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An energy recovery electron accelerator for DIS at the LHC

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The Large Hadron Electron Collider (LHeC) is a proposed facility which will exploit the LHC beams for electron–proton/nucleus scattering, using a new 60 GeV electron accelerator. Following the release of its detailed conceptual design report last year, the configuration of a linac with racetrack shape has been chosen for its default design. Further work has been pursued in order to adapt the electron and high luminosity beam optics, to design an LHeC Test Facility at CERN and to maximise the ep luminosity to achieve values close to 10^{34} cm^{-2}s^{-1} as is desirable for precision Higgs physics with the LHeC. The talk presents an overview on the design, recent activities and an outlook for further developments.

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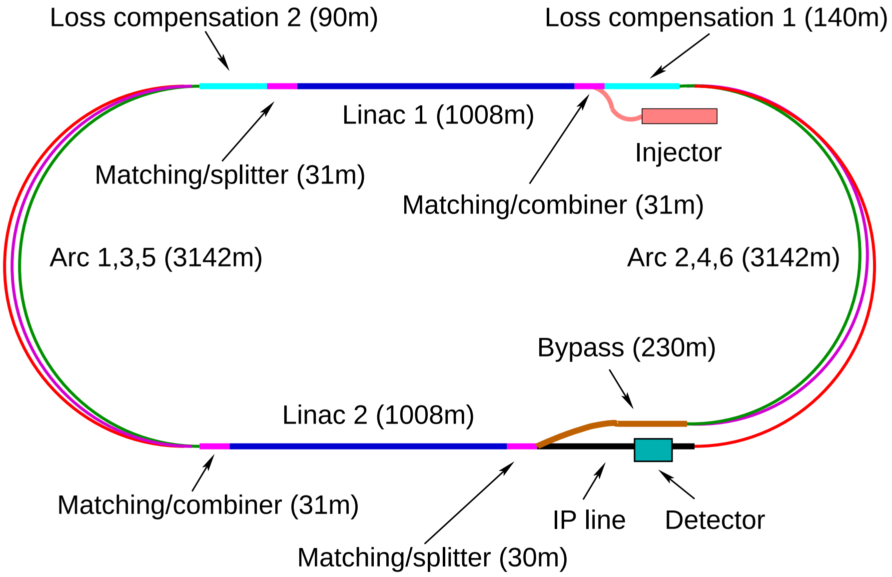

Figure 1: The baseline conceptual layout of LHeC.

1. LHeC Goal

The LHeC is a proposed electron-hadron collider, in which a new facility would produce the electron beam to collide with the LHC proton or ion beam. A CDR has been published in 2012, which presents the project and its feasibility in detail [1]. The scope of the studies is to provide a polarised electron beam (and potentially positron beam) of 60 GeV to collide with the LHC hadron beam. The goal is to reach a luminosity of 10^{33} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ or higher with a total power consumption of the lepton facility below 100 MW.

Two different main options have been studied for the CDR. Firstly, a ring-ring option, in which the leptons are accelerated and stored in a large ring that is integrated into the LHC tunnel. Secondly, a linac ring-option based on an recirculating energy recovery linac for the electrons. Both options have been found to be feasible, as documented in the CDR. However one would expect that the installation of the ring-ring option will interfere significantly more with the LHC operation. Therefore the linac-ring option has been chosen.

2. Design Overview

A schematic layout of the electron complex can be seen in Fig. 1. Some key parameters are given in table 1. The machine has a racetrack configuration with two roughly 1 km-long superconducting linacs in the straight sections, the total voltage of each linac is 10 GV. The arcs have a radius of about 1km leading to a total circumference of 8.9 km, one third of the LHC circumference.

After injection, the beam passes each linac three times, which yields a total energy of 60 GeV. The beam then collides with the proton beam before it passes through each linac another three times in order to extract the beam energy back into RF energy stored in the cavities. The superconducting linacs use five-cell cavities with a frequency of about 800 MHz, i.e. 20 times the LHC bunch frequency at the nominal 25 ns spacing. This frequency differs from the baseline in [1]. It has been chosen since the same frequency will be used in the LHC and since it offers good beam stability and the potential of a reduced cryogenic load compared to higher frequencies.

Each bunch will pass six times through the arc on the left-hand side of the complex, see Fig. 1. During the first three turns the beam energy will increase from 10 to 30 and 50 GeV. For the next three turns it will decrease from 50 to 30 and 10 GeV. Therefore only three different transport lines are required in the arc to accomodate all beam energies. This is also true for the arc on the right-hand side. Lattice designs for the arcs exist. They require a total of about 3500 dipoles and 1500 quadrupoles. The total energy radiated by one particle over all turns is about 2 GeV and the synchrotron induced emittances growth is well within the budget.

The energy loss in the arcs is compensated in additional short sections with RF. The accelerating cavities in these sections have a different frequency than in the main linacs so that they can accelerate both beams.

3. Power Consumption

The three main drivers of the power consumption are

- The beam emits synchrotron radiation in the arcs. The radiated power needs to be replaced by the RF system in the loss compensation sections, which transform wall plug power to beam power with an efficiency of about 60%. This leads to a power consumption of $P_{comp} =$ 20 MW.

- The energy stored in the fields of the accelerating cavities in the long linacs will induce losses in the walls of these cavities. The rate of these losses is given by the quality factor of the cavity Q_0, which is assumed to be $Q_0 = 2.5 \times 10^{10}$, the shunt impedance (assumed $R/Q = 570\Omega$ in linac convention) and the gradient (18 MV/m). The power consumption of the cooling system is about 700 times larger than the power lost in the cavity. The resulting power consumption is $P_{cryo} \approx 21$ MW.

- Due to the energy recovery, in first approximation the power flowing from the cavities to the beam and from the beam to the cavity balance. However additional RF power is needed to control the field and to avoid that small imperfections lead to a significant modification of field amplitude or phase. These imperfections for example include microphonic vibrations of the cavity that modify its frequency or small phase errors of the beam. The total power for RF control is estimated to be $P_{control} \approx 24$ MW.

Obviously, the power required to compensate the synchrotron radiation can only be changed significantly by changing the arc radius. In contrast, the power required for the cryogenic system depends strongly on the cavity quality factor Q_0 as $P_{cryo} \propto 1/Q_0$. The quality factor depends on the fabrication and treatment of the cavity and therefore needs to be experimentally established in order to avoid overdesign of the cryogenics system; this calls for cavity prototype development. The RF power required to control the fields depends on the cavity as well as on the beam operation. To establish this value more precisely requires prototype development and beam tests in a recirculating facility.

parameter [unit]	LHeC	
species	e^-	p, $^{208}\mathrm{Pb}^{82+}$
beam energy (/nucleon) [GeV]	60	7000, 2760
bunch spacing [ns]	25, 100	25, 100
bunch intensity (nucleon) [10^{10}]	0.1 (0.2), 0.4	17 (22), 2.5
beam current [mA]	6.4 (12.8)	860 (1110), 6
rms bunch length [mm]	0.6	75.5
polarization [%]	90	none, none
normalized rms emittance [μm]	50	3.75 (2.0), 1.5
geometric rms emittance [nm]	0.43	0.50 (0.31)
IP beta function $\beta^*_{x,y}$ [m]	0.12 (0.032)	0.1 (0.05)
IP spot size [μm]	7.2 (3.7)	7.2 (3.7)
synchrotron tune Q_s	—	1.9×10^{-3}
hadron beam-beam parameter	0.0001 (0.0002)	
lepton disruption parameter D	6 (30)	
crossing angle	0 (detector-integrated dipole)	
hourglass reduction factor H_{hg}	0.91 (0.67)	
pinch enhancement factor H_D	1.35	
CM energy [TeV]	1300, 810	
luminosity / nucleon [10^{33} cm^{-2}s^{-1}]	1 (10), 0.2	

Table 1: LHeC *ep* and *eA* collider parameters. The numbers give the default CDR values, with optimum values for maximum *ep* luminosity in parentheses and values for the *ePb* configuration separated by a comma.

4. Beam Performance

The beam will pass through each linac six times with different energy. The lattice design has thus to be optimised to provide good conditions for each turn and to minimise short- and long-range transverse wakefield effects. Studies show that these effects are indeed acceptable [1].

An important effect is the fast beam ion instability. The rest gas molecules in the beam pipe can be ionised if they collide with the circulating beam. The resulting positive ions are attracted by the negativly charged beam and in the LHeC will be trapped in a volume around the beam trajectory. The ions will create a small focusing field for the beam, which needs to be limited since it changes the optics experienced by the beams. In addition, an individual bunch that has an offset with respect to the normal orbit will also kick the ions such that they start to oscillate coherently kicking the subsequent bunches of the passing beam. If the ion density is too high, this can lead to a beam instability. It is therefore necessary to remove the ions from the beam. One method is to have a gap in the electron beam. In this gap the ions are not focused by the beam and hence drift away from the beam orbit. Such a gap requires obviously that all six different turns of the beam have a gap. Analytic estimates show [1] that a gap of about 10 μs and a train length of 20 μs is a good choice. The luminosity can be recovered by increasing the electron bunch charge by 50%. The implication of the electron ring fill pattern is that not all proton bunches will collide with an electron bunch, if the LHC is completely filled. Chosing the electron complex circumference to be

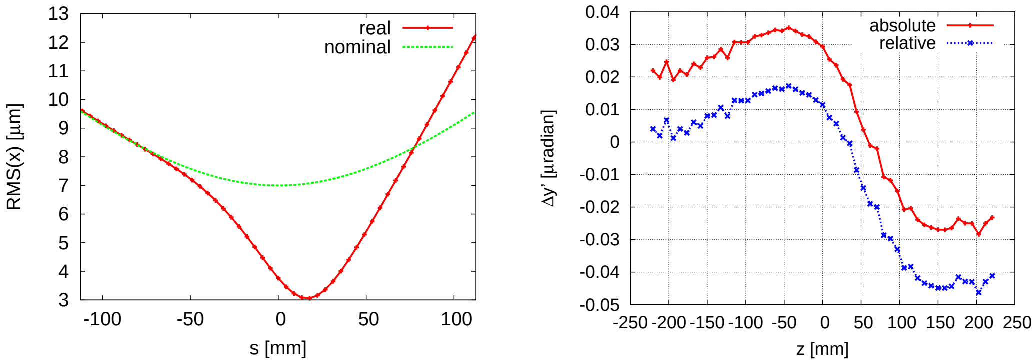

Figure 2: Left-hand side: The RMS electron beam size as a function of the longitudinal bunch position at the interaction point. Right-hand side: The transverse deflection induced by an electron beam with initial offset $y = \sigma_y$. The average deflection of each proton bunch slice is shown in red as function of their longitudinal position within the bunch. The angle of each slice with relative to the mean angle is shown in blue.

one third of the LHC circumference however ensures that each proton bunch either always or never collides with an electron bunch.

Of high importance is the beam-beam effect in LHeC. The electron beam is subjected to a strong focusing electron magnetic field of the proton beam. It will change its transverse size during the collision by about a factor two, see Fig. 2. The electron beam phase space after the collision will be strongly deformed due to this effect. This can be largely compensated by adjusting the post collision optics. However, in this case the optics is not well adapted for an electron bunch that passes with no collision.

If the electron beam has an offset, the proton beam will deflect it so strongly that the electron bunch can even pass to the other side of the proton beam. Hence the electron beam will excert a force in one direction one the head of the proton bunch and in the opposite directection on the tail. Figure 2 shows the transverse deflection of the proton beam as a function of the longitudinal particle position for an initial beam-beam offset of 1σ. The induced transverse deflection will lead to an emittance growth in each collision; a preliminary, rough estimate expects $\Delta\varepsilon/\varepsilon \approx O(10^{-7})(\sigma_{jitter}/\sigma_{x,y})^2$. Incoming bunch-to-bunch orbit jitter of the electron beam is assumed to be the most important source of the beam-beam offsets. To obtain an acceptable emittance growth during one luminosity run, one requires an electron beam jitter of the order of $O(0.01\sigma)$. This appears possible by adding a feedforward on the electron beam, which corrects the orbit jitter across the arcs.

5. High Luminosity Parameters

The baseline LHeC design would produce a few 1000 Higgs per year with a luminosity of $10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$. This allows to perform coupling measurements, in particular $h \longrightarrow b\bar{b}$. A luminosity increase by a factor of ten would make the bb measurement very precise (to about 1%) and also allow access to rarer decay channels such as cc and tautau [2].

One can envisage such a luminosity increase by a combination of several improvements [3], see table 1. Firstly, one assumes that the proton beam bunch charges and emittances foreseen for the high luminosity upgrade of LHC are reached. Secondly, one assumes a smaller beta-function at the interaction point. Thirdly, one would double the electron beam current. This would increase the RF power consumption to compensate the beam synchrotron radiation losses by about 20 MW.

6. Key Future Research and Development

- A test facility will be instrumental in establishing the cavity quality factor Q_0 and the required RF power for the cavity control. It is under consideration at CERN, a detailed description of the study status can be found in [4].
- The experimental insertion design needs to be carefully studied. The magnet design is challenging and a careful beam pipe and masking system design is required in order to prevent background.
- The civil engineering and the provision of service infrastructure will be a main cost item for LHeC. A further detailed study is required. A specific issue is the connection of the electron and proton tunnels.
- The magnet design for the arcs should be optimised for cost efficiency.
- The proton beam might be affected by electron beam via beam-beam interaction. This needs to be studied in more detail including the required mitigation methods.

7. Conclusion

A conceptual design for LHeC exists for a luminosity of $10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The design appears robust and the beam dynamics issues have been largely addressed. The two main issues that need to be further studied in detail are the impact of the beam-beam effect on the proton beam and the fast beam-ion instability. A test facility will be essential to more precisely determine the required cooling power of the cryogenics system and the required RF power to control the linac cavities.

A well founded parameter set exists for an increased luminosity of $10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. However, further beam dynamics studies will have to be performed to fully validate this design.

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