SRF Material Options for FCC

Sarah Aull
on behalf of the
FCC RF & WP3 working group

Cryogenic Losses in CW Machines

\[ P_{\text{dyn}} = \frac{V_{RF}^2}{R \cdot Q_0} \cdot \frac{1}{\eta_{\text{carnot}} \cdot \eta_{\text{tech}}} \]
Cryogenic Losses in CW Machines

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Cryogenic Losses in CW Machines

![Graph showing cryogenic losses in CW machines]

- **Graph 1:**
  - **Y-axis:** Total Cryopower in MW for 0.2 GY/Total RF Voltage
  - **X-axis:** Temperature in K
  - **Legend:**
    - Black line: Carnot
    - Red line: 20% Carnot
    - Blue line: 30% Carnot

- **Graph 2:**
  - **Y-axis:** Total Cryopower in MW for 11 GY/Total RF Voltage
  - **X-axis:** Eacc in MV/m
  - **Legend:**
    - Blue line: 400 MHz, 4.5 K, 100 nΩ
    - Red line: 800 MHz, 2.0 K, 30 nΩ

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Cryogenic Losses in CW Machines

- Total Cryopower in MW for 0.2 GV Total RF Voltage
- Total Cryopower in MW for 11 GV Total RF Voltage

- Required Cryogenic Grid Power in kW
- Surface Resistance in nΩ

- Temperature in K
- Eacc in MV/m
Cryogenic Losses in CW Machines

Accelerating gradient is a design choice
Q₀ is given by the temperature, frequency and material choice
Surface Resistance

\[ R_S = R_{BCS} + R_{res} \]
Surface Resistance

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- \( R_{BCS} \) increases with \( f^2 \)
- \( R_{BCS} \) decreases with \( \exp(T/T_c) \)
- \( R_{BCS} \) depends on the mean free path

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Surface Resistance

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- \( R_{BCS} \) decreases with \( \exp(T/T_c) \)
- \( R_{BCS} \) depends on the mean free path

- \( R_{res} \) is independent of \( T \)
- \( R_{res} \) depends only slightly on \( f \)
- Field dependence depends on material

### Material Achieved Expected in mass production

<table>
<thead>
<tr>
<th>Material</th>
<th>Achieved</th>
<th>Expected in mass production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk Nb</td>
<td>0.5 - 20 nΩ</td>
<td>10-15 nΩ</td>
</tr>
<tr>
<td>Nb/Cu</td>
<td>0.5 - 30 nΩ</td>
<td>20 nΩ</td>
</tr>
</tbody>
</table>

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Bulk Niobium - A Well-Known Technology

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

Improved surface preparation techniques
Higher $E_{\text{acc}}$ in mass production

K. Hernández-Chahín, THPB09, SRF2015
A. Macpherson, MOPB074, SRF2015

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N Doping - Pushing the Limits of Bulk Niobium

- Very high Q at 2 K
- High cost for raw material
- Requires magnetic shielding
- Reduced quench field

Performance at lower frequencies?
Performance at 4.2 K?
Nb/Cu - New Coating Techniques on the Rise

Lower raw material costs
High thermal stability
No magnetic shielding
Reduced microphonic

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

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Nb/Cu - New Coating Techniques on the Rise

Flat disk of 75 mm diameter; Coated at JLab, measured at CERN

- Lower raw material costs
- High thermal stability
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Energetic Condensation

Energetic Condensation techniques like ECR and HIPIMS promise improved film microstructure and interface.
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Thermal boundary resistance model (Palmieri/Vaglio, SUST 29, 2016) yields 0.002 % detached surface area.

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Energetic Condensation

Energetic Condensation techniques like ECR and HIPIMS promise improved film microstructure and interface.

Biased HIPIIMS samples show denser film for non-normal incident angle.

Thermal boundary resistance model (Palmieri/Vaglio, SUST 29, 2016) yields 0.002% detached surface area.

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**Nb₃Sn/Nb - Beyond Niobium**

- Very high Q at 4.2 K
- High cost for raw material
- Requires magnetic shielding
- Premature quenching

**Not a mature technology yet**
- Multicell cavities
- Higher quench field
- Mechanical behavior
- Nb₃Sn/Cu (See Poster by K. Ilyina)


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Perspectives for R&D

4.5 K operation:
Optimise mean free path
Cure Q-slope
A15 materials

2 K operation:
Optimise residual resistance
Cure Q-slope

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The perspective of cavity performances yields similar cryogenic losses for Nb/Cu at 400 MHz and 4.5 K and bulk Nb at 800 MHz and 2.0 K. A15 Materials might further reduce the cryogenic power.
Cryogenic Power for the Top Machine

The perspective of cavity performances yields similar cryogenic losses for Nb/Cu at 400 MHz and 4.5 K and bulk Nb at 800 MHz and 2.0 K. A15 Materials might further reduce the cryogenic power.
Cryo power is not everything: more considerations
Cryo power is not everything: more considerations

Installation Cost

Nb/Cu → Bulk Nb → N Doping → Nb3Sn/Nb

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Cryo power is not everything: more considerations

**Installation Cost**
- Nb/Cu
- Bulk Nb
- N Doping
- Nb3Sn/Nb

**Magnetic Shielding**
- Nb/Cu
- Nb3Sn/Nb
- Bulk Nb
- N Doping

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Cryo power is not everything: more considerations

**Installation Cost**

- Nb/Cu
- Bulk Nb
- N Doping
- Nb3Sn/Nb

**Magnetic Shielding**

- Nb/Cu
- Nb3Sn/Nb
- Bulk Nb
- N Doping

**Microphonics**

- Nb/Cu
- Bulk Nb

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Conclusion

• The application of Nb/Cu technology would reduce the installation and running costs of the cryogenic system as well as the cost of cavities and cryomodules.

• Energetic condensation techniques promise cavity performances at 4.5 K comparable to bulk niobium.

• A15 materials such as Nb3Sn may even further decrease the dynamic losses at 4.5 K.