Accelerating Axion Haloscope Experiments

: Strategies and Innovations at CAPP

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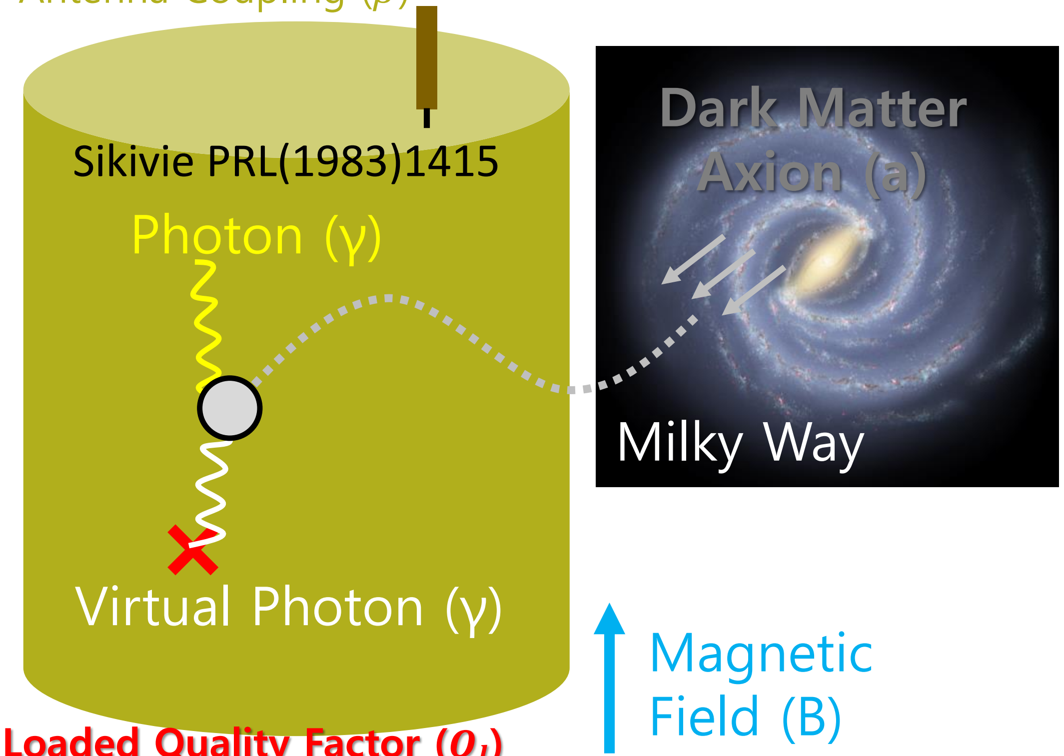
Introduction

Cavity Haloscope Experiment for Dark Matter Axion Search

Antenna Coupling (β)



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; Dark Matter Axion Density; Axion Mass; Axion Quality Factor

Kim *et al*. JCAP03(2020)066

Scanning speed

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

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

System Noise Temperature ~ 200 mK

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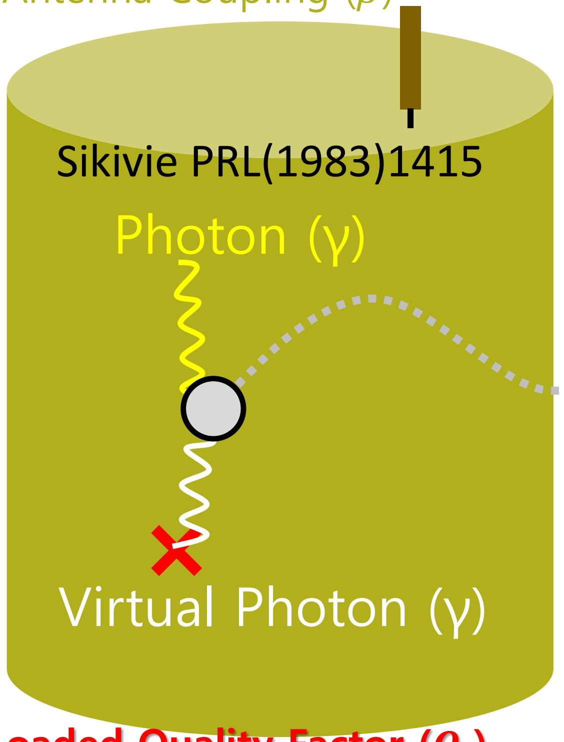
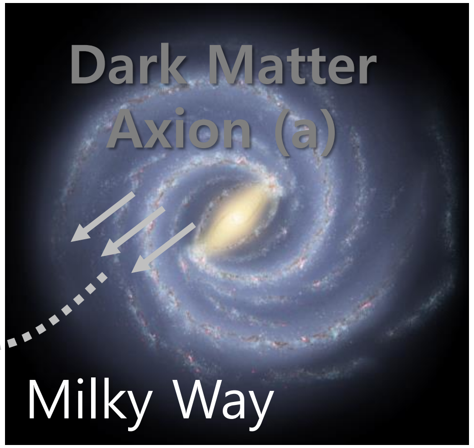
Introduction

High Field and Big-Bore Magnet is Needed





Magnetic Field (B)

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

Signal Power

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

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

Kim *et al*. JCAP03(2020)066

Scanning speed

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

System Noise (T_{sys})

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

High Magnetic Field, Cavity Volume

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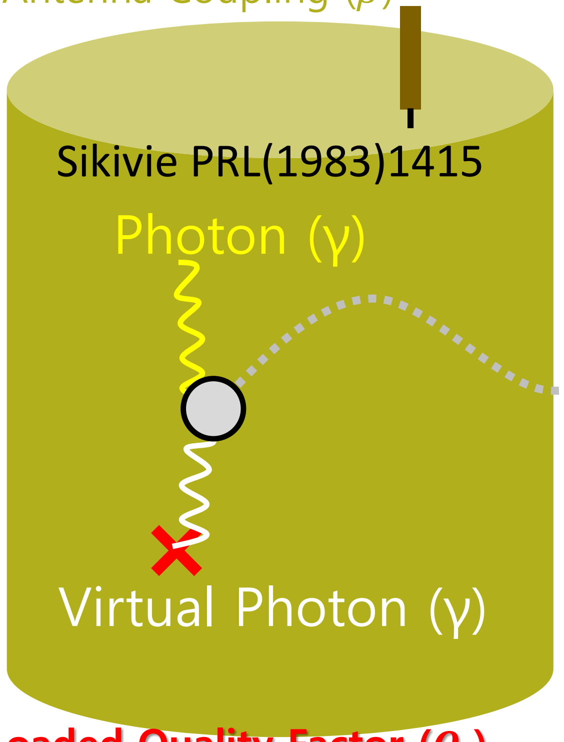
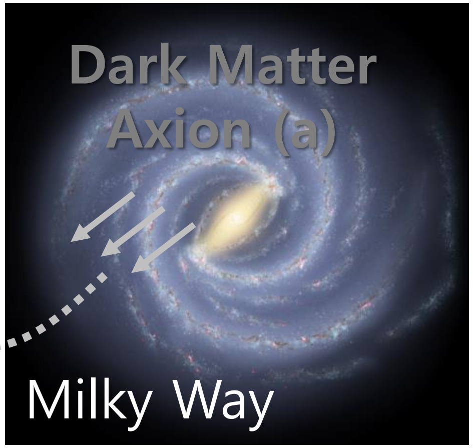
Introduction

Quantum Noise Amplifier is Needed





Magnetic Field (B)

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

Coupling Constant; Dark Matter Axion Density; Axion Mass; Axion Quality Factor

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Scanning speed

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

System Nois

$Q_l \gg Q_a \sim 10^6$

Low Noise Temperature

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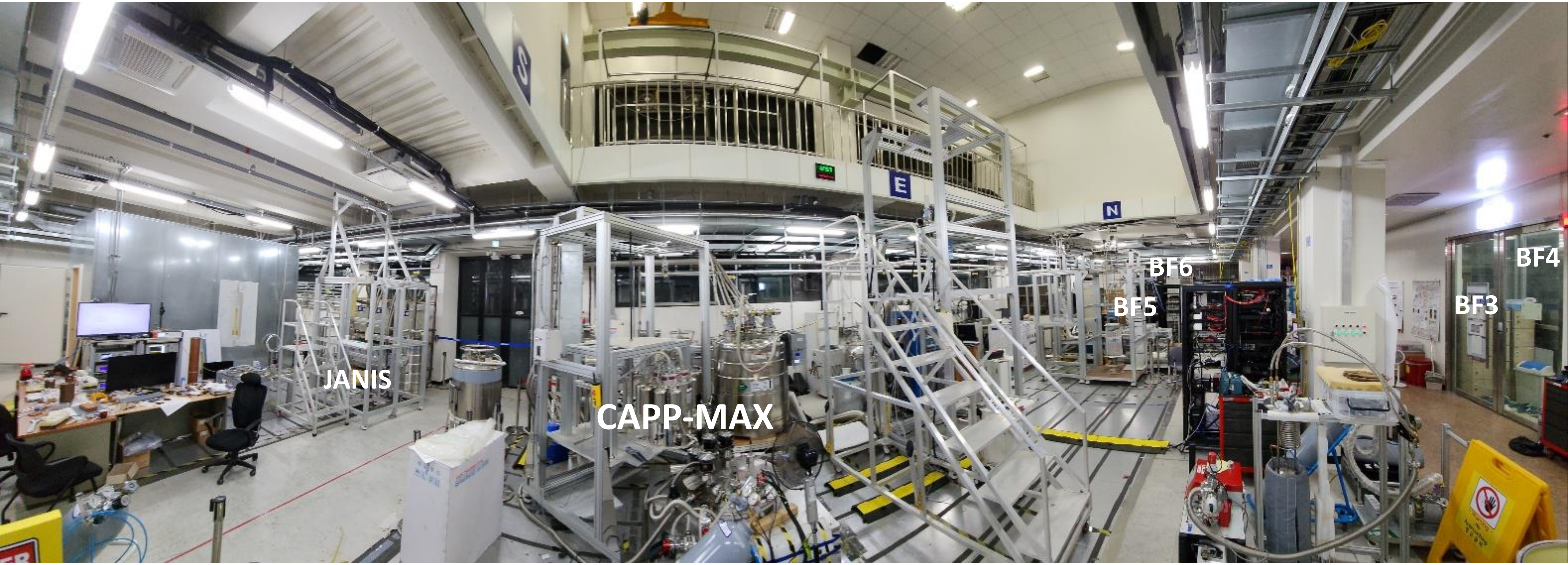
Experiments at CAPP

Overview



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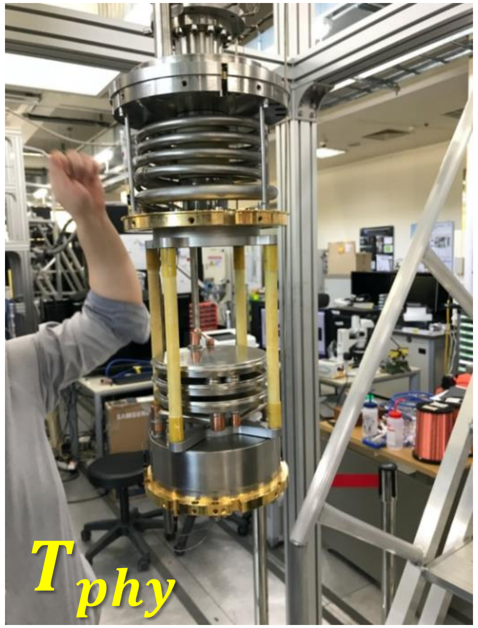
Main Axion eXperiment (CAPP-MAX)

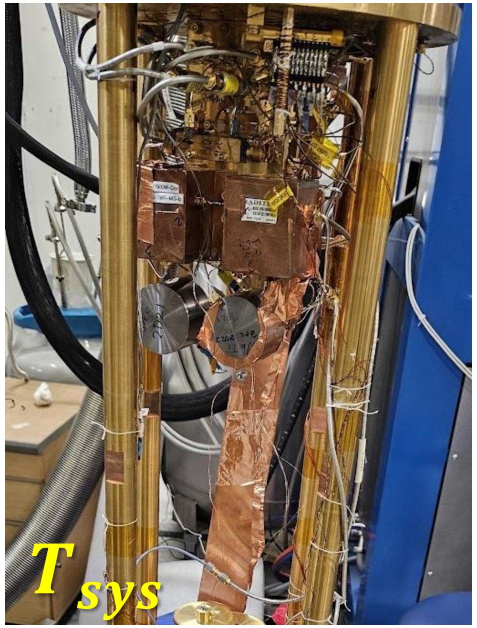
Overview

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



Dilution refrigerator 25mK

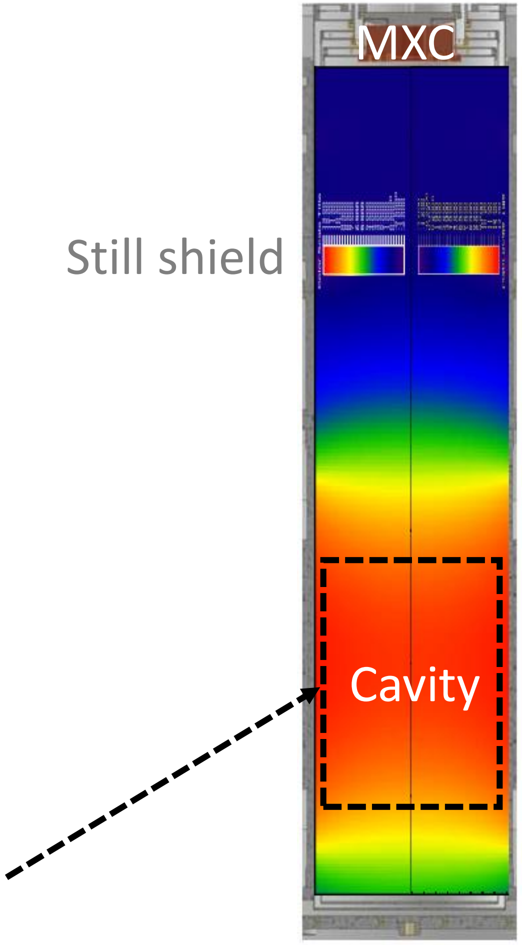
+



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

+

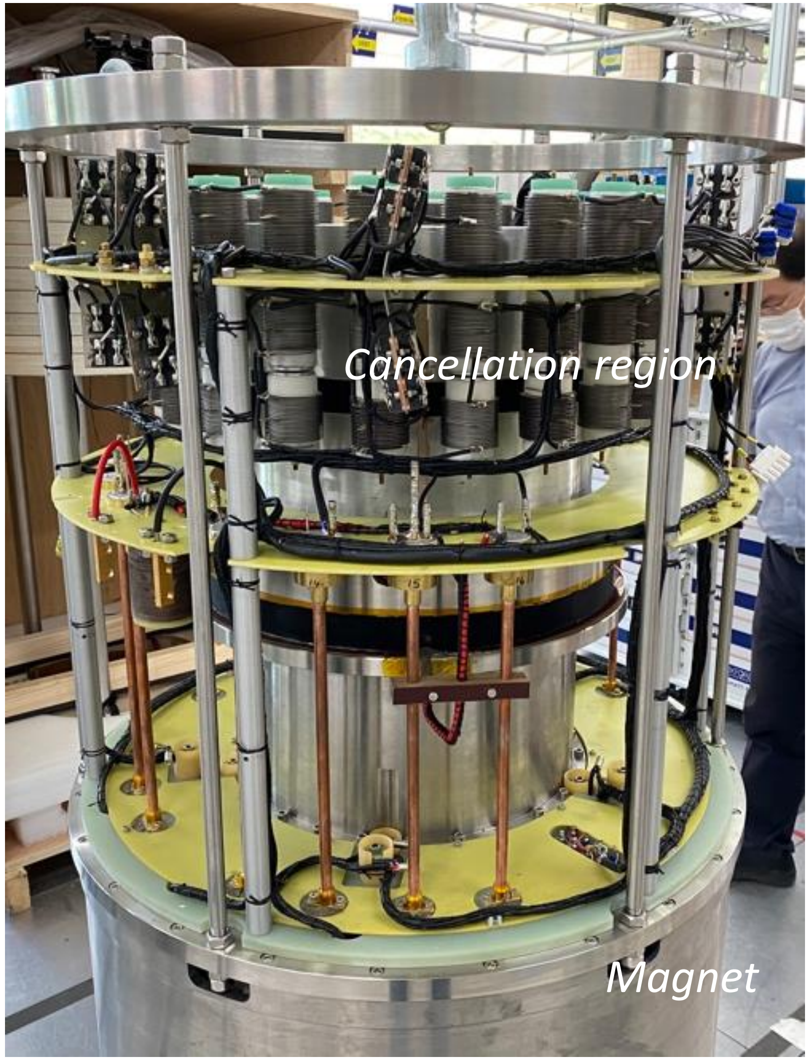
12 Tesla SC magnet
320mm bore diameter



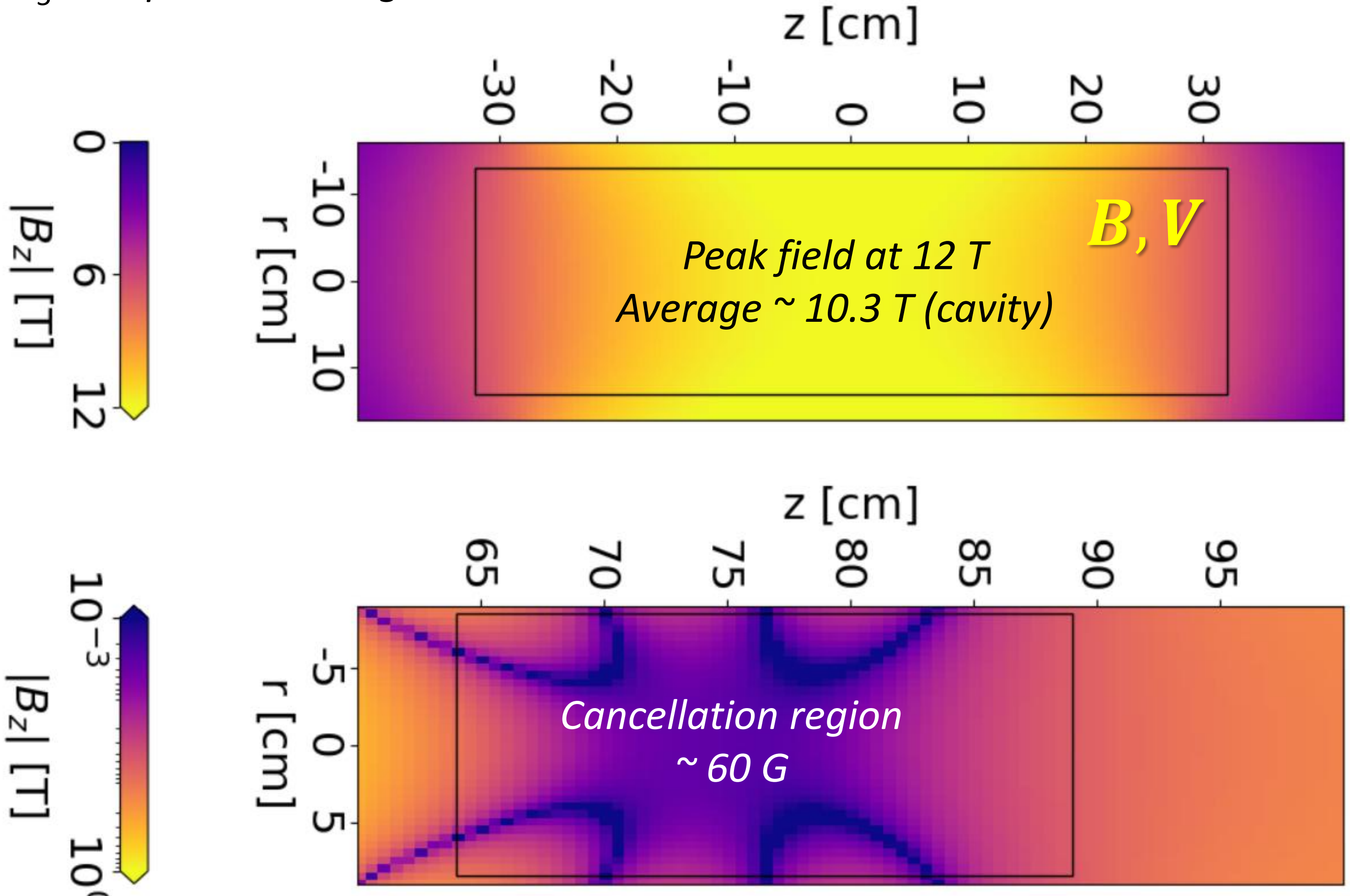
B-field map

Main Axion eXperiment (CAPP-MAX)

Magnet



Nb_3Sn Superconducting coil



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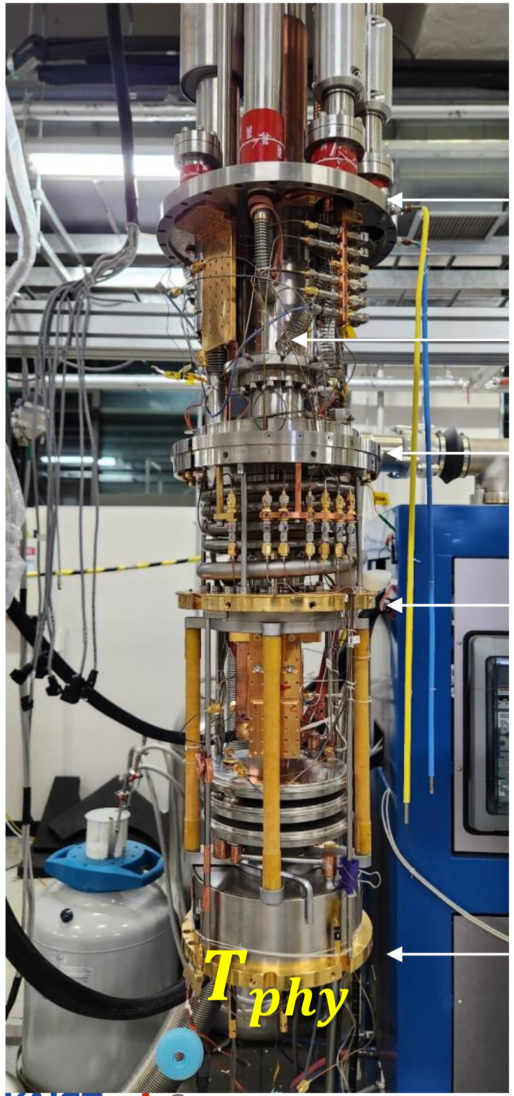
Main Axion eXperiment (CAPP-MAX)

The Cryogenic System



4 K plate

1 K pot (1.5 K)

STILL (600 mK)

Cold plate (100 mK)

MXC plate (20 mK)

Wet type LEIDEN dilution refrigerator

- 5.6 mK of base temperature (bare fridge)
- Cavity physical temperature ~ 30 mK
- Noise temperature ~ 40 mK

$$T_{cav} = \frac{h\nu}{k_B}\left(\frac{1}{e^{h\nu/k_B T_{phy}} - 1} + \frac{1}{2}\right)$$

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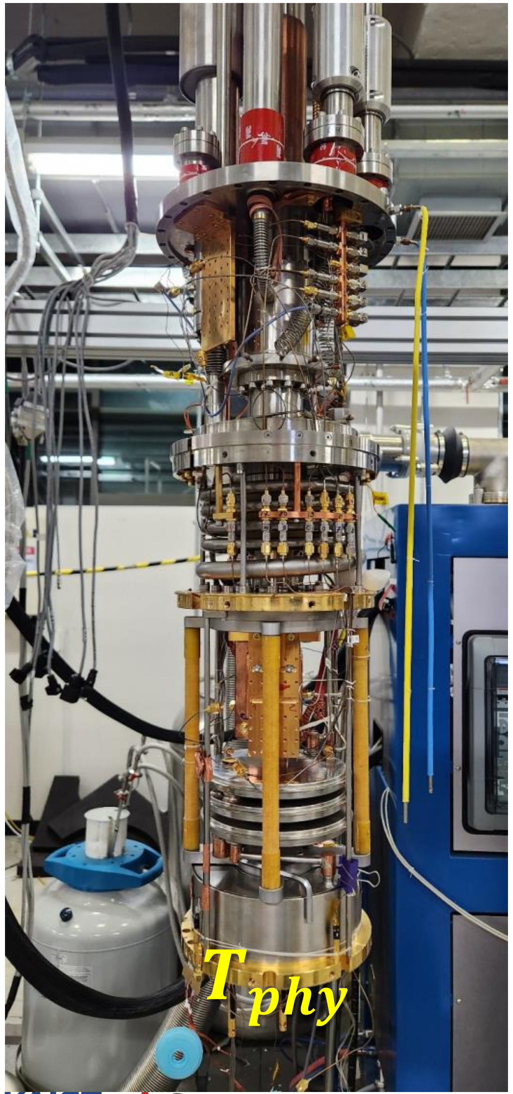
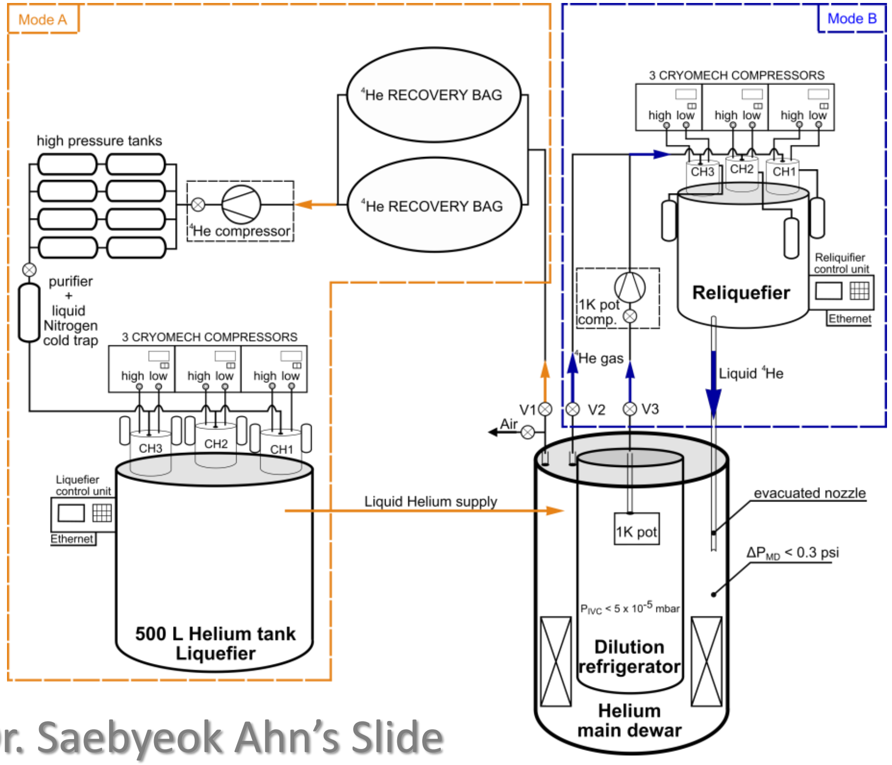
Main Axion eXperiment (CAPP-MAX)

The Cryogenic System



- ✓ *He recovery system ~ 160 L capacity*
- ✓ *He liquefier with 60 L / day rate*
- ✓ *He Re-liquefier with 60 L / day rate*



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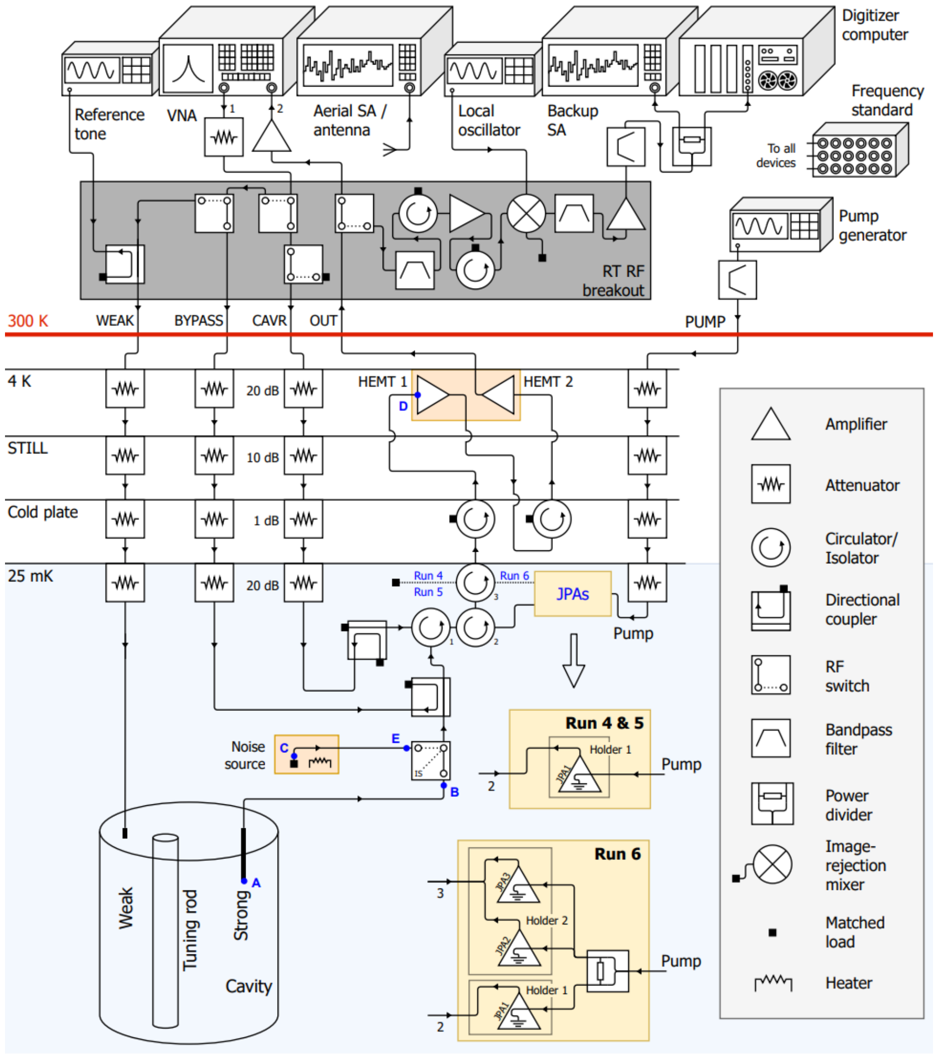
Main Axion eXperiment (CAPP-MAX)

Receiver Chain



- Cavity
  - ✓ Axion signal is generated in the cavity immersed in a magnetic field.
  - ✓ Noise is also generated in the cavity. (Noise temperature ~ 40 mK)
  - ✓ Signal and noise are picked up by strong port.

T_{phy}

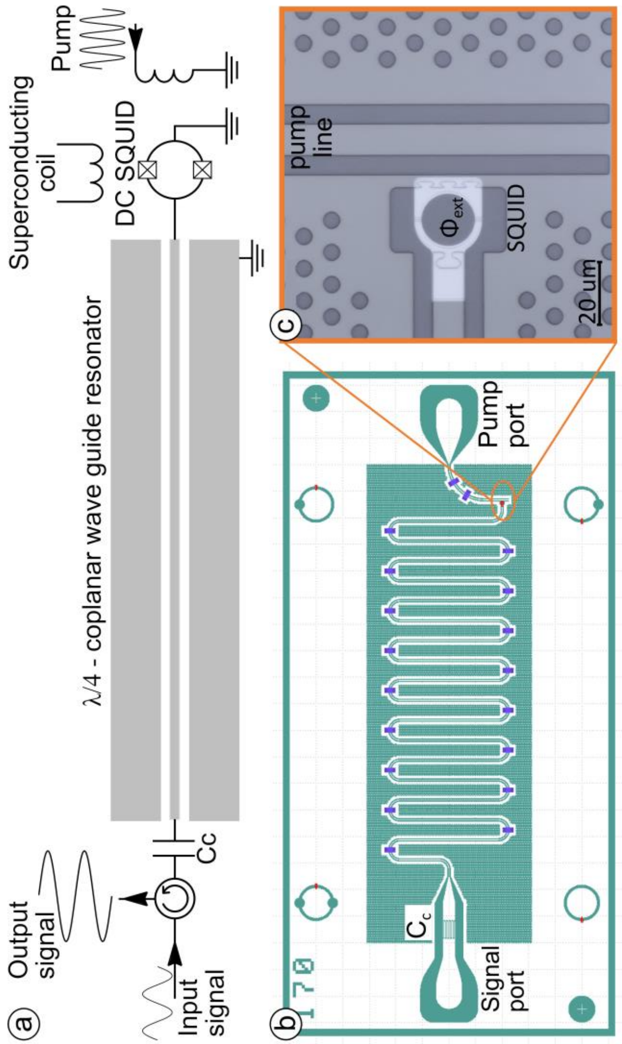
- Josephson Parametric Amplifier (JPA)
  - ✓ Quantum limited noise amplifier (~ 200 mK noise)
  - ✓ Primary amplification
  - ✓ Typical gain ~ 20 dB
- High Electron Mobility Transistor (HEMT)
  - ✓ Low noise linear amplifier (~ 2 K / G_{jpa} noise)
  - ✓ Subsequent amplification
  - ✓ Typical gain ~ 60 dB

T_{sys}

- Noise source
  - ✓ Heating up to 400 mK
  - ✓ JPA-off calibration / System noise double-check

Main Axion eXperiment (CAPP-MAX)

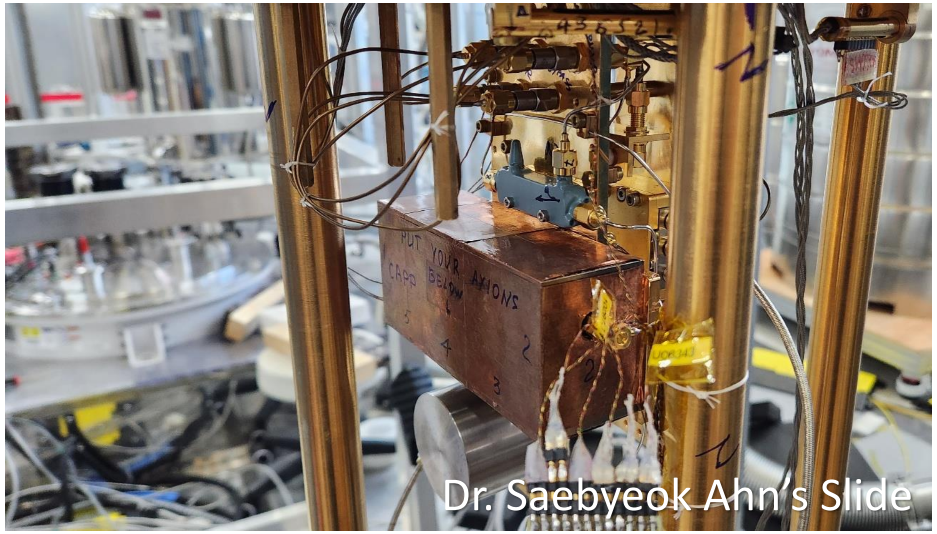
Josephson Parametric Amplifier

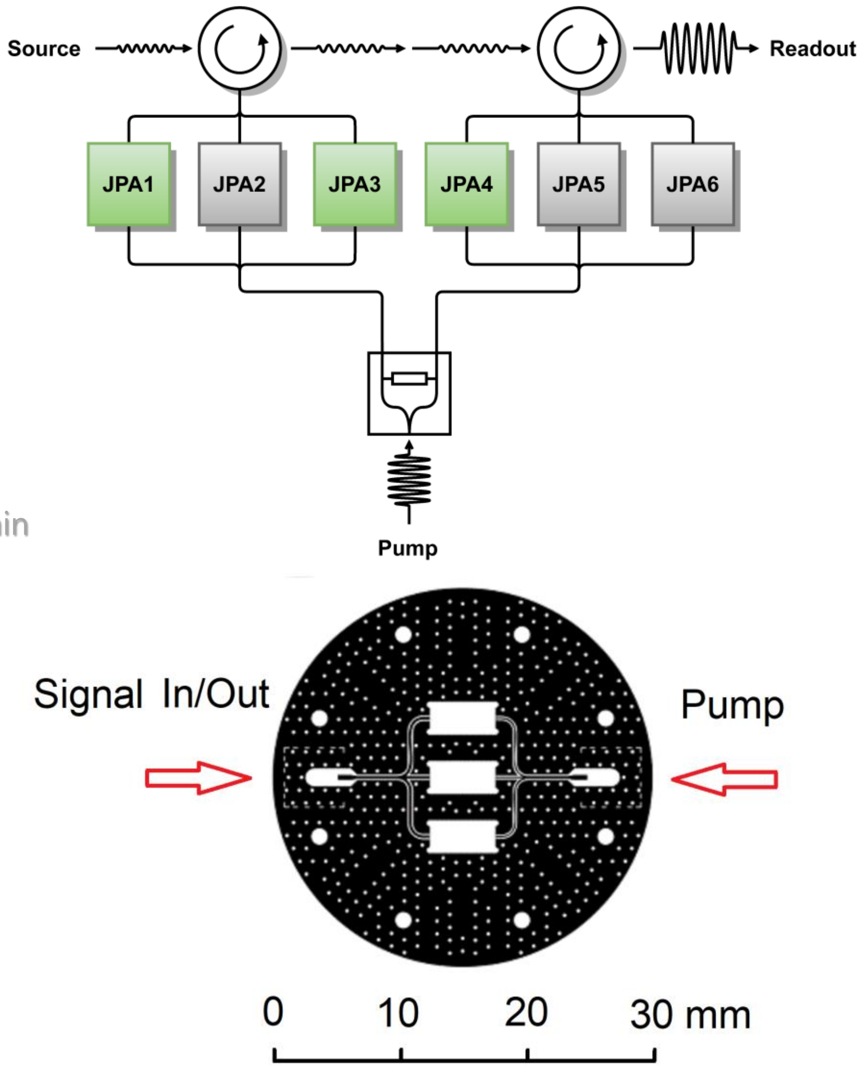


- ✓ Flux-driven JPAs
- ✓ Collaborating with U. of Tokyo
- ✓ 3 Parallel JPAs
- ✓ T_{sys} ~ 200 mK

$$T_{sys} = T_{cav} + T_{JPA} + T_{off}/G_{jpa}$$

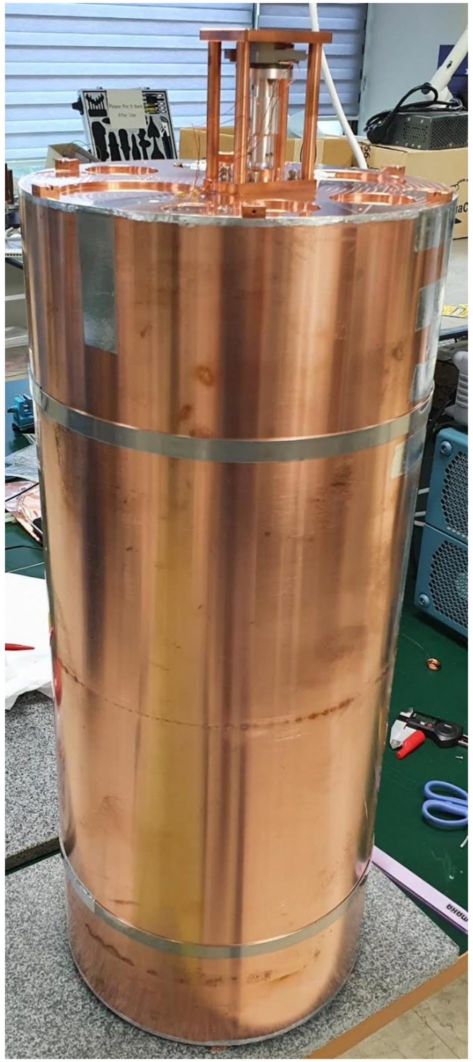
Total system noise; Noise from cavity; JPA added noise; JPA off noise; JPA gain





High-temperature Superconducting Cavities at CAPP

Superconducting Cavity for CAPP-MAX



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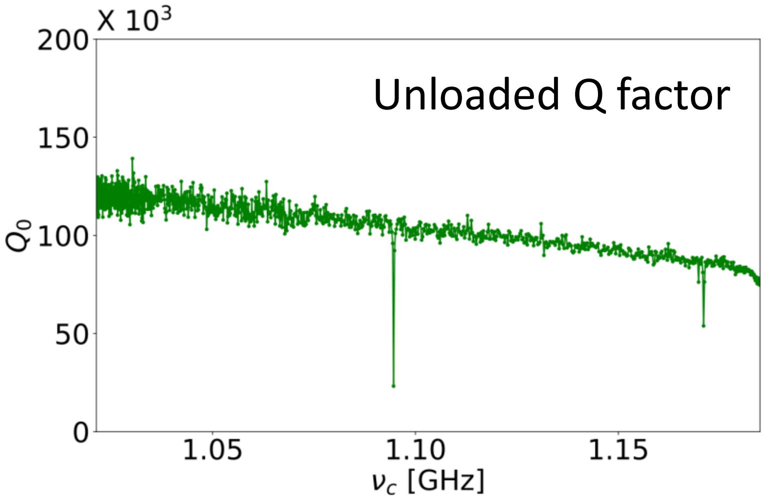
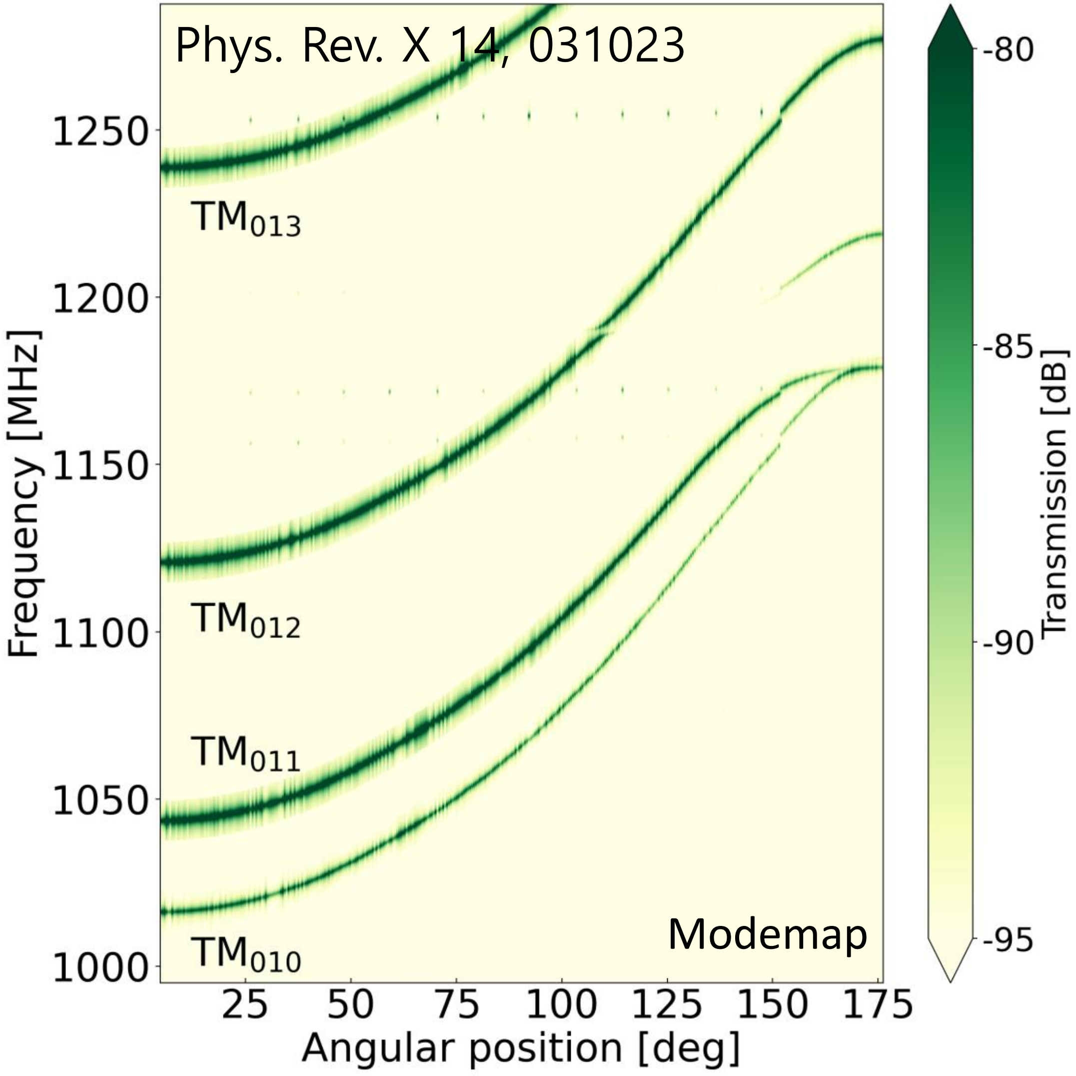
Total weight **~ 5 kg**

1.02 – 1.18 GHz tuning range

Geometrical factor ~ [0.5, 0.7]





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Superconducting Cavity for CAPP-MAX

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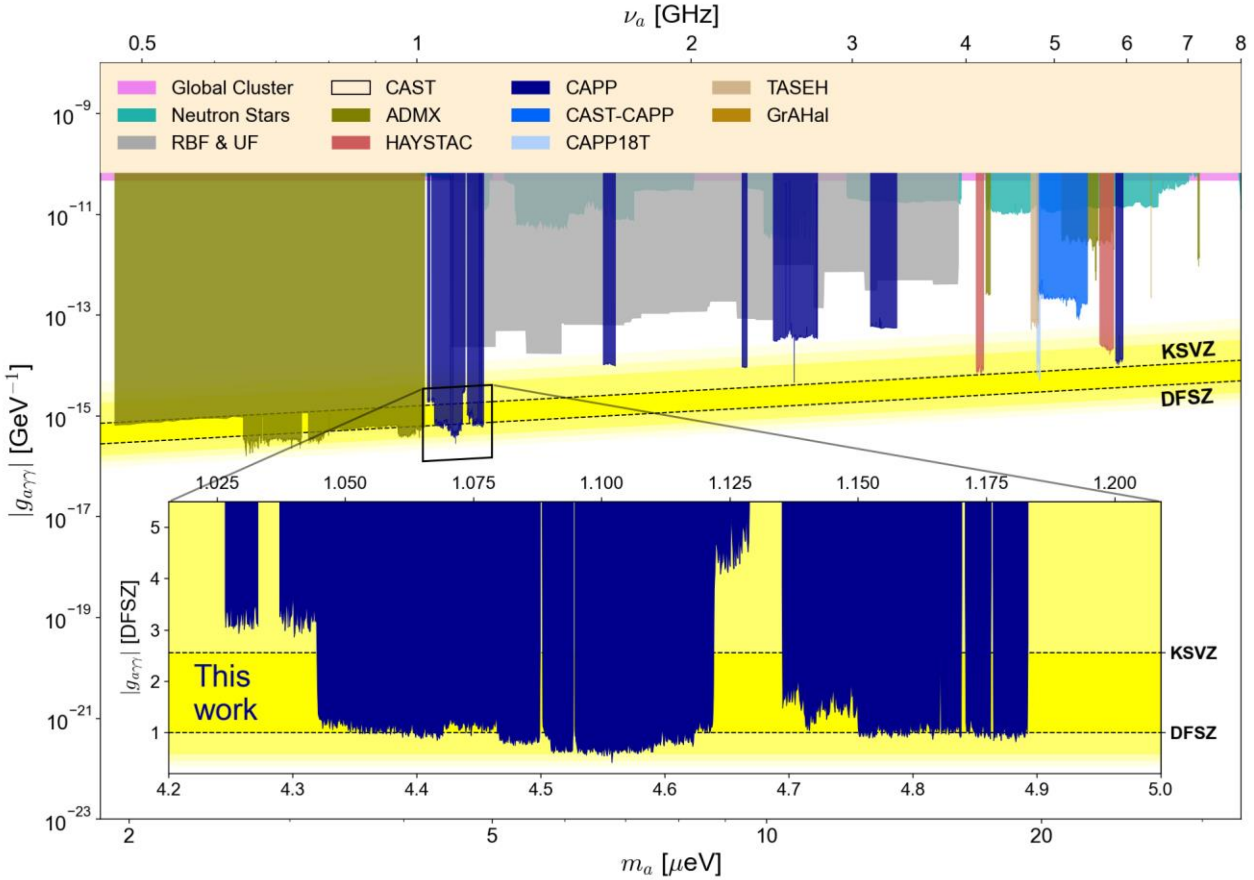
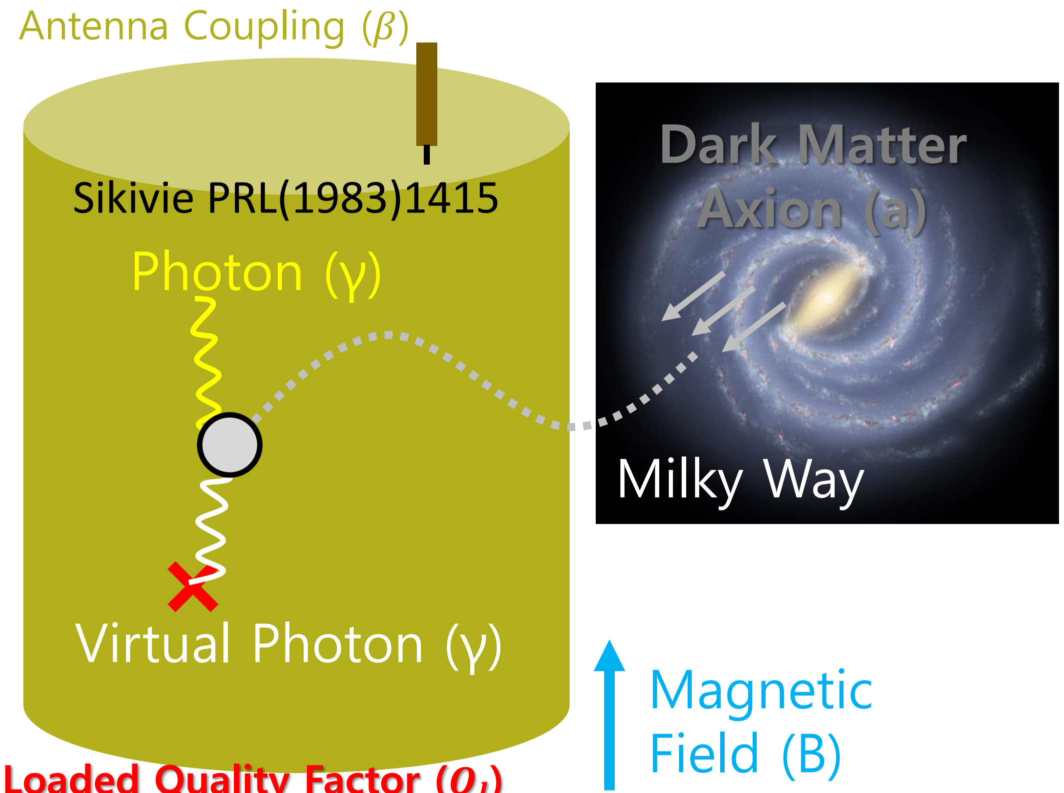


Accelerating Axion Haloscope

Quality Factor is also Important to Enhance a Scanning Speed



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Coupling Constant
Dark Matter Axion Density
Axion Mass
Axion Quality Factor

Kim *et al*. JCAP03(2020)066

Scanning speed

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

System Noise

$Q_l \gg Q_a \sim 10^6$

High Cavity Quality Factor

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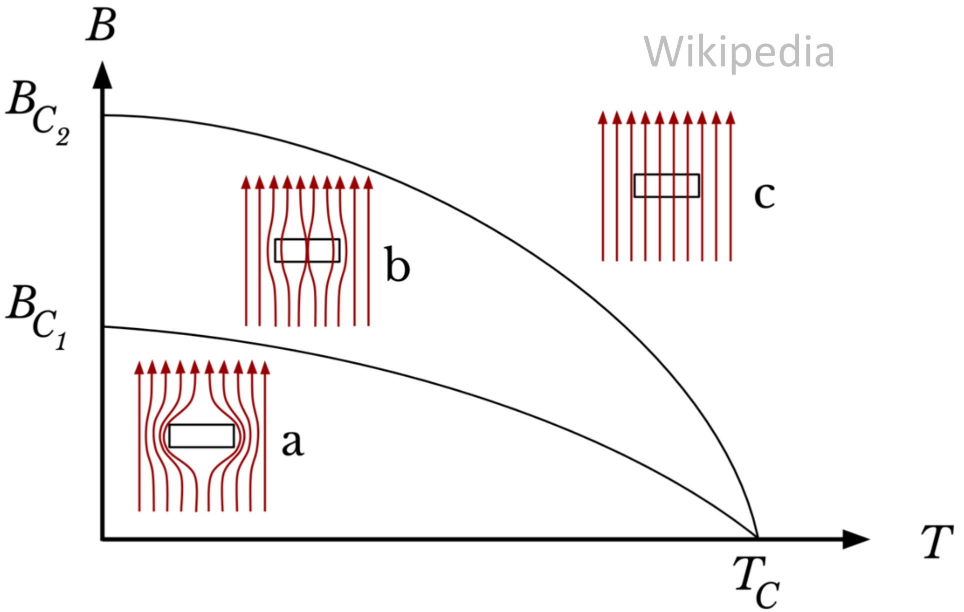
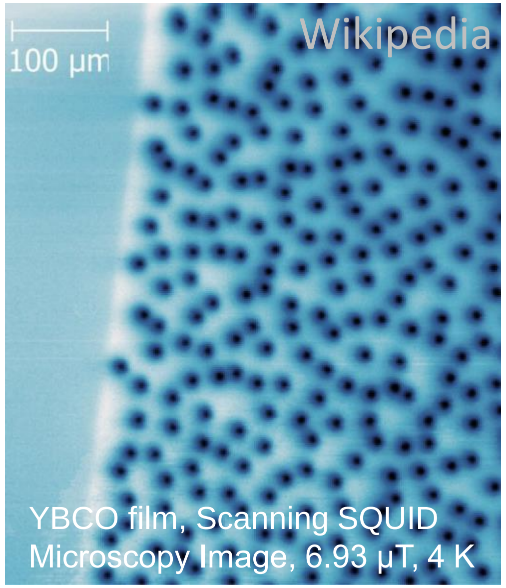
Type II Superconductor in a Magnetic Field

Vortex Dynamics & Energy Dissipation Mechanism

➤ Type II superconductor forms vortices (quantized magnetic flux, $\overrightarrow{\Phi_0}$) in a magnetic field.

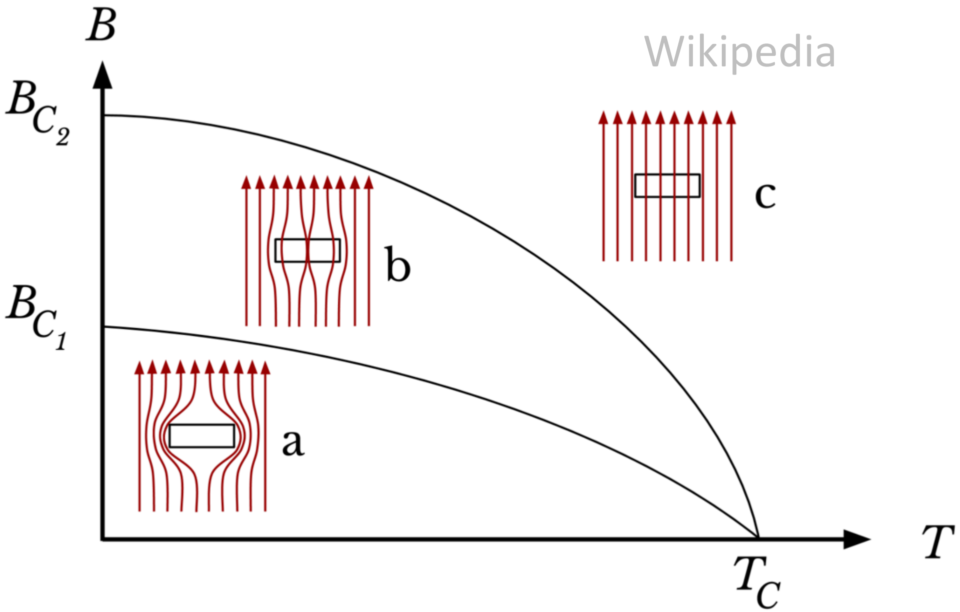


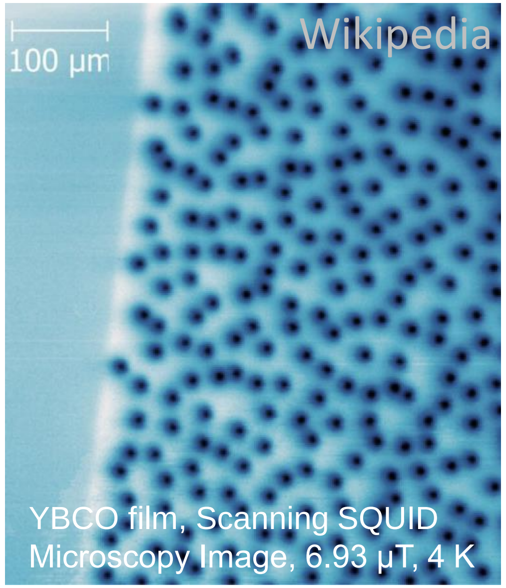


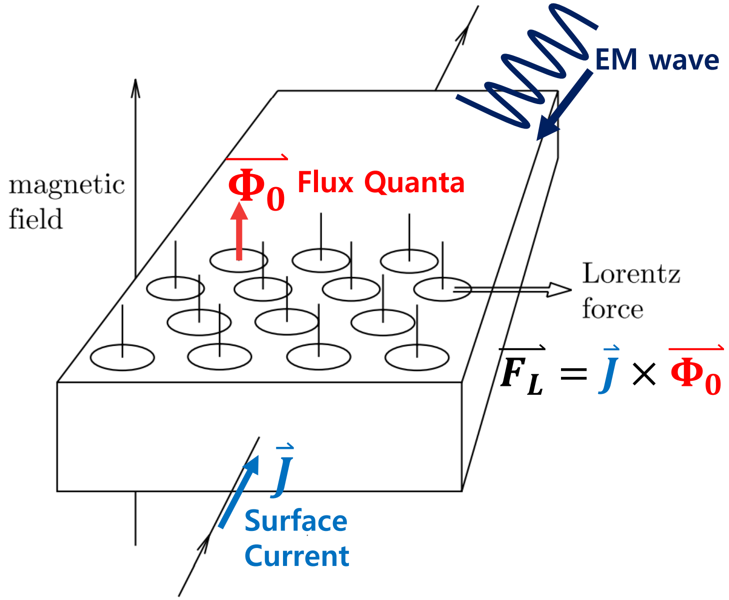
Type II Superconductor in a Magnetic Field

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.



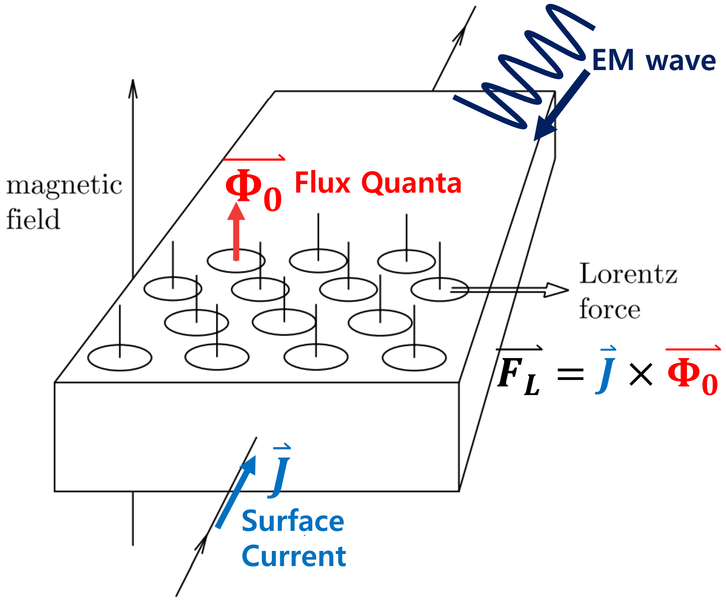


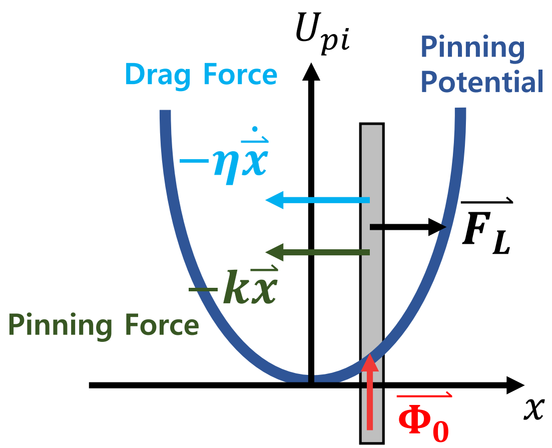


Type II Superconductor in a Magnetic Field

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.



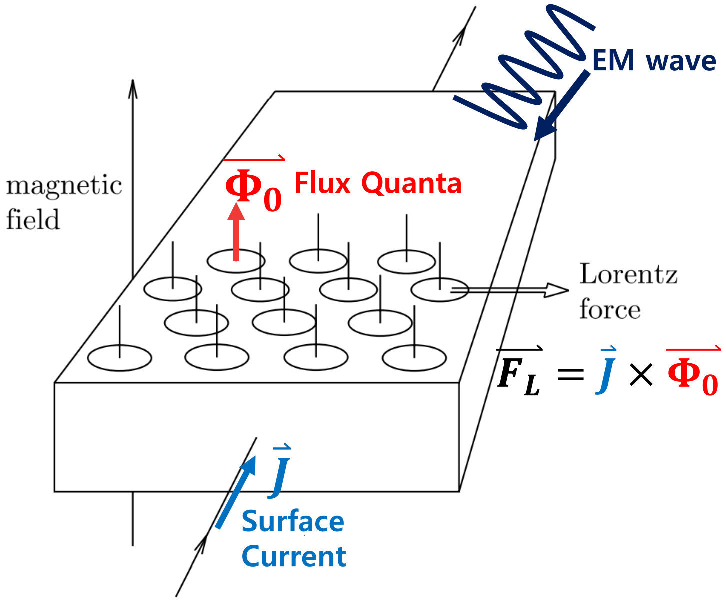


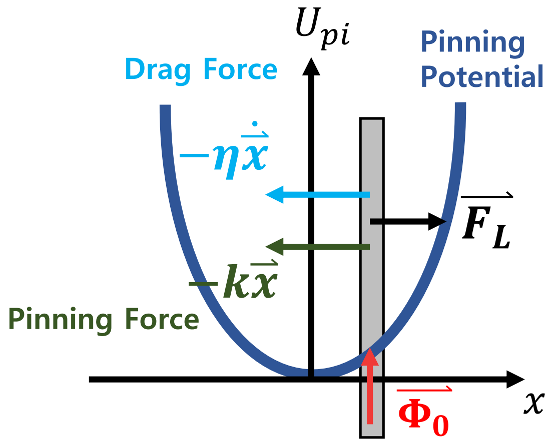
Type II Superconductor in a Magnetic Field

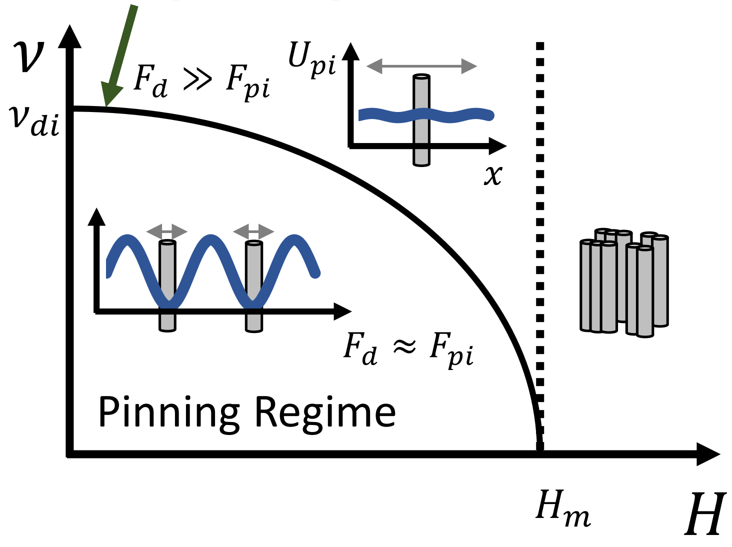
Vortex Dynamics & Energy Dissipation Mechanism

- 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.
- Above a depinning frequency, pinning force become negligible.

High Depinning Frequency (ν_{di})





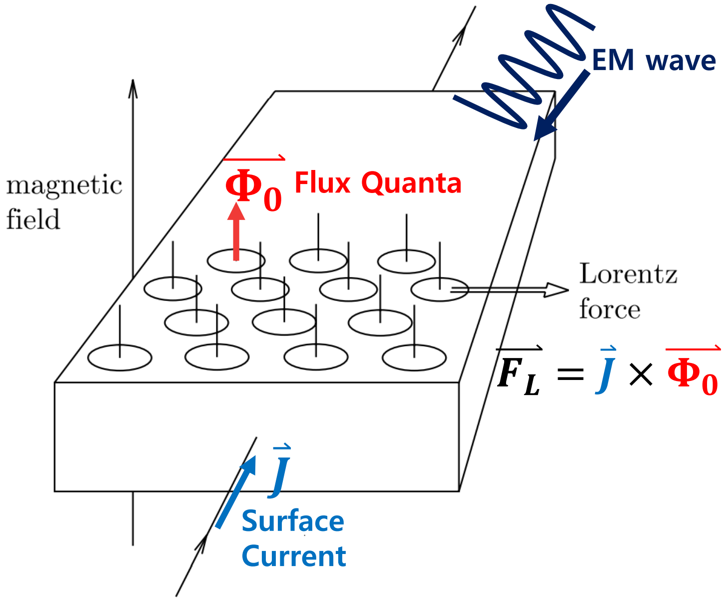


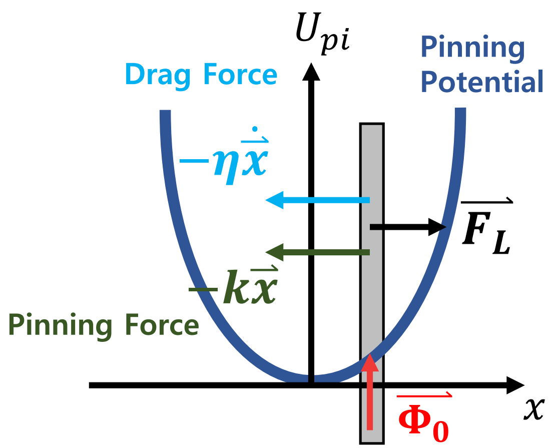
Type II Superconductor in a Magnetic Field

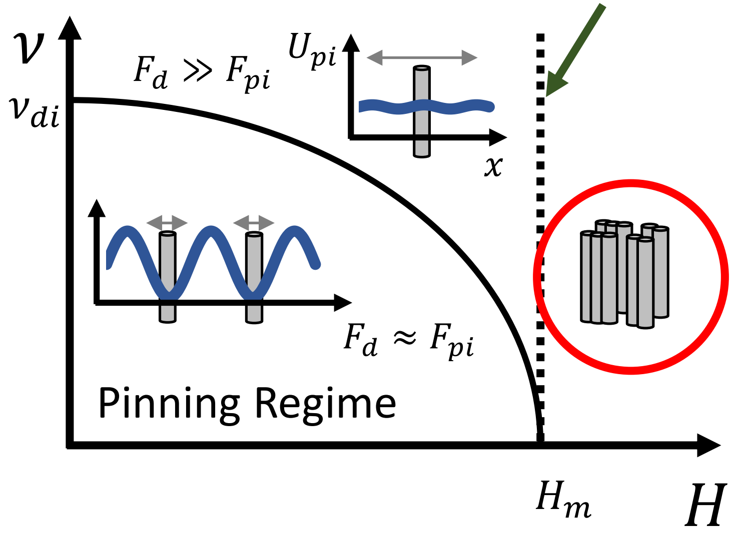
Vortex Dynamics & Energy Dissipation Mechanism

- 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.
- Above a melting field, vortices are mixed each other.

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



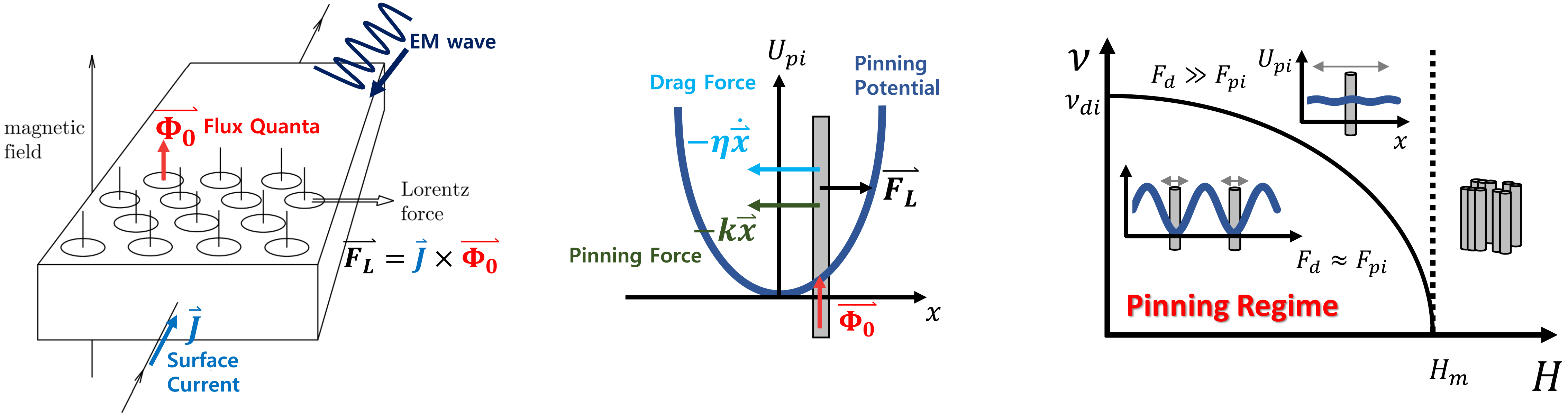




Type II Superconductor in a Magnetic Field

Vortex Dynamics & Energy Dissipation Mechanism

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

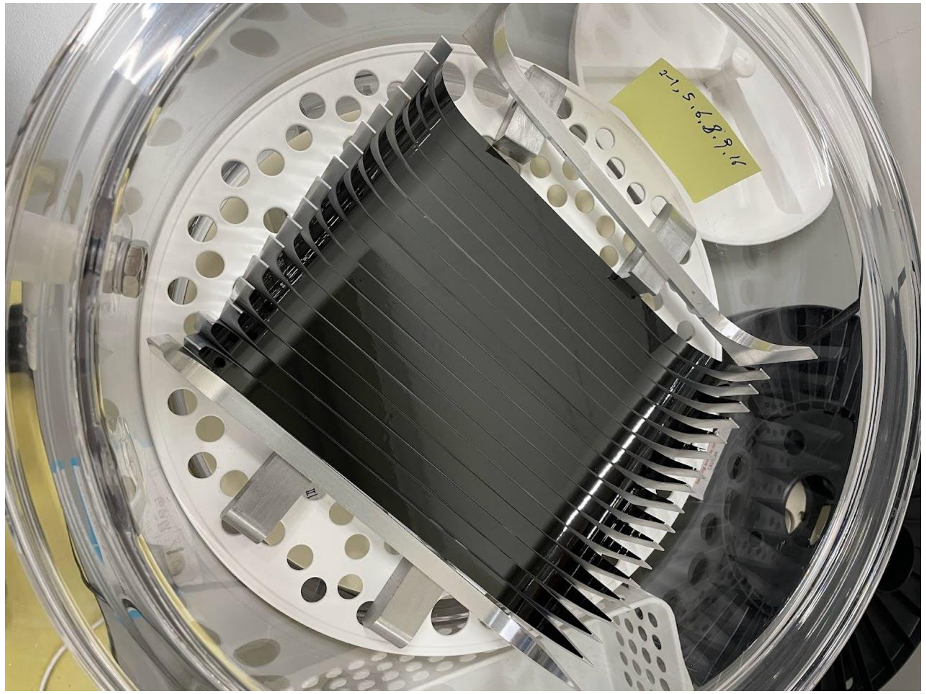
Material Evaluation

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)

High-temperature Superconducting Cavity R&D

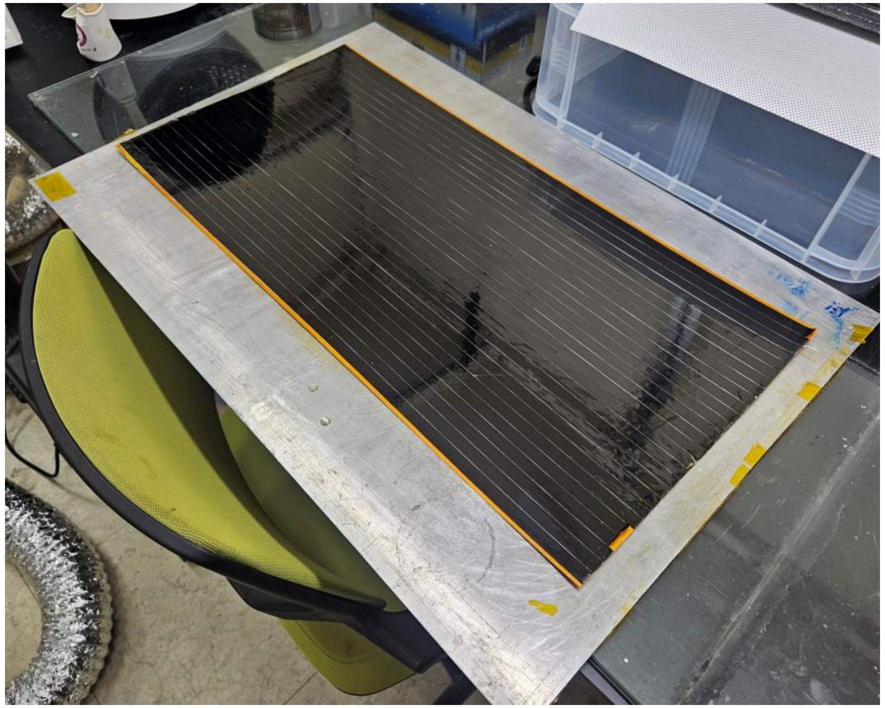
Development Methods

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 Cavity R&D

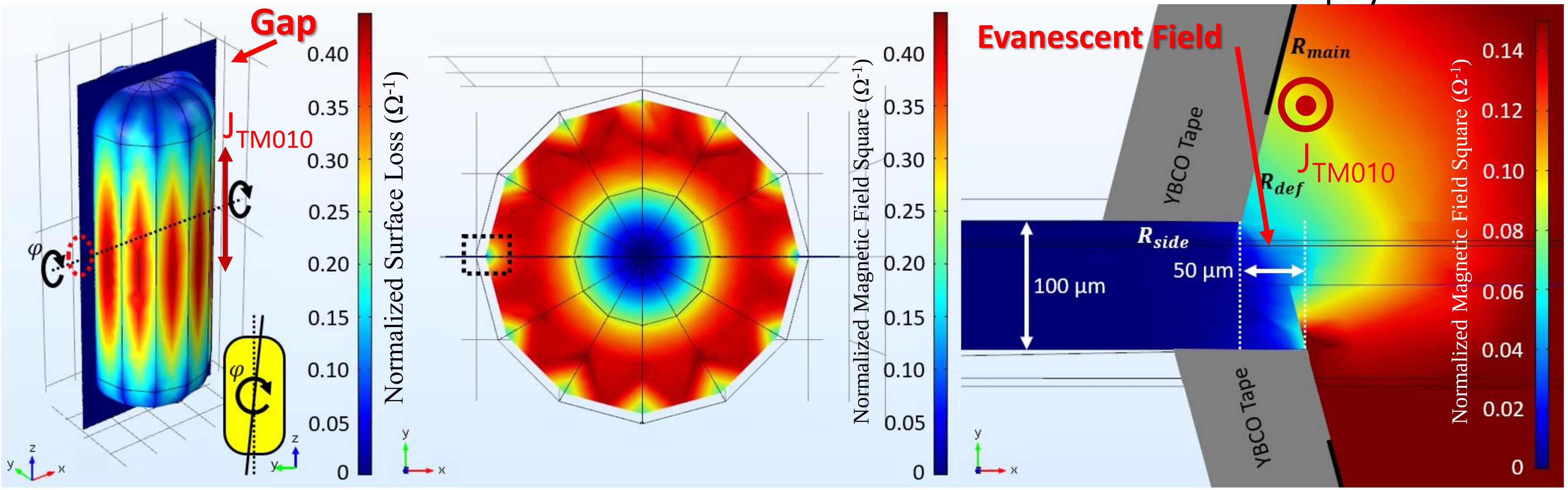
Strategy 1

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

$Q_{ext} > 10^7$

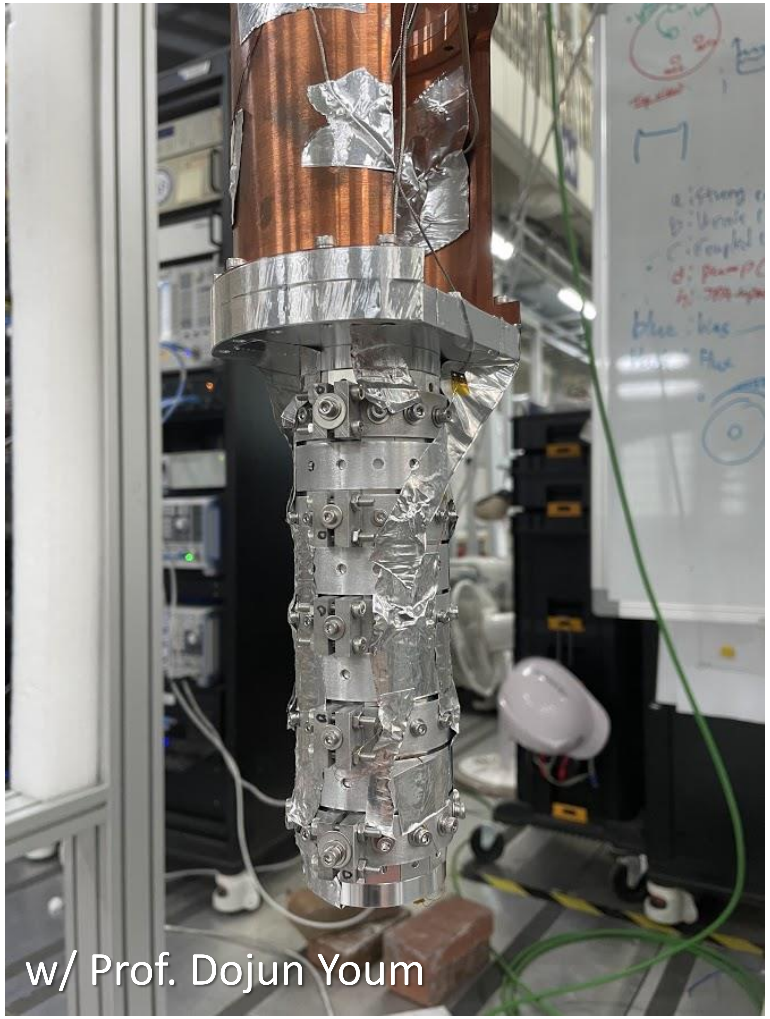
Ahn *et al*. PRApplied(2022), 17, L061005

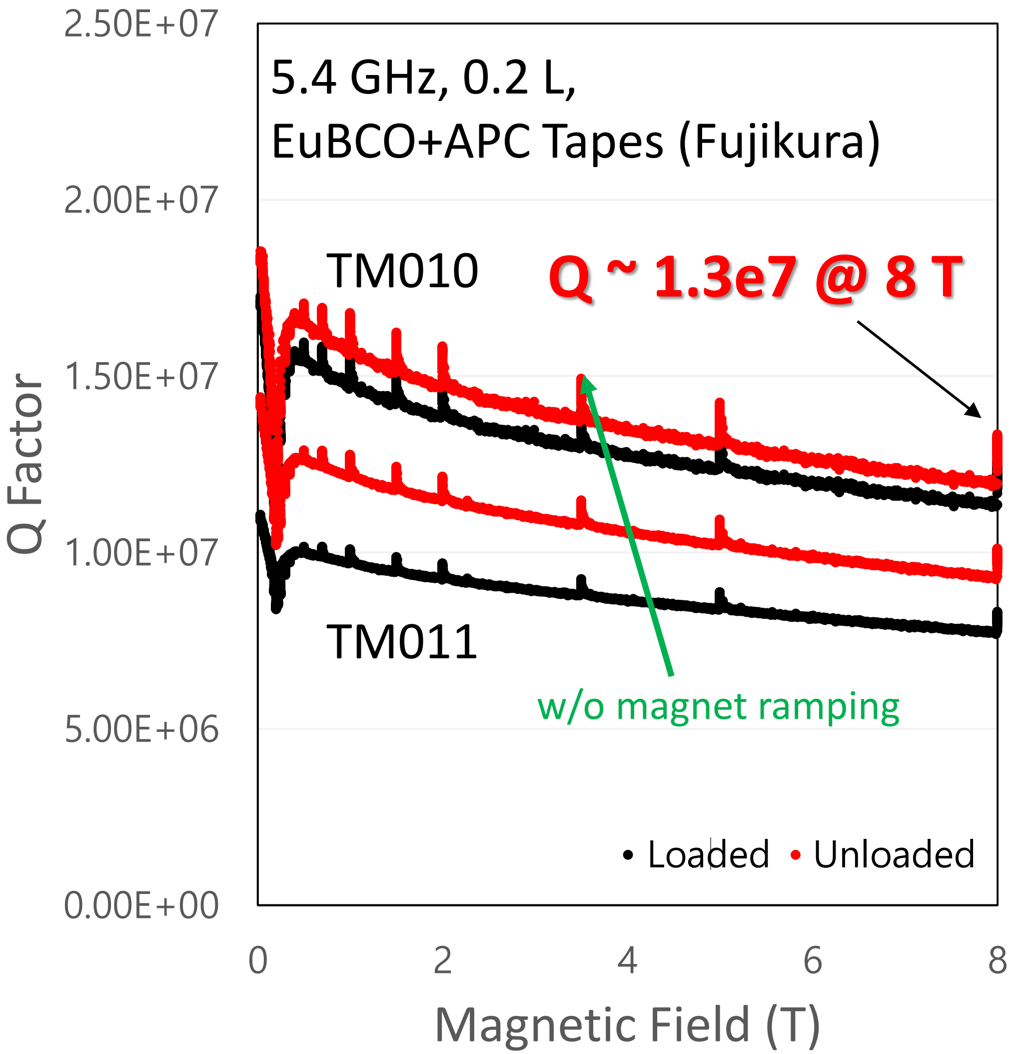
COMSOL Multiphysics Result



High-temperature Superconducting Cavity

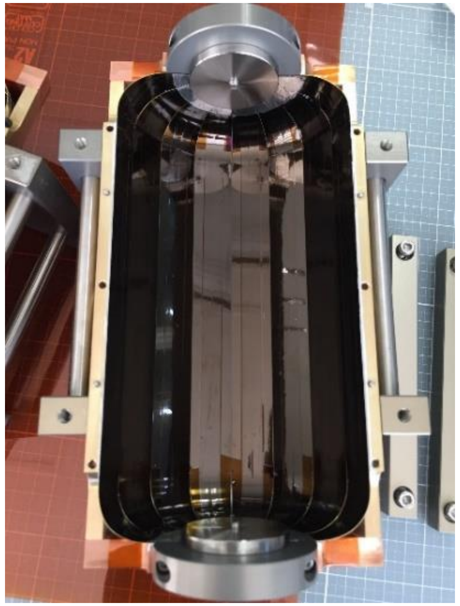
CAPP Successfully Achieved 13 Million Quality Factor Cavity at 8 T Field

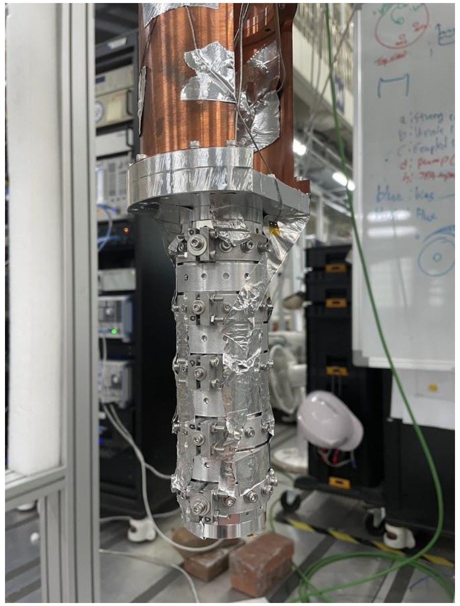
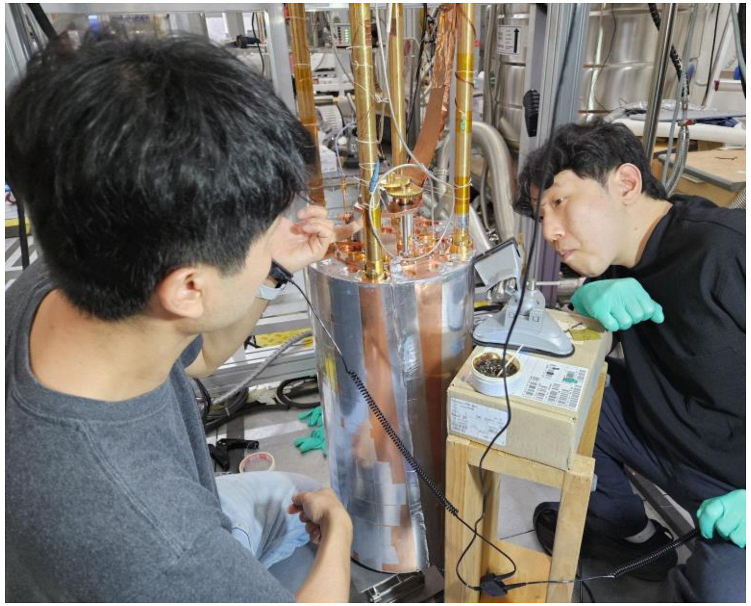




High-temperature Superconducting Cavities at CAPP

Summary

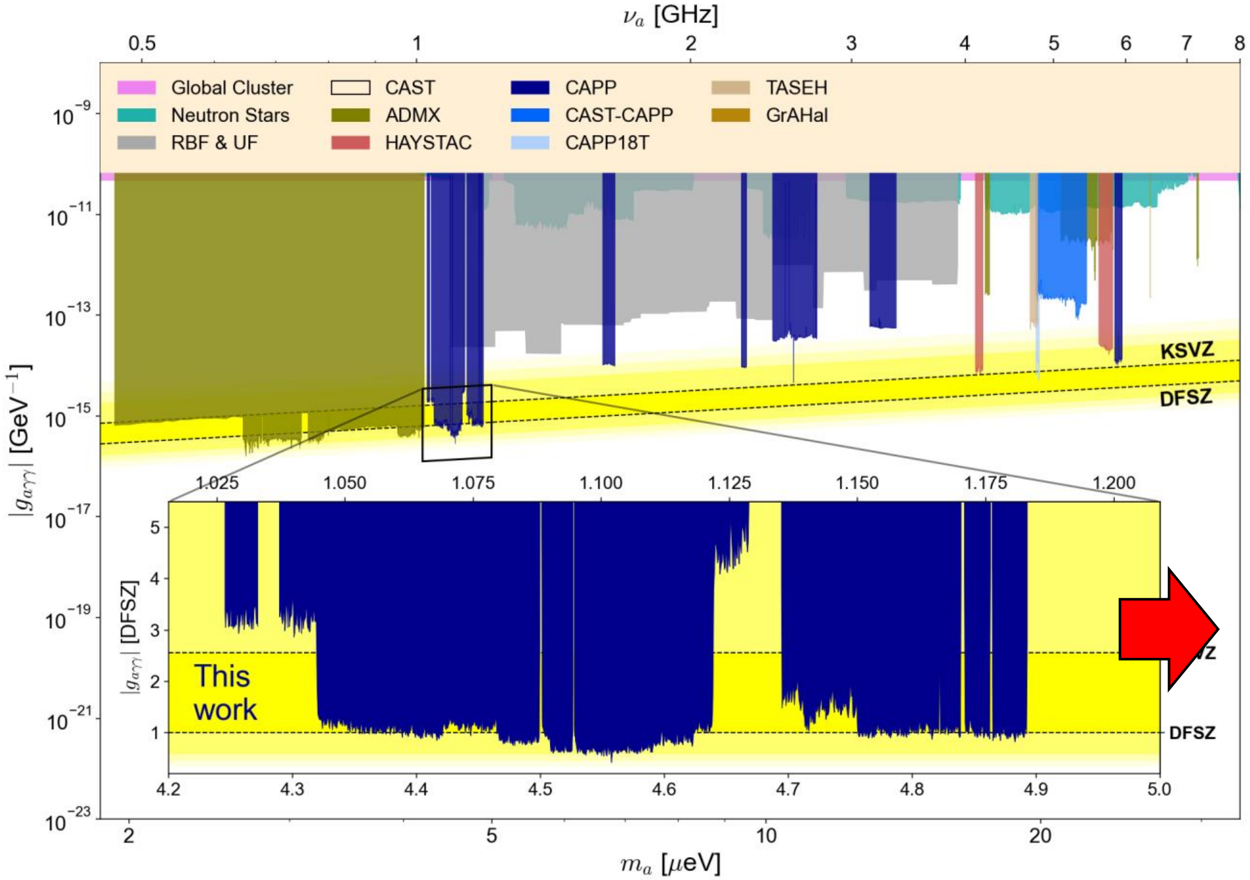



Date	Tape	f (GHz)	n_{gap}	Q (0 T)	Q (8 T)	Q_{gap}	Experiment
1	YBCO	6.9	12	0.22 M	0.33 M		Prototype
2	GdBCO	2.3	32	0.60 M	0.50 M		Cavity Haloscope
3	EuBCO+APC	2.3	34	5.0 M	3.5 M	> 10 M	Axion Quark Nugget Search
4	EuBCO+APC	5.4	14	20 M	13 M		Cavity Haloscope
5	EuBCO+APC	1.2 ~ 1.5	0	1.1 M	0.8 M		**Axion Haloscope (CAPP-MAX)**

High-temperature Superconducting Cavities at CAPP

Superconducting Cavity for CAPP-MAX

Phys. Rev. X 14, 031023



High-temperature Superconducting Cavities at CAPP

Superconducting Cavity for CAPP-MAX

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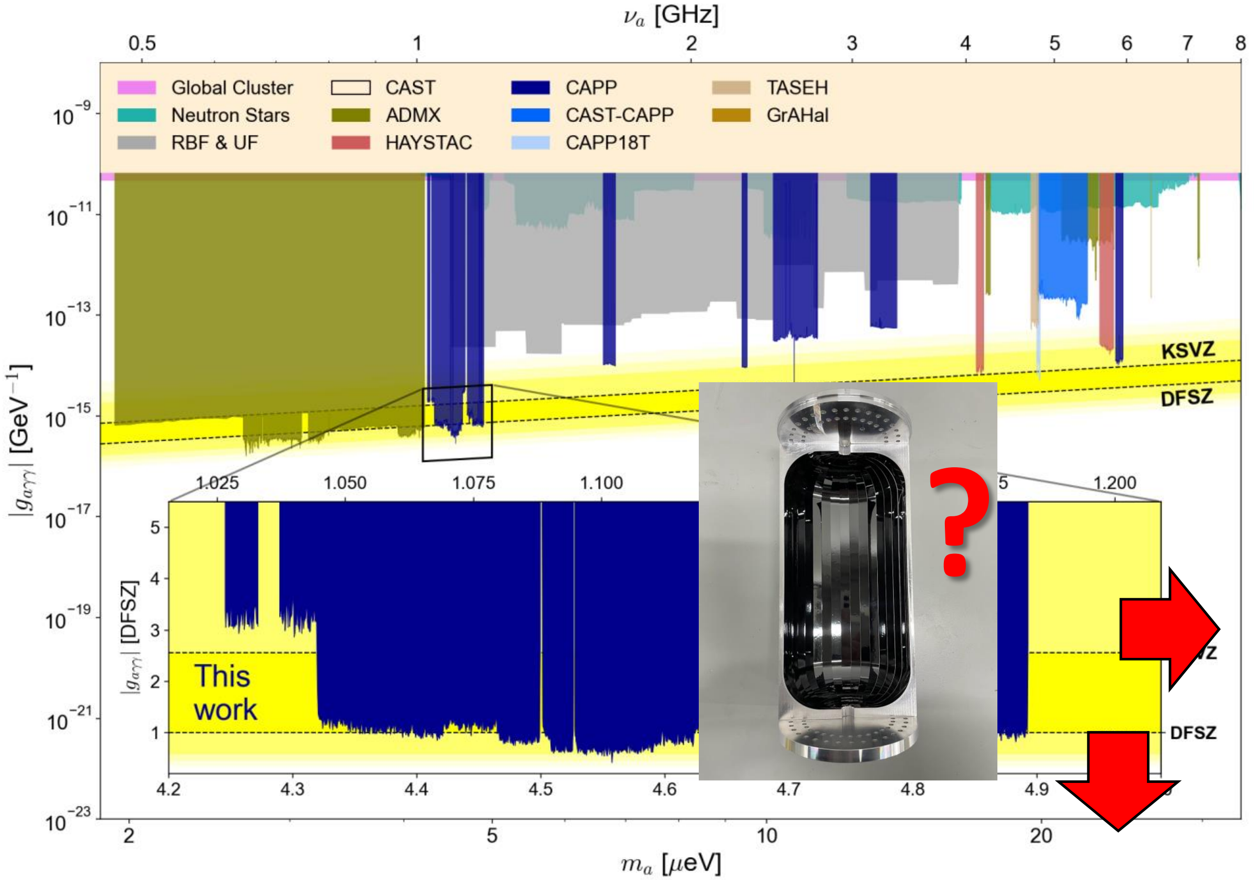
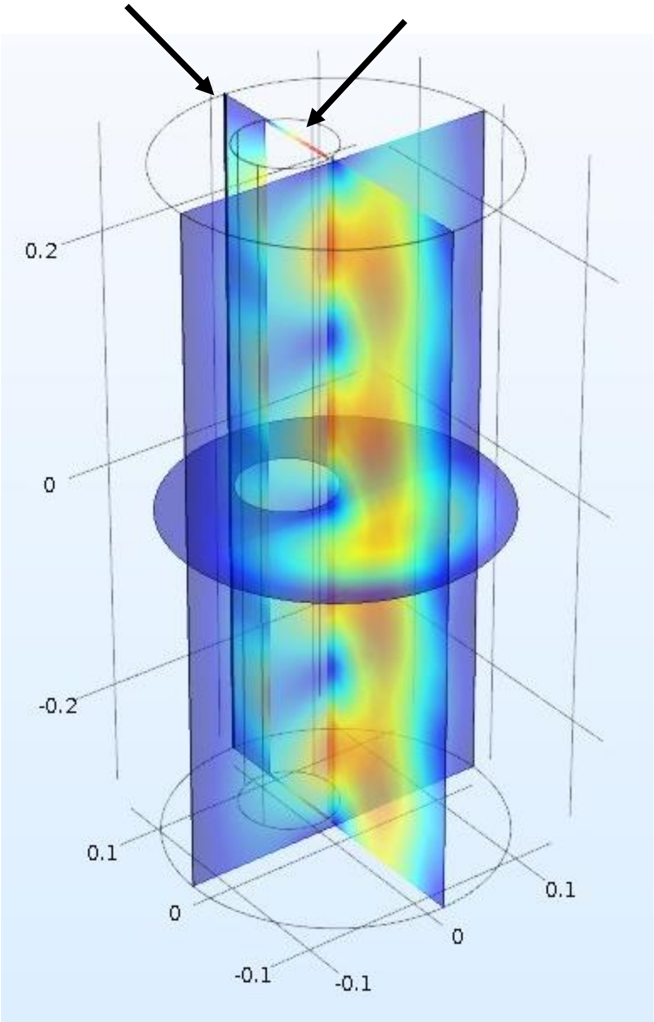


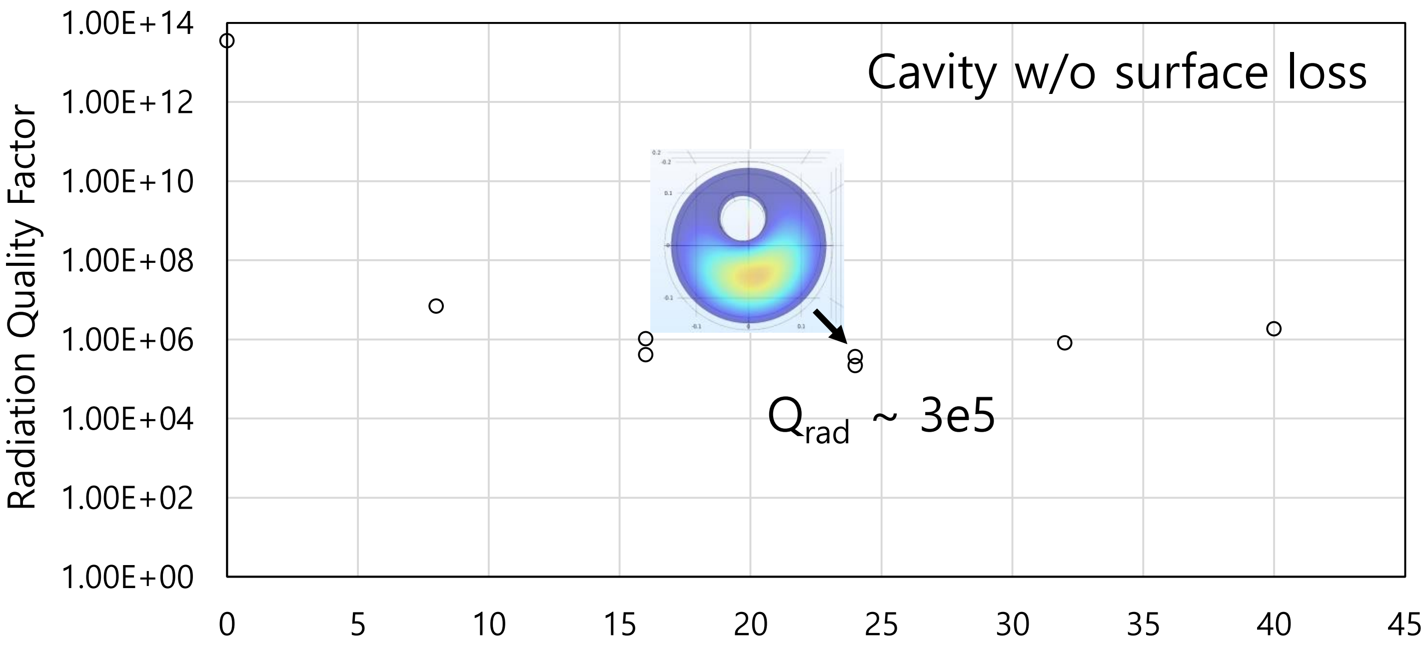
Below DFSZ sensitivity or Axion as 20% of Dark Matter

High-temperature Superconducting Cavity R&D

Gap geometry degrades Q factor with tuning rods



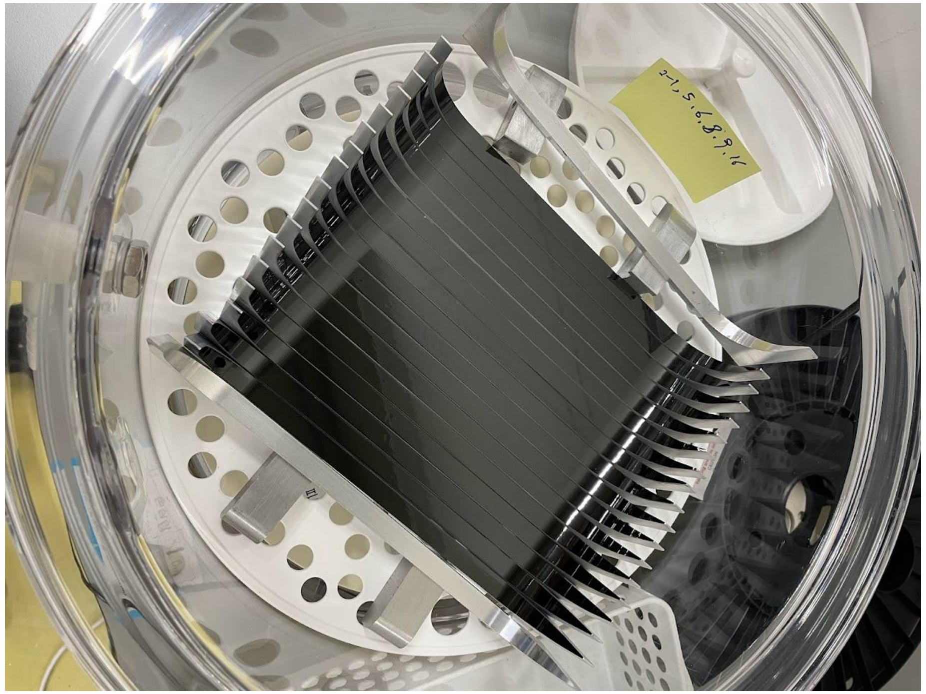
- Sensitive to Contact Problem
- Gaps should be closed electrically to prevent a radiation



High-temperature Superconducting Cavity R&D

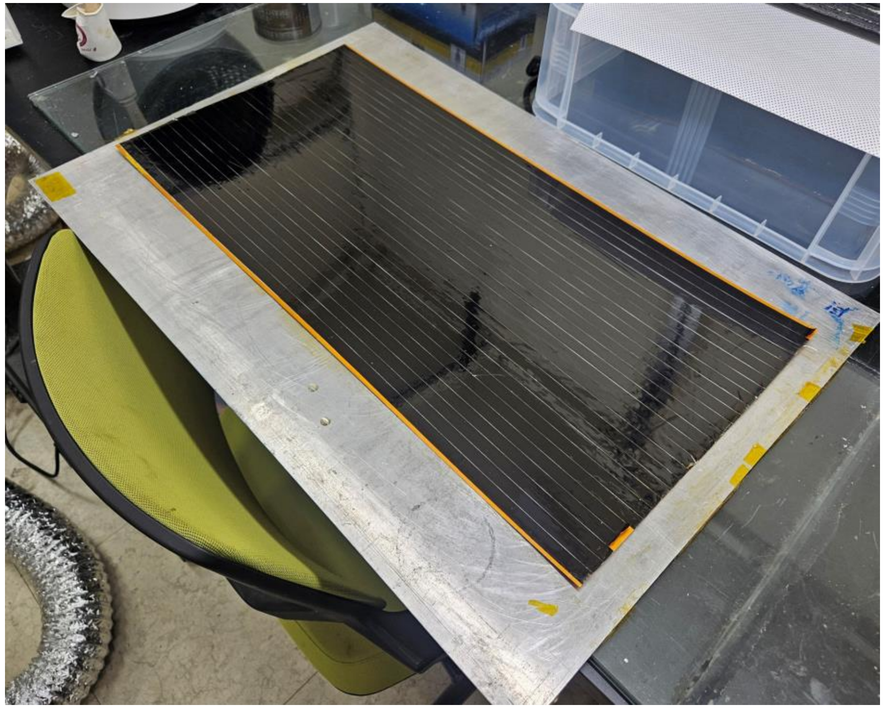
Development Methods

Strategy 1



Pros: Clean Surface
Cons: Slow Fabrication, Electrically Disconnected

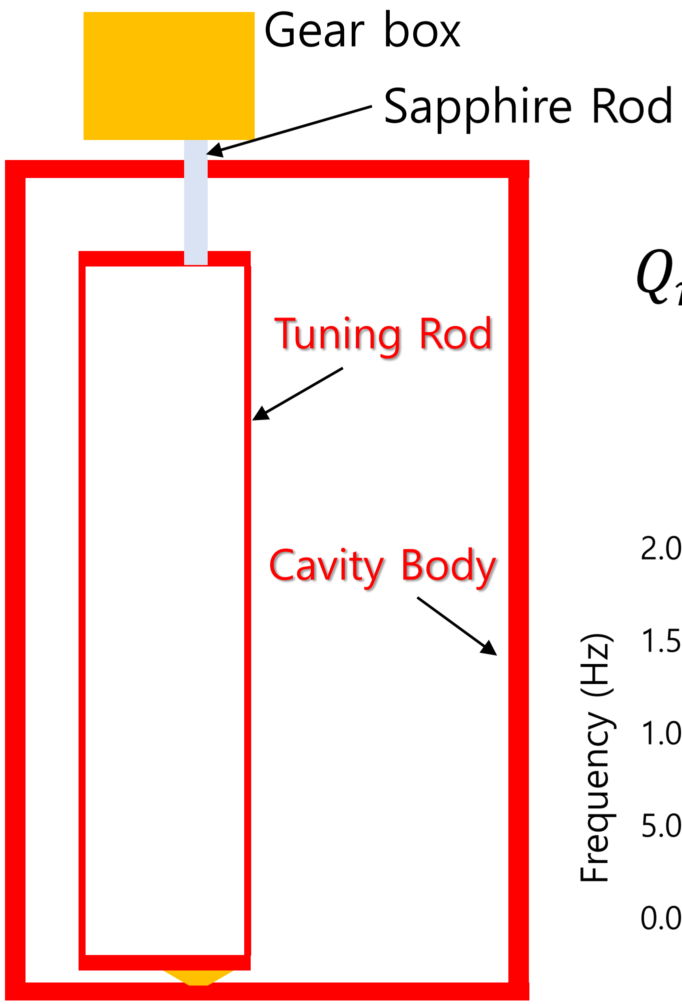
Strategy 2



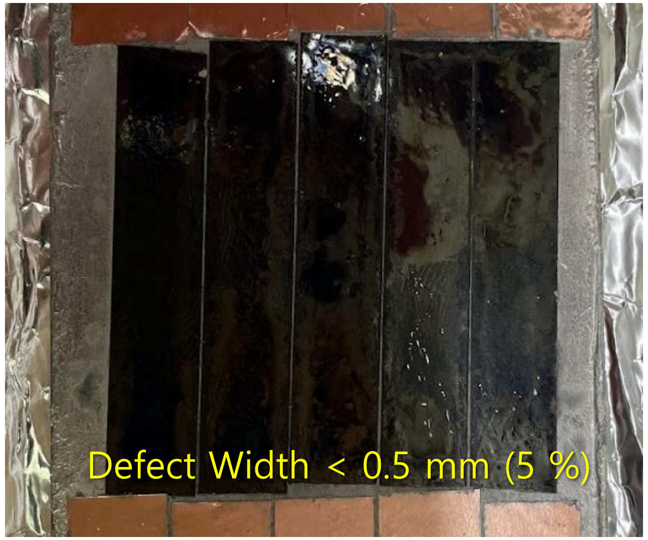
Pros: Easy to Fabricate, Electrically Connected
Cons: Surface Defect (~ 10%)

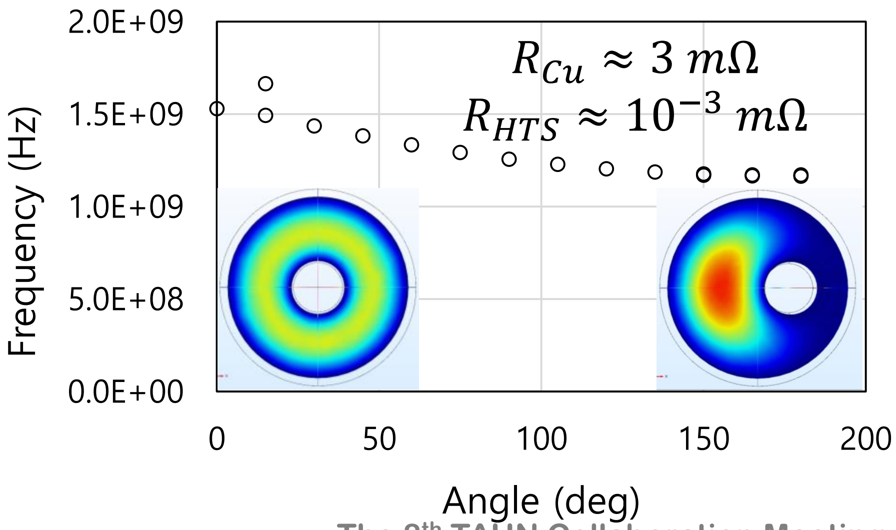
High-temperature Superconducting Cavity R&D

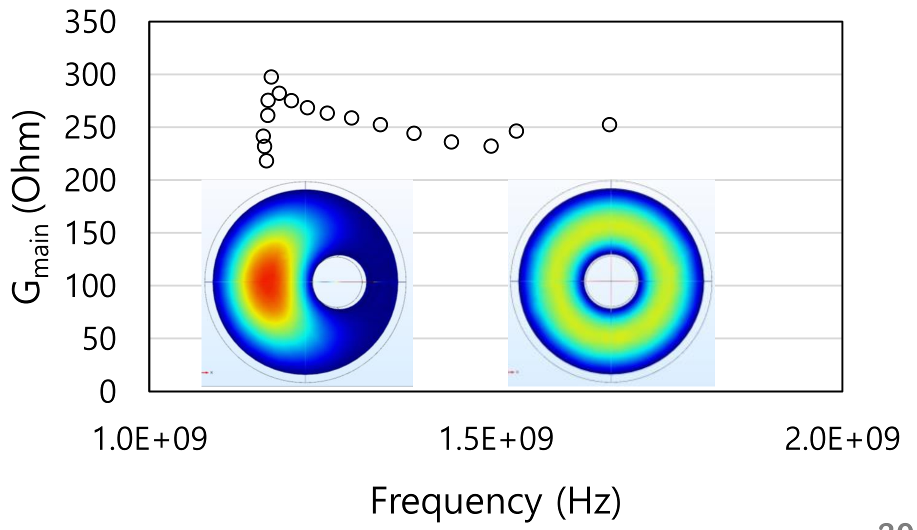
Strategy 2



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

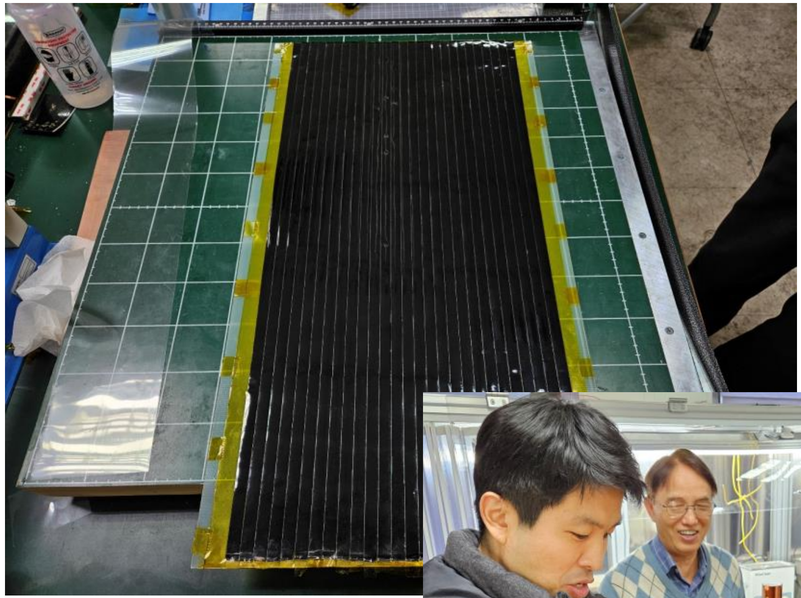


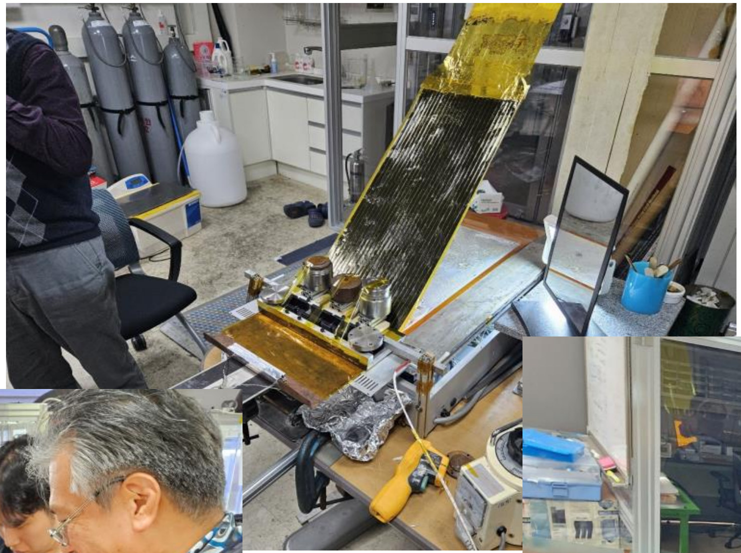




High-temperature Superconducting Cavity R&D

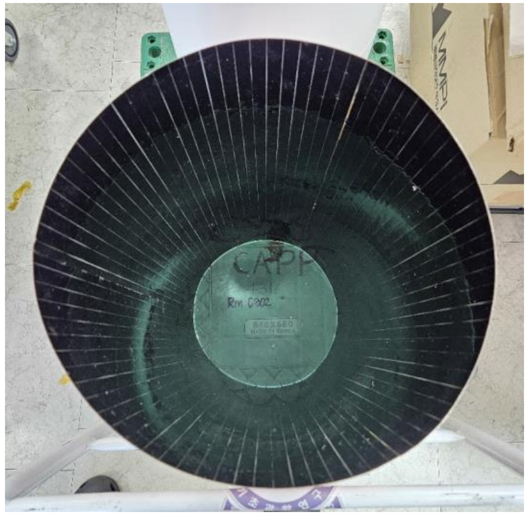
Strategy 2

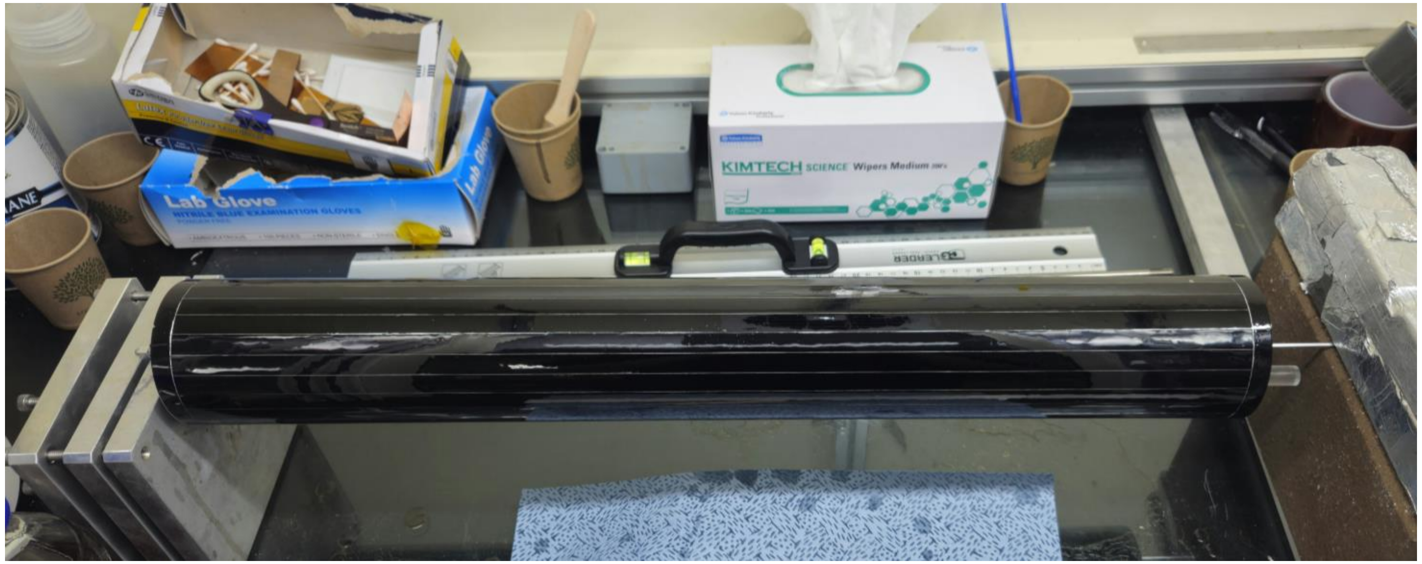


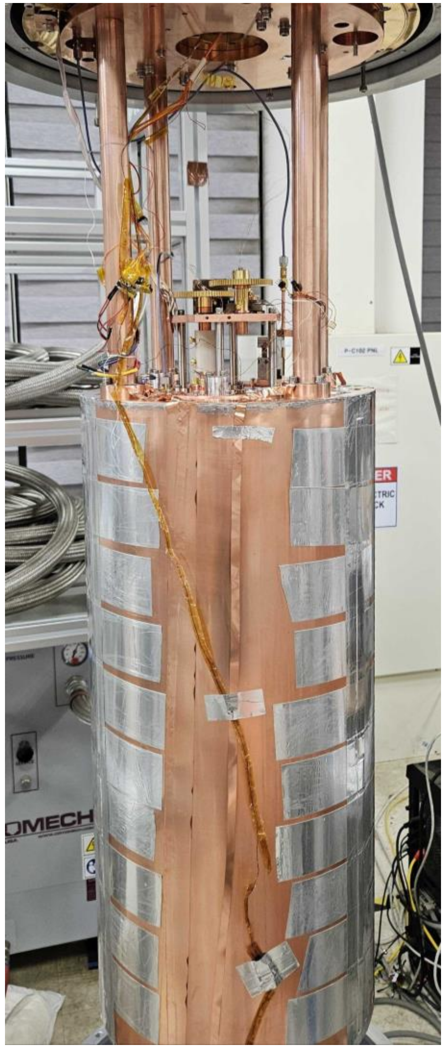


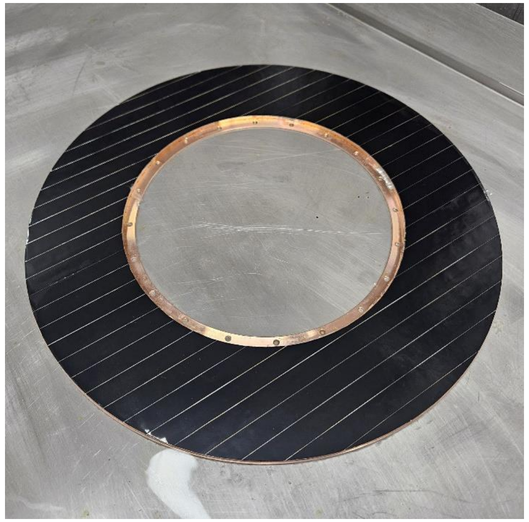
High-temperature Superconducting Cavity R&D

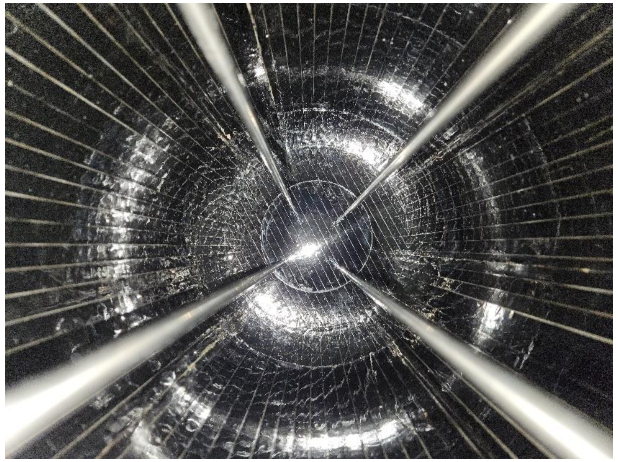
Strategy 2











High-temperature Superconducting Cavity R&D

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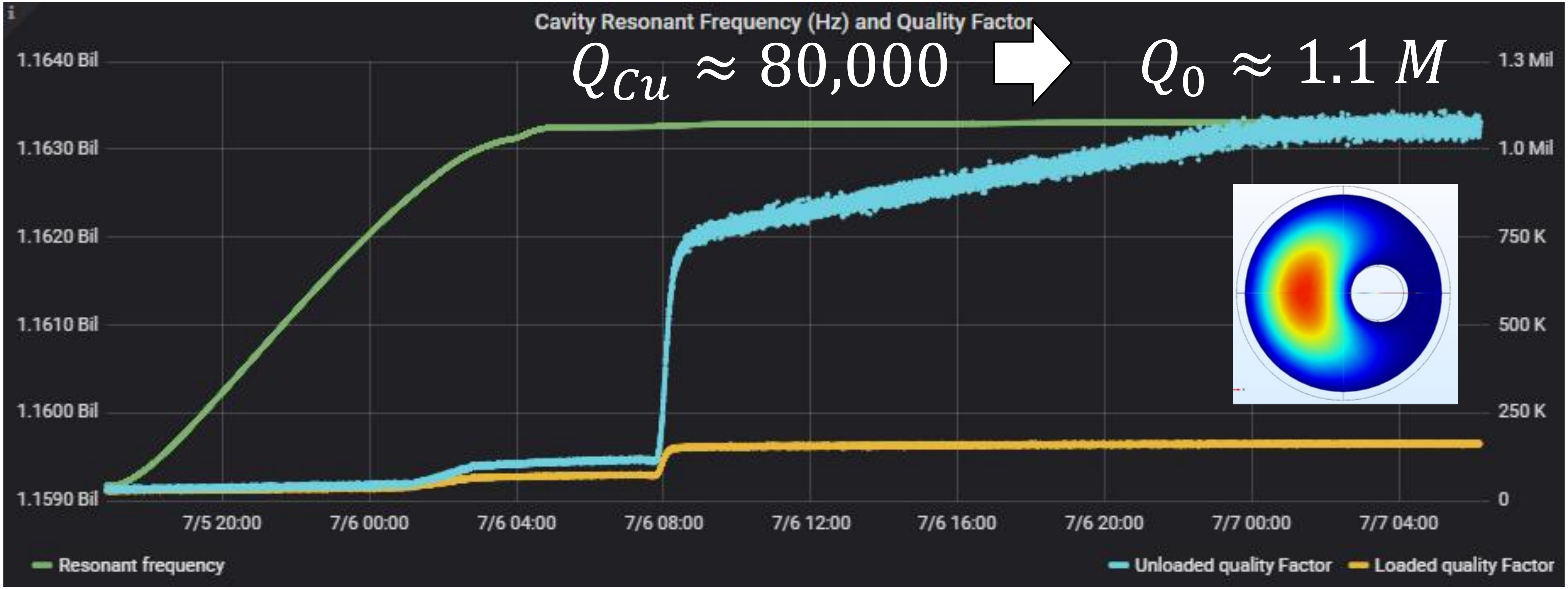
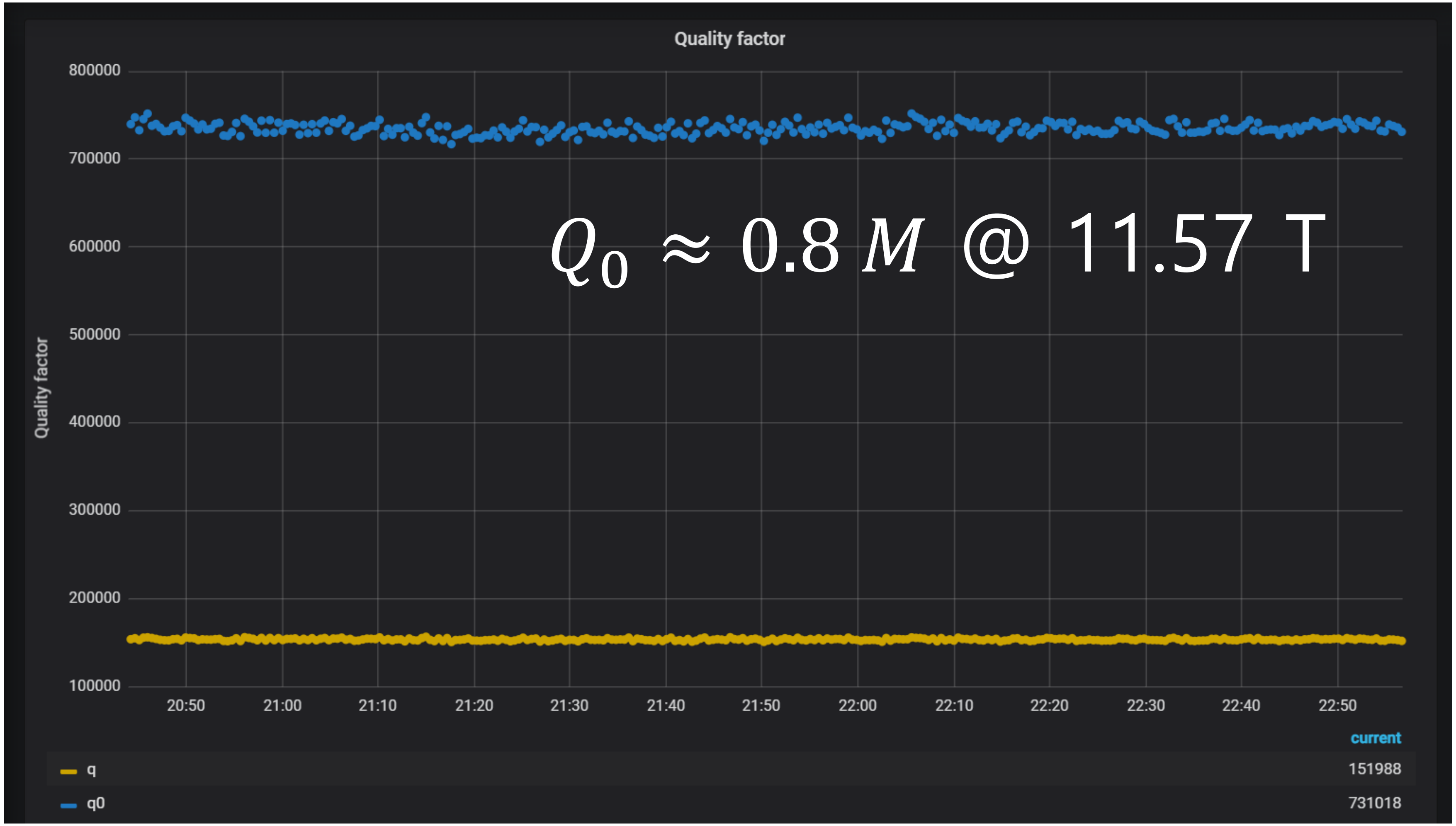


High-temperature Superconducting Cavity R&D

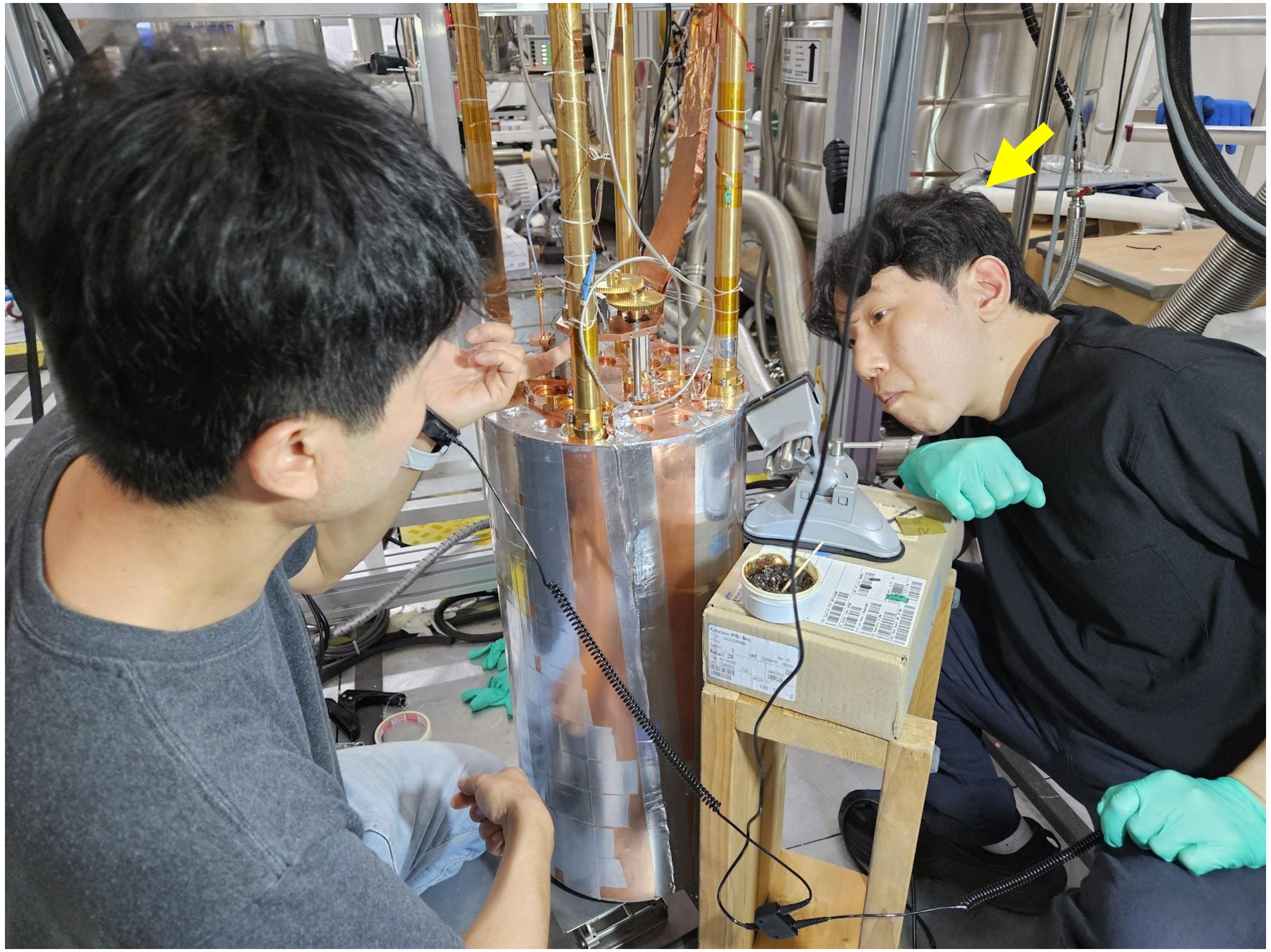
Strategy 2

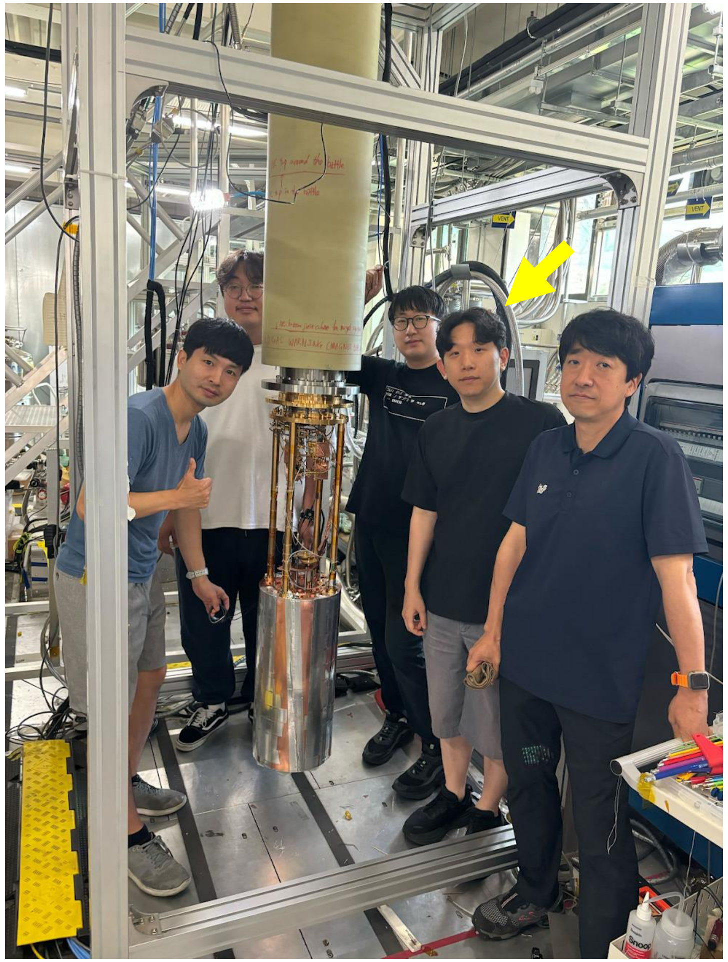


$Q_0 \approx 0.8\,M$ @ 11.57 T

Dark Matter Axion Search

CAPP-MAX with a High-Temperature Superconducting Cavity





Accelerating Axion Haloscope Experiments

Strategies and Innovations at CAPP

- The Center for Axion and Precision Physics Research (CAPP) has made significant progress in advancing axion haloscope experiments.
- The flagship experiment at CAPP, the Main Axion eXperiment (CAPP-MAX), features a powerful large-bore magnet integrated into a wet cryogenic system.
- The system employs a LEIDEN refrigerator capable of cooling the cavity to 30 mK, one of the lowest physical temperatures achieved in axion haloscope experiments.
- Furthermore, the use of a Josephson Parametric Amplifier introduces only quantum-limited noise to the RF chain, enabling a remarkably low system noise temperature of approximately 200 mK.
- CAPP has also developed a high-temperature superconducting (HTS) cavity for the CAPP-MAX system, which maintains a quality factor in the millions even under a 12 T magnetic field.
- Currently, CAPP is preparing to cool down the cryogenic system and begin data acquisition.