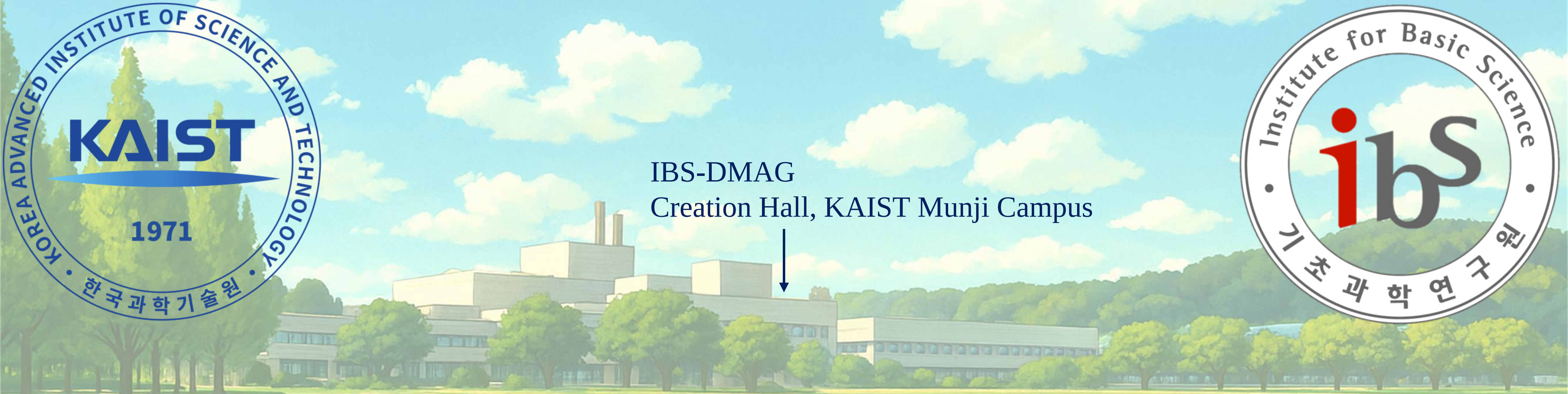

High-Temperature Superconducting (HTS) Multiple-Cell Cavities for High-Mass Axion Search

Jiwon Lee

KAIST & IBS-DMAG

※ IBS-DMAG is the successor of IBS-CAPP

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  - HTS Cavities
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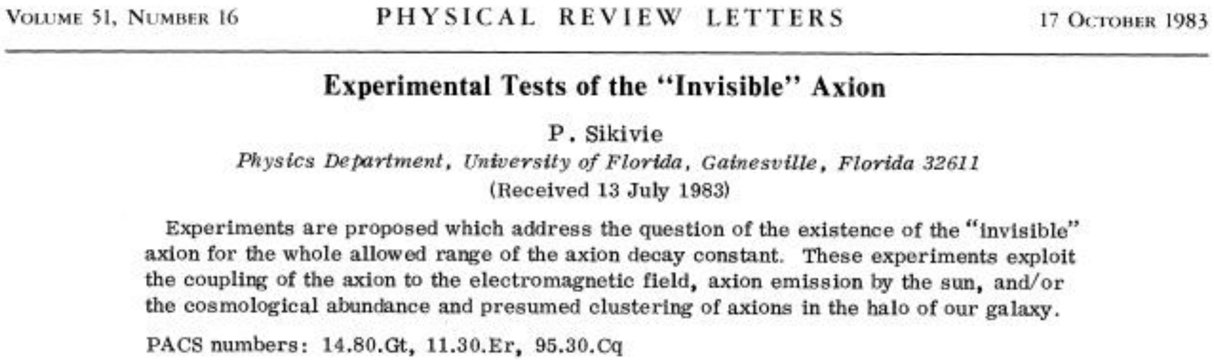
- Toward the Axion Search
- Summary

Axion detection setup

Introduction


VOLUME 51, NUMBER 16 PHYSICAL REVIEW LETTERS 17 OCTOBER 1983

Experimental Tests of the "Invisible" Axion

P. Sikivie
Physics Department, University of Florida, Gainesville, Florida 32611
(Received 13 July 1983)

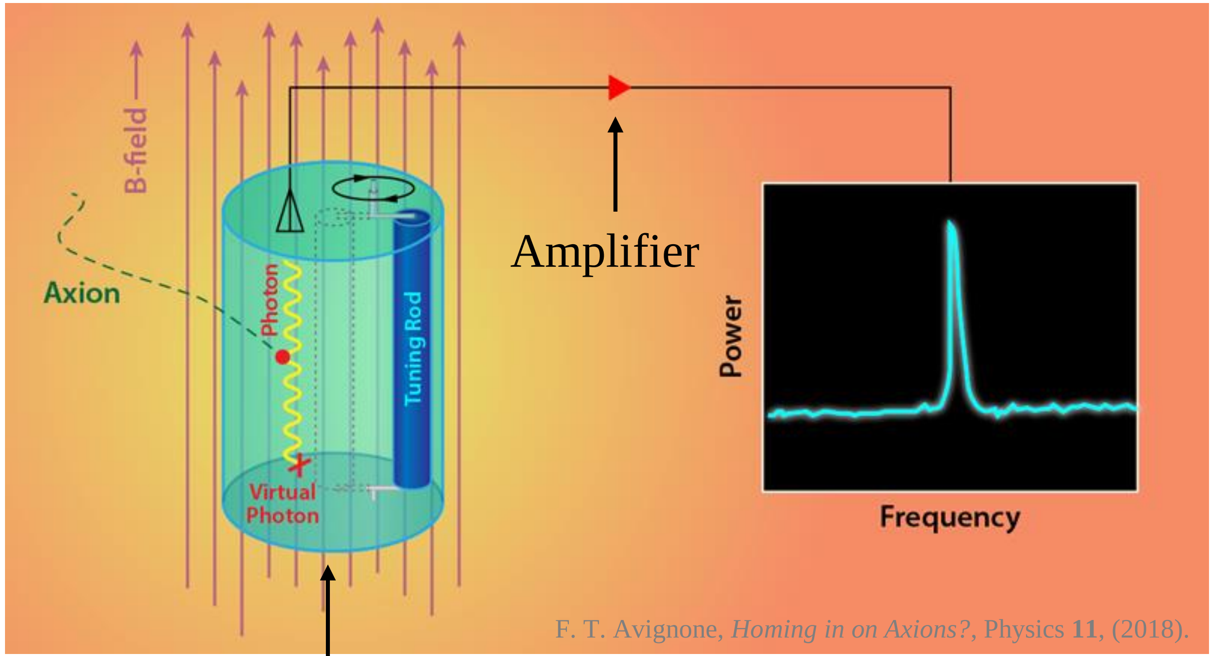
Experiments are proposed which address the question of the existence of the "invisible" axion for the whole allowed range of the axion decay constant. These experiments exploit the coupling of the axion to the electromagnetic field, axion emission by the sun, and/or the cosmological abundance and presumed clustering of axions in the halo of our galaxy.

PACS numbers: 14.80.Gt, 11.30.Er, 95.30.Cq

- Cavity Axion Haloscope

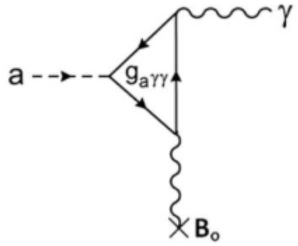
Proposed by Pierre Sikivie in 1983

→ 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

Research topics pursued since IBS-CAPP
(IBS-DMAG is the successor of IBS-CAPP)

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 🚩

$\boldsymbol{B^4, V^2, C^2, Q_l}$

$\rightarrow$ 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

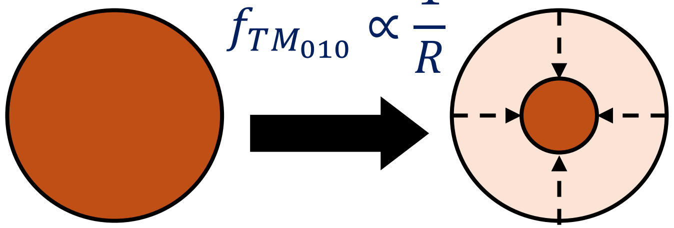
$\rightarrow$ Enhancing $\frac{df}{dt}$

※ In the previous slide

- Why are Multiple-Cell Cavities needed?

For higher frequency searches

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

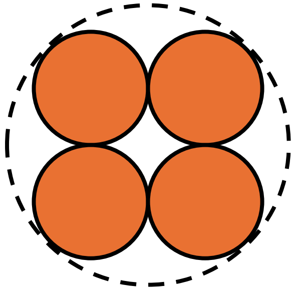
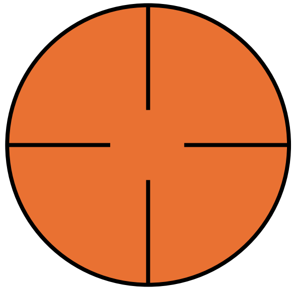
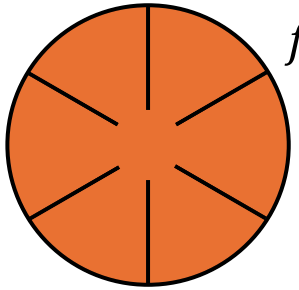


Unavoidable volume loss

(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	
 $f_{TM_{010}} = 7.30\ GHz$, $V = 0.62\ L$, $\frac{df}{dt} = 1.0$, 4 antenna	 $f_{TM_{010}} = 5.89\ GHz$, $V = 1.08\ L$, $\frac{df}{dt} = 2.72$, 1 antenna	 $f_{TM_{010}} = 7.60\ GHz$, $V = 1.02\ L$, $\frac{df}{dt} = 1.98$, 1 antenna
Quad cavity	Quad-cell cavity	Sext-cell cavity

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

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

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

※ In the previous slide

- Why are HTS cavities needed? 🤔

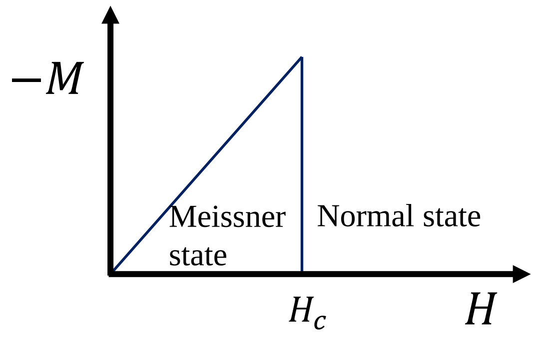
To improve the axion scanning speed,

Cavity quality factor: $Q = \omega \frac{U}{P_d} = \omega \frac{\frac{\mu_0}{2} \int |\boldsymbol{H}|^2 dV}{\frac{R_S}{2} \oint |\boldsymbol{H}|^2 dS} = \frac{G}{R_S} \propto \frac{1}{R_S}$

$\rightarrow$ Superconductor are ideal materials.

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

However, Type-I superconductors are vulnerable to B-fields.



Material	T_c [K]	H_c [T]
Aluminum	1.2	0.01
Indium	3.4	0.03
Lead	7.2	0.08
60Sn-40Pb	7.8	0.2
97Sn-3Ag	3.7	0.02

https://www.mtm-inc.com/when-superconductivity-is-unanticipated.html

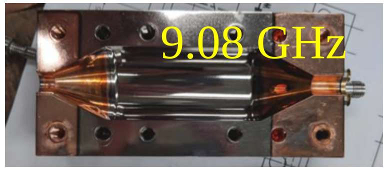
※ Type-I superconductors

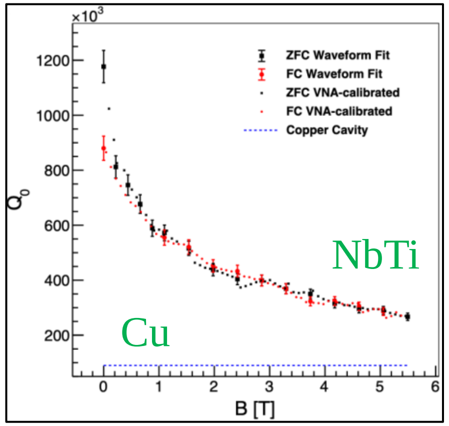
HTS Cavities

※ Type-II superconductors

- Why are HTS cavities needed? 🤔

QUAX
NbTi cavity





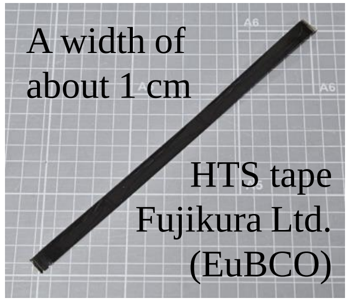
Performance comparable to Cu above 5 T

100 mK 8 GHz	R_S (B=0T) (Ohm)	R_S (B=8T,$\parallel_c$) (Ohm)	Critical Field (H_{c2})	Depinning Frequency
OFHC cu	$\sim 7 \times 10^{-3}$	$\sim 7 \times 10^{-3}$	None	None
NbTi (LTS) Gatti et al. PRD(2019)	$\sim 1 \times 10^{-6}$	$\sim 4 \times 10^{-3}$	~ 13 T	~ 45 GHz
Nb_3Sn (LTS) Alimenti et al. SUST(2020)	$\sim 1 \times 10^{-6}$	?	~ 25 T	$\mathcal{O}(10)$ GHz
Tl-1223 (HTS)	$\sim 1 \times 10^{-5}$	$\sim 1 \times 10^{-4}$ Calatroni et al. SUST(2017)	> 100 T ($\parallel$ab) Larbalestier et al. Nature(2001)	$12 - 480$ MHz Calatroni et al. SUST(2017)
ReBCO (HTS)	$\sim 1 \times 10^{-5}$ Ormeno et al. PRB(2001)	$\sim 1 \times 10^{-4}$ Romanov et al. Scientific Reports(2020)	> 100 T ($\parallel$ab) Larbalestier et al. Nature(2001)	$10 - 100$ GHz Romanov et al. Scientific Reports(2020)

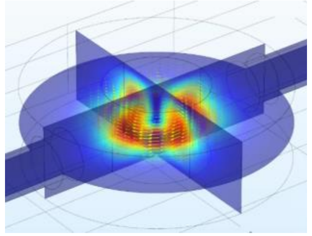
※ Depinning frequency: the frequency at which vortices move due to an external force.

Therefore, we looked at ReBCO.

HTS Cavities



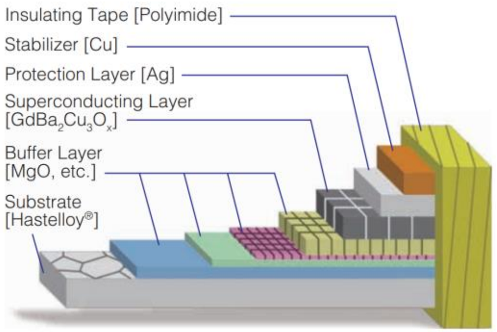
I assembled these resonators with Dr. Danho Ahn



7.95 GHz
TE_{011} mode

- Measurement of the Surface Resistance of HTS (ReBCO)

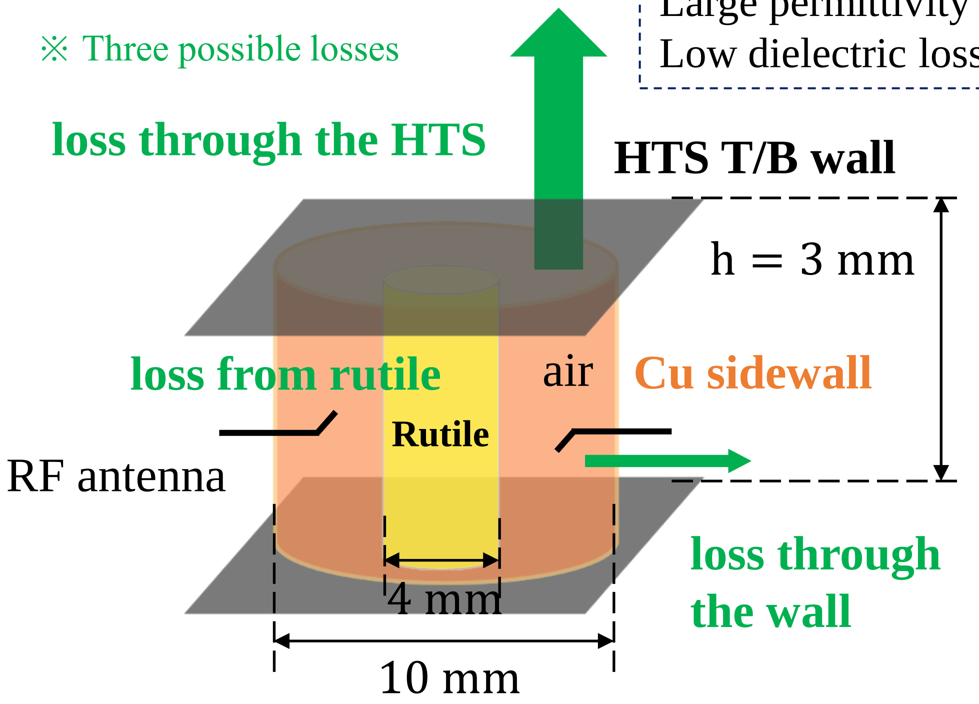
※ IBS-DMAG is the successor of IBS-CAPP



Various HTS tapes are commercially available from different global companies

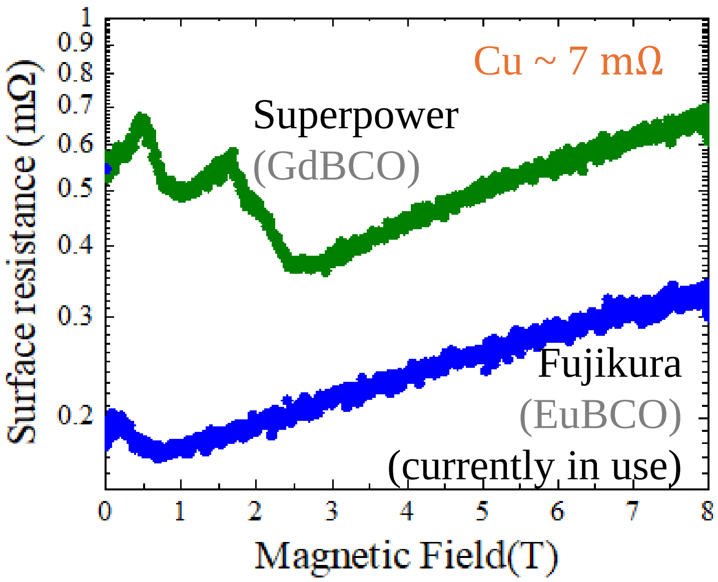
e.g., Theva, Superpower, Fujikura, and others.

※ Three possible losses



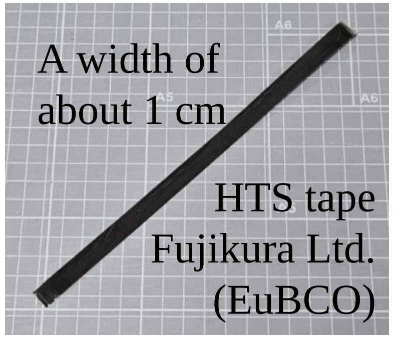
Rutile (TiO2) at 4 K
Large permittivity $\varepsilon_c \sim 250, \varepsilon_{ab} \sim 100$
Low dielectric loss $tan\delta \sim 10^{-7}$

※ Measured data



Up to 8 T, the Rs did not deteriorate much.

HTS Cavities

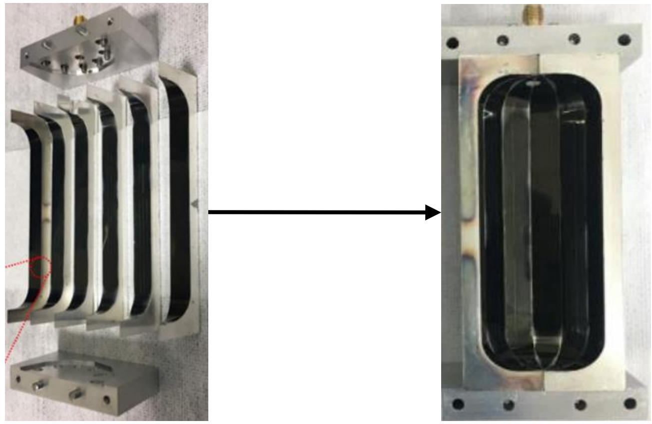


Commercially available 2D HTS tapes
→ Attach to the inside of the cavity

- HTS cavity developed by the CAPP-HTS team

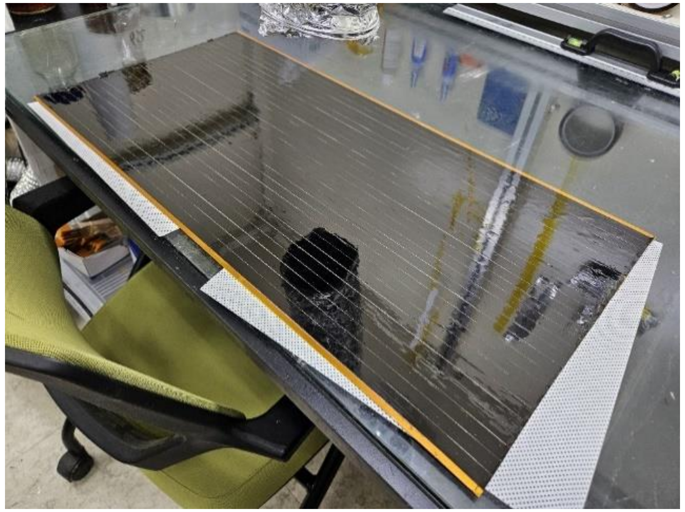
※ IBS-DMAG is the successor of IBS-CAPP

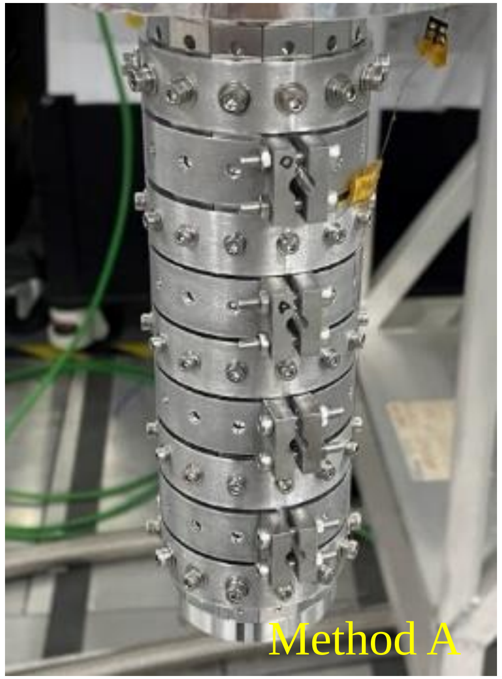
Method A – Gluing



Attach tapes to melon-shaped wedges and combine them

Method B – Soldering

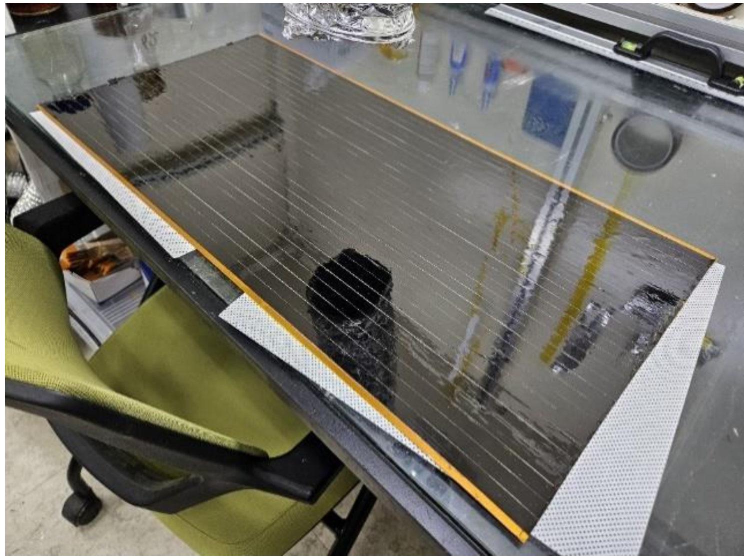




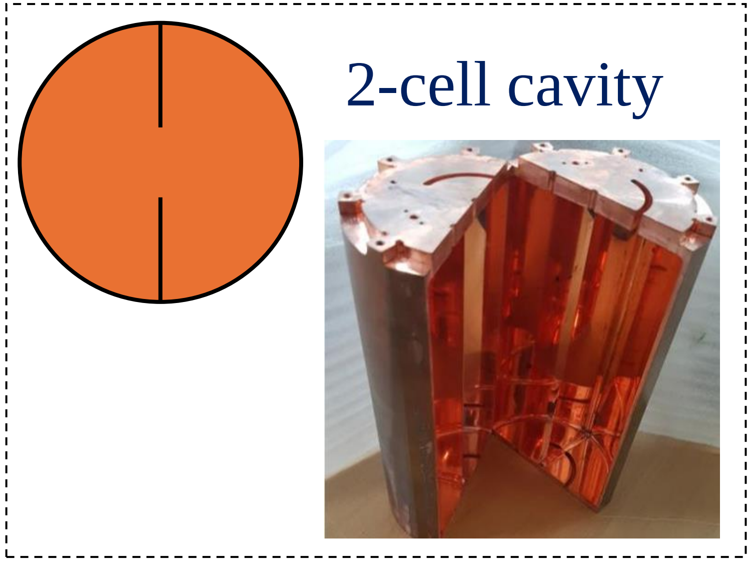
The best-performing cavity
Frequency: 5.4 GHz
Q-factor: 13 M at 8 Tesla
(→ 100 times better than Cu cavity)

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



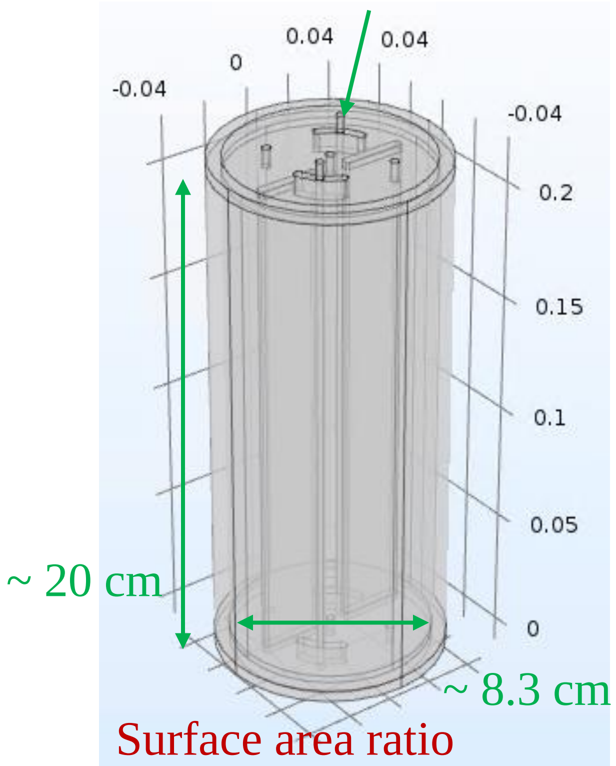
Multiple-cell design

Development of an HTS double-cell cavity

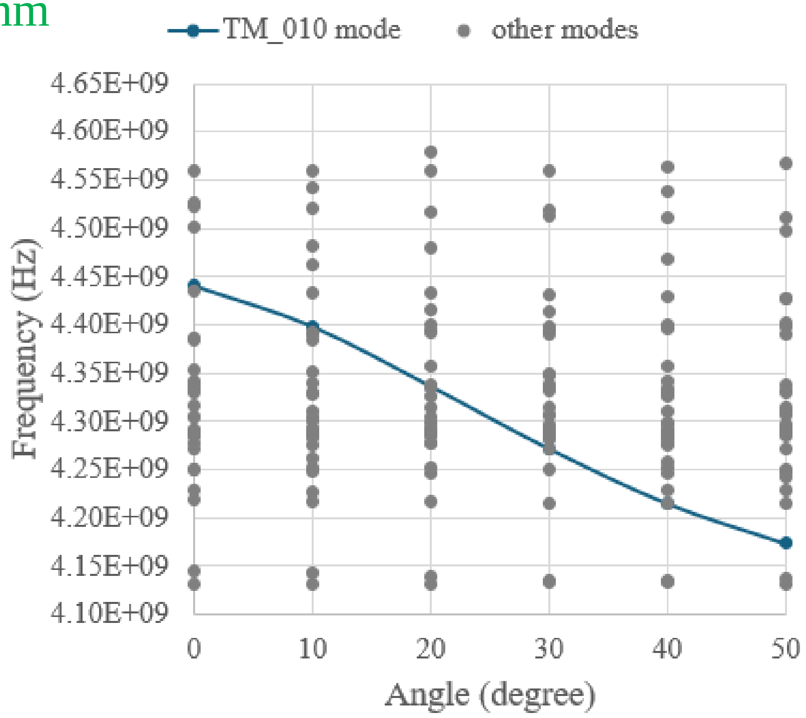
The cavity design and copper components fabrication were carried out by Dr. Sungwoo and Dr. Sungjae.

- COMSOL simulation study

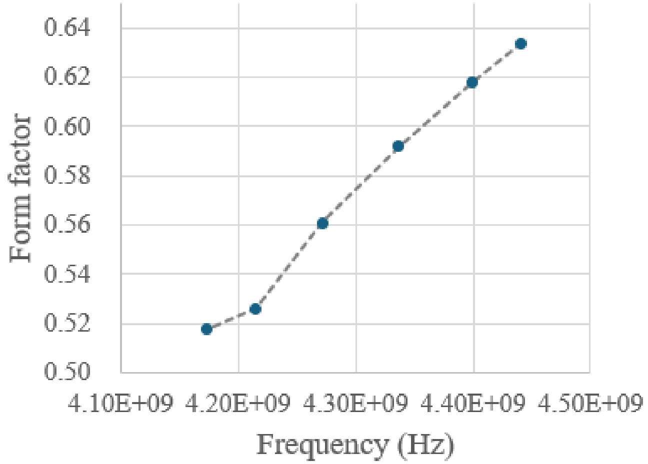
Alumina rod D3.5mm

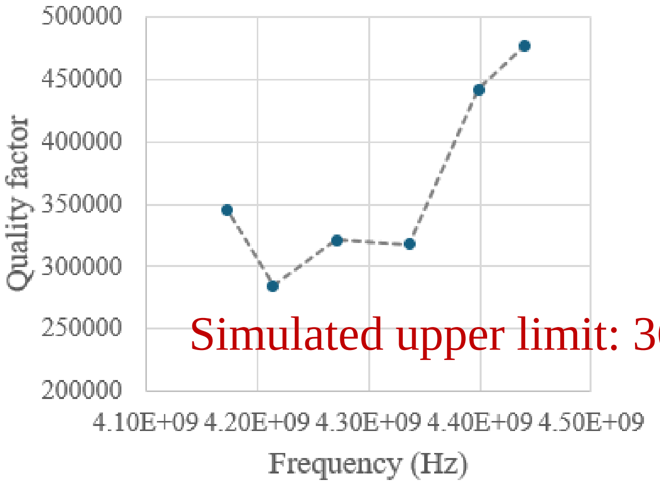


Surface area ratio
→ HTS (99%) : Cu (1%)



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



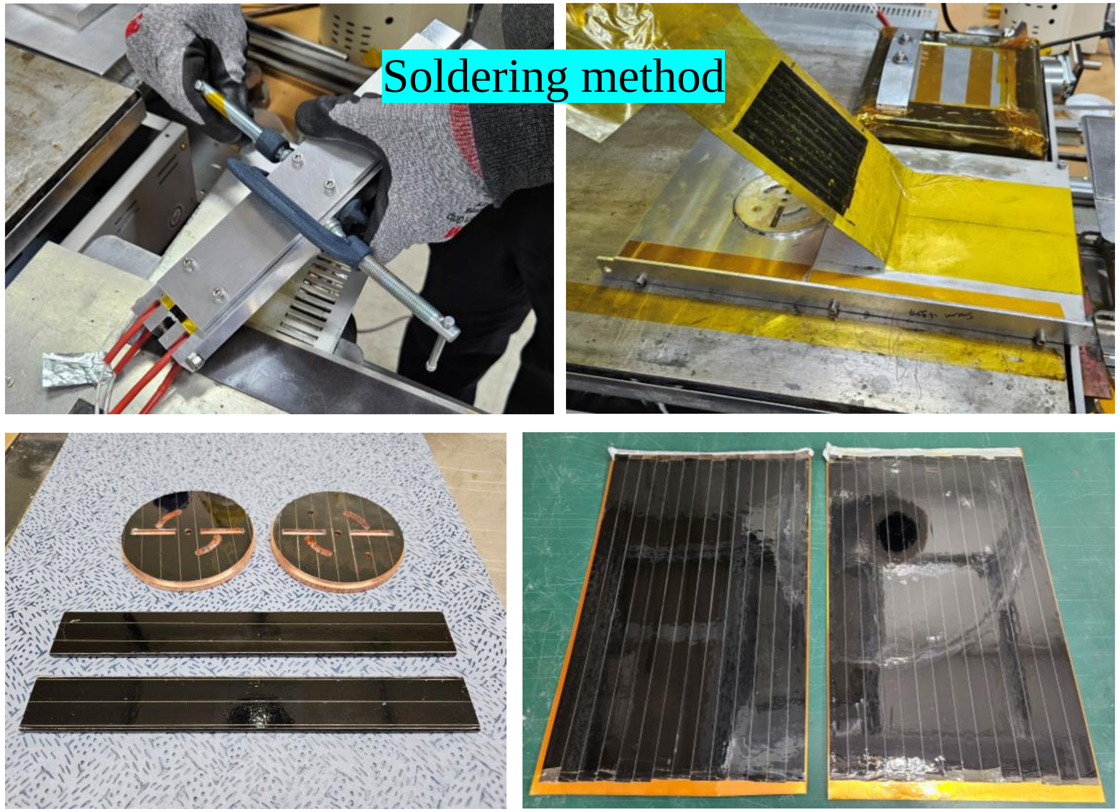


Simulated upper limit: 360k

Development of an HTS double-cell cavity

- Fabrication Process

1. 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.



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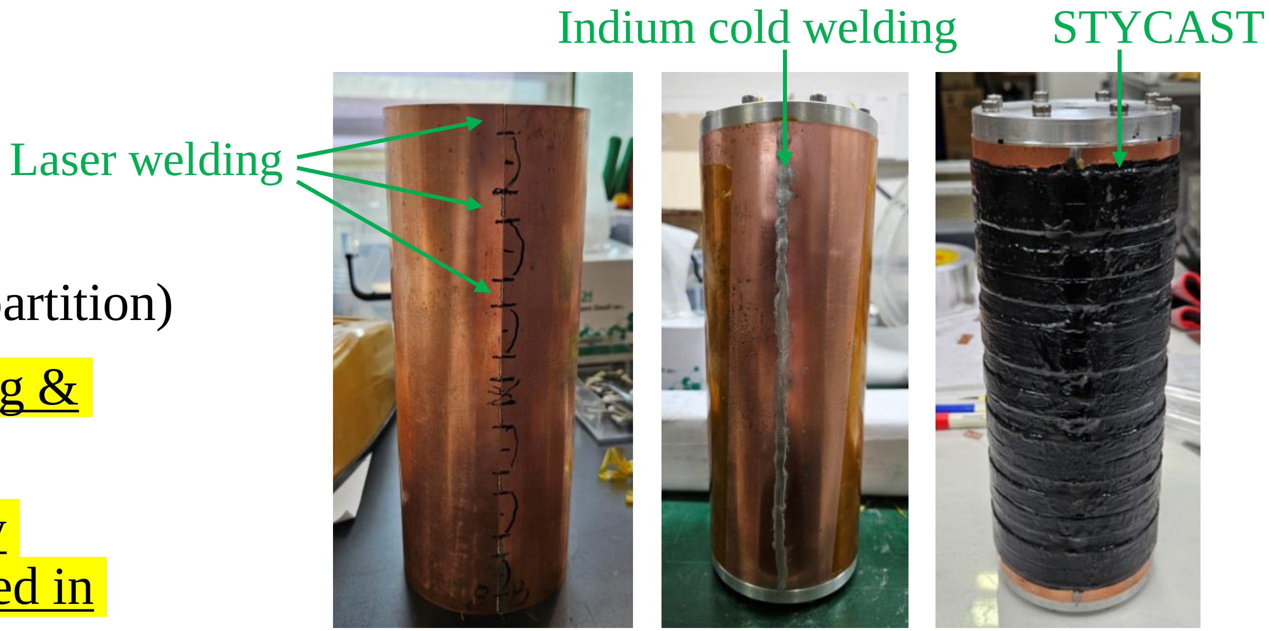

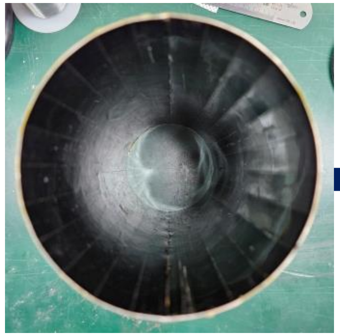

Inside view of the sidewall

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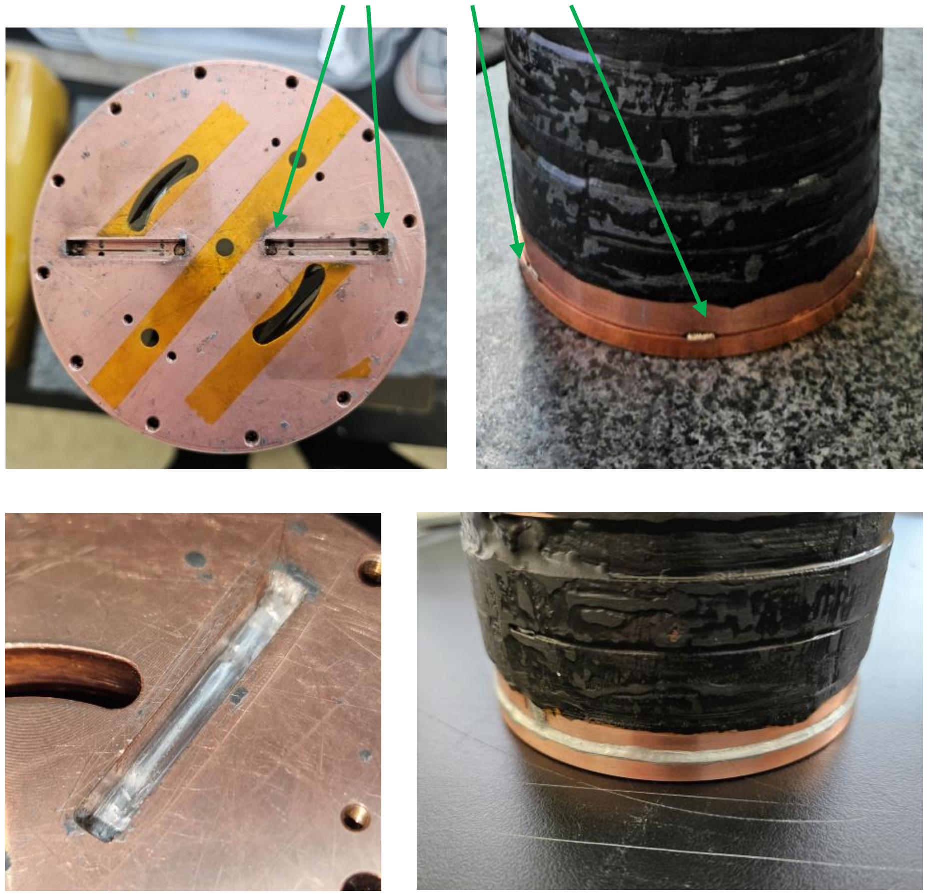
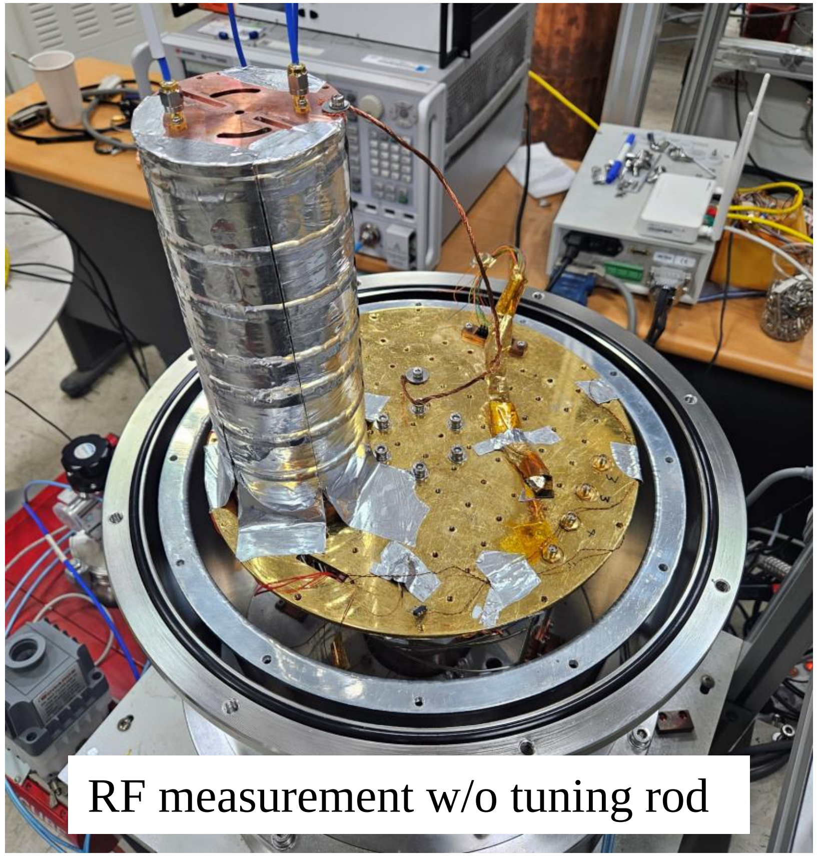


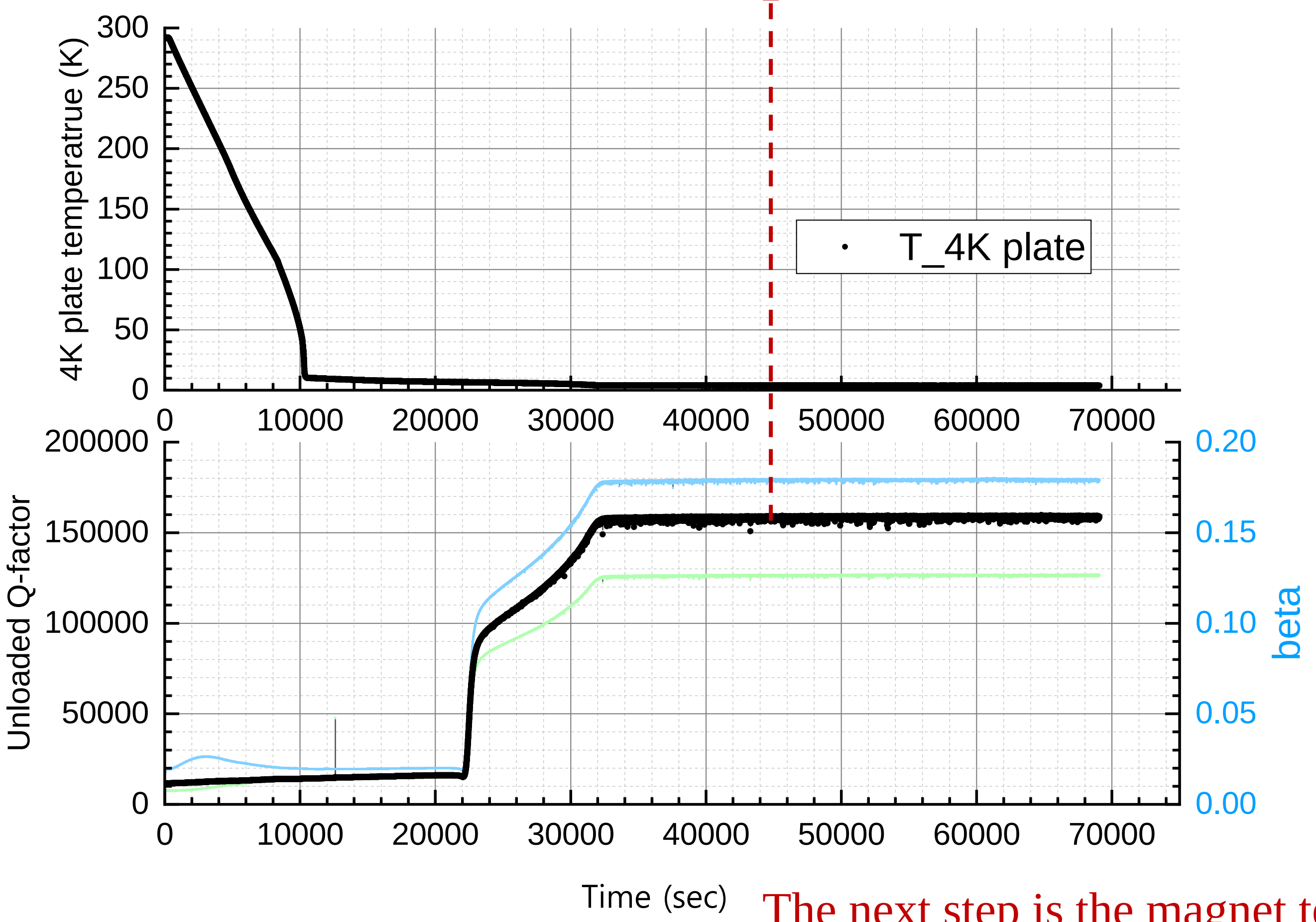
Performance Test

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

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.





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

< 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.

Thank you! 🙂