

# The Large Hadron Electron Collider Project

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A Conceptual Design Report (CDR) for the Large Hadron Electron Collider, the LHeC, is being prepared to which an introduction was given [1] for the plenary panel discussion on the future of deep inelastic scattering held at DIS09. This is briefly summarised here. The CDR will comprise designs of the ep/eA collider, based on ring and linear electron accelerators, of the interaction region, designed for simultaneous *ep* and *pp* operation, of a new, modular detector, and it will present basics on the physics motivation for a high luminous Tera scale electron-nucleon collider as a complement to the LHC.

## 1 Introduction

Much of the current thinking on the future of particle physics is focused on the mechanism of electroweak symmetry breaking. Current limits from electroweak precision measurements and from the Tevatron experiments restrict the mass range of the standard model Higgs particle mass to a narrow window above the direct LEP limit, and with increasing intensity one considers alternative mechanisms for the origin of mass of the vector bosons [2]. The origin of baryonic mass is as fascinating a problem. It is not rooted in the electroweak symmetry breaking but in the dynamics of parton interactions as described in QCD. With the possibility of standard expectations not becoming confirmed and experiment, with the LHC, moving into Terascale physics, the prospects for new physics become wider and the need for precision measurements in a new kinematic range apparent. A new electron-proton and electron-ion collider operating at the Terascale certainly would be a major instrument to study the new horizon of particle physics and contribute substantially to its further development based on high energy particle accelerators.

The LHeC has a fascinating physics programme, as has been presented to this workshop [3, 4, 5] and will be summarised below. Based on current considerations, also presented at this conference, both the machine [6] and a new detector [7] represent as fascinating opportunities. In a broader context a TeV *ep* collider is related to a number of fundamental questions worth dealing with prior to a more detailed discussion of its physics and its technical challenges. Apart from the strong force, there is not much difference between leptons and quarks, and it still is a mystery why these form two types of matter instead of one as Abdus Salam had already observed three decades ago [8]. HERA was mankind's highest resolution microscope and established a limit of  $6 \cdot 10^{-19}$  m for quarks to be pointlike. Nowadays much effort is devoted to build microscopes to study molecules using particle accelerators, or to look to the outer space. A new, high resolution microscope is due to move the frontier of exploring the substructure of matter to even smaller dimensions. Here, resonant electron-quark states or a further layer of substructure may be found, at distances smaller than four orders of magnitude than the radius of the proton. The LHeC probes a quark radius as small as  $7 \cdot 10^{-20}$  m. If a proliferation of new states, possibly obeying supersymmetry, would be discovered at the LHC, it was for an *eq* collider based on lepton charge and polarisation variations to unfold much of the new spectroscopy and determine the quantum numbers of

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new states. If physics signals from still higher scales should occur at the LHC, as via contact interaction enhancements, a Terascale  $ep$  collider was necessary to distinguish signs for new physics from variations of parton distributions by virtue of high precision measurements of partons into the kinematic range of the LHC. At the LHeC radically new phenomena in the dynamics of parton interactions are expected to be established, as the saturation of the rise of the gluon density or instantons, and the mechanism of parton emission at low  $x$ , often related to the BFKL or BK equations, may be clarified. For the first time ever, owing to the high energy, luminosity and variation of charge and polarisation, a DIS experiment will be able, completely and essentially directly, to unfold the partonic content of the proton by measuring the valence, light and all heavier sea quark and the gluon distributions. The LHeC would extend the knowledge on the structure of the neutron and of nuclei by four orders of magnitude. Thus it represented the necessary base for the study of deconfinement and collective phenomena in nuclei, and it would support the development of postulated links between QCD and string theory.

The present write-up describes the brief introduction [1] given on the LHeC project [9] to the panel discussion on the future of deep inelastic scattering at the DIS09 workshop. The panel also discussed the options for lower energy electron-nucleon and polarised  $ep$  collisions as are considered at BNL and Jlab [10]. Previous summaries of the status of the LHeC project have been given to DIS08 [11], with a basic discussion on the ring-ring (RR) and the linac-ring (LR) configurations, and to ECFA in 2008 [9].

The intense proton and ion beams of the LHC are the basis for a new  $ep$  and  $eA$  collider of unprecedented luminosity, 100 times larger than achieved at HERA. Thus CERN, ECFA and NuPECC have joined efforts in designing a reliable and affordable concept. The CDR on the LHeC is being worked out within a joint workshop, see [9], the first of which took place in 2008 with a follow-up meeting in 2009. The CDR is foreseen to be delivered in 2010, further design work is being pursued on the ILC, CLIC and a multi-TeV muon collider, and with the first observations at the LHC expected soon, the deliberations on the future of HEP will eventually rely on solid experimental grounds. A strategic goal may be to explore the Terascale phenomena with complementary  $pp$ ,  $l^+l^-$  and  $ep$  colliders, guided by future expectations and in view of the successful exploration of the Fermi scale with the Tevatron, LEP and HERA experiments, now being completed.

## 2 The Accelerator Alternative

As is discussed e.g. in [11, 12], two options for the electron beam are under study, one based on a synchrotron and one using an electron linac. An electron ring with newly designed magnets installed above the LHC would provide energies between a few tens of GeV up to about 80 GeV, as is limited by synchrotron radiation losses and rf. A first rather complete design study is [13]. At  $E_e = 50$  GeV and  $P = 50$  MW power, such a configuration may deliver  $5 \cdot 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$  luminosity, i.e. a factor of 100 higher than the maximum achieved with HERA. Such values may be obtained in the standard LHC beam configuration and slightly increase with the sLHC upgrade [6]. Such a luminosity potential may provide integrated luminosities of order  $100 \text{ fb}^{-1}$ .

An electron linac may be independently installed providing energies between a few tens of GeV up to perhaps 150 GeV, a limit essentially determined by cost, and possibly the proximity of the river Rhone. At 50 GeV and 50 MW power, such a configuration may deliver  $5 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$  luminosity, assuming the LHC was upgraded [6] to reduce emittances

and enhance the proton bunch current. Because of the constant  $e$  current, unlike the ring situation where the  $e$  current decreases with time, the peak luminosity is worth a factor of about two more than in the RR scenario. It varies proportional to  $P/E_e$ . Integrated luminosities of tens of  $\text{fb}^{-1}$  appear in reach for the linac-ring configuration. Efficient use of power may be made if energy recovery (ER) techniques may be applicable to such a high energy beam configuration as has been suggested to be worth seriously considering [14]. An ERL linac-ring LHeC had the potential of exceeding  $10^{33} \text{ cm}^{-2}\text{s}^{-1}$  luminosity, which, however, requires significant R+D efforts. Energy recovery as a technique may deserve much higher attention as particle physics needs to explore smaller and smaller cross sections while the cost of power and the need for it rise.

### 3 Physics

HERA has taught that an electron-proton collider at the energy frontier represents a laboratory, in which a wide range of questions can be studied [15]. For the purpose of the CDR, so far, the attention is focussed to six, related areas of physics as introduced below. These are being studied in three working groups [3, 4, 5].

#### 3.1 Unfolding the Partonic Structure of the Proton

The focus of  $ep$  is on the structure of the proton. HERA, despite its success, was limited in kinematic range and luminosity. It therefore could not exploit fully the potential of  $W$  and  $Z$  exchange tree level physics in unfolding the partonic structure of the proton. Its measurements at high  $x$  are limited, for charged currents (CC) to  $x < 0.5$ , and at low  $x$  to protons only, and just below where one expects unitarity to limit the growth of the gluon distribution in DIS. Much of the present information on parton distributions is only obtained in parameterised QCD fits with a number of assumptions on sum rules or quark-antiquark symmetry. The LHeC, in a kinematic range of  $Q^2$  and  $x$  much better adapted to the LHC, will be able to measure the valence quarks between a few times  $10^{-4}$  and 0.8 in  $x$ , exploiting huge  $\gamma Z$  interference effects in charge and polarisation asymmetries and the abundant CC  $e^\pm p$  scattering events. The up and down quark distributions are measured from CC and, using deuterons, employing Gribovs relation between shadowing and diffraction to control shadowing at low  $x$ . Tagging of spectator protons can be expected to essentially remove Fermi motion effects in  $en$  scattering at large  $x$ . At the LHeC precision measurements of the charm and beauty structure functions will be possible over a huge kinematic range, around and away from threshold, based on an increased cross section and on  $c$  and  $b$  tagging using dedicated tracking detectors and exploiting the fact that the LHeC beam spot will be of order  $10 \times 25 \mu\text{m}^2$ , much more narrow than at HERA. For the first time ever, accurate measurements of the strange and the anti-strange quark densities can be performed owing to the high  $Q^2$  and large luminosity in CC  $e^\pm p$  reactions where charm is tagged. The LHeC further is a single top and anti-top quark factory with a cross section of order  $10 \text{ pb}^{-1}$  for the  $Wb$  fusion cross section in the rather clean single  $t$  production environment of CC scattering. Finally, the much extended range and projected precision of the measurements, including a dedicated measurement of  $F_L$ , will constrain the gluon density over 6 orders of magnitude in  $x$  including the edges of the Bjorken  $x$  range, where  $xg$  currently is most uncertain. If ever one was interested in the partonic contents of the proton, here lies an answer which comprises all flavours and the gluon.

### 3.2 Exploration of Superhigh Energy Scales

The current studies on accessing higher scales than with direct measurements focus on electroweak couplings,  $\alpha_s$  and contact interactions (CI), all exploiting the precision and kinematic range of simulated LHeC data. The LHeC is an electroweak precision machine. In initial studies measurements of the light quark weak NC couplings have been simulated achieving a more than tenfold improvement in accuracy over current measurements from LEP, the Tevatron and HERA. This hints to a unique potential for precision electroweak physics reaching high scales and effective couplings. The experimental accuracy on  $\alpha_s$  is of order per mille, ten times better than currently achieved. This suddenly moves the strong coupling to a level of accuracy similar to  $\alpha$  and  $G_F$  when extrapolated to the Planck scale. Such an accuracy is of crucial importance to explore supersymmetric unification scenarios. It is also long overdue to precisely measure  $\alpha_s$  independently of BCDMS data, which require it to be very small, and thus to possibly resolve a tension between the DIS and jet based data [16]. A tenfold increase in accuracy on  $\alpha_s$  would also represent a huge challenge to the techniques and scale dependence of pQCD calculations. A study of contact interactions leads to limits of O(50) TeV and corresponding results on extra dimensions. The LHeC, owing to its well specified  $eq$  initial state, its kinematic range and high precision, is an accelerator for looking into the super-high energy range, i.e. for much beyond what today is called the Terascale.

### 3.3 Complementing the LHC

The LHC is built as the machine to find new physics beyond the SM by accessing the Terascale. It relies on the ATLAS and CMS multipurpose detectors and there is a huge variety of physics predictions to study [17, 18]. New states may be largely expected to be produced via gluon ( $g$ ) or  $b$ -quark induced reactions. An example is the Higgs particle,  $H$ . In the SM,  $H$  is predominantly produced via  $gg$  fusion. In the MSSM, however, at large  $\tan\beta$ , a Higgs particle  $A$  is produced via  $b\bar{b} \rightarrow A$ . The knowledge of the gluon and  $b$ -quark distributions becomes crucial particularly at large and at small  $x$ , which in Drell-Yan scattering are related to large masses and rapidities. The best possible knowledge of these and the other parton distributions is provided by the LHeC, and it should render any pdf related uncertainty in LHC studies negligible. The production cross section of the Higgs particle at the LHC is not large but the rarer production modes, as  $H \rightarrow \gamma\gamma$  and  $H \rightarrow \tau\tau$ , have a higher probability to discover and study the  $H$  than the dominating channel  $H \rightarrow b\bar{b}$ . That decay, however, appears to be promising for being studied in  $WW \rightarrow H$  fusion in CC scattering at the LHeC where the unique signature of large missing  $E_T$  and efficient  $b$  tagging should allow for its decent measurement. The cross section is of order 200 fb at masses below 150 GeV. Therefore a measurement of the Higgs coupling to per cent accuracy may be possible. A special study is being pursued, in which contact interaction effects, as possibly observed in Drell-Yan scattering at the LHC, are confronted with the freedom of adjusting parton distributions. In the model studied, accessing 40 TeV CI interference effects, the parton distributions would be so well constrained by the LHeC that the CI would be unambiguously identified as new physics, while the HERA and BCDMS data alone would allow some rearrangement of anti-quark distributions at larger  $x$  to be compliant with the CI effects and DIS. The subject of complementing the LHC with  $ep$  is being studied further, it concerns not only genuine signals for physics beyond the SM but also subjects like parton dynamics, parton emission and evolution, factorisation or jet physics, subjects which can be

expected to become crucial for understanding Terascale physics in  $pp$  as here it is mainly QCD which leads to BSM.

### 3.4 New Physics in the eq Sector

An  $ep$  machine is naturally suited to search for singly produced new states coupling to an electron- (or neutrino-) quark pair such as lepto-quarks or supersymmetric particles in RPV SUSY. The cross section for single LQ production is about a hundred times higher than in  $pp$  at a given mass. It depends on the unknown coupling  $\lambda$  of the LQ to the electron-quark pair and means for a coupling of  $O(0.1)$ , that LQ masses up to nearly  $\sqrt{s} = 2\sqrt{E_e E_p}$  may be directly probed. If such states would be discovered at the LHC, most likely in pair production [17], the LHeC appeared most suited to determine their quantum numbers: the fermion number from a charge asymmetry measurement reaching higher masses than the LHC [13], the spin from the angular distribution of the decay products, possible neutrino decay modes, the coupling down to small values, and the chiral structure of the coupling using the polarisation of the lepton beam. At the LHC from LQ pair production and dilepton production via LQ  $t$ -channel exchange much information may be obtained, a clear spectroscopy, however, of such states required a polarised, high luminosity  $ep$  collider at the appropriate energies. It is possible that this physics requires a linac to be chosen for the LHeC as this potentially reaches values of  $\sqrt{s}$  of 2 TeV with a 143 GeV electron beam or even higher cost permitting. A further example for genuine new physics with the LHeC is the search for excited electrons and neutrinos, which may couple to a gauge boson via gauge mediated interactions proportional to the ratio of the unknown coupling to the compositeness scale,  $f/\Lambda$ , or phenomenologically similarly to quarks and leptons via a CI. As has been shown in a first study, the sensitivity of the LHeC extends to much smaller values of  $f/\Lambda \simeq 10^{-4}$  than the LHC and possibly to higher masses. Detection of excited fermions would hint to their compositeness. It is to be noted that the LHC had been chosen for good reasons, for its high energy and large luminosity, as the pilot machine to explore the Terascale. Coming after a decade of LHC experimentation, neither a lepton-lepton nor an electron-proton collider may be expected to have a huge resource of undetected physics to discover at TeV scales. However, their salient features and complementarity will turn out to be vital for understanding new Terascale physics, and their salient precision measurements will lead much further in energy.

### 3.5 Parton Saturation at low $x$

At small Bjorken  $x$  the gluon and sea quark distributions rise strongly when  $x$  decreases at fixed  $Q^2$ . There are arguments based on unitarity that the gluon distribution should not rise stronger than  $Q^2/\alpha_s \text{GeV}^{-2}$ . Therefore a qualitative change is expected on the parton dynamics at small  $x$ , in which non-linear recombination effects are predicted to modify the so-far successful DGLAP equations. Without a considerable extension of the kinematic range as compared to HERA, combined with high precision and large acceptance in forward and backward region, one will not be able to discover parton saturation. For the CDR on the LHeC, it has been shown that inclusive structure function measurements, at low  $Q^2$  between 0.5 and about 1000  $\text{GeV}^2$  and  $x$  down to  $10^{-6}$ , of highest possible precision, a per cent on  $F_2$  and about 5% on  $F_L$ , will allow to discover saturation in the DIS region. This would lead to a new understanding of low  $x$  theory, as of resummation and the consistent

treatment of  $F_L$  and  $F_2$ . It would also be the discovery, in  $ep$ , of a new phase of matter, in which partons interact collectively while  $\alpha_s$  is small. A new regime at low  $x$ , which long had been searched for at HERA, would also directly affect neutrino-astro physics, which deals with neutrino-nucleon interactions at extremely small  $x$ . An observation of saturation at the LHeC would perhaps first be made in diffractive DIS, in which  $xg$  enters squared. With the phase space extended to a few hundreds of GeV in  $M_X$ , the diffractive production of charm and beauty states, of the  $Z, W$  and possibly the Higgs would become a major field of research in  $ep$ . From DVCS generalised parton distributions would become measurable owing to the polarisation and high luminosity. It went without much notice that HERA and new theoretical insight has lead to a significant extension of the parton model with the introduction of parton amplitudes and interferences, which are at the basis of proton holography [19]. This physics so far is at its infancy.

### 3.6 Parton Structure of Nuclei

While any generation of fixed target DIS experiments was given the opportunity to study lepton-nucleon scattering, i.e. the structure of the neutron and nuclei besides that of the proton, HERA was not. As a result the knowledge on the parton distributions in nuclei is restricted to the region of large  $x$  and low  $Q^2$ . It may be extended with the LHeC by four orders of magnitude. If one wants to understand the plasma effects in  $AA$  collisions at the LHC or to verify theories in nuclear shadowing at low  $x$  one needs an adequate experimental  $eA$  input. The genuine interest in  $eA$  physics is also related to the expectation that the gluon density in a nucleus  $A$  shall be amplified proportional to  $A^{1/3}$ . If one assumes  $xg$  to grow like  $x^{-\lambda}$  towards low  $x$ , then this amplification implies that a gluon density is measured at an effective  $x$  value reduced by  $A^{-1/3 \cdot \lambda}$ , i.e. for  $x = 10^{-4}$ ,  $A = Pb = 208$  and  $\lambda = 0.2$  one would probe  $x$  values close to  $10^{-8}$ , which is where superhigh energy neutrino physics is sensitive to. Such high densities are deep beyond unitarity limits and therefore a radically new behaviour of cross sections,  $A$  dependences and parton distributions is expected, with, for example, a logarithmic limit  $\propto \ln(1/x)$  of the  $x$  dependence of  $F_2^N$  or a nearly 50% fraction of diffraction on the inclusive cross section. This is in fact is very high energy physics with extremely large energies  $W$  in the proton rest frame, and particle astrophysics needs to understand the partonic dynamics and collective behaviour in nuclei much of which may be investigated at the LHeC.

## 4 Design

There is design work ongoing on all relevant components of the LHeC in order to be able to present a design concept including an evaluation of the installation and operation interferences with the LHC. It has been assumed in these studies that the  $ep$  collider can operate synchronous to  $pp$ , i.e. that it is operational while there still is a significant part of the LHC programme to be pursued. Extrapolating from the Tevatron or HERA it is likely that the LHC will be operated for two decades or longer, given the exceptional efforts and investments in the machine and detectors and the expected broadness of its physics program. Upgrading the LHC with an electron beam thus appears as a rather natural option, although presently it is impossible to safely predict the future of the LHC.



## 4.1 Accelerator

The design work on the ring has been divided into ten work packages, the lattice, rf, injector, beam dump, beam-beam effects, impedance, vacuum, integration and machine protections, magnets and powering. Similarly there are ten work packages for the linac, i.e. baseline concepts, rf, positron source, lattice and impedance, beam-beam effects, vacuum, integration and machine protections, interaction region, magnet design and powering. There have been contact persons nominated to coordinate this work. There have been contributions made by accelerator physicists from CERN in collaboration with physicists from BNL, the Cockcroft Institute, Cornell, DESY, Novosibirsk, Lausanne and SLAC. With the CDR envisaged for 2010, there is quite some detailed work ahead and some particular questions deserve special attention. Among those are, for the ring: i) the injection using the SPL or alternatives; ii) the detailed evaluation of a new synchrotron and its installation on top of the LHC; iii) the design of the bypasses for then existing LHC experiments and the installation of rf. in these and iv) the availability of crab cavities to compensate for the small  $ep$  crossing angle of  $< 2$  mrad; and for the linac: i) more detailed designs and selection of options, as currently one has not decided between pulsed or CW, racetrack or linear layouts; ii) the evaluation of energy recovery at high energies and iii) the intensity of the positron source. A common ongoing task is the calculation of direct and backscattered synchrotron background within a chosen IR layout, both for the ring and the linac. As was mentioned above, from the studies performed so far, an LHeC, in both options, could be built without considerable further research and development effort, basically because HERA and LEP have provided the necessary experience for a ring and the linac would require TESLA type cavities of modest,  $\sim 25$  MV/m, gradient as will be used for the XFEL at DESY. In the proposed physics programme, the LHC would have to maintain the possibility to inject heavy ions, also in the upgraded injector configuration, and be complemented with a deuteron source and injector.

## 4.2 Detector

The LHeC requires a newly designed  $ep$  detector capable of dealing with a few TeV of energy in the hadronic and electron final state in forward direction. Due to the asymmetry in  $ep$  beam energies, the low (high)  $x$  programme requires acceptance of the electron (hadronic final state) close to the beam pipe in backward (forward) direction. The detector has to be complemented by forward taggers for protons, neutrons and deuterons. In backward direction photons and electrons have to be tagged. The precision demands are such that the alignment and calibration are assumed to be twice as accurate as has been achieved with the H1 detector, designed more than 20 years ago. Currently a first layout of the inner detector including options for the solenoidal field exists [7]. In this design, the region near the beam pipe is occupied with different track detectors, considered to be inner pixel layers followed by a GOSSIP (gas on slimmed silicon pixels) type tracker which combines high resolution with low material budget. These are surrounded by calorimeter modules including a Calice type forward and backward insert for resolving the particle flow. Such a design would incorporate the possibility to remove central parts when focussing magnets need to be placed closer to the IR. The asymmetry of  $ep$  in the current design is reflected in different granularity of the forward and backward detectors, which need to resolve a dense hadronic final state and to measure backward going electrons, respectively. A further iteration of the detector will be performed when the IR calculations of the synchrotron background have converged as

these determine the beam pipe dimensions and thus the size and layout of the detector to a considerable extent. The design makes much use of the experience with H1 and ZEUS, with the LHC detectors and of the considerations for precision calorimetry for the ILC.

## 5 Summary

The LHeC has so far passed the first obvious tests on its feasibility and parameters. More will follow, including possibly new ideas and surprises, and it is for a CDR to comprehensively describe the project and its implications. The LHeC enjoys increasing attention as has been demonstrated at the DIS09 workshop, with widening participation or with the decision of NuPECC to now officially support the LHeC workshop series directed towards the CDR. The future of particle physics depends on the LHC, its performance and findings. An  $ep$  collider operating at the Terascale has a fundamental physics programme, a large part of which is independent of these findings. Only when seen in conjunction with these, however, one understands its full potential and the need to reach highest energy and luminosity. It likely will be the new physics, which is to define the parameters of the  $ep$  collider should the CDR be followed by a TDR. There clearly is an exciting future of luminous deep inelastic scattering, when one thinks of the exploration of the Terascale and lowest Bjorken  $x$  with polarised  $e^\pm$  beams attached to the LHC, and including electron-nucleon collisions.

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