A STORAGE RING BASED OPTION FOR THE LHEC

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Abstract

The LHeC aims at the generation of hadron-lepton collisions with center of mass energies in the TeV scale and luminosities of the order of 10^{32}–10^{33} cm^{-2} sec^{-1} by taking advantage of the existing LHC 7 TeV proton ring and adding a high energy electron accelerator. This paper presents technical considerations and potential parameter choices for such a machine and outlines some of the challenges arising when an electron storage ring based option, constructed within the existing infrastructure of the LHC, is chosen.

INTRODUCTION

It was originally foreseen to allow for both an electron ring (LEP itself in the earliest versions) and a hadron ring in the LHC tunnel [1]. Interest in a lepton-hadron collider, LHeC, was rekindled recently by the proposal to add a new lepton ring to the LHC [2]. Here we build on that study to look more closely into aspects of the lepton ring. This could store positrons or electrons given investment in sources and polarity-switching capability. An alternative ring-linac option is discussed in [3] and more general aspects in [4].

The main parameters, from [2], are summarized in Table 1 (see also [5]) and are driven by assumptions on RF power available. Clearly there is ample scope for staging installed power and e$^{\pm}$ energy from 50–70 GeV, ultimately to approach the parameters of Table 1. If, e.g., the lepton beam current is kept constant, the e$^{\pm}$ energy scales as $E \propto P_{\rm RF}^{1/4}$.

Table 1: Main parameters for e$^{\pm}$p collisions

Quantity	unit	e$^{\pm}$	p
Beam energy	GeV	70	7000
Total beam current	mA	74	544
Particles/bunch N_b	10^{10}	1.40	17.0
Horiz. emittance	nm	7.6	0.501
Vert. emittance	nm	3.8	0.501
Horizontal β_x^*	cm	12.7	180
Vertical β_y^*	cm	7.1	50
Energy loss per turn	GeV	0.707	6×10^{-6}
Radiated power	MW	50	0.003
Bunch frequency	MHz	40	
CMS Energy ($\sqrt{s}$)	GeV	1400	
Luminosity $/10^{33}$	cm^{-2}s^{-1}	1.1	

LAYOUT AND BYPASS

The idea is to add a lepton ring to the LHC with minimal interference for the continuing high-luminosity pp program. This will require a separation bypass for the lepton ring around the high luminosity experiments ATLAS, in the interaction region IR1, and CMS in IR5. We assume that the low-luminosity LHC insertions, IR2 and IR8, can be adapted to the needs of the LHeC with RF, injection and new experiments. Fig. 1 shows the LHC underground structures and extensions considered for the LHeC while Table 2 lists the bypass tunnels considered necessary.

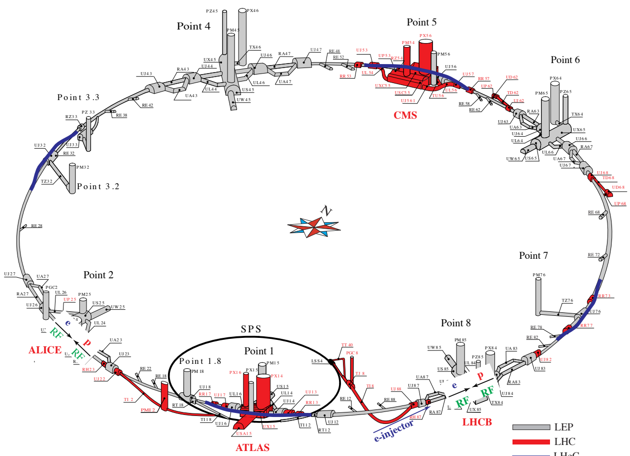

Figure 1: Civil engineering for the LHeC.

The RF system will require shielded areas to house the RF power amplifiers and associated electronics. At lower energies, 50 GeV, say, the superconducting cavities (1GHz) can be accommodated at one long straight section (LSS). At higher energy it may be preferable to divide the system between two LSSs to avoid beam dynamics effects associated with high synchrotron tune and energy. The total number of cavities will depend on the RF coupler capability rather than the accelerating gradients (MV/m) achievable.

Table 2: Bypass tunnels and approximate dimensions.

	IR1/IR5 ATLAS/CMS	IR2 and/ or IR 8	IR3/IR7
Bypass for	Experiments	RF	Collimation
Diameter	4.4/3.8 m	5.50 m	4.2/3.8 m
Length	500 m	500 m	500 m
Separation	10–13 m		

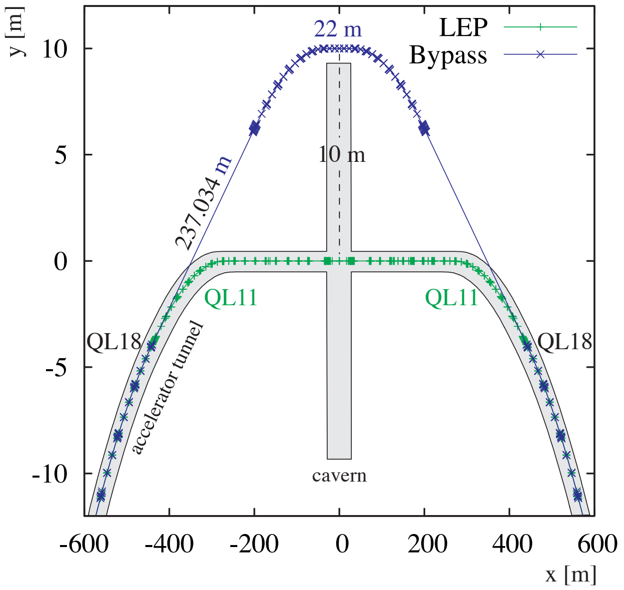

Figure 2: By-pass layout study, derived from the LEP lattice without addition of bending magnets. The y-scale is stretched by a factor of 50.

INTERACTION REGION (IR)

The bypasses around the experiments in IR1 and IR5 are expected to be the most demanding because they require 10–13 m of horizontal separation at the interaction point (IP). We have therefore started to look into possible designs in some detail. Fig. 2 shows a bypass which was derived from the LEP lattice without addition of bending magnets, thus avoiding any increase in synchrotron radiation losses.

The design of the new interaction region for the $e^{\pm}$-hadron collisions is based on the principle that the two hadron storage rings of the LHC can be operated independently of the lepton ring. This is an unavoidable consequence of the need to maintain the standard pp operation of the LHC simultaneously with $e^{\pm}$p collisions and the fact that the lepton and hadron beam rigidities differ by a factor of a hundred. The principle of the IR layout has been presented in various papers and a possible arrangement of the low-β quadrupole lenses, as discussed, e.g., in [2], is shown in Fig. 3.

While the 7 TeV proton beam will pass through the mini-β triplet of the lepton storage ring, any proton magnet will only be placed where the two beams are sufficiently separated so the electron beam is not affected by the much stronger magnetic fields of the proton lenses. The focusing and the separation are therefore closely coupled. On the other hand, whatever the design of the IR, the protons will be affected by some focusing and bending fields of the electron ring. Therefore the IR layout presented here is based on a robust proton beam optics that is adequate for the required luminosity and can also tolerate (and compensate) the perturbation by the common magnets as they vary through the full operational cycle of the electron storage ring. Thanks to the large difference in momentum it can be

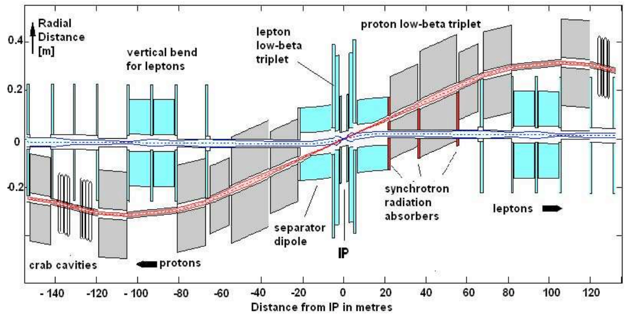

Figure 3: Schematic interaction region layout.

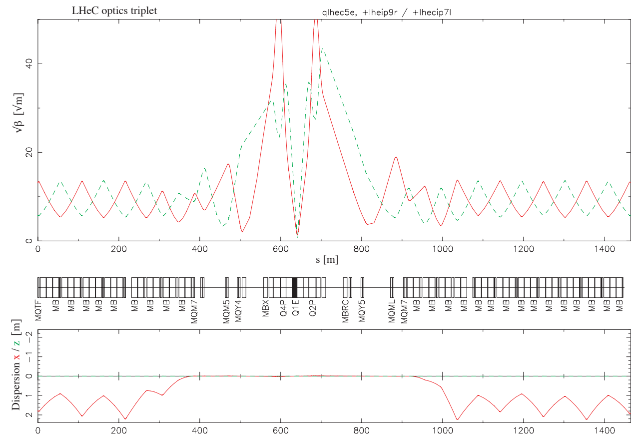

Figure 4: Hadron beam optics for e-p collisions in IP8

assumed that the fields of the lepton ring have little impact on the hadron beam and compensation of the optics and the orbit will not be difficult.

Furthermore, the large momentum difference of the two colliding beams provides a very elegant way to separate the lepton and the hadron beam: Shifting the mini-β quadrupoles of the electron beam and installing a long but weak bending magnet close to the IP provides the gentle separation scheme needed to keep the synchrotron radiation level in the IR within reasonable limits. For the hadron beam optics presented here, the constraints arise from the β-functions at the IP (Table 1), the separation scheme (mainly the length of the dipole separator magnet determining the distance of the first hadron quadrupole to the IP) and, above all, matching to the present LHC FODO structure in the arc. The basic problem for any $e^{\pm}$p collision scheme is that the present layout of IR8 is anti-symmetric in that the first main superconducting quadrupole on the right of the IR is focusing, on the left, defocusing. While anti-symmetric solutions for a round beam optics ($\beta_x = \beta_y$) are easily established, flat $e^{\pm}$ beams ($\epsilon_x \simeq 2\epsilon_y$) require unequal β-functions for the hadron beam and a symmetric quadrupole arrangement can no longer be maintained. Thus, the hadron beam optics proposed here is based on a mini-β triplet on both sides of the IP in which the focusing magnets have different strengths on the right and left of the IR.

Figure 4 shows a possible solution. The first quadrupole is located at a distance of 22 m from the IP, determined by the separation scheme of the lepton beam. The β-function inside the mini-β quadrupoles reaches a maximum value in both planes of about 2200 m, low enough to provide flexibility and aperture for beam separation during lepton injection and to allow the lepton quadrupole magnets to be powered for either $e^{\pm}$ running mode. The influence of the lepton magnets on the hadrons will be compensated locally, i.e., correction currents will be applied in the hadron low β quadrupoles and orbit corrector dipoles to counteract this external distortion as a function of the $e^{\pm}$ energy and charge.

Special care has to be taken at lower hadron energies during injection and acceleration as the emittance of the hadron beam scales inversely with energy and will be as large as $8\,\mu\mathrm{m}$ at injection. It is not expected that a luminosity optics as presented in Fig. 4 will be required. Instead one must find an optical solution where the emphasis is put on aperture rather than minimum β at the IP.

A first result of such a beam optics is sketched in Fig. 5: based on the same element layout as in Fig. 4, it has relaxed aperture requirements. Work is in progress to find a smooth interpolation between the two extreme situations.

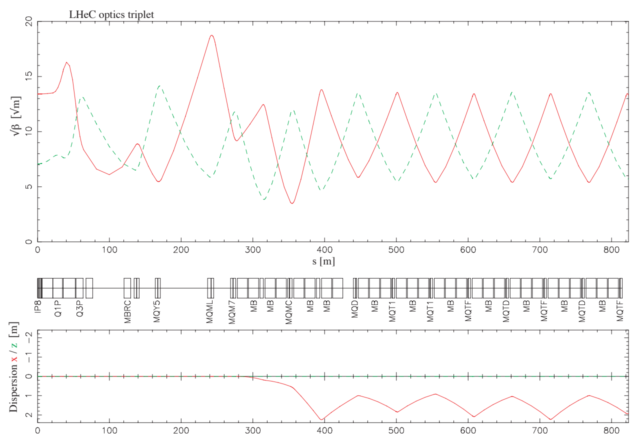

Figure 5: Hadron beam optics for injection and ramp e-p

In practice, the operational cycle of the LHeC IR in the case of an $e^{\pm}p$ run will be as follows: first, the proton beam will be injected into an optics like Fig. 5 which is then ramped up to top energy of 7 TeV. During this procedure the lepton ring magnets, (triplet quadrupoles and separator dipole) are at *minimum* fields to minimise perturbations of the more sensitive 450 GeV proton beam. At top energy in the hadron ring, separation bumps will be set up at the IP to prepare for the lepton injection.

Then the lepton magnets will be cycled to their injection settings and leptons will be injected and ramped to their top energy. During these procedures, correction settings in the proton ring will continuously compensate for the perturbation from the lepton ring. It is foreseen to keep the optics of the lepton ring constant through injection, ramp and collisions, so that the compensation currents for the protons will be scalable throughout. Finally, having accelerated the lepton beam, the β-squeeze optics of the protons will be applied, and the separation bump switched off, to bring them into collision with the leptons.

LEPTON-NUCLEUS COLLISIONS

It is natural to take advantage of the LHC's second role as a nucleus-nucleus collider to extend its physics reach with $e^{\pm}$-ion collisions. Here we briefly consider the potential of using the existing ion injector chain to provide $e^{\pm}$-Pb collisions, keeping in mind that a range of both light and heavy nuclei are expected to be available in the LHC in coming years.

Let us assume the same number (592), intensity (7×10^7 ions/bunch) and emittance of $^{208}\mathrm{Pb}^{82+}$ ion bunches as for the present nominal Pb-Pb collision parameters [5] and that the lepton injectors can create matching trains of lepton bunches. The Pb beam sizes are the same as the protons'. With the same single bunch current as for $e^{\pm}p$ (Table 1), we find a lepton-nucleus luminosity $L \approx 1.09 \times 10^{29}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (or a lepton-nucleon luminosity of $L_{\mathrm{en}} \approx 2.2 \times 10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$) but with the radiated power reduced by the ratio of the number of bunches, $2800/592 \approx 4.7$. In principle, the lepton bunch current (hence, the luminosity) could be increased by about this factor to exploit the RF power available for $e^{\pm}p$ operation without exceeding single-bunch current limits.

LEPTON INJECTORS

The LEP pre-injectors have been dismantled and the infrastructure re-used for the CLIC test facility CTF3. The RF cavities that accelerated leptons in the SPS have been removed to reduce its impedance. Re-installation of an injector chain similar to LEP's through the PS and SPS would be costly and potentially limit the proton performance so the LHeC needs new lepton injectors [6]. The required bunch intensities of 1.4×10^{10} are well below the 4×10^{11} used for LEP. This should lower the injection energy from the 22 GeV of LEP and reduce the cost of new lepton injectors. A scaled-down version of ELFE [7] may be a candidate for the LHeC lepton injector.

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