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ADR AND ELECTROMAGNETIC SHIELDING

Adiabatic demagnetization refrigeration

- Magnetization of paramagnetic salt yields cooling
- Two salt pill stages for base $T \sim 40\text{mK}$
- Residual magnetic field at sample ($B_{\text{earth}} + B_{\text{ADR}}$)

Superconducting quantum devices

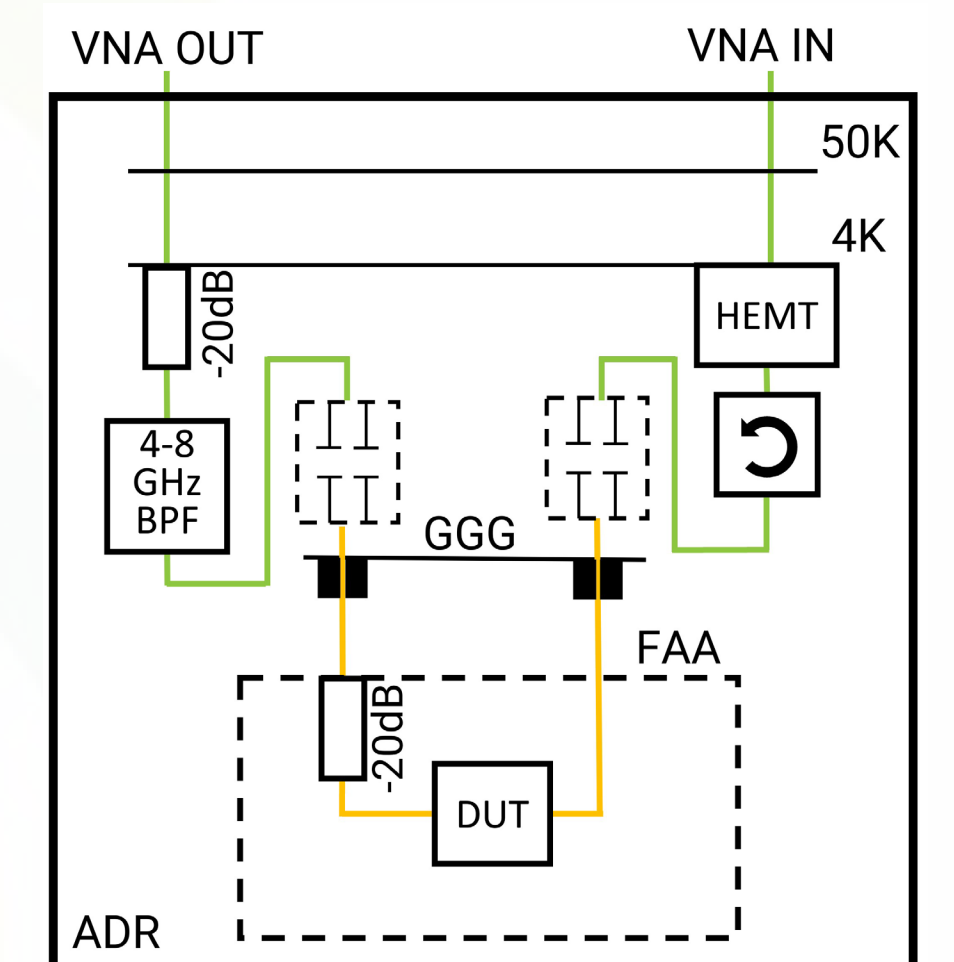
- Sensitive to magnetic fields and radiation
- Impacts quality factors of resonators



Image of ADR cryostat with magnetic shielding attached

MEASUREMENT SETUP

- Niobium resonators coupled to stripline
- Bandpass filter, isolator and amplifier for signal quality
- Attenuators on input RF line for thermalization
- Inner/outer DC blocks for touch sensing
- CuNi coaxes until DC block, NbTi afterwards



Cryogenic microwave setup for resonator measurements

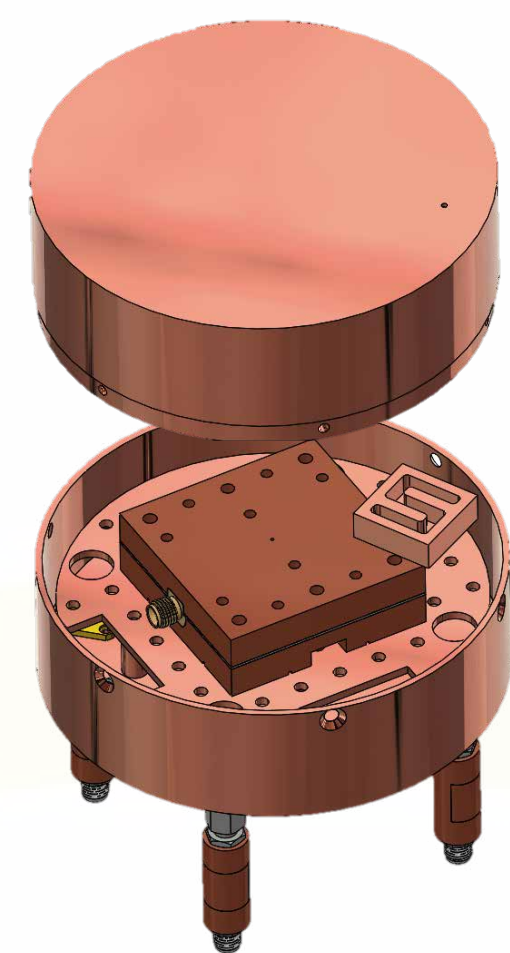
SHIELD DESIGN

μ -metal and Niobium^[1]

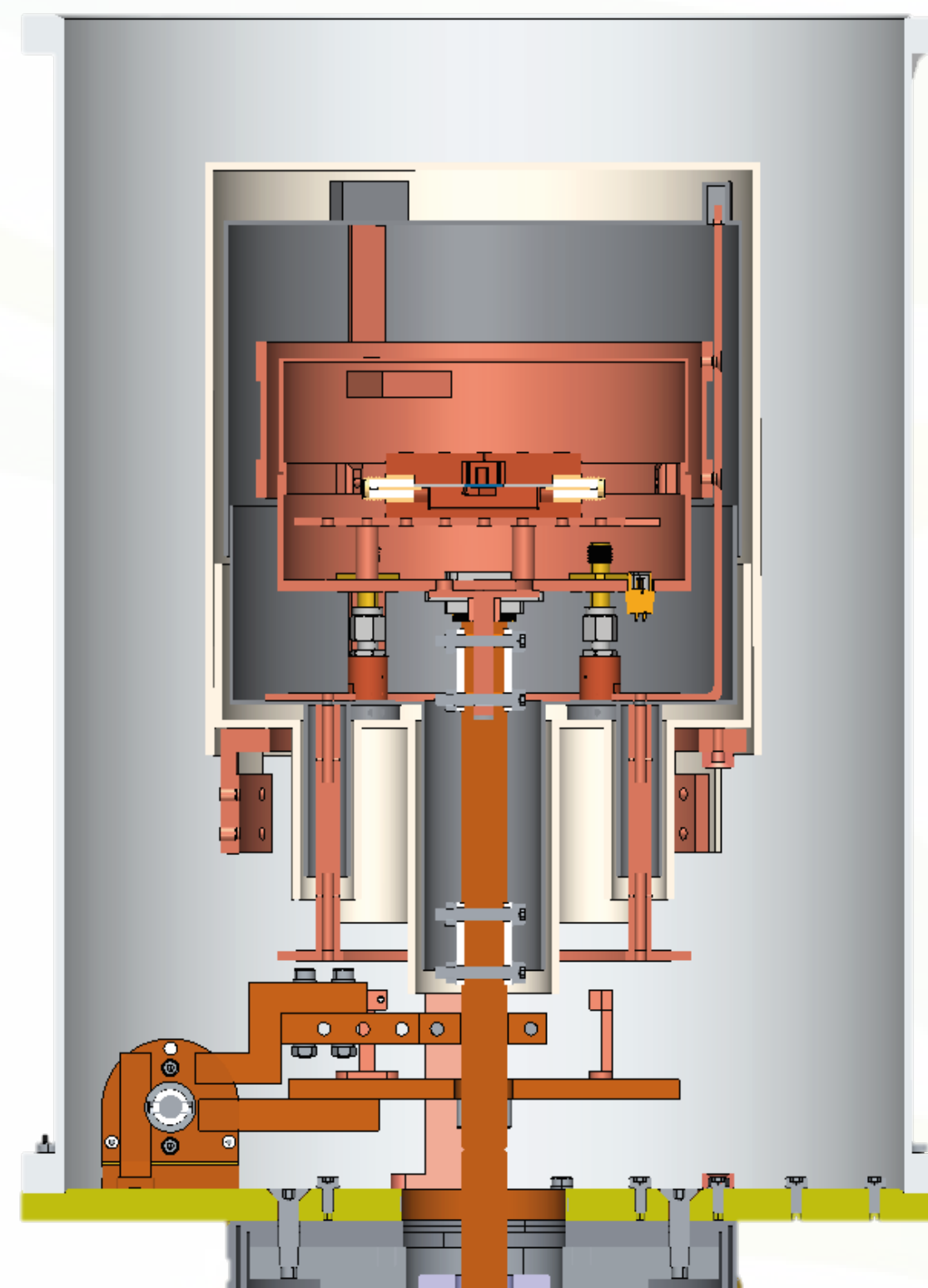
- Coupled to 4K stage (PT cooled)
- Feedthrough for 4 RF lines & 48 DC lines
- μ -metal mounted with leaf springs
- Nb shield separately operable

Radiation shield^[2]

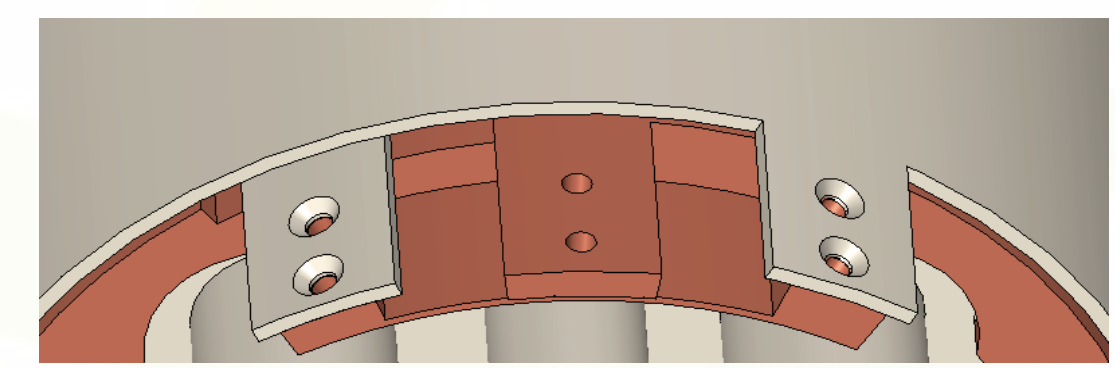
- Coupled to lowest T salt pill stage
- Light-tight connectors
- Coating to absorb entering photons



Opened radiation shield with resonator box attached



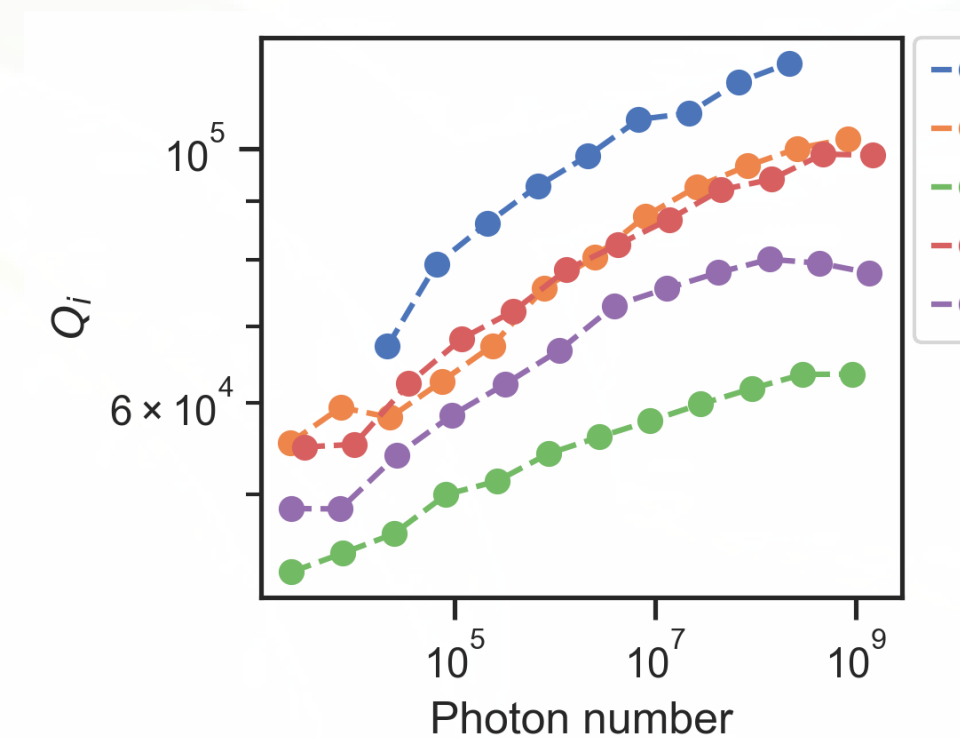
Schematic cross-section of mounted shields



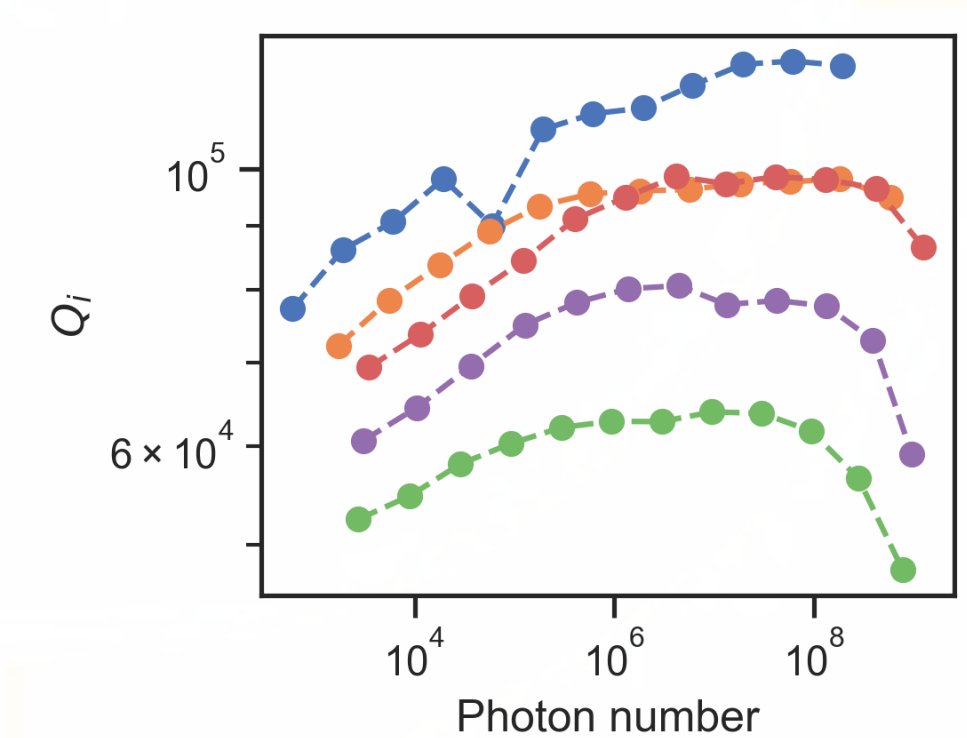
Strain mitigating mouning solution for μ -metal shield

MEASUREMENT RESULTS

- Measure transmission through stripline
- Fit response to^[3] $S_{21}^{-1} = 1 + \frac{Q_i}{Q_c} e^{i\Phi} \frac{1}{1 + i2Q_i\delta x}$
- Extract photon number, internal and coupling quality factor
- **ADR performs as good as dilution refrigerator**

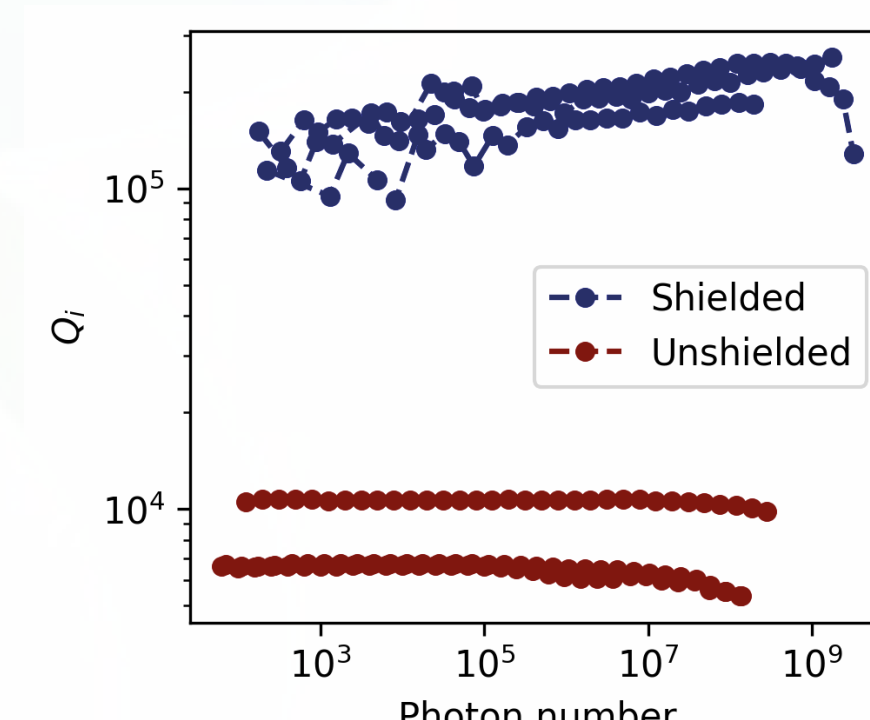


Internal quality factor of sample 1 resonators in dilution refrigerator

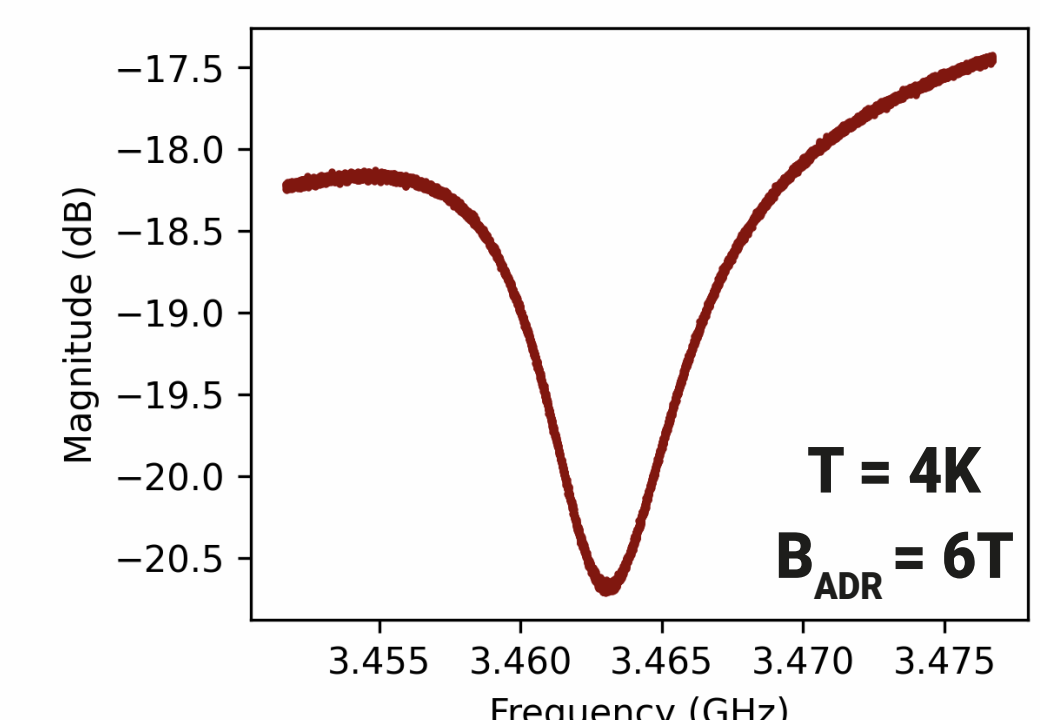


Internal quality factor of sample 1 resonators in ADR

- **Q_i one order of magnitude larger with shields**



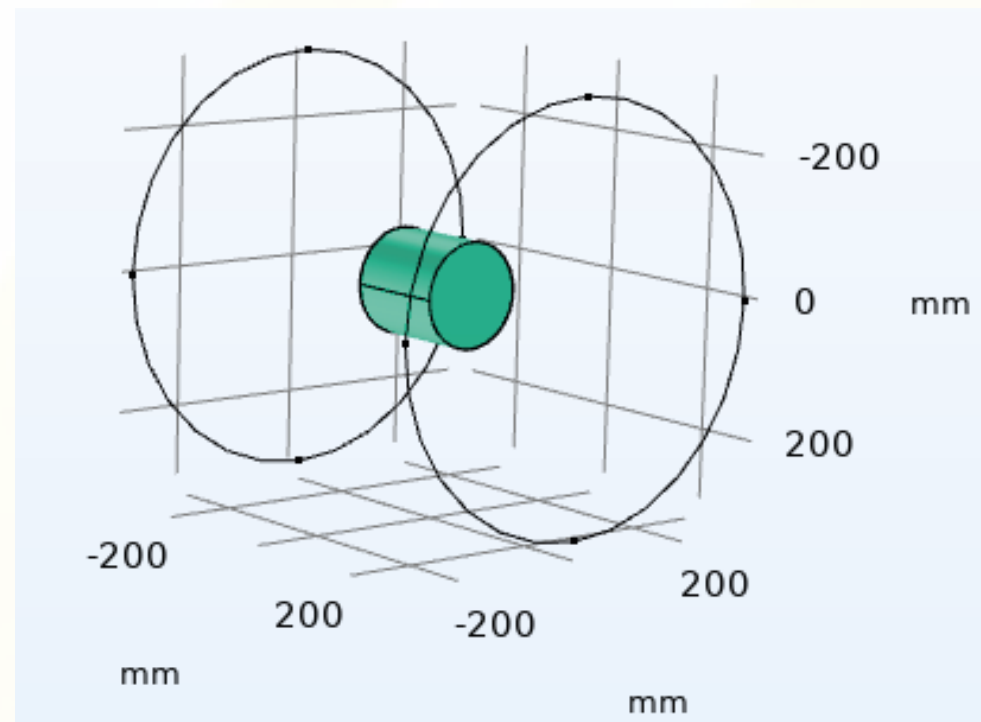
Comparison of internal quality factors with and without magnet shields (sample 2)



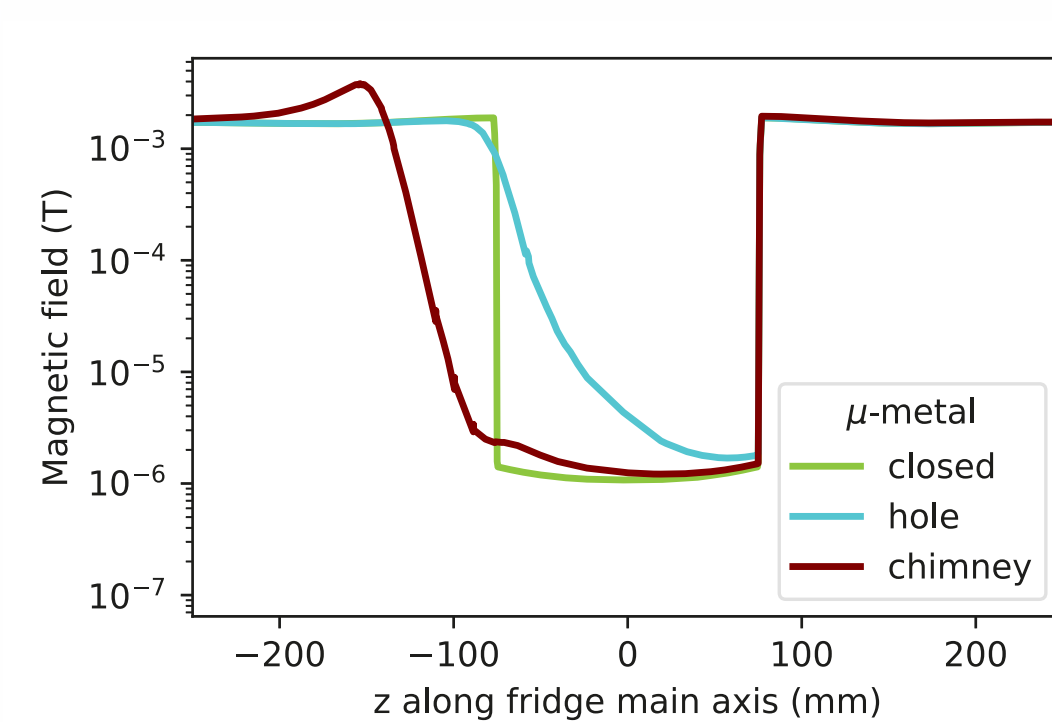
Resonator dip at maximum ADR field and pulse tube base temperature (4K) (sample 2)

SIMULATION

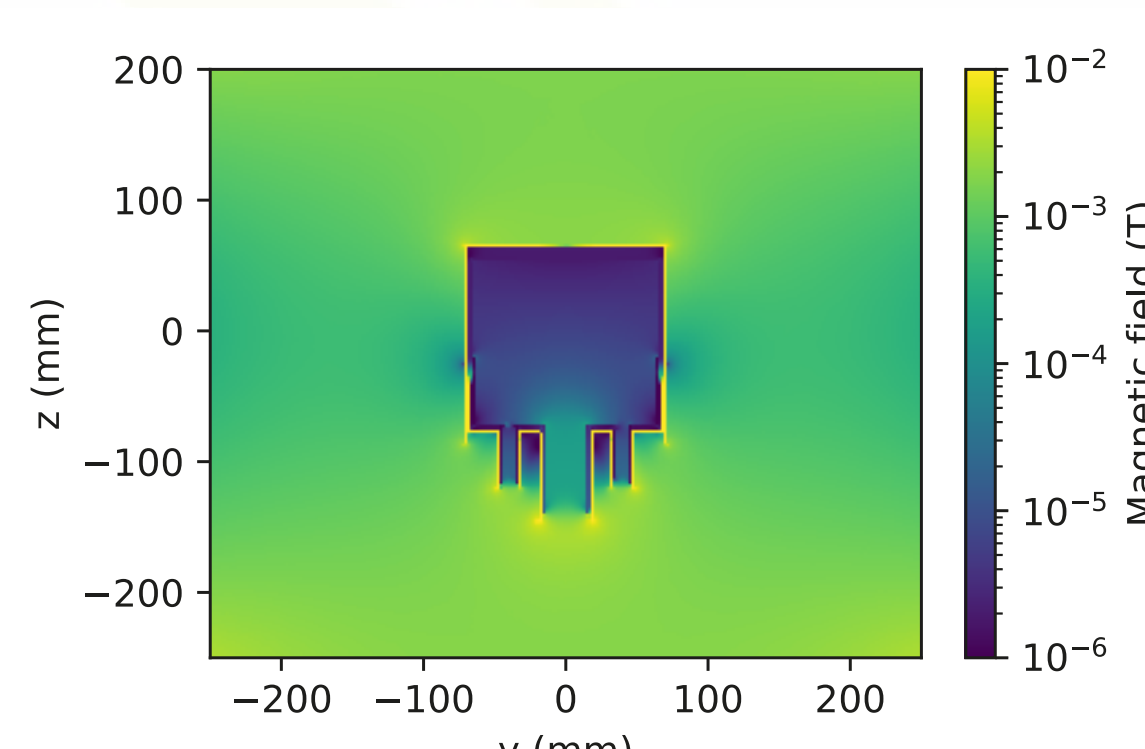
- Magnetic shielding factor B_{res}/B_0 simulated in Comsol Multiphysics
- Helmholtz pair generating typical residual field of PID temperature sweep $B_0 > 1\text{mT}$
- μ -metal simulated as nonlinear magnetic material, Nb with small μ_r
- **Shielding factor >100 at sample achievable**



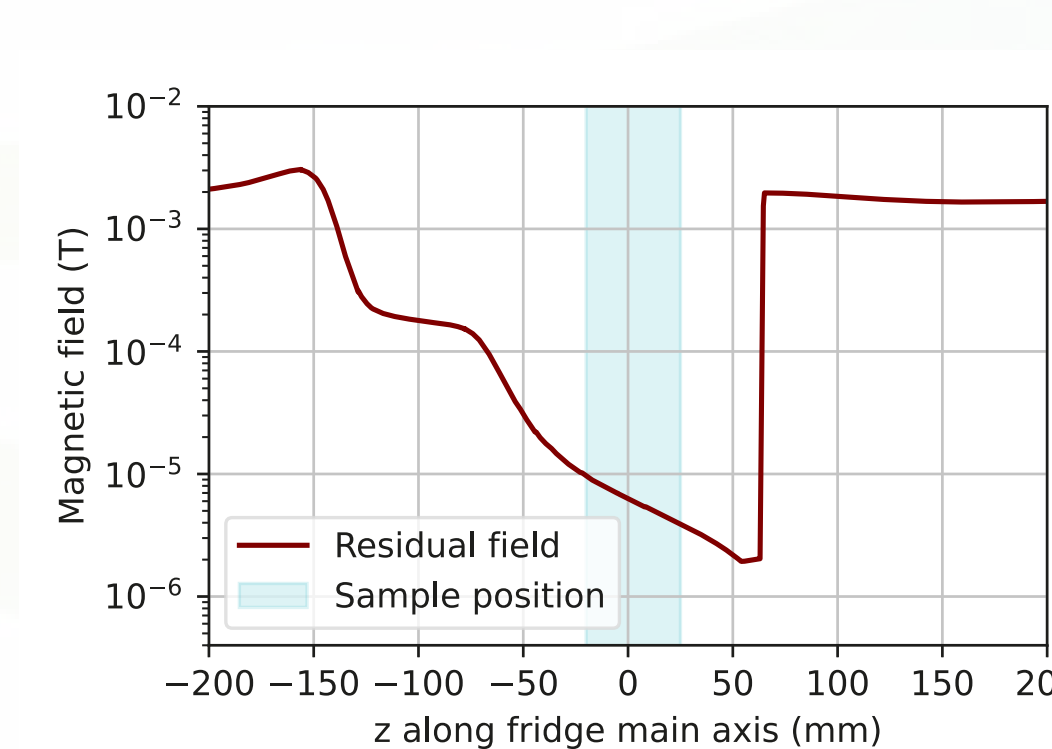
Simulation model: Helmholtz coils with centered shield



Simulation of chimney vs hole as feedthrough



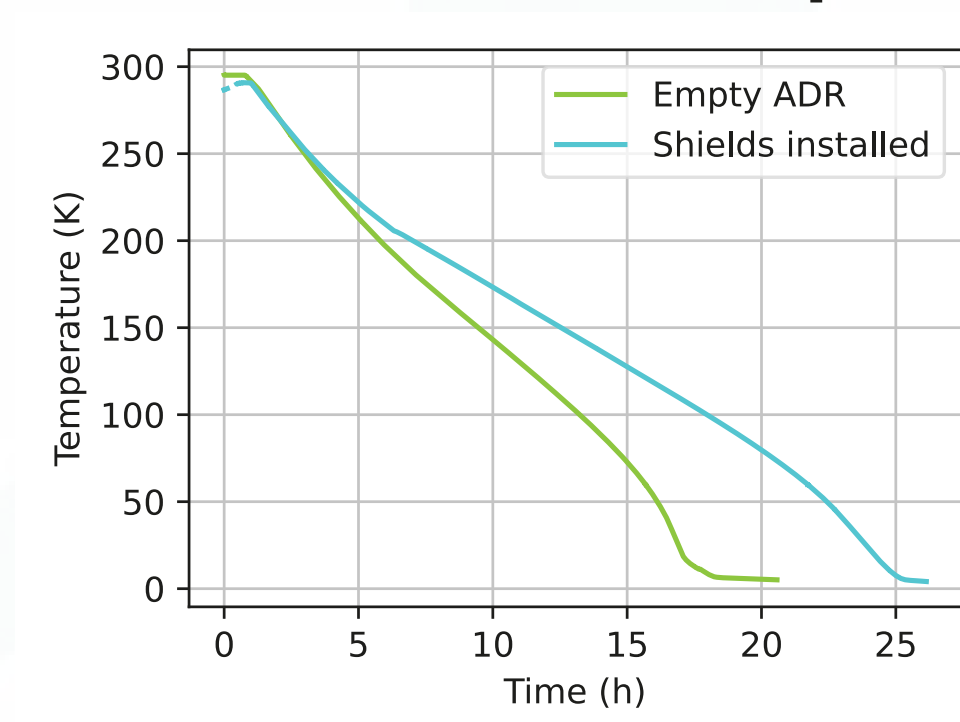
Simulation of Nb ($\mu_r=10^{-3}$) and μ -metal shielding



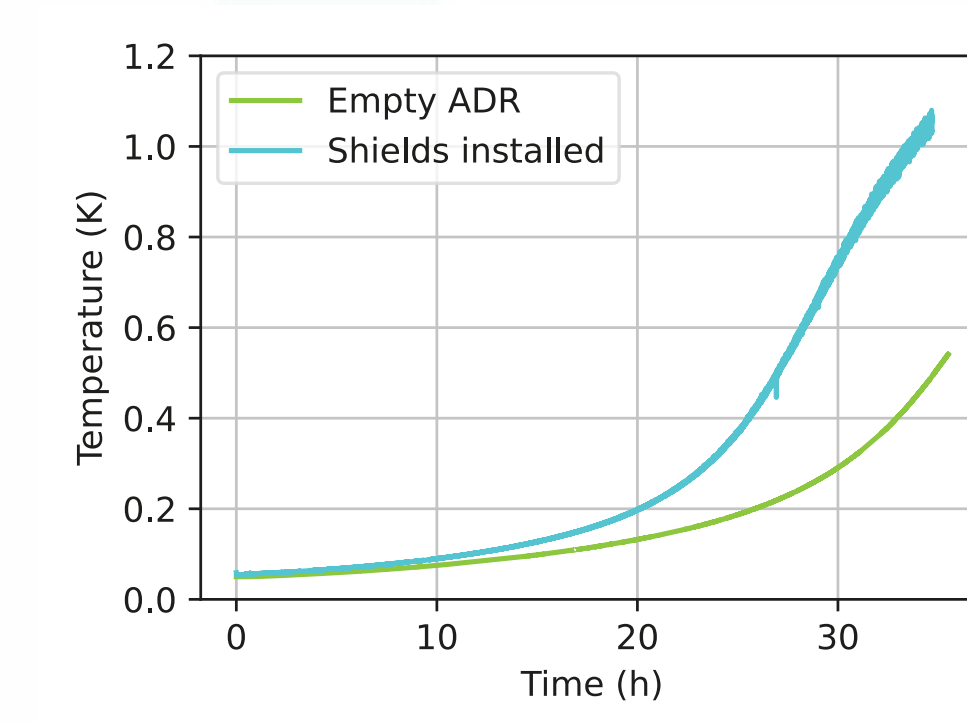
Linecut through middle chimney of full simulation Sample position indicated

THERMAL BENCHMARKING

- Total cooldown time increases from 18h to 26h
- ~6kg added with low thermal conductivity materials
- Thermalization of shields after recharging works
- **Reaches same base temperature**



Cooldown from room temperature to 4K



Cooldown to base temperature with ADR stage

OUTLOOK AND REFERENCES

- Magnet inside shields for co-integration of supeconducting circuits and spin qubits
- Quantification of shielding properties by sensitive Hall probe and SQUIDS
- Low I_c Josephson junctions for material optimization

- [1] Bergen, A. et al., Rev. Sci. Instrum. 87, 105109 (2016)
[2] Barends, R. et al., Appl. Phys. Lett. 99, 113507 (2011)
[3] Megrant, A. et al., Appl. Phys. Lett. 100, 113510 (2012)