FCC-eh Accelerator Studies and Considerations

Motivation
- Physics: e-p and e-A physics program
- Full exploitation of LHC (and FCC) infrastructure
- Accelerator innovation and development (ERL)

CDR Choices and Studies:
- Ring-Ring and Linac-Ring options ➔ ERL baseline
- Optics and layout: arc and IR
- Magnets: superconducting and normal conducting
- SRF Frequency choice
- Site options
- Simulations

Summary
CDR Options for LHeC Infrastructure:

F. Zimmermann

[Diagram of CERN infrastructure with various particle accelerators and detectors, including LHC, ALICE, ATLAS, CMS, SPS, LHCb, and others, with notes on dates and distances.]
CDR Options for LHeC Infrastructure:

F. Zimmermann

RR LHeC: new ring in LHC tunnel, with bypasses around existing experiments
CDR Options for LHeC Infrastructure:

RR LHeC: new ring in LHC tunnel, with bypasses around existing experiments

RR LHeC e-/e+ injector 10 GeV, 10 min. filling time

F. Zimmermann
CDR Options for LHeC Infrastructure:

F. Zimmermann

RR LHeC: new ring in LHC tunnel, with bypasses around existing experiments

LR LHeC: recirculating linac with energy recovery, or straight linac

RR LHeC e-/e+ injector 10 GeV, 10 min. filling time
CDR Options for LHeC Infrastructure:

CDR Study assumptions:
- Assume parallel operation to HL-LHC
- TeV Scale collision energy
  ➔ 50-150 GeV Beam Energy
- Limit power consumption to 100 MW
  ➔ (beam & SR power < 70 MW)
  ➔ 60 GeV beam energy
- Int. Luminosity > 100 * HERA
- Peak Luminosity > 10^{33} \text{ cm}^{-2}\text{s}^{-1}
  Higgs @ 125 GeV ➔ > 10^{34} \text{ cm}^{-2}\text{s}^{-1}
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  Higgs @ 125GeV ➞ $> 10^{34}$ cm$^{-2}$s$^{-1}$
CDR Choices:

Ring-Ring versus Linac-Ring:

Linac-Ring:

- Installation largely decoupled from LHC operation ✔
- can accept larger beam-beam ➔ larger bunch current ✔
- energy efficiency and luminosity reach ❌

➔ Recirculating Linac with Energy Recovery Mode (ERL) ✔

➔ New accelerator concept & SRF technology \((Q_0, \text{HOM damping})\)
LHeC: RL with ERL Operation as Baseline

Super Conducting Recirculating Linac with Energy Recovery

Choose $\frac{1}{3}$ of LHC circumference

Two 1 km long, 10 GeV SC LINACs with 3 accelerating and 3 decelerating passes in CW operation

$\Rightarrow$ SRF sees 6*current at the IP ($\approx$ 4 ns spacing)

$\Rightarrow$ $Q_0 = 10^{10}$ requires cryogenic system comparable to LHC system! $Q_0 > 10^{10}$

$\Rightarrow$ 944 cavities; 59 cryo modules per linac

$\Rightarrow$ ca. 9 km underground tunnel installation

$\Rightarrow$ more than 4500 magnets (same magnet design as for RR option)
**LHeC: RL with ERL Operation as Baseline**

Super Conducting Recirculating Linac with Energy Recovery

Choose ⅓ of LHC circumference ➔

- 944 cavities; 59 cryo-modules per linac
- ca. 9 km underground tunnel installation
- more than 4500 magnets (same magnet design as for RR option)

**10^{33} \text{cm}^{-2} \text{s}^{-1} \text{Luminosity reach}**

<table>
<thead>
<tr>
<th></th>
<th>PROTONS</th>
<th>ELECTRONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy [GeV]</td>
<td>7000</td>
<td>60</td>
</tr>
<tr>
<td>Luminosity \left[10^{33} \text{cm}^{-2} \text{s}^{-1}\right]</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Normalized emittance $\gamma \varepsilon_{x,y}$ [μm]</td>
<td>3.75</td>
<td>50</td>
</tr>
<tr>
<td>$\beta_{x,y}^*$ [m]</td>
<td>0.1</td>
<td>0.12</td>
</tr>
<tr>
<td>$\sigma_{x,y}^*$ [μm]</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>$\sigma_{x,y}^*$ [μrad]</td>
<td>70</td>
<td>58</td>
</tr>
<tr>
<td>Beam Current @ IP [mA]</td>
<td>430 (860)</td>
<td>6.6</td>
</tr>
<tr>
<td>Bunch Spacing [ns]</td>
<td>25 (50)</td>
<td>25 (50)</td>
</tr>
<tr>
<td>Bunch Population</td>
<td>$1.7 \times 10^{11}$</td>
<td>( (1 \times 10^9) ) $2 \times 10^9$</td>
</tr>
<tr>
<td>Bunch charge [nC]</td>
<td>27</td>
<td>(0.16) 0.32</td>
</tr>
</tbody>
</table>
**LHeC: RL with ERL Operation as Baseline**

Super Conducting Recirculating Linac with Energy Recovery

Choose $\frac{1}{3}$ of LHC circumference ➔ Two 1 km long, 10 GeV SC LINACs with 3 accelerating and 3 decelerating passes in CW operation

<table>
<thead>
<tr>
<th>10$^{34}$ cm$^{-2}$s$^{-1}$ Luminosity reach</th>
<th>PROTONS</th>
<th>ELECTRONS</th>
<th>PROTONS</th>
<th>ELECTRONS</th>
</tr>
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<tbody>
<tr>
<td>Beam Energy [GeV]</td>
<td>7000</td>
<td>60</td>
<td>7000</td>
<td>60</td>
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<tr>
<td>Luminosity [10$^{33}$cm$^{-2}$s$^{-1}$]</td>
<td>16</td>
<td>16</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Normalized emittance $\gamma \varepsilon_{x,y}$ [$\mu$m]</td>
<td>2.5</td>
<td>20</td>
<td>3.75</td>
<td>50</td>
</tr>
<tr>
<td>Beta Function $\beta^*_{x,y}$ [m]</td>
<td>0.05</td>
<td>0.10</td>
<td>0.1</td>
<td>0.12</td>
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<tr>
<td>rms Beam size $\sigma^*_{x,y}$ [$\mu$m]</td>
<td>4</td>
<td>4</td>
<td>7</td>
<td>7</td>
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<tr>
<td>rms Beam divergence $\sigma_{x,y}$ [$\mu$rad]</td>
<td>80</td>
<td>40</td>
<td>70</td>
<td>58</td>
</tr>
<tr>
<td>Beam Current @ IP [mA]</td>
<td>1112</td>
<td>25</td>
<td>860</td>
<td>6.6</td>
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<tr>
<td>Bunch Spacing [ns]</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Bunch Population</td>
<td>2.2*10$^{11}$</td>
<td>4*10$^9$</td>
<td>1.7*10$^{11}$</td>
<td>1*10$^9$</td>
</tr>
<tr>
<td>Bunch charge [nC]</td>
<td>35</td>
<td>0.64</td>
<td>27</td>
<td>0.16</td>
</tr>
</tbody>
</table>
Various applications:

- LHeC could operate parallel to HL-LHC
- PDFs; preparation for FCC-hh
- ERL could potentially provide collisions with FCC-hh
- ERL could operate as injector for FCC-ee

John Osborne @ 2014 FCC Kick-off meeting
Optics:

- SRF Linac with quadrupoles between the cryo modules
- Flexible Momentum Compaction [FMC] arc optics
Linac 1 and 2 – Multi-pass ER Optics

A. Bogacz (JLab) @ ERL2015, Stony Brook University, June 9, 2015

Acceleration/Deceleration

Linac 1

Linac 2

FCC Week in Rome: April 14th 2016

Oliver Brüning, CERN
Vertical Separation of the Three Arcs

A. Bogacz (JLab) @ ERL2015, Stony Brook University, June 9, 2015
**Arc Optics: Emittance preserving FMC cells**

*Flexible Momentum Compaction*

- **Emittance dilution due to quantum excitations:**

\[
N = \frac{55 r_0 \hbar c}{48\sqrt{3} mc^2} 6 I_5
\]

- **Imaginary \( \gamma_t \) Optics**
  \[\langle H \rangle = 8.8 \times 10^{-3} \, m\]

- **DBA-like Optics**
  *Double Bend Achromat*
  \[\langle H \rangle = 2.2 \times 10^{-3} \, m\]

- **TME-like Optics**
  *Theoretical Minimum Emittance*
  \[\langle H \rangle = 1.2 \times 10^{-3} \, m\]

  total emittance increase in Arc 1-5: \( \Delta \varepsilon_x = 4.9 \, \mu m \, rad \)

\[I_5 = \int_0^L \frac{H}{\rho^3} ds = \frac{\theta \langle H \rangle}{\rho^2}\]

\[H = \gamma D^2 + 2\alpha DD' + \beta D'^2\]

A. Bogacz (JLab) @ ERL2015, Stony Brook University, June 9, 2015

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FCC Week in Rome: April 14th 2016

Oliver Brüning, CERN
CDR Choices: Technology and Design

Magnets:

- Arc magnets (both for Linac-Ring and Ring-Ring):
  - light and low cost normal conducting arc magnets
- IR design ➔ SC magnet magnet requirements
Alternative coil arrangement

- keep the idea of recycling Ampere-turns
- stack the apertures vertically but offset them also transversally
- same vertical gap, 25 mm
- simple coils / bus-bars, same powering circuit
- as before, trim coils can be added for two of the apertures, to give some tuning
Have optics compatible with HL-LHC ATS optics and $\beta^*=0.1\text{m}$
Head-on collisions mandatory $\rightarrow$
High synchrotron radiation load, dipole in detector

**Optimize LHeC to LHC ATS optics**

**Specification of Q1 – NbTi prototype**

Revisit SR (direct and backscattered),
Masks+collimators
Beam-beam dynamics and 3 beam operation studies

**Beam pipe:** in CDR 6m, Be, ANSYS calculations

Composite material R+D, prototype, support..
$\rightarrow$ Essential for tracking, acceptance and Higgs

S. Russenschuck
IR Design: Synchrotron Radiation

Scaling LHeC CDR  
HL-LHC triplet

Beam separation [m]

0.3
0.25
0.2
0.15
0.1
0.1
10 12 14 16 18 20 22
L* [m]  R. Tomas

SR Power [kW]

80
70
60
50
40
30
20

FCC Week in Rome: April 14th 2016

Oliver Brüning, CERN
CDR Choices: Technology Choices and Design:

Super Conducting RF:

- Requirements imposed by LHC beam structure (n * 40 MHz)
- Existing technologies worldwide (e.g. ILC, ESS)
- Beam stability considerations
- RF Power considerations
- Synergies with other projects (e.g. FCC)
Review of the SC RF frequency:

- HL-LHC bunch spacing requires bunch spacing with multiples of 25ns (40.079 MHz)

Frequency choice: $h \times 40.079$ MHz

$h=18$: 721 MHz  or  $h=33$: 1.323 GHz

SPL & ESS: 704.42 MHz;  ILC & XFEL: 1.3 GHz

Existing technologies do not quite match that requirement (20MHz)!
Beam-Beam effects:

N=3 \times 10^9
Beam-beam effect included as linear kick

Result depends on seed for frequency spread
“worst” of ten seed shown

F_{rms}=1.135 \text{ for ILC cavity}
F_{rms}=1.002 \text{ for SPL cavity}

Beam is stable but very small margin with 1.3GHz cavity \Rightarrow \text{ lower frequency}

Optimum choice for LHeC RF frequency?
Optimum RF Frequency: Power Considerations

Results from F. Marhauser

Erk Jensen at Daresbury meeting 12 March 2013

Small-grain (normal) Nb:
Optimum frequency at 2K between 700 MHz and 1050 MHz
Lower T shift optimum f upwards

Large-grain Nb:
Optimum frequency at 2K between 300 MHz and 800 MHz
Lower T shift optimum f upwards
Optimum RF Frequency: Power Considerations

Results from F. Marhauser

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Optimum frequency at 2K between 700 MHz and 1050 MHz
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Large-grain Nb:
Optimum frequency at 2K between 300 MHz and 800 MHz
Lower T shift optimum f upwards
Optimum RF Frequency: Power Considerations

Results from F. Marhauser

Erk Jensen at Daresbury meeting 12 March 2013

Optimum frequency between 700MHz and 800MHz (large and small grain Nb and 1.6K and 2K)

Chose 801MHz for bucket matching in the LHC and for synergies with FCC

Started discussions with JLab for Cavity construction in Washington 2015 ➔ collaboration contract under signature under the FCC umbrella
Site Considerations:

LHeC Interaction Region options:
- IR1 and IR5 house the LHC General Purpose detectors and parallel operation with HL-LHC excludes IR1 and IR5
- IR4 is excluded due to LHC RF installation
- IR3 and IR7 have no caverns and are excluded due to the LHC collimation system
- IR6 is excluded due to the installation of the LHC beam dumping system

⇒ Leaves only IR2 and IR8 as options assuming that ALICE or LHCb Physics program has finished
Site Considerations:

John Osborne June 2014
Site Considerations: IR2

CDR-like 60GeV with IR at Point 2

FCC Week in Rome: April 14th 2016

John Osborne June 2014
Site Considerations: IR8

CDR-like 60GeV with IR at Point 8

John Osborne June 2014
Beam Dynamics and ‘front-end’ Simulations:

Key Studies (performed with PLACET2 code from CLIC):

- Synchrotron radiation
  bunch shape and acceptance for deceleration and dump
- Beam-beam interaction
  bunch shape and beam stability
- RF Wakefields and HOM
  beam stability
- Recombination patterns
  beam stability (filling of the RF buckets can be controlled by tuning the arc lengths)
- Cavity alignment requirements
  orbit and emittance control
Synchrotron Radiation
Evolution of the Longitudinal Phase Space

D. Pellegrini (EPFL/CERN) @ ERL’15
Synchrotron Radiation and Beam-Beam

Transverse Plane at Dump

D. Pellegrini (EPFL/CERN) @ ERL’15

Aperture radius of the SPL cavity is 40 mm.
Auxiliary applications:

-A test setup presents a unique infrastructure on its own
   ➔ Could eventually serve as injector for the LHeC
   ➔ Launched early on discussions with other potential clients

-Interesting auxiliary applications beyond LHeC:
   ➔ SC magnet and cable development: quench tests with beam
   ➔ Generic SC RF development: Cavity tests with beam
       ➔ relevant for any SC RF development (CC in SPS)
   ➔ Test facility for Beam Diagnostics (after closure of CTF3)
   ➔ Detector component tests?
   ➔ Physics applications (electron and photon beam via Compton)
Parameter choices for LHeC demonstration:

- 3 re-circulations
- Beam current of at least 10 mA
- Use of LHeC proto-type SC RF Cryomodule
- Beam energy of approximately 1 GeV (chosen for physics)
- Sufficient space and infrastructure for SC magnet tests

With a photo-injector the facility could test a range of RF frequencies [E. Jensen]

- Staged implementation to build up expertise in steps and to tailor facility to different applications and tests
Staged Installation

Stage 1 – 2 CMs, test installation – injector, cavities, beam dump.

Stage 2 – 2 CMs, set up for energy recovery, 2…3 passes

Stage 3 – 4 CMs, set up arcs for higher energies – reach up to 905 MeV
**PERLE Parameters: CDR by 2016:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>injection energy</td>
<td>5MeV</td>
</tr>
<tr>
<td>RF frequency</td>
<td>801MHz</td>
</tr>
<tr>
<td>acc. voltage per cavity</td>
<td>20MV</td>
</tr>
<tr>
<td># cells per cavity</td>
<td>5</td>
</tr>
<tr>
<td>total cavity length</td>
<td>4</td>
</tr>
<tr>
<td># cavities per cryomodule</td>
<td>4</td>
</tr>
<tr>
<td>RF power per cryomodule</td>
<td>80MV</td>
</tr>
<tr>
<td># cryomodules</td>
<td>2-4</td>
</tr>
<tr>
<td>max. acceleration per module pass</td>
<td>80MV</td>
</tr>
<tr>
<td>bunch repetition</td>
<td>10-15mA</td>
</tr>
<tr>
<td>injected beam current</td>
<td></td>
</tr>
<tr>
<td>nominal bunch charge</td>
<td></td>
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<tr>
<td>number of passes</td>
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<td>top energy</td>
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<td>number of passes</td>
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<tr>
<td>top energy</td>
<td>905Gev</td>
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<tr>
<td>duty factor</td>
<td>CW</td>
</tr>
</tbody>
</table>
Remarks on the Project Status

**LHeC**: CERN Mandate in 2014 to continue the study:

Mandate to the International Advisory Committee 2014-2017  
Chair: Herwig Schopper

Advice to the LHeC Coordination Group and the CERN directorate by following the development of options of an ep/eA collider at the LHC and at FCC, especially with:

Provision of scientific and technical direction for the physics potential of the ep/eA collider, both at LHC and at FCC, as a function of the machine parameters and of a realistic detector design, as well as for the design and possible approval of an ERL test facility at CERN.

Assistance in building the international case for the accelerator and detector developments as well as guidance to the resource, infrastructure and science policy aspects of the ep/eA collider.

**Next major goals:**
Development of SRF (802 MHz) with Jlab. Design minimum Demonstrator (10mA, 3 turn, ERL)
Update of the CDR by 2018: LHC physics, \(10^{34}\) lumi, detector and accelerator updates

**FCC-eh**: Utilize the LHeC design study to describe baseline ep/A option.
Emphasis: 3 TeV physics, IR and Detector: synchronous ep-pp operation.
Analyse other configurations and new physics developments (750..)
**ERL Demonstrator for LHeC:**

**IAC outcome:**

- Develop a Conceptual Design Report for a minimal test facility @ CERN

  ➡ Footprint, and required infrastructure
  ➡ Reduced version of PERLE Stage 2

**Stage 2** – 2 CMs, set up for energy recovery, 2...3 passes
**ERL Demonstrator**

Demonstration of high current (10mA), multi(3)turn ERL

Test and development of 802MHz SCRF technology

\[ E_e = 200 \ (400) \ \text{MeV with 1(2) module} \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipoles per arc</td>
<td>3/4</td>
</tr>
<tr>
<td>Dipole length</td>
<td>50 cm</td>
</tr>
<tr>
<td>Max B Field</td>
<td>1.1 T</td>
</tr>
<tr>
<td>Quadrupoles per arc</td>
<td>5</td>
</tr>
<tr>
<td>Quadrupoles in straight lines</td>
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</tr>
<tr>
<td>Dipoles in Spreader/Combiner</td>
<td>1-3</td>
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<tr>
<td>Quads in Spreader/Combiner</td>
<td>3</td>
</tr>
<tr>
<td>Dipoles for Injection-Extraction</td>
<td>6</td>
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</table>

Figure 3.9: SNS high \( \beta \) module adapted to house \( \beta = 1 \) 5-cell cavities for LHeC.

A.Valloni 2/16
Summary:

- LHeC ERL design is viable:
  - But requires demonstration of multi-turn, high beam current!

- LHeC offers a further exploitation of the LHC infrastructure
  - Allowing parallel operation with HL-LHC

- LHeC is a unique application for the novel ERL concept
  - Innovative accelerator concept with many applications
  - New infrastructure for CERN with applications beyond LHeC

- The LHeC ERL design has also been adopted as baseline for FCC-eh and could operate as injector to FCC-ee
  - synergy with FCC studies
Outstanding Issues and Next Steps

Machine:
- IR layout finalization with SR power optimization
- IR optics design with integration into HL-LHC ATS optics
- SC IR magnet
- SC RF development
- Comparative study for different ERL sizes (1/3<sup>th</sup>; 1/4<sup>th</sup>; 1/5<sup>th</sup>)
- ERL demonstration with high current (>10mA) & multi-turn (≥ 3)

Next Steps:
- ERL demonstrator
  ➔ Test Facility TDRs under preparation
  (PERLE and minimum scale demonstrator)
Reserve Transparencies
The mandate for the technology development includes studies and prototyping of the following key technical components:

- Superconducting RF system for CW operation in an Energy Recovery Linac (high $Q_0$ for efficient energy recovery)
- Superconducting magnet development of the insertion regions of the LHeC with three beams. The studies require the design and construction of short magnet models
- Studies related to the experimental beam pipes with large beam acceptance in a high synchrotron radiation environment
- The design and specification of an ERL test facility for the LHeC.
- The finalization of the ERL design for the LHeC including a finalization of the optics design, beam dynamics studies and identification of potential performance limitations

The above technological developments require close collaboration between the relevant technical groups at CERN and external collaborators. Given the rather tight personnel resource conditions at CERN the above studies should exploit where possible synergies with existing CERN studies.
Study Structure as of 2014:
Coordination Group for DIS at CERN:

The coordination group was invited end of December 2013 by the CERN directorate with the following mandate (2014-2017):

The group has the task to coordinate the study of the scientific potential and possible technical realization of an ep/eA collider and the associated detectors at CERN, with the LHC and the FCC, over the next four years.

It should also coordinate the design of an ERL test facility at CERN as part of the preparations for a larger energy electron accelerator employing ERL techniques.

The group will cooperate with CERN and an International Advisory Committee.

*) LCG Composition early March 2014
International Advisory Committee:

The IAC was invited in December 2013 by the CERN DG

Guido Altarelli (Rome)
Sergio Bertolucci (CERN) *)
Frederick Bordry (CERN)
Stan Brodsky (SLAC)
Hesheng Chen (IHEP Beijing)
Andrew Hutton (Jefferson Lab)
Young-Kee Kim (Chicago)
Victor A Matveev (JINR Dubna)
Shin-Ichi Kurokawa (Tsukuba)
Leandro Nisati (Rome)
Leonid Rivkin (Lausanne)
Herwig Schopper (CERN) – Chair
Jurgen Schukraft (CERN)
Achille Stocchi (LAL Orsay)
John Womersely (STFC)

Mandate 2014-2017

Advice to the LHeC Coordination Group and the CERN directorate by following the development of options of an ep/eA collider at the LHC and at FCC, especially with:

Provision of scientific and technical direction for the physics potential of the ep/eA collider, both at LHC and at FCC, as a function of the machine parameters and of a realistic detector design, as well as for the design and possible approval of an ERL test facility at CERN.

Assistance in building the international case for the accelerator and detector developments as well as guidance to the resource, infrastructure and science policy aspects of the ep/eA collider.

*) IAC Composition End of February 2014 + Oliver Brüning Max Klein ex officio
LHeC: Motivation

Physics:

- Unique opportunity for realizing an ep and e-ion collider in the TeV center of mass region

Infrastructure

- Full exploitation of the existing LHC infrastructure
- New installation with a potential user community beyond HEP and LHeC

Technology and Accelerator Physics

- Unique opportunity for realizing a revolutionary new accelerator concept with a manifold of potential applications beyond HEP!
LHeC: Motivation

Physics:

LHeC:
- Most powerful microscope
- Electro-Weak High precision measurements
- Higgs production with e-p collisions
- Structure functions for precision physics with HL-LHC
- Exploring the unknown @ the TeV scale
- Unique possibility of an EIC @ the TeV scale

Plus Test Facility applications:
- electron and photon physics with high precision (electromagnetic, weak, nuclear, BSM subjects)
  - SRF, SC magnets, Beam Instrumentation etc.
Motivation: Precision for Higgs @ LHC:

Experimental uncertainty H cross section becomes 0.25% (stat + uncertainty) with LHeC

Leads to mass sensitivity

Needs $N^3$LO calculations

arXiv:1305.2090, MPLA 2013
Motivation: EIC facilities as a microscope:

Finest microscope with resolution varying like $\sqrt{1/Q^2}$

Parton momentum fixed by electron kinematics:

$$x = \frac{Q^2}{s y}$$

$$Q^2 = (k - k')^2$$

$$y_{lab} = 1 - \frac{E_e'}{E_e}$$

$$s = 4E_e E_p$$
Motivation: LHeC as a Higgs Factory

- Cross section of 200fb @ LHeC
- Clean bb final state (S/B ≈ 1)
- e-h cross calibration ➞ precision
- Pile-up in ep @ $10^{34}$cm$^{-2}$s$^{-1}$ is 0.1
- Pile-up in pp @ $5 \times 10^{34}$cm$^{-2}$s$^{-1}$ is 140