SYNCHROTRON RADIATION STUDIES FOR A RING-RING LHeC INTERACTION REGION AND LONG STRAIGHT SECTION

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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. In the design for an electron synchrotron (alternative designs for a linac are also under development), a 60GeV e beam is collided with a 7TeV LHC proton beam to produce TeV-scale collisions. Despite being much lower energy than the proton beam, the electron beam is high enough energy to produce significant amounts of synchrotron radiation (SR). This places strong constraints on beam optics and bending. In particular challenges arise with the complex geometry required by the long straight section (LSS) and interaction region (IR). This includes the coupled nature of the proton and electron optics, as SR produced by the electron beam must not be allowed to quench the superconducting proton magnets or create problems with beam-gas backgrounds. Despite this, the electron beam must be deflected significantly within the IR to produce sufficient separation from the proton beam.

INTRODUCTION

Synchrotron radiation (SR) emission is a key constraint in the design of an electron storage ring. Much energy is lost to SR, and in the LHeC this takes up roughly half of the total 100 MW wall power requirement. This figure increases when considering the interaction region (IR) and long straight section (LSS) at LHC interaction point (IP) 2. In this region, significant amounts of strong bending and focusing are required for high luminosity e-p collisions. Both proton beams pass through the electron IR elements, but effects including proton SR are relatively small due to higher rigidity and proton mass. The electron IR is bounded by the final proton triplet, which begins at 22.96 m from the IP. High levels of SR result in, amongst other effects, background processes, damage to components and quenching of superconducting magnets.

The LSS transports the beam from the IR to the ring, and must not conflict with LHC elements. The beam is separated horizontally, and vertically by 1 m since the ring sits above the LHC machine. The factors in IR and LSS design relating to SR emission are beam separation, focusing, and LSS geometry. The electron beam must be separated from the proton beam quickly to avoid significant beam-beam effects. Due to the 25 ns bunch spacing, parasitic nodes occur every 3.75 m. $5\sigma_e$+$5\sigma_p$ separation between the beam centroids is required at each parasitic interaction. Since the electron beam in particular expands quickly after the IP, this is challenging. The beam separation requirement is further strengthened by the need to achieve at least 55 mm horizontal separation between the electron and proton beam at the face of the proton triplet. This is to allow the use of a "half-quadrupole" for the proton Q1, with a quasi-field free electron aperture; without this the strong proton fields would cause the electron beam to be lost. These factors are discussed elsewhere in these proceedings [1, 2].

Two IR designs are studied for the Conceptual Design Report (CDR). A high luminosity (HL) layout uses final focusing quadrupoles embedded in the detector to give an l^* of 1.2 m. A high acceptance (HA) layout places the final quadrupoles outside the detector, giving an l^* of 6.2 m. This gives greater detector coverage, allowing the study of low x and Q^2 physics but at a somewhat lower luminosity. Both IR designs must achieve a luminosity of $\sim 10^{33}$ cm^{-2}s^{-1}. These designs are discussed in the LHeC CDR [3] and elsewhere [4].

In both designs, the final quadrupoles are offset to induce a dipole field and thus begin bending as early as possible. In the HL design dipole bending thus occurs at 1.2 m from the IP, prior to the first parasitic node. Bending continues at constant radius for most of the length of the electron IR, maximising use of space. However in the HA design bending can only begin at 6.2 m from the IP, and less length overall is available for bending in the IR. A crossing angle, with the side-effect of reducing luminosity, is required for sufficient separation at 3.75 m. The minimum angle is $\sim$0.7 mrad. The HL design does not strictly require a crossing angle, but using only bending generates excessive SR. In both layouts, a crossing angle of 1 mrad is chosen to balance bending and luminosity loss.

SR emission in both electron IRs has been studied in detail [5] using analytic methods, Geant4 simulation and IRSYN, a simple monte carlo based code written by R. Appleby [6]. Table 1 details the key results. While the HA IR produces more SR power, fan distribution is better with significantly less SR power escaping down the proton aperture in the superconducting half quadrupole.

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Table 1: SR Power for the HL and HA IRs

IR	Geant4 [kW]	IRSYN [kW]	Analytic [kW]
HL	33.2	33.7	33.8
HA	51.1	51.3	51.0

METHODS

Multiple methods are used to study SR generation in the LSS. Analytic results are easily obtained for SR power emitted from dipoles using well-known formulae. Analytic estimates of quadrupole SR emission are also possible using a model developed by N. Bernard [7]. Each infinitesimal volume of the quadrupole aperture, dV, is treated as a dipole, whose field depends on radial position. Integrating over the volume with a gaussian beam profile determined by β allows the dipole SR power formula to be adapted for use in a quadrupole, giving total SR power as

$$P[\mathrm{kW}] = P_0 I_0 g \left[\epsilon_x \int_0^L \beta(z)_x dz + \epsilon_y \int_0^L \beta(z)_y dz \right] \tag{1}$$

where

$$P_0 = 1.26 \times \frac{E^4}{E^2 - (mc^2)^2} \tag{2}$$

with energies and mass in GeV. I_0 [A] is the beam current, g [T/m] is the quadrupole gradient and L [m] is the quadrupole length. To use this model, a polynomial is fitted to the beta function within a quadrupole and used in the integral. While this method is quick to run, setting it up for each layout is currently extremely time-consuming and so it has only been used for the current LSS layout.

IRSYN is being developed to facilitate study of the LSS designs. As seen above it shows good agreement with Geant4 in the IR. In the LSS, the analytic methods are used to cross-check. IRSYN is currently only reliable when simulating certain sections of the lattice, and results are presented from the IP to the beginning of the right arc.

LSS DESIGN

Multiple iterations of the LSS design have been created [8, 1]. All use double bend achromat (DBA) vertical bending schemes as vertical dispersion is difficult to match to the ring, which is discussed in these proceedings [1]. All designs are currently matched to the HA IR design, but matching to the HL IR presents no additional challenges. Earlier designs used interleaved horizontal and vertical bends to divert the electron beam out and above the LHC in both planes at once to efficiently use space. This introduces rotation of the beam around the s axis, or roll, effectively giving all following quadrupoles a skew component which is not easily corrected. This "coupled" (CPL) design is shown in Figure 1. Later designs have avoided this at the expense of tighter space constraints. The "Early Vertical Separation" (EVS) design, shown in Figure 2, began vertical bending shortly after the IR to remove the electron beam from the LHC quickly. This proved infeasible as the first vertical DBA conflicted with proton elements. The current "Late Vertical Separation" (LVS) design, shown in Figure 3, allows horizontal separation from the IR to propagate before separating vertically. The LVS design also incorporates the solution for the non-colliding proton beam presented in these proceedings [2], which beneficially increases horizontal separation. However overall space constraints are tighter and the LVS design emits more SR than the EVS design, which emits more than the CPL design.

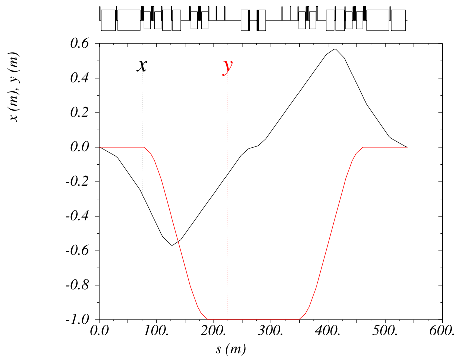

Figure 1: Geometry of the CPL LSS design.

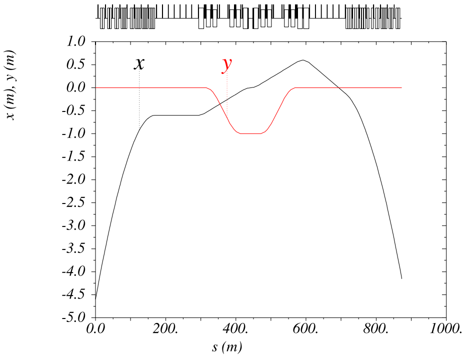

Figure 2: Geometry of the EVS LSS design.

RESULTS

In general, IRSYN's tracking shows reasonable agreement with the β function output of the MADX Twiss module as seen in Figure 4. Similar agreement is seen with the EVS and CPL layouts.

Table 2 shows results of calculations of SR power for the right hand side (RHS) of the LVS LSS design. Not all permutations are presented due to current limitations in IRSYN. Table 3 shows results for all three LSS designs using IRSYN and the analytic dipole method. This includes an estimate of the total SR power emission for each using the analytic dipole method only.

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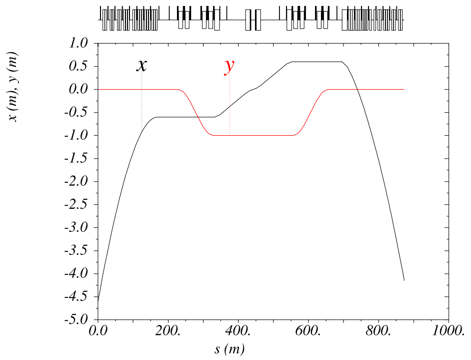

Figure 3: Geometry of the current LVS LSS design.

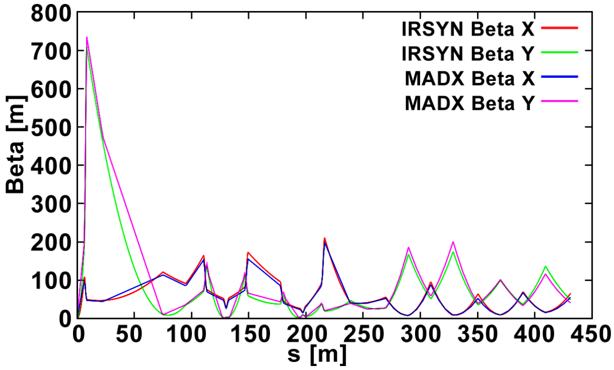

Figure 4: β comparison for LVS design in IRSYN vs. MADX.

Table 2: SR Power for the LVS RHS for Various Methods

LVS RHS	Power [MW]
IRSYN Total	0.814
IRSYN Dipoles	0.794
Analytic Total	0.820
Analytic Dipoles	0.803
Analytic Quadrupoles	0.017

Table 3: SR Power for all Three Layouts, for RHS and Entire LSS

	IRSYN RHS Total [MW]	Analytic RHS Dipoles [MW]	Analytic LSS Dipoles [MW]
LVS	0.814	0.803	1.516
EVS	0.671	0.656	1.344
CPL	0.653	0.638	1.276

Good agreement is seen between the methods. The LVS design produces more power than the other two designs. This is largely due to the so-called compensator dipole used on the right hand side; this dipole, needed to match beam angle to the ring since the right dispersion suppressor (DS) dipoles are weakened to provide the 1.2 m offset [1], is short and strong, using a significantly higher B field than any other element in any of the designs. The compensator dipole alone, using the analytic method, produces 0.26 MW (c.f. 0.12 MW total power emitted by dipoles in the right DS). There is room to significantly increase the length of the compensator dipole. Note that the left side of the LVS design is much closer in power output to the other designs, albeit still slightly higher. The DBA modules also produce approximately 0.36 MW each. This is over a longer distance than the compensator dipole and is thus more easily absorbed. The DBAs may be weakened and the dogleg made longer to compensate, but this further restricts space between the DBAs and the right DS. Due to the strong quadrupoles used in the DBAs, optical matching is challenging, and matching to the arc cannot begin until vertical separation is achieved. Therefore, ending vertical separation later gives less optical flexibility. The overall SR power for each LSS design is reasonable compared to the 50 MW ring lattice SR power.

CONCLUSION

IR and LSS designs for a ring-ring LHeC have been studied using various methods. IRSYN, a simple monte carlo code, is under continued development and shows good agreement with Geant4 and analytic dipole methods. The current LSS design emits a total SR power of $\sim$1.52 MW, compared to $\sim$1.34 MW and $\sim$1.27 MW for previous designs. This does not represent a major increase and is within reasonable bounds compared to the $\sim$50 MW produced by the rest of the ring. The distribution of SR power requires further study and optimisation, but there appears to be sufficient flexibility to solve any outstanding issues.

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