Search for Dark Matter Axion with TASEH

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on behave of the TASEH collaboration

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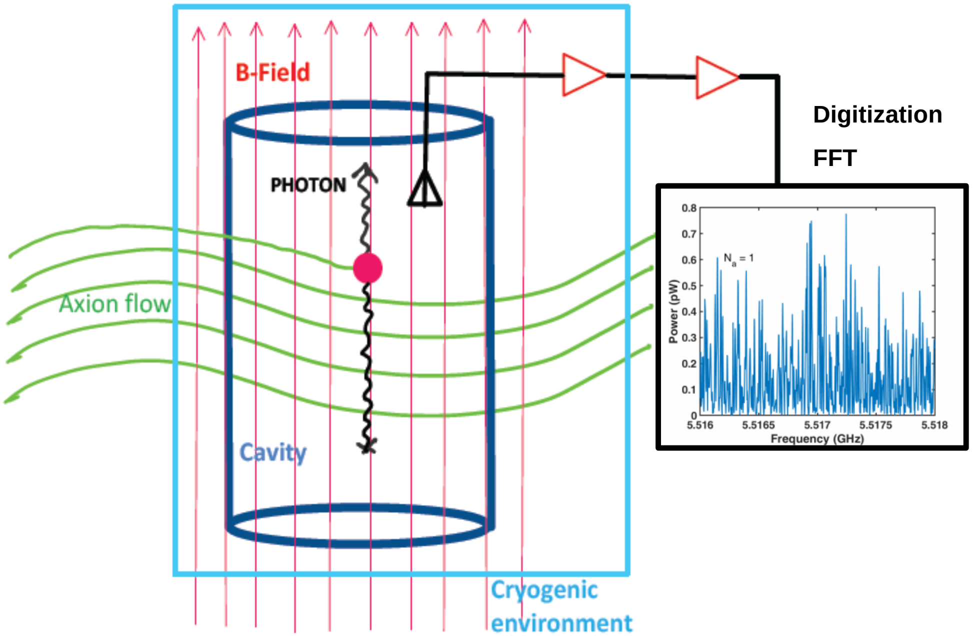
Outline

- First results of Taiwan Axion Search Experiment with Haloscope (TASEH)
- TASEH ongoing development
  - Conic shell cavity
  - JPA
  - Gain and noise calibration from heated cavity
- Conclusion

Axion Haloscope Search

Axion search via tunable cavity:

- *E*·*B* inverse Primakoff coupling
- Listening to extremely weak radio signal (tuning and averaging)



P. Sikivie, *PRL* **51**, 1415 (1983); *PRD* **32**, 2988 (1985)

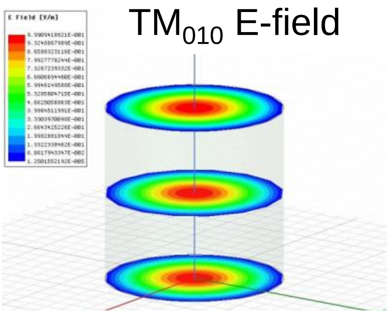
1 μeV < m_a < 1 meV

0.25 GHz < $\omega_a/2\pi$ < 250 GHz

Signal power

$$P_s = \left(\frac{\hbar^2 c^5}{\mu_0}\right)\eta g_{a\gamma\gamma}^2\left(\frac{\rho_a}{m_a}\right)C_n B_0^2 V Q$$

Form factor $C_n = \dfrac{\left(\int d^3x \vec{E}_n \cdot \vec{B}\right)^2}{B_0^2 V \int d^3x \epsilon \left|\vec{E}_n\right|^2}$



High form factor mode for uniform B-field

Noise power

$$P_N = k_B T_{sys}\Delta f$$

$$\sigma_{P_N} = P_N/\sqrt{N_{ave}} = k_B T_{sys}\sqrt{\Delta f/t_{ave}}$$

Detection signal-to-noise ratio

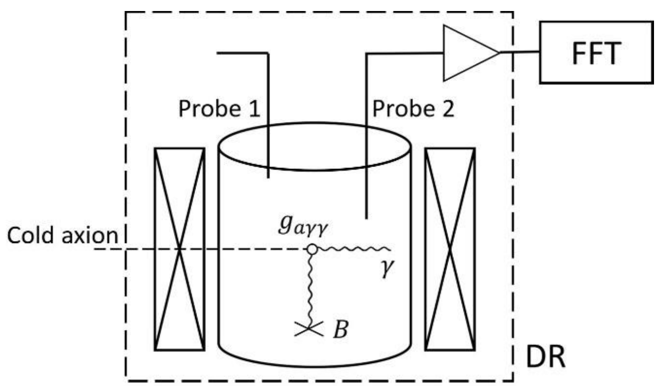
$$\Sigma = P_s/\sigma_{P_N} \propto \sqrt{t_{ave}}/T_{sys}$$

Taiwan Axion Search Experiment with Haloscope TASEH

Taiwan Axion Search Experiment with Haloscope

Collaboration launched in Year 2020

Axion haloscope detection



10 μeV < m_{a} < 25 μeV

2.5 GHz < $\omega_{\mathrm{a}}/2\pi$ < 6 GHz

Setup for the first physics experiment

Existing cryostat and magnet in NCU

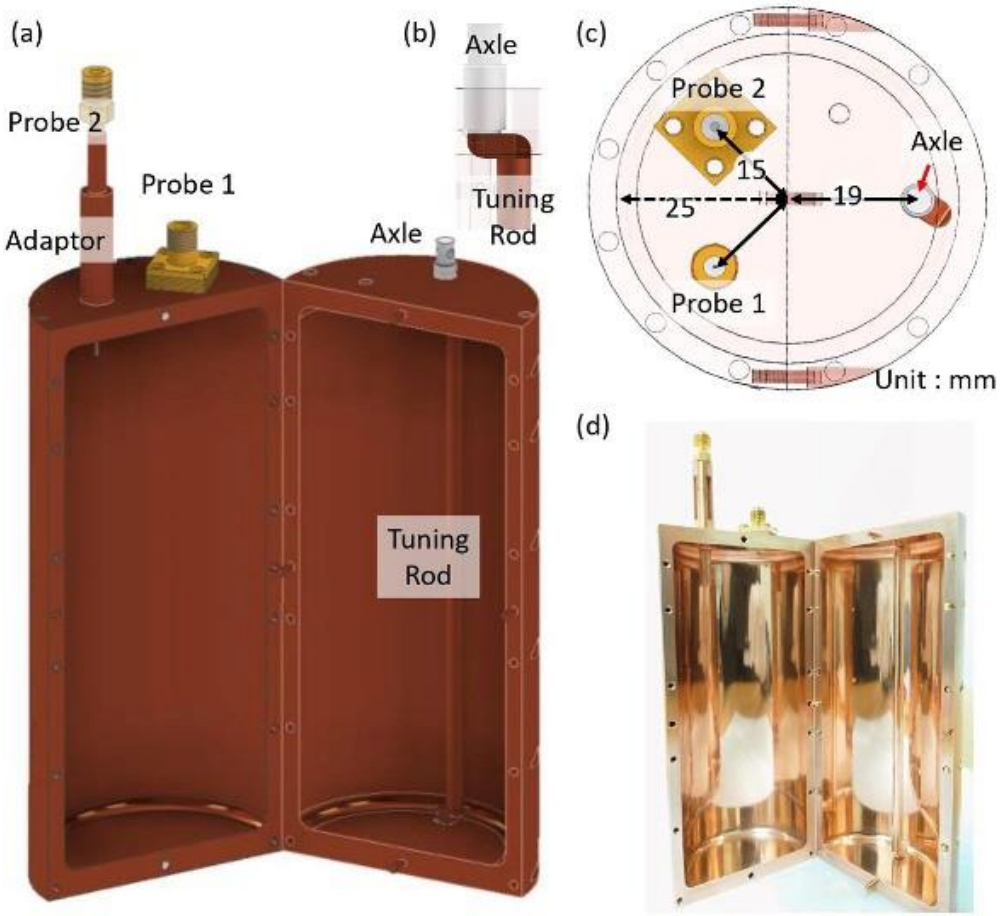
Bluefors DR:

- base: 27 mK

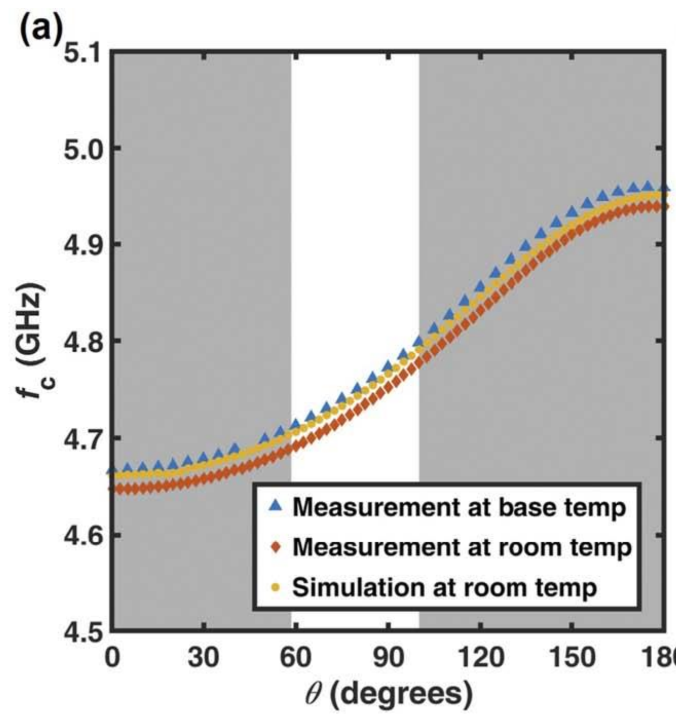
AMI magnet:

- field: 8 T
- bore: 6.8 mm

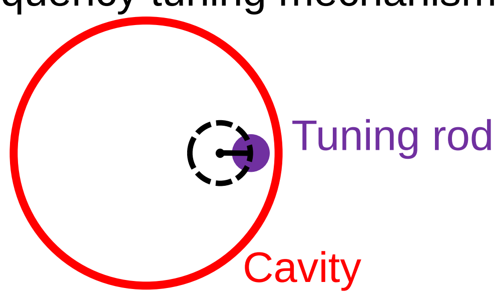
Cavity Detector



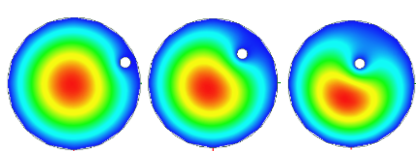
- OFHC copper, split cavity
- Volume V: ~ 0.234 L
- High quality Q: ~ 62000
- Large form factor C_{010}: ~ 0.62
- Tunable frequency f_c: 4.65 – 4.95 GHz
- Tunable coupling β_2 : 0.5 – 3
- Signal power P_s : ~ 1.4 x 10^{-24} W (KSVZ)



Frequency tuning mechanism

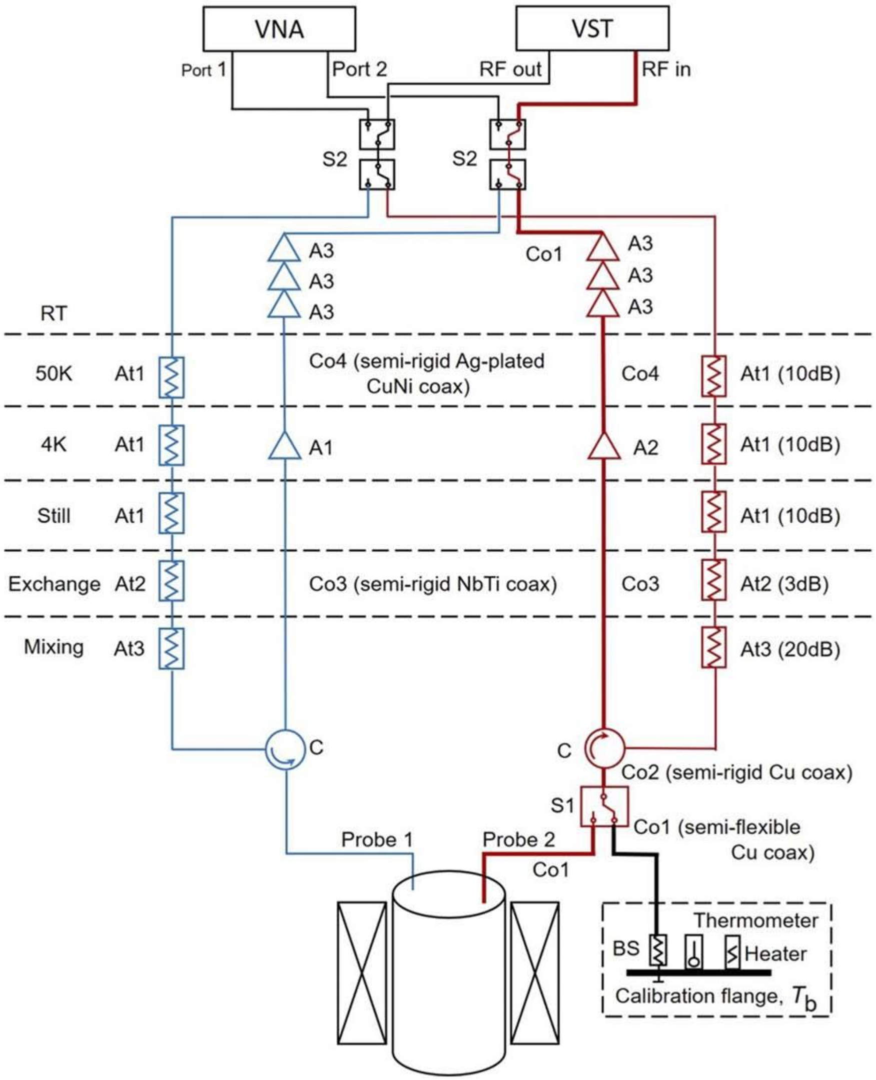


TM_{010} mode pattern



TASEH collaboration, *RSI* **93**, 084501 (2022)

Signal Receiver Wiring

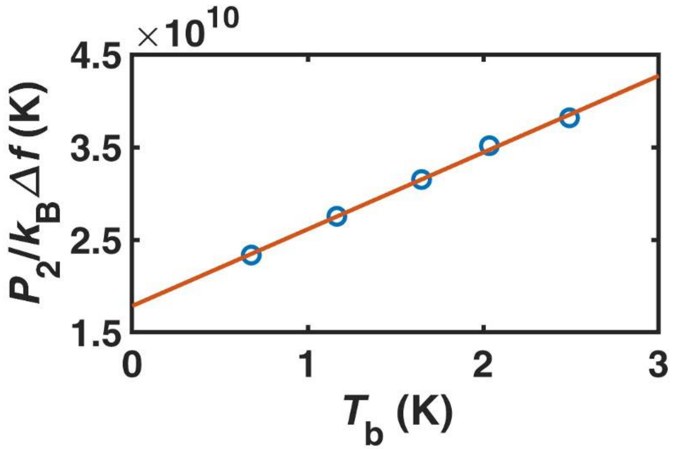


- Probe 2 for readout (strong coupling)
- Probe 1 for test signal (weak coupling)
- Two readouts to characterize cavity
- First-stage amplifier: HEMT
- Separate noise source for readout 2 calibration

TASEH collaboration, *RSI* **93**, 084501 (2022)

Gain Calibration and Noise Performance

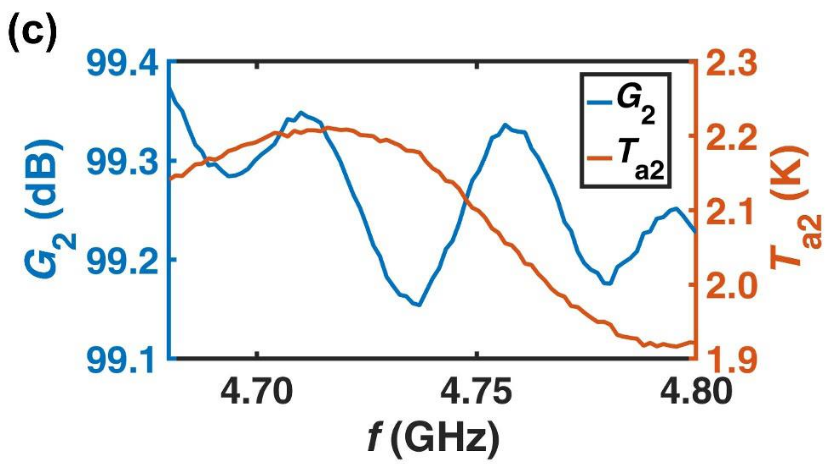
Y-factor method



$$P_2 = G_2 k_B (\tilde{T}_b + T_{a2}) \Delta f$$

$$\tilde{T}_b = \frac{\hbar\omega}{k_B}\left(\frac{1}{\exp(\hbar\omega/k_B T_b) - 1} + \frac{1}{2}\right)$$

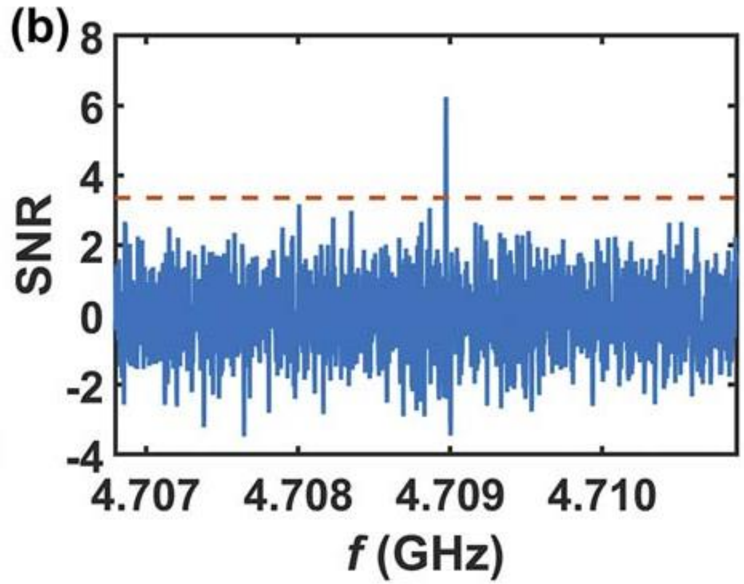
thermal vacuum



- G_2: ~ 100 dB
- T_{sys}: ~ 2.3 K
- ~ 10 times higher than quantum limit
- Dominated by HEMT amplifier

TASEH collaboration, *RSI* **93**, 084501 (2022)

Synthetic Signal Test



- Inject synthetic signal to verify the procedures of data acquisition and physics analysis.
- Test signal power corresponding to $g_{a\gamma\gamma} \approx 20 g_{a\gamma\gamma}^{KSVZ}$.
- The test signal was found at 4.708970 GHz with SNR = 6.12.

TASEH collaboration, *RSI* **93**, 084501 (2022)

TASEH collaboration, *PRD* **106**, 052002 (2022)

Experimental Benchmark Parameters

B_0	8 T
V	0.234 L
C_{010}	0.614 – 0.630
Q_0	58000 – 65000
T_{sys}	2.1 – 2.4 K
β_2	1.9 – 2.3
Δf_s	95 – 115 kHz
Δt	32 – 42 min
N_{step}	837
f_{lo}	4.70750 GHz
f_{hi}	4.79815 GHz

Operation parameters

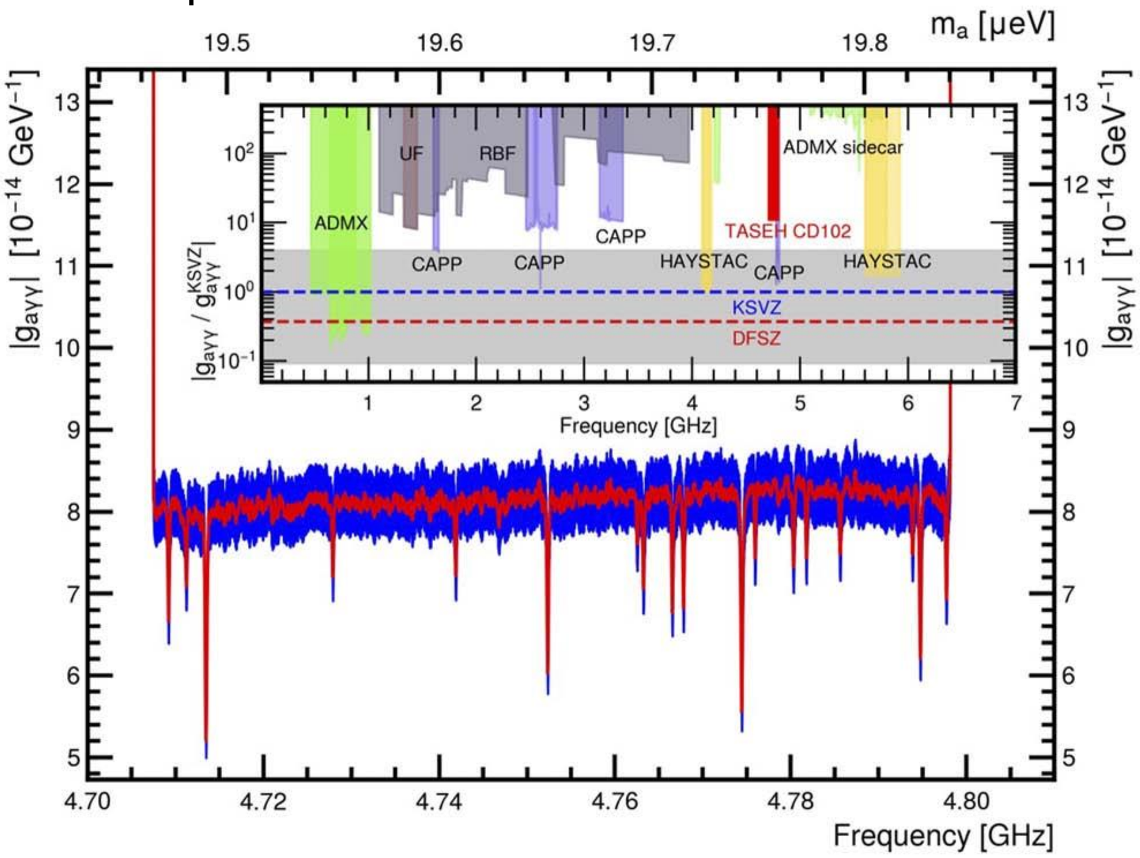
- Maximize search rate with fixed sensitivity
- Cover search range continuously
- Reach ~ 10 times KSVZ sensitivity

TASEH collaboration, *RSI* **93**, 084501 (2022)

TASEH First Results

Search exclusion plot

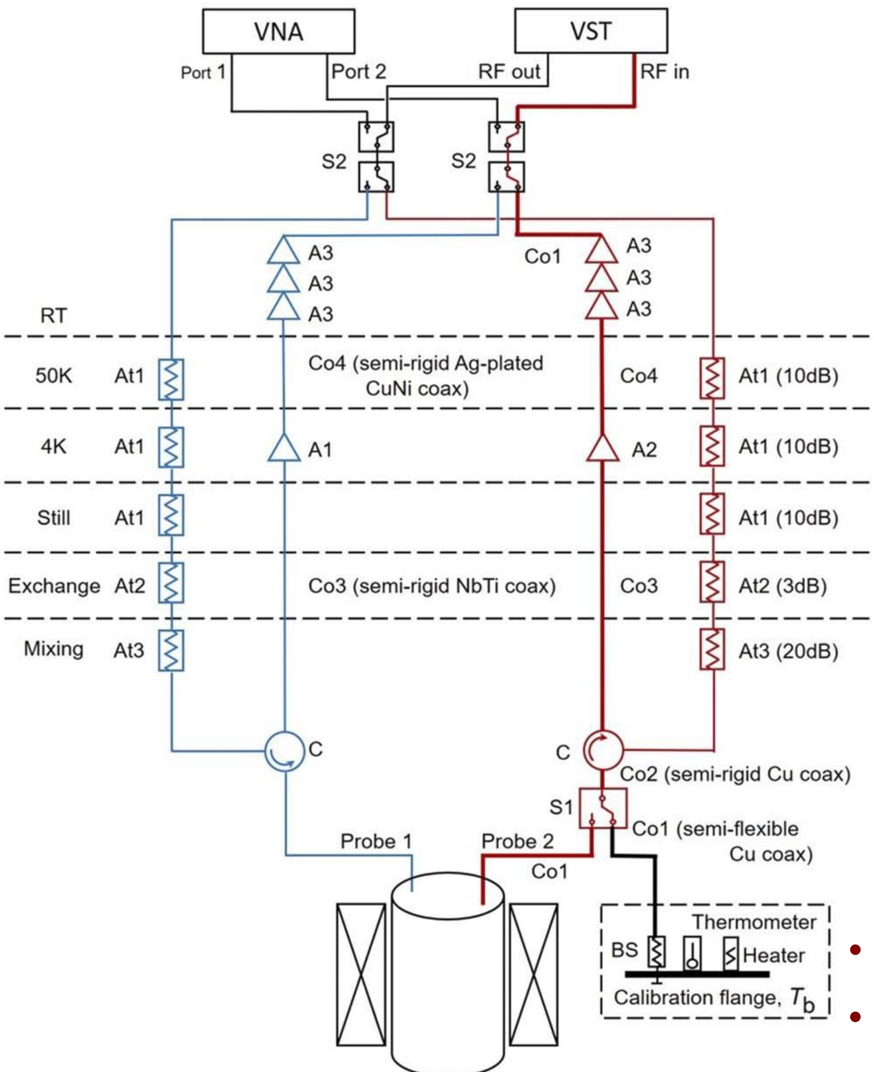
TASEH collaboration, *PRL* **129**, 111802 (2022)



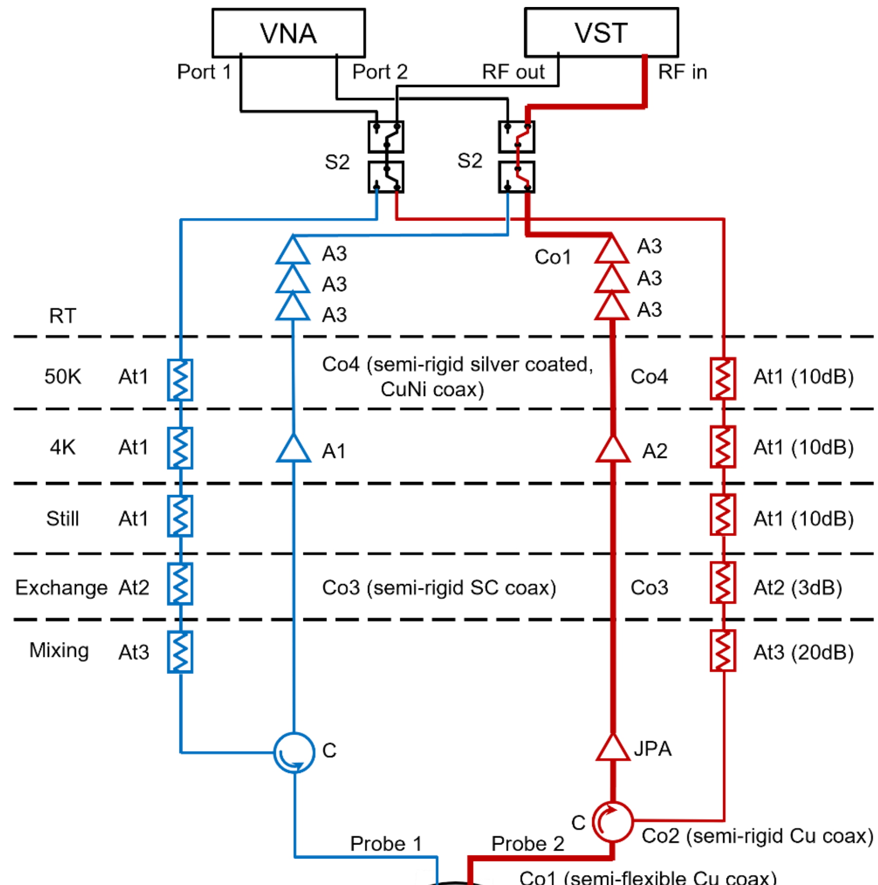
- ~ 1 month data taking in the end of Year 2021
- 19.4687 – 19.8436 μeV (4.707 50 and 4.798 15 GHz, ~ 90 MHz search range)
- Excludes models with the axion-two-photon coupling $g_{a\gamma\gamma} \geq 8.1 \times 10^{-14}$ GeV^{-1} (~ 11 times above QCD KSVZ model limit) at 95% C.L.
- First-hand experience of operating axion haloscope

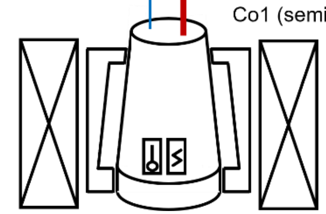
Haloscope Upgrade

Existing



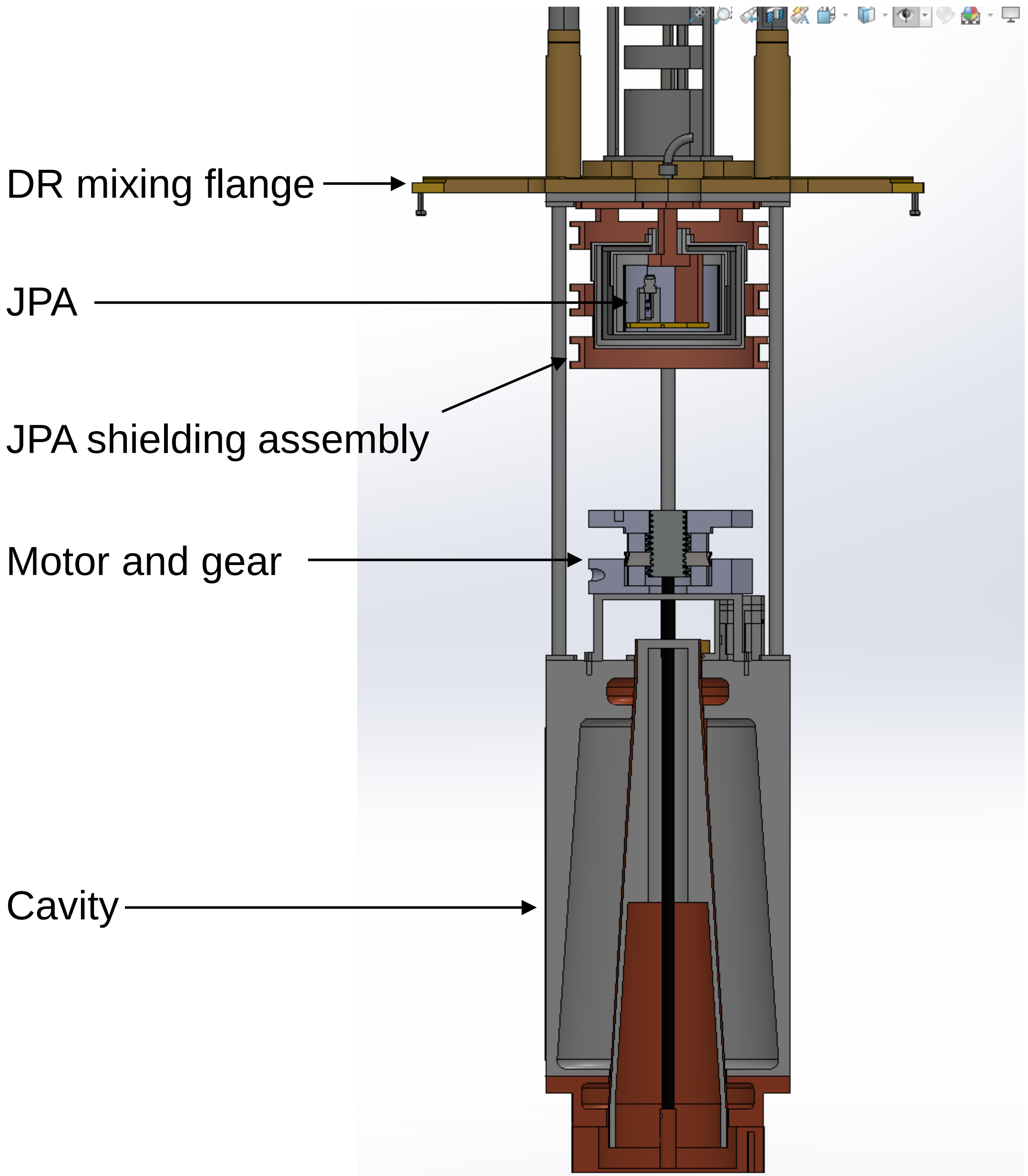
Upgrade





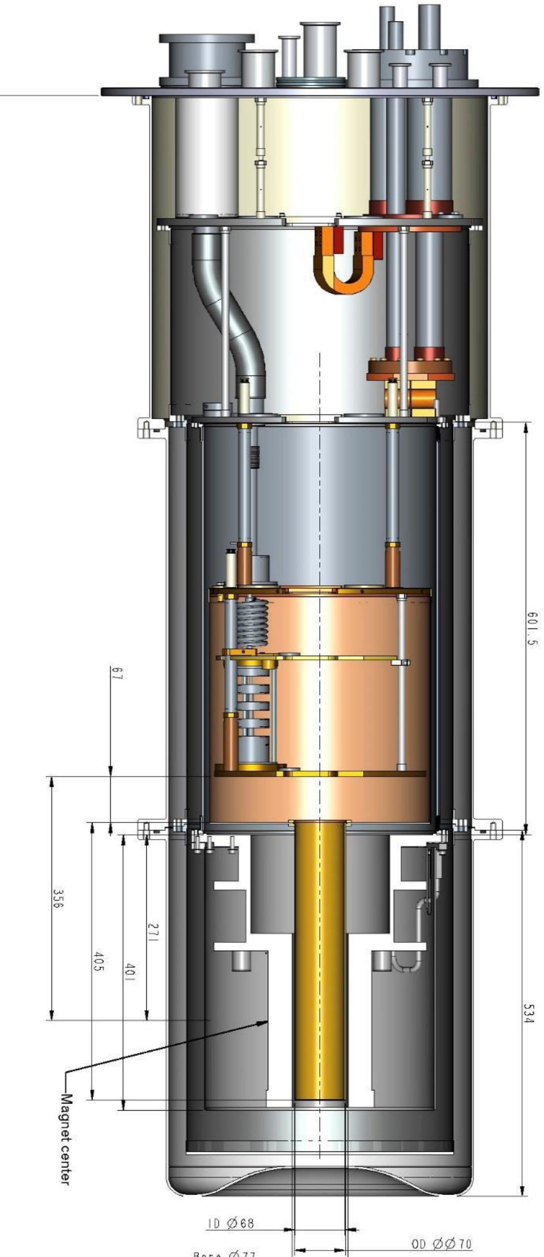
- Magnet upgrade
- Conic shell cavity
- JPA
- Cavity for noise calibration

Layout

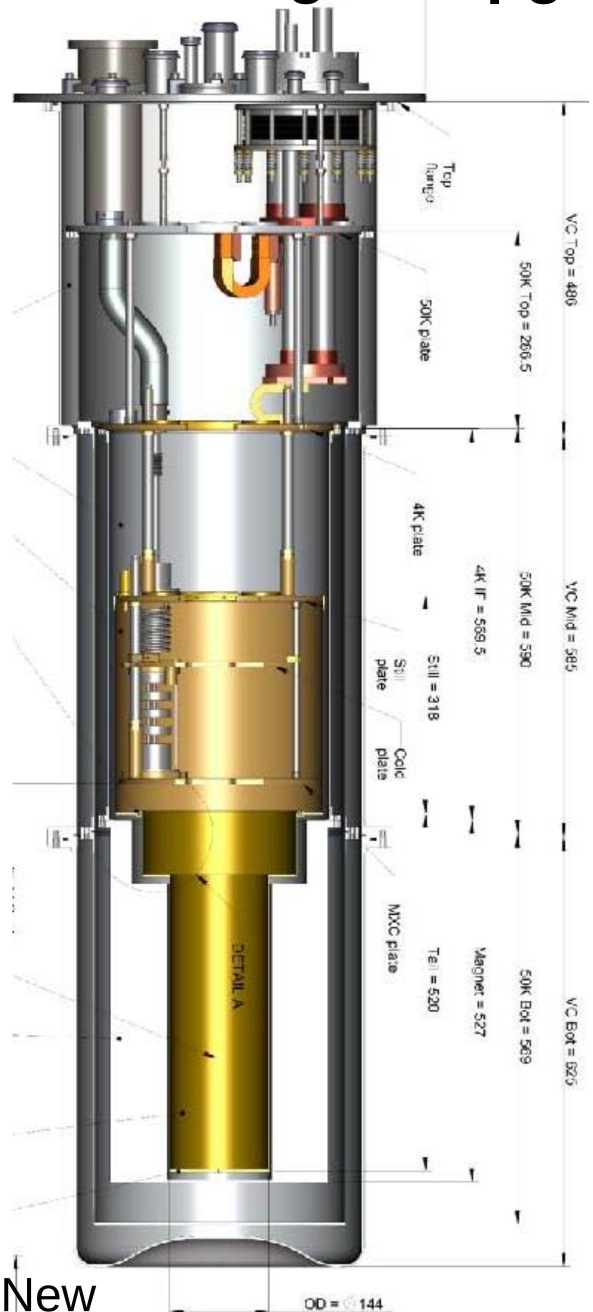


DR mixing flange
JPA
JPA shielding assembly
Motor and gear
Cavity

New DR and Magnet Upgrade



Existing



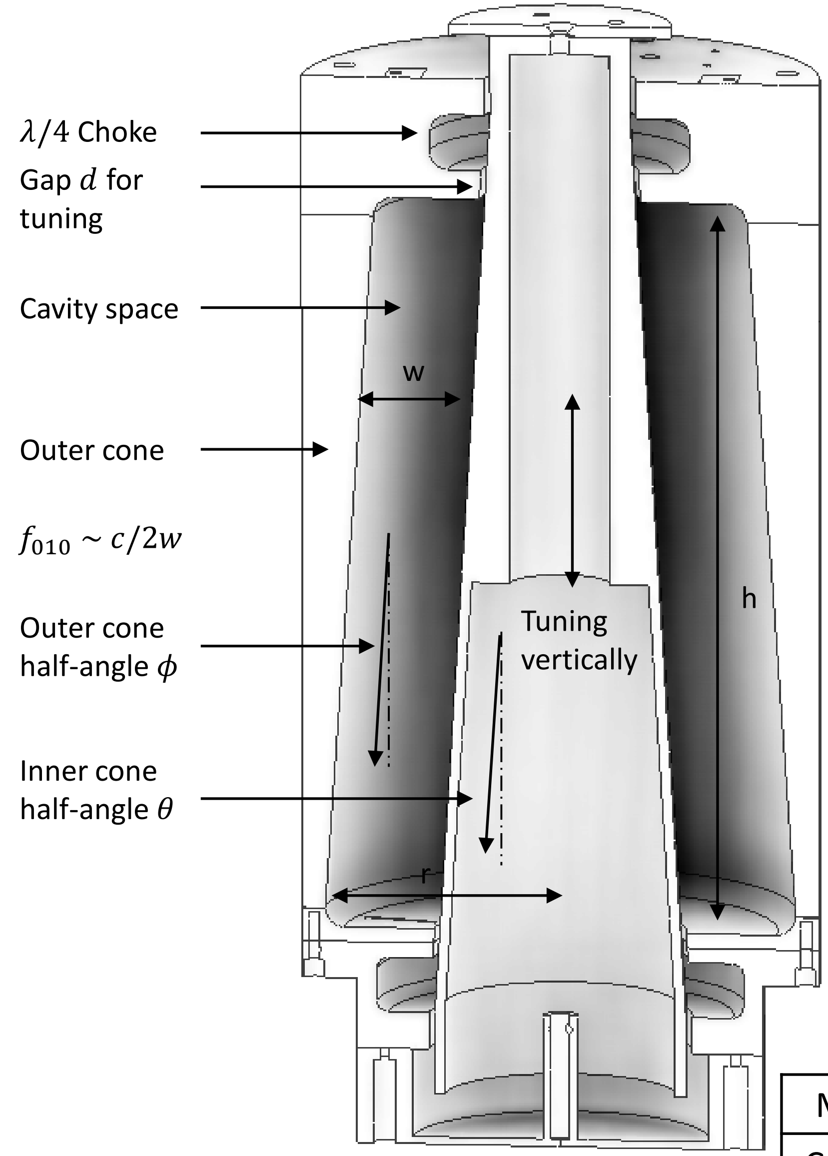
New

Magnet parameter	Old	New
B_0 (T)	8	9
Bore diameter (mm)	68	142
Length (mm)	400	400
Within 30% reduction (mm)	170	250
Inductance (H)	12	93

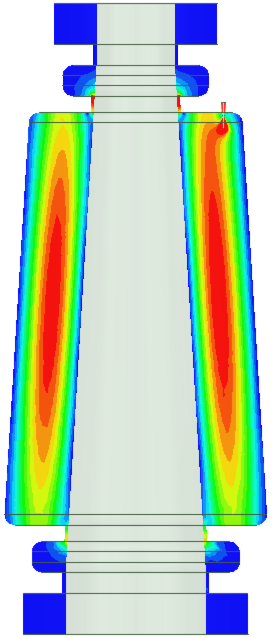
Conic Shell Cavity

Ref: C. Kuo, *JCAP* **2021**, 02 018 (2021)

Design model (assisted by HFSS simulation)



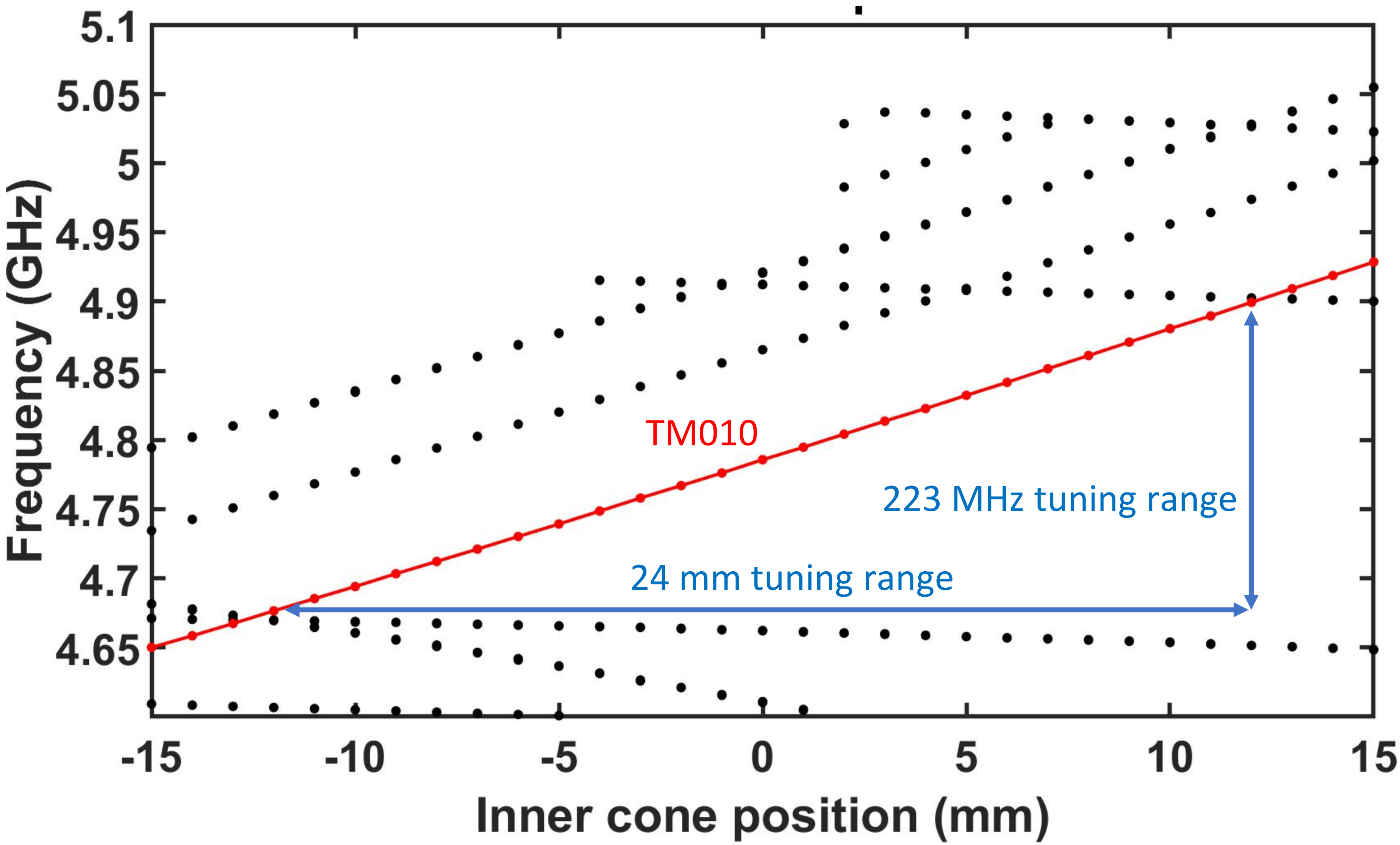
- TM_{010} mode exists in cavity between two cones
- Maximize available space in magnet bore
- f_{TM010} ~ 4.75 GHz
- Frequency tuning via inner position and different angles of cones
- TE modes are away from zero tuning
- $\lambda/4$ RF choke to reduce radiation loss from gap



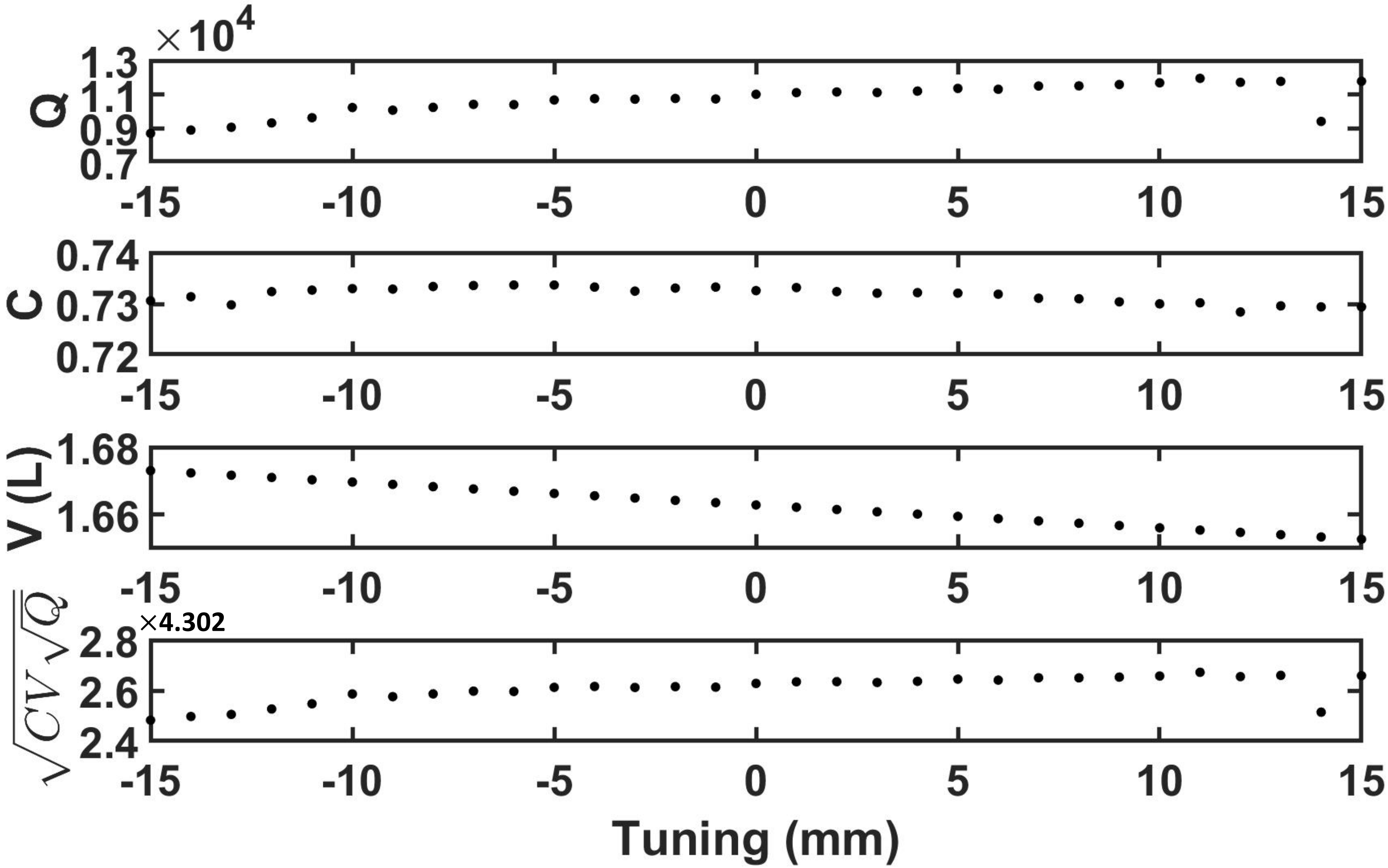
E-field pattern of TM_{010}

Material	R	w	h	f_{TM010}	θ	ϕ	d
Cu coated s.s.	64 (mm)	31.35 (mm)	200 (mm)	4.785 (GHz)	3.5 (deg)	3.55 (deg)	1.5 (mm)

Mode Map Simulation



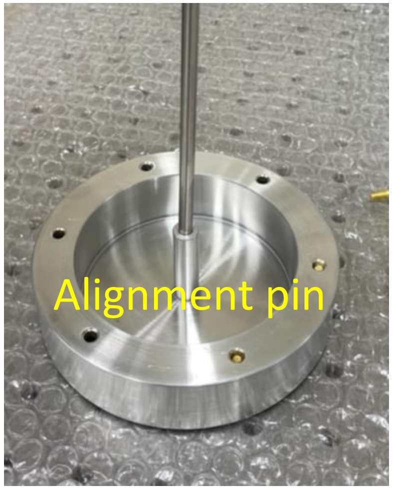
Form Factor and Expected Cavity Performance



- Volume V ~ 1.66 L, form factor C_{010}: ~ 0.73
- Intrinsic quality factor Q ~ 42000 is expected for Cu cavity at cryogenic temperature
- ~ 2.6 sensitivity improvement refer to the 1st results

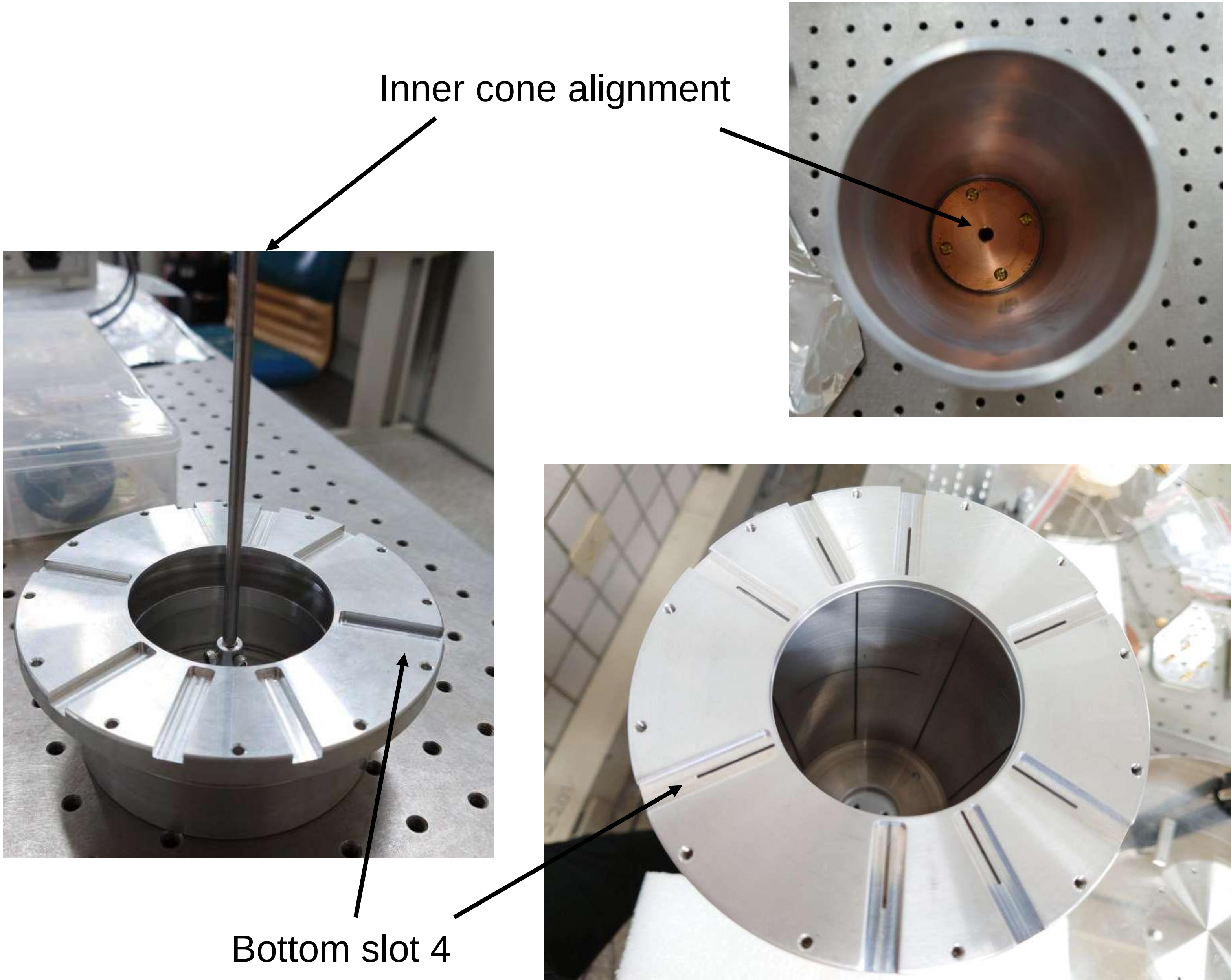
Fabrication of Test Cavity

- Aluminum
- Whole weight ~ 6 kg
- Inner cone weight ~ 1 kg

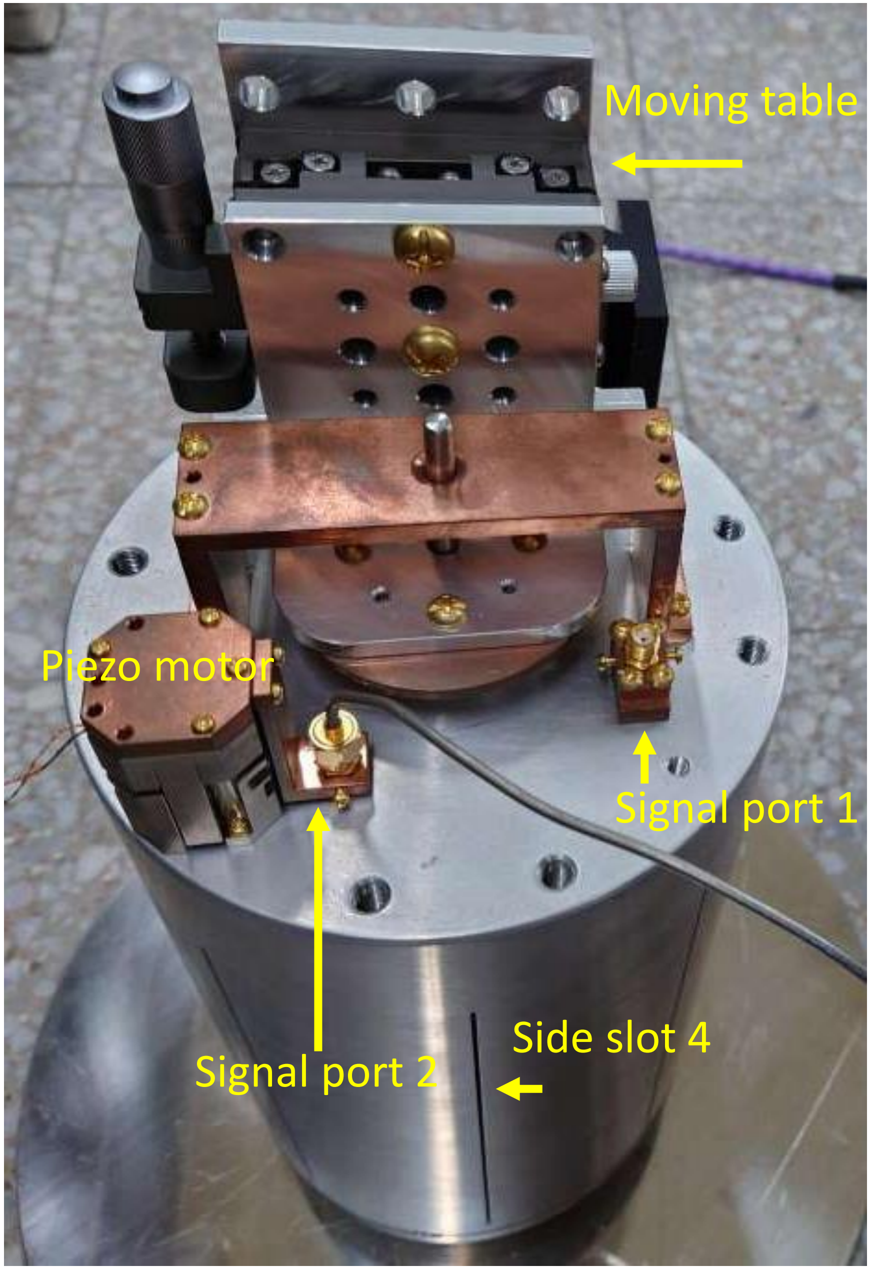


Material	R	w	h	f_{TM010}	θ	ϕ	d
6061 Al alloy	64 (mm)	31.35 (mm)	200 (mm)	4.855 (GHz)	3.5 (deg)	3.95 (deg)	1.5 (mm)

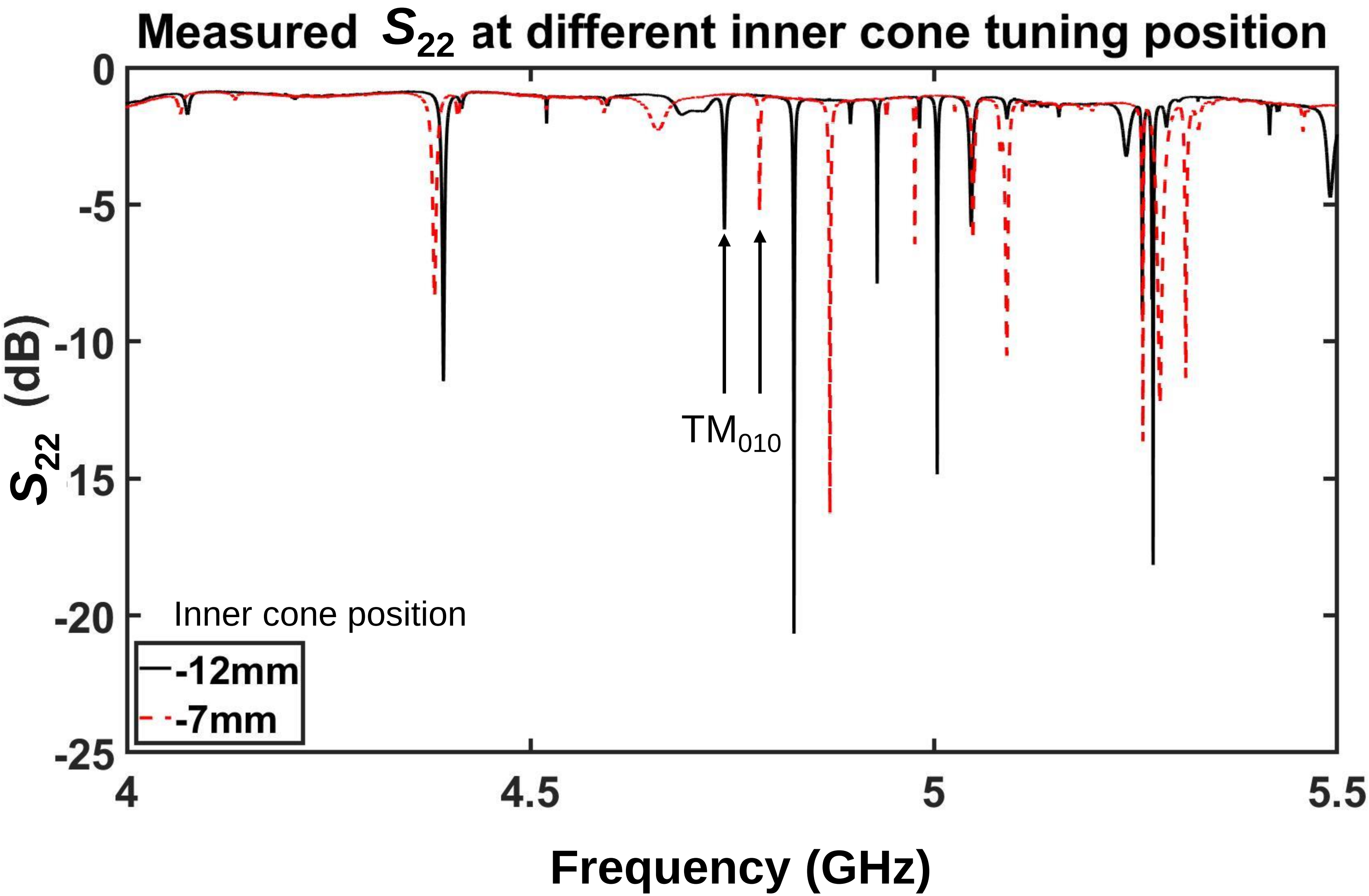
Details



Top View

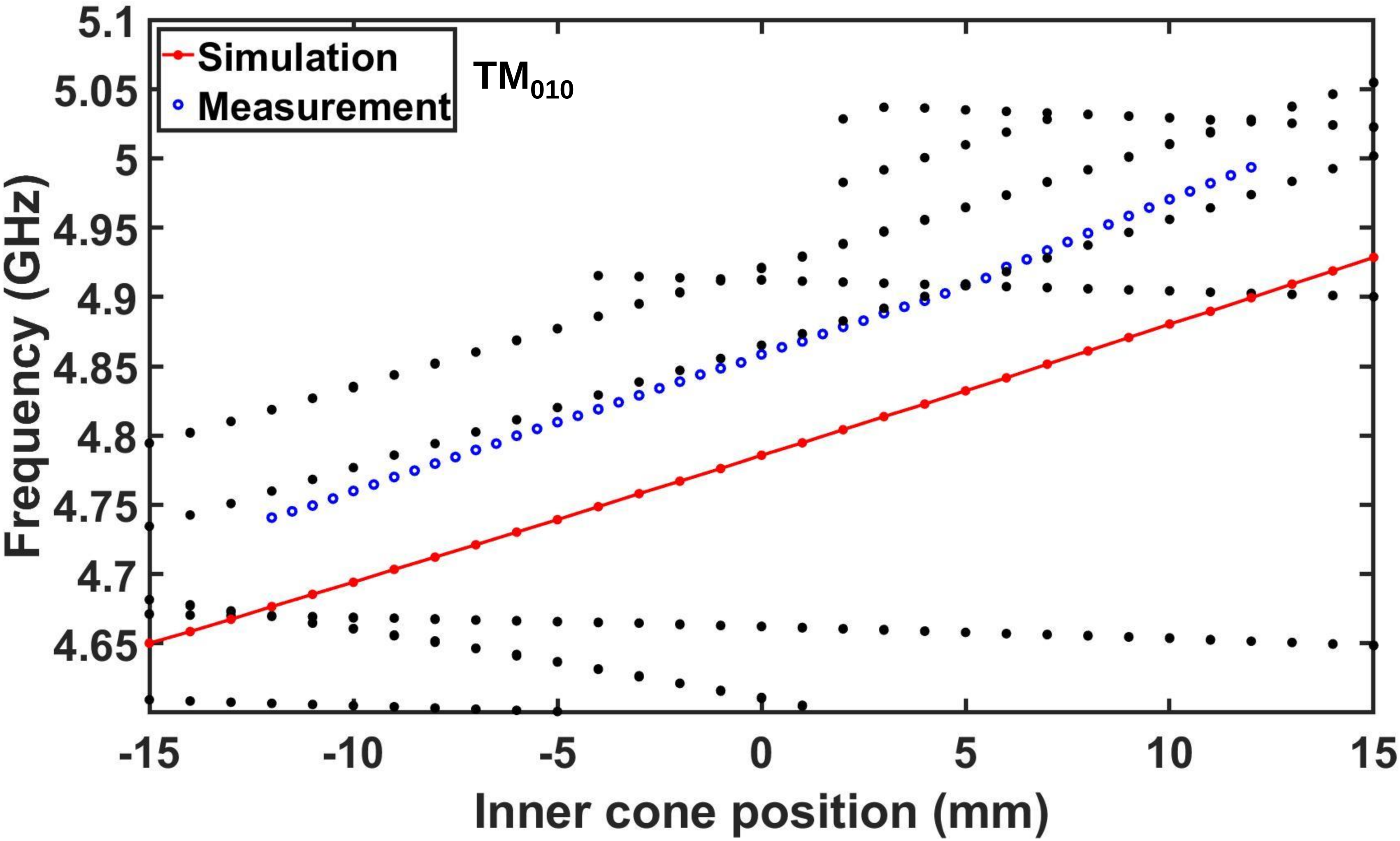

Moving table
Piezo motor
Signal port 1
Signal port 2
Side slot 4

Scattering Matrix Measurement



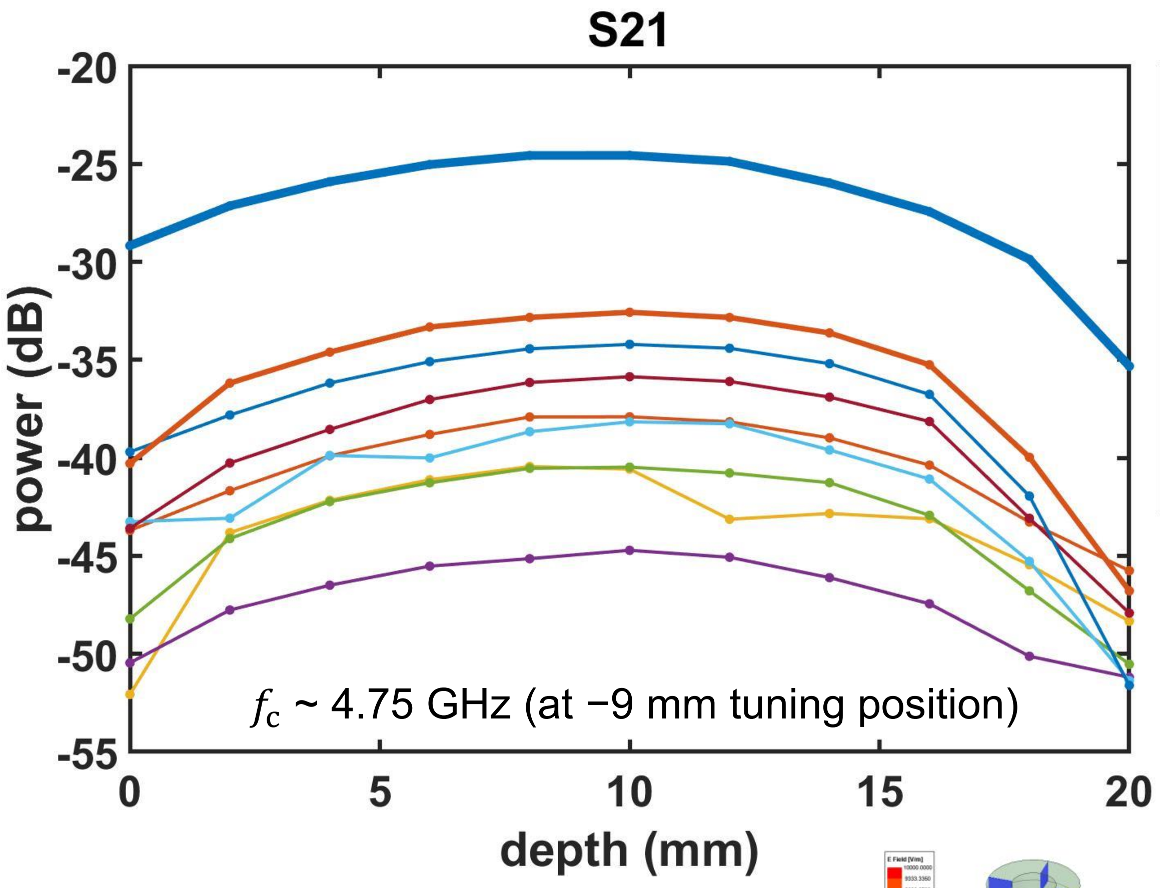
- TM_{010} mode is identified.

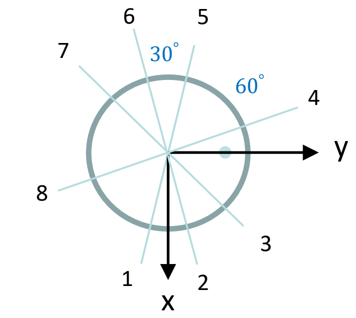
Mode Map

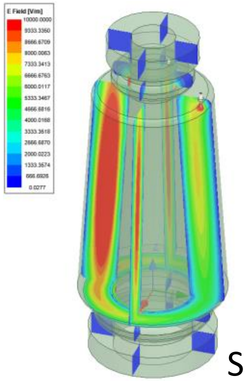


- Frequency tuning has nearly identical tuning range as design
- ~ 70 MHz off from design

E-Field Distribution Measurement via Bottom Slots



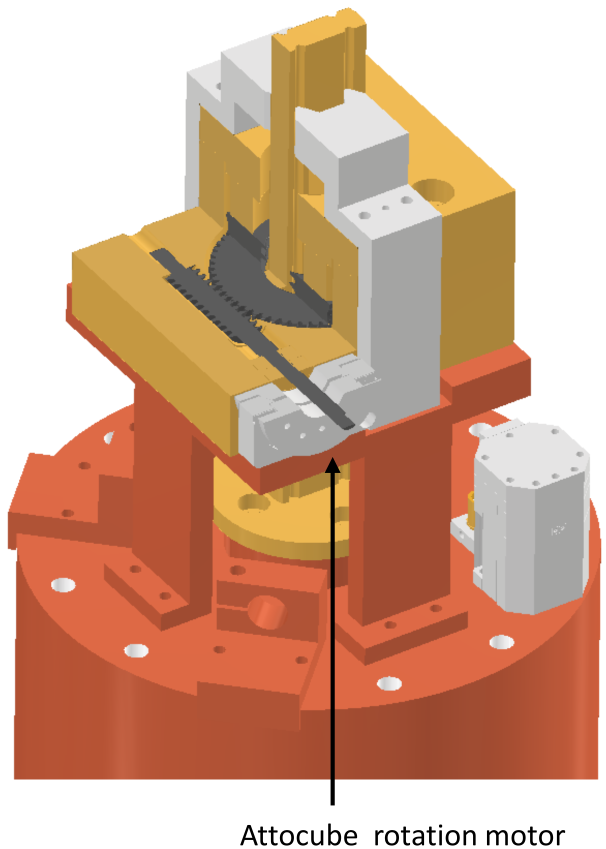


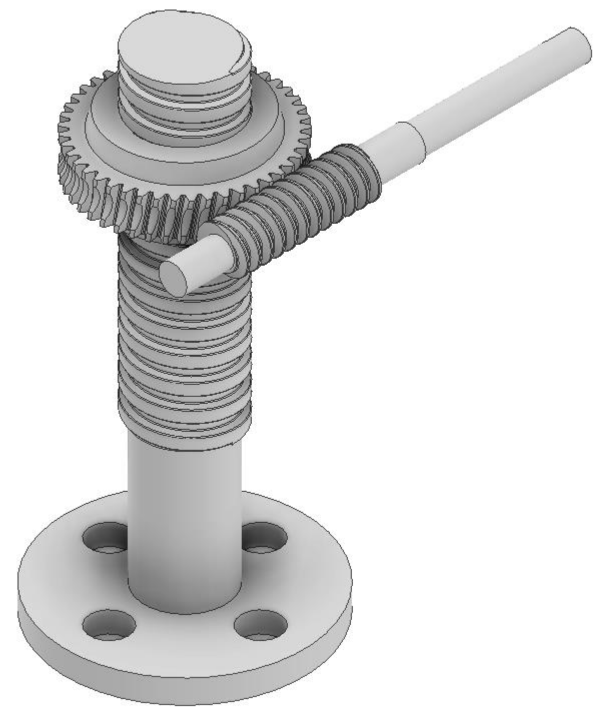


- TM010 is confirmed.
- Angular dependence of field strength possibly due to inner cone offset.

Shift of 0.2 mm along y axis

Preliminary Gear Design





- Gear: 5 mm pitch / 45 teeth
- Motor output normal force: 2 N
- Lift weight: 50 kg
- Cavity tuning: 0.93 MHz/mm
- Frequency tuning 150 kHz, 0.15 mm tuning position, 1.4 turn, slow operation

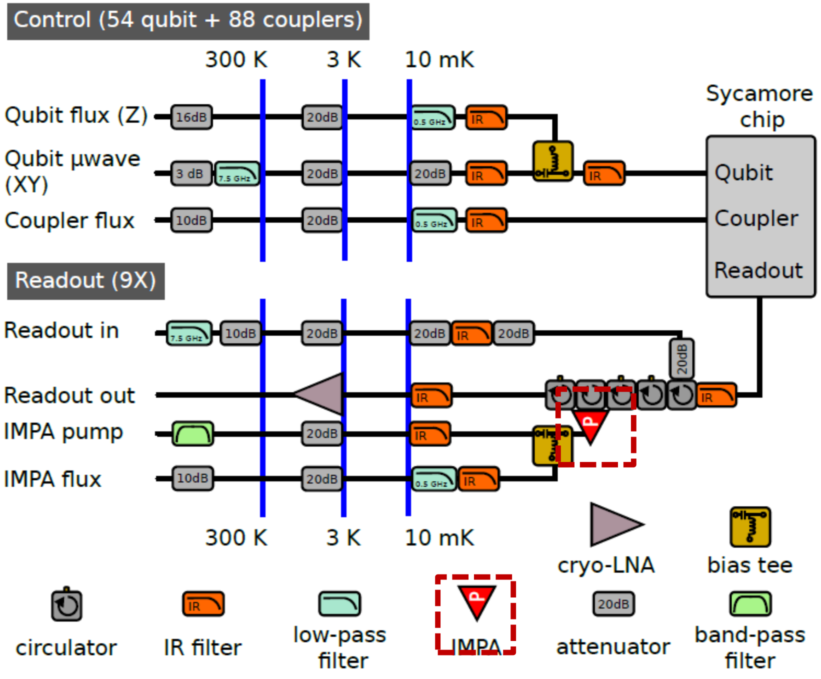
Work Items

- Copper-coated stainless steel cavity
    - Electrical and thermal conductivity
- Alignment of inner and outer cones
- Gear box:
    - Design
    - Material
    - Coating
- Heating by motor and gear box

Josephson Parametric Amplifier (JPA)

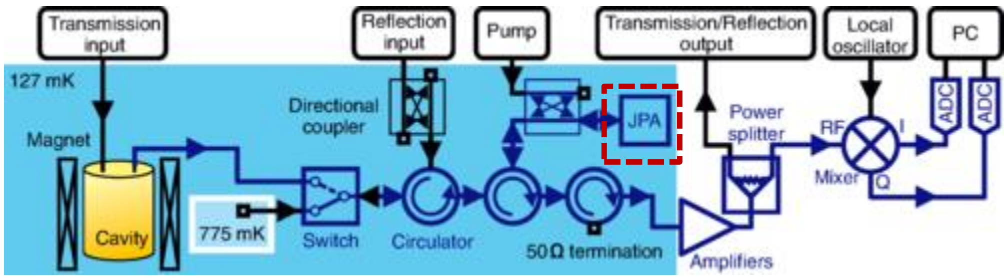
JPAs reach quantum-limited performance (added noise of half photon) in 1-10 GHz band

Superconducting qubit readout



F. Arute *et al.*, *Nature* **574**, 505 (2019)

Axion dark matter search (HAYSTAC)



B. Brubaker *et al.*, *PRL* **118**, 061302 (2017)

JPA Variety

- Current-driven JPA (quantum limited noise, narrowband)
- Flux-driven JPA (quantum limited noise, narrowband)
  - Good noise performance
  - Simple design and easy operation
  - Decent frequency tunability
- Lumped-element JPA (quantum limited noise, wider band)
- Impendence-transformed JPA (quantum limited noise, wideband)
- Travelling-wave JPA (more noisy, ultra wideband)

Device Layout and Fabrication

Via all-ebeam lithography process developed by Chii-Dong Chen in ASIoP

- One ebeam writing/lithography
- Depositions in single vacuum
- Cross-junction fabrication
- Oxidation parameters

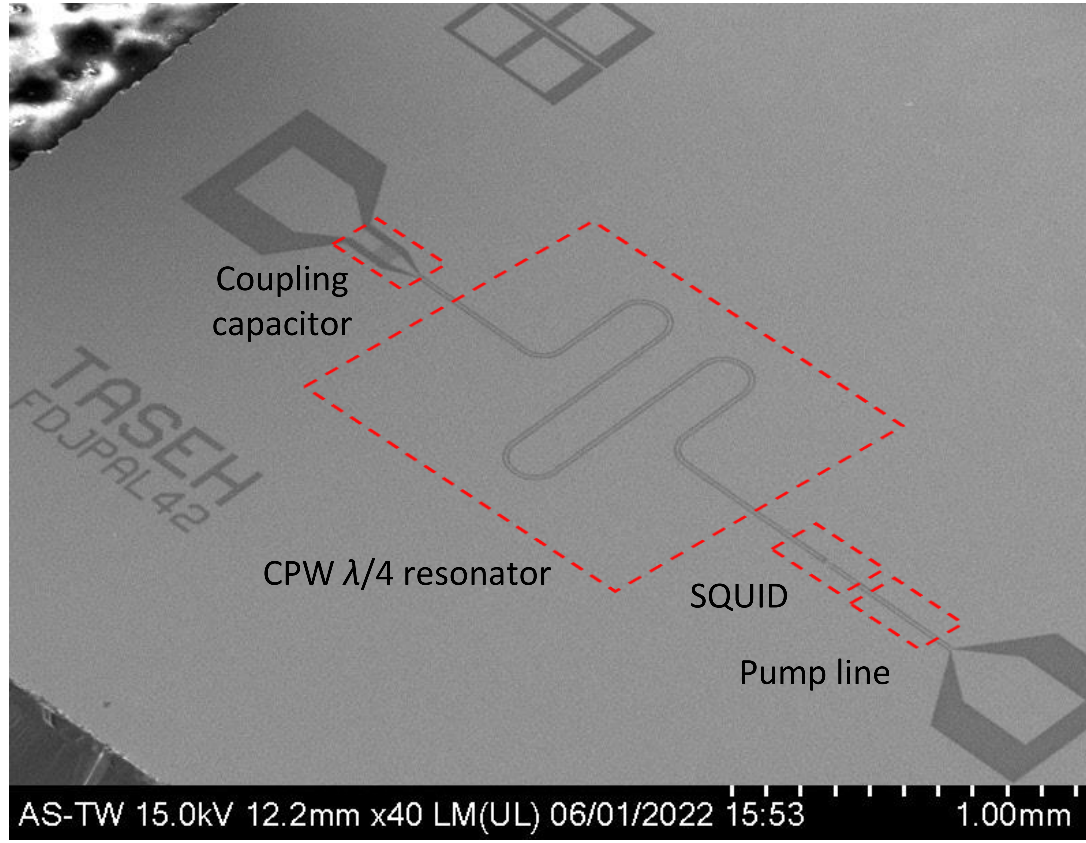
  P_{O2} ~ 38 mTorr, t_{O2} ~ 30 min

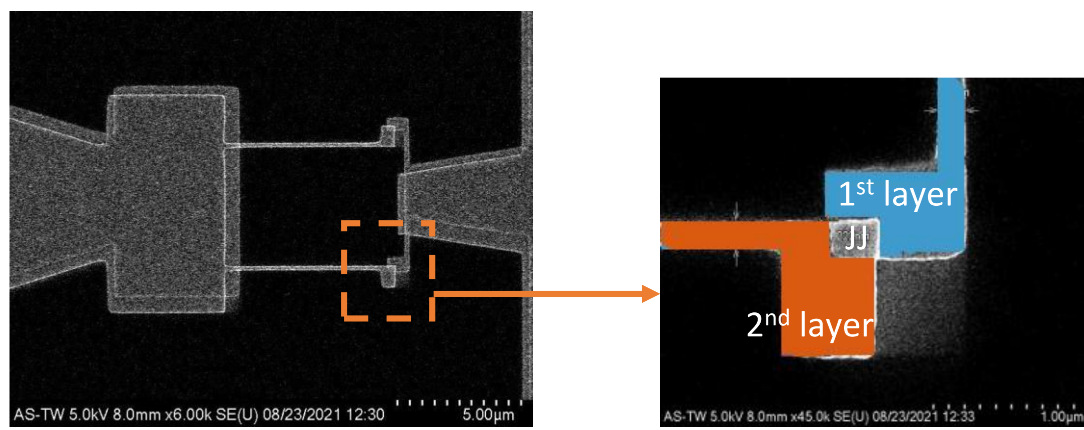
  $R_{\square}$ ~ 50 Ωum^2
- Junction parameters

  A_J ~ 0.3 um x 0.2 um

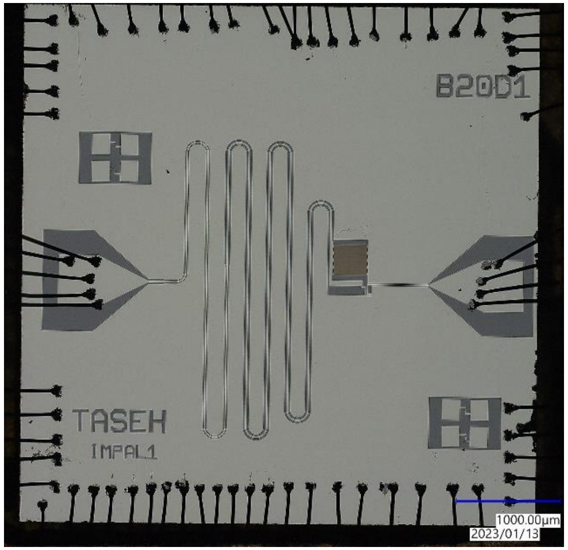
  $R_{sq} = R_{\square}/2A_J$ ~ 420 Ω

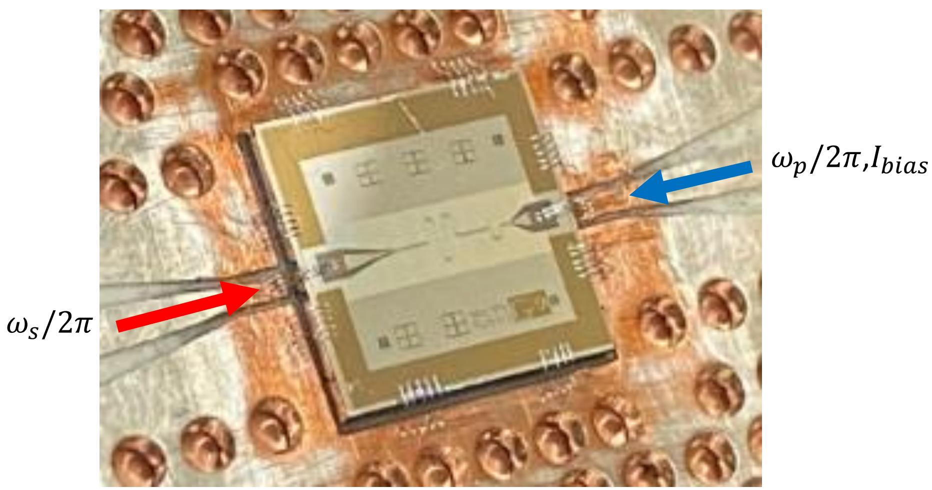
  R_{tJ} ~ 400 Ω

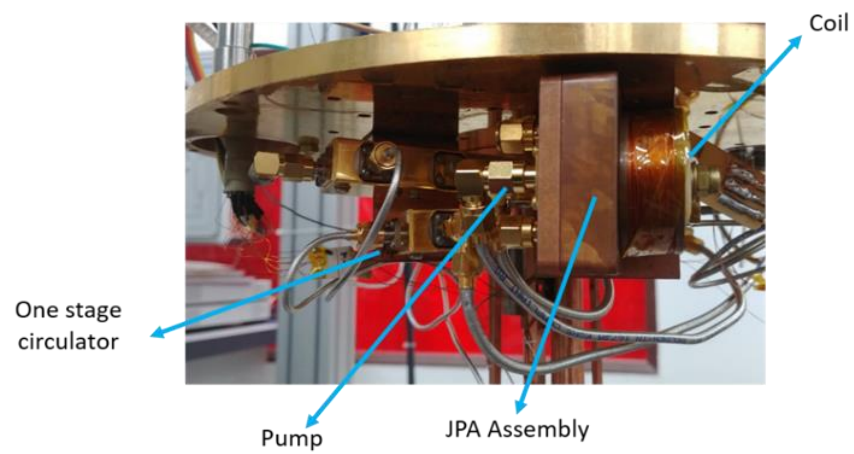




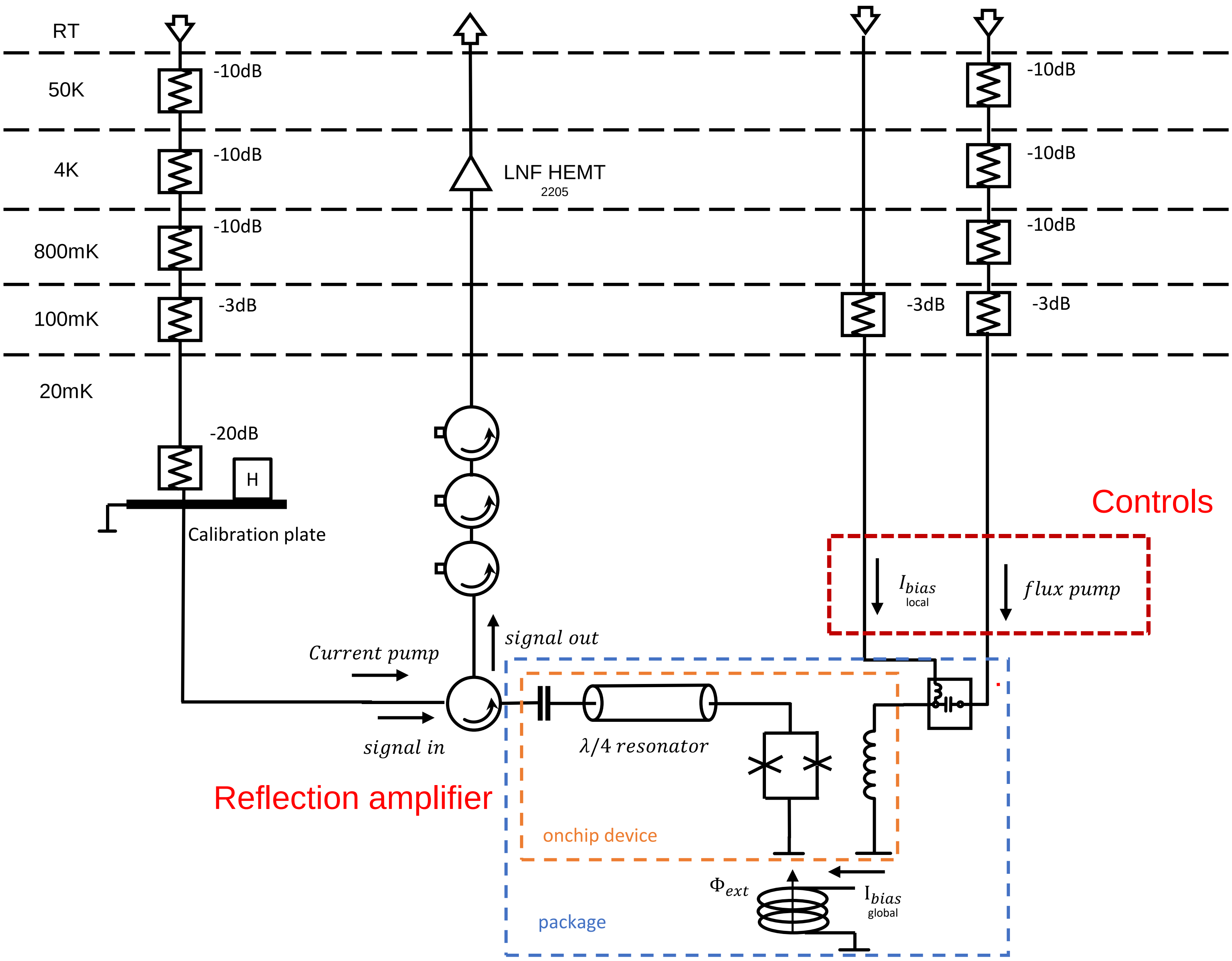
Device Packaging and Wiring





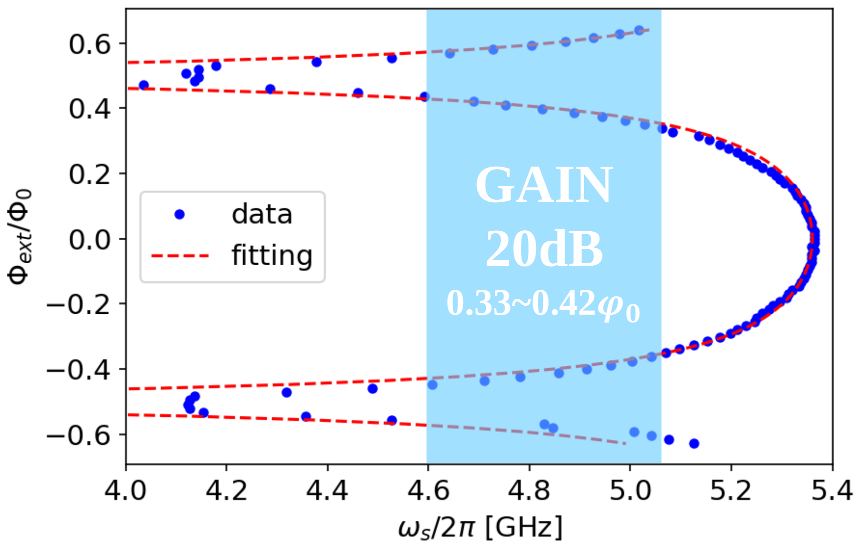


Cryogenic Wiring

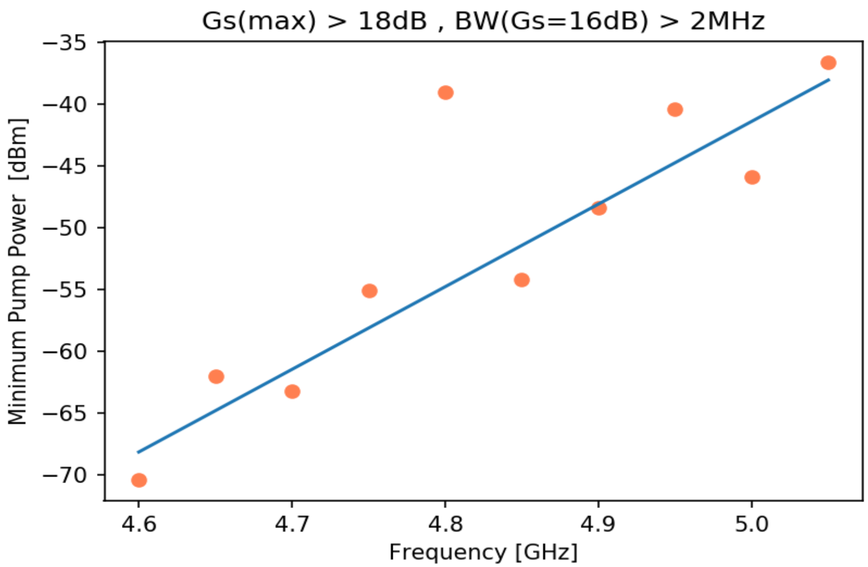


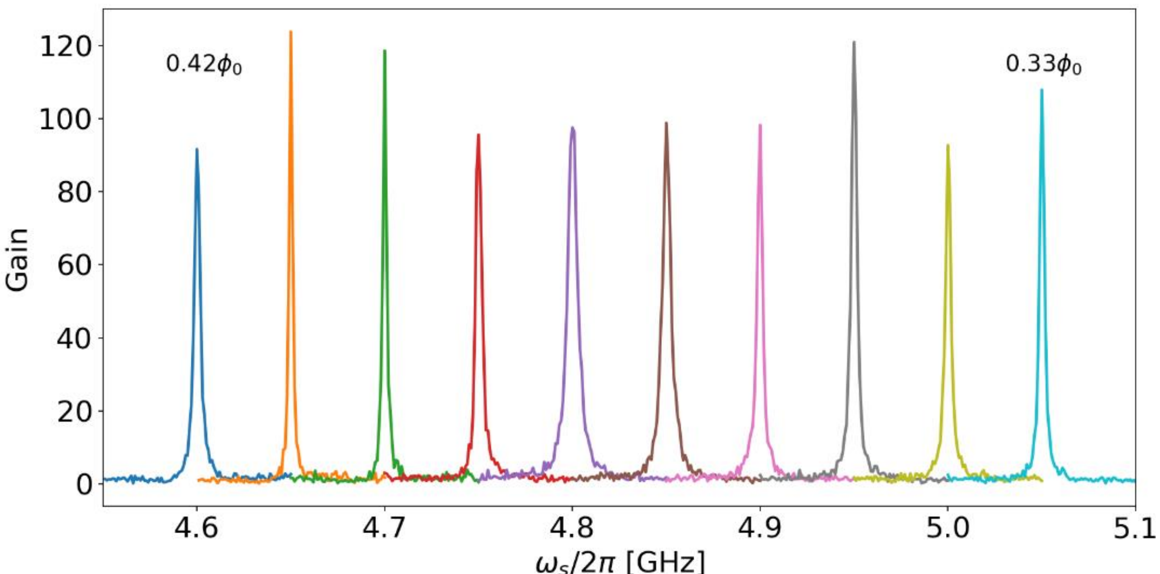
Amplifier Operation (Phase Insensitive)

Pump off



Pump on, $\omega_p = 2\omega_r$ (2ω pumping)





- Resonance frequency tuning via flux
- Gain-bandwidth product

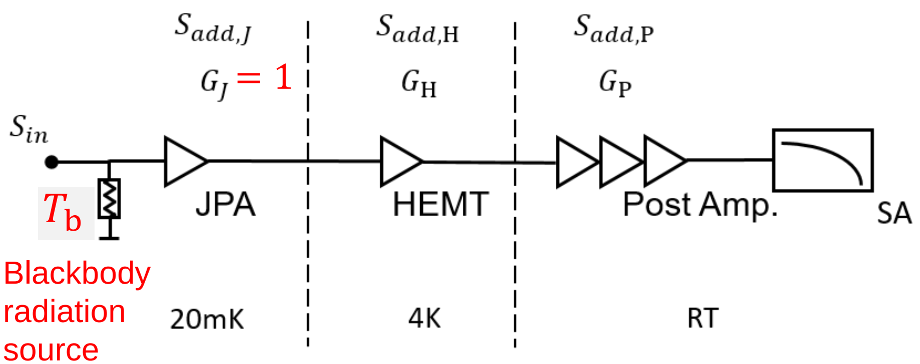
  40 MHz
- Tunability

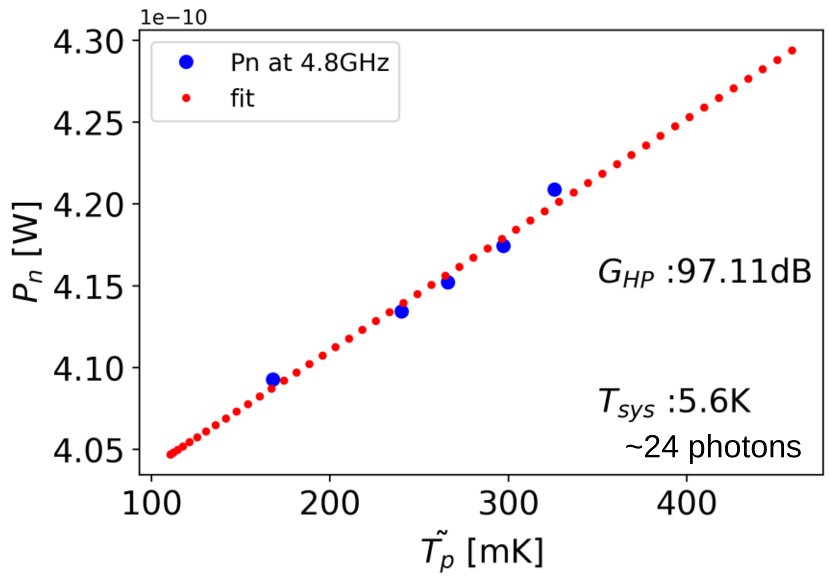
  $0.42 - 0.38\Phi_0$

  $4.60 - 5.05$ GHz

Gain and Noise Calibration

Y-factor method to characterize system noise with JPA pump off





$$P_n = G k_B (\tilde{T}_b + T_a)\Delta f$$

$$\tilde{T}_b = \frac{\hbar\omega}{k_B}\left(\frac{1}{\exp(\hbar\omega/k_B T_b) - 1} + \frac{1}{2}\right)$$

thermal vacuum

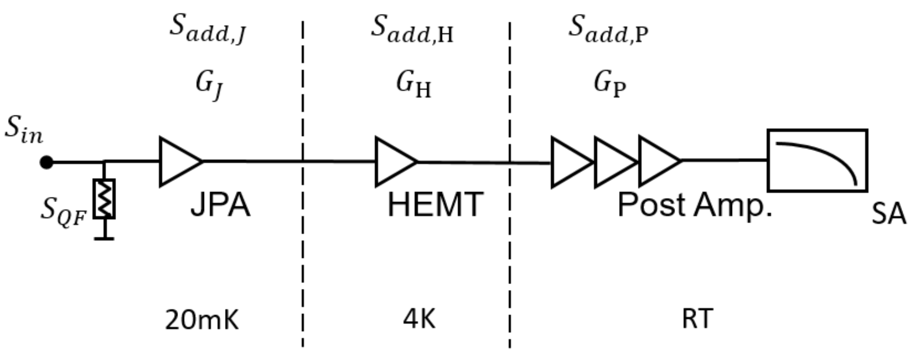
For ω ~ 5 GHz,

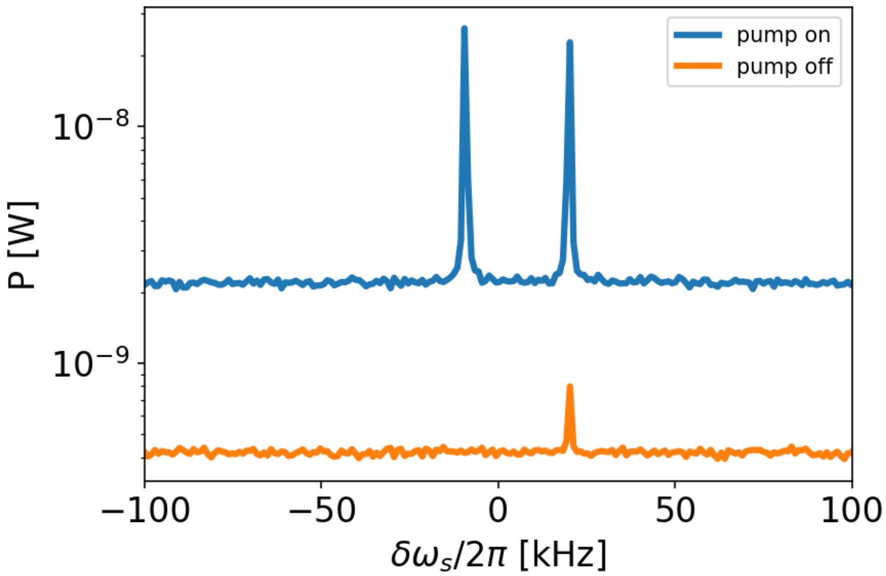
$\tilde{T}_b \approx 0.12$ K, as $T_b \ll 0.12$ K

$\tilde{T}_b \approx T_b$, as $T_b \gg 0.12$ K

Noise Performance

Signal-to-noise improvement method





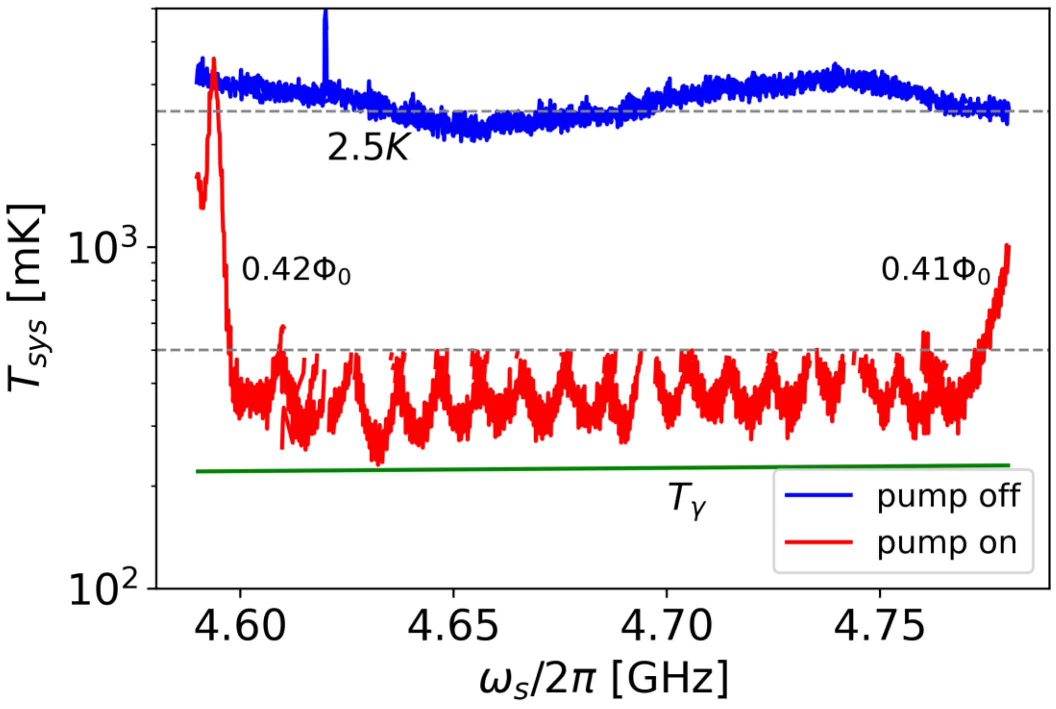
$P_{\mathrm{s,off}} = 0.368$ nW $\quad P_{\mathrm{s,on}} = 24.0$ nW

$P_{\mathrm{n,off}} = 0.430$ nW $\quad P_{\mathrm{n,on}} = 2.07$ nW

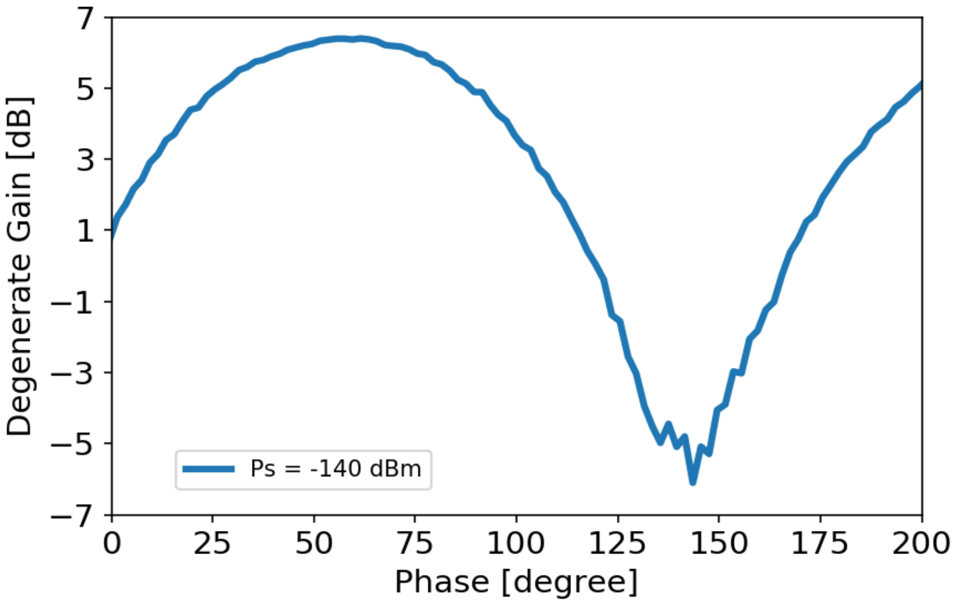
- $G_{\mathrm{JPA}} \sim 65.2 = 18.1$ dB
- SNR improvement $\beta \sim 13.5$
- Reduce detection time by a factor of $\beta^2 \sim 182$
- $T_{\mathrm{sys,on}} = T_{\mathrm{sys,off}}/\beta \sim 0.41$ K ($T_{\mathrm{sys,off}} \sim 5.6$ K)
- $T_{\mathrm{JPAa}} = T_{\mathrm{sys,on}} - T_{\mathrm{q}}/2 - T_{\mathrm{sys,off}}/G_{\mathrm{JPA}} \sim 0.21$ K

Noise Performance vs. Operation Frequency

Consistent noise performance over frequency tuning



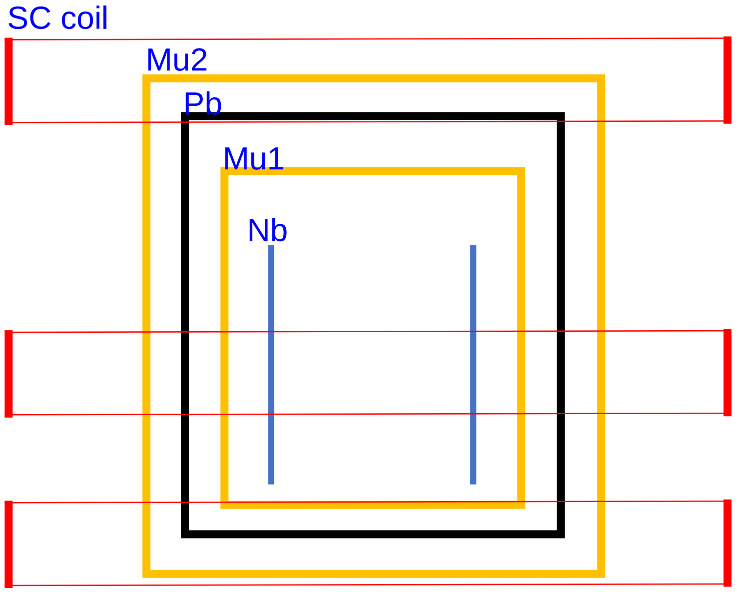
Degenerate Mode Operation

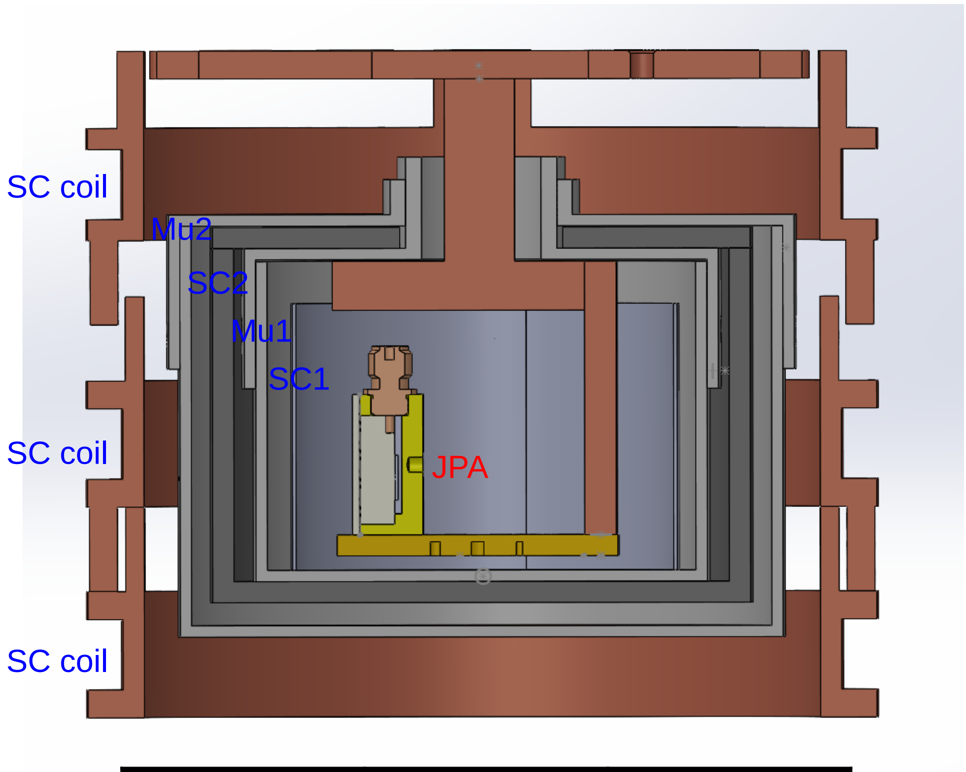


- Gain depends on phase of signal (relative to phase of pump)
- Maximum deamplification $G_Q \sim -6.5$ dB
- $\sqrt{G_I} \cdot \sqrt{G_Q} = 1$
- Precursor of squeezed vacuum state

Static Magnetic Field Shielding

Multilayer shielding





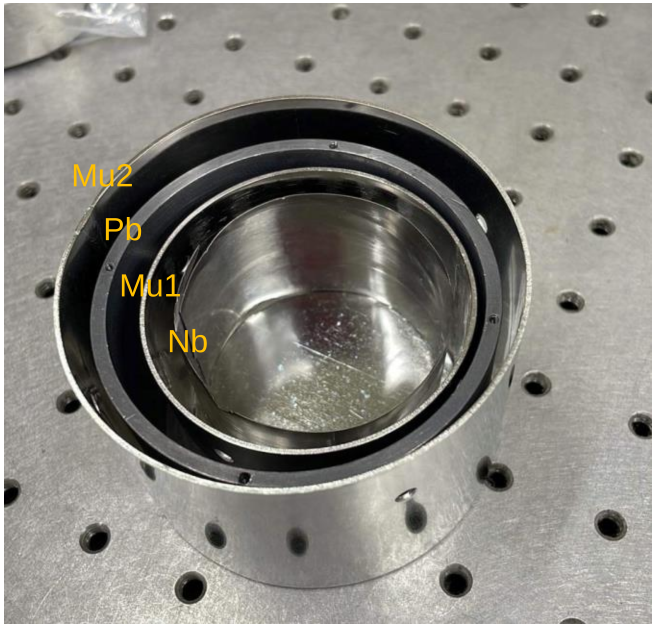
Goal: field reduced by a factor of 1000

Layer	Material	OD/ID (mm)
SC1	Nb	65.2/62.0
Mu1	A4K	68.4/65.2
SC2	Pb	77.4/71.4
Mu2	A4K	89.8/86.3

Ref: S. Kenany *et al.*, *Nucl. Instrum. Meth. A* **854**, 11 (2017)

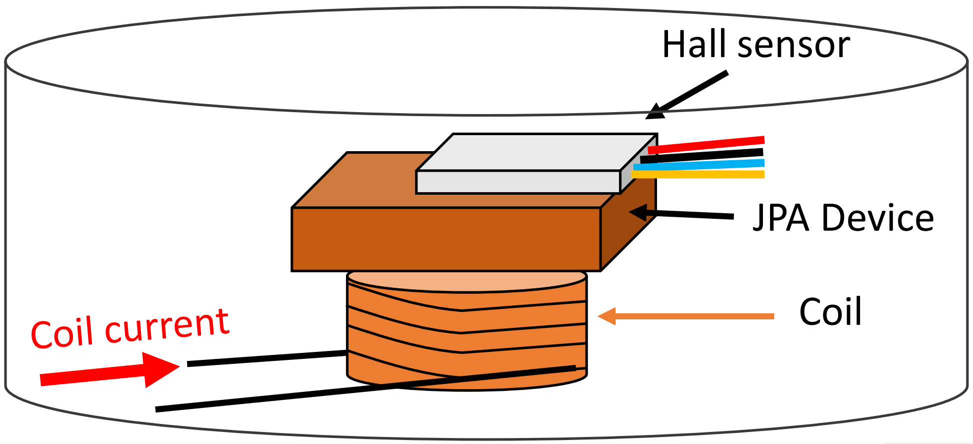
Shielding Set

Multilayer shielding



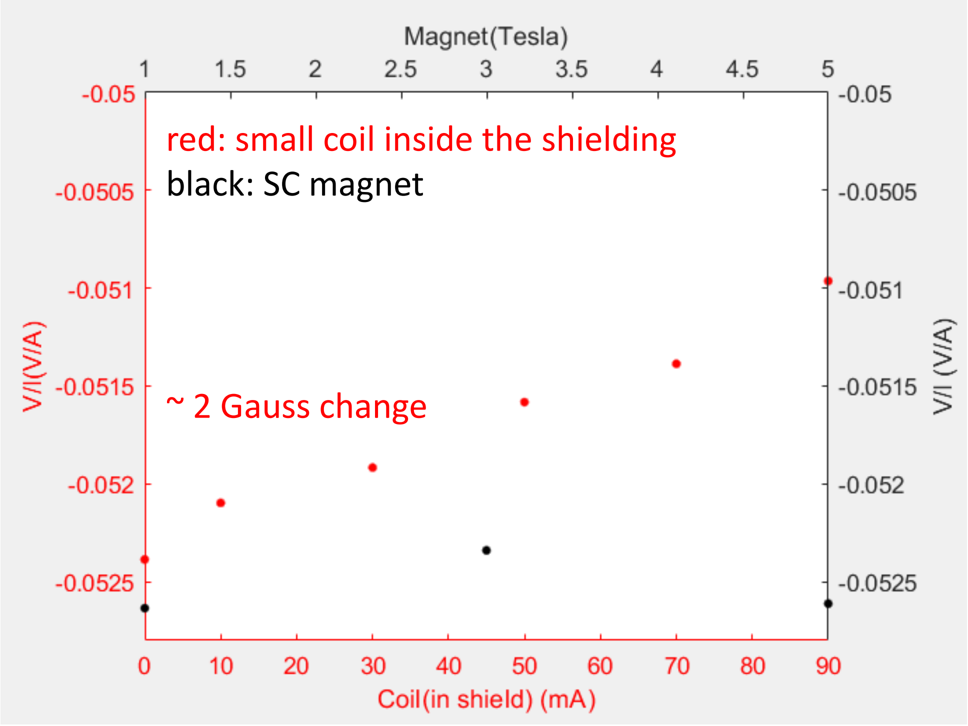
Shielding Effect

Setup

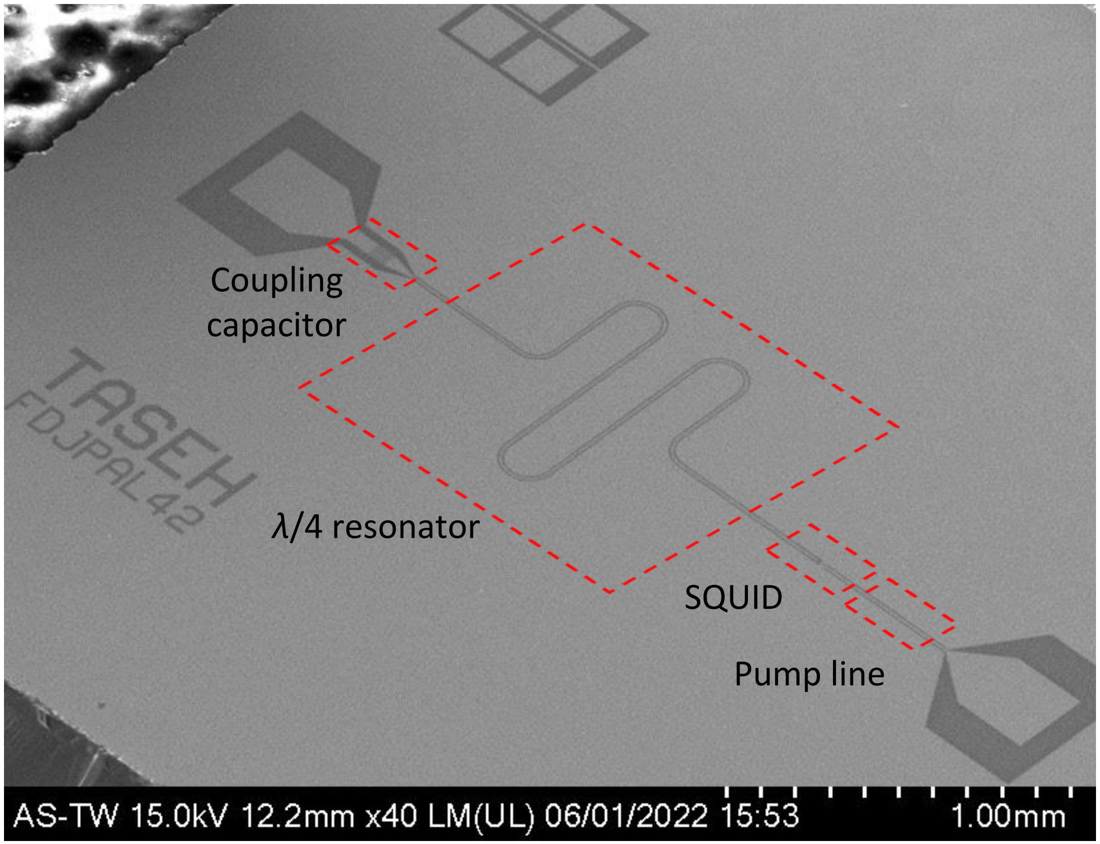


1~5 T from SC magnet in z-direction

Hall sensor calibrated sensitivity:
1200 gauss/(V/I)



JPA Performance Summary



Type	FDJPA
Gain	20 dB
Bandwidth	~ 5 MHz
Central frequency	4.60 – 5.05 GHz
Added noise	~ 210 mK
1dB compression	−135 dBm
Deamplification	−6.5 dB
Pump power	−65 – −40 dBm

Reasonable for axion haloscope application

Expected Performance of Upgrade Setup

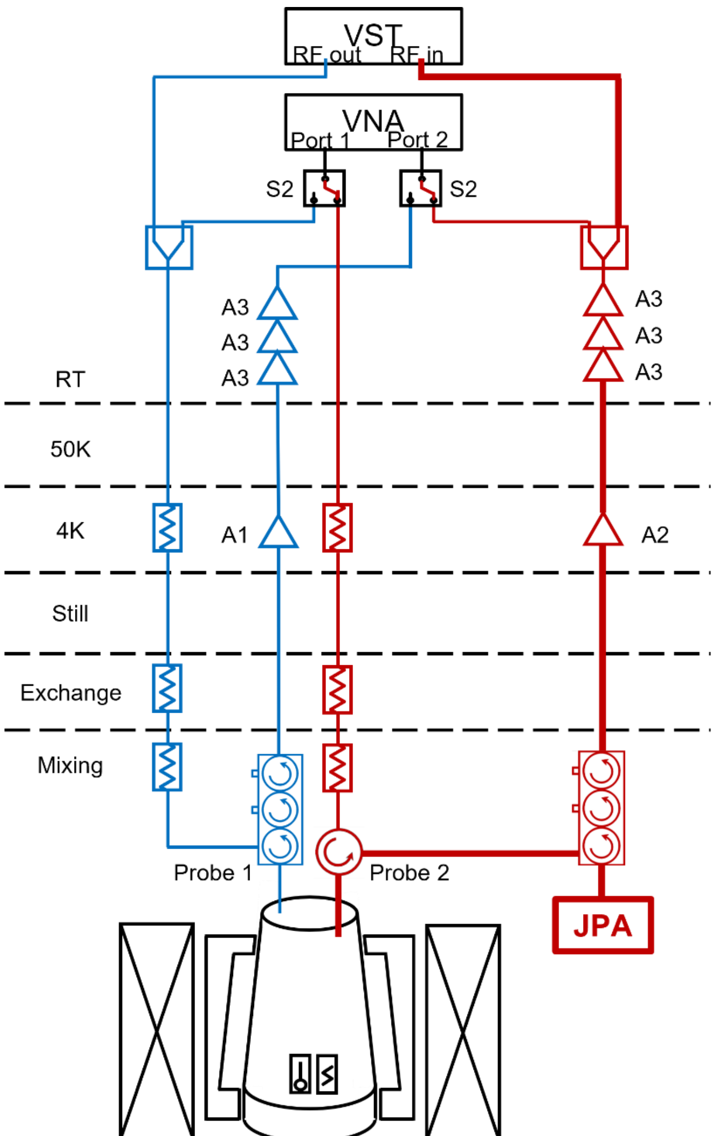
- Magnet upgrade
- Large conic shell cavity design
- JPA

Improvement

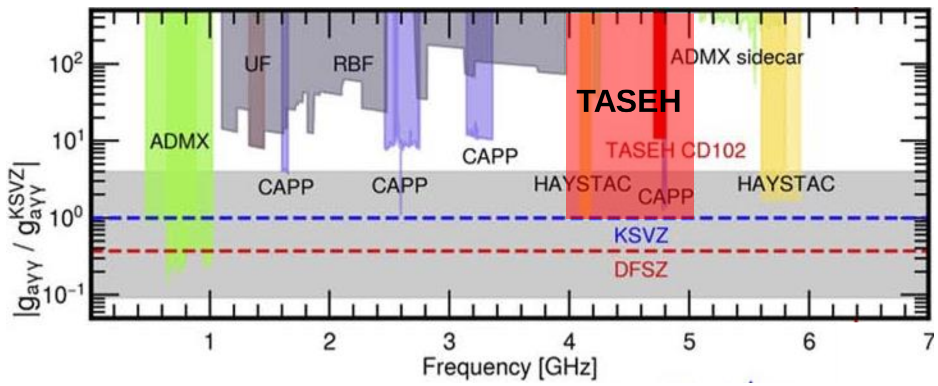
Haloscope performance	1st results	Planned goal
B_0 (T)	8	9
V (L)	0.23	1.66
C_{010}	0.62	0.73
Q_0	62000	42000
T_{sys} (K)	2.2	0.3
$g_{a\gamma\gamma}$ (GeV^{-1})	8.1×10^{-14}	9.0×10^{-15}
Refer to KSVZ	11	1.2

Planned Search Goal

Upgrade haloscope scheme:



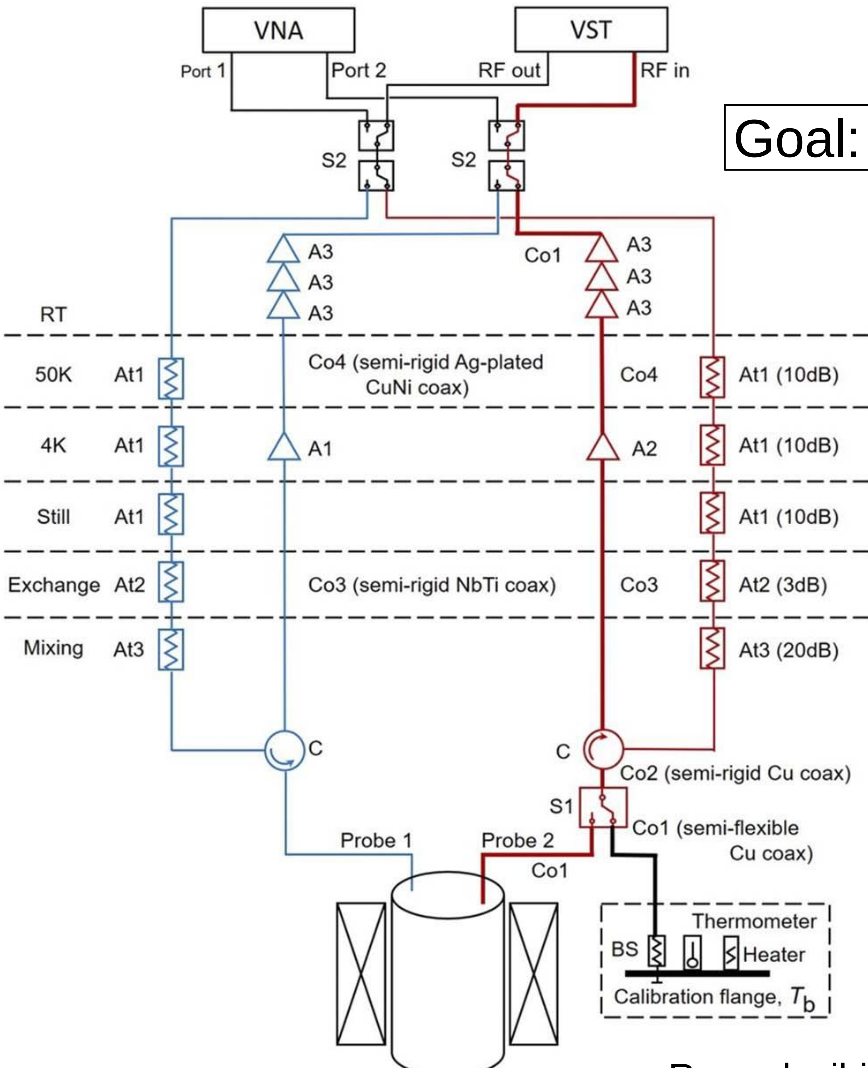
Search exclusion plot



- Improve SNR by 8 – 10 times with magnet + cavity + readout upgrade, improve detection limit by ~ 3 times
- Reach QCD benchmark model
- Search 4 – 5 GHz axion via several cavities with similar design

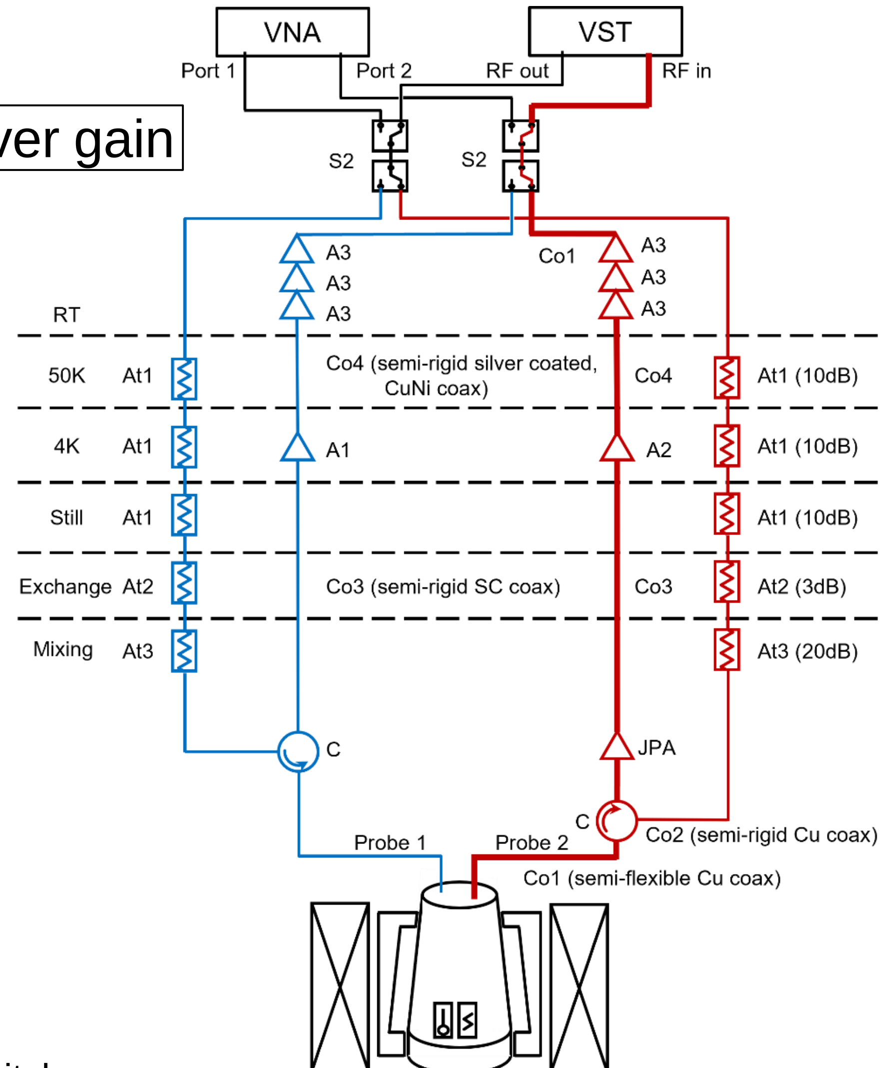
Cavity as Noise Source for Receiver Calibration

Original calibration setup



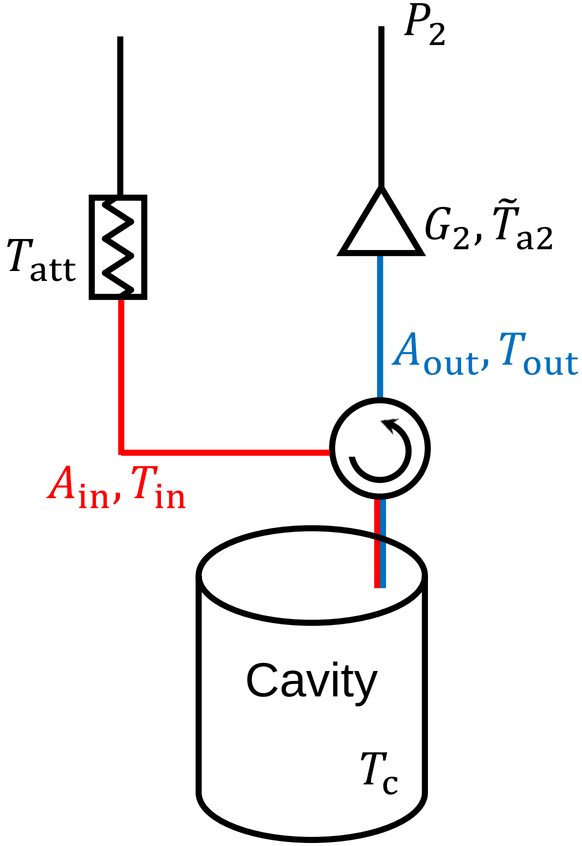
Goal: receiver gain

Cavity calibration setup



- Reproducibility of switch
- Similarity of different lines

Noise Power in Readout



No loss

$$P_2 = k_B \Delta f G \{|S_{22}|^2 \tilde{T}_{\mathrm{att}} + |S_{20}|^2 \tilde{T}_{\mathrm{c}} + \tilde{T}_{\mathrm{a2}}\}$$

$$\tilde{T}_i = \frac{\hbar\omega}{k_{\mathrm{B}}}\left(\frac{1}{\exp(\hbar\omega/k_{\mathrm{B}}T_i) - 1} + \frac{1}{2}\right)$$

$$|S_{22}|^2 = \frac{(\kappa_0 - \kappa_2)^2 + 4\Delta^2}{(\kappa_0 + \kappa_2)^2 + 4\Delta^2} \qquad \Delta = \omega - \omega_{\mathrm{c}}$$

$$|S_{20}|^2 = \frac{4\kappa_0\kappa_2}{(\kappa_0 + \kappa_2)^2 + 4\Delta^2}$$

With cable loss

$$P_2 = k_B \Delta f G_2 \{A_{\mathrm{out}} \{|S_{22}|^2 [A_{\mathrm{in}} \tilde{T}_{\mathrm{att}} + (1 - A_{\mathrm{in}}) \tilde{T}_{\mathrm{in}}] + |S_{20}|^2 \tilde{T}_{\mathrm{c}}\} + (1 - A_{\mathrm{out}}) \tilde{T}_{\mathrm{out}} + \tilde{T}_{\mathrm{a2}}\}$$

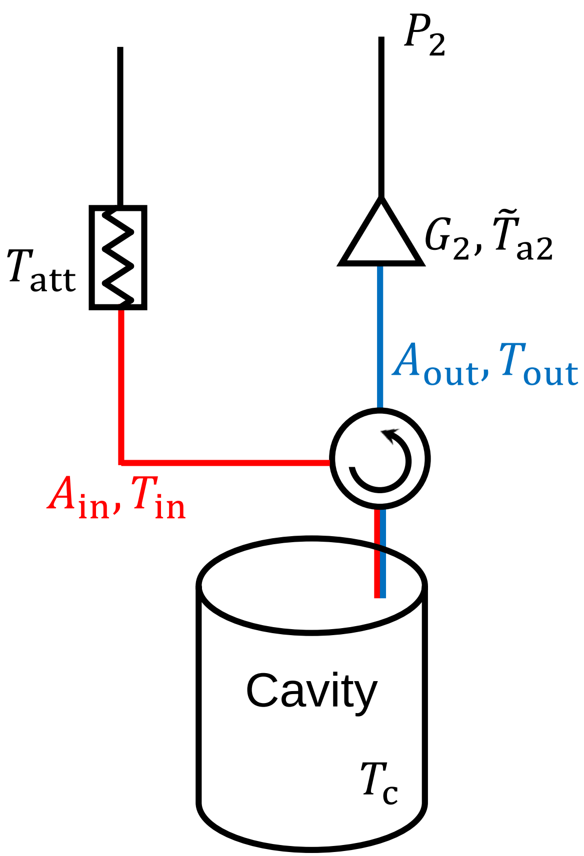
Simplified

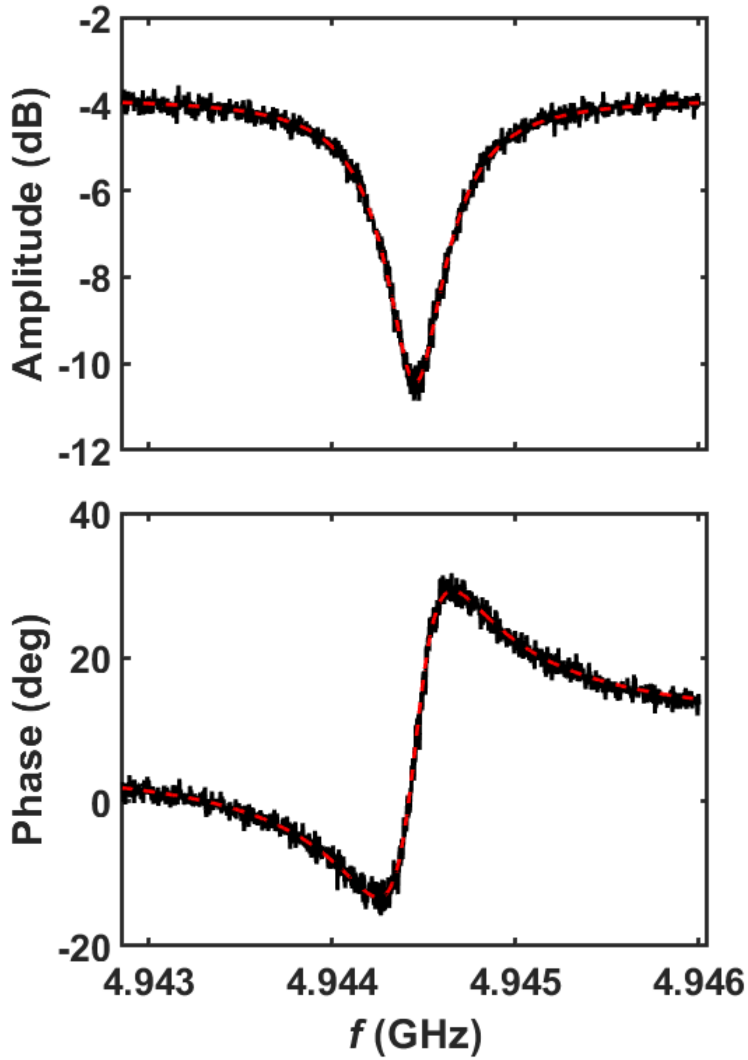
$$P_2 = k_B \Delta f G_2' \left\{\{|S_{22}|^2 [A_{\mathrm{in}} \tilde{T}_{\mathrm{att}} + (1 - A_{\mathrm{in}}) \tilde{T}_{\mathrm{in}}] + |S_{20}|^2 \tilde{T}_{\mathrm{c}}\} + \tilde{T}_{\mathrm{a2}}'\right\}$$

$$G_2' = G_2 A_{\mathrm{out}}$$

$$\tilde{T}_{\mathrm{a2}}' = (1 - A_{\mathrm{out}}) \tilde{T}_{\mathrm{out}} + \tilde{T}_{\mathrm{a}}$$

S_{22} Measurement

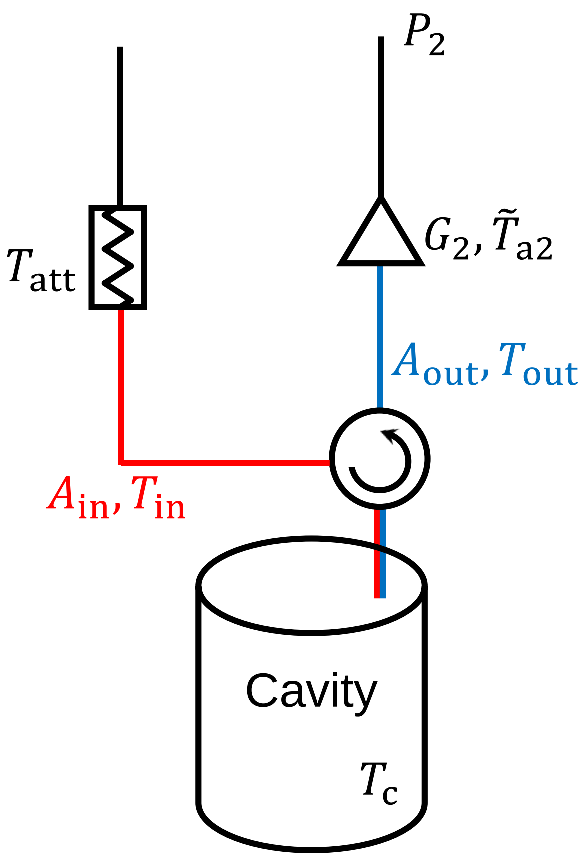


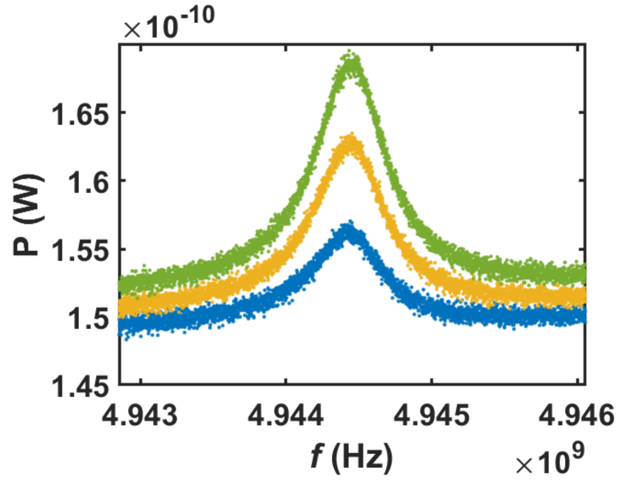


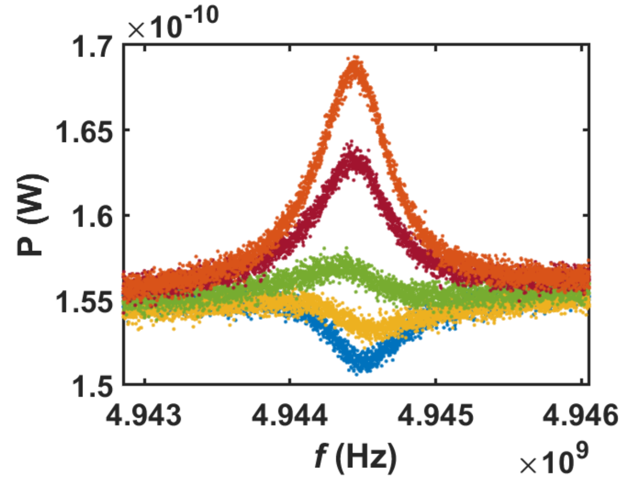
$f_c = 4.9445$ GHz
$\kappa_2/2\pi = 156$ kHz
$\kappa_0/2\pi = 432$ kHz

$$\frac{V_2^-}{V_2^+} \equiv S_{22} = \frac{\kappa_0 - \kappa_2 + i2(\omega - \omega_c)}{\kappa_0 + \kappa_2 + i2(\omega - \omega_c)}$$

Noise vs. Temperatures





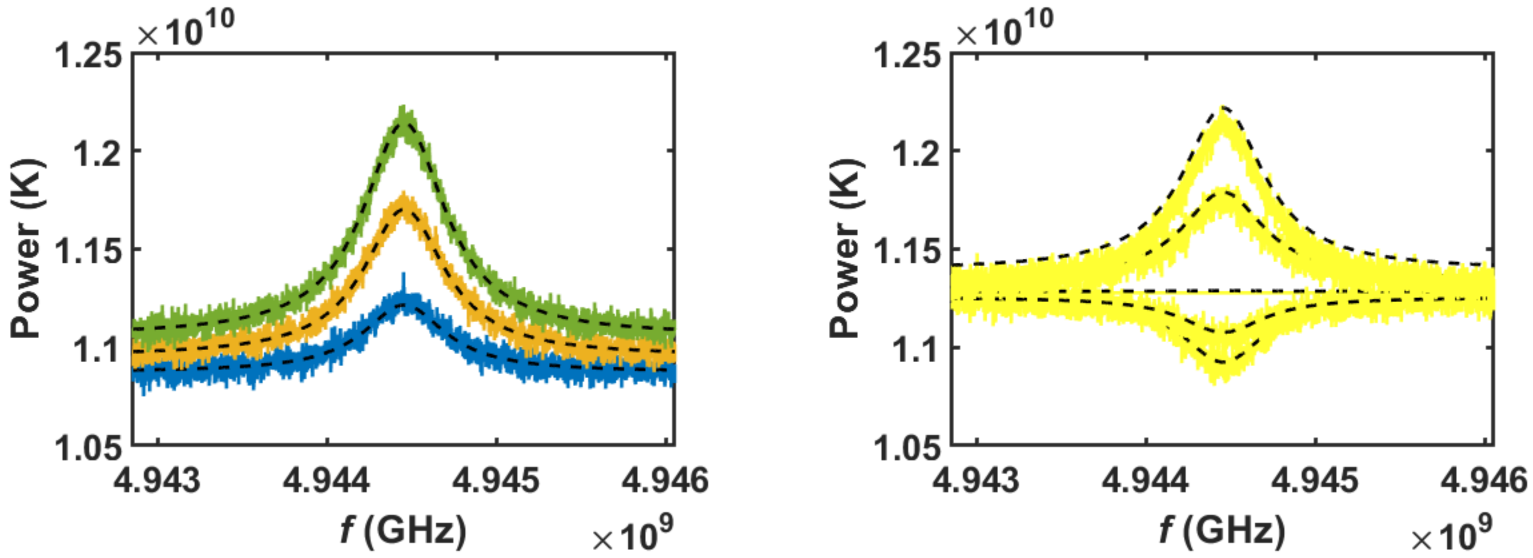


Tatt (mK)	Tc (mK)
147	910
108	646
83	348

Tatt (mK)	Tc (mK)
341	909
339	648
336	338
332	202
342	78

- Vary T_{att} and T_c and measure noise power
- Excess noise at cavity resonance frequency as $T_c > T_{att}$
- Frequency dependence of noise comes from gain
- Other sets of data normalized by data of $T_c \approx T_{att}$

Gain and Noise Calibration



$$P_2 = k_B \Delta f\, G_2' \left\{ \{ |S_{22}|^2 [A_{\rm in} \tilde{T}_{\rm att} + (1 - A_{\rm in}) \tilde{T}_{\rm in}] + |S_{20}|^2 \tilde{T}_{\rm c} \} + \tilde{T}_{\rm a2}' \right\}$$

$$G_2' = 93.1\ \text{dB},\ \ \tilde{T}_{\rm a2}' = 5.12\ \text{K},\ \ A_{\rm in} = 0.83$$

- Estimate $T_{\rm in} \equiv \frac{T_{\rm att} + T_{\rm c}}{2}$
- Fit the 1st set of data
- Obtain fitting parameters $G_2',\ \tilde{T}_{\rm a2}',\ A_{\rm in}$
- Use fitting result and plot expected power on the 2nd set of data
- Model is reasonable; heated cavity can be used for gain/noise calibration

Thanks to Our Collaboration

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PA development

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Jeng-Chung Chen (NTHU)
Chao-Te Li (ASIAA)
Tse-Jun Chen (ASIAA)

Taiwan Axion Search
Experiment with Haloscope

Summary

- First results of TASEH
  - 19.4687 – 19.8436 μeV (4.707 50 and 4.798 15 GHz, ~ 90 MHz search range)
  - Excludes models with the axion-two-photon coupling $g_{a\gamma\gamma} \geq 8.1 \times 10^{-14}$ GeV^{-1} (~ 11 times above QCD KSVZ model limit)
- TASEH ongoing development
  - Cone-shell cavity design: under development
  - JPA: ready
  - Gain and noise calibration via heated cavity: ready

Thank you for listening.
Comment/question?