

# Axion Dark Matter Search using Multi-cell and Superconducting Microwave Cavities and Flux-driven Josephson Parametric Amplifiers

## PhD thesis project timeline

Pallavi Parashar<sup>1,2</sup>

**Advisor:** Prof. Hyoungsoon Choi

**Co-Advisor:** Dr. Sungwoo Youn

**Mentors:** Dr. Saebyeok Ahn, Dr. Boris Ivanov, Dr. Jinsu Kim

1 Department of Physics, Korea Advanced Institute of Science and Technology

2 Dark Matter Axion Group, Institute for Basic Science



# PhD thesis objectives

## Goals

Axion haloscope search with multicell and HTS cavities + JPA readout (scan-ready, end-to-end pipeline).

## Scan targets (2026)

- **Scan 1 - 5.4 - 5.6 GHz:** with 8-cell Cu cavity (primary, near term data-taking)
- **Scan 2 - 3.2 - 3.6 GHz:** with SC/HTS cavity (design/fabrication in parallel; exact frequency band and cavity design TBD)

## **Workshop focus**

What was achieved last year + a detailed PhD research timeline for this year.

## 2025 achievements

- **RF/DAQ pipeline:** System noise calibration (HEMT Y-factor + JPA paramaps + working-point selection through Nelder–Mead;  $T_{\text{sys}} \sim 500$  mK), IQ downconversion + digitizer primary acquisition setup, scan related data logging (.ROOT files storage + some analysis scripts), automated measurement scripts for runs.
- **Infrastructure recovery:** BF6 leaks repaired + maintenance performed.
- **Post-quench:** Started new 8-cell cavity development, targeted at 5.4 - 5.6 GHz with systematic quality checks (Q factor + field-uniformity).

### Additional

- Bolometer RnD team (bolometer characterization, heterodyne signal injection tests).
- Learned about HTS tape extraction, alignment, preparation and soldering from the HTS team (Dr. Youm and Jiwon).
- Passed PhD thesis proposal in September 2025.
- Talks at KPS Spring and KPS Fall sessions 2025. Received best presentation award for the Spring session.

## Scan 1: 5.4 - 5.6 GHz scan with 8-cell Cu cavity

**Objective** Start data-taking in April 2026 and complete a full ~200 MHz scan (+ rescans) by Oct - Nov 2026.

### Milestones

- **End of Feb 2026:** new 8-cell cavity development complete (Q, tuning range, Cd/field uniformity within acceptable range).
- **Mar 2026:** cavity installation + system reconfiguration for scan, finalize axion spectra data analysis pipeline.
- **Early Apr 2026:** Commissioning run (Tsys validation, JPA NM optimization under 8T, noise stationarity).
- **Apr - Nov 2026:** Scan operation + candidate rescans. Periodic calibration checks and data analysis.
- Other deliverables by **Nov 2026:** Internal notes keeping (personal for thesis) + scan paper draft ready

Immediate focus: New 8-cell cavity → everything else (commissioning/scan) is ready to redeploy.

## Scan 2: 3.2 - 3.6 GHz scan with SC/HTS cavity (design TBD)

**Objective** Finalize SC/HTS cavity design once Scan 1 is stable, complete fabrication, HTS wrapping and assembly by Oct - Nov 2026. Begin scan by Dec 2026.

### Milestones

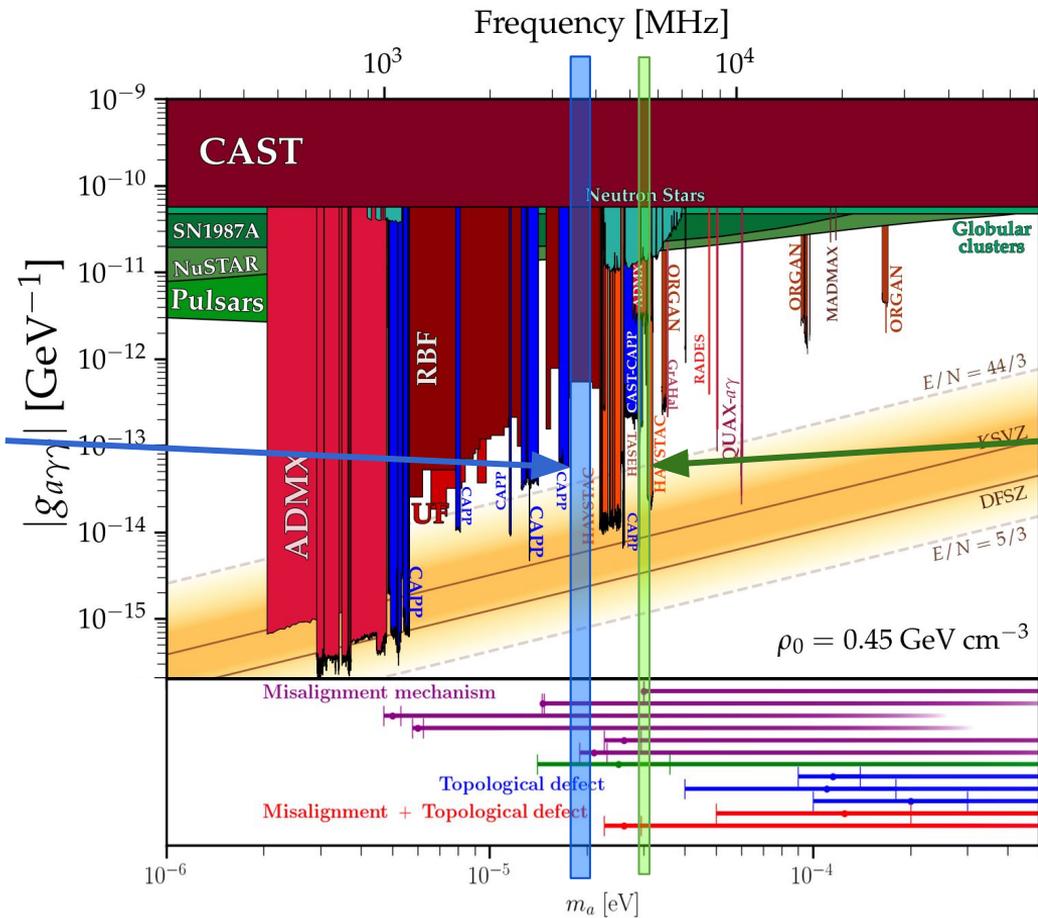
- **Apr 2026:** finalize frequency range + cavity design.
- **May - Oct 2026:** fabrication + HTS tape wrapping R&D + assembly. Q factor validation at RT and 4K, tuning and mode map check.
- **Nov - Dec 2026:** Dismantle previous scan components, install new cavity and RF components (HEMT/JPA as needed), recommission system and restart scanning.

Key dependency: Scan 2 happens only after Scan 1 finishes.

## 2026 research timeline overview

	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan (2027)	
<b>Scan 1: 8-cell Cu 5.4 - 5.6 GHz scan</b>	Cavity build + install + prep system (Analysis code dev)		Commissioning + Scan 200 MHz (+ rescans) + Data analysis										
<b>Scan 2: SC/HTS 3.2 - 3.6 GHz</b>			Cavity design finalize + fabrication		HTS wrapping + Assembly + Quality checks					Cavity install	Start scan with HTS cavity		
<b>Writing (parallel)</b>	Thesis manuscript (expected grad. ~ Aug 2027, 5 years)			8-cell scan paper (draft)									
<b>Bolometer (flexible)</b>			Bolometer R&D (Time flexible and dependent on fridge availability)										

**Milestones:** 8-cell Cu cavity ready → Installation + cooldown + calibrate sys → **Scan 1** → HTS cavity dev → Installation + cooldown + re-calibrate sys → **Scan 2**.



2. Future target:  
(3.2 - 3.6 GHz)  
DMAG-8TB run  
with JPA + HTS  
cavity

1. Current target:  
(5.6 - 5.4 GHz)  
DMAG-8TB run  
with JPA + 8-cell  
Cu cavity

## Parallel deliverables + bolometer work

### Personal Writing (continuous)

- **Thesis manuscript:** outline + chapters drafting in parallel with scanning.
- **8-cell scan paper:** paper draft prepared during scan, finalize after completing the 200 MHz band (Nov 2026).

### Bolometer (schedule flexible)

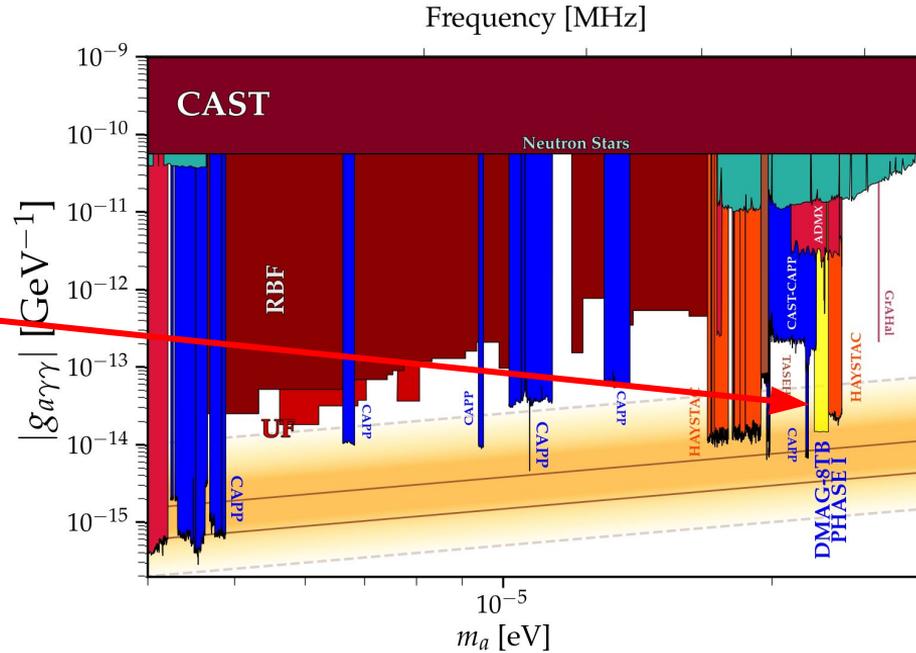
- Maintain readiness for follow-up characterization/heterodyne tests during schedule gaps (does not block main scan timeline).
- Pursue once Scan 1 operations are stable and there is cooldown access afterwards.

**THANK YOU!**

# Axion Haloscope Experiment - 8-cell Cu Cavity Target

**Projected target for  
this experiment**

**5.4 GHz - 5.6 GHz**



Parameters for this experiment :

$ g_{a\gamma\gamma} $	$\rho_{\text{dm}}$	$m_a$	B	$V_c$	C	$Q_a$	$Q_0$	$T_{\text{sys}}$	SNR
$1.5 \times g_{\text{KSVZ}}$ (KSVZ model [4])	0.45 GeV/cm <sup>3</sup>	~22 $\mu\text{eV}$	~7.2 T	3.5 L	~0.6	~10 <sup>6</sup>	~40000	~0.5 K Due to Quantum noise limited JPAs	5

Estimated Output signal power is  $\sim 32.3 \text{ yW}$ , and scanning rate is  $\sim 1.3 \text{ MHz/day}$ .

## Jan – March 2025

- Initial scan preparation (5.6–8 GHz)
- JPA+ (8-CELL) integration
- DAQ automation implemented
- Noise calibration pipeline developed
- Tuning mechanism + Beta tuning set prepared for operations

## April – July 2025

- **Incident #1:** Condensing line leak
- **Incident #2:** Sensor feedthrough leak
- Pump performance degradation

## July – October 2025

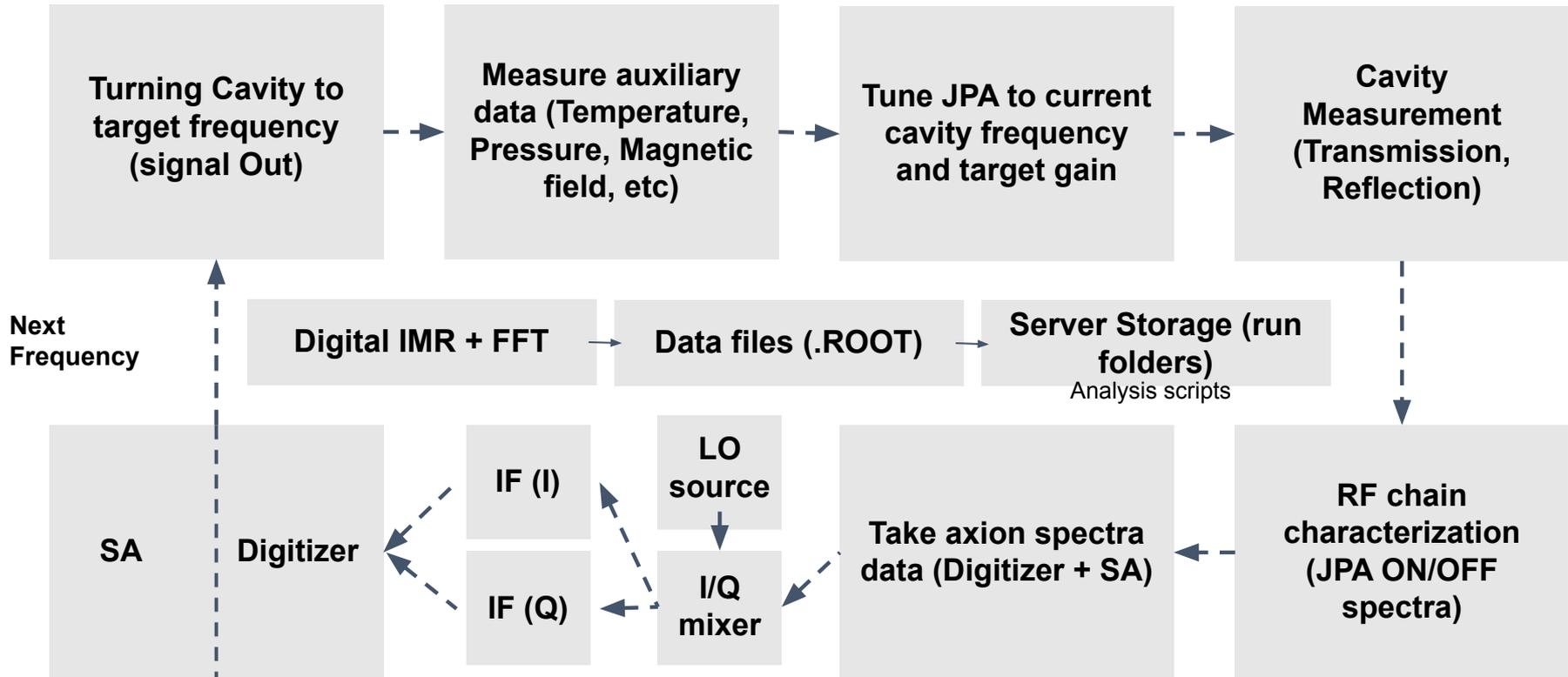
- **Incident #3:** JPA repositioning (inadequate shielding)
- **Incident #4:** Magnet quench #1: Cavity degradation
- **Incident #5:** Magnet quench #2
- Result: Original cavity unusable

## November 2025 – Jan 2026

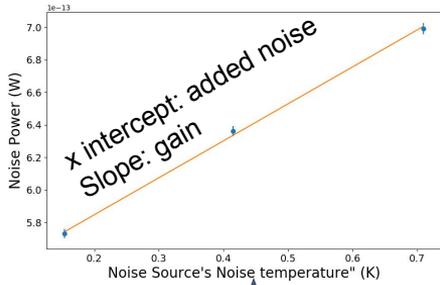
- New 8-cell cavity development (Target 5.4 – 5.6 Ghz)

Finished DAQ consolidation (software + automated workflow) and downconversion setup implementation for the BF6 system with the help of Dr. Saebyeok Ahn.

- Unified **culdaq2 / groundcontrol** to avoid multiple divergent local versions (single import path).
  - Centralized inventory of device models + addresses + protocols (IP/USB/GPIB/HiSLIP).
  - Run documentation: operation log + structured run notes / catalog.
  - Scheduling script for digitizer DAQ runs
  - Runinfo/db table for runmanager
  - Automatic storage of outputs (DAQ + digitizer ROOT + JPA cal) to server directory structure.
  - ThinkRF/SA for validation (“aerial”/parallel data taking).
  - Pre-scan checklist suite: HEMT noise, JPA paramap/LUT, system noise temperature, noise sweeps.
- 4–8 GHz IQ demod/mixer → two digitizer channels (I/Q) → digital image rejection (IMR).
  - Verified I/Q port mapping experimentally (avoid sideband rejection mistakes).
  - IF choice ~ 3 MHz (drives LPF requirement; DC–5 MHz LPF).
  - $f_s$ : ~12.5 MHz used in test (tens of MHz regime)
  - IMR: >30 dB (sufficient for commissioning)
  - Calibration integrity - SA vs digitizer gain agreement achieved.



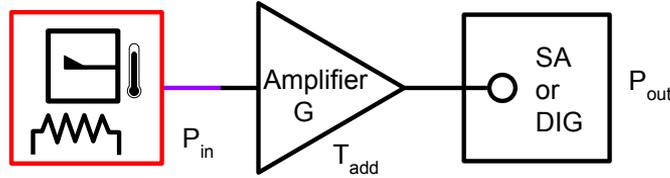
# RF Chain - JPA OFF Noise measurements - Y factor method



Noise Source ( $T_{phy}$ )  
100 mK, 400 mK, 700 mK

$$T_n(f, T_{phy}) = \frac{hf}{k_B} \left[ \frac{1}{e^{\frac{hf}{k_B T}} - 1} + \frac{1}{2} \right]$$

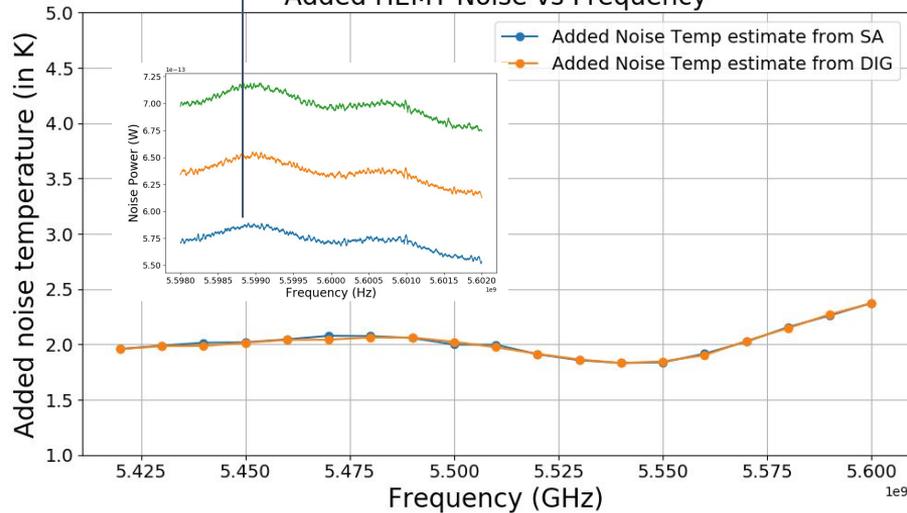
Effective Noise temperature: Johnson Nyquist Noise + Quantum noise



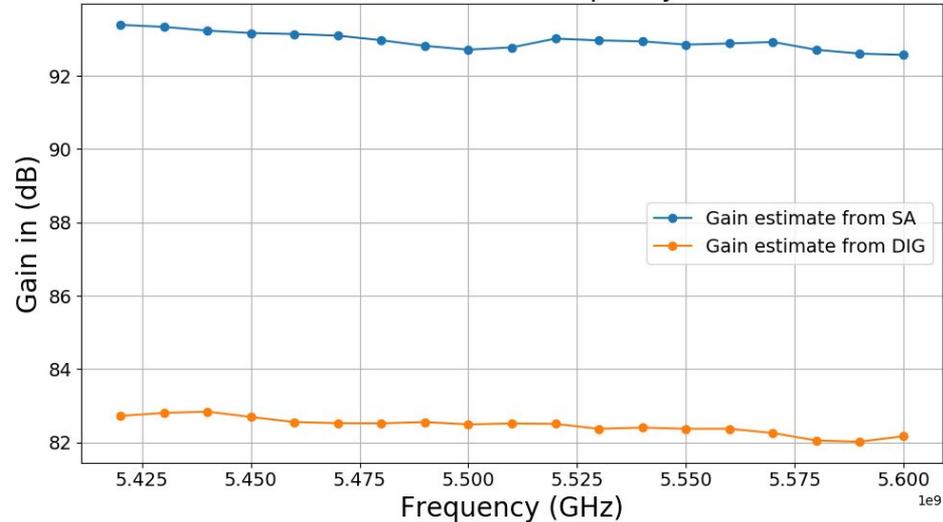
$$P_{in} = k_B T_n \Delta f$$

$$P_{out} = G k_B (T_n + T_{add}) \Delta f$$

Added HEMT Noise vs Frequency

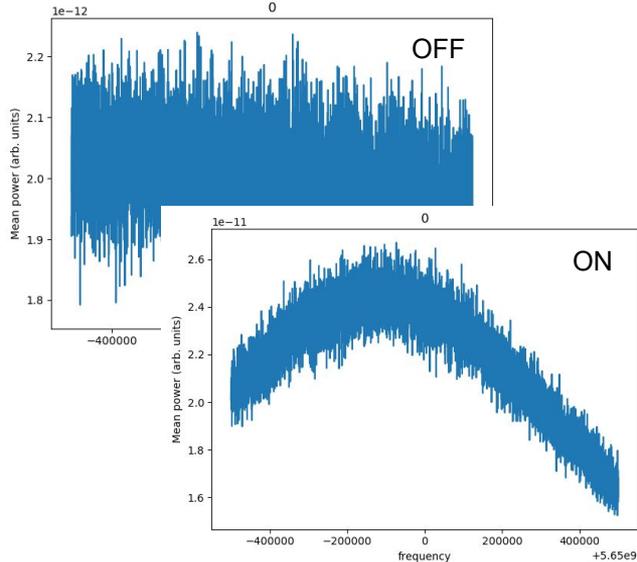


HEMT Gain vs Frequency



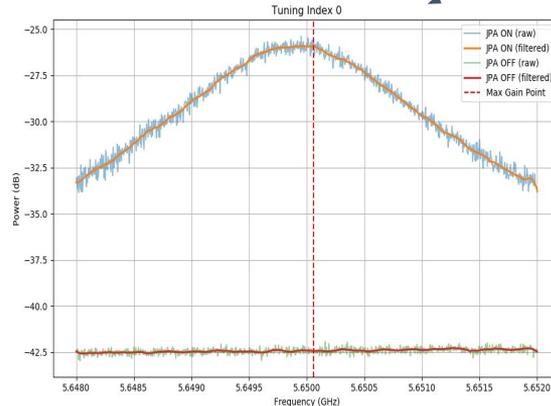
## STEP 1

1. Capture JPA OFF Spectra with DIG/SA.
2. Measure VNA baseline



## STEP 2

1. Turn ON JPA
2. Capture JPA ON Spectra with DIG/SA
3. Measure JPA Gain with VNA

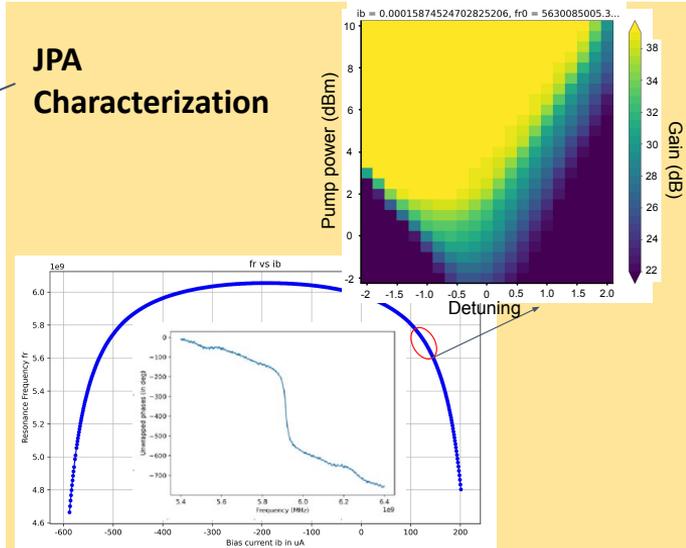


## STEP 3

$$R \equiv \frac{S_{ON}}{S_{OFF}} = G_{JPA} \frac{T_{sys}}{S_n(f, T_{MXC}) + T_{OFF}}$$

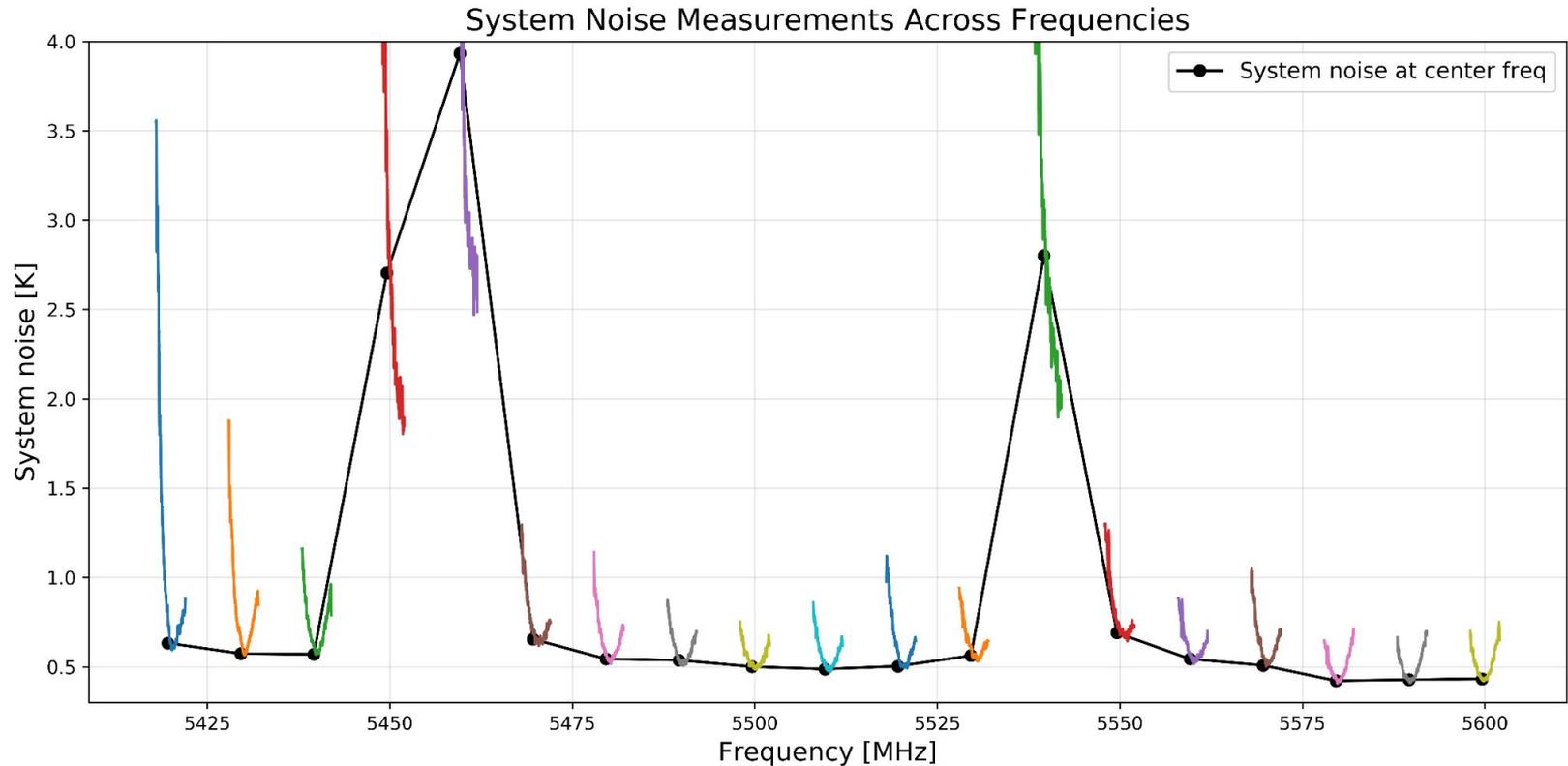
$$T_{sys} = G_{JPA}^{-1} R (S_n(f, T_{MXC}) + T_{OFF})$$

## JPA Characterization



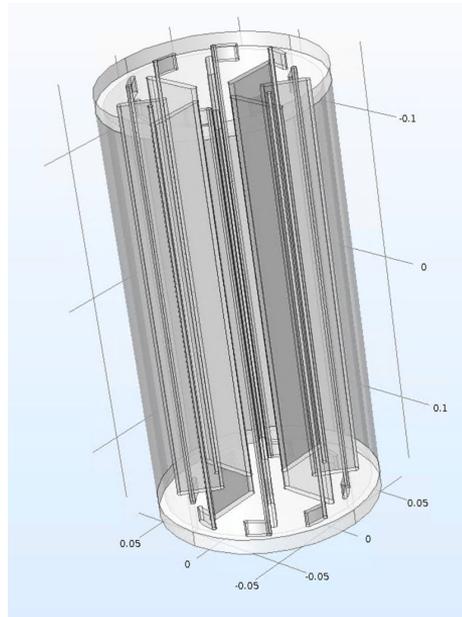
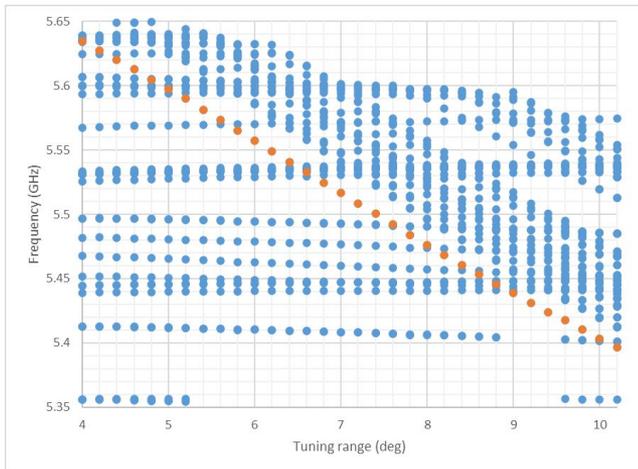
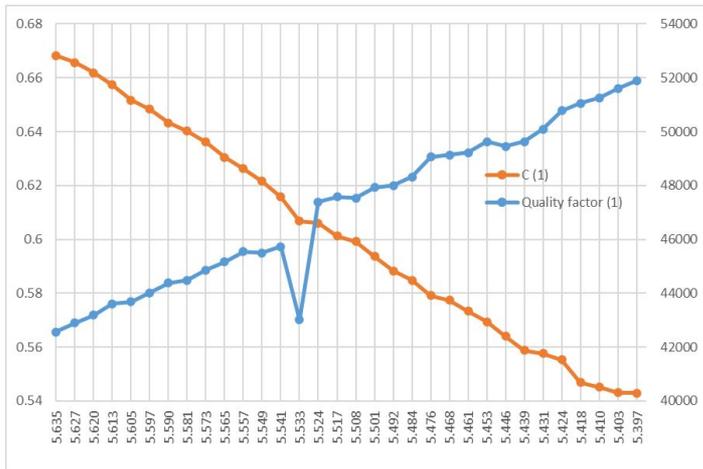
# RF Chain - JPA ON Noise measurements - Spectra Comparison

Optimal JPA working point,  $G = 18\text{-}20$  dB (Nelder-Mead optimization).  $T_{\text{sys}} \sim 500$  mK ( $< 2$  quanta @ 5.5 GHz)



## New 8-cell Cavity development (5.4 GHz - 5.6 GHz)

- **Why the change in range?** Before commissioning, I found that there was overlap with HAYSTAC Phase II above  $\sim 5.6$  GHz range, motivating  $\leq 5.6$  GHz range.
- Major cavity quality control metrics during development:
  - Q @RT and @4 K agreement with simulation results
  - Field uniformity of the TM<sub>010</sub> mode.



## STEP 1 Empty cavity test (no partitions)

- To verify surface cleanliness, end-cap contacts and wall integrity before introducing partition-contact losses.
- Final result currently after surface repairs/cleaning: empty cavity measured Q @RT ~ 32.5k and Q @4K ~ 120k.
- Cleaning methods - Isopropyl Alcohol, ultrasonic cleaning with Citranox

## STEP 2 Partitions assembly + “field map”

- Measure Q, fres, antenna coupling, and cell-by-cell field distribution.
- If Q @RT is low: remove partitions → re-clean → reassemble

## STEP 3 Optimization loop

- Partition swapping/ reseating/ re-torquing to reduce mode localization and improve uniformity. Also improves Q factor.
- Re-test and compute Cd each time; stop when:
  - Q within acceptable band
  - Field uniformity target - ≤2% degradation

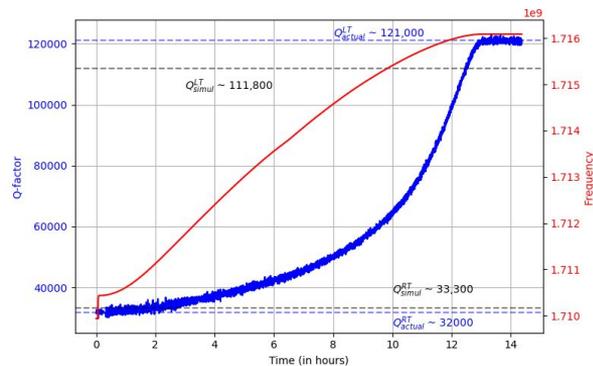
Cd - Field uniformity factor:

- Calculated from E field coupling dip at each cell.  $E_i \propto \sqrt{\beta_i}$
- Is 1 when all cells contribute equally (uniform field). Decreases when the mode localizes.

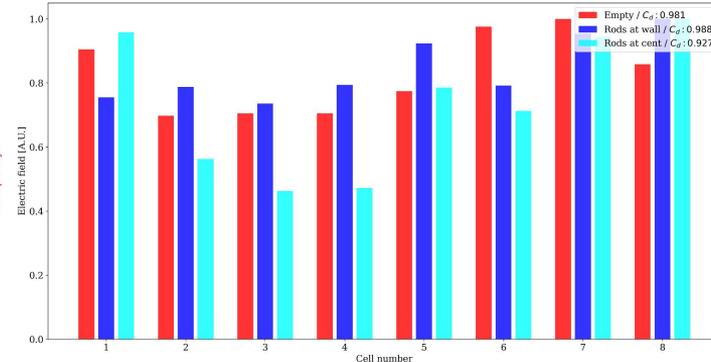
$$C_d \equiv \frac{\left(\frac{1}{N} \sum_{i=1}^N E_i\right)^2}{\left(\frac{1}{N} \sum_{i=1}^N E_i^2\right)}, \quad 0 < C_d \leq 1$$

# New 8-cell Cavity development (5.4 GHz - 5.6 GHz) - Current Status

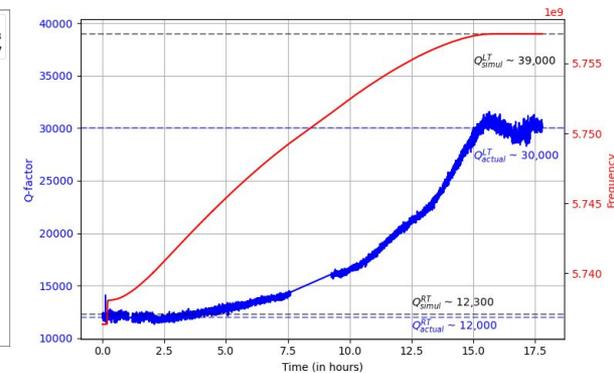
- Empty cavity, Q @RT ~ 32.5k and @4 K ~ 120k. Good agreement with simulation.
- Early partition assemblies showed less than favorable results; Q ~ 9800 - 9400. Reason → bad contact between the partitions and end caps. (Pt height < Sidewall height by 50  $\mu$ m on average.)
- New partitions ordered (height 100  $\mu$ m > Sidewall height). Assembly now shows better Q @RT ~ 11500 → better contact.
- Also faced various mechanical accidents and challenges with early partitions (Screw body and heads breaking, uneven torque) → New partitions' width increased by 200  $\mu$ m. No new accidents.
- Most recent best Cd = 0.982 after targeted partition swaps/adjustments.
- Next step is to assemble the tuning mechanism and test @4 K to validate that RT improvements and check for suspected mode crossing (from previous 4K result)



Empty Cavity Q measurements

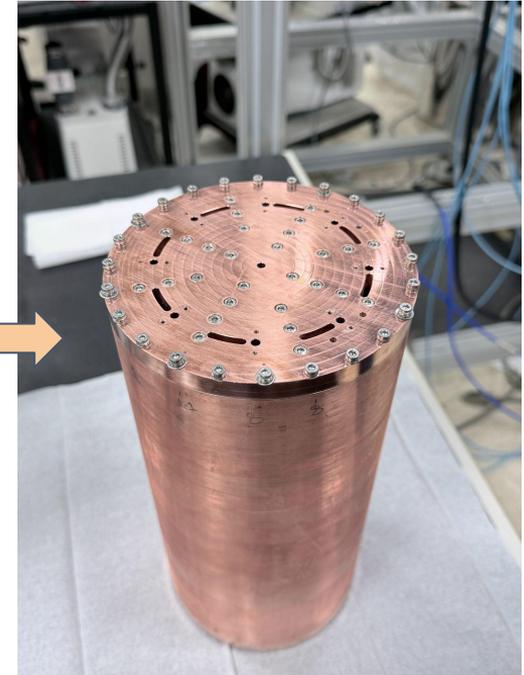
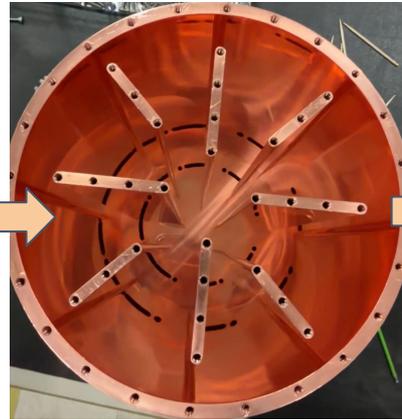
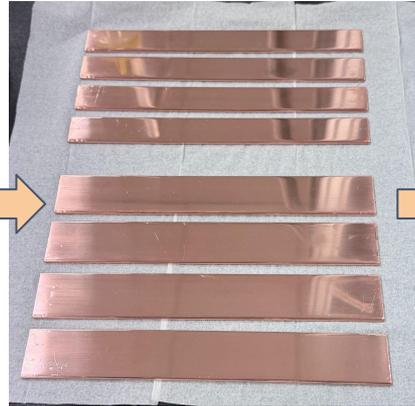
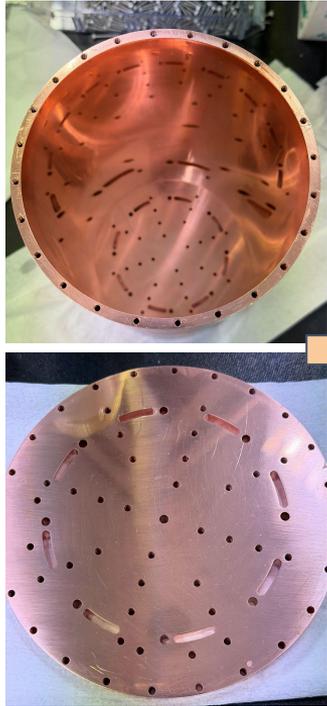


Field distribution of TM010 mode in each cell after assembling with partitions (latest)



Cavity with partitions Q measurements

# New 8-cell Cavity development (5.4 GHz - 5.6 GHz) - Pictures



Empty Cavity

Cavity with partitions

