IBS - Dark Matter Axion Group (DMAG)
Daejeon, South Korea

Creation Hall, KAIST Munji Campus

※ IBS-DMAG is the successor of IBS-CAPP

DMAG-8T: Axion Search with a Widely Tunable HTS Cavity via Indium-Soldering

Jiwon Lee
(on behalf of DMAG-8T)

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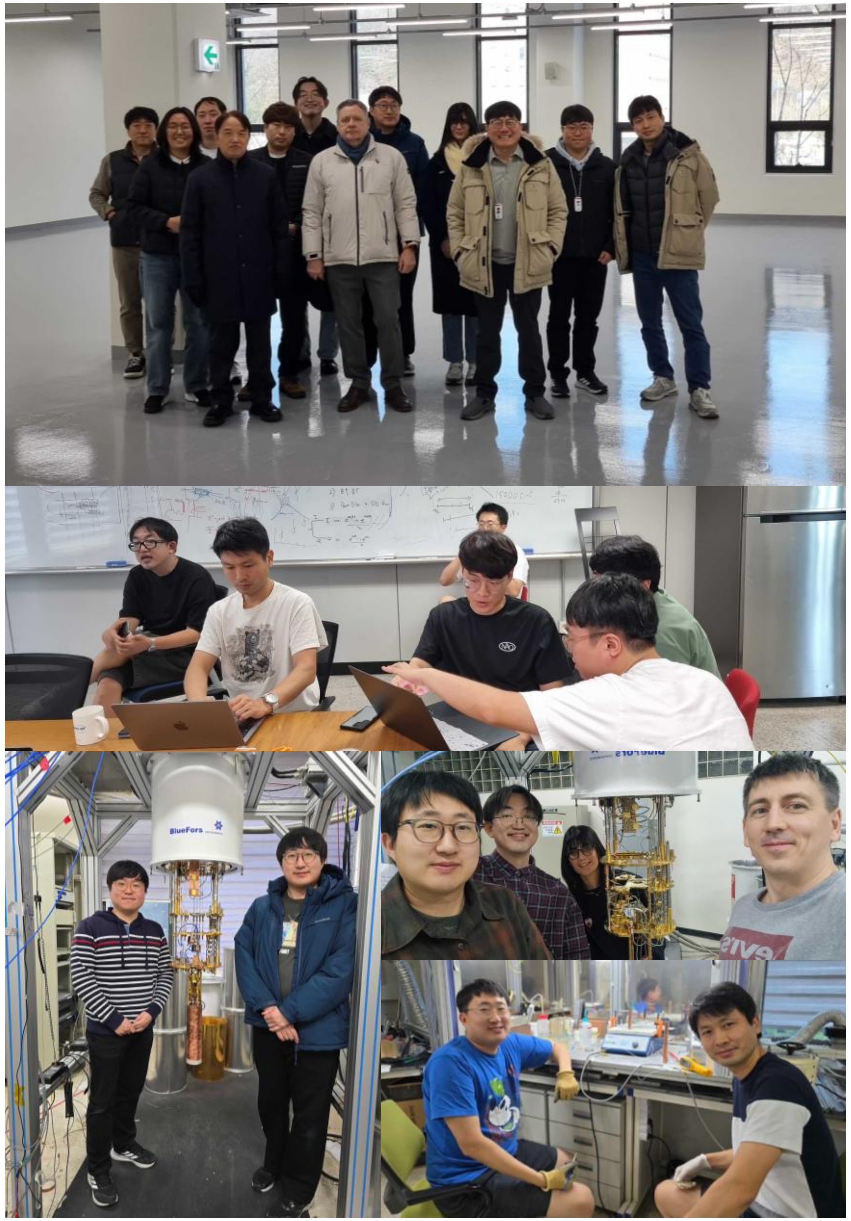
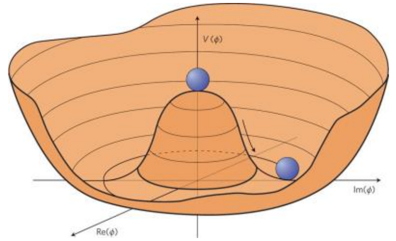
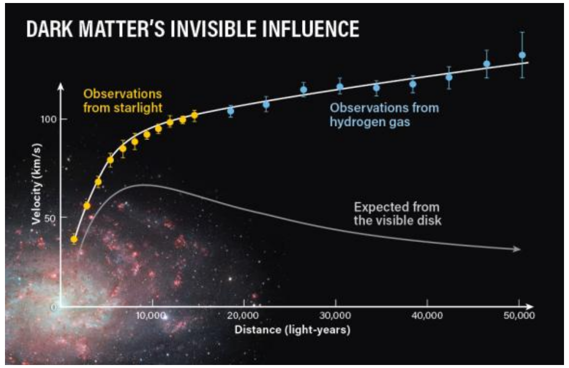


Introduction: Axion Haloscope

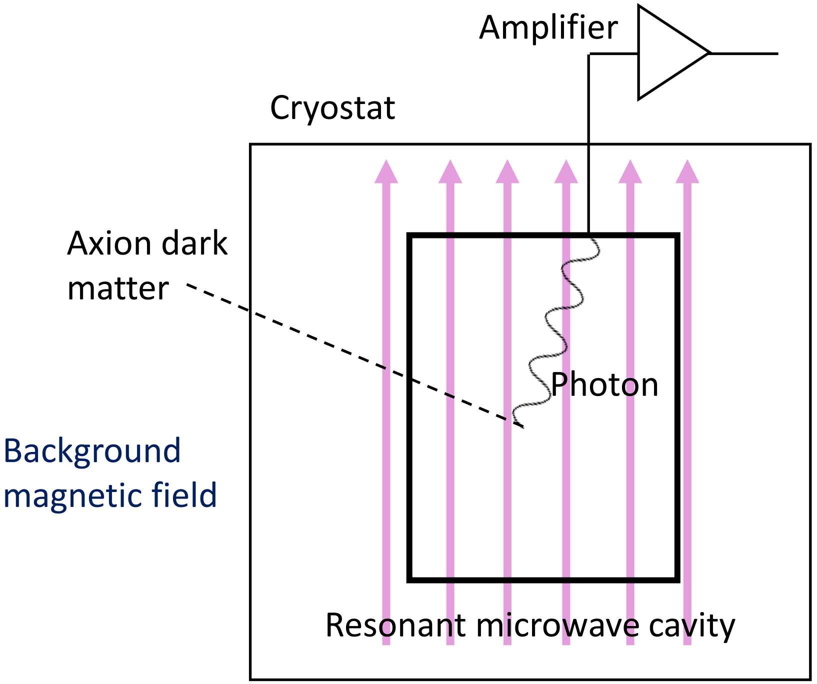


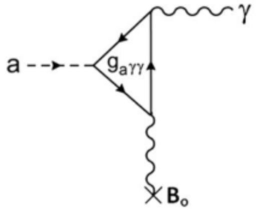


The axion is a leading dark matter candidate that dynamically resolves the Strong CP problem.

- Cavity Axion Haloscope

Invented by Pierre Sikivie in 1983.

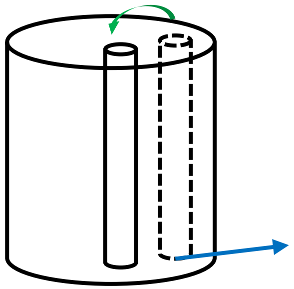




Axion-photon interaction

When $f_{axion} = f_{cavity}$

→ resonant conversions of axions to photons



Unknown mass

→ Frequency tuning is essential.

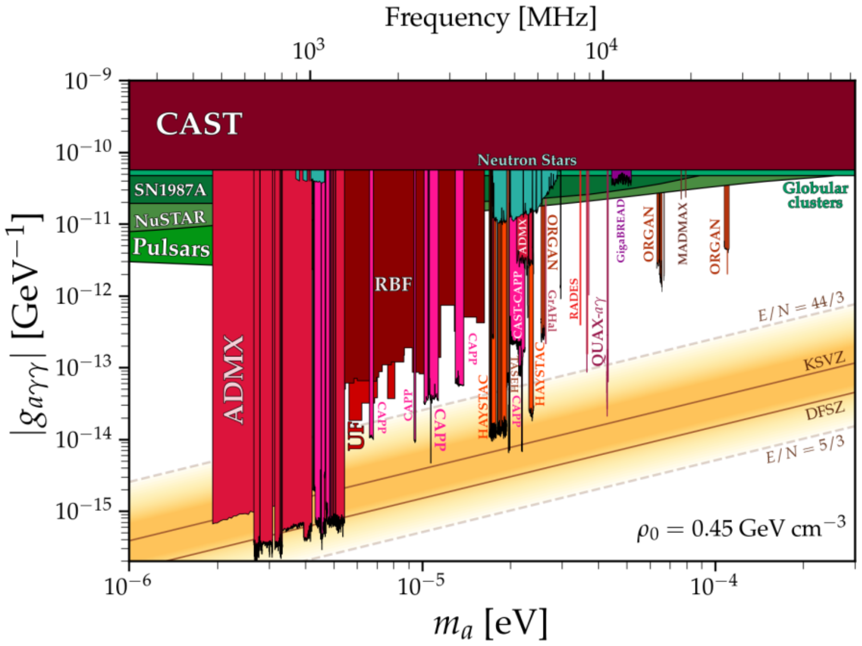
$$f_{axion} = \frac{m_{axion} c^2}{h}$$

Dielectric or metal rod

Motivation: Why HTS Cavity in High B-field?

- ➢ Exclusion limit

Extensive global efforts, including ADMX, DMAG, and HAYSTAC, are underway to probe the vast axion parameter space.



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

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

$g_{a\gamma\gamma}$: 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

To improve the scan rate,

Magnetic field B^4
Cavity Volume V^2

High cost
Predetermined by commercially available SC magnets

Cavity form factor C^2 — By utilizing the TM_{010} mode ($C \sim 0.69$)

System Noise Temperature T_{sys}^2

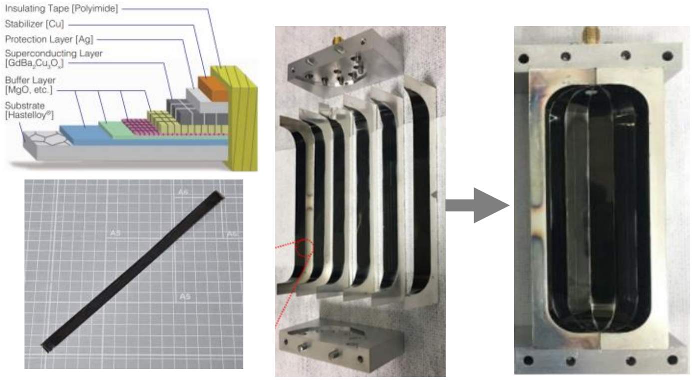
Josephson Parametric Amplifiers (JPA)
Near quantum-limited amplifier
$T_{sys} = T_1 + \frac{T_2}{G_1} + \cdots$ (Friis' formula)

Loaded cavity Q-factor Q_l

Copper: Limited by the anomalous skin effect at cryogenic temperatures.
LTS: Vulnerable to High B-field
HTS (EuBCO): Maintains high Q-factor in multi-tesla fields

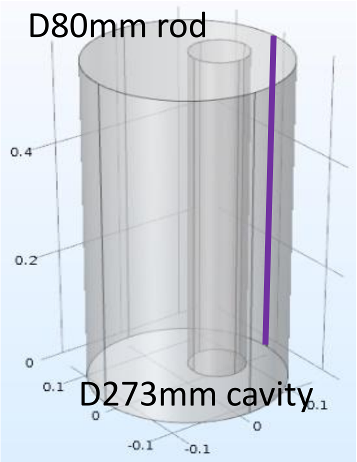
Symmetry Breaking & Indium-Soldering Technique

- Previous HTS cavities



Even achieved $Q > 1$M
Vertical gaps that are not electrically blocked

- Gap simulation method



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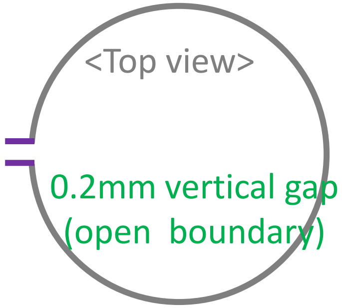
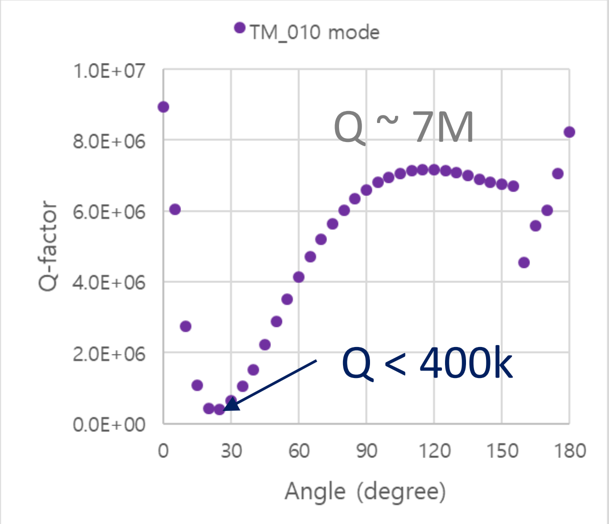


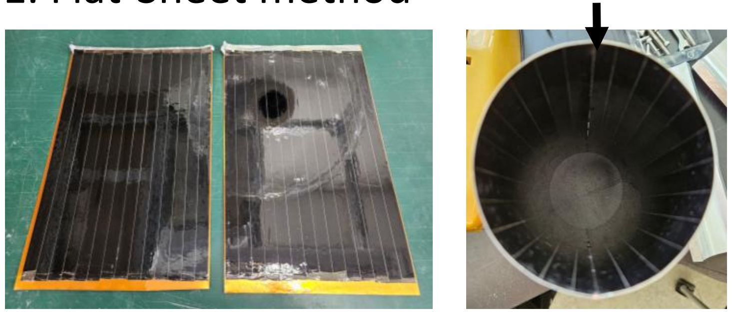


Soldering mitigates RF losses caused by transverse surface currents across HTS tape boundaries during rod rotation.

- Development of Indium Soldering Technology

1. Flat-Sheet method

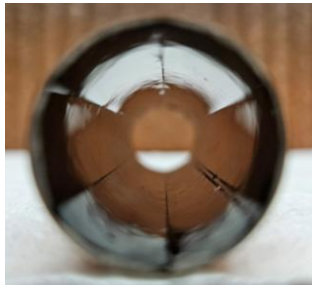
Welding seams (high-loss region)



Bending + laser welding

Limitations
Structure limit: restricted to thin OFHC sheet (< 0.3 mm) → Weak **mechanical strength**
RF performance limit: Longitudinal welding seams cause higher surface resistance (R_s)

Recently Developed
2. Pipe-soldering method



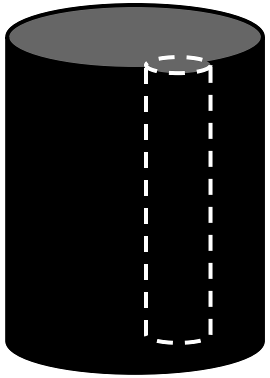
GrAHal cavity

DMAG-8T cavity

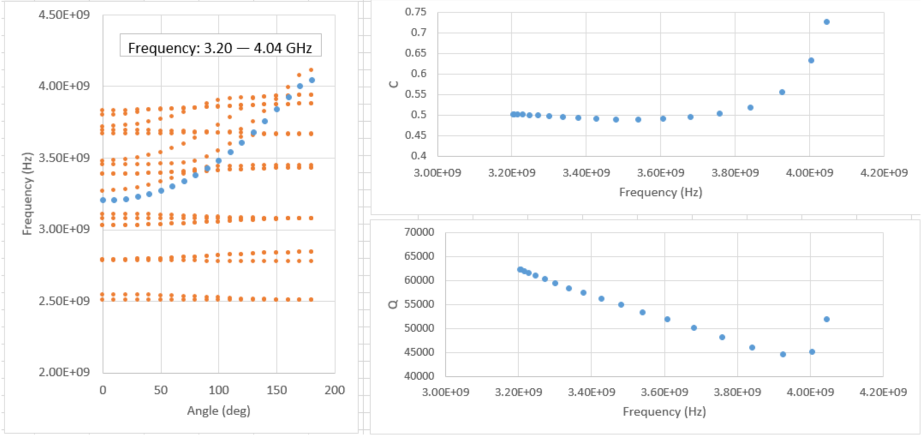
HTS cavity for DMAG-8T

Details to follow on the next slide.

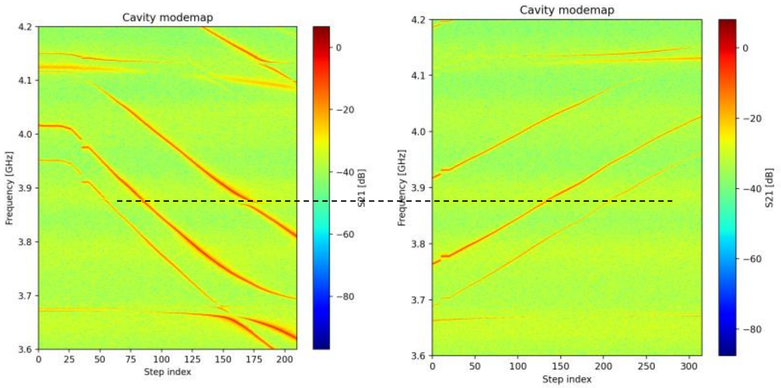
- ➢ Design optimization via COMSOL



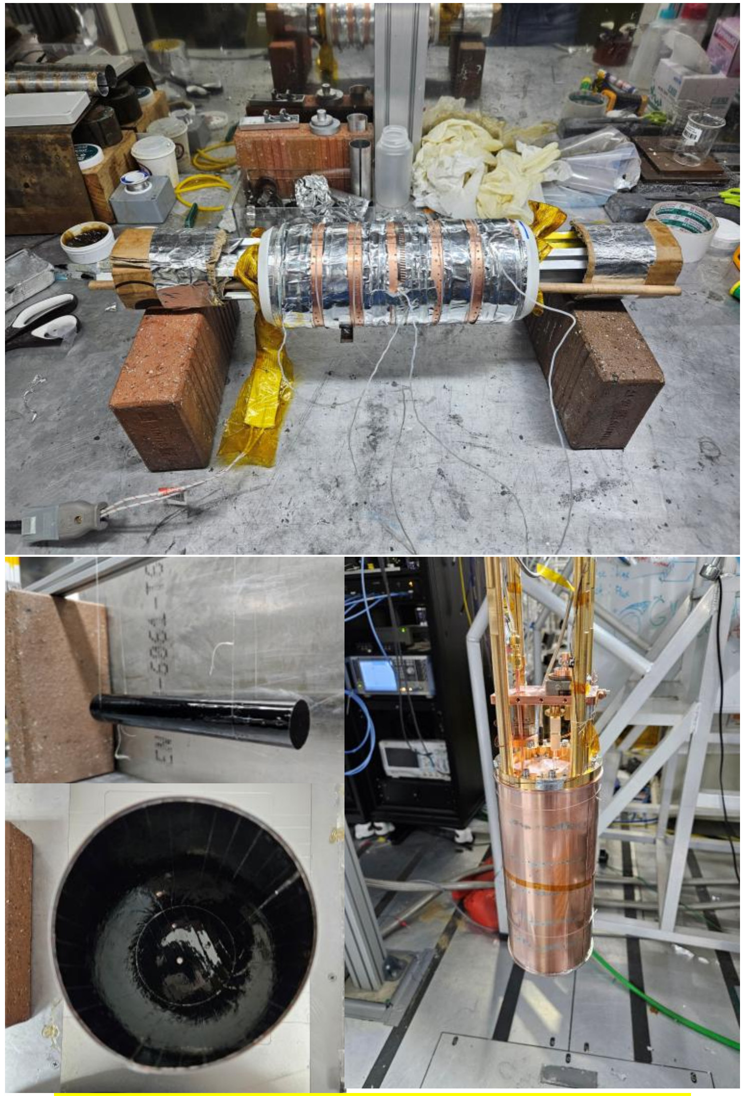
Cavity tuning range: 3.20 – 4.04 GHz



- ➢ Measure performance: Mode Map & Q-factor



Axion search region: 3.7 – 4.0 GHz
Mode crossing region (~ 3.88 GHz) excluded from analysis



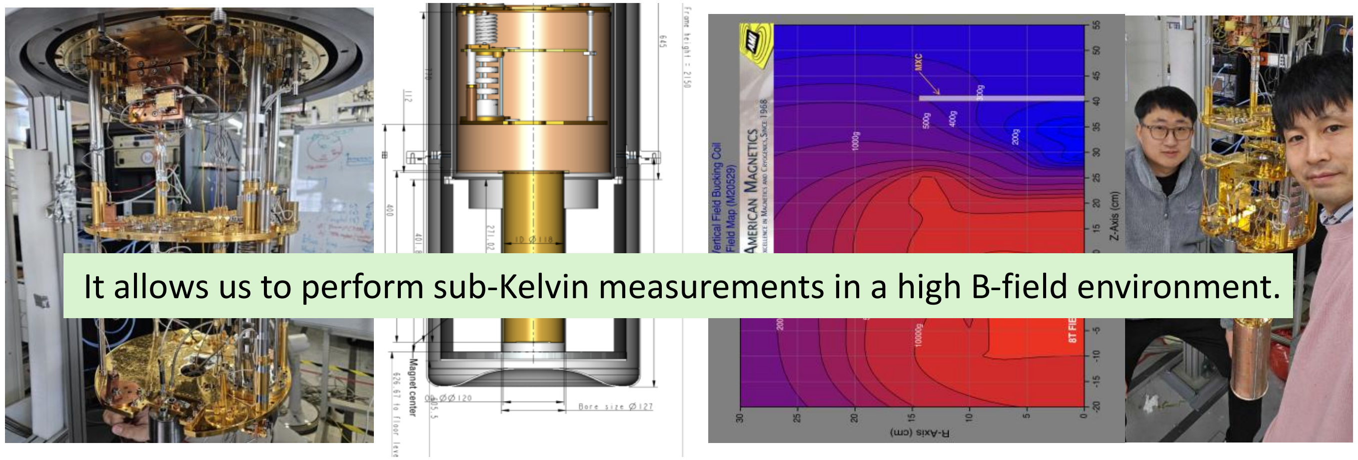
$Q_0 \approx 2.0 \times 10^5$ at 50 mK, 8 T

A four-fold enhancement compared to the Cu cavity

Experimental Setup: DMAG-8T

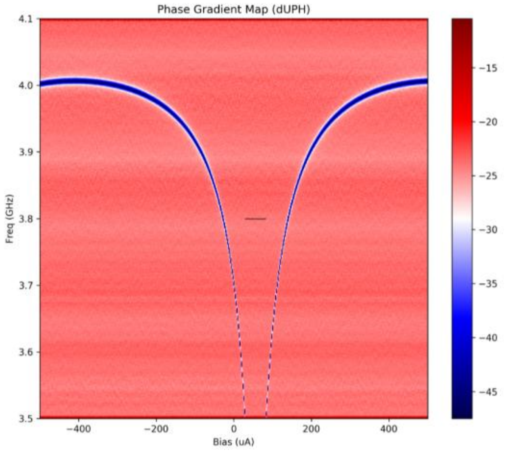
- ➢ Bluefors dilution refrigerator LD400 & AMI 8T

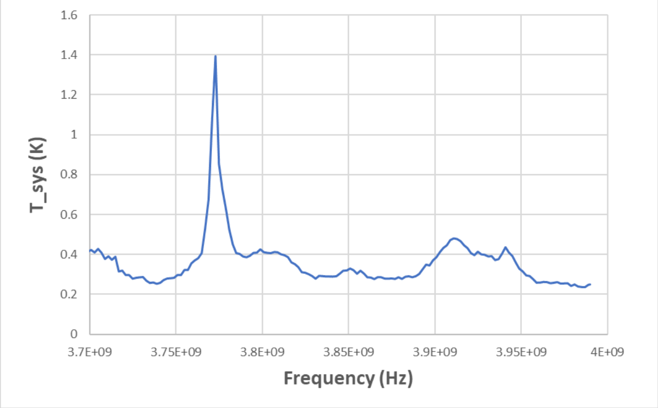
12cm bore magnet



It allows us to perform sub-Kelvin measurements in a high B-field environment.

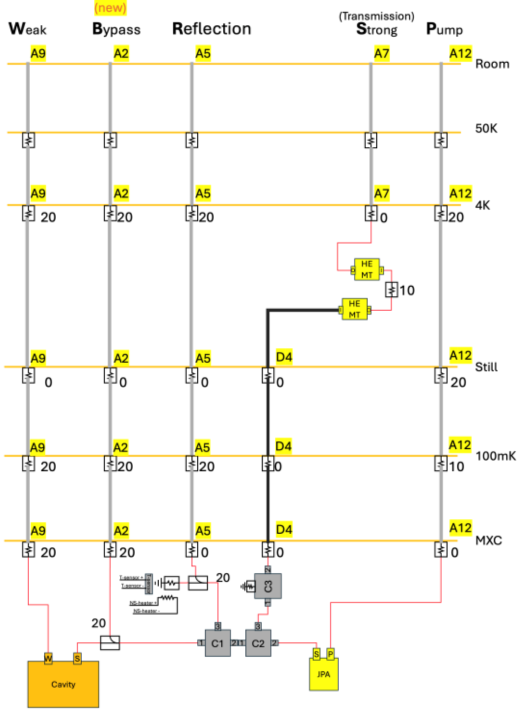
- ➢ Josephson parametric amplifier (JPA) $T_Q = \frac{hf}{2k_B}$



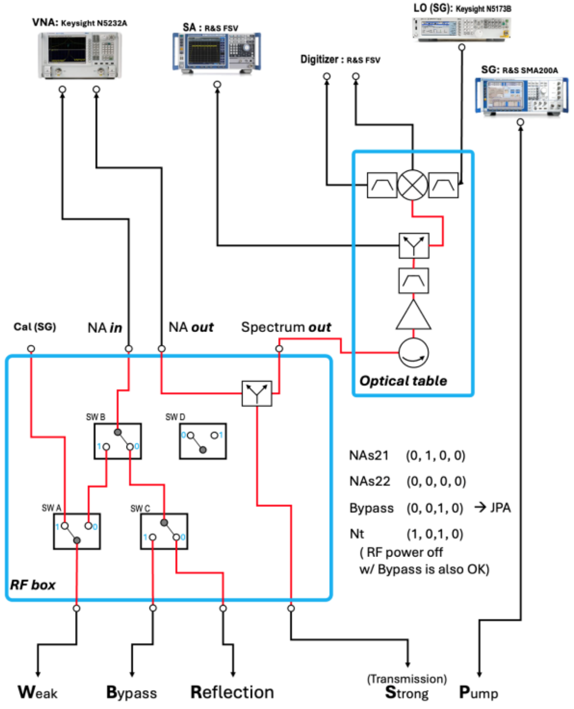


Int'l collaboration w/ Nakamura's group

- ➢ RF chain



Inside Cryostat

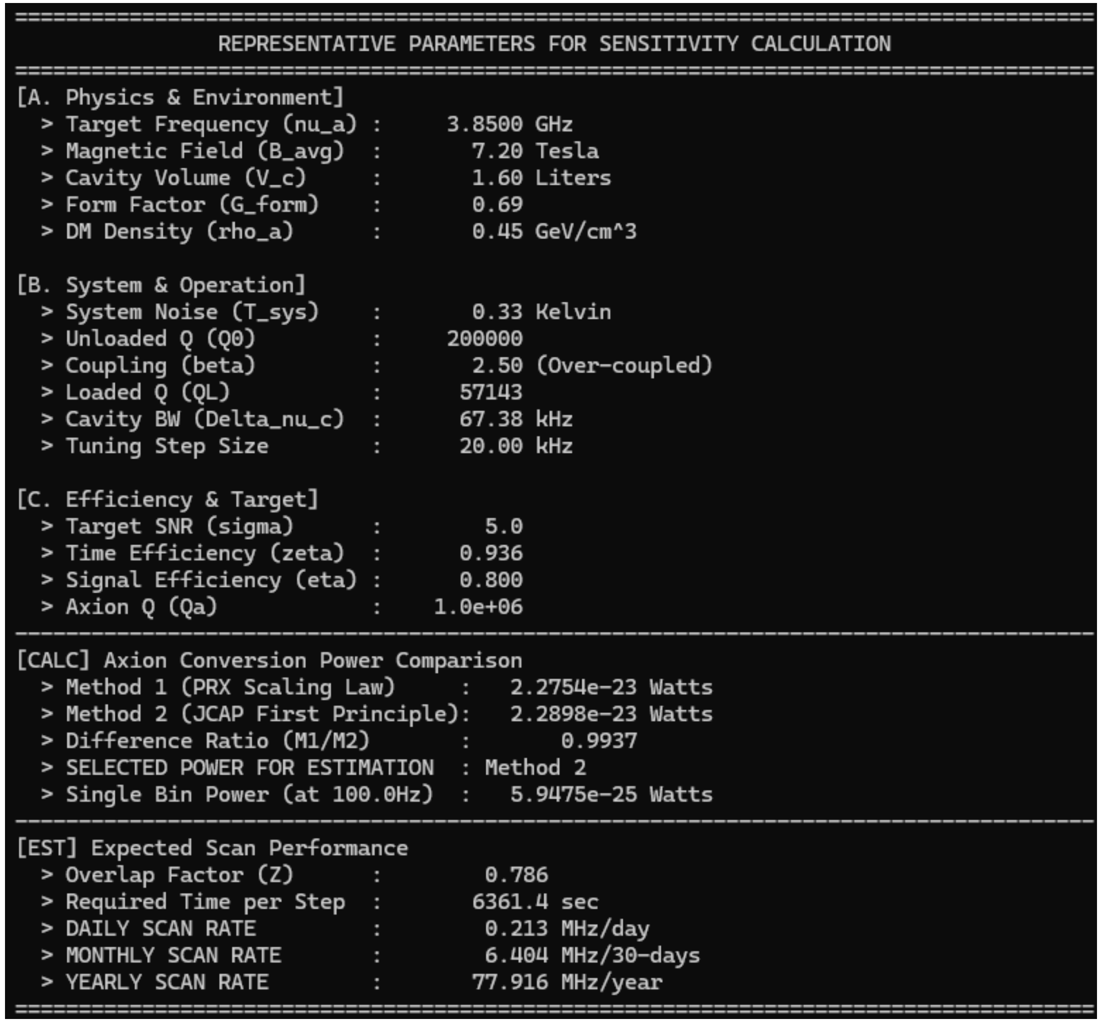


NAs21	(0, 1, 0, 0)
NAs22	(0, 0, 0, 0)
Bypass	(0, 0,1, 0) → JPA
Nt	(1, 0,1, 0) (RF power off w/ Bypass is also OK)

Outside Cryostat

Working range: 3.7 – 4.0 GHz
Gain: 15 – 18
T_{sys} = 250 – 500 mK (~1.5 qaunta)
※ half quanta: 89 – 96 mK

Estimated Scanning Sensitivity & Speed



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=======================================================================================
                    REPRESENTATIVE PARAMETERS FOR SENSITIVITY CALCULATION
=======================================================================================
[A. Physics & Environment]
  > Target Frequency (nu_a) :     3.8500 GHz
  > Magnetic Field (B_avg)  :       7.20 Tesla
  > Cavity Volume (V_c)     :       1.60 Liters
  > Form Factor (G_form)    :       0.69
  > DM Density (rho_a)      :       0.45 GeV/cm^3

[B. System & Operation]
  > System Noise (T_sys)    :       0.33 Kelvin
  > Unloaded Q (Q0)         :     200000
  > Coupling (beta)         :       2.50 (Over-coupled)
  > Loaded Q (QL)           :      57143
  > Cavity BW (Delta_nu_c)  :      67.38 kHz
  > Tuning Step Size        :      20.00 kHz

[C. Efficiency & Target]
  > Target SNR (sigma)      :        5.0
  > Time Efficiency (zeta)  :      0.936
  > Signal Efficiency (eta) :      0.800
  > Axion Q (Qa)            :    1.0e+06
---------------------------------------------------------------------------------------
[CALC] Axion Conversion Power Comparison
  > Method 1 (PRX Scaling Law)       :   2.2754e-23 Watts
  > Method 2 (JCAP First Principle):   2.2898e-23 Watts
  > Difference Ratio (M1/M2)         :       0.9937
  > SELECTED POWER FOR ESTIMATION    : Method 2
  > Single Bin Power (at 100.0Hz)    :   5.9475e-25 Watts
---------------------------------------------------------------------------------------
[EST] Expected Scan Performance
  > Overlap Factor (Z)      :        0.786
  > Required Time per Step  :       6361.4 sec
  > DAILY SCAN RATE         :        0.213 MHz/day
  > MONTHLY SCAN RATE       :        6.404 MHz/30-days
  > YEARLY SCAN RATE        :       77.916 MHz/year
=======================================================================================
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1. Axion Conversion Power Calculation

Method 1: PRX Scaling Law

S. Ahn et al., Phys. Rev. X 14, 031023 (2024).

$$P_{a\gamma\gamma} = 8.7 \times 10^{-23}\,\mathrm{W} \left(\frac{g_\gamma}{0.36}\right)^2 \left(\frac{\rho_a}{0.45\ \mathrm{GeV/cm^3}}\right) \times \left(\frac{\nu_a}{1.1\ \mathrm{GHz}}\right) \left(\frac{\langle \mathbf{B}_e^2 \rangle}{(10.3\ \mathrm{T})^2}\right) \left(\frac{V_c}{37.1}\right) \left(\frac{G}{0.6}\right) \times \left(\frac{Q_a \cdot Q_c}{Q_a + Q_c} \frac{10^6 + 10^5}{10^6 \times 10^5}\right) \approx 2.2754 \times 10^{-23}$$

Method 2:

D. Kim, J. Jeong, S. W. Youn, Y. Kim, and Y. K. Semertzidis, JCAP 03, 066 (2020).

$$P_a = g_{a\gamma\gamma}^2 B^2 \frac{\rho_a}{m_a} V_c C \frac{Q_0 \beta}{(1+\beta)^2} \approx 2.2898 \times 10^{-23}$$

$\sim 0.63\%$ **difference**

2. Scan Rate Calculation

$$Z = \frac{1}{F} \sum_{k=-100}^{100} \frac{1}{(1 + (2k/F)^2)^2}, \quad \text{where } F = \frac{\Delta\nu_{\mathrm{cav}}}{\Delta\nu_{\mathrm{step}}}$$

$$\frac{df}{dt} = \frac{\Delta\nu_{\mathrm{step}} \cdot Z}{t_{\mathrm{step}}}$$

Z: overlap factor
ζ: time efficiency
η: signal efficiency

$$t_{\mathrm{step}} = \frac{1}{\zeta} \cdot \left[\left(\frac{\mathrm{SNR}_{\mathrm{target}} \cdot k_B T_{\mathrm{sys}}}{P_a} \right)^2 \cdot \frac{\Delta\nu_a}{\eta^2} \right]$$

$$\frac{df}{dt} \propto g_{a\gamma\gamma}^4$$

1 KSVZ → **0.213 MHz/day**
1.7 KSVZ → **1.78 MHz/day**
(excludes rod stuck events).

DAQ Workflow & Status

To address **unexpected tuning rod stuck issues**, Dr. Ohjoon developed an **autonomous recovery** algorithm and code, which has been continuously optimized for stable operation.

➢ Unified & Autonomous DAQ Workflow (Measurement loop)

Step 1. Cavity tuning

1. Automated stuck tuning rod detection
2. Magnetic field ramping and precision frequency alignment

Step 2. Cavity characterization (Per Run)

1. Parameter extraction (f_0, Q_L, β)
2. Full S-parameter traces (S21, S22) recorded

※ Temporarily detunes JPA bias during VNA sweeps

Step 3. JPA optimization (Per 5 Runs)

1. Lookup table assistance
2. Autonomous minimum T_{sys} search: re-optimizes bias and pump power to minimize T_{sys}

Step 4. Axion data acquisition

1. Digitizer acquisition: 780s
2. Parallel processing: Asynchronous background processing and storage to eliminate dead time

Step 5. Real-time monitoring & logging

1. MySQL & Grafana
2. Independent Multi-Stage Safety: Monitoring thermal stability ($T < 51.4$ mK) and hardware limits.

EXP # 3

Run # 65

Cavity resonant freq (Hz) 3715559000

Magnetic field (T) DAQ B-field LIVE B-field 8.00

Pump Power (dBm) -13.2

Gain (dB) 12.9

Pump Freq (Hz) 7431279000

Nsys 0.228

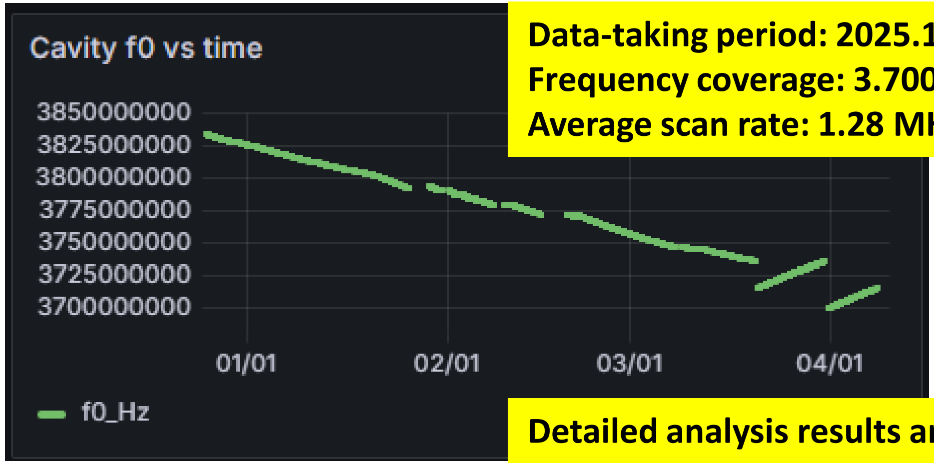
JPA Bias (uA) -342

Tsys 0.436

Memo

Water Input Temperature? 🤔

Oil Temperature? 🤔

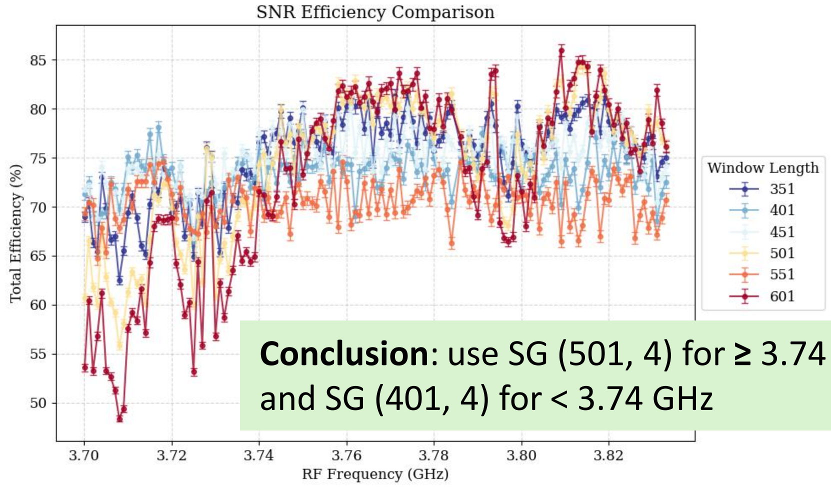


Data-taking period: 2025.12.25 17:13 – 2026.04.08 10:37
Frequency coverage: 3.700 – 3.833 GHz (Total 133 MHz)
Average scan rate: 1.28 MHz/day

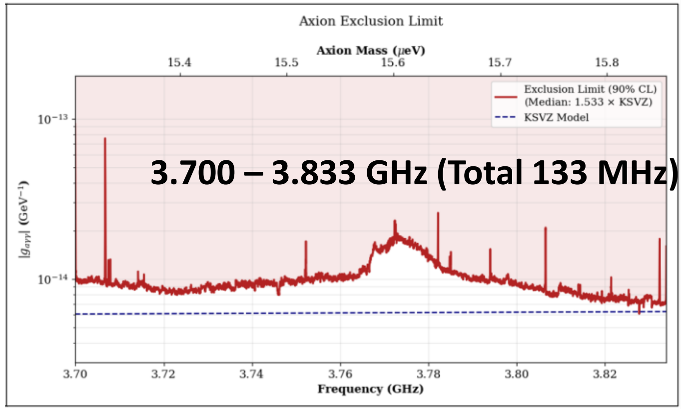
Detailed analysis results are presented in the next slide.

Data Analysis Results

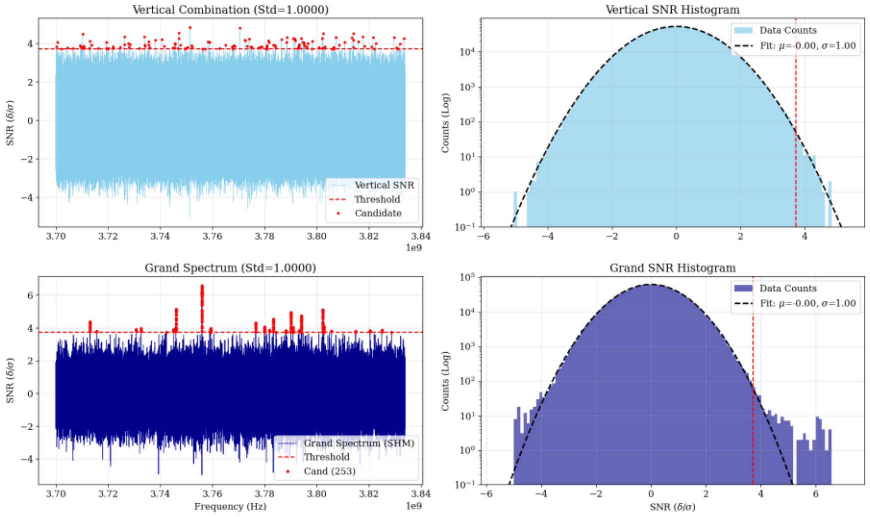
➢ Baseline removal efficiency (Monte Carlo simulation)

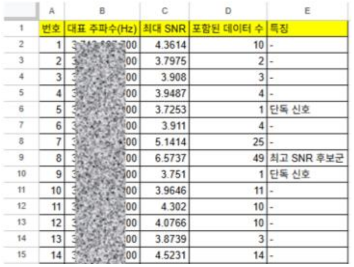


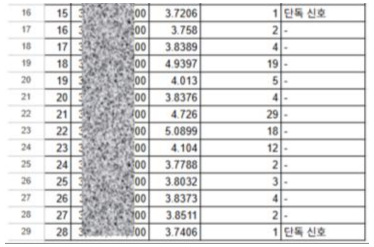
Conclusion: use SG (501, 4) for ≥ 3.74 GHz and SG (401, 4) for < 3.74 GHz



3.700 – 3.833 GHz (Total 133 MHz)







	A	B	C	D	E
1	번호	대표 주파수(Hz)	최대 SNR	포함된 데이터 수	특징
2	1	[redacted]	4.3614	10	-
3	2	[redacted]	3.7975	2	-
4	3	[redacted]	3.908	3	-
5	4	[redacted]	3.9487	4	-
6	5	[redacted]	3.7253	1	단독 신호
7	6	[redacted]	3.911	4	-
8	7	[redacted]	5.1414	25	-
9	8	[redacted]	6.5737	49	최고 SNR 후보군
10	9	[redacted]	3.751	1	단독 신호
11	10	[redacted]	3.9646	11	-
12	11	[redacted]	4.302	10	-
13	12	[redacted]	4.0766	10	-
14	13	[redacted]	3.8739	3	-
15	14	[redacted]	4.5231	14	-
16	15	[redacted]	3.7206	1	단독 신호
17	16	[redacted]	3.758	2	-
18	17	[redacted]	3.8389	4	-
19	18	[redacted]	4.9397	19	-
20	19	[redacted]	4.013	5	-
21	20	[redacted]	3.8376	4	-
22	21	[redacted]	4.726	29	-
23	22	[redacted]	5.0899	18	-
24	23	[redacted]	4.104	12	-
25	24	[redacted]	3.7788	2	-
26	25	[redacted]	3.8032	3	-
27	26	[redacted]	3.8373	4	-
28	27	[redacted]	3.8511	2	-
29	28	[redacted]	3.7406	1	단독 신호

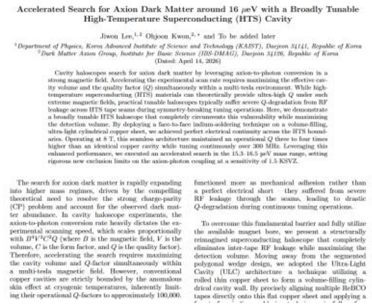
A total of **28 rescan candidates** have been identified, and the **rescan process is currently underway**.

➢ Next Plans

Rescan progress:
Rescan of 28 candidates is expected to be completed by May 10, 2026.

Remaining Sweep (3.833 – 4.000 GHz):
Total 167 MHz
Estimated completion
Scenario A (current rate of 1.50 MHz/day)
→ August 29, 2026
Scenario B (conservative, 1.28 MHz/day)
→ September 17, 2026

Publication strategy:
Manuscript actively in preparation for submission to PRL or PRD immediately following DAQ completion.



Accelerated Search for Axion Dark Matter around 16 μeV with a Broadly Tunable High-Temperature Superconducting (HTS) Cavity

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(Dated: April 14, 2026)

Cavity haloscopes search for axion dark matter by leveraging axion-to-photon conversion in a strong magnetic field. Accelerating the experimental scan rate requires maximizing the effective cavity volume and the quality factor (Q) simultaneously within a multi-tesla environment. While high-temperature superconducting (HTS) materials can theoretically provide ultra-high Q under such extreme magnetic fields, practical tunable haloscopes typically suffer severe Q-degradation from RF leakage across HTS tape seams during symmetry-breaking tuning operations. Here, we demonstrate a broadly tunable HTS haloscope that completely circumvents this vulnerability while maximizing the detection volume. By deploying a face-to-face indium-soldering technique on a volume-filling, ultra-light cylindrical copper sheet, we achieved perfect electrical continuity across the HTS boundaries. Operating at 8 T, this seamless architecture maintained an operational Q three to four times higher than an identical copper cavity while tuning continuously over 300 MHz. Leveraging this enhanced performance, we executed an accelerated search in the 15.3–16.5 μeV mass range, setting rigorous new exclusion limits on the axion-photon coupling at a sensitivity of 1.5 KSVZ.

The search for axion dark matter is rapidly expanding into higher mass regimes, driven by the compelling theoretical need to resolve the strong charge-parity (CP) problem and account for the observed dark matter abundance. In cavity haloscope experiments, the axion-to-photon conversion rate heavily dictates the experimental scanning speed, which scales proportionally with $B^4V^2C^2Q$ (where B is the magnetic field, V is the volume, C is the form factor, and Q is the quality factor). Therefore, accelerating the search requires maximizing the cavity volume and Q-factor simultaneously within a multi-tesla magnetic field. However, conventional copper cavities are strictly bounded by the anomalous skin effect at cryogenic temperatures, inherently limiting their operational Q-factors to approximately 100,000.

functioned more as mechanical adhesion rather than a perfect electrical short — they suffered from severe RF leakage through the seams, leading to drastic Q-degradation during continuous tuning operations.

To overcome this fundamental barrier and fully utilize the available magnet bore, we present a structurally reimagined superconducting haloscope that completely eliminates inter-tape RF leakage while maximizing the detection volume. Moving away from the segmented polygonal wedge design, we adopted the Ultra-Light Cavity (ULC) architecture — a technique utilizing a rolled thin copper sheet to form a volume-filling cylindrical cavity wall. By precisely aligning multiple ReBCO tapes directly onto this flat copper sheet and applying a

Summary

- Technological Breakthrough
    - DMAG-HTS team successfully fabricated a **300 MHz tunable HTS cavity** for the DMAG-8T experiment using a novel **indium-soldering technique**.
- High-Q Performance
    - Maintained **$Q_0 \approx 2.0 \times 10^5$ at 8 T / 50 mK**, representing a **four-fold improvement** over the conventional copper limit.
- Data Acquisition Progress
    - Acquired a **133 MHz dataset** (3.700 – 3.833 GHz).
    - Maintained an average scan rate of **1.28 MHz/day** despite unexpected tuning rod challenges.
- Preliminary Results
    - Identified **28 axion candidates** for rescan with a sensitivity of **1.5 × KSVZ**.
- Future Roadmap
    - **Phase 2**: Complete the remaining **3.833 – 4.000 GHz** sweep immediately following the current rescan process.
    - **Publication**: Manuscript preparation for **PRL/PRD** is actively in progress, with submission planned immediately upon DAQ completion.

Thank you