FCC-eh summary

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with input from O. Bruning, J. D'Hondt, W. Kaabi, T. Von Witzleben, Y. Yamazaki, M. Chamizo Llatas

FCC Week 2023, 09/06/2023
FCC-eh accelerator session

• FCC-eh and LHeC: Project overview and developments on ERL and sustainable technology, Jorgen D'Hondt

• PERLE: Status and prospects for high power ERL, Walid Kaabi

• Design and optimisation of the ep (and possibility joint ep/pp) Interaction Region, Tiziana Von Witzleben

• Physics and design of the eh detector, Yuji Yamazaki

• EIC-FCC synergies, Maria Chamizo Llatas
The ep/eA landscape

For ep/eA physics, the 2030’ies will be the decade of the EIC

The next ambition for the community will be to enable ep/eA physics both at higher luminosities and at higher energies

The LHeC and FCC-eh high-energy electron-proton programs represent great strides into uncharted territories

At high energies e-p colliders provide a General-Purpose experiment

Jorgen D'Hondt
The LHeC program

**LHeC** (>50 GeV electron beams)

\[ E_{\text{cms}} = 0.2 – 1.3 \text{ TeV}, (Q^2,x) \text{ range far beyond HERA} \]

run ep/pp together with the HL-LHC (\( \geq \text{Run5} \))

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**Kinematic range Parton Distribution Functions**

Not to scale

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Jorgen D'Hondt
The FCC-eh program

**FCC-eh** (60 GeV electron beams)

\(E_{\text{cms}} = 3.5 \text{ TeV}, \) described in CDR of the FCC

run ep/pp together: FCC-hh + FCC-eh

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**FCC-eh**

8 point FCC: point D

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J. Osborne, W. Bromiley, A. Navascues

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**Kinematic range Parton Distribution Functions**
## Complementarity for Higgs physics of ee/ep/pp in the FCC program

(Higgs coupling strength modifier parameters \( \lambda \) – assuming no BSM particles in Higgs boson decay)

(\text{expected relative precision})

<table>
<thead>
<tr>
<th>( \kappa_0 ) (HL)</th>
<th>HL+EE@240</th>
<th>HL+EE</th>
<th>HL+EE (4 IP)</th>
<th>HL+EE/HH</th>
<th>HL+EE/HH/HH</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \kappa_W ) [%]</td>
<td>0.86</td>
<td>0.38</td>
<td>0.23</td>
<td>0.27</td>
<td>0.17</td>
</tr>
<tr>
<td>( \kappa_Z ) [%]</td>
<td>0.15</td>
<td>0.14</td>
<td>0.094</td>
<td>0.13</td>
<td>0.27</td>
</tr>
<tr>
<td>( \kappa_t ) [%]</td>
<td>1.1</td>
<td>0.88</td>
<td>0.59</td>
<td>0.55</td>
<td>0.56</td>
</tr>
<tr>
<td>( \kappa_H ) [%]</td>
<td>1.3</td>
<td>1.2</td>
<td>0.1</td>
<td>0.29</td>
<td>0.32</td>
</tr>
<tr>
<td>( \kappa_{Z_H} ) [%]</td>
<td>10.</td>
<td>10.</td>
<td>1.0</td>
<td>0.7</td>
<td>0.71</td>
</tr>
<tr>
<td>( \kappa_H ) [%]</td>
<td>1.5</td>
<td>1.3</td>
<td>0.88</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>( \kappa_{h} ) [%]</td>
<td>3.1</td>
<td>3.1</td>
<td>3.1</td>
<td>0.95</td>
<td>0.95</td>
</tr>
<tr>
<td>( \kappa_h ) [%]</td>
<td>0.94</td>
<td>0.59</td>
<td>0.44</td>
<td>0.5</td>
<td>0.52</td>
</tr>
<tr>
<td>( \kappa_H ) [%]</td>
<td>4.</td>
<td>3.9</td>
<td>3.3</td>
<td>0.41</td>
<td>0.45</td>
</tr>
<tr>
<td>( \kappa_{H} ) [%]</td>
<td>0.9</td>
<td>0.61</td>
<td>0.39</td>
<td>0.49</td>
<td>0.63</td>
</tr>
<tr>
<td>( \Gamma_H ) [%]</td>
<td>1.6</td>
<td>0.87</td>
<td>0.55</td>
<td>0.67</td>
<td>0.61</td>
</tr>
</tbody>
</table>

\[ \text{Ultimate Higgs Factory} = \{ \text{ee} + \text{eh} + \text{hh} \} \]
The challenge

high-intensity electron beam

From HERA to LHeC/FCC-eh

3 orders in magnitude in luminosity
1 order in magnitude in energy

beam current × beam energy = beam power

LHeC/FCC-eh ~ 1 GW beam power

equivalent to the power delivered by a nuclear power plant

Jorgen D'Hondt
The challenge

high-intensity electron beam

From HERA to LHeC/FCC

With the planned R&D on Energy Recovery Linacs we will prepare the path to provide a 1 GW electron beam with only 100 MW power

Jorgen D'Hondt
The principle of Energy Recovery

- Technology is proven in operational facilities with lower energies and lower beam power.

1. Energy recovered to accelerate the next particle beam.
2. Beam dump at low energy.
3. Beam brightness is maintained from the injector.

ACCELERATE
energy in cavities is given to the particle beam.

DECELERATE
energy of particle beam goes back to cavities.

ACCELERATOR CAVITIES

multiple turns towards higher energies

>99.9999% particles

100% particles

experiment

other beam for collisions

phase-shift 180°

Jorgen D'Hondt
ERL - The global landscape

Energy in MeV vs. Average current in mA

- Completed
- Ongoing (cold)
- Ongoing (warm)
- In progress
- Proposed

Cities and Projects:
- S-DALINAC
- ALICE
- CBETA
- MESA
- Recup.
- CEBAF (1-pass)
- CEBAF (2-pass)
- CERC
- PERLE
- BIC CeC
- LHeC
- EXMP
- bERLInPRO
- Recup. (1-pass)
- Recup. (4-pass)

Technology Limited
Funding Limited

Walid Kaabi
FCC Week 2023
Key building block for beam acceleration: the SRF cryomodule

SRF: Superconducting Radio Frequency

Transferring grid power to the particle beam
Three main innovation directions

RF power generation

- Efficiency ~30-60%
- RF power load by detuned cavities ~ \( \frac{1}{Q_0} \)

Cryogenics

- Dissipated heat efficiency ~ \( \frac{T}{300K - T} \)
- Energy savings from the RF power
- Energy savings from the cryogenics

Grid

Energy savings from the beam

Beam power dumped or radiated

Jorgen D'Hondt
Energy savings from the cryogenics

Three main innovation directions

Innovate for Sustainable Accelerating Systems (iSAS)

[https://indico.iijlab.in2p3.fr/event/9521/](https://indico.iijlab.in2p3.fr/event/9521/)

(ambition: significantly reduce the energy footprint of SRF accelerators)

Energy-saving technologies widely applicable in SRF cryomodules:

- synergies between R&D at PERLE/bERLinPro
- and implementation in FCC-ee/eh/hh

Jorgen D'Hondt
PERLE: first multi-turn ERL, based on SRF technology, designed to operate at 10MW (20 mA, 500 MeV) power regime to explore a broad range of accelerator phenomena and to validate technical power regime on the pathway of the ERL technology development for future energy and intensity frontier machines.

- Total gradient 82 MeV
- 3 acc & 3 decc beams at different energies travelling in the CM.

**Target Parameter**

<table>
<thead>
<tr>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection energy</td>
<td>MeV</td>
</tr>
<tr>
<td>Electron beam energy</td>
<td>MeV</td>
</tr>
<tr>
<td>Normalised Emittance $\gamma\epsilon_{x,y}$</td>
<td>mm mrad</td>
</tr>
<tr>
<td>Average beam current</td>
<td>mA</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>pC</td>
</tr>
<tr>
<td>Bunch length</td>
<td>mm</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>ns</td>
</tr>
<tr>
<td>RF frequency</td>
<td>MHz</td>
</tr>
<tr>
<td>Duty factor</td>
<td>CW</td>
</tr>
</tbody>
</table>
A 5-Cell copper cavity is under fabrication @Jlab to allow end group design optimisation and to test several HOM couplers combinations to assess the best HOM damping scheme.

CW operation
- High dynamic losses
- The highest cavity Q

Cavity post treatment (Doping, infusion…)

High current operation
- High HOMs excitation
- Efficient HOMs extraction
- Act on cavity design: low frequency cavity choice (<1GHz), larger cavity aperture, fewer cells for a given gradient, optimisation of end-cell design.

Muti-bunches operation
- Beam instabilities
- The highest BBU threshold

Regular spacing of bunches: optimisation of the bunch filling pattern during Lattice design + BBU study after HOM optimisation (including collective effects).

First Nb 802 MHz 5-Cell cavity fabricated @ JLAB


Walid Kaabi
Cryomodule design:

ESS Cryomodule design was selected:

- Intermediate supporting structure (spaceframe)
- Cavity string hung by rods
- Insertion of the cavity string by the extremity (rollers)
- Trap doors for tuner access
- Connexion to the valve box on the top of the vacuum vessel
- Important space available inside
- Design validated: series fab. & tests ongoing (Qty 30)

- 1st Cryomodule: Foreseen for 2027
  Adapted from ESS design, it will be optimised for efficient high current ERL operation within the European Infra-Tech program iSAS*. It will host cavities equipped with HOM couplers and FPC optimised and developed within the same program.

- 2nd Cryomodule: Foreseen for 2030
  May include some/all the technologies studied within iSAS program to improve the efficiency of Cryomodules: Fast Reactive Tuner (FRT) for microphonics mitigation, LLRF managed by AI and 4.2 K Cavities operating.

* More information on iSAS program: https://indico.ijclab.in2p3.fr/event/9521/
Concurrent Operation of e-h and h-h

- New FCC-hh lattice: talk Gustavo
- Optimized electron interaction region to minimize SR power Kevin’s Thesis
- The impact of the electron magnets can be corrected locally for the proton beams
- Concurrent operation implies 3 beams at the IR
- The two protons need to be separated at the e-p interaction point

Tiziana Von Witzleben
2 possible separation schemes for the h-h beams:

only e-h collisions

K.D.J. André

2 possible separation schemes for the h-h beams:

e-h and h-h collisions

Both schemes will be implemented as soon as the FCC-hh lattice is fully available

Tiziana Von Witzleben
**FCC-eh physics and detector**

- Detector for DIS designed for LHeC extended to FCC-eh
  - similar $E_e$ 50 ⇒ 60 GeV: similar e-side
  - proton 7 ⇒ 20 or 50 TeV: need to cope with stronger energy and denser particle flow on p/A side
    - Tracker and Calo extended to more forward
- Study item 1: machine-detector interface
  - weak dipole around IP for head-on collision as proposed for LHeC: detector needs to avoid SR fan
  - Need to optimise for FCC-eh design
- Study item 2: optimisation for higher energy h beam
  - cutting technologies for 2050 and beyond? in collaboration with ee/hh studies
- Possibility to run pp/AA for precision physics at eh IP
  - better calibrated by kinematic constraints of DIS events

Yuji Yamazaki
EIC design

- Hadron storage Ring (RHIC Rings) 40-275 GeV (existing)
  - 1160 bunches, 1A beam current (3x RHIC)
  - Bright vertical beam emittance 1.5 nm
  - Strong hadron cooling

- Electron storage ring 2.5–18 GeV (new)
  - Many bunches,
  - Large beam current, 2.5 A \(\rightarrow\) 9 MW S.R. power
  - S.C RF cavities
  - Polarized bunches (up to 70%)

- Electron rapid cycling synchrotron 0.4- 18GeV (new)
  - 1-2 Hz
  - Spin transparent due to high periodicity

- High luminosity interaction region(s) (new)
  - \(L = 10^{34}\text{cm}^{-2}\text{s}^{-1}\)
  - Superconducting magnets
  - 25 mrad Crossing angle with crab cavities
  - Spin Rotators (longitudinal spin)
  - Forward hadron instrumentation
The US Department Of Energy approved the EIC accelerator and one detector in Dec 2019 (CD-0)

EIC is currently in the design and prototype phase

Baseline/start of construction approval expected April 2025 **Start of operations ~2033**

Second interaction region and second detector delayed by ~5 years

**Maria Chamizo Llatas**
EIC-FCC parameters

The EIC electron beam features great similarities with the FCC-ee beam (EIC has higher beam currents, and shorter bunch spacing).

<table>
<thead>
<tr>
<th></th>
<th>EIC e beam</th>
<th>FCC-ee Z pole (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy [GeV]</td>
<td>10 (18)</td>
<td>45.6 (80)</td>
</tr>
<tr>
<td>Bunch population [10^{11}]</td>
<td>1.7</td>
<td>1.7</td>
</tr>
<tr>
<td>Bunch spacing [ns]</td>
<td>10</td>
<td>15, 17.5 or 20</td>
</tr>
<tr>
<td>Rms bunch length [mm]</td>
<td>2</td>
<td>3.5 from SR</td>
</tr>
<tr>
<td>Beam current [A]</td>
<td>2.5 (0.27)</td>
<td>1.39</td>
</tr>
<tr>
<td>SR power / beam / meter [W/m]</td>
<td>9000</td>
<td>600</td>
</tr>
<tr>
<td>Critical photon energy [keV]</td>
<td>9 (54)</td>
<td>19 (100)</td>
</tr>
</tbody>
</table>
Key updates towards the EIC

• EIC challenging design parameters require much accelerator R&D, prototyping, synergistic with other facilities.

• Areas of common interest between the EIC and FCC-ee have been identified and are being addressed through joint workshops.

A few selected topics will be discussed in this presentation:


ESR=Electron Storage Ring
HSR=Hadron Storage Ring

Maria Chamizo Llatas
Synergies EIC-FCC

Areas for mutually beneficial collaboration
• SRF cavities, electron gun (high current, high brightness beams)
• Beam instrumentation: SR monitors, BLM, BPMs, Beam feedback systems, crab angle measurements
• Vacuum systems
• IR region magnets, prototypes, production
• MDI, IR shielding
• Collimation
• Beam-beam interactions, beam-gas interactions
• Impedance model, instabilities, HOM, ion instability