FERMILAB-SLIDES-25-0037-SQMS

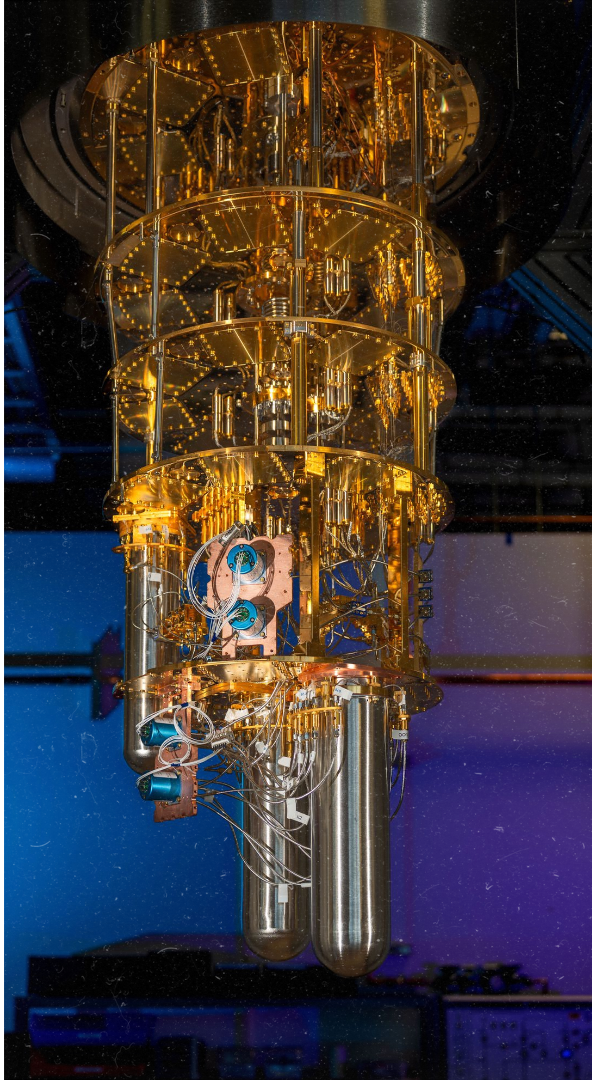
Characterizing Microwave Losses in Superconducting Coaxial Cables for Quantum Systems

Global Physics Summit, 2025

MAR-N18.13

André Vallières, Sergey Kazakov, Timergali Khabiboulline, Jae-Yel Lee, Akshay Murthy, Roman M. Pilipenko, Oleg V. Pronitchev, Vyacheslav P. Yakovlev, Anna Grassellino, Jens Koch, Yao Lu

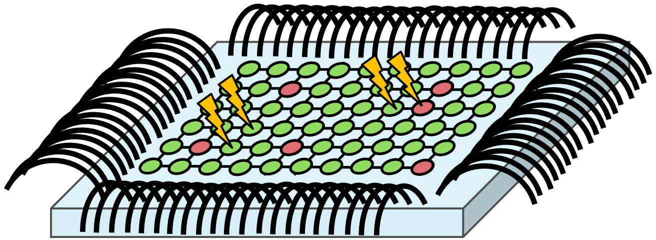
This document was prepared by the SQMS Collaboration using the resources of the Fermi National Accelerator Laboratory (Fermilab), a U.S. Department of Energy, Office of Science, Office of High Energy Physics HEP User Facility. Fermilab is managed by FermiForward Discovery Group, LLC, acting under Contract No. 89243024CSC000002.



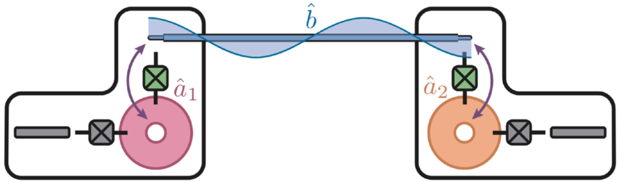
Why?

As quantum systems become larger, we encounter:

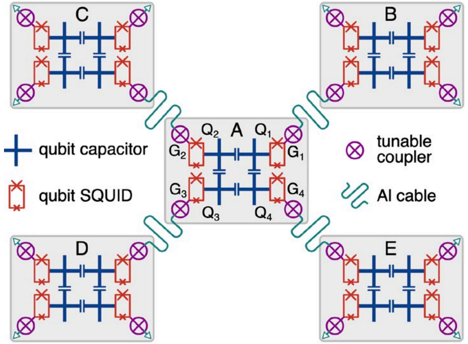
- Increased crosstalk
- Fabrication yield challenges
- Wiring complexity
- …



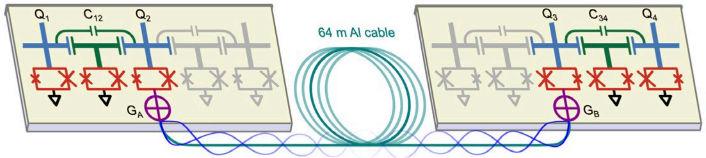
Modularity is a natural solution to tackle some of these issues



Burkhart, L. D. et al. *PRX Quantum* **2**, 030321 (2021)



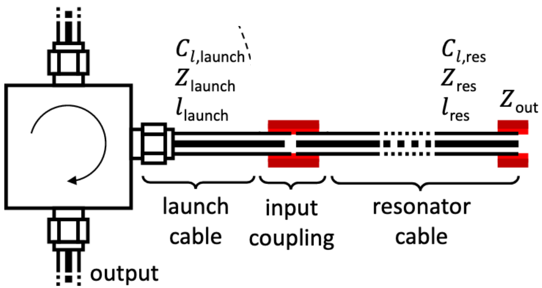
Niu, J. et al. *Nat Electron* **6**, 235–241 (2023)



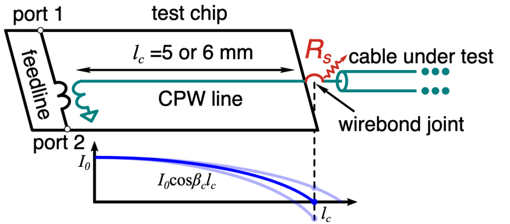
Qiu, J. et al. *Science Bulletin* **70**, 351–358 (2025)

Previous works on characterizing cables

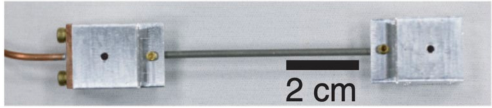
Kurpiers, P. et al. *EPJ Quantum Technol.* **4**, 8 (2017)



Martin, Y. et al. arXiv/2409.04634 (2024)



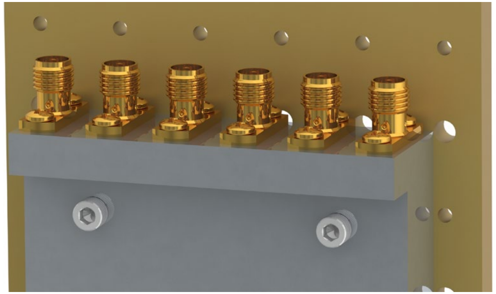
Niu, J. et al. Nat Electron **6**, 235–241 (2023)



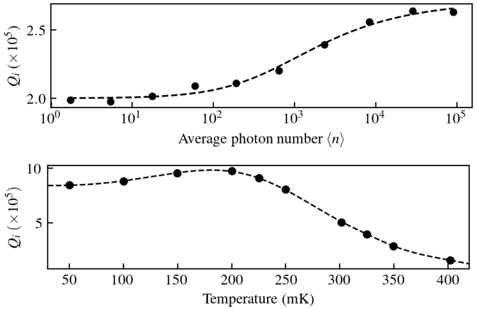
Burkhart, L. D. et al. PRX Quantum **2**, 030321 (2021)

In this talk

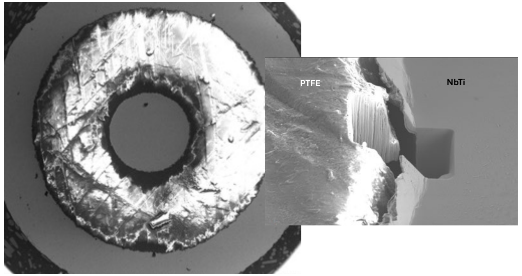
Measurement setup



TLS/QP

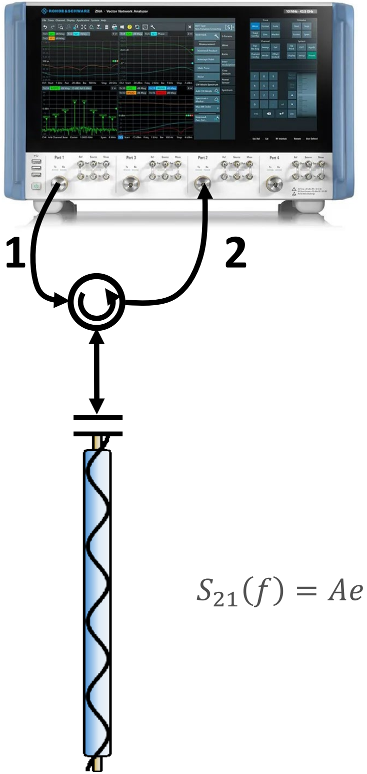


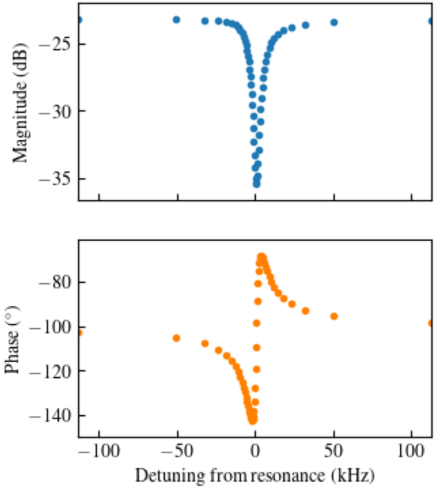
Materials



Cryogenic microwave measurements setup

Internal quality factor extraction

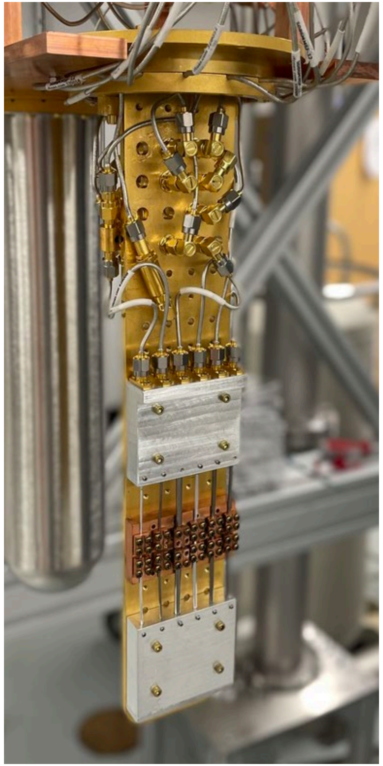


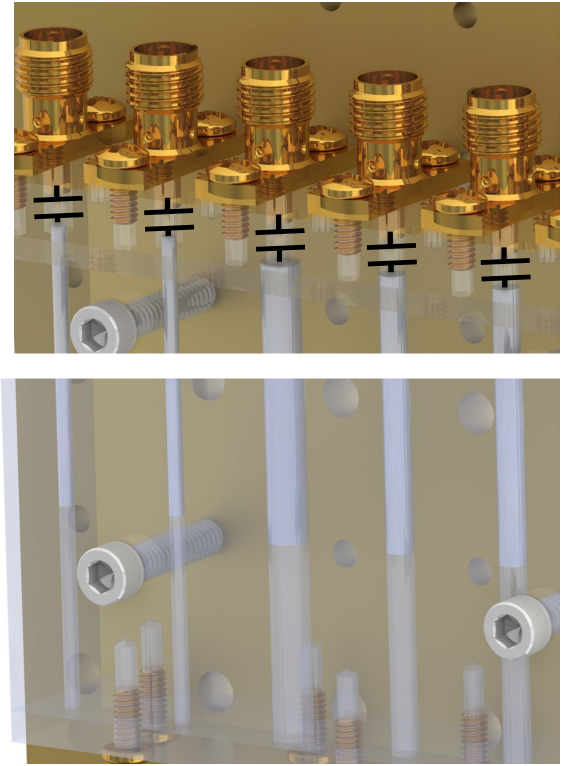


$$S_{21}(f) = Ae^{-i2\pi f\tau}\left(1 - \frac{2Q/|Q_c|e^{i\phi}}{1 + 2iQ(f/f_r - 1)}\right)$$

$$\frac{1}{\boldsymbol{Q_i}} = \frac{1}{Q} - \frac{\cos\phi}{|Q_c|}$$

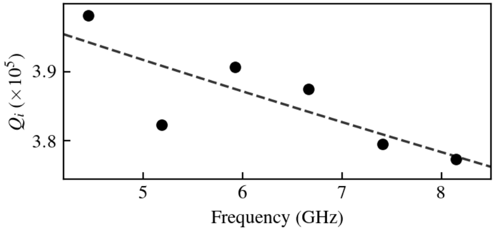
Experimental setup





Quality factor dependence on frequency, power, and temperature

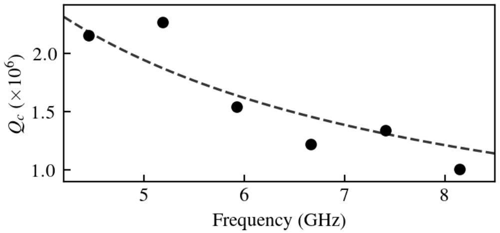
Frequency



Conductor loss

$$\frac{1}{Q_i} = \frac{g_c}{2\pi\mu_0}\frac{R_s(f_n)}{f_n} + \tan\delta$$

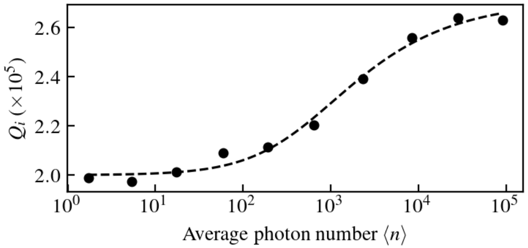
Dielectric loss



$$Q_c = \frac{C_\ell \ell}{2\pi f_n C_c^2 Z_0} + Z_0 C_\ell \ell 2\pi f_n$$

Coupling capacitance

Power

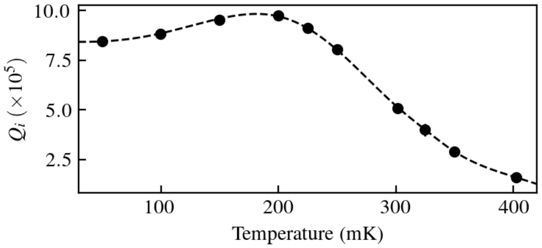


$$\frac{1}{Q_i} = F\delta^0_{\mathrm{TLS}} \frac{\tanh\left(\frac{\hbar\omega}{2k_BT}\right)}{\left(1+\frac{\langle n\rangle}{n_c}\right)^{\beta}} + \delta_{\mathrm{PI}}$$

Two-level systems loss

BUT in practice, not all cables show this behavior

Temperature



$$\frac{1}{Q_\mathrm{i}} = F\delta^0_{\mathrm{TLS}} \frac{\tanh\left(\frac{\hbar\omega}{2k_BT}\right)}{\sqrt{1+\left(\frac{\langle n\rangle^{\beta_2}}{TD^{\beta_1}}\right)\tanh\left(\frac{\hbar\omega}{2k_BT}\right)}} + \delta^0_{\mathrm{QP}} \frac{\sinh\left(\frac{\hbar\omega}{2k_BT}\right)K_0\left(\frac{\hbar\omega}{2k_BT}\right)}{e^{\Delta_0/k_BT}} + \delta_{\mathrm{other}}$$

Quasi-particles loss

Kurpiers, P. et al. *EPJ Quantum Technol.* **4**, 8 (2017)
McRae, C. R. H. et al. *Review of Scientific Instruments* **91**, 091101 (2020)
Crowley, K. D. et al. *Phys. Rev. X* **13**, 041005 (2023)

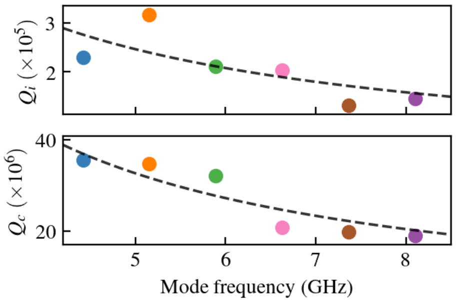
Preliminary results

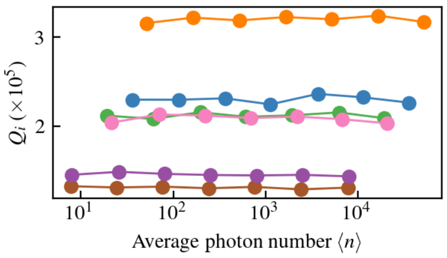
Cable	ϵ_r	$\tan\delta\ (\times 10^{-6})$	R_s (μΩ)	$\delta^0_{QP}\ (\times 10^{-4})$
Keycom (2.2 mm)				
Keycom (1.2 mm)				
Hermerc (2.05 mm)				
Hermerc (1.2 mm)				
CryoCoax (2.2 mm)				

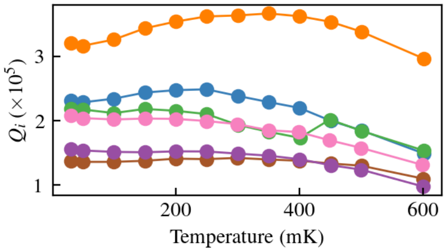
@ 5 GHz

Preliminary results

KEYCOM Characteristic Technologies



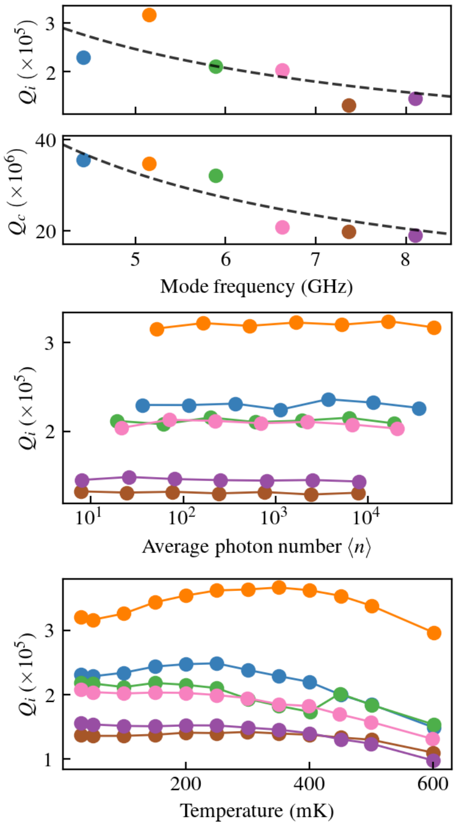




Cable	ϵ_r	$\tan\delta$ ($\times 10^{-6}$)	R_s ($\mu\Omega$)	δ^0_{QP} ($\times 10^{-4}$)
Keycom (2.2 mm)	1.84	2.4	1.3	1.5
Keycom (1.2 mm)				
Hermerc (2.05 mm)				
Hermerc (1.2 mm)				
CryoCoax (2.2 mm)				

@ 5 GHz

Preliminary results

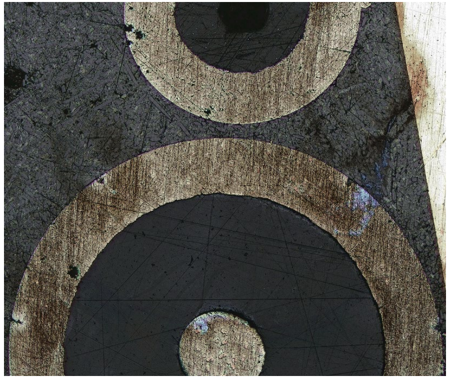


Cable	ϵ_r	$\tan\delta$ $(\times 10^{-6})$	R_s (μΩ)	δ^0_{QP} $(\times 10^{-4})$
Keycom (2.2 mm)	1.84	2.4	1.3	1.5
Keycom (1.2 mm)	2.02	3.1	3.2	0.6
Hermerc (2.05 mm)	1.56	0.1	4.9	0.2
Hermerc (1.2 mm)	1.86	0.8	1.1	22.8
CryoCoax (2.2 mm)	1.81	1.6	0.6	0.2

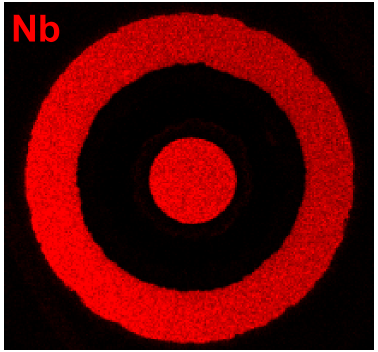
@ 5 GHz

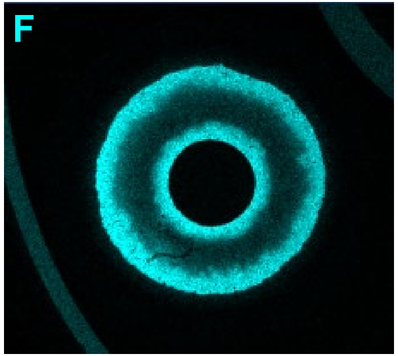
Materials characterization

Structure



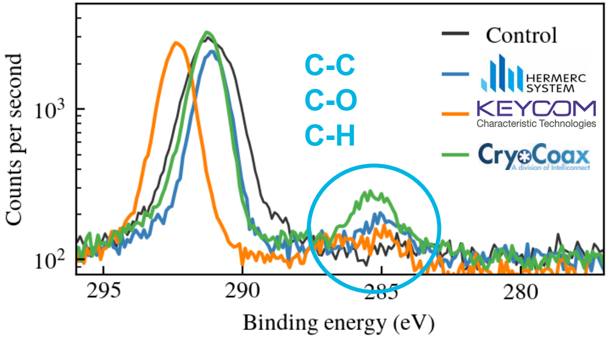
Optical microscopy



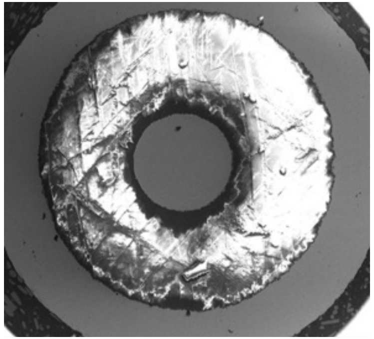


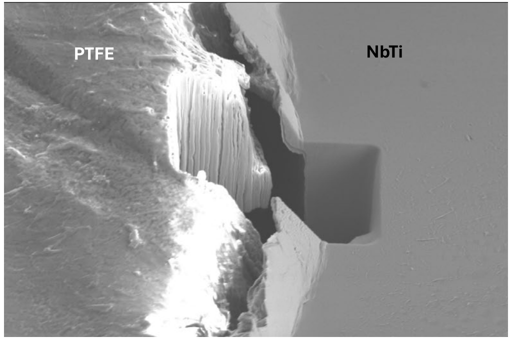
Energy-dispersive x-ray spectroscopy

Chemistry



X-ray photoelectron spectroscopy





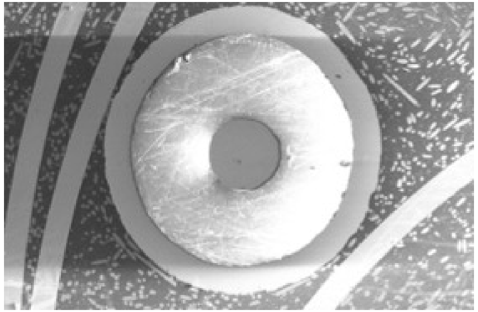
Scanning electron microscopy

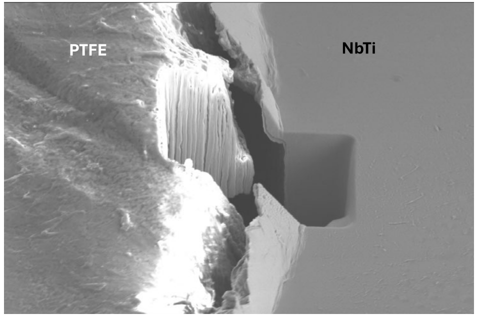
Coming up

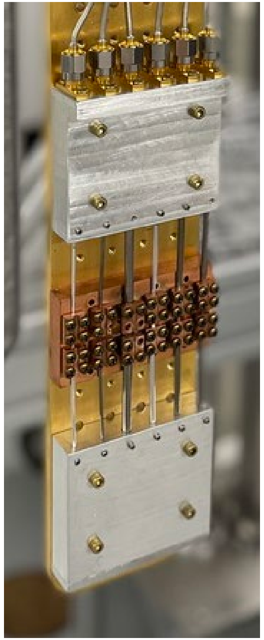
- Materials characterization at cryogenic temperatures
- Time of flight - secondary ion mass spectrometry
- Mechanical property testing
- Porosity measurements
- Low temperature DC measurements

Where to go from here?

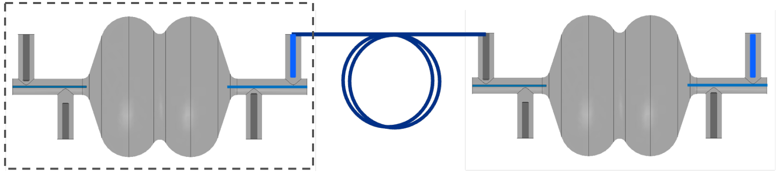
- Continue probing relation between microwave losses and materials characteristics







- Develop high-Q superconducting coaxial cable
- Use it in upcoming 2D and 3D interconnect experiments



See MAR-Q33.2 and MAR-Q33.3 tomorrow!