Energy Frontier eh Scattering - LHeC and FCC-eh

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1 Introduction and Parameters

The energy frontier in deep inelastic electron-proton scattering (DIS) is held by HERA, the first *ep* collider ever built. The intense hadron beams of the LHC offer the unique opportunity to extend the cms energy from 0.3 to beyond 1 TeV by adding an about 50 GeV electron beam to the LHC facility. The preferred technical solution for achieving luminous *ep* and *eA* collisions is to build two superconducting linacs placed opposite to each other in a racetrack configuration, tangential to the LHC ring. This concept has been termed the Large Hadron electron Collider (LHeC) and worked out to considerable detail in an initial report [1] published in 2012, which has recently been updated [2]. The electron beam is configured as an energy recovery linac (ERL) with three turns which economises power and cost permitting to reach instantaneous luminosities almost three orders of magnitude higher than at HERA. This ERL electron beam configuration has also been applied for the concept of electron-hadron scattering at the Future Circular Collider as has been presented with the FCC CDR [3] and also been discussed in [2]. The main parameters of the LHeC and the FCC-eh are summarised in Tab. 1, also considering a lower energy version of the FCC-hh. It is possible to achieve about ab^{-1} of integrated luminosity which would change the impact of deep inelastic scattering physics to the development of energy frontier particle physics dramatically.

Parameter	Unit	LHeC				FCC-eh	
		CDR	Run 5	Run 6	Dedicated	E_p=20 TeV	E_p=50 TeV
E_e	GeV	60	30	50	50	60	60
N_p	10^{11}	1.7	2.2	2.2	2.2	1	1
ϵ_p	μm	3.7	2.5	2.5	2.5	2.2	2.2
I_e	mA	6.4	15	20	50	20	20
N_e	10^9	1	2.3	3.1	7.8	3.1	3.1
β^*	cm	10	10	7	7	12	15
Luminosity	$10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1	5	9	23	8	15

Table 1: Summary of luminosity parameter values for the LHeC and FCC-eh. Left: CDR from 2012; Middle: LHeC in three stages, an initial 30 GeV run, possibly during Run 5 of the LHC, the 50 GeV operation during Run 6, both concurrently with the LHC, and a final, dedicated, stand-alone *ep* phase; Right: FCC-eh with a 20 and a 50 TeV proton beam, in concurrent $eh - hh$ operation.

2 Physics

DIS is the most suited process for exploring the nature of matter, and the LHeC its deepest possible manifestation. It thus constitutes an instrument with which the theory of strong interactions may be questioned 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 jets is purely phenomenological. The reach of the LHeC (and FCC-eh) and its huge luminosity may thus lead to genuine surprises.

The LHeC (FCC-eh) extends the kinematic range of DIS to momentum transfers squared, Q^2, up to 1(10) TeV^2, and from small Bjorken x $10^{-6(7)}$ to 1. With unprecedented precision, it resolves the partonic structure of the proton for the first time completely. It will decisively establish a new state of matter, non-linear parton interactions in dimensions below 0.1 fm, should that exist, with profound consequences for any QCD prediction for the LHC and a future 100 TeV hadron collider.

The LHeC (FCC-eh) extends the kinematic range in lepton nucleus (eA) scattering by about three (four) orders of magnitude. It therefore is the most powerful electron-ion research facility one can build in the next decade: for clarifying the partonic substructure and dynamics inside nuclei for the first time and elucidating the chromodynamic mechanism of the Quark-Gluon-Plasma.

Discoveries may be possible in the anomalous top sector or with precision electroweak measurements. Due to the clean final state, absence of pile-up and high energy, the LHeC has quite a potential for discovery beyond the SM such as on sterile neutrinos or SUSY electroweakinos [2] .

The clean final state, the unique distinction of ZZH and WWH production and a well controlled theory enable per cent level ep measurements of the Higgs boson couplings in several decay channels, mostly complementary to those in pp. The HL-LHC and LHeC prospects have been analysed jointly leading to estimated O(1)% precision for the couplings for the seven most abundant Higgs decay channels representing 99.8% of the total SM decay width.

Higgs physics is the most prominent example for how the addition of electron-hadron DIS substantially extends the discovery, search and precision measurement potential of the LHC facility. It thus exploits the so far largest investment for particle physics further which requires an additional about 20 % of the total LHC cost to be newly invested.

3 Further Study

Further study on the LHeC and FCC-eh will be pursued in a number of directions: i) The basic LHeC configuration and parameters have been adopted for PERLE, a 500 MeV ERL development facility, which will be built at IJCLab Orsay in an international collaboration. With 20 mA electron current, PERLE will be the first 10 MW power ERL facility and as such be instrumental in the development of components and for the accumulation of operation experience for the LHeC, while having further accelerator design goals, some of which in synergy with other colliders; ii) the physics program will be further developed in connection with the findings at the LHC and theory progress; iii) a crucial element of the LHeC and the FCC-eh is the interaction region (IR) because of the high electron beam energy and since both are designed for concurrent eh and hh operation. This requires further study and prototyping of the most inner focusing magnet; iv) The IR and the detector will be in the near term focus since it has been suggested to evaluate whether the LHeC detector may be combined with a new heavy ion detector concept which is being followed for what is called ALICE3. Both a novel AA detector and the LHeC are considering to use IP2 at the LHC, and there "unification" has the potential to resolve the visionary conflict about how to use IP2 in the thirties.

Several LoIs have been submitted for LHeC, for PERLE and the other FCC options. It is hoped that the visions for exploiting fully the LHC and for the FCC with DIS will attract the attention of a large part of the American PP community with which we have been collaborating ever since. Parts of the LHeC study are related to the EIC at BNL, which, however, has lower energy than HERA, different physics goals and a ring-ring eh accelerator configuration.

References

[1] J. L. Abelleira Fernandez et al. A Large Hadron Electron Collider at CERN: Report on the Physics and Design Concepts for Machine and Detector. *J. Phys.*, G39:075001, 2012.

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[3] A. Abada et al. FCC-hh: The Hadron Collider. *Eur. Phys. J. ST*, 228(4):755–1107, 2019.