DMRadio-50L Inductor and Resonator Components

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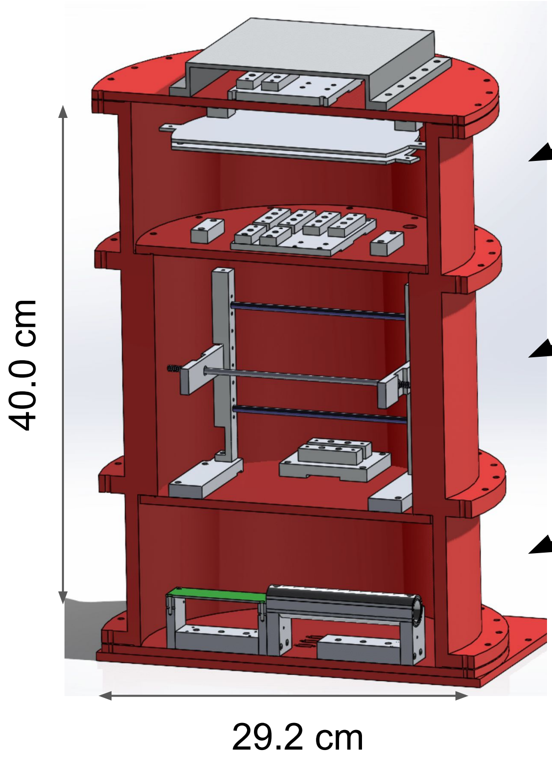
Outline

1. Overview of the resonator testing apparatus
2. Custom Hardware components
3. Initial Q vs T measurements
4. Next Steps and Timeline

Resonator[1] testing apparatus: overview



SolidWorks drawing, general view; red = 5N Al

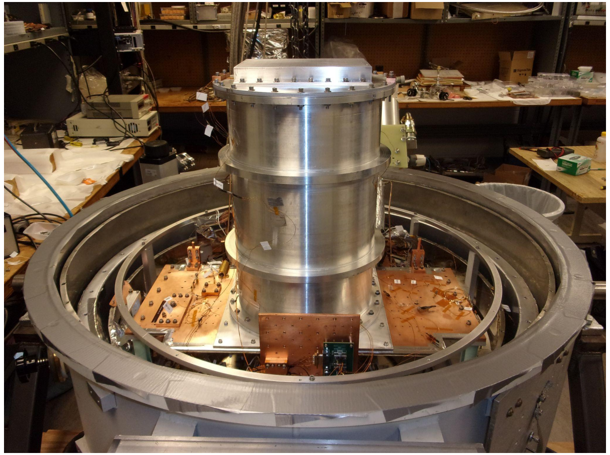
Capacitor chamber
- Circular-plate Al capacitor
- Vacuum dielectric
- C = 220 pF

Inductor chamber
- NbTi wire
- Al frame
- Alumina rods
- L = 500 uH

SQUID chamber
- First-stage SQUID PCB
- Readout port

Baseline design resonance frequency:
f ≅ 480 kHz

[1] P. Falferi, M. Cerdonio, L. Franceschini, R. Macchietto, S. Vitale, J. P. Zendri; A high inductance kHz resonator with a quality factor larger than 10^6



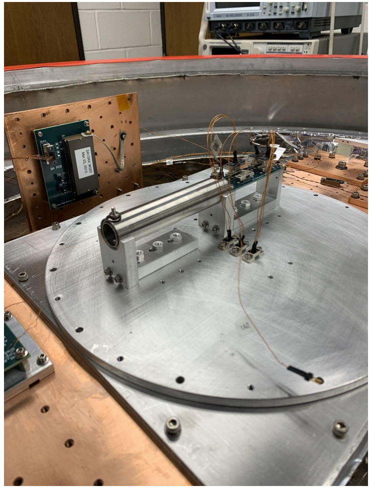
5N Al shield mount inside the cryostat.
Cold stage = 750 mK

Lots of efforts to eliminate loss: superconducting materials

Resonator testing apparatus: motivation

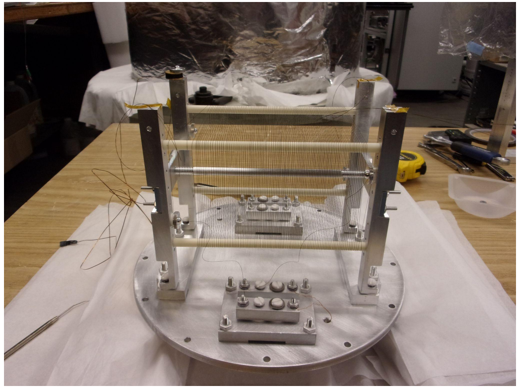
- Optimizing Q of superconducting resonator
- Get high-Q (~10^6) in ~100 kHz - 5 MHz frequency range:
  - Frequency tuning by coarse tuning of capacitor, C
  - Frequency tuning by inductor swaps, L
- Materials qualification:
  - Example: what kind of Al is better (6061 vs 1100)?
- Test the resonator components (L, C, DC SQUID)
  - Components are tested and characterized separately beforehand
    - L and C are disconnected, DC SQUID is disconnected
    - Easier to troubleshoot separately
  - After individual testing, the resonator circuit is completed just in one step by connecting L and C (current stage)
- Test frequency stability

Resonator testing apparatus: components



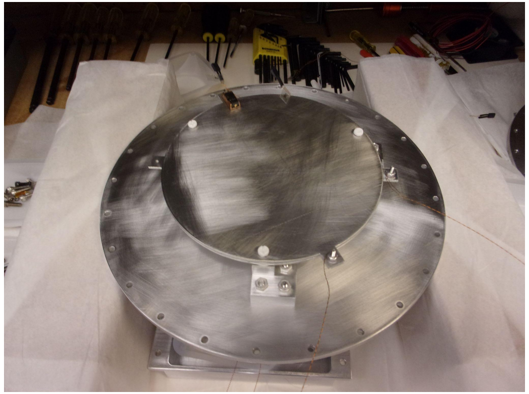
SQUID chamber:

- 2-stage SQUID system
- SQUID1 + SA
- Cylindrical shield around PCB
- Shells: Nb+Cryoperm+Nb
- Al trace PCB is out from fabrication



Inductor coil:

- NbTi wire
- Alumina horizontal rods
- Al 1100 frame
- Al 1100 threaded rod
- Teflon screw
- Tantalum washers
- Transformer and injection loops winded on Alumina rods

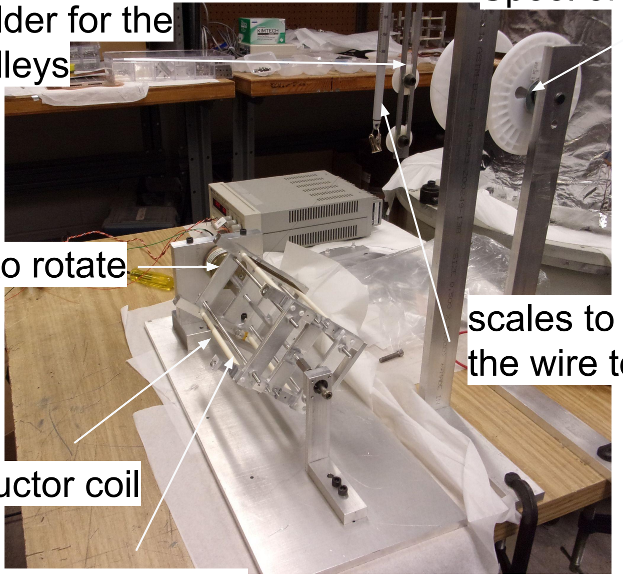


Circular-plate capacitor:

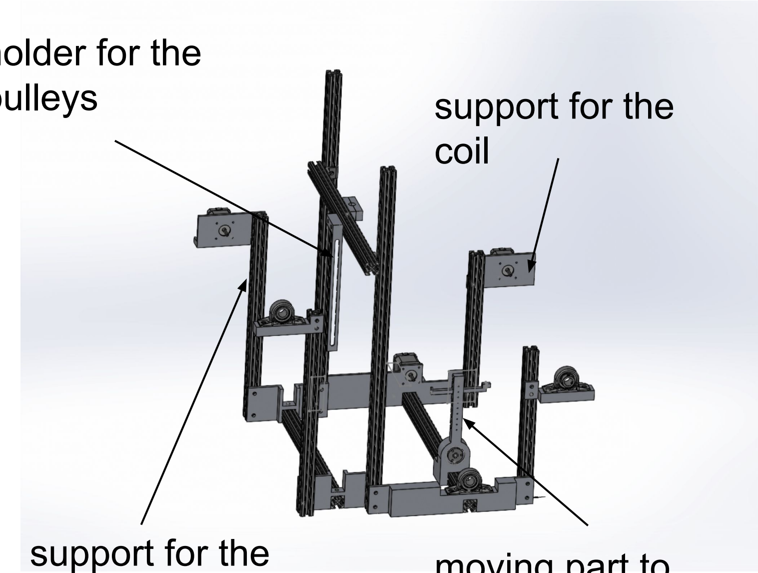
- Separated by vacuum
- Alumina washers to separate the plates
- Al 1100
- Teflon screw
- Tantalum washers

Custom Hardware: Coil Winder

Current version:



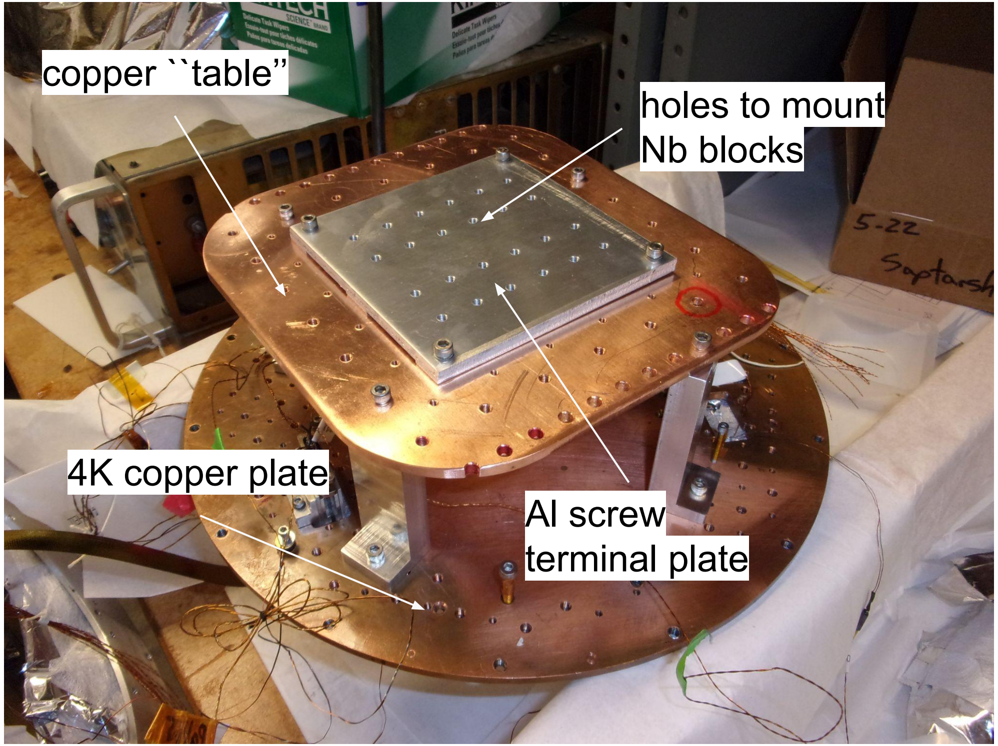
Coming upgrade:



The scaled version of the upgraded coil winder will be sent to Stanford to DM Radio 50L

work in progress by summer undergrads: Nastassia Patnaik and Oyu Enkhbold

Custom Hardware: Screw Terminal Recipe

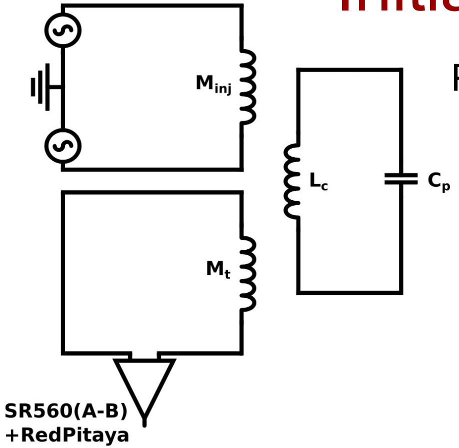


- 4K small cryostat, which allows quick turnaround
- will be used for experiments to find the ``screw terminal recipe”
- The experiments will be going in parallel with the main ``high-Q resonator” R&D

Screw terminal recipe:

- Nb blocks w/ Al fasteners
- Surface preparation (?)
- Torque (?)
- Evaluate resistance with:
  - Lakeshore 372
  - DC SQUIDs

Initial Q vs T measurement w/ Al 6061

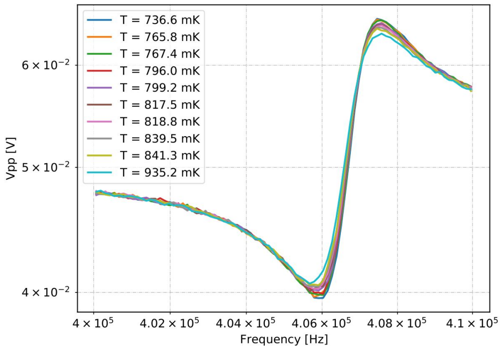


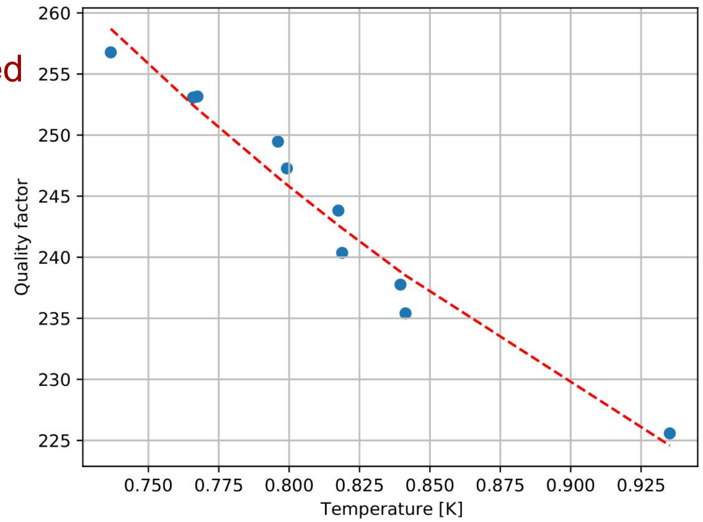
Preliminary measurement of Q:

- Resonator was intentionally damped
- LC circuit:
  - L of inductor coil
  - C of the PhBr twisted pair (parasitic)
- PhBr twisted pair:
  - One end at 750 mK
  - Another end at 300K
- Fit the observed response around the resonance @ ~406 kHz
- Fit to the function:

$$V_{\rm out} = i\omega I_{\rm in}\left(M_{\rm p} + \frac{M_{\rm inj}M_{\rm t}}{L}\frac{iQ}{1+2iQ\dfrac{\Delta\omega}{\omega_0}}\right)$$

- Repeat the measurement as the cryostat is cooling, to get Q vs T

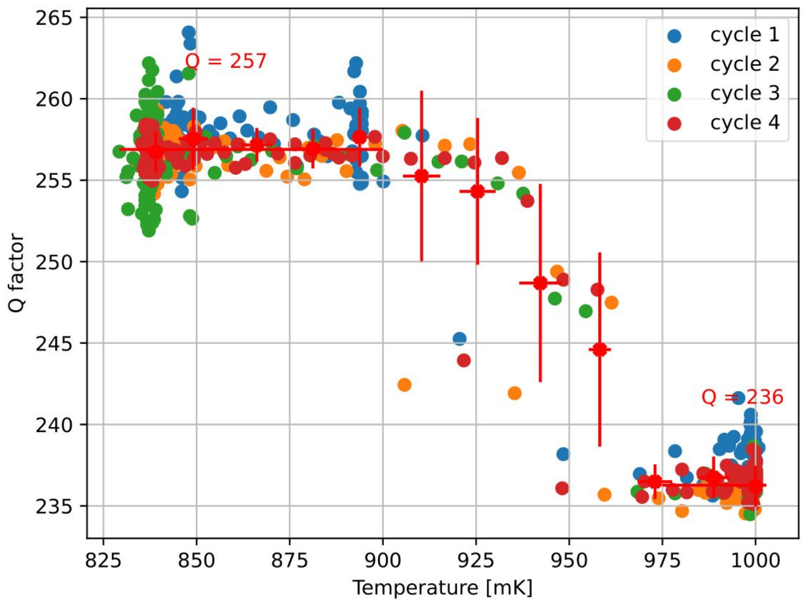


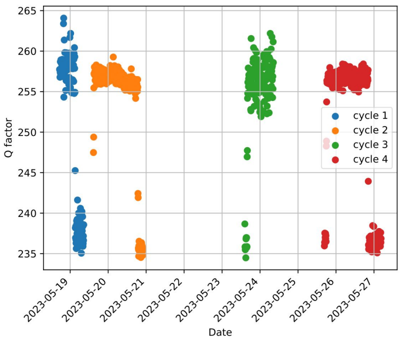


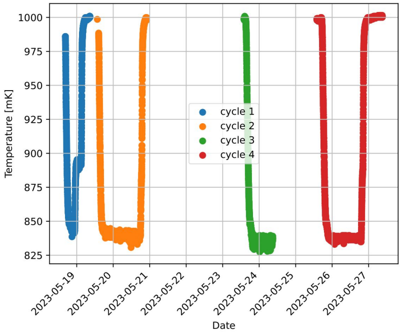
Observed temperature dependence of Q: residual resistance of Al 6061

Initial Q vs T measurement Q vs T w/ Al 1100

- **Replaced Al 6061 w/ Al 1100**
- Mounted ROX (calibrated) on the inductor frame
- Repeated the measurements during the next cooldown. Results:
  - T< 900 mK, Q = 257
  - T > 975 mK, Q = 236
  - 900 mK < T < 975 mK, transition region
- **Main conclusions and results:**
  - **Al 1100 is preferable for high-Q resonator**
  - **We can predict the Q theoretically**







Q = 257 agrees with the theoretical estimation, assuming fill factor times loss tangent = $5*10^{-4}$

Next cooldown: superconducting resonator

Done:

- Capacitor and inductor are connected to complete the resonator circuit
- Resonator is installed in the cryostat

To do:

- Measure Q at room temperature (by July 1st, 2023)
  - Input: a square wave; Output: a decaying sine
  - High resistance of NbTi wire: Q ~ 0.75
  - Decay constant: $\tau = 1/\beta \sim 0.5\ \mu s$, and oscillations period $T \sim 2.8\ \mu s$
  - Initial amplitude ~ 80 μV (assuming 1V input and amplifier gain of 150)
  - Newly acquired Spectrum digitizer will help
- Measure Q vs T as the cryostat cooling down (by July 10th, 2023)

Timeline

- **high-Q superconducting resonator:**
  - **By July 31st, 2023**: get the first measurement of Q of the superconducting resonator
  - **By September 30th, 2023**: demonstrate that Q is not degraded by coupling to the DC SQUIDs
  - **By October 31st, 2023**: demonstrate a Q in a fixed-frequency range that exceeds the state-of-art by a factor of ~2 in the 100 kHz - 5 MHz frequency range
- **Inductor coil and coil winder:**
  - **By August 31st, 2023**: automated coil winder (ready to wind inductors for the swaps)
  - **By October 31st, 2023**: scaled version of the coil winder for DM Radio 50L
  - **By November 30th, 2023**: scaled version of the of inductor coil for DM Radio 50L

Risks and Mitigation, Questions

- Resonator addresses the question of what superconductors can be used for the 1K shield in 50L
- Resonator directly informs winding strategy and mechanical infrastructure for 50L

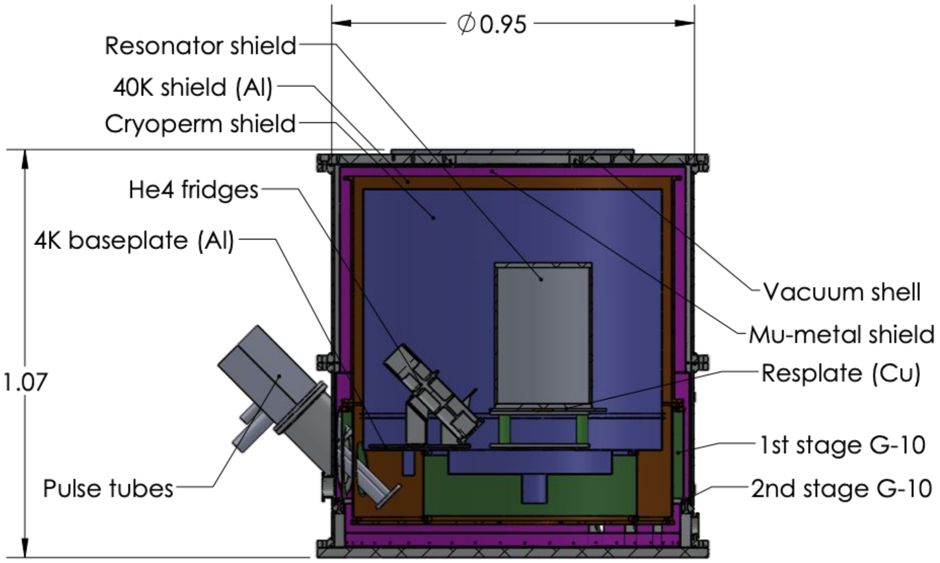
Commissioning: calibration of the inductor circuit parameters (mutual inductances and self-inductances)

Question to the Collaboration: how do we cool the inductor frame and mount to the 4K-20 mK puck system?

Backup Slides

Initial Q vs T measurement: Cryogenics

1. 4K Cryoperm 10 shell
2. 40K (Aluminum) shell
3. 300K Mu-metal
4. Vacuum shell



SolidWorks. Cross-section view of the shells

Cryostat. Closed up during cooldown

- Inductor frame temperature during He4 cycle ~ 840 mK
- Next step: incorporating He3 fridge ~ 350 mK (soon)

Cryostat inherited from ABS collaboration: T. Essinger-Hileman et al. arXiv:1008.3915