Update on the booster design

Acknowledgements:
Thanks to F. Antoniou and T. Tydecks for their input!
What is new since Berlin?

1. New parameters for injector chain
2. Lattice and optics update
3. We converged on 20 GeV injection energy
4. Wigglers were installed to mitigate IBS and decrease damping time at injection energy
5. Dynamic aperture studies
### Parameter overview

**6 GeV linac & damping ring at 1.5 GeV**

**optional pre-booster synchrotron 6-20 GeV**

**100 km top-up booster**

20 GeV – 182.5 GeV

<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>BR # of bunches</td>
<td>16640</td>
<td>2000</td>
<td>393</td>
<td>39</td>
</tr>
<tr>
<td>BR cycle time [s]</td>
<td>51.74</td>
<td>14.4</td>
<td>7.53</td>
<td>5.49</td>
</tr>
<tr>
<td># of BR cycles</td>
<td>10</td>
<td>1</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>1</td>
<td>20</td>
<td>1</td>
</tr>
<tr>
<td>Filling time (both species) [sec]</td>
<td>1034.8</td>
<td>103.5</td>
<td>288</td>
<td>28.8</td>
</tr>
<tr>
<td>Injected bunch population [10^{10}]</td>
<td>3.3</td>
<td>0.16</td>
<td>6.0</td>
<td>0.12</td>
</tr>
</tbody>
</table>
Figure 1.2: Expected luminosity of FCC-ee (TLEP) as a function of the centre-of-mass energy $p_{\text{s}}$ compared to ILC and CLIC [9].

Figure 1.3: Schematic layout of FCC-hh. Long arcs are in black, short arcs in gray. The dispersion suppressors are shown in green. Image by A. Langner.

Key parameters and baseline optics design

- Double ring $e^+ e^-$ collider, $\sim 100$ km
- Follow the footprint of FCC-hh, except for around the IPs
- 2 IPs with crab-waist scheme, large horizontal crossing angle of $30$ mrad.
- Flexible design, for all energies:
  - common lattice, except for a small rearrangement in the RF section
  - $L^* = 2.2$ m (length of the free area around the IP), $B$ detector $= 2$ T
  - $E_{\text{critical}} < 100$ keV (critical energy of the synchrotron radiation) of incoming beam toward IP from $450$ m
- Top-up injection scheme to maintain the stored beam current and the luminosity at the highest level during experiment runs. It is necessary to have a booster synchrotron in the same tunnel as the collider.
- Synchrotron radiation power $50$ MW/beam at all energies.
- “Tapering” of magnets along the ring to compensate the sawtooth effect.
- Common RF cavities for $e^+$ and $e^-$ at $t\bar{t}$, $e^+$ (RF frequency $400$ MHz and $400+800$ MHz at $t\bar{t}$).

M. Boscolo, FCCWEEK18

The layout of the booster follows the footprint of FCC-hh $\rightarrow$ inside of the experiments.
Lattice and optics

- 90°/90° optics for $H$ and $tt$
- 60°/60° optics for $W$ and $Z$
- Non-interleaved sextupole scheme, 1 family per plane

Long arcs
$L_{\text{cell}} \approx 54$ m
$R = 13.15$ km

FCC-hh
disp. suppressor
$L_{\text{cell}} = 56.6$ m
$R = 15.06$ km

straight section
with RF
$L_{\text{cell}} = 100$ m
Equilibrium emittances

<table>
<thead>
<tr>
<th>beam energy (in GeV)</th>
<th>emittance booster (in nm rad)</th>
<th>emittance collider (in nm rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>182.5</td>
<td>1.30</td>
<td>1.48</td>
</tr>
<tr>
<td>120.0</td>
<td>0.55</td>
<td>0.63</td>
</tr>
<tr>
<td>80.0</td>
<td>0.73</td>
<td>0.84</td>
</tr>
<tr>
<td>45.5</td>
<td>0.24</td>
<td>0.24</td>
</tr>
</tbody>
</table>

90°/90° optics

60°/60° optics

Low synchrotron radiation at 20 GeV beam energy:

\[ \varepsilon_x = 15 \text{ pm rad (90°/90° optics)} \]
\[ \tau_x = 10.05 \text{ s} \]
Emittance with IBS

Hor. equilibrium emittance $\varepsilon_x$:

@ 45.5 GeV
@ 20 GeV

Emittances after 0.7 s

Emittance blow-up due to IBS
$\varepsilon_x = 722 \text{ pm rad}$
$\approx 48 \times \varepsilon_x$ without IBS
## Wiggler parameters and locations

<table>
<thead>
<tr>
<th>Wiggler parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_{\text{pole}}$</td>
<td>(T)</td>
</tr>
<tr>
<td>$B_{\text{wiggler}}$</td>
<td>(T)</td>
</tr>
<tr>
<td>$L_{\text{pole}}$</td>
<td>(cm)</td>
</tr>
<tr>
<td>$g$</td>
<td>(cm)</td>
</tr>
<tr>
<td># poles</td>
<td></td>
</tr>
<tr>
<td>$L$</td>
<td>(m)</td>
</tr>
<tr>
<td># wigglers</td>
<td></td>
</tr>
<tr>
<td>$\tau_x$</td>
<td>(s)</td>
</tr>
<tr>
<td>$\varepsilon_x (60^\circ/60^\circ)$</td>
<td>(pm rad)</td>
</tr>
<tr>
<td>$\varepsilon_x (90^\circ/90^\circ)$</td>
<td>(pm rad)</td>
</tr>
</tbody>
</table>

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Figure 1.3: Schematic layout of FCC-hh. Long arcs are in black, short arcs in gray. The dispersion suppressors are shown in green. Image by A. Langner.

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FCC Week 2018  
12 April 2018, Amsterdam, Netherlands
Emittance evolution with wigglers

New damping time: $\tau_x = 104$ ms
New eq. emittance: $\varepsilon_x = 196$ pm rad

Emittances after 7 damping times:
$\varepsilon_x = 197$ pm rad
$\approx 1.003 \times \varepsilon_x$ without IBS
$\varepsilon_y = 1.96$ pm rad
$\approx 1.000 \times \varepsilon_y$ without IBS*

* assuming 1 % coupling
Additional synchrotron radiation

- Wigglers need to be ramped down during the acceleration process
- RF voltage was increased to $V_{\text{rf}} = 140 \text{ MV}$
- Synchrotron radiation power per wiggler: $P_w \approx 2.1 \text{ MW (Z, full filling)}$

<table>
<thead>
<tr>
<th>$E$ (GeV)</th>
<th>$U_0$ (MeV)</th>
<th>$U_0$ (MeV) with wiggler</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.0</td>
<td>1.3</td>
<td>126.2 ✓</td>
</tr>
<tr>
<td>45.5</td>
<td>34.7</td>
<td>681.3 X</td>
</tr>
<tr>
<td>182.5</td>
<td>9.057.1</td>
<td>19981.2 X</td>
</tr>
</tbody>
</table>
Dynamic aperture studies

The studies include

• radiation damping and quantum excitation
• 100 μm quadrupole misalignments (100 seeds)
• 55 μm resolution

and were performed for 20 GeV beam energy
DA of 60°/60° optics with misalignments

- with $\varepsilon_x = 45$ pm rad
  and $\beta_x = \beta_y = 100$ m
  $\Rightarrow x_{\text{max}} = 16.0$ mm
  $\Rightarrow y_{\text{max}} = 9.7$ mm

On-axis on-energy injection foreseen.

**Ideal lattice**
Lattice with misalignments (100 seeds)

* for 1 % coupling
DA of 90°/90° optics with misalignments

- with $\varepsilon_x = 15$ pm rad
- and $\beta_x = \beta_y = 100$ m

$\Rightarrow x_{\text{max}} = 8.7$ mm
$\Rightarrow y_{\text{max}} = 2.6$ mm

On-axis on-energy injection foreseen.

Without wigglers

Ideal lattice*
Lattice with misalignments (100 seeds)

* for 1 % coupling
Momentum aperture

Energy spread of injected beam:

\[ \frac{\sigma_E}{E} \approx 0.001 \text{ (pre-booster)} \]
\[ \approx 0.01 \text{ (linac)} \]
DA with wigglers

Work in progress

for $\beta_x = \beta_y = 100$ m

Emittance $\varepsilon_x = 15$ pm rad (no wiggler)

196 pm rad (with wiggler)

$0.4 \, \text{mm} \simeq \text{sawtooth amplitude}$
Outlook

- Move wigglers to RF sections
- Finalise DA studies with wigglers
- Studies of TMCI due to resistive wall are ongoing (E. Belli)
- Tolerance studies of gradients and fields will allow to determine the minimum injection energy