

Axion Search with HAYSTAC Phase III Multi-Rod Cavity Upgrade

Claire Laffan (Yale University)

CPAD Workshop

October 8th, 2025

HAYSTAC is a collaboration between...

Yale
(host)

**University
of California
Berkeley**



Located at...

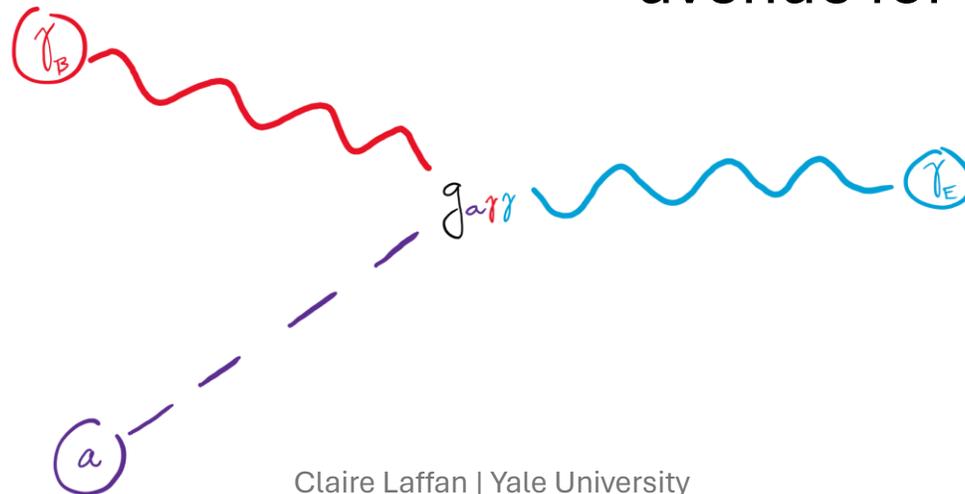


Axions as Dark Matter

- Originally proposed axion field as solution to strong CP problem
- Later found that axions are also dark matter candidates
- One of the lightest DM candidates, making direct detection challenging

Inverse Primakoff Effect: Mixing between axion field & B-field induces E-field of frequency ν_a

- $\nu_a \propto m_a$
- Coupling strength = $g_{a\gamma\gamma}$
- m_a & $g_{a\gamma\gamma}$ both unknown
- This interaction is a promising avenue for detection



HAYSTAC: Past, Present & Future

A Brief History of HAYSTAC

(Haloscope At Yale Sensitive To Axion CDM)

Phase I (PI):

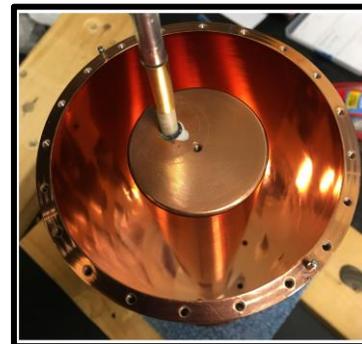
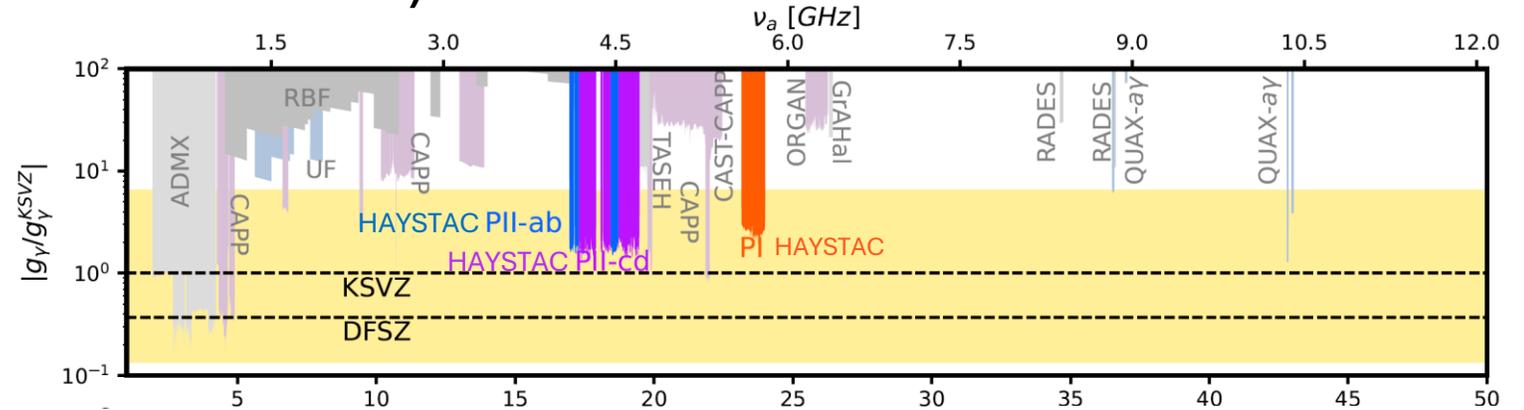
- Jan. 2016 – Jul. 2017
- 23.15-24.00 μeV (5.6-5.8 GHz)
- 1 JPA

Phase II-ab & Phase II-cd (PII):

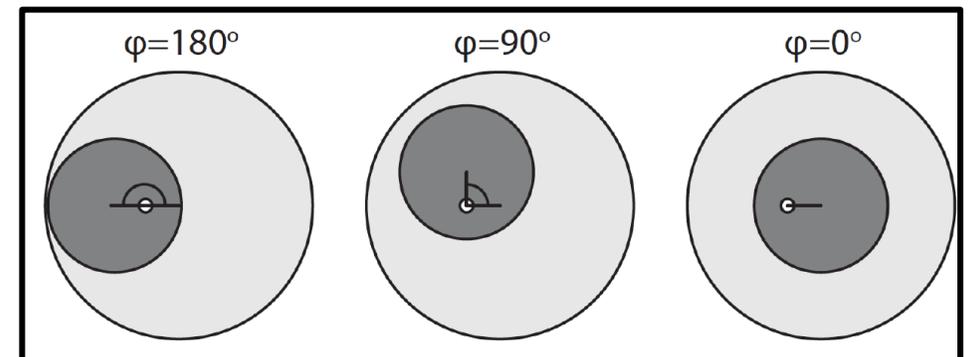
- Sep. 2019 – Aug. 2024
- 16.96 – 19.46 μeV (4.1 – 4.7 GHz)
- Quantum squeezing with 2 JPAs

Cavity:

- Cu-plated stainless steel
- Unfilled $V_c = 1.545$ L
- 1 tuning rod



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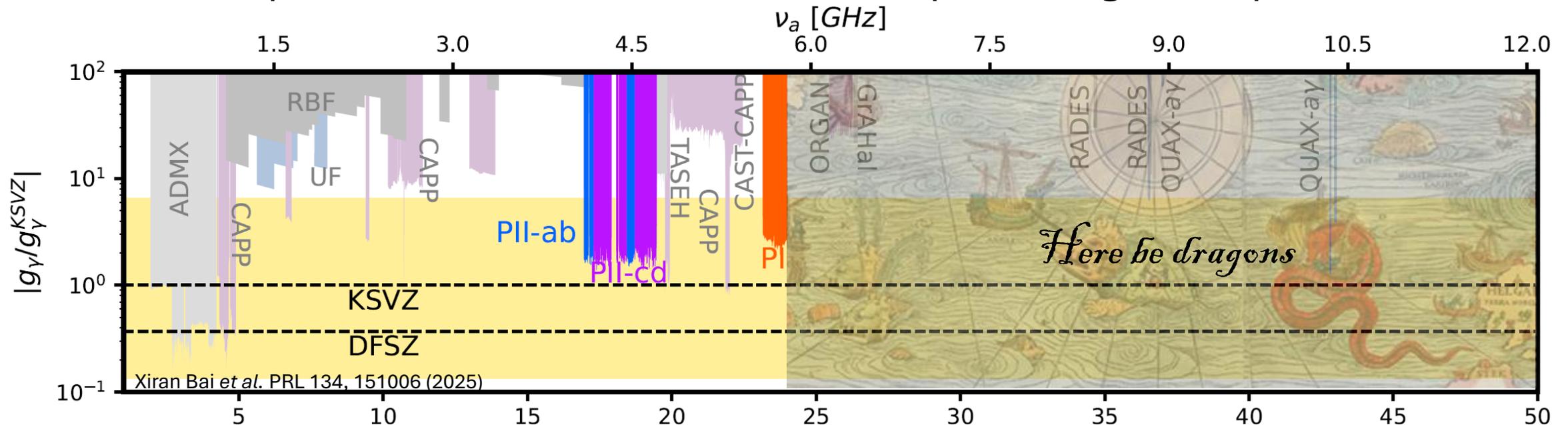
Top: Xiran Bai *et al.* PRL 134, 151006 (2025)

Bottom left: M. Simanovskaia. Ph.D. thesis, UC, Berkeley (2019)

Bottom right: K. M. Backes. PhD thesis, Yale University (2021)

Onto Higher Frequencies

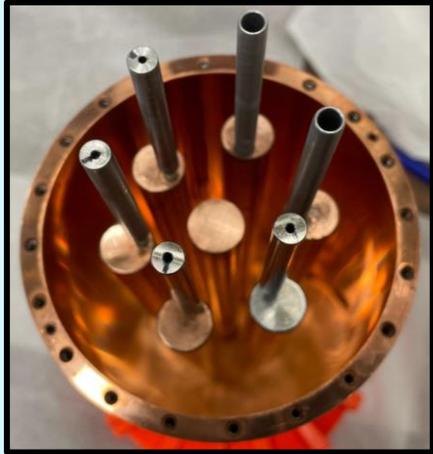
- Post-inflation axion models motivate high masses
- Cavity frequency scales inversely with volume: $V_c \propto \nu_c^{-3}$
- Higher mass axion searches necessitate smaller cavities which have...
 - Degraded signal power
 - Higher intruder mode density
- Electronic losses also increase with frequency
- HAYSTAC plans to address these issues as we pursue higher frequencies



Xiran Bai et al. PRL 134, 151006 (2025)

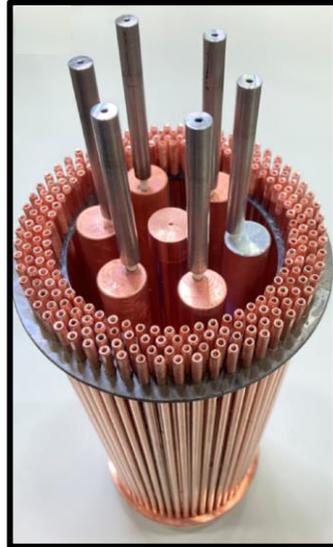
HAYSTAC: Onto Higher Frequencies

PIIIa: 7-Rod Cavity



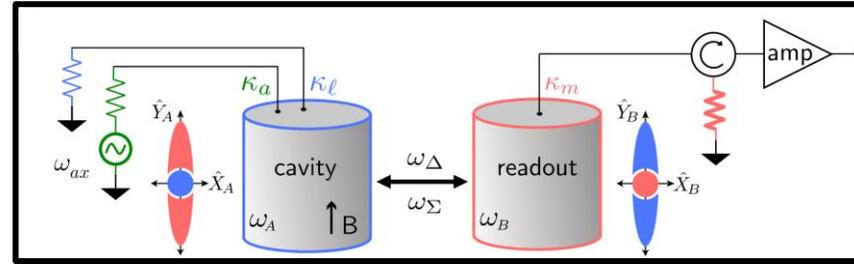
- 7 tuning rods
- 5.5 – 7.3 GHz
(22.75 – 30.19 μeV)

PIIIb: 7-Rod + PBG



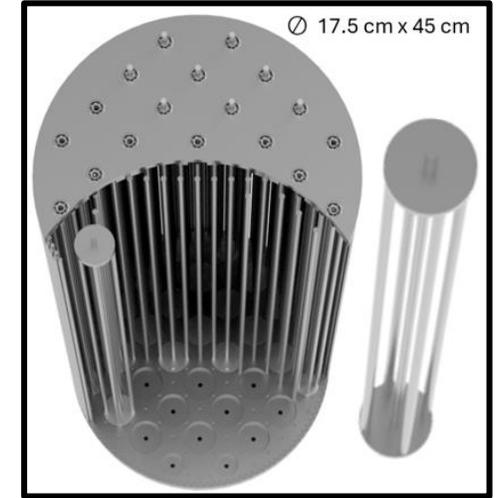
Rev.Sci.Instrum. **96** 094704 (2025)

PIV: CEASEFIRE

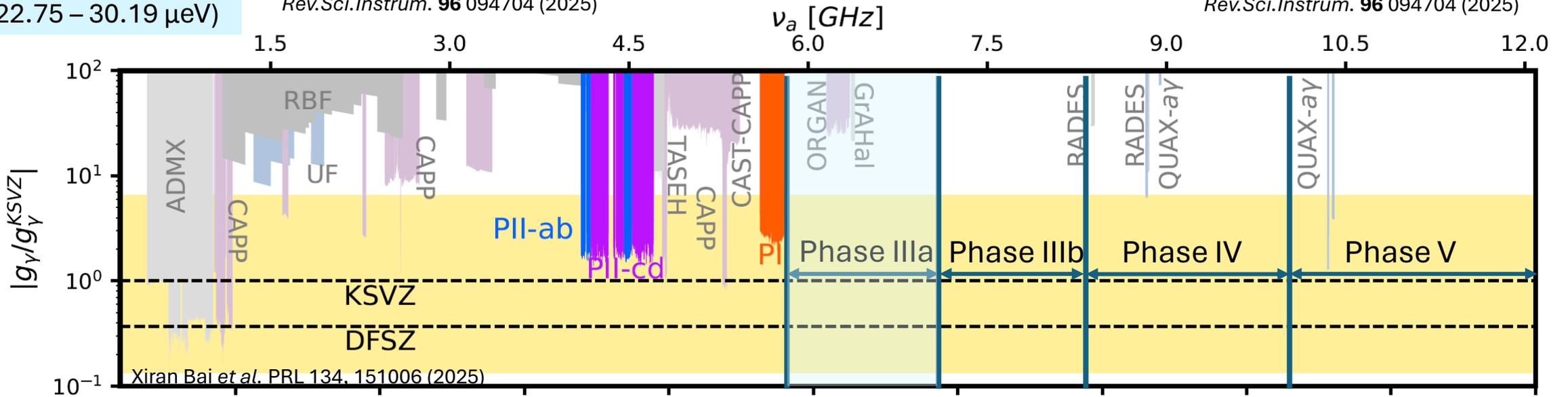


Y. Jiang et al., PRX Quantum **4** (2024)

PV: Plasma Haloscope (ALPHA)



Rev.Sci.Instrum. **96** 094704 (2025)



Xiran Bai et al. PRL **134**, 151006 (2025)

Motivation for 7-Rod Cavity

Goal: Maximize cavity figure of merit (FOM) for given V_c

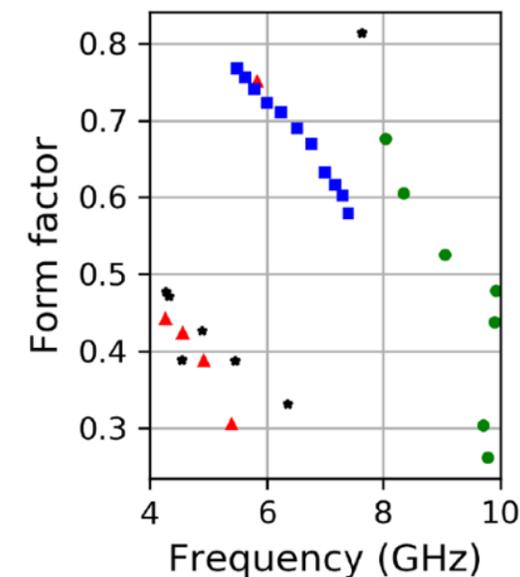
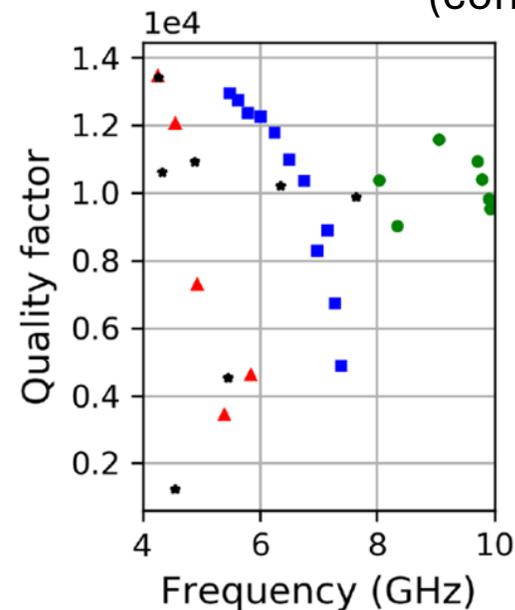
$$FOM = QC^2V_c^2$$

↑ Quality factor ↑ Form factor

- Many designs were simulated
- Simulated Q & C , combined with V to calculate FOM
- 7-rod cavity configuration maximizes FOM for given volume

| Symbol | # Tuning Rods | Tuning Rod OD | |
|--------|---------------|---------------|---------|
| ▲ | 1 | 2.00" | ← PI/II |
| ★ | 1 | 2.46" | |
| ■ | 7 | 0.625" | ← PIIIa |
| ● | 7 | 0.875" | |

Comparing Performance of 4 Cavity Configurations (constant volume)

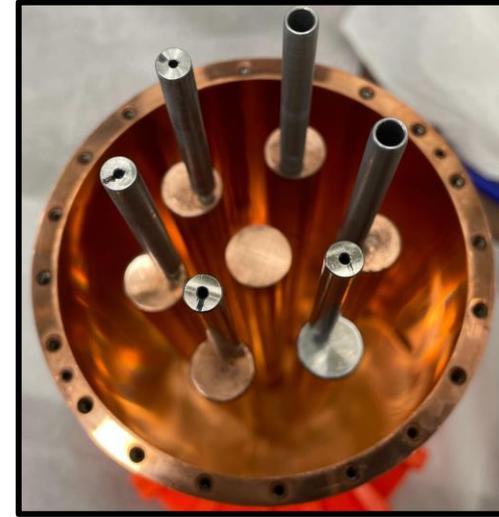
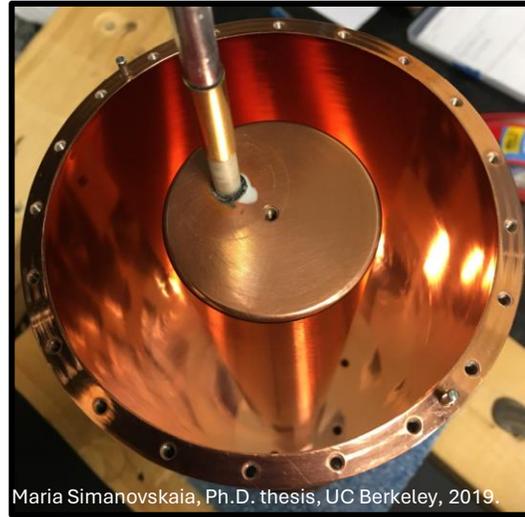


7-Rod Cavity Design

PI & II vs. PIII: Cavity Design

Phases I & II

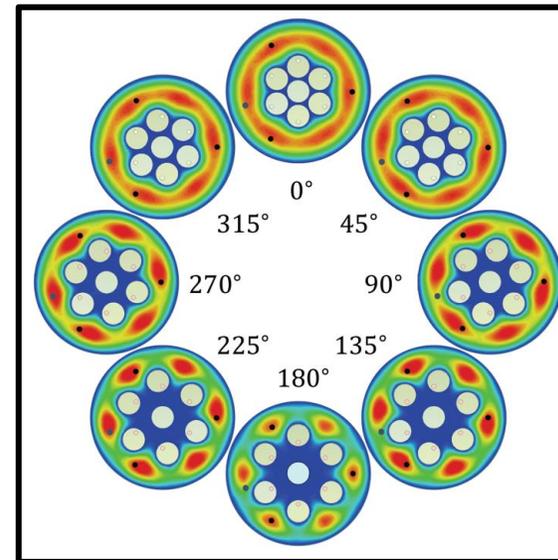
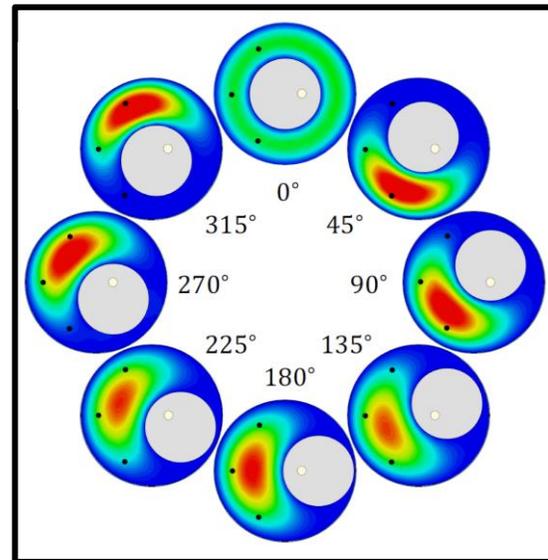
- $\Delta\nu_c$: 4.1 – 5.8 GHz
- Single tuning rod
- Asymmetrical mode structure
- ID: 4”, height: 10”
- Unfilled $V_c \sim 1.545$ L



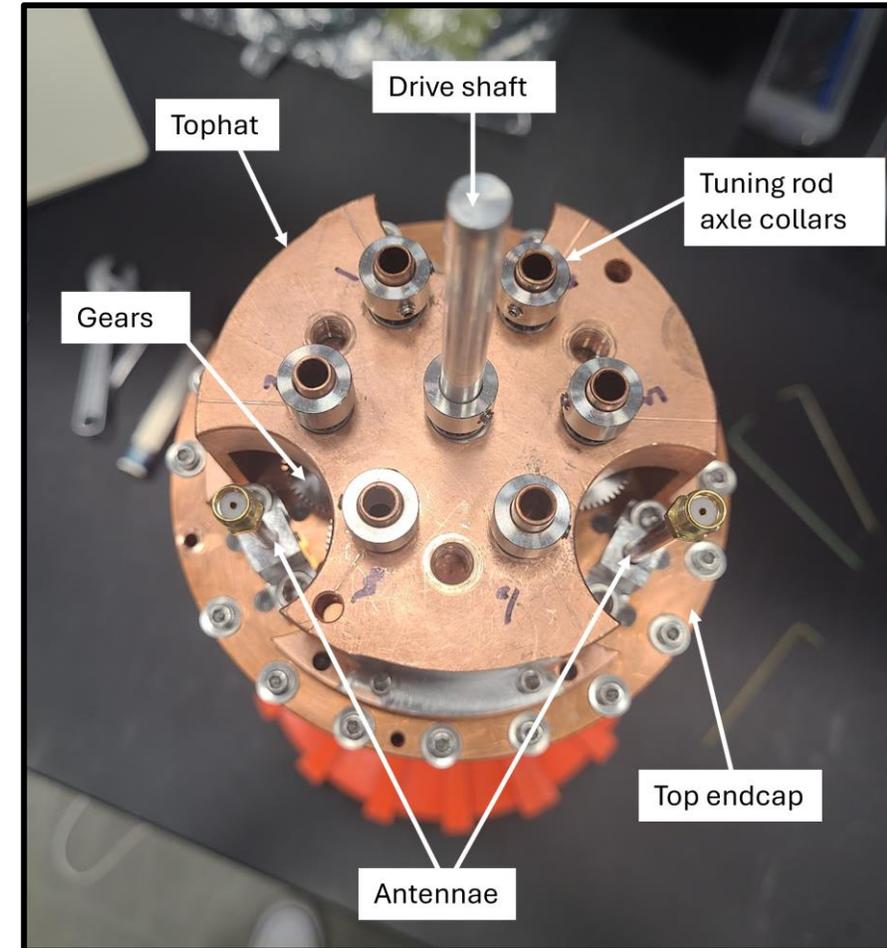
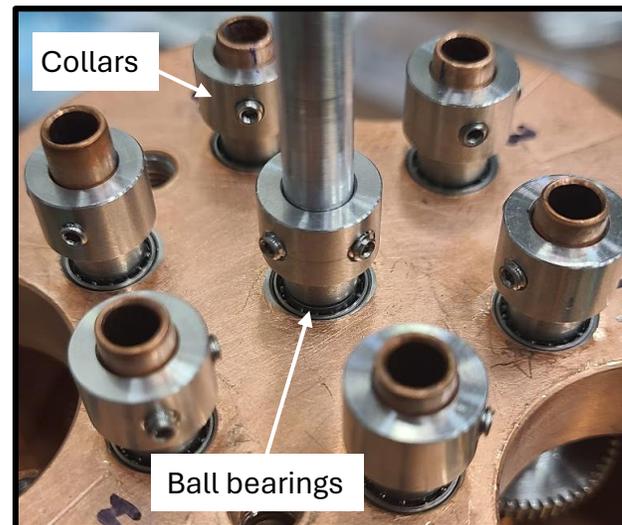
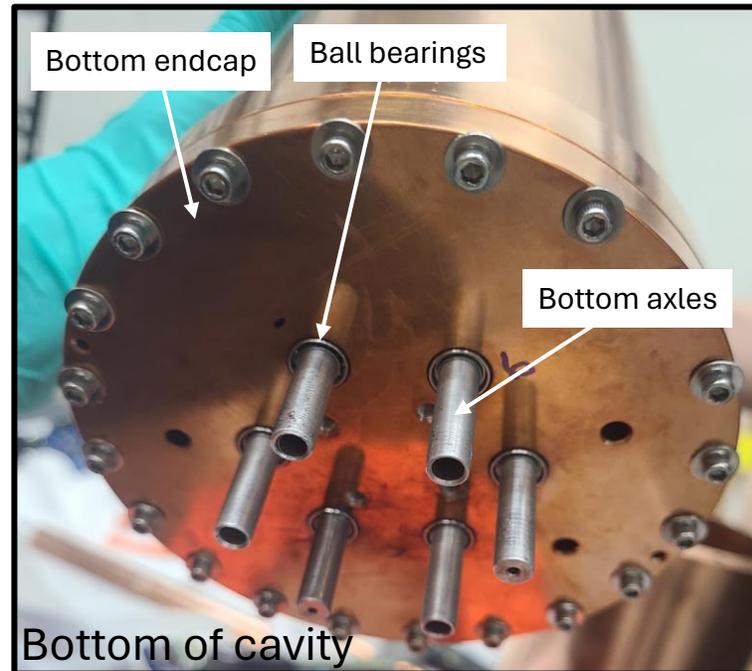
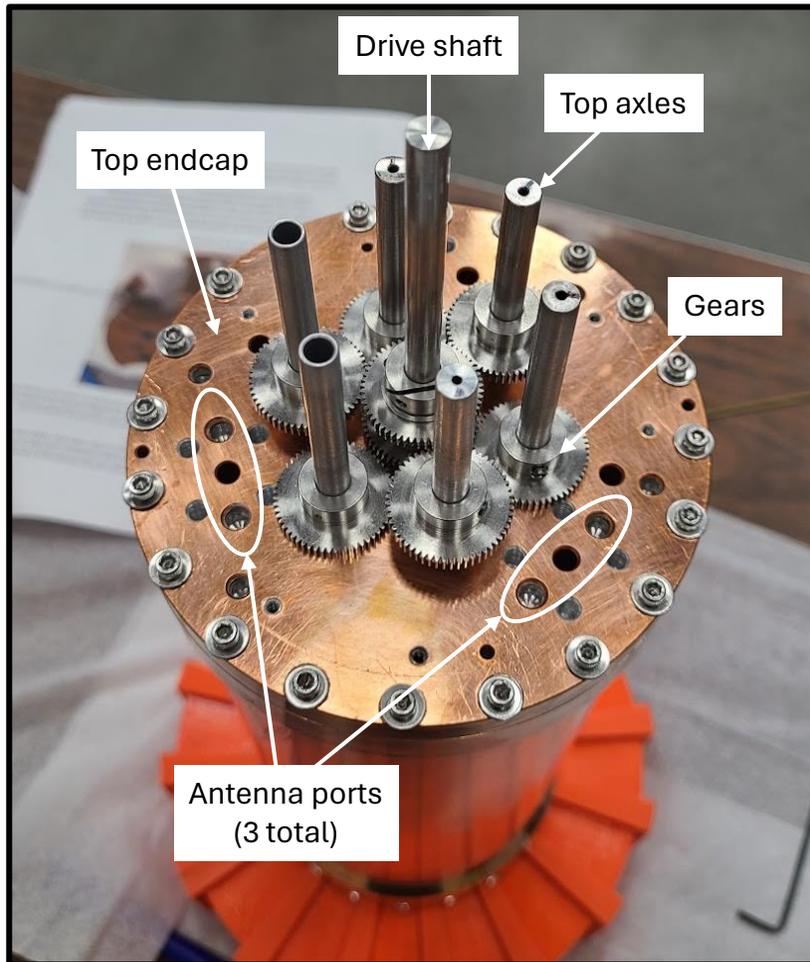
Phase IIIa

- $\Delta\nu_c$: 5.5 – 7.3 GHz
- 7 tuning rods
- 6-fold symmetrical mode structure
- ID: 4”, height: 10”
- Unfilled $V_c \sim 1.707$ L

Simulated E-field density maps of TM_{010} -like mode



Let's take a closer look...



Top of cavity (with tophat)

7-Rod Cavity Testing & Optimization

Dedicated Cryogenic Testing Setup

- First 7-rod cryo tests began at Yale in April
- Testing at 15K in He fridge for fast turnarounds
- Two critical functionalities need to work before data taking:
 - Mechanical tuning
 - Cryogenic Q

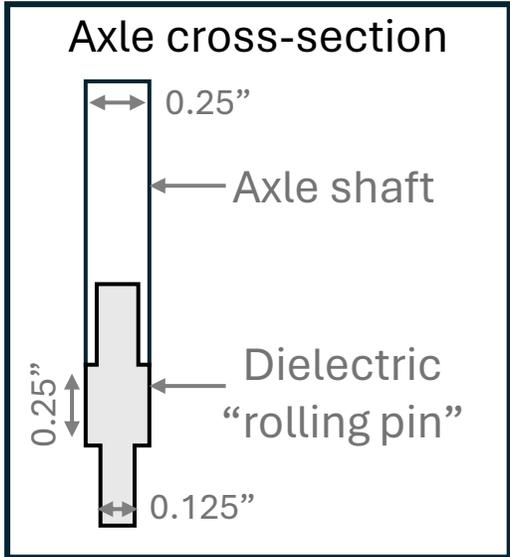
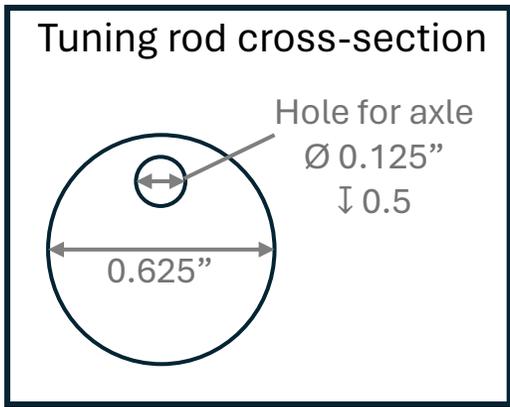


Fridge with cavity testing setup, insulated with MLI



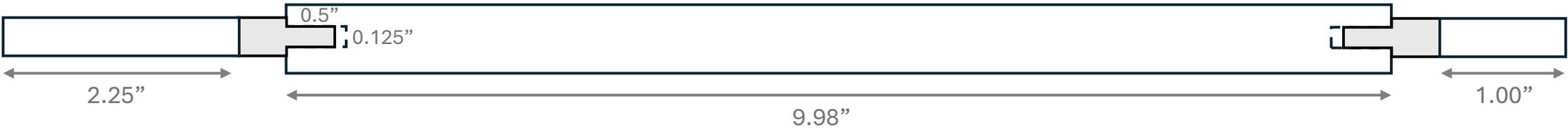
Mechanical Tuning: Rod Design

- Cu-plated Al, OD 0.625", ~9.98" long
- 1/8" holes on both ends to insert axle
- Dielectric joints between axle shaft & rod prevent RF leakage
- Axles attached to rod with Stycast
- Cure for 24hrs in alignment jig



Challenges:

- Axles must be perfectly coaxial
- Thermalization through dielectric joint
- RF leakage through axles

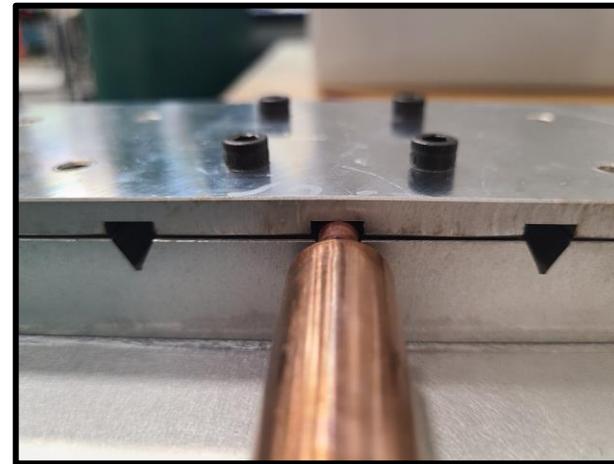
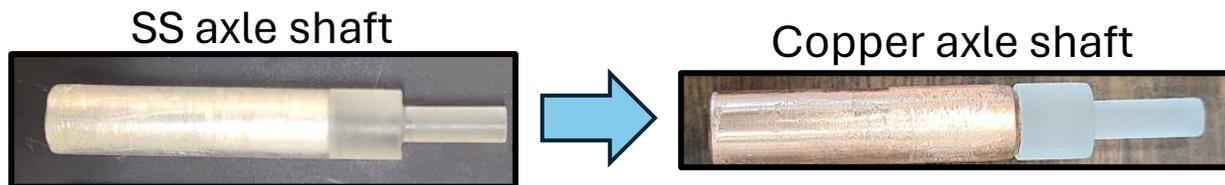


Mechanical Tuning: Optimization

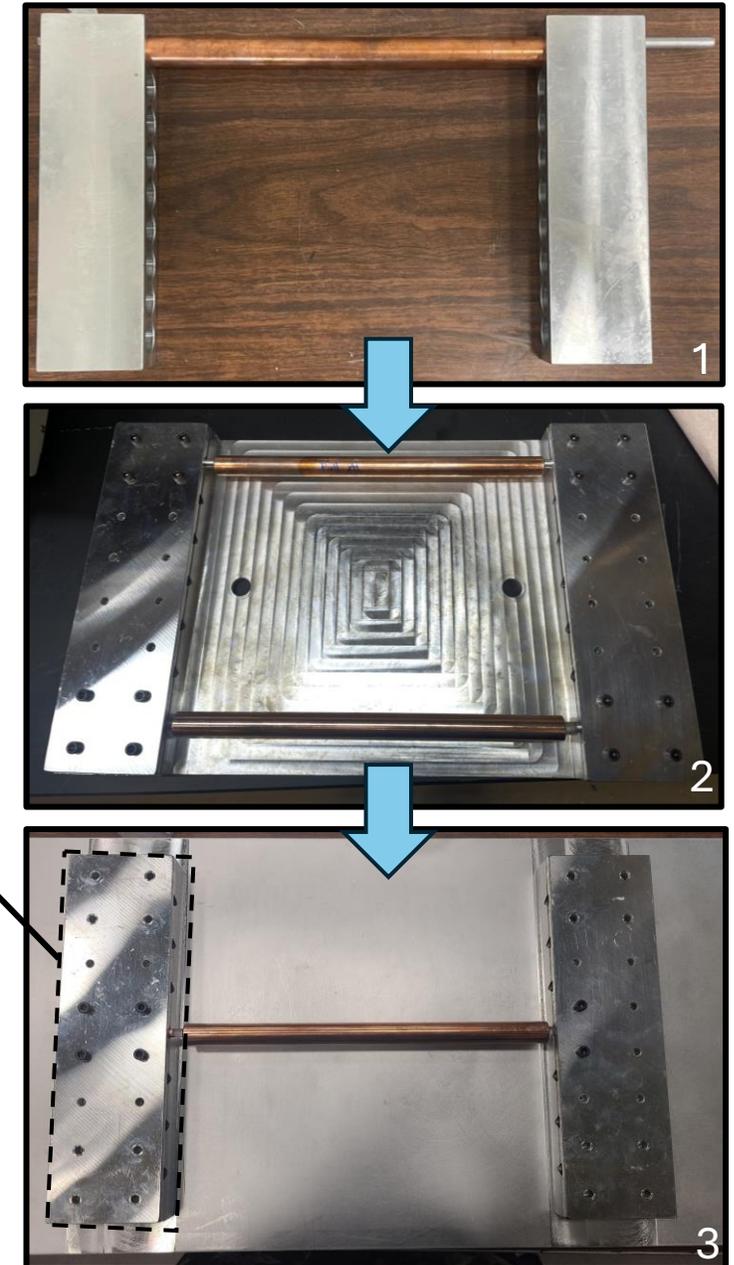
Successful tuning requires perfect cooperation of all tuning rods & gears

Factors to optimize for tuning:

- Smooth bearings
- Radial tuning rod alignment
- Gear engagement
- Tuning rod axle-alignment
 - Very challenging
 - 3 alignment jig iterations
- Tuning rod thermalization
 - Change axle shaft material

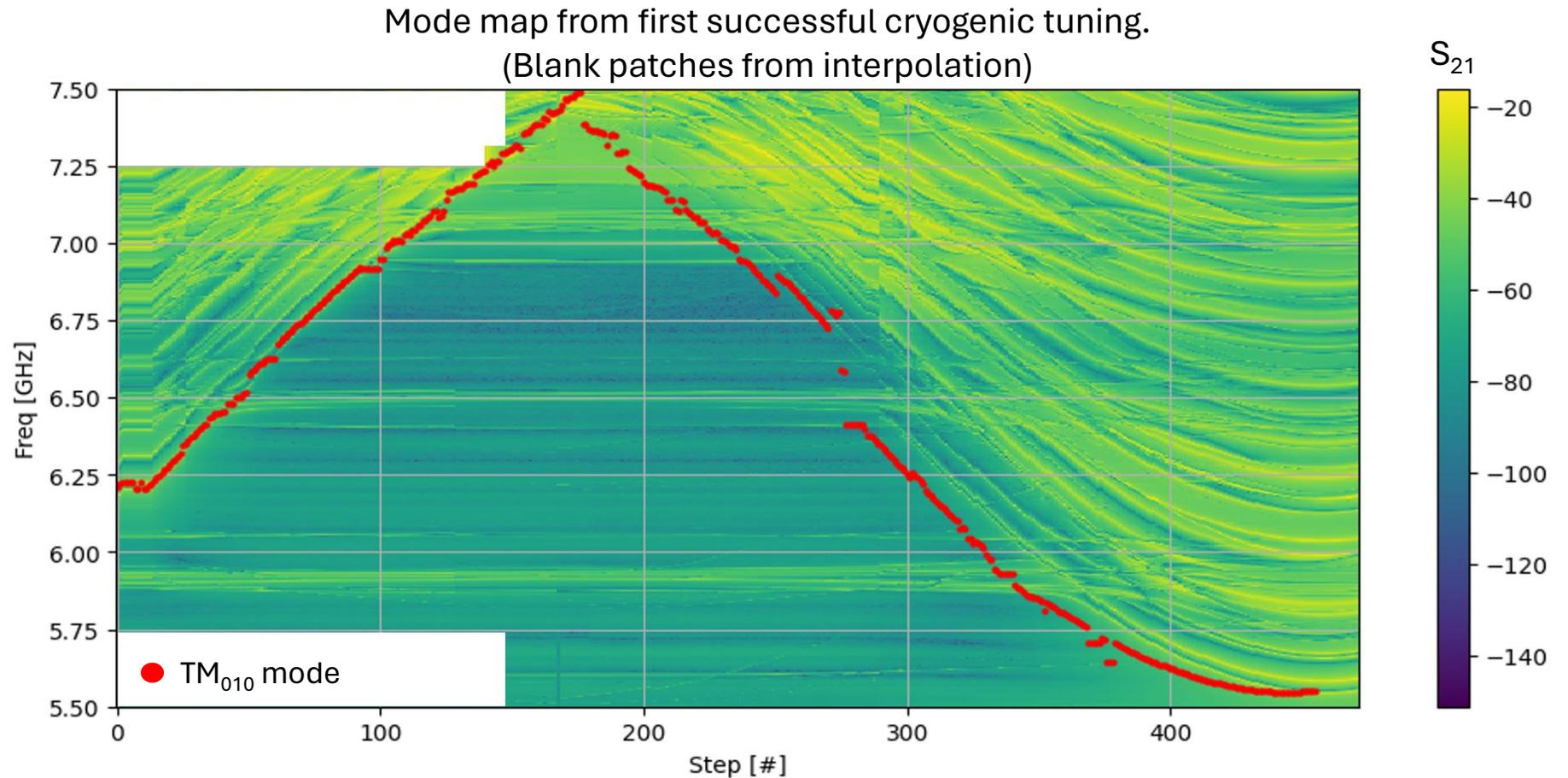


Alignment Jig Iterations



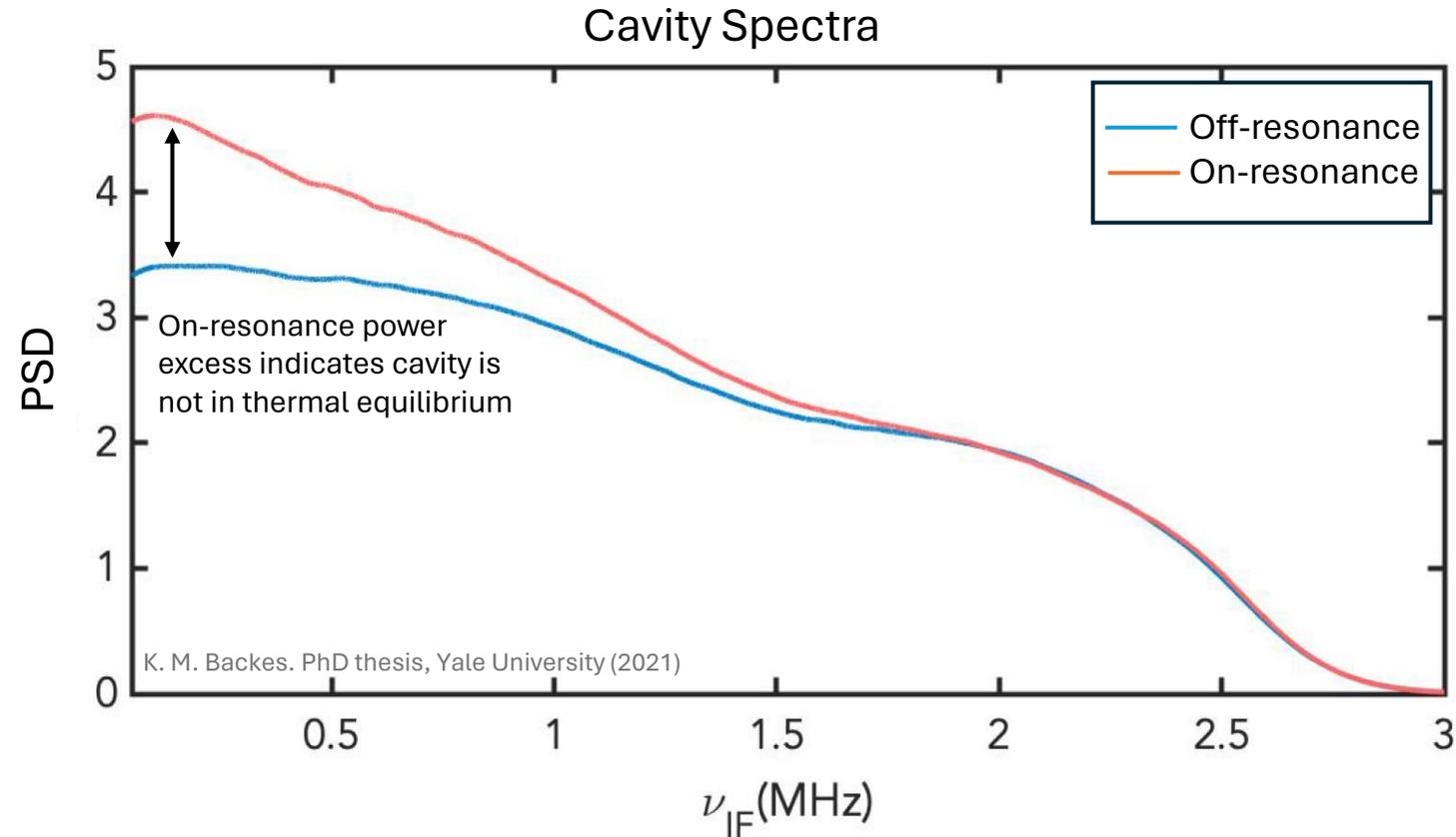
Mechanical Tuning: Success!

- Achieved full cryogenic tuning range
- 5.5 - 7.5 GHz
- Now to tackle cryogenic Q...



Cryogenic Q: The “Hot Rod” Problem

- HAYSTAC has always observed excess cavity noise
- Potential culprits:
 - Vibrations (publication pending)
 - RF leakage through tuning rod axles
 - Tuning rod not thermalizing
- Improved in PII:
 - Copper stems inserted through alumina axles improved thermalization
 - Did not fully fix problem
 - Difficult to implement in 7-rod
- Needs to be addressed for upgrade to multi-rod cavity



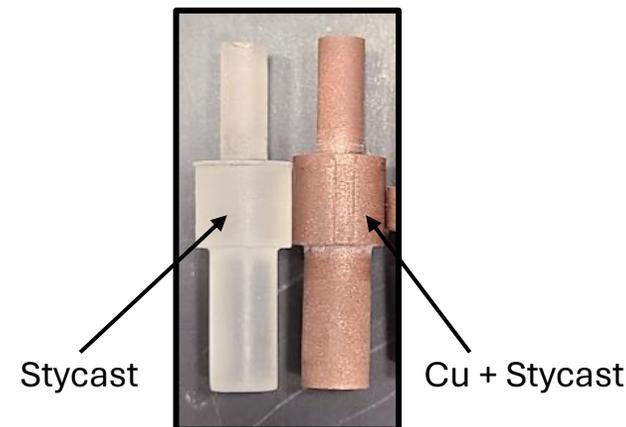
Cryogenic Q: Optimization

Features to optimize:

- Rod thermalization
 - Switching to Cu axle shafts helped
 - Could be further improved by changing *dielectric joint* material
- RF leakage through axles
 - Need *dielectric joint* that conducts heat well

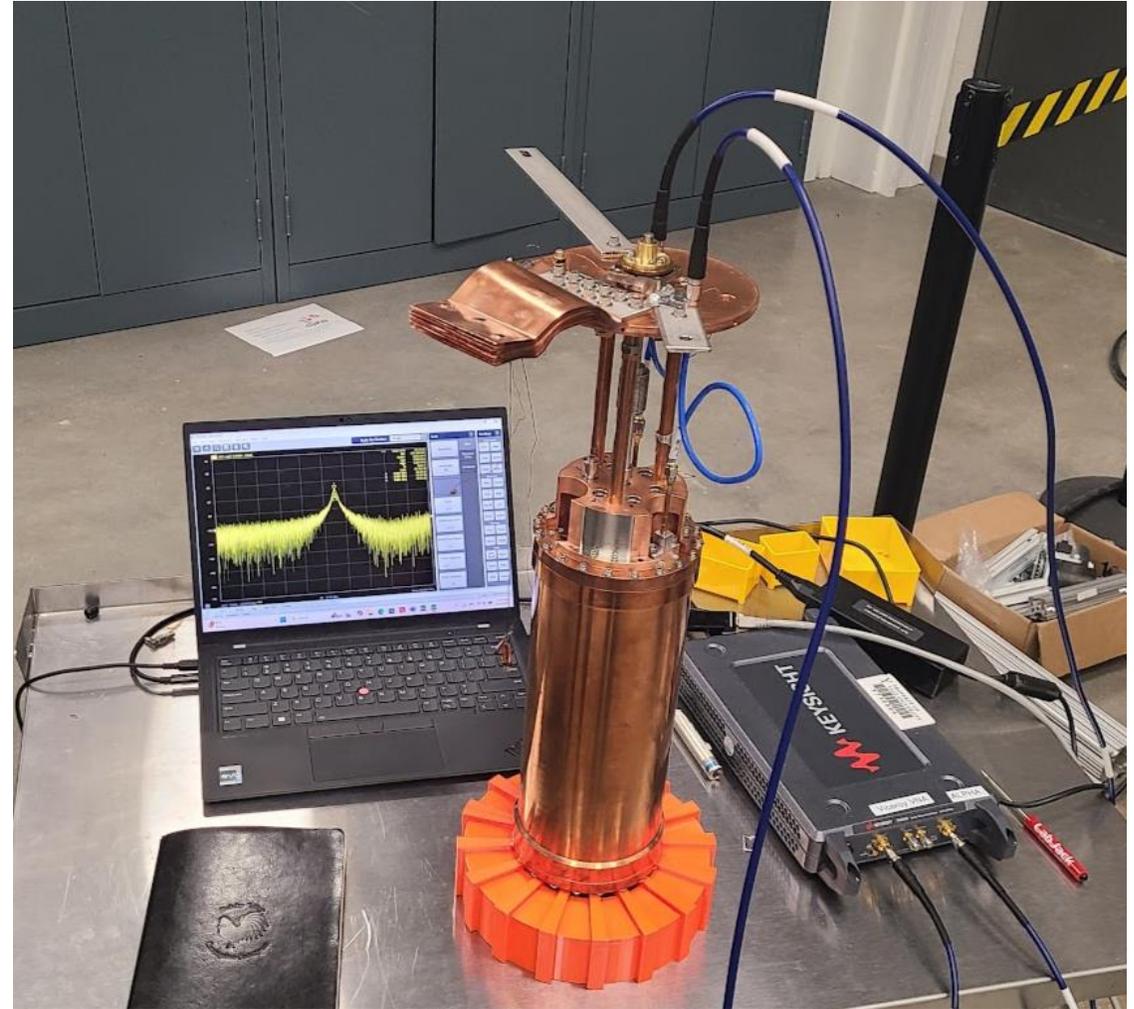
Search for new dielectric joint material:

- Promising candidate: 50/50 Stycast & copper powder (by volume)
- Hypothesis: Stycast serves as dielectric, Cu improves thermal conductivity & acts as filter against RF leakage
- Promising, but still being characterized

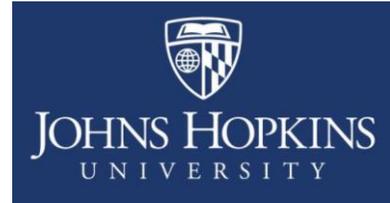


Current Status & Outlook

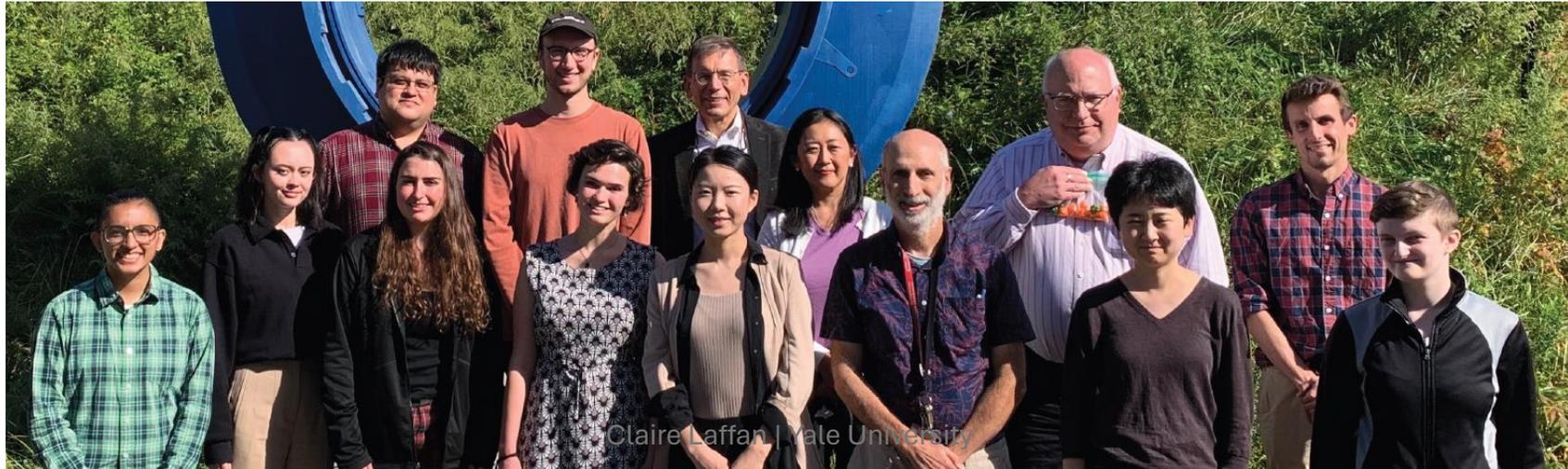
- Quality factor optimization studies still underway
 - Testing full 7-rod assembly with Cu-Stycast dielectric joints
 - Will move ahead with install if cryogenic Q is good
 - Will continue investigating this problem with PII cavity
- Cryogenic tuning is well understood & optimized
- Installation by end of year



Thank You!



Yale

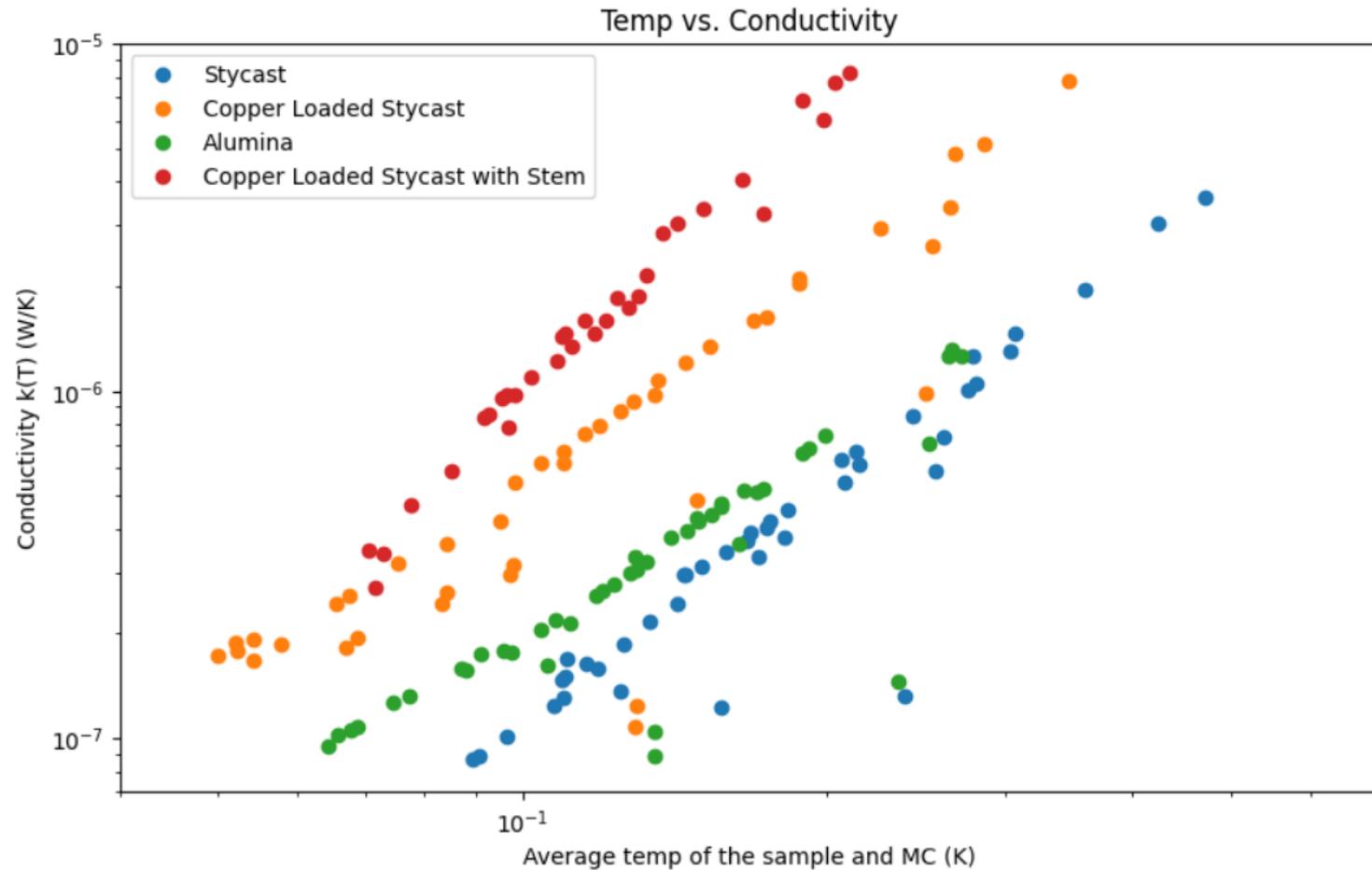
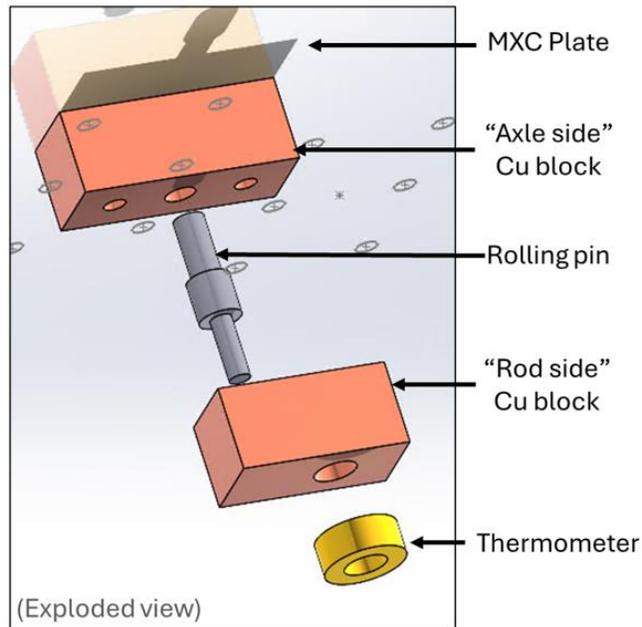


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Backup Slides

Thermal Conductivity Measurements

- Thermal conductivity of samples measured in BlueFors dilution refrigerator
- Cu-Stycast promising



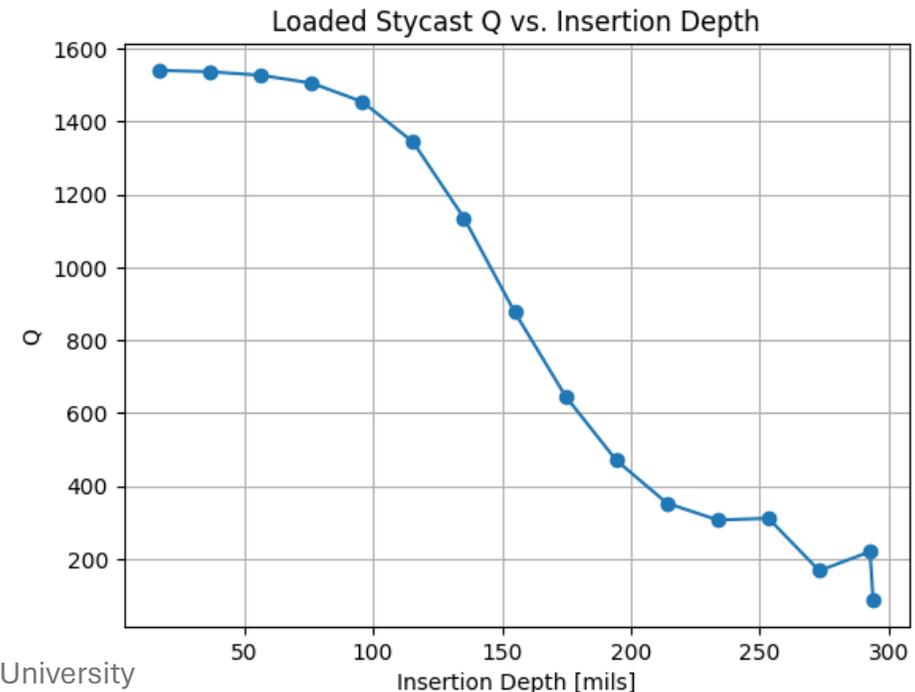
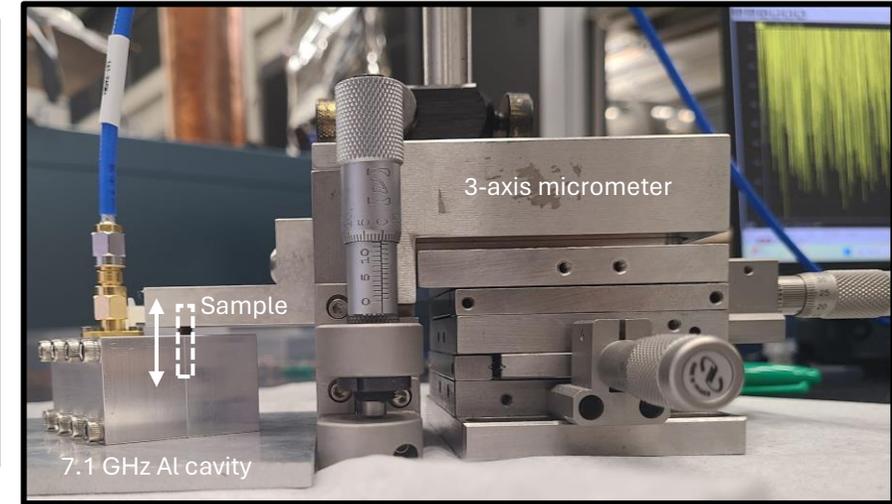
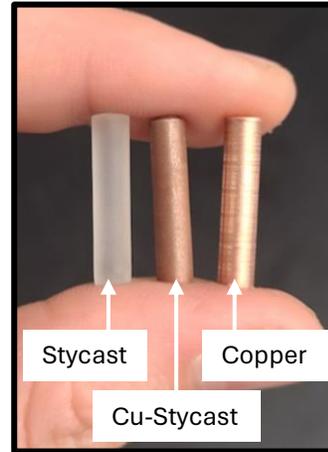
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 - Need *dielectric joint* that conducts heat well

Search for new dielectric joint material:

- Promising candidate: 50/50 Stycast & copper powder (by volume)
- Stycast serves as dielectric, copper improves thermal conductivity
- Suspended copper powder may also serve as filter against RF leakage



Cu-Stycast sample had promising results for Q retention

