INTERACTION-REGION DESIGN OPTIONS FOR A LINAC-RING LHEC

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Abstract

The interaction-region design for a linac-ring electron-proton collider based on the LHC ("LR-LHeC") [1, 2] poses numerous challenges related to collision scheme, synchrotron radiation, aperture, magnet technology, and optics. We report a first assessment and various options.

INTRODUCTION

We shall collide an electron (positron) beam of 60-GeV energy with the LHC 7-TeV proton beam [3]. At the interaction point (IP) the electron beam size is matched to the proton beam size, $\sigma_p^* = \sigma_e^*$. We assume the LHC design values for the proton rms normalized transverse emittance and bunch length. The proton IP beta function is taken to be $\beta_{x,y}^* = 0.1$ m [4, 5]. Table 1 lists other key parameters. The disruption angle θ_0. is a conservative upper bound for the largest deflection angle experienced during the collision [6]. Its numerical value for the electrons equals about 10 times the rms divergence of a non-colliding beam.

Table 1: IP beam parameters of protons and electrons.

	protons	electrons
energy [GeV]	7000	60
Lorentz factor γ	7460	117400
tr. norm. emittance $\gamma\epsilon_{x,y}$ [μm]	3.75	50
tr. geom. emittance $\epsilon_{x,y}$ [nm]	0.50	0.43
IP beta function $\beta_{x,y}^*$ [m]	0.10	0.12
rms IP beam size $\sigma_{x,y}^*$ [μm]	7	7
rms IP divergence $\sigma_{x,y}^{\prime *}$ [μrad]	70	58
disruption parameter D	2×10^{-6}	6.0
disruption angle θ_0 [μrad]	0.06	572
beam current [mA]	430–580	6.6

HOURGLASS AND CROSSING ANGLE

The rms electron (positron) bunch length of 300 μm is small compared with the proton bunch length of 7.5 cm. Approximating the longitudinal electron bunch distribution by a delta function, and assuming $\sigma^*\theta_c \ll \sigma_{z,p}$, the geometric luminosity loss factor $H_{\rm hg}$, describing the effect of the "hourglass" and of the finite (full) crossing angle θ_c, is

$$H_{\rm hg} = \sqrt{\pi} z e^{z^2} {\rm erfc}(z)/S, \quad \text{where} \tag{1}$$

$$z \equiv 2\frac{(\beta_e^*/\sigma_{z,p})(\epsilon_e/\epsilon_p)}{\sqrt{1+(\epsilon_e/\epsilon_p)^2}} S \quad \text{and} \quad S \equiv \sqrt{1+\frac{\sigma_{z,p}^2\theta_c^2}{8\sigma^{*\,2}}} \, .$$

The dependence of the geometric loss factor on the crossing angle is illustrated in Fig. 1, for the parameters of Table 1. The geometric loss factor of 0.91 for zero crossing angle ($\theta_c = 0$) arises due to the long proton bunch length and the small IP beta functions $\beta_{x,y}^*$. The factor $H_{\rm hg}$ decreases quickly for increasing θ_c values. A head-on collision is optimum, and any residual crossing angle should not exceed 150 μrad (about $2\sigma_{x,y}^{\prime *}$) where $H_{\rm hg} \approx 0.8$.

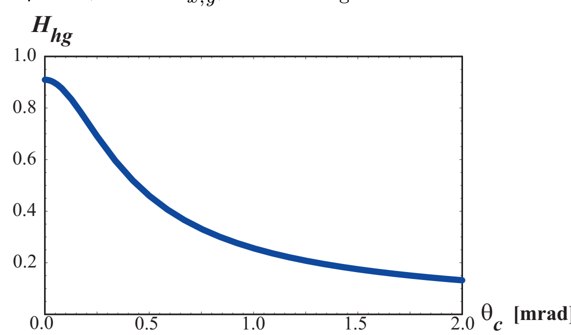

Figure 1: Geometric loss factor $H_{\rm hg}$ vs. crossing angle.

A collision with zero crossing angle can be realized either (1) by inserting dipoles between the proton final quadrupole triplets and the IP for aligning the two colliding beams, or (2) by tilting the proton bunches using crab cavities so as to yield an effective head-on collision while the bunch centroids intersect at a large angle.

CONCEPTUAL LAYOUT

The LHeC detector encompasses a 3.5 T solenoid extending ±6 m from the interaction point (IP) [7]. The free length, l^*, between the end of the last quadrupole and the IP is taken to be 10 m, so that the first proton quadrupole magnet on either side is located 4 m beyond the end of the detector. The most important region for the inner detector spans ±1.5 m on either side of the IP [7]. A detector acceptance down to 1° is desired.

For a first-quadrupole half aperture of 26 mm an electron-beam exit hole in the magnet iron yoke could start at 60 mm from the magnet center. With a smaller aperture the hole could be moved closer to the axis, and vice versa. A cooled beam screen may be required since the chamber inside this hole is likely to be hit by synchrotron radiation (SR). A dipole field inside the exit hole could help to deflect the e$^-$ beam further away from the rest of the triplet. The size of the hole should provide sufficient beam stay clear for both disrupted and non-colliding electron beams.

Head-on collisions can be provided by a dipole field that stretches from about 1.5 m to 9 m from the IP on either side, leaving 1 m free space between the end of the dipole and the entrance of the proton triplet (for shielding) and a 3-m gap around the IP (for the inner detector). In order for the 7.5-m long dipole to displace the 60-GeV electron beam at the quadrupole entrance by 80 mm from the proton beam axis, a dipole field of 0.45 T is required, implying significant SR. The IR configuration with separation dipoles and SR fan is illustrated in Fig. 2. From this figure it also is evident that the paths of both electron beam and SR will make it difficult to provide a full ϕ coverage and forward-backward symmetry of the detector acceptance down to $\theta = 1^\circ$. Figure 2 also indicates the computed minimum stay clear corresponding to beam envelopes of 10σ for the electrons and 11σ for the protons. with an additional constant radial margin of 10 mm for orbit errors, misalignments, optics errors etc.

For a proton-bunch spacing of 25 ns the first parasitic collision occurs at a distance s of 3.75 m from the IP. The 0.45-T dipole field produces a transverse separation of more than 50σ at this location.

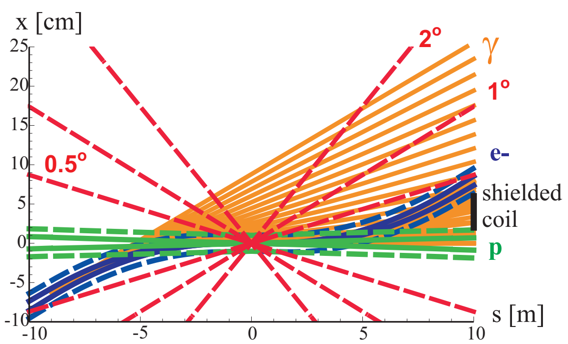

Figure 2: Beam envelopes of 10σ (electrons) [solid blue] or 11σ (protons) [solid green], the same envelopes with an additional constant margin of 10 mm [dashed], the synchrotron-radiation fan [orange], and the approximate location of the magnet coil between incoming protons and outgoing electron beam [black].

An alternative approach for realizing head-on collision is via crab cavities. It has the merit of avoiding any SR sources near the IP. Considering the same quadrupole geometry as above, a crossing angle of 8 mrad is required. This crossing angle is about 25 times larger than those for the regular LHC pp collisions and for the LHC high-luminosity upgrades (SLHC). It would require a crab cavity voltage above 100 MV at 400 MHz RF frequency [8], to be compared with typical crab-cavity voltages of 2–5 MV needed for various SLHC scenarios. Thus this paper focuses on the dipole-based collision scheme.

SYNCHROTRON RADIATION

SR power from both the downstream and upstream bend magnets is deposited on the face of the proton triplet. With a deflection angle of 34 mrad on either side of the IP, the number of photons emitted per bunch passage is 8×10^{10}. Their critical energy of 1.07 MeV approximately equals the threshold for pair creation. For 6.6-mA beam current the average SR power from the dipole magnets is 87 kW. More than one quarter of these photons, corresponding to about 26 kW of power, mainly from the downstream bend fan, will hit the shield protecting the magnet coil (Fig. 2), one eighth (11 kW) will enter the proton beam pipe inside the first quadrupole Q1, and more than half of the total (50 kW) will pass into the electron-beam exit channel. Figure 3 (left) illustrates the horizontal distribution of photons at the entrance face of the first proton quadrupole.

The peak SR power density at the absorber shield is about 1000 W/mm^2 (Fig. 3 right). The surface of the magnet-coil protection shield should be sloped to reduce the power density and to make it acceptable for ordinary materials like copper. An acceptable number is 10-20 W/mm^2, the higher value referring to GlidCop (a dispersion strengthened copper alloy). The SR absorbers have to be water cooled. They could further be tailored to minimize the scattering of photons into the proton triplet beam pipe. Another proposal is installing X-ray mirrors with extremely small grazing angle to deflect part of the SR away from the proton magnets [10]. The SR power entering the electron beam pipe strikes at a shallow angle so that the power density is not an issue.

The upstream bend magnet deposits significant SR power on any central beam pipe in the horizontal plane. One possible solution is to open up the inner-detector beam pipe and let the radiation strike a beam-pipe surface outside of the detector region [9]. The inner-detector beam pipe could be elliptical with horizontal and vertical half apertures of 6 cm (Fig. 2) and 2.5 cm, respectively, assuming an off-center collision point and that the pipe can hold the vacuum pressure. This option removes a potential source of background for the detector. However, if the beam pipe grows then so does the downstream dipole magnet, which reduces the detector acceptance. An alternative approach would be to have the SR hit the inner pipe [9]. The SR surface density power would be reasonable for a pipe with a few-cm radius. However, the pipe would have to be quite thick and shielded in order to keep the detector backgrounds acceptably low. A future study of these various options should include a simulation of the SR impact onto the beam pipe, and the associated magnet designs.

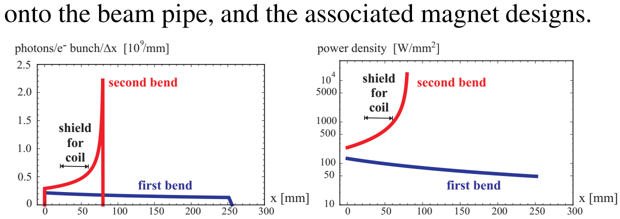

Figure 3: Line density of photons hitting the entrance plane of the final quadrupoles per electron bunch passage ($N_e = 2\times10^9$) and peak power density ($I_e = 6.6$ mA) at $s = 10$ m from the IP as a function of horizontal position.

OPTICS

The proton IP beta function is a crucial parameter for the LHeC luminosity [3]. It is constrained by the aperture in the triplet and by the chromatic correction. The nominal β^* value for LHC pp collisions is 0.55 m. For LHeC we target a smaller value of 0.1 m, which, according to scaling laws [11], should be achievable by a combination of three ingredients: (1) A shorter free length to the interaction point, l^*, of 10 m, instead of 23 m for the LHC pp collisions, eases the requirements on the magnet aperture ($\propto l^*$) and reduces the chromaticity ($\propto l^*/\beta^*$). (2) The triplet aperture must accommodate only one squeezed proton beam, instead of two for pp collisions, which increases the aperture available for the single main beam by some 50%. By itself this would allow decreasing β^* by more than a factor of 2 aperture-wise. (3) Changing the superconductor material from Nb-Ti to Nb_3Sn may increase the maximum field and/or aperture by up to a factor of 2 [11]. Since (1) and (2) together can already achieve $\beta^* \approx 0.1$ m, the new superconductor is not strictly necessary for reaching $\beta^* = 0.1$ m, but it provides additional safety margin, e.g. for a thicker beam screen and cold bore or for spurious dispersion.

If the LHC IPs 1 and 5 are squeezed to their nominal value of $\beta^* = 0.55$ m, the unused sextupole strength around the ring will suffice to correct the LHeC final-focus chromaticity for $\beta^* = 0.1$ m, possibly after adjusting phase advances between arcs. If the other IPs are also squeezed to sub-nominal β^* values, additional measures may be necessary, for example, introducing a large beta beat in the two adjacent arcs [12] or a local chromatic correction.

Figure 4 (left) shows the formal solution of squeezing the present IR8 optics, with l^* of 23 m, to $\beta^* = 0.1$ m by varying the matching quadrupoles Q4 to QT11, with all but one staying within their present strength limits. The triplet gradient is kept the same as for the nominal LHC. Aperture has not been included as constraint. Figure 4 (right top) presents a proposed new proton optics with $\beta^* = 0.1$ m and $l^* = 10$ m. For the electron beam the distance l^* is not a critical parameter. We have chosen $l^* = 20$ m (Fig. 4).

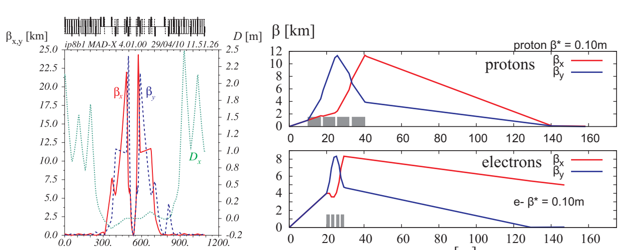

Figure 4: LHC proton interaction-region optics for $\beta^*_{x,y} = 0.1$ m, scaled from the nominal IR optics (left) [5], and a new IR optics with $\beta^*_{x,y} = 0.1$ m for protons [$l^* = 10$ m] (top right) and electrons [$l^* = 20$ m] (bottom right) [4].

MAGNETS

Table 2 lists parameters of the first two quadrupoles in the final triplets for the proton beam, corresponding to the optics in Fig. 4 (right). Magnets with the desired gradients and aperture could be realized with Nb_3Sn superconductor, including an exit hole for the electron beam. Nb_3Sn quadrupoles will be available by 2014 [13]. The electron triplet magnets pose no particular challenge [4].

Table 2: Parameters of the first two proton quadrupoles [4].

magnet	pipe radius	gradient	field at pipe
Q1	26 mm	318.6 T/m	8.4 T
Q2	36 mm	250.0 T/m	9.1 T

One option for implementing the dipole field would be a permanent magnet made from SmCo, as in PEP-II [9]. The SR could be extracted with a proper opening in the dipole or else it will hit the beam pipe inside the magnet. Effects of exposure to SR and collision debris will need to be looked at. Another option for generating the dipole field would be via a pair of helical coils [14]. For a 0.4-T field, these coils could be either normal- or superconducting. A single tilted helical coil rather than a pair might suffice, and the solenoid part of the field could conceivably be used to partially compensate part of the detector solenoid. A similar field could also be obtained by deforming the coils of the detector solenoid, like the detector-integrated dipole of the ILC [15], which would be a third option.

SECOND PROTON BEAM

A second LHC proton beam moving in opposite direction may need to be transported across the LHeC interaction region. If this second proton beam shares a common IR vacuum chamber with the main proton beam the physical aperture available for either beam will be reduced. This loss in aperture can be partially mitigated by not squeezing the second beam, so that the latter would have a much smaller size inside the final quadrupole triplet. However, in this case, the inner detector beam pipe might need to be opened up for the second proton beam.

Another possibility would be designing the LHeC detector with a bypass hole for the second proton beam. An easily achievable transverse separation would be 0.4–0.5 m. The triplet magnet cryostat for the colliding proton beam must then also feature a hole for the second proton beam with 2–3 cm radius at about 50 cm from its axis.

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