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High-Temperature Superconducting Cavities for Dark Matter Axion Search at CAPP

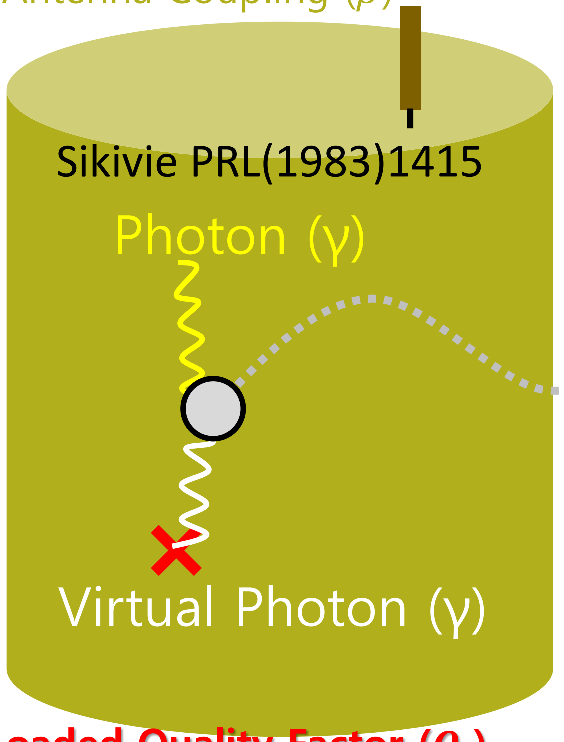
Danho Ahn (IBS-CAPP)

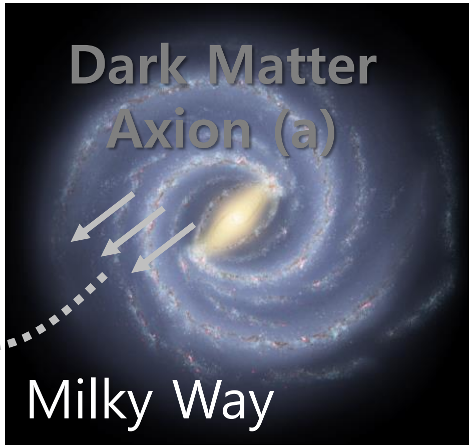
Center for Axion and Precision Physics Research, Institute of Basic Science, Daejeon 34051, Republic of Korea

Introduction:

Cavity Haloscope Experiment for Dark Matter Axion Search

Antenna Coupling (β)





Magnetic Field (B)

Loaded Quality Factor (Q_l)
Volume (V)
Resonant Angular Frequency (ω_0)
Form Factor (C)
System Temperature (T_{sys})

Signal Power

$$P_{sig} = \frac{\beta}{1+\beta} g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a^2} \boldsymbol{B^2} V \omega_0 C \frac{Q_a \boldsymbol{Q_l}}{Q_a + \boldsymbol{Q_l}}$$

Coupling Constant ($g_{a\gamma\gamma}^2$); Dark Matter Axion Density (ρ_a); Axion Mass (m_a); Axion Quality Factor (Q_a)

Kim *et al*. JCAP03(2020)066

Scan Rate

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

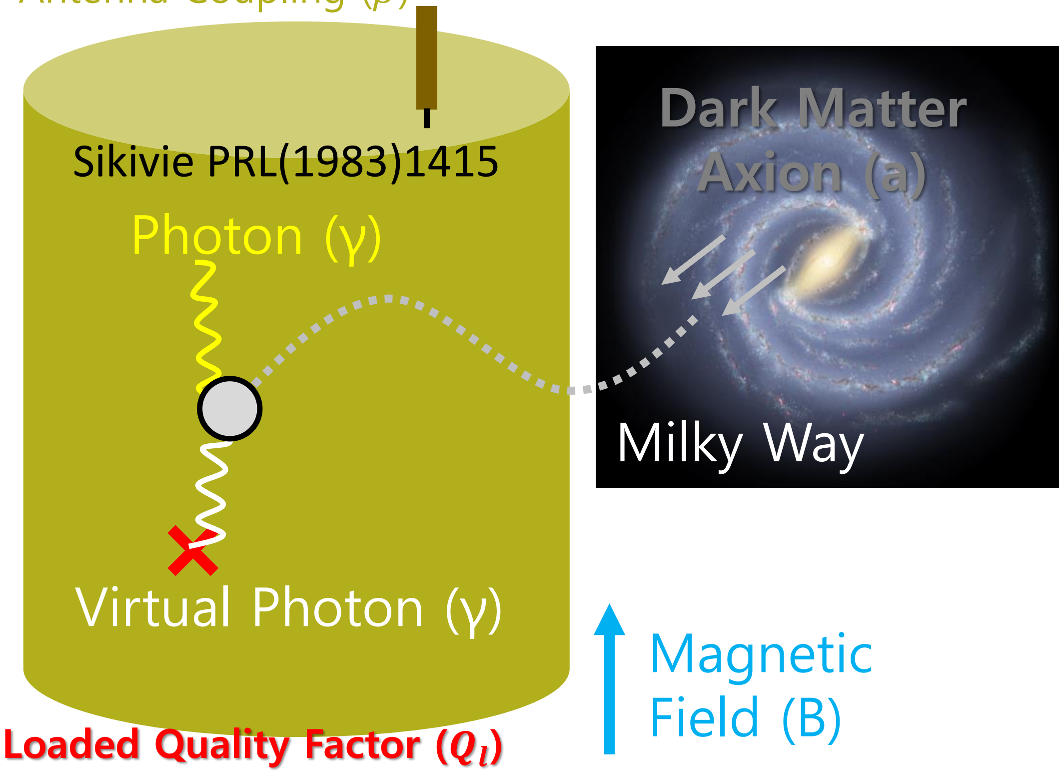
System Noise Temperature ~ 200 mK

$\boldsymbol{Q_l} \gg Q_a \sim 10^6$

Dr. Jinsu Kim, Patras Workshop, 2023

Introduction:

High Quality Factor Cavity is Needed for Faster Axion Search



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Signal Power — Coupling Constant — Dark Matter Axion Density — Axion Mass — Axion Quality Factor

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Scan Rate — System Noise

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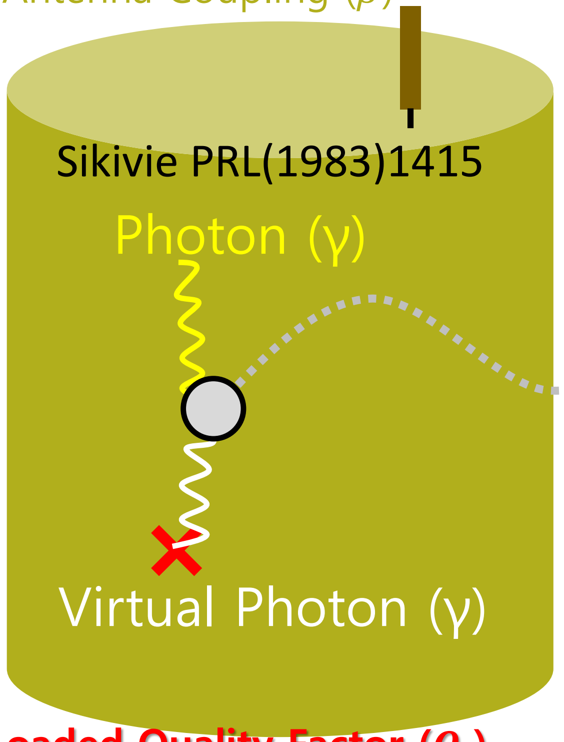
High Cavity Quality Factor

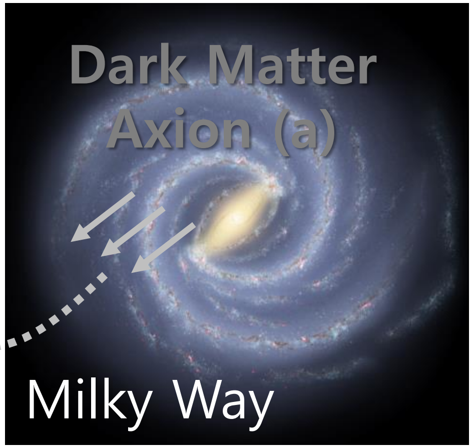
Dr. Jinsu Kim, Patras Workshop, 2023

Introduction:

High Quality Factor Should be Maintained in a High Magnetic Field

Antenna Coupling (β)





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Kim *et al*. JCAP03(2020)066

Scan Rate

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System Noise (T_{sys})

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High Magnetic Field

Dr. Jinsu Kim, Patras Workshop, 2023

Material Evaluation Criteria

Two Preferred Conditions for Cavity Haloscopes

High-Temperature Superconductor

$$\frac{R_S}{R_{Cu}} \ll 1 \text{ in a magnetic field}$$

Biaxially-Textured Film

Minimizing Surface Defect
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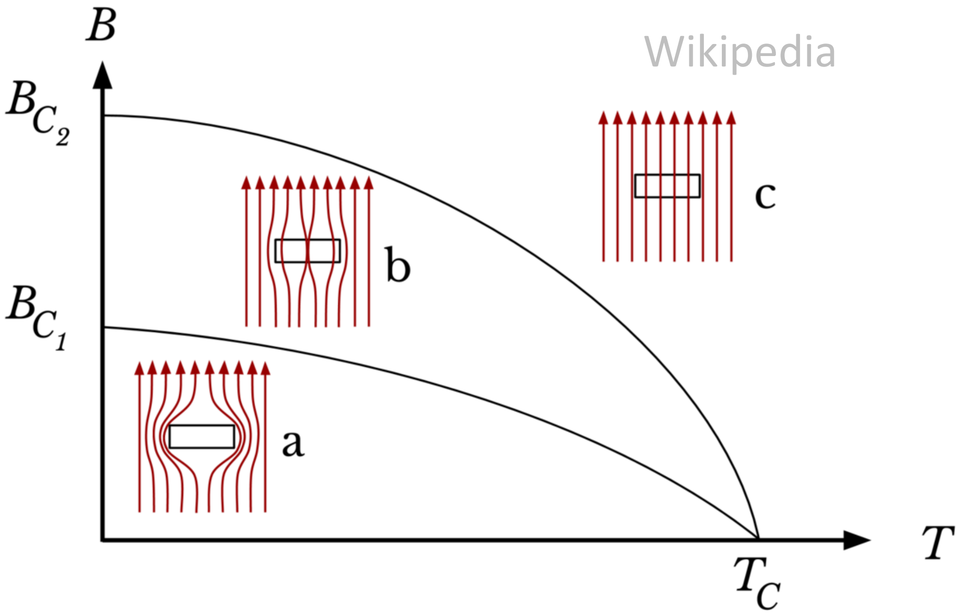
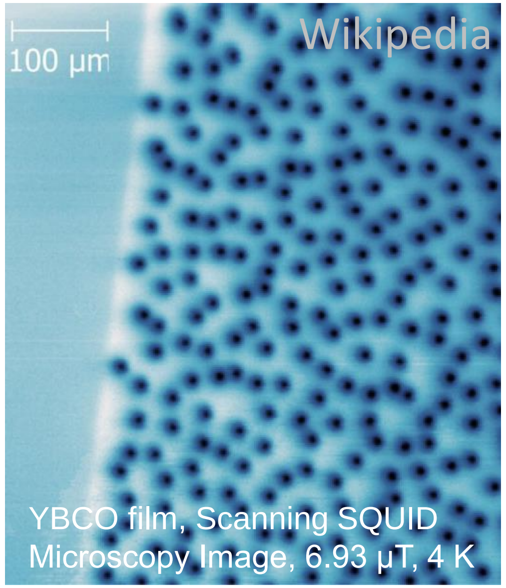
Type II Superconductor in a Magnetic Field

Vortex Dynamics & Energy Dissipation Mechanism

- Type II superconductor forms vortices (quantized magnetic flux, $\vec{\Phi}_0$) in a magnetic field.





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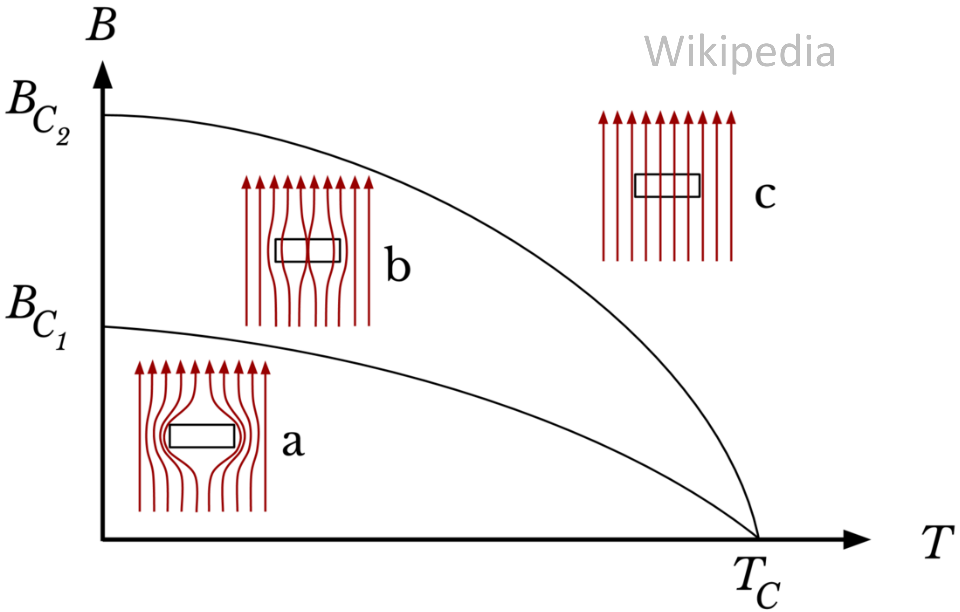

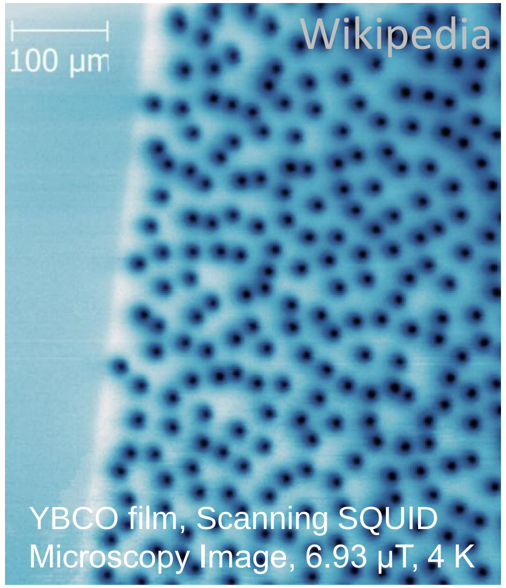

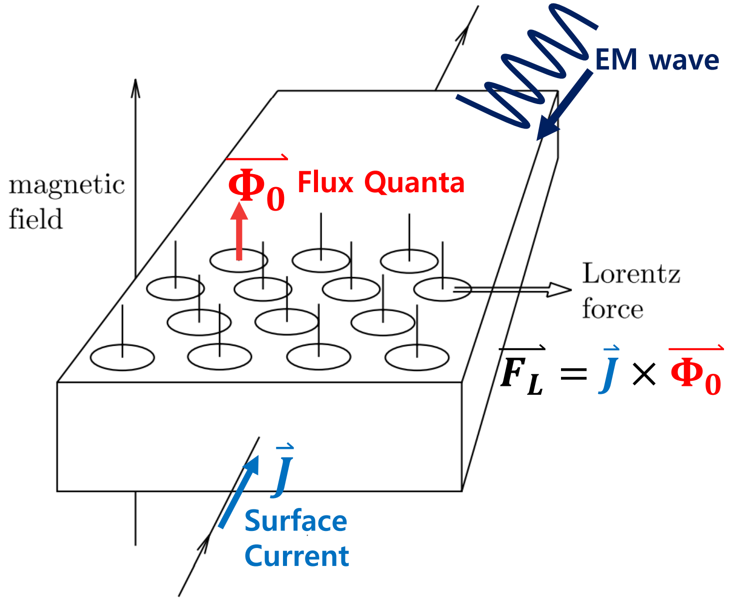

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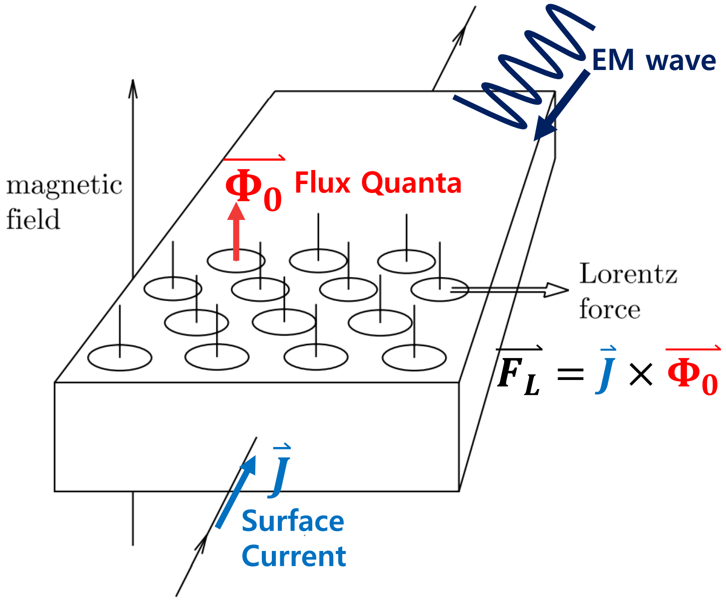
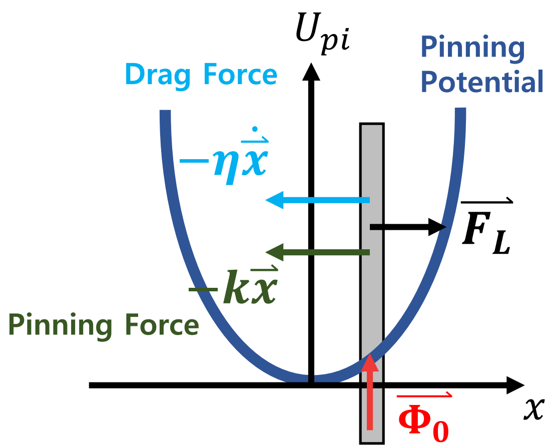
- Every vortex is trapped in each pinning potential well.





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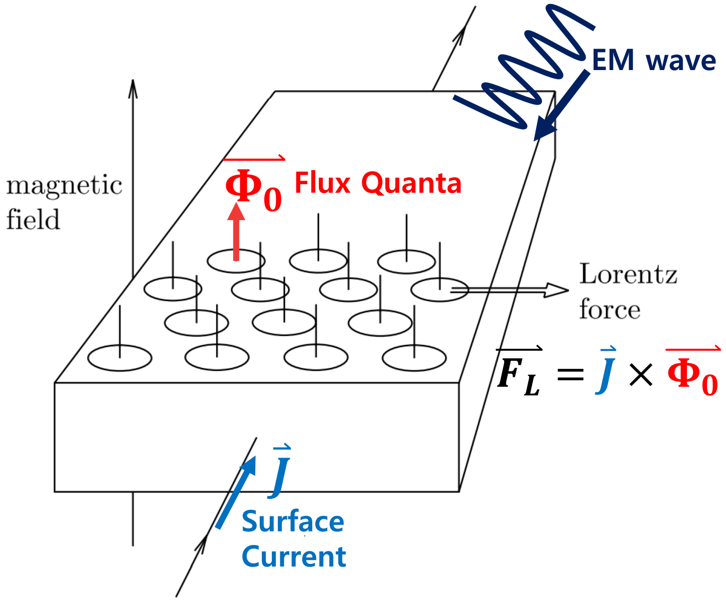
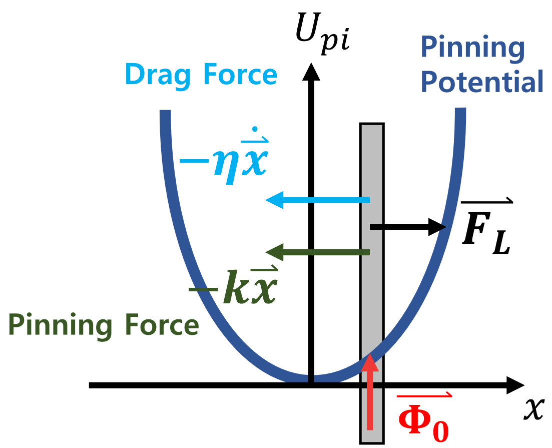
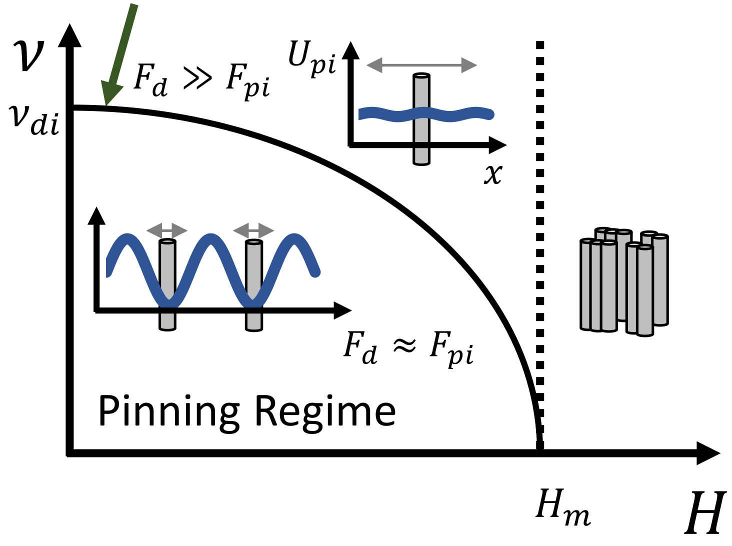
- Every vortex is trapped in each pinning potential well.
- Above a depinning frequency, pinning force become negligible.

High Depinning Frequency (ν_{di})







Type II Superconductor in a Magnetic Field

Vortex Dynamics & Energy Dissipation Mechanism

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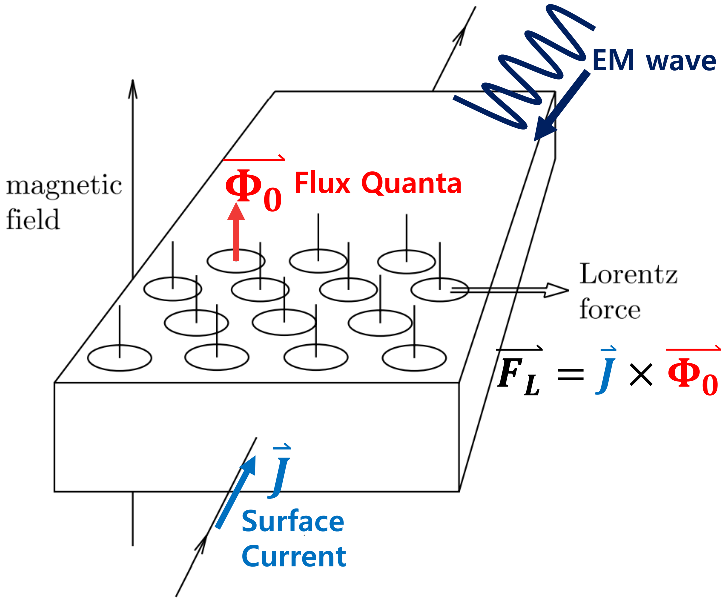
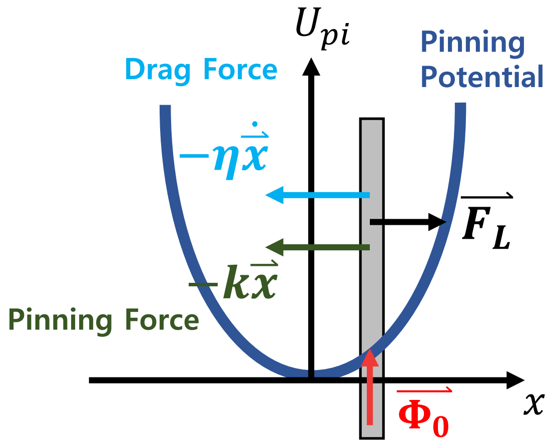
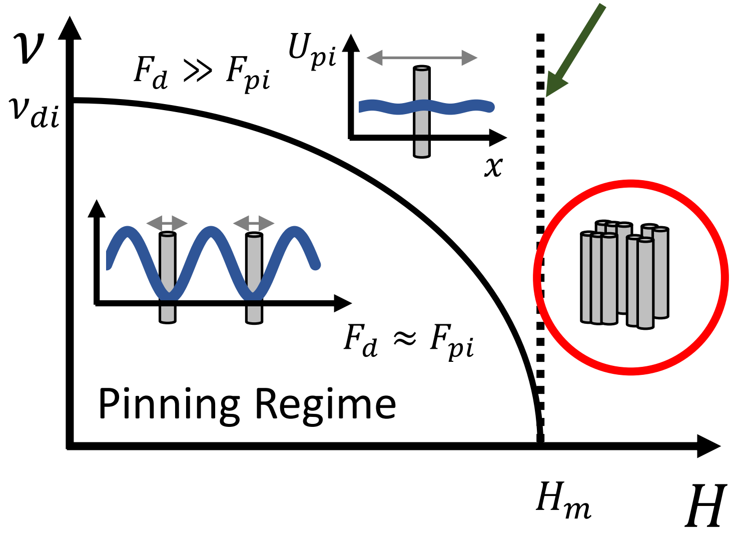
- Every vortex is trapped in each pinning potential well.
- Above a melting field, vortices are mixed each other.





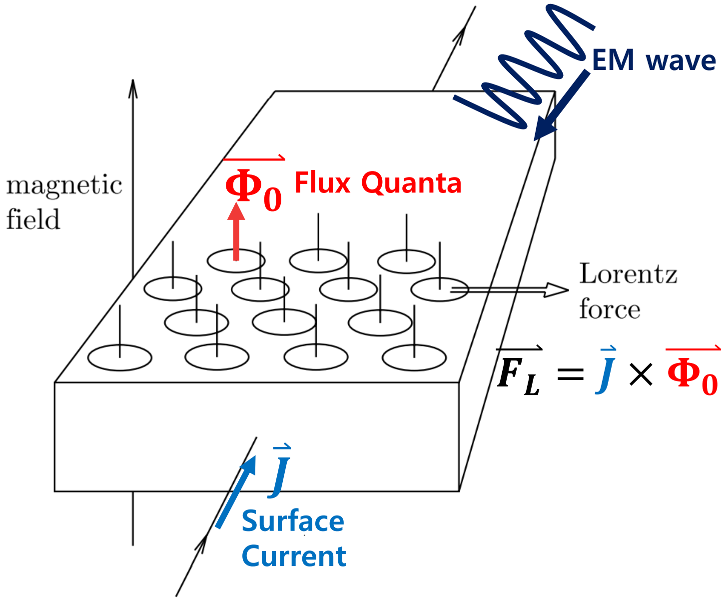
High Melting Field (H_m) ~ High Critical Field (H_{c2})

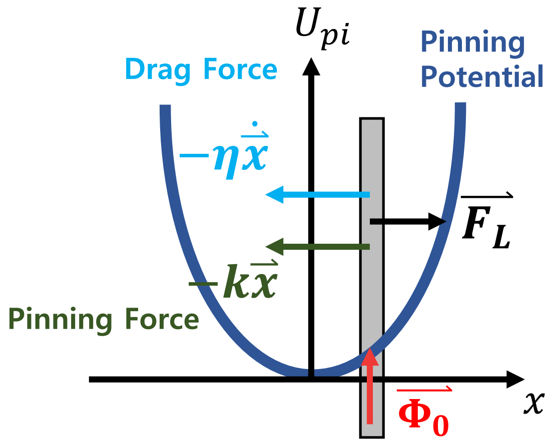


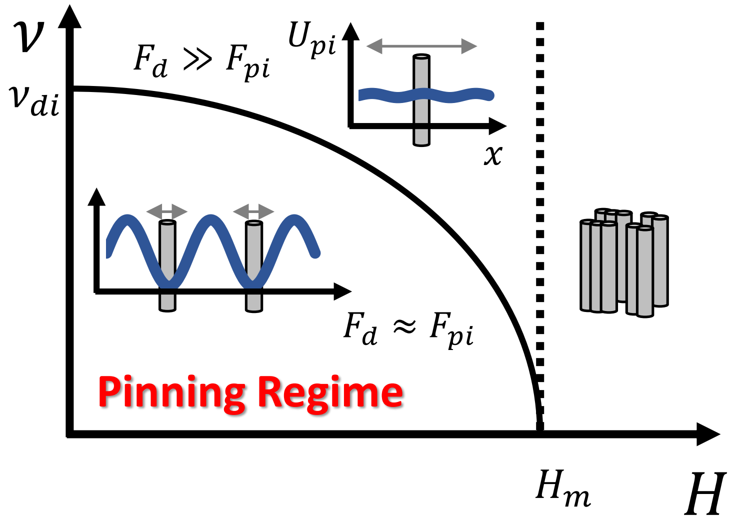
Type II Superconductor in a Magnetic Field

Vortex Dynamics & Energy Dissipation Mechanism

- Type II superconductor forms vortices (quantized magnetic flux, $\overrightarrow{\Phi_0}$) in a magnetic field.
- Vortices respond to the incident electromagnetic wave.
- Every vortex is trapped in each pinning potential well.
- In the pinning regime, the surface resistance is much smaller than that of copper.







Type II Superconductor in a Magnetic Field

Considering Cavity Haloscope Experimental Condition

100 mK 8 GHz	R_s (B = 0 T) (Ohm)	R_s (B = 8 T, ∥ c) (Ohm)	Critical Field (H_{c2})	Depinning Frequency
OFHC Cu (Metal)	~ 7E-3	~ 7E-3	None	None
Low Temperature Superconductors (LTS)				
NbTi (LTS) Gatti *et al.* PRD(2019)	~ 1E-6	~ 4e-3	Small ~ 13 T	~ 45 GHz
Nb_3Sn (LTS) Alimenti *et al.* SUST(2020)	~ 1E-6	?	~ 25 T	Small ~ 6 GHz
High Temperature Superconductors (HTS)				
Bi-2212 (HTS) Bi-2223 (HTS)	~ 1E-5	?	> 100 T (∥ ab) Larbalestier *et al.* Nature(2001)	?
Tl-1223 (HTS)	~ 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 (HTS) Re = Y, Gd, Eu, …	~ 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)

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Biaxially-Textured Film

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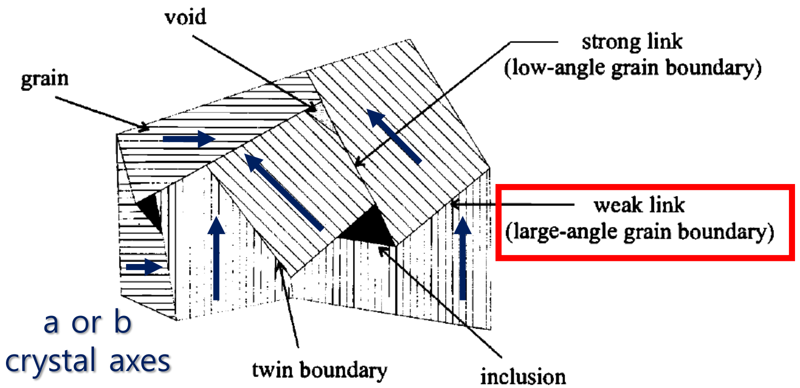
Second Generation ReBCO Coated Conductors

Biaxially-Textured ReBCO Coated Conductor Architecture

- Larger energy dissipation is originated due to flowing current at high angle grain boundaries.



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

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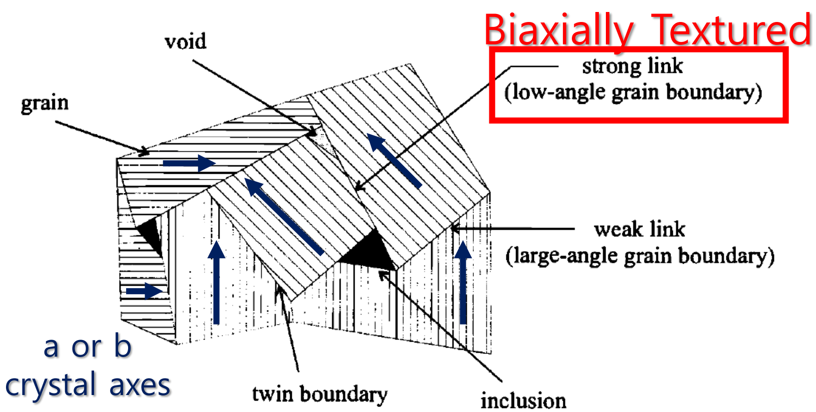
- Second generation ReBCO coated conductor technology realizes low angle grain boundaries which have misorientation angles less than 4 degree. (biaxially-textured)



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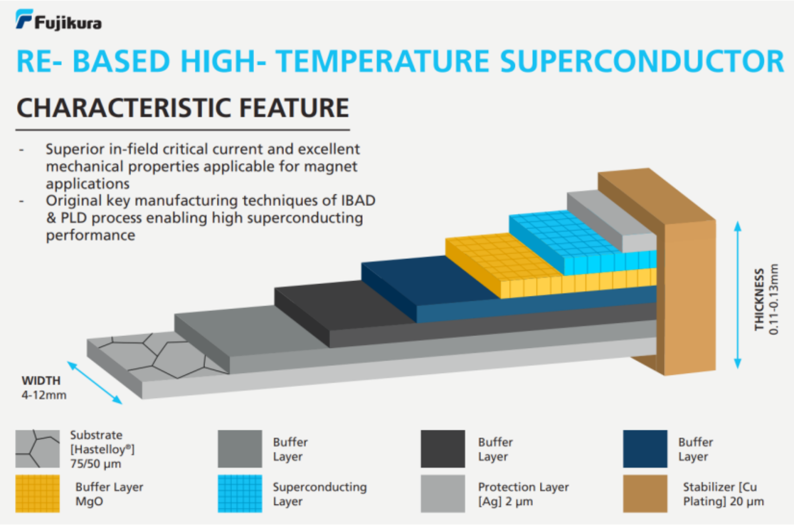

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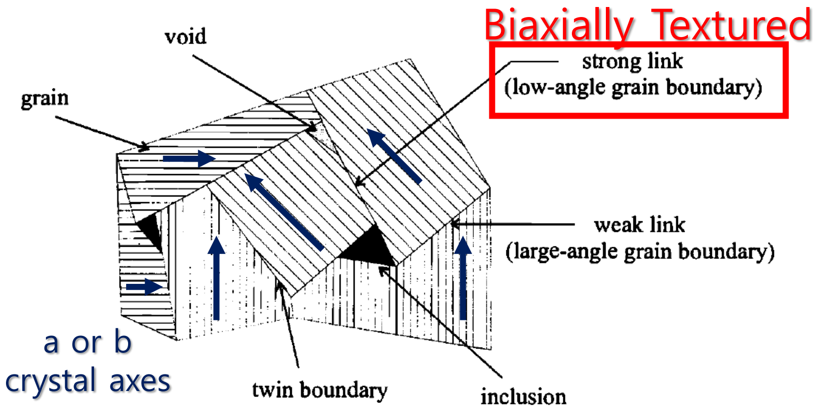
- 2 dimensional high-quality ReBCO coated conductor is flexible to manipulate.



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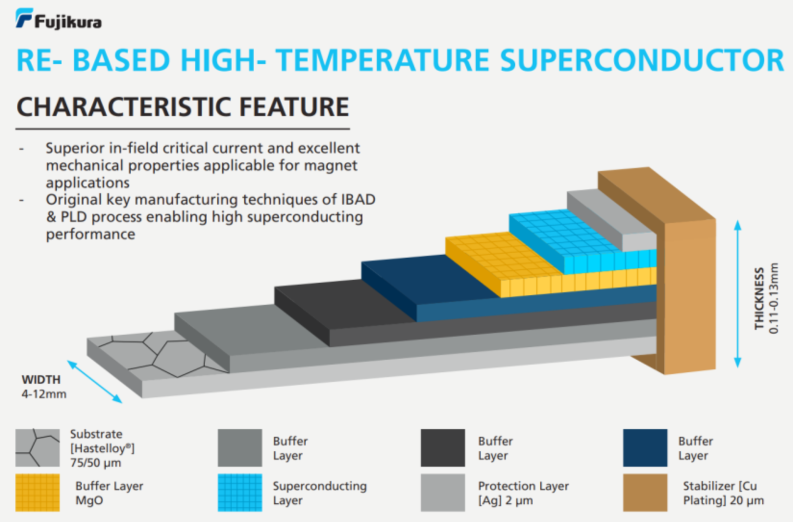

Second Generation ReBCO Coated Conductors

Biaxially-Textured ReBCO Coated Conductors Shows Low Surface Resistance

Cavity Haloscope: $\nu = O(1\sim10^2)$ GHz, $T_{phy} = O(10^2)$ mK, $B = O(10)$ T

$$R_s(\nu, T_{phy}, B) = R_{BCS}(\nu, T_{phy}, 0) + R_{defect}(\nu, T_{phy}, 0) + R_{vortex}(\nu, T_{phy}, B) + R_{magnetism}(\nu, T_{phy}, B)$$

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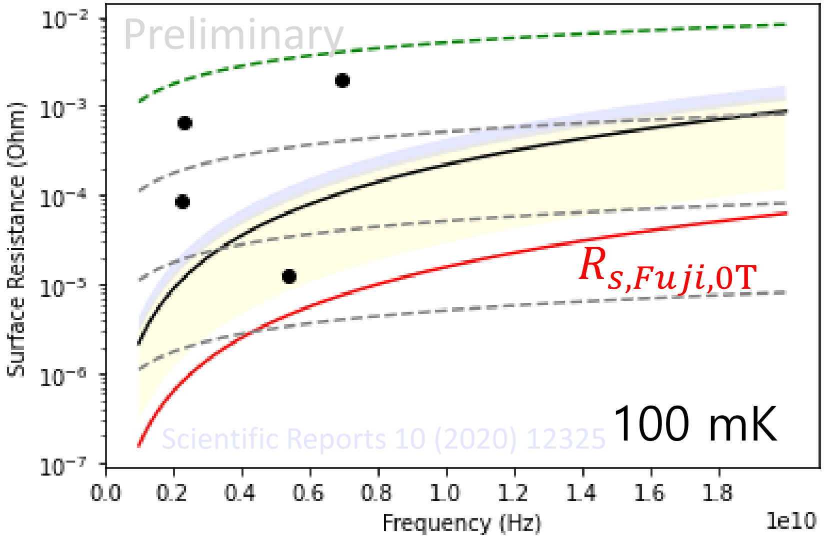

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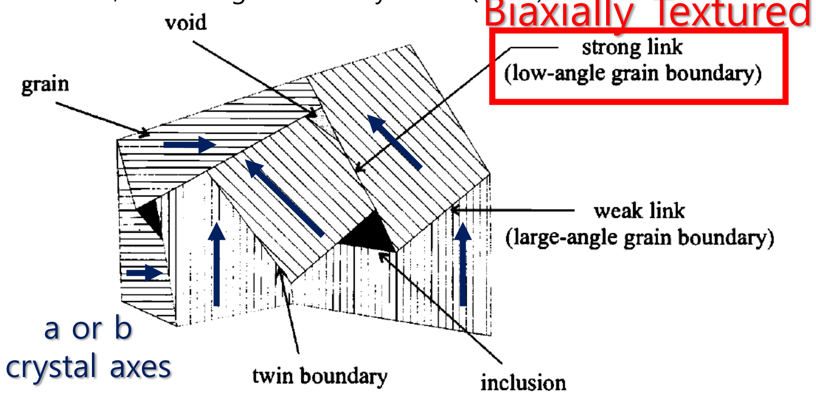

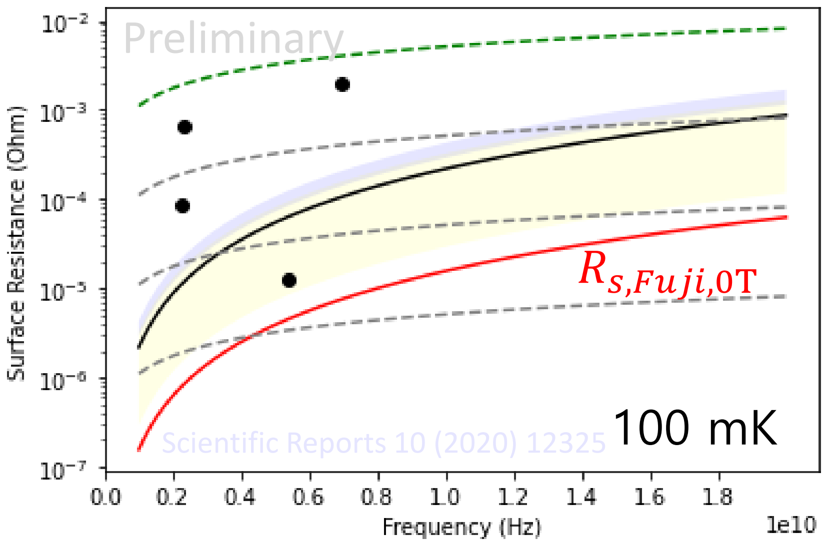

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For Y & Eu atoms

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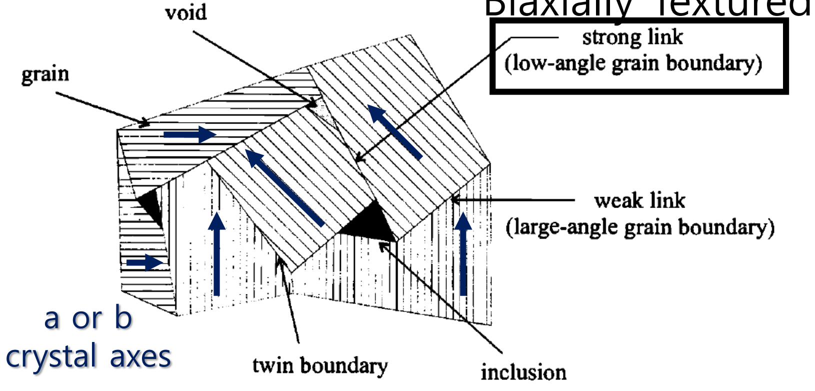

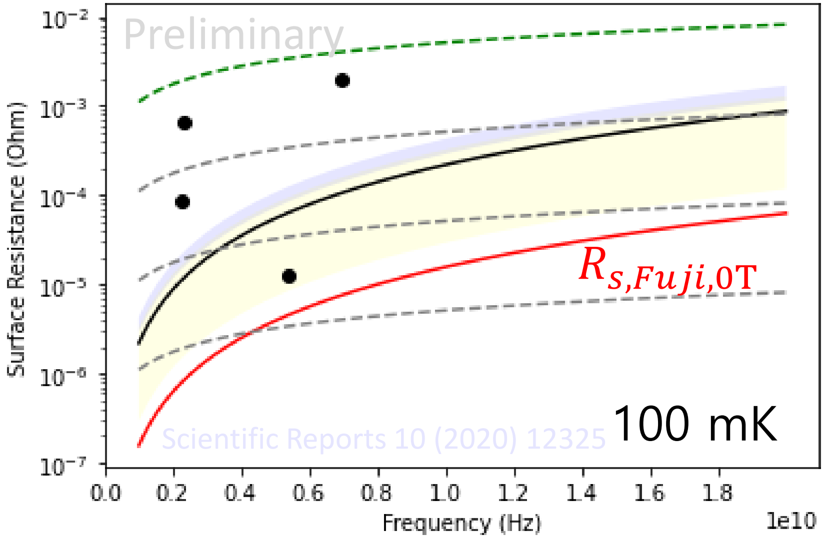

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$\sim\nu^2$

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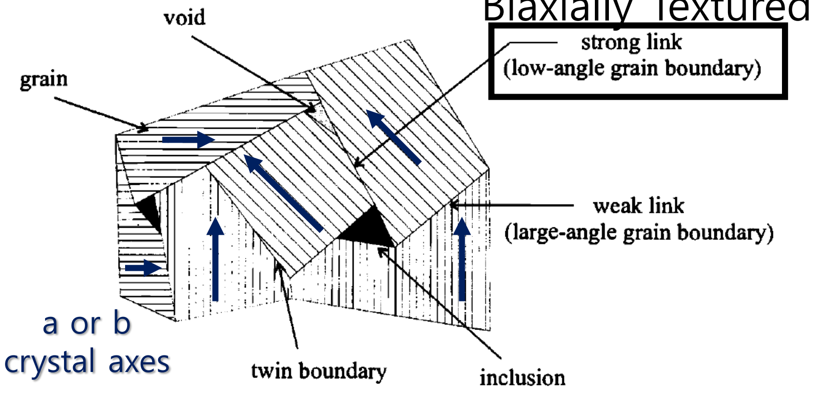
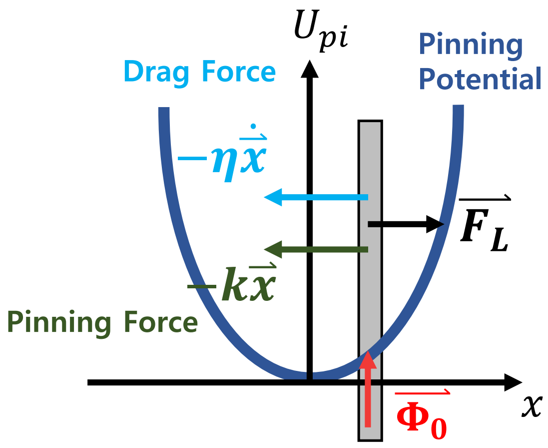
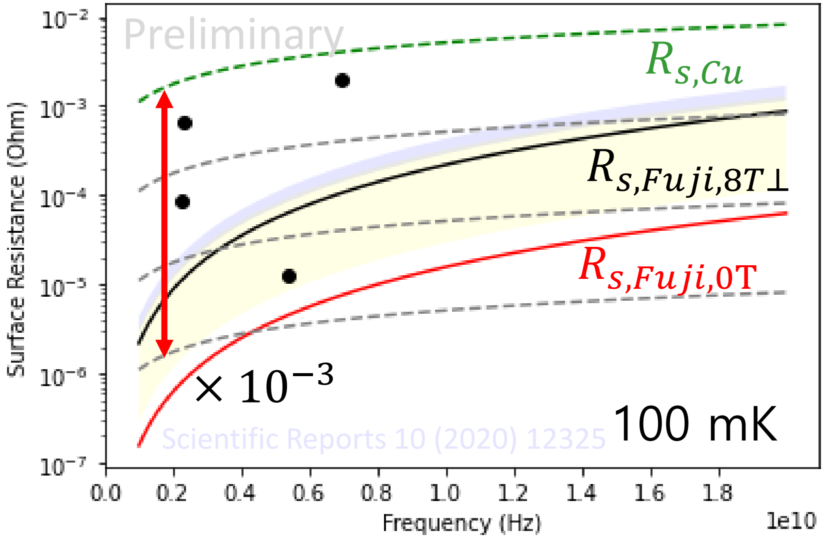


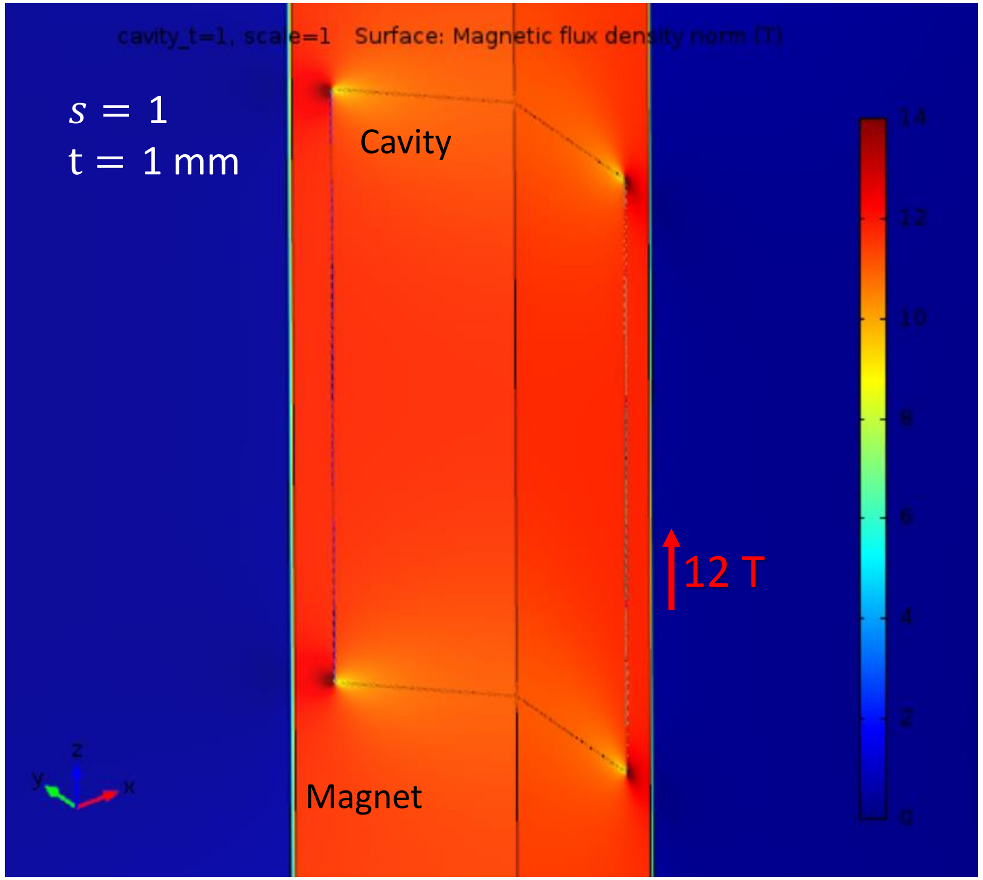


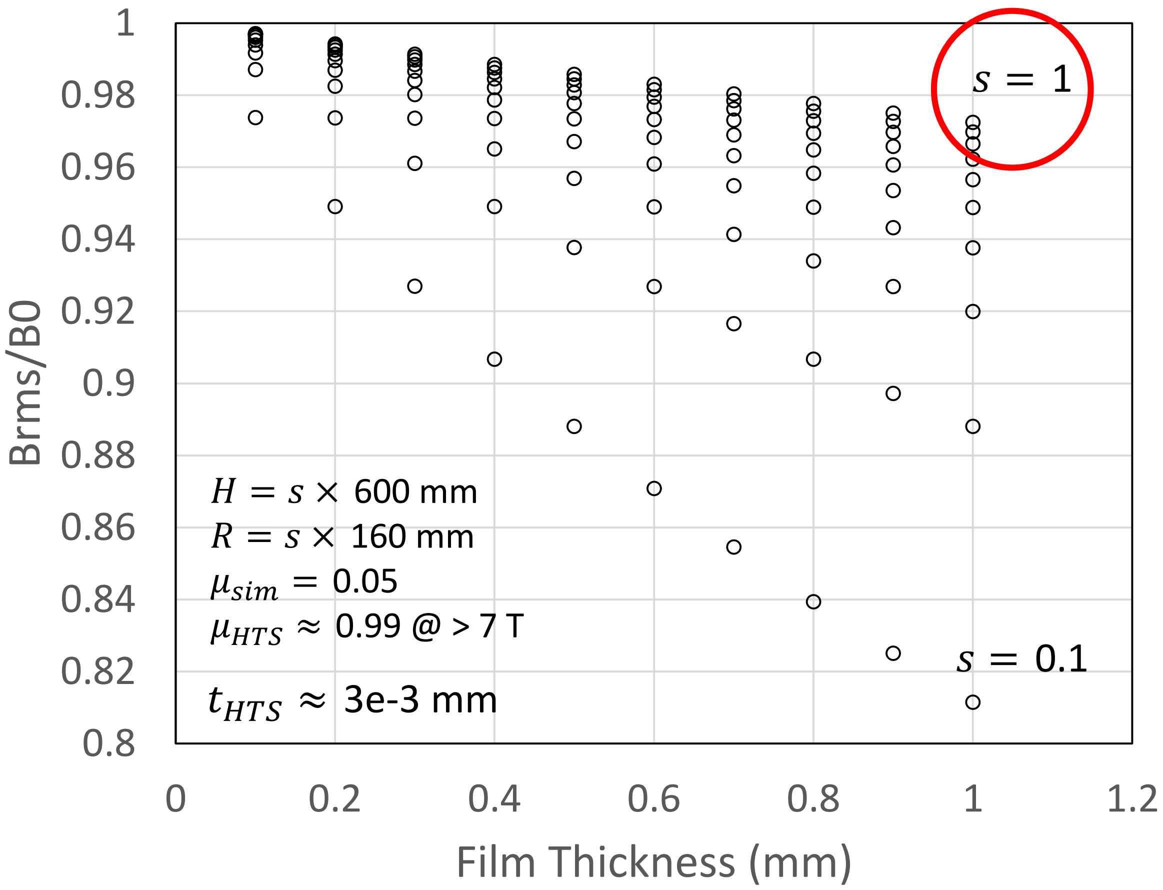


Second Generation ReBCO Coated Conductors

Thin Film Does Not Degrade External Tesla-Scale Magnetic Field

- Thin film geometry does not affect to magnetic fields in the cavity volume.





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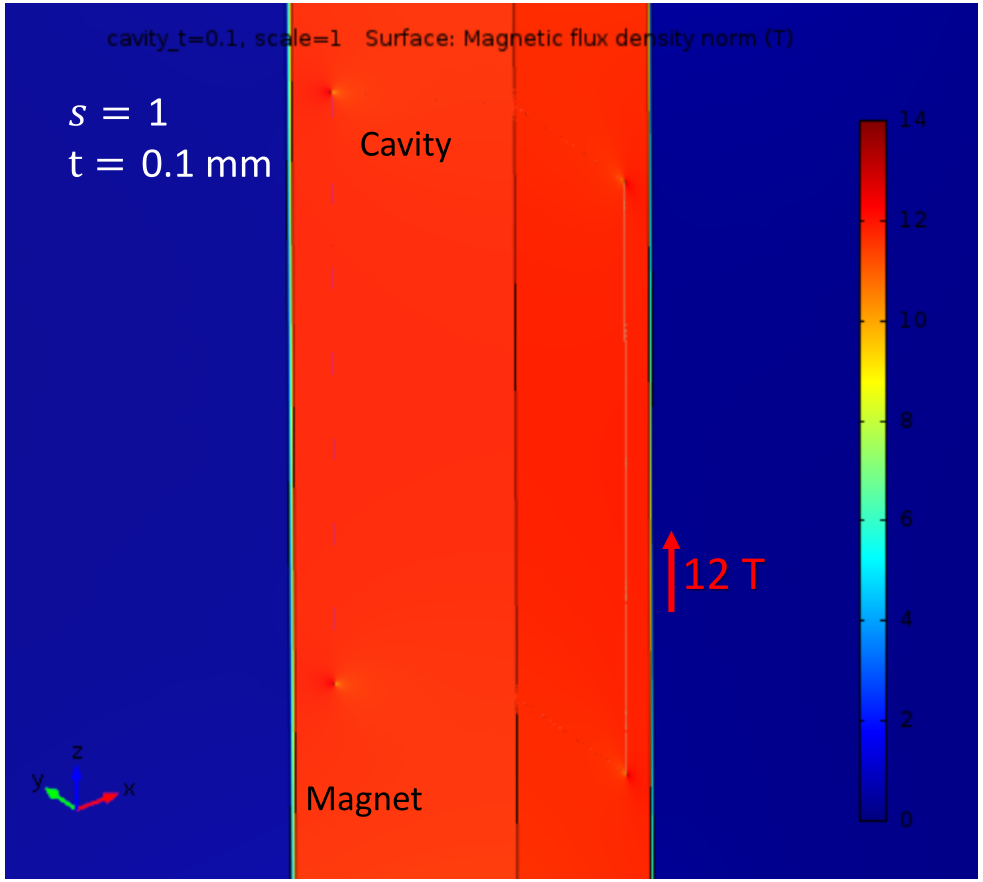

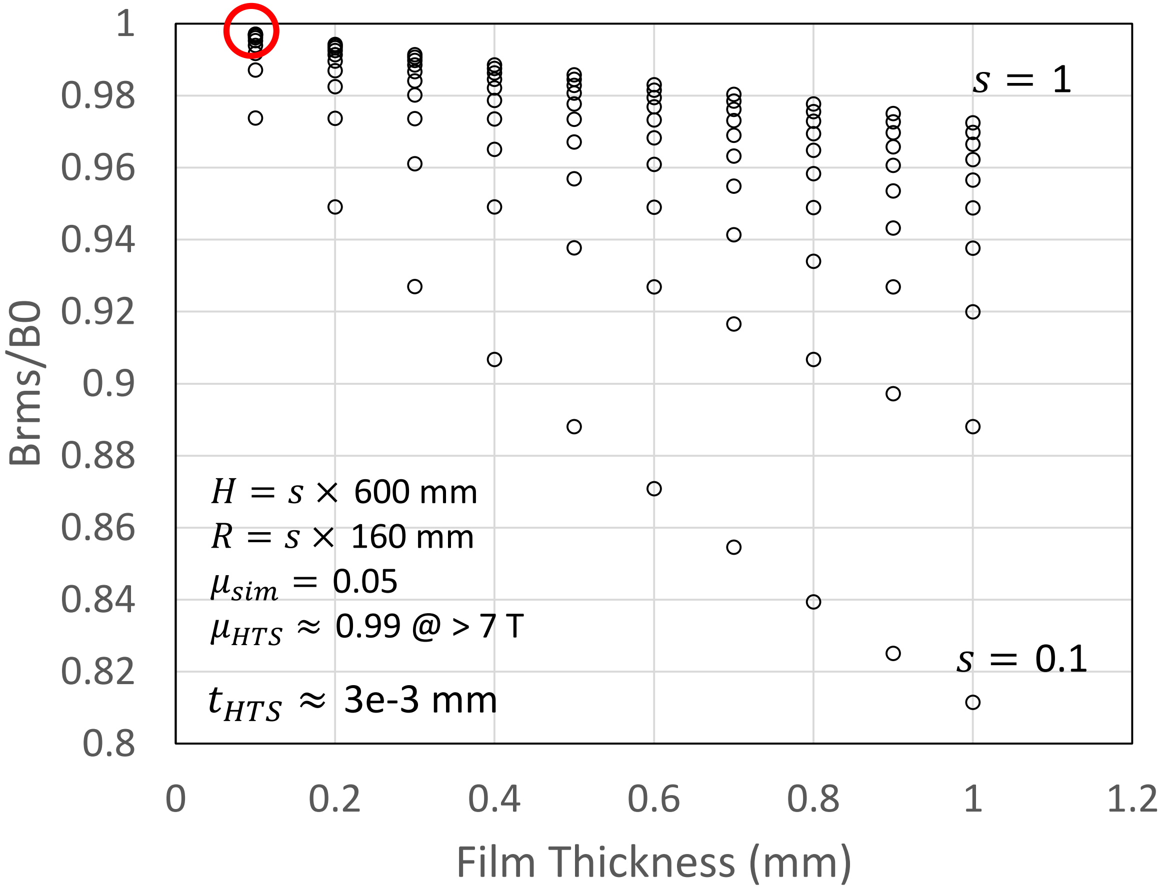

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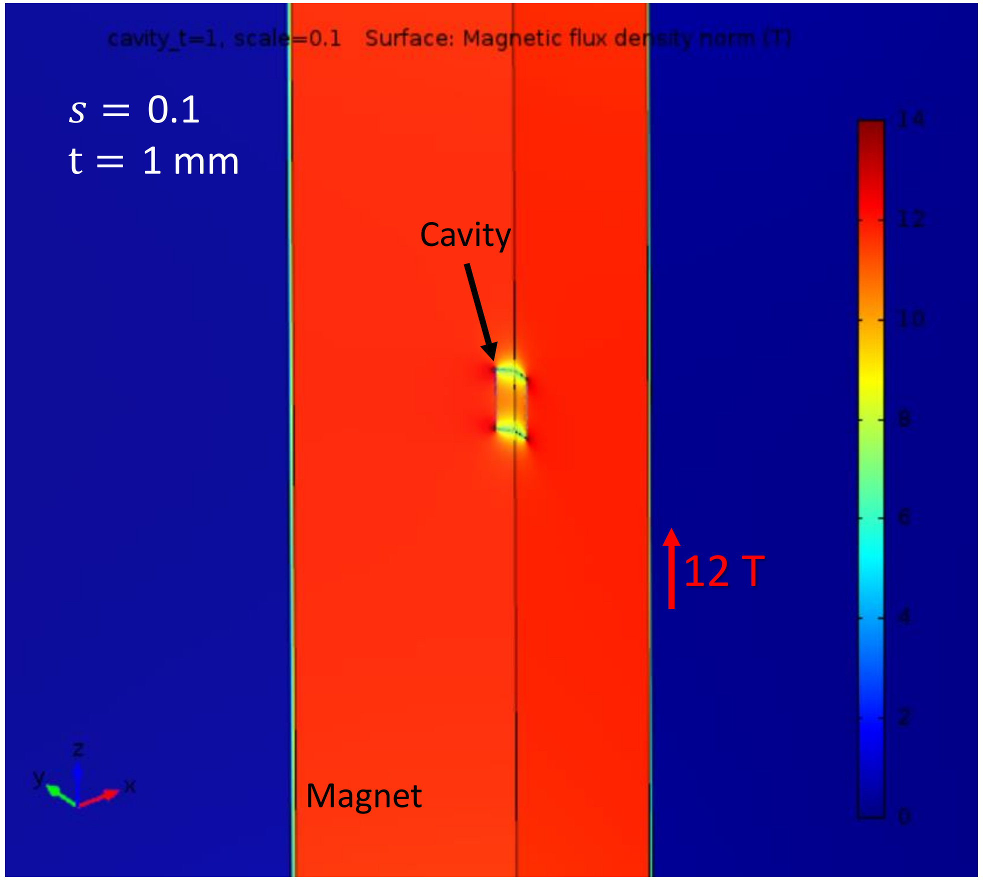

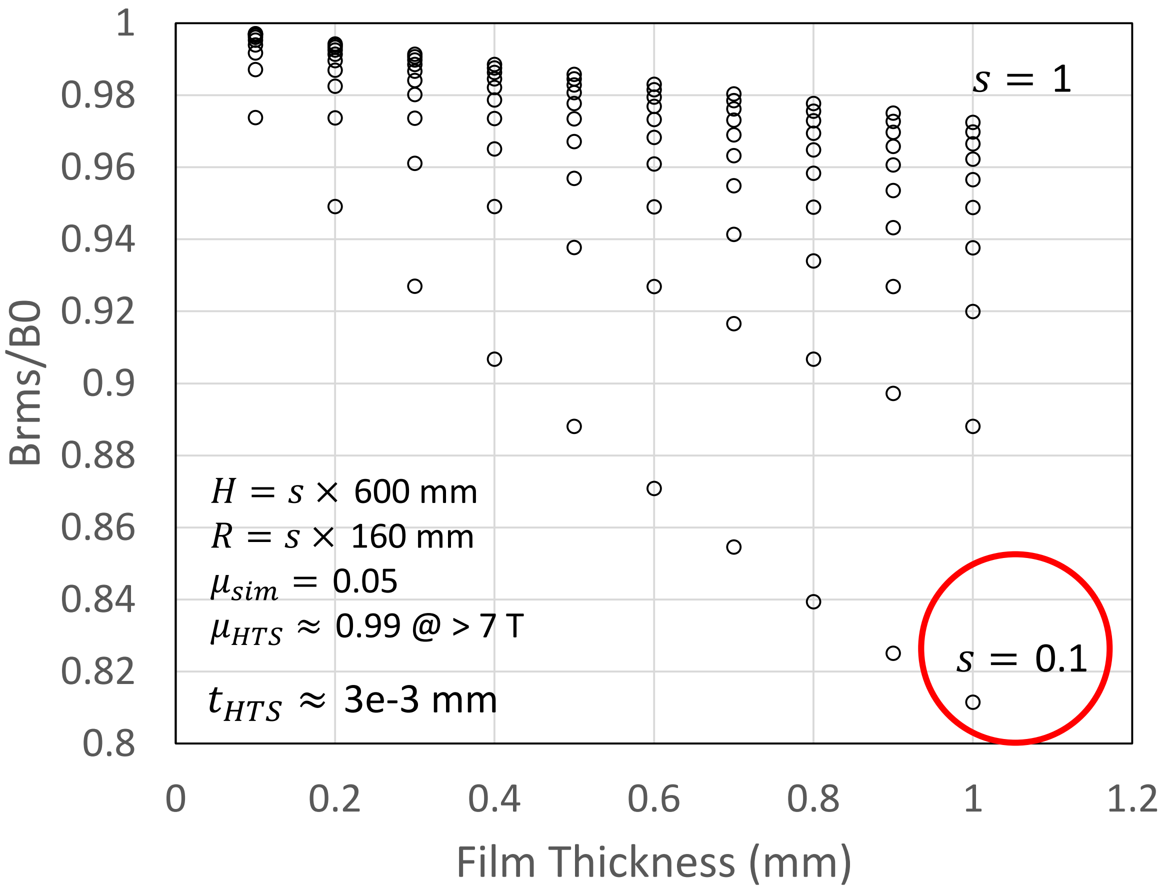

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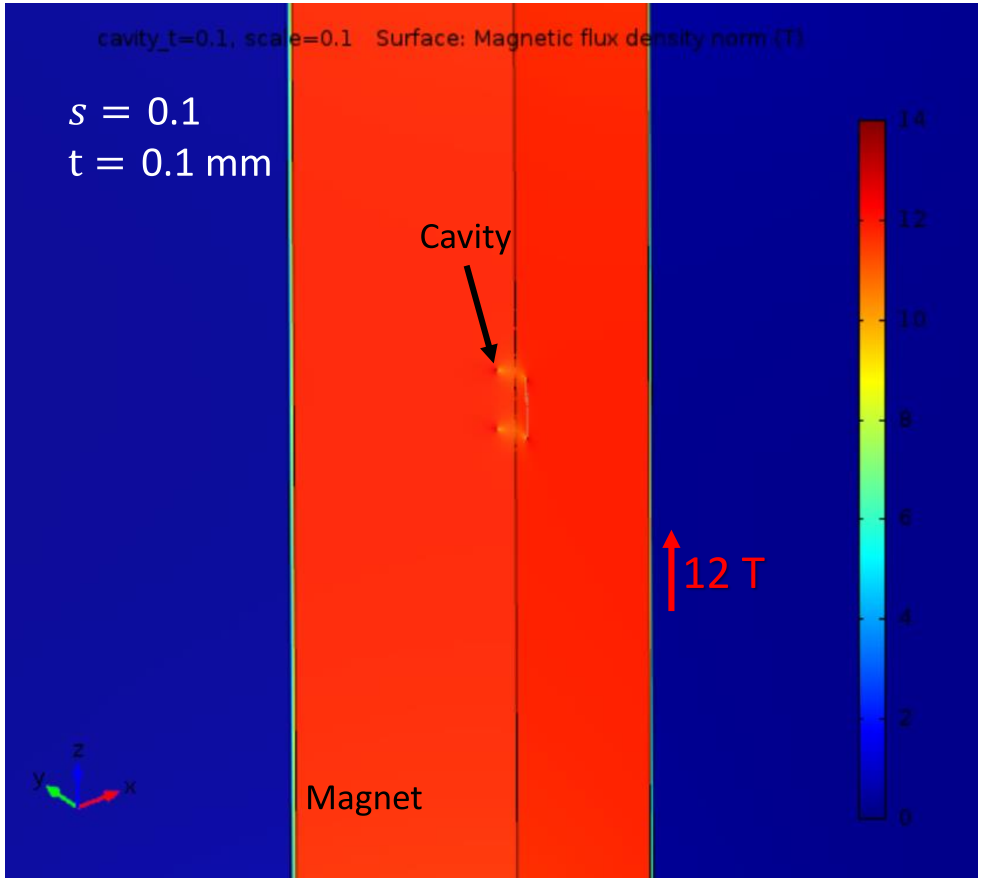

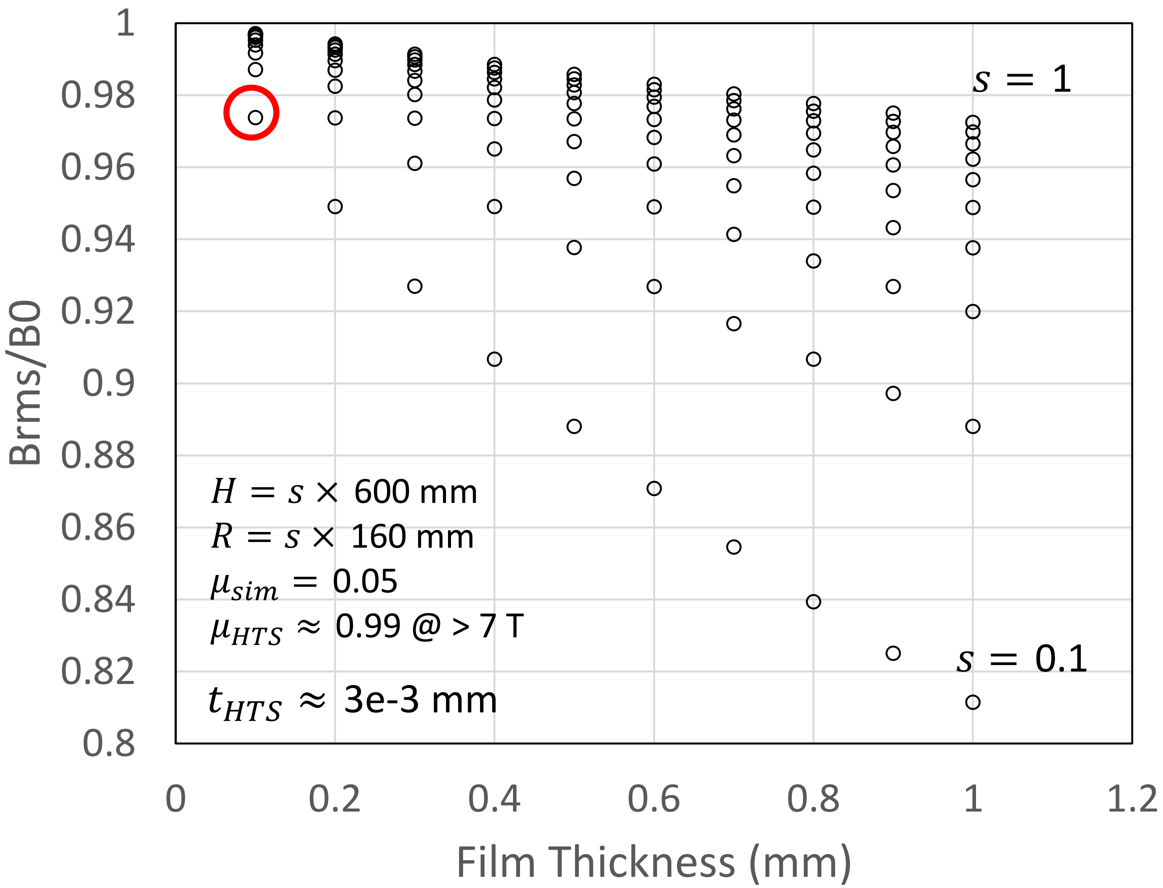

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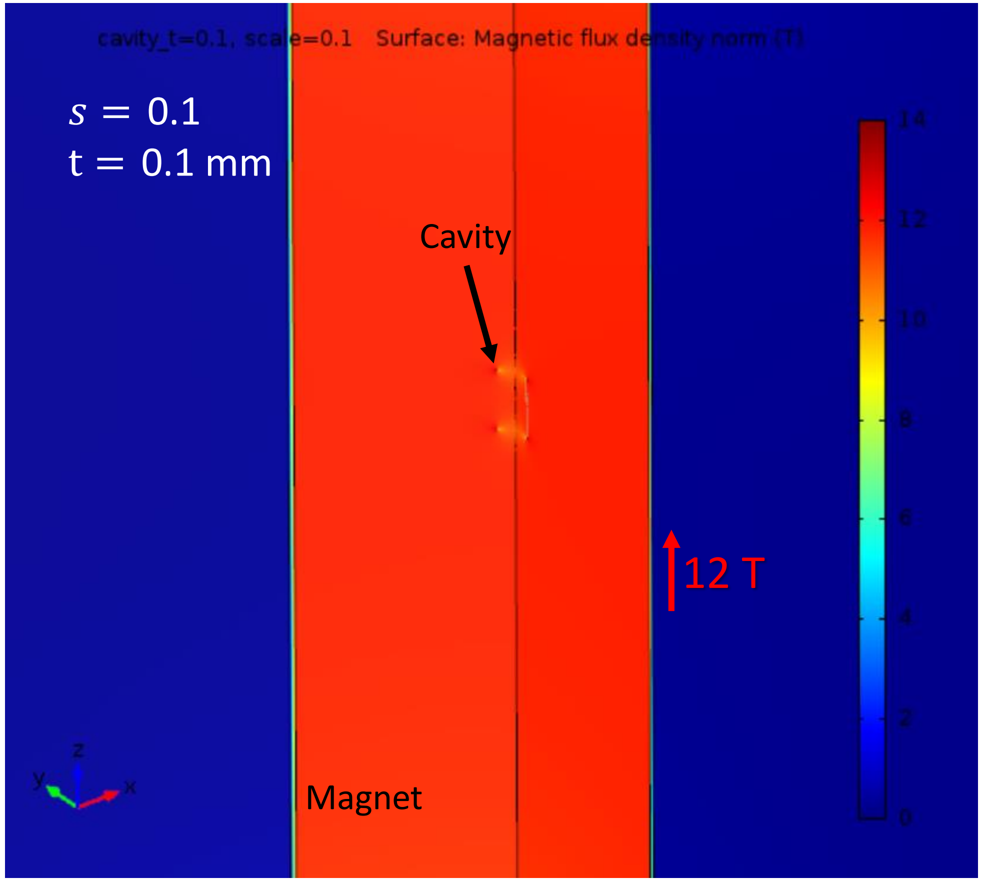
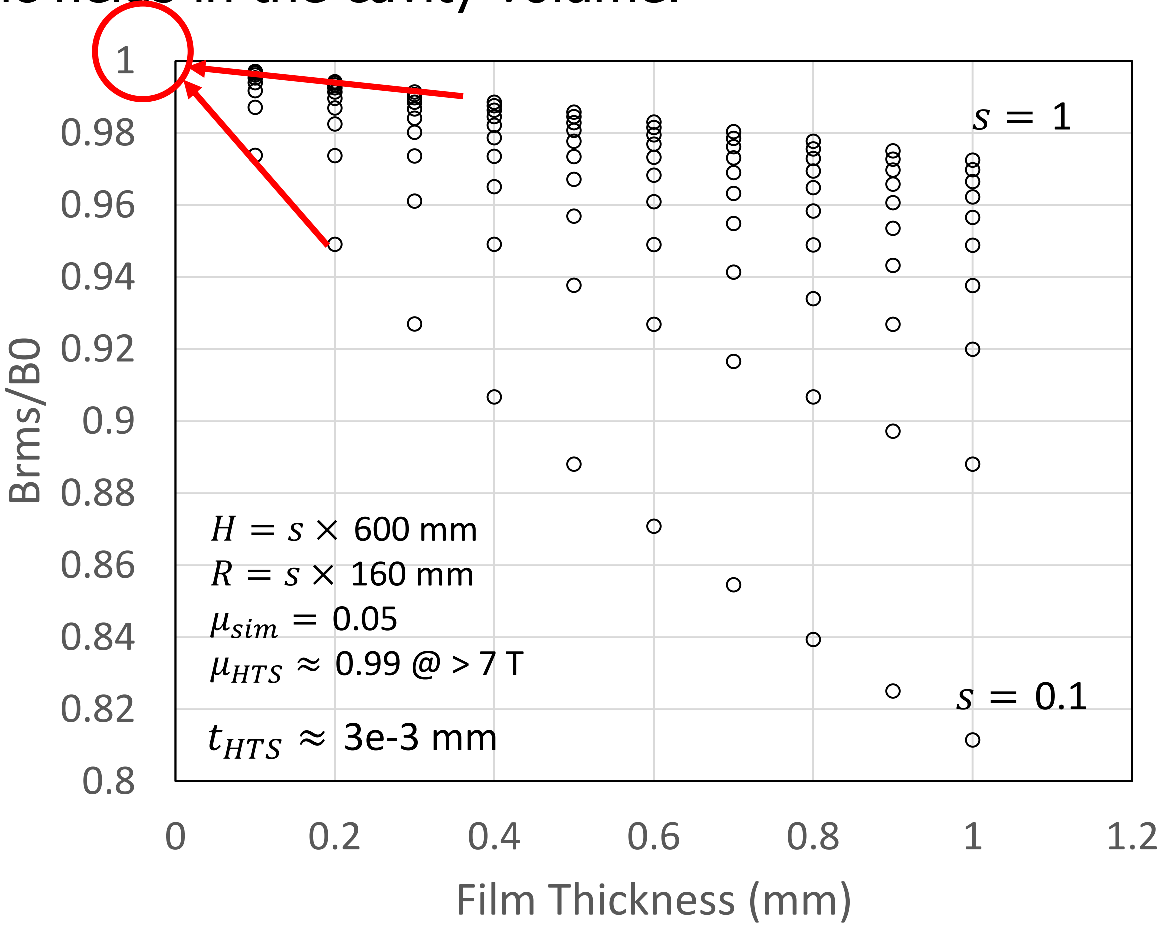
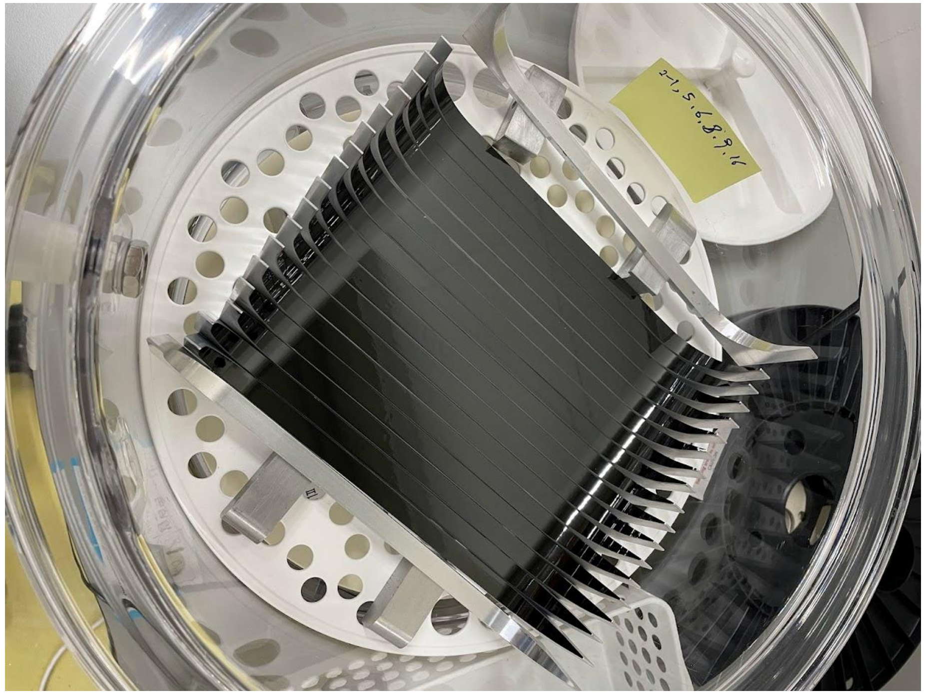




High-temperature Superconducting Cavities at CAPP

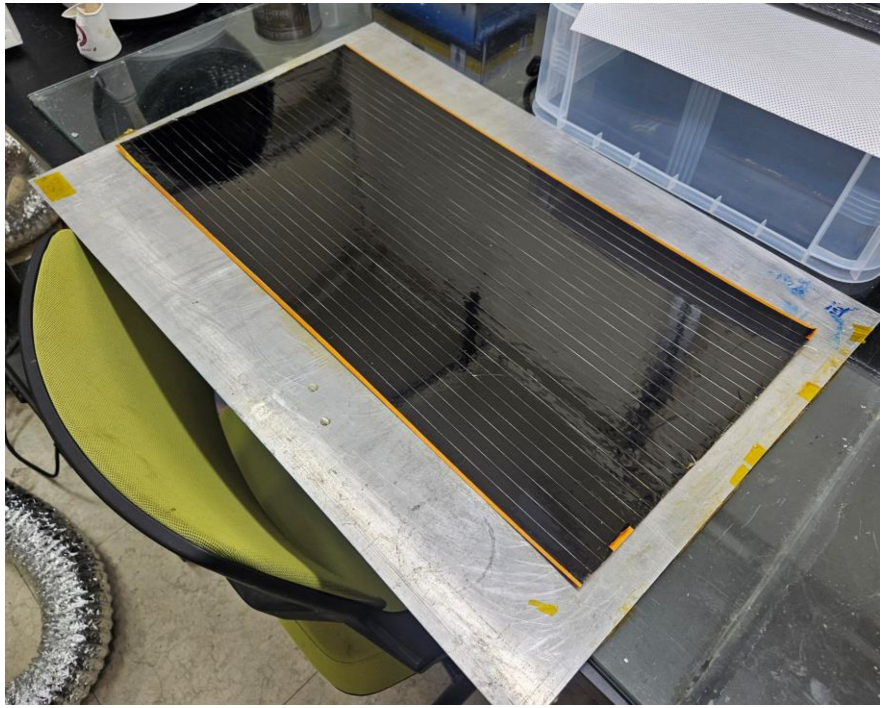
Development Methods

Strategy 1



Pros: Clean Surface
Cons: Slow Fabrication, Electrically Disconnected

Strategy 2



Pros: Easy to Fabricate, Electrically Connected
Cons: Surface Defect (~ 10%)

High-temperature Superconducting Cavities at CAPP

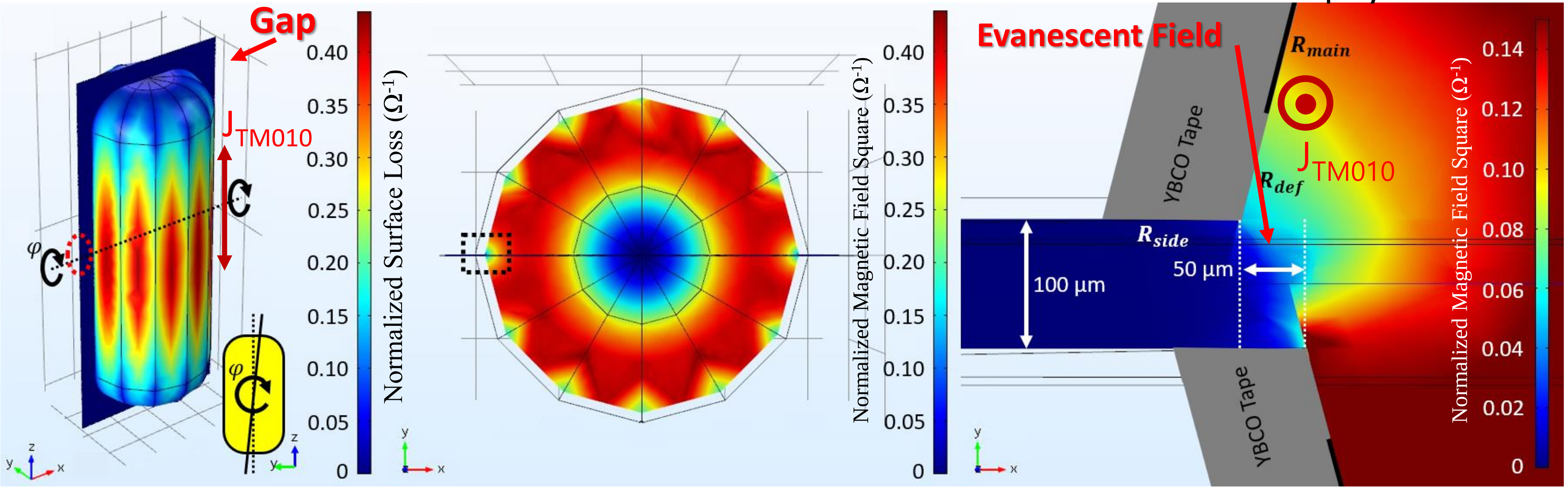
Strategy 1

- Simulation study can estimate energy loss from gaps.
- Misalignments and defects are considered based on fabrication error.
- Only evanescent field enter into a gap.

$Q_{ext} > 10^7$

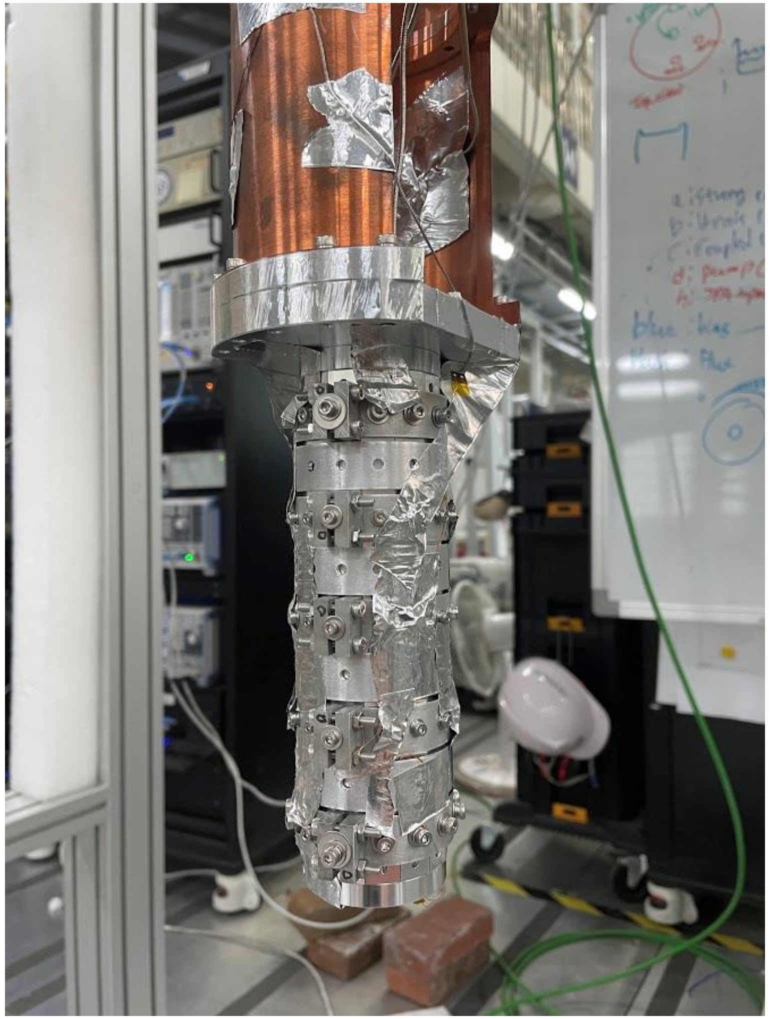
Ahn *et al*. PRApplied(2022), 17, L061005

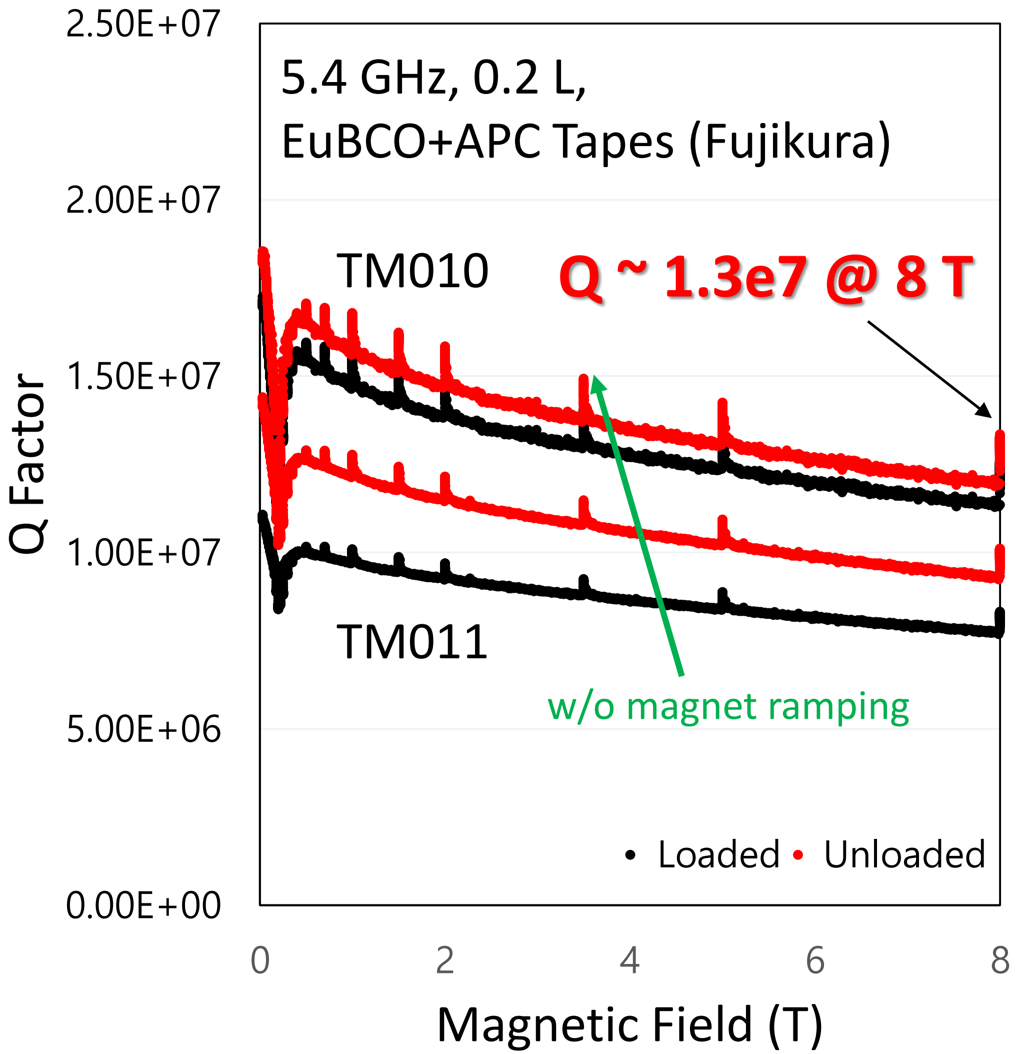
COMSOL Multiphysics Result



High-temperature Superconducting Cavities at CAPP

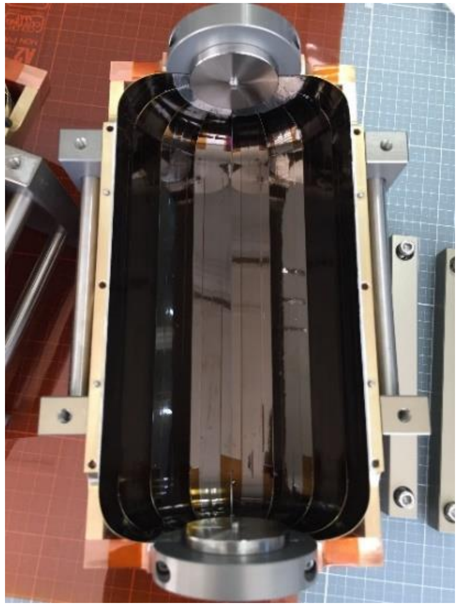
Strategy 1

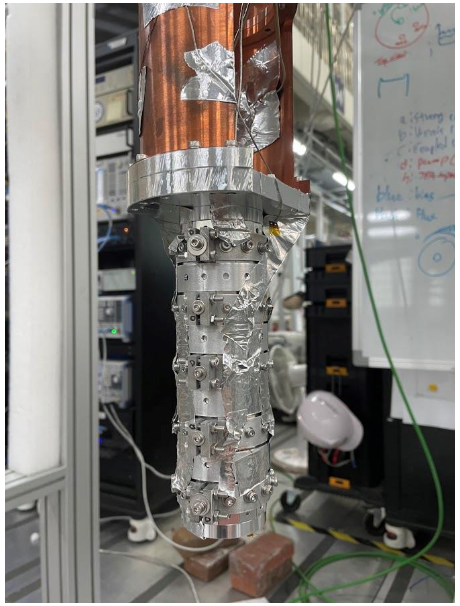




High-temperature Superconducting Cavities at CAPP

History of Development



?

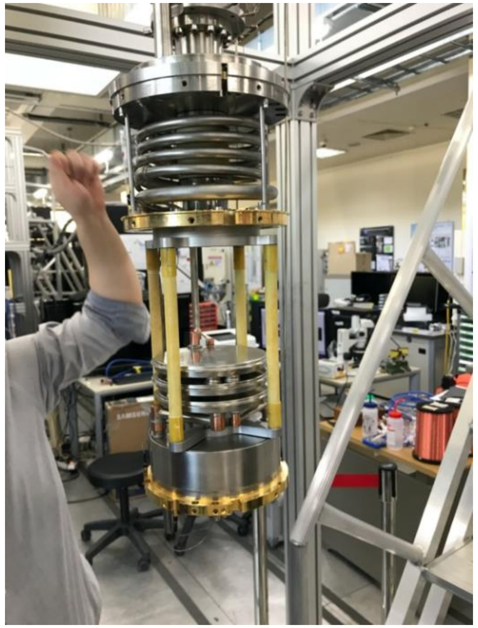
Date	Tape	f (GHz)	n_{gap}	Q (0 T)	Q (8 T)	Q_{gap}	Experiment
1	YBCO	6.9	12	0.22 M	0.33 M		Prototype
2	GdBCO	2.3	32	0.60 M	0.50 M		Cavity Haloscope
3	EuBCO+APC	2.3	34	5.0 M	3.5 M	> 10 M	Axion Quark Nugget Search
4	EuBCO+APC	5.4	14	20 M	13 M		Cavity Haloscope
5	**EuBCO+APC**	**1.2 ~ 1.5**	**?**	**?**	**?**		**Axion Haloscope (CAPP-MAX)**

High-temperature Superconducting Cavities at CAPP

Superconducting Cavity for CAPP-MAX

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

Ahn's talk on Mon 13:30
Ivanov's talk on Fri 13:55



Dilution refrigerator 25mK

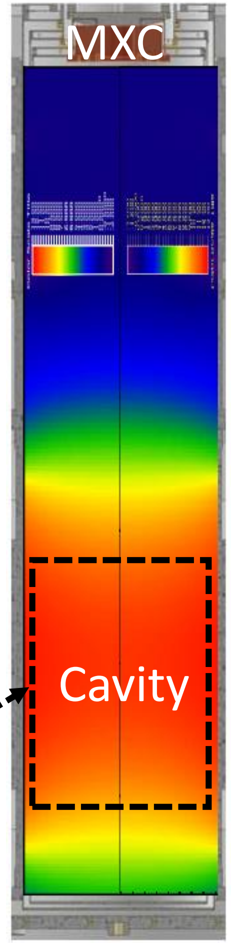
+

Josephson Parametric Amplifier
$T_{sys} \approx 200$ mK

+

12 Tesla SC magnet
320mm bore diameter

Still shield

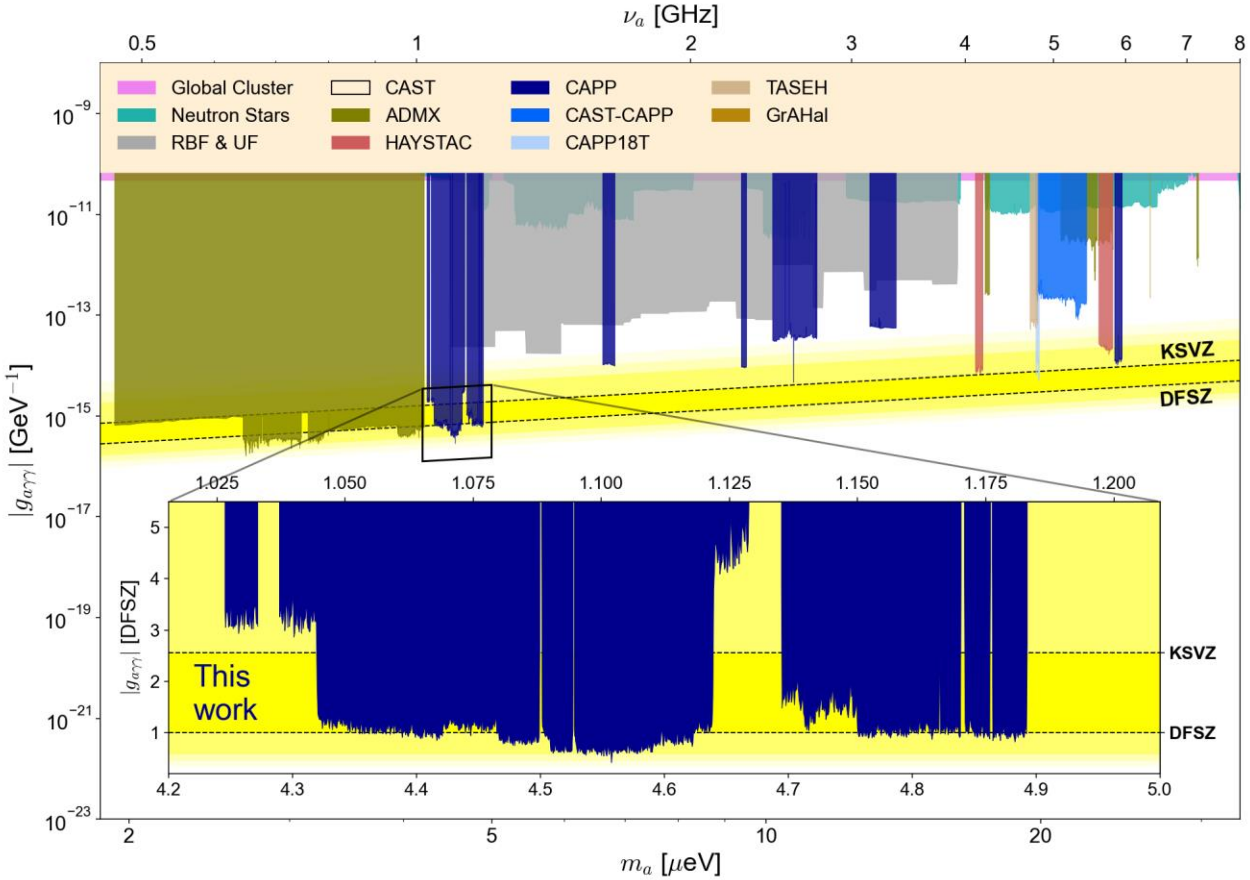


B-field map

High-temperature Superconducting Cavities at CAPP

Superconducting Cavity for CAPP-MAX

arXiv:2402.12892, Submitted to PRX, Accepted



High-temperature Superconducting Cavities at CAPP

Superconducting Cavity for CAPP-MAX

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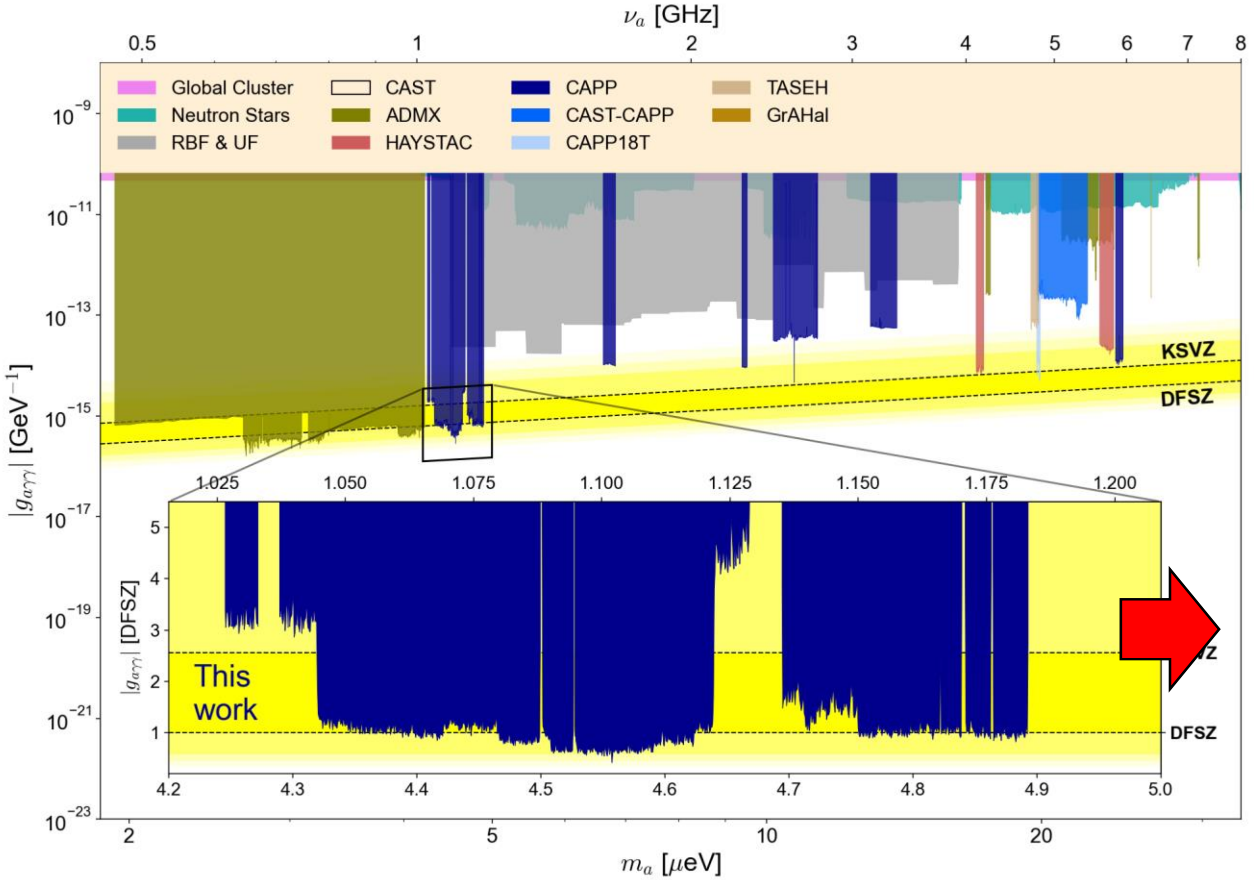

High-temperature Superconducting Cavities at CAPP

Superconducting Cavity for CAPP-MAX

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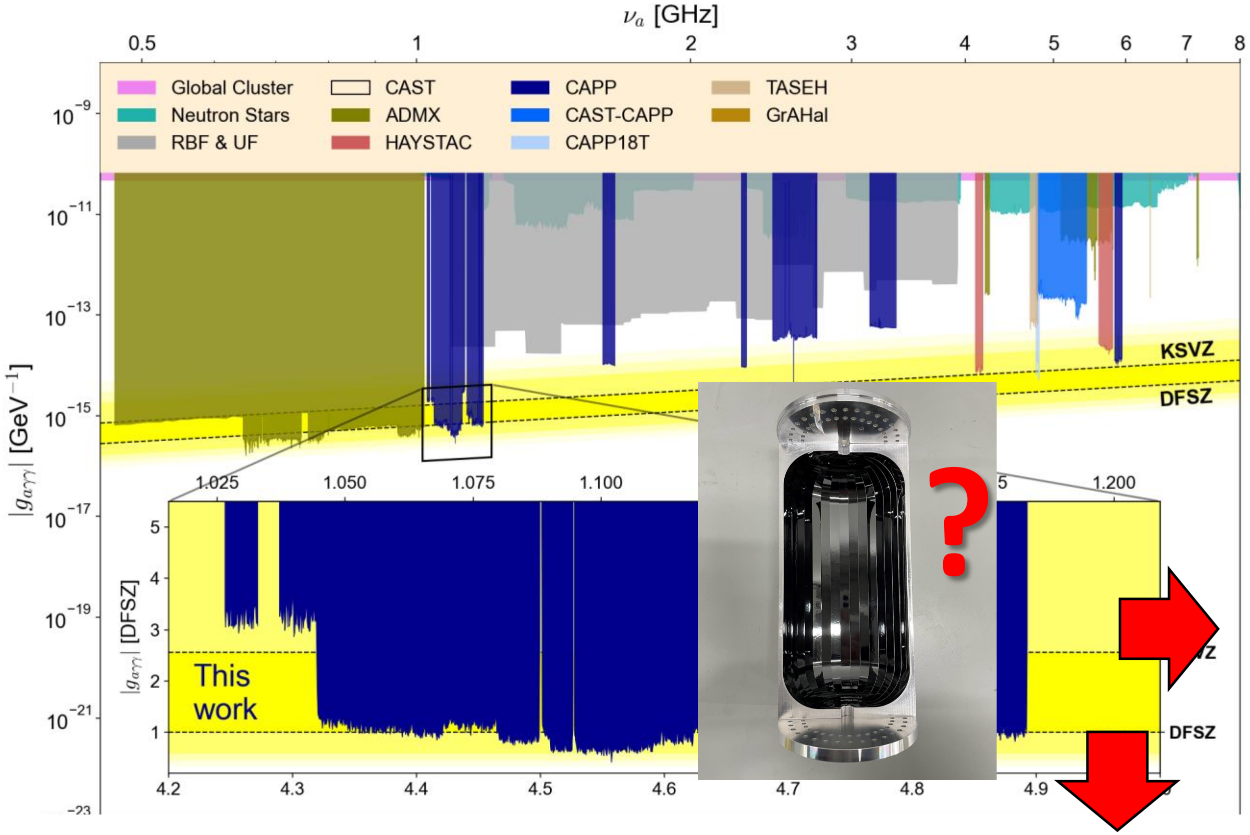


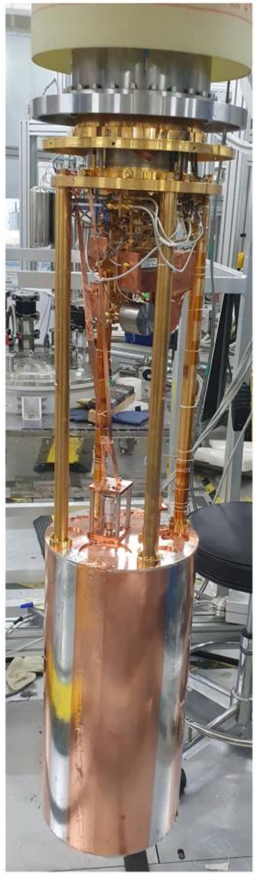
Below DFSZ sensitivity or Axion as 20% of Dark Matter

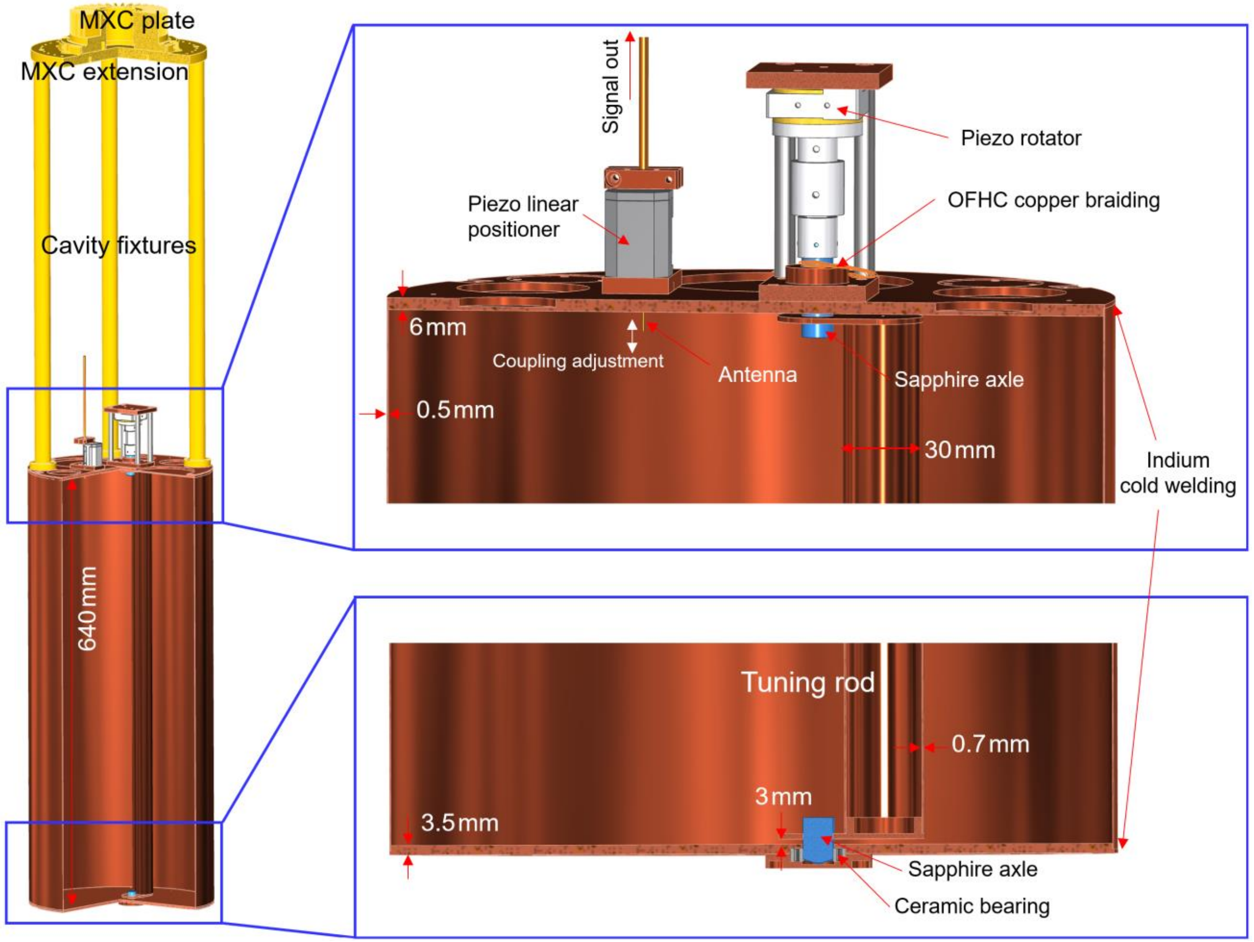
Yannis K. Semertzidis's Opening Talk on Mon 10:00

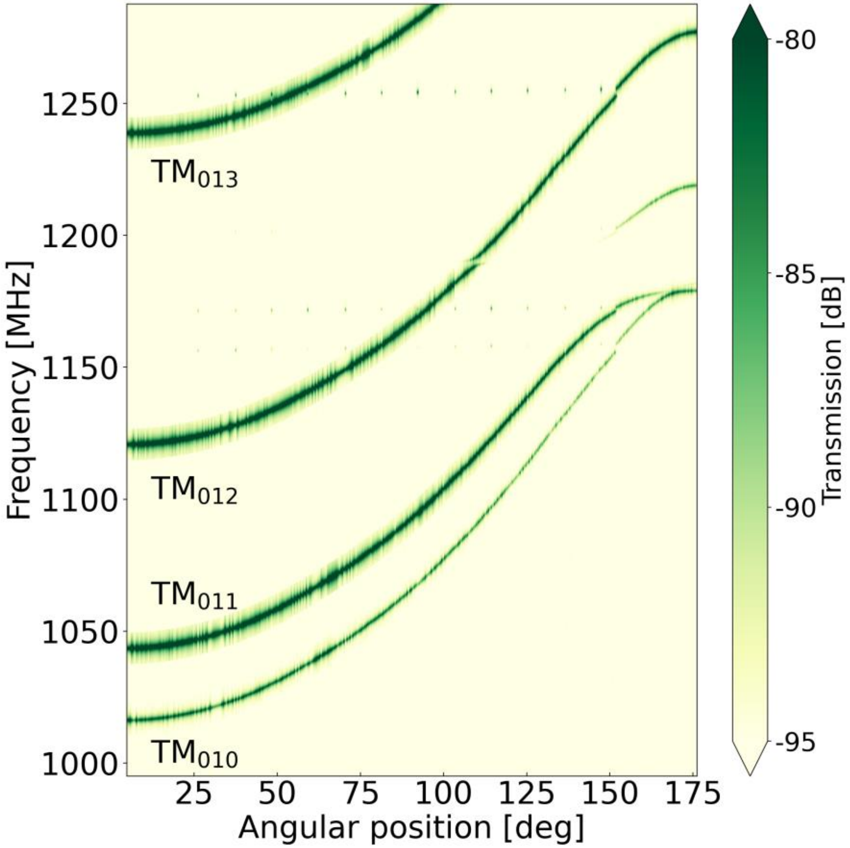
High-temperature Superconducting Cavities at CAPP

Superconducting Cavity for CAPP-MAX

arXiv:2402.12892, Submitted to PRX, Accepted

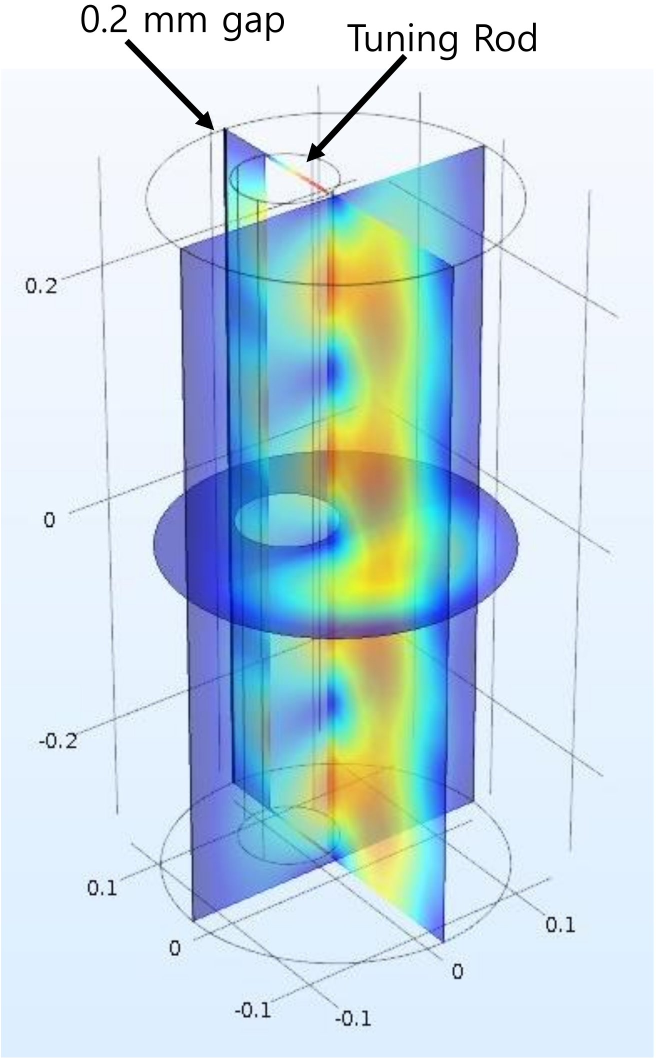




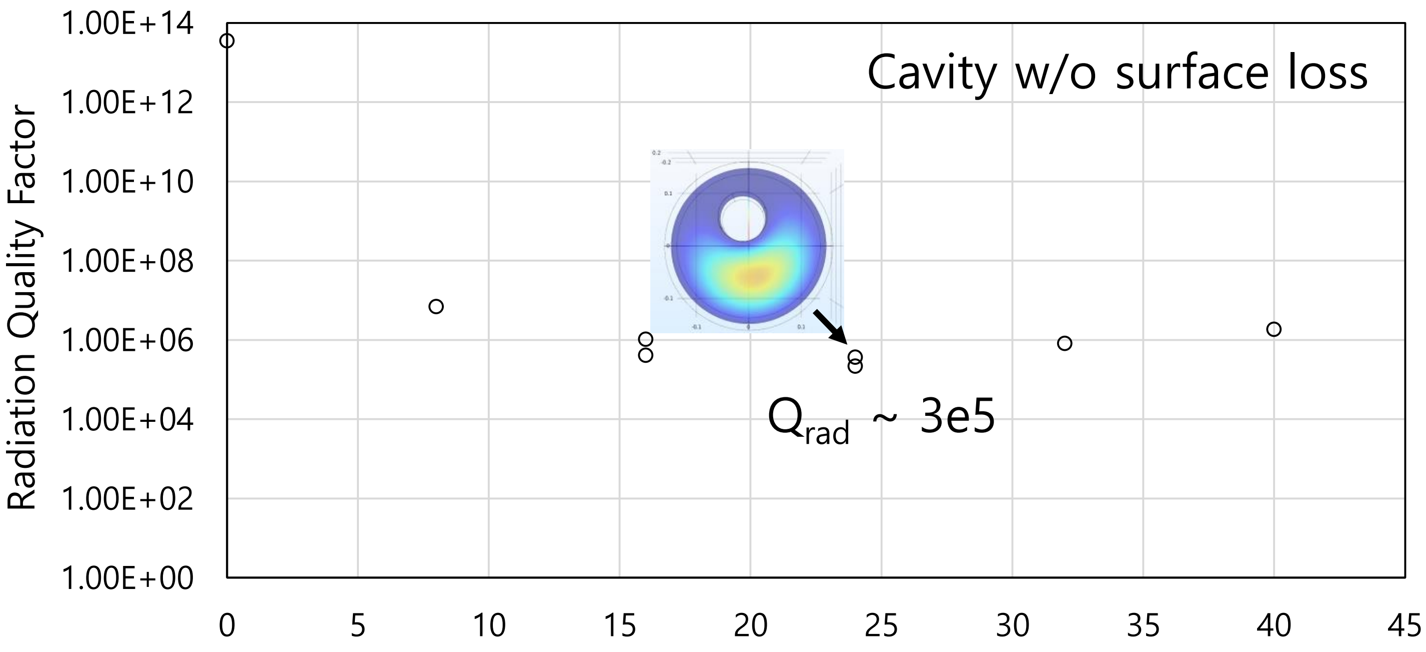


High-temperature Superconducting Cavities at CAPP

Strategy 2



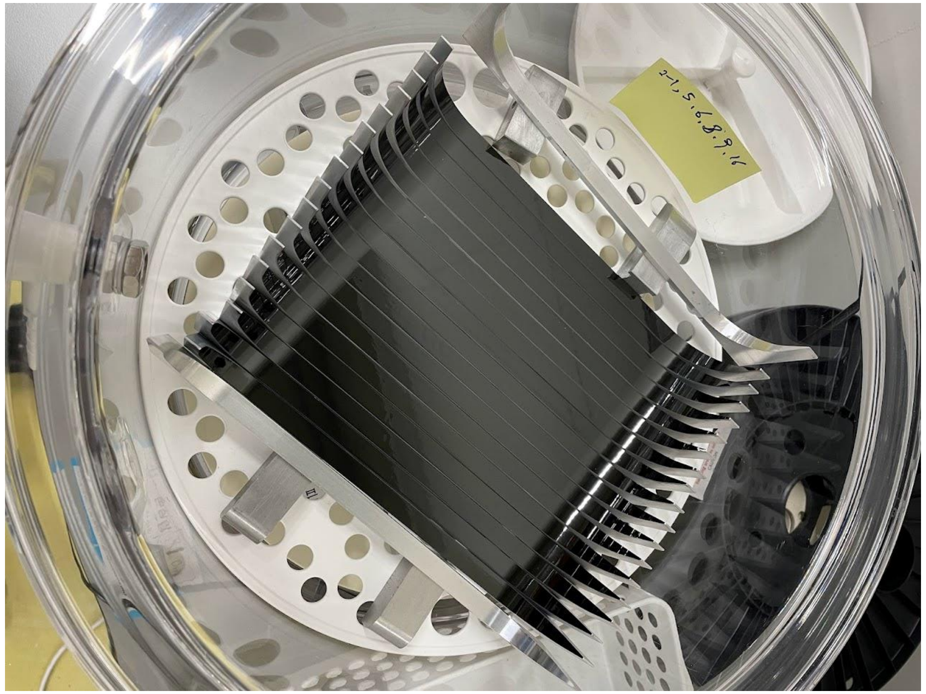
- ➢ Sensitive to Contact Problem
- ➢ Gaps should be closed electrically to prevent a radiation



High-temperature Superconducting Cavities at CAPP

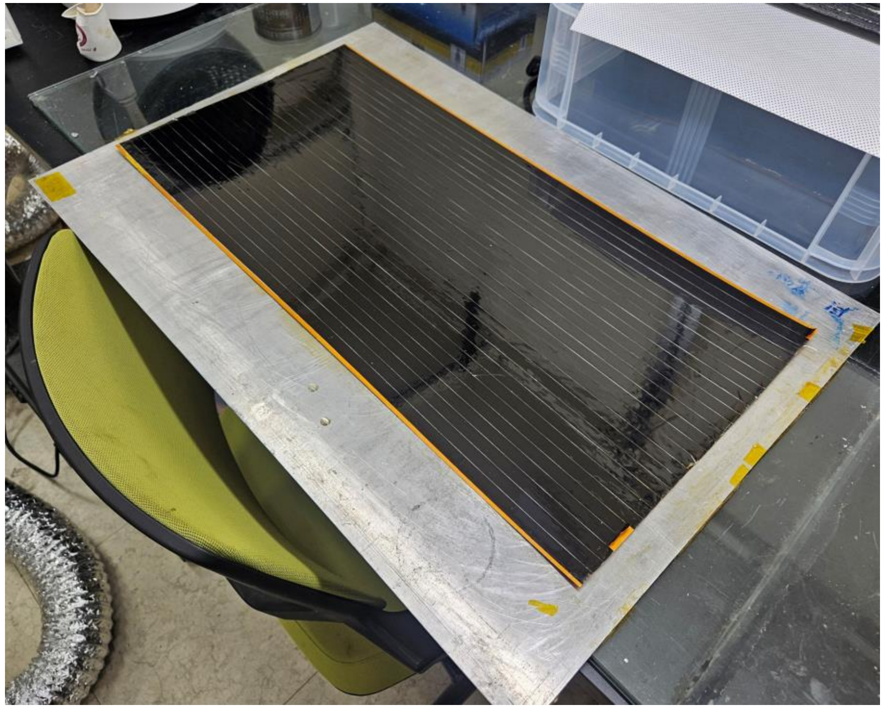
Development Methods

Strategy 1



Pros: Clean Surface
Cons: Slow Fabrication, Electrically Disconnected

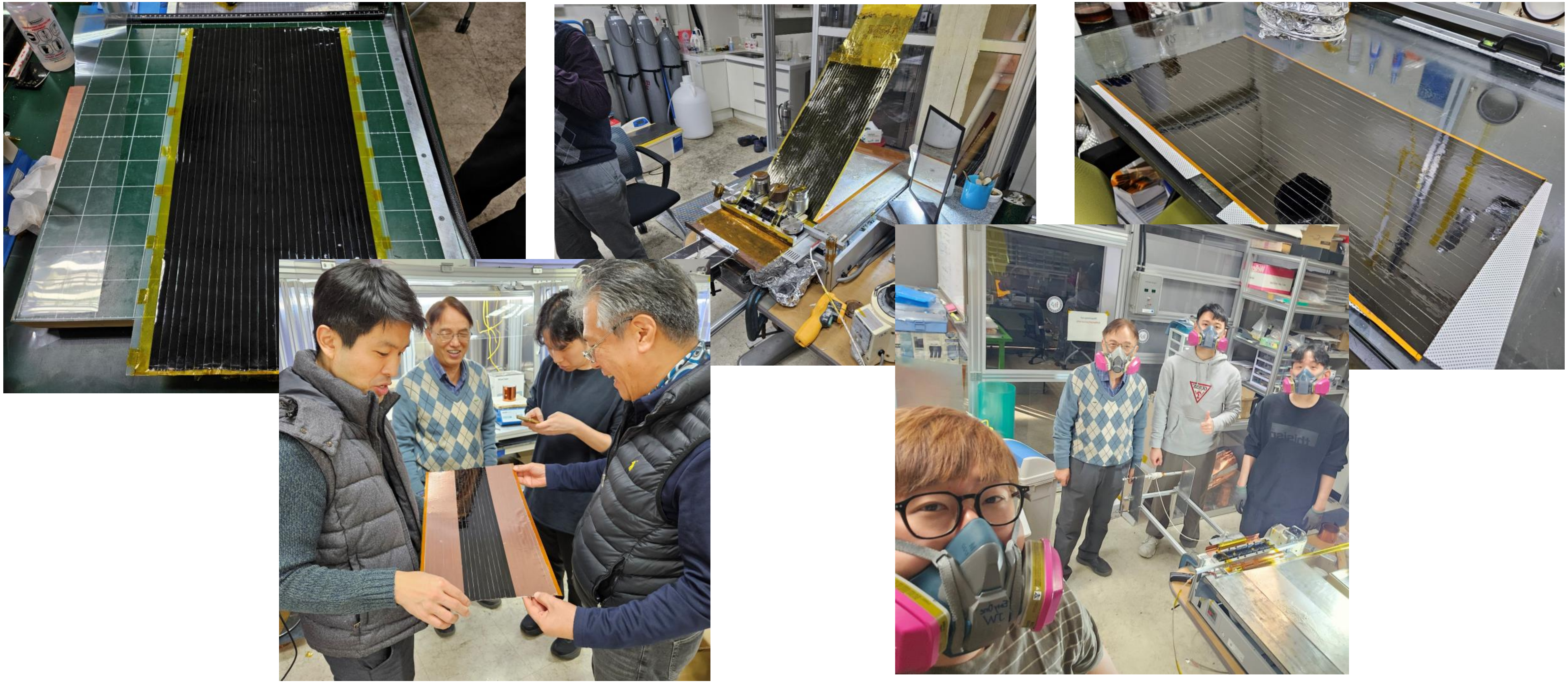
Strategy 2



Pros: Easy to Fabricate, Electrically Connected
Cons: Surface Defect (~ 10%)

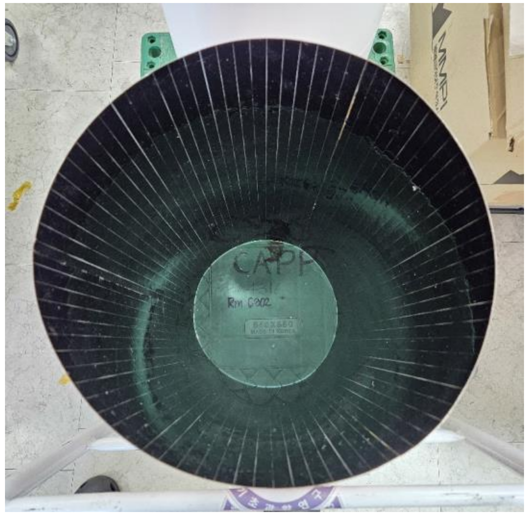
High-temperature Superconducting Cavities at CAPP

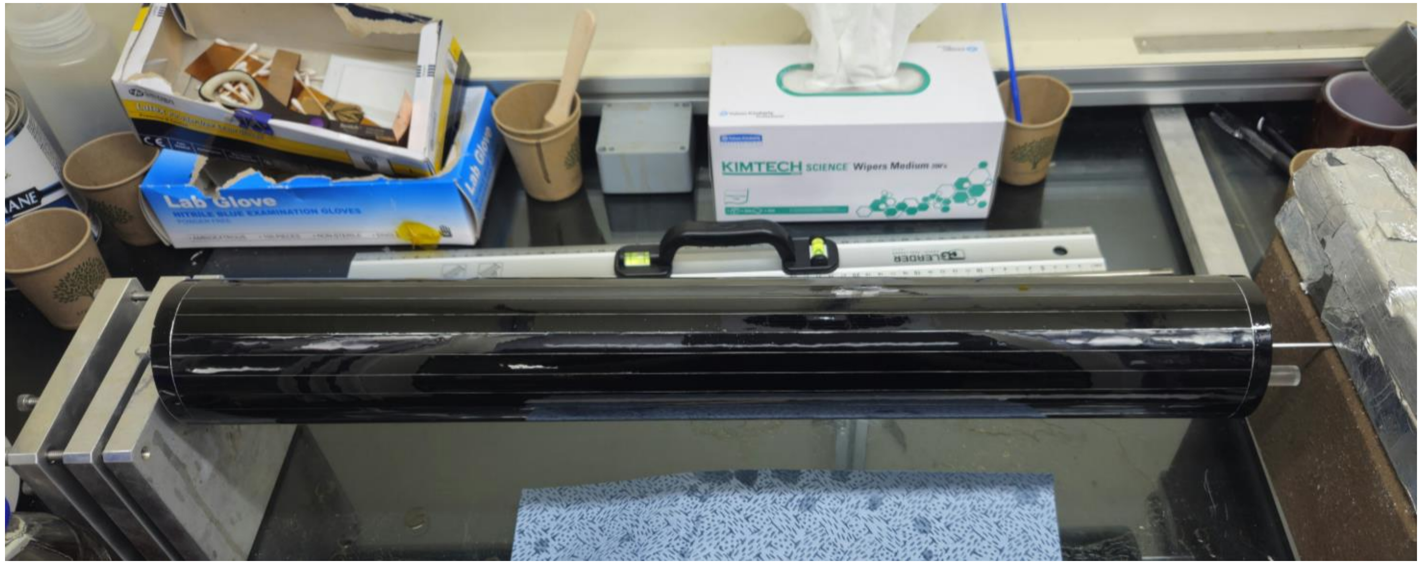
Strategy 2

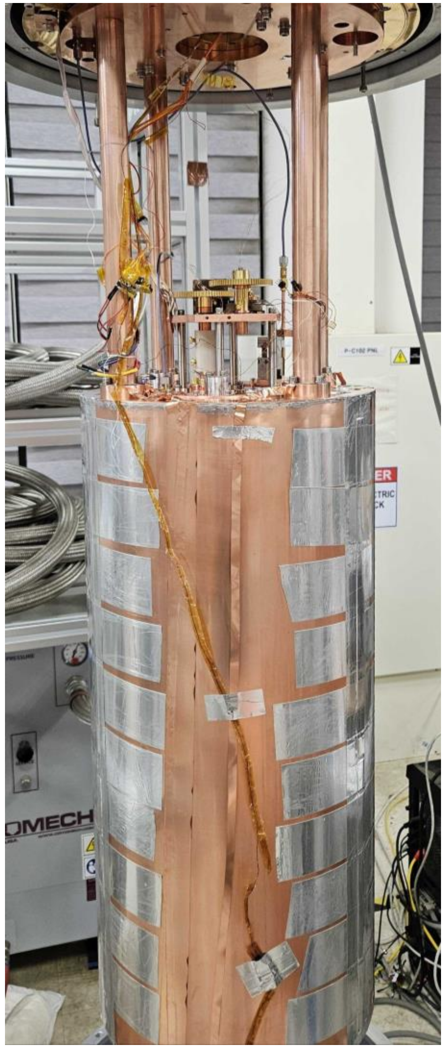


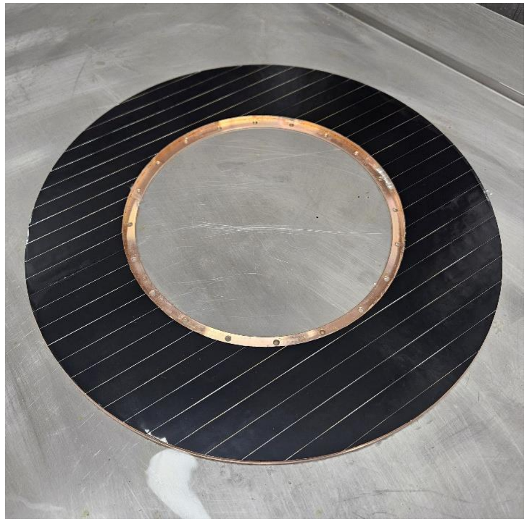
High-temperature Superconducting Cavities at CAPP

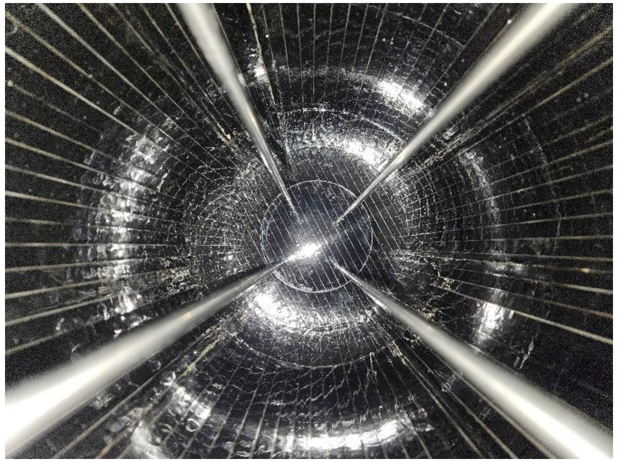
Strategy 2





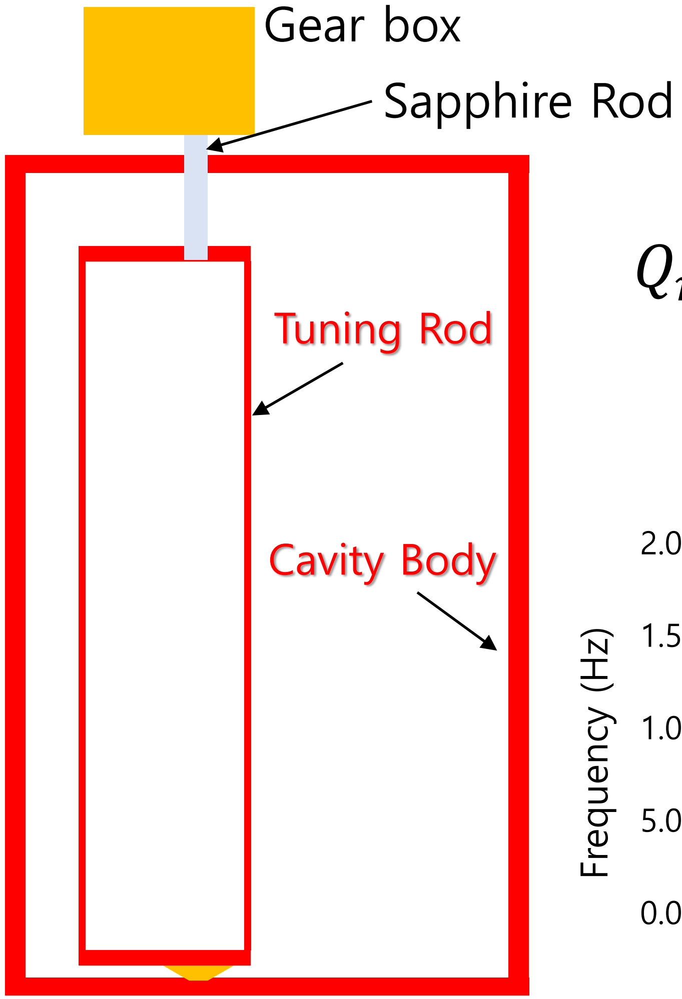




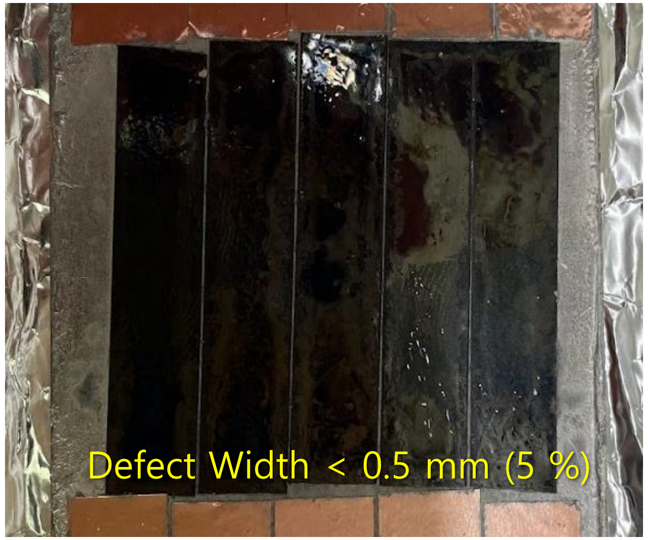


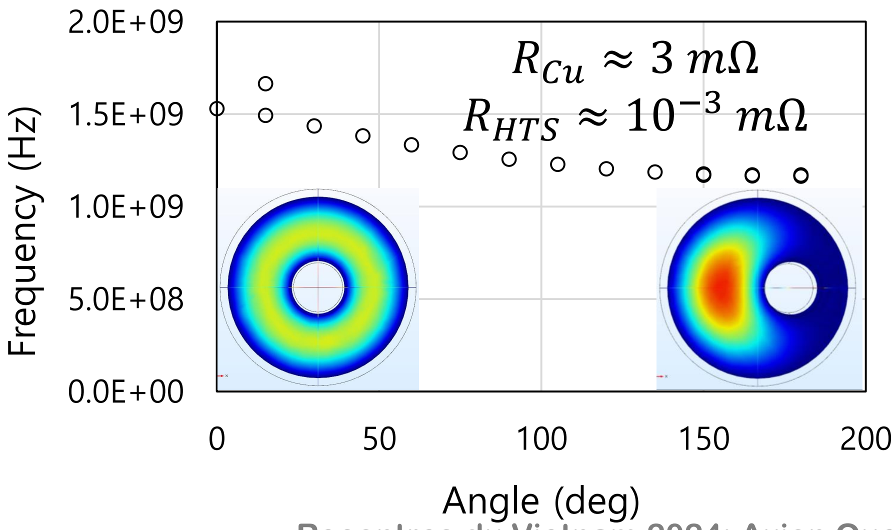
High-temperature Superconducting Cavities at CAPP

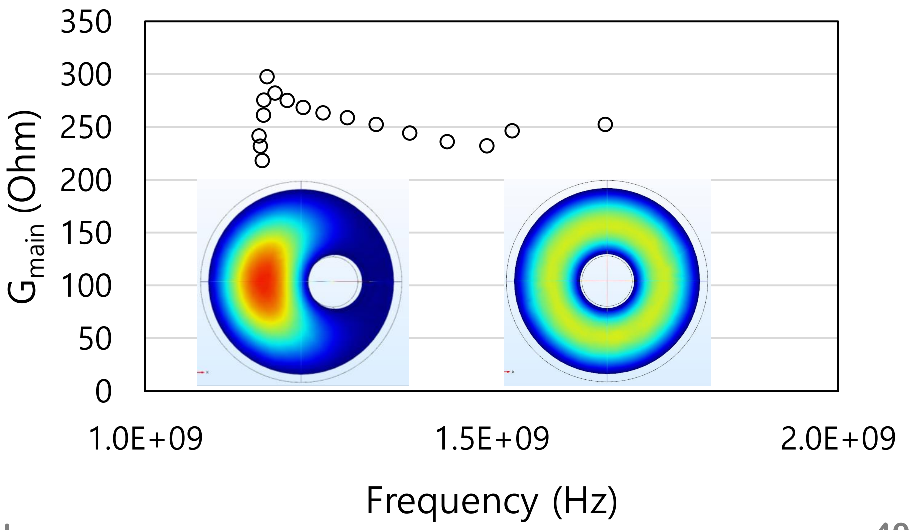
Strategy 2



$$Q_{main} \approx \frac{250\Omega}{3m\Omega \times 10\%} = \mathbf{8 \times 10^5}$$

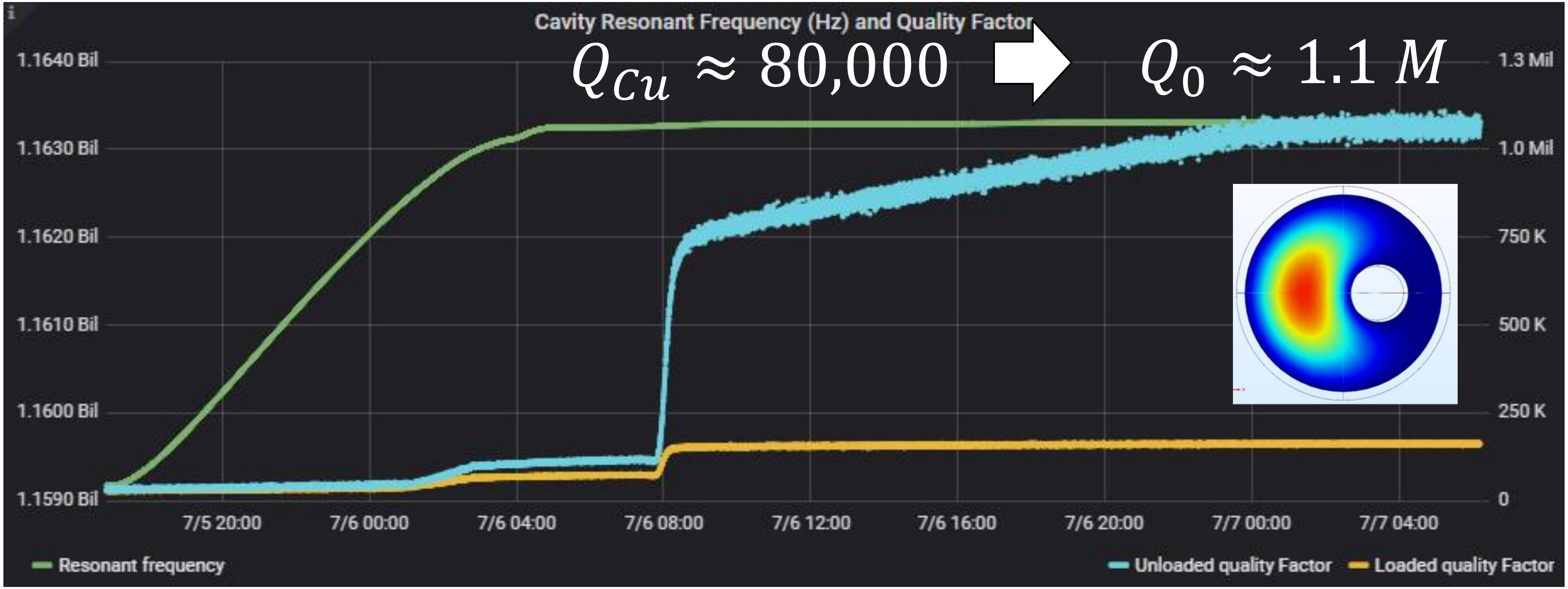






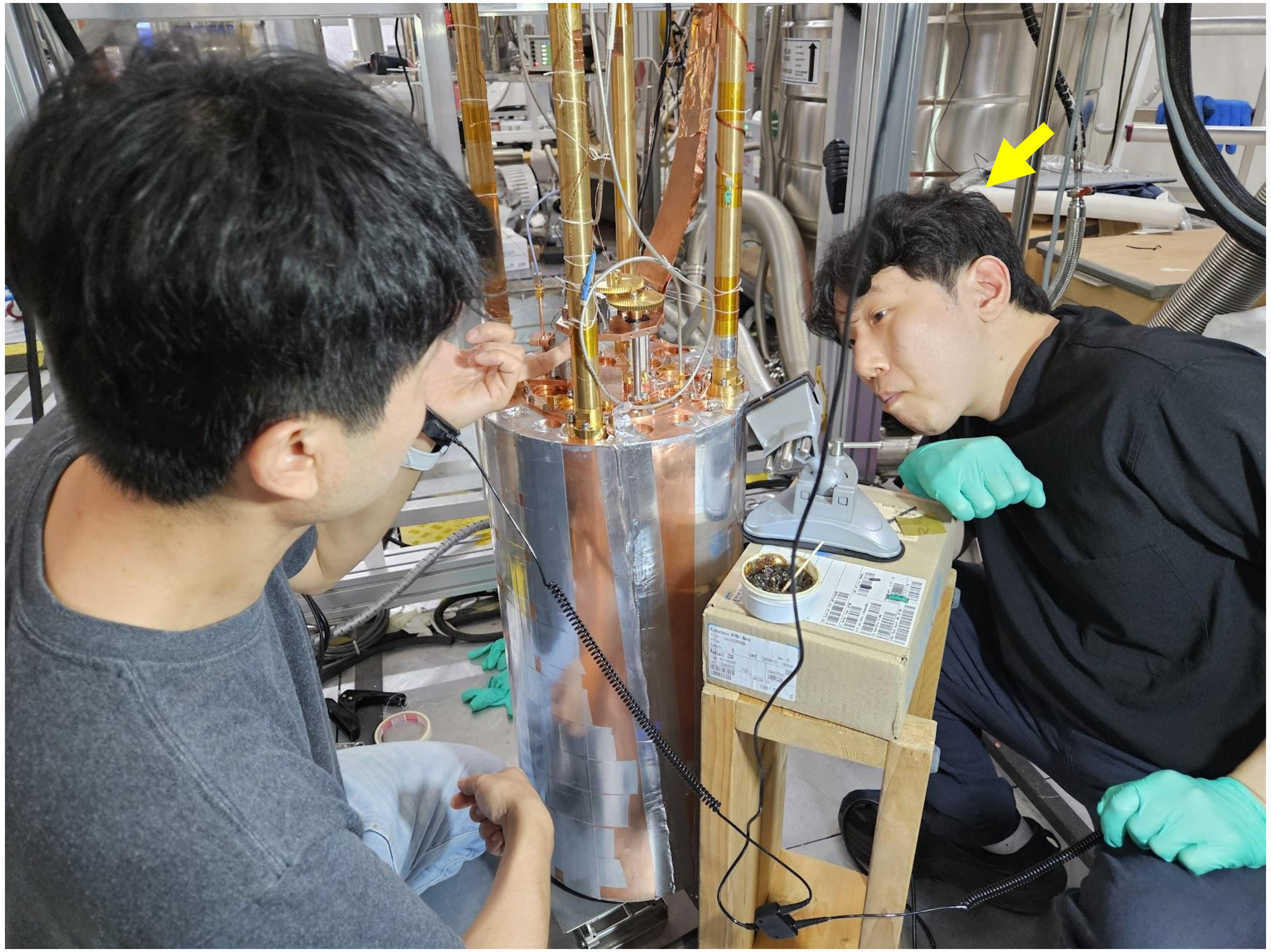
High-temperature Superconducting Cavities at CAPP

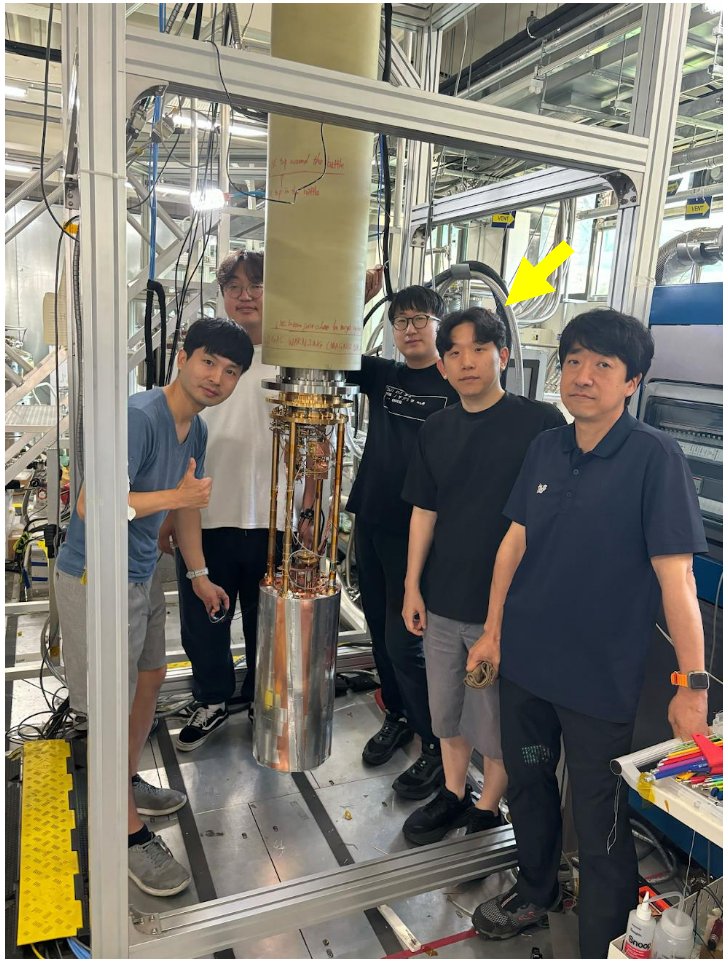
Strategy 2



High-temperature Superconducting Cavities at CAPP

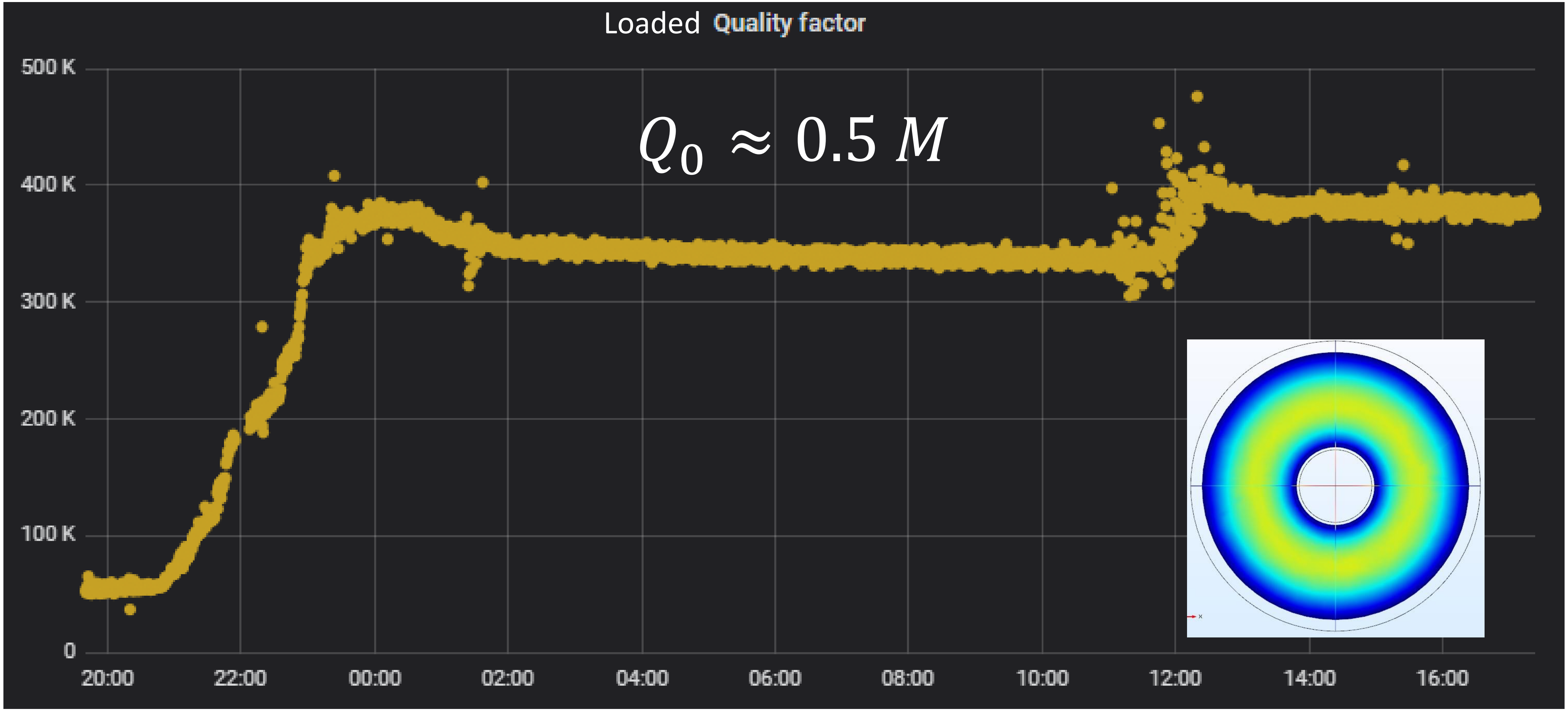
Superconducting Cavity for CAPP-MAX





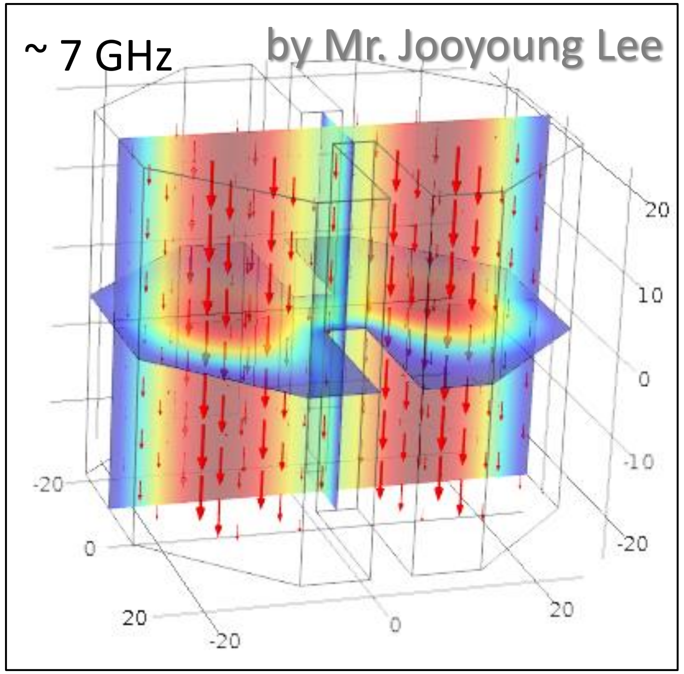
High-temperature Superconducting Cavities at CAPP

Superconducting Cavity for CAPP-MAX

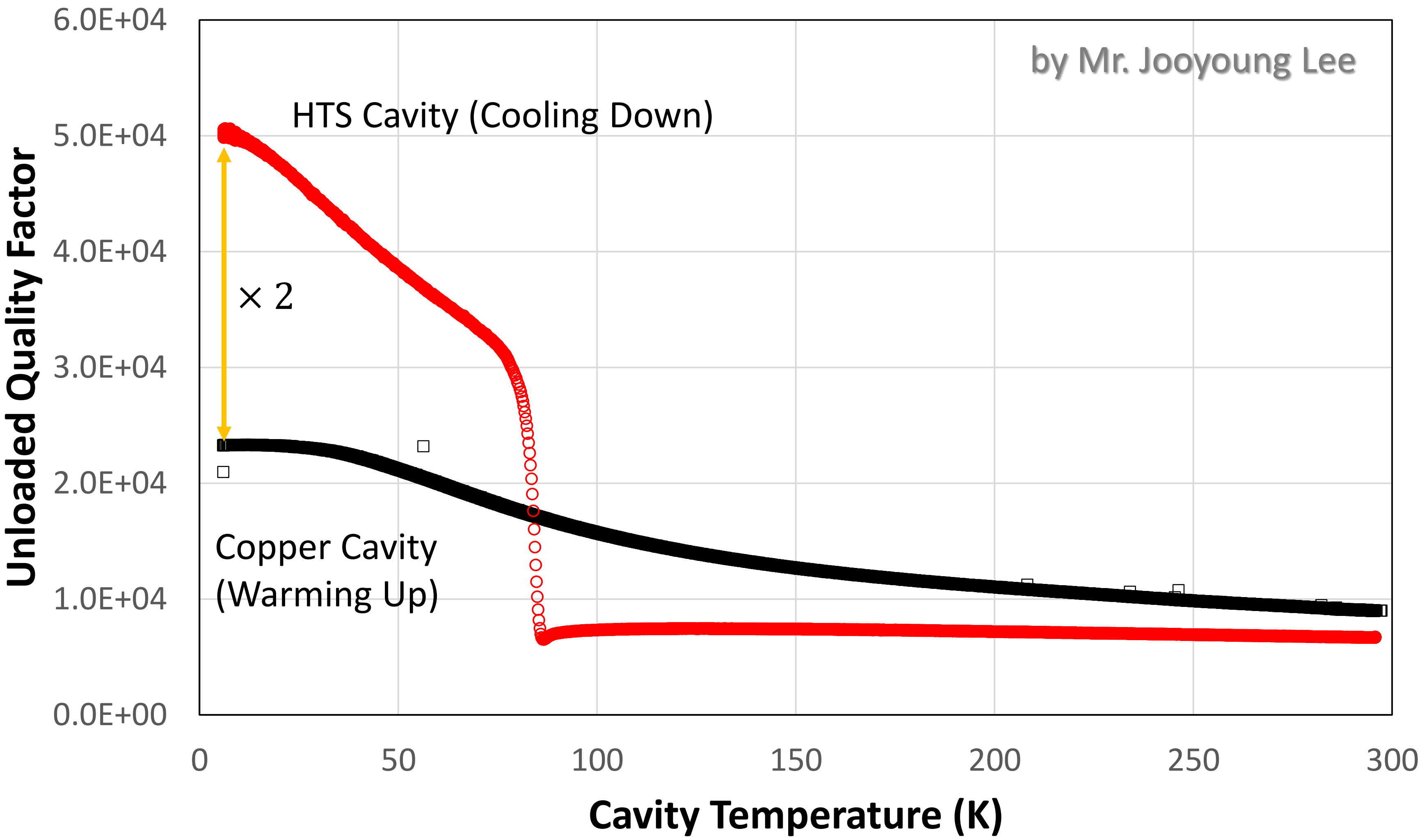


High-temperature Superconducting Cavities at CAPP

Superconducting Cavity for High-frequency Axion Search

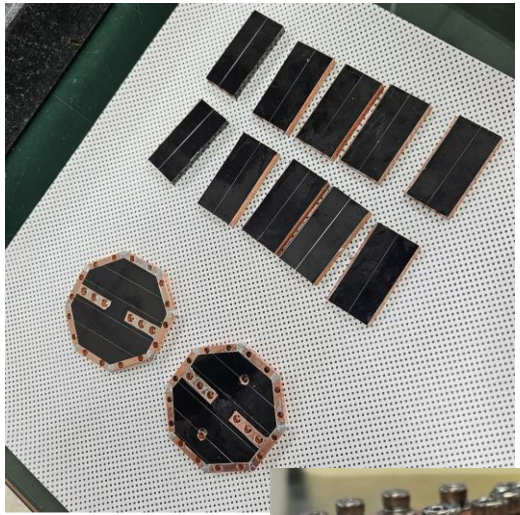


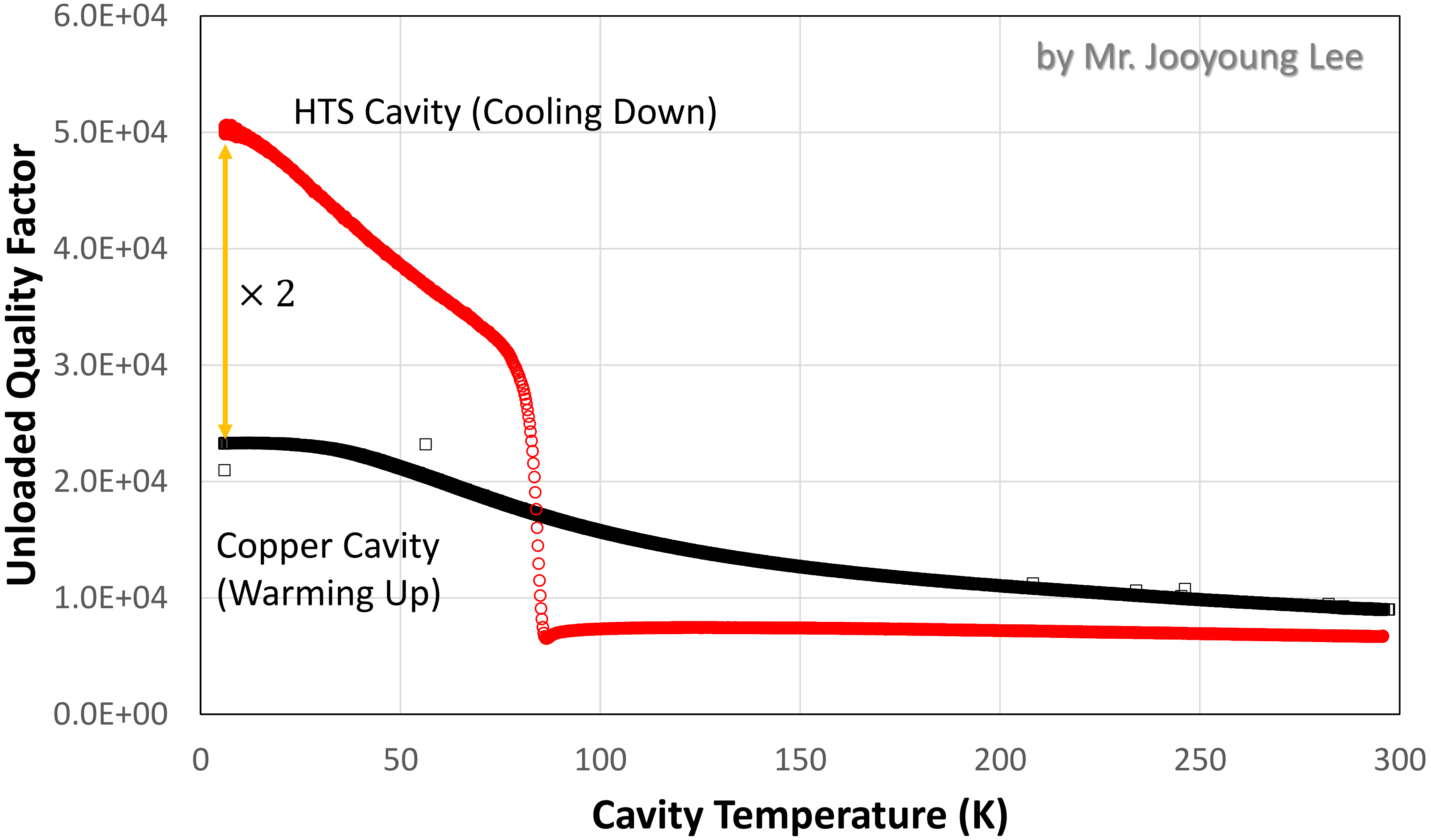
Youn's talk on Wed 08:55



High-temperature Superconducting Cavities at CAPP

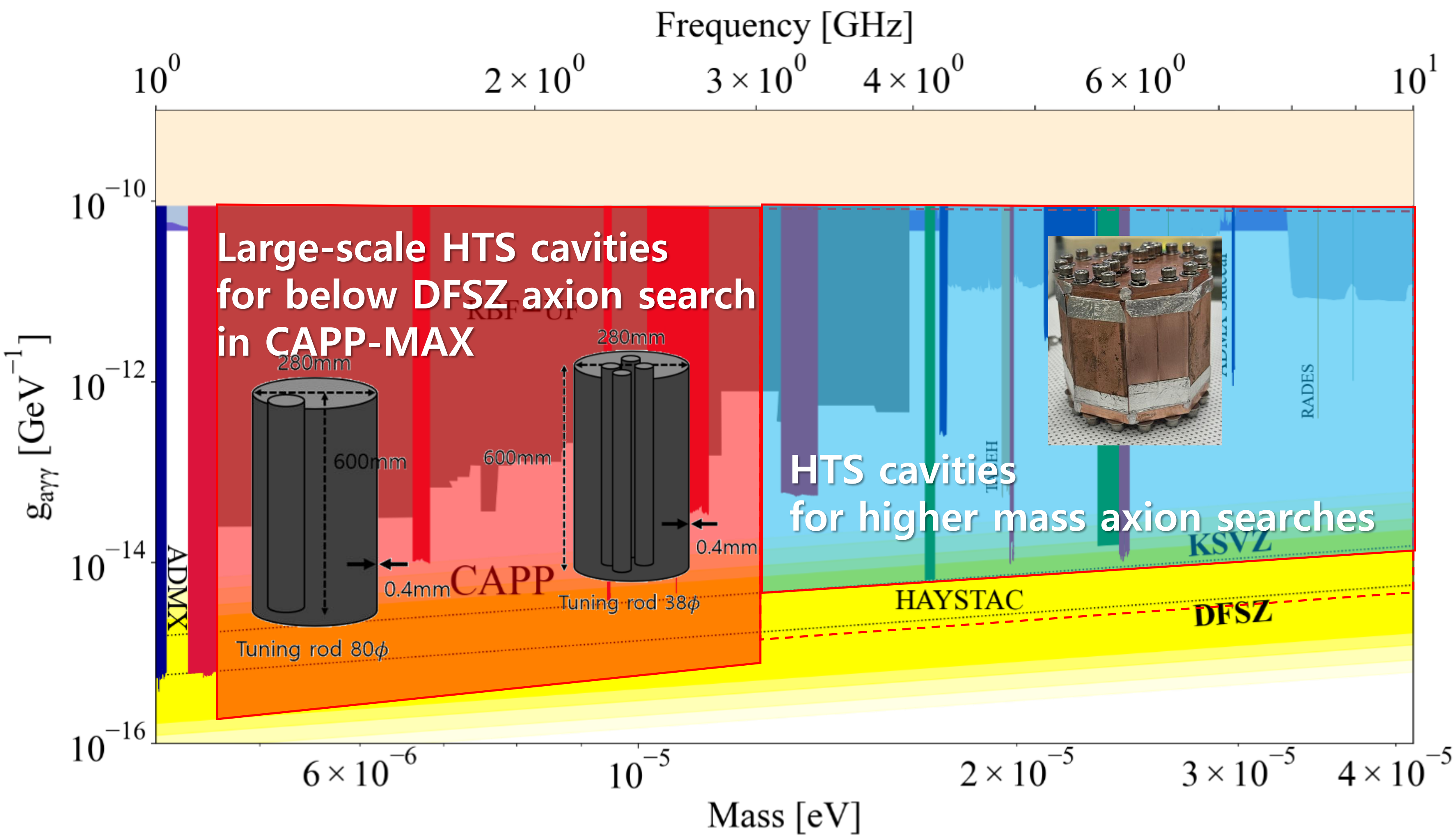
Superconducting Cavity for High-frequency Axion Search





High-temperature Superconducting Cavities at CAPP

Superconducting Cavity for CAPP-MAX



Summary:

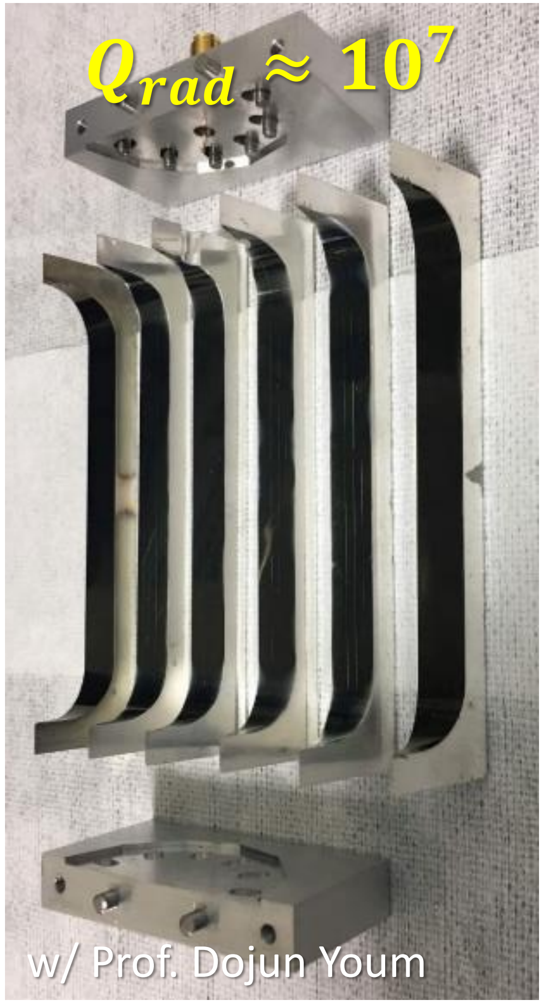
High-temperature Superconducting Cavities for Axion Search at CAPP

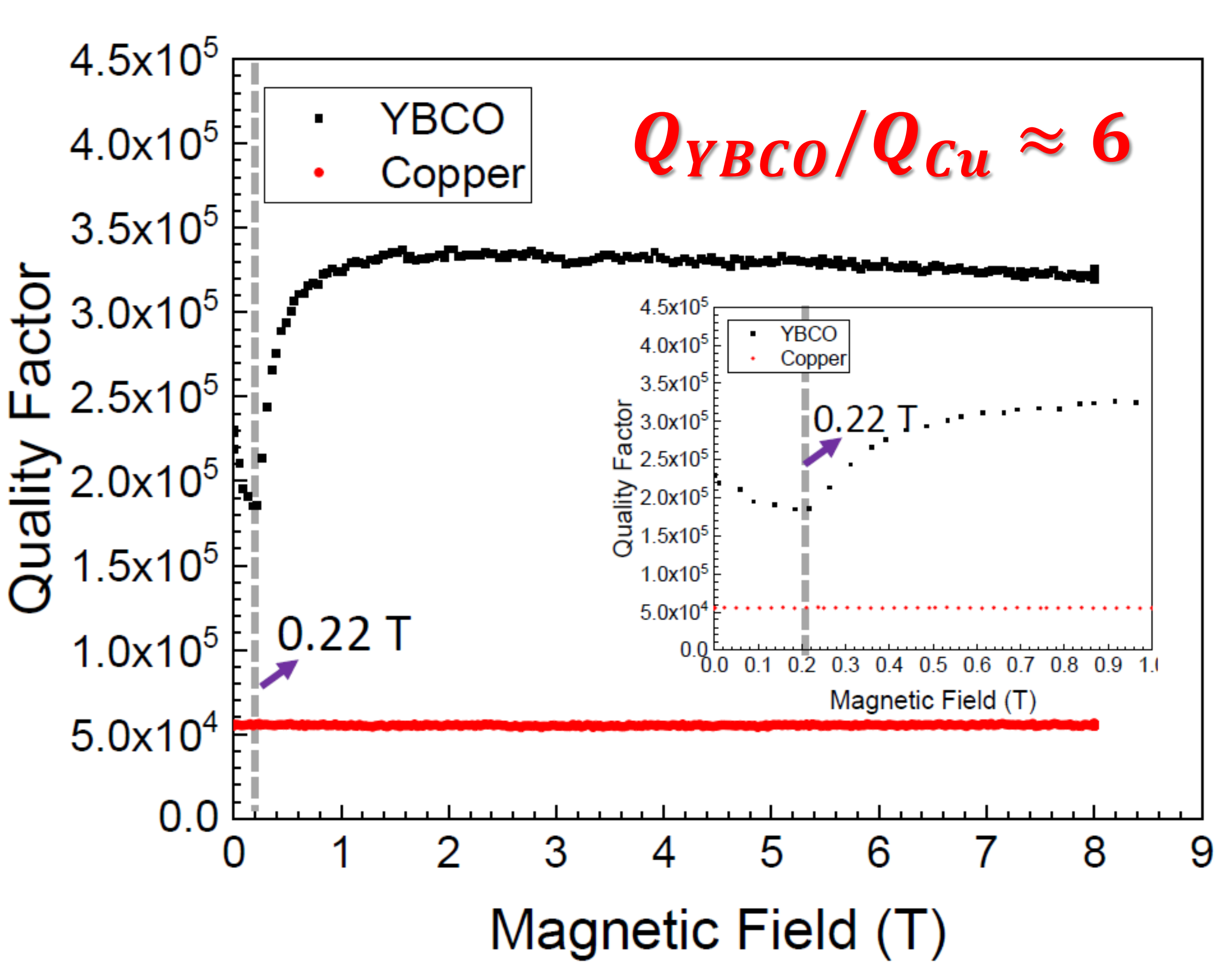
- Superconducting RF technology can enhance the scan rate of axion haloscope.
- High-temperature superconductors (HTS) are one of the most promising superconductors for realizing a high Q factor cavity in a high magnetic field.
- The Center for Axion and Precision Physics Research (CAPP) have successfully fabricated 10 million Q factor cavity.
- Recently, CAPP developed large-scale HTS cavities for the CAPP-MAX experiment, aiming to achieve sensitivity below DFSZ levels or even to detect 20% of axions as dark matter.
- The physics run with the large-scale HTS cavity for CAPP-MAX will start soon.
- HTS cavities for high-mass axion search in R&D process.

Stay tuned!

High-temperature Superconducting Cavities at CAPP

Strategy 1





High-temperature Superconducting Cavities at CAPP

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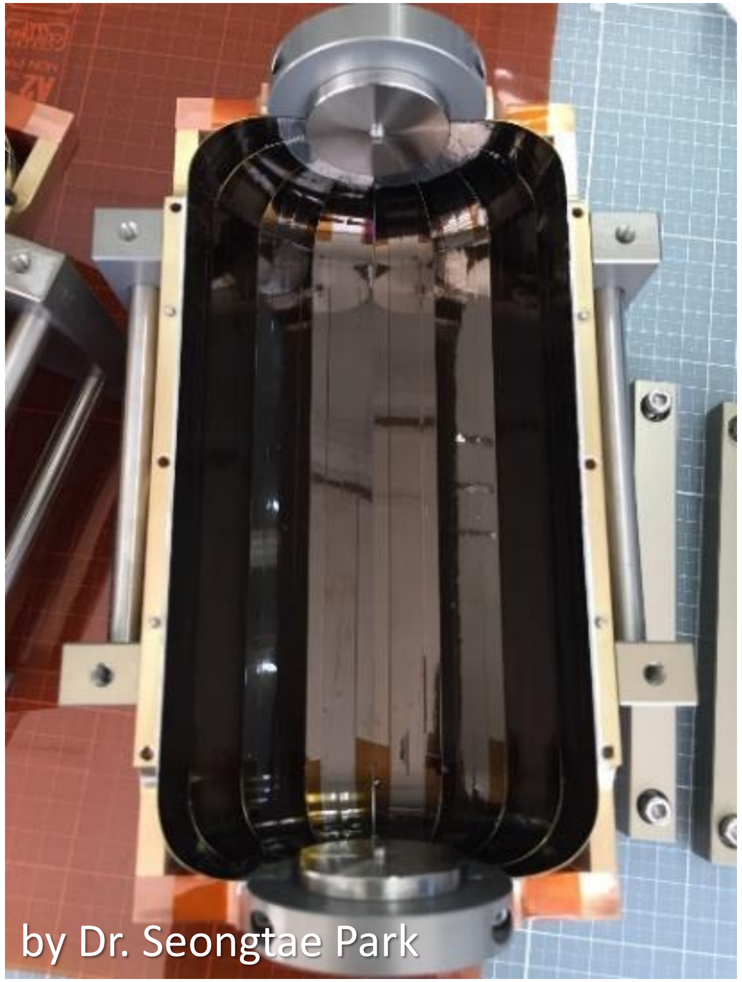
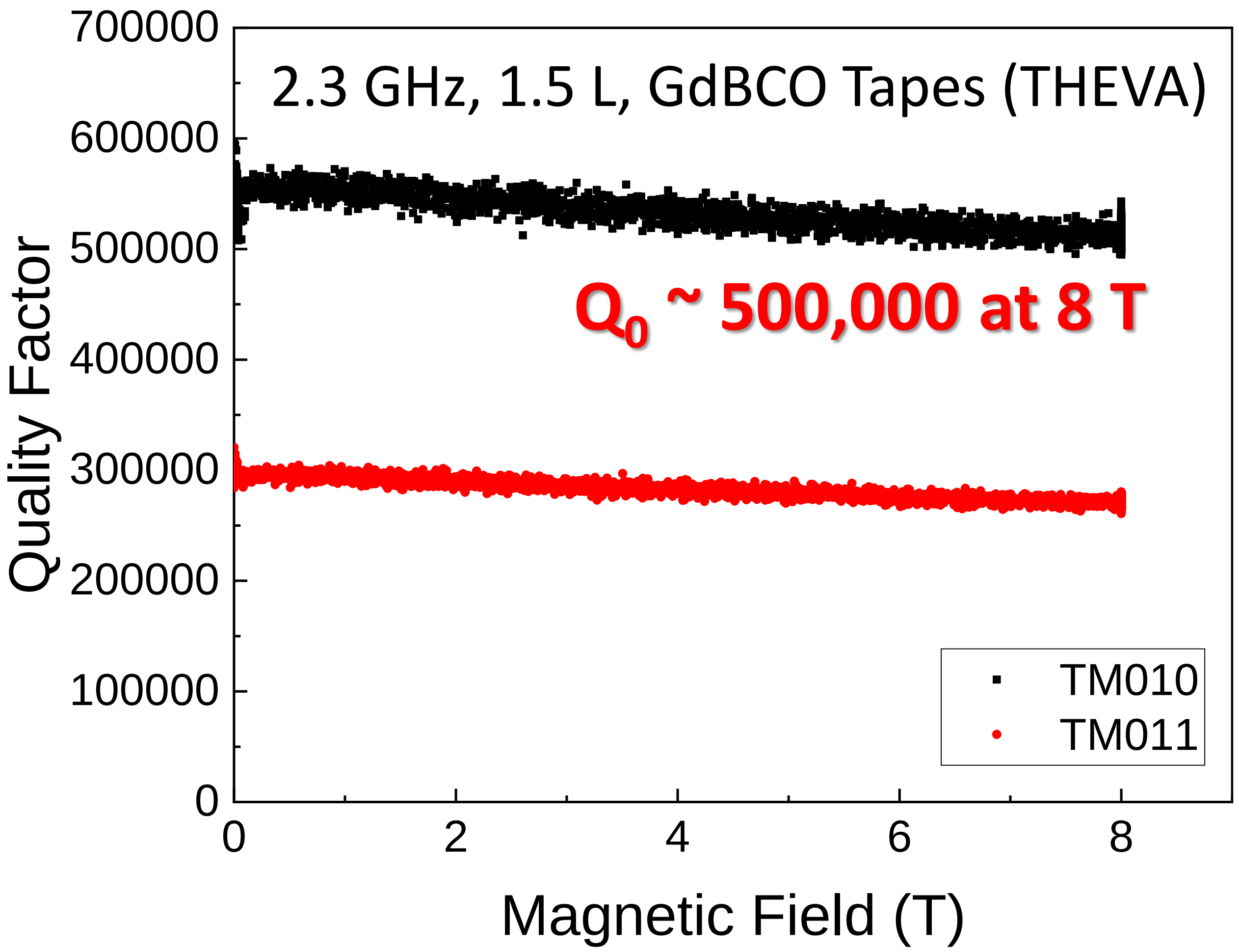
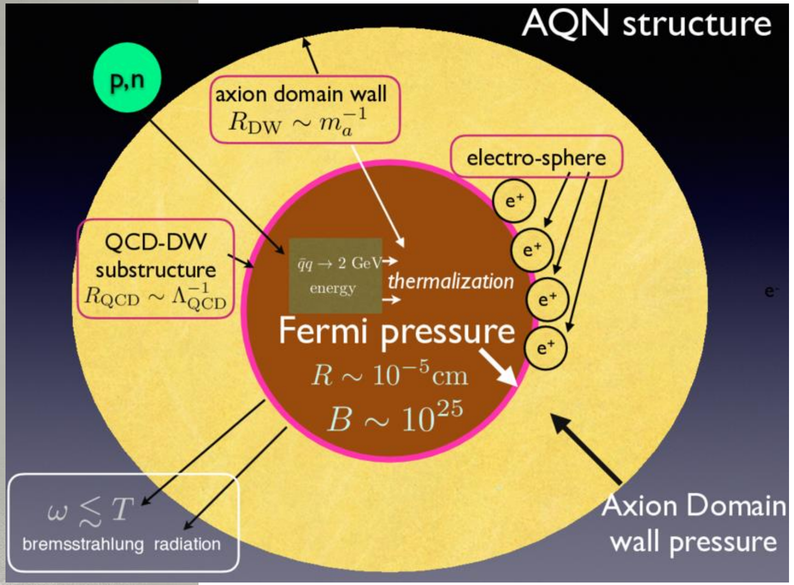




High-temperature Superconducting Cavities at CAPP

Strategy 1



A. Zhitnitsky, "Structure formation paradigm and axion quark nugget dark matter model", Scientific Reports 40 (2023) 101217