LHeC Race track as Injector to FCC-ee

Y. Papaphilippou (CERN) with input from O. Brunning, R. Corsini, M. Klein, K. Oide, F. Zimmermann
Content

• Brief overview of FCCee injector
  • Design principle
  • Layout and parameters

• LHeC recirculating linac injector (RLI) for FCCee
  • Basic considerations and tentative parameters

• Conclusions and future work
Due to extremely high luminosity, beam lifetime limited to $\leq 20$ min (radiative Bhabha scattering, beamstrahlung) maintaining constant luminosity and beam current requires quasi-continuous “top-up injection” (demonstrated @ PEP-II, KEKB, SuperKEKB, light sources) → full-energy booster (same tunnel)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Z</th>
<th>WW</th>
<th>H (ZH)</th>
<th>ttbar</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam energy [GeV]</td>
<td>45</td>
<td>80</td>
<td>120</td>
<td>182.5</td>
</tr>
<tr>
<td>beam current [mA]</td>
<td>1390</td>
<td>147</td>
<td>29</td>
<td>5.4</td>
</tr>
<tr>
<td>no. bunches/beam</td>
<td>16640</td>
<td>2000</td>
<td>393</td>
<td>48</td>
</tr>
<tr>
<td>bunch intensity [$10^{11}$]</td>
<td>1.7</td>
<td>1.5</td>
<td>1.5</td>
<td>2.3</td>
</tr>
<tr>
<td>SR energy loss / turn [GeV]</td>
<td>0.036</td>
<td>0.34</td>
<td>1.72</td>
<td>9.21</td>
</tr>
<tr>
<td>total RF voltage [GV]</td>
<td>0.1</td>
<td>0.44</td>
<td>2.0</td>
<td>10.9</td>
</tr>
<tr>
<td>long. damping time [turns]</td>
<td>1281</td>
<td>235</td>
<td>70</td>
<td>20</td>
</tr>
<tr>
<td>horizontal beta* [m]</td>
<td>0.15</td>
<td>0.2</td>
<td>0.3</td>
<td>1</td>
</tr>
<tr>
<td>vertical beta* [mm]</td>
<td>0.8</td>
<td>1</td>
<td>1</td>
<td>1.6</td>
</tr>
<tr>
<td>horiz. geometric emittance [nm]</td>
<td>0.27</td>
<td>0.28</td>
<td>0.63</td>
<td>1.46</td>
</tr>
<tr>
<td>vert. geom. emittance [pm]</td>
<td>1.0</td>
<td>1.7</td>
<td>1.3</td>
<td>2.9</td>
</tr>
<tr>
<td>bunch length with SR / BS [mm]</td>
<td>3.5 / 12.1</td>
<td>3.0 / 6.0</td>
<td>3.3 / 5.3</td>
<td>2.0 / 2.5</td>
</tr>
<tr>
<td>luminosity per IP [$10^{34}$ cm$^{-2}$s$^{-1}$]</td>
<td>230</td>
<td>28</td>
<td>8.5</td>
<td>1.55</td>
</tr>
<tr>
<td>beam lifetime Bhabha/BS [min]</td>
<td>68 / &gt;200</td>
<td>49 / &gt;1000</td>
<td>38 / 18</td>
<td>40 / 18</td>
</tr>
</tbody>
</table>
Conceptual Design of FCCee injectors

- **S-Band linac** (as in SLAC and SuperKEKB) @ 6 GeV with **positron** generation @ 4.46 GeV and **Damping Ring** @ 1.54 GeV
- **Modified SPS** as pre-booster ring up to 20 GeV (now 16 GeV)
- **Top-up booster** shares tunnel with collide and accelerates e+/e- beam to final energies
Filling scheme for Z-pole

Booster: 16640 bunches
2.1x10^{10} p/b

14 cycles of
3.3 sec

10 cycles** of
48 sec

Collider: 16640 bunches
1.7x10^{11} p/b (~80% efficiency)

SPS: ~1190 bunches*
2.1x10^{10} p/b

595 injections

6 GeV Linac: 2 bunches/Pulse
200 Hz repetition
2.1x10^{10} p/b

* 198 mini-trains with 6 b (20 ns) and 71/126 mini-train gaps (15/17.5 ns), kicker gap of 120 ns
** 10 cycles for either species keep charge imbalance within ±5% needed to prevent beam-beam flip-flop (“bootstrapping”)

Ni = 594 (x10)+595 (x4)

2.8 GHz LINAC @ 200 Hz, 6 GeV

Ni = 14
3.3 s
1188/1190 b

SPS from 6 to 16 GeV

Ni = 10
48 s
16640 b

BR from 16 to 45.6 GeV
## FCCee injector parameters

<table>
<thead>
<tr>
<th>Accelerator</th>
<th>FCCee-Z</th>
<th>FCCee-W</th>
<th>FCCee-H</th>
<th>FCCee-&lt;i&gt;tt&lt;/i&gt;</th>
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</thead>
<tbody>
<tr>
<td>Energy [GeV]</td>
<td>45.6</td>
<td>80</td>
<td>120</td>
<td>182.5</td>
</tr>
<tr>
<td>Type of filling</td>
<td>Full</td>
<td>Top-up</td>
<td>Full</td>
<td>Top-up</td>
</tr>
<tr>
<td>LINAC # bunches, with 2.8 GHz RF</td>
<td>2</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LINAC repetition rate [Hz]</td>
<td>200</td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LINAC/PBR bunch population [10&lt;sup&gt;10&lt;/sup&gt;]</td>
<td>2.13</td>
<td>1.06</td>
<td>0.94</td>
<td>0.56</td>
</tr>
<tr>
<td># of LINAC injections</td>
<td>594/595</td>
<td>500</td>
<td>328</td>
<td>48</td>
</tr>
<tr>
<td>PBR bunch spacing [ns]</td>
<td>15/17.5/20 ns</td>
<td>22.5</td>
<td>67.5</td>
<td>450</td>
</tr>
<tr>
<td># PBR cycles</td>
<td>14</td>
<td>2</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>PBR # of bunches</td>
<td>1188/1190</td>
<td>1000</td>
<td>393</td>
<td>50</td>
</tr>
<tr>
<td>PBR cycle time [s]</td>
<td>3.3</td>
<td>5.4</td>
<td>3.6</td>
<td>0.8</td>
</tr>
<tr>
<td>PBR duty factor</td>
<td>0.76</td>
<td>0.49</td>
<td>0.23</td>
<td>0.05</td>
</tr>
<tr>
<td>BR # of bunches</td>
<td>16640</td>
<td>2000</td>
<td>328</td>
<td>48</td>
</tr>
<tr>
<td>BR cycle time [s]</td>
<td>47.9</td>
<td>13</td>
<td>6.9</td>
<td>5.7</td>
</tr>
<tr>
<td># of BR cycles</td>
<td>10</td>
<td>1</td>
<td>20</td>
<td>1</td>
</tr>
<tr>
<td># of injections/collider bucket</td>
<td>10</td>
<td>1</td>
<td>20</td>
<td>1</td>
</tr>
<tr>
<td>Total number of bunches</td>
<td>16640</td>
<td>2000</td>
<td>328</td>
<td>48</td>
</tr>
<tr>
<td>Filling time (both species) [sec]</td>
<td>958.8</td>
<td>95.9</td>
<td>520</td>
<td>26</td>
</tr>
<tr>
<td>Injected bunch population [10&lt;sup&gt;10&lt;/sup&gt;]</td>
<td>2.13</td>
<td>1.06</td>
<td>1.44</td>
<td>1.44</td>
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</table>
**FCCee injector parameters**

<table>
<thead>
<tr>
<th>Accelerator</th>
<th>FCCee-Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy [GeV]</td>
<td>45.6</td>
</tr>
<tr>
<td>Type of filling</td>
<td>Full</td>
</tr>
<tr>
<td>LINAC # bunches, with 2.8 GHz RF</td>
<td>2</td>
</tr>
<tr>
<td>LINAC repetition rate [Hz]</td>
<td>200</td>
</tr>
<tr>
<td>LINAC/PBR bunch population (10^{10})</td>
<td>2.13</td>
</tr>
<tr>
<td># of LINAC injections</td>
<td>594/595</td>
</tr>
<tr>
<td>PBR bunch spacing [ns]</td>
<td>15/17.5/20 ns</td>
</tr>
<tr>
<td># of PBR cycles</td>
<td>14</td>
</tr>
<tr>
<td>PBR # of bunches</td>
<td>1188/1190</td>
</tr>
<tr>
<td>PBR cycle time [s]</td>
<td>3.3</td>
</tr>
<tr>
<td>PBR duty factor</td>
<td>0.76</td>
</tr>
<tr>
<td>BR # of bunches</td>
<td>16640</td>
</tr>
<tr>
<td>BR cycle time [s]</td>
<td>47.9</td>
</tr>
<tr>
<td># of BR cycles</td>
<td>10</td>
</tr>
<tr>
<td># of injections/collider bucket</td>
<td>10</td>
</tr>
<tr>
<td>Total number of bunches</td>
<td>16640</td>
</tr>
<tr>
<td>Filling time (both species) [sec]</td>
<td>958.8</td>
</tr>
<tr>
<td>Injected bunch population (10^{10})</td>
<td>2.13</td>
</tr>
</tbody>
</table>

- **Injector linac** provides average current < 1.4 μA
- This is ~4 orders of magnitude lower than average current of LHeC ERL (20 mA)
- PBR (SPS) **duty factor** of 76% for FCCee-Z
- **BR cycle time** of ~48 sec dominated by injection
**LHeC ERL parameters**

- Based on **2 SRF Linacs (~800 MHz)** with **3 recirculating arcs**, total length of **~5.3 km** (~1/5 of LHC), reaching **energy** of **~49 GeV** (longer version for reaching **60 GeV**)
- Bunch **intensity** of **~500 pC (~3×10⁹ p/b)** for **~25ns spacing**, **average current** of **20 mA**
- Could be used for **full energy top-up injector** for FCCee-Z and **pre-injector** for other collider energies
- Small footprint **PERLE-like version** could be used as **pre-injector** to (P)BR~6-20GeV

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injector energy</td>
<td>GeV</td>
<td>0.5</td>
</tr>
<tr>
<td>Total number of linacs</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Number of acceleration passes</td>
<td></td>
<td>3</td>
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<tr>
<td>Maximum electron energy</td>
<td>GeV</td>
<td>49.19</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>pC</td>
<td>499</td>
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<tr>
<td>Bunch spacing</td>
<td>ns</td>
<td>24.95</td>
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<tr>
<td>Electron current</td>
<td>mA</td>
<td>20</td>
</tr>
<tr>
<td>Transverse normalized emittance</td>
<td>μm</td>
<td>30</td>
</tr>
<tr>
<td>Total energy gain per linac</td>
<td>GeV</td>
<td>8.114</td>
</tr>
<tr>
<td>Frequency</td>
<td>MHz</td>
<td>801.58</td>
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<tr>
<td>Acceleration gradient</td>
<td>MV/m</td>
<td>19.73</td>
</tr>
<tr>
<td>Cavity iris diameter</td>
<td>mm</td>
<td>130</td>
</tr>
<tr>
<td>Number of cells per cavity</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>Cavity length (active/real estate)</td>
<td>m</td>
<td>0.918/1.5</td>
</tr>
<tr>
<td>Cavities per cryomodule</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>Cryomodule length</td>
<td>m</td>
<td>7</td>
</tr>
<tr>
<td>Length of 4-CM unit</td>
<td>m</td>
<td>29.6</td>
</tr>
<tr>
<td>Acceleration per cryomodule (4-CM unit)</td>
<td>MeV</td>
<td>289.8</td>
</tr>
<tr>
<td>Total number of cryomodules (4-CM units) per linac</td>
<td></td>
<td>112 (28)</td>
</tr>
<tr>
<td>Total linac length (with with spr/rec matching)</td>
<td>m</td>
<td>828.8 (980.8)</td>
</tr>
<tr>
<td>Return arc radius (length)</td>
<td>m</td>
<td>536.4 (1685.1)</td>
</tr>
<tr>
<td>Total ERL length</td>
<td>km</td>
<td>5.332</td>
</tr>
</tbody>
</table>
ERL Configuration for LHC and FCC

- **Common hardware and infrastructure:** one could use FCC-ee pre-series SRF
- **Installation near point L** to minimize transfer line length
- **Would be used as re-circulating linac (RLI) not ERL mode**

![Different Size Variations: e.g LHeC and HE-LHC-eh](image1)

![Interaction region ‘L’ as baseline choice for FCC-eh](image2)
Design and prototyping of a **full dressed SRF cavity**: demonstration of level of SRF performance required in CW operation, high-average current environment, adequate damping of **HOM**.

**Linac cryomodule design**: study the possibility of **SPL cryomodule adaptation** to PERLE need, complete design of a cryomodule for PERLE later.

Design and prototyping of an **input power coupler**.
Filling scheme for Z

- RLI @ ~800 MHz accelerating 832 bunches with 17.5 ns bunch spacing (compatible with collider)
  - Other bunch structures can be envisaged, compatible with present bunch structure collider considerations (see talk of D. Shatilov)
- Injected 20 times @ 45.6 GeV into collider rise (accumulation cycle), for filling 16640 buckets with required gaps for injection/dump kicker
- For 70 accumulating cycles need bunch population of $3 \times 10^9$ for ultra-fast filling (< 1sec), reaching required collider $1.7 \times 10^{11}$ with 80% injection efficiency
  - Intensity can be significantly reduced lowering power while still allowing full filling in a few seconds
- Very comfortable parameters also for top-up, allowing RLI to provide beam to other users
- For other collider energies, injection in the booster for top-up is necessary, with feasible intensities and filling time of a few secs
## Tentative injector parameters with RLI @ 50 GeV (high power)

<table>
<thead>
<tr>
<th>Accelerator</th>
<th>FCCee-Z</th>
<th>FCCee-W</th>
<th>FCCee-H</th>
<th>FCCee-tt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy [GeV]</td>
<td>45.6</td>
<td>80</td>
<td>120</td>
<td>182.5</td>
</tr>
<tr>
<td>Type of filling</td>
<td>Full</td>
<td>Top-up</td>
<td>Full</td>
<td>Top-up</td>
</tr>
<tr>
<td>RLI # bunches (800 GHz RF)</td>
<td>832</td>
<td>1000</td>
<td>328</td>
<td>48</td>
</tr>
<tr>
<td>RLI bunch population [$10^9$]</td>
<td>3.0</td>
<td>0.15</td>
<td>1.3</td>
<td>0.04</td>
</tr>
<tr>
<td>RLI injections</td>
<td>1400</td>
<td>140</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td># of BR cycles</td>
<td>-</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td># of injections/collider bucket</td>
<td>70</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Total number of bunches</td>
<td>16640</td>
<td>2000</td>
<td>328</td>
<td>48</td>
</tr>
<tr>
<td>Filling time (both species) [sec]</td>
<td>0.3</td>
<td>0.3</td>
<td>5.8</td>
<td>5.8</td>
</tr>
</tbody>
</table>
Summary – next steps

- **RLI** very attractive option for FCCee injector
- Several **synergies** with respect to technology (SRF) but also physics (FCCee, FCCeh, other physics program for a high flux electron beam facility)

- **Next steps**
  - Refine **parameters** to include low **power/energy** options
  - **Positron production** scheme (including damping ring)
  - Detailed **beam dynamics design**