Studies of the cool-down dynamics around $T_c$ using a flux expulsion lens

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Why improve expulsion efficiency?
Main goal: mitigate residual resistance $R_B$ due to trapped flux

$R_B = B_0 \times S(\mathbf{f}, B_{RF}, ...) \times \eta(\nabla T, ...)$
- Remove external field
- Reduce sensitivity
- Increase expulsion efficiency

What impacts flux expulsion?

History of material preparation
Flux trapped in defects:
- Impurities, dislocations, grain boundaries
Consensus:
- Recrystallization by heat treatment improves expulsion

History of cool-down
Observed from: $Q_0$ and magnetometry
Correlated to: Cooling rate, SC front speed, $\nabla T$
Consensus:
- $\nabla T$: Bare cavities
- $R_B$: Thermoelectric-prone setups
  - Improves by “fast” cool-down
  - Related to the setup

What is a useful experiment to study flux expulsion?
Relate material preparation to cool-down dynamics near $T_c$
Goal and outline

What have we done?
A standalone magnetometry instrument to measure expulsion efficiency prior to cavity production — proof of concept reported at TTC 2020

What is the goal of this study?
Can we correlate trapped flux to the cool-down dynamics around $T_c$?

Outline
- Magnetic Flux Lens Concept
- Measurement and control of the cool-down dynamics
- Results from measurement campaigns
- Summary and contributions
○ Sample: sheet Nb disc
○ Magnetic field: Along axis and homogeneous

○ Cool-down on a closed thermal topology: expelled flux collimated at aperture

○ Flux expulsion efficiency $\eta$ with $0 < \eta < 1$ obtained from:

Flux density measured with a fluxgate:

$$\eta = \frac{B_{\text{meas}}}{B_{\text{sc}}}/B_0 - 1$$

Expelled flux measured with a search coil:

$$\eta = \Delta \Phi_{\text{coil}}/\Phi_0$$

$$\Delta \Phi_{\text{coil}} = -\int_{t_{\text{NC}}}^{t_{\text{SC}}} V_c dt$$

$$\Phi_0 = B_0 A_{\text{Annulus}}$$
Instrument design and setup

- Flux density measurement
  Bartington Mag-F

- Sample
  Diameter = 9 cm
  Aperture = 0.6 cm
  $B_{SC}^{sim}/B_0 \approx 2$

- Earth’s magnetic field used
  Small setup — homogeneous field

- Conduction cooling in vacuum

- Cryocooler
  Cooling power = 1 W at 10 K

- Thermoelectric current mitigated by symmetry

- Contact thermometry
  SD-type CERNOX
  CU-type CERNOX

- Control of the SC transition

Prototype
Setup

Cryocooler interface
Spring loading for the cold contact
Cold edge
Nb sample
Heater
Resistor

Power ↦
Power ↧
Control of cool-down dynamics near $T_c$

**Short** heating pulse — **strong** expulsion

**Long** heating pulse — **weak** expulsion

○ **Control** of the NC/SC transition via sample heater

Heating pulse length $\uparrow$  $B_{SC}/B_0 \downarrow$  $\Rightarrow$  $\nabla T \downarrow$
Measurement of cool-down dynamics near $T_c$

**Short** heating pulse — **strong** expulsion

**Long** heating pulse — **weak** expulsion

- **Measurement** of spatial temperature gradient:

$$\nabla T = \frac{dT}{dr} = \frac{1}{\nu_{SC}} \frac{dT}{dt}$$

- Cooling rate: 0.04 to 0.2 K/s
- SC front speed: 2 to 18 cm/s

Measurement procedure:

- Measurement procedure:
  - Assemble and initial cool-down
  - Perform expulsion for a given pulse length
  - Thermalize ~20 min
  - Repeat

- A total of 669 expulsion measurements over 7 measurement campaigns

- Tested sample: benchmark cavity-grade RRR = 300 niobium (unworked sheet material)
Results from measurement campaigns

* C1 Poor thermal contact

![Graphs showing cooling rate, (SC front speed)^{-1}, and spatial gradient](image)
Results from measurement campaigns

- **C1**  Poor thermal contact
- **C2**  Indium gasket added

Predicted from simulation:

\[
\frac{B_{SC}^{sim}}{B_0} \approx 2
\]
Results from measurement campaigns

- **C1** Poor thermal contact
- **C2** Indium gasket added
- **C3** Indium gasket reused, C4 repeated without disassembly
- **C4**
Results from measurement campaigns

- **C1** Poor thermal contact
- **C2** Indium gasket added
- **C3** Indium gasket reused, C4 repeated without disassembly
- **C4**
- **C5** Force at cold contact tripled -> affects thermal contact resistance

**Cooling rate (SC front speed) -1**

**Spatial gradient**
Measurement campaigns

- **C1**: Poor thermal contact
- **C2**: Indium gasket added
- **C3**: Indium gasket reused, C4 repeated without disassembly
- **C4**: Force at cold contact tripled, affects thermal contact resistance
- **C5**: Design change: fixed gasket, improved assembly

Results from measurement campaigns:

- **Cooling rate**: (SC front speed)$^{-1}$
- **Spatial gradient**
Cool-down conditions are repeatable within a given campaign and can be controlled by the heating pulse length.

Cool-down conditions vary from campaign to campaign — thermal contact resistance varies.

Cooling at high rate not uniquely related to high ER.
Cool-down conditions are **repeatable within a given campaign** and can be controlled by the heating pulse length.

Cool-down Conditions **vary from campaign to campaign** — thermal contact resistance varies.

Cooling at high rate not uniquely related to high ER.

- **ER vs \(\text{grad } T\) is insensitive on the thermal contact resistance and reproducible across campaigns**
  - Allows to characterize expulsion efficiency

### Observations

- **Cooling rate**
  - \(\frac{dT}{dt} \text{ [K/s]}\)
  - \(B_{sc}/B_0\)

- **(SC front speed)\(^{-1}\)**
  - \(1/\nu_{SC} \text{ [m/s]}\)
  - \(B_{sc}/B_0\)

- **Spatial gradient**
  - \(dT/dr \text{ [K/m]}\)
  - \(B_{sc}/B_0\)
Strategy to control and resolve the cool-down dynamics near $T_c$ in the flux Lens developed.

Amount of trapped flux linked to the cool-down dynamics near $T_c$.

- Reproducible result for $\frac{B_{SC}}{B_0}(\nabla T)$ allows to characterize material.

<table>
<thead>
<tr>
<th>Campaign</th>
<th>N expulsions</th>
<th>$\max{\nabla T}$ [K/m]</th>
<th>$\max{\frac{B_{SC}}{B_0}}$</th>
<th>Slope $^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>3</td>
<td>0.4</td>
<td>1.01</td>
<td>–</td>
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<tr>
<td>C2</td>
<td>300</td>
<td>5.3</td>
<td>2.24</td>
<td>0.27</td>
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<td>C3</td>
<td>75</td>
<td>4.8</td>
<td>2.07</td>
<td>0.23</td>
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<tr>
<td>C4</td>
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<td>C5</td>
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<td>2.9</td>
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<tr>
<td>C6</td>
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<tr>
<td>C7</td>
<td>35</td>
<td>3.5</td>
<td>1.69</td>
<td>0.27</td>
</tr>
</tbody>
</table>

Independent confirmation of studies performed on bare cavities:

- Cooling at high rate is not uniquely related to high expulsion.
- Expulsion improves for cooling at high temperature gradients.