CAPP
Center for
Axion and Precision
Physics Research

Superconducting cavities in CAPP

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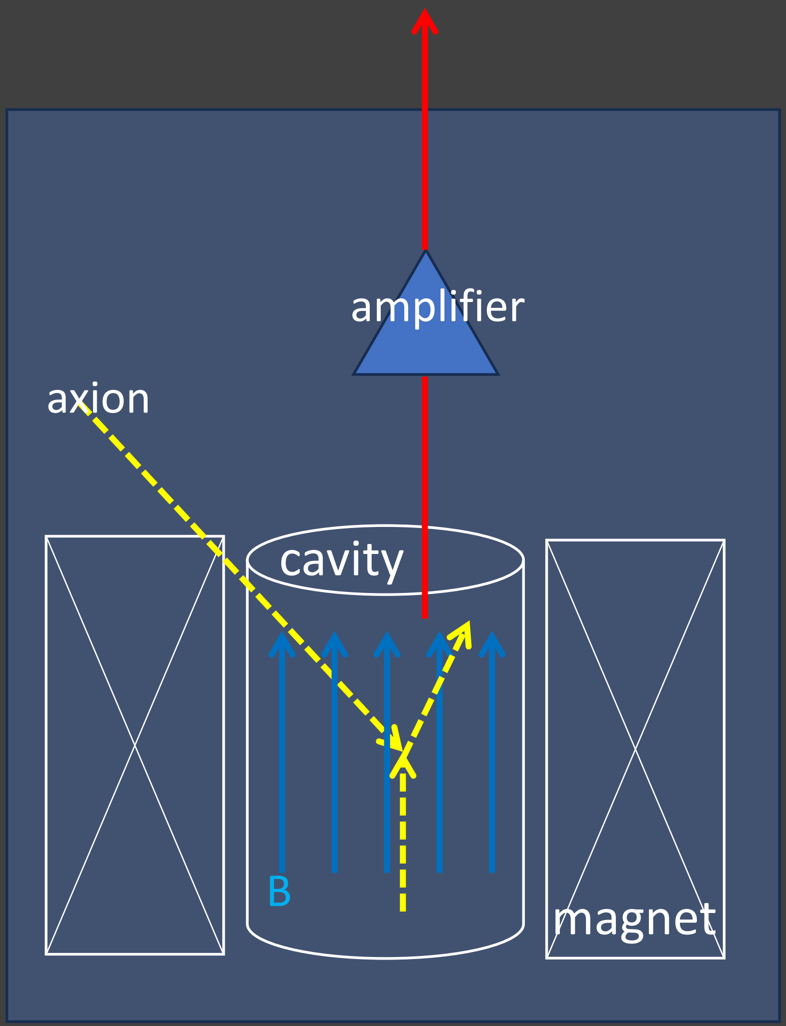
- Summary

Axion haloscope



D. kim, et al (2020)

Axions conversion power

$$P_{signal} = \frac{\beta}{1+\beta} g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a} B^2 V C \frac{Q_l Q_a}{Q_l + Q_a}$$

- $g_{a\gamma\gamma}$: coupling constant
- C : Form factor of the cavity mode ※ 0.6 for TM_{010} mode
- V: Cavity volume ※ 35L for ULC
- T_{sys} : Noise temperature
- B : Applied B-field ※ 12T for CAPP-MAX
- Q_l : Cavity Q-factor ※ 100k for Cu ULC

Scan rate

$$\frac{df}{dt} \propto \frac{B^4 C^2 V^2}{T_{sys}^2} Q_l$$

Goal: Making High-Q superconducting cavities that can withstand high B-field are required.

High Q factor 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 $Q_{cavity} << Q_a$

$$P_{signal} \propto Q_L$$

When $Q_{cavity} >> Q_a$

$$P_{signal} \propto Q_a$$

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

R. Cervantes et al., arXiv:2208:03183

Superconductor in a magnetic field

- ***Type I***

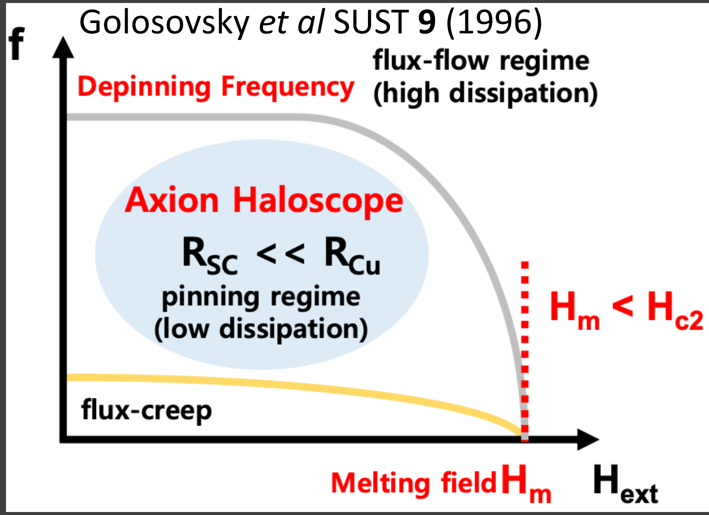
  $T_c < 10$ K

  $H_c << 1$ T

  Eg. Hc_{Al}: 0.02 T $Q_{Type1} < Q_{Cu}$ in $\mathbf{B_{ext}}$

  CANNOT use in axion haloscope search

- ***Type II*** Type II superconductors form vortices in a magnetic field.
  - ✓ Stronger B field → More vortices ➔ Higher dissipation
  - ✓ **Vortex pinning** reduces the vibration of vortices ➔ Less dissipation.



- Two criteria for evaluating materials
  - ✓ **Large upper critical field (H_{c2})**
  - ✓ **High depinning frequency**

High-temperature superconductor (HTS): ReBCO

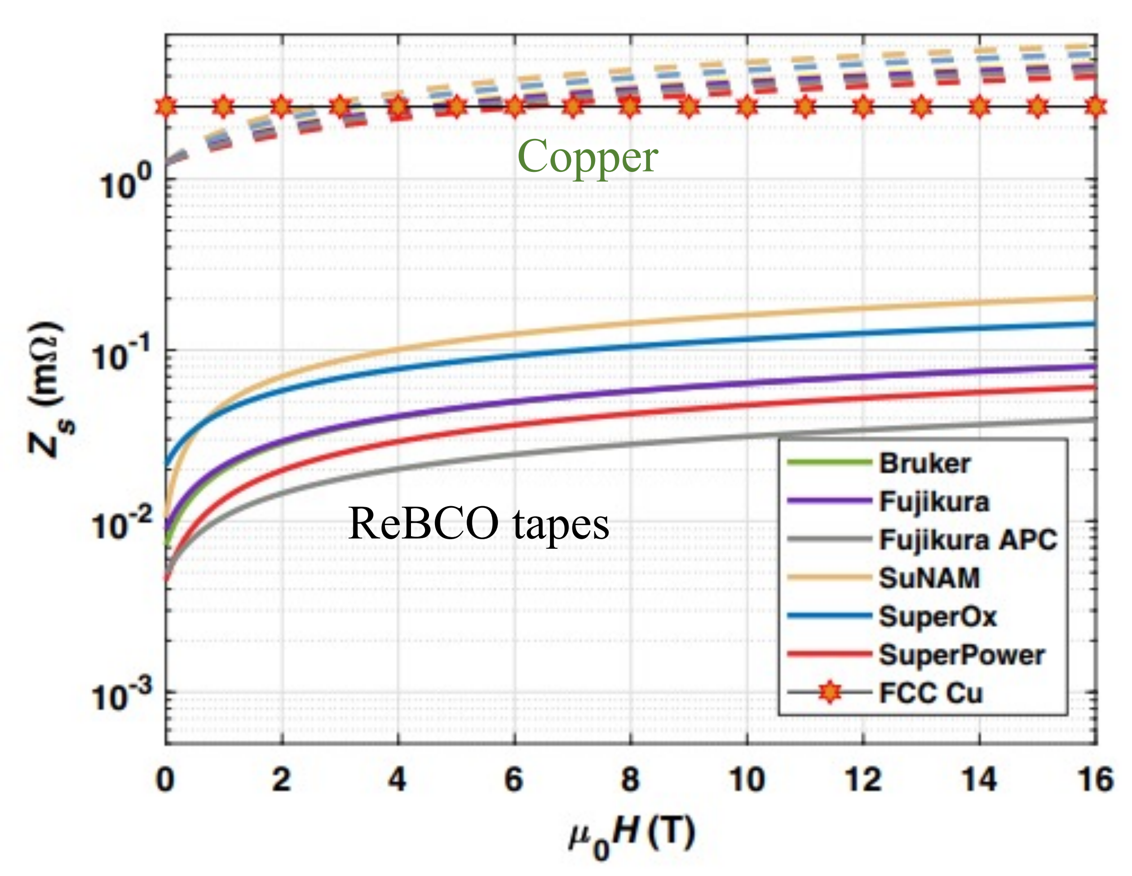
	100 mK 8 GHz	R_s (B = 0 T) (Ohm) (ref. Rs_{Cu}~7e-3)	R_s (B = 8 T, ∥c) (Ohm) (ref. Rs_{Cu}~7e-3)	Critical Field (H_{c2})	Depinning Frequency
*LTS	Nb	~ 1E-6			
	NbTi Gatti *et al*. PRD(2019)	~ 1E-6	~ 4e-3	~ 13 T *small*	~ 45 GHz
	Nb_3Sn Alimenti *et al*. SUST(2020)	~ 1E-6	?	~ 25 T	~ 6 GHz *small*
**HTS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

High-temperature superconductor (HTS): ReBCO

From Dr. Danho Ahn's slide

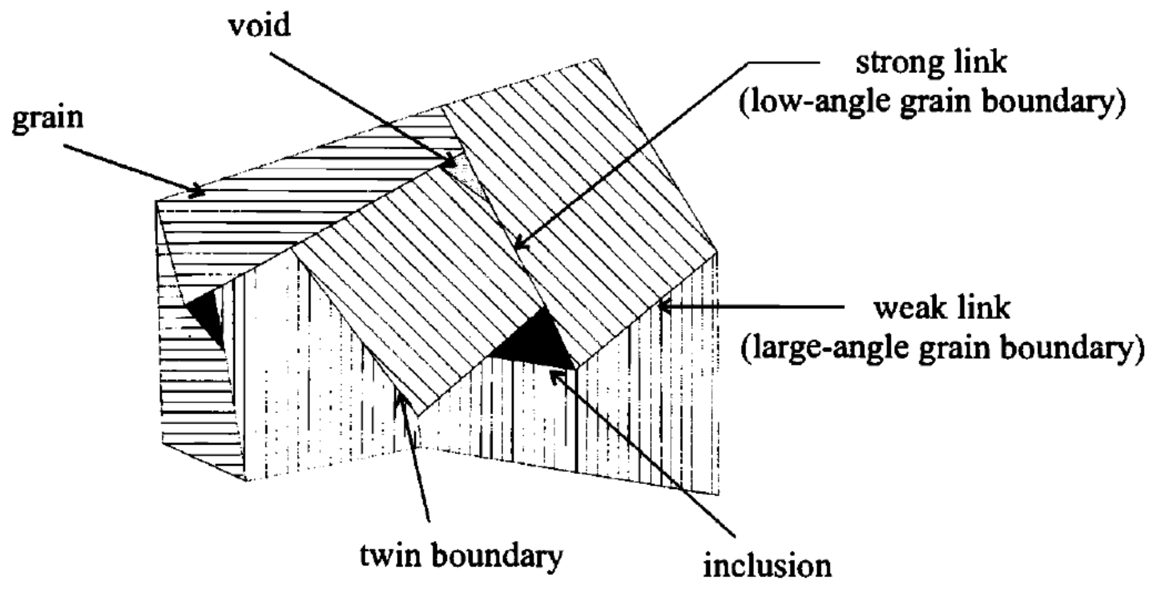


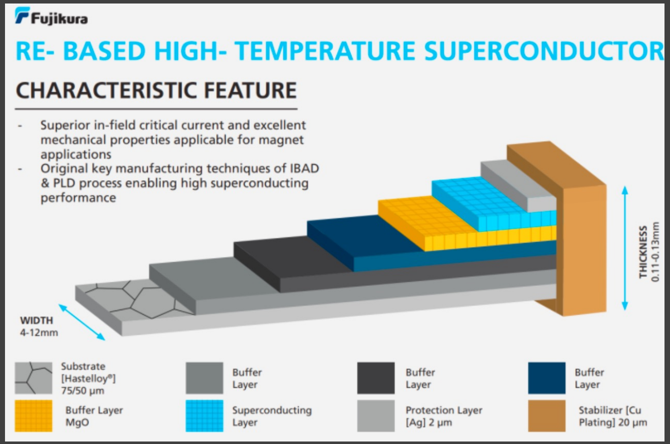
А.М. Романов, et al (2020) $T = 50K, \nu = 1GHz$

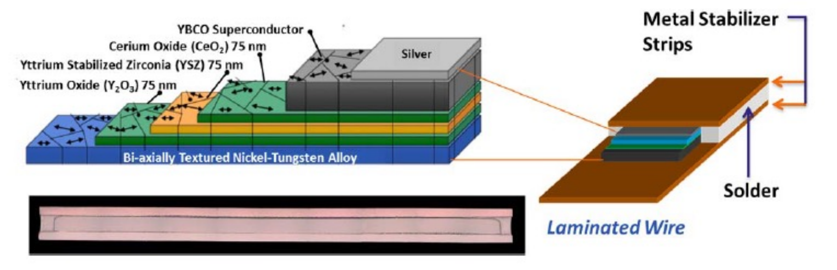
ReBCO (HTS) wins !

Biaxially-Textured ReBCO

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







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

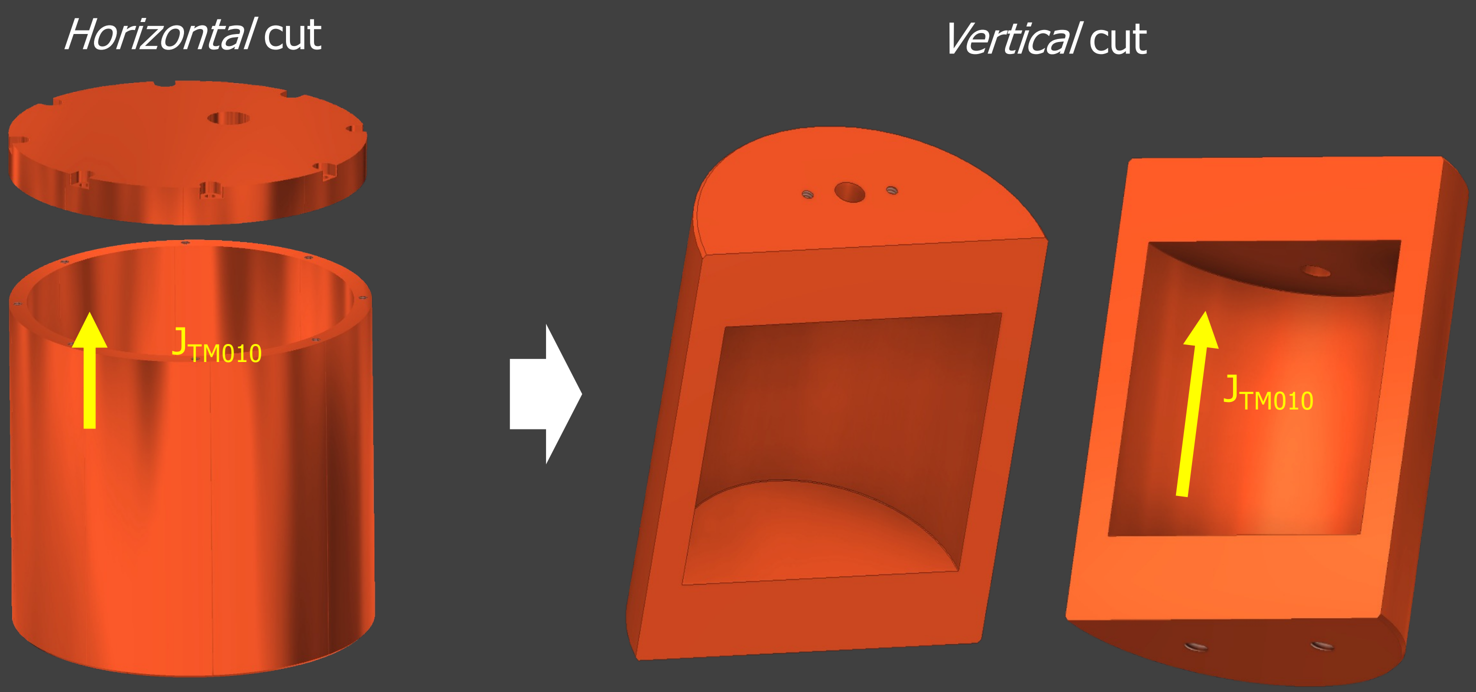
Multi-layered structure

- ✓ Weak links at grain boundaries degrades surface resistance.
- ✓ ***Biaxial texture is essential*** to avoid weak links

➔ Impractical to construct 3D microwave cavity

Split cavity maintains Q-factor if…

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



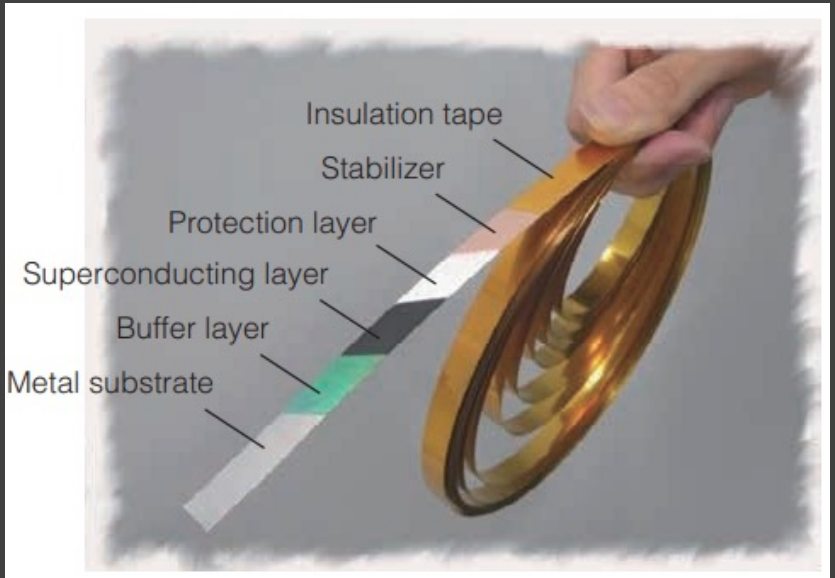
Parallel polarization of E-field and the cutting direction doesn't harm Q-factor much

* Phys. Rev. Lett. **126**, 191802 (2021)
** Phys. Rev. Lett. **125**, 221302 (2020)

Woohyun's innovative idea:
what if the cavity is composed of multiple pieces of HTS sheets or wires?

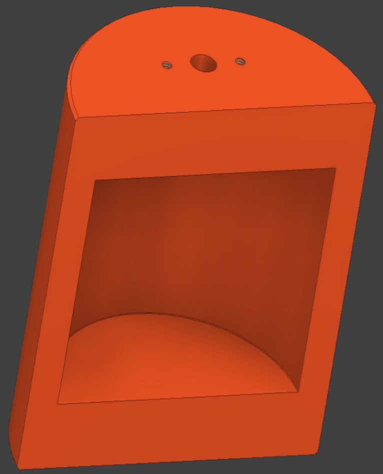
CAPP's recipe to make HTS cavity

Flexibility of the ReBCO film + split cavity structure

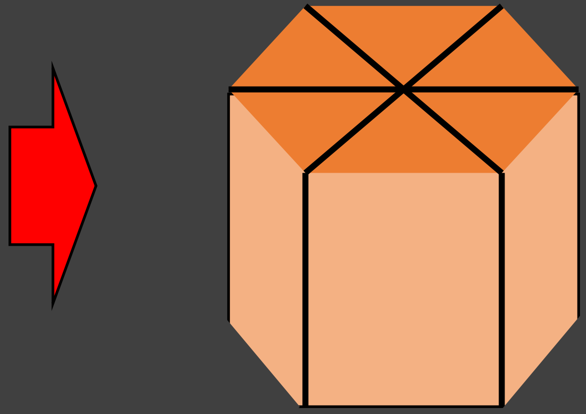


Well–textured **flexible ReBCO tapes**

+

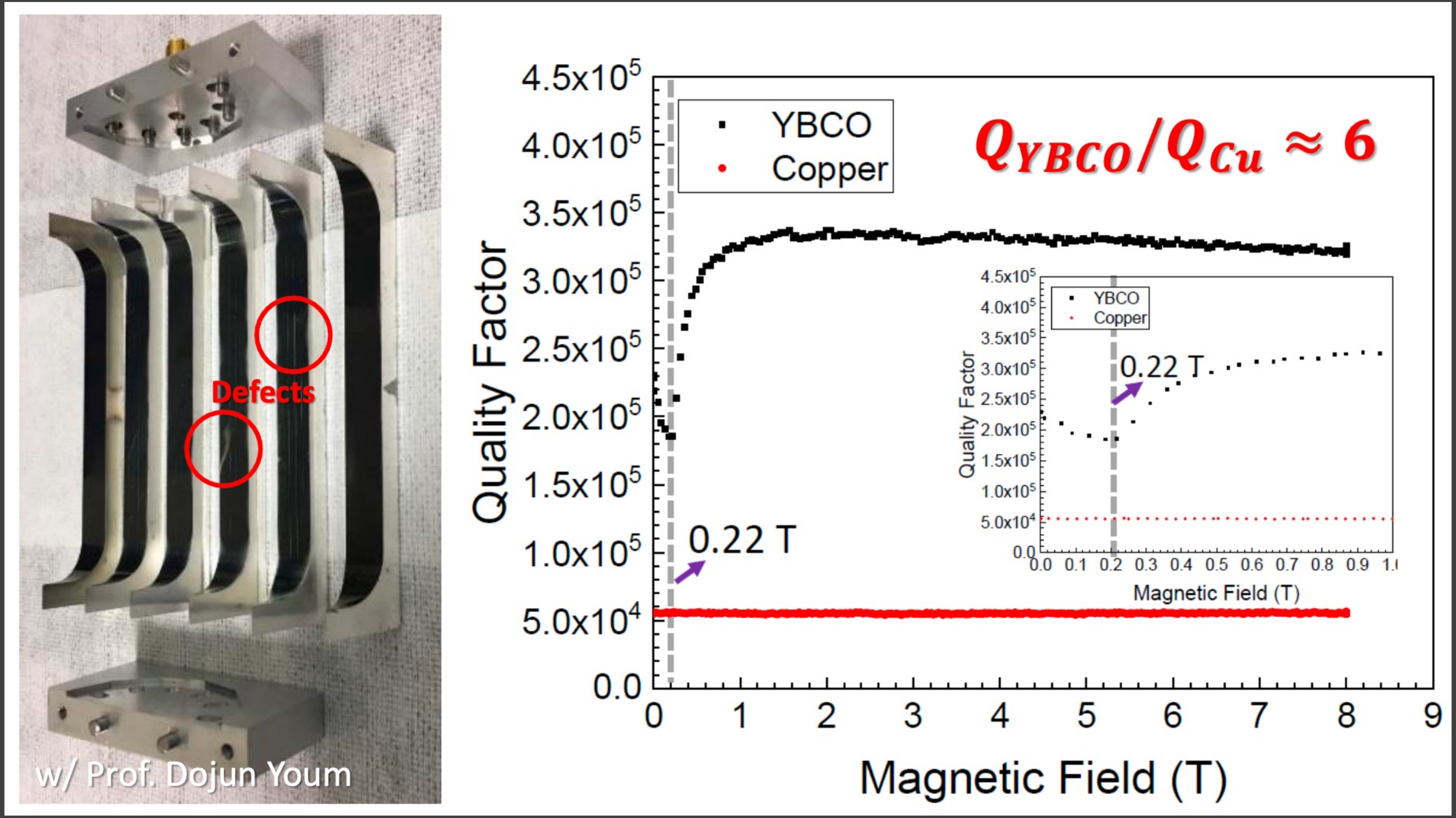


Split cavity structure



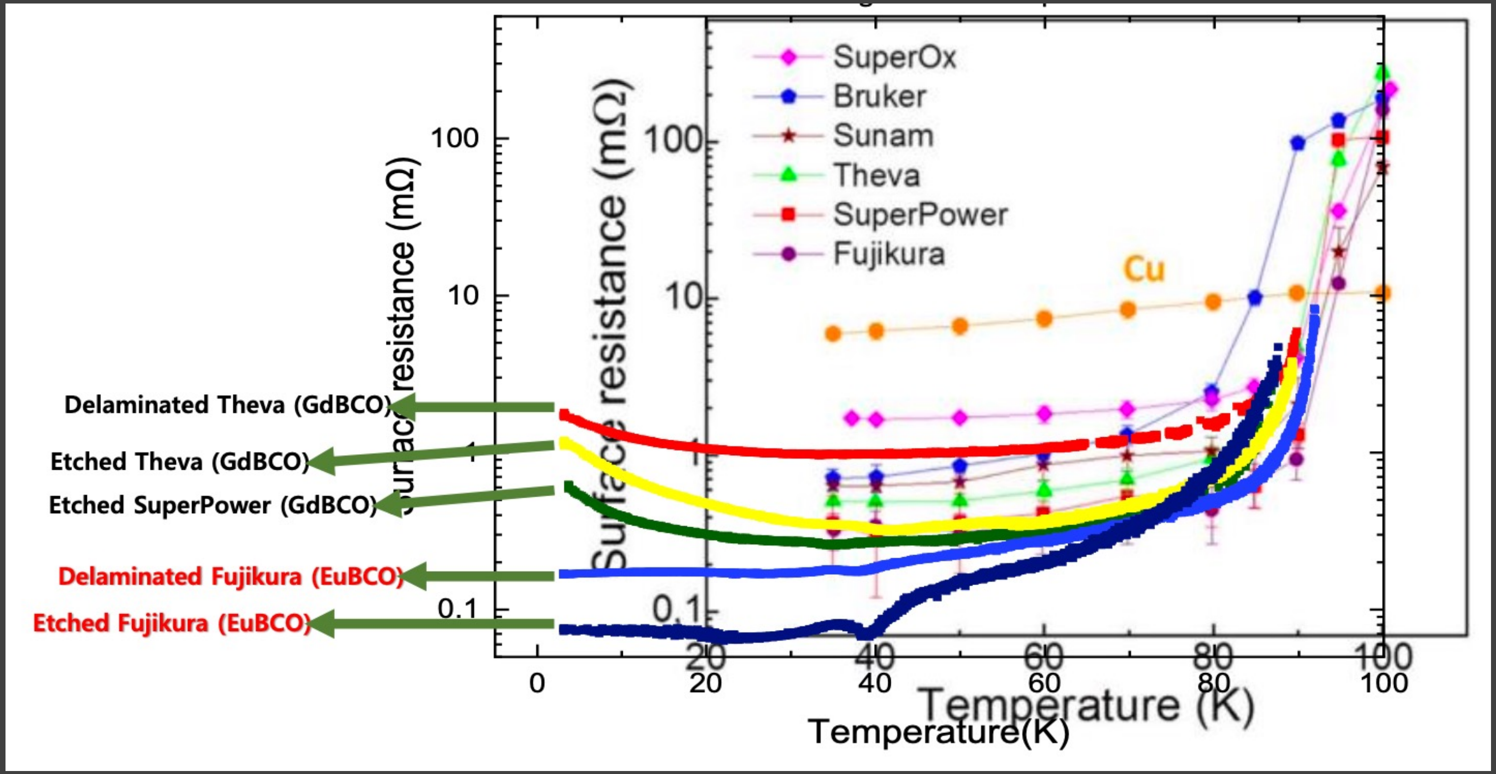
→ N-polygon structure with ***N*** gaps

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



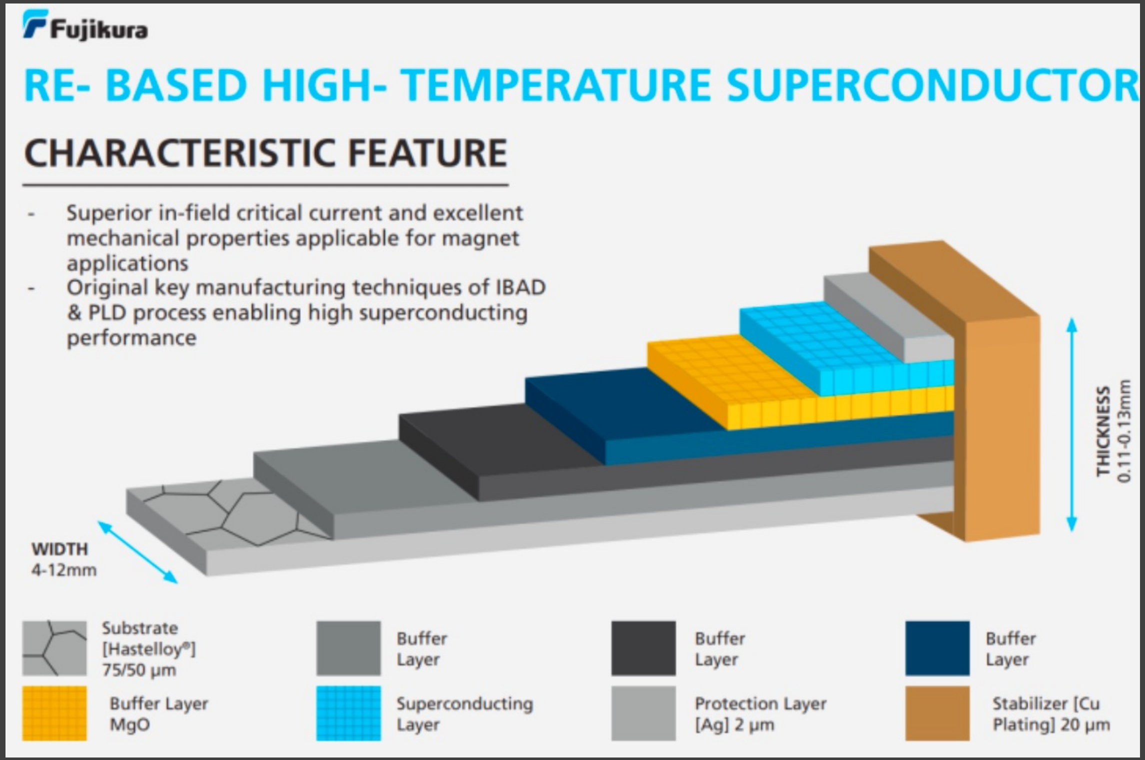
* Phys. Rev. A. **17**, L061005 (2022)

The Rs measurements show more!



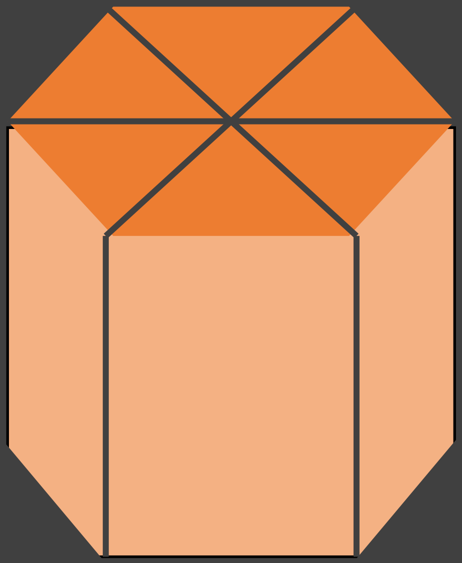
We may reach 10^8 ?

HTS cavity project: suppressing losses caused at HTS boundaries



- ~1um HTS layer
- Electrically open (buffer layer)
- High low substrate!
- Bigger loss at sharp edge..

HTS cavity project: suppressing losses caused at HTS boundaries



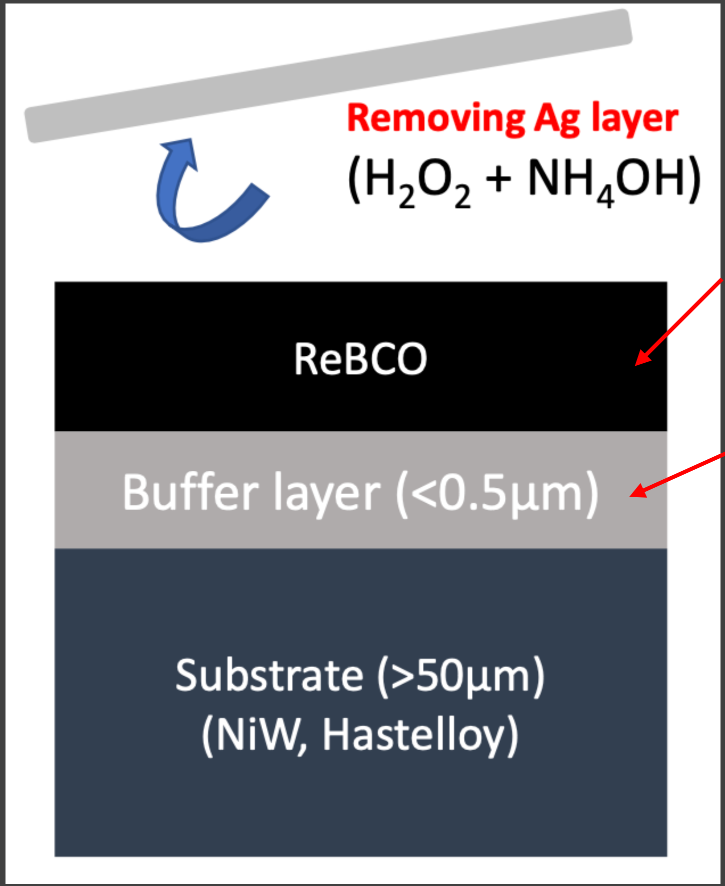
Major loss

- RF leak
- Thermal loss

Caused by
1. misaligment
2. Surface defect
   during etching or cutting

ReBCO preparation

Method 1



Only 1um thickness

Dielectric region

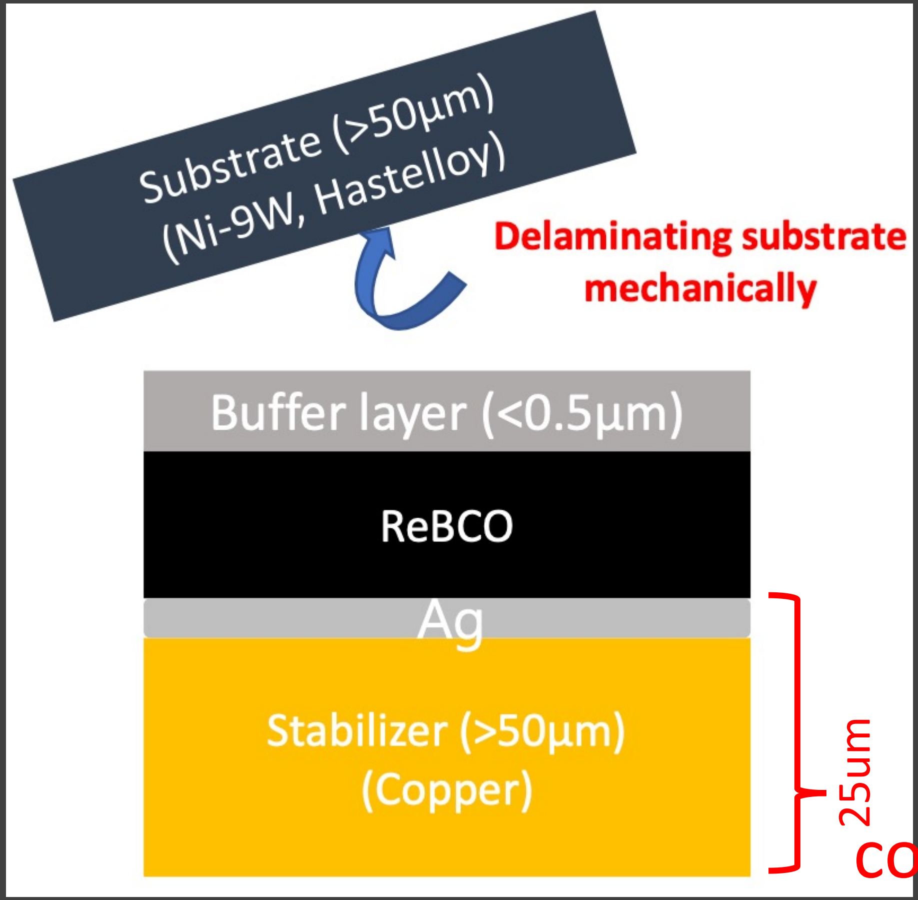
Electrically

disconnected!!

Pros: Easy handling

Cons: Easy to leak RF

Method 2



Electrically

connected!!

Pros: better to keep RF, less loss below HTS

Cons: harder handing

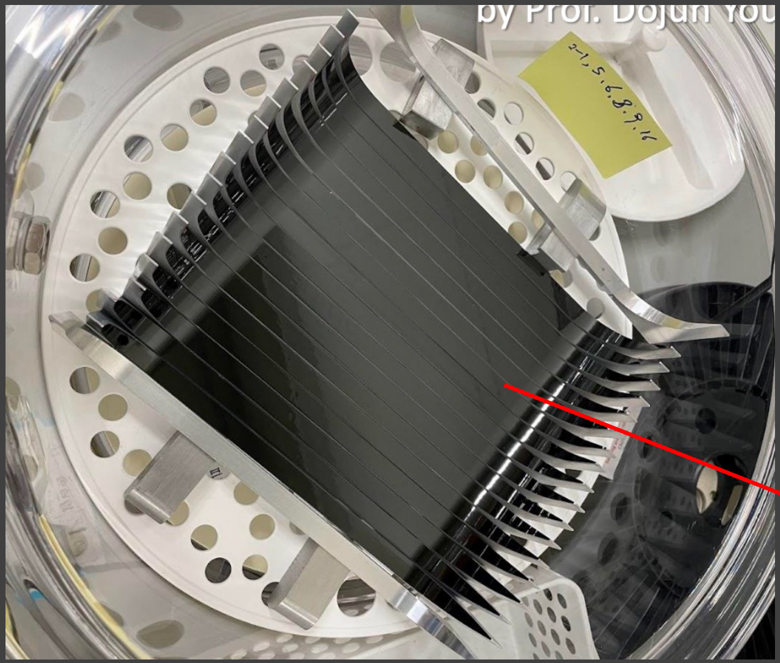
CAPP's two tracks strategy

1st track: The Highest Q-factor in a magnetic field

Fabricating a perfect unit

→ perfect alignment

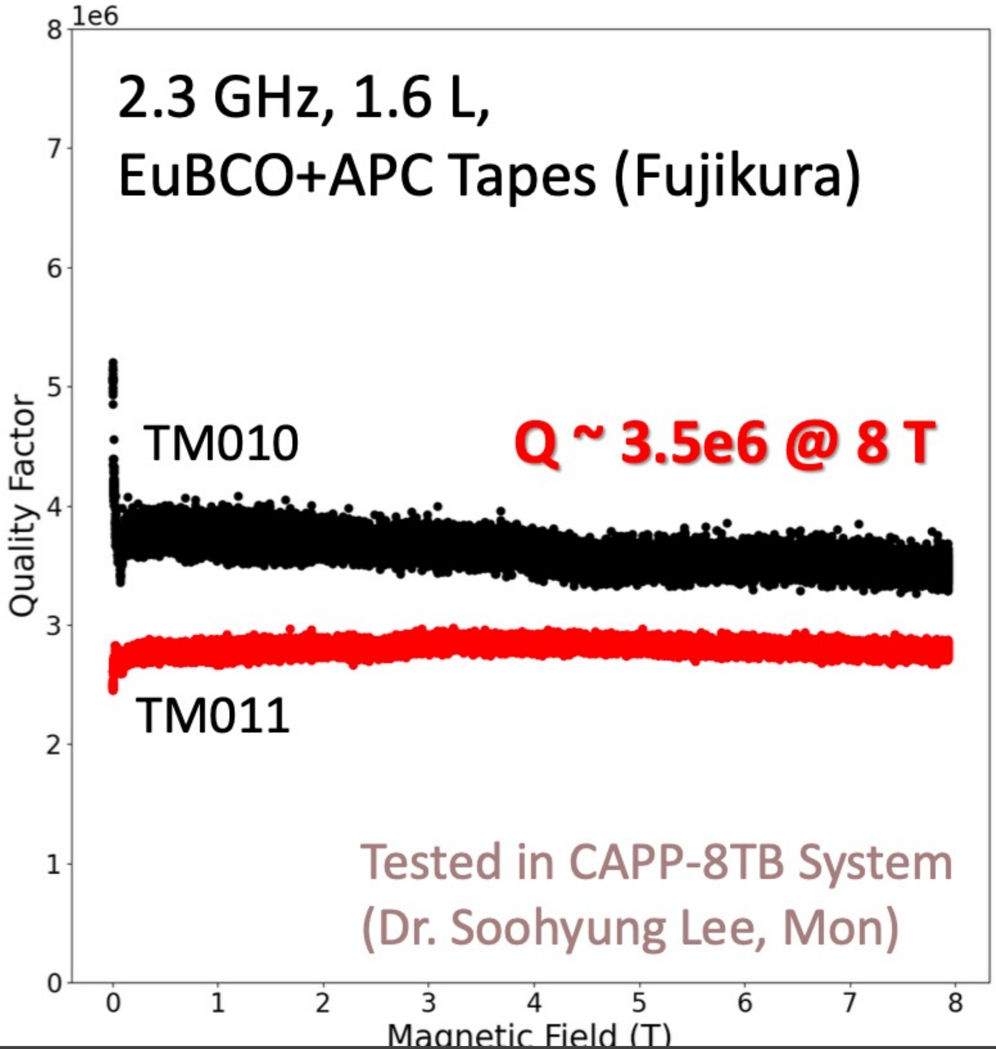
→ Construct cavity with minimum defect or non-ReBCO area.



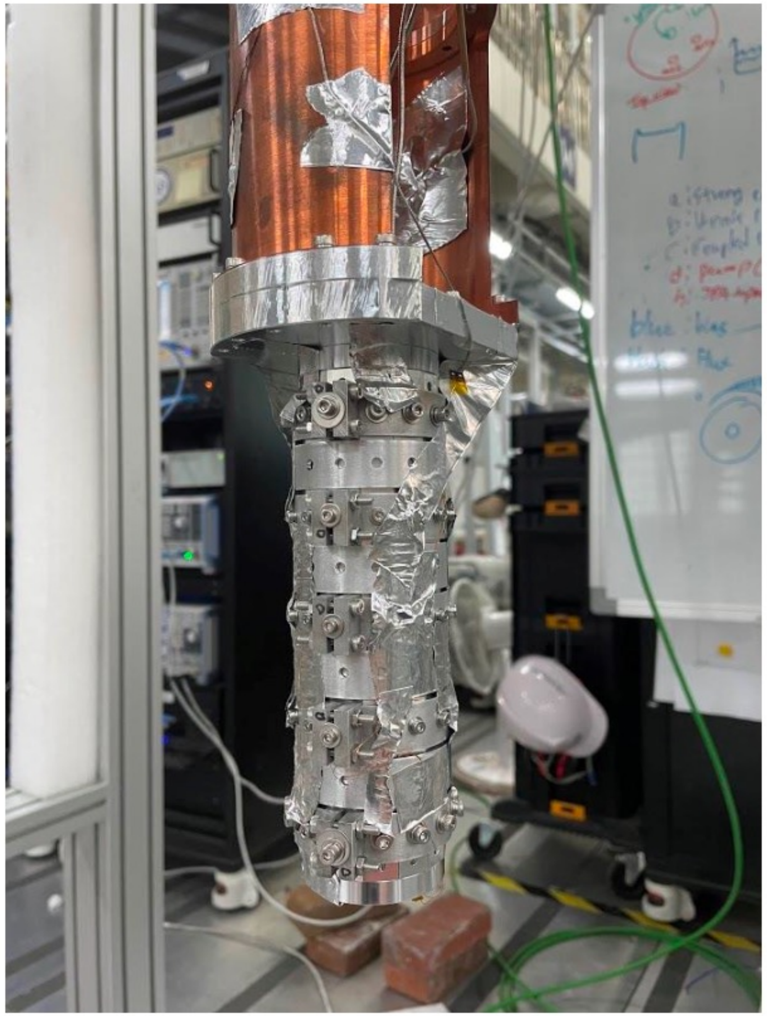
- High Q-factor possible
  but sensitive to unit condition and alignment
- New frequency tuning method
  not to break azimuthal symmetry

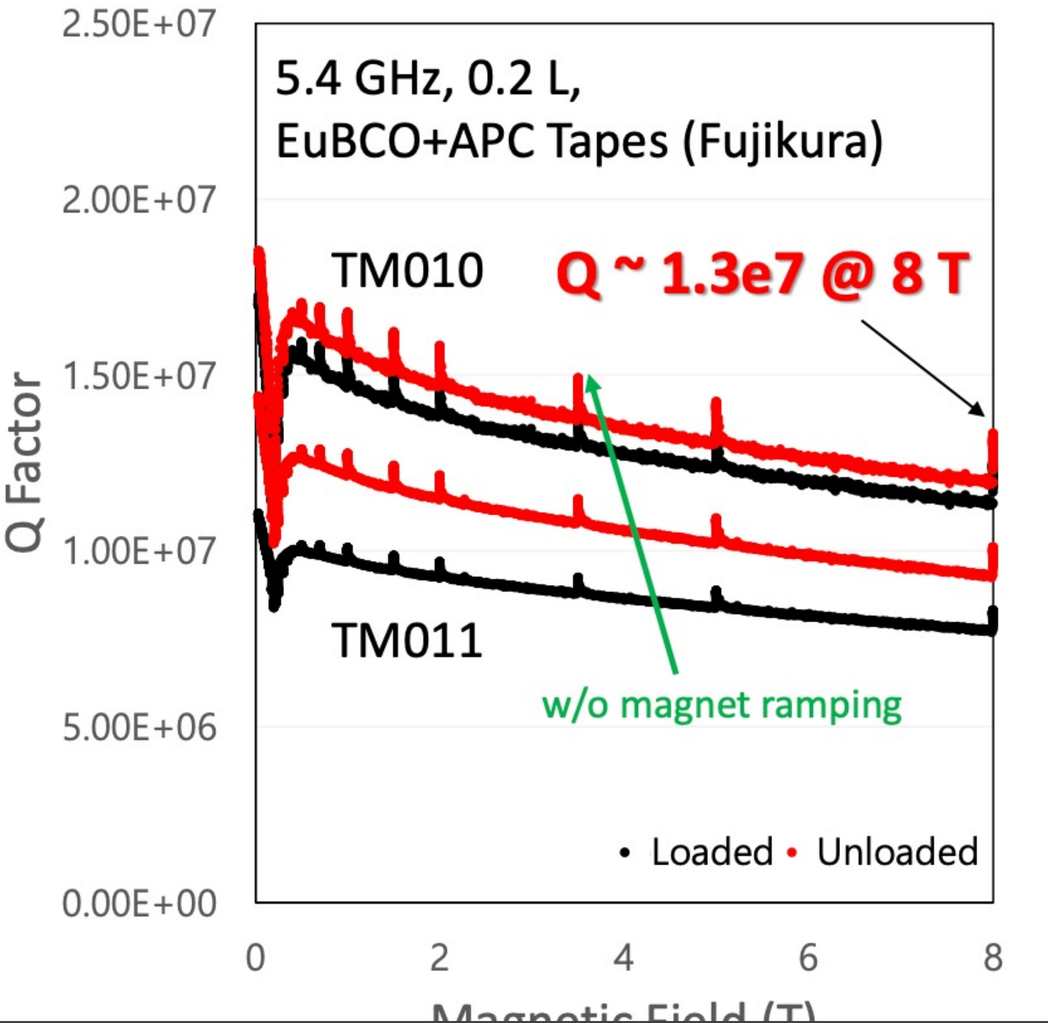
Perfect ReBCO surface but units are not electrically connected

1st track results: **> 3M Q-factor!!**



1st track results: > 10^7 Q-factor!!!!!

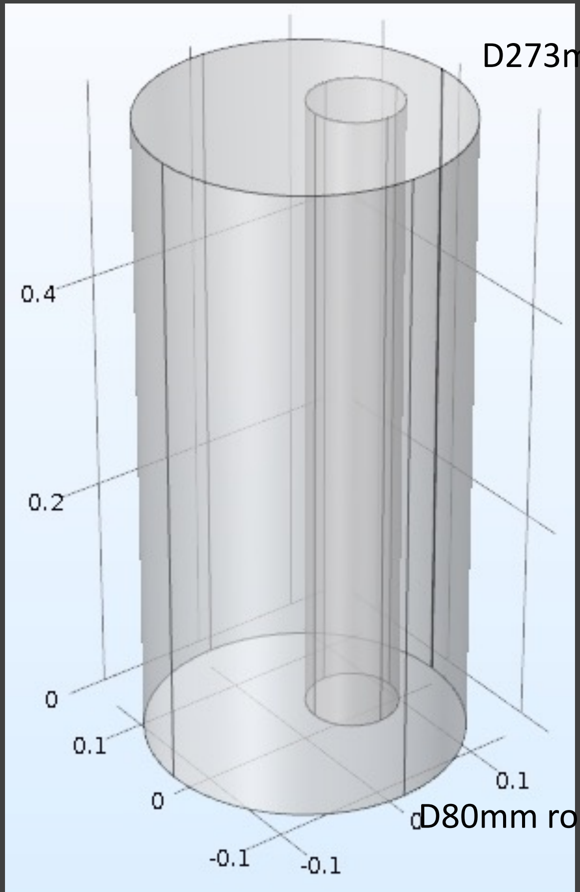


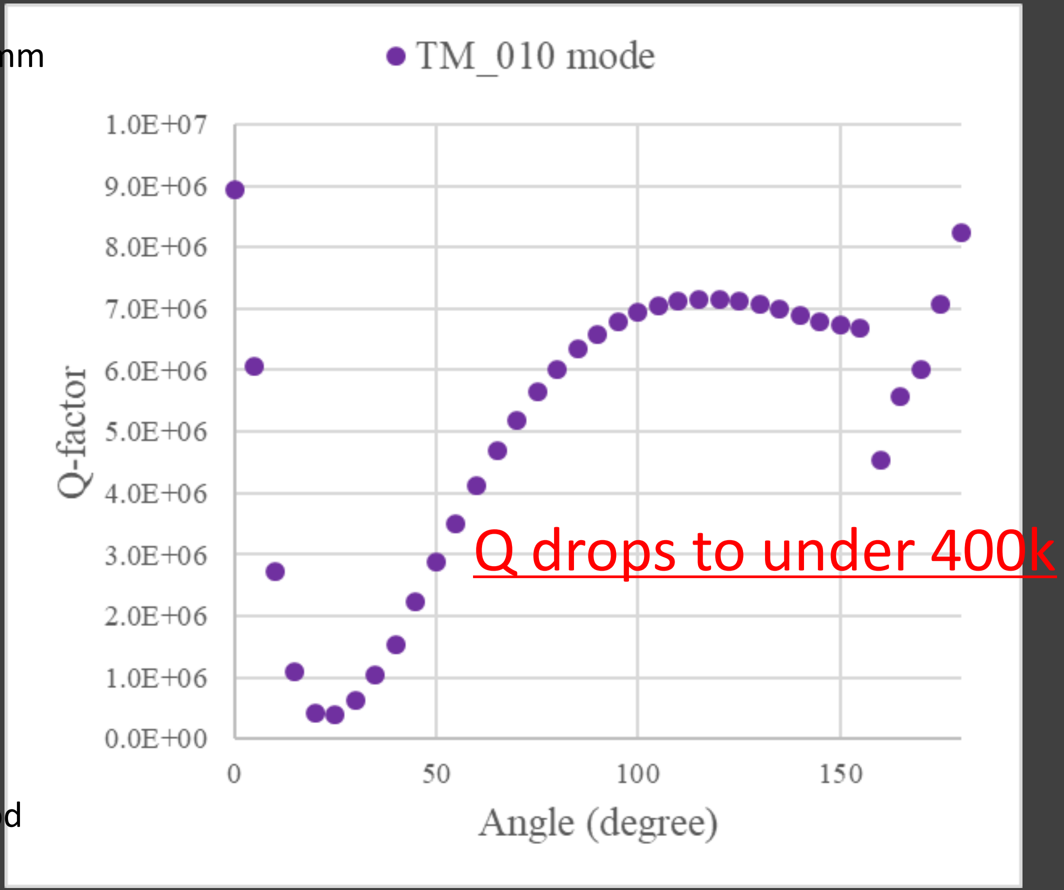


CAPP's two tracks strategy

2nd track: Electrically closed cavity w/ a Q-factor high enough

Simulation result (perfect HTS-ULC w/ 0.2mm vertical gap)





CAPP's two tracks strategy

2nd track: Electrically closed cavity w/ a Q-factor high enough

Make an electrically closed wide sheet (by electrically connecting the boundary of copper stabilizers)

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

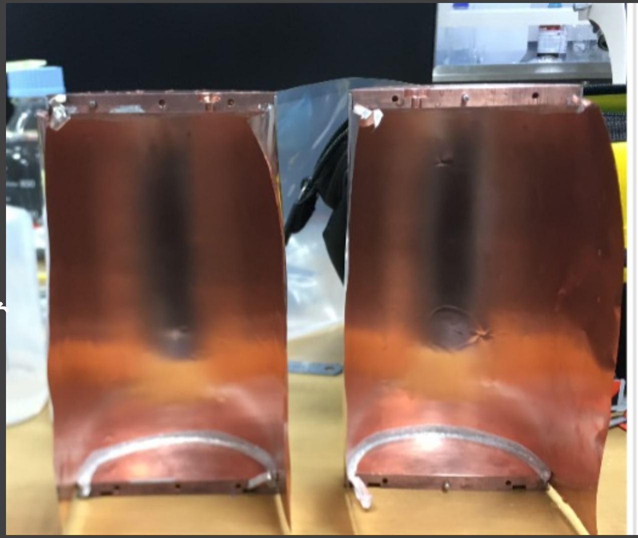
- not sensitive to any kind of tuning method

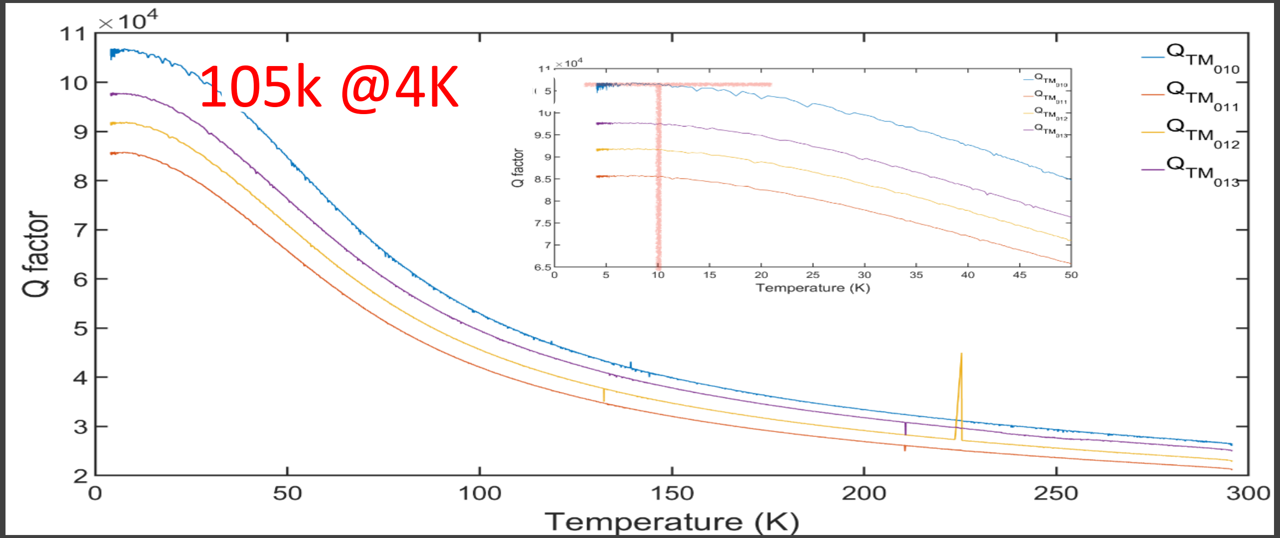
- possible to harm HTS surface during electrical connection (heat, chemical)

less Q factor than track 1, but very easy (costs less, easier to fabricate)

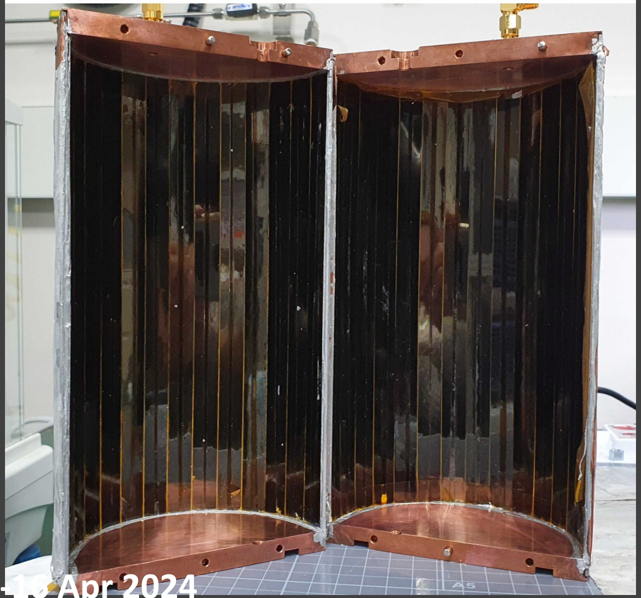
2nd track results - 1

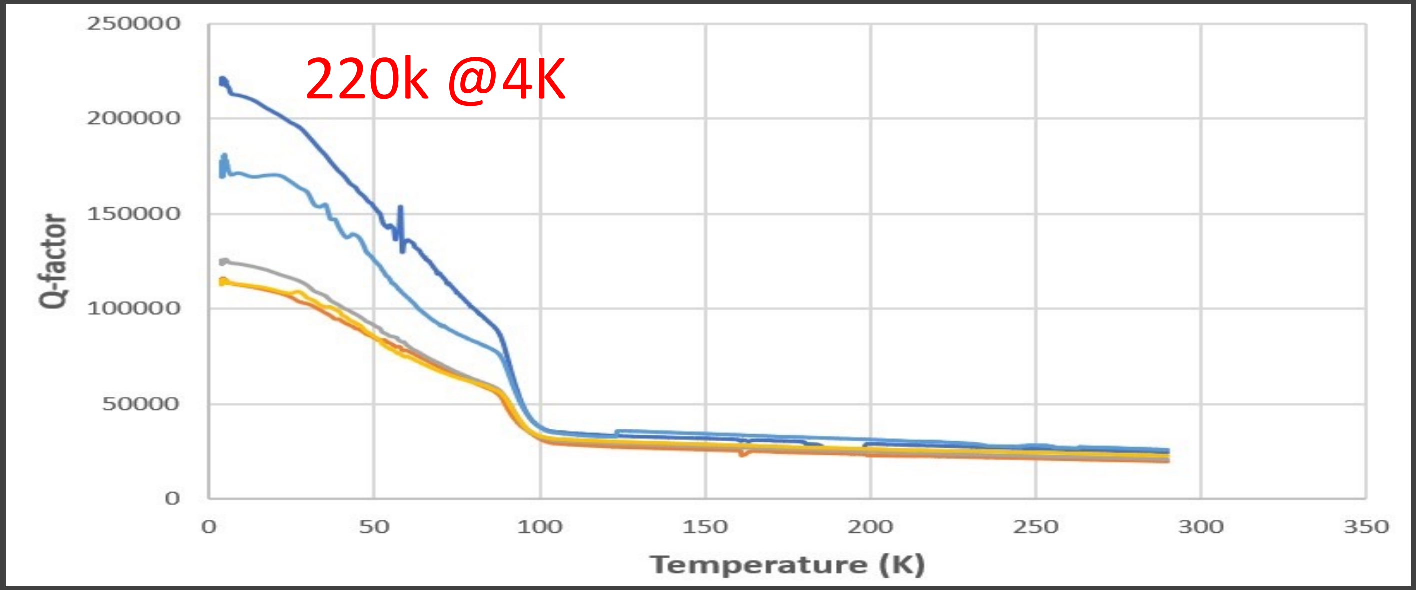
Just Copper



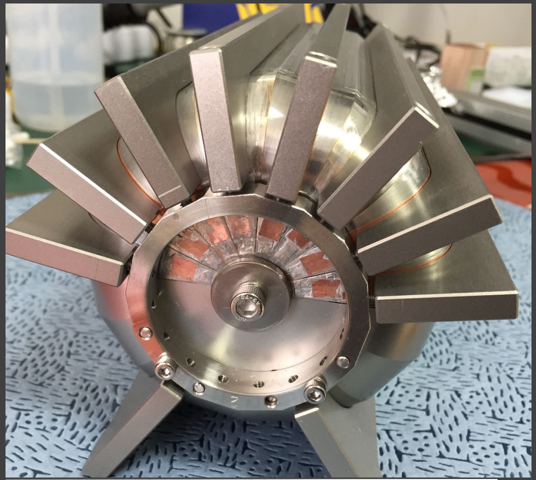


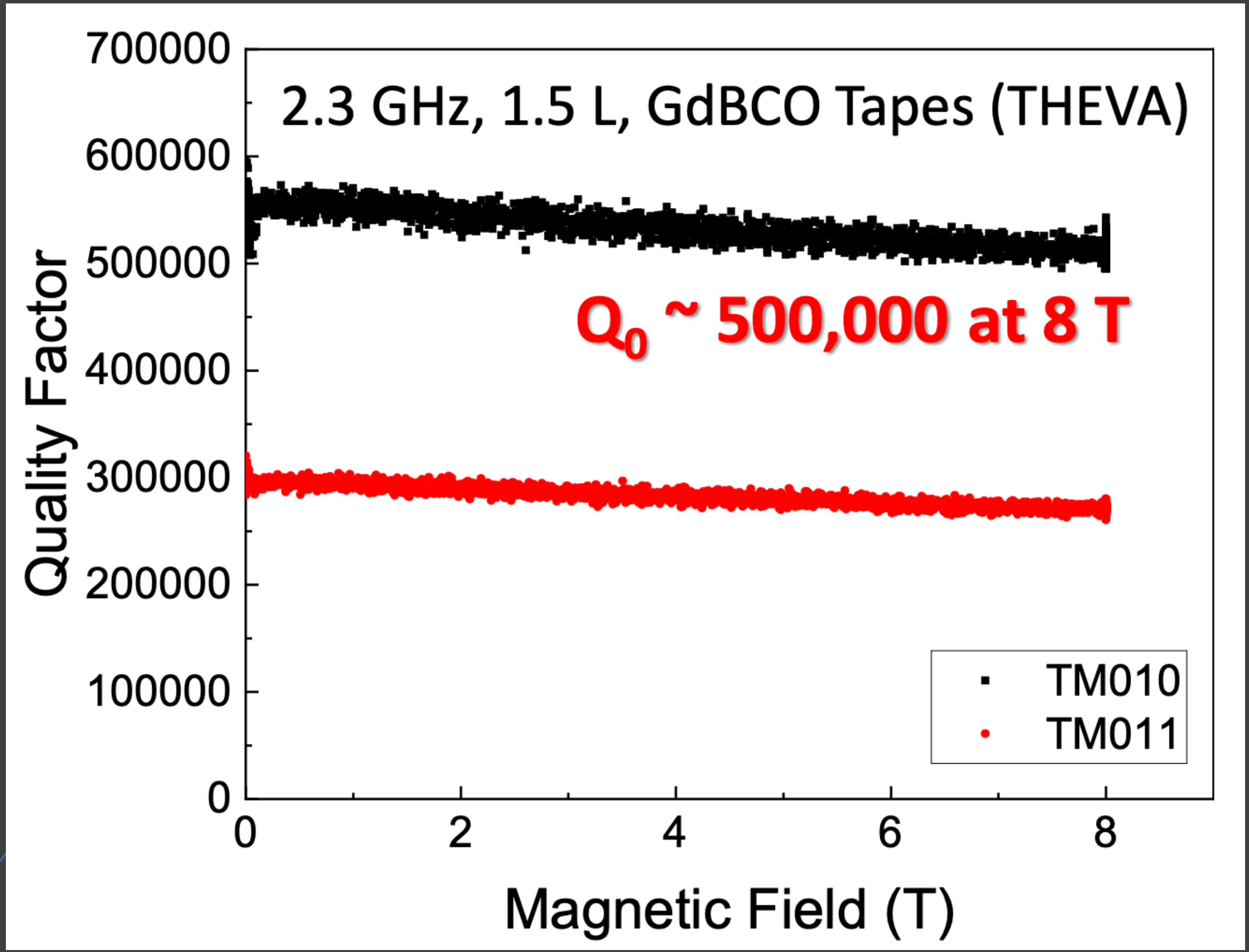
Side wall YBCO





2nd track results - 2

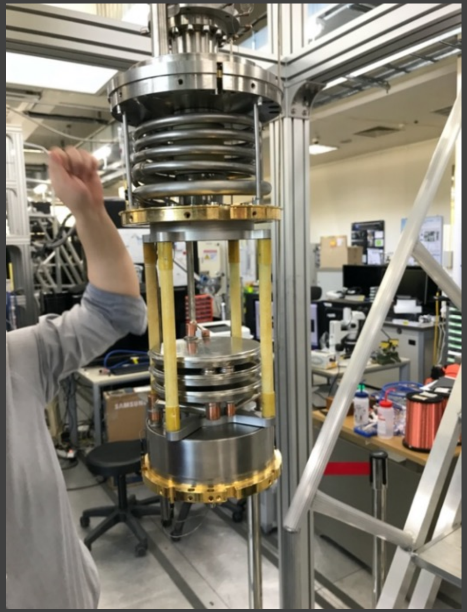




We took data using this cavity!!

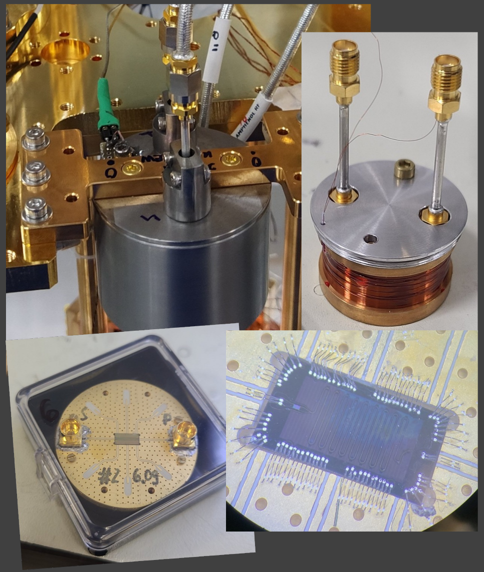
CAPP's main axion experiment (CAPP-MAX)

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



Dilution refrigerator
25mK

+



JPA (quantum amplifier)
1~2 GHz

+

12 Tesla SC magnet
320mm bore diameter

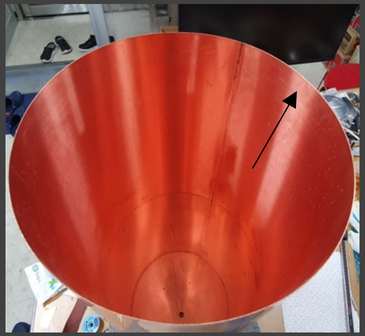
+

?

Large cavity

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

Ultra-light cavity (ULC) for CAPP-MAX



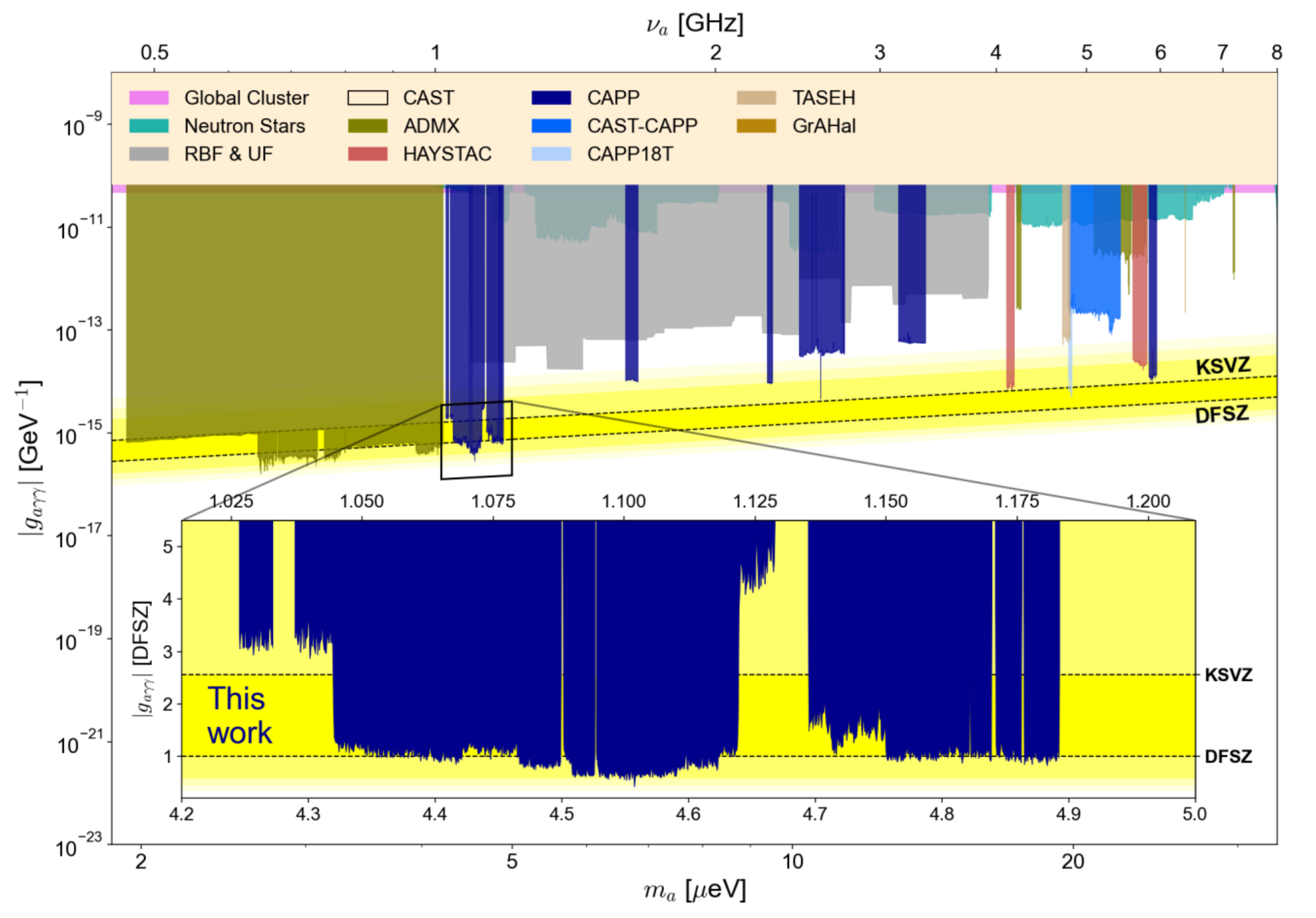
0.5mm thickness

37L, total ~6kg

< 10 hrs cooling time using typical 4K cooler, tuning assembly included

Q_0 > 170k w/o tuning rod
>100k w/ tuning rod

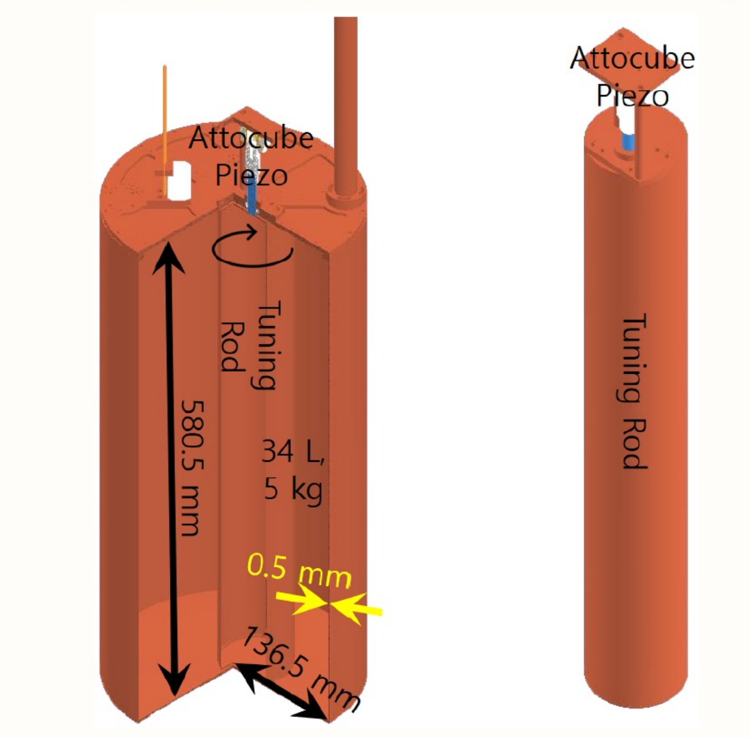
Ultra-light cavity (ULC) for CAPP-MAX

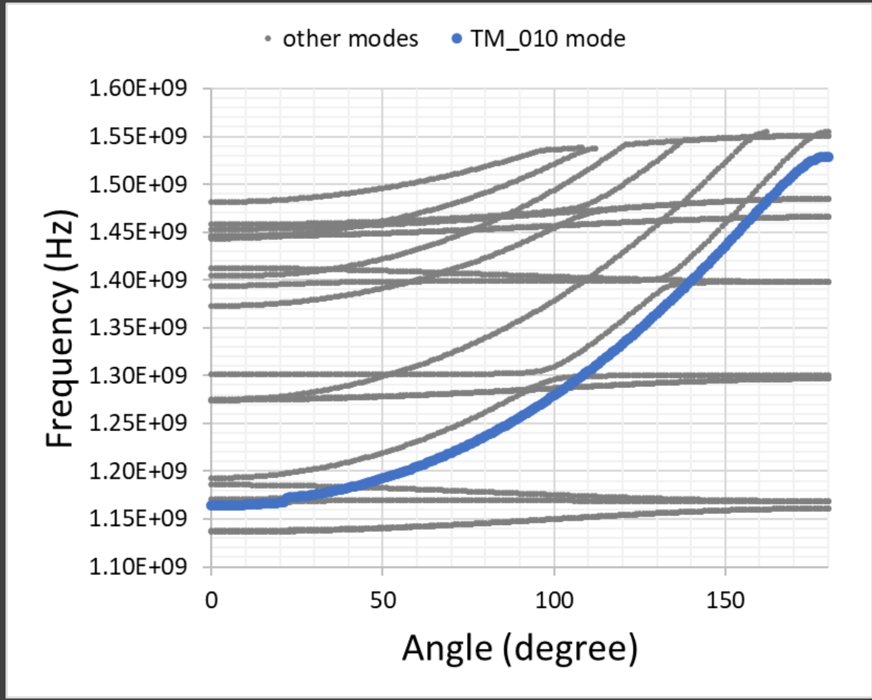


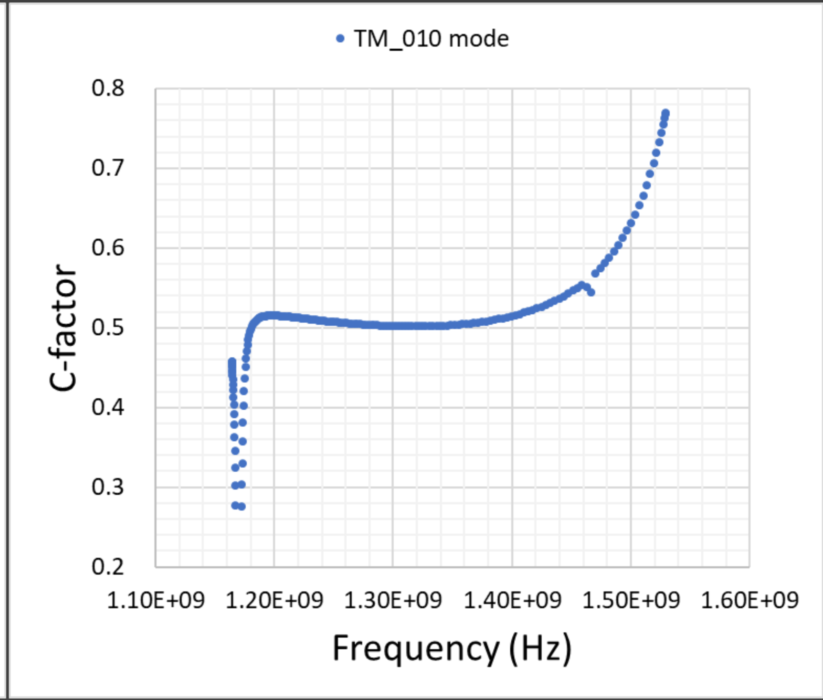
arXiv 2402.12892

ULC2: 1.2-1.5 GHz cavity

Comsol results

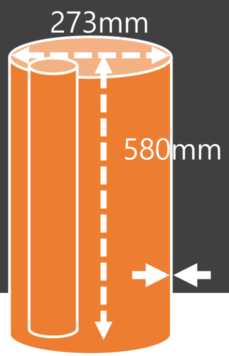


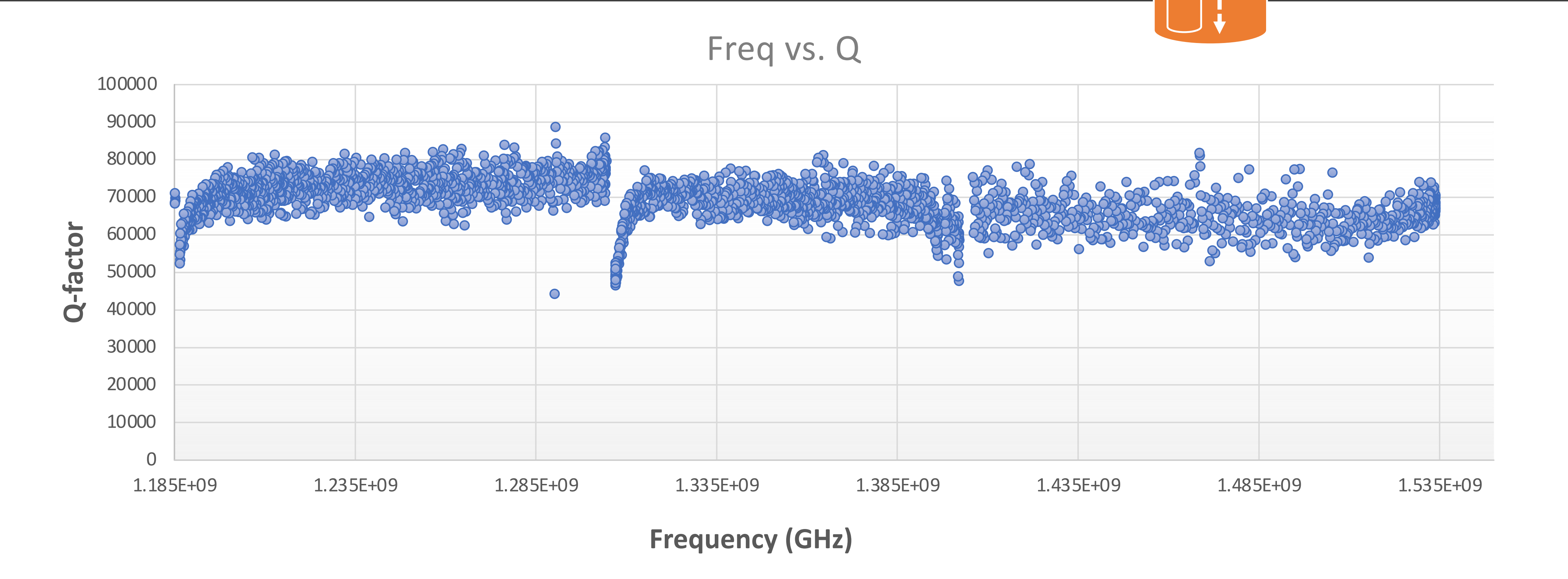




Copper cavity? Or HTS cavity??

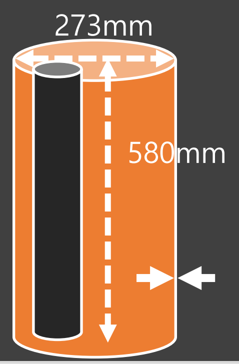
ULC2 with OFHC tuning rod

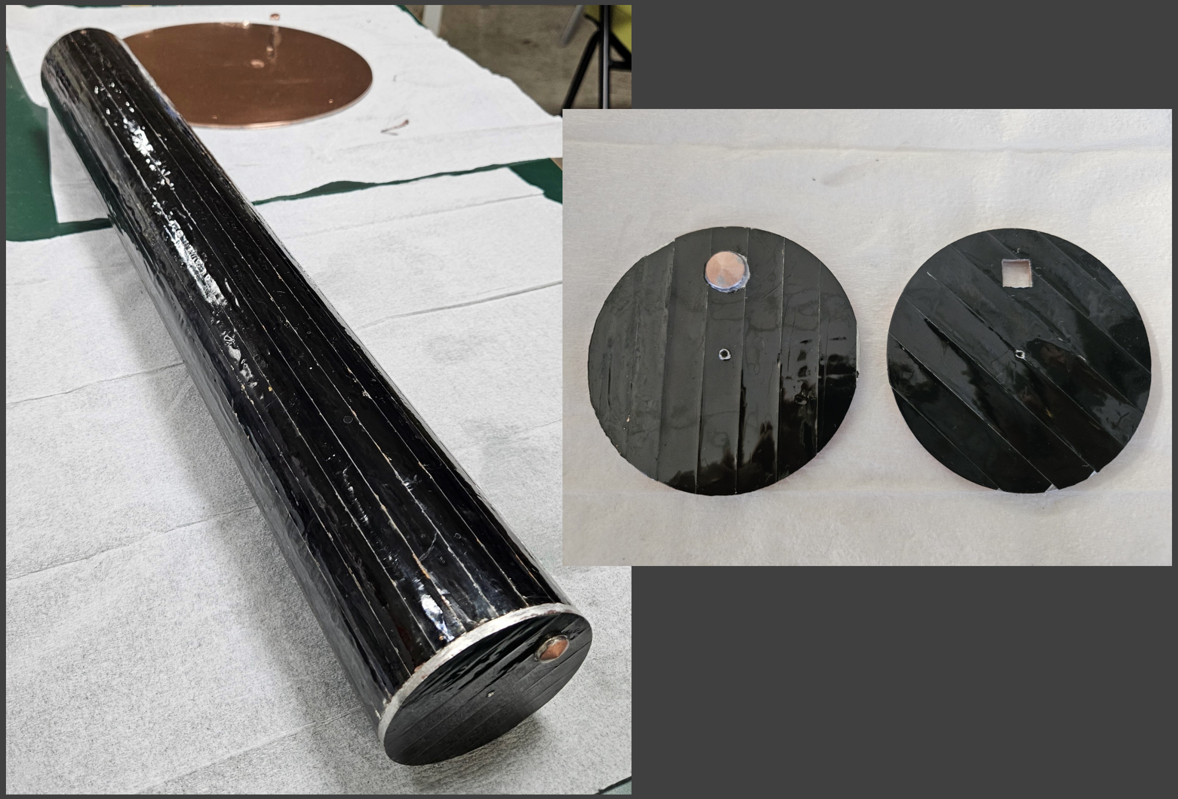


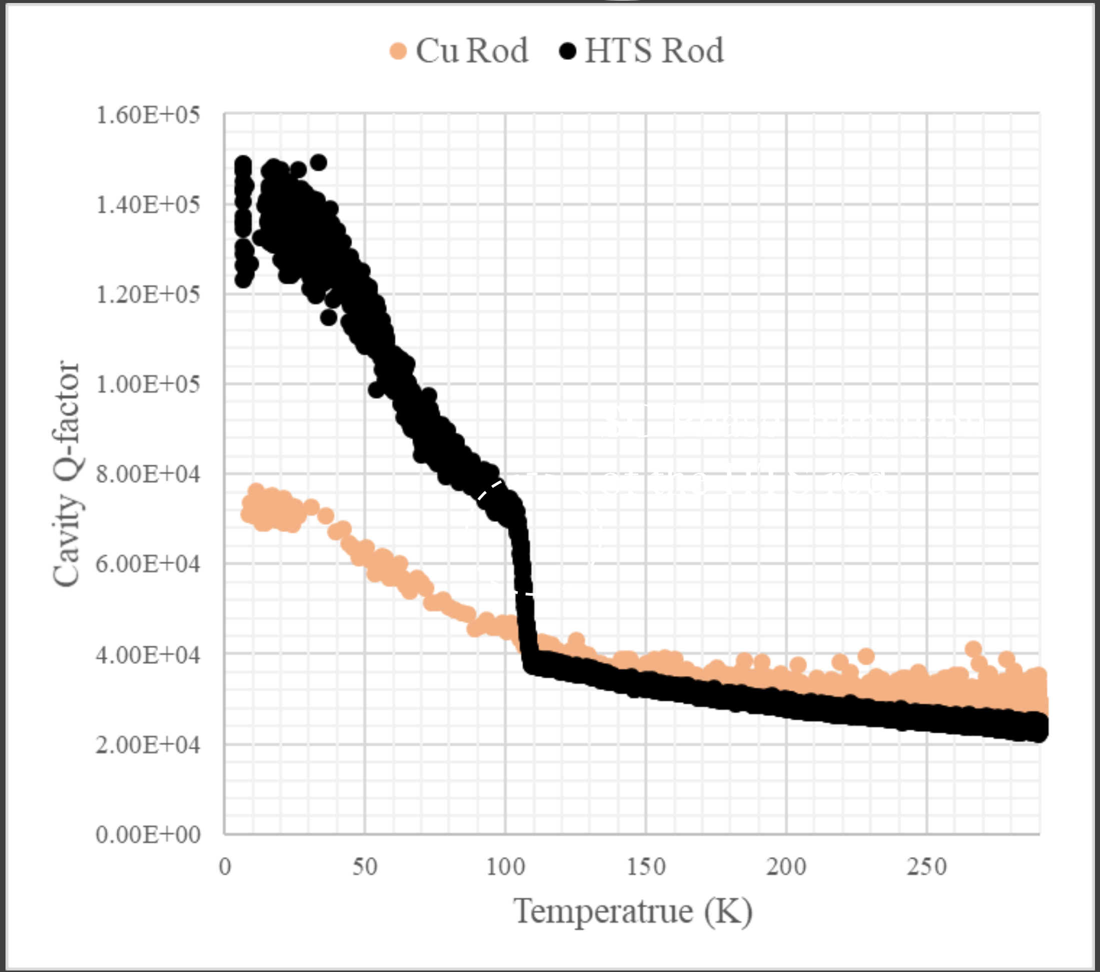


Due to the relatively big tuning rod (80mm dia), Q0 < 100k in the whole range

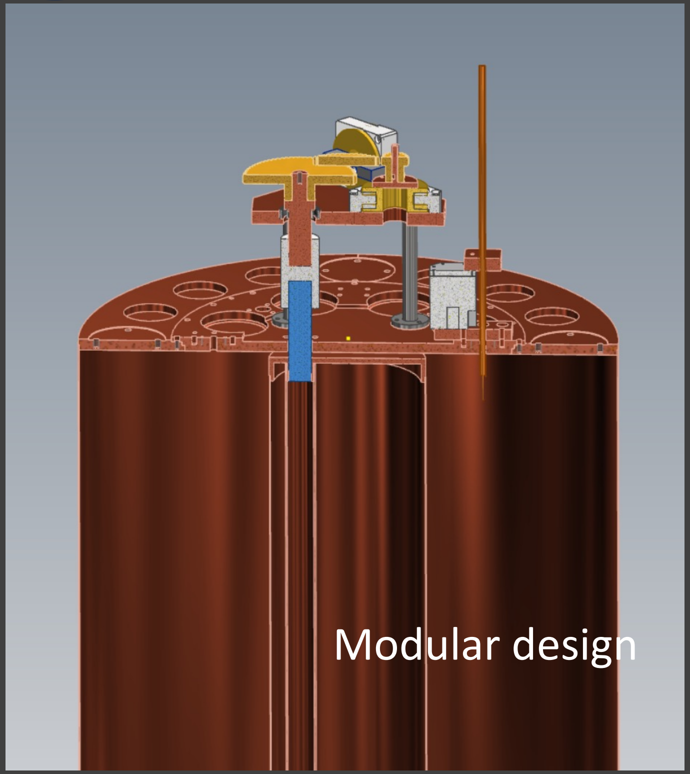
ULC2 with ReBCO tuning rod

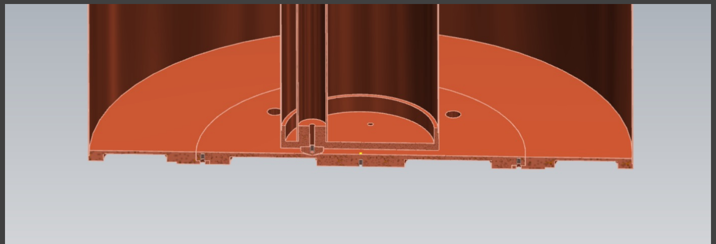


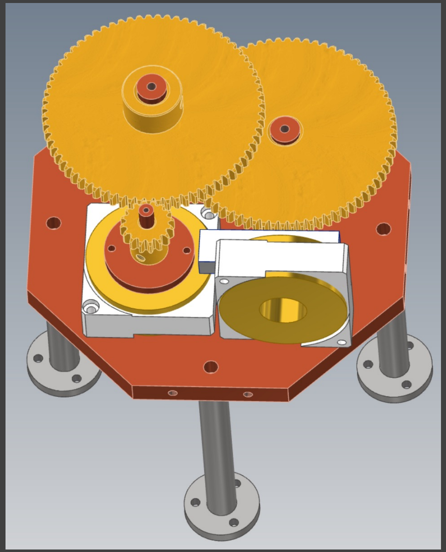


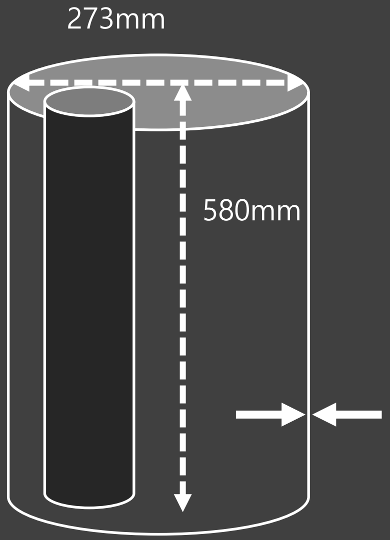


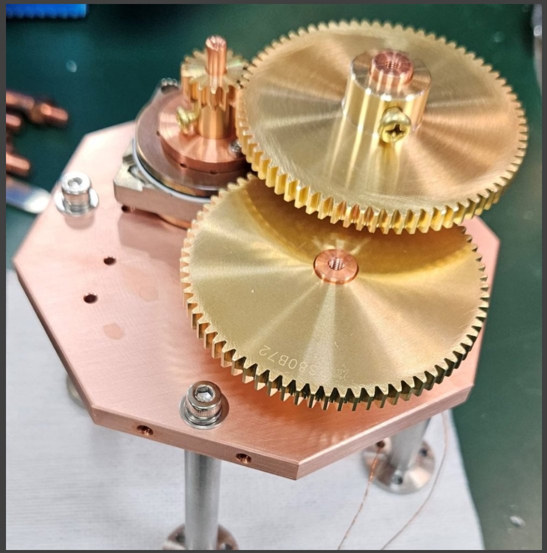
ULC2: Full HTS cavity → HTS-ULC





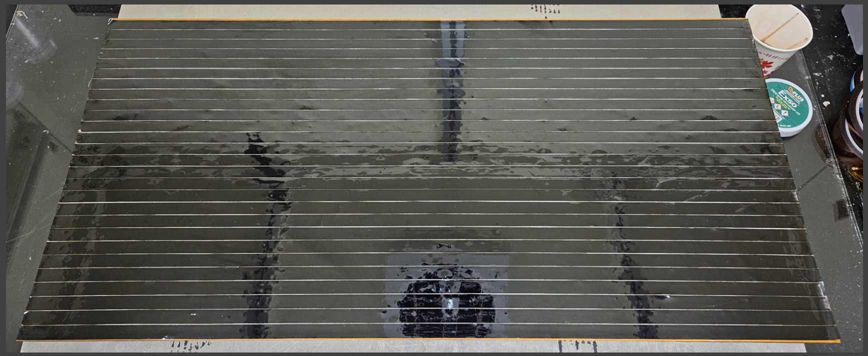


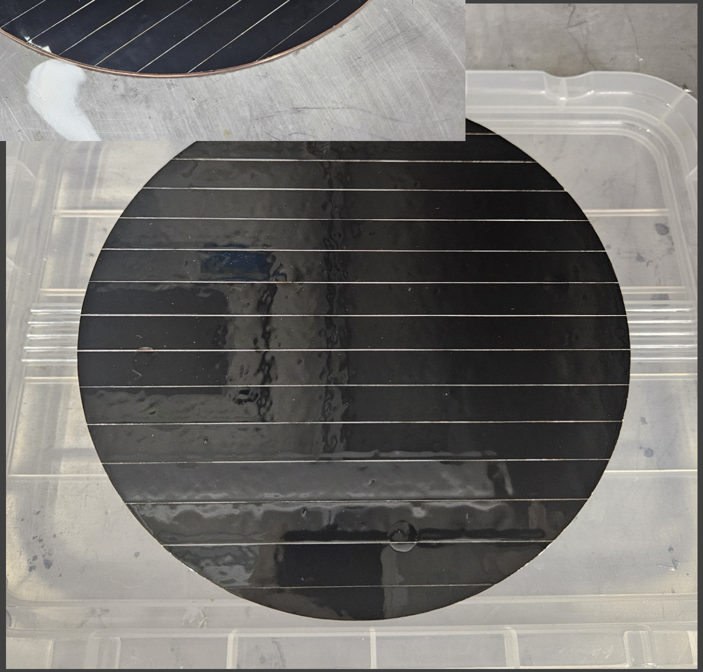




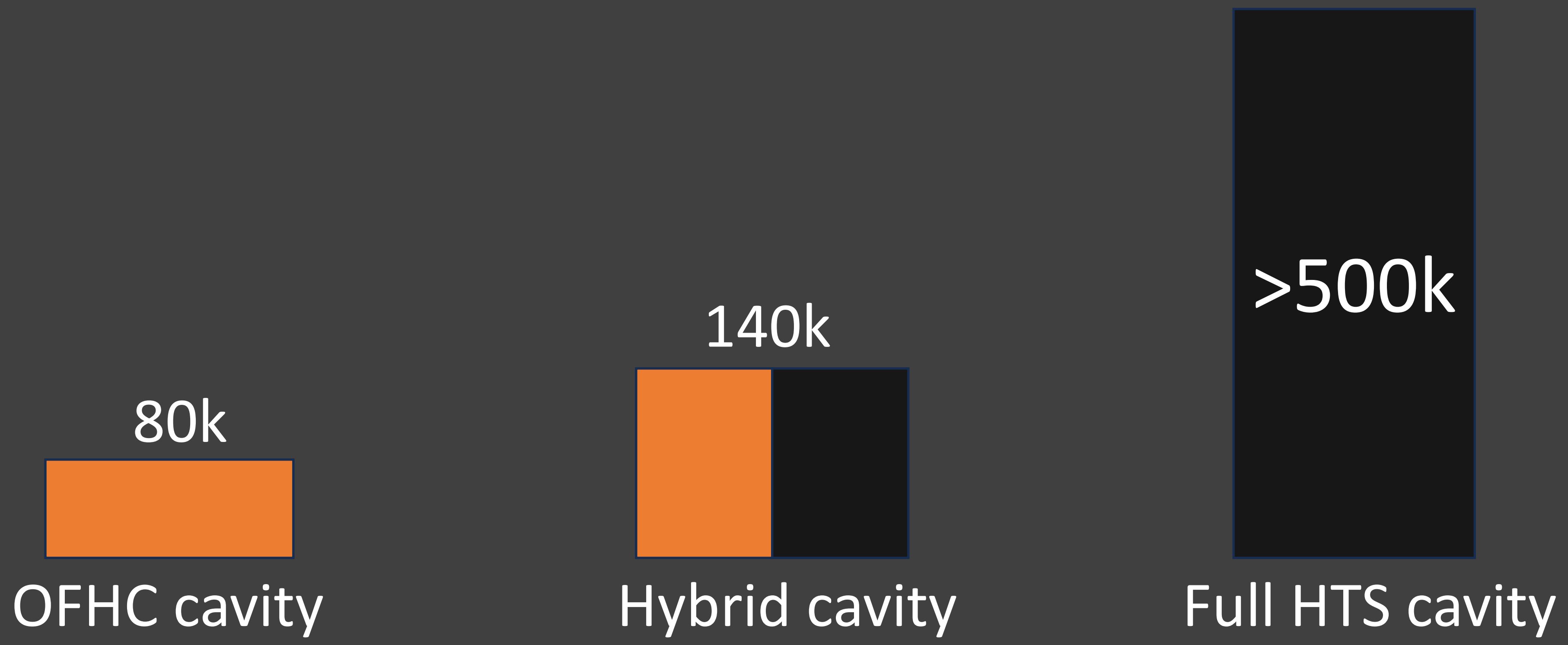
Gearbox (1:20) is ready to move HTS tuning rod

All the parts are ready to assemble





< DFSZ axion search using HTS-ULC



Search <1 DFSZ or <100% axion in dark matter halo using HTS-ULC

CAPP-GrAHal collaboration

arXiv: 2110.14406

Magnetic Field (Tesla)	Warm Diameter (mm)
43	34
40	50
27	170
17.5	375
9.5	812

20mm x 30cm

ReBCO cavity

(~2024)

70cm x 1500mm (580L) OFHC copper cavity

(~2025)

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 ready to assemble for 1.2-1.5GHz and 1.5-1.9GHz CAPP-MAX.