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Quantifying trapped magnetic vortex losses in *niobium resonators at mK temperatures*

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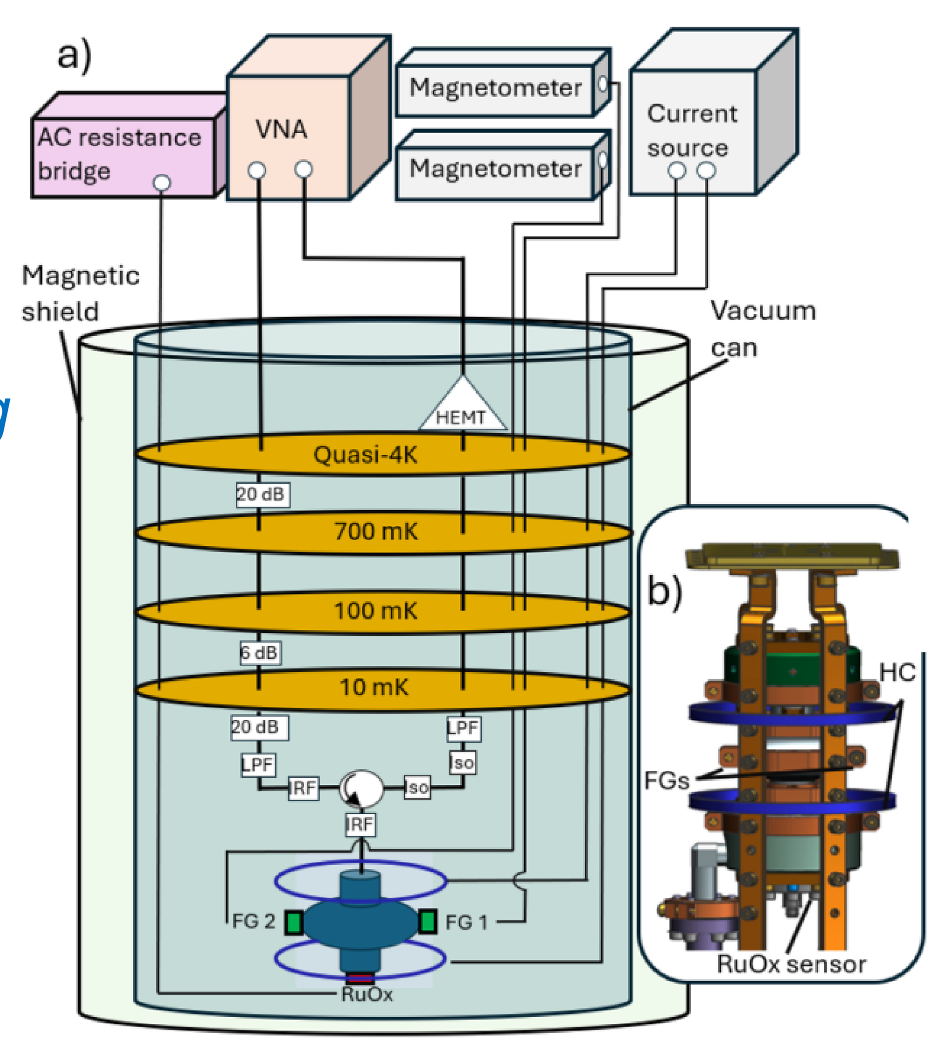
Abstract

Trapped magnetic vortices in niobium introduce microwave losses that degrade the performance of superconducting resonators. While such losses have been extensively studied above 1 K, *we report here their direct quantification in the millikelvin and low-photon regime relevant to quantum devices*. Using a high-quality factor 3D niobium cavity cooled through its superconducting transition in controlled magnetic fields, we *isolate vortex-induced losses* and find the resistive component of the sensitivity to trapped flux S to be approximately *2 nOhm/mG at 10 mK and 6 GHz*. The decay rate is initially dominated by two-level system (TLS) losses from the native niobium pentoxide, with vortex-induced degradation of T_1 occurring above B_{trap}~50 mG. In the absence of the oxide, even 10 mG of trapped flux limits performance, Q0 ~ 10^{10}, or T_1 ~350 ms, *underscoring the need for stringent magnetic shielding*. *The resistive sensitivity, S, decreases with temperature* and remains largely field-independent, *whereas the reactive component, S', exhibits a maximum near 0.8 K*. These behaviors are well modeled within the *Coffey–Clem framework* in the zero-creep limit, under the assumption that *vortex pinning is enhanced by thermally activated processes*. Our results suggest that niobium-based transmon *qubits can tolerate vortex-induced dissipation at trapped field levels up to several hundred mG*, but achieving long coherence times still requires careful magnetic shielding to suppress lower-field losses from other mechanisms

Experimental Method

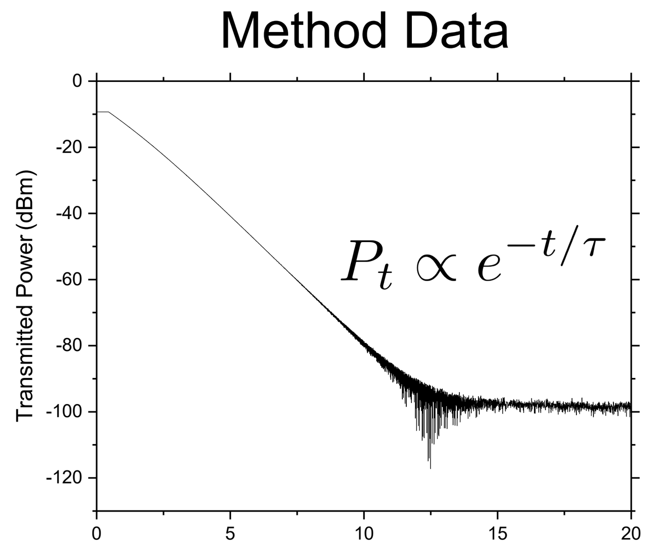
A 6 GHz bulk Nb cavity was repeatedly tested in a DR after cooling down in distinct applied magnetic fields using Helmholtz coils, *thus trapping various levels of magnetic vortices in the cavity walls*.



Cool Down Parameters

CD#	Current (mA)	B_{NC} (mG)	B_{SC} (mG)	B_{SC}/B_{NC}
1	3.45	0.0 ± 5.2	-0.1 ± 6.4	···
2	20.25	50.4 ± 7.5	51.3 ± 7.7	1.02 ± 0.22
3	37.20	100.9 ± 9.0	102.5 ± 9.3	1.02 ± 0.13
4	87.46	250.5 ± 13.3	254.8 ± 13.7	1.02 ± 0.08

Sample Ring-down Method Data



$$Q_L(t) = \omega\tau$$

$$\frac{1}{Q_0} = \frac{1}{Q_L} - \frac{1}{Q_1}$$

Extracted flux driven losses using "Sensitivity to trapped flux"

→ Resistance introduced per unit of trapped magnetic flux

Resistive Sensitivity to Trapped Flux

$$S = \frac{R_{\mathrm{Fl}}}{B_{\mathrm{trap}}} = \frac{G}{B_{\mathrm{trap}}}\left(\frac{1}{Q_{0,n}} - \frac{1}{Q_{0,1}}\right)$$

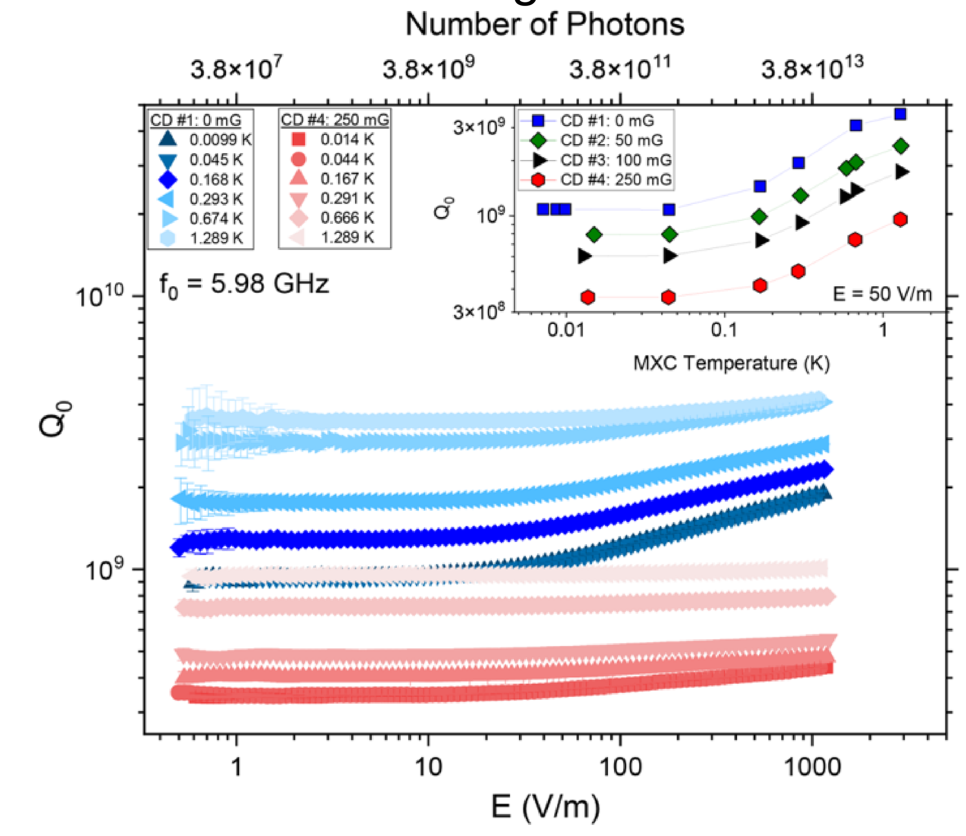
Reactive Sensitivity to Trapped Flux

$$S' = \frac{\Delta X_{\mathrm{Fl}}}{B_{\mathrm{trap}}} = -\frac{2G}{B_{\mathrm{trap}}}\left(\frac{f_{0,n} - f_{0,1}}{f_{0,1}(0)}\right)$$

Raw Cavity RF Data

Trapping *greater levels of magnetic* field in cavity walls drives *greater dissipation* as a function of temperature and field

Cavity Data Post Cooling in Various Magnetic Fields

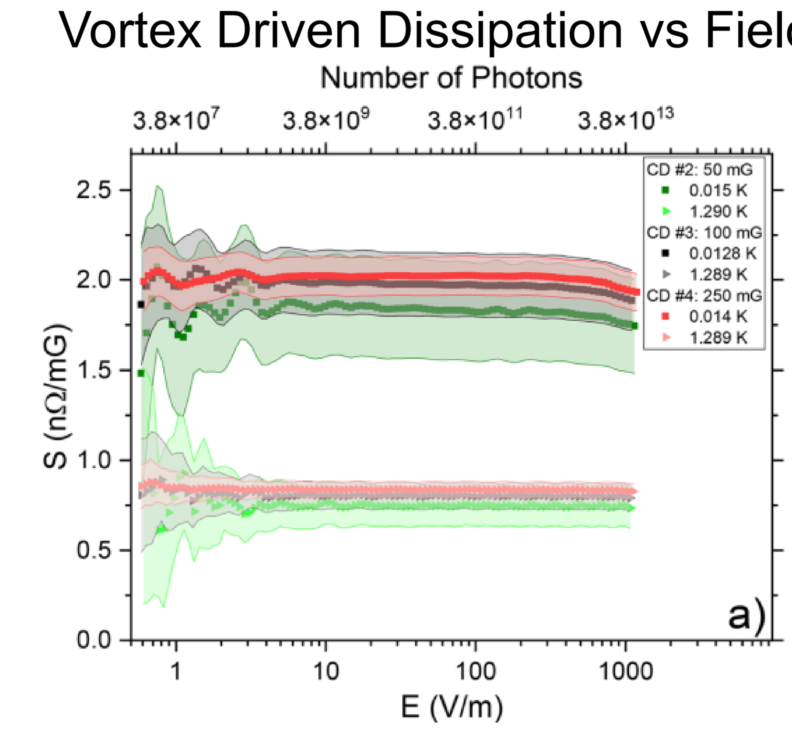


Extracting Vortex Driven Dissipation

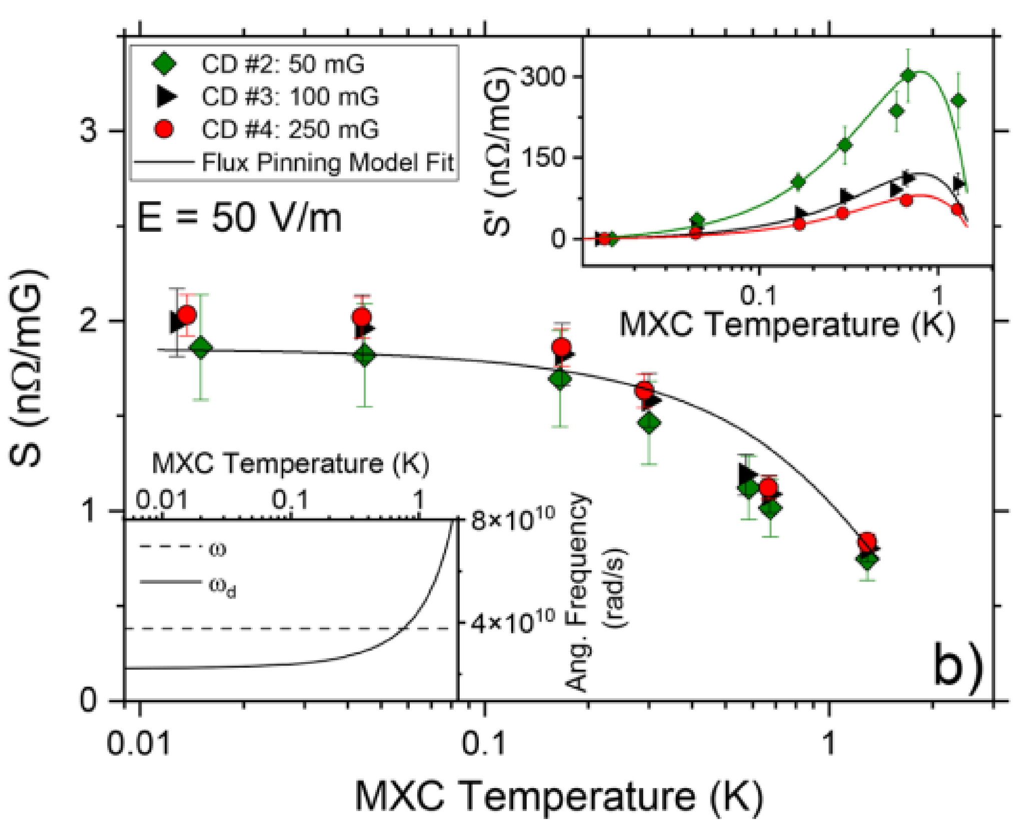
Vortex driven dissipation remains constant as a function of *electric field*

→ Linear response

Vortex Driven Dissipation vs Field



Vortex Driven Dissipation vs Temperature



- *Resistive dissipation decreases* with *increasing temperature*
- Reactive dissipation shows *Nonmonotonic behavior*
- Modeled by Coffey-Clem formalism with a temperature *activated pinning strength → hydrides!*

$$\frac{Z_{\mathrm{Fl}}(T)}{B_{\mathrm{trap}}} = S + \mathrm{i}S' = \frac{\rho_n}{2\lambda_s(T)B_{c2}(T)}\,\frac{\omega^2 + \mathrm{i}F\omega\omega_d(T)}{\omega^2 + \omega_d^2(T)} \qquad \omega_d(T) = \omega_0 e^{\alpha T}$$

Implications on Cavity T_1

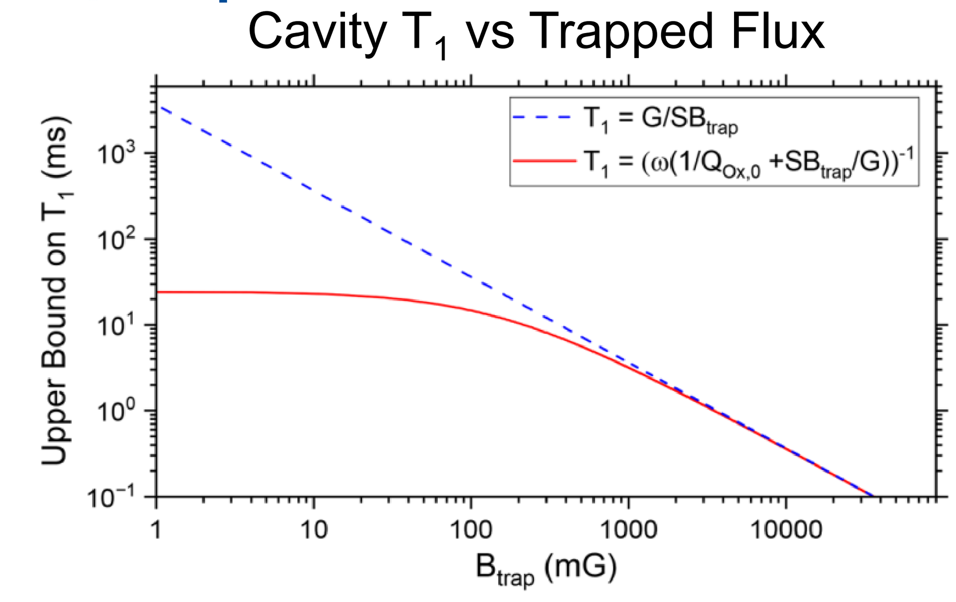
In presence of Nb_2O_5:

- T_{trap} > 50 mG affects T_1

W/o Nb_2O_5

- T_{trap} ~ 50 mG limits T_1 ~ 350 ms

Cavity T_1 vs Trapped Flux



Conclusions

Trapped vortices in Nb create measurable loss at millikelvin temperatures, with resistive sensitivity around 2 nΩ/mG. They remain tolerable up to a few hundred mG, but long coherence times still require strong magnetic shielding.

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