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

Lucas Brouwer, Tengming Shen, Ryan Norris, Aurelio Hafalia, Ross Schlueter, Li Wang, Jim Ciston, Peter Ercius, Qing Ji, Marian Mankos, Colin Ophus, Alexander Stibor, Andreas Schmid, Andrew Minor, and Peter Denes

Lawrence Berkeley National Laboratory

27th Magnet Technology Conference

November 16, 2021

Furuoka, Japan

Outline

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

Design and fabrication of a superconducting prototype objective lens

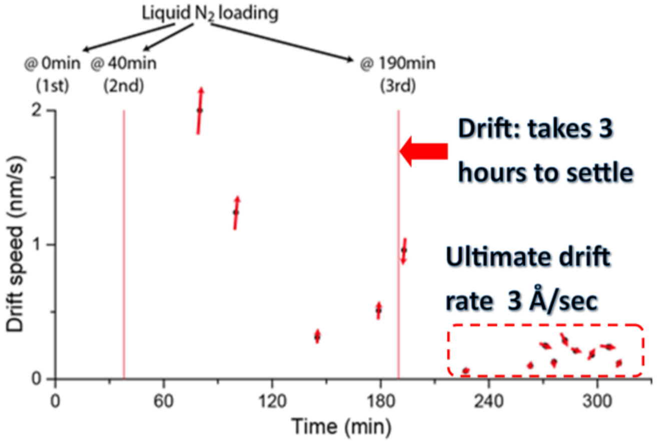
- Nb-Ti coil and pole pieces
- superconducting joints + persistent current switch
- novel persistent current stabilization/adjustment device

Testing of the lens

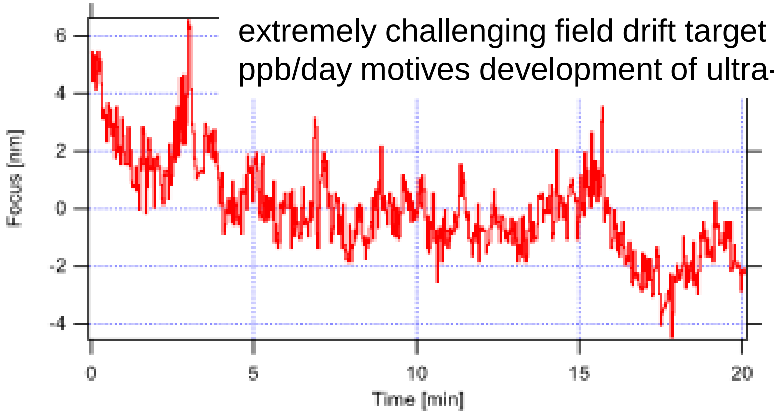
- Hall probe and SQUID-based field measurement
- persistent current operation and active stabilization

Mechanical and field stability are critical challenges for electron microscopy, an “all-cold” microscope can potentially overcome these issues

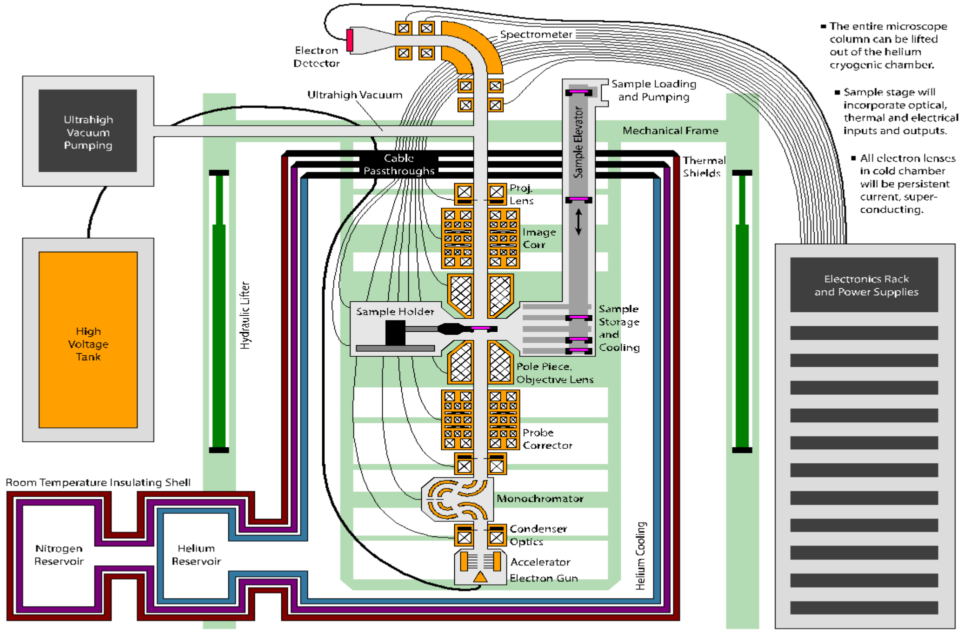
Drift stability on TEAM I microscope



Focus stability (after settling) on TEAM I Microscope

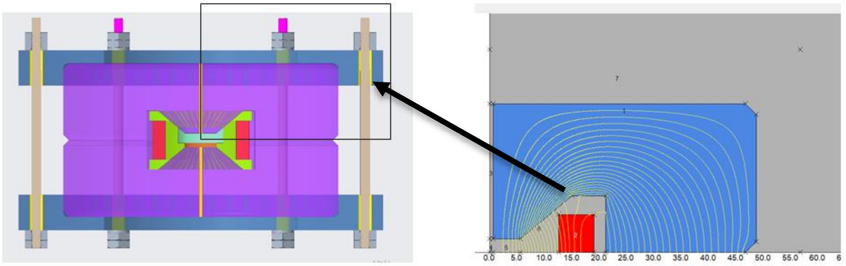


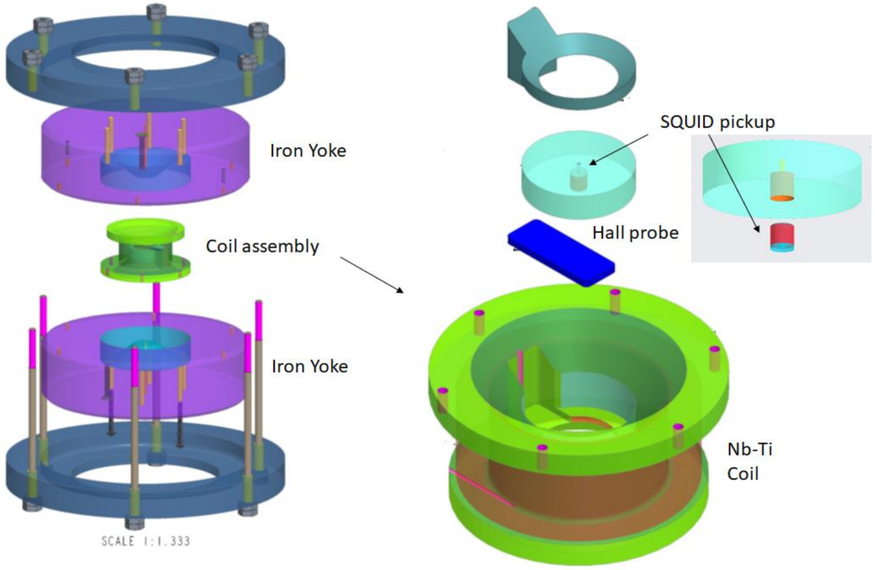
extremely challenging field drift target of 1 nm/day = 1 ppb/day motives development of ultra-stable SC magnets

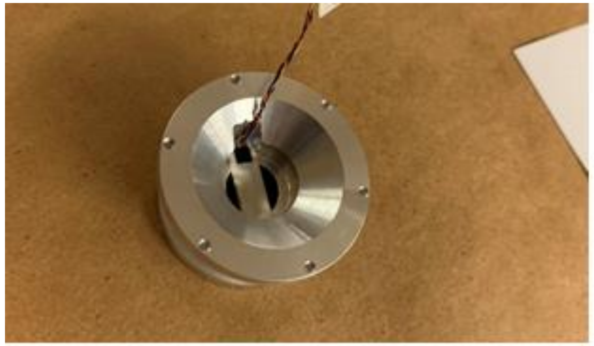


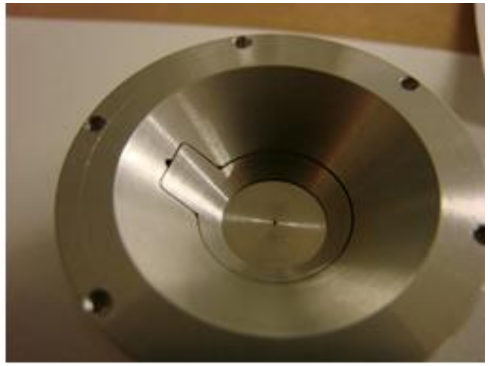
issue	solution explored by 1K-TEM project at LBNL
mechanical drift	cool entire microscope to LHe temp
mag. field drift	ultra-stable, persistent current SC magnets
	superconducting magnetic shielding

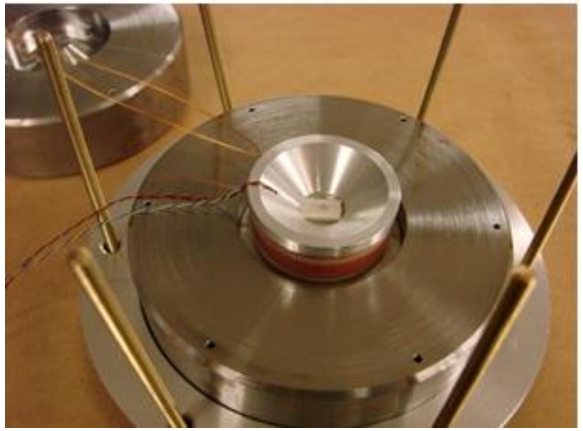
A 1.95 T, Nb-Ti, prototype electron lens built to probe magnet stability

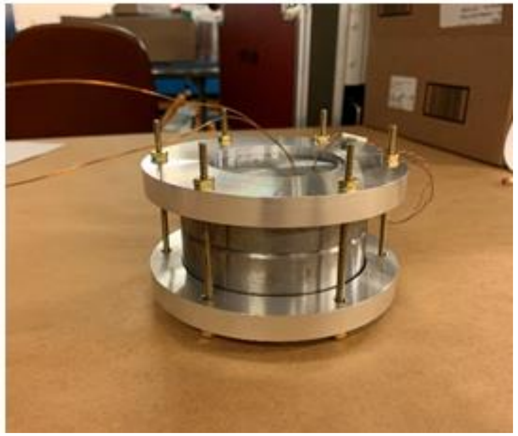




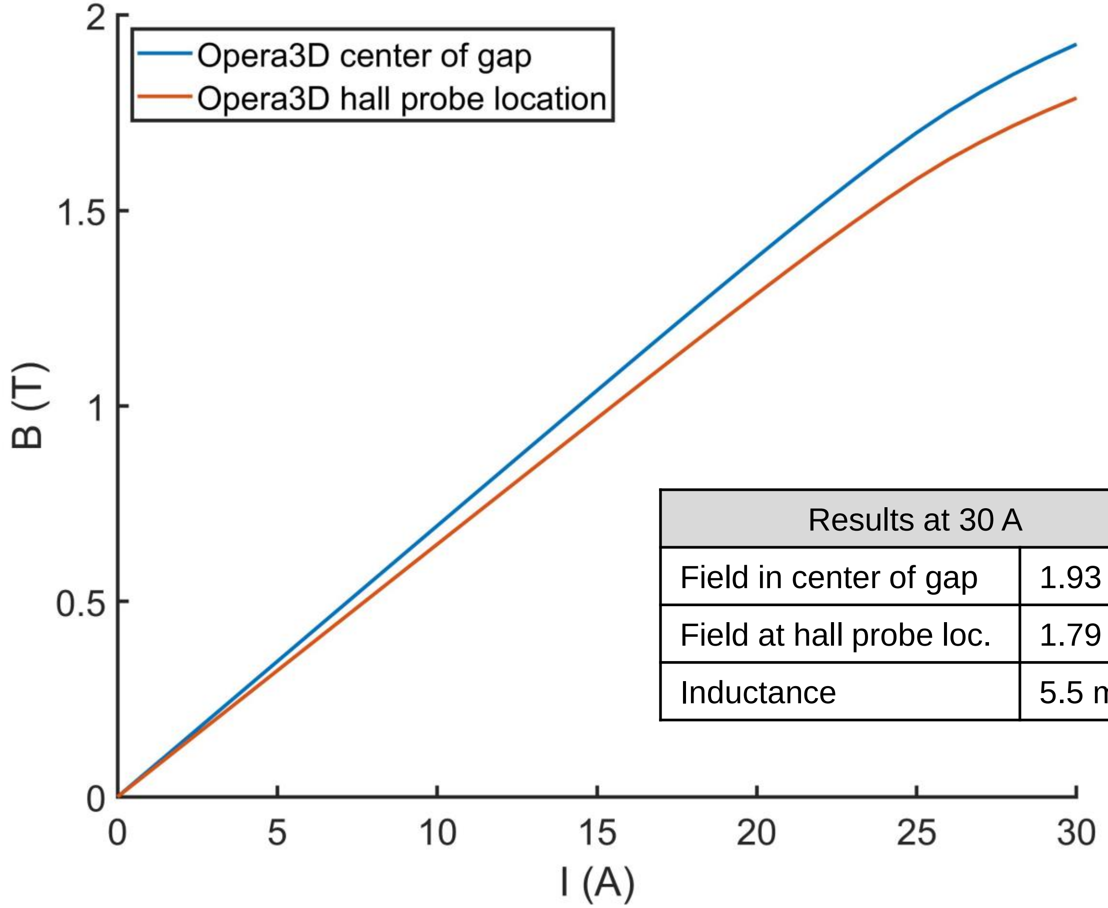




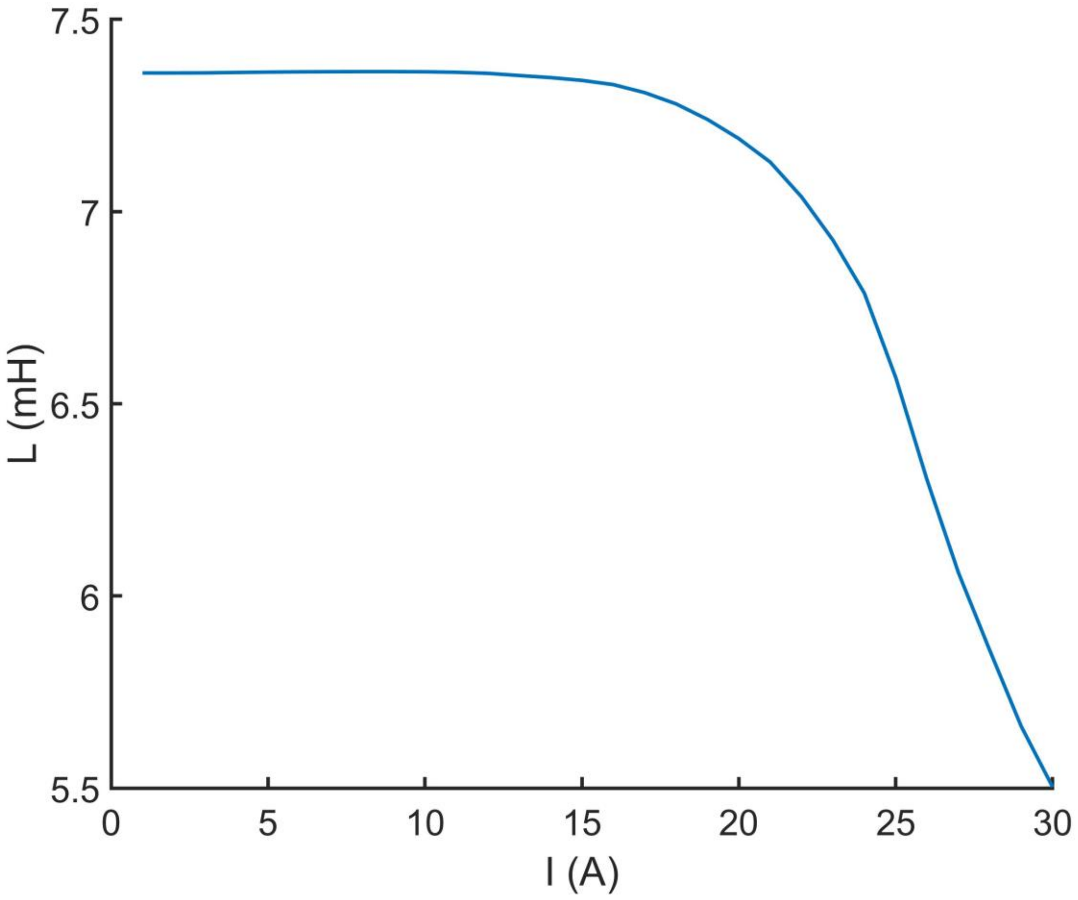




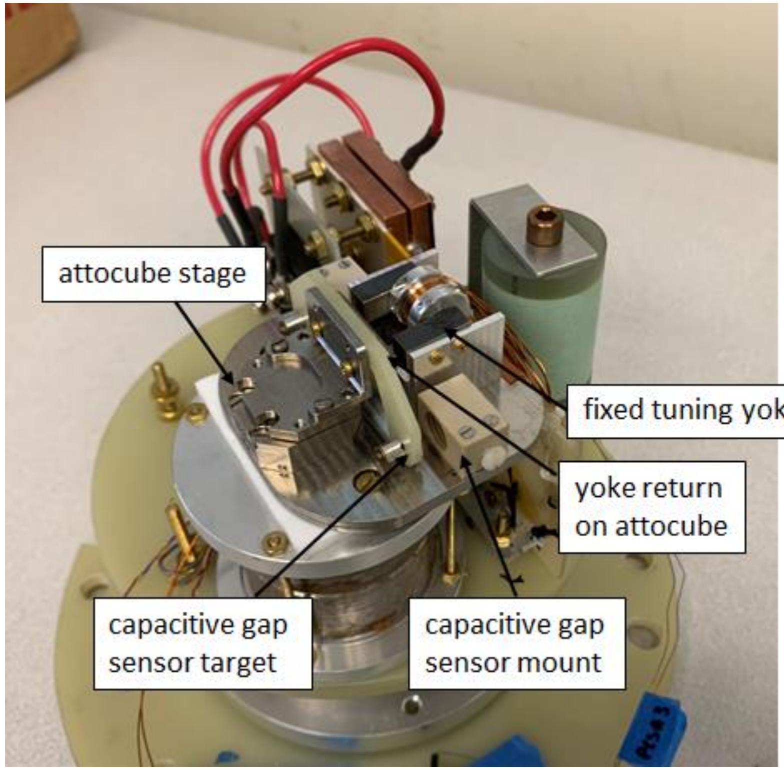
Field and inductance of the lens from the Opera3D model

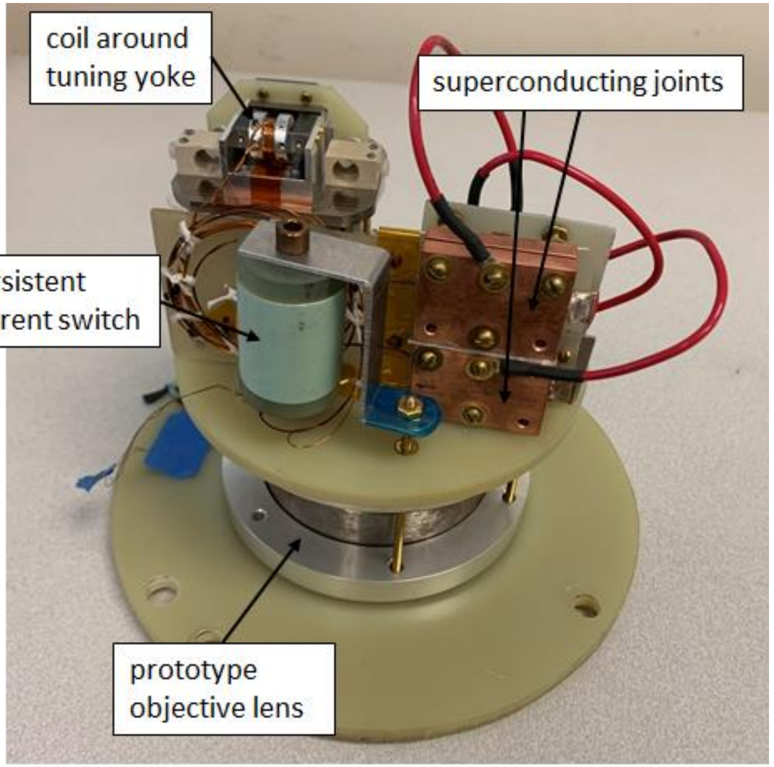


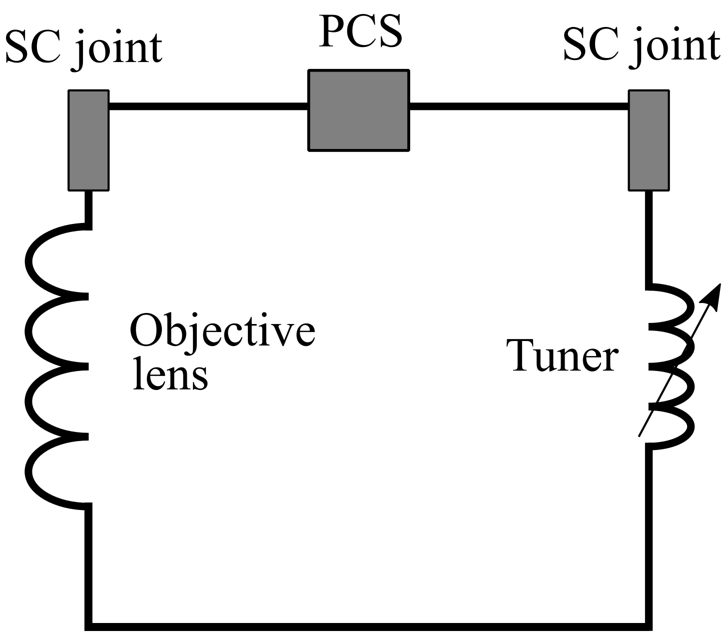
Results at 30 A	
Field in center of gap	1.93 T
Field at hall probe loc.	1.79 T
Inductance	5.5 mH



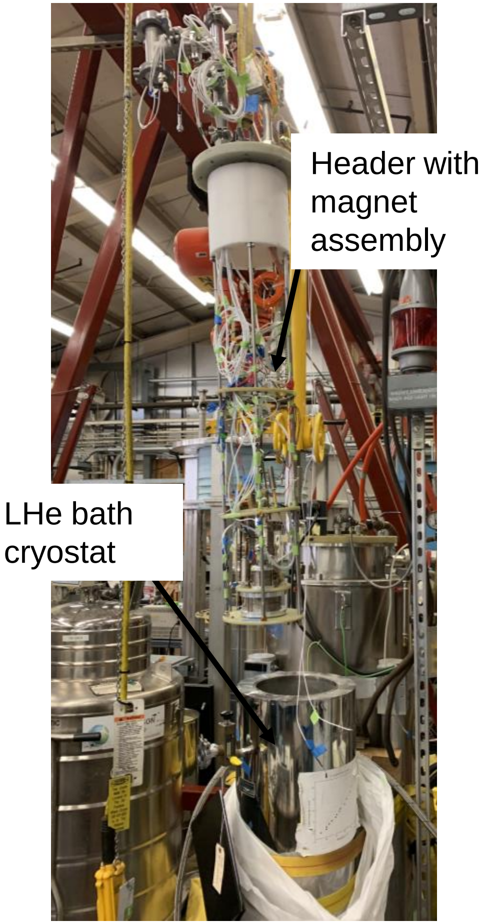
Superconducting joints integrate the lens with a persistent current switch tuner for operation with active stabilization

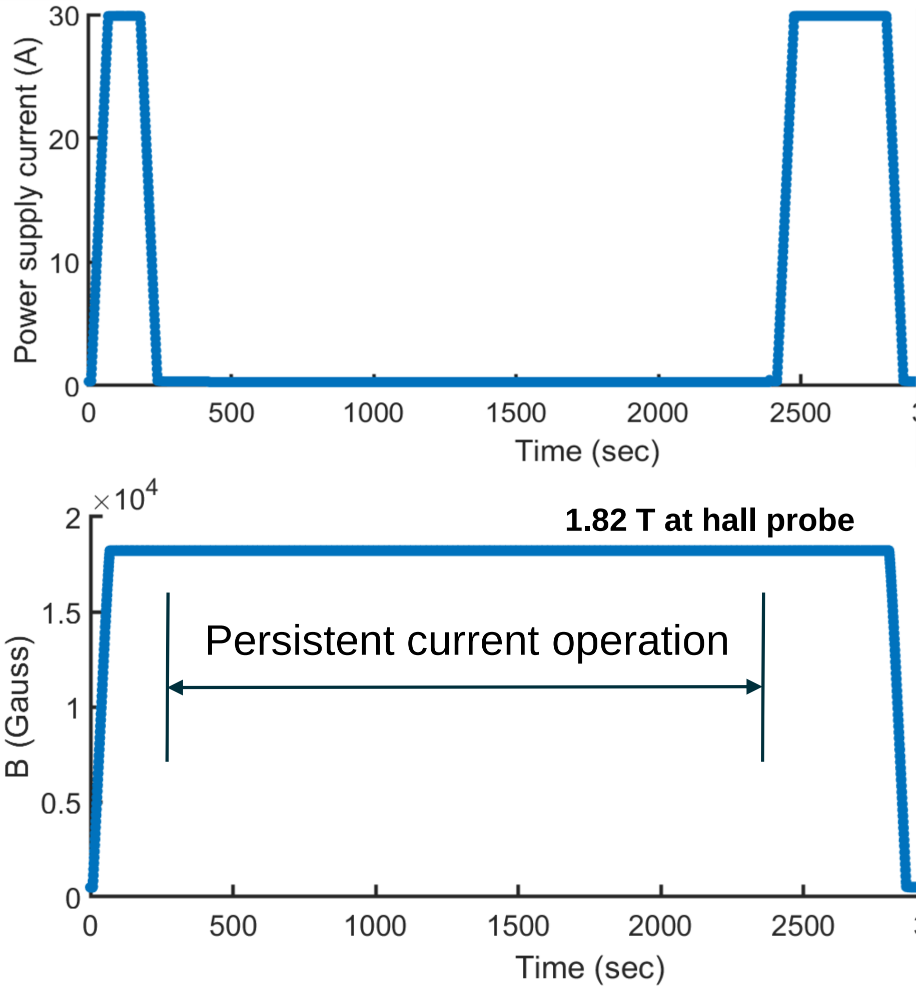




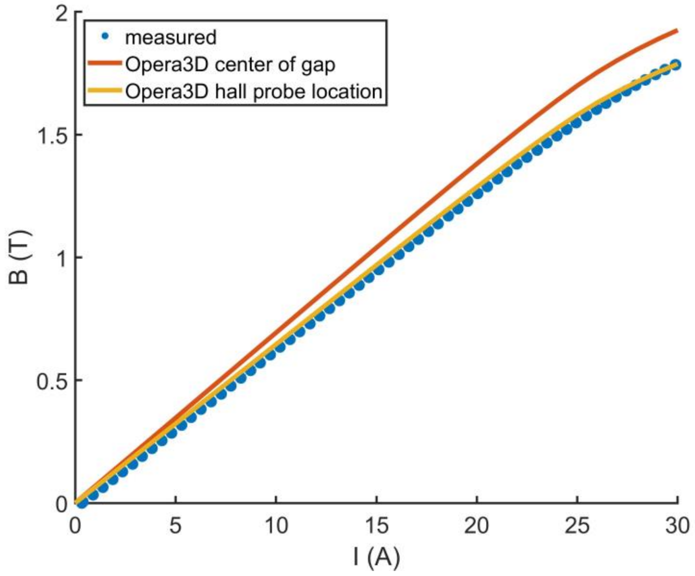


Persistent current operation at 30 A routinely established without quench





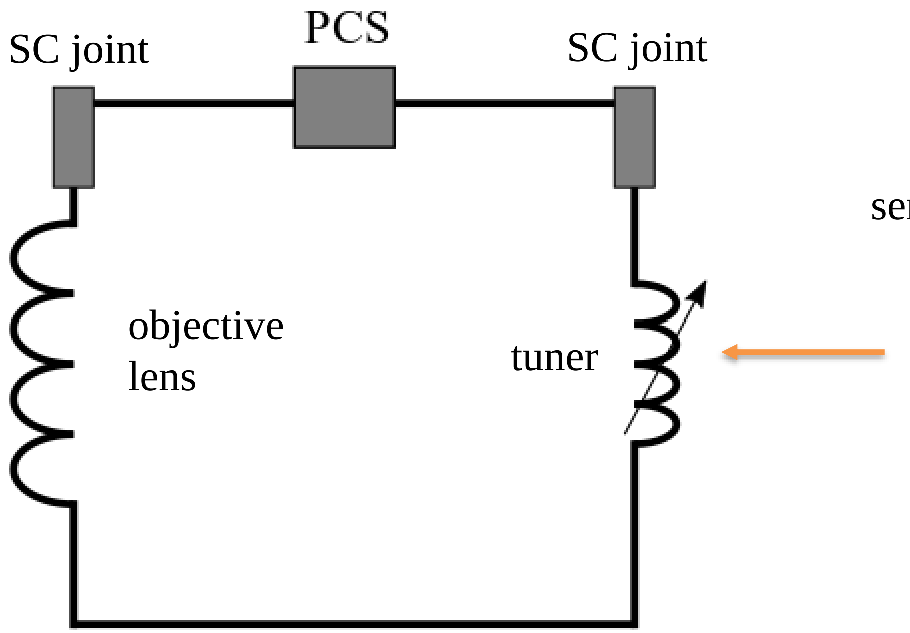
Measured field vs. current is in agreement with Opera3D (shows saturation effects)

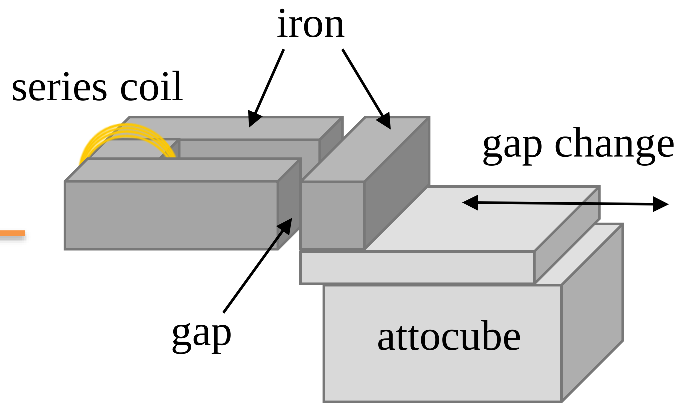


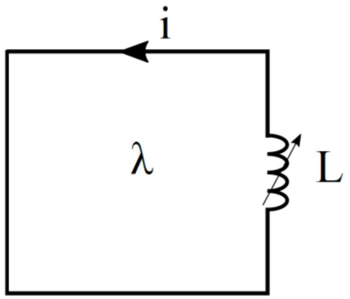
Movement of the cryogenic stage changes the inductance of the "tuner" magnet which shifts flux to or from the main lens

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





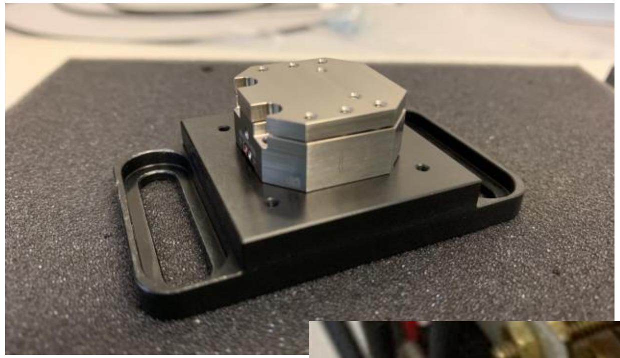


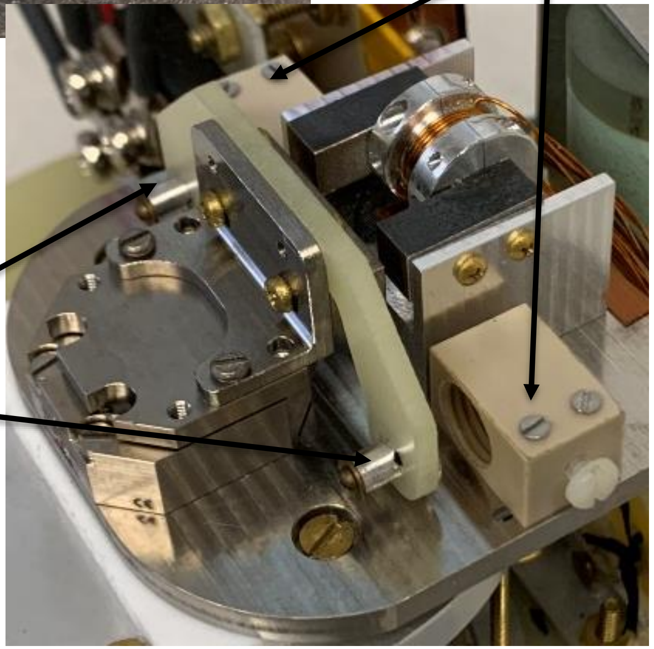
$$L\frac{di}{dt} + i\frac{dL}{dt} = \frac{d\lambda}{dt} = 0$$

$$\boxed{i(t) = \frac{i_0 L_0}{L(t)}}$$

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

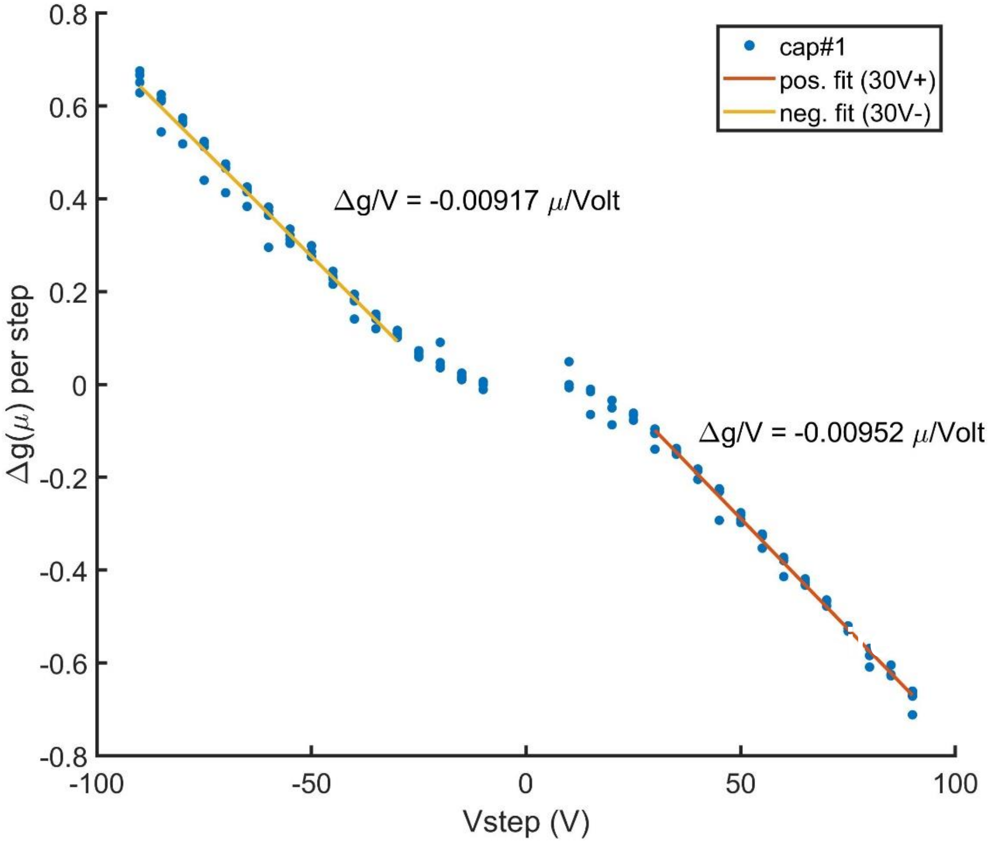




Cap probe mounts

Cap sensor targets

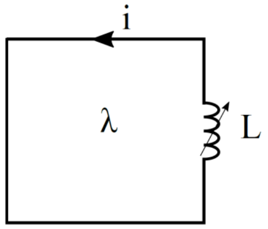
Capacitive gap sensors independently measure stage position in LHe

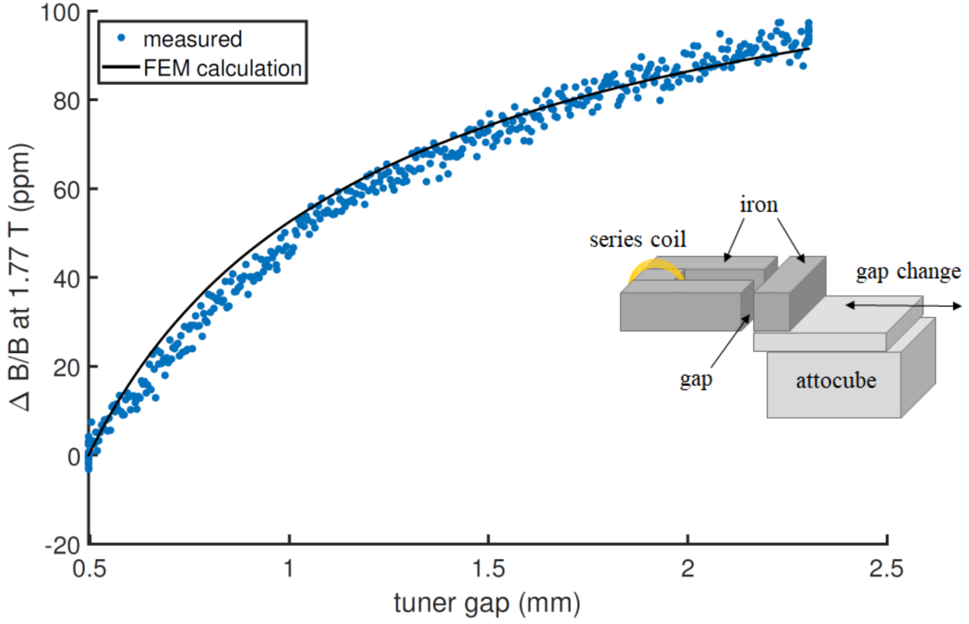


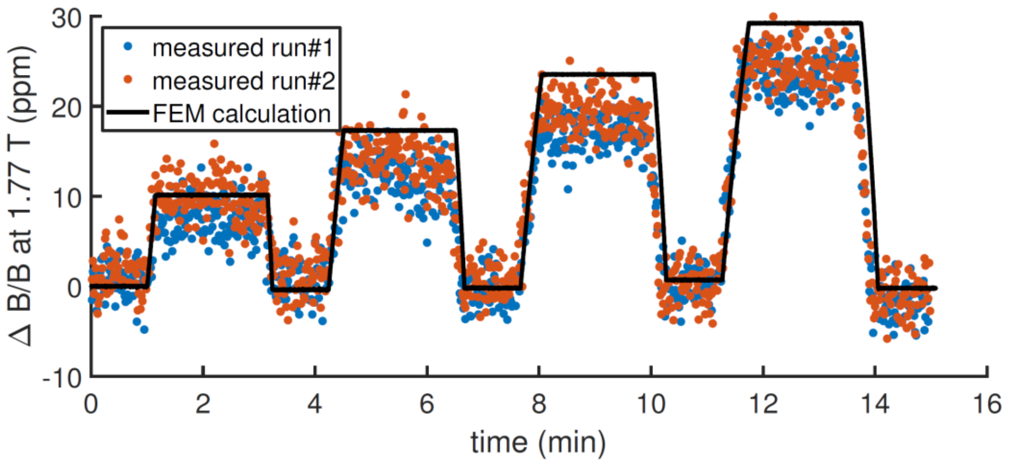
Experimental demonstration: inductance tuning gives precise control over the level of persistent current

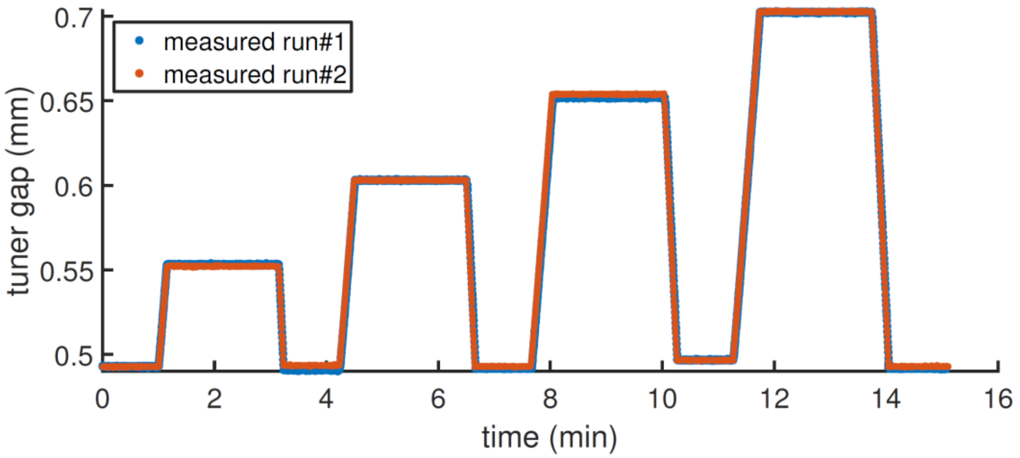
$$L\frac{di}{dt} + i\frac{dL}{dt} = \frac{d\lambda}{dt} = 0$$

$$\boxed{i(t) = \frac{i_0 L_0}{L(t)}}$$







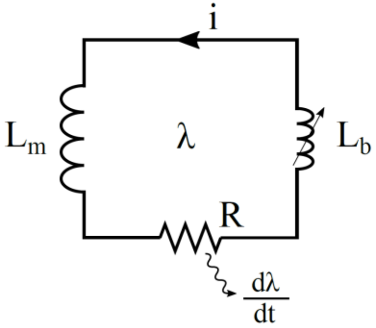


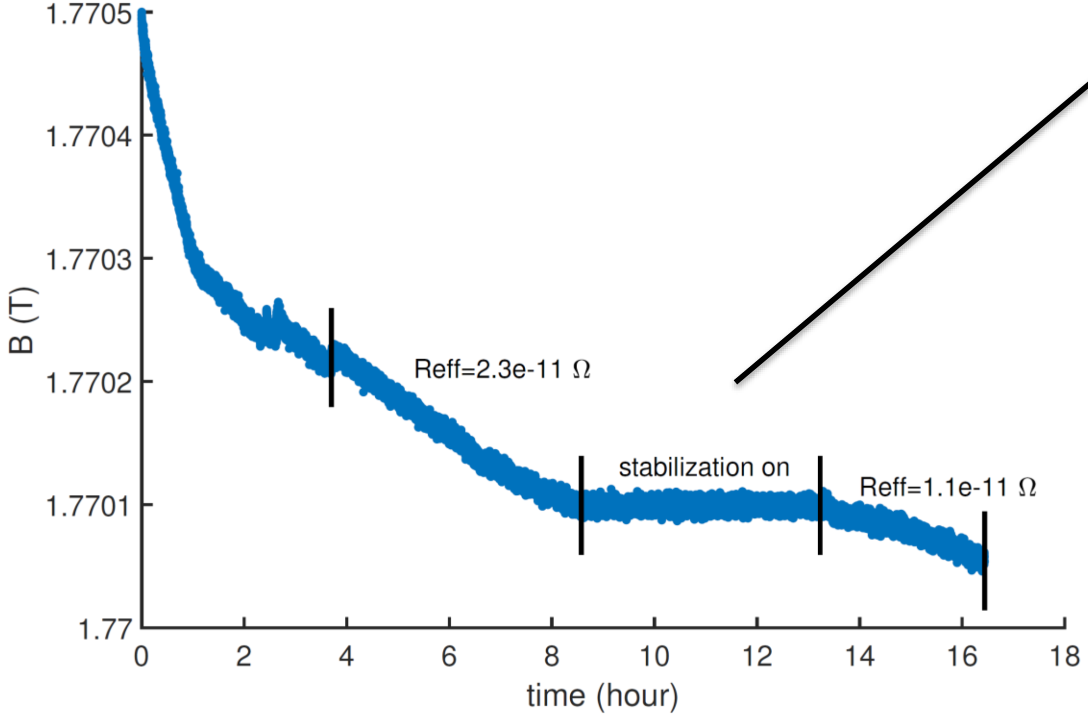
This technique also works for HTS, see TUE-PO1-804-09

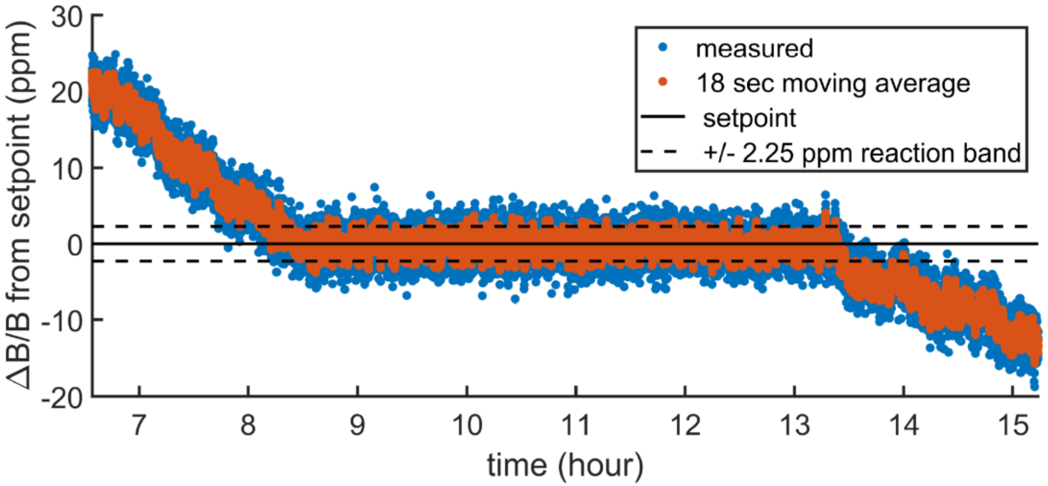
Experimental demonstration: stabilizing to the noise level of the Hall probes (a few ppm at 1.95 T)

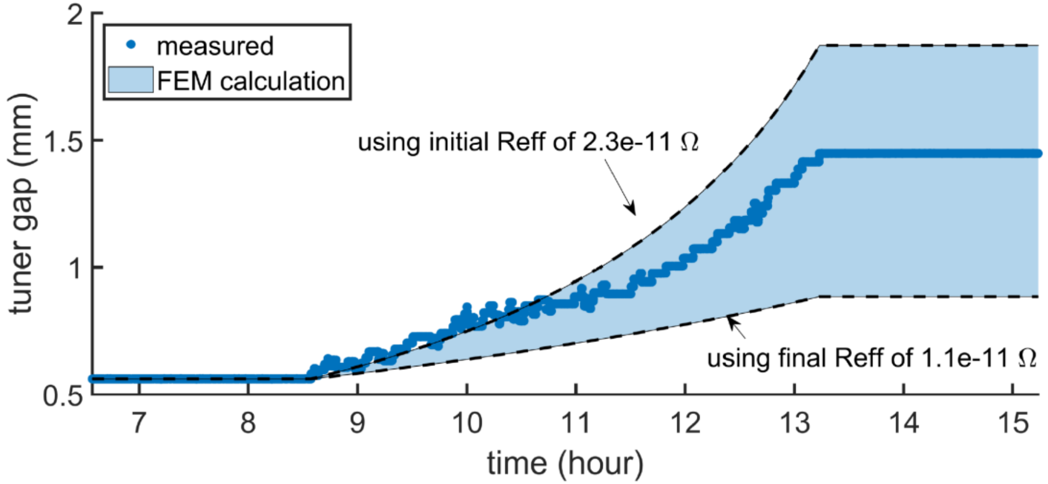
$$(L_m + L_b)\frac{di}{dt} + i\frac{dL_b}{dt} + iR = 0.$$

$$\boxed{\frac{dL_b}{dt} = -R.}$$

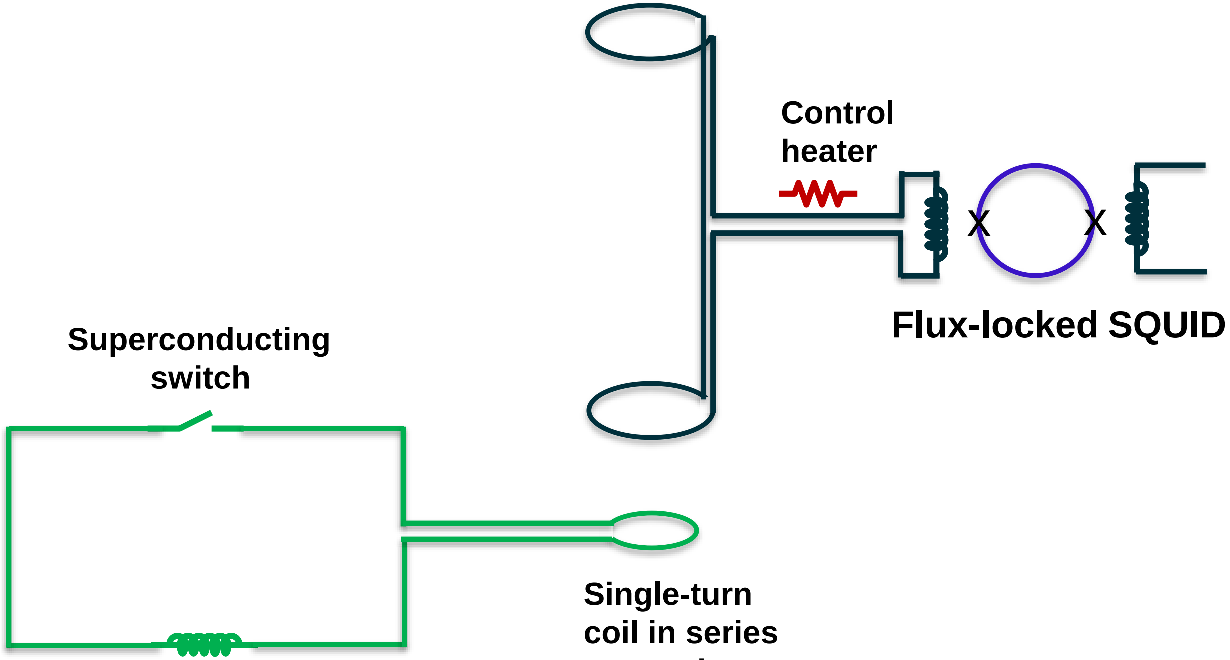




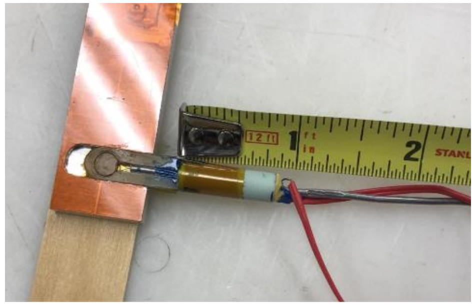


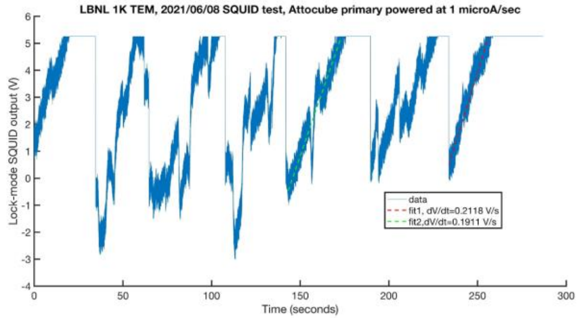


SQUID-based magnetometer for field decay measurement: design and prototype

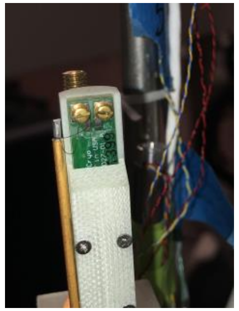


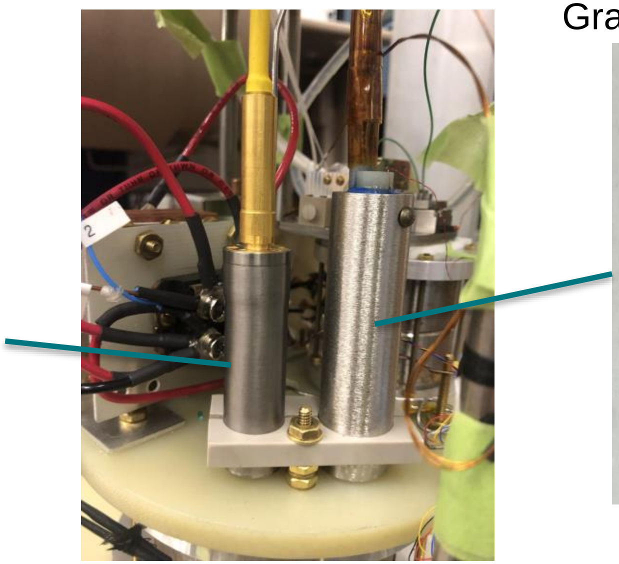
dB/dt = 9 nanoT/s





SQUID





Gradiometer prototype

Summary

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

Backup Slides

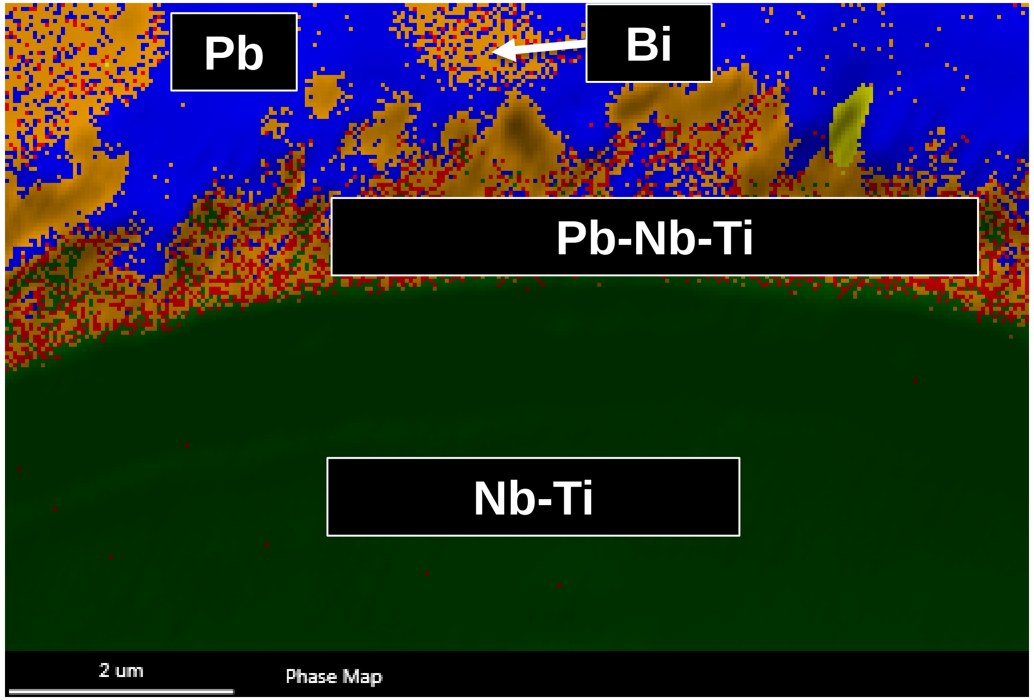
Superconducting joints fabricated by solder replacement method, with eutectic Pb-Bi solder, with recipe verified with SEM/EDX after ion milling

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

	Lens Wire	Switch Wire
mat.	NbTi/Cu	NbTi/Cu-10%Ni
dia.	.381 mm	0.5 mm
# fil.	450	18
Cu:SC	2.35:1	1.5:1

Overall scan

Nb-Ti filament



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