FCC-eh and LHeC– Energy Frontier Electron-Hadron Scattering

Contributed to PPAP, 31 October 2020, by a group of physicists from the Universities of Birmingham, Glasgow, Liverpool, Oxford, Queen Mary London, Royal Holloway, Sheffield, Southampton, University College London, in Collaboration with ASTeC Daresbury and Cockcroft Institute [see Appendix]
Contact: Uta Klein, University of Liverpool, uta.klein@liverpool.ac.uk

Physics at the Fermi scale has been established through the synergy of LEP/SLC, HERA and the Tevatron. It is crucial to explore the TeV scale with a similar triple of *ee/eh* and *hh* colliders, especially since we move into the unknown with less theory guidance than hitherto. This situation is reminiscent of the 60ies when the discovery of substructure in deep-inelastic electron proton (*ep*) scattering (DIS) through the 2-mile linac at Stanford opened the path to the Standard Model of particle physics.

1. Project Overview

CERN's intense, high energy hadron beam prospects entail exciting opportunities for future energy frontier DIS operating synchronously to *pp*, when a high current energy recovery linac (ERL) is added to the HL-LHC, for the LHeC [1,2], and to the FCC, to establish the FCC-eh [3]. The LHeC may come into operation after LS4 (in the mid thirties) and will complement the HL-LHC with a unique electron-hadron programme at $\sqrt{s}$=1.2 TeV. Exploitation of the LHC facility has been and will be for long, to 2040 and possibly beyond, the prime task of European high energy physics, and the addition of an *ep/eA* experiment fundamentally expands its physics programme, both its precision measurement and the search prospects. The FCC-eh, with much enhanced energy $\sqrt{s}$=3.5 TeV, is planned to be built together with the FCC-hh, towards the end of the 40ties if FCC-hh succeeds HL-LHC, or much later if an e^+e^- collider is built and operated at CERN after the LHC. Both the LHeC and FCC-eh have a design luminosity almost three orders of magnitude higher than HERA's which radically changes the landscape of deep-inelastic physics. These are the only realistic ways to keep DIS and its unique physics potential as part of high energy physics. As sketched in the appendix, this rests on decades of UK leadership in this field and is being prepared through substantial leading roles at present. Embedded in international developments, UK particle physicists have begun a fruitful collaboration with UK accelerator experts who bring strong experience and a renewed interest to the technology of superconducting electron ERLs. Following the recent publications of Conceptual Design Reports for the LHeC [1,2], FCC-eh [3] and an ERL development facility, PERLE [4], the next phase is characterized by forming collaborations to develop detector and accelerator technology, in which the UK has everything to maintain its leading role, subject to continued and strengthened support by STFC/UKRI and by our Universities and Laboratories. The project has recently been highlighted, and summarized, by ECFA in its summer 2020 Newsletter [5].

2. Physics with ep and eA at HL-LHC and FCC

DIS constitutes the cleanest microscope with which the substructure and theory of strong interactions may be probed principally. Despite its major successes, QCD has no proof of confinement, no dynamical reason for quarks to exist, no explanation of why there are 4 heavy quarks, and the transition of fractionally charged quarks into hadrons is purely phenomenological. The LHeC and FCC-eh are electron-hadron colliders of unprecedented reach. The parton dynamics in nuclei is unknown and the QCD understanding of the QGP impossible without high energy *eA* scattering. Energy frontier DIS may lead to fundamental discoveries in QCD. Owing to the high energy, beyond a TeV in the cms, LHeC and FCC-eh are Higgs and top quark factories. As stated by the International Advisory Committee, chaired by emeritus DG of CERN, Herwig Schopper, "the sensitivity for discoveries of new physics is comparable, and in some cases superior, to the other projects envisaged" [2]. Theory has no firm prediction, its major questions, on deeper substructure, grand unification, higher symmetries, dark matter, hierarchy and others remain unanswered by the SM. It needs new, high energy experiments, the HL-LHC and beyond.

3. Intense High Energy Electrons from an Energy Recovery Linac and the PERLE Facility

The electron beam is generated with two linacs, each of them composed of about 500 superconducting cavities at 802 MHz frequency [in total ~1/10 of what ILC requires], which are embedded in a 3-turn racetrack configuration. ERLs have now been recognized as one of the pioneering new high energy accelerator technologies, which are to be developed much further in the coming years. Owing to energy recovery in high quality SC cavities, the luminosity of the LHeC and FCC-eh is achieved with a total power consumption of only 100 MW which otherwise would exceed 1 GW. The PERLE Collaboration (ASTeC Daresbury, BINP Novosibirsk, CERN, Cockcroft Institute, Cornell University, Irene Joliot Curie Laboratory Orsay (host lab), Jefferson Laboratory, University of Liverpool) develops and builds a 500 MeV machine [4], with a lattice configuration, parameters and technology adapted from the LHeC. PERLE has its own particle and nuclear precision physics programme, with an intensity, for example, of 1000 that of ELI. It also has several industrial applications (such as on nuclear decommissioning, isotope production, lithography), and it is an important possible step towards a UK FEL under consideration.

4. Detector

There exists a complete detector design for the LHeC and the FCC-eh which requires adjustment to technology developments, more thorough simulation, deeper technical inspection, studies on trigger and readout, and prototyping of critical items. An *ep* detector resembles in forward direction a detector for *pp* and in backward direction (i.e. that of the electron beam) a fixed target electron beam spectrometer. The radiation level is about three orders of magnitude lower than in *pp*, and there is no pile-up. The FCC-eh detector has approximately the outer dimensions of CMS.

5. Synergy in Technology

- The *eh* programs of LHC and FCC are designed to operate synchronously with *hh*, which is a maximum synergy one may have, as the expensive hadron beams exist or will exist;
- The racetrack electron beam arrangement is suited as an injector for FCC-ee, which at lower energies avoids a further, intermediate acceleration step;
- An ERL configuration has been proposed for the FCC-ee in order to reach highest energy at enhanced luminosity;
- The FCC-eh ERL can be realized with the relocated electron lattice of the LHeC;
- The 802 MHz cryomodule, under development for PERLE in Collaboration of IJCLab Orsay and CERN, will be a prototype for FCC-ee, which in its high energy phase adds 802 MHz technology to the 401 MHz machine;
- A first 802 MHz cavity was built at Jlab for LHeC and FCC-ee. It reached an excellent Q_0 of 3 10^{10} within a wide plateau of stability extending to 30 MV/m (the CW ERL needs about 20 MV/m);
- The electron gun of ALICE (ASTeC) has been delivered to Orsay and will provide first beam with PERLE;
- The detector has much in common with precision detectors for e^+e^- and *pp* (e.g. CMOS Si technology and Si-W calorimetry). This invites joint detector developments;
- There is a novel development to possibly design a "dual detector", which could be suitable for recording both *hh* and *eh* collisions. This for LHC, see [5], is directed to serve both a new detector proposed by parts of the ALICE Collaboration and the LHeC, potentially resolving the problem of having only 4 IRs at LHC, and at FCC. A joint *AA* and the *ep/A* detector would use a common lightweight CMOS Silicon tracker. This will enable an intimate collaboration of particle and nuclear physicists around a common apparatus.

6. Physics Complementarity

• A combination of *ep* and *pp* Higgs measurements challenges and in parts exceeds the precision of comparable e^+e^- colliders, specifically HL-LH(e)C is as accurate as ILC [5] while FCC-eh meets the sub-percent precision of FCC-ee [3], expressed in the kappa framework.
• Precision PDFs, external to *pp*, have to be provided for the Higgs and electroweak measurements at the LHC and the FCC-hh, including the clarification of the gluon saturation hypothesis at low x without which there is no reliable precise prediction of pp cross sections, at FCC-hh and in the HL-LHC forward direction. The search range of the hadron colliders can be extended by decades of TeV through the clarification of the high x behaviour of partons enabled only by *ep*.
• A variety of searches for new physics, such as for heavy neutrinos, is complementary for *ee/ep/pp*. A discovery such as of compressed SUSY in one of the channels should be verified and complemented in the others;
• The strong coupling constant can be measured to per mille accuracy at FCC-ee and LHeC/FCCeh using different reactions. This is so precise that it challenges lattice QCD prospects. It is the least known of all coupling constants and its precision measurement may reveal new physics. FCC-hh measures its evolution to otherwise not accessible scales.
• High energy and high-density measurements of heavy ion collisions demand that the study of the Quark-Gluon Plasma is underpinned by the resolution of the parton dynamics (and hadronization mechanism) in nuclei. Nuclear DIS is extended by 3-4 orders of magnitude in x and Q^2.

7. Theory Developments

The anticipation of such a precision, energy frontier DIS program has been and will be a strong boost for theoretical developments, such as higher order QCD, event generators, low x physics, electroweak precision theory, Higgs physics, and BSM theory, such as on the dark or r.h. neutrino sector. The UK, at ITTP Durham and various Universities, has world leading theorists, who can steer educating a next generation to prepare and then accompany this program. For example, QCD to N^3LO (or N^4LO) will be required, together with energy frontier DIS data, to obtain a coherent, complete and precise PDF set for interpreting Higgs precision measurements which will be obtained at FCC-hh (and the HL-LHC). UK holds a leading role also in the area of event generators, such as HERWIG and SHERPA, which ought to be developed further.

8. Relation to the EIC

The EIC is a new low energy electron-proton and electron-ion collider which is now likely to be built at BNL. It foresees a spectrum of energies to pursue polarised *ep* beam measurements for the reconstruction of proton spin, inherited by EMC and not resolved by HERMES, COMPASS nor RHIC. It intends to study the proton in 3D at medium Bjorken x. The EIC energy range is set to be optimum for spin physics, with a maximum Q^2 ten times lower than that of HERA. The EIC represents a continuation of HERMES and COMPASS rather than of H1 and ZEUS. It has an electron-ion scattering programme extending the kinematic range accessed by former muon-hadron scattering experiments. It reserves time to explore a variety of nuclei, as opposed to the LHC which (so far) focused on Pb. Compared with LHeC and FCC-eh, it lacks the Higgs, BSM, top and small x programs. The EIC has its own identity and goals but does not enter the TeV scale energy range. It is (funded as) a nuclear physics project.

The spin and 3D measurements demand very high luminosity, very much larger than $10^{33}cm^{-2}s^{-1}$. The EIC thus has an R&D programme on very high current (100 mA) electron ERL for cooling the hadron beam phase space. This has caused initial contacts to the PERLE Collaboration.

9. Programme until about 2025

The following focus points are evident for the coming years:

• Detailed study of the relation of *ep* and *pp*, as well as *eA* with *AA* (*pA*), physics, as e.g. for BSM and Higgs, in close Collaboration with theorists;
• Theory developments as indicated in paragraph 7;
• The realisation of the first phase of PERLE (injector) towards a 250 MeV *e* beam at IJClab Orsay;
• The formation of an international proto-detector Collaboration able to present the LHeC to the LHCC at CERN and to collaborate on detector technology R&D, with strong, leading UK contributions;
• Layout of the machine-detector interface, including a mock-up of the first quadrupole, a plan for absorbers+masks, and a prototype solution of the elliptic beam pipe.

The project had been evaluated and this programme supported by the International Advisory Committee of the LHeC/FCC-eh, please see the brief IAC statement reproduced in [2], p.343-345.

10. Request for Resources (2021-2025)

In order to keep the exciting *eh* options open, maintain our capabilities and leadership, rather limited extra resources are required:

• Support for a PhD program (6 PhD jointly supervised, with emphasis on detector development)
• Detector development (2 FTE)
• Physics Study (2 FTE)
• £0.3M capital

As outlined above, there is much synergy to be exploited with the other FCC (and HL-LHC) developments as well as in the collaboration of particle and accelerator physicists which is a remarkable advantage only few have worldwide. The accelerator development resources, especially for PERLE, are submitted independently.

The cost framework of *eh* has been studied and published [2]. The machine cost of LHeC with a 50 GeV beam has been estimated to be 1.37 GCHF [3]. That is fundable out of the CERN budget. The wall-plug power is limited to 100 MW. The detector, in [1], has been estimated with a core cost of 106 MCHF in 2012. The detector update in [2] has not yet been costed. The FCC-eh ERL tunnel, RF galleries and shaft cost have been evaluated by external companies to be 300 MCHF [3] for a 9 km tunnel suitable for a 60 GeV beam. If the LHeC is built before the FCC, it may be relocated to serve point L on the FCC ring [3] which will render the FCC-eh cost indeed low. In any case, the FCC-eh cost will be a small (< 10%) fraction of that of FCC-hh since it is not a direct part of the 100 km infrastructure. The relation of physics gain and effort of the energy frontier DIS projects under consideration is outstanding.

References

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[2] LHeC at HL-LHC: arXiv:2007.14491, submitted to J.Phys.G (2020)
[3] FCC CDR Vol 1 and Vol 3, published in EPJ (2019)
[4] PERLE CDR: arXiv: 1705.08783, published in J.Phys.G (2018)
[5] ECFA Newsletter Nr 5, 8/2020, https://cds.cern.ch/record/2729018/

Appendix

Deep-Inelastic Scattering and the UK

Since the foundation in 1968 of deep-inelastic scattering with the discovery of substructure inside the proton at Stanford, this physics has made major contributions to the development of elementary particle physics. The UK has participated in all these developments with leading roles in theory and experiment: back in the neutrino CERN Bubble Chamber times, at subsequent lepton scattering experiments and at HERA. It is only natural to prepare for a similar engagement of UK physicists in the deeper exploration of the substructure of matter and search for new physics using high energy electron-hadron scattering.

On energy frontier DIS, the UK holds internationally a remarkable leadership position, with seven UK scientists as convenors and/or members of the LHeC/FCC-eh Coordination. Together with further experienced colleagues, they have led the development of most essential programme elements: the BSM (M. D'Onofrio, O. Fischer), Higgs (U. Klein), PDF (C. Gwenlan), Small x and Diffraction (P. Newman), Detector (P Kostka, visiting professor at Liverpool). The ERL injector design is led by B. Militsyn (ASTeC). Together with O. Brüning (CERN), M. Klein is the coordinator of the LHeC and FCC-eh developments, while he and John Ellis are the two of only three non-CERN members of the central FCC coordination group. M. Klein was elected as PERLE spokesperson in June this year. Deepa Angal-Kalinin (ASTeC), Peter Ratoff (Cockcroft) and Carsten Welsch (Liverpool) serve as members of the PERLE Collaboration Board. Paul Newman has become Co-Chair of the DIS Conference Advisory Committee. The LHeC is a complement to the LHC, in which the UK has been a leading contributor since long. Continuing to hold such eminent positions requires an extended level of support because the coming phase is more about building a facility, prototypes and funding R+D than the past.

Authors and Collaboration with Accelerator Institutes

This paper is signed by a tentative list of colleagues and open to much wider participation in the time hence. The current signatories are:

P.Allport[1], S.Belyaev[8], T. Berry[6], J.Bracinik[1], M.Campanelli[9], A. Cooper-Sarkar[4], M.D'Onofrio[3], T.Doyle[2], O.Fischer[3], C.Gwenlan[4], M.Klein[3], U.Klein[3], P.Kostka[3], J.Kretzschmar[3], K.Lohwasser[7], S.Moretti[8], P.Newman[1], E.Rizvi[5], J.Vossebeld[3]

1 Birmingham
2 Glasgow
3 Liverpool
4 Oxford
5 Queen Mary London
6 Royal Holloway London
7 Sheffield
8 Southampton
9 University College London

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