HIGH Q₀ RESEARCH: THE DYNAMICS OF FLUX TRAPPING IN SC NIOBIUM

Julia Vogt, Oliver Kugeler and Jens Knobloch, Helmholtz-Zentrum Berlin, Germany
\[
G / Q_0 = R_{\text{surface}} = R_{\text{BCS}}(f, T) + R_{\text{residual}}(?)
\]

- Trapped vortices under rf field (up to 100% of ambient field)
- Lossy oxides or metallic hydrides on surface
- Grain boundaries
- Precipitates
- Generation of hypersound
- Localized electron surface states
- ...

→ Surface treatment, Bake out
TRAPPED VORTICES UNDER RF FIELD

Reduction of trapped vortices

• Shielding (earth field)
• Can we reduce pinning centers? Impact niobium material properties the trapping behavior?
• Are there additional ways to optimize Meissner effect?
• Do temperature gradients generate trapped flux?

Impact of trapped vortices on losses

\[ R_{\text{residual}} \propto B_{\text{applied}} \]

→ Phys Rev B 87, Gurevich and Ciovati (2012)

Empiric: 1μT ↔ 3.5nΩ (TESLA)


→ Vogt, Kugeler and Knobloch, PRSTAB (accepted for publication, Sept. 11, 2013)
- Mimics thermoelectric properties of cavity-tank system
- Nb rod 300RRR (84x84x300mm^3)
- 3 FM probes (1nT resolution)
- 7 Cernox sensors
- Conduction cooled (LHe)
- 2 heaters
- Shielding (50nT ambient)
Two contact points on different temperatures

Level of trapped flux correlates with $\Delta T$ at the instance of phase Transition. Thermoelectric effect:

$$B \leftrightarrow I = \Delta V / R = \Delta S \cdot \Delta T / R$$

Thermopower of System $\Delta S = S_{Nb} - S_{Ti}$
MODEL SYSTEM: THERMOCURRENTS

- Two contact points on different temperatures

Level of trapped flux correlates with $\Delta T$ at the instance of phase transition. Thermoelectric effect:

$$ B \leftrightarrow I = \Delta V / R = \Delta S \cdot \Delta T / R $$

Thermopower of system $\Delta S = S_{Nb} - S_{Ti}$

- Measure temperature difference during phase transition of Nb rod
- System settles
- Measure trapped flux

Thermoelectrically induced magnetic field gets trapped in sc niobium!

Is this measurement able to explain the observed variation in $R_{res}$?
**MODEL SYSTEM VS. DRESSED CAVITY: TEST 1**

**Model system:** \( B = 0.12\mu T \) for \( \Delta T = 0.6K \)

0.12\(\mu T\) trapped in a TESLA Cavity:

\[ \rightarrow \Delta R_{res} = 0.4n\Omega \]

**Surface resistance in the 10 nΩ range for \( \Delta T \) in the 10’s K range can reasonably be expected!**

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Kugeler, Vogt and Knobloch, SRF2013, TUIOA01
Is this measurement able to explain the observed variation in $R_{res}$?

$$B \leftrightarrow I = \frac{\Delta V}{R} = \frac{\Delta S \cdot \Delta T}{R}$$

Thermopower: $\Delta S \approx 10\mu V/K$

Literature is not consistent for titanium.

Independent measurement performed in HoBiCaT.

Parameter of cavity-tank system @10K: $R \approx 100\mu\Omega$ (dominated by titanium tank)


$$= 10\mu V/K \cdot 100K / 100\mu\Omega = 1A$$
MODEL SYSTEM VS. DRESSED CAVITY: TEST 2

\[ B \leftrightarrow I = \Delta V / R = \Delta S \cdot \Delta T / R = 10 \mu V/K \cdot 100K / 100 \mu \Omega = 1A \]

TESLA half cell, TM\textsubscript{010} \(\pi\)-mode, surface H-field

Maximum field at minimum radius (mechanical stabilisation):
2 \(\mu\)T at surface

Tapped flux existst in high surface magnetic field regions → Power dissipation!

Courtesy: Axel Neumann
MODEL SYSTEM VS. DRESSED CAVITY: TEST 2

**Model system results**

**TESLA Cavity results**

- **ΔB per ΔT**
  - $B_{sc}$ [µT]
  - $ΔB$ per $ΔT$

- **ΔR$_{res}$ ≈ 8 nΩ**

- **Measurements are consistent!**

- **2 µT trapped flux for $ΔT = 100K$**

- **1 µT ↔ 3.5 nΩ**

- **B at $I = 1 A$**

cause 7 nΩ additional surface resistance
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Impact of trapped vortices on losses

\[ R_{\text{residual}} \propto B_{\text{applied}} \]

[Empiric: 1µT \(\leftrightarrow\) 3.5nΩ (TESLA)]

FLUX TRAPPING IN DISK-SHAPED NIОBIУM SAMPLES

Helmholtz coil applies magnetic field

Field cooled

HC off, Measure magnetization

Sample

Courtesy: Sarah Aull
<table>
<thead>
<tr>
<th>#</th>
<th>Crystal structure</th>
<th>Treatment</th>
<th>Fraction of trapped flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Polycrystalline</td>
<td>None</td>
<td>100%</td>
</tr>
<tr>
<td>2</td>
<td>Polycrystalline</td>
<td>BCP</td>
<td>100%</td>
</tr>
<tr>
<td>3</td>
<td>Polycrystalline</td>
<td>BCP + 800°C bake out</td>
<td>(83.1 ± 0.8)%</td>
</tr>
<tr>
<td>4</td>
<td>Single crystal</td>
<td>BCP</td>
<td>[(72.9 + 0.1 lnν) ± 0.8]%</td>
</tr>
<tr>
<td>5</td>
<td>Single crystal</td>
<td>BCP + 800°C bake out</td>
<td>[(61.6 + 1.3 lnν) ± 0.8]%</td>
</tr>
<tr>
<td>6</td>
<td>Single crystal</td>
<td>BCP + 1200°C bake out</td>
<td>[(42.1 + 0.13 lnν) ± 0.6]%</td>
</tr>
</tbody>
</table>

Consistant with results that Q's of large grain cavities are greater. For example W. Singer, MOIOA03: “Large grain cavities on average have 60% higher Q”

*Aull, Kugeler and Knobloch, PRSTAB 15, 062001 (2012)*

depends on cooling rate ν = ΔT/Δt
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\[ \rightarrow \text{Phys Rev B 87, Gurevich and Ciovati (2012)} \]

Empiric: \(1 \mu T \leftrightarrow 3.5 \text{n}\Omega\) (TESLA)

\[ \rightarrow \text{Phys. Rev. STAB 3, B. Aune, et al. (2000)} \]
COOLING RATE

- Ambient field increased to 3μT (0.3μT in FM1 direction)
- Vary cooling rate during isothermal cooldown (max ΔT < 0.1K)
- Slower transition supports Meissner effect on helium short
- Logarithmic correlation

WHY?

\[
\frac{B_{sc} - B_{nc}}{\mu T} = \begin{cases} 
\text{Slower} & \Rightarrow \text{More expelled flux} \\
\text{Less trapped flux} & \Rightarrow \text{Less trapped flux}
\end{cases}
\]

cooling rate [mK/s]
INCREASED FLUX MOBILITY CLOSE TO TRANSITION TEMPERATURE

Level ambient field

Initially expelled flux:
$\Delta B \approx 50\text{nT}$

Starting temperature of rod

Vogt, Kugeler and Knobloch, IPAC2013, WEPWO004
INCREASED FLUX MOBILITY CLOSE TO TRANSITION TEMPERATURE

Level ambient field
Initially expelled flux:
$\Delta B \approx 50\text{nT}$
Increased expelled flux

4 $\times$ more flux expelled
Increasing Meissner effect

Increased flux mobility close to transition temperature

Vogt, Kugeler and Knobloch, IPAC2013, WEPWO004
Increasing Meissner effect

Phase transition

Slower cooling rate = niobium longer in region with increased flux mobility

INCREASED FLUX MOBILITY CLOSE TO TRANSITION TEMPERATURE

\[ (B_{sc} - B_{nc}) [\mu T] \]

Sarah Aull et al., SRF2013, WEIOC01
RF measurements demonstrate that \( R_s \) is impacted by the cooling rate
| SUMMARY |
|----------------|-----------------|-----------------|
| **Do temperature gradients generate trapped flux?** | Thermoelectrically induced magnetic fields exist and get trapped in sc niobium. | Avoid temperature gradients as you transition to the SC state! |
| **Can we reduce pinning centers? Impact niobium material properties the trapping behavior?** | Material defects and contaminants affect trapped flux | Use large grain material and/or high temperature treatment! |
| **Are there additional ways to optimize Meissner effect?** | Flux shows increased mobility close to transition temperature | Decrease cooling rate near $T_c$ to take advantage of increased flux mobility! |

- Cavity cooldown without $\Delta T$ (time to settle before transition or add cycling)
- Cool slowly and smoothly through $T_c$

*Vogt, Kugeler and Knobloch, PRSTAB (accepted for publication, Sept. 11, 2013)*
THANK YOU FOR YOUR ATTENTION

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