Magnetic Field Limits of Superconducting RF Cavities

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Some images from linearcollider.org
Superconducting RF Cavities

- Muscle of many large particle accelerators
- RF input power → accelerating electric field

Image from linear collider.org
• SRF cavity: high quality EM resonator
• Particle beam gains energy as it passes through

Input RF power at 1.3 GHz

Slowed down by factor of approximately $4 \times 10^9$

• Electric field provides acceleration
• Magnetic field can’t be avoided
• How high in field can we take SRF cavities?
• State of the art niobium cavities are limited by peak surface magnetic field
• For relatively small applied magnetic fields, superconductors expel flux: **Meissner state**

• At higher fields, Type II superconductors allow flux to enter in packets: **Vortex state**

*Images from Wikipedia and Rose-Innes and Roderick, Introduction to Superconductivity*
For relatively small applied magnetic fields, superconductors expel flux: **Meissner state**

Avoid flux penetration.

At RF frequencies → **excessive heating** state

Images from Wikipedia and Rose-Innes and Roderick, Introduction to Superconductivity
Superheating Field

- Flux free Meissner state is stable up to $H_{c1}$
- Favorable for flux to be deep in bulk above $H_{c1}$
- BUT surface energy barrier allows metastable state!
**Why a superheating field?**

\[ \lambda: \text{B-field decay constant} \]

\[ \xi: \text{Cooper pair interaction distance} \]

**Energy cost:** creation of normal conducting vortex core

**Energy benefit:** flux from high magnetic field region into low magnetic field region

Costly core \( \xi \) enters first; gain from field \( \lambda \) later

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*Slide adapted from J. P. Sethna*
• **NbTi** (magnet quality):
  • Lots of pinning centers – $H_{c2} \sim 15$ T
  • $T_c \sim 9$-$10$ K, ductile

• **Niobium** (SRF quality):
  • Robust barrier to magnetic flux – $H_{sh} \sim 0.2$ T
  • $T_c \sim 9$ K, ductile

• **Nb$_3$Sn** (can be either!):
  • Can be made with pinning centers – $H_{c2} \sim 30$ T
  • Predicted robust barrier to flux – $H_{sh} \sim 0.4$ T?
  • $T_c \sim 18$ K, brittle
• Used in accelerators: Pb and Nb, either bulk or sputtered
• Many film deposition methods researched: ECR, ALD, CVD, HPCVD, MOCVD, HiPIMS, e-beam, thermal vapor diffusion, liquid diffusion, co-sputtering+annealing, cathodic arc deposition
• Many alternative superconductors considered
### Experimental Properties of Promising Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>$\lambda(0)$ [nm]</th>
<th>$\xi(0)$ [nm]</th>
<th>$B_{sh}$ [mT]</th>
<th>$T_c$ [K]</th>
<th>$\rho_n(0)$ [µΩcm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb</td>
<td>50</td>
<td>22</td>
<td>210</td>
<td>9.2</td>
<td>2</td>
</tr>
<tr>
<td>Nb$_3$Sn</td>
<td>111</td>
<td>4.2</td>
<td>410</td>
<td>18</td>
<td>8</td>
</tr>
<tr>
<td>MgB$_2$</td>
<td>185</td>
<td>4.9</td>
<td>210</td>
<td>40</td>
<td>0.1</td>
</tr>
<tr>
<td>NbN</td>
<td>375</td>
<td>2.9</td>
<td>160</td>
<td>16</td>
<td>144</td>
</tr>
</tbody>
</table>

Parameters for: Nb from [1] assuming RRR = 10; Nb$_3$Sn from [2]; NbN from [3]; MgB$_2$ from [4] and [5]. $B_{sh}$ for Nb found from equation in [6] and for others calculated from [7]. $B_c$ used to calculated $B_{sh}$ found from [8] eq. 4.20.


**Material parameters vary with fabrication.** References were chosen to try to display realistic properties for polycrystalline films.
• Alternative geometries considered, including **multilayer SIS’ films** studied in depth
• No significant increase predicted for maximum flux-free field [Posen et al. 2013, Kubo et al. 2013, Gurevich 2015]

Images adapted from A. Gurevich, APL 012511 (2006)
Pulsed Quench Field

Radio Frequency Magnetic Field Limits of Nb and Nb$_3$Sn
See Nick Valles’s thesis, Cornell University, 2014
DC Flux Penetration

See Nick Valles’s thesis, Cornell University, 2014
Before $B_{DC} = 0 \text{ T}$

- Quality Factor: $1.351 \times 10^8$
- Eacc [MV/m]: 4.23
- Beta_R: 0.514
- Beta_E: 0.525

After $B_{DC} = 0.3 \text{ T}$

- Quality Factor: $9.908 \times 10^6$
- Eacc [MV/m]: 1.07
- Beta_R: 0.899
- Beta_E: 0.743

Raw data measured by Nick Valles, Cornell University, 2013
• Realistic expectation: $B_{\text{max}} \sim 0.2 \, \text{T}$ at walls of superconducting cavity to maintain high $Q_0$

• Alternative materials may increase limit up to $0.5 \, \text{T}$ with a few years of development
• Poloidal field coils
• Large field in cavity interior
• Smaller field at walls