The LHeC:[1] Electron-Hadron Scattering at the Tera-scale

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Abstract

The LHC is likely to be the dominant resource at the energy frontier for a considerable time and offers possibilities well beyond the first phase of proton-proton collisions. It is natural to ask whether the unprecedented intensities and energies of the LHC proton and heavy ion beams can be exploited for electron-proton and electron-nucleus scattering. The LHeC is a fledgling project with strong and leading UK involvement, which is investigating this possibility. This document briefly outlines the physics motivation and current status of the project, including the likely time profile of resource requirements to maintain the current level of UK involvement.

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[1] No formal attempt has yet been made to gather signatures for this project. The names listed here are those in the UK who have taken major roles in the preparation of the CDR so far.

1 Introduction

Since HERA ceased operation in 2007, there has been no high energy facility for lepton-hadron scattering. The output of HERA was ultimately limited as much by the luminosity (5×10^{31} $\mathrm{cm^{-2}s^{-1}}$ was the largest achieved) as by centre of mass energy. The LHeC project is an investigation of the possibility of colliding an electron beam from a new accelerator with the existing LHC proton or heavy ion beams, whilst maintaining currently planned LHC operation. Preliminary studies [1] have shown that luminosities in excess of 10^{33} $\mathrm{cm^{-2}s^{-1}}$ would be possible at an ep centre of mass energy beyond 1 TeV. If realised, an LHeC would thus complement pp and hopefully e^+e^- facilities in working towards a full understanding of the new Terascale physics which is likely to emerge as the LHC era unfolds. A recent overview of the state of the project can be found in [2] and many more details are available on the project web site [3].

Under the auspices of CERN and ECFA, later joined by NuPECC, a workshop was initiated to evaluate the physics potential of an electron beam at the LHC, as well as details of the electron beam accelerator, the interaction region, detector requirements, impact on the existing LHC programme and cost. The first major meeting of the workshop [4] took place in September 2008 and gathered together around 90 accelerator scientists, experimentalists and theorists. Following other smaller scale meetings of individual working groups, the next full meeting will be in September 2009 [5]. The initial aim is to produce a Conceptual Design Report (CDR).

Since 2005, the LHeC project has been discussed with increasing intensity at the annual workshops on Deep Inelastic Scattering [6], the European and World Accelerator Conferences [7] and elsewhere. Having initially been instrumental in launching the LHeC, the UK continues to be very well positioned in the project. Our involvement includes the chair and two other members of the steering committee and four convenors of working groups.

2 Scientific Programme

Electron-proton collisions at TeV energies and their physics motivation have previously been considered for LEP+LHC, TESLA+HERA and a special CLIC+LHC configuration [8]. The LHeC promises to yield around two orders of magnitude higher luminosity than any of these earlier projects, which opens up a much wider spectrum of physics possibilities. First studies have been made in the LHeC context [4], the results have been reported to ECFA, ICFA and NuPECC, and are summarised for example in [9]. A brief overview is given below and is illustrated in the context of the LHeC kinematic plane in figure 1.

- Colliding electrons with large x quarks at high momentum transfers (Q^2 up to 10^6 $\mathrm{GeV^2}$) gives sensitivity to the production of new particles at the energy frontier and new physics on distance scales below 10^{-19} m. Where initial state leptons are an advantage, there is some unique sensitivity. Promising channels include lepton-quark bound states, supersymmetric electrons produced via $eq \rightarrow \tilde{e}\tilde{q}$ and excited leptons.

- For a wider range of new processes, the relatively simple final states produced at the LHeC could help to clarify new physics observed at the LHC, for example by determining quantum numbers of new states.

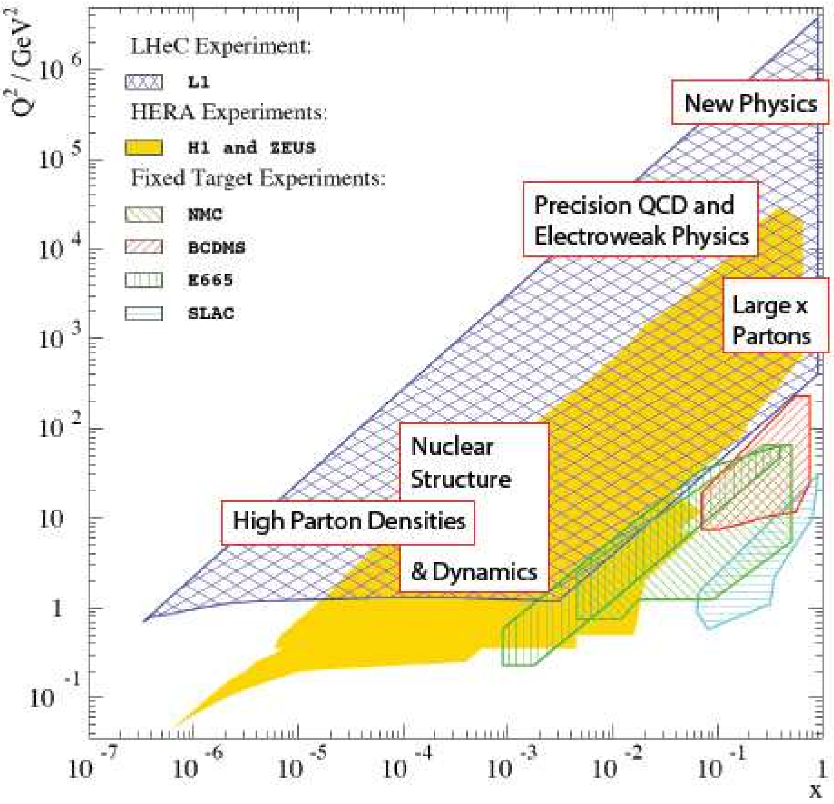

Figure 1: Kinematic plane in Bjorken-x and resolving power, Q^2, showing the coverage of fixed-target experiments, HERA and an LHeC. The mapping of the planned physics programme onto this plane is also indicated.

- Some hitherto relatively unexplored Standard Model processes (for example light Higgs and single top quark production) have promisingly large cross sections at the LHeC, which could thus play a role in their evaluation. For example, the Higgs could be studied in its $b\bar{b}$ decay mode.

- An LHeC would permit the complete determination of the structure of the nucleon in the kinematic range accessed by the LHC. This would include a full decomposition into light and heavy quark flavours and much improved precision at high x, where for example the gluon density and d/u ratio are currently rather poorly known. Constraining these parton densities could be essential to distinguish new LHC physics from poor Standard Model descriptions arising from parton density extrapolation and parameterisation assumptions.

- An LHeC would lead to the most precise measurements of some Standard Model electroweak and strong parameters, such as the vector and axial weak couplings of the light quarks and the strong coupling constant. The latter would be measured to an experimental precision below 1 per mille, an order of magnitude better than hitherto achieved.

- With heavy ions in the LHC, measurements could be made of the deep inelastic structure of nuclei. There would be an increase of four orders of magnitude in the accessible kinematic range compared with previous (fixed target) electron-nucleus scattering experiments. The initial state of heavy ion collisions at the LHC, where models diverge wildly in particular for the low x gluon density, would thus be known for the first time.

- In the low Bjorken-x limit of proton and nuclear structure, unitarity constraints become important and parton densities are widely expected to saturate, the proton approaching a 'black-disk' limit. By measuring inclusive and diffractive cross sections, the LHeC would elucidate the non-linear dynamics behind this transition to a very different regime of the strong interaction, which may ultimately be connected with the confinement of quarks and gluons within hadrons. Precise low x measurements would also provide crucial input to ultra-high energy neutrino physics.

3 Accelerator and Detector Possibilities

A first possible layout for an LHeC was detailed in [1]. Since then, there have been many new ideas and accelerator scientists from most major world particle physics laboratories have become involved. Different configurations are being considered for the CDR, in order to understand fully the advantages and drawbacks of each.

A new electron ring in the LHC tunnel (figure 2a), carried on top of the proton ring, yields the largest luminosities. The beam energy and luminosity are limited by synchrotron radiation losses and available RF components. The correlations between luminosity and electron energy for fixed power consumptions are illustrated in figure 2b. With $50\ \mathrm{GeV}$ beam particles at $50\ \mathrm{MW}$ power, an electron ring configuration could deliver $5 \times 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$, a factor of 100 beyond the highest luminosity achieved at HERA. By-passes for the electron beam to pass around other LHC pp experiments have been designed, which could also be used to host RF structures. Injection could be provided by the Superconducting Proton Linac (SPL), which is currently under consideration as part of the LHC injection upgrade [10]. It would also be possible to use multiple passes around the SPL for the full electron acceleration in an initial phase, which could provide electron energies up to around $20\ \mathrm{GeV}$.

An alternative solution for the electron beam is a linear accelerator (figure 2c), which has the advantages of installation being relatively decoupled from the existing LHC and potentially larger electron beam energies. As shown in figure 2d, a luminosity of $5 \times 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ could be achievable for $50\ \mathrm{GeV}$ electron energy and $50\ \mathrm{MW}$ power, assuming an LHC luminosity upgrade. Unlike the ring scenario, for which the electron current in a fill decreases with time and average luminosities are considerably below peak luminosities, the beam current is constant for the linac scenario. The luminosity in the linac case is also more weakly dependent on electron beam energy for fixed power. Energies up to $150\ \mathrm{GeV}$ are therefore under consideration, limited mainly by civil engineering costs. More efficient use of power may be possible if energy recovery techniques may be applied to such a high energy beam configuration [11]. At the Cockcroft Institute, the UK has one of only two energy recovery linac prototypes operating in the world.

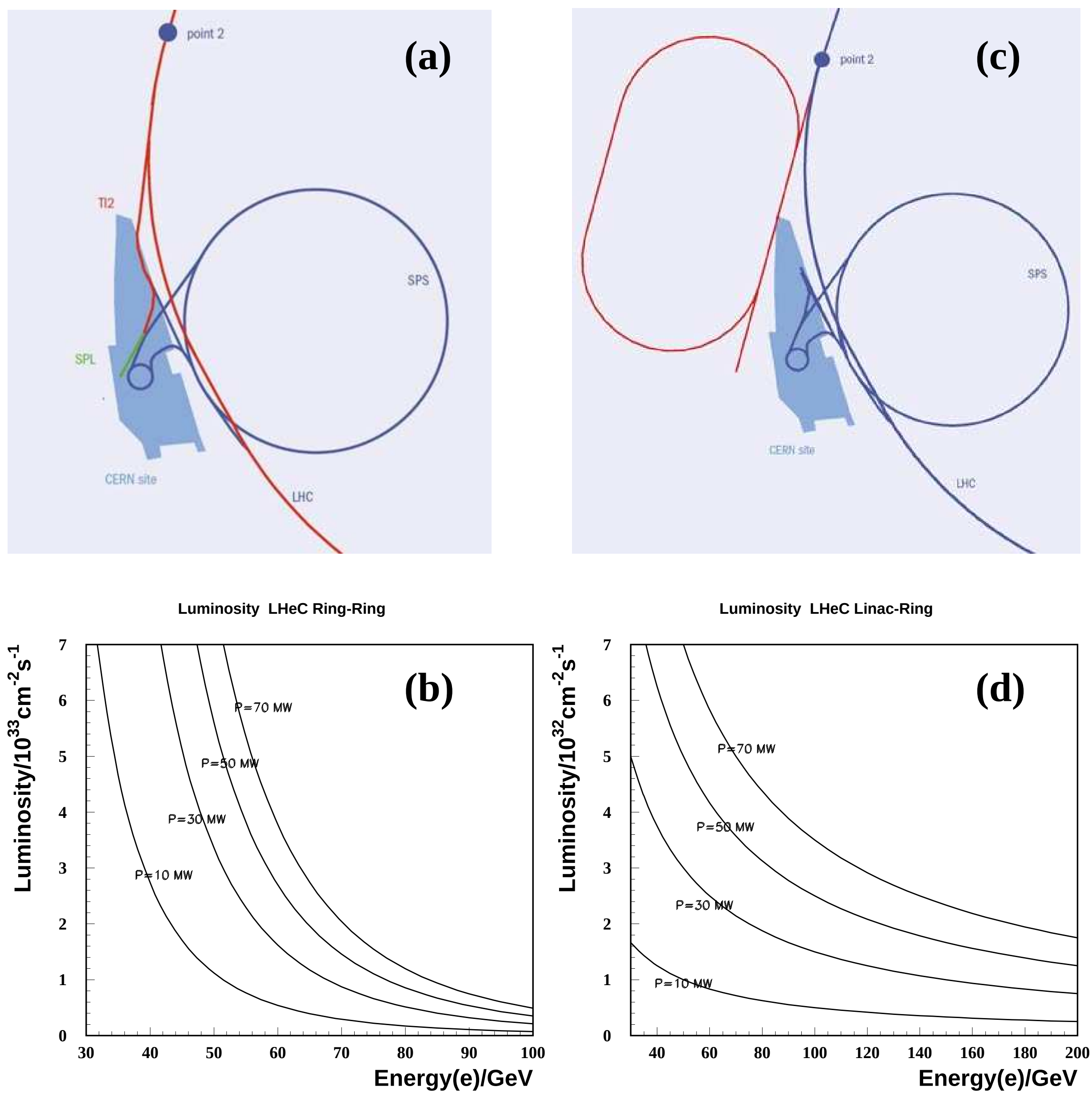

Figure 2: (a) Sketch of a possible layout to inject an electron beam into the LHC ring using the SPL and TI2 connection to the LHC tunnel. (b) Curves of constant power consumption in the electron energy versus luminosity plane for an electron ring solution. (c) A possible layout in which an electron linac arrives tangentially to the LHC, after multiple passes around a 'racetrack' that makes full use of the linac accelerating structures. (d) Curves of constant power consumption in the electron energy versus luminosity plane for an electron linac solution.

There are therefore two basic scenarios for ep collisions being worked on for the CDR:

- An electron accelerator inside the LHC tunnel, providing an electron energy of $50\ \mathrm{GeV}$ and a luminosity of $5 \times 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$, corresponding to an integrated luminosity of order $100\ \mathrm{fb}^{-1}$.
- An electron linac providing an electron energy of up to $150\ \mathrm{GeV}$ and a luminosity of up to $5 \times 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$, corresponding to an integrated luminosity of order $10\ \mathrm{fb}^{-1}$.

In each case, the possibility also exists of replacing the protons with, in the first instance, lead ions. For example in the electron ring scenario, an energy of $2.7\ \mathrm{TeV}$ per nucleon can be achieved with an electron-nucleon luminosity of order $10^{31}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$. The possibility of running the LHC with other heavy ion species or deuterons is also under consideration.

For both the ring and the linac scenarios, the accelerator design is divided into work packages, as listed in [12]. These are currently being worked on by accelerator physicists from BNL, CERN, the Cockcroft Institute, Cornell, DESY, EPFL Lausanne, Novosibirsk and SLAC.

The present thinking involves IP2 as an interaction point. A new detector is being designed as part of the CDR, which has to deal with multi-TeV energies for both the hadronic final state and the scattered lepton, and has to provide wide acceptance, extending as close as possible to the beam pipe. Complete forward tagging of protons and neutrons and backward tagging of electrons and photons is an integral part of the design. Present studies assume a factor of about two improvement in calibration accuracy over the HERA experiments, based on modern tracking, calorimetry and readout technology, and a modular detector structure.

4 Timeline and UK Resources

The initial aim of the CERN-ECFA-NuPECC workshop is to produce a CDR on the timescale of 2010. The CDR will feed into the pursuant CERN and European future strategy planning, alongside other proposals for exploiting and upgrading the LHC. The LHeC is also being considered within the upcoming long term strategy plan for European nuclear physics, being prepared for 2010 by NuPECC.

The next logical step after endorsement of the CDR will be to prepare a full Technical Design Report (TDR), which is likely to take a further two years. It is not yet possible to estimate accurately the time required for development and building of accelerator and detector components, together with the necessary civil engineering. Depending on the chosen configuration and possible staging options adopted, initial operation of an LHeC could be envisaged for possibly 2020.

In the short term, the UK involvement in this project, including its leadership, requires funding to enable travel to working group meetings as the CDR is prepared. In the TDR phase, bids to STFC for seed-corn and other project funding are anticipated, to facilitate detector and accelerator R & D. The magnitude and scope of such bids will be determined by the responsibilities which the UK takes on for the preparation of the TDR. The project could be approved around

2013, including agreement on the impact of LHeC preparations on the proton-proton and ion-ion LHC running. The UK groups expect to take responsibility for a significant fraction of the electron acceleration system and for a detector component. Cost estimates will similarly depend on the details, though the cost-effectiveness of the overall project is considerably enhanced by the fact that it takes advantage of the existing LHC.

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