Options for the FCC Superconducting RF System

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Thanks to: O Brunner, R Calaga, S Gorgi Zadeh, I Karpov, E Shaposhnikova
Outline

• FCC-hh requirements
• FCC-ee operating modes and timeline
• Cavity designs for each operating mode
• Staging and evolution of the RF system through the program
• Summary and final comments
FCC-hh

- 400 MHz single-cell cavity
  - LHC-type (Nb/Cu @ 4.5K)
  - possibly same as FCC-ee Z
- 48 MV total RF voltage per beam
  - 24 cavities/beam with 2 MV/cavity or 48 with 1 MV/cav.
FCC-hh

• Voltage requirements defined by:
  • Filling factor of the RF bucket (0.9/0.8 in ramp/physics)
  • Longitudinal emittance sufficiently large to prevent TMCI

• Final RF power requirements depend on:
  • total voltage $V$ and power loss (SR)
  • acceleration rate (optimisation of voltage program)
  • number of RF cavities (voltage/cavity: 1 - 2 MV)
  • coupling $Q_L$

Ivan Karpov, *Longitudinal dynamics and RF requirements*, Thursday FCC-hh session
FCC-ee

- 2 RF sections
  - Each 2.8 km length
  - symmetric wrt IPs
- Number and type of cavities evolves with FCC-ee program
FCC-ee RF operating modes

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Z</th>
<th>W</th>
<th>H</th>
<th>$t\bar{t}_1$</th>
<th>$t\bar{t}_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy [GeV]</td>
<td>45.6</td>
<td>80</td>
<td>120</td>
<td>175</td>
<td>182.5</td>
</tr>
<tr>
<td>Beam current [mA]</td>
<td>1390</td>
<td>147</td>
<td>29</td>
<td>6.4</td>
<td>5.4</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>16640</td>
<td>2000</td>
<td>328</td>
<td>59</td>
<td>48</td>
</tr>
<tr>
<td>Bunch length (SR / BS) [mm]</td>
<td>3.5 / 12.1</td>
<td>3.3 / 7.65</td>
<td>3.15 / 4.9</td>
<td>2.5 / 3.3</td>
<td></td>
</tr>
<tr>
<td>Beam RF voltage [MV]</td>
<td>100</td>
<td>750</td>
<td>2000</td>
<td>9500</td>
<td>10930</td>
</tr>
<tr>
<td>Runtime [year]</td>
<td>4</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>

- All operation modes assume 50 MW/beam of SR power
- Extreme range of beam intensities and energies between Z and $t\bar{t}$ modes
- “One size fits all” RF system not possible
- Each operating mode is a different machine
- 3 types of cavity to cover different requirements
- Staged installation + removal of cavities throughout the FCC-ee program
Cavities: Z machine

- Low RF voltage → not limited by gradient
- Highest beam intensity
  → Fundamental power couplers: max 1 MW CW per coupler (challenging)
- Strong HOM damping, low longitudinal loss factor
  → low frequency, large aperture, low number of cells per cavity

- Baseline FCC–ee Z: single cell 400 MHz “LHC-like” cryomodule
  - Nb/Cu @ 4.5K
  - 10 MV/m (5.1 MV/m in Z operation)
  - intended as baseline for further studies (impedance, HOM damping)
  - possible re-use for FCC-hh

Ivan Karpov, *Beam-cavity interaction challenges for FCC_ee cavities*
Cavities: $t\bar{t}$ machine

- Lowest beam intensity
  - Moderate fundamental and HOM powers
  - Modest power requirement per cavity $\rightarrow$ smaller RF power sources

- Highest RF voltage
  - Optimize: RF section length, cost, cryogenic power

- Material options:
  - Nb/Cu 400 MHz (10 MV/m) @ 4.5K
  - Bulk Nb 800 MHz (20 MV/m) @ 2K
  - With optimistic assumptions about long term Nb film cavity performance, the 2 options are roughly equivalent in overall cost and cryogenic power requirements

<table>
<thead>
<tr>
<th>Material</th>
<th>$E_{acc}$ in MV/m</th>
<th>$\eta$-cell</th>
<th>Total Cryopower in MW</th>
<th>LIIC performance</th>
<th>ECR on flat sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb/Cu</td>
<td>400 MHz, 4.5 K</td>
<td>0.85</td>
<td>60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulk Nb</td>
<td>800 MHz, 2 K</td>
<td>0.85</td>
<td>20</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Comparison of cavity material options for $t\bar{t}$

S. Aull
Cavities: $t\bar{t}$ machine

- Baseline chosen for FCC–ee $t\bar{t}$ is 5-cell 800 MHz due to other advantages:
  - 5-cell cavity has ~20% better real-estate gradient
    $\Rightarrow$ RF sections shorter by few 100m
  - Smaller waveguides: better for radiation shielding
  - More compact power sources

- But small decrease in luminosity (~7%)

- Detailed study and design of 4 and 5 cell cavities by S. Gorgi Zadeh (Uni. Rostock)

Shahnam Gorgi Zadeh, *Accelerating cavity and HOM coupler design study for the Higgs and top operation modes of FCC-ee*
Cavities: W machine

• High RF voltage (4 times more than for Z)
  → need to run close to maximum available gradient
  → multi-cell cavities

• Moderately high beam intensity
  → W machine still at the limit of fundamental power couplers
  → Higher order mode power still an issue at W

• Baseline FCC–ee W: 4-cell 400 MHz “LEP-like” cavity
  • Nb film @ 4.5K, 10 MV/m

• Detailed study and design by S. Gorgi Zadeh (Uni. Rostock)

Number of cavities, HOM power and input power vs. number of cells per cavity
($E_{acc} = 10\text{ MV/m} @ 400\text{ MHz}, W$ beam parameters with SR bunch length )

Shahnam Gorgi Zadeh, Accelerating cavity and HOM coupler design study for the Higgs and top operation modes of FCC-ee
Cavities: H machine

- Using the same arguments as for $\tau \bar{\tau}$:
- Nb/Cu 400 MHz and bulk Nb 800 MHz options are roughly equivalent in cryogenic power consumption

- Baseline FCC–ee H: 4-cell 400 MHz Nb/Cu cavity as for W
- lower longitudinal loss factor, HOM power advantage
- re-use of 400 MHz RF power installation
Booster ring

• Fast repetition rate booster for top-up injection at collision energy
• RF voltage approximately same as collider ring
• Low beam loading \(\rightarrow\) can use multi-cell cavities at all energies
• In order to optimize the cryogenic system and distribution, it is proposed to use the same technology at each stage as for the collider-ring itself
  • 4-cell 400 MHz Nb/Cu @ 4.5K and 5-cell 800 MHz Nb @ 2K
• Modest beam current and duty cycle (~10%) offers the possibility to use compact RF power systems
### 400 MHz cavities

<table>
<thead>
<tr>
<th>Frequency [MHz]</th>
<th>Z per beam</th>
<th>Z booster</th>
<th>W per beam</th>
<th>W booster</th>
<th>H per beam</th>
<th>H booster</th>
<th>tt₁ 2 beams</th>
<th>tt₁ booster</th>
<th>tt₂ 2 beams</th>
<th>tt₂ booster</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>100</td>
<td>36</td>
<td>750</td>
<td>750</td>
<td>2000</td>
<td>1720</td>
<td>9500</td>
<td>7800</td>
<td>10930</td>
<td>9210</td>
</tr>
</tbody>
</table>

### 800 MHz cavities

<table>
<thead>
<tr>
<th>Frequency [MHz]</th>
<th>Z per beam</th>
<th>Z booster</th>
<th>W per beam</th>
<th>W booster</th>
<th>H per beam</th>
<th>H booster</th>
<th>tt₁ 2 beams</th>
<th>tt₁ booster</th>
<th>tt₂ 2 beams</th>
<th>tt₂ booster</th>
</tr>
</thead>
<tbody>
<tr>
<td>800</td>
<td>5500</td>
<td>6080</td>
<td>7000</td>
<td>7580</td>
<td>19.8</td>
<td>19.8</td>
<td>19.8</td>
<td>19.8</td>
<td>19.8</td>
<td>19.8</td>
</tr>
</tbody>
</table>

### CDR baseline

- **RF system staging**
- **Eₜ [MV/m]**
- **# cell / cav**
- **Vₜ [MV]**
- **# cavities**
- **T operation [K]**
- **dyn losses/cav [W]**
- **stat losses/cav [W]**
- **Qₜ [x10⁶]**
- **P₂₁ [kW]**
- **# RF source**
RF system staging: Z → W → H

Z:
- 52 single-cell 400 MHz cavities per beam
  - total 26 cryomodules
- 1 cryomodule (4 x 4-cell cavities) in booster

W:
- All 26 CM are replaced by 4-cell cavity cryomodules
  - RF power plant unmodified
- 12 additional cryomodules in booster

H:
- 42 additional 400 MHz cryomodules installed
- Existing RF power units are split and moved to power new cryomodules
- 14 additional cryomodules in booster
RF system staging: $H \rightarrow \bar{t} \bar{t}$

- Small number of bunches
  - arrange filling pattern so no bunches collide in RF sections
- Rearrange existing RF system to share it between the two beams
  - doubles the RF voltage available for each beam
  - beam crossing removed, separators installed at the entrance and exit of each RF straight section

$\bar{t} \bar{t}$: (long shutdown)
- 74 new 800 MHz cryomodules (4 x 5-cell) installed
- 82 new 800 MHz cryomodules in booster
  - may be installed earlier

$\bar{t} \bar{t}$2:
- 20 additional 800 MHz cryomodules installed
- 20 additional 800 MHz cryomodules in booster
FCC-ee vs LEP2

- LEP2: 20 cryomodules installed during winter shutdown 1996
- FCC-ee: between 2 and 3 times as many to install during each winter shutdown
Summary

• A baseline scenario has been prepared for gradual evolution of the FCC-ee complex
  • step-wise expansion and reconfiguration of the superconducting RF system
  • matches the latest FCC-ee parameters and timeline

• A series of cavity designs comprising single-cell and 4-cell 400 MHz and 5-cell 800 MHz is being developed to cover the different operation energies

• Use of a 400 MHz RF system for the Z, W, H and FCC-hh maximizes the re-use of the existing hardware

• A hybrid 400/800 MHz system offers the best perspectives for the highest energy $t\bar{t}$ machine
  • cost, diversity of technology and integration constraints

• Each of the transitions between stages requires extensive installation work to be carried out in a very short time frame
  • feasible, but management and organization of the workload remains a major challenge
Thank you for your attention
FCC-ee parameters (4 machines)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Z</th>
<th>W</th>
<th>H</th>
<th>ttbar</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam energy [GeV]</td>
<td>45.6</td>
<td>80</td>
<td>120</td>
<td>182.5</td>
</tr>
<tr>
<td>momentum compaction [$10^{-5}$]</td>
<td>1.48</td>
<td>0.73</td>
<td>0.73</td>
<td>0.73</td>
</tr>
<tr>
<td>horizontal emittance [nm]</td>
<td>0.27</td>
<td>0.28</td>
<td>0.63</td>
<td>1.45</td>
</tr>
<tr>
<td>synchrotron tune</td>
<td>0.0125</td>
<td>0.0115</td>
<td>0.018</td>
<td>0.035</td>
</tr>
<tr>
<td>longitudinal damping time [ms]</td>
<td>414</td>
<td>77</td>
<td>23</td>
<td>6.6</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</td>
<td>10.93</td>
</tr>
<tr>
<td>RF acceptance [%]</td>
<td>1.9</td>
<td>1.9</td>
<td>2.3</td>
<td>4.9</td>
</tr>
<tr>
<td>energy acceptance [%]</td>
<td>1.3</td>
<td>1.3</td>
<td>1.5</td>
<td>2.5</td>
</tr>
<tr>
<td>energy spread (SR / BS) [%]</td>
<td>0.038/0.132</td>
<td>0.066/0.153</td>
<td>0.099/0.151</td>
<td>0.15/0.20</td>
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<td>bunch length (SR / BS) [mm]</td>
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</tr>
<tr>
<td>bunch intensity [$10^{11}$]</td>
<td>1.7</td>
<td>1.5</td>
<td>1.5</td>
<td>2.8</td>
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<tr>
<td>no. of bunches / beam</td>
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</tr>
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4 years  | 1 year  | 3 years  | 1 + 3 years