Design and Test of a Superconducting Lens for an Ultra-Stable Electron Microscope

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Field and mechanical stability motivates an “all-cold” electron microscope

Design and fabrication of a superconducting prototype objective lens
  • Nb-Ti coil and pole pieces
  • superconducting joints + persistent current switch
  • novel persistent current stabilization/adjustment device

Testing of the lens
  • Hall probe and SQUID-based field measurement
  • persistent current operation and active stabilization
Mechanical and field stability are critical challenges for electron microscopy, an “all-cold” microscope can potentially overcome these issues

Drift stability on TEAM I microscope

Focus stability (after settling) on TEAM I Microscope

<table>
<thead>
<tr>
<th>issue</th>
<th>solution explored by 1K-TEM project at LBNL</th>
</tr>
</thead>
<tbody>
<tr>
<td>mechanical drift</td>
<td>cool entire microscope to LHe temp</td>
</tr>
<tr>
<td>mag. field drift</td>
<td>ultra-stable, persistent current SC magnets</td>
</tr>
<tr>
<td></td>
<td>superconducting magnetic shielding</td>
</tr>
</tbody>
</table>
A 1.95 T, Nb-Ti, prototype electron lens built to probe magnet stability
Field and inductance of the lens from the Opera3D model

Results at 30 A

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field in center of gap</td>
<td>1.93 T</td>
</tr>
<tr>
<td>Field at hall probe loc.</td>
<td>1.79 T</td>
</tr>
<tr>
<td>Inductance</td>
<td>5.5 mH</td>
</tr>
</tbody>
</table>
Superconducting joints integrate the lens with a persistent current switch tuner for operation with active stabilization.
Persistent current operation at 30 A routinely established without quench

- LHe bath cryostat
- Header with magnet assembly

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**Graph:**

- **X-axis:** Time (sec)
- **Y-axis:** Power supply current (A)

- **Graph 1:**
  - Title: 1.82 T at hall probe
  - Persistent current operation
  - Measured field vs. current is in agreement with Opera3D (shows saturation effects)

- **Graph 2:**
  - *measured*
  - Opera3D center of gap
  - Opera3D hall probe location
Movement of the cryogenic stage changes the inductance of the “tuner” magnet which shifts flux to or from the main lens

Inductance change in a closed superconducting loop results in change of persistent current level (conservation of flux linkage)

• if you can implement a tunable superconducting inductor, you can stabilize or adjust the persistent current level

\[
L \frac{di}{dt} + i \frac{dL}{dt} = \frac{d\lambda}{dt} = 0
\]

\[
i(t) = \frac{i_0 L_0}{L(t)}
\]
Tuner design employs an attocube stage (stick/slip with piezos) for which 0.1 micron steps are repeatable in liquid helium. ANPx101 with 5 mm range

Capacitive gap sensors independently measure stage position in LHe

Cap sensor targets

Cap probe mounts

Δg/V = -0.00917 µ/Volt

Δg/V = -0.00952 µ/Volt

https://www.attocube.com/en
https://www.capacitec.com/
Experimental demonstration: inductance tuning gives precise control over the level of persistent current

\[ L \frac{di}{dt} + i \frac{dL}{dt} = \frac{d\lambda}{dt} = 0 \]

\[ i(t) = \frac{i_0 L_0}{L(t)} \]

This technique also works for HTS, see TUE-PO1-804-09
Experimental demonstration: stabilizing to the noise level of the Hall probes (a few ppm at 1.95 T)

\[
(L_m + L_b) \frac{di}{dt} + i \frac{dL_b}{dt} + iR = 0.
\]

\[
\frac{dL_b}{dt} = -R.
\]
SQUID-based magnetometer for field decay measurement: design and prototype

- Gradiometer to minimize external noise
- Control heater
- Flux-locked SQUID
- Superconducting switch
- Superconducting lens
- Single-turn coil in series with main magnet

Gradiometer prototype

\[ \frac{dB}{dt} = 9 \text{ nanoT/s} \]
design, fabrication, and test of a 1.95 T lens for electron microscopy

- routine persistent current operation without quench or other issues
- development of a novel persistent current stabilization method based on inductance tuning
- active field stabilization to the level of hall probe noise (ppm range)
- initial testing of SQUIDs are limited by external noise

next steps focus on repeating tests with better environmental stabilization

- superconducting shielding
- cryostat level/pressure
- goal: implement active tuning based on SQUID measurement to go beyond ppm level towards ultimate ppb goal
Superconducting joints fabricated by solder replacement method, with eutectic Pb-Bi solder, with recipe verified with SEM/EDX after ion milling

Overall scan

Detailed image at the interface/combined EDS elemental map is consistent with understanding of solder-replacement method*

<table>
<thead>
<tr>
<th>Lens Wire</th>
<th>Switch Wire</th>
</tr>
</thead>
<tbody>
<tr>
<td>mat.</td>
<td>NbTi/Cu</td>
</tr>
<tr>
<td></td>
<td>NbTi/Cu-10%Ni</td>
</tr>
<tr>
<td>dia.</td>
<td>.381 mm</td>
</tr>
<tr>
<td></td>
<td>0.5 mm</td>
</tr>
<tr>
<td># fil.</td>
<td>450</td>
</tr>
<tr>
<td></td>
<td>18</td>
</tr>
<tr>
<td>Cu:SC</td>
<td>2.35:1</td>
</tr>
<tr>
<td></td>
<td>1.5:1</td>
</tr>
</tbody>
</table>

Microstructure work with help from Rohan Dhall, LBNL, National Center for Electron Microscopy
Closed loop stabilization of the lens using field measured by the hall probe

Every time the moving average of the field crosses the bounds about a set point
- interpolate cube step to bring the field back to the set point from calibration run
- move cube and wait for moving average to reset