High-Q Operation of SRF Cavities:
The Impact of Thermocurrents on the RF Surface Resistance


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Why bother?

• Demand for high duty cycle or **cw beams** in modern application (LCLS-II, XFEL, bERLinPro...)

• Elevated **dynamic losses**

• Refrigeration efficiency ≈ 1/1000

→ **Minimization of power loss and costs**

• BCS resistance decreases with temperature, residual resistance not

• General interest in understanding loss mechanisms in sc cavities
Status SRF 2013: Cooling conditions and thermal cycle can significantly impact and degrade the quality factor

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- First reported 2009
  
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Cooling conditions can significantly impact and degrade the quality factor
Cornell confirmed: Thermal cycle improves Q

*Courtesy R. Eichhorn*

- After a 10 K thermal cycle significant increase in the Q (up to a Q of $6 \cdot 10^{10}$ design operation parameters being three times higher than targeted)
- Measurements suggest that effect is related to magnetic fields


Remark: only one flux direction was measured
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Status SRF 2013:
Community still in doubt if thermocurrents are origin of that magnetic flux

Open questions:

1. More detailed study of the impact of temperature difference on the surface resistance
2. Exact Seebeck coefficients in the temperature regime of interest to analyze magnitude of thermocurrents
3. Geometry and distribution of thermocurrents
4. Direct measurement of the magnetic field in the cavity tank system and especially on RF surface
1. More detailed study of the impact of temperature difference on the surface resistance

\[ R_s(T) = A \cdot \exp \left( \frac{-B}{T} \right) + R_{\text{res}} = \frac{G}{Q_0} \]

BCS resistance is the same for all modes (at fixed \( E_{\text{acc}} \)),
depends on \( T \)

Depending on amount of trapped flux but not on \( T \)

\[ G_\pi = 271.2 \, \Omega \]
\[ G_{8\pi/9} = 271.5 \, \Omega \]
\[ G_{\pi/9} = 268.3 \, \Omega \]
\[ A = (31.8 \pm 2.2) \, \mu \Omega \]
\[ B = (15.7 \pm 0.2) \, K \]

"accelerating mode"
"mid cell mode"
"end cell mode"

Simulation

Courtesy Axel Neumann
1. More detailed study of the impact of temperature difference on the surface resistance

Ambient field in the HoBiCaT cryostat:
- less than 0.2 μT at the center cells
- about 0.5 μT maximum in the end cells

Evaluation of \( \langle R_{\text{res}} \rangle \) and hence the change in trapped flux in different cells of the cavity

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1. More detailed study of the impact of temperature difference on the surface resistance

- Temperature difference at the start of the phase transition:

\[ \Delta T = \left| \frac{T_{Cx1} + T_{Cx2}}{2} - \frac{T_{Cx3} + T_{Cx4}}{2} \right| \] when the first sensor drops below 9.2K

- Drives thermoelectric current through the system
1. More detailed study of the impact of temperature difference on the surface resistance

\[ R_s(T) = A \cdot \exp\left(\frac{-B}{T}\right) + R_{\text{res}} \]

A smaller temperature difference (10 - 30K) reduces the RF losses significantly. Even when cooled down from room temperature, low residual resistance is achievable when the cavity is parked above \( T_c \) for several hours (here 48h).

Mark: all modes are mirror symmetric
1. More detailed study of the impact of temperature difference on the surface resistance

Parked cooldown:
- 1.4 nΩ
- 9.9 nΩ
- 6.4 nΩ
- 1.4 nΩ

Initial cooldown:
- 14.2 nΩ
- 13.6 nΩ
- 10.6 nΩ

Lower temperature difference (10-30K) reduces RF losses significantly. Even when cooled down from room temperature, low residual resistance is achievable when the cavity is parked above $T_c$ for several hours (here 48h).

Mark: all modes are mirror symmetric

See poster MOPB017

The parked cooldown kills thermocurrents
Additional question: How does it apply to a doped cavity?

Doped cavity at Fermilab:
60 min N doping with 10 µm final EP
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See poster MOPB019
How can we validate the thermocurrent hypothesis?

Temperature difference \( \Delta T \) → Surface resistance \( R_{\text{res}} \)

Correlation confirmed by experiment

Thermocurrent \( I \) → Trapped flux in the superconducting (sc) material \( B \)

Magnetic field \( B \) → Magnetic field at the RF surface \( B \)
How can we validate the thermocurrent hypothesis?

1. Thermocurrent $I$

2. Exact Seebeck coefficients in the temperature regime of interest

- Temperature difference
- Magnetic field $B$
- Surface resistance $R_{res}$
- Trapped flux in the sc material $B$
- Magnetic field at the RF surface $B$

Correlation confirmed by experiment
2. **Exact Seebeck coefficients in the temperature regime of interest**

Samples from material as used in cavity fabrication:
- Niobium (RRR = 300)
- Titanium (grade 2)
How can we validate the thermocurrent hypothesis?

Temperature difference $\Delta T$

Surface resistance $R_{\text{res}}$

Thermocurrent $I$

Magnetic field at the RF surface $B$

Magnetic field in the superconducting material $B$

Correlation confirmed by experiment

$S$ values
2. **Exact Seebeck coefficients in the temperature regime of interest**

Samples from material as used in cavity fabrication:
- Niobium (RRR = 300)
- Titanium (grade 2)

$\Delta S$ has maximum between 50K and 100K

$$I = \Delta S \cdot \Delta T / R = 1 \mu \text{V/K} \cdot 100 \text{ K} / 100 \mu \Omega = 1 \text{ A}$$

10cm distance of a 1 A line current: 2µT
How can we validate the thermocurrent hypothesis?

- Temperature difference \( \Delta T \)
- Surface resistance \( R_{\text{res}} \)
- Thermocurrent \( I \)
- Trapped flux in the sc material \( B \)
- Magnetic field at the RF surface \( B \)

Correlation confirmed by experiment

S values
3. Geometry of thermocurrents

COMSOL simulation:
• Niobium:
  Inner cylinder (cavity)
• Titanium:
  Outer cylinder (He vessel)
  End plates (vessel head)
3. **Geometry of thermocurrents**

**COMSOL simulation:**
- **Niobium:**
  - Inner cylinder (cavity)
- **Titanium:**
  - Outer cylinder (He vessel)
  - End plates (vessel head)

![Diagram showing helium vessel head (titanium) and helium vessel (red) with cavity (blue)].
3. Geometry of thermocurrents

Symmetric current configuration creates no field on the RF surface.
3. **Geometry of thermocurrents**

Symmetric current configuration creates no field on the RF surface.
3. Geometry of thermocurrents: Breaking the symmetry

Symmetry can be broken by:


- Temperature dependance of electrical resistance:

  Tank is filled from bottom to top → Additional temperature difference bottom to top
3. **Geometry of thermocurrents: Additional temperature difference bottom to top**

![Diagram showing thermocurrents and temperature difference](image)

- **Study 1**: Angle for magnetic field distribution inside inner cylinder
- **Study 2**: Cut plane for temperature distribution
- **Study 3**
- **Study 4**
- **Study 5**

**Legend:**
- Magnetic field [T] inside the inner cylinder (a = 102mm)
- Number of Study
- Temperature [K]
3. Geometry of thermocurrents
3. **Geometry of thermocurrents:** Highest degree of asymmetry when parts of the cavity are superconducting

*Courtesy R. Eichhorn*

How can we validate the thermocurrent hypothesis?

- Temperature difference $\Delta T$
- Magnetic field $B$
- Thermocurrent $I$
- Magnetic field at the RF surface $B$
- Surface resistance $R_{\text{res}}$
- Trapped flux in the SC material $B$

$S$ values

Correlation confirmed by experiment
Mark: $\Delta T$ is not mean but maximum value
How can we validate the thermocurrent hypothesis?

- Temperature difference $\Delta T$
- Thermocurrent $I$
- Magnetic field $B$
- Surface resistance $R_{\text{res}}$
- Trapped flux in the sc material $B$
- Magnetic field at the RF surface $B$

Correlation confirmed by experiment

$S$ values
Summary: Thermocurrents in horizontal cavity test

- $R_{\text{res}}$ from RF test
- COMSOL simulation
- B on RF surface

**Graphs:**
- Scatter plot showing $\langle R_{\text{res}} \rangle [\Omega]$ vs. $|\Delta T_{\text{max}}| [K]$ at sc transition.
- Scatter plot showing $|B| [\mu T]$ vs. $|\Delta T_{\text{max}}| [K]$.
- Scatter plot showing $|B| [\mu T]$ vs. $\langle R_{\text{res}} \rangle [\Omega]$.

Legend:
- $\langle R_{\text{res}} \rangle [\Omega]$
- Comsol [μT]
- Measurement [μT]
How can we validate the thermocurrent hypothesis?

Thermocurrent \( I \)

Temperature difference \( \Delta T \)

Surface resistance \( R_{res} \)

Trapped flux in the sc material \( B \)

Magnetic field at the RF surface \( B \)

Magnetic field \( B \)

Correlation confirmed by experiment

Argumentation loop closed: Thermocurrents exist and can significantly deteriorate a otherwise perfectly prepared cavity.

S values
Does the effect apply to every setup?

Not, if...

... only one aspect is satisfied

... There is no LHe tank (undressed vertical test)
  → no closed circuit

... The system is (electrically) symmetric (vertical test)
  → no gradient across cavity

... The system allows for symmetric LHe fill (modified LHe tank)
  → no gradient along cavity

Yes, if...

... both aspects are satisfied

... especially with couplers and tuners!
Thank you for your attention!

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References
- O. Kugeler et al., “Manipulating the intrinsic quality factor by thermal cycling and magnetic fields”, SRF’09, Berlin, Germany, p. 352 (2009)