Energy frontier DIS at CERN: the LHeC and the FCC-eh, PERLE

G. Arduini (CERN) for the LHeC and FCC-eh Study Groups and the PERLE Collaboration

Outline

• LHeC at CERN
  • CDR parameters and evolution
• HE-LHeC and FCC-eh
• Design concepts/choices and challenges
• Electron accelerator demonstrator ➔ PERLE
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- LHeC at CERN
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LHeC CDR

- CDR Study assumptions:
  - Parallel operation with LHC/HL-LHC
  - TeV Scale c.o.m energy
    \[ \Rightarrow \] 40-150 GeV Beam Energy
  - Limit power consumption to 100 MW (beam & SR power < 70 MW)
    \[ \Rightarrow \] 60 GeV beam energy
  - Int. Luminosity > 100 \times\ HERA
  - LHeC as Higgs factory \[ \Rightarrow \] \( \sim 10^{34} \text{ cm}^{-2}\text{s}^{-1} \)
LHeC CDR

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

Linac Ring LHeC: linac or recirculating linac with energy recovery

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

F. Zimmermann
60 GeV ERL Configuration (LHeC baseline)

- Super Conducting Recirculating Linac with Energy Recovery (1/3 of LHC circumference) to minimize power consumption
- Two 1 km long, 10 GeV SC LINACs with 3 accelerating and 3 decelerating passes in CW operation
- Circulating bunches = $6 \times$ colliding bunches
- $Q_0 > 10^{10}$ to minimize requirements on cryogenic cooling power

Schematic
Total circumference ~ 8.9 km
Recirculating Linac with Energy Recovery

- 60 GeV acceleration with Recirculating Linacs
- Three accelerating passes through each of the two 10 GeV linacs (efficient use of LINAC installation!)
- RF systems (at twice the LINAC frequency) to compensate for the synchrotron radiation loss in the arcs

Animation from A. Bogacz (JLab)
Recirculating Linac with Energy Recovery

- 1/2 RF wave length shift on return arc following the collision
Recirculating Linac with Energy Recovery

- 60 GeV deceleration with Recirculating Linacs
- Three decelerating passes through each of the two 10 GeV linacs (energy recovery).
- Beam dump at injection energy (e.g. 500 MeV)

Animation from A. Bogacz (JLab)
Why ERLs?

• (nearly) linac quality/brightness beam at (nearly) storage ring beam powers:
  • beam quality source limited: $\varepsilon_{\text{beam}} < \varepsilon_{\text{ring equilibrium}}$
  • Virtual $P_{\text{beam}} \gg P_{\text{RF}}$ power differential made up by recovered beam

• high power beam with reduced RF drive $\Rightarrow$ cost savings!

• radiation control: beam is dumped at low energy
LHeC layout (IP2)
# LHeC with ERL Operation as Baseline

## Beam Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CDR - LHeC</th>
<th>HL-LHeC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Beam Energy [GeV]</strong></td>
<td>7000</td>
<td>7000</td>
</tr>
<tr>
<td><strong>Luminosity ([10^{33}\text{cm}^{-2}\text{s}^{-1}])</strong></td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td><strong>Normalized emittance (\gamma e_{x,y} [\mu\text{m}])</strong></td>
<td>3.75</td>
<td>2.5</td>
</tr>
<tr>
<td><strong>Beta Function (\beta^<em>_x,\beta^</em>_y [\text{m}])</strong></td>
<td>0.1</td>
<td>0.05</td>
</tr>
<tr>
<td><strong>rms Beam size (\sigma_{x,y} [\mu\text{m}])</strong></td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td><strong>Beam Current @ IP [mA]</strong></td>
<td>860</td>
<td>1100</td>
</tr>
<tr>
<td><strong>Bunch Spacing @ IP [ns]</strong></td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td><strong>Bunch Population ([10^{11}])</strong></td>
<td>1.7</td>
<td>2.2</td>
</tr>
<tr>
<td><strong>Bunch charge [nC]</strong></td>
<td>27</td>
<td>35</td>
</tr>
</tbody>
</table>

## Notes

- \(\sqrt{s} = 1.3 \text{ TeV}\)
- ~10\(^{34}\) cm\(^{-2}\)s\(^{-1}\) allows to collect ~1 ab\(^{-1}\) to study the Higgs in many channels
- 0.9 GW beam power → ERL 90 mA circulating!
- HL-LHC beam parameters
  - Very low beta functions at the IP!
  - >20 mA e\(^{-}\) current achievable/exceeded with DC guns

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O. Brüning, J. Jowett, M. Klein, D. Pellegrini, D. Schulte, F. Zimmermann

18/04/2018 G. Arduini et. al, Energy Frontier DIS at CERN
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HE-LHeC/FCC-eh

- Based on:
  - the same electron machine concept (ERL @ 60 GeV)
  - HE-LHC (~13 TeV/beam hadron collider with 16 T superconducting magnets) in existing LHC tunnel
  - FCC-hh (~50 TeV/beam hadron collider with 16 T superconducting magnets) in 97.7 km new tunnel
FCC-eh layout

- Several IP considered
- Since Rome FCC meeting (2016):
  - Reduced depth below surface level.
  - Reduced length of straight sections at J and D.
  - Increased tunnel length from A-L, A-B and G-F, G-H.
  - Avoids Jura Limestone and Pre-Alps region.
  - Reduced Total Tunnel Length.
**FCC-eh Structures**

- **Small Experimental Caverns**
  - 30 m x 35 m x 66 m

- **Junction Caverns**
  - 16.8 m x 16 m x 100 m
  - 25 m x 15 m x 50 m
  - 16.8 m x 16 m x 90 m

- **Tunnels:**
  - 9.091 km of 5.5m dia. machine tunnel.
  - 2 x 1.04 km of 5.5m dia RF tunnel.

- **Service Caverns**
  - 25 m x 15 m x 50 m

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**Point L selected for e-h IR sharing with injection area – asymmetric optics**
HE-LHC/FCC parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>HE-LHeC</th>
<th>FCC-he</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy [GeV]</td>
<td>12500</td>
<td>50000</td>
</tr>
<tr>
<td>Luminosity [10^{33} cm^{-2}s^{-1}]</td>
<td>12</td>
<td>15</td>
</tr>
<tr>
<td>Normalized emittance $\gamma\varepsilon_{x,y}$ [\mu m]</td>
<td>2.5</td>
<td>2.2</td>
</tr>
<tr>
<td>Beta Function $\beta^*_{x,y}$ [m]</td>
<td>0.1</td>
<td>0.15</td>
</tr>
<tr>
<td>rms Beam size $\sigma^*_{x,y}$ [\mu m]</td>
<td>4</td>
<td>2.5</td>
</tr>
<tr>
<td>Beam Current @ IP [mA]</td>
<td>1250</td>
<td>500</td>
</tr>
<tr>
<td>Bunch Spacing @ IP [ns]</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Bunch Population $[10^{11}]$</td>
<td>2.5</td>
<td>1.03</td>
</tr>
<tr>
<td>Bunch charge [nC]</td>
<td>40</td>
<td>16</td>
</tr>
</tbody>
</table>

$\sqrt{s} = 1.7$ TeV

Smaller electron beam emittance but 1 $\mu$m expected at the source!

O. Brüning, J. Jowett, M. Klein, D. Pellegrini, D. Schulte, F. Zimmermann
Parameters for e-Pb operation

<table>
<thead>
<tr>
<th>parameter [unit]</th>
<th>LHeC (HL-LHC)</th>
<th>eA at HE-LHC</th>
<th>FCC-he</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{\text{Pb}}$ [PeV]</td>
<td>0.574</td>
<td>1.03</td>
<td>4.1</td>
</tr>
<tr>
<td>$E_e$ [GeV]</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>$\sqrt{s_{eN}}$ electron-nucleon [TeV]</td>
<td>0.8</td>
<td>1.1</td>
<td>2.2</td>
</tr>
<tr>
<td>bunch spacing [ns]</td>
<td>50</td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>no. of bunches</td>
<td>1200</td>
<td>1200</td>
<td>2072</td>
</tr>
<tr>
<td>ions per bunch [$10^8$]</td>
<td>1.8</td>
<td>1.8</td>
<td>1.8</td>
</tr>
<tr>
<td>$\gamma \epsilon_A$ [$\mu$m]</td>
<td>1.5</td>
<td>1.0</td>
<td>0.9</td>
</tr>
<tr>
<td>electrons per bunch [$10^9$]</td>
<td>4.67</td>
<td>6.2</td>
<td>12.5</td>
</tr>
<tr>
<td>electron current [mA]</td>
<td>15</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>IP beta function $\beta^*_A$ [cm]</td>
<td>7</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>hourglass factor $H_{\text{geom}}$</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>pinch factor $H_{b-b}$</td>
<td>1.3</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>bunch filling $H_{\text{coll}}$</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>luminosity [$10^{32}$cm$^{-2}$s$^{-1}$]</td>
<td>7</td>
<td>18</td>
<td>54</td>
</tr>
</tbody>
</table>
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Interaction Region layout

- Complex geometry:
  - Collision of electron beam with counter clock-wise LHC proton beam (a.k.a. Beam 2 – red beam)
  - “Spectator” clock-wise rotating beam (a.k.a. Beam 1 – blue beam)

“Field free” area for unfocussed (spectator) proton beam and electron beam
IR Magnet Design

- Stray fields in the 'field-free' region → difficult to match the e⁻ beam + additional synchrotron radiation

- Use of outer coils to create a reduced field region inside the quadrupole (Sweet Spot)

- Higher gradient for a given aperture → more space to put masks through the whole length of Q1
Interaction Region

- LHeC has largest challenge in the SR
- FCC-eh looks easier in terms of SR but optics design is now challenged by short and asymmetric IR
- Designed optics for $\beta^* = 30$ cm, work ongoing towards $\beta^* = 15$ cm

Compare with LHeC: $P_{\text{synch}} = 49$ kW, $E_{\text{crit}} = 718$ keV

R. Martin

$P_{\text{synch}} = 13$ kW, $E_{\text{crit}} = 176$ keV
ERL optics

- Energy change at the various passages through the linac leads to a mismatched optics to be recovered in the arcs

A. Bogacz
Choice of ERL RF frequency

- Cost, dynamic heat losses, resistance, high-$Q_0$... point to $f < 1$ GHz

- Stability in the presence of Higher Order RF Modes and beam-beam interactions: unstable for $f > 1$ GHz

- Compatibility with LHC/HL-LHC/FCC potential developments. Decision for 802 MHz
Main RF System at 802 MHz

- High Q₀, Superconducting (SC) RF cavities, 5-Cell design minimizing High Order Modes to minimize beam instabilities and losses (together with an optimized filling scheme)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Ver 1 (Scaled)</th>
<th>Ver 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency [MHz]</td>
<td>801.58</td>
<td>801.58</td>
</tr>
<tr>
<td>Number of cells</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Active cavity length [mm]</td>
<td>935</td>
<td>935</td>
</tr>
<tr>
<td>Voltage [MV]</td>
<td>18.7</td>
<td>18.7</td>
</tr>
<tr>
<td>(E_p) [MV/m]</td>
<td>45.1</td>
<td>48.0</td>
</tr>
<tr>
<td>(B_p) [mT]</td>
<td>95.4</td>
<td>98.3</td>
</tr>
<tr>
<td>R/Q [Ω]</td>
<td>430</td>
<td>393</td>
</tr>
<tr>
<td>Cell-cell coupling (mid-cell)</td>
<td>4.47%</td>
<td>5.75%</td>
</tr>
<tr>
<td>Stored Energy [J]</td>
<td>154</td>
<td>141</td>
</tr>
<tr>
<td>Geometry Factor [Ω]</td>
<td>276</td>
<td>283</td>
</tr>
<tr>
<td>Field Flatness</td>
<td>97%</td>
<td>96%</td>
</tr>
</tbody>
</table>
SC RF cavity prototype: JLab Collaboration

• J-Lab/CERN collaboration
  • to build:
    • Single-cell fine-grain niobium 802 MHz cavity (completed)
    • One 5-cell fine-grain niobium 802 MHz cavity (completed)
    • Two single-cell OFHC 802 MHz cavities for R&D (advanced)
  • to design
    • Higher Order Mode (HOM) coupler
    • Cryomodule
SC RF cavity prototype: JLab Collaboration

Tooling

Electro-polishing
SC RF cavity prototype: JLab Collaboration

• Requirements:
  • 18 MV/m
  • $Q_0 > 2 \times 10^{10}$

• Design parameters exceeded!

• Next: HOM adapter and cryomodule design – cavity production to proceed.
SC RF cavity prototype: JLab Collaboration

- HOM wake-field analysis:
  - no crucial HOMs close to beam spectral lines
  - At 25 mA injected current low HOM power of ~30 Watts (here shared by 3 coaxial HOM couplers and beam tubes)
  - Optimized filling scheme
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ERL challenges

- Multi-pass recirculation and energy recovery at high current and energy (~1 GW beam power)

- Need demonstrator of this key LHeC element ➔ PERLE (Powerful Energy Recovery Linac for Experiments)

**Why PERLE [as seen from LHeC]?**

**FUNDAMENTAL MOTIVATION:**

- Validation of key LHeC Design Choices
- Build up expertise in the design and operation for a facility with a fundamentally new operation mode:
  ERLs are circular machines with tolerances and timing requirements similar to linear accelerators (no ‘automatic’ longitudinal phase stability, etc.)
- Proof validity of fundamental design choices:
  Multi-turn recirculation (other existing ERLs have only 1-2 passages)
  Implications of high current operation (2 * 3 * [6mA – 25mA] ➔ 30-150mA!!)
- Verify and test machine and operation tolerances before designing a large scale facility
  Tolerances in terms of field quality of the arc magnets and cavity alignment
  Required RF phase stability (RF power) and LLRF requirements
  Halo and beam loss tolerances
Powerful ERL for Experiments (PERLE)

- Collaboration of BINP, CERN, Daresbury/Liverpool, JLab, Orsay INP+LAL (CDR in press)

- ERL Demonstrator for ep at LHC/FCC
  - Key questions to be addressed: Beam Break-up limit, ERL efficiency, beam size evolution (CSR and μ bunching), etc

- SC-RF beam based development facility

- Low energy electron and high energy photon beams (O(10) MeV) physics
  - low energy nuclear, particle and astro physics

https://doi.org/10.1088/1361-6471/aa171
Only one operating facility

Only 3 SC-RF systems have run CW with $P_{\text{beam}}/P_{\text{RF}} \gg 1$

All 3 single turn

Under construction

Decommissioned
Operating
Under construction
Proposed

D. Douglas
C. Tennant

G. Arduini et. al, Energy Frontier DIS at CERN
PERLE @ Orsay (LAL/INP)

3 turns 2 × 65.5 MeV Linacs
400 MeV – 20 mA (~10 MW virtual beam power)
802 MHz (h=20)

5.5 × 24 m²

A. Bogacz

G. Arduini et. al, Energy Frontier DIS at CERN
PERLE @ Orsay
Summary and Conclusions

- The conceptual design of LHeC and its “higher energy” brothers (HE-LHeC and FCC-eh) is progressing in preparation of the next Review of the European Strategy for Particle Physics: effort in the design of the complex Interaction Region towards $10^{34}$ cm$^{-2}$s$^{-1}$

- The design relies on a high energy/high current/multipass Energy Recovery Linac (~ 1 GW virtual beam power)

- A collaboration towards the realization of a ERL demonstrator (PERLE) in the 10 MW region has been launched
Electrons for the LHC
LHeC/FCCh and PERLE Workshop
June 27-29, 2018
LAL-Orsay, France

Join us!

https://indico.cern.ch/event/698368/
Tunnels

RF Gallery

Arc

M. Stewart

LINAC
Reduced Depth & alignment change; area surrounding L no longer in limestone.

Point L selected for e-h IR (700 m available) – sharing with injection area – asymmetric optics.
ERL optics

- Minimize emittance growth due to quantum excitation ($\sim \gamma^6$)
- Tunable cells:
  - Highest energy arcs tuned to minimize energy spread induced by synchrotron radiation,
  - Lowest energy arcs tuned to contain beam size and compensate for bunch lengthening.