Prospects for a Large Hadron-*e*lectron Collider (LH*e*C) at the LHC[1]

F Bordry, H-H Braun, O S Brüning, H Burkhardt, A de Roeck, R Garoby, J Jowett, T Linnecar, K-H Mess, J Osborne, L Rinolfi, D Schulte, R Tomas, J Tuckmantel, F Zimmermann (CERN, Geneva), A Eide (EPFL, Lausanne), F J Willeke (BNL, Upton, NY), S Chattopadhyay, J Dainton (Cockcroft Institute, Daresbury), M Klein (Univ. Liverpool), B Holzer (DESY, Hamburg), A Vivoli (LAL, Orsay), S Sultansoy (TOBB ETU, Ankara), A K Ciftci (Univ. Ankara), H Aksakal (Univ. Nigde)

[1]Presented by J Dainton (J.B.Dainton@cockcroft.ac.uk); coordination is by the LH*e*C Steering Committee, chair M Klein (mklein@hep.ph.liv.ac.uk),.

Abstract

Sub-atomic physics at the energy frontier probes the structure of the fundamental quanta of the Universe. The Large Hadron Collider (LHC) at CERN opens for the first time the "terascale" (TeV energy scale) to experimental scrutiny, exposing the physics of the Universe at the sub-attometric ($\sim 10^{-19}$ m, 10^{-10} as) scale. The LHC will also take the science of nuclear matter to hitherto unparalleled energy densities (low-x physics). The hadron beams, protons or ions, in the LHC underpin this horizon, and also offer new experimental possibilities at this energy scale. A Large Hadron electron Collider, LH*e*C, in which an electron (positron) beam of energy (70 to 140 GeV) is in collision with one of the LHC hadron beams, makes possible terascale lepton-hadron physics. The LH*e*C is presently being evaluated in the form of two options, "ring-ring" and "linac-ring", either of which operate simultaneously with *pp* or ion-ion collisions in other LHC interaction regions. Each option takes advantage of recent advances in radio-frequency, in linear acceleration, and in other associated technologies, to achieve *ep* luminosity as large as 10^{33} cm^{-2}s^{-1}. An overview is presented here of the scientific motivation and technical status of the LH*e*C project.

LEPTONS AND QUARKS AT THE TERASCALE?

Our understanding of the physics of the Universe is based on the dynamics of a set of fundamental quanta. It is encapsulated in the Standard Model (SM) of Particle Physics, and in particular in the existence of each of three generations of quarks (q, namely u/d, c/s, t/b)[†] and of leptons (e/ν, μ/ν, τ/ν)[†]. The SM specifies the nature of the interaction between leptons and quarks in the form of the electroweak "gauge field theory" involving vector boson (γ, Z^0, $W^\pm$) exchange (Quantum FlavourDynamics QFD), and between quarks in terms of a different, self-contained, gauge theory, Quantum ChromoDynamics (QCD) involving gluon exchange. These quanta show up in experiments which probe at the ~200 GeV energy scale (1 am) and which have been made possible by the HERA (*ep*), LEP (e^+e^-), and TeVatron (*pp*) storage rings[†].

The SM is however manifestly incomplete. It fails to account for 96% of the necessary "dark matter" and "dark energy" in the Universe, an understanding of which is essential if the physics that we understand is to be applied to describe what we measure in the Cosmos. It is thus the fervent hope of all physicists that at the "terascale" (TeV energy scale, < 1 am distance scale) there will be found a new quantum framework which will identify the nature of dark matter and energy, and at the same time reveal why the SM is founded on quarks, leptons and unified, gauge, field theories in the way that it is.

The Large Hadron Collider (LHC) at CERN is the means by which we probe the terascale. Experiment at the LHC will guide how we progress in our understanding of the laws of Nature, and thereby of our place in the Universe, and how we exploit and apply this understanding for the betterment of our existence.

The experimental methodology, which has revealed the SM for what it is, is founded on measurements of interactions between SM quanta at the highest possible energy, namely at the last triumvirate of quantum colliders, e^+e$^-$ (LEP), *eq* (HERA) and *qq*, *gq*, *gg* (the TeVatron).

The construction of a triumvirate of such colliders at the terascale is more problematic, not least because of the issue of increased (geographical) scale and cost, but also because of fundamental limitations in technology related to requirements for luminosity and beam storage, which arise for fundamental physics reasons. Most familiar of these is synchrotron radiation (SR) loss in *e*-beam storage. The influence of these limitations was already apparent in the construction of the world's first, multi-100 GeV, collider of different particle species, the *ep* collider HERA at DESY, Hamburg, where the requirements of centre-of-mass (CM), energy, of large luminosity, and of e^+/e^- spin polarisation, led to asymmetric beam energies (~27.6 GeV $e \otimes 920$ GeV p) in each storage ring. The imminent turn-on of the LHC *pp* collider is testament to the relative insignificance of these limitations for a terascale, hadron-hadron, collider. In contrast, the recent difficulties experienced in progress *towards* terascale, lepton-antilepton, collisions, in the form of the International Linear Collider (ILC), can ultimately be traced to the

[†] The following shorthand, proton (p), electron/positron (e), muon (μ), tau (τ), neutrino (ν), quark (q), gluon (g), up-quark (u), down-quark (d), charm-quark (c), strange-quark (s), top-quark (t), and bottom-quark (b), is here assumed throughout. Following Feynman, the term "parton" is also used as a collective noun for q and g.

relative signficance of these limitations for electron machines at TeV energies.

The LHC, with its unique proton beams stored at an energy of 7 TeV/u and with an intensity (p) of 0.5 A is now imminent. We are thus on the threshold of terascale parton[†]-parton physics. The LH*e*C makes possible terascale lepton-parton physics by means of *ep* and *e*-ion interactions using one of the LHC hadron beams and a new, purpose-built, *e*-beam. The asymmetry in *e* and hadron beam energies (~100 GeV $e \otimes$ 7 TeV p) is larger than at HERA because of the fundamental issues of beam physics for e^+/e^- storage, or because of (less fundamental) limitations due to linear acceleration, "single–pass" delivery and collision of ~140 GeV *e*. Both approaches include operation with *pp* or ion-ion collisions in other LHC interaction regions. In this way the LH*e*C amounts to an upgrade which enables a substantial increase in the scope of LHC physics in the foreseeable future.

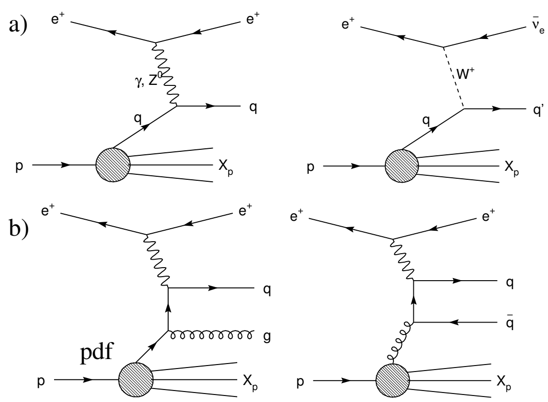

Figure 1: Feynman diagrams indicating LH*e*C *ep* (*e*-ion) interactions schematically: a) vector boson (γ, Z^0, $W^{\pm}$) exchange within the framework of SM $eq \rightarrow eq$ and $eq \rightarrow \nu q$ ("neutral and charged current") scattering; the interacting q momentum is specified by the "parton density function" (pdf) of the incoming proton; b) a q in the dense QCD field of the p (ion), which has evolved chromodynamically (g radiation), interacting with the e.

The LH*e*C is a feasible terascale collider because of both the immense energy of its hadron beams, p and ion, *and* its putative luminosity, which then enables it to deliver enough *eq* luminosity. The latter is dependent on the distribution of parent hadron (p or ion) beam momentum amongst its q and g content (the "parton density function" or pdf – figure 1b). The pdf must specify enough q flux with enough energy for terascale *eq* interactions. The *ep* (*e*-ion) luminosity is achieved by means of the immense intensity of the LHC p (ion) beam and by careful optimisation of the proposed e beam to match the LHC p (ion) beam's bunch structure and frequency. An *ep* luminosity of order 10^{32} to 10^{33} cm^{-2}s^{-1} is then possible. As well as being the first *ep* facility to reach the terascale, the LH*e*C will thereby also be the most luminous lepton scattering apparatus since the Nobel Prize experiment at SLAC in the late 1960s where quarks were discovered.

The physics potential of the LH*e*C is well summarised in the SM event rate for *eq* scattering at Q^2~1 TeV^2 momentum transfer squared; ~1000 events are expected from an integrated luminosity of 100(10) fb^{-1} of 70(140) GeV $e \otimes$ 7 TeV p collisions, which seems possible in the first 3 (conservative) years of data-taking [1,2,3,4,5]. The possibility of observing new terascale physics with an a priori statistical sensitivity then follows, given its anticipated cross section.

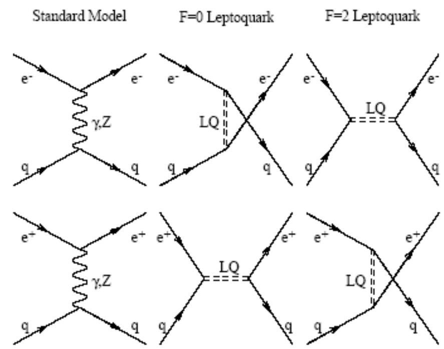

Figure 2: Feynman diagrams indicating schematically the Standard Model (SM) picture of (neutral current) *eq* interactions (left), and possible contributions (centre and right) arising from new *eq* physics in the form of quantum exchanges with "leptoquark" quantum numbers (LQ). The sensitivity to new physics of any form in *eq* interactions is large because of the straightforward nature of the SM contribution.

The importance and significance of LH*e*C physics is exemplified by a scope which includes both fermion number F=0 (e^+q) and F=2 (e^-q) interactions (figure 2). The new dynamics will be manifest directly in the primary *eq* interaction (formation), rather than as a feature of part of the interaction, as in parton-parton and e^+e^- collisions (production). This is sometimes glibly referred to as there being "only leptoquark sensitivity in *ep*", implying that *ep* interactions are only good for the discovery of leptoquark particles in *ep* interactions. In practice, it is the SM prediction for *eq* physics in figure 2, and the precise template which it provides and against which any new physics will be discovered, that underpins the major impact of LH*e*C on new terascale physics.

Terascale physics with ions at LH*e*C is equally important and significant for the conundrum of hadronic physics. The immense *e*-ion CM energy secures a huge phase space for *eq* interactions in which the struck q emerges from being embedded in its parent hadron (figure 1b) in a state in which it reflects the relativistic chromodynamics of its dense, quantised, gauge field, environment, rather than of its (valence) structure. The terascale energy at LH*e*C exposes a huge phase space for such interactions, which, when combined with the sub-femtoscopic spatial resolution (Q^2) of the e probe, make possible completely new insight into hadron (p or ion) dynamics and the inter-play of partonic and nucleonic degrees of freedom. These measurements at LH*e*C of "low-x" physics in hadronic matter will be essential for the quantification of the phase equilibria of dense chromodynamics in terms of colour singlet and non-singlet degrees of freedom. Experimentally, they will be limited only by systematic uncertainties of measurement, the *ep* and *e*-ion interaction cross sections for such low-*x* processes being substantial.

But for the misfortune that Nature chose not to have new physics below an energy scale of 300 GeV, there would have been a swathe of discoveries, *and* precision measurements of these discoveries, at HERA for the reasons discussed above. Experience at HERA tells us that sensitivity to new discoveries in *ep* interactions at a collider is at least as good as outlined above, and that future *ep* experiments will hone their systematic uncertainties to a level of precision which matches experiments at e^+e^- colliders. At the LH*e*C this will again be the case, but this time truly at the terascale.

THE LH*e*C PROJECT

The LH*e*C poses a number of experimental challenges if it is to meet its specification as a terascale, 10^{33} cm^{-2}s^{-1} (or more) luminosity, *ep* collider, able to take data alongside the *pp* experiments ATLAS (IR1), ALICE (IR2) and CMS (IR5) at the LHC. These challenges arise primarily because of already having a 7 TeV/u hadron beam of huge intensity, with which suitably energetic, spin-polarised, e^+ and e^- beams must collide.

Two approaches are being considered, ring-ring (RR) and linac-ring (LR). They derive from a number of early initiatives going right back to before the days of LEP at CERN [6]. The status of each approach is presented for RR in [2] and for LR in [3]. More comprehensive details can be found in [4,5]. A tolerable increase in power consumption at CERN by the LH*e*C is the starting point.

The RR option achieved a first design in terms of a 70 GeV *e*-ring (1.4 TeV *ep* CM energy) in the LHC tunnel and luminosity 1.1×10^{33} cm^{-2}s^{-1}, which amounts to 1000 events at 1 TeV^2 from 100 fb^{-1} in a conservative three years [1]. It requires a finite bunch crossing angle, RF-cavity bunch-crabbing, civil engineering for *e*-beam bypass round the *pp* experiments in (IR1) and (IR5), and an "over-pass" through the *ep* experiment in IR8 for the other hadron beam [1,2,4]. Power consumption for the *e*-ring is 50 MW (SR). No attention has yet been paid to longitudinal spin-polarisation. Important background issues such as SR shielding at the IR and details of a design for the final focus, were included and shown to be no more challenging than at HERA. First consideration of bunch-bunch (*p* and *e*) interactions, and their impact on on-going *pp* physics in IR1 and IR5, show that they are not prohibitive. Recent progress has included assessment of how such an RR option would inject and ramp *e* for *ep* collisions after LHC has been filled and has gone to "luminosity run" status for *pp* collisons in IR1 and IR5. A first look at *e* injection is underway, where it is already clear that there are features which are easier than at LEP; the lower *e* bunch intensity leading to lower injection energy than at LEP (22 GeV) and thus lower cost. Innovative application of energy-recovery linac (ERL) technology, as proposed for *e*RHIC, may be possible [7].

The LR option, which has the potential for higher *e* beam energy, includes a number of different scenarios, including the use of ERL technology, and the integration of an e^+ source using the e^- beam and an amorphous tungsten target [3,5,7]. Recirculation and ERL loops could possibly be housed in the new PS2 tunnel, or in the existing tunnels of the ISR or the SPS. At highest energy, recirculation in the LHC tunnel itself may also be an option. Civil engineering for LR is less disruptive to the LHC *pp* and ion-ion programs than for RR. The requirement for spin-polarised e^+ as well as for e^- has not yet been considered; it could be that an ILC-baseline, helical, *e*-undulator, approach is appropriate [8]. Different scenarios, including normal and super-conducting cavity technology, and pulsed and CW cavity operation, are examined and compared for cavity field and power consumption. A luminosity of between 10^{31} and 5×10^{32} cm^{-2}s^{-1} seems feasible (10^{33} cm^{-2}s^{-1} or more with ERL technology), plausible cavity fields of 10 to 30 MVm^{-1}, 0^{o} crossing angle, and 20 MW wall-plug power. This luminosity, with higher *e*-beam energy of 140 GeV, rather than 70 GeV for RR, also secures 1000 SM events at 1 TeV^2 from a conservative first 3 years of data-taking.

The LH*e*C project [9] is coordinated by a steering committee overseen by a scientific advisory committee. Work, endorsed by both ECFA and NuPECC, and supported by CERN, progresses towards a CDR to be presented in 2010 to the LHC Committee after planned workshops. A time-line is thereby suggested for LH*e*C (alongside LHC *pp* and ion-ion physics) which could have first terascale *ep* and *e*-ion physics towards the end of the next decade. Details of the project, including the working groups concerned with physics, experiment, and machine, and concerned with future workshops, are in [9].

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