{32}
θ	1×10^{-3}	1×10^{-3}
$S(\theta)$	0.746	0.858
$L(\theta)$	1.34×10^{33}	7.33×10^{32}
β_x*	0.18 m	0.4 m
β_y*	0.1 m	0.2 m
σ_x*	3.00×10^{-5} m	4.47×10^{-5} m
σ_y*	1.58×10^{-5} m	2.24×10^{-5} m

The triplet is currently used in the HL scheme for various

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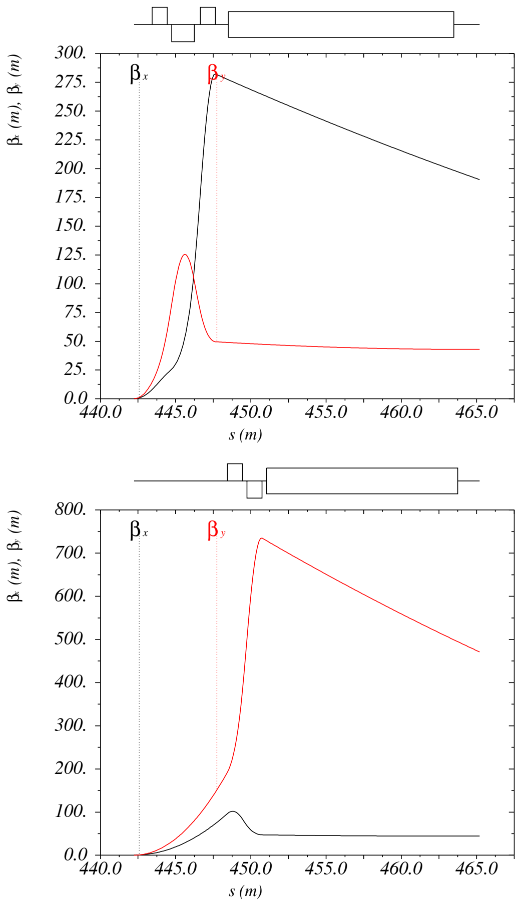

Figure 1: IR layout for the HL (top) and HA (bottom) options. Note that the IP is located at $S = 442.24$ m.

reasons including controlling peak β functions. Given the more relaxed conditions for the HA option and the slightly flatter beam profile, a doublet was chosen. A final doublet design may be favourable for the HL option as well, possibly allowing lower chromaticity, and this will be studied. Synchrotron radiation characteristics of the interaction region designs are presented in [4].

LSS DESIGN SCHEMES

Current DBA Design

A preliminary design is in progress, currently for the HA option, using a double bend achromat (DBA) scheme. This involves an overall s-shaped dogleg, using two DBA sections, to displace the beam vertically by 1 m. This eliminates vertical dispersion outside the DBA sections. Horizontal dispersion is handled using the matching quadrupoles and the existing DS.

In the thin lens and small angle approximations, an analytical achromat condition can be derived for the DBA scheme by requiring that $D' = 0$ at the centre of the section. With a single quadrupole in the centre this reduces to a fixed strength, given in Equation 1 [5].

$$f = \frac{1}{2}\left(L_1 + \frac{L}{2}\right) \qquad (1)$$

L_1 is the distance between the end of the dipole and the centre of the quadrupole, L is the length of the dipole and f is the focal length of the quadrupole.

This has the disadvantages of requiring a high strength and not allowing any flexibility for twiss matching, rendering this scheme infeasible[1]. In the case of three central quadrupoles, a dependency between the strengths can be derived such that a range of strengths will result in achromaticity. This provides flexibility to alter strengths to aid twiss matching. This analytical relationship is used as the starting point for an optical matching loop which changes the strengths independently to account for the error introduced by the thin lens and small angle approximations. Required strengths are also lower, but the central quadrupoles are in the region of 25 Tm^{-1}. The optical solution is matched from IP to DS in sections. The current geometry of the solution is shown in Figure 2 and a DBA section is detailed in Figure 3.

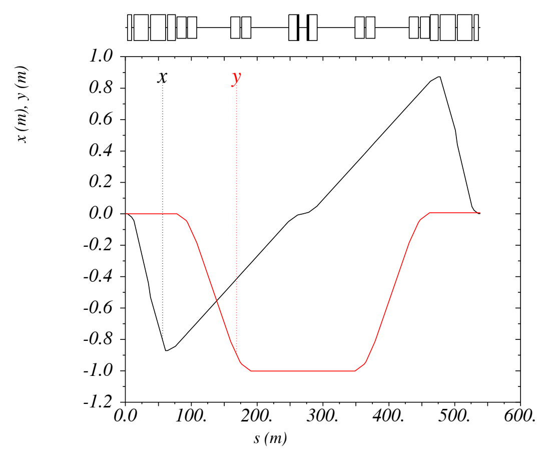

Figure 2: Current LSS geometry. The smaller elements in the beam line shown are the vertical DBA sections.

The DBA sections are consistent with the available space between LHC elements. However it is difficult to immediately obtain a satisfactory optical match with quadrupole positions constrained to available space. The preliminary solution is being studied with more freedom in quadrupole placement, with the intention of iterating until an optimal solution is found for all constraints. Elements after the second vertical DBA section are not constrained by LHC elements as the electron beam is now out of the proton machine entirely. Additionally, a symmetric layout in the electron LSS as used in Figure 2 are preferable for various reasons. This can potentially make the LSS sub-optimal on either side since available space in the LHC lattice is

[1] Additionally, a single quadrupole DBA cell is unstable since the phase advance is greater than π; however in this context it is used as part of an insertion with other matching quadrupoles so this is not an issue.

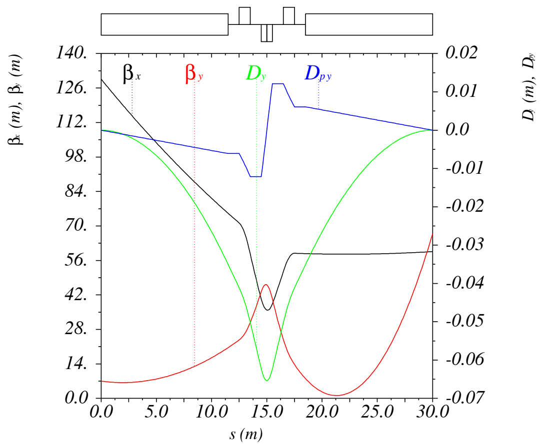

Figure 3: Triplet DBA module example.

asymmetric. While each side is less optimal than it could be, symmetric optics simplify horizontal dispersion matching, twiss matching and power supply. Some asymmetry is inevitable however due to the asymmetric DS scheme.

Achromatic FODO

A variety of other solutions are being studied. A second-order FODO achromat scheme as proposed by Sun [6] can simplify matching due to the large number of quadrupole elements, reducing distance between focusing. However such a scheme is bulky for the same reason, and is unlikely to fit into the LHC lattice. Furthermore, gradient could be used in dipoles in the other schemes to regain some of the benefits of the FODO achromat.

Triple Bend Achromat

A triple bend achromat (TBA) allows weaker quadrupoles, but again in requiring more elements makes available space an issue. Given this it is likely impractical to use the triplet quadrupole scheme as in the DBA, reducing matching flexibility. The principal use of TBA lattices is for their lower natural emittance, which is not relevant in this context. As such, it is unlikely that the TBA scheme will offer any advantages over the DBA one.

Quadruple Bend Achromat

A more useful concept is a quadruple bend achromat (QBA) scheme where the entire vertical s-bend scheme is a single achromatic module. Rather than eliminate dispersion entirely within the first bend-quadrupole-bend structure, and then again independently in the second, weaker quadrupoles would be used to merely control the growth of the dispersion. Quadrupoles between the two sets of bends would be used for twiss matching while satisfying the achromat condition that $D' = 0$ at the centre. In this sense this structure could be more efficient, only matching the dispersion constraint once rather than twice independently. It also allows weaker quadrupoles since dispersion is handled over a larger distance. Flexibility could be reduced compared to the DBA scheme however as the central matching quadrupoles are no longer independent of the dispersion match, and both DBA-like subsections must be the same. Furthermore this could hinder matching of the horizontal dispersion. Space issues are also a potential concern as a QBA has more element position restrictions than two independent DBAs, since the entire bend structure must be symmetrical. The most obvious type of QBA would involve a central quadrupole, and in this case there is no immediately available space for this in the LHC layout. However this may be soluble; a small quadrupole may be able to fit above the LHC at this point, as the electron beam is already displaced vertically by 0.5 m. Other solutions could do without a central quadrupole, instead having two quadrupoles at an arbitrary symmetric distance from the centre. This may more easily fit in the available space.

Achromatic Telescopic Squeezing

Independently of the above schemes, and applicable to any or all of them, is the achromatic telescopic squeezing concept developed for the LHC by Fartoukh [7]. LSS and IR quadrupoles are matched to an IP β^* of intermediate size, then quadrupole strengths in neighbouring LSS regions are varied to squeeze this further while keeping the IP optics constant. This experimental technique may be well suited to the LHeC as there are fewer constraints on the remainder of the ring compared to the LHC. For example, the other LHeC IRs are not used for mini-β insertions so their phase advances are not strongly constrained.

CONCLUSIONS

A preliminary LSS/IR design is in progress, the status of which has been presented here. Other schemes are being studied to find an optimal solution satisfying all constraints.

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