Design of the Interaction Region for Concurrent e-p and p-p Operation

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The FCC-eh Collider

- New layout of the FCC-hh collider:
  
  **FCC-hh ring: overview of the new layout**

  **New FCC-hh ring layout: arc and insertion optics**

Possible layout of the FCC [1]

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The FCC-eh Collider

- New layout of the FCC-hh collider:

  - FCC-hh ring: overview of the new layout
  - New FCC-hh ring layout: arc and insertion optics

  - High precision microscope for inner hadron structure
  - Deep inelastic scattering physics
  - Collisions of \(50\text{TeV}\) protons with \(60\text{GeV}\) electrons
  - Center of mass energy: \(\sqrt{s} = 3.5\ \text{TeV}\)
  - Peak Luminosity: \(10^{34}\ \text{cm}^{-2}\ \text{s}^{-1}\)
The energy recovery linac (ERL)

- The electrons are accelerated over three turns to 60GeV
- $C \approx \frac{1}{3} C_{LHC} \approx \frac{1}{10} C_{FCC} \approx 9\text{km}$

**Table with the main parameters of the FCC-eh [2].**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Electron</th>
<th>Proton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>GeV</td>
<td>60</td>
<td>50000</td>
</tr>
<tr>
<td>Beam current</td>
<td>mA</td>
<td>20.0</td>
<td>640.0</td>
</tr>
<tr>
<td>Bunch population</td>
<td>$10^{10}$</td>
<td>3.1</td>
<td>10.0</td>
</tr>
<tr>
<td>Normalised emittance at IP</td>
<td>mm.mrad</td>
<td>20.0</td>
<td>2.2</td>
</tr>
<tr>
<td>Betatron function at IP</td>
<td>cm</td>
<td>7.3</td>
<td>30.0</td>
</tr>
<tr>
<td>Beam size at IP</td>
<td>pm</td>
<td>3.5</td>
<td></td>
</tr>
<tr>
<td>RMS bunch length $\sigma_z$</td>
<td>cm</td>
<td>0.06</td>
<td>8.00</td>
</tr>
<tr>
<td>Installed RF voltage</td>
<td>GV</td>
<td>21.2</td>
<td>$48 \times 10^{-3}$</td>
</tr>
<tr>
<td>Beam-beam parameter $\xi$</td>
<td>$10^{-4}$</td>
<td>$1.1 \times 10^4$</td>
<td>1.7</td>
</tr>
<tr>
<td>Luminosity</td>
<td>cm$^{-2}$s$^{-1}$</td>
<td>$7.9 \times 10^{33}$</td>
<td></td>
</tr>
</tbody>
</table>

- The remaining electrons have a phase advance of 180° when entering the linac again
- 97.92% of the energy can be recovered
Due to Liouville’s theorem the phase space of the beam is conserved. Blowup of the beta function before the IP.

- **Beta function at a distance $l$ before a symmetry point $\beta^*$:**
  \[
  \beta(l) = \beta^* + \frac{l^2}{\beta^*}
  \]

- **Find optimal $\beta^*$:**
  \[
  \frac{d\beta(s)}{d\beta^*} = 1 - \frac{l^2}{\beta^*} = 0
  \]

- **Smallest beta at a distance $l$ for:** $\beta^* = l$

The focusing magnets before the IP need the biggest aperture.
The electron interaction region (optimized by K.D.J André)

- Optimized to minimize the synchrotron radiation power
- An electron doublet is used for round electron beams
- Two dipoles are used to bend the electrons
- The protons pass the electron magnets with a scaling factor of \( \frac{60 \text{ GeV}}{50\,000 \text{ GeV}} \approx 0.0012 \)

Impact of the electron magnets on the proton orbits (B1). The blue line marks the position of the IP.

\[ L_p^* = 40\text{m} \]
Impact of the electron IR on the proton beam dynamics

Local correction of the proton orbit:

Introduction of a beta-beat of about 1.5% in the proton optics. They are corrected locally at the dispersion suppressors.

Scaling:
\[
\frac{60 \text{ GeV}}{50 \,000 \text{ GeV}} \approx 0.0012
\]
Concurrent Operation of e-h and h-h

- Concurrent operation implies 3 beams at the IR
- The two protons need to be separated at the e-p interaction point
- How will this IP be used?
Concurrent Operation of e-h and h-h

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- The two protons need to be separated at the e-p interaction point
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Option 1: only e-p interaction in this IP

Option 2: e-p and p-p interaction alternate in this IP
Option 1: only e-p interaction in this IP

- Separate apertures for the proton beams
- Shift the IP position by ¼ of the bunch distance
- The spectating proton beam crosses with a strong angle (~7 mrad)
- $L^*$ can be lowered and optimized for the e-p data acquisition
- Lower $L^*$ allows a lower $\beta^*$

$$L = \frac{N_1 \cdot N_2 \cdot n \cdot f}{4\pi \sigma_x \sigma_y} \sim \frac{1}{\beta^*}$$

Luminosity for round beams

Schematic of an optional LHeC interaction region. Courtesy to K.D.J. André [2]

**Drawback:** no h-h collision possible in this IP
Option 2: e-p and p-p interaction alternate in this IP

- The two proton beams share the same aperture
- Separation of the two proton beams with the use of orbit bumps
- Further separation in the shared aperture with the use of asymmetric optics for the protons

Separation of 9\sigma

Schematic of an optional LHeC separation scheme [3]
Option 2: e-p and p-p interaction alternate in this IP

Betafunction before a drift space of the length $l$ with minimum betafunction $\beta^*$:

$$\beta(l) = \beta^* + \frac{l^2}{\beta^*}$$

- A high $\beta^*$ of the spectating proton beam at the IP keeps it at a smaller beam size in the shared aperture.
- Use asymmetric proton beam optics to maximize the distance between the beams in the shared aperture.
- A low $\beta^*$ of the colliding beam increases the Luminosity.

Luminosity for round beams:

$$L = \frac{N_1 \cdot N_2 \cdot n \cdot f}{4\pi \sigma_x \sigma_y} \sim \frac{1}{\beta^*}$$

Asymmetric proton beam optics for the LHeC.
Summary & Outlook

- An electron interaction region has been optimized to **minimize the synchrotron radiation power**
- The local **impact of the electron magnets** on the proton beam orbit and optics can be corrected in the **new FCC-hh lattice**
- 2 schemes to separate the proton beams have been designed for the LHeC → they can be adapted for the FCC-eh
- **Outlook**: implement both separation schemes into the new h-h lattice
- Tracking simulations to investigate the impact of the proton beams on each other
Thank you for your attention.
Background Slides
Sources


Mini-beta Insertion

Due to Liouville’s theorem the phase space of the beam is conserved – blowup of the beta function before the IP

- Beta function at a distance $l$ before a symmetry point $\beta^*$:
  $$\beta(l) = \beta^* + \frac{l^2}{\beta^*}$$

- Find optimal $\beta^*$:
  $$\frac{d\beta(s)}{d\beta^*} = 1 - \frac{l^2}{\beta^*} = 0$$

- Smallest beta at a distance $l$ for: $\beta^* = l$

The focusing magnets before the IP need the biggest aperture
How does this affect our collider?

- The beam-size is defined as: \(1\sigma_u(s) = \sqrt{\varepsilon\beta(s)} = \sqrt{\varepsilon\beta^*}\) at the IP with \(u=x,y\)

- Using the formula for the betafunction in a drift: \(\beta(l) = \beta^* + \frac{l^2}{\beta^*}\)

- For the FCC- hh collider with \(\beta^* = 0.3\) and \(L^* = 40m\) this yields: \(\beta(40) = 0.3m + \frac{40m^2}{0.3m} = 5333.56m\)

- How far can we go in betastar with a drift of 15m?

  \[
  \beta(20) = \beta^* + \frac{20m^2}{\beta^*} = 5333.64m
  \]

  \[
  \beta^* = 0.074m
  \]

\[L = \frac{N_1 \cdot N_2 \cdot n \cdot f}{4\pi \sigma_x \sigma_y} \text{[cm}^{-2}\text{s}^{-1}]\]

Proportional impact on the luminosity
The development of ERLs has been recognized as one of the five main axes of accelerators R&D in support of the European Strategy for Particle Physics (ESPP).

The ERL Roadmap Panel, chaired by Max Klein and Andrew Hutton, has done a tremendous job with broad and active participation. **PERLE & bERLinPro projects** were recognized as one of the "essential pillars of the ERL development," with milestones to be achieved by the next ESPP in 2026.

**ESPP R&D Accelerator RoadMap:**

Walid Kaabi, “PERLE: a novel facility for ERL development and applications in multi-turn configuration and high-power regime”, IPAC 2023
Optimization Scheme for the electrons
Courtesy K.D.J. André [2]

Optimizations for different focusing schemes of the LHeC

Synchrotron radiation at the IP of the LHeC
LHeC interaction region for Concurrent e-p and p-p Operation [3]


Possible separation scheme of the LHeC [3]
LHeC interaction region for Concurrent e-p and p-p Operation [3]