FACILITY PLANS FOR THE LHEC

B.J. Holzer, CERN, Geneva, Switzerland

Abstract

The LHeC aims at the generation of hadron-lepton collisions with center of mass energies in the TeV scale. The existing LHC storage ring with its 7 TeV proton beams is extended by a high energy electron accelerator in the energy range of 60 to 140 GeV. This paper presents technical considerations and parameter choices for such a machine and outlines the challenges of colliding a high intensity high energy proton and electron beam.

The LHeC is presently being evaluated in the form of two options, 'ring-ring' and 'linac-ring', either of which operate simultaneously with pp or ion-ion collisions in other LHC interaction regions. Each option takes advantage of recent advances in radio-frequency, in linear acceleration, and in other associated technologies, to achieve ep luminosity as large as 10^{33} $cm^{-2}s^{-1}$.

General Considerations

The possibility of electron hadron collisions in the LHC tunnel was already foreseen at an early stage of the LHC project (using LEP itself in its first version) [1]. Now with the LHC machine coming into operation, there is new interest to investigate an e-p option in detail [2] and the possibility of such "LHeC" collider is being investigated under an ECFA mandate [3, 4, 5].

Two options are being considered and studied in parallel: On one hand the electron beam could be accelerated and stored in a LEP like storage ring that would be built in the LHC tunnel [6, 7]; a second alternative is based on a superconducting electron linac, configured as recirculator [8]. We will refer to them as Ring-Ring (RR) and Ring-Linac (RL) options. Both options need a specific layout of one of the present LHC interaction regions.

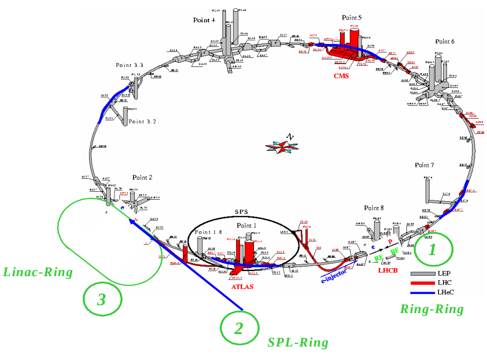

Figure 1: Schematic layout of possible electron proton interaction regions. The numbers in the figure refer to the interaction region forma ring ring scenario "1", and to linac ring options using the CERN SPL "2" and a dedicated new electron linac "3".

The Ring Ring Option

General RR and RL LHeC concepts and their layout with respect to the LHC geometry are sketched in Fig. 1. For the RR option a lepton ring will be added to the LHC with minimal interference for the continuing high-luminosity proton-proton 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 as indicated in Fig 1 and a new design of one of the LHC interaction regions.

The main parameters of the LHeC study are summarized in table 1. In order to exploit the full potential of the high bunch number in LHC also for the electron proton collisions, an equivalent number of electron bunches is foreseen, leading to an overall beam lepton current of 71 mA. Especially the large number of bunches in LHC (2808) and the corresponding small bunch distance is a challenging requirement for the layout of the interaction region and the design of the electron storage ring. Given the stored electron current, the electron energy is defined by the available rf power: Limiting the required rf power consumption to about 50 MW an electron energy of 70 GeV can be achieved.

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	

Table 1: The parameters for the LHeC ring ring version. The beta functions chosen here at the ep interaction point lead to matched beam conditions of the electron and proton beam and a luminosity in the range of 10^{33}.

The new electron ring will be located on top of the LHC proton ring (Fig.2) for the largest part of the tunnel. Only at the high luminosity experiments ATLAS and CMS in IR1 & IR5 respectively, the electron beam will be separated from the proton ring lattice to pass the experiment on a bypass whose geometry is sketched in Fig 3.

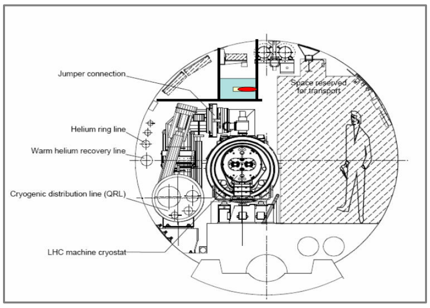

Figure 2: Geometry of the proton ring in the LHC tunnel and a new electron ring located on top of it.

A detailed layout of the bypass regions is shown in Fig 4. Guiding the electron beam for a large part in parallel to the present pp interaction regions and keeping these parts dispersion free, there will be enough space even to install the required rf structures in the electron machine.

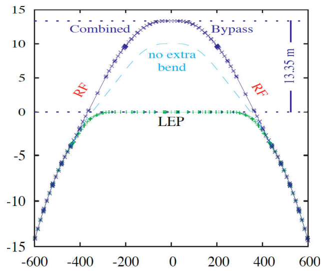

Figure 3: Geometry of the electron beam in IR 1 & 5: To guide the electron beam on a separated lattice around the high energy detectors, the design orbit has to be modified. The resulting new lattice for these "bypass regions" is compared in the picture to the former LEP geometry.

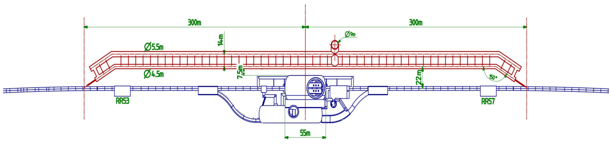

Figure 4: Detailed layout of the new bypass structure for the electron beam at IP 1 and IP 5.

The Interaction Region and Beam Optics

For the design of the ep Interaction Region a special lattice has been chosen: A focusing scheme that leads to well matched electron and proton beams has been combined with a fast beam separation to avoid parasitic beam encounters. In general 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 proton beam optics presented here, have been optimised according to the constraints that 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 (see figure 5)

Therefore the mini beta quadrupoles of the electron storage ring are positioned of-centre with respect to the design orbit. An additional crossing angle of 1.5 mrad leads to well separated beams already at the first parasitic bunch encounter at a distance of 3.75m

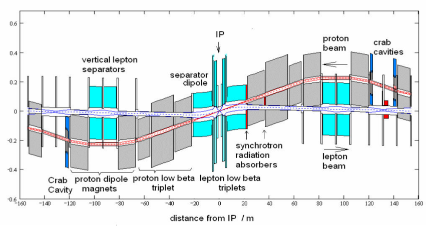

Figure 5: Layout of the LHeC interaction region.

For the design of the proton beam optics in LHeC a special boundary condition had to be observed: For the layout of the four present proton proton interaction regions in the LHC machine an anti symmetric option had been chosen: A solution that is appropriate for a round beam optics ($\beta_x = \beta_y$). An optimised design for collisions with the flat e± beams however require unequal β-functions for the hadron beam and the existing LHC optics can no longer be maintained. Therefore the optical layout of the existing triplet structure in the LHC had to be modified to match the required beta functions (βx=1.8m, βy=0.5m) to the regular optics of the FoDo in the arc (Fig 6).

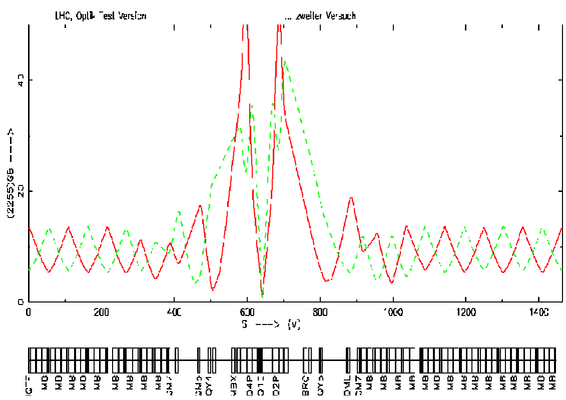

Figure 6: Proton beam optics at the ep collision point matched to the existing LHC proton optics.

For the electron case again a symmetric triplet structure has been chosen.The main requirements for a well balanced solution here are given by the need to match the optical parameters of the interaction region to the regular pattern in the arcs, to limit beam beam tune shift in the electron machine to tolerable values and to obtain the required beam emittance that - unlike to the emittance of the protons - depend on the focusing properties in the ring. Fig 7 shows the result of the electron beam optics in the new e-p interaction region.

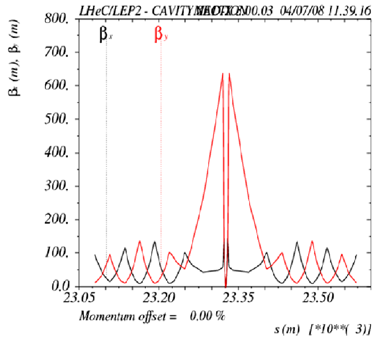

Figure 7: Electron beam optics at the ep collision point matched to the FoDo structure of a new electron storage ring.

The electron beam optics in the arc is based on a LEP like FODOstructure; however a smaller cell length has been chosen to reduce the emittance of the beam: Accordingly, for the length of 59m in the FODO structure and a phase advance of 72 degrees an overall number of 384 cells will be required (Fig 8).

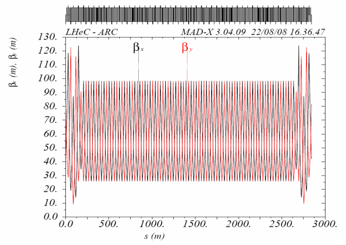

Figure 8: Beam optics in the arc of the new electron ring for the LHeC RR version.

Challenges of the RR Option:

The main challenges for the RR option are related to the layout of the interaction region: Due to the large number of bunches in the LHC (2808) and the corresponding mall bunch distance of 25 ns first parasitic - and unwanted - bunch crossings appear already at a distance of 3.75 m from the IP. To overcome this problem, a fast separation of the electron and proton beam is required: The separation effect due to the shifted electron triplett quadrupoles is combined with a crossing angle between the electron and proton beam of 1.5 mrad. The resulting beam orbits and -schematically the location of the first parasitic bunch crossings - are visualised in Fig 9.

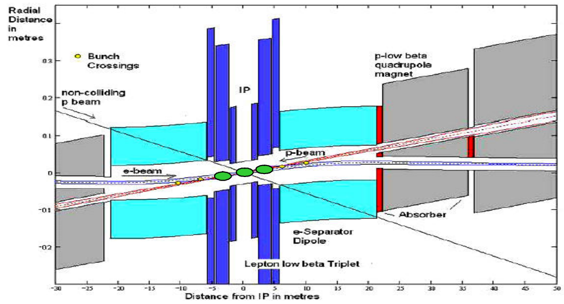

Figure 9: Beam separation scheme using of centre quadrupole magnets and a separator dipole magnet. Schematically the location of the first parasitic bunch collision points have been added (green dots).

Still the separation at the location of the first proton magnet is small and at this point a half quadrupole design for this super conducting magnet has to be chosen. The resulting beam parameters - including the expected luminosity for this ring ring option - are summarised in table 2. Colliding two beams of different characteristics, the luminosity obtained is given by the equation

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

and according to the parameters of table 2 a value of 1.1*10 33 is obtained for the RR design.

Having chosen the main parameters as beam optics, energy and current, the main performance limitation for a RR design will be related to the available rf power that is needed at a given energy to compensate the synchrotron radiation losses. The synchrotron radiation power is a steep function of the energy,

$$(2) \quad P_\gamma = \frac{e^2 c}{6\pi \varepsilon_0} * \gamma^4 * r^2 * N_e$$

Being limited by the available rf power that can be installed (or paid), the equations (1) and (2) can be combined to establish a relation between the beam energy and the resulting luminosity that will be obtained [9] Fig 10. Two examples are pointed out in the plot: If a luminosity of 10^{33} is aimed for, a beam energy of 50 GeV corresponds to an rf power consumption of 10 MW. Increasing the beam energy to 75 GeV the power consuption reaches 50 MW, which is still considered as a tolerable limit.

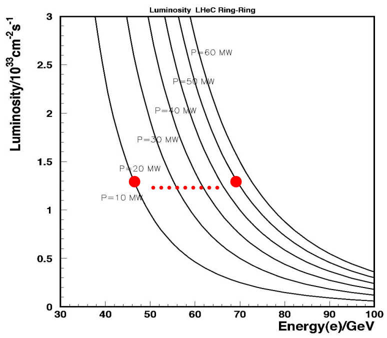

Figure 10: Scaling the luminosity that is obtained in a LHeC RR version for a given power consumption and beam energy.

Linac Ring Options

For the linear accelerator version of the LHeC two scenarios are considered at present: The construction of a dedicated new linac (a design similar to the XFEL and ILC versions), or alternatively the use of the future CERN super conducting SPL accelerator. The later is being optimised for proton acceleration but it can be used as well for the acceleration of an LHeC electron beam. While this option would present a perfect synergy and reduce the cost for the LHeC project considerably, the electron energy obtained in this case however would be limited to about 30 GeV. A dedicated new linac is needed if higher electron beam energy is requested. In this case the design is optimised to conceive the operation as a recirculating linac. Unlike to the RR version where the rf power consumption is determined by the synchrotron radiation losses, in the RL case, the rf power is defined by the acceleration itself and the performance of the machine is related to the efficient transformation of available rf power to beam energy. Three possible linac parameters are summarized in Table 2. Each of them is optimised for an overall power consumption of 100 MW, which - assuming an rf efficiency of 50% - corresponds to the limit that as well had been foreseen in the RR option.

		Pulsed	CW
e- energy [GeV]	30	100	100
comment	SPL* (20)+TI2	LINAC	LINAC
#passes	4+1	2	2
wall plug power RF+Cryo	100 (1 cr.)	100 (3 cr.)	100 (35 cr.)
bunch population [10^9]	10	3.0	0.1
duty factor [%]	5	5	100
average e- current [mA]	1.6	0.5	0.3
emittance $\gamma\varepsilon$ [μm]	50	50	50
RF gradient [MV/m]	25	25	13.9
total linac length β=1 [m]	350+333	3300	6000
minimum return arc radius [m]	240 (final bends)	1100	1100
beam power at IP [MW]	24	48	30
e- IP beta function [m]	0.06	0.2	0.2
ep hourglass reduction factor	0.62	0.86	0.86
disruption parameter D	56	17	17
luminosity [10^{32} cm^{-2} s^{-1}]	**2.5**	**2.2**	**1.3**

Table 2: Parameter lists for the two linac options described in the paper: The future super conducting SPL proton linac, used here in electron mode, and a dedicated new electron linac. An additional column has been added to compare the latter if set up in cw mode.

Fig 11 shows a possible location of the recirculating linac (in red) located in the plot opposite to the SPS machine marked in green.

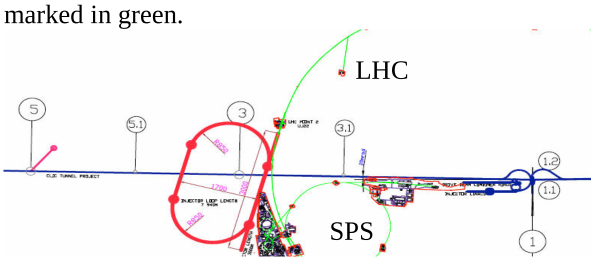

Figure 11: Possible layout and geometry of the recirculating linac for the LHeC RL option with respect to the existing SPS and LHC rings.

A construction-cost optimization suggests that for a final beam energy between 60 and 140 GeV, a single recirculation loop is the cost minimum [10]. The bending radius in this loop can be chosen large enough, e.g. 1.5 km, that the SR energy loss does not exceed 2% of the beam energy. At present an additional option for the RL version is being studied: The feasibility to regain the beam energy after collision (so called energy recovery mode) and thus allow at constant wall plug power a considerable increase of the obtained luminosity.

Challenges and Limitations:

As in the case of the RR option, the LHeC scenario based on a linear accelerator has to be optimised concerning the performance of the machine luminosity. The synchrotron radiation power can be neglected in this case, as the only contribution comes from the arc of the recirculating loop and can be neglected in this context. The strong limitation is the beam power itself and the obtained luminosity can be rewritten as a function of the electron beam power to obtain:

$$L = \frac{N_p \gamma}{4\pi\, \varepsilon_{pn} \beta^*} * \frac{P_{total}}{E_e}$$

The corresponding graph is shown in Fig 12. Assuming again - as in the case of the ring ring option - an rf power limit of 50 MW, a beam energy of 120 GeV is within reach. The resulting luminosity will be in the range of 2.5*10 [32].

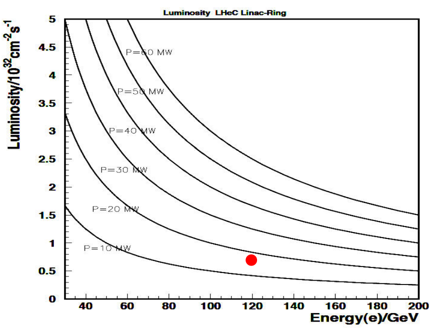

Figure 13: Scaling the luminosity for he LHeC RL version

References

[1] E. Keil, "LHC ep option", LHC-Project-Report-093, CERN Geneva 1997

[2] J. B. Dainton, M. Klein, P. Newman, E. Perez, and F. Willeke, "Deep inelastic electron nucleon scattering at the LHC", *JINST* 1 (2006) P10001

[3] LHeC web site: http://www.lhec.org.uk

[4] First ECFA-CERN LHeC Workshop, Divonne, Sept. 2008.

[5] J. Dainton et al, Proc. EPAC'08 Genoa, p. 1903 (2008).

[6] J.B. Dainton *et al*, JINST 1: P10001 (2006).

[7] F. Willeke *et al*, Proc. EPAC'08 Genoa, p. 2638 (2008).

[8] F. Zimmermann *et al*, Proc. EPAC'08 Genoa, p. 2847 (2008).

[9] Max Klein, "Towards a Large Hadron electron Collider at the LHC", Report at the CERN Institute for Colliders Beyond the LHC, Feb 2009

[10] J. Skrabacz, CERN-AB-Note-2008-043 (2008).