FCC-eh Configuration and Performance

Configuration:

Modular design elements:

- 60 GeV ERL configuration for the ‘e’ beam documented in the LHeC CDR → varied sizes;
  applicable to LHC, HE-LHC and FCC
- 800MHz SRF: synergy with FCC-ee and FCC-hh
- IR configuration with head-on collisions
  → without Crab Cavities (vs EI in US)!
  → SR acceptance in detector and beam separation
  → Dipole integrated into detector
  → ‘Sweetspot’ IR magnet design
CDR Options for LHeC Infrastructure:

CDR Study assumptions:
- Assume parallel operation [HL-LHC & FCC]
- 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 > $10^{33}$ cm$^{-2}$s$^{-1}$
  Higgs @ 125GeV ➔ $>10^{34}$ cm$^{-2}$s$^{-1}$
60GeV ERL Configuration:

Super Conducting Recirculating Linac with Energy Recovery

Choose ⅓ of LHC circumference ➔

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

⇒ SRF sees 6*current at the IP (∼4ns spacing)

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

⇒ 944 cavities; 59 cryo modules per linac
⇒ ca. 9 km underground tunnel installation
⇒ 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 1/3 of LHC circumference ➔ Two 1 km long, 10 GeV SC LINACs with
3 accelerating and

<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>
</thead>
<tbody>
<tr>
<td>Beam Energy [GeV]</td>
<td>7000</td>
<td>60</td>
<td>7000</td>
<td>60</td>
</tr>
<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 γε_{x,y} [μm]</td>
<td>2.5</td>
<td>20</td>
<td>3.75</td>
<td>50</td>
</tr>
<tr>
<td>Beta Function β^{*}_{x,y} [m]</td>
<td>0.05</td>
<td>0.10</td>
<td>0.1</td>
<td>0.12</td>
</tr>
<tr>
<td>rms Beam size σ^{*}_{x,y} [μm]</td>
<td>4</td>
<td>4</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>rms Beam divergence σ_{x,y}^{*} [μrad]</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>
</tr>
<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 \times 10^{11}</td>
<td>4 \times 10^{9}</td>
<td>1.7 \times 10^{11}</td>
<td>1 \times 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>
FCC-eh Configuration: Layout & Civil Engineering

**Configuration:**

- **Independent FCC-he**
  - Point L, F, H or B

- **LHeC / FCC-he**
  - LHC P8 & FCC PB

---

FCC Week in Berlin: May 29th to June 2nd 2017

Oliver Brüning, CERN
FCC-eh Configuration: Layout & Civil Engineering

Racetrack Layout:

- Connection to FCC straight section at point B, F, H, or L
- 1070m ERLs - 400m BDS – 979m radius arcs - 400m beam transfer
- 9091m total length, \( \frac{1}{11} \) of FCC

![Diagram of racetrack layout]
FCC-eh Configuration: Layout & Civil Engineering

Racetrack Layout Point L:

Tunnel Geology
• Molasse rock (sandstone)
• High risk of hitting (hazardous) Jura limestone

Construction
• Tunnel Boring Machine (TBM) in straight sections
• Roadheader in arcs

Civil Engineering challenges
• High geological risk of travelling through karstic limestone
• Not feasibility issue but special probing measures could be required (increase costs)
FCC-eh Configuration: Layout & Civil Engineering

Racetrack Layout Point B:

Tunnel Geology
• Molasse rock (sandstone)

Construction
• Tunnel Boring Machine (TBM) in straight sections
• Roadheader in arcs

Civil Engineering challenges
• Biggest challenge is avoiding interaction with main FCC tunnel(s) (junction caverns, sloped FCC-he)
• Geological hazards are low if in molasse
**FCC-eh Configuration and Performance**

**IR challenges and configurations:**

- Aim of the interaction region design: Collide one of the proton beams head-on with the electron beam from the ERL while the other proton beam bypasses the interaction.

- LHeC has to work alongside HL-LHC and built within an existing IR2 cavern layout, designed for a different experiment.

- FCC-he can be designed for the required purposes.

---

**P1**
Non focused beam
Bypasses the interaction

**P2**
Focused interacting proton beam
FCC-eh Configuration and Performance

Hadron IR design:

IP | Inner Triplet | Separation Dipoles | Matching Section
---|---------------|--------------------|------------------
    | Q1 Q2 Q3 D1   | D2 Q4 Q5 Q6 Q7    |

Implementation of new triplet Q1-Q3 with aperture for 2 proton beams and one electron beam

We need:
- $\beta^* = 10$ cm
  $(10^{33} \text{ cm}^2\text{s}^{-1})$
- $\beta^* = 5$ cm
  $(10^{34} \text{ cm}^2\text{s}^{-1})$

SEVERE LIMITATIONS
1. Quadrupole apertures
2. Quadrupole gradients
3. Limits of the chromatic correction scheme
Consideration of the magnets for the LHeC included the design of a half quadrupole for Q1 given the short distance between the proton beam and the electron beam.

This design presents stray fields in the 'field-free' region difficulting to match the electron beam. Also, beam is off-axis so there is a deflection on the focussed proton beam.
Asymmetric IR Layout: example LHeC

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**

Synchrotron Radiation (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]

L* [m]  
10  12  14  16  18  20  22

SR Power [kW]

R. Tomas
Asymmetric IR Layout: Magnet Design

Magnet design planned for eRHIC IR.
With the use of outer coils a reduced field region is created inside the

Various options on the table with solutions at hand!
Final implementation strongly depends on actual IR choice and
FCC-hh optics configuration!!

Possible new design for the Q1

"Sweet Spot" design for Interaction Region
Septum Magnets in IPAC 2016 by Brett Parker.
Asymmetric IR Layout: Magnet Design

The sweet spot quadrupole has double the gradient for a given aperture, or double the aperture for the same gradients. Leaving more space to put masks through the whole length of Q1.

The baseline LHeC IR geometry is particularly challenging as it requires very wide Sweet Spot regions to locate both the electron and proton beams.

B. Parker, LHeC Workshop, Chavannes, 2015.
ERL Arc Optics: Emittance preservation

[Flexible Momentum Compaction]

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

Emittance dilution due to quantum excitations:

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

\[ I_5 = \int_0^L \frac{H}{|\rho|^3} ds = \left( \frac{\theta \langle H \rangle}{\rho^2} \right) \]

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

Arc 1, Arc 2

Imaginary \( \gamma \) Optics

Arc 3, Arc 4

DBA-like Optics

[Double Bend Achromat]

Arc 5, Arc 6

TME-like Optics

[Theoretical Minimum Emittance]

\[ \langle H \rangle = 8.8 \times 10^{-3} \text{ m} \]

\[ \langle H \rangle = 2.2 \times 10^{-3} \text{ m} \]

\[ \langle H \rangle = 1.2 \times 10^{-3} \text{ m} \]

total emittance increase in Arc 1-5: \( \Delta \varepsilon_x^N = 4.9 \mu \text{m rad} \)

factor of 20 smaller than FODO
HOM & Beam-Beam

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

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

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

Beam is stable but very small margin with 1.3GHz cavity ➔ lower frequency

➔ Choice of 802MHz for FCC-eh & LHeC!

Daniel Schulte @ LHeC Seminar 12. March 2013
ERL SRF: FCC-eh, LHeC, PERLE

PERLE: 150, 450, 900 MeV
Frequency: 801.58 MHz

High current, multi-turn (3) ERL concept with 802MHz SRF to be tested at PERLE facility in LAL in Orsay!!!

Max Klein later in this session

Basic unit: 5-cell cavity into 4-cavity module

FCC-eh: 60 GeV, ERL
1km SRF linac; 944 cavities; 59 cryo modules / linac
Number of passes: 6
Beam current: 6.6-25.6 mA
### SRF: 802 MHz 5-Cell design minimizing HOM

#### HOM Coupler: LHC-like dual concept

<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>$B_0$ [mT]</td>
<td>95.4</td>
<td>98.3</td>
</tr>
<tr>
<td>$R/Q$ [$\Omega$]</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 [$\Omega$]</td>
<td>276</td>
<td>283</td>
</tr>
<tr>
<td>Field Flatness</td>
<td>97%</td>
<td>96%</td>
</tr>
</tbody>
</table>
SRF: Prototyping in collaboration with JLab

Evaluate scaled LHC type coupler and HOM dampers
[CERN model by Rama Calaga]

- LHC power coupler is well proven but may be overkill
- JLab FEL waveguide dampers may be overkill*
- LHC HOM dampers are somewhat narrow band (tuned)
- High power capability (~1 kW), active cooling
- Demountable
- Evaluate scaled TESLA couplers in the same location

*R or not, depending on filling pattern
SRF: JLab Collaboration

Fabricate dies. **Q2 FY17**
Test dies with Al or Cu disks, check dimensions etc.
Fabricate one or more copper 1-cell cavities. **Q3 FY17**
   Check tuning procedure and useful for CERN coating tests
   Can add ports for development of HOM couplers
Fabricate one bare Nb single cell. **Q3 FY17**
   Validate frequency, Qo and gradient
   Option to make one large grain single cell
Fabricate bare 5-cell cavity (no He vessel) with ports. **Q4 FY17**

*Robert Rimmer JLab*

☑️ = in plan, ? = option
SRF Design: Power

Chain of 8 IOTs installed powering two cavities in the SPS

800 MHz IOTs (~60 kW) for the SPS 3rd harmonic system

Rama Calaga
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

-6  -4  -2  0  2  4  6
z [mm]  head <---> tail

-200  -150  -100  -50  0  50  100  150  200
Internal energy difference [MeV]

dump (500 MeV)
injector (500 MeV)
Synchrotron Radiation and Beam-Beam
Transverse Plane at Dump

Aperture radius of the SPL cavity is 40 mm.
## FCC-eh ERL Configuration:

### Consistent Performance Projections for ep:

<table>
<thead>
<tr>
<th>parameter [unit]</th>
<th>LHeC CDR</th>
<th>ep at HL-LHC</th>
<th>ep at HE-LHC</th>
<th>FCC-he</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_p$ [TeV]</td>
<td>7</td>
<td>7</td>
<td>12.5</td>
<td>50</td>
</tr>
<tr>
<td>$E_e$ [GeV]</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>$\sqrt{s}$ [TeV]</td>
<td>1.3</td>
<td>1.3</td>
<td>1.7</td>
<td>3.5</td>
</tr>
<tr>
<td>bunch spacing [ns]</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>protons per bunch [$10^{11}$]</td>
<td>1.7</td>
<td>2.2</td>
<td>2.5</td>
<td>1</td>
</tr>
<tr>
<td>$\gamma\epsilon_p$ [µm]</td>
<td>3.7</td>
<td>2</td>
<td>2.5</td>
<td>2.2</td>
</tr>
<tr>
<td>electrons per bunch [$10^9$]</td>
<td>1</td>
<td>2.3</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>electron current [mA]</td>
<td>6.4</td>
<td>15</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>IP beta function $\beta_p^* [cm]$</td>
<td>10</td>
<td>7</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>hourglass factor $H_{geom}$</td>
<td>0.9</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>
<td>1.3</td>
</tr>
<tr>
<td>proton filling $H_{coll}$</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>luminosity [$10^{33}\text{cm}^{-2}\text{s}^{-1}$]</td>
<td>1</td>
<td>8</td>
<td>12</td>
<td>15</td>
</tr>
</tbody>
</table>

EDMS 17979910 FCC-ACC-RPT-0012 V1.0, 6 April, 2017, “A Baseline for the FCC-he”

Oliver Brüning, John Jowett, Max Klein, Dario Pellegrini, Daniel Schulte, Frank Zimmermann
### FCC-eh ERL Configuration:

**Performance Simulations for FCC-ep:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Protons</th>
<th>Electrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>GeV</td>
<td>50000</td>
<td>60</td>
</tr>
<tr>
<td>Normalised emittance</td>
<td>μm</td>
<td>2.2 → 1.1</td>
<td>10</td>
</tr>
<tr>
<td>IP betafunction</td>
<td>mm</td>
<td>150</td>
<td>42 → 52</td>
</tr>
<tr>
<td>Nominal RMS beam size</td>
<td>μm</td>
<td>2.5 → 1.8</td>
<td>1.9 → 2.1</td>
</tr>
<tr>
<td>Waist shift</td>
<td>mm</td>
<td>0</td>
<td>65 → 70</td>
</tr>
<tr>
<td>Bunch population</td>
<td>10^{10}</td>
<td>10 → 5</td>
<td>0.31</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>ns</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Luminosity</td>
<td>10^33 cm^{-2}s^{-1}</td>
<td>18.3 → 14.3</td>
<td>1.2</td>
</tr>
<tr>
<td>Int. luminosity per 10 years</td>
<td>[ab^{-1}]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

EDMS 17979910 FCC-ACC-RPT-0012 V1.0, 6 April, 2017, “A Baseline for the FCC-he”
### FCC-eh ERL Configuration:

<table>
<thead>
<tr>
<th>parameter</th>
<th>LHeC (HL-LHC)</th>
<th>eA at HE-LHC</th>
<th>FCC-he</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{Pb}$ [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 [$10^6$]</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 $H_{geom}$</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 $H_{coll}$</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>

EDMS 17979910 FCC-ACC-RPT-0012 V1.0, 6 April, 2017, "A Baseline for the FCC-he"

John Jowett, Frank Zimmermann
End
SNS like cryomodule

Cavity fits well in SNS type (805 MHz) cryomodule
Cost and fabrication processes well understood
Some updates for pressure code have been made by ORNL
Plans to build new modules for SNS Power Upgrade
Fresh cost estimate in hand, can be adapted to PERLE
Jlab Modular Cryostat

- Take the best features of previous JLab designs
- Modular approach to hold various different cavities
- Design suitable for industrial production
- Simple concepts, low parts count to reduce costs
FCC-eh Configuration: Layout & Civil Engineering

Racetrack Layout Point H: FCC-hh RF

Tunnel Geology
- Molasse rock (sandstone)

Construction
- Tunnel Boring Machine (TBM) in straight sections
- Roadheader in arcs

Civil Engineering challenges
- Low geological risk
- Interaction with main FCC tunnel(s)