IBS-DMAG
Creation Hall, KAIST Munji Campus

High-Temperature Superconducting (HTS) Multiple-Cell Cavities for High-Mass Axion Search

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KAIST & IBS-DMAG

※ IBS-DMAG is the successor of IBS-CAPP

Table of contents

- Introduction: Cavity Axion Haloscope
- Motivation & Key Technologies
  - Multiple-Cell Cavities
  - HTS Cavities
- Development of an HTS double-cell cavity
- Performance Test
- Toward the Axion Search
- Summary

Axion detection setup

Introduction

- ## Cavity Axion Haloscope

Proposed by Pierre Sikivie in 1983

→ The most sensitive method for detecting axion dark matter

F. T. Avignone, *Homing in on Axions?*, Physics **11**, (2018).

Resonant microwave cavity in a cryogenic environment

Axion-photon interaction

$$f_a = \frac{m_a c^2}{h}$$
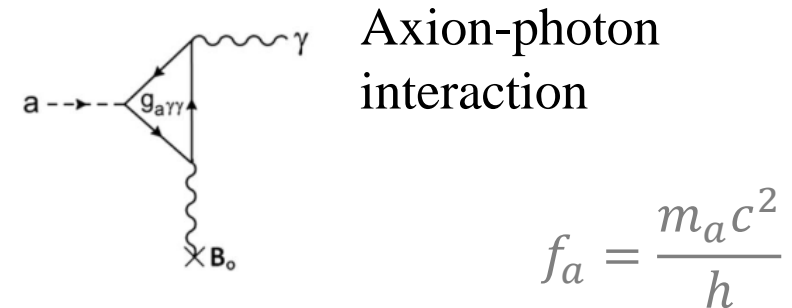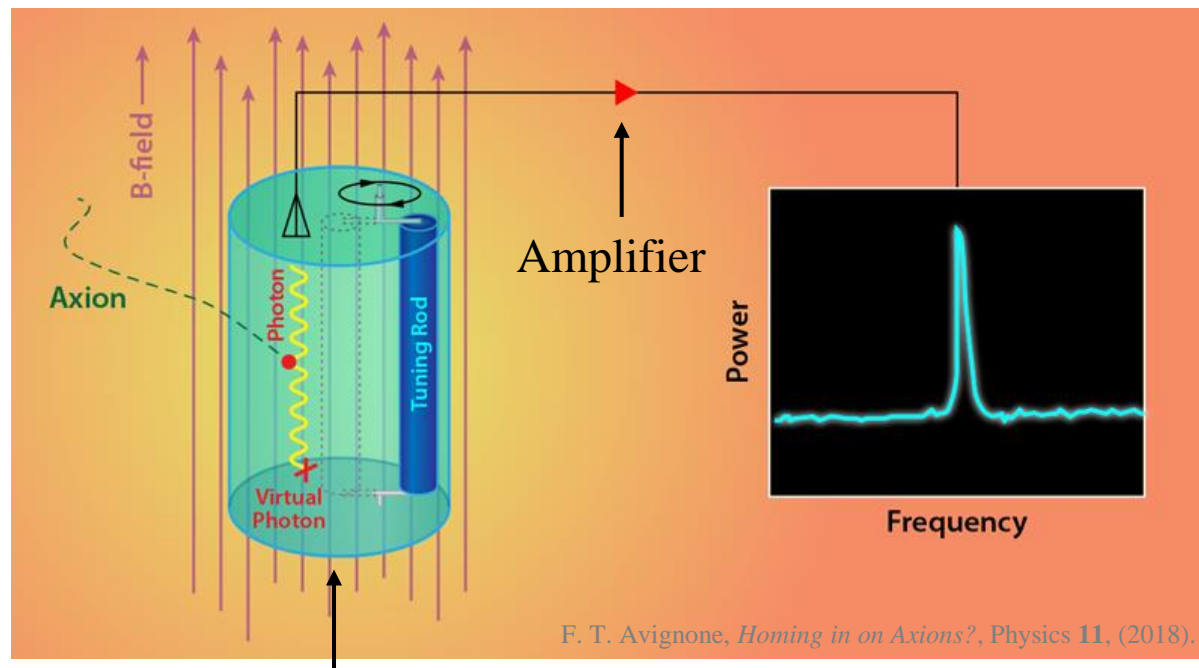
When $f_a = f_{cav}$
→ resonant conversion

Unknown m_a
→ Resonant frequency tuning
→ Dielectric or metal rod

Motivation & Key Technologies

- Axion conversion power

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

- Scan rate

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

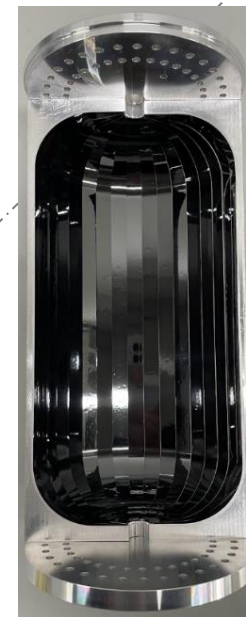$Q_l \gg Q_a$ or $Q_l \ll Q_a$
Jinsu Kim, Patras (2023)

- Goal 🚩

$$\boldsymbol{B^4, V^2, C^2, Q_l}$$
$$\rightarrow \text{Enhancing } \frac{df}{dt}$$

$g_{a\gamma\gamma}$: Axion photon coupling
ρ_a: Axion density in the local dark-matter halo
B: Externally applied B-field
V: Cavity volume
C: Cavity form factor
Q_l: Loaded Cavity Q-factor
Q_a: Axion Q-factor
β: antenna coupling coefficient
T_{sys}: system noise temperature

1. Multiple-Cell Cavities

Maximize V for higher f

$Q_l \uparrow \sim \frac{1}{R_S \downarrow}$

2. HTS Cavities

D. Kim *et al.*, Journal of Cosmology and Astroparticle Physics **2020**, (2020).
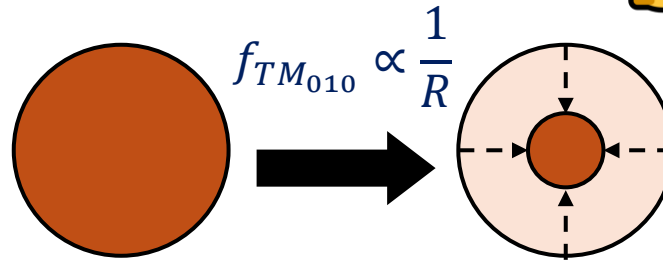
Multiple-Cell Cavities

- Goal 🚩

$$B^4, V^2, C^2, Q_l$$
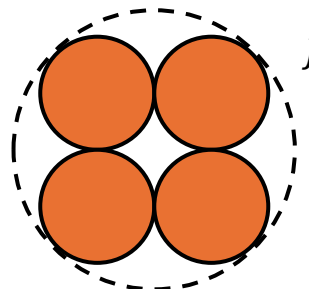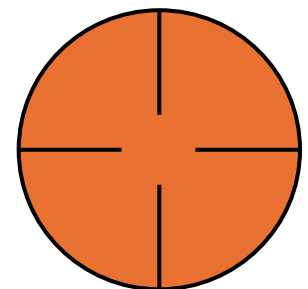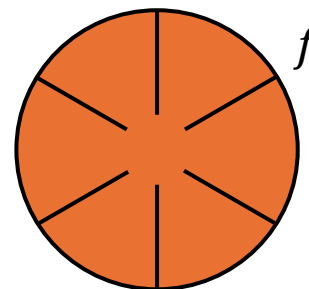$$\rightarrow \text{Enhancing } \frac{df}{dt}$$

- Why are Multiple-Cell Cavities needed? 🤔

For higher frequency searches

$$f_{TM_{010}} \propto \frac{1}{R}$$

Unavoidable volume loss
(Meanwhile, the fixed magnet bore radius)

(Example: 100 mm diameter, 200 mm height, 5 mm wall thickness)

Two times higher

Multiple cavity	Array of identical cavities	Multiple-cell cavity	

Multiple cavity — Array of identical cavities

$f_{TM_{010}} = 7.30\ GHz$
$V = 0.62\ L$
$\frac{df}{dt} = 1.0$
4 antenna

Quad cavity

Intuitive, but…
Inefficient use of volume.
Complicated tuning system.

Multiple-cell cavity

$f_{TM_{010}} = 5.89\ GHz$
$V = 1.08\ L$
$\frac{df}{dt} = 2.72$
1 antenna

Quad-cell cavity

$f_{TM_{010}} = 7.60\ GHz$
$V = 1.02\ L$
$\frac{df}{dt} = 1.98$
1 antenna

Sext-cell cavity

Minimize volume loss
Use a single antenna
→ Simplified readout chain

J. Jeong *et al.*, Physics Letters B **777**, 412 (2018).

HTS Cavities

ω: resonant frequency
U: energy stored in the cavity
P_d: power dissipated in the cavity
R_s: surface resistance

• Goal 🚩

$$B^4, V^2, C^2, Q_l$$
$$\rightarrow \text{Enhancing } \frac{df}{dt}$$

• Why are HTS cavities needed? 🤔

※ In the previous slide

Cavity quality factor: $Q = \omega \dfrac{U}{P_d} = \omega \dfrac{\frac{\mu_0}{2}\int |H|^2 dV}{\frac{R_s}{2}\oint |H|^2 dS} = \dfrac{G}{R_s} \propto \dfrac{1}{R_s}$ → Superconductor!

Magnetic fields on the order of 10 tesla are used at IBS-DMAG.

Most superconductors (such as Type-I, NbTi, and Nb$_3$Sn) cannot maintain their performance at such high magnetic fields.

※ Due to their low critical field or depinning frequency

E.g. At QUAX NbTi cavity

9.08 GHz
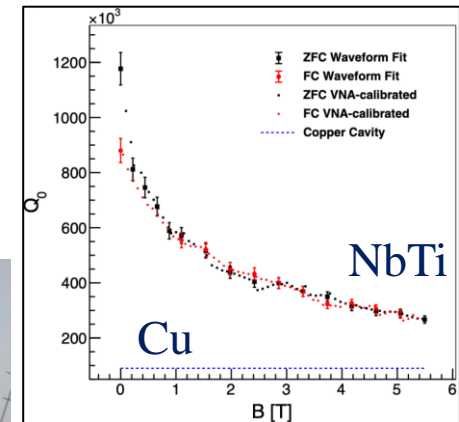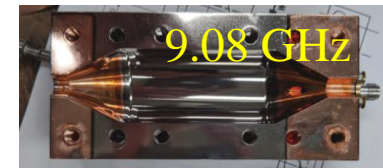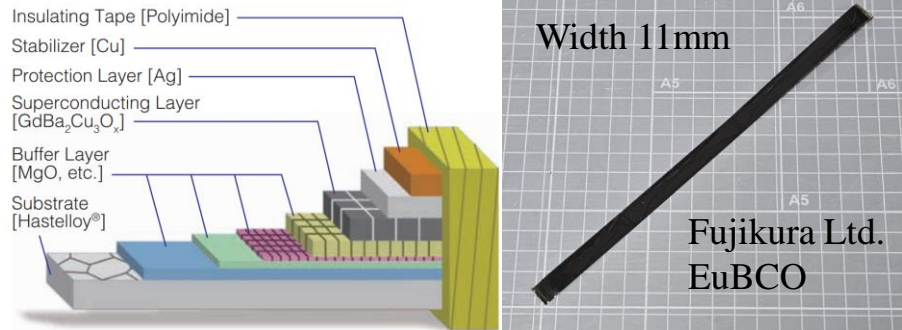
Performance comparable to Cu above 5 T

NbTi

Cu

However, ReBCO (one of the HTS) is suitable since its upper critical field (H_{c2}) exceeds 100 tesla.

HTS Cavities

• HTS cavity developed by the CAPP-HTS team

  ※ IBS-DMAG is the successor of IBS-CAPP

Insulating Tape [Polyimide]
Stabilizer [Cu]
Protection Layer [Ag]
Superconducting Layer [GdBa₂Cu₃Oₓ]
Buffer Layer [MgO, etc.]
Substrate [Hastelloy®]

Width 11mm

Fujikura Ltd. EuBCO

Commercially available 2D HTS tapes
→ Attach to the inside of the cavity

by soldering or gluing

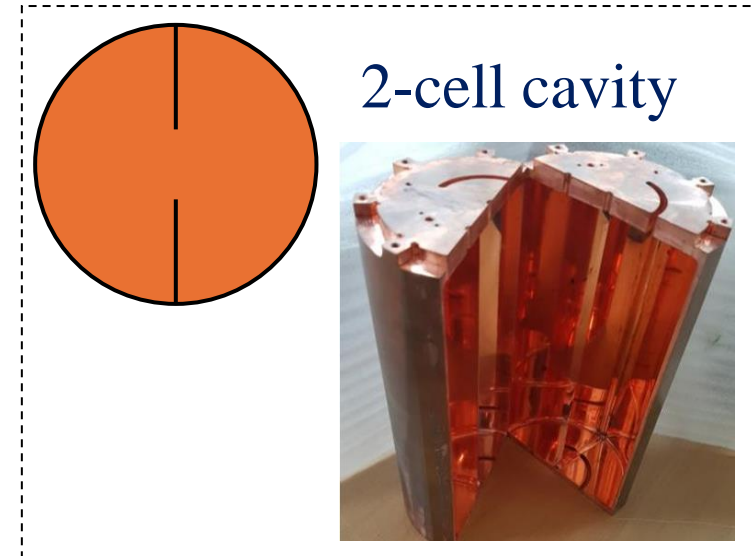$$\frac{df}{dt} \propto Q_l \ (Q_l \gg Q_a)$$
100 years → 1 year
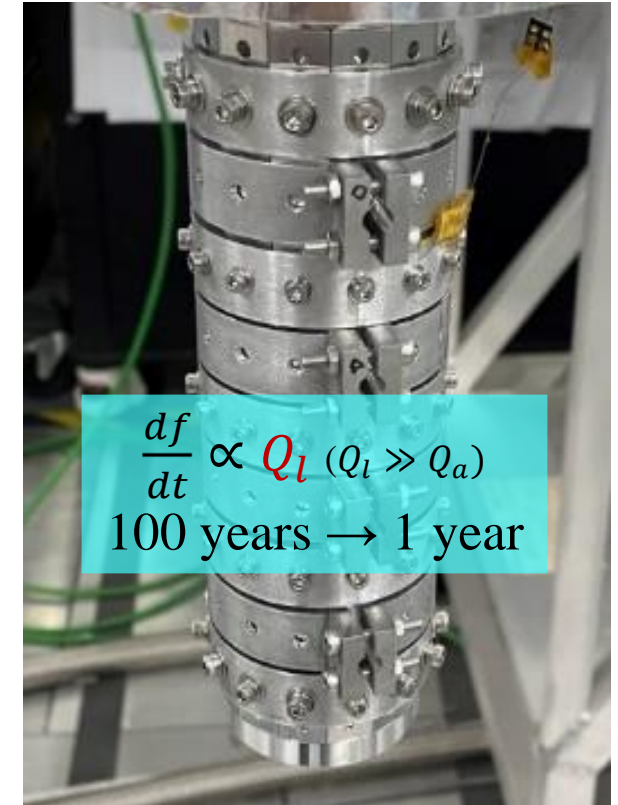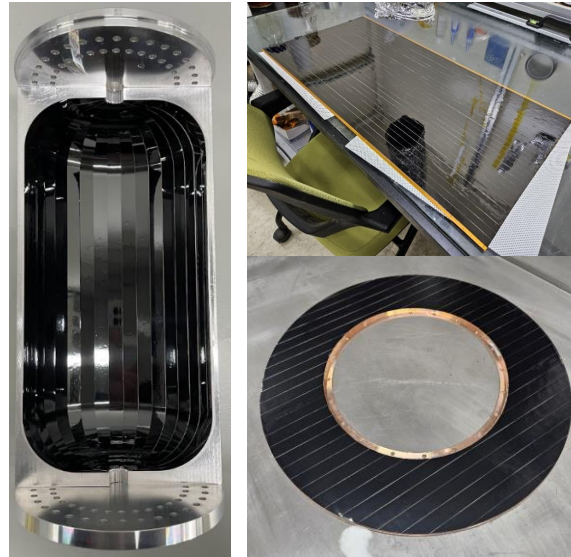
The best-performing cavity
Frequency: 5.4 GHz
Q-factor: 13 M at 8 Tesla
(→ 100 times better than Cu cavity)

Goal: Integration of the Two Technologies

We are moving toward integrating HTS cavity technology with multiple-cell design for the next-generation axion experiment.
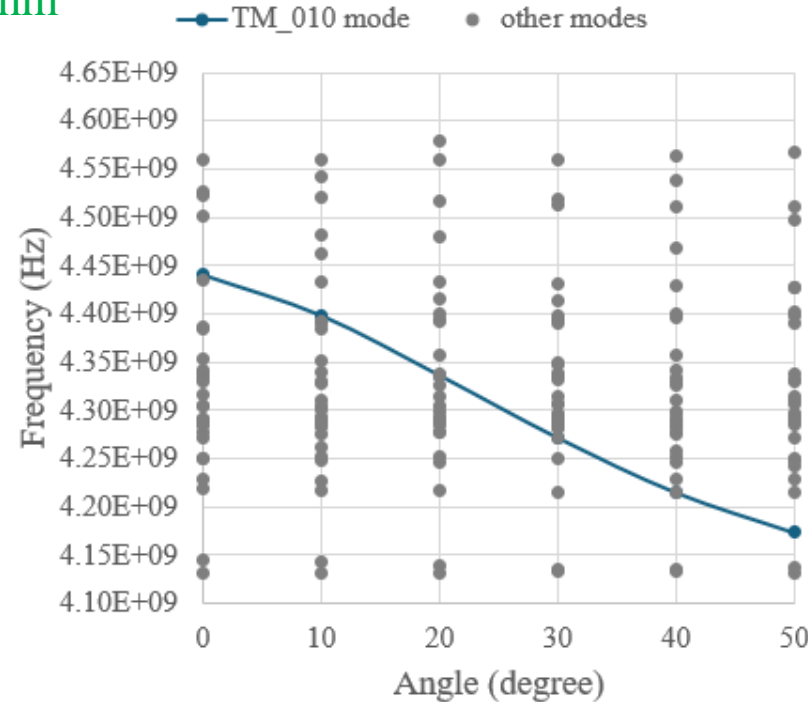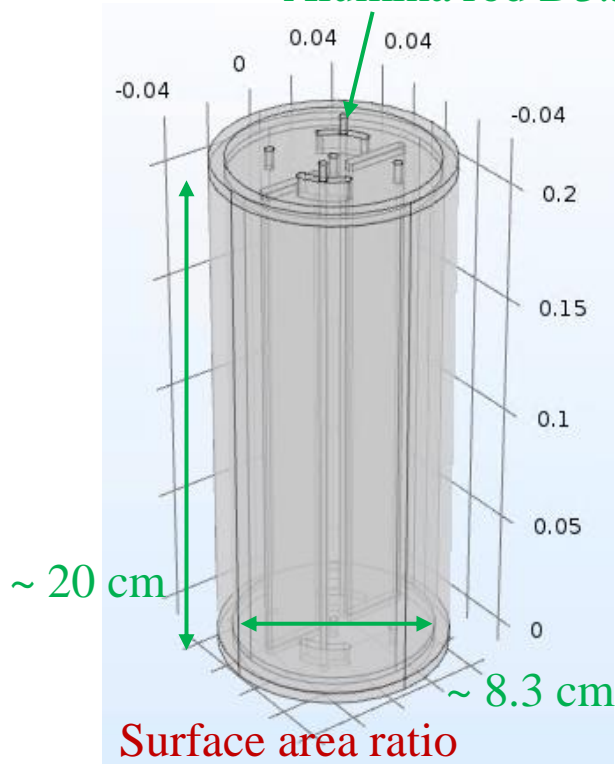

HTS cavity technology

+

2-cell cavity

Multiple-cell design

Development of an HTS double-cell cavity

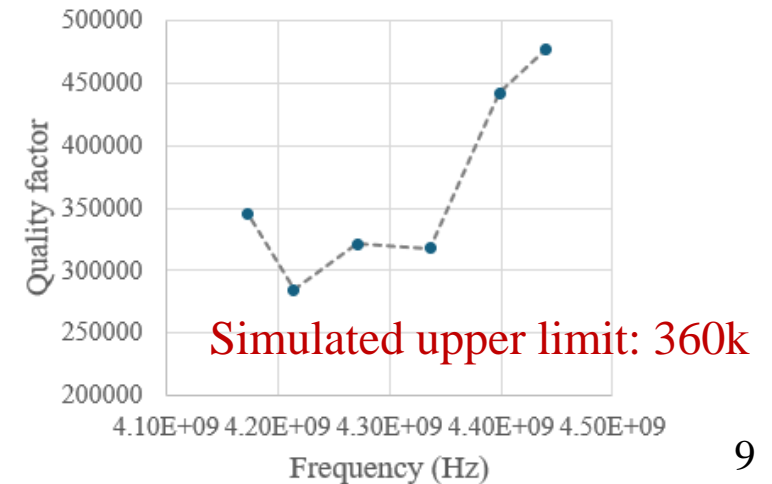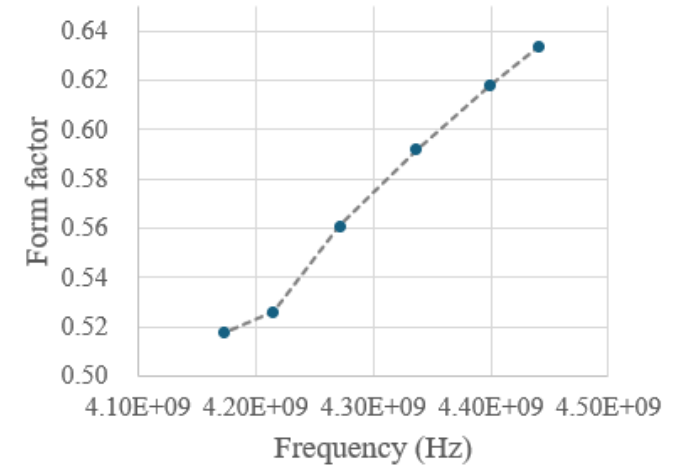The cavity design and copper components fabrication were carried out by Dr. Sungwoo and Dr. Sungjae.

- COMSOL simulation study

Alumina rod D3.5mm

~ 20 cm

~ 8.3 cm

Surface area ratio
→ HTS (99%) : Cu (1%)

Frequency: 4.17 − 4.44 GHz
Mass: 17.27 − 18.37 μeV

Simulated upper limit: 360k

Development of an HTS double-cell cavity

- Fabrication Process

1. <mark>HTS tapes are soldered onto copper components (endcap, sidewall, and partition)</mark>

2. Sidewalls are joined via laser welding & indium cold welding

3. 0.8 mm thick copper rings are tightly clamped around the sidewall and fixed in place using STYCAST 2850FT

4. The endcap is laser welded to both the sidewall and the partition.

5. Finally, they are electrically connected via indium cold welding.

Soldering method
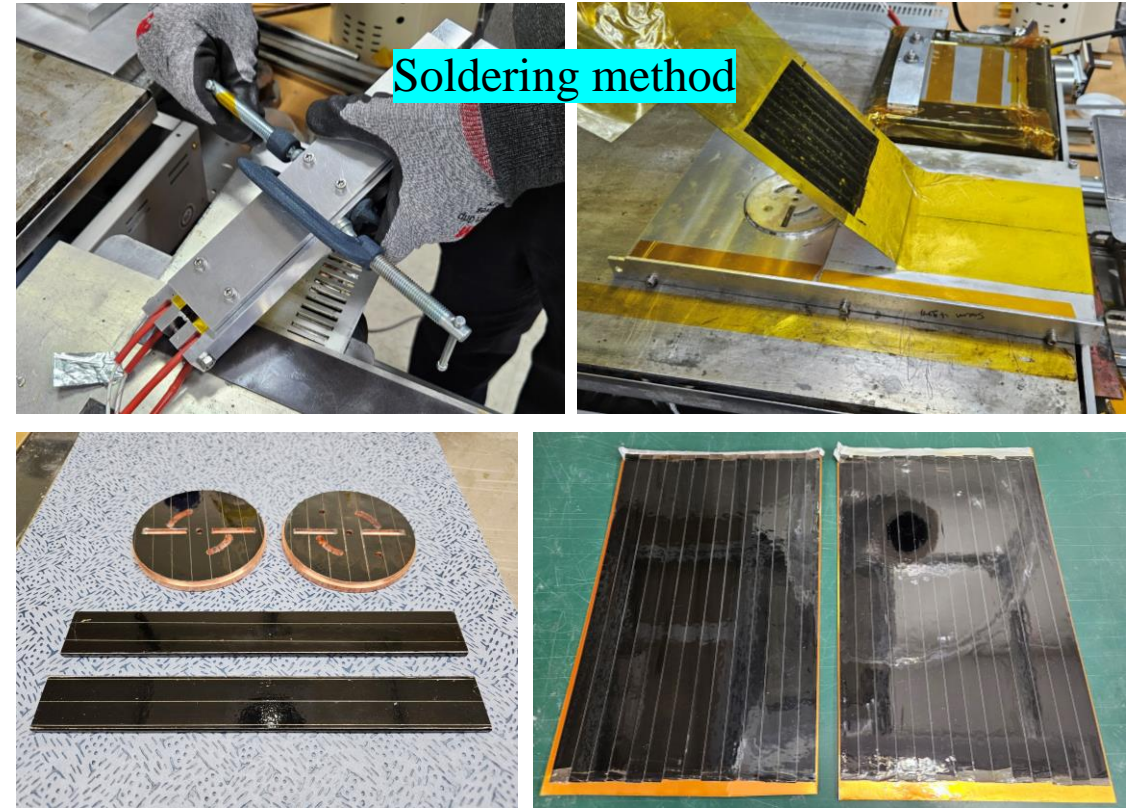
Development of an HTS double-cell cavity

• Fabrication Process

1. HTS tapes are soldered onto copper components (endcap, sidewall, and partition)

2. ==Sidewalls are joined via laser welding & indium cold welding==

3. ==0.8 mm thick copper rings are tightly clamped around the sidewall and fixed in place using STYCAST 2850FT==

4. The endcap is laser welded to both the sidewall and the partition.

5. Finally, they are electrically connected via indium cold welding.

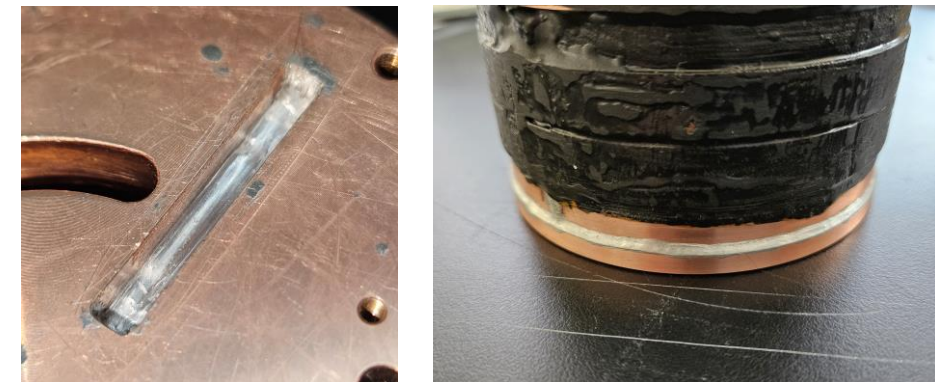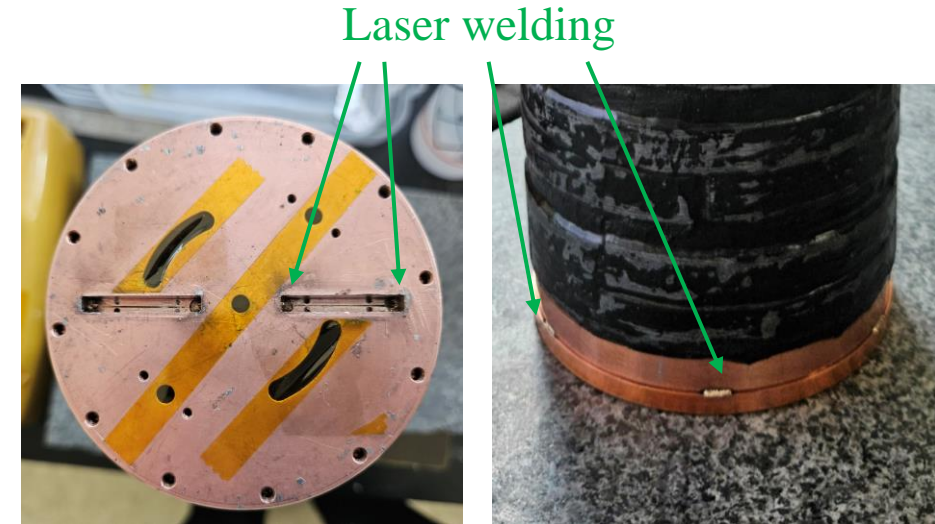Indium cold welding   STYCAST

Laser welding

Inside view of the sidewall

Development of an HTS double-cell cavity

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Laser welding

Indium cold welding

Performance Test

$$\frac{df}{dt} \propto Q_l$$

RF measurement w/o tuning rod

More than 3 times higher than that of a copper cavity

We achieved a Q-factor of $\sim 1.6 \times 10^5$ at a temperature near 10 K.

- T_4K plate
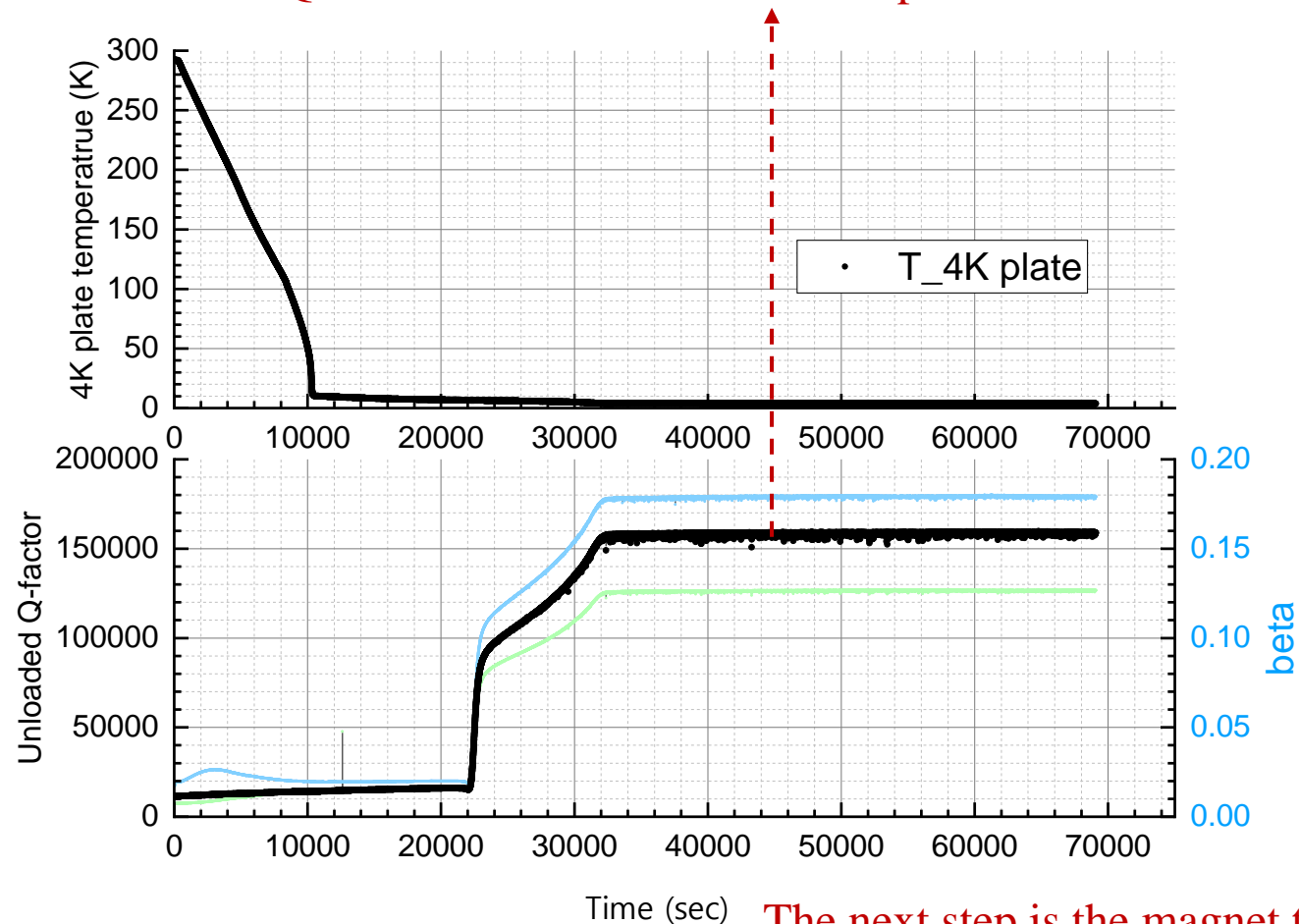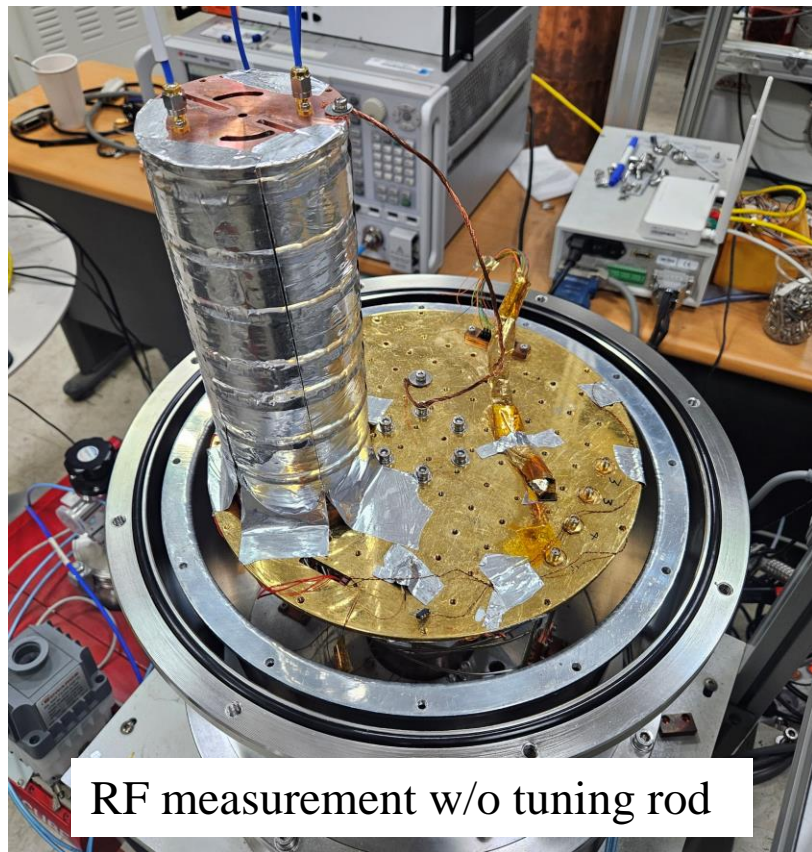
The next step is the magnet test.

Toward the Axion Search (Next Plans 🚩)

Alumina or Sapphire (high dielectric constant ε_r, low dissipation factor $tan\delta$)

- Design and assembly of the tuning system, including a dielectric tuning rod → May

- Cryogenic performance tests with the tuning rod → May

- To perform an axion search in the frequency range $4.17 - 4.44$ GHz (mass range $17.27 - 18.37$ μeV), this cavity will be integrated into the **DMAG-12T** cryostat. → Starting in June

Starting in June

< DMAG-12T >
Refrigerator
- Model: LD400
- 10 mK (Base)
- 580 μW (100 mK)
- Dry type
Magnet
- 12 Tesla
- 96mm Bore
- Nb_3Sn
- Vendor: AMI

Summary

- The axion haloscope continues to be the most sensitive and promising method for detecting axion dark matter.

- IBS-DMAG succeeded IBS-CAPP and continues to carry forward the axion search.

- To accelerate the search, IBS-DMAG is integrating independently developed multiple-cell design and HTS cavity technology.

- The HTS double-cell cavity, excluding the tuning system, has been fabricated and demonstrated a Q-factor more than 3 times that of a copper double-cell cavity at cryogenic temperatures.

- This cavity is scheduled to be installed in DMAG-12T in June for the next phase of the axion search experiment.

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Thank you! 🙂