60GeV ERL Baseline Configuration:

Super Conducting Recirculating Linac with Energy Recovery

1072 cavities; 134 cryo modules per linac
ca. 9 km underground tunnel installation
more than 4500 magnets

Operation in parallel with LHC/HE-LHC/FCC-hh

- TeV scale collision energy
  ➔ 50-150 GeV electron beam energy

- power consumption < 100 MW
  ➔ 60 GeV beam energy

- int. luminosity > 100 * HERA
- peak luminosity $L > 10^{34}$ cm$^{-2}$s$^{-1}$

* LHeC CDR, arXiv:1206.2913
courtesy H.Burkhardt, BE-ABP CERN (layout scaled !)

Electrons for the LHC-LHeC/FCC-eh and PERLE Workshop: Orsay, 27th to 29th June 2018
Oliver Brüning, CERN
Various options on the table with solutions at hand! Design work on the ‘Sweet Spot’ magnet is still ongoing! Need to select and develop one option!!!
LHeC / FCC-eh Configuration and Performance

Hadron IR design:

<table>
<thead>
<tr>
<th>IP</th>
<th>Inner Triplet</th>
<th>Separation Dipoles</th>
<th>Matching Section</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Q1  Q2  Q3</td>
<td>D1</td>
<td>D2  Q4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Q5  Q6  Q7</td>
</tr>
</tbody>
</table>

E. Cruz @ FCC week in Rome

Implementation of new triplet Q1-Q3 with aperture for 2 proton beams and one electron beam ➔ current studies based on layout WITHOUT Crab Cavities!
➔ strong synchrotron radiation and dipole inside detector!

We need:
- $\beta^* \approx 50 \text{ cm (}10^{33} \text{ cm}^2\text{s}^{-1}\text{)}$
- $\beta^* \approx 5 \text{ cm (}10^{34} \text{ cm}^2\text{s}^{-1}\text{)}$

**SEVERE LIMITATIONS**

1. Quadrupole apertures
2. Quadrupole gradients
3. Limits of the chromatic correction scheme
# LHeC: RL with ERL Operation as Baseline

## Performance:

* LHeC CDR, arXiv:1206.2913

<table>
<thead>
<tr>
<th>10^{33} \text{ cm}^{-2} \text{s}^{-1} \text{ Luminosity reach}</th>
<th>PROTONS</th>
<th>ELECTRONS</th>
<th>10^{34} \text{ cm}^{-2} \text{s}^{-1} \text{ Luminosity reach}</th>
<th>PROTONS</th>
<th>ELECTRONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity [10^{33} \text{ cm}^{-2} \text{s}^{-1}]</td>
<td>1</td>
<td>1</td>
<td>Luminosity [10^{33} \text{ cm}^{-2} \text{s}^{-1}]</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Normalized emittance $\gamma \varepsilon_{x,y} [\mu \text{m}]$</td>
<td>3.75</td>
<td>50</td>
<td>Normalized emittance $\gamma \varepsilon_{x,y} [\mu \text{m}]$</td>
<td>2.5</td>
<td>20</td>
</tr>
<tr>
<td>Beta Function $\beta^*_{x,y} [\text{m}]$</td>
<td>0.1</td>
<td>0.12</td>
<td>Beta Function $\beta^*_{x,y} [\text{m}]$</td>
<td>0.05</td>
<td>0.10</td>
</tr>
<tr>
<td>rms Beam size $\sigma^*_{x,y} [\mu \text{m}]$</td>
<td>7</td>
<td>7</td>
<td>rms Beam size $\sigma^*_{x,y} [\mu \text{m}]$</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>rms Beam divergence $\sigma_{x,y}^* [\mu \text{rad}]$</td>
<td>70</td>
<td>58</td>
<td>rms Beam divergence $\sigma_{x,y}^* [\mu \text{rad}]$</td>
<td>80</td>
<td>40</td>
</tr>
<tr>
<td>Beam Current @ IP [mA]</td>
<td>860</td>
<td>6.6</td>
<td>Beam Current @ IP [mA]</td>
<td>1112</td>
<td>25 (\rightarrow) 15</td>
</tr>
<tr>
<td>Bunch Spacing [ns]</td>
<td>25</td>
<td>25</td>
<td>Bunch Spacing [ns]</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Bunch Population</td>
<td>$1.7 \times 10^{11}$</td>
<td>$1 \times 10^9$</td>
<td>Bunch Population</td>
<td>$2.2 \times 10^{11}$</td>
<td>$2.3 \times 10^9$</td>
</tr>
<tr>
<td>Bunch charge [nC]</td>
<td>27</td>
<td>0.16</td>
<td>Bunch charge [nC]</td>
<td>35</td>
<td>0.64</td>
</tr>
</tbody>
</table>

*Post LHeC CDR, using HL-LHC parameters*
LHeC / FCC-eh Configuration: Layout Options

C. Cook @ FCC week in Rome

Configuration:

LHeC

FCC-he considers Point ‘L’ since FCC Week in Berlin
FCC Layout Changes (profile)

Rome 2016 Layout

Berlin 2017 Layout

Reduced Depth & alignment change; area surrounding L no longer in limestone.
**LHeC & FCC-eh Machine Configuration**

**Configuration:**

Modular design elements:

- 60 GeV ERL configuration with 3 re-circulations for the ‘e’ beam documented in the LHeC CDR applicable to LHC, HE-LHC and FCC ➔ varied sizes possible;
- IR configuration with head-on collisions ➔ without Crab Cavities (vs EI in US)! ➔ Performance boost with CC?
- SR acceptance in detector and beam separation
- Dipole integrated into detector ➔ Impact of Crab Cavities?
- ‘Sweetspot’ IR magnet design ➔ $\beta^*$ reach versus e-beam current!
- 802MHz SRF: synergy between LHeC, FCC-eh, FCC-ee and FCC-hh

* LHeC CDR, arXiv:1206.2913

**Impact of Crab Cavities?**

* $\beta^*$ reach versus e-beam current!
Difference in LHeC and FCC-eh costing:

Civil Engineering:

- Geological conditions are different for the LHeC and the FCC-eh
  - Different consultancy companies with different estimates

- Different tunnel depth
  - Different cost for the shafts even for equal tunneling cost

- In the following we concentrate on the LHeC costing

- FCC-eh civil engineering costing will be part of the FCC costing
Cost Items not simply Scaling with Energy:

**IR Magnets:**
Assume these require a comparable development as the HL-LHC triplet magnets

- 15 years of R&D cost + production cost ➔ ca. 80MCHF

**Auxiliary Systems:**
Not yet fully evaluated ➔ assume a placeholder of 69MCHF for this exercise;
including 19MCHF for surface buildings based on Amberg estimate

**ERL Injector:** One off proto-type like object

- cost estimate based on CERN SRF R&D and cost for SPL and PERLE facility
- ca. 40MCHF
Cost Items not simply Scaling with Energy:

- **ERL Tunnel without RF and arc:**
  Assume 400m for transfer lines and 400m space in each straight for beam dump and ERL spreader and combiner sections \(\Rightarrow\) ca. 30MCHF

- **Access shafts and Access Shaft Caverns: Amberg; ILF and HL-LHC**
  Assume 2 shafts with LHC depth \(\Rightarrow\) ca. 34MCHF for 2 shafts
  [for comparison: the HL-LHC shafts cost 10.4MCHF per shaft]

- **Beam Dump:** \(\Rightarrow\) ca. 5MCHF placeholder
ERL Cost Items scaling with Energy: 802 MHz 5-Cell SRF

### Parameter

<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>

**HOM Coupler: LHC-like dual concept**
ERL Cost Items scaling with Energy: 802 MHz 5-Cell SRF

JLAB / CERN collaboration

F. Marhauser Feb 2018

✓ = in plan, ? = option
Primary source of estimate: European XFEL

Project finished with comparable size of SRF system [albeit pulsed and not CW]

Assume the SRF cost per Cryomodule scales roughly with CM length

Add 30% to account for non-linear scaling between [e.g. 1.3GHz / 800MHz size]

Secondary cost comparison: LCLSII

Project has a comparable size of SRF system [and CW] but is not yet finished

Assume the SRF cost per Cryomodule scales roughly with CM length

Tertiary cost comparison: SRF Prototypes and Special Cryomodules:

C-BETA @ Cornell University; SPL SRF development at CERN

-Use the estimates for the SRF Prototypes for the injector costing

Ca. 3MCHF per 7.5m long ERL Cryo Module

Ca. 6.1MCHF per 7.5m long R&D Cryo Module
ERL Cost Items scaling with Energy: Cryogenic System:

- Primary source of estimate: LHC experience

  - Cryo-plant cost as a function of achievable $Q_0$ in the SRF system

Analysis of optimum number of Cryo-plants

$Q_0 = 10^{10}$ implies Cryo-Plants comparable in size to that of the LHC

- The baseline configuration assumes $Q_0 = 2.5 \times 10^{10}$
- Attractive options of 2 or 4 cryo-plants
- For the scaling we assume 4CPs [100MCHF] and scale the cryo cost with the SRF linac length

$\Rightarrow$ reducing the system to 2 plants might bring further savings of up to 25MCHF

[Laurent Tavian and Serge Claudet]
LHeC Baseline Configuration Costing

60 GeV ERL Beam Energy:

<table>
<thead>
<tr>
<th>Budget Item</th>
<th>Cost</th>
</tr>
</thead>
</table>

- SRF System and Cavity System: 800 MCHF
- Based on XFEL and LCLS2 costing scaled by CM length

- Based on CERN SPL studies
- Based on CERN SPL prototype costs
- Based on LEP experience and estimates by CERN
- Based on the HL-LHC IR magnet cost
- Based on CERN expert estimates
- Based on scaling from the LHC and HL-LHC infrastructure
- Placeholder estimate from HL-LHC and LHC studies
- Based on LEP cost corrected by inflation and on dedicated Civil Engineering studies

- All cost estimates have a significant uncertainty [ca. +/− 30%]
- [e.g. Cryo with 2 vs 4 plants; 50% addition to SRF tunnel; SRF R&D cost and Injector cost; etc.]

- But SRF is clearly the main cost driver!
- Motivation to look at energy and size cost scaling!!!

For this we keep the budget for SR power and total Wall-Plug Power consumption constant

- Main cost drivers are SRF [scales with linac length] and return arcs [scales with $E^4$]
Assumptions and Boundary Conditions for Scaling

Baseline Assumptions:

Limit the Wall-plug Power consumption of the ERL to 100MW
- Assume 50% of that are required for SR [rest for cryo and magnets]
  documented in the LHeC CDR

Synchrotron Radiation Power per arc:

\[ P_{arc} = \frac{N_b e^2 \gamma^4}{n_b 6 \epsilon_0 \rho} \]

Scales with \( E^4 \) and \( \rho^{-1} \) \( \rightarrow \) ca. 40% of SR power comes from high energy return arc
- Assume 50MW limit for energy consumption for SR losses
  \( \rightarrow \) scale return arc radius of curvature for a given beam energy to stay within this limit
Assumptions and Boundary Conditions for Scaling

- **Civil Engineering:**
  LEP cost as a reference $\Rightarrow$ inflation adapted cost
  Plus two estimates from external consultant companies:
  Amberg for LHeC and ILF for FCC related CE $\Rightarrow$ ca. 25kCHF / m for scaling

- **SRF Tunnel:**
  Scales with $E$. For CE costing we assume a 50% tariff for the CE cost per meter to account for the required space for RF power sources

- **Magnet and vacuum system:** scales with $E^4$
  The full magnets and vacuum system had been costed for the LHeC CDR:
  140MCHF for the complete LHeC system $\Rightarrow$ ca. 11.15kCHF per arc meter
FCC-eh Configuration: Layout & Civil Engineering

**Configuration:**
- Preliminary cost estimates based on XFEL, LCLS-II budgets
- These estimates also fit well with estimates from CBETA and ESS studies:

**→ SRF is the main cost driver up to energies of 70GeV!!!**

The $E^4$ dependence on the arc length only becomes dominant for beam energies above 75GeV!

[Unless the SRF cost becomes significantly lower!]

---

Electrons for the LHC-LHeC/FCC-eh and PERLE Workshop: Orsay, 27th to 29th June 2018

Oliver Brüning, CERN
Cost and Configuration Option

- **Motivation:** look for a configuration where the ERL cost comes down to 1BCHF.

- **Approach 1:**
  
  With the SRF as the primary cost driver: reduce SRF system by 50% $\rightarrow$ 30GeV

- **Approach 2:**
  
  Keep remaining infrastructure compatible with a later energy upgrade.
  $\rightarrow$ Design the arcs, linac tunnel, cryo etc for a beam energy of 50GeV.

- **Costing:**
  
  Provide cost estimate for initial 30GeV version plus the required additional funds for an upgrade to 50GeV beam energy.
Sanity Check ➔ apply costing model to ILC

Geoffrey Norman Taylor @ FCC Week in Amsterdam

500GeV Version with 1824, 12m long XFEL CM modules
30km accelerator with 22km SRF linacs

• Tunnel ca. 1.5BCHF [but ILC tunnel should be cheaper]
• SRF ca 8.8BCHF
• Cryo ca. 1BCHF ➔ total ca 11BCHF

➔ fits to ILC estimates [we assumed +30% for SRF scaling!]

➔ total of ca. 8BCHF quoted by Barry Barish
End
Sanity Check ➔ apply costing model to ILC

Geoffrey Norman Taylor @ FCC Week in Amsterdam

500GeV Version with 1824, 12m long XFEL CM modules
30km accelerator with 22km SRF linacs

➔ 250GeV Version with 11km SRF:

- Tunnel ca. 0.75BCHF
- SRF ca 4.4BCHF
- Cryo ca. 0.5BCHF ➔ total ca 5.5BCHF

➔ fits to ILC estimates [we assumed +30% for SRF scaling!]

Nominal 60 GeV Configuration:
30GeV to 50GeV Variation:

➔ The scaled ERL circumference corresponds to 1/5th of the LHC circumference: 5.4km

Sanity Check ➔ apply costing model to ILC

Geoffrey Norman Taylor @ FCC Week in Amsterdam

500GeV Version with 1824, 12m long XFEL CM modules
30km accelerator with 22km SRF linacs

➔ 250GeV Version with 11km SRF:

- Tunnel ca. 0.75BCHF
- SRF ca 4.4BCHF
- Cryo ca. 0.5BCHF ➔ total ca 5.5BCHF

➔ fits to ILC estimates [we assumed +30% for SRF scaling!]
### 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>$\gamma\epsilon_p$ [$\mu$m]</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 [$10^{33}$cm$^{-2}$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”

Daniel Schulte
## FCC-eh ERL Configuration:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LHeC (HL-LHC)</th>
<th>eA at HE-LHC</th>
<th>FCC-eh</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>
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<td>50</td>
<td>100</td>
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<tr>
<td>no. of bunches</td>
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<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>$\gamma \varepsilon_A$ [\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>
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<tr>
<td>luminosity [$10^{32} \text{cm}^{-2} \text{s}^{-1}$]</td>
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<td>18</td>
<td>54</td>
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</tbody>
</table>

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John Jowett, Frank Zimmermann