Picture from https://patrascasale.gr/en/blog/rio-antirio-bridge

CAPP

Center for
Axion and Precision
Physics Research

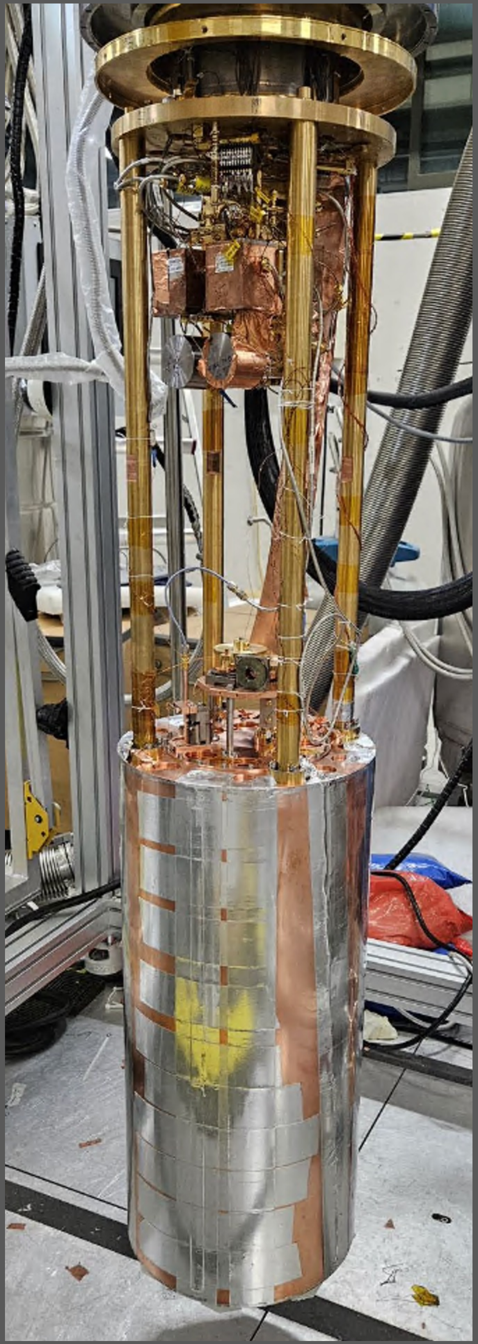
CAPP's Main Axion eXperiment (CAPP-MAX)
with *High-Temperature Superconducting* Cavity

19th September 2024

Ohjoon Kwon on behalf of

CAPP-PACE team & all CAPP members who participated in the CAPP-MAX

IBS-CAPP, Daejeon, South Korea



HTS cavity is implemented to CAPP-MAX!!

- 10^6 Q-factor!!
- In 12 tesla magnetic field
- 33.8 L of large volume
- 3MHz/day @~1DFSZ sensitivity
  → 3MHz/day @ ~0.65DFSZ

Contents

- Axion haloscope with high Q-factor cavity
- HTS-ReBCO microwave cavity in CAPP
- CAPP's Main Axion eXperiment
- CAPP's main axion experiment (CAPP-MAX) w/ ReBCO cavity
- Summary & Future plan

Axion haloscope: High-Q boosts axion scanning speed

D. Kim et al., Physics A *(2020), 03*

$$P_{sig} = \frac{\beta}{\beta+1} g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a} B_0^2 V C_{lmn} \frac{Q_a Q_l}{Q_a + Q_l}$$

$$P_{sig} = \frac{\beta}{\beta+1} g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a} B_0^2 V C Q_{all}$$

$$\frac{1}{Q_{all}} = \frac{1}{Q_0} + \frac{1}{Q_{ext}} + \frac{1}{Q_a}$$

surface coupling axion

When $Q_{cavity} << Q_a$

$$P_{sig} \propto Q_l$$

$$\Delta f_{sig} \sim f_a / Q_a$$

When $Q_{cavity} >> Q_a$

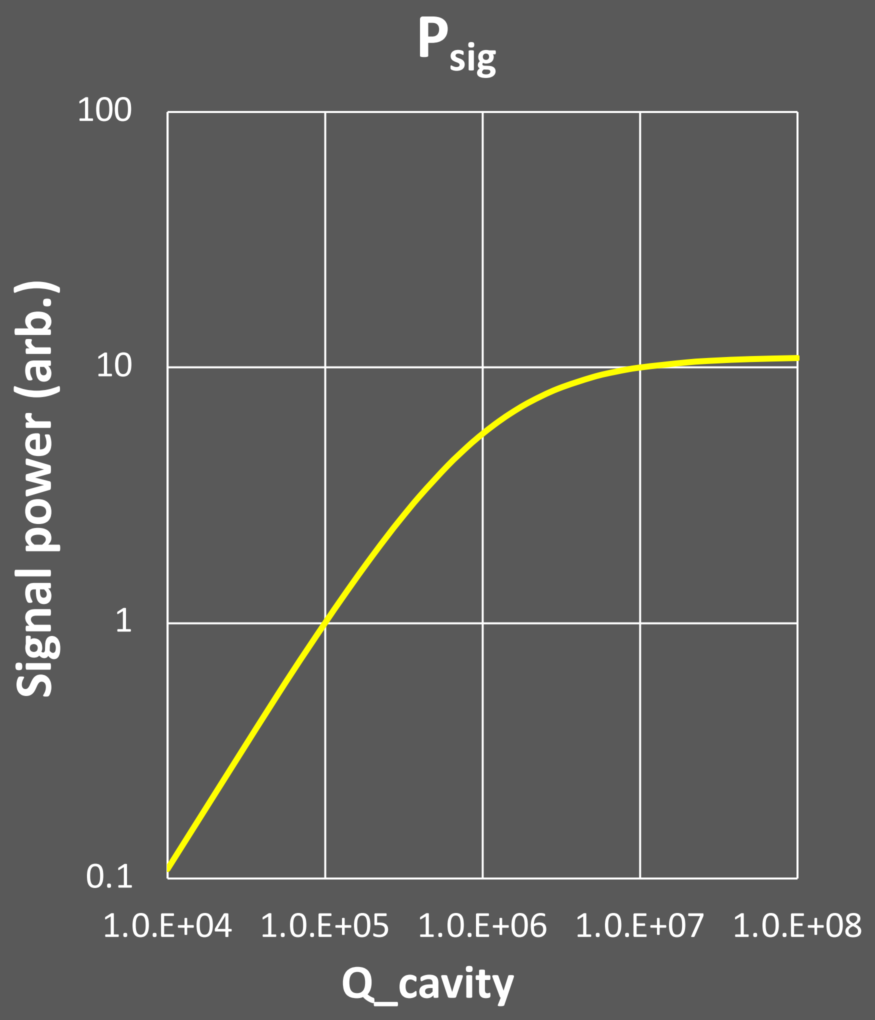
$$P_{sig} \propto Q_a \text{ = constant}$$

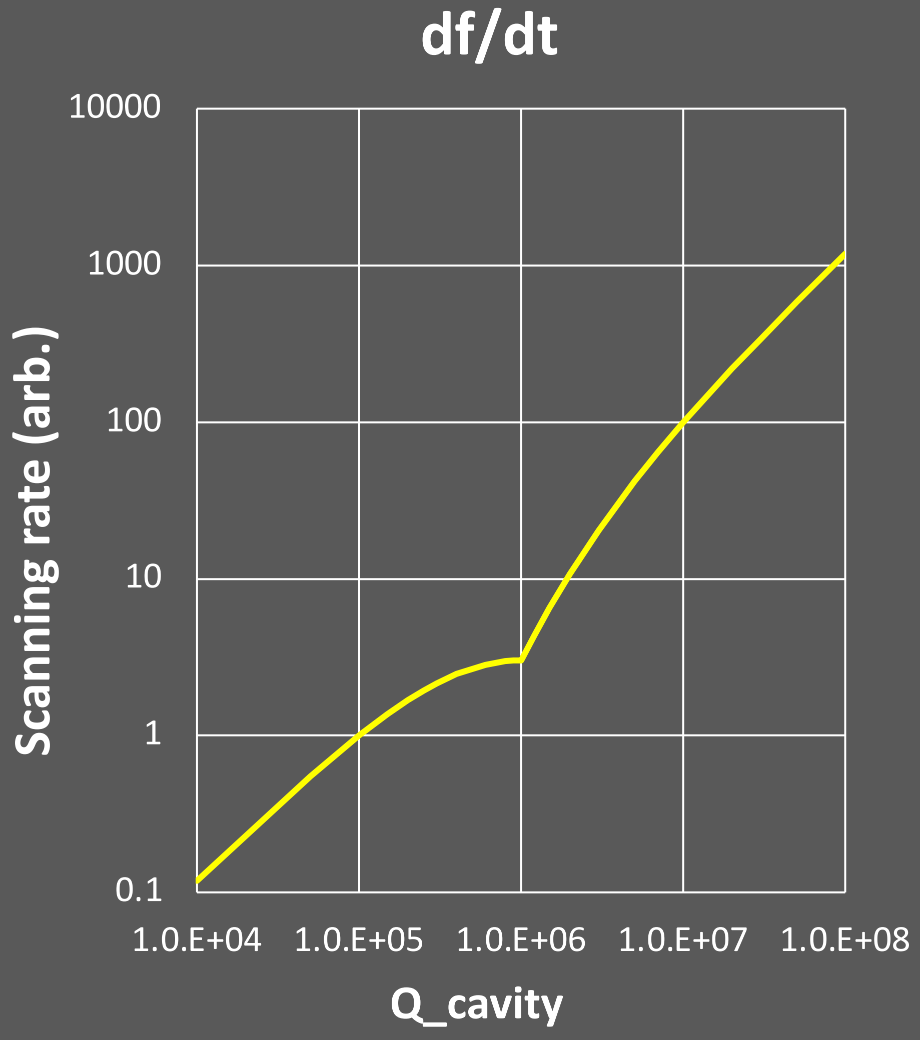
$$\Delta f_{sig} \sim f_a / Q_l$$

$$\frac{d\nu}{dt} \propto Q_l$$

R. Cervantes et al., Phys. Rev. D 110, 043022

High-Q boosts axion scanning speed





Goal:

High Q-factor microwave cavity

inside **strong magnetic field**

needed !!

Superconducting cavity?

rare-earth barium copper oxide

High-temperature superconductor (HTS): ReBCO

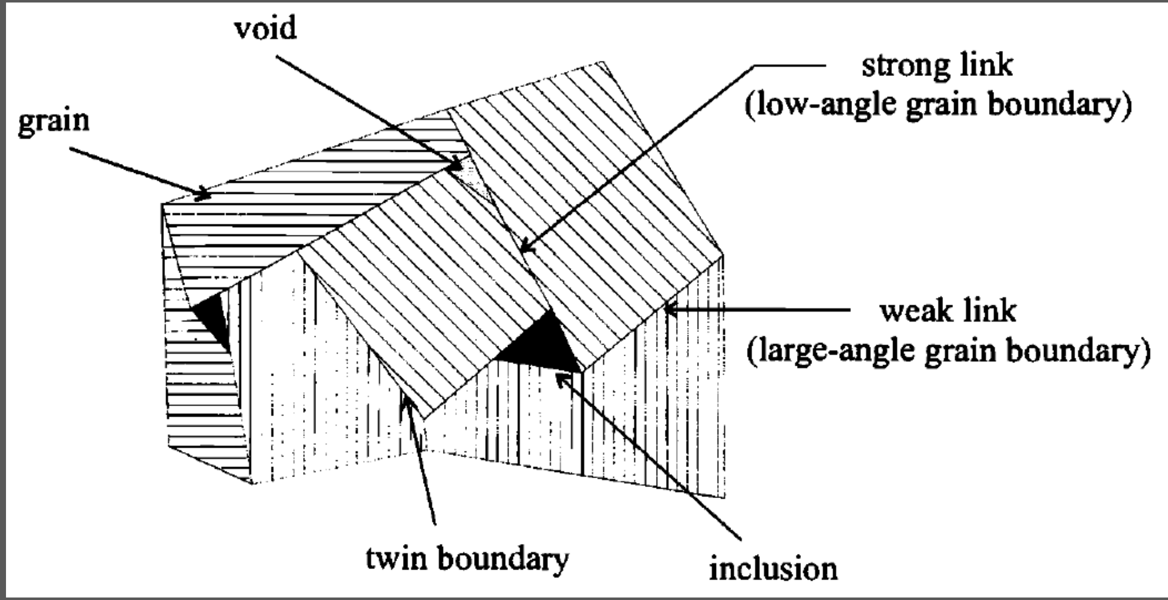
	100 mK 8 GHz	R_s (B = 0 T) (Ohm) (ref. Rs_{Cu}~7e-3)	R_s (B = 8 T, ∥c) (Ohm) (ref. Rs_{Cu}~7e-3)	Critical Field (H_{c2})	Depinning Frequency
*LTS	Nb	~ 1E-6			
	NbTi Gatti *et al*. PRD(2019)	~ 1E-6	~ 4e-3	~ 13 T small	~ 45 GHz
	Nb_3Sn Alimenti *et al*. SUST(2020)	~ 1E-6	?	~ 25 T	~ 6 GHz small
**HTS	Bi-2212 Bi-2223	~ 1E-5	?	> 100 T (∥ab) Larbalestier *et al*. Nature(2001)	? Weak pinning
	Tl-1223	~ 1E-5	~ 1e-4 Calatroni *et al*. SUST(2017)	> 100 T (∥ab) Larbalestier *et al*. Nature(2001)	12 – 480 MHz Calatroni *et al*. SUST(2017)
	ReBCO	~ 1E-5 Ormeno *et al*. PRB(2001)	**~< 1e-4** Romanov *et al*. Scientific Reports(2020)	**> 100 T (∥ab)** Larbalestier *et al*. Nature(2001)	Strong Pinning **10 – 100 GHz** Romanov *et al*. Scientific Reports(2020)

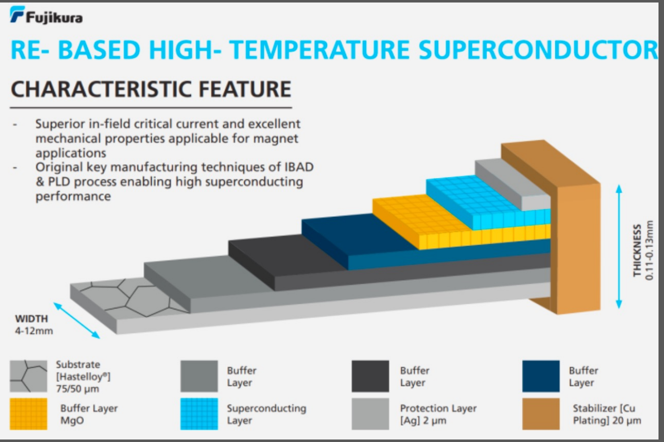
*low temperature superconductor
**high temperature superconductor

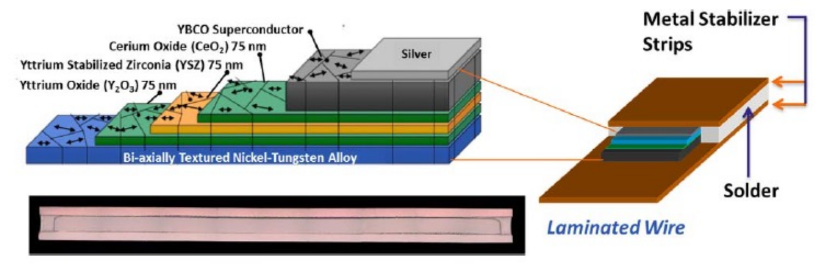
From Dr. Danho Ahn's slide

Biaxially-Textured ReBCO

M. J. Lancaster, "Passive microwave device applications of HTS", Cambridge University Press (2006).







IEEE Trans. Appl. Supercond. 23 (2013) 6601205

Multi-layered structure

- ✓ Weak links at grain boundaries degrades surface resistance.
- ✓ ***Biaxially textured structure is essential***

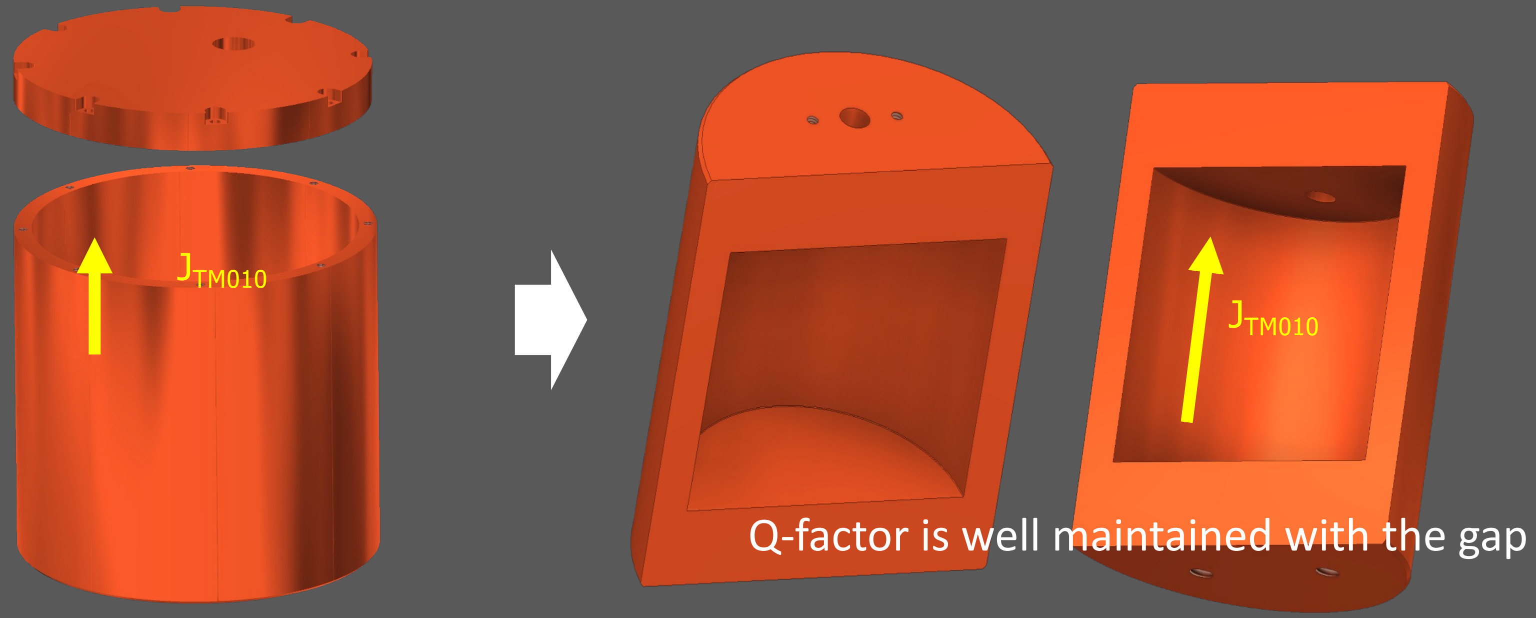
➔ Impractical to construct 3D microwave cavity

Split cavity maintains Q-factor if…

➢ ***TM010 mode is compatible with vertical division***

Horizontal cut

Vertical cut



Parallel polarization of E-field and the cutting direction doesn't harm Q-factor much

- O. Kwon et al,
  Phys. Rev. Lett. **126**, 191802 (2021)

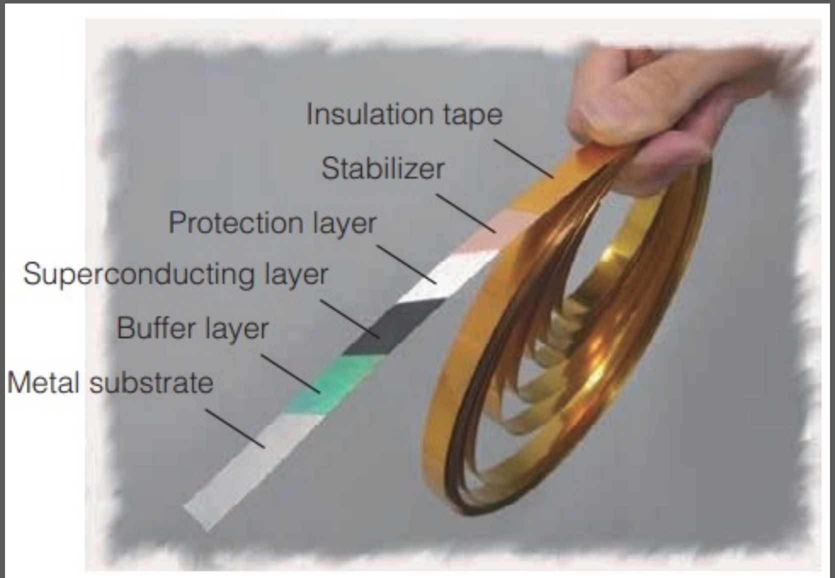
Dr. Woohyun's innovative idea:

what if the cavity is composed of multiple pieces of HTS sheets or wires?

CAPP's recipe to make HTS cavity

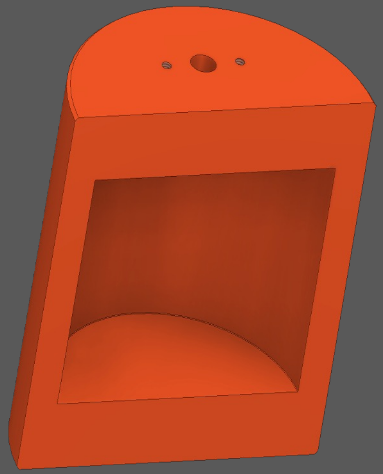
Flexibility of the ReBCO film + split cavity structure

With the help of Prof. Dojun Youm

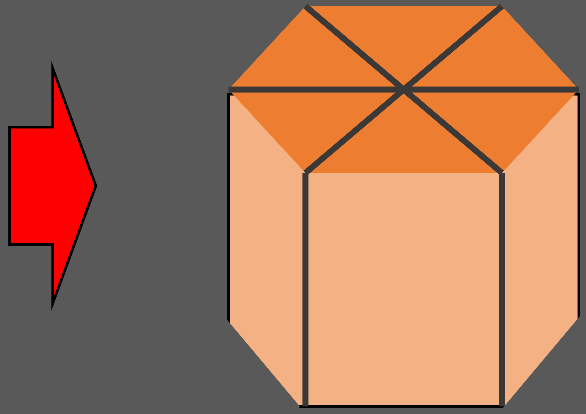


Well–textured **flexible ReBCO tapes**

+



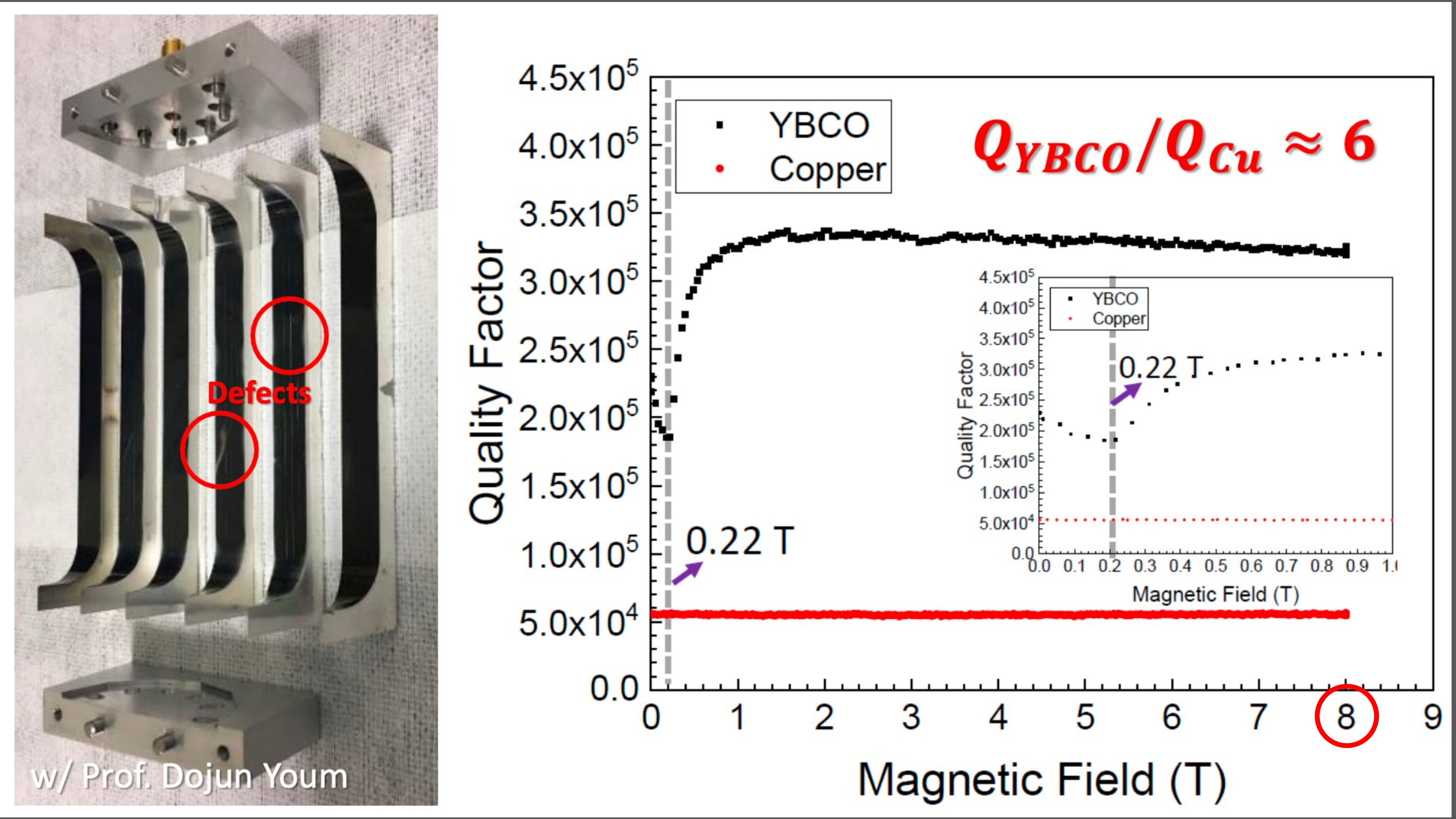
Split cavity structure



→ N-polygon structure
with ***N*** gaps

CAPP's 1st success on high-Q HTS cavity

in 2018



* Phys. Rev. A. **17**, L061005 (2022)

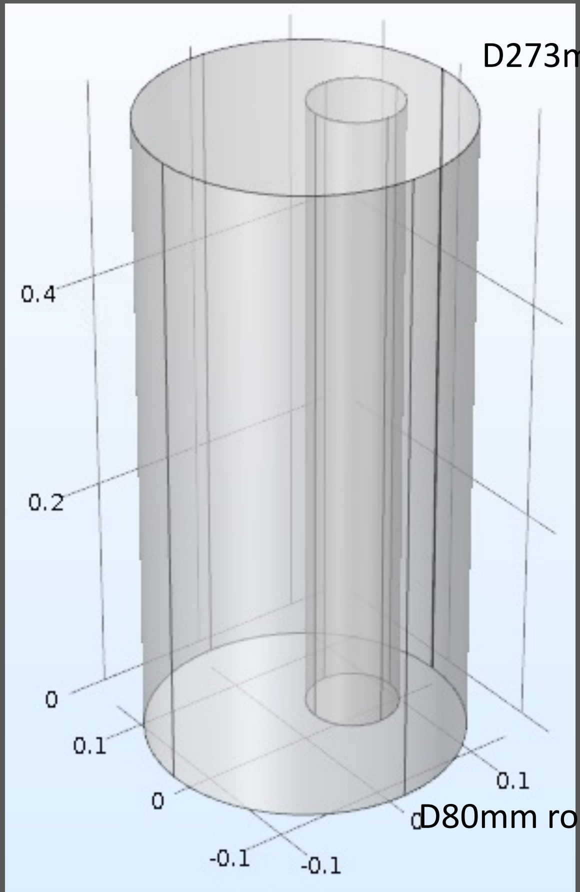
CAN we use this HTS cavity

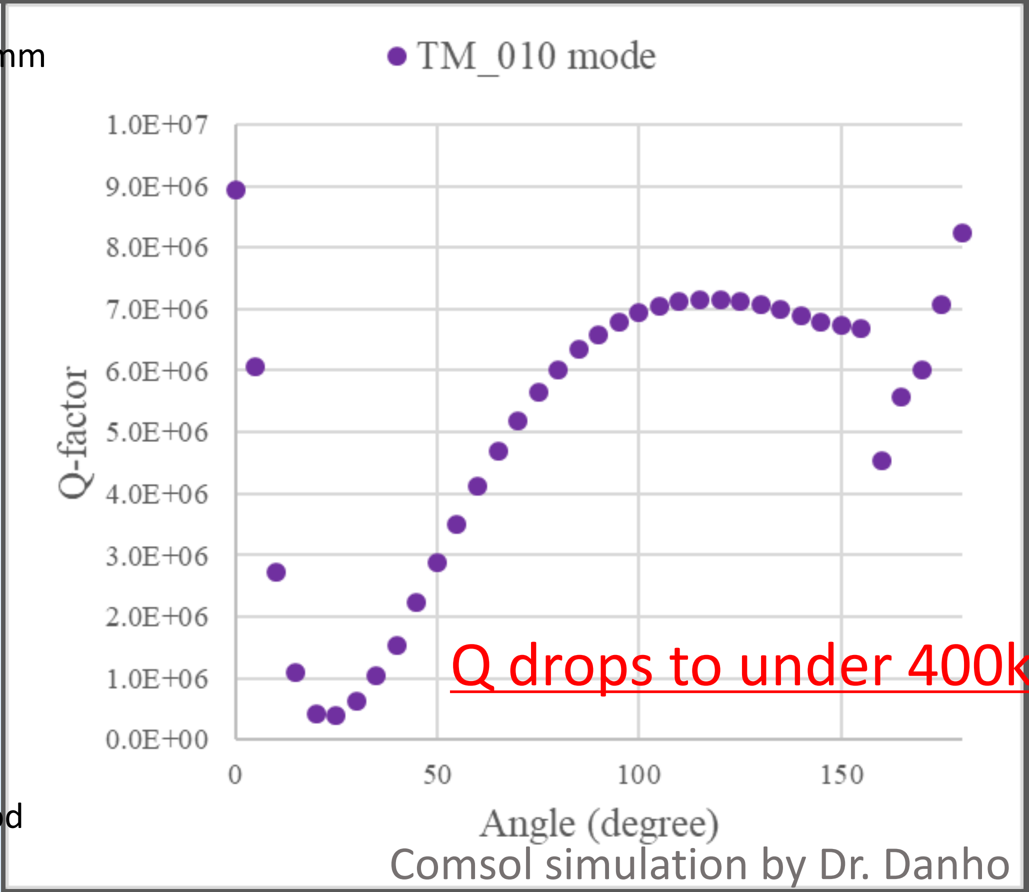
for taking real axion data??

How to tune the cavity w/o losing Q-factor!

Contact problem w/ conventional tuning rod

Simulation result (perfect conductor w/ 0.2mm vertical gap)





CAN we use this HTS cavity

for taking real axion data??

↓

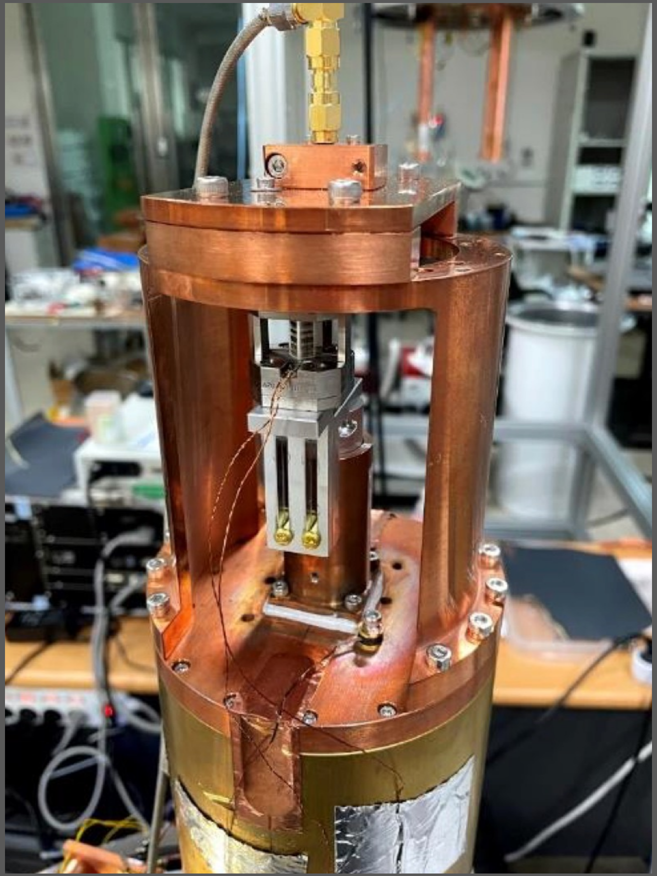
Two approaches

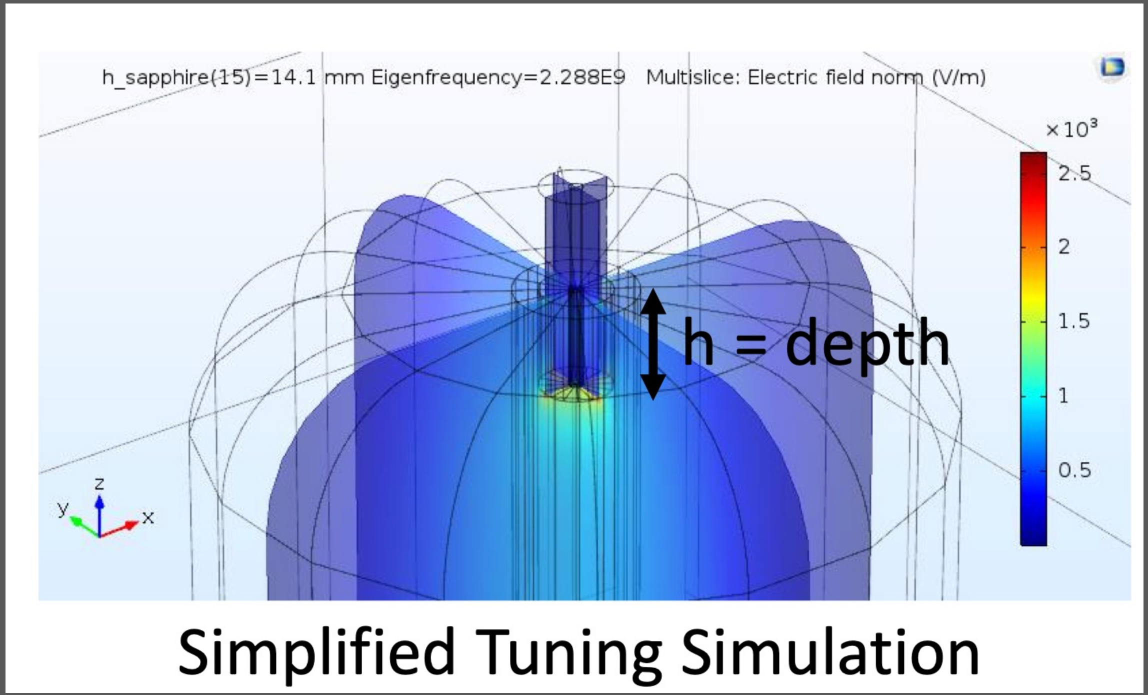
Changing tuning mechamism
w/ azimuthal symmetry
(or no tuning)

Electrically blocking all the gaps

1st approach: w/ azimuthal symmetry

Ex3) moving the tuning rod in the cavity center vertically

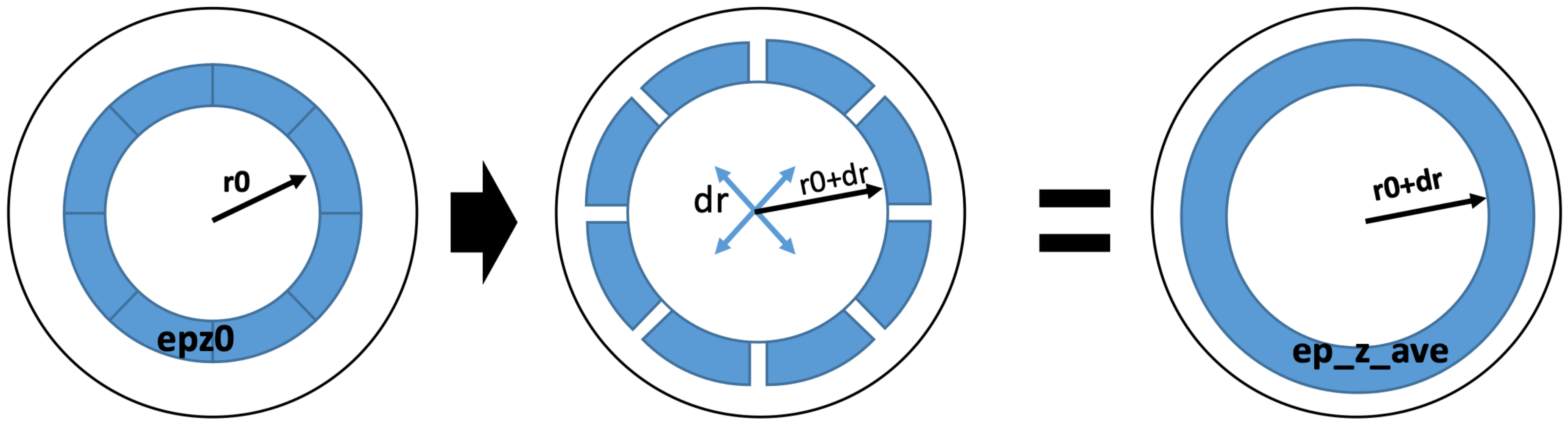




10mm movement – 30MHz frequency tuning
(2.27-2.30GHz)

1st approach: w/ azimuthal symmetry

Ex1) Dielectric metamaterial tuning of TM0n0 mode

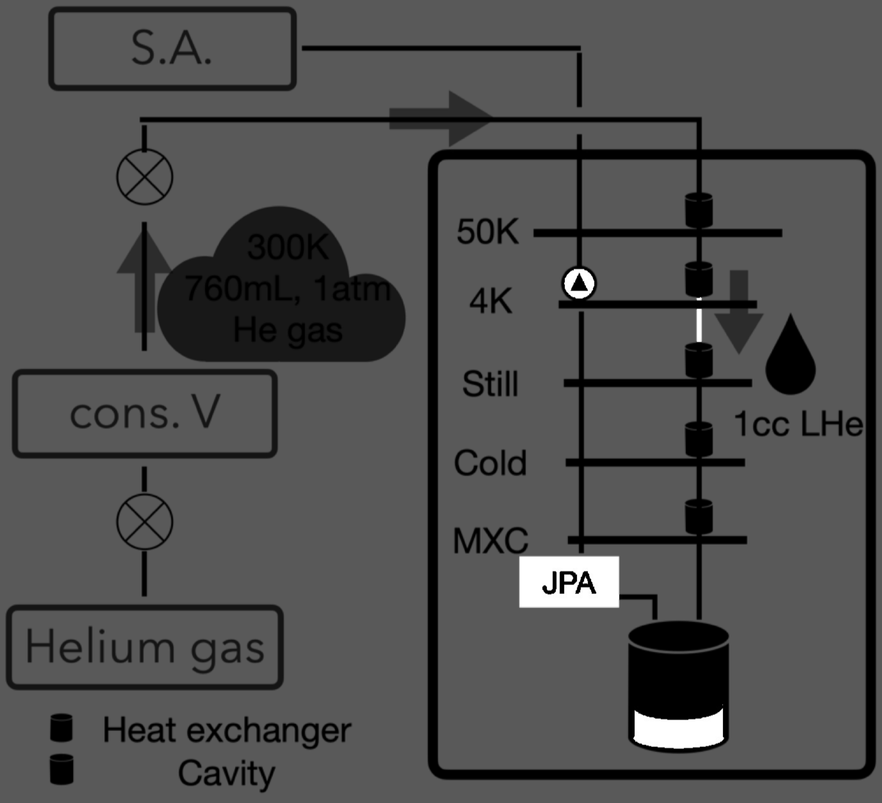


Spreading the dielectric pieces effectively changes inner radius as well as effective dielectric constant

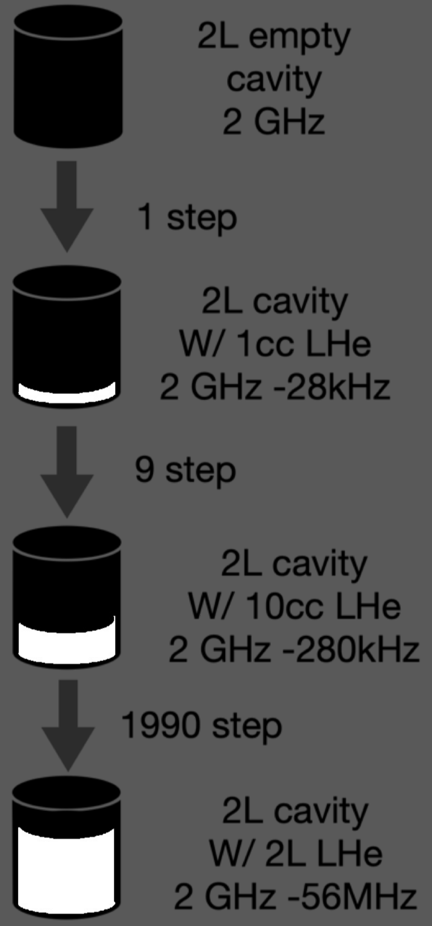
Ohjoon Kwon, Patras 2019

1st approach: w/ azimuthal symmetry

Ex2) Superfluid Liquid Helium tuning method   By Dr. HeeSu Byun



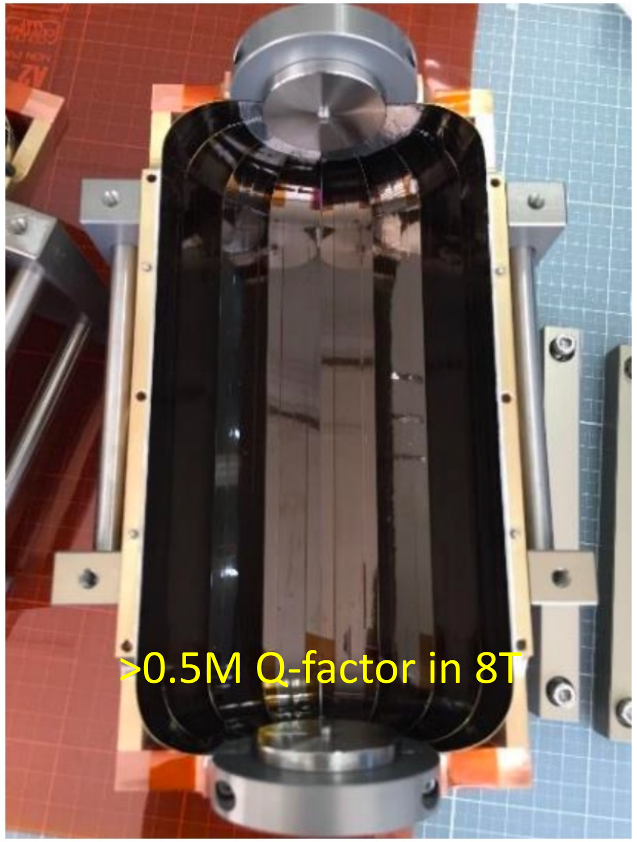
Ohjoon Kwon, Patras 2019

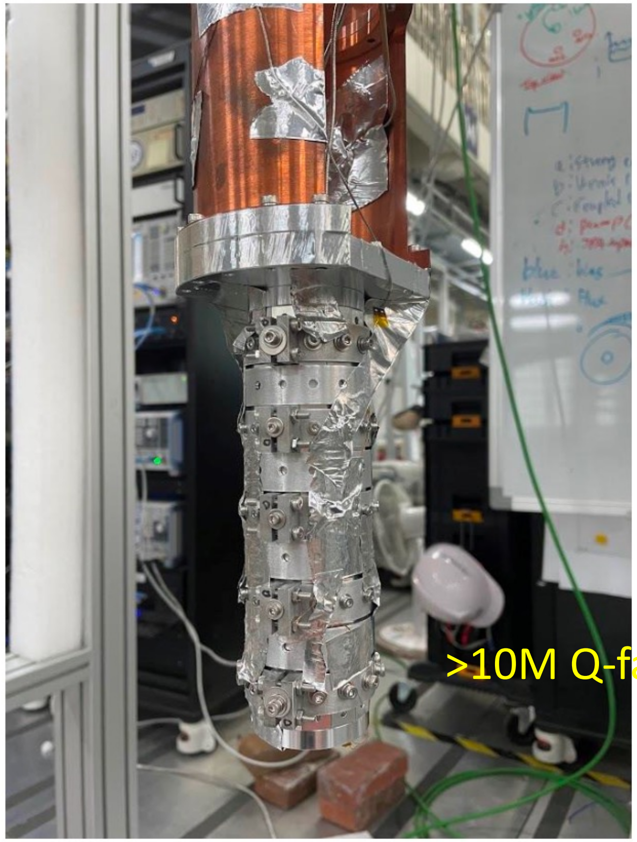


No big change of

Cavity form factor
&
Cavity Q-factor

1st approach: w/ azimuthal symmetry





- Vertical movment of sapphire rod
- Axion experiment performed

  *Dr. D.Ahn, Patras2022

- No tuning
- AQN experiment performed

  **J. Kim's talk on Wednesday*

- Superfluid LHe tuning
- Underway

  *Dr. H.Byun, Patras2023

2nd approach: Electrical blocking

Cover all the gap electrically!!

Multiple ReBCO tapes are soldered on OFHC sheet and become one electrically closed sheet

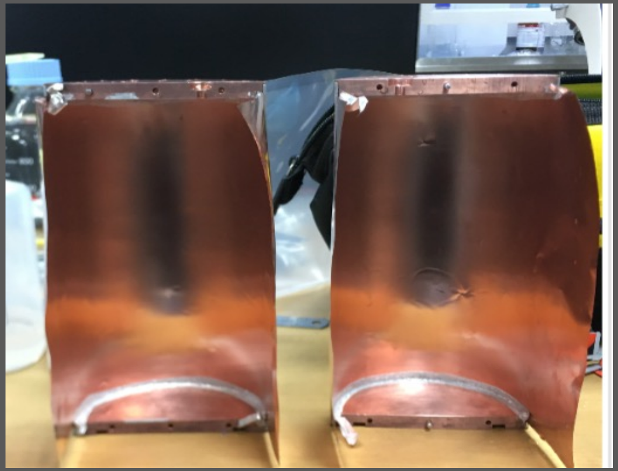
- Conventional tuning is available

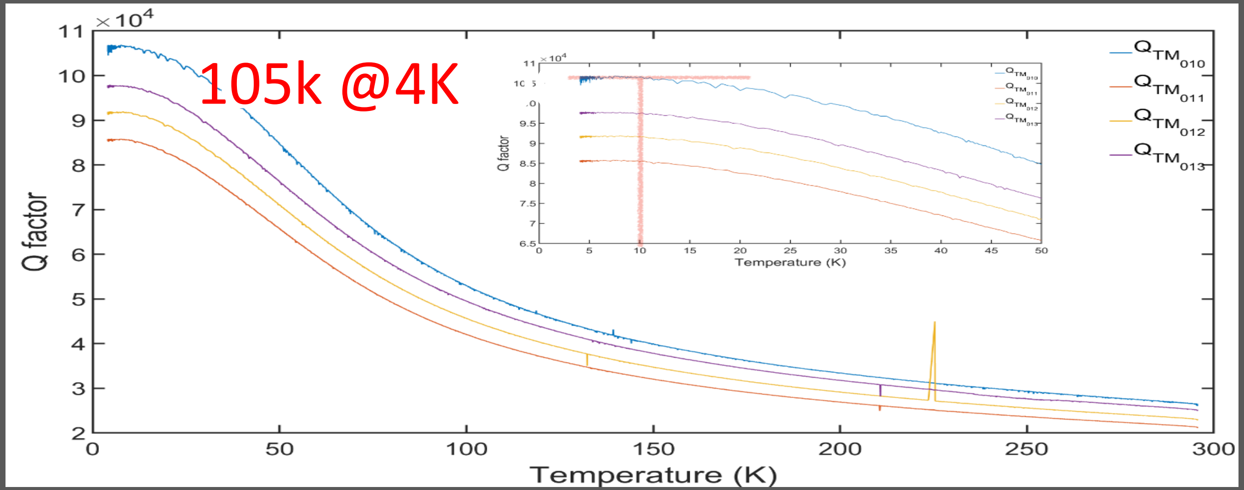
- Easy to harm HTS surface during electrical connection
  (heat, chemical)
  less Q factor than 1st approach

2nd approach: Electrical blocking

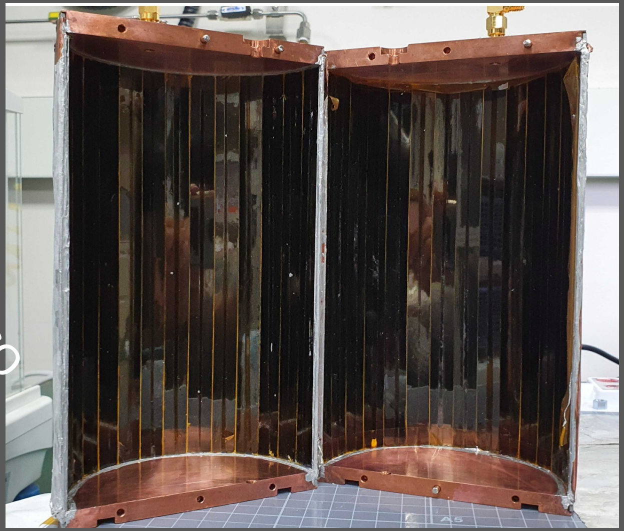
Cover all the gap electrically!!

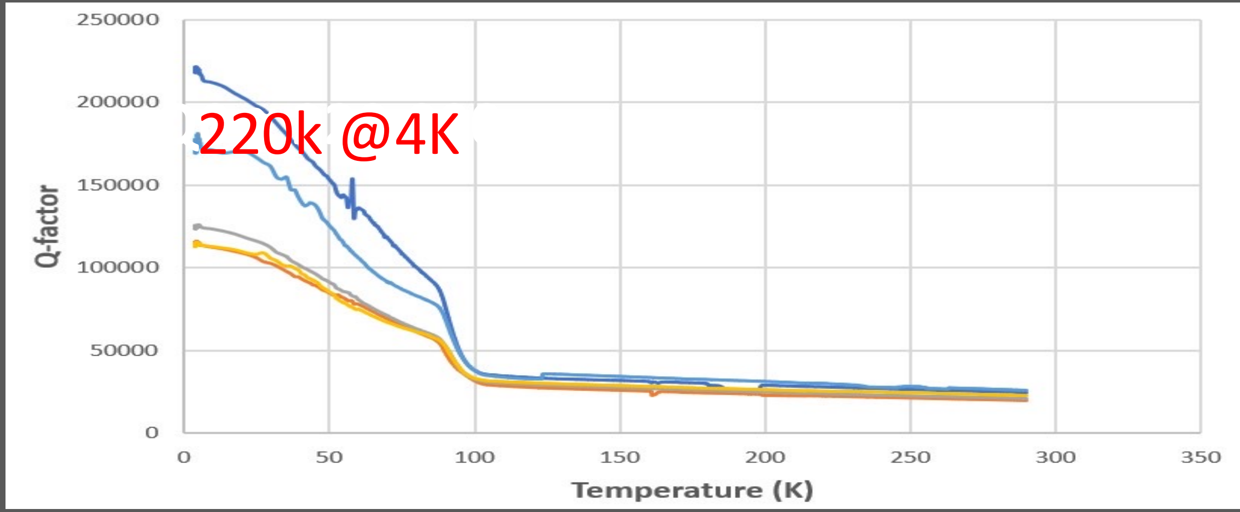
Just Copper





Side wall YBCO





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Cover all the gap electrically!!

Multiple ReBCO tapes are soldered on OFHC sheet and become one electrically closed sheet

- Conventional tuning is available

- Easy to harm HTS surface during electrical connection (heat, chemical)
  less Q factor than 1^{st} approach

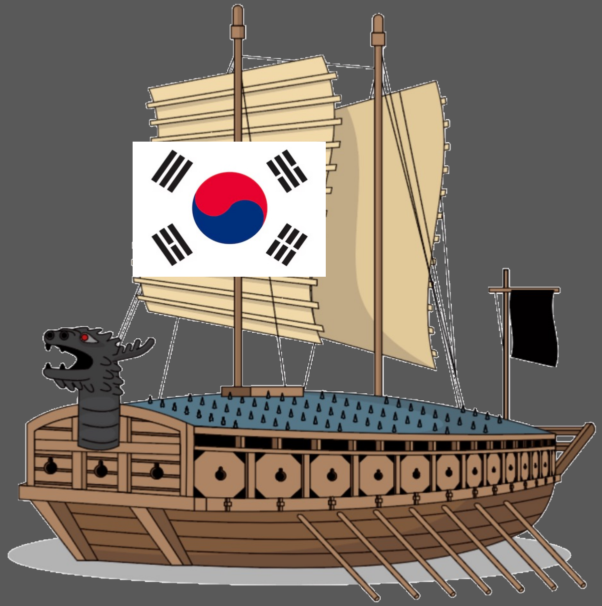
Consiering the size

- Applicable to CAPP-MAX experiment right away

CAPP's main axion experiment (CAPP-MAX)

**Phys. Rev. X 14, 031023 (2024)

- CAPP's flagship experiment to search for axion above 1GHz
- Dine-Fischler-Srednicki-Zhitnitsky (DFSZ) sensitivity



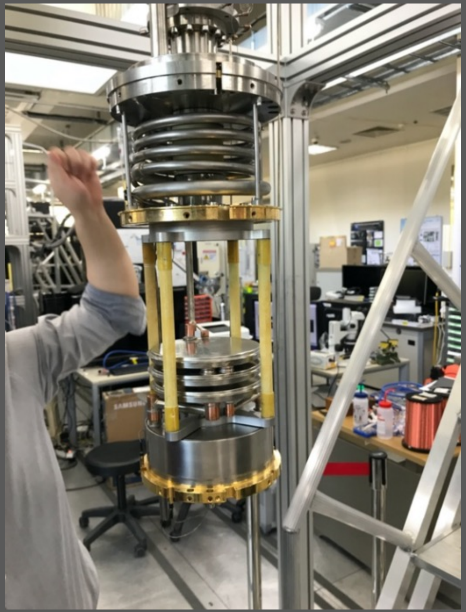
CAPP's main axion experiment (CAPP-MAX)

**Phys. Rev. X 14, 031023 (2024)

- CAPP's flagship experiment to search for axion above 1GHz
- Dine-Fischler-Srednicki-Zhitnitsky (DFSZ) sensitivity

12 Tesla SC magnet
320mm bore diameter
By Oxford. Inc

+



Dilution refrigerator
T_{base} ~ 5.6 mK
By Leiden

+

JPA (quantum amplifier)
> 1 GHz
By collaboration w/ Tokyo Univ.
RIKEN

+

?

Large cavity

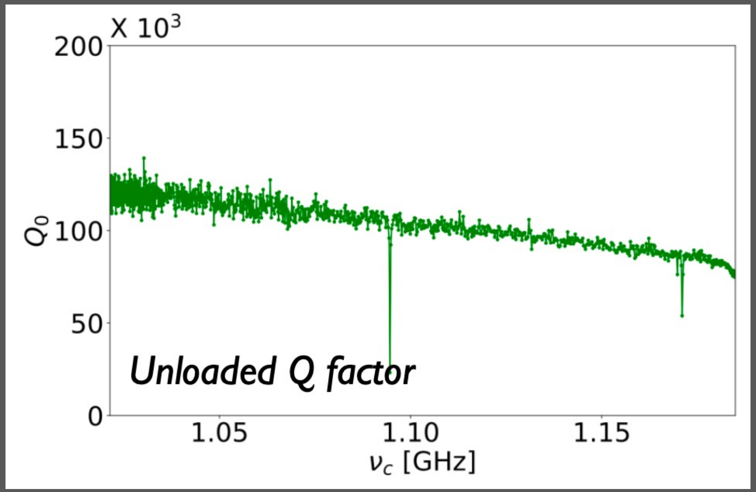
- maximum volume
- high Q
- easy cooling
- frequency tunable

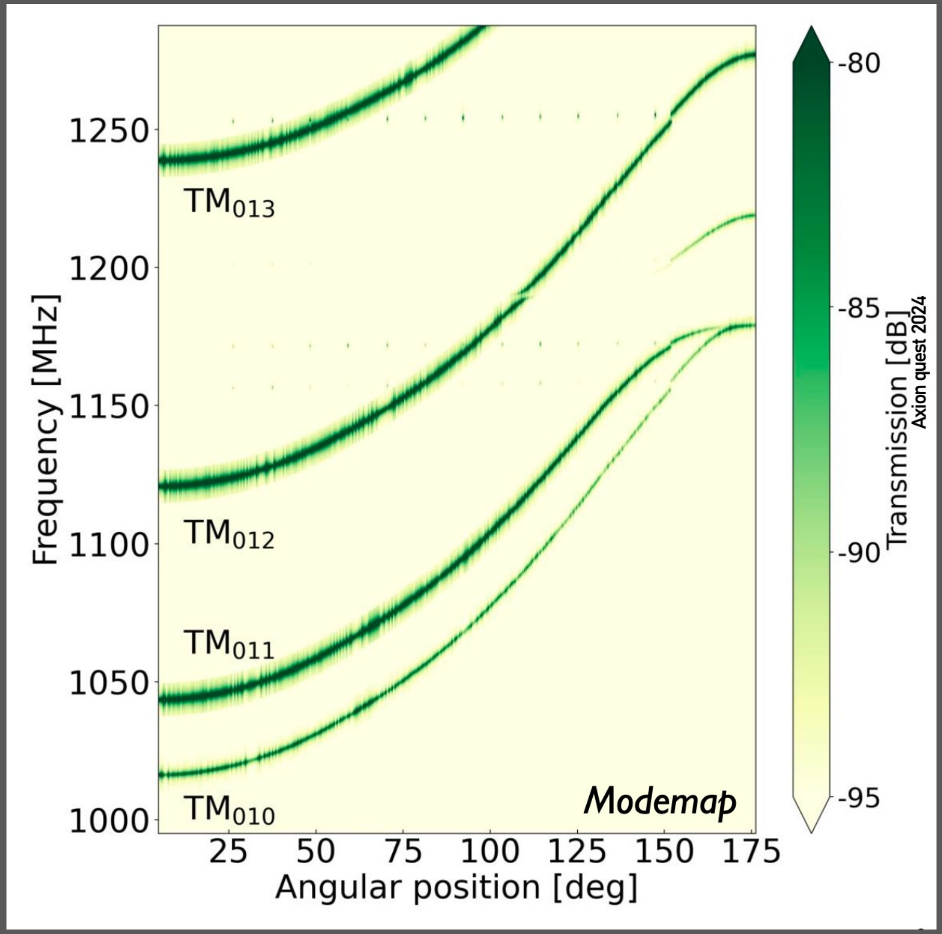
Ultra-light cavity (ULC) for CAPP-MAX

*Phys. Rev. Lett. 130, 071002 (2023).

**Phys. Rev. X 14, 031023 (2024)

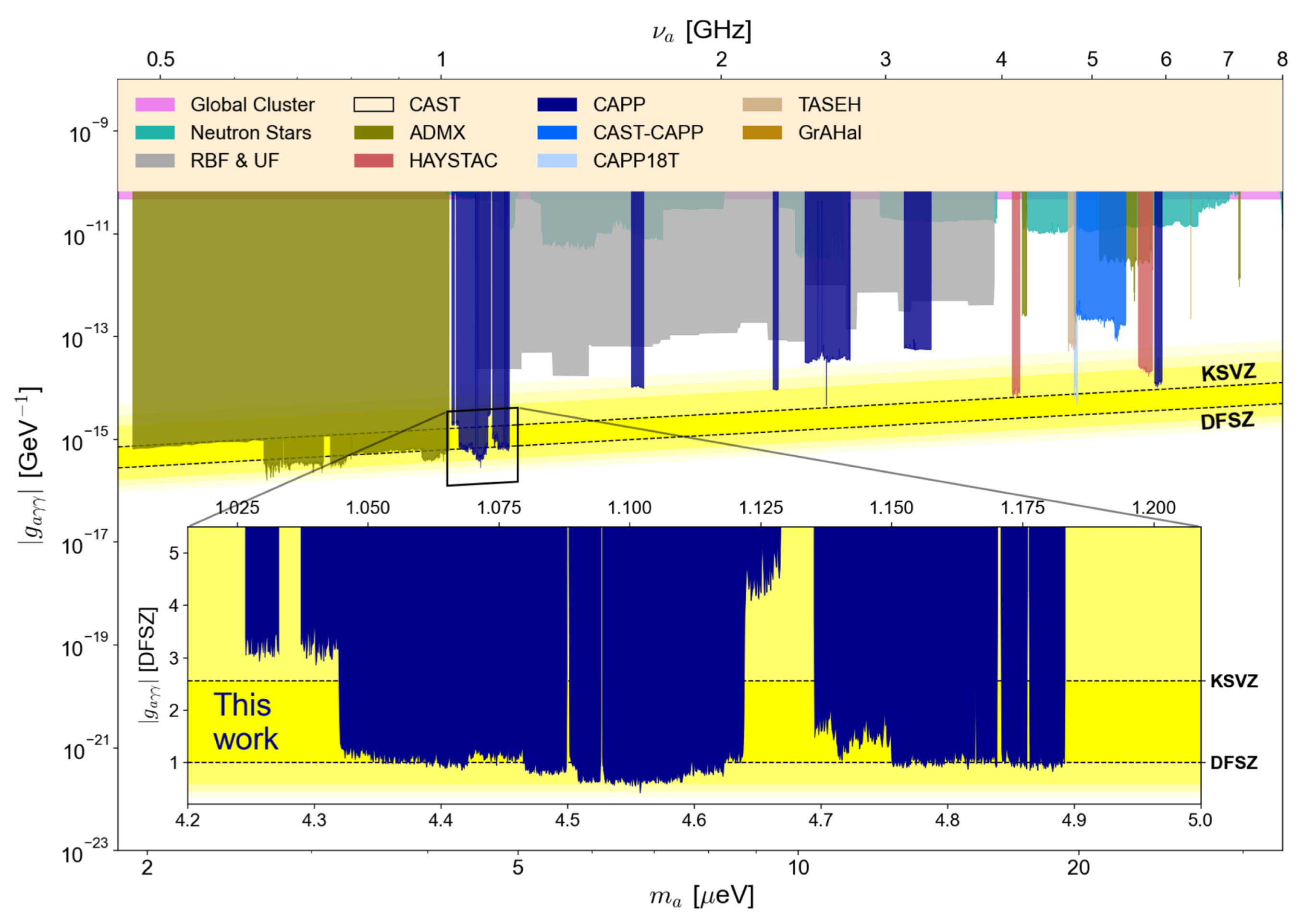
- 37L, total ~6kg
  - Easy tuning
  - Fast cooling
- Q_0 > 170k w/o tuning rod
  >100k w/ tuning rod





Recent progress

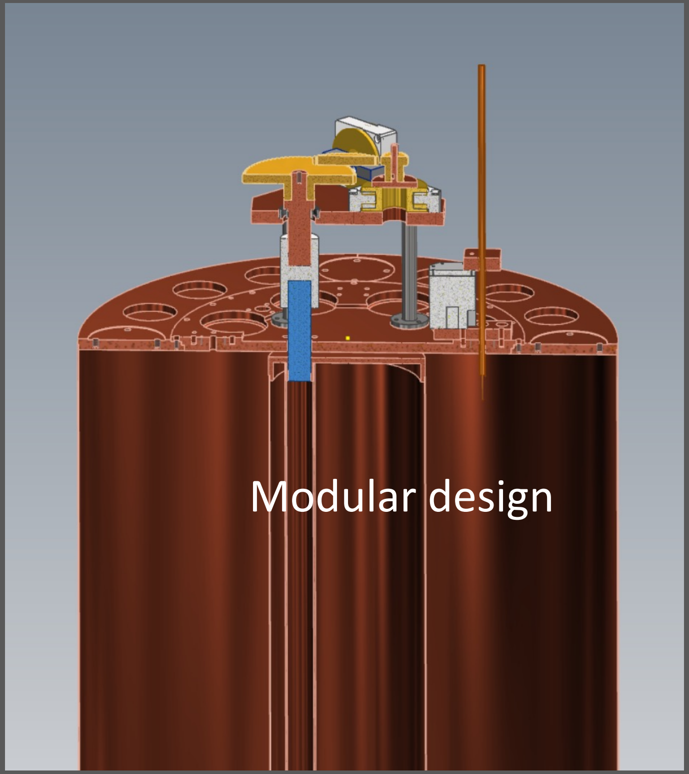
**Phys. Rev. X 14, 031023 (2024)

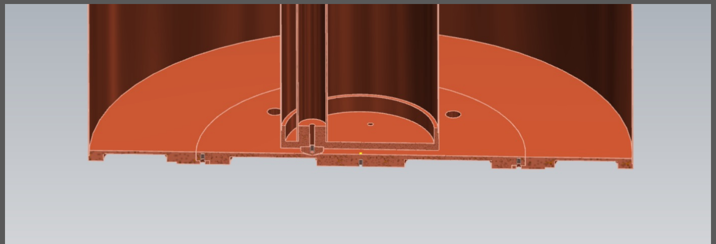


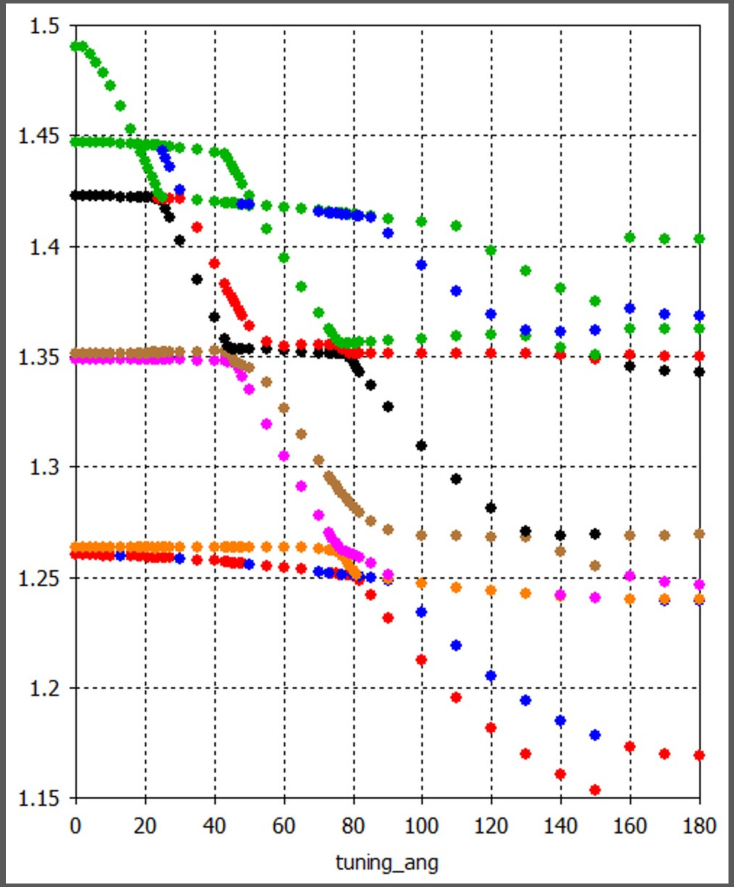
- 1.024-1.18GHz scan completed
- T_{phy} ~ 30mK
- T_{sys} ~ 230mK
- 3 parallel JPAs readout
- 3MHz/day in DFSZ sensitivity

1.2-1.5 GHz cavity for CAPP-MAX

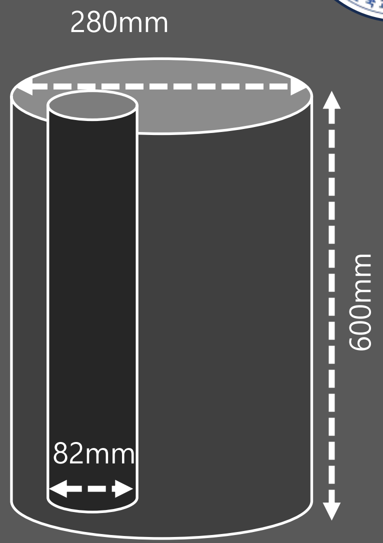
: Full HTS cavity

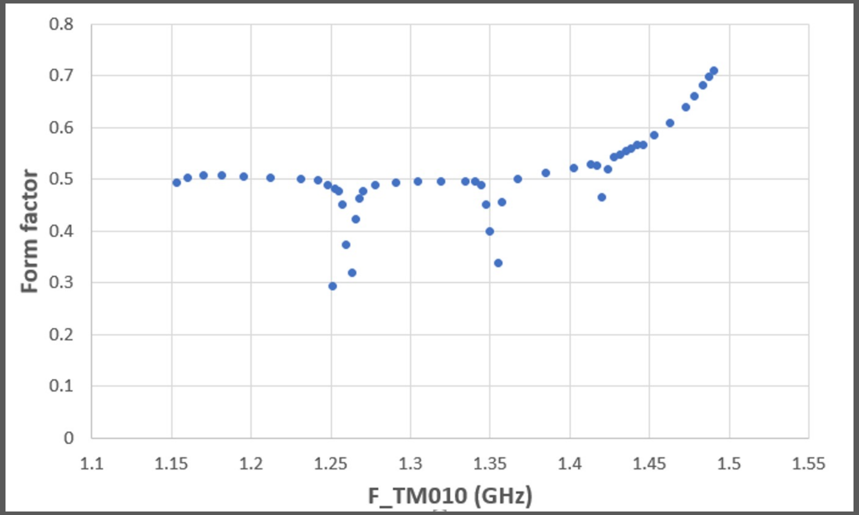






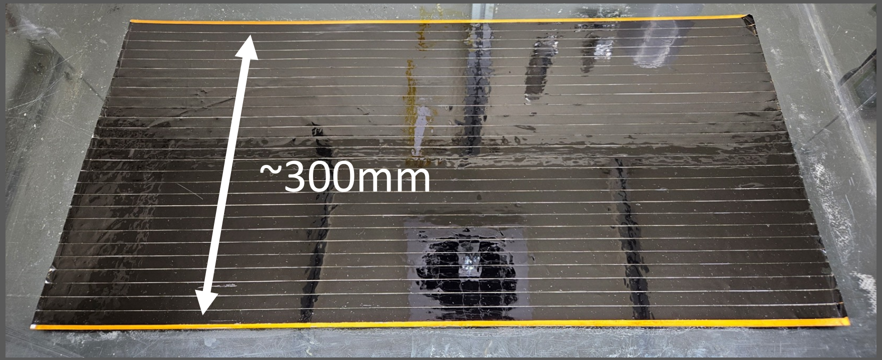
*CST MWS simulation

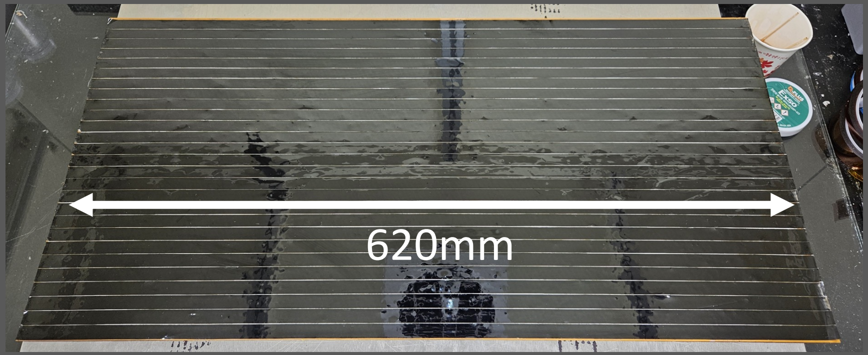




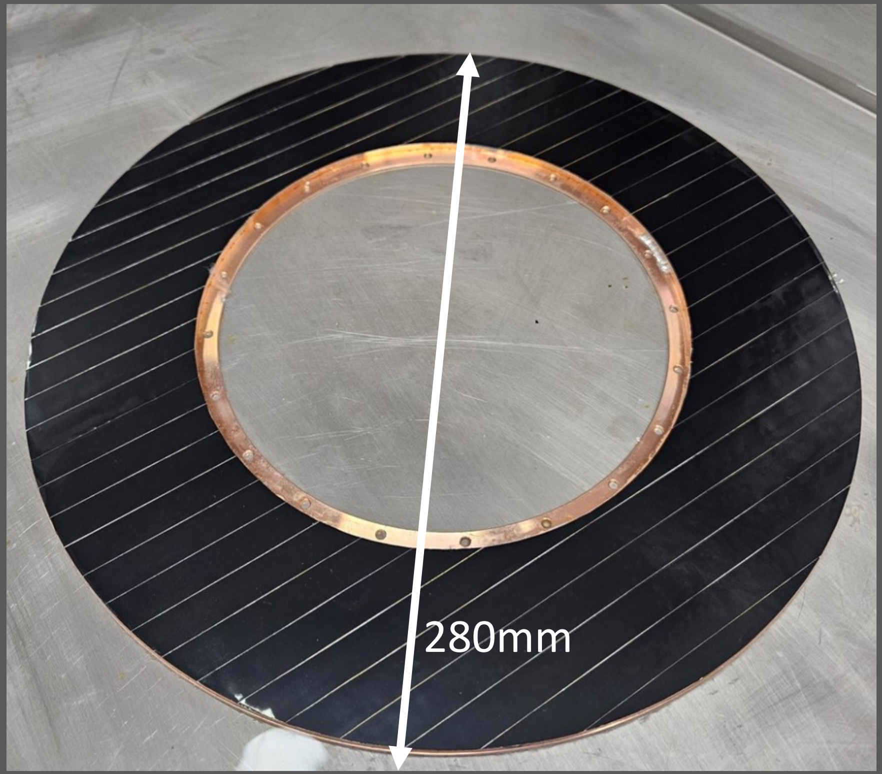
Covering HTS on copper parts

On side wall

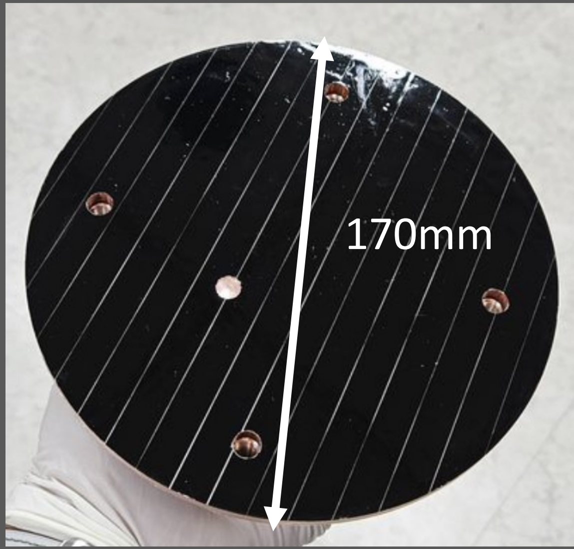




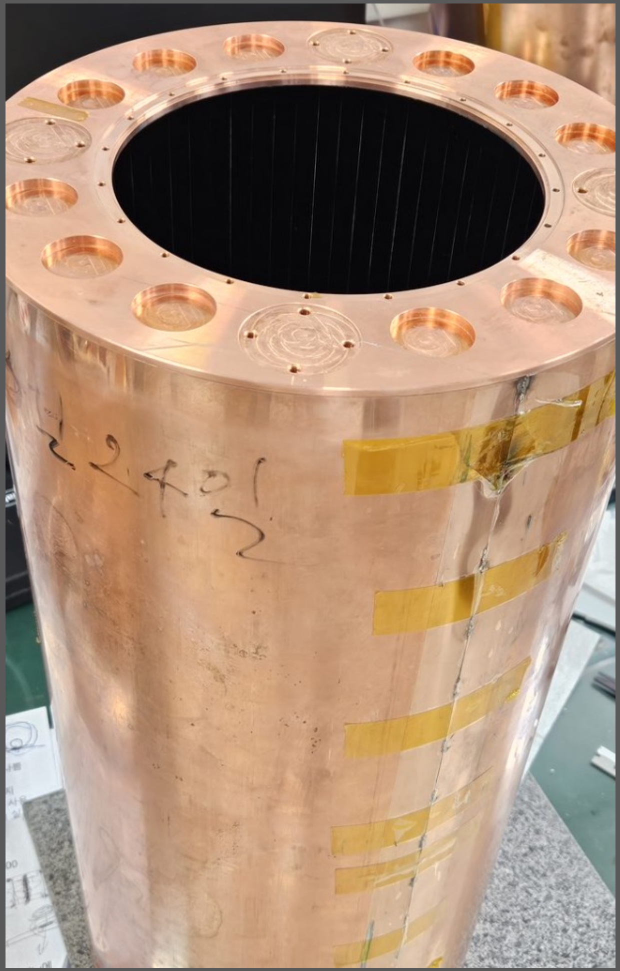
Cavity top-outer plate

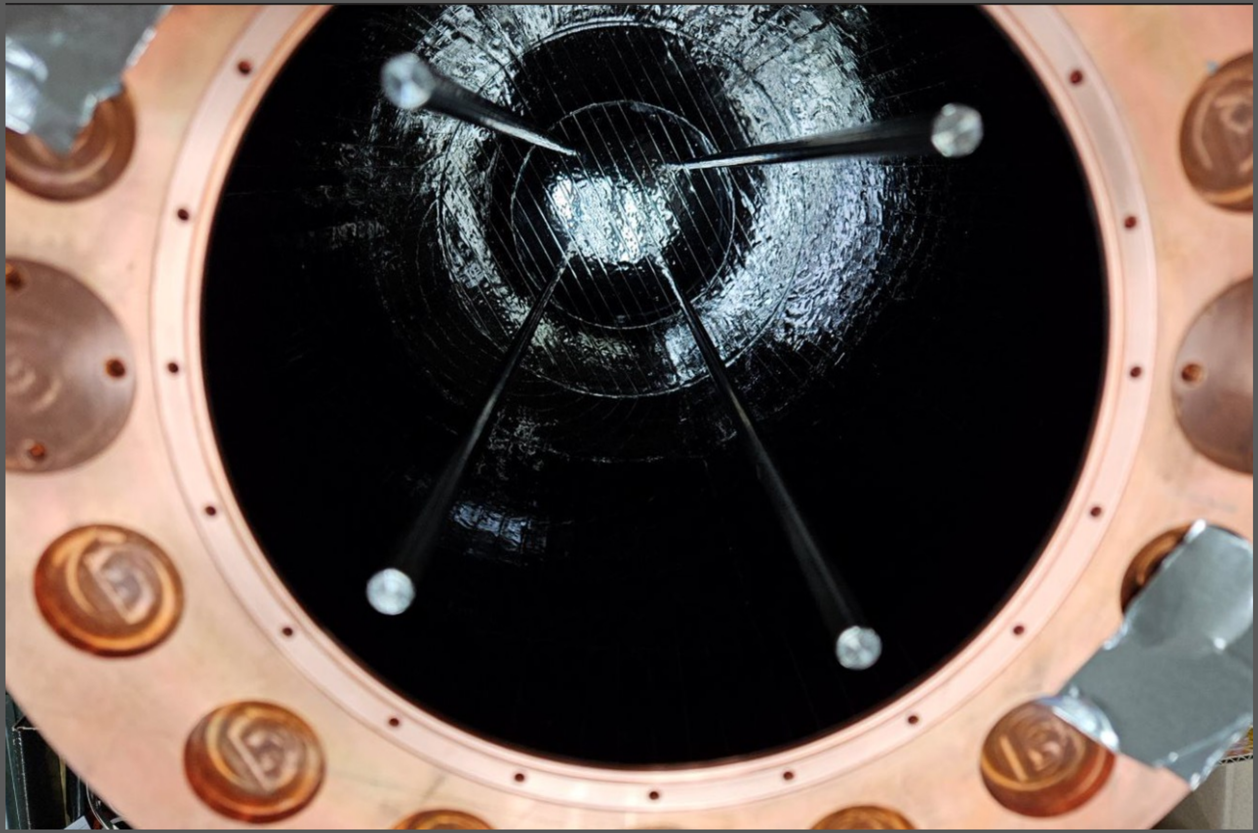


Cavity top-inner plate



Connecting to endcaps → cavity frame!

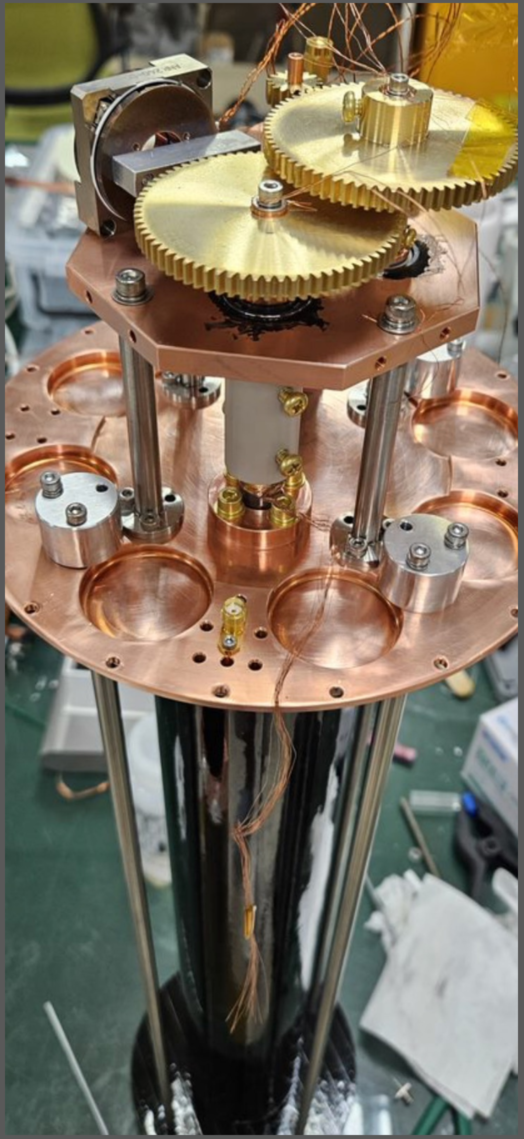




Tuning rod & gear box

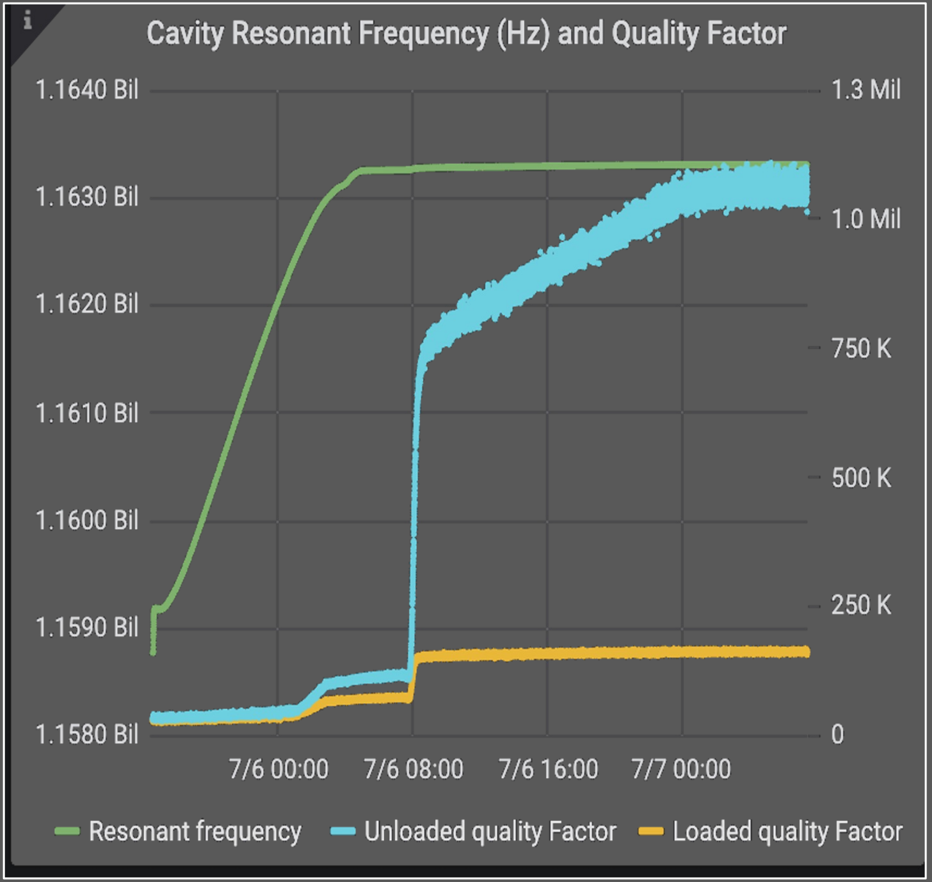
Gearbox (~1:20) is designed to move HTS tuning rod


82mm diameter of HTS tuning rod

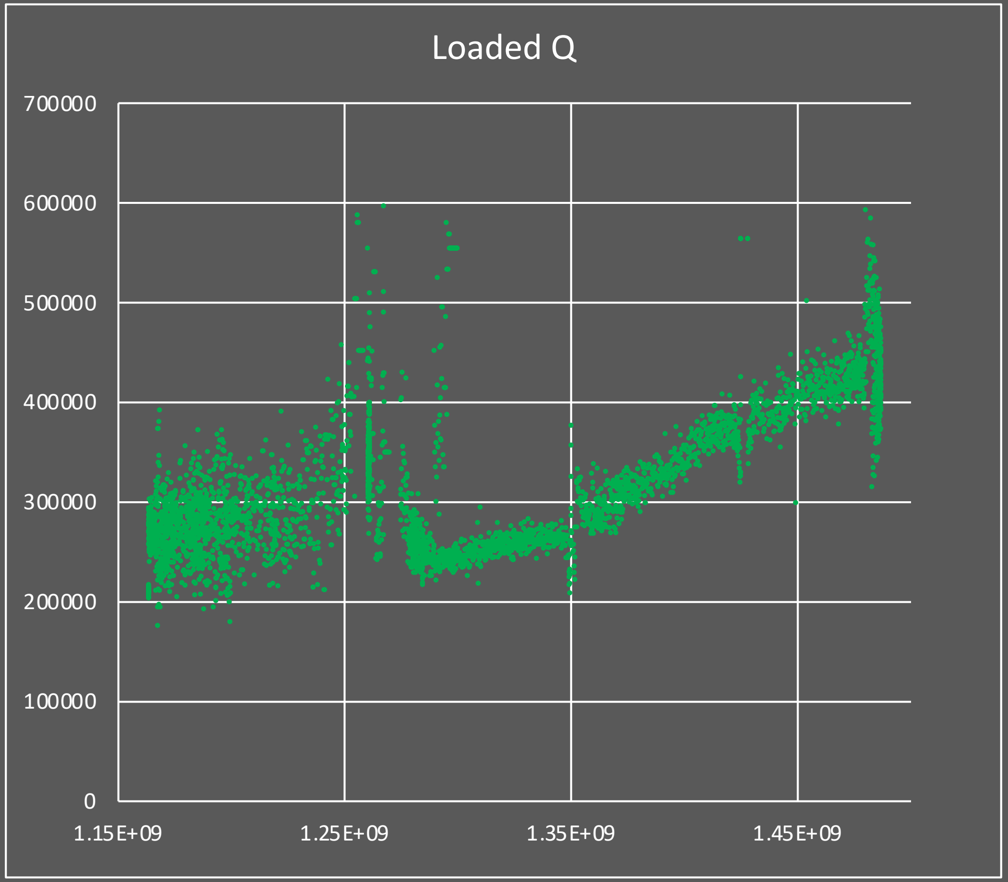


Full HTS cavity in CAPP-MAX system

During cooling down @1.163 GHz



w/ frequency tuning

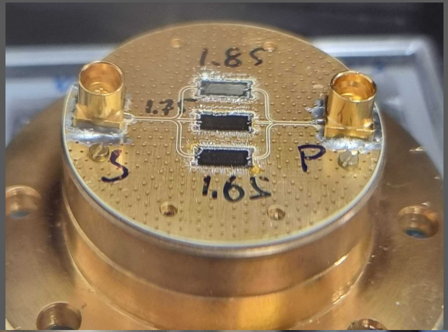


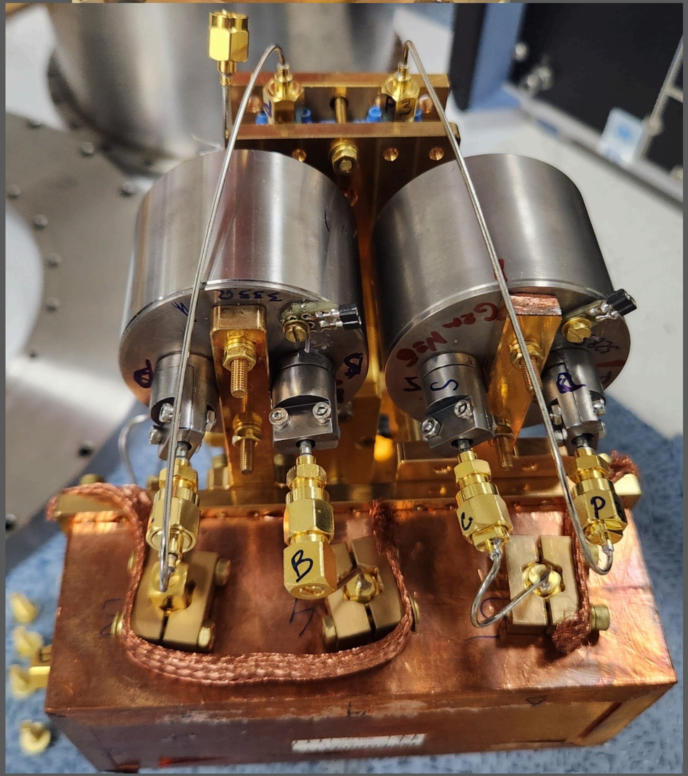
- **The unloaded Q-factor: 0.5 – 1.2 milion. $Q_{average}$ ~ 0.8milion**
- **Gearbox works well, *<u>20V</u>* piezo bias voltage can tune the cavity**

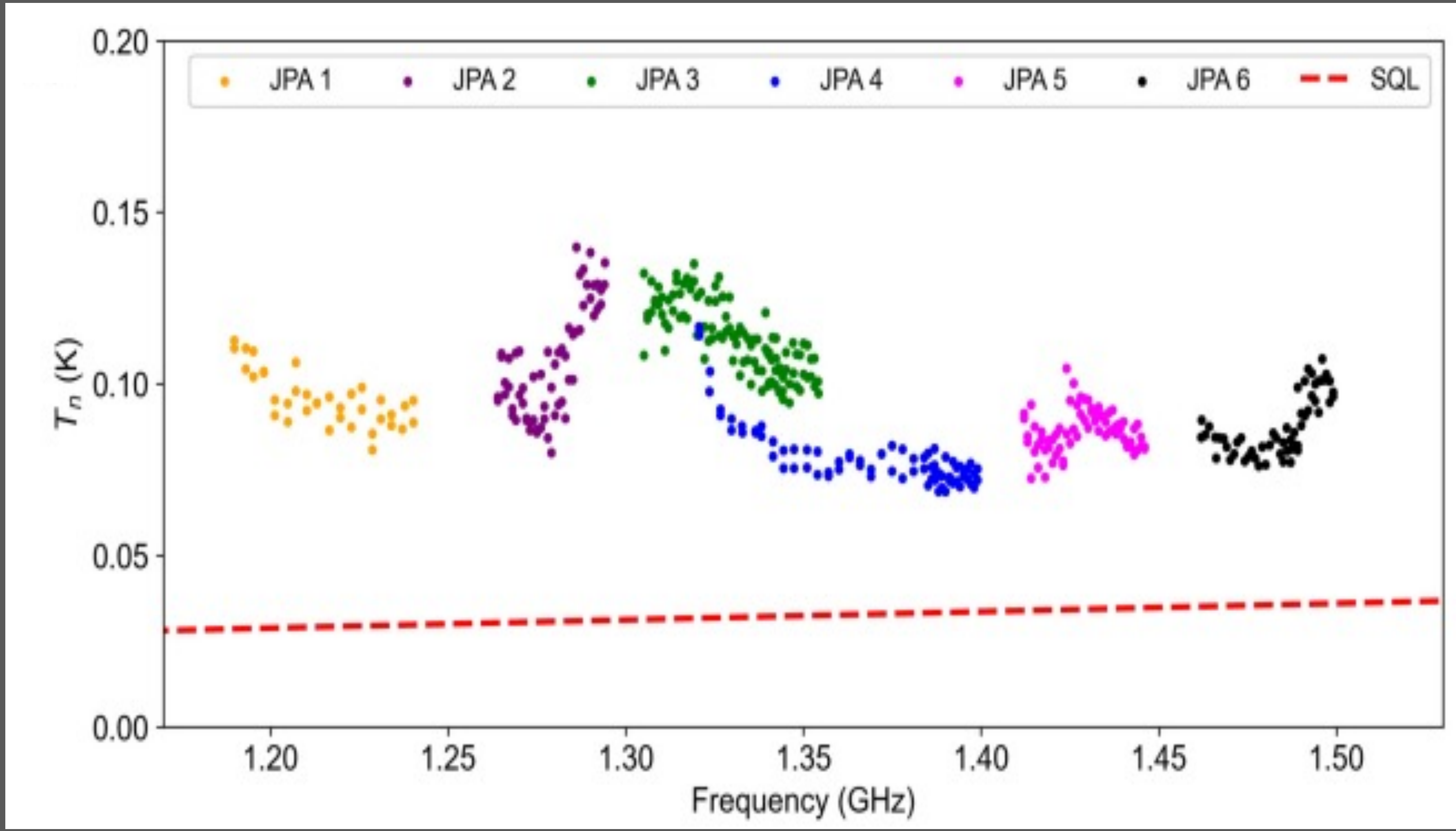
Combined efforts on CAPP-MAX

CAPP-MAX run: 6JPAs are installed

(Dr. Sergey Uchakin presented on Tuesday)







CAPP-MAX run: Q-factor w/ Bfield

The engineering run has started

w/ 11.2 tesla,
we achieved 1M around 1.3GHz

CAPP-MAX specification

	This run	Previous run
Frequency range:	1.2-1.49 GHz	1.02-1.18 GHz
MXC temperature:	22 mK	MXC temperature: 30 mK
Cavity top temperature:	25 mK	Cavity top: 40 mK
Cavity bottom temperature:	45 mK	Cavity bottom: 45 mK
System noise:	~210 mK	System noise: ~230 mK
Average B-field:	10.8 tesla	Average B-field: 10.5 tesla
Cavity volume:	33.8 liter	Cavity volume: 37 liter
Cavity Q-factor:	**600k-1.2M**	110k

Engineering run has stared!

1. w/ 0-field

We took darkphoton data around 1.49GHz

2. w/ 11.2 tesla-field

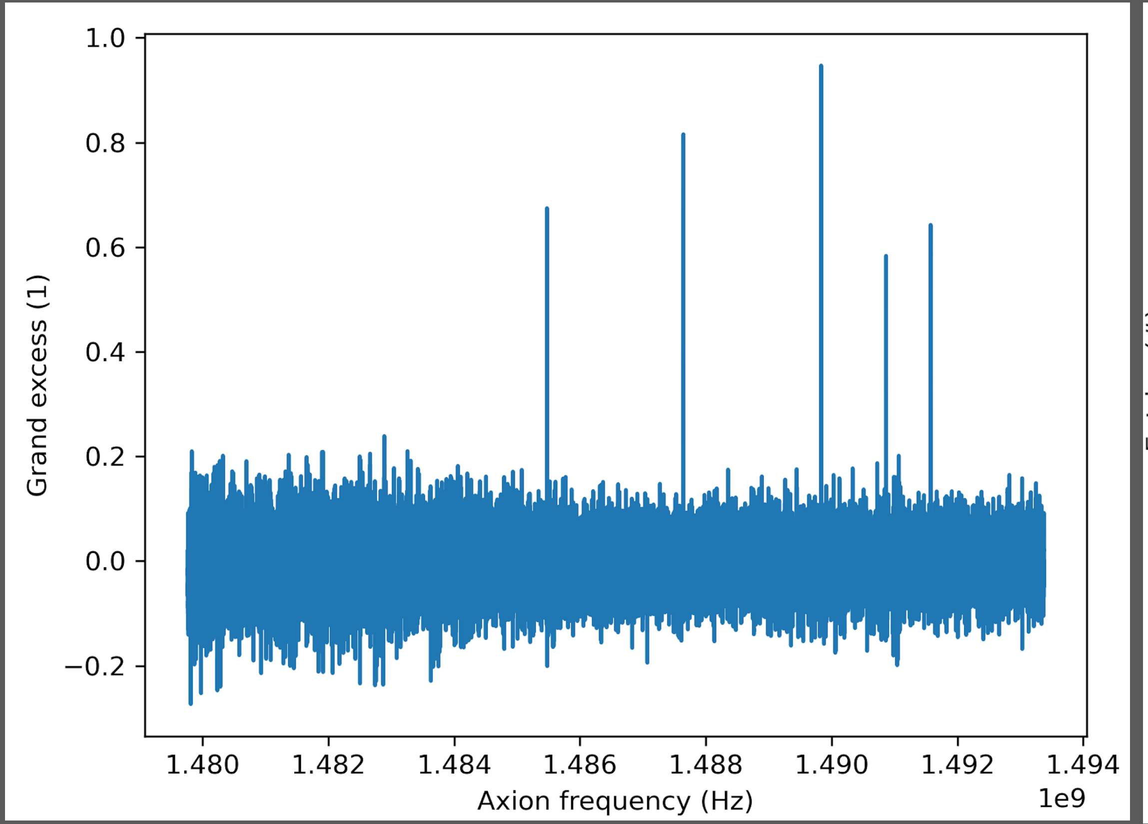
We took data around 1.3GHz

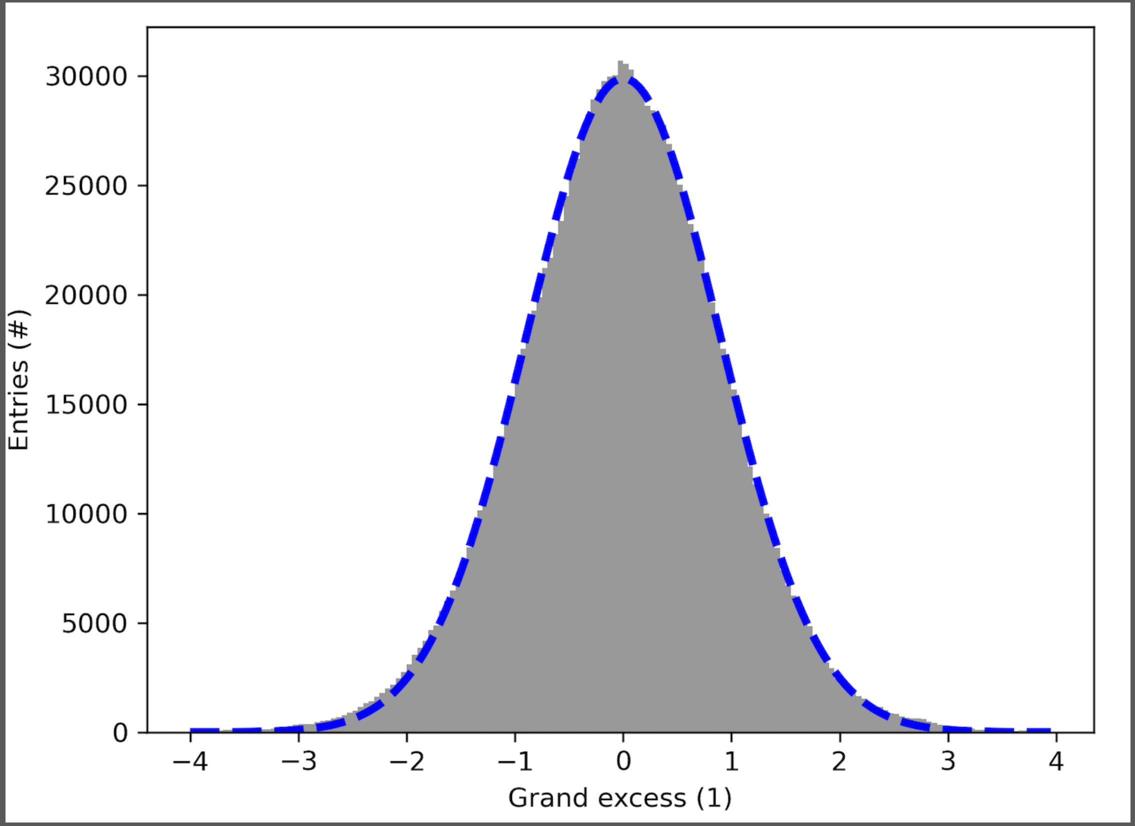
- Data taking time in each step: ~30seconds
- Tuning step: 2kHz
- Bin size : 10Hz
- Time efficiency: ~0.7

3MHz per day with 0.6-7 DFSZ sensitivity

Engineering run has started

Pre-pre-pre… liminary grand spectra analyzed last night by Dr. Jinsu, Mr. Jiwon Lee



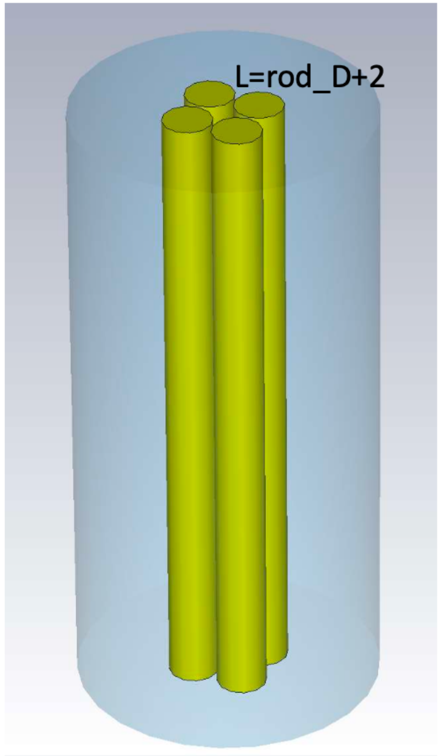


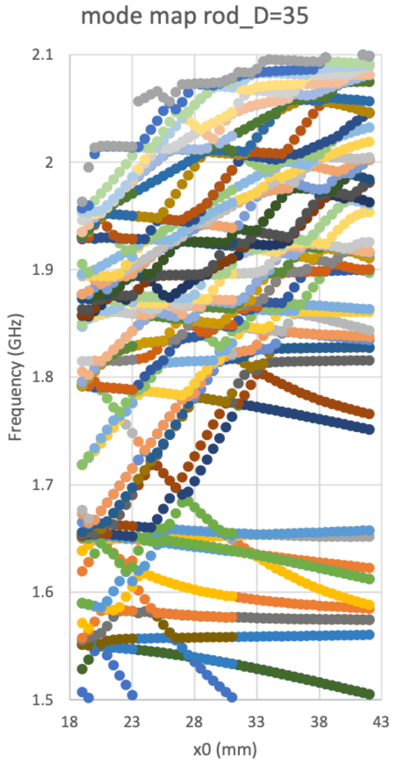
Next cavity..

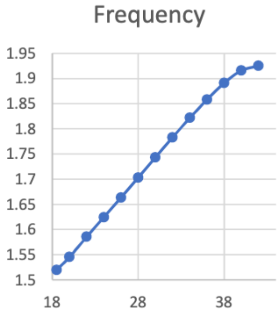
When # of rods = 4, very promising

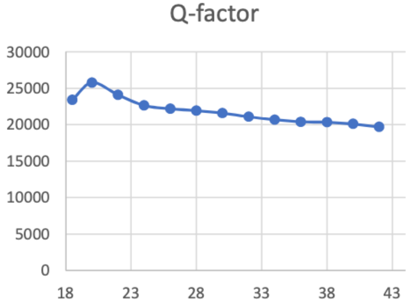
They tune the cavity frequency as one single rod becomes bigger

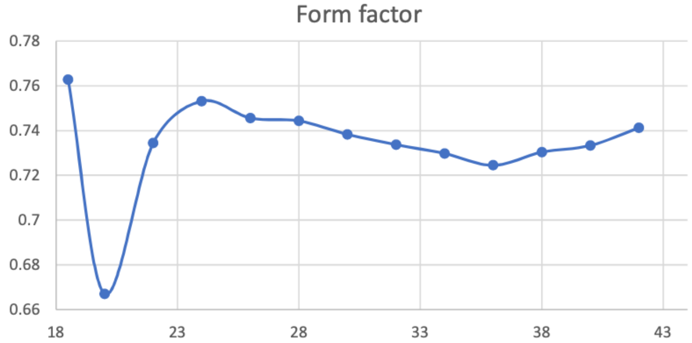
When cav_D= 273, rod_D=35











CST MWS result

Summary

- High Q-factor cavity boost axion scanning speed.
- HTS-ReBCO is the promising material for high Q-factor within a strong magnetic field.
- CAPP has achieved 10^7 Q-factor even inside 8T magnetic field.
- Large size (>30L) HTS cavity is assembled for 1.2-1.5 GHz and the Q-factor of the cavity is around 10^6 in the 11.2 tesla magnetic field
- Engineering run is underway!