SRF Material Options for FCC

Sarah Aull
on behalf of the
FCC RF & WP3 Working Group
Cryogenic Consumption of FCC-ee

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

\[ P_{\text{cryo,grid}} \sim \frac{V^2}{R/Q} \frac{1}{Q_0} \sim R_S (f, T, \ell, E_{\text{acc}}) \]
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\[ P_{\text{cryo,grid}} \sim \frac{V^2}{R/Q_0} \sim R_S (f, T, \ell, E_{\text{acc}}) \]

- Machine Impedance
- Design Choice
- Material
Cryogenic Consumption of FCC-ee

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

\[ P_{\text{cryo,grid}} \sim \frac{V^2}{R/Q} \left( \frac{1}{Q_0} \right) \sim R_S(f, T, \ell, E_{\text{acc}}) \]

- 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
Bulk Niobium
A Well-Known Technology

- High level of expertise
- High cost for raw material
- Requires magnetic shielding
- Only operation at < 2.1 K

K. Hernández-Chahín, THP050, SRF2015
A. Macpherson, MOPB074, SRF2015
Bulk Niobium
A Well-Known Technology

Collaboration with FNAL to explore potential of N doping at lower frequencies and 4.5 K operation.

High level of expertise
High cost for raw material
Requires magnetic shielding
Only operation at < 2.1 K
Nb/Cu
Energetic Condensation Techniques

Lower raw material costs
High thermal stability
No magnetic shielding

Only low $E_{\text{acc}}$ due to strong Q-Slope
Mitigated Q-Slope for energetic condensation techniques
Nb/Cu
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Mitigated Q-Slope for energetic condensation techniques

Nb/Cu R&D on 1.3 GHz cavities at CERN; and in collaboration with LNL and STFC

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Beyond Niobium: Nb3Sn
Minimum Performance Target

Higher carnot efficiency at 4.5 K
+ Higher technical efficiency at 4.5 K

Lower cryogenic consumption than bulk niobium at 2 K for
\( R_s(Nb_3Sn@4.5K) < 50 \text{ n\Omega} \)

![Graph showing surface resistance vs. accelerating gradient]

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\[ R_s(\text{Nb}_3\text{Sn}@4.5\text{K}) < 50 \text{ n}\Omega \]

Details about the A15 R&D program:
Alternative materials and coating techniques for cavities, K. Ilyina (CERN)
RF requirement for FCC-ee W

<table>
<thead>
<tr>
<th>OPTION 1</th>
<th>OPTION 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frequency in MHz</strong></td>
<td>400</td>
</tr>
<tr>
<td><strong>Technology</strong></td>
<td>Nb/Cu</td>
</tr>
<tr>
<td><strong>$E_{\text{acc}}$ in MV/m</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Temperature in K</strong></td>
<td>4.5</td>
</tr>
<tr>
<td><strong># of cells/cavity</strong></td>
<td></td>
</tr>
<tr>
<td><strong># of cavities FCC W</strong></td>
<td>428 – 108</td>
</tr>
<tr>
<td><strong># of CM for FCC W</strong></td>
<td>108 – 28</td>
</tr>
</tbody>
</table>

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The diagram shows the relationship between $E_{\text{acc}}$ and total cryopower for FCC-ee W, with LHC performance marked. The table compares different options for frequency, technology, $E_{\text{acc}}$, temperature, and number of cells, cavities, and CM for FCC W.
RF requirement for FCC-ee W

<table>
<thead>
<tr>
<th>Technology</th>
<th>Frequency in MHz</th>
<th>Temperature in K</th>
<th># of cells/cavity</th>
<th># of cavities FCC W</th>
<th># of CM for FCC W</th>
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<tr>
<td>Nb/Cu</td>
<td>400</td>
<td>4.5</td>
<td>1 – 4</td>
<td>428 – 108</td>
<td>108 – 28</td>
</tr>
<tr>
<td>Bulk Nb</td>
<td>400</td>
<td>2.0</td>
<td></td>
<td></td>
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</tbody>
</table>

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<th>( E_{acc} ) in MV/m</th>
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<tr>
<td>10</td>
<td></td>
<td></td>
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LHC performance

ECR on flat sample

NB

Bulk Nb

Nb/Cu is the material of choice for FCC-ee W

Number of cells to be determined by machine impedance considerations and staging scenarios

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RF requirement for FCC-ee Higgs & top

Two competing options for the SRF system for FCC-ee $t\bar{t}$

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<td>10</td>
</tr>
<tr>
<td>Temperature in K</td>
<td>4.5</td>
</tr>
<tr>
<td># of cells/cavity</td>
<td>3 – 5</td>
</tr>
<tr>
<td># of cavities FCC H</td>
<td>534 – 322</td>
</tr>
<tr>
<td># of cavities FCC t</td>
<td>846 – 508</td>
</tr>
<tr>
<td># of CM for FCC H</td>
<td>134 – 82</td>
</tr>
<tr>
<td># of CM for FCC t</td>
<td>212 – 127</td>
</tr>
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RF Model
Cost Estimate

RF scenarios and parameters layout for FCC
N. Schwerg (CERN)
RF Model Cost Estimate

RF scenarios and parameters layout for FCC
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Production Cost
from Sheet to Bare Cavity
<table>
<thead>
<tr>
<th>Raw Material (1/m^2)</th>
<th>Cavity Size</th>
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<td>800 MHz &amp; 4 cells</td>
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## Production Cost from Sheet to Bare Cavity

<table>
<thead>
<tr>
<th>Raw Material (1/m²)</th>
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<th>Fabrication of a cell</th>
<th>Deep drawing of half cells</th>
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<td>400 MHz &amp; 4 cells</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Spinning of seamless cells</td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

*Image credits: SRF, FCC, CERN*
Production Cost from Sheet to Bare Cavity

400 MHz & 4 cells
- Spinning of seamless cells

800 MHz & 4 cells
- Deep drawing of half cells

Raw Material (1/m²)
- Cavity Size

Fabrication of a cell

Electron Beam Welding of the cavity cells
Production Cost from Sheet to Bare Cavity

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<tr>
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Raw Material (1/m²)
### Production Cost from Sheet to Bare Cavity

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<tr>
<th>Raw Material (1/m²)</th>
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<tr>
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<td>Fabrication of a cell</td>
<td>Electron Beam Welding of the cavity cells</td>
<td>Electron Beam Welding of stiffening rings and beam tubes</td>
</tr>
<tr>
<td>Spinning of seamless cells</td>
<td>Chemical &amp; Heat Treatments</td>
<td>Bulk EP + 800 °C + Light EP</td>
<td></td>
</tr>
</tbody>
</table>
Bare Cavity
Sensitivity to Production Cost

![Graph showing the sensitivity of various costs in producing bare cavities, with categories such as Raw Material, Cell Forming, Fabrication, Extras, EBW, Bulk EP Nb, Bulk EP Cu, 800 °C heat treatment, Coating, light EP, and SUBU. The graph compares the costs between bulk Nb and Nb/Cu.]
Bare Cavity
Sensitivity to Production Cost

- Cost driver for bulk Nb cavities:
  - Raw material
  - Surface treatments

- Cost driver for Nb/Cu cavities:
  - Fabrication
  - Raw material
## Production Cost
from Bare Cavity to Cryomodule

<table>
<thead>
<tr>
<th>Item</th>
<th>Quantity per Cryomodule</th>
<th>Quantity per CM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/cavity</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Helium tank</td>
<td>1</td>
<td>1/cavity</td>
</tr>
<tr>
<td>1/cavity</td>
<td>2</td>
<td>1/cavity</td>
</tr>
<tr>
<td>Power Coupler</td>
<td>1</td>
<td>1/cavity</td>
</tr>
<tr>
<td>2/cavity</td>
<td>4</td>
<td>2/cavity</td>
</tr>
<tr>
<td>HOM coupler</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>tuner</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2 per CM</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Cryo valves</td>
<td>2</td>
<td>2 per CM</td>
</tr>
<tr>
<td>2 per CM</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Magnetic shielding</td>
<td>1</td>
<td>1/meter</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Cryostat</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>CM assembly</td>
<td>1</td>
<td></td>
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Cryomodule
Sensitivity to Production Cost

The cost of a dressed cavity is well distributed among the single components and dominate the CM cost.
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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.
Conclusion

• 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.

• Our cost model estimates a reduction of a Nb/Cu cryomodule of 20% compared to its bulk Nb counterpart.

• Biggest potential for further cost reduction:
  • Fabrication of cavities, helium tanks, power and HOM couplers.