# A Large Hadron Electron Collider at the LHC

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Following HERA, the LHeC represents a new ep/eA collider of much increased luminosity and energies. Using the LHC, with $E_p$ between 1 and 7 TeV, complemented by an electron ring or linac, with $E_e$ possibly up to 140 GeV, a new range of DIS opens up and precise investigations of the proton structure and new phenomena at TeV energies become possible. A brief summary is given on machine and physics considerations as were presented at DIS08, towards a Conceptual Design Report by the end of 2009.

## 1 Introduction

This writeup is on a plenary talk [1] held at the 2008 conference on Deep Inelastic Scattering (DIS). At the time of the conference it became known that the community had lost Pief Panofsky. Besides making many other prominent contributions to science and society, Pief had played an essential role in the development, realisation and exploration of the 2 mile linear electron accelerator at SLAC at which 40 years ago the physics of deep inelastic lepton-nucleon scattering was born and the quark sub-structure of the proton was discovered. The center of mass energy squared at SLAC was $s = 2M_pE_e \simeq 40\,\mathrm{GeV}^2$. The energy $s$ of the Large Hadron Electron Collider, the LHeC under consideration today, may become as large as $4E_eE_p \simeq 4\cdot 10^9\,\mathrm{GeV}^2$, with possibly a linear electron accelerator a few times longer only than 2 miles. As an upgrade to the LHC, the LHeC provides up to $\sim 2\,\mathrm{TeV}$ of energy in the electron-quark center of mass system, an energy of unprecedent reach in DIS and of key interest for new physics beyond the Standard Model. At the times of preparation of the SLAC-MIT (and originally CalTech) experiment, the humble goal was "for a general survey of the basic cross-sections which will be useful for future proposals" [2]. Today a proposal is required to be worked out in more detail. DIS has evolved into a genuine branch of HEP, and HERA turned out to be a laboratory rich of new and also unexpected insight into mainly strong interaction physics [3]. It is obvious that the LHeC data would be of use for complementing the LHC pp, pA and AA experiments which are about to start this year. Following early considerations of an LHC based $ep$ collider, a recent paper, devoted to the physics and the machine, revived such a concept when it was shown that in a ring-ring configuration a luminosity of up to $10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ may be reached and

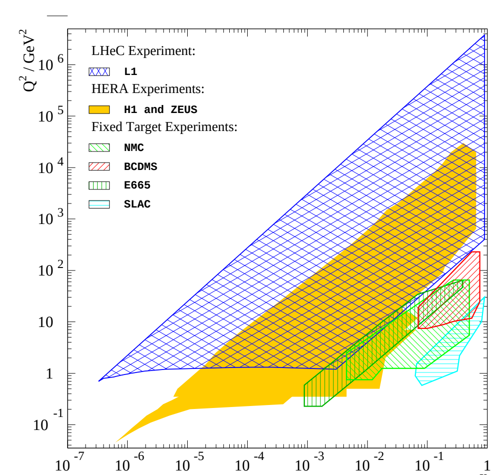


Figure 1: Kinematic plane of lepton-proton experiments with stationary protons, of HERA and of the LHeC.

simultaneous operation of *ep* and *pp* collisions seemed possible [4]. Subsequently this concept was developed further until end of 2007 ECFA and CERN endorsed the proposal to work out a Conceptual Design Report (CDR) on the LHeC [5]. At the DIS08 meeting as part of the session on the future of DIS new ideas were presented, both on the machine [6, 7] and on its physics potential [8, 9, 10, 11]. This writeup represents a brief summary of previous developments, the parallel session contributions and the future plans towards the LHeC.

## 2 Machine

There have been two options discussed, one based on a linear electron accelerator directed to the LHC, the linac-ring option (LR), and a circular electron accelerator mounted on top of the proton/ion ring of the LHC which is called the ring-ring option (RR).

The RR design study [4] and further discussions assume that an *ep* collider phase was proceeding in parallel with the upgraded LHC operation. The LHeC needs at least one interaction region. The accelerator may start operation unlikely before in 10 years from now. By about then it is possible that the programme of ALICE, at point 2, or/and LHCb, at point 8, may have been realised and a new *ep* detector can be installed. Given the occupation of other caverns, by ATLAS, CMS and machine structures, these are the likely caverns one may envisage for the LHeC.

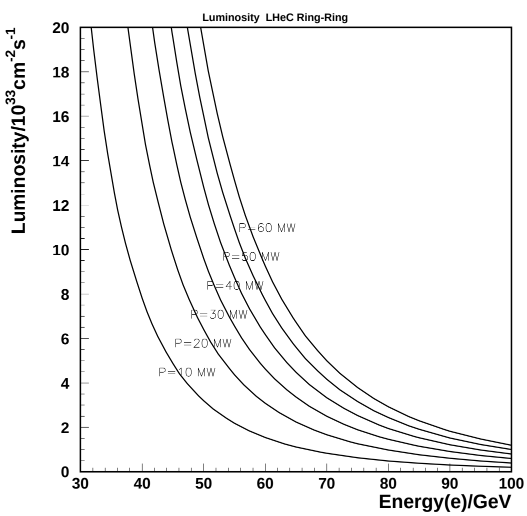


Figure 2: Estimates of the peak luminosity in *ep* collisions as functions of the electron beam energy for a ring-ring LHeC, with the beam power as a parameter. The calculations use the upgraded LHC proton beam. HERA-I did operate at $10^{31}\text{cm}^{-2}\text{s}^{-1}$ and reached about a fourfold increase with the luminosity upgrade. The LHeC may reach a factor O(100) higher luminosity.

### 2.1 Ring-Ring Option

The RR option, as was presented to this meeting in [7], needs a new injector since the injector elements of LEP have been dismantled. There are various possibilities [7], and the injection is generally considered to be of no principal problem. It may use energies well below the LEP injection energy of 22 GeV because of the reduced electron bunch intensity of the LHeC as compared to LEP [a]. A possibility may be a scaled down version of the ELFE project [7, 12]. Another concept is to build a superconducting Linac of $\sim 750$ m length using ILC type cavities which may provide a 20 GeV electron beam. This beam could be an injector into the *e*-ring, but it may also be a first step of the LHeC in a linac-ring configuration. At electron beam energies lower than are finally foreseen for the

[a] Note that LEP stored $4 \cdot 10^{11}$ electrons in 4 bunches while the LHeC, in the version of [4], has $1.4 \cdot 10^{10}$ electrons in 2800 bunches as adapted to the LHC.

LHeC, first measurements at $\sqrt{s} \sim 700$ GeV may become possible prior to realising the full electron accelerator. Such ideas are of interest for a staged realisation of the LHeC. It should be noted in this context that HERA has not performed any $eN$ measurements other than with protons, i.e. there is quite a programme to be pursued [13] even if initially the energies would not much exceed the ones of HERA[b].

The luminosity in the RR configuration, for matched $e$ and $p$ beams and tolerable tune-shifts [4], can be estimated as follows

$$L = \frac{N_p \gamma_p}{4\pi e \epsilon_{pN}} \cdot \frac{I_e}{\sqrt{\beta_{xp}\beta_{yp}}} = 2.4 \cdot 10^{33} \cdot \frac{I_e}{50mA} \frac{m}{\sqrt{\beta_{xp}\beta_{yp}}} cm^{-2}s^{-1}. \quad (1)$$

In this equation, $I_e$ is the total lepton beam current, $N_p$ is the number of protons per bunch, $\gamma_p$ is the Lorentz factor of the protons which depends on the proton beam energy, $\epsilon_{pN}$ is the normalized proton transverse beam emittance (which is assumed to be equal in both planes) and $\beta_{xp}$ and $\beta_{yp}$ are the values of the proton beam amplitude function ($\beta$-function) at the interaction point. The electron beam current is a function of the power $P$ and the energy given by

$$I_e = 0.35mA \cdot \frac{P}{MW} \cdot (\frac{100GeV}{E_e})^4. \quad (2)$$

The proton beam parameters assumed in Fig. 2 correspond to expectations on the upgraded LHC beam [16] $N_p = 5 \cdot 10^{11}$ and $\epsilon_{pN} = 3.75\mu$m, using a horizontal $\beta$ function of 1.8 m and a vertical $\beta$ function of 0.5 m. This yields a factor of $\simeq 3$ higher luminosity than was considered in [4] which was based on the non-upgraded LHC, using the same $\beta$ functions. A similarly improved parameter range was used in [6] with $N_p = 3.4 \cdot 10^{11}$ and $\epsilon_{pN} = 1.9\mu$m. With such a super proton beam, the luminosity of the LHeC in its RR configuration may well exceed the HERA values by two orders of magnitude. For example, at $E_e = 70\,(50)$ GeV with a modest power of 20 MW one obtains a luminosity of $2\,(7)\,10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

The ring-ring option for the LHeC has two particular features. It is limited in energy to about 80 GeV because of a then too strong synchrotron radiation and limited space for the $rf$ installation [17]. It also rather seriously interferes with the LHC installations. First checks in the preparation of the project to ECFA, in November 2007, had not revealed any real hinderance, the ring may be mounted on top of the LHC, with some modifications, ATLAS, CMS and a few other of the 8 points of the LHC may be bypassed and the changed diameter be compensated by a small adjustment of the $e$ ring radius, the $rf$ may be installed in the bypasses, etc. However, it is clear that for the CDR a more detailed consideration of the implications is required in order to judge upon the feasibility of a RR LHeC. The overriding attraction of the ring is its very high luminosity. A summary of the RR configuration is given in [18].

## 2.2 Linac-Ring Option

Adding a linear $e$ accelerator to the LHC $p/A$ beams is attractive because it may lead to higher energy than the RR option and the interference of the LHeC with the proton ring

[b]A low electron energy beam combined with the LHC leads to a very asymmetric beam configuration. At low $x$, however, which is the most interesting region for $eA$ physics, the collisions appear rather central. Such a first phase of the LHeC would represent a higher energetic version of the eRHIC $eA$ programme [14], at moderate accelerator cost if the SPL was used [15]. As part of the overhaul of the LHC injectors, a new superconducting proton linac (SPL) is considered as injector to a new 50 GeV PS.

installations is much reduced. The question then is as to how large the luminosity can be expected and which power would be available for increasing it. Following [19], the luminosity of an LR type LHeC can be estimated as

$$L = \frac{N_p \gamma_p}{4\pi e \epsilon_{pN} \beta^*} \cdot \frac{P}{E_e} = 5.0 \cdot 10^{32} \cdot \frac{P/MW}{E_e/GeV} cm^{-2} s^{-1}. \tag{3}$$

which uses as before the SLHC parameters on the proton intensity and emittance. It also is assumed that a $\beta^*$ of 10 cm may be reached [6, 20]. With these parameters the luminosity, illustrated in Fig. 3, for comparison with the RR option quoted above, at $E_e = 70\,(50)$ GeV for a beam power of 20 MW is $1.4\,(2)\,10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The LR luminosity is constant unlike the RR case, with a synchrotron radiation caused decrease of the $I_e$ current in the ring. This provides an estimated gain of about a factor of two for the integrated luminosity in favour of the LR.

At 140 GeV the LR, following Eq. 3, may reach $0.7\,10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ which is about 2-3 times higher than the HERA-II luminosity. Fig. 4 shows a calculation of the integrated event rate as a function of $Q^2$ for HERA conditions, and a 70 GeV high luminosity LHeC compared with a 140 GeV LHeC of 10 times lower luminosity. The luminosity needs to be increased when the collider energy is raised since the cross sections dramatically decrease with energy, $Q^2$ in the case of DIS. While at lower $Q^2$ there is no real luminosity problem in DIS, for most of the physics, the highest values require a maximum luminosity. One also sees in Fig. 4 that at $Q^2 \sim 5 \cdot 10^5\,\mathrm{GeV}^2$ doubling the energy compensates for a factor of 10 less luminosity and the extremely high values of $Q^2$ may naturally be reached only with the highest beam energy. If efficient use of the power may be made by implementing energy recovery as discussed in [20] or by cooling the protons as reported at this conference [6] one may significantly go beyond $10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ also for a LR option at high energies. This requires considerable $R + D$ efforts.

There are further differences of the RR and the LR option since the Linac has a high degree of polarisation, difficult to achieve with the ring. On the other hand, to obtain intense positron beams at luminosity of order $10^{32}$ is an extraordinary requirement on the intensity of the positron source.

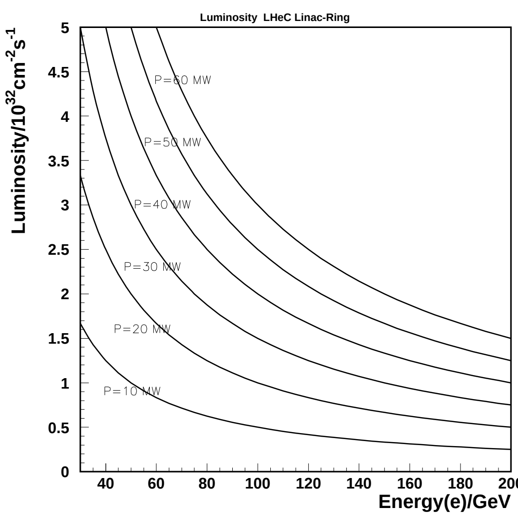


Figure 3: Estimates of the luminosity in *ep* collisions as functions of the electron beam energy for a linac-ring LHeC, with the beam power as a parameter. The calculations use the upgraded LHC proton beam.

## 3 Physics

The physics programme of the LHeC comprises four major areas: i) exploitation of *eq* physics around and beyond a TeV of energy which includes resolving the proton structure down to nearly $10^{-20}$ m; ii) precision measurements of the partonic structure of the proton and tests of QCD in the or close to the kinematic range of the LHC; iii) exploration of nuclear structure and dynamics in $eN$ scattering in a kinematic range extended by 4 orders of magnitude as compared to previous measurements; iv) the investigation of high density partonic matter when $\alpha_s$ is small, and gluon saturation is predicted to occur. This programme is being worked out in the course of preparing for the CDR, see [4, 5].

At this conference 4 contributions have been presented [8, 9, 10, 11] on the four major physics themes of the LHeC as are very briefly reported here. In [8] leptoquarks and contact interactions at the LHeC are considered. The LHeC has a remarkable potential on so far unknown physics related to new *eeqq* interactions, which may appear as contact interaction terms related to leptoquarks or extra dimensions. An *ep* collider produces first generation leptoquarks as resonances in the $s$ channel with fermion number $F = 0$ in $e^+p$ and $F = 2$ in $e^-p$ collisions. Because of the preferred production mechanism, the LHeC covers a similar discovery range as the LHC despite its lower *cms* energy and its lower luminosity. Should such states indeed be observed at the LHC, the LHeC would provide an ideal laboratory for their exploration with clearly defined initial conditions and, for the LR option, a high polarisation of the electron beam. The reach of the LHeC on CI interactions is impressive, for example about 60 TeV for a parity conserving VV CI model or 5.5 TeV for the mass $M_s^+$ in the AAD model for extra dimensions [8].

Table 1: *Estimated limits, read off from [8], on leptoquark masses in TeV for I (LHC, 100fb$^{-1}$), II (LHeC, 70 GeV, 2 x 10fb$^{-1}$) and III (LHeC, 140 GeV, 2 x 1fb$^{-1}$), assuming a Yukawa coupling of $\lambda_{LQ} = 0.1$. The luminosities may be higher by a factor of 10 for all cases which provides a better, albeit not much better, discovery potential. The effects of lepton beam polarisation deserve further study.*

| LQ Type | I - LHC | II - 70 GeV LHeC | III - 140 GeV LHeC |
|---|---|---|---|
| $S_0^L$ | 1.3 | 1.4 | 1.6 |
| $S_1$ | 1.6 | 1.3 | 1.6 |
| $V_0^L$ | 1.7 | 1.1 | 1.4 |
| $V_1$ | 2.1 | 1.2 | 1.5 |

In [9] a study was presented of the potential measurement accuracy of the strong coupling constant $\alpha_s$ at the LHeC. Using a simulation of the inclusive DIS NC and CC cross sections, a value of about 0.2% was obtained for the experimental uncertainty on $\alpha_s$. This includes the systematic errors and their correlations for a hypothetical detector which was assumed to be about twice as well calibrated as the H1 detector [21]. Such an accuracy would be a major step in measuring a most fundamental constant of nature and lead to further insight on the possible unification of the interactions at the Planck scale. It would also finally resolve the question of how large $\alpha_s$ in DIS really is in that this measurement, for the first time, would be independent of the BCDMS data which for decades determine the DIS value of $\alpha_s$ to be rather low. Measuring the coupling to such an accuracy would pose many theoretical questions, as on the treatment of heavy flavours and or the scale dependence requiring pQCD to N$^k$LO, $k > 2$.

In [10] an extremely wide potential was discussed of the physics at the LHeC. Much emphasis was given to the unknown features of hadron structure and parton dynamics embedded in the final state at larger $x$, which puts high demands on the instrumentation of the LHeC detector in the proton beam (forward) direction. It was also pointed out that this machine should be a factory for top quark production and also allow $W$ boson fusion of the Higgs particle to be investigated, should the latter exist. These questions, the investigation of single top and anti-top quark production in $e^+p$ and $e^-p$ CC scattering, respectively, and the calculation of Higgs production at the LHeC were subsequently considered further [22] in the first ECFA-CERN workshop on the LHeC [23].

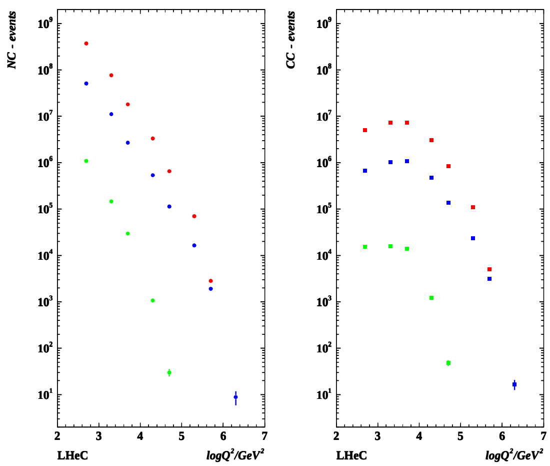


Figure 4: NC (left) and CC event rates (right) in $e^-p$ scattering as a function of $Q^2$ for $27.5 \times 920\,\mathrm{GeV}$, and $1\,\mathrm{fb}^{-1}$ (lowest points, green), which is about the combined H1 and ZEUS luminosity, disregarding the $e$ beam charge, for $70 \times 7000\,\mathrm{GeV}$ and $100\,\mathrm{fb}^{-1}$, as expected for the RR option of the LHeC (top points in red), and for $140 \times 7000\,\mathrm{GeV}$ and $10\,\mathrm{fb}^{-1}$, as expected for the LR option (middle points in blue).

The fourth contribution to the parallel session on the LHeC [11] was devoted to low $x$ physics. From unitarity one expects saturation of the gluon density to occur. In a study using simulations of measurements of $F_2$ and $F_L$ at the LHeC it was shown that due to the extended kinematic range and the anticipated high accuracy on $F_2$ and also $F_L$ it would become impossible to fake a DGLAP behaviour should it not exist at such low $x$ despite the unknown $x$ dependence of the input parton distributions. It also was pointed out that further measurements on heavy quark structure functions, DVCS and diffraction would be vital to complete the picture. The physics at low $x$ does not require very high luminosity but it needs acceptance in the backward region down to 1°, at least, and the highest electron beam energy in order to have a maximum range of $Q^2 = 4E_eE_pxy$ at fixed $x$.

## 4 Summary

The LHeC promises to become an upgrade option of the LHC which has an unprecedented physics potential for the physics of $eq$ interactions at TeV scales, the understanding of proton structure and QCD dynamics, for precision measurements of a variety of quantities, as the beauty and gluon densities and of $\alpha_s$, for discovering the mechanism of nuclear and high parton densities in the so far unexplored range of low $x$. The plan has been to work out a Conceptual Design Report in about one year's time when the first signs for physics at the Tera scale are expected to appear. The CDR will lay out the most important challenges and the potential for the machine, the interaction region, the detector and in the new $ep$ and $eA$ physics. The CDR will also carefully describe the main aspects of the possible ring-ring and linac-ring realisations of the LHeC. It is attractive to consider resuming lepton-nucleon scattering experiments starting with injector energies and developing the programme to the highest possible energy and luminosity. The LHeC promises to be a PeV energy equivalent of the generations of fixed target lepton-proton scattering experiments. Its worth a yet closer view and it may become realised.

## Acknowledgments

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