Set of RF parameters for the FCC-ee machines

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& the FCC RF Working Group

presented by Erk Jensen
CERN
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Outline

• Introduction: What is the FCC and what are its challenges

• Parameter choices & Layout

• Staging scenarios

• Nb on Cu – potential advantages

• Relevant R&D subjects at a glance

• Summary
The Future Circular Collider Study

International FCC collaboration (CERN as host lab) to study:

- **pp-collider (FCC-hh)**
  - main emphasis, defining infrastructure requirements
  - ~16 T ⇒ 100 TeV pp in 100 km

- ~100 km tunnel infrastructure in Geneva area, site specific

- **e⁺e⁻ collider (FCC-ee)**, as potential first step (SRF challenge!)

- **p-e (FCC-he) option**, integration one IP, e from ERL

- HE-LHC with FCC-hh technology

- CDR for end 2018
The FCC-ee is similar to the CEPC

**FCC-ee**

- 100 km circumference
- Z, W, Higgs & $t\bar{t}$
- Staging

**CEPC**

- 100 km circumference
- Z, W, Higgs
- Staging not foreseen
Parameters and challenges

<table>
<thead>
<tr>
<th></th>
<th>Z</th>
<th>W</th>
<th>H</th>
<th>t(\bar{t})</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (per beam)</td>
<td>45.5</td>
<td>80</td>
<td>120</td>
<td>175</td>
<td>GeV</td>
</tr>
<tr>
<td>Luminosity</td>
<td>(10^{36})</td>
<td>(1.8 \cdot 10^{35})</td>
<td>(5 \cdot 10^{34})</td>
<td>(10^{34})</td>
<td>cm(^{-2})s(^{-1})</td>
</tr>
<tr>
<td>Current</td>
<td>1450</td>
<td>150</td>
<td>30</td>
<td>6.5</td>
<td>mA</td>
</tr>
<tr>
<td>Voltage</td>
<td>0.25</td>
<td>0.8</td>
<td>3</td>
<td>10</td>
<td>GV</td>
</tr>
<tr>
<td>RF Power (per beam)</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>MW</td>
</tr>
</tbody>
</table>

• Requires a large scale, highly reliable RF system, to deliver 100 MW in CW!
• ... under varying beam current conditions
• Energy efficiency is a major concern
• R&D in these different areas has been launched and is progressing (1 MW CW FPC’s, high efficiency klystrons, Nb on Cu cavity technology, low impedance crab cavities, ...
RF System for FCC

Sequence of 5 different machines ranging from high current to high gradient:
- with maximum re-use of components and
- minimum down-time for the installation of upgrades

Challenges:
- Dynamic environment with changing parameters
- RF System between the technical feasible and R&D projects
Full Model of the RF System

- Model of all dependencies
- Study of parameter choices
- Direct comparison of scenarios
- Sensitivity analysis
- Constant monitoring of all constraints for non-compliance
### Parameter Layout

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Cryomodules</td>
<td>72</td>
</tr>
<tr>
<td>Material</td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td></td>
</tr>
<tr>
<td>Acc. Gradient</td>
<td></td>
</tr>
<tr>
<td>Number of Cells</td>
<td></td>
</tr>
<tr>
<td>Number of Cavities</td>
<td>&lt; 4 &gt;</td>
</tr>
<tr>
<td>HOM Couplers</td>
<td>0</td>
</tr>
<tr>
<td>Fund. Power Couplers</td>
<td>FPC$<em>{500}$, FPC$</em>{1000}$</td>
</tr>
<tr>
<td>Number of Amplifiers</td>
<td>144</td>
</tr>
<tr>
<td>Power Splitting</td>
<td>144</td>
</tr>
<tr>
<td>Power Source</td>
<td>P$_{1300}$</td>
</tr>
</tbody>
</table>

**Constraints**
- Wide aperture $\rightarrow$ 400 MHz
- low number of cavities $\rightarrow$ 10 MV/m
- Fall-back for FPC $\rightarrow$ lower field

**Further developments**
- Need for FPC up to 1 MW
- HOM Load Study
- HOM Coupler and Absorber Design
**Parameter Layout**

<table>
<thead>
<tr>
<th>Number of Cryomodules</th>
<th>Z</th>
<th>W</th>
<th>H</th>
<th>t</th>
<th>Booster</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>72</td>
<td>36</td>
<td></td>
<td>159</td>
<td></td>
</tr>
</tbody>
</table>

**Material**

**Temperature**

**Frequency**

**Acc. Gradient**

**Number of Cells**

**Number of Cavities**

<table>
<thead>
<tr>
<th></th>
<th>&lt; 4 &gt;</th>
<th>&lt; 4 &gt;</th>
</tr>
</thead>
</table>

**HOM Couplers**

| FPC<sub>500</sub> | FPC<sub>1000</sub> |

**Fund. Power Couplers**

| FPC<sub>250</sub> |

**Number of Amplifiers**

| 144 | 144 | 636 |

| P<sub>1300</sub> | P<sub>220</sub> |

**Power Splitting**

**Power Source**

Constraints

- Both beams go through the same cavities and beam pipe
- Beam-pipe and installation need to be re-aligned
- For the needed total voltage of 10 GV use of **bulk Nb** at 20 MV/m
- Change of Frequency to **800 MHz**
- RF power requirements are low and may be fulfilled with small sources such as SSPA
SRF Performance Nb/Cu has the potential to compete with bulk Nb
- maximise use of **400 MHz** equipment
- ease installation effort
- slight cost reduction

Fall-back for Nb/Cu $\rightarrow$ bulk Nb @ 800 MHz
Parameter Layout

Machine runs for only 2 years:
- Effort can be reduced by either using equipment similar to the Z- or the H-machine
- Using H-machine cavity with stronger HOM couplers gives advantages for installation

Further developments
- Need for FPC up to 1 MW
- High HOM Load Study
- HOM Coupler and Absorber Design

Fall-back for FPC —> lower field
- Booster needs to accelerate up to 0.255 ...9.5 GV
- Installation in stages
- Use same cryomodules as for t-machine
- Low RF power requirement (10%) allow for small individual RF sources per cavity or module
# Parameter Layout (Values)

<table>
<thead>
<tr>
<th></th>
<th>Z</th>
<th>W</th>
<th>H</th>
<th>t</th>
<th>Booster</th>
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<tbody>
<tr>
<td>Number Cryomodules</td>
<td>72</td>
<td>36</td>
<td>56</td>
<td>28</td>
<td>102</td>
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<tr>
<td>Material</td>
<td>Nb/Cu</td>
<td>Nb/Cu</td>
<td>Nb/Cu</td>
<td>Nb/Cu</td>
<td>bulk Nb</td>
</tr>
<tr>
<td>Temperature</td>
<td>4.5 K</td>
<td>4.5 K</td>
<td>4.5 K</td>
<td>4.5 K</td>
<td>2 K</td>
</tr>
<tr>
<td>Frequency</td>
<td>400 MHz</td>
<td>400 MHz</td>
<td>400 MHz</td>
<td>400 MHz</td>
<td>800 MHz</td>
</tr>
<tr>
<td>Acc. Gradient</td>
<td>5 MV/m</td>
<td>10 MV/m</td>
<td>5 MV/m</td>
<td>10 MV/m</td>
<td>10 MV/m</td>
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<td>1</td>
<td>1</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>HOM Couplers</td>
<td>~3 kW</td>
<td>~3 kW</td>
<td>~1 kW</td>
<td>~1 kW</td>
<td>&lt; 1 kW</td>
</tr>
<tr>
<td>Fund. Power Couplers</td>
<td>~500 kW</td>
<td>~ 1 MW</td>
<td>~500 kW</td>
<td>~ 1 MW</td>
<td>~250 kW</td>
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<tr>
<td>Number of RF Sources</td>
<td>144</td>
<td>144</td>
<td>108</td>
<td>112</td>
<td>102</td>
</tr>
<tr>
<td>Power Splitting</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>4</td>
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<tr>
<td>Power Source</td>
<td>~1.3 MW</td>
<td>~1.3 MW</td>
<td>~1.3 MW</td>
<td>~1.3 MW</td>
<td>~1.3 MW</td>
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Staging Scenario
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<p>| | |</p>
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>28</td>
<td>102</td>
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<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>FPC_{1000}</td>
<td>FPC_{250}</td>
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</table>

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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<tr>
<td>102</td>
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<p>| | |</p>
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<tr>
<th></th>
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<tbody>
<tr>
<td>P_{1300}</td>
<td>P_{1300}</td>
</tr>
</tbody>
</table>
Staging Scenario
Staging Scenario
Installation Sequence

Installation pace during LEP: up to 30 cryomodules per 4 months break

Installing more cryomodules to win time for H-installation

Installation could be concentrated in 1 stop

Booster installation in the shadow
Cryogenic Consumption for FCC-ee H: bulk Nb vs. Nb/Cu

Cryogenic power consumption is one of the cost drivers in a CW machine, in particular for FCC-ee

\[ P_{\text{cryo,grid}} \sim \frac{V^2}{R/Q_0} \sim R_S(f, T, \ell, E_{\text{acc}}) \]

Approach:
- Collect representative \( R_s(f, T, \ell, E_{\text{acc}}) \) data
- Define baseline performance
- Calculate the cryogenic consumption for each (material, frequency, temperature, field)-combination

Machine Impedance
Design Choice
Material
Cryogenic power consumption is one of the cost drivers in a CW machine, in particular for FCC-ee.

Successful R&D on the energetic condensation techniques will make Nb/Cu at 400 MHz and 4.5 K competitive to bulk Nb at 800 MHz and 2.0 K in terms of cryogenic consumption.
## Cost Estimate

### Sensitivity to Production Cost

<table>
<thead>
<tr>
<th>Cavity Production Cost Sensitivity (%)</th>
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</thead>
<tbody>
<tr>
<td>Raw Material</td>
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<tr>
<td>Cell Forming</td>
</tr>
<tr>
<td>Fabrication Extras</td>
</tr>
<tr>
<td>EBW</td>
</tr>
<tr>
<td>Bulk EP Nb</td>
</tr>
<tr>
<td>Bulk EP Cu</td>
</tr>
<tr>
<td>800 °C heat treatment</td>
</tr>
<tr>
<td>Coating</td>
</tr>
<tr>
<td>light EP</td>
</tr>
<tr>
<td>SUBU</td>
</tr>
</tbody>
</table>

### Cavity Production

- **Bulk Nb**
- **Nb/Cu**
The cost for a CM with 400 MHz Nb/Cu cavities is about 20% less than for a CM with 800 MHz bulk Nb cavities.
Cavity design and beam-cavity interaction

1. Cavity design:
   - High energy
     - Aim at acceleration efficiency
   - High intensity
     - Optimize cell shape with regard to HOMs
     - HOM damping schemes

2. Beam dynamics:
   - Single and coupled bunch stability
   - Impedance studies & HOM power
   - Implications of 5 ns bunch spacing for the FCC-hh injector chain

3. Analysis of the need for a RF harmonic system

4. Low Level RF
Cavity material & performance

Collaborative effort to evaluate and understand the ultimate performance of the 400 - 800 MHz cavities

1. Review of technology choices and limits
   - *SRF Material Options for FCC (S. Aull et al.)*

2. R&D and perspectives
   - Bulk Nb:
     - $N_{\text{doping}}$: (FNAL collaboration)
   - Nb/Cu:
     - Development of innovative coating techniques (HIPIMS (CERN), HIPIMS & ECR (JLAB), ECR (FNAL))
     - Improvement surface preparation and Nb coating (CERN-LNL-STFC collaboration)
     - Characterization facility and benchmarking (STFC)
   - Alternative materials A15, strong potential - long term R&D
     - $\text{Nb}_3\text{Sn}$ on Nb (FNAL collaboration)
     - $\text{Nb}_3\text{Sn}$ on Cu
     - $\text{V}_3\text{Si}$
     - Characterization facility and benchmarking (STFC, UNIGE, CERN)
Innovative cavity fabrication techniques

Development of fast & cost effective cavity fabrication techniques

1. High velocity hydroforming:
   • Determine forming limits of high-velocity Electro-Hydraulic Forming (EHF) for Cu structures as substrate for superconducting coating (and for bulk Nb)

2. Spinning:
   • Efforts towards seamless cavity fabrication (LNL)

3. Surface treatment: Electro-polishing:
   • Developments on vertical and/or horizontal EP for 400/800MHz copper cavities
Cryomodule challenges

Specific topics of interest for FCC (and many other machines!)

1. Modular CM design approach to hold various different cavities
2. Impact of cooling control on CM design
3. Optimisation of clean room assembly procedures
4. CM cost model
Fundamental power couplers

Impedance reduction is crucial

→ minimize the number of cavities
→ more power per FPC (beyond the S-o-A)

1. Very high CW power FPC (1MW?)
2. Variable and Adjustable FPC
   • Adaptable to different $Q_{ext}$
3. Large series production

E. Montesinos, CERN
High efficiency klystron technology

FCC: 100 MW beam power ≈ 165 MW grid power
→ every 1% gain in efficiency ≈ 10 GWh/year (saves ≈ 0.4 M€/year)

1. Development of new klystron bunching technologies to strongly increase RF power production efficiency was initiated at CERN in 2013 (HEIKA)
2. Fabrication of the first high efficiency CSM tube

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**HEIKA**: High Efficiency International Klystron Activity

**CSM**: Core Stabilization Method

**L-band**, **S-band**, **C-band**, **X-band**

- **Core Stabilization Method (CSM)**: LHC, FCC, ESS, ILC
  - 1/6 MW
- **Medical/industrial**
- **Kladistron**
- **Bunching, Aligning and Collecting Method (BAC)**
  - 5-10 MW, <60kV
- **CLIC, klystron based X-band FEL**
- **Core Oscillation Method (COM)**
  - 50+ MW

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See I. Syratchev’s talk on Tuesday
Innovative crab cavity design for FCC_hh

- Very interesting development which provides:
  - low longitudinal and transverse impedances
  - natural damping for HOMs

1. Design and simulation
2. Fabrication is ongoing
3. Nb coating system is under development

---

**Table:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF frequency [MHz]</td>
<td>400</td>
</tr>
<tr>
<td>Total voltage V [MV]</td>
<td>18 (uncertainty ±20%)</td>
</tr>
<tr>
<td>Available length [m]</td>
<td>20</td>
</tr>
<tr>
<td>Beam separation [mm]</td>
<td>250 (maybe 204 soon)</td>
</tr>
<tr>
<td>Average beta in the ring [m]</td>
<td>[339+67]/2 = 203</td>
</tr>
<tr>
<td>Beta* [m]</td>
<td>0.3</td>
</tr>
<tr>
<td>Crossing angle [rad]</td>
<td>89</td>
</tr>
<tr>
<td>Beta at CC location [m]</td>
<td>10100 + 10900</td>
</tr>
</tbody>
</table>

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**Diagram:**

Schematic layout: E. Cruz-Alaniz, Nov. 2016, Barcelona

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*See R. Calaga’s talk on Tuesday*
Conclusion

• Relevant R&D subjects:
  • Successful R&D on the energetic condensation techniques will make Nb/Cu at 400 MHz and 4.5 K competitive to bulk Nb at 800 MHz and 2.0 K in terms of cryogenic consumption.
  • Significant reduction of the cryogenic consumption requires the development of alternative SRF materials such as Nb3Sn and V3Si.
  • FPC of 1 MW
  • HOM power mitigation (for the Z-Machine)
  • Fabrication of cavities, helium tanks, power and HOM couplers.
  • Staging Scenario allows to re-use components for next accelerator and installation mainly during winter shut down
Thank you very much!