

Pulse Tube Induced Systematic Effects and their Characterization

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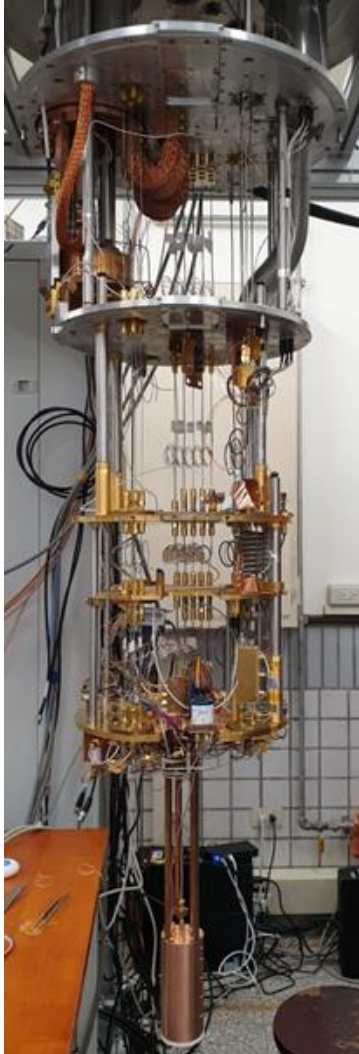
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Outline

- TASEH CDT045 preliminary run setup and result
- Observations of the Pulse Tube induced effect
- Similar effects reported by other groups
- Where the systematic effect enters – JPA on off experiment
- Quantifying the systematic uncertainty
- Conclusion and Future plan

CDT045 Experimental Setup and results

CD102



CDT045



$$P_{a \rightarrow \gamma} = \eta g_{a\gamma\gamma}^2 \left[\frac{\rho_a}{m_a} \right] B^2 V C Q_L, \quad \text{FoM} \propto \frac{B \sqrt{V C \sqrt{Q_L t}}}{\sqrt{T_{\text{sys}}}}$$

Parameter	CD102	CDT045
m_a (μeV)/ f_c (GHz)	19.47 – 19.84/ 4.71 – 4.80	8.92 – 9.02/ 2.156 – 2.180
T_{sys} (mK)	2300	350
η	0.69	0.67
B (Tesla)	7.8	6
V (L)	0.23	4
C	0.67	0.46
Q_L	2.0×10^4	6×10^3
$ g_{a\gamma\gamma}/g_{a\gamma\gamma}^{\text{KSVZ}} $	11	3.5

Data acquisition

Sampling & frequency resolution

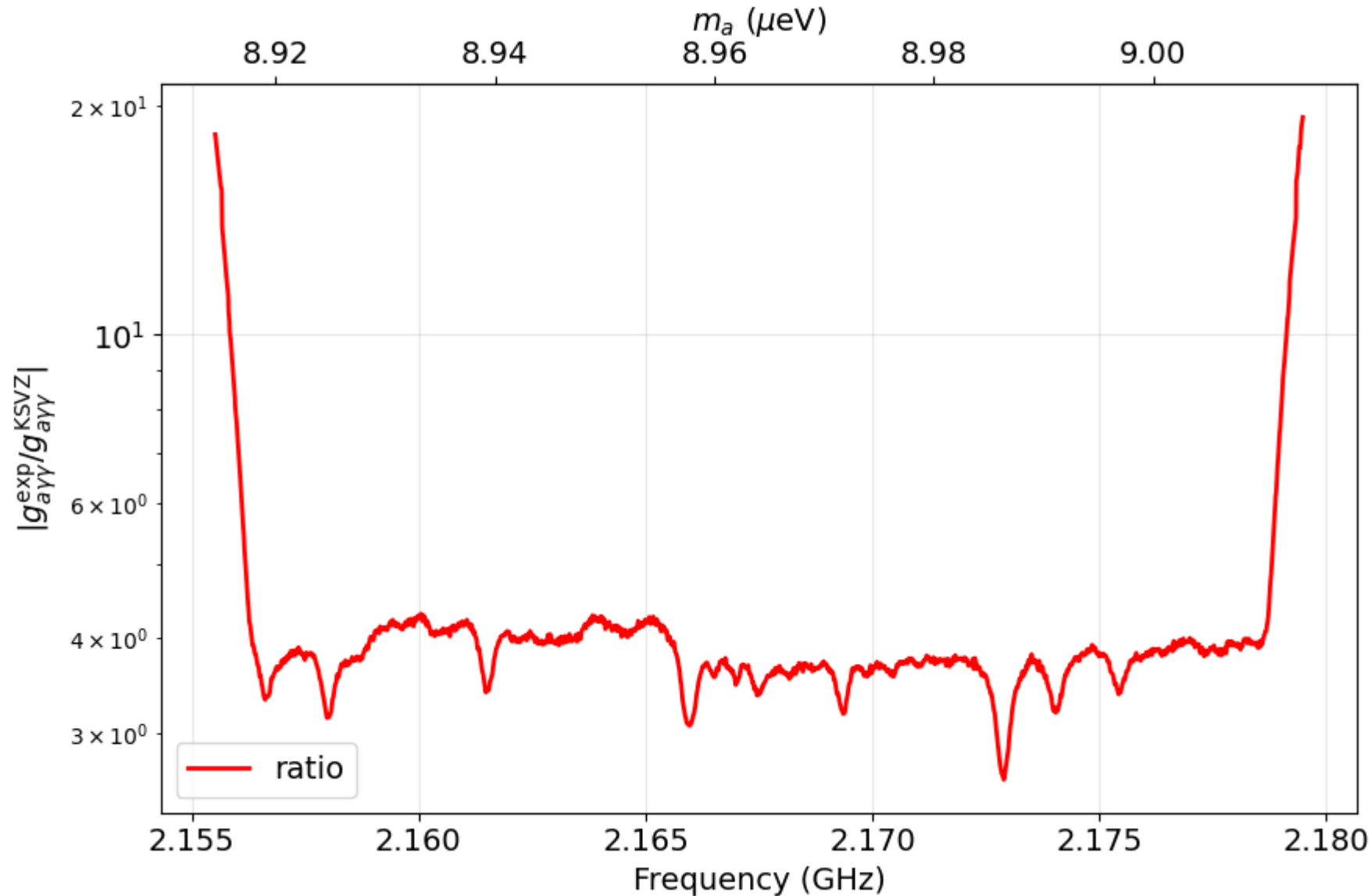
- VNA sampling rate: **2 MHz** $\rightarrow$ 2 MHz analysis span
- Target resolution: $\Delta f = 1 \text{ kHz} \rightarrow T = \frac{1}{\Delta f} = 1 \text{ ms}$

Data taking procedure (in each step)

- Perform the JPA on/off calibration, find G_{JPA} and SNR improvement η_{SNR} .
- Acquire data for 40 minutes.

In CDT045, we performed 146 steps + 26 rescans

CDT045 Experimental Setup and results



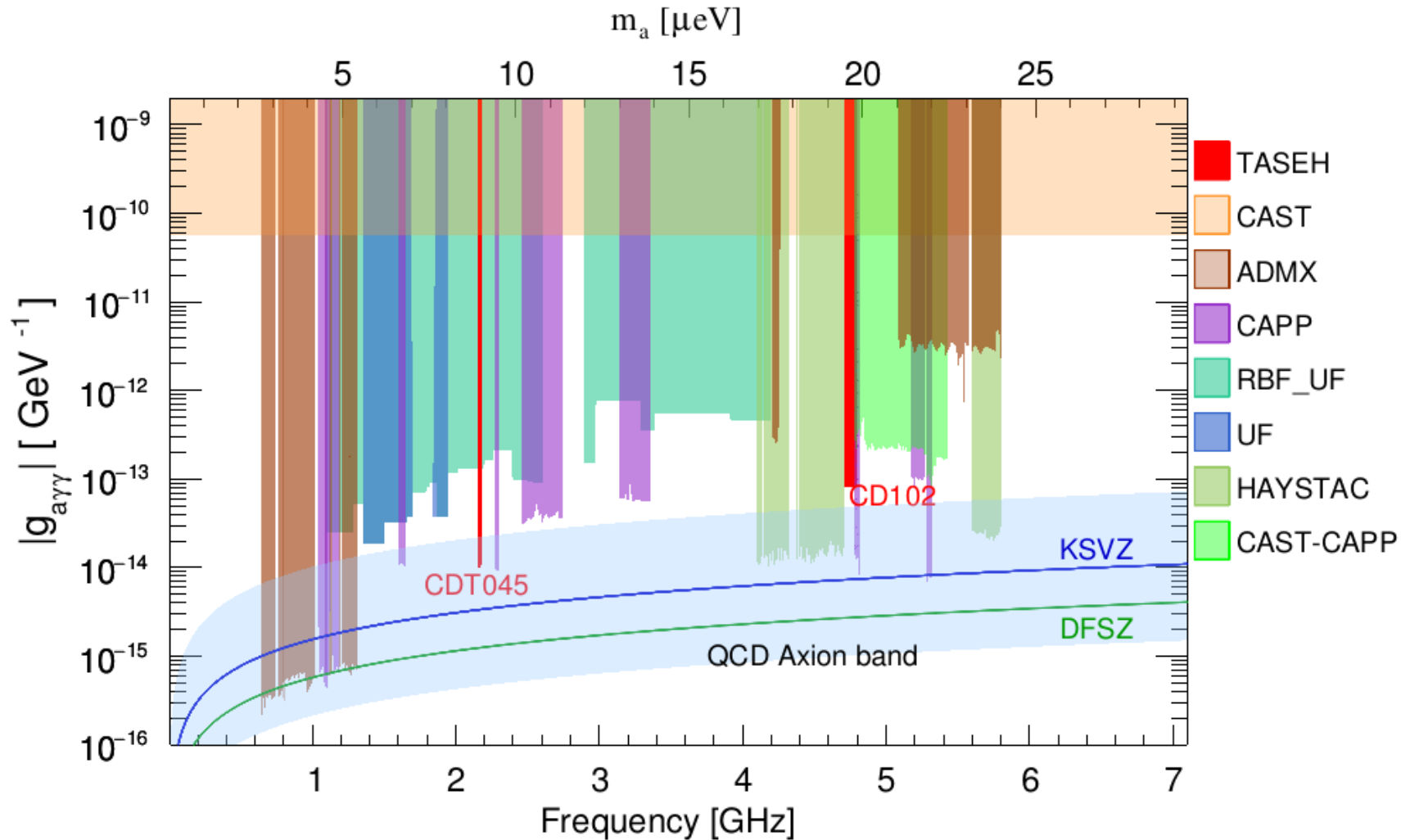
$B = 6 \text{ T}$

$T_{\text{sys}} \sim 350\text{mK}$

5σ SNR target was chosen, which correspond to a candidate threshold of 3.355σ at 95% C.L.

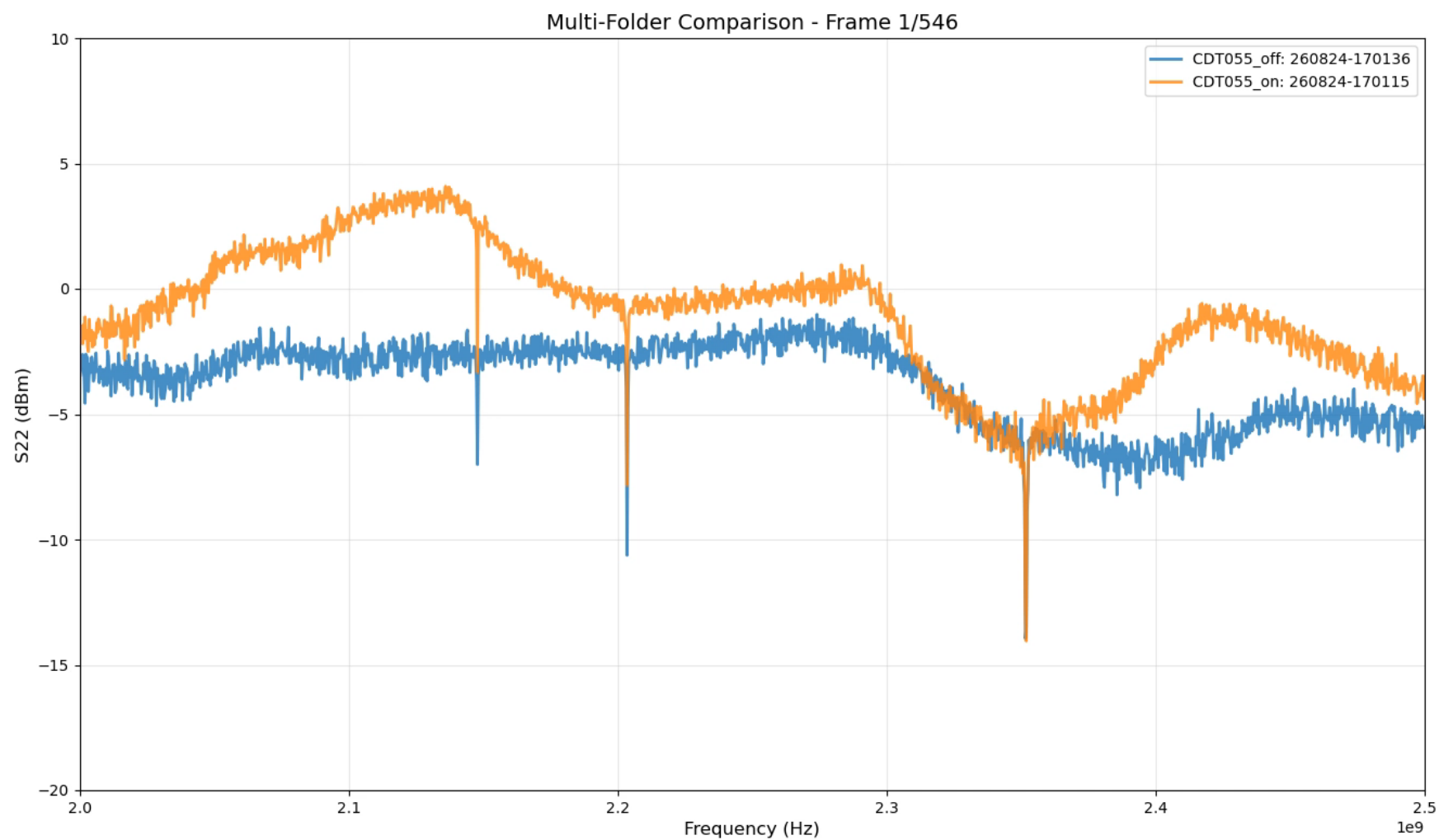
We can set an exclusion limit a factor of 3.5 above the KSVZ model.

CDT045 Experimental Setup and results



Pulse Tube Induced Effects

S matrix measurements while ramping the field to 9 T



Pulse Tube Induced Effects

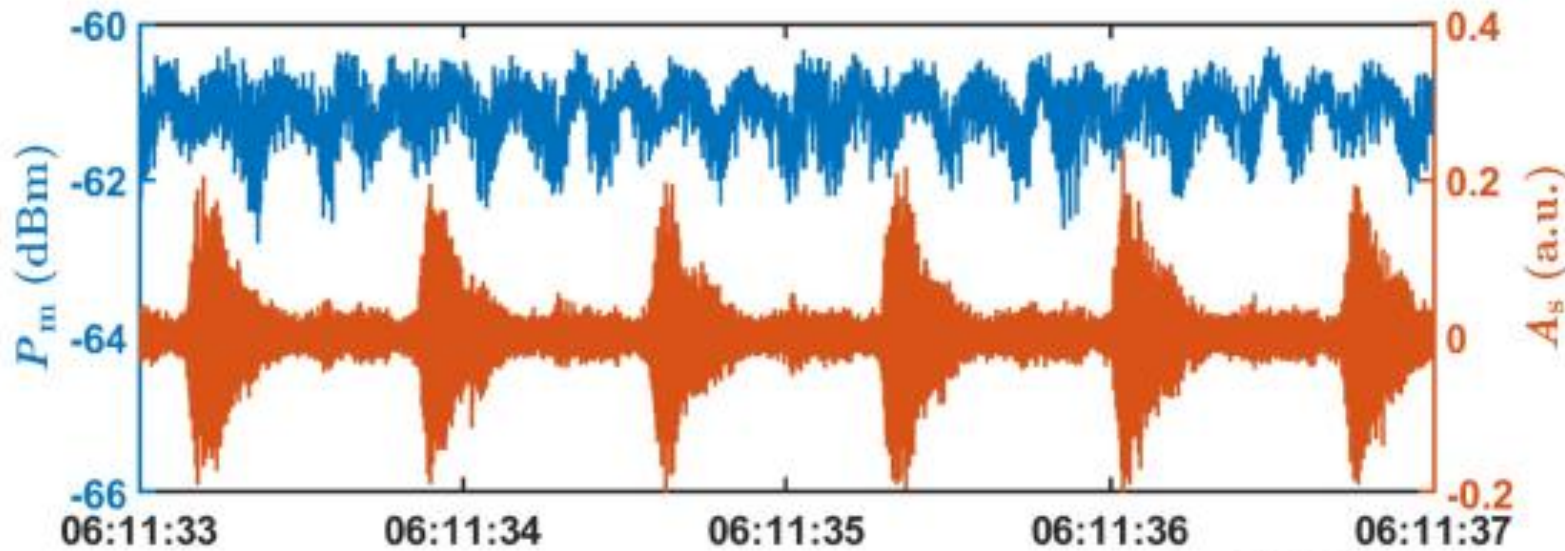


Fig. Time domain Power data from IQ measurement and PT sound record.

When the strong magnetic field is applied and the JPA is turned on, the **S-parameter** and **IQ measurements** show variations, which are synchronized to the pulse tube operating cycle.

Dec 10. 2025

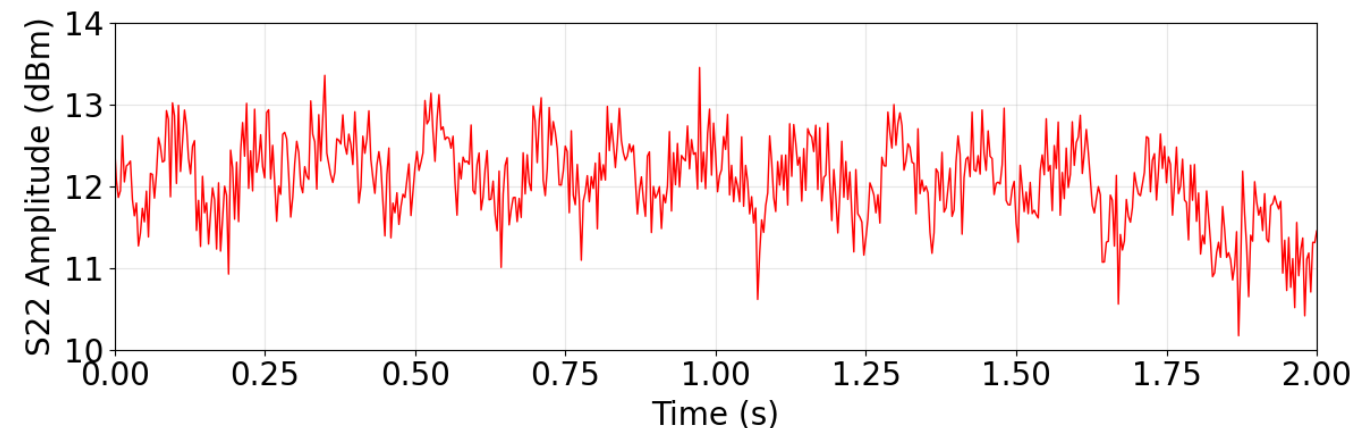
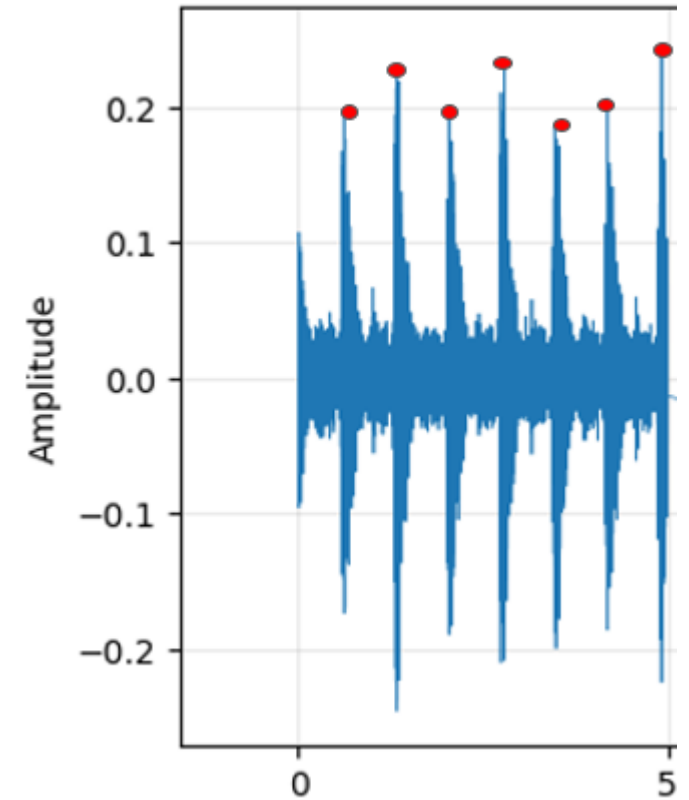
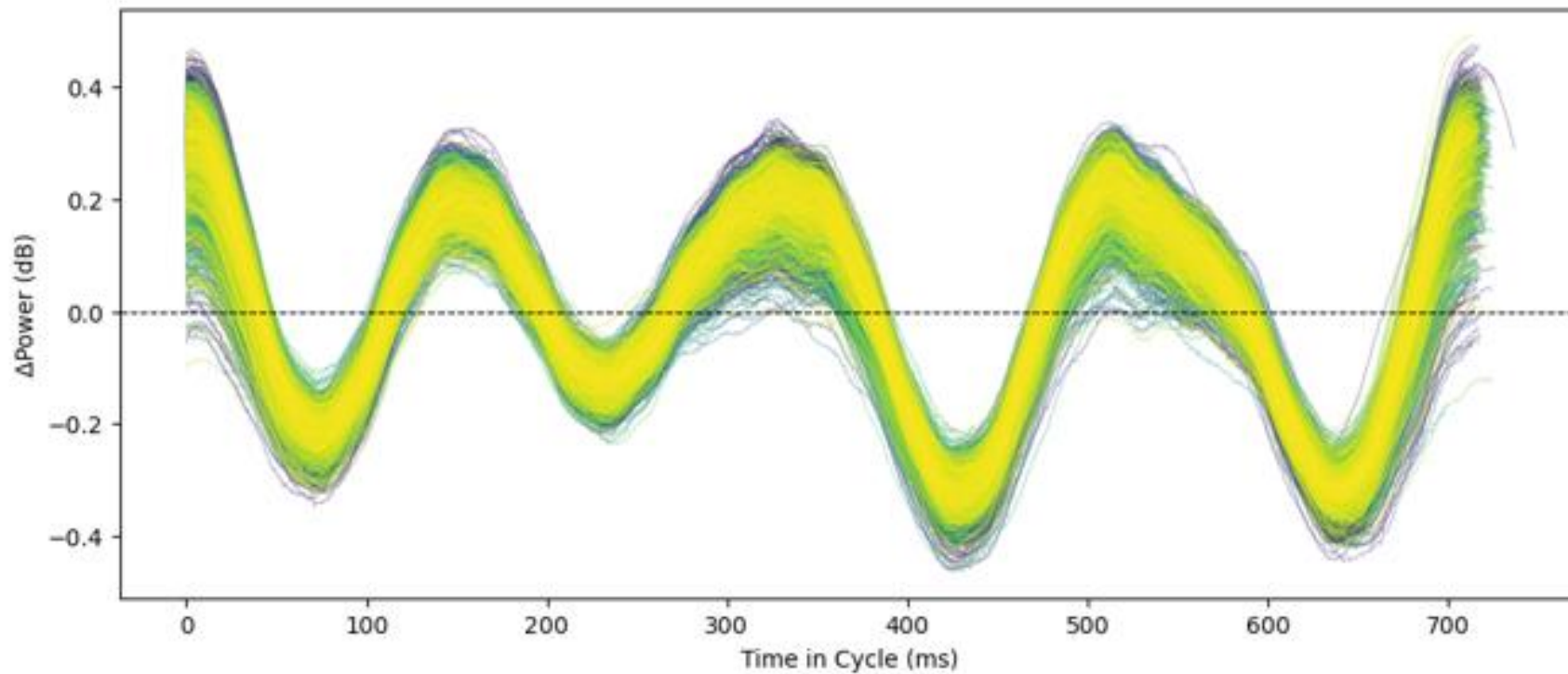


Fig. S22 measurement v.s. Time

PT Analysis w/out using time stamp

Overlay all cycles' power time series, smoothed by SG filter



Pulse Tube sound data

Similar effects reported by other groups

HAYSTAC – Benjamin M. Brubaker thesis 2018

- A strong modulation of the JPA gain by vibrational fluctuations, initially observed when the magnet was first ramped up to a few T.
- Total “chopping” of the gain (i.e., 100% modulation depth), correlated with the audible ≈ 1 **Hz cryocooler pulses**
- After JPA’s magnetic shielding improvement, the vibrational fluctuations were indeed significantly mitigated.
- The residual vibrational fluctuations were not due to appreciable penetration of the magnetic shielding by the external field; instead, some **unknown mechanism** through fridge vibrations can **modulate the pump power**.
- Fortunately, the vibration fluctuations exhibit strong temperature dependence, the effect completely disappear if the fridge is never allowed to cool below $T_{mc} \approx 100$ mK.

Similar effects reported by other groups

Article | [Open access](#) | Published: 10 May 2024

Mechanically induced correlated errors on superconducting qubits with relaxation times exceeding 0.4 ms

[Shingo Kono](#) , [Jiahe Pan](#), [Mahdi Chegnizadeh](#), [Xuxin Wang](#), [Amir Youssefi](#), [Marco Scigliuzzo](#) & [Tobias J. Kippenberg](#) 

[Nature Communications](#) **15**, Article number: 3950 (2024) | [Cite this article](#)

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Abstract

Superconducting qubits are among the most advanced candidates for achieving fault-tolerant quantum computing. Despite recent significant advancements in the qubit lifetimes, the origin of the loss mechanism for state-of-the-art qubits is still subject to investigation. Furthermore, the successful implementation of quantum error correction requires negligible correlated errors

between qubits. Here, we realize long-lived superconducting transmon qubits that exhibit fluctuating lifetimes, averaging 0.2 ms and exceeding 0.4 ms – corresponding to quality factors above 5 million and 10 million, respectively. We then investigate their dominant error mechanism. By introducing novel time-resolved error measurements that are synchronized with the operation of the pulse tube cooler in a dilution refrigerator, we find that mechanical vibrations from the pulse tube induce nonequilibrium dynamics in highly coherent qubits, leading to their correlated bit-flip errors. Our findings not only deepen our understanding of the qubit error

mechanisms but also provide valuable insights into potential error-mitigation strategies for achieving fault tolerance by decoupling superconducting qubits from their mechanical environments.

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With PT off:

Qubit stay at ground state.

With PT on:

Qubit is periodically excited to 1st even 2nd excited state.

Excitation occurs **only during the gas-flow-in phase** of the PT cycle

An electromagnet-driven hammer reproduces the excitations with the PT off → rules out electrical noise from the cryocooler

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Similar effects reported by other groups

Journal of Instrumentation

PAPER • OPEN ACCESS

Decoupling pulse tube vibrations from a dry dilution refrigerator at milli-Kelvin temperatures

A. Wex, J. Rothe, L. Peters, H. Abele, G. Angloher, B. Arnold, M. Atzori Corona, A. Bento, E. Bossio, J. Burkhardt [Show full author list](#)

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DOI 10.1088/1748-0221/20/05/P05022



Authors [▼](#) References [▼](#)

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Abstract

With the rising adoption of dry dilution refrigerators across scientific and industrial domains, there has been a pressing demand for highly efficient vibration decoupling systems capable of operation at cryogenic temperatures in order to achieve the low vibration levels required for operation of sensitive equipment like cryogenic detectors or quantum devices. As part of the NUCLEUS experiment, a cryogenic spring pendulum has been engineered to effectively isolate pulse tube vibrations by establishing an autonomous frame of reference for the experimental volume, while sustaining temperatures below 10 mK. Attaining attenuation of up to two orders of magnitude within the region of interest of the NUCLEUS cryogenic detectors, we achieved displacement RMS values in the order of 1 nm in the axial direction and 100 pm radially, thereby reducing vibrations below typical environmental levels. Our successful detector operation across multiple cooldown cycles demonstrated negligible sensitivity to pulse tube induced vibrations, culminating in the achievement of an ultra-low (6.22 ± 0.07) eV baseline resolution on a gram-scale CaWO_4 cryogenic calorimeter during continuous pulse tube operation over the course of several weeks.

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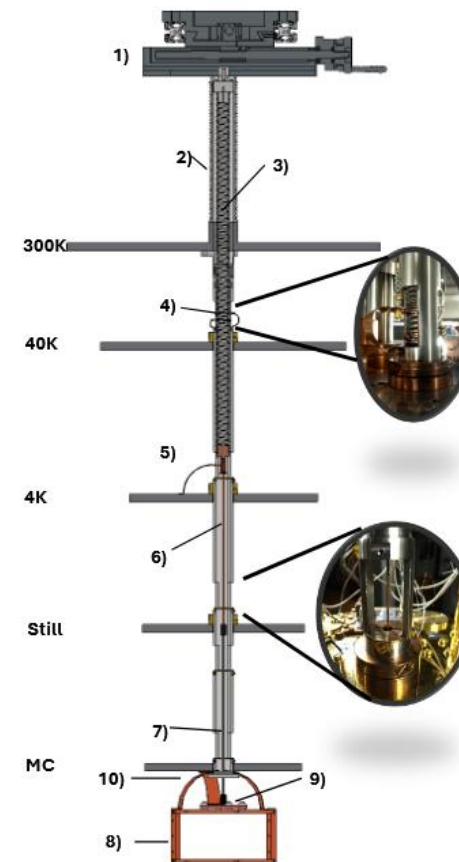
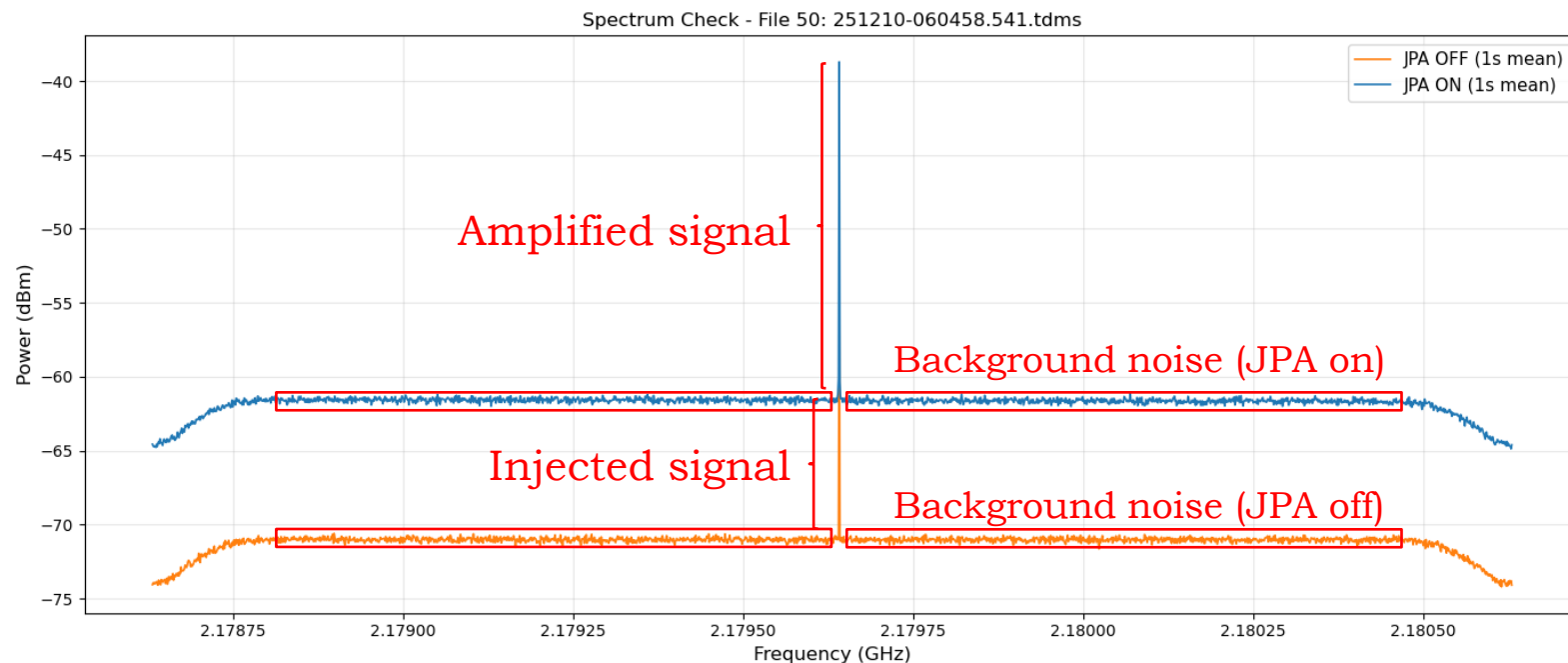


Figure 1. Schematic of the vibration decoupling system in a simplified cryostat for illustration, comprising in-plane positioning stage (1), vacuum bellow (2), steel extension spring (3), inner-spring radiation shields (4), 4 K thermal link (5), copper wire (6), Kevlar string (7), detector box (8), thermal decoupling stage (9) and thermal links to mixing chamber (10). Details are described in the text. The inset pictures show the inner-spring radiation shields (top) and a piece of the copper section fed through a radiation shield at still level (bottom).

PT effects on analysis and JPA on/off calibration

(1) 40 mins IQ data: we use 40 mins, 240,000 subspectrum averaged PS, over 3000 up PT cycles are averaged, PT effect nearly washed out.

(2) System temperature calibration: $T_{sys} = \frac{T_{sys}^{off}}{\eta_{SNR}}$, η_{SNR} : signal to noise ratio (SNR) improvement

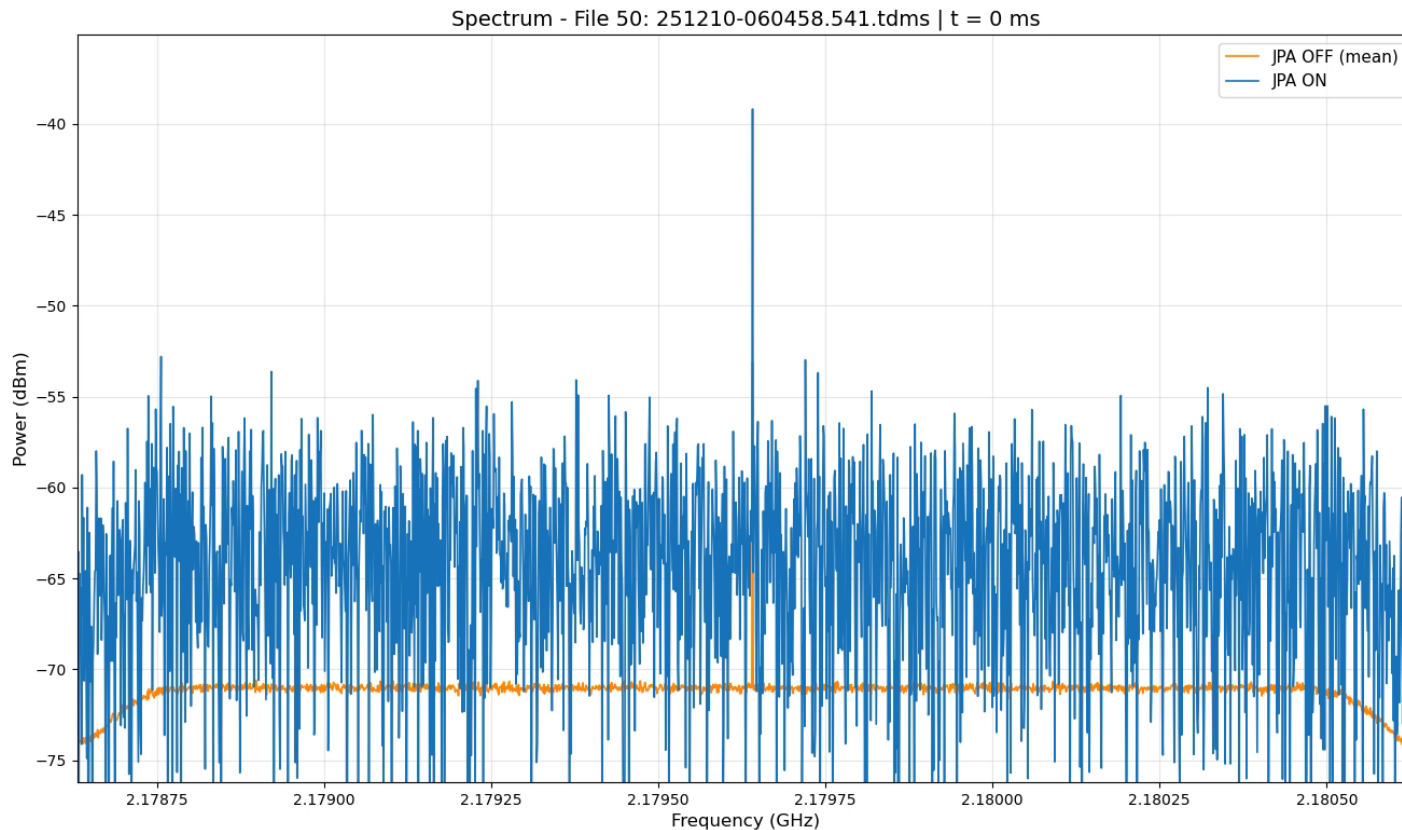


$$G_{JPA} = \frac{\text{Amplified signal}}{\text{Injected signal}}$$

$$\eta_{SNR} = \frac{\frac{\text{Amplified signal}}{\text{noise on}}}{\frac{\text{Injected signal}}{\text{noise off}}}$$

Fig. 1 s averaged power spectrum from JPA on/off calibration

PT effects on analysis and JPA on/off calibration

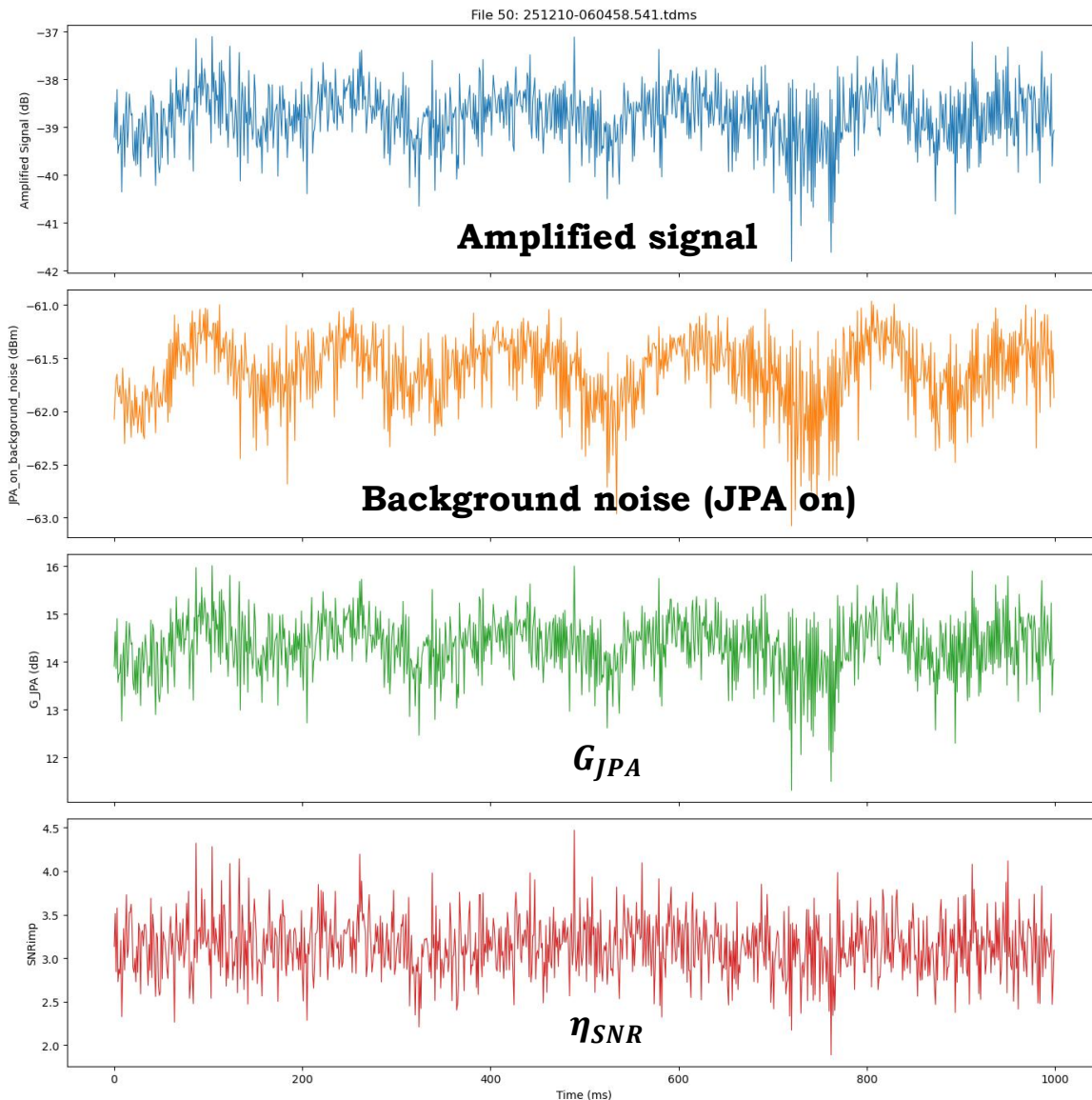


JPA off: 1-s averaged spectrum
(Injected signal & noise_off fixed).

JPA on: 1-ms * 1000 snapshots.
Each frame = one 1-ms spectrum

From each 1-ms frame we compute G_{JPA} and η_{SNR} , so we obtain their evolution over the full 0-1000 ms window.

PT effects on analysis and JPA on/off calibration



- **Amplified signal**, **noise_on**, and G_{JPA} all breathe together, ~ 0.8 dB peak-to-peak swing.

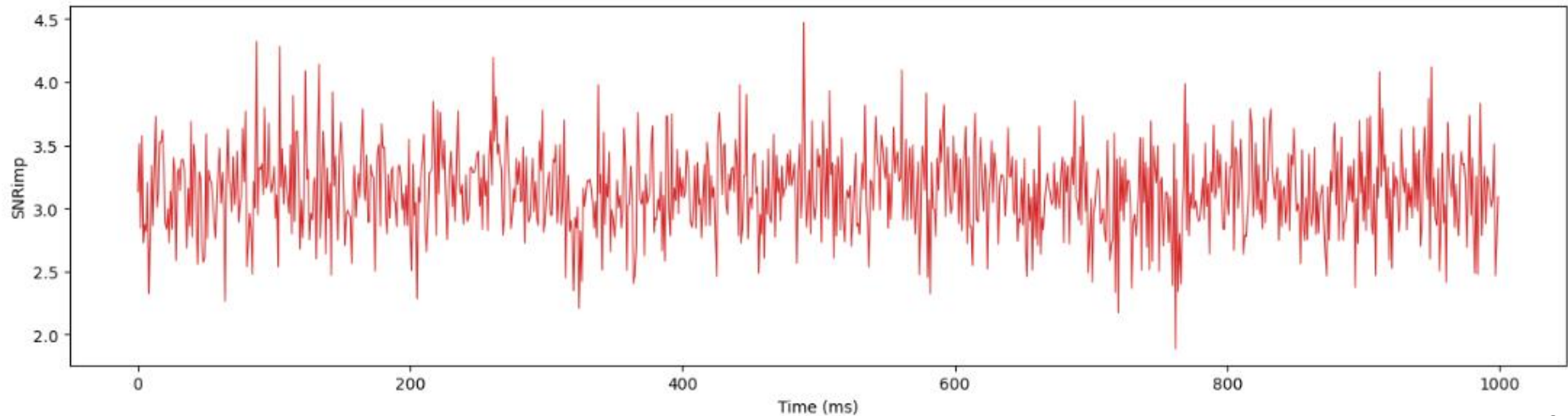
- $\eta_{SNR} = \frac{\frac{\text{Amplified signal}}{\text{noise on}}}{\text{noise off}}$, signal and noise share the same gain, so the PT effect largely cancels in the ratio.

η_{SNR} shows no apparent PT periodic structure — its fluctuation is dominated by white noise.

The residual PT effect still exists, but is buried under the noise.

Uncertainty of the 1-s averaged η_{SNR}

- One η_{SNR} value = average of 1000 * 1-ms samples in 1-s, how accurate is it?



N=1000 for 1-s data

- **If the 1000 samples were independent:**

$$\sigma_{\bar{\eta}} = \frac{\sigma_{\eta}}{\sqrt{N}} = \frac{\sigma_{\eta}}{\sqrt{1000}}, \text{ uncertainty of } \bar{\eta}_{SNR}, \text{ where } \sigma_{\eta} \text{ is the spread of the 1000 samples}$$

Uncertainty of the 1-s averaged η_{SNR}

- However, neighboring samples are correlated if PT effect exists. Therefore, we separate σ_η into σ_{white} and σ_{PT} :

$$\sigma_\eta^2 = \sigma_{white}^2 + \sigma_{PT}^2 \rightarrow \sigma_\eta^2 = \underbrace{\frac{\sigma_{white}^2}{N}}_{\text{indep.}} + \underbrace{\sigma_{PT}^2}_{\text{correlated}}$$

- σ_{PT} cannot be obtained from σ_η directly. To figure out how PT affects the system, we use the **data blocking method**[1][2], which is for efficiently arriving at the error of the mean for time-correlated data.

[1] H. Flyvbjerg and H. G. Petersen, "Error estimates on averages of correlated data" , J. Chem. Phys. 91, 461 (1989).

[2] Markus Deserno, "Analytical expressions for the blocking error of exponentially correlated Gaussian data"

Uncertainty of the 1-s averaged η_{SNR}

meas(b)

white(b)

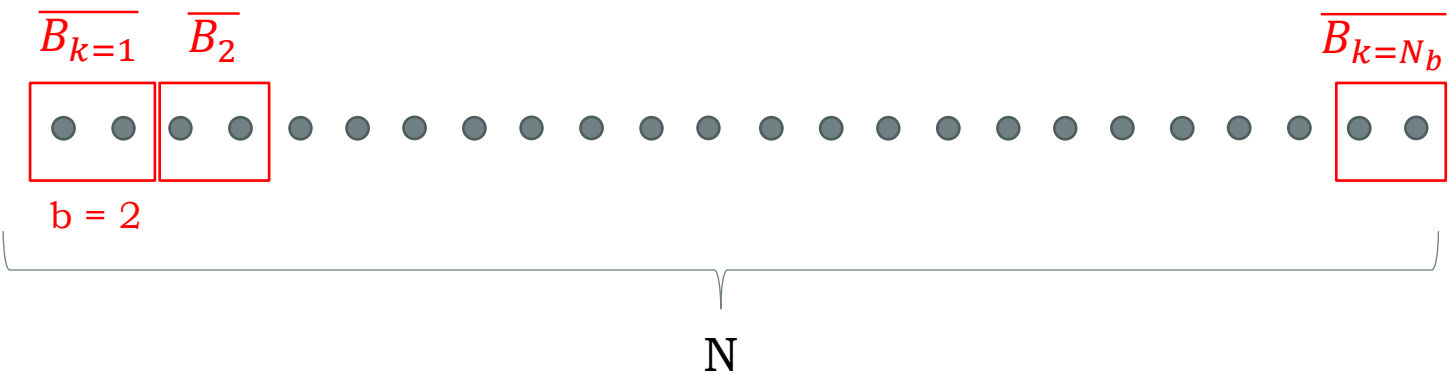
- Compare **the measured spread of block means** against **the pure white noise prediction**:

If all samples are independent, $white(b) = \frac{\sigma_\eta}{\sqrt{b}}$, so $meas(b) = white(b)$.

If PT exists, the samples are correlated and $meas(b) > white(b)$, and the excess gives σ_{PT} .

- σ_{PT} can be obtained by:

$$\sigma_{PT} = \sqrt{meas(b)^2 - white(b)^2}$$



symbol	meaning
b	Block size
N_b	# blocks
B_k	k-th block mean
$meas(b)$	Std of B_k
$white(b)$	Std of B_k if indep.
$r(b)$	=1 white, >1 cor.

Uncertainty of the 1-s averaged η_{SNR}

- Collect all η_{SNR} data and apply data blocking method, take the median over all data for the representative trend.

b	N_b	meas(b)%	white(b)%	r(b)	$\sigma_{PT}(b)\%$
1	1000	11.216	11.216	1.0000	0.000
2	500	7.952	7.931	1.0015	0.435
4	250	5.688	5.608	1.0176	1.057
5	200	5.172	5.016	1.0301	1.240
8	125	4.111	3.965	1.0456	1.211
10	100	3.736	3.547	1.0518	1.156
20	50	2.649	2.508	1.0746	0.987
25	40	2.380	2.243	1.0926	0.987
40	25	1.914	1.773	1.1068	0.841
50	20	1.745	1.586	1.1358	0.854
100	10	1.250	1.122	1.1724	0.686
125	8 *	1.145	1.003	1.1780	0.625
200	5 *	0.861	0.793	1.1228	0.405
250	4 *	0.769	0.709	1.1406	0.389
500	2 *	0.431	0.502	0.8587	0.000

- $r(b) = \frac{meas(b)}{white(b)}$

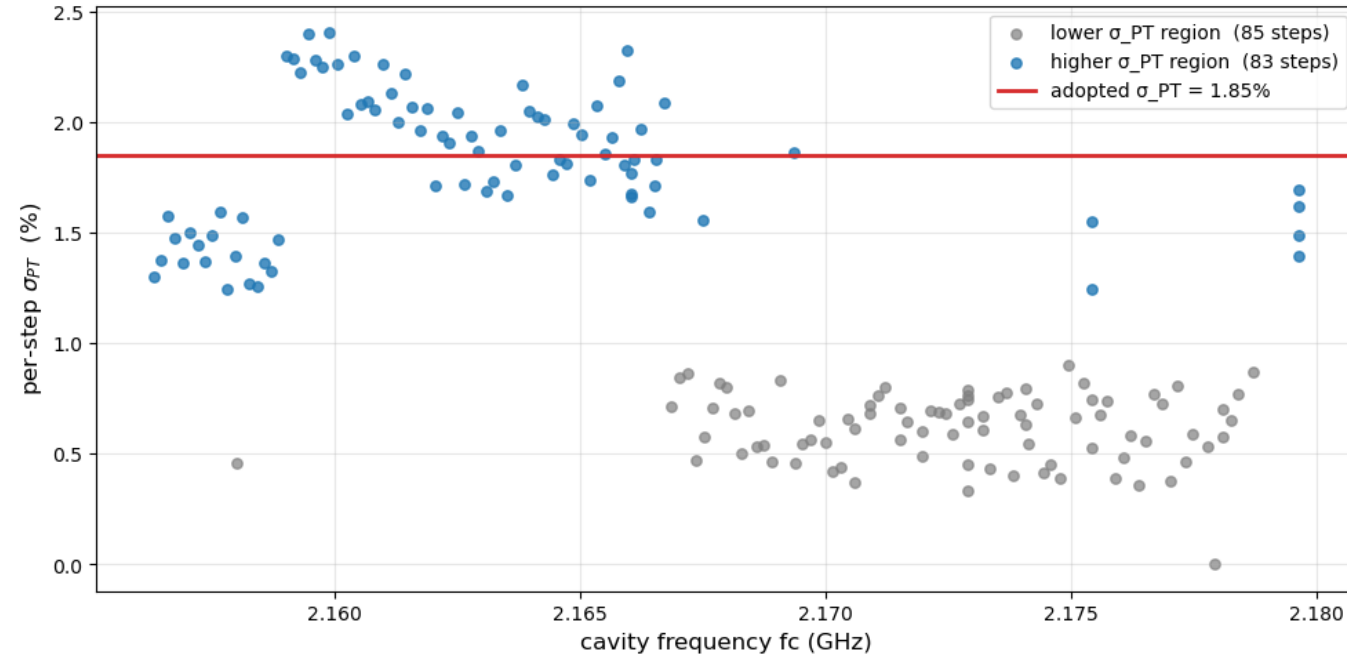
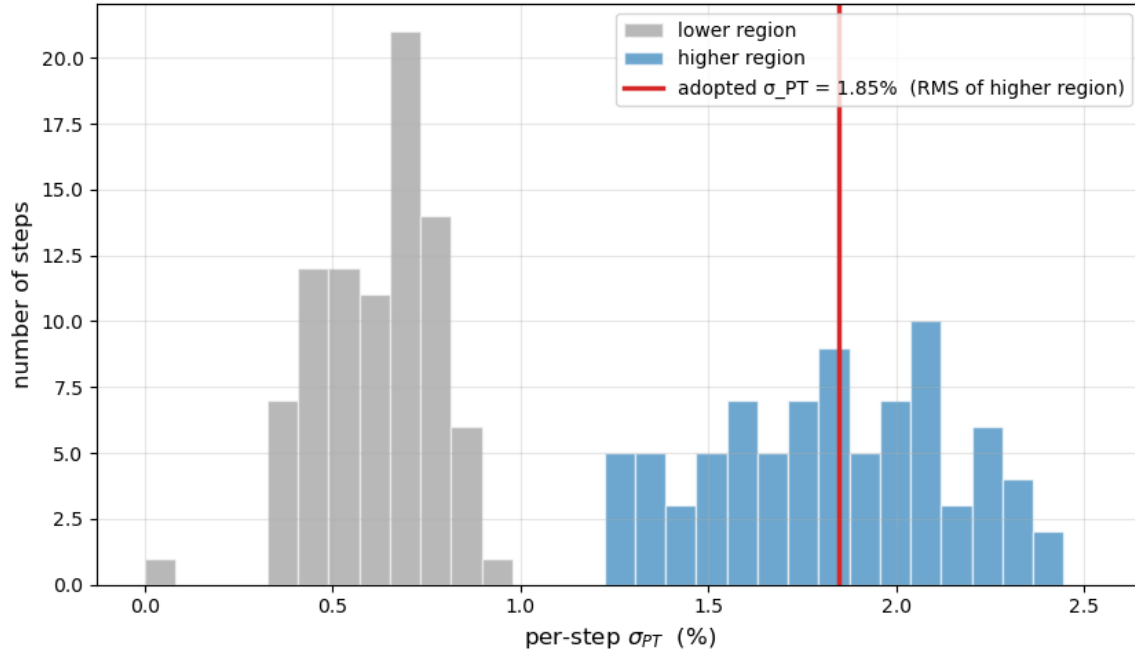
$r = 1$ for pure white noise,

$r > 1$ when correlated

- $r(b) > 1$ for reliable b, the correlated (PT) component exists.
- $\sigma_{PT}(b)$ decreases with b as the PT effect is averaged out. At large b, too few blocks N_b make it unreliable.

*here σ is relative to η_{SNR} ($\frac{\sigma}{\eta_{SNR}} \times 100\%$)

Uncertainty of the 1-s averaged η_{SNR}



- For each cavity step, extract one σ_{PT} (median over reliable b)
- Two populations appear — due to a different JPA operating point used during the run.
- We conservatively adopt the RMS of the higher region: $\sigma_{PT} = 1.85\% \rightarrow \sigma_{\bar{\eta}} = \sqrt{\frac{\sigma_{white}^2}{N} + \sigma_{PT}^2} \approx 2.15\%$

*here σ is relative to η_{SNR} ($\frac{\sigma}{\eta_{SNR}} \times 100\%$)

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Conclusion & Future Plan

Conclusion

- Pulse Tube synchronized gain modulation observed in CDT045: ~ 1 dB peak to trough, the induced effect scales with B field and depends on JPA operation parameters.
- Similar Pulse Tube induced effects reported across axion, quantum computing, neutrino communities.
- Data blocking method gives $\sigma_{PT} \approx 2\%$ on η_{SNR} , contributing to $\frac{\delta g}{g} \approx 2\%$

Future plan

- Upgrade the magnetic shielding assembly (i.e. add compensation coils, revise JPA mounting, circulator shielding improvement...)
- And your valuable suggestions !

Backup slides

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Experimental Results-Gain calibration

- Calibration is crucial for finding gain of the output signal in the detection chain and the system noise of the system.

$$P_o = Gk_B\Delta f(|S_{11}|^2\tilde{T}_{att} + |S_{10}|^2\tilde{T}_c + \tilde{T}_a), \begin{cases} S_{11}(f) = \frac{(\kappa_0 - \kappa_1)/2\pi + 2i(f - f_0)}{(\kappa_0 + \kappa_1)/2\pi + 2i(f - f_0)} \\ S_{10}(f) = \frac{2\sqrt{\kappa_1\kappa_0}/2\pi}{(\kappa_0 + \kappa_1)/2\pi + 2i(f - f_0)} \end{cases}$$

$$G = G_{off} \times G_{JPA}$$

- We have a known radiation power near cavity as our calibration source, to precisely characterize G_{off} when the JPA is off.
- We inject a signal at each step and measure the output power with the JPA turned on and off. G_{JPA} is determined from the ratio between them.

