Electron-Nucleon Scattering at the Tera Scale

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The following paper briefly summarizes a poster, which describes the design and the physics of the Large Hadron Electron Collider (LHeC). The poster may be viewed at the LHeC webpage http://cern.ch/lhec, which leads to talks, papers and references too.

1 Introduction

The Large Hadron Electron Collider is a new colliding beam facility under study, which is based on the LHC at CERN. It exploits very high cms energies of $s = 4E_eE_p \simeq 4 \cdot 60 \cdot 7000 \simeq 2 \cdot 10^6$ GeV^2 in order to pursue a rich programme of inelastic, polarised electron/positron-proton, deuteron and heavy ion scattering measurements. Reaching momentum transfer values squared of Q^2 above 10^6 GeV^2 and correspondingly low values of Bjorken $x \propto Q^2/s \sim 10^{-6}$ in the region of deep inelastic scattering (DIS), at luminosities of 10^{33}cm^{-2}s^{-1}, the LHeC surpasses the HERA kinematic reach and performance by about two orders of magnitude. In a plot of past, current and future DIS projects, in terms of luminosity versus energy, the LHeC stands out as a unique possibility for deep inelastic scattering to explore the high energy frontier, alongside with the LHC and a future pure lepton collider, much as HERA, with the TeVatron and LEP, explore the Fermi energy scale of $\sqrt{s} \sim M_W$.

This poster illustrates part of the still ongoing work on the machine, interaction region and detector designs as well as on the physics potential of the LHeC at high mass scales, high parton densities and with high precision. The study is pursued in a wide international collaboration under the auspices of CERN, ECFA, NuPECC and a Scientific Advisory Committee. It is directed to a Conceptual Design Report by 2010, as a contribution to the deliberations of the HEP community on its future programme of exploring the energy frontier with accelerators. If further supported, the LHeC may come into operation in the early twenties, constituting a new experiment at the LHC in the high luminosity running phase.

2 Machine and Detector

The biggest challenge of the *ep* collider is its luminosity. At TeV energies one becomes sensitive to so far unobserved processes. A scale is set perhaps by the $WW \to H$ fusion process, which has a cross section of order 100 fb in charged current scattering at the LHeC for masses of $m_H \sim 150$ GeV. To explore the highest Q^2 and large Bjorken x region, the luminosity can hardly be large enough because the (photon exchange) cross section diminishes like Q^{-4} and the parton distributions tend like $(1-x)^3$ to $x \to 1$. For the LHeC a ring-ring (RR) and a linac-ring (LR) configuration are designed. The choice between these for a next phase, the Technical Design Report, has many aspects, technology, cost, infrastructure, accelerator strategy, schedule etc., but their comparison and design starts with the luminosity potential. In *ep* collisions the beams have to be matched. The luminosity in a ring-ring (RR) configuration can be approximated as

$$L = \frac{N_p\gamma}{4\pi e\epsilon_{pn}} \cdot \frac{I_e}{\sqrt{\beta_{px}\beta_{py}}} = 8.2 \cdot 10^{32} cm^{-2}s^{-1} \cdot \frac{I_e}{50\text{mA}} \cdot \frac{N_p 10^{-11}}{1.7} \cdot \frac{\text{m}}{\sqrt{\beta_{px}\beta_{py}}} \tag{1}$$

with the electron beam current given as $I_e = 0.35 \cdot P[\text{MW}]/50 \cdot (100/\text{E}_\text{e}[\text{GeV}])^4\,\text{mA}$. With the so-called ultimate LHC proton beam parameters, $N_p = 1.7 \cdot 10^{11}$, $\epsilon_{pn} = 3.75\,\mu\text{m}$ and $\beta px(y) = 1.8(0.5)\,\text{m}$, and assuming $P = 40\,\text{MW}$ synchrotron radiation induced power loss, one obtains a luminosity, for 60 GeV of electron beam energy, of about $2 \cdot 10^{33}\,\text{cm}^{-2}\text{s}^{-1}$. The corresponding formula for the linac-ring (LR) configuration is

$$L = 8 \cdot 10^{31} cm^{-2}s^{-1} \cdot \frac{I_e}{1\text{mA}} \cdot \frac{N_p 10^{-11}}{1.7} \cdot \frac{0.2\text{m}}{\beta^*} \tag{2}$$

where the current now is given as $I_e = P[\text{MW}]/\text{E}_\text{e}[\text{GeV}]$. With a possibly reachable β^* of 10 cm one obtains for the ultimate beam a luminosity of $1.6 \cdot 10^{32} \cdot P/E_e \simeq 0.7 \cdot 10^{32}\,\text{cm}^{-2}\,\text{s}^{-1}$ for $P = 25\,\text{MW}$ and $E_e = 60\,\text{GeV}$. This is a factor of about two higher than the HERA II value. There are two ways for increasing the luminosity further: the LHC high luminosity upgrade programme envisages up to about $N_p = 4 \cdot 10^{11}$ protons per bunch which yet requires upgrades and refurbishment of the LHC injector chain. Such a high value is currently not included in the LHeC luminosity estimates. This leaves the power as a main source. Given a design power limit of 100 MW wall-plug, as compared to a 400 MW power limit of CLIC, one finds that energy recovery techniques are the only viable method to effectively increase P to $P_b/(1-\eta)$. Assuming a recovery efficiency of $\eta = 94\,\%$ and an available beam power of about $P_b = 25\,\text{MW}$, aside with cryogenic power and efficiency considerations, one estimates a LR luminosity figure of about $10^{33}\,\text{cm}^{-2}\text{s}{-1}$. The design is based on about ten work packages for each of the options, as on the beam optics, interaction regions, cryogenics, magnets, rf. or infrastructure.

The CDR on the LHeC comprises a detector design concept. This must cope with a a number of demands: i) polar angle acceptance for electrons, backwards, and hadrons, forward, to 179° and 1°, respectively; ii) calibration uncertainties about twice smaller than achieved with H1, in order to perform high precision QCD and electroweak measurements; iii) high modularity and minimum dimensions for optimum installation and maintenance and iv) integration of beam separation (of 3 beams) and focussing functions combined with efficient screening from direct and backscattered synchrotron radiation. For the present design status see the LHeC web page.

3 Physics Programme

The physics programme of the LHeC naturally is extremely rich. One may summarize it with four items, for which illustrations are on the poster, HERA, precision, BSM and low x/eA:

- HERA's achievements lead further: While there are large logarithmic terms $\propto \ln(1/x)$ in the perturbative evolution, yet, no deviations from the linear DGLAP evolution had been observed so far, despite some indications from recent precision measurements. The saturation of the gluon density remains to be observed. Parton densities at high x have not been accurately measured due to lack of luminosity. The neutron and the nuclear structure were not studied, a unique omission in the history of DIS experiments. New concepts have been introduced with parton amplitudes, diffractive partons and uninegrated parton distributions, which require much deeper exploration. No instantons, no odderons, no leptoquarks have been observed, which calls for larger phase space and luminosity.

- The LHeC is a unique precision machine for electron-quark and photon-gluon interactions. With Q^2 exceeding M_Z^2 by a factor of 100, the electroweak interactions become very large, i.e. weak neutral (NC) and charged currents (CC) explore the partonic structure in a unique way: for the first time the complete set of parton distributions can be measured, including for example the strange and anti-strange quark density from $e^{\pm}p$ CC scattering, and one eventually overcomes the many assumptions used in today's extractions of parton distributions. The LHeC is a single top and anti-top quark factory with the single t production cross section in CC of about 10 pb. Per mille accuracy may be achieved for the strong coupling constant, α_s, and the light quark weak NC couplings, etc.

- Owing to the very high energy and luminosity the LHeC complements ideally the search for and interpretation of possibly observed new physics at the LHC. With precision pdf measurements it disentangles new effects from variations of proton structure. By itself the ep machine has unique sensitivity to singly produced new states, as there possibly are excited electrons or neutrinos, RPV SUSY or leptoquark states. With its high precision the LHeC explores $eeqq$ contact interactions up to 50 TeV. One measures the $H \rightarrow b\bar{b}$ coupling, and a new level of accuracy for the gluon and the beauty density will determine the production cross sections of the SM or MSSM Higgs particles, respectively.

- The high energies lead into the regime of saturated parton distributions, which is one of the most intensely studied problems of modern strong interaction theory, related to non-linear parton interactions or superhigh energy neutrino physics. The LHeC is bound to find new physics as it surpasses the unitarity limit both in ep and in eA scattering at very low x and $Q^2 > 1\,\mathrm{GeV}^2$ where α_s is small. Parton distributions in nuclei may be studied in a range of DIS extended by nearly four orders of magnitude, thus accompanying AA physics at the LHC and studying a plethora of effects related to the quark-gluon plasma, shadowing and its relation to diffraction etc. If there were new states diffractively produced at the LHC, precision diffraction measurements at the LHeC are of possibly crucial value. With variations of charge and polarisation, generalised parton distributions can be studied.

The CDR of the LHeC will be available in spring 2011. At that time one will have obtained some first reliable information from the LHC about the TeV mass range. Difficult decisions on the direction of particle physics and the future of CERN are ahead. Building an affordable ep/A collider for the exploration of the Terascale so far is an attractive possibility, not to exploit the hadron beams at the LHC for a combination with high energy electron beams would appear to be a waste of resources and exploration potential. Besides ATLAS, CMS, LHCb and ALICE, the LHeC appears to be worth being the 5^{th} element of experimentation at the LHC.

4 Acknowledgments

Thanks are due to many colleagues for an exciting collaboration on the future of high energy deep inelastic scattering, to Mme Fabienne Marcastel for the design and fabrication of the poster and to Ties Behnke and colleagues for including it in the poster session of Lepton-Photon09.