

Progress on the Large Hadron electron Collider

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In this work we examine the motivation and design of the Large Hadron electron Collider (LHeC). This proposed addition to the LHC will collide 60 GeV electrons with 7 TeV protons to study deep inelastic physics. We discuss the overall physics motivations for the accelerator, the proposed layout, current design considerations, and some beam-dynamics studies. The current design calls for an energy recovery linac to provide the electron beam. Preliminary designs for the optics and interaction region have been included, as well as analyses of the dynamics of both the electron and proton beams.

The European Physical Society Conference on High Energy Physics

22–29 July 2015

Vienna, Austria

¹Presenter

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1. Introduction

The Large Hadron electron Collider (LHeC) is a proposed addition to the LHC to study deep inelastic physics. The current design envisions a multipass recirculating linac as the source for a 60 GeV electron beam that will collide with one of the 7 TeV proton beams in the LHC. These collisions will occur simultaneously with normal LHC operations. A parameter list for the proposed accelerator is shown in Table 1.

Table 1. A list of the baseline and proposed high luminosity parameters of the LHeC.

	PROTONS (nominal)	ELECTRONS (nominal)	PROTONS (High Luminosity)	ELECTRONS (High Luminosity)
Beam Energy [GeV]	7000	60	7000	60
Luminosity [$10^{33}\text{cm}^{-2}\text{s}^{-1}$]	1	1	16	16
Normalized Emittance $\gamma\epsilon_{x,y}$ [mm]	3.75	50	2.5	20
Beta Function $\beta^*_{x,y}$ [m]	0.1	0.12	0.05	0.10
rms Beam Size $\sigma^*_{x,y}$ [mm]	7	7	4	4
rms Beam Divergence $\sigma^*_{x,y}$ [mrad]	70	58	80	40
Beam Current @ IP [mA]	430 (860)	6.6	1112	25
Bunch Spacing [ns]	25 (50)	25 (50)	25	25
Bunch Population	$1.7 \cdot 10^{11}$	$(1 \cdot 10^9) 2 \cdot 10^9$	$2.2 \cdot 10^{11}$	$4 \cdot 10^9$
Bunch Charge [nC]	27	(0.16) 0.32	35	0.64

In Section 2 we will examine some of the Physics goals of the LHeC. In Section 3 we will examine the layout and design of the LHeC, and in Section 4 we will look at some beam dynamics studies that have been performed so far.

2. LHeC Physics

The LHeC is the successor of HERA for deep inelastic physics at the energy frontier. It will be the world's finest microscope, a next Higgs facility as well as a precision QCD and electroweak physics laboratory, also providing a so far inaccessible insight to nuclear structure. Designed for synchronous ep-pp operation, the LHeC will substantially enhance the discovery potential of HL LHC. In its default configuration, the FCC-he employs the LHeC electron beam for a yet bigger step forward in the further future. The available physics reach of the LHeC is shown in Fig 1.

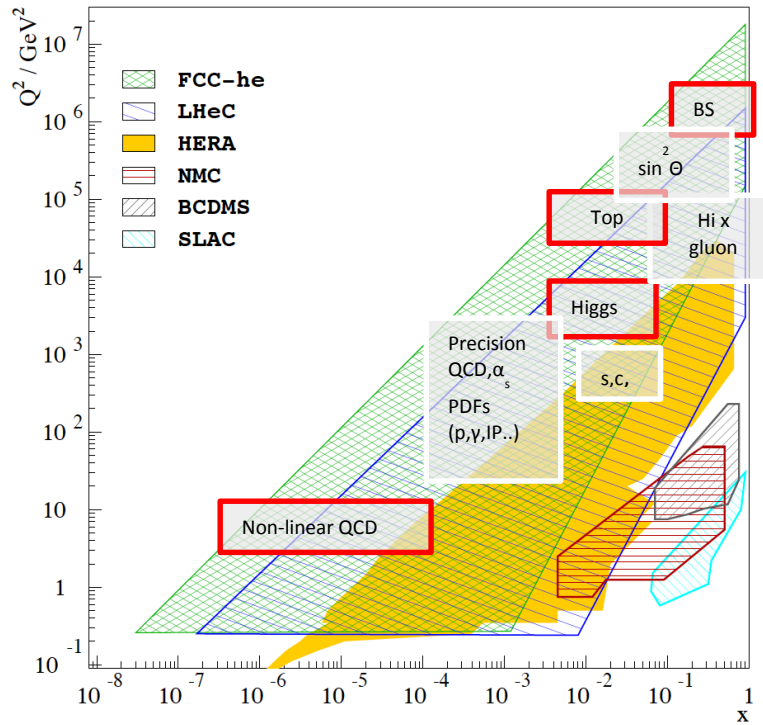


Figure 1. Kinematic range in 4-momentum transfer squared, Q^2 , and Bjorken x of the LHeC compared to previous deep inelastic scattering experiments. The plot indicates the placement of key physics subjects in the kinematics plane. It marks also the extension of the range by the electron-proton version of the Future Circular Collider, FCC, currently under study.

3. LHeC Layout and Design

The electron beam of the LHeC is provided with a recirculating energy recovery linac [1], the outline of which is shown in Fig 2. A recirculating linac bends the beam around through the same accelerating structures multiple times before collision. The arc sections spread and recombine the different energy beams so that top energy electrons can be continuously fed into the experiment. An example of this type of accelerator is CEBAF at Jefferson Lab. This particular design will also recover the energy of the spent beam after collisions with the proton beam. In this case the spent beam is bent around and goes through the accelerating cavities 180° out of phase. As the spent beam is slowed down by the accelerating structure the energy can be used to accelerate a fresh beam. This allows for larger beam currents and larger luminosities with lower power consumption, and simplified beam disposal.

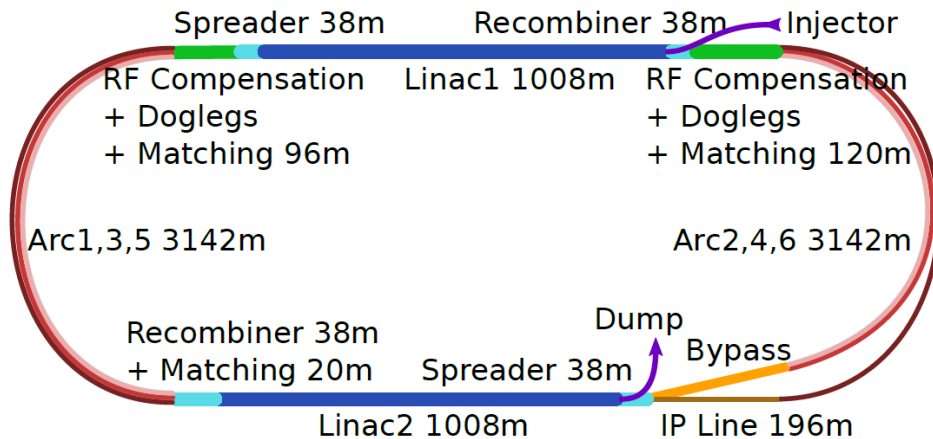


Figure 2. An outline of the proposed 60 GeV electron linac, a part of the LHeC.

3.1 Lattice Design

The lattice for the LHeC electrons has been designed both for the accelerating cavities as well as the return arcs [2]. The linac optics have been designed taking into account collective effects; it allows the linacs to accommodate multiple energies, with the lowest energy pass adjusted to minimize the required aperture. The arcs have a 1 km bending radius and adopt a flexible momentum compaction cell that has been tuned to allow the lower energy arcs to compensate for bunch elongation, and high energy arcs to prevent the harmful effects of synchrotron radiation. The lattice functions of the linac are shown in Fig 3. while the lattice functions of the accelerating sections are shown in Fig 4.

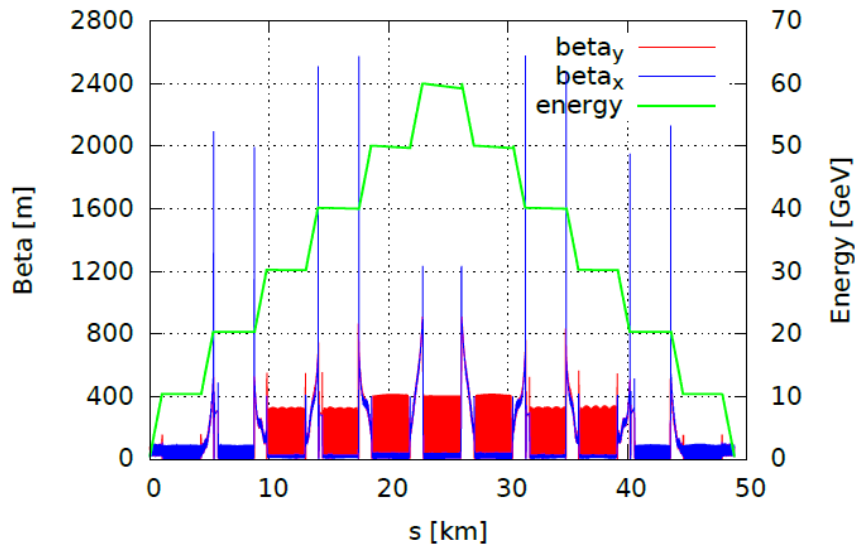


Figure 3. The lattice functions of the electron linac going from injection to extraction energy.

3.2 Detector Bypass Section

After the linac 2 spreader, the 60 GeV beam can go straight to the detector. However, the 20 and 40 GeV beams need to be further separated to avoid interference. A bypass section has been recently designed to allow this [2]. It consists of an initial horizontal bend followed by a straight section to generate a separation of about 10 m at the detector location. To connect with Arc 6 the initial 10 cells of the Arc 2 and 4 have been replaced with seven cells with a slightly higher bending field. This layout allows us to reduce the additional impact of synchrotron radiation. The lattice and physical dimensions of this bypass section are shown in Fig 4.

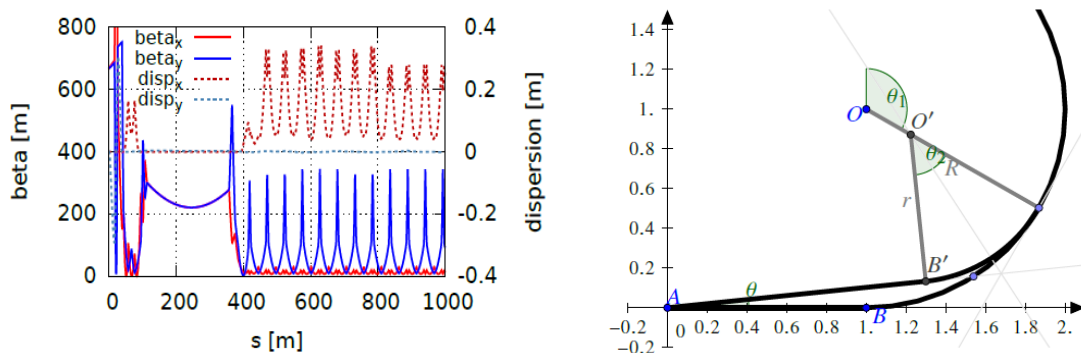


Figure 4. On the left are the lattice functions of the detector bypass section. On the right is the geometry of the bypass section.

3.3 Interaction Region Studies

The aim of this ongoing study is to explore the flexibility of the interaction region design to find the optimal solution that will achieve the highest luminosity while controlling the chromaticity, reducing the synchrotron radiation and maintaining the dynamic aperture (DA) required for stability.

A nominal design was given with a $\beta^*=10$ cm and a new inner triplet L^* at 10 m [3] making use of an extension of the Achromatic Telescopic Squeezing Scheme [4] used for the HL-LHC. The flexibility of this design was explored in terms of minimizing the β^* and increasing L^* [5] and different chromatic correction schemes were analyzed [6].

The complete study shows that a solution with $\beta^*=10$ cm is enough to achieve the desired luminosity of the baseline version, but considerable benefits arise for the cases $L^*>10$ m, in particular for $L^*=15$ m. For this value of L^* , normal quadrupoles can be used, the chromaticity is controlled, there is a minimization of synchrotron radiation power, and the DA reduction is minimal with respect to the nominal case. The results of these studies can be seen in Fig 5.

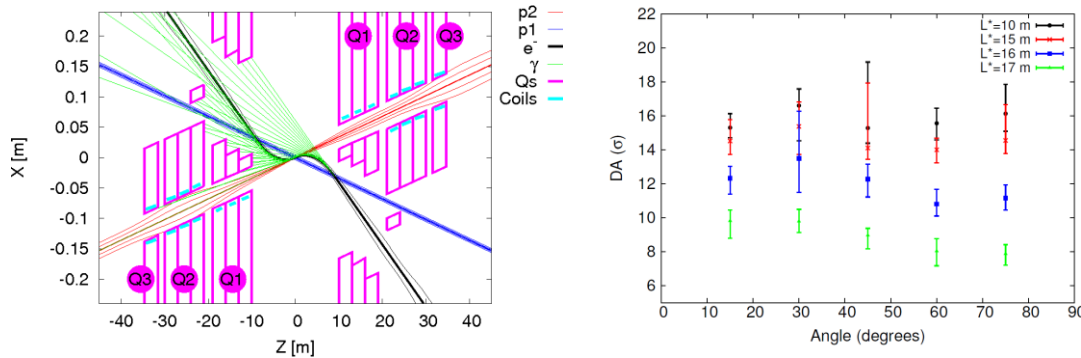


Figure 5. On the left, a schematic view of the LHeC IR where focused proton beam 2 (red) colliding with electron beam (black) while unfocused proton beam 1 bypasses the interaction [7]. Each proton and electron beam passes through its corresponding aperture in the inner triplet. On the right, a comparison of DA studies for different values of L^* . Cases with $L^*=10,15,16,17$ m with a fixed $\beta^*=10$ cm are shown.

4. LHeC Beam Physics

Several studies have been performed to monitor the behaviour of both the proton and electron beams. Since the 60 GeV electron beam and 7 TeV proton beam have significantly different rigidities, they can effect each other in very different ways.

4.1 Proton Motion and the Beam Beam effect

When two beams collide they act on each other like non-linear lenses. This can cause both a shift in the tune as well as an angular change if the beams are not perfectly centered. Jitter in the offsets between the electron and proton beam can cause emittance growth in both beams, due to both the nonlinear focusing of the beam and the angular shift imparted on the electron beam. The proton beam can gather emittance growth over many turns due to this action. The turn by turn growth rate in the normalized emittance can be estimated [8],

$$\Delta\varepsilon_n = \frac{1}{2}\gamma\beta^* <\Delta p_x^2> > \frac{\sigma_{jitter}^2}{\sigma_x^2}.$$

Where $<\Delta p_x^2>$ can be estimated either using a strong-strong beam-beam code like Guinea-Pig [9], or numerically using the Bassetti Erskine formula. γ is the relativistic quantity, β^* is the beta function at interaction, $<\Delta p_x^2>$ refers to the transverse momentum of the protons, and $\sigma_{jitter}^2/\sigma_x^2$ is the size of random offset jitters. The results of this are shown in Fig 6. Calculations using this formula show that if the beam-beam jitter can be kept below 5-7% σ_x then the doubling time for the proton beam would be greater than 1 day.

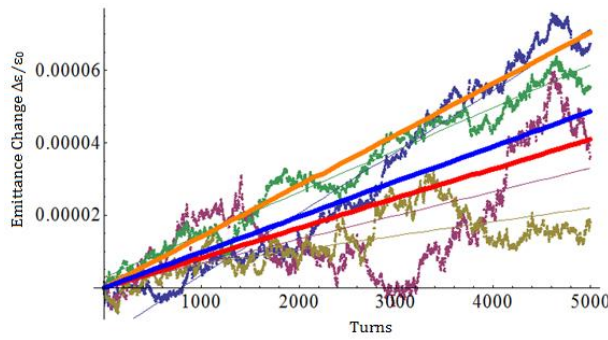


Figure 6. This shows the emittance growth in the nominal proton beam over 5000 turns using 4 different randomly seeded initial conditions, generated using the code Guinea-Pig [9]. The blue line shows the average growth rate from the simulations, the orange line shows the growth rate calculated using Guinea Pig, and the red line shows the growth rate calculated using a numerically solved trajectory.

4.2 Electron Motion in the Linac

Studies have been performed to measure the effects of multibunch wakefields within the electron linac [2], the results are shown in Fig 7.

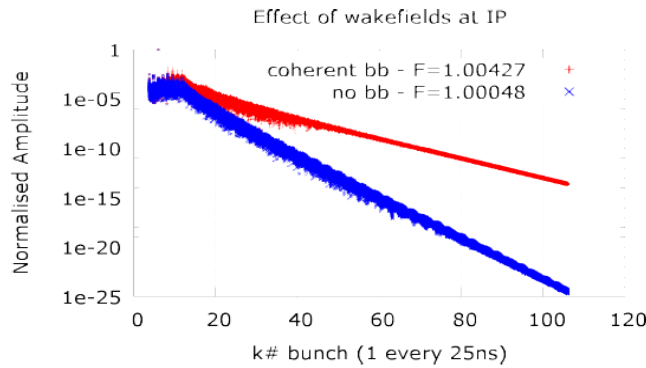


Figure 7. The plot shows how the excitation introduced by a single misaligned bunch is propagated to other bunches by means of long-range wake fields. In both cases (with and without beam-beam interactions) the excitation is damped and the beam remains stable. However the amplification caused by the beam-beam effect is not negligible.

The transport of the beam at the IP and at the dump has been verified with tracking simulations. It has been verified that the beam properties are well preserved at the IP and that it is possible to decelerate the beam with negligible losses. Most of the beam degradation is caused by synchrotron radiation. The results are shown in Figs 8,9.

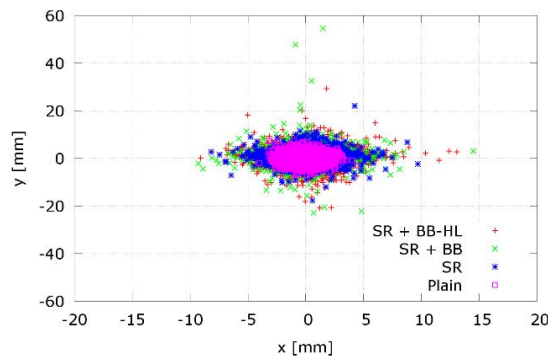


Figure 8. In this figure we see the transverse plane at the last cavity using combinations of Synchrotron Radiation and the beam-beam effect.

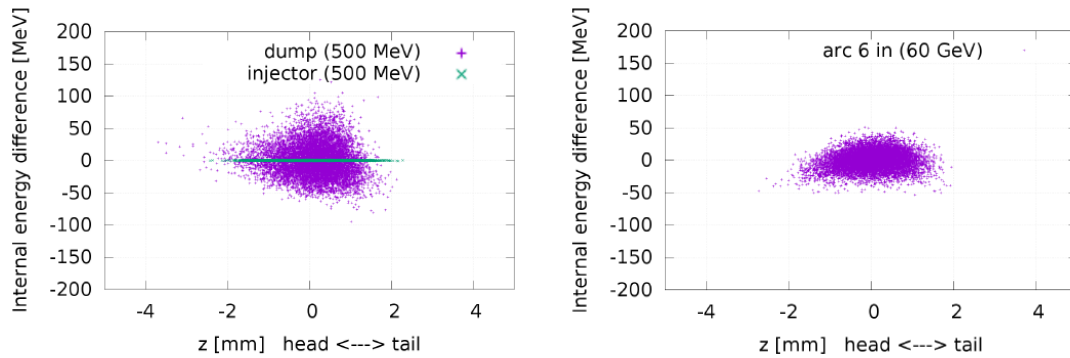


Figure 9. On the left we see the longitudinal phase space of the beam at injection and extraction, on the right we see the longitudinal phase space of the beam at collision.

5. Conclusions

The current design of the LHeC will allow for deep inelastic physics in energy ranges previously unreachable. Significant design work has already been achieved on the lattice of the machine, including how the earlier passes will bypass the detectors, and how the interaction region will be arranged. We have also examined the dynamics of both the electron and proton beams in the LHeC over short and long terms. With sufficient control systems in place the machine should operate properly. The LHeC could be the next accelerator for the study of the Higgs boson.

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