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INTERACTION REGION DESIGN FOR A RING RING VERSION OF THE LHEC STUDY

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Abstract

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Abstract

The LHeC aims at colliding hadron-lepton beams with center of mass energies in the TeV scale. For this purpose the existing LHC storage ring is extended by a high energy electron accelerator in the energy range of 60 to 140 GeV. The electron beam will be accelerated and stored in a LEP like storage ring in the LHC tunnel. In this paper we present the layout of the interaction region which has to deliver at the same time well matched beam optics and an efficient separation of the electron and proton beams. In general the large momentum difference of the two colliding beams provides a very elegant way to solve this problem: A focusing scheme that leads to the required beam sizes of the electrons and protons is combined with an early but gentle beam separation to avoid parasitic beam encounters and still keep the synchrotron radiation level in the IR within reasonable limits. We present in this paper two versions of this concept: A high luminosity layout where the mini β magnets are embedded into the detector design as well as an IR design that is optimised for maximum acceptance of the particle detector.

INTRODUCTION AND REQUIREMENTS

The possibility of an ep and an eA option at the LHC was forseen early [1] and is now being studied with the approval of ECFA [2], for an electron beam energy of 60 to 140 GeV. The inclusion of an electron beam into the CERN LHC accelerator complex can be achieved with a LEP-like electron storage inside the LHC tunnel [3, 4], or using a superconducting electron linac [5]. The ring-ring (RR) option requires that the electron ring is added of the LHC ring with minimal disruption to the LHC physics programme and requires the design of bypasses around existing experiments and a suitable electron injector [4].

The design of the ring-ring electron-proton interaction region is particularly challenging, and needs to deliver a well matched optics and sufficiently separate the two beams. The LHeC proposed physics programme [3] follows two themes - a high luminosity high Q^2 programme requiring a forward detector acceptance of around 10° and a low x, low Q^2 programme, which requires a forward detector acceptance of at least 1° and could proceed with lower luminosity. Therefore two machine scenarios have been studied for the RR IR design. Firstly, a high luminosity ($10^{33}\,\mathrm{cm}^{-1}\,\mathrm{s}^{-1}$) for high Q^2 events, with a forward acceptance of 10° and secondly, a high acceptance, lower luminosity ($10^{32}\,\mathrm{cm}^{-1}\,\mathrm{s}^{-1}$) design. The high acceptance IR gives a machine-detector integration challenge as no magnetic elements can be placed in a 1 degree cones in the forward region to beyond the HCAL, located approximately 6.2 m from the IP. In comparison the 10° forward cone for the high luminosity option allows mini β quadrupoles as close as 1.2 m from the IP and accordingly a higher luminosity can be reached.

Many machine parameters are constant for both designs, determined by the electron and proton ring lattices and injected beam parameters. Table 1 shows these parameters. The luminosity in an electron-proton machine is given by

$$L = \sum_{i=1}^{n_b} (I_e * I_p) \frac{1}{e^2 f_0 2\pi \sqrt{\sigma_{xp}^2 + \sigma_{xe}^2}\sqrt{\sigma_{yp}^2 + \sigma_{ye}^2}}, \quad (1)$$

where σ_{ex}/σ_{px} denotes the electron/proton horizontal and vertical beam size and I_e/I_p denotes the electron/proton beam current. In all IR layouts the electron beam size at the IP is matched to the proton beam size in order to optimise the delivered luminosity. This implies matching of an electron beam to a round emittance proton beam in the IR optics, and the minimisation of the optical functions at the IP.

Table 1: Main parameters for e/p collisions

Quantity	unit	e	p
Beam energy	GeV	60	7000
Total beam current	mA	70	582
Number of bunches		2808	2808
Particles/bunch N_b	10^{10}	1.40	11.5
Horiz. emittance	nm	7.6	0.5
Vert. emittance	nm	3.8	0.5
Bunch frequency	MHz	40	

A central aspect of the LHeC IR design is proton-electron beam-beam interaction. The bunch structure of the electron beam will match the proton for maximal luminosity, giving equal bunch spacings to both beams. The nominal LHC parameters assume a bunch spacing of 25 ns, and so there exists a parasitic bunch crossing every 3.75 m around the IP, and the IR design is required to separate the bunches as quickly as possible to avoid excess bunch interactions. The detailed impact of one beam on another is evaluated from a dedicated beam-beam interaction study, and the absolute requirement is a minimum of $5\sigma_e + 5\sigma_p$ separation at every parasitic crossing node. The larger electron emittance means the separation is dominated by the electron beam parameters, and the rapid growth of the β-function in the drift around the IP,

$$\beta(s) = \beta * + \frac{l^2}{\beta *}, \quad (2)$$

mean the layouts with smaller β* and larger l* are harder to separate the beams due to the large growth of β and the increased beam separation requirement.

The differing momentum of the two colliding beams provides an elegant solution to the electron-proton separation. This is achieved using near-IP dipoles to bend the electron beam away from the proton beam, with additional bending provided by offsetting the electron final triplet, and the offset electron final triplet implies a coupling between the electron trajectory and optics. In the schemes presented in this paper, the electron triplet and separation dipoles are placed inside the proton triplet, which is placed at the nominal LHC location [6] . The nearest proton quadrupole to the IP is assumed to be a half-quadrupole to ease the extraction of the outgoing electron beam. However, due to the proximity of the first parasitic crossing to the IP, dipoles cannot be placed close enough to the IP to sufficiently separate the beams and a crossing angle is required at the IP to supplement the separation. This early separation scheme aims to minimise the production of synchrotron radiation close to the detector and superconducting elements of the proton lattice, because the emitted power is a strong function of the electron beam energy,

$$P_\gamma = \frac{e^2 c}{6\pi\epsilon_0}\gamma^4\rho^2 N_e, \tag{3}$$

where the electron bending radius is denoted by ρ. This is achieved through small and constant bending radii (giving a smooth electron trajectory) of separating elements and the placement of absorbers in regions of high synchrotron radiation photon load. The emission of synchrotron radiation is dominated by the electron quadrupoles. The bending radii in the IRs is around 26 km, in contrast to the 3060 m of the main LHC dipoles, implying an electron triplet offset of approximately 1/10 mm. The combination of beam separation through the bending radii and the production of synchrotron radiation is optimized through iteration - it is always possible to increase the bending and separation at the price of increased synchrotron radiation load on the absorbers, magnets and detector.

In this paper, we present the IR layout, beam optics, separation scheme and synchrotron radiation calculations for the 10 degree and 1 degree layouts. A full set of parameters and a comparison is presented, showing the designs meet the requirements of the physics programme. The electron and proton IR optics have been matched into a preliimary LHeC ring optics and the nominal LHC optics respectively.

HIGH LUMINOSITY OPTION

The high luminosity IR layout is designed for around 10 ° forward detector coverage. The electron final triplet is positioned 1.2 m from the IP, giving a β_x* of 12.7 cm and a β_y* of 7.1 cm, followed by a long dipole separator magnet. The proton triplet is placed following the nominal LHC IR layout, and the proton β-functions at the IP are β_x* of 180 cm and β_y* of 50 cm. Figure 1 shows the high luminosity IR layout design, showing the offset electrons quadrupoles and the dipole, and all the separating elements have a bending radius of 26.3 km. The beam separation for the design is driven by the electron β_x-function rapid growth, the need to avoid parasitic bunch interactions and the separation requirement at the proton triplet. The baseline crossing angle is 1.5 mrad. The parameters for the high luminosity IR layout are shown in table 2.

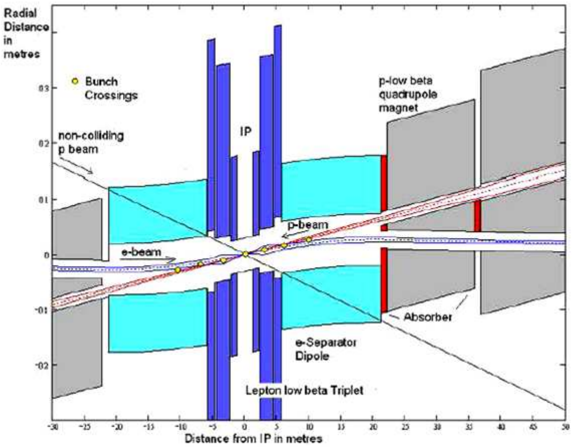

Figure 1: The high luminosity IR layout.

The smooth bending of the electron beam minimises the overall synchrotron radiation power. The layout, with the parameters in tables 1 and 2 generates approximately 25 kW of power for an electron beam energy of 60 GeV. As a comparison, HERA generated 30 kW [7] in the IR. This radiation is generated in the separation dipole and electron triplet, and falls on synchrotron radiation absorbers on the face of the final proton triplet.

Quantity	unit	Value
l*	m	1.2
β_{xe}^*	cm	12.7
β_{ye}^*	cm	7.1
Bending radius	km	26.3
Crossing angle	mrad	1.5
Luminosity $(0)/10^{33}$	cm^{-2}s^{-1}	0.80
$\Delta\nu_{ex}$		0.041
$\Delta\nu_{ey}$		0.043
SR power	kW	25

Table 2: The IR parameters for the high luminosity IR layout.

Design variants have been studied to optimize the luminosity and parameters. For example, an early separation dipole located at 1.2 m, with an increased distance to the electron final triplet, gives an increased space for synchrotron radiation absorbers at the cost a larger crossing angle due to a rapid rise in the electron β-function. It is also possible to increase the delivered luminosity with a stronger electron triplet at 6.2 m (small β* option) at the expense of a larger crossing angle.

HIGH ACCEPTANCE OPTION

The high acceptance IR layout is designed for 1° forward detector coverage, with a luminosity of $10^{32}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. The forward calorimeters mean the closest machine elements can be 6.2 m from the IP, and as such the first parasitic crossing is encountered before the final triplet and necessitating a crossing angle at the IP. In general, the lower luminosity results from a large β* and smaller β-function growth in the IR region. The beam separation is achieved in an analogous manner to the high luminosity layout, with electron-proton separation occurring with the crossing angle, offset electron triplet and a separation dipole. The smooth bending minimises synchrotron radiation emission. Two variants of the IR have been studied - the 'QB' option with the electron triplet the closest magnet to the IP, and the 'BQ' (or early separation) option, with short bending magnet placed at 6.2 m from the IP and inside the electron final triplet. The delivered luminosity is comparable for the two schemes and to compare to the high luminosity IR, the'QB' option is used as the canonical scheme. The electron triplet is placed 6.2 m from the IP, with β_x* of 0.63 m and β_y* of 0.35 m. A full set of parameters, together with delivered head-on luminosity can be seen in table 3, and the IR β-functions are shown in figure 3.

Quantity	unit	Value
l*	m	6.2
β^*_{xe}	cm	63.0
β^*_{ye}	cm	35.0
Bending radius	km	26.0
Crossing angle	mrad	1.44
Luminosity (0)/10^{33}	$\mathrm{cm}^{-2}\mathrm{s}^{-1}$	0.16
$\Delta\nu_{ex}$		0.038
$\Delta\nu_{ey}$		0.040
SR power	kW	10

Table 3: The IR parameters for the high acceptance IR layout.

The high acceptance IR layout has weaker electron quadrupoles than the high luminosity layout, and as such synchrotron generation is lower, and overall SR power is 10 kW for an electron beam energy of 60 GeV.

CONCLUSION

The ring-ring option of the LHeC requires two interaction region designs, one with a lumi of $10^{33}\,\mathrm{cm}^{-1}\,\mathrm{s}^{-1}$ and an acceptance of 10° and ones with a lumi of $10^{32}\,\mathrm{cm}^{-1}\,\mathrm{s}^{-1}$ and an acceptance of 1°. The IR design is characterised by coupled optics and separation scheme, and driven by a smooth electron proton separation scheme and the minimisation of electron beam synchrotron radiation emission. In this paper the high luminosity and the high acceptance IRs are presented, together with the design challenges, and shown to meet the requirements of the physics programme.

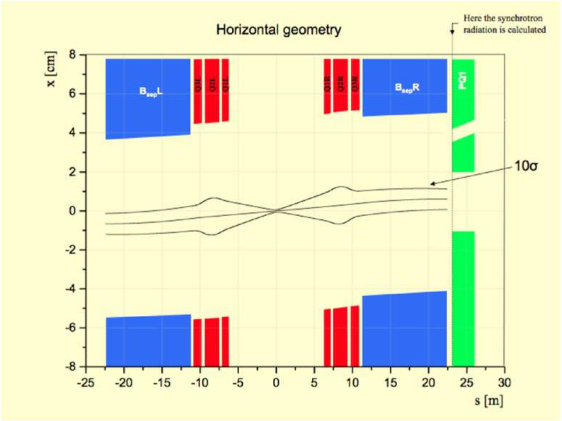

Figure 2: The high acceptance IR layout, showing the electron final triplet (red), separator dipole (blue) and the 10σ electron beam envelope.

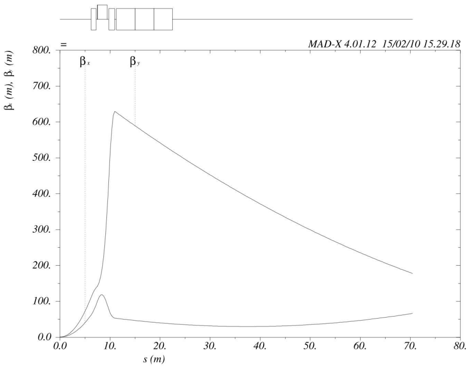

Figure 3: The IR β-functions for the high acceptance IR.

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