



# Approaching the Quantum Limit in Axion Detection at IBS/CAPP

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For QNLA team

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# Motivation: Increasing scan rate in axion experiment

Axion mass is unknown, so large frequency range should be scanned (from hundredth kHz to hundredth GHz)

Expected signal is about 10-100 yoctoW ( $10^{-24}$ )

## Scanning rate:

Model constant (KSVZ/DFSZ)

Detector Efficiency

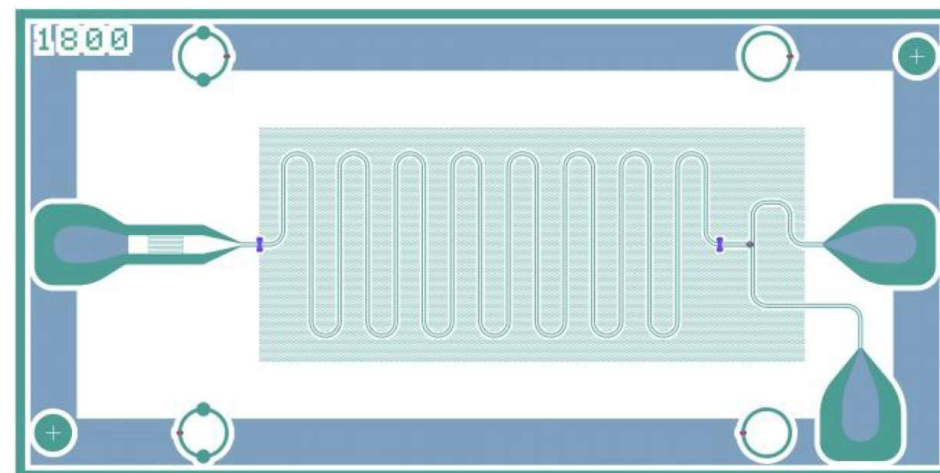
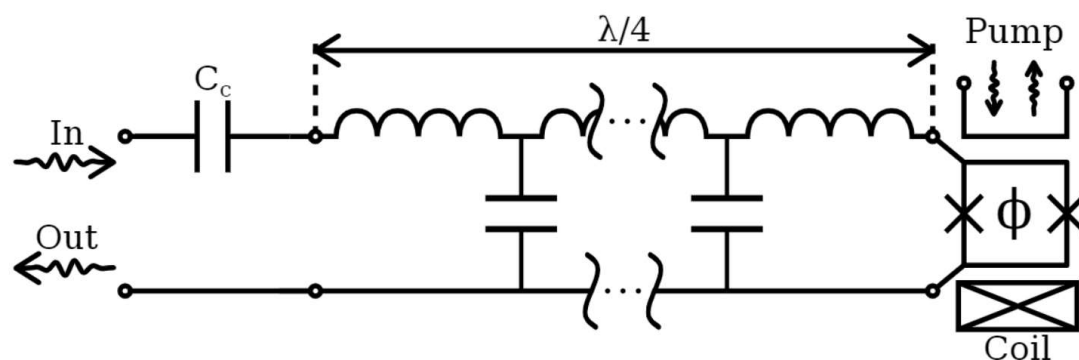
$$S \propto \frac{g_\gamma^4}{\text{SNR}^2} \eta \frac{1}{T_s^2} B_0^4 V^2 C_{nlm}^2 Q L$$



With best cold HEMT amplifier (1-2K noise temperature)  $\rightarrow$   **$\approx 100$  years per 1GHz**

Lowest  $T_s \rightarrow$  **JPA**s

# Flux-driven Josephson Parametric Amplifiers (JPA)



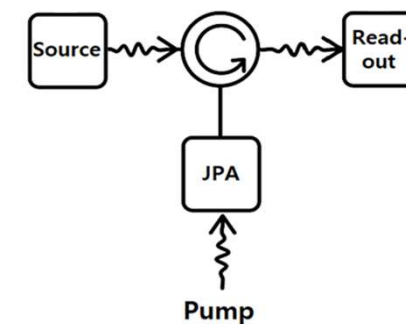
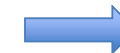
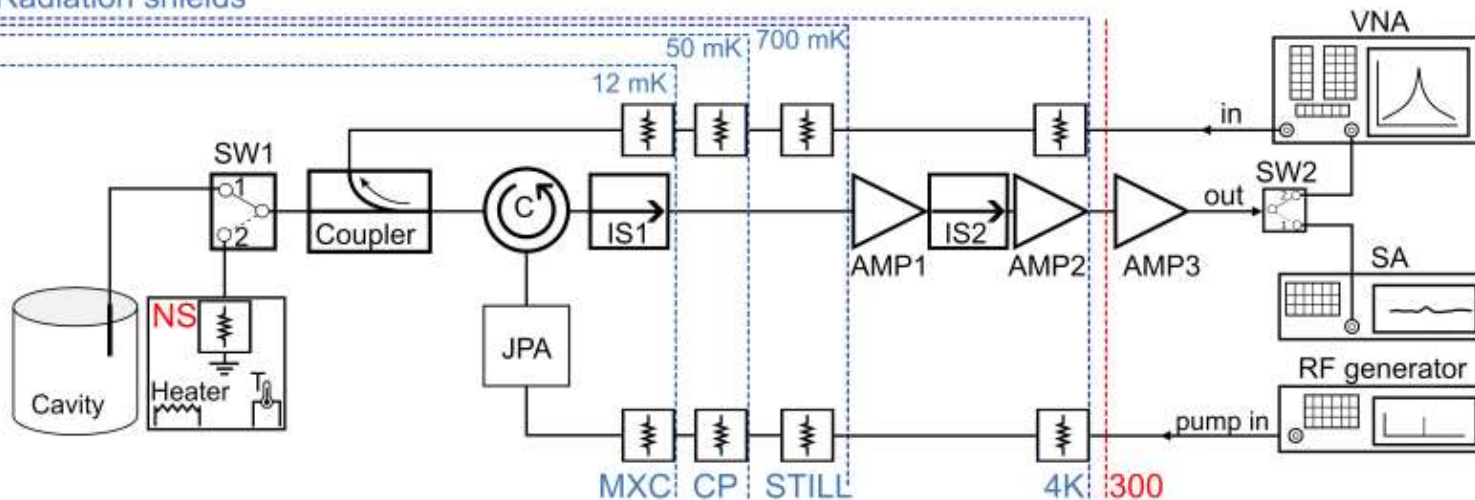
- 1) JPA is a coplanar waveguide  $\lambda/4$  Nb resonator terminated with SQUID
- 2) To tune frequency we use dc flux bias  $\Phi$  which change average inductance of a SQUID
- 3) RF pump signal is applied to modulate nonlinear inductance of SQUID

**Our JPAs:**

- Central frequency 1-6 GHz
- Instantaneous bandwidth ~200 kHz
- Tunable range 45-60 MHz
- Noise 1-3 QNL (quantum noise limit)

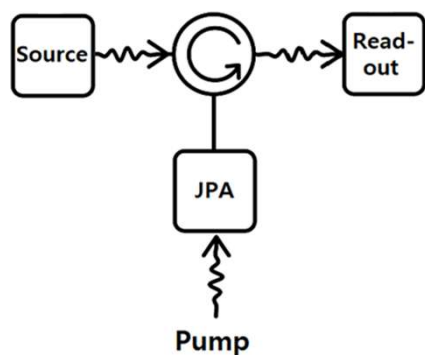
# JPA read-out

Radiation shields

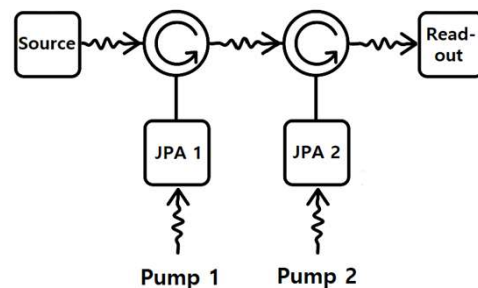


# JPA readout

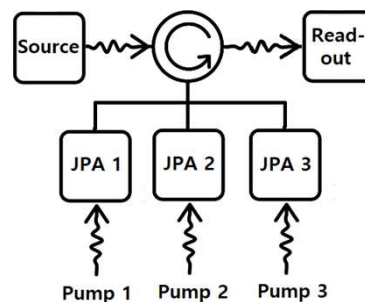
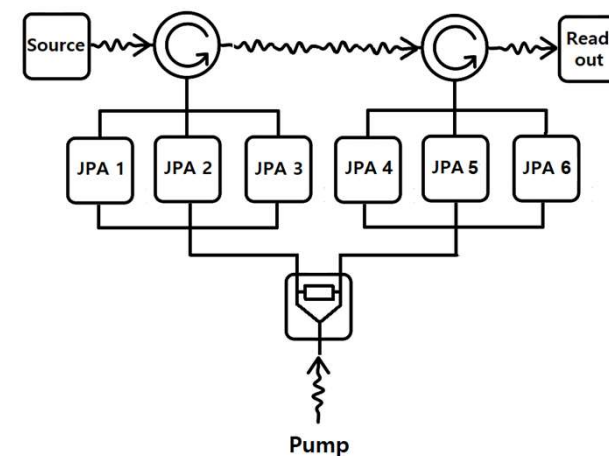
One JPA readout



Serial JPA readout (2 JPAs)



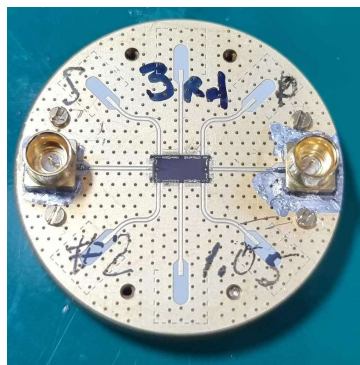
Split-band (Dulcimer) Amplifier  
(up to 6 JPAs)



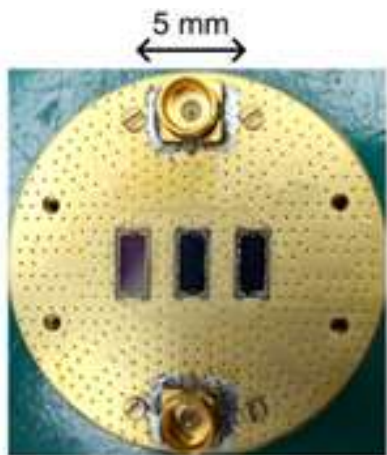
Parallel JPA readout (3 JPAs)  
In Proceedings of LTD20 conference

*Uchaikin S.V. et al. Front. Phys., v.12-2024*  
<https://doi.org/10.3389/fphy.2024.1437680>

# JPA holder

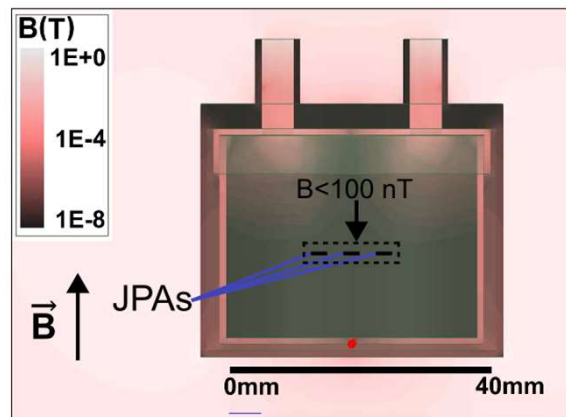
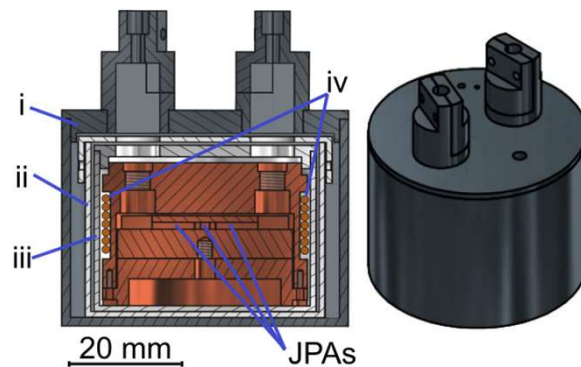


Single JPA chip PCB



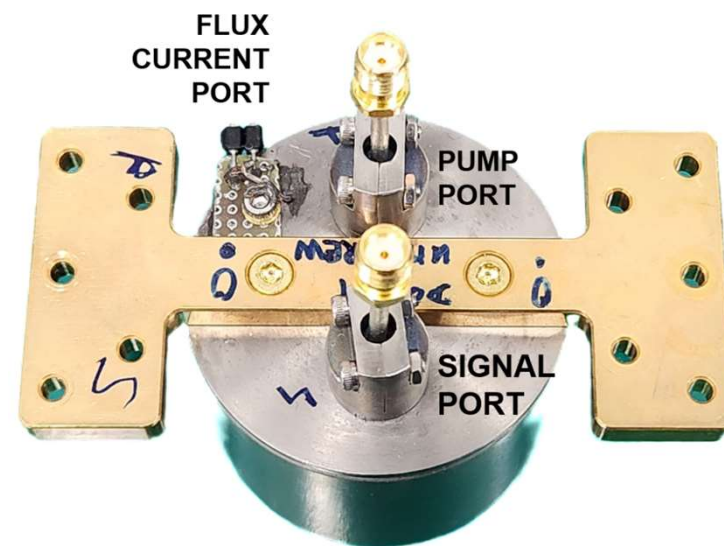
Triple JPA chip PCB

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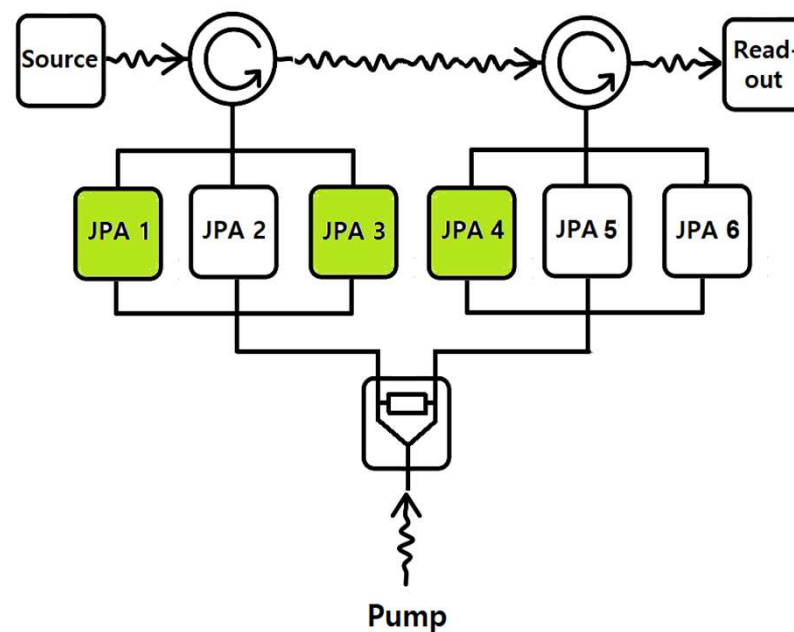
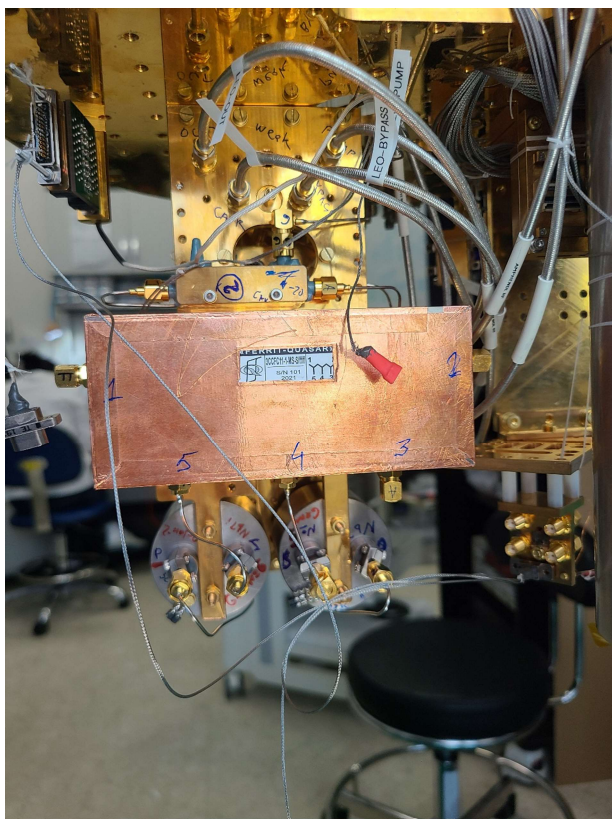
Cross section of the three layer magnetic shield and 3D simulation with the field strength of 50 mT

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The JPA holder

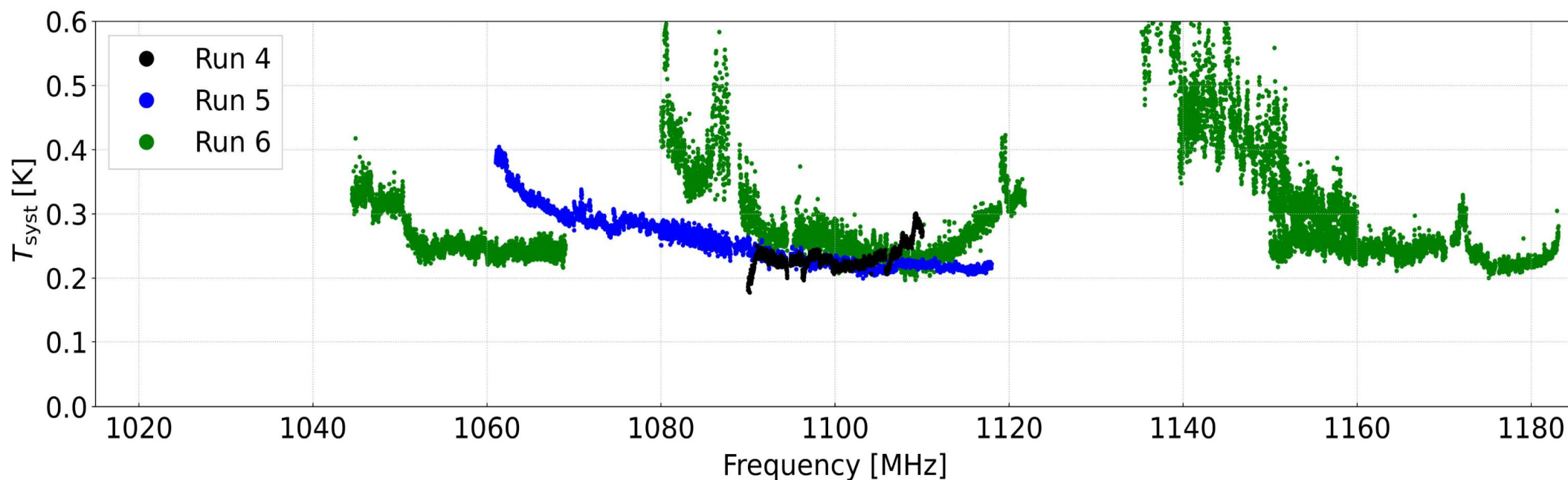
# Run 6: Leo I amplifier, 3 JPAs



## Run 6: 130 MHz (DSVZ) with 3 JPAs

S. Ahn et al. *Phys. Rev. X* 14, 031023, 12 August 2024

# System noise vs frequency for single JPA and three JPA set

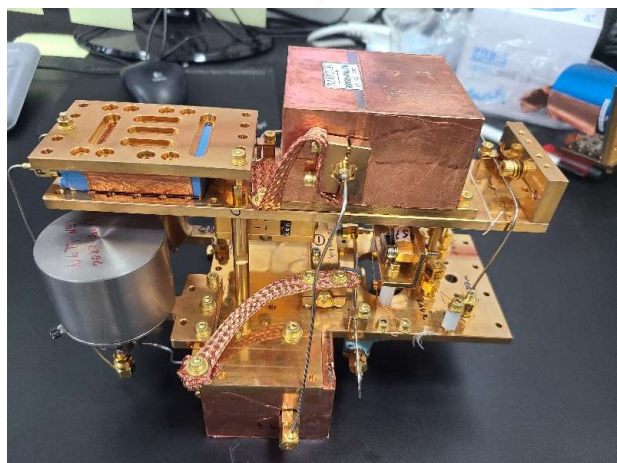
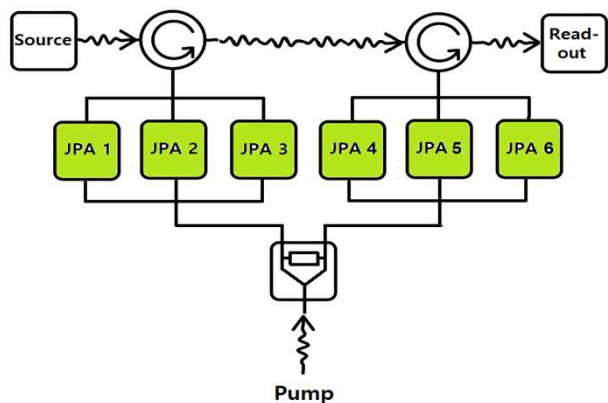


Run 4 – One JPA

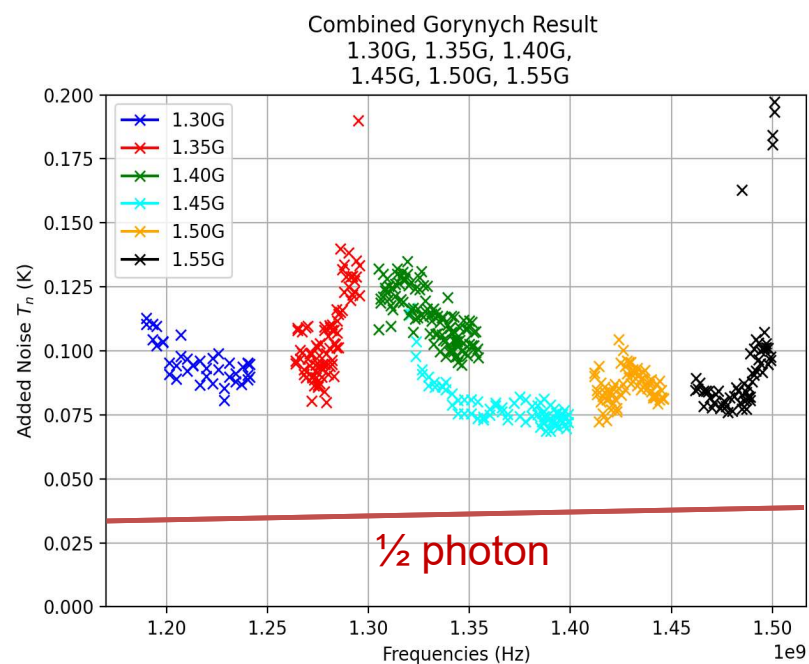
Run 5 – One JPA

Run 6 – Three JPA

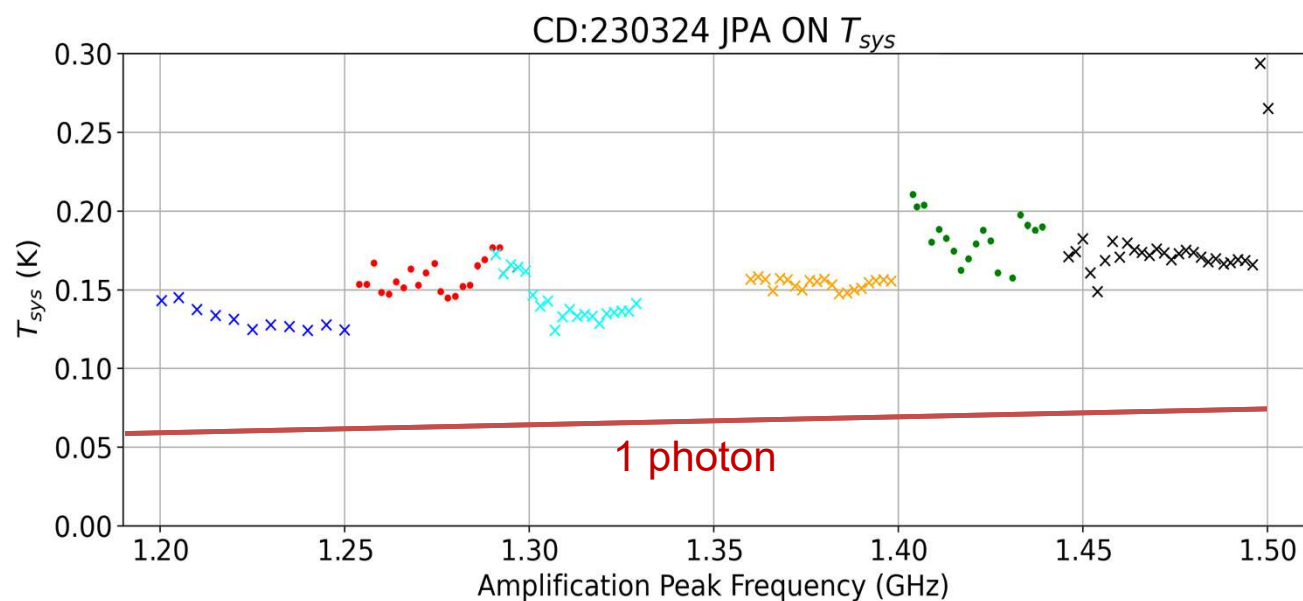
# Leo II (Run 7): 6 JPA assembly



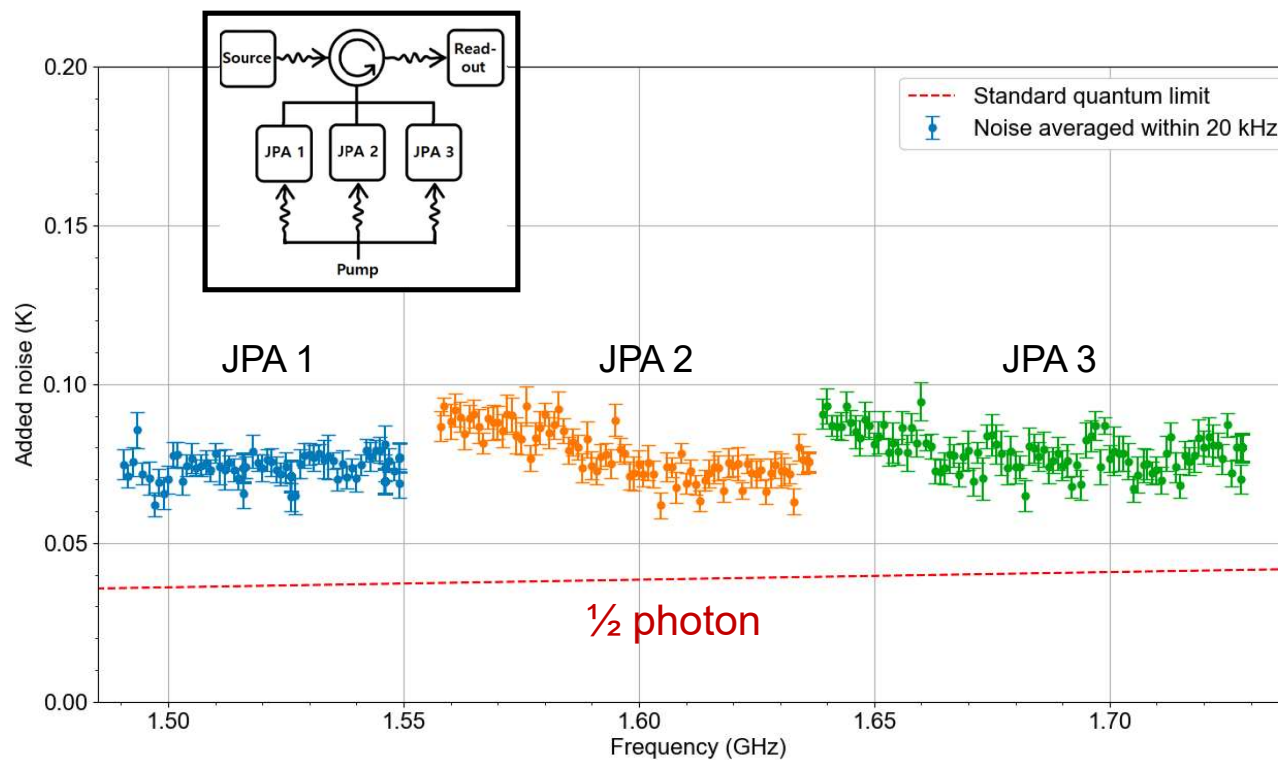
In the current Run 7 we use 6 JPA (3+3), 1.2-1.5 GHz



# Current Run 7: 1.2-1.5 GHz (Leo-II)



# Next Run (8): 1.5-1.75 GHz (Leo III)



# Lump-element JPA

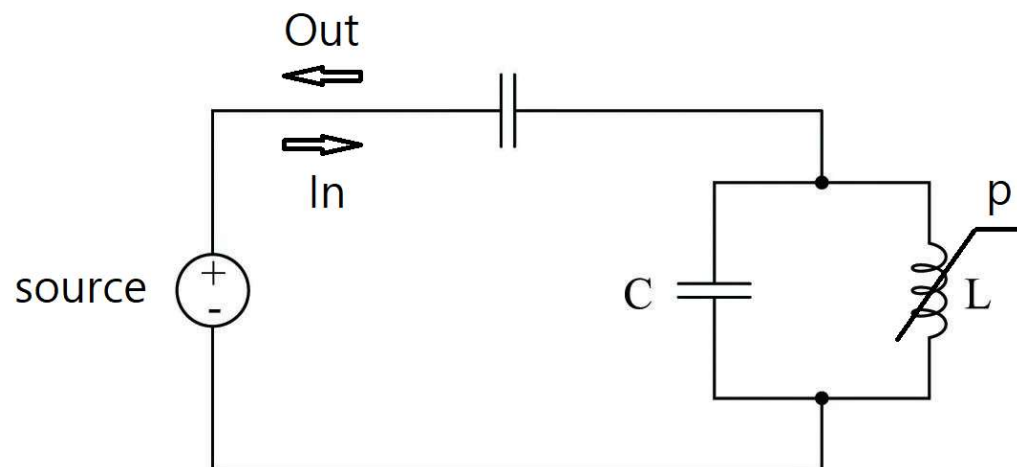
$\lambda/4$  JPA:

$$L = L_{\text{geom}} + L_{\text{SQUID}}$$

Limited tunable range because small  $L_{\text{SQ}}/L_{\text{geom}}$

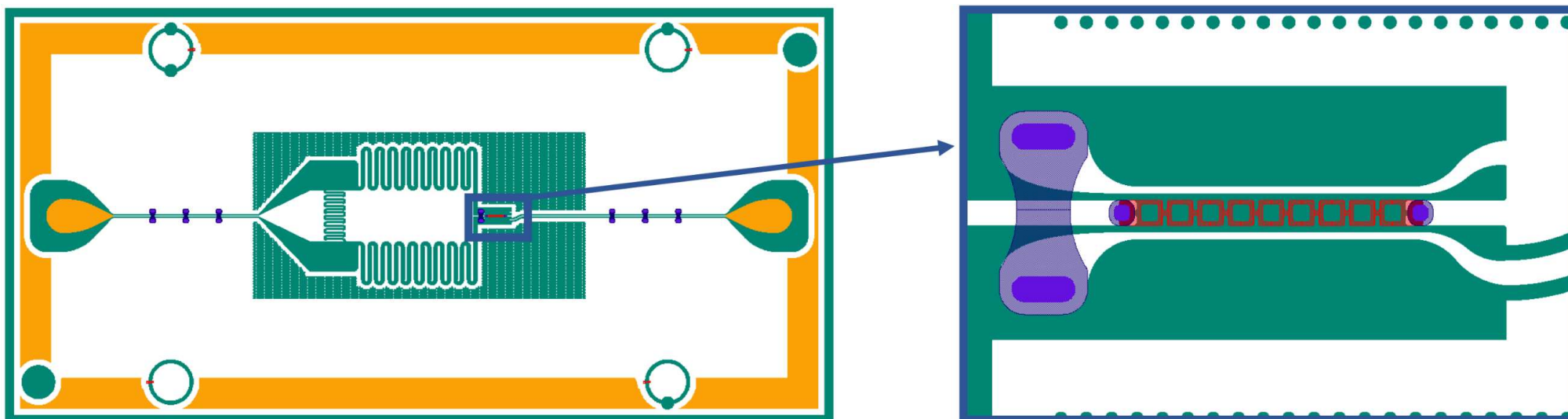
Lump-element JPA:

$L_{\text{geom}}$  is minimal



# Lump-element JPA

Lump-JPA for a range 1.7-7 GHz

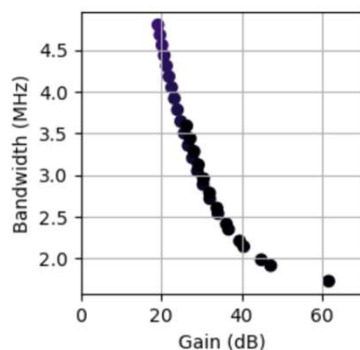
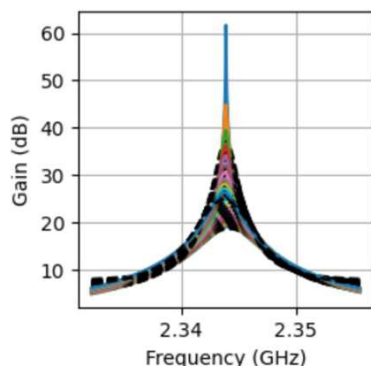


# Simulation, 2.4GHz L-JPA

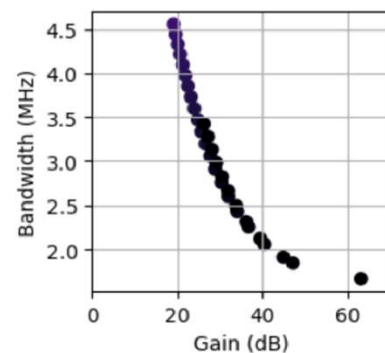
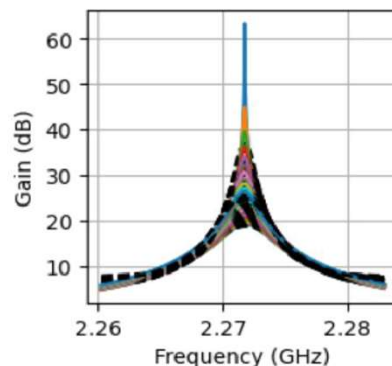
Gain vs freq

Band vs freq

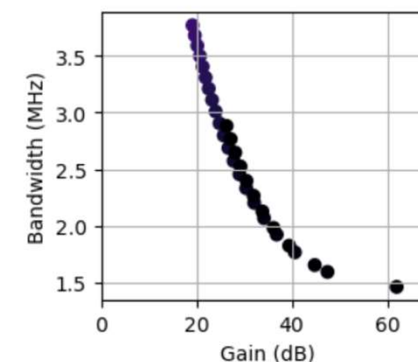
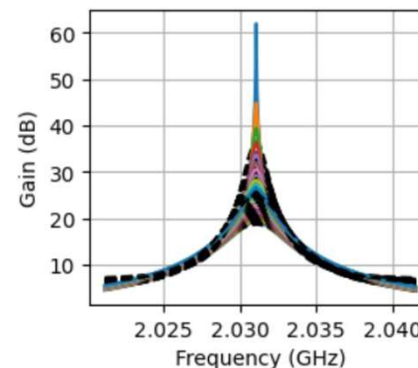
Bias point is  $0.1 \Phi_0$



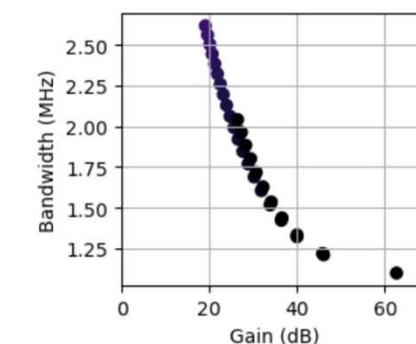
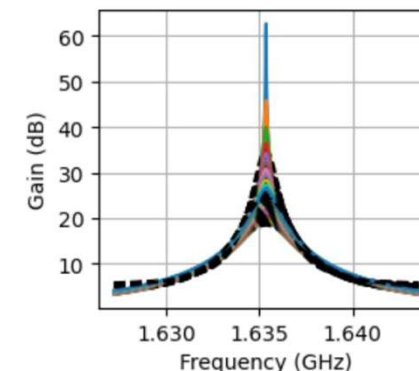
Bias point is  $0.15 \Phi_0$



Bias point is  $0.25 \Phi_0$

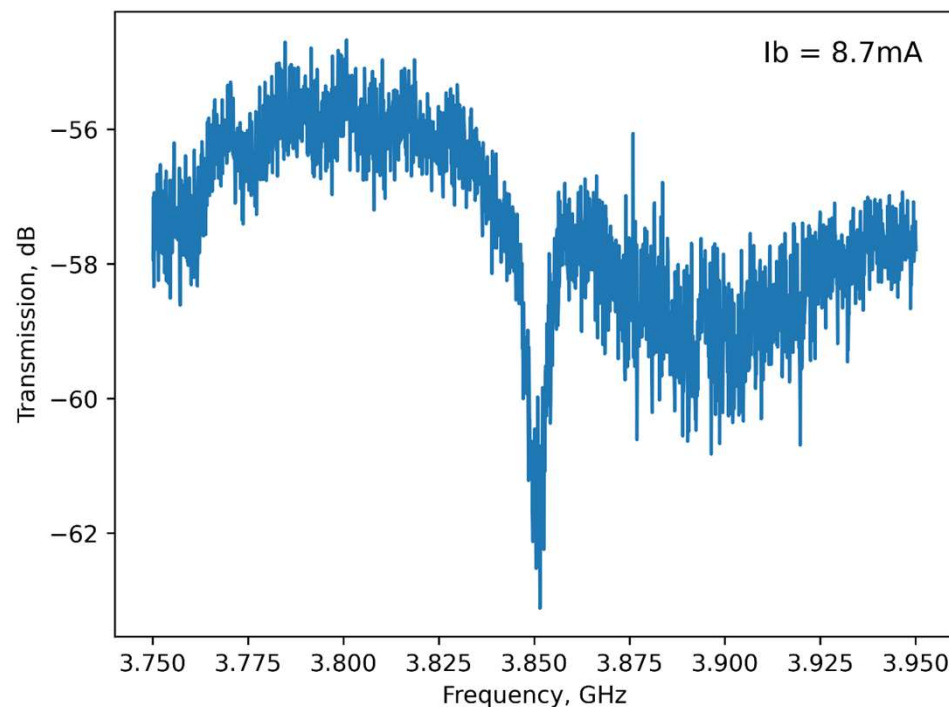


Bias point is  $0.35 \Phi_0$

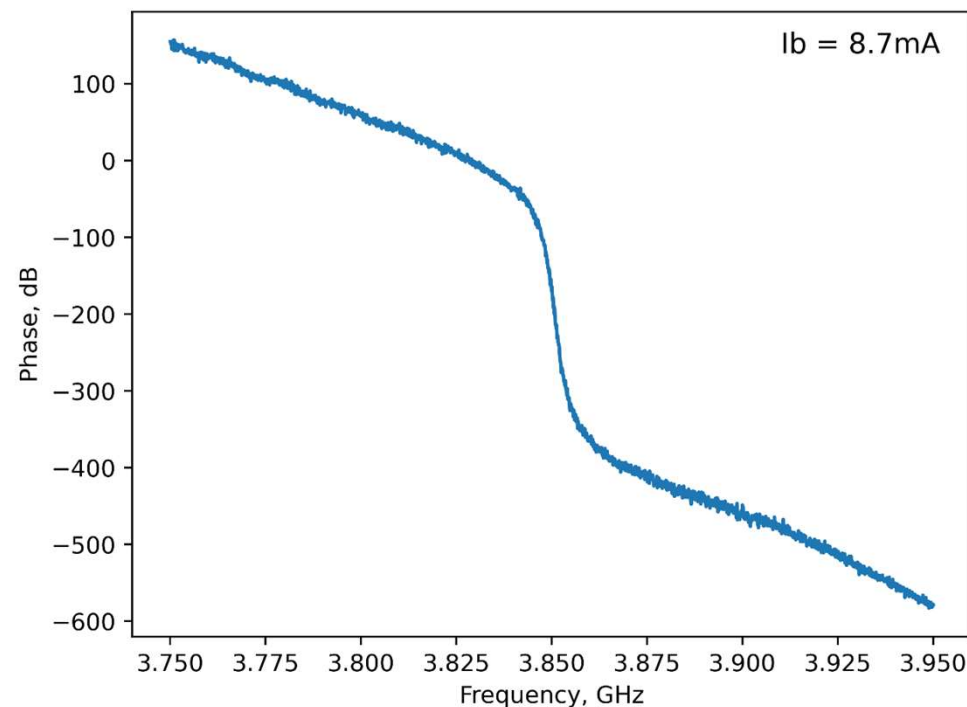


Simulations: Bandwidth 2.5-4.5 MHz Tunable range 700MHz (30%)

# Measurement: Lump-JPA Frequency response w/o pump



Amplitude vs freq

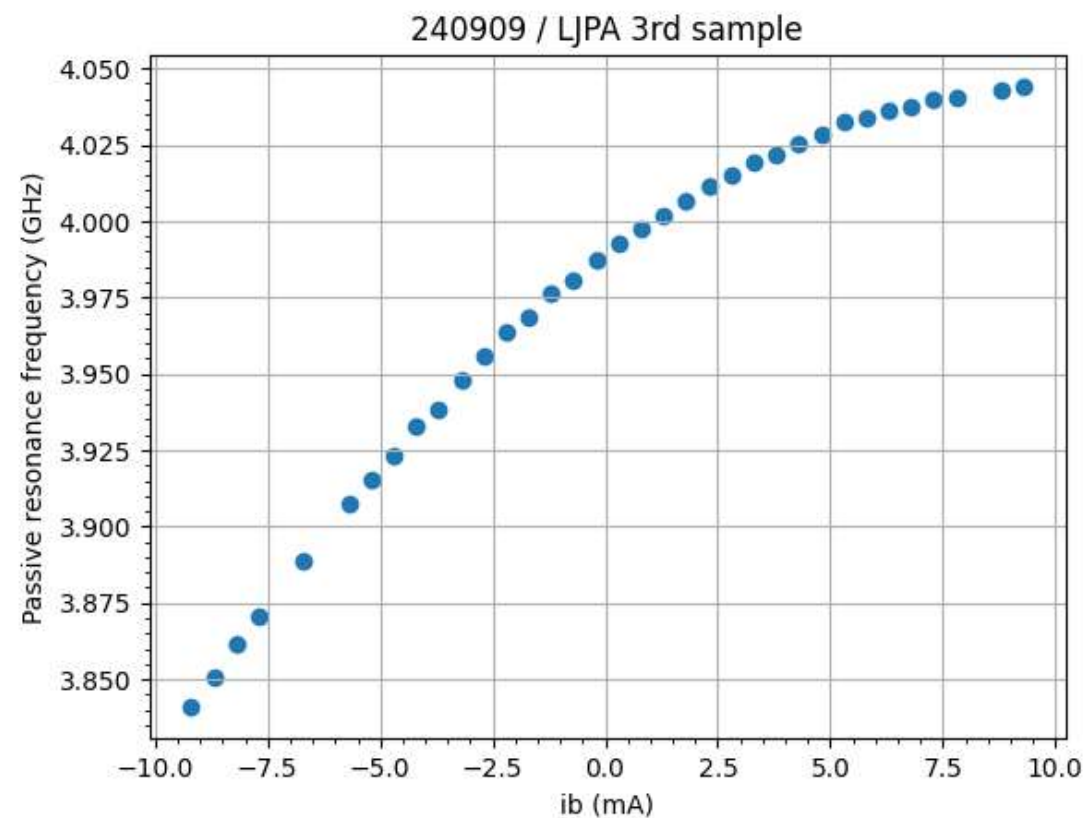


Phase vs freq

# L-JPA Flux-to-Frequency

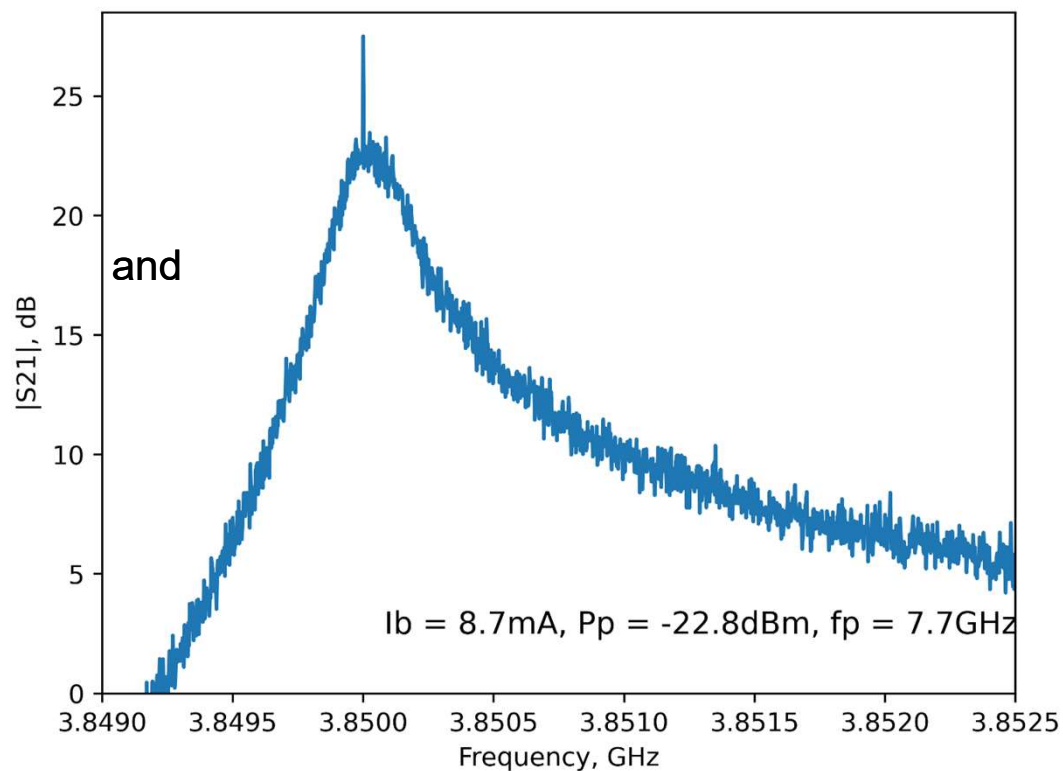
Tunable range >200 MHz

Gain >20dB



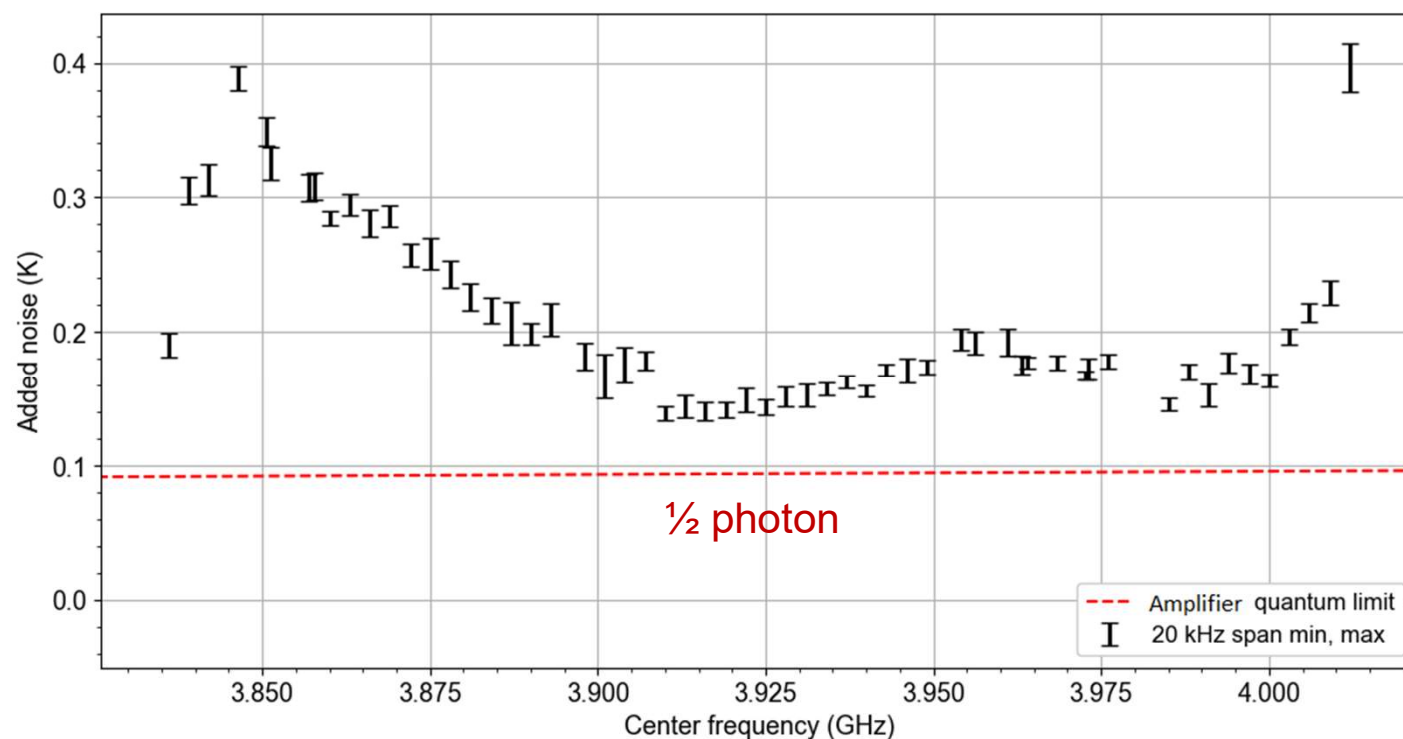
# Amplitude-Frequency Characteristics @ 20 dB gain

Instant bandwidth ~3-5 MHz  
@ 20dB gain



# Preliminary noise temperature measurements in the range of 3.85-4 GHz

Measurements below 4 GHz are suffer from 4-8 GHz band of circulator/isolators





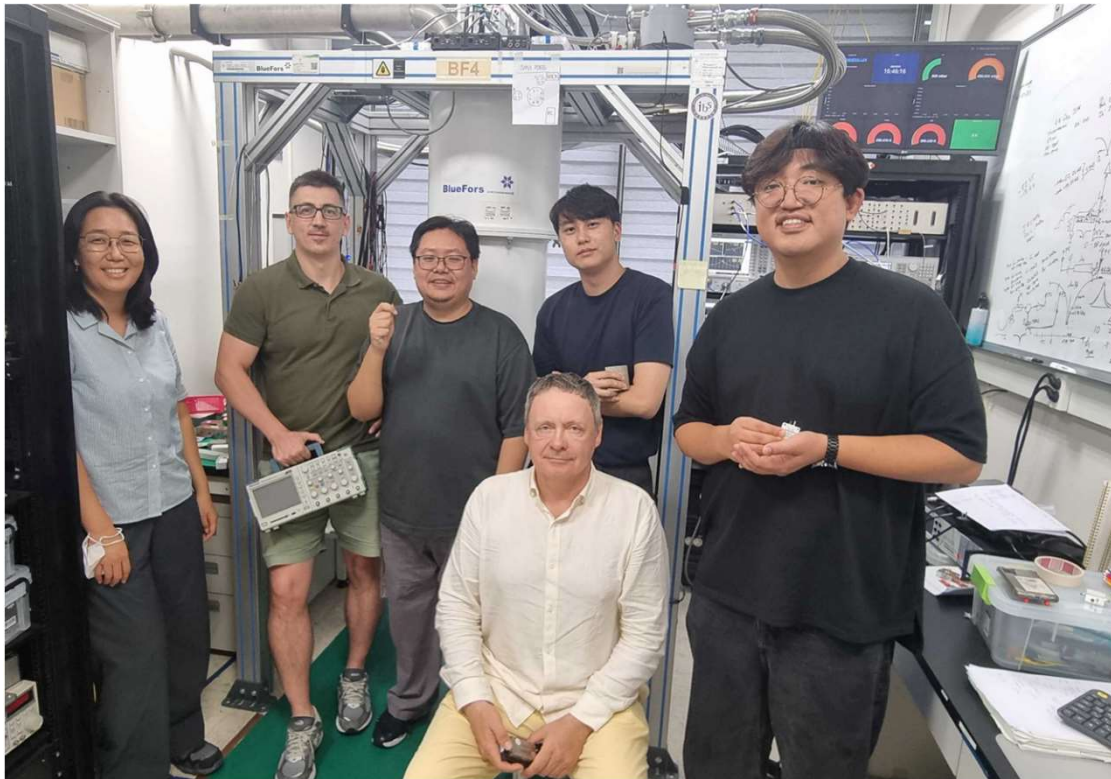
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Arjan von Loo  
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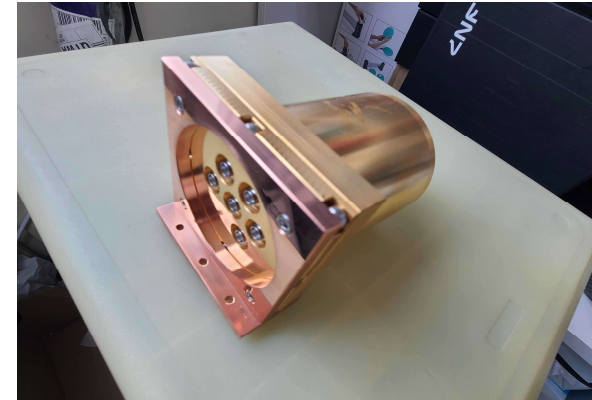
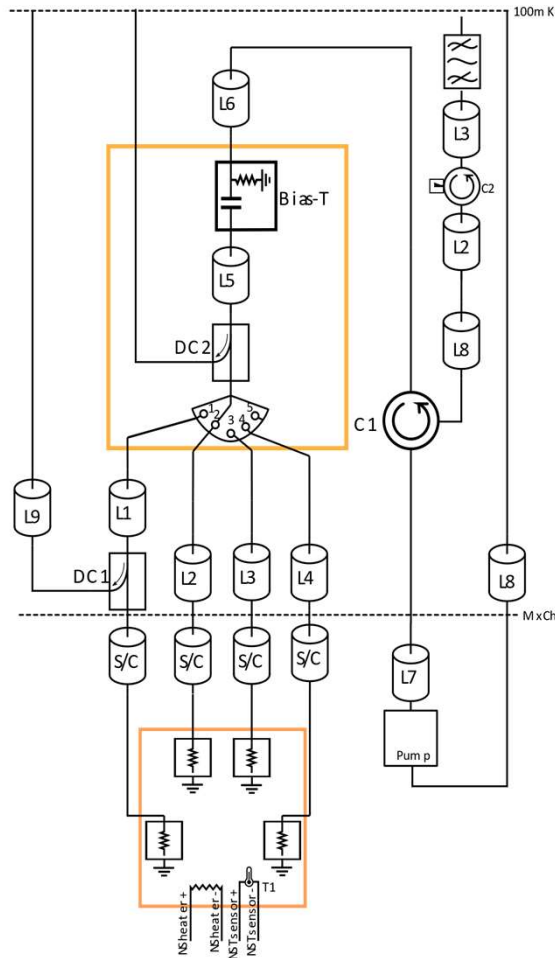
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# SUMMARY

- ***Based on narrow band flux driven JPA we created split band dulcimer amplifier which can cover up to 300 MHz band***
- ***Dulcimer amplifier keeps the low noise temperature of the flux-driven JPAs***
- ***We developed wideband lump JPAs for 0.6-7GHz frequency range***
- ***The preliminary tests of the lump JPA were promising show noise close to  $\frac{1}{2}$  photon***

# Cold Switch

C - cryo circulator  
 DC - Directional coupler  
 F1 - band pass filter  
 SW - RF switch  
 S/C - superconducting coax cables



Problem:

Switch Set/Reset pulses:

Up to **0.4** Ampere, 50 msec

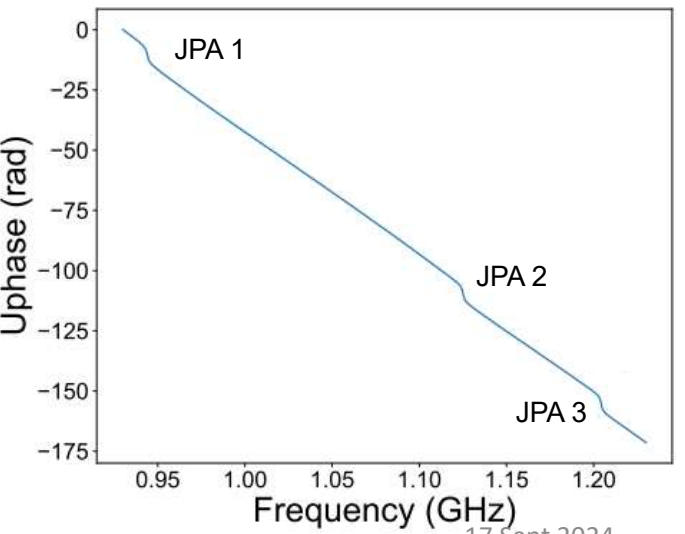
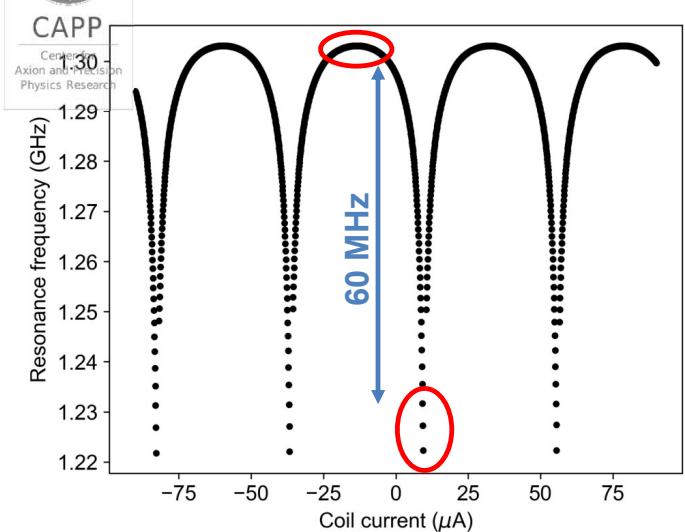
Wires should stand high current

Current can **heat** wires/contact resistance

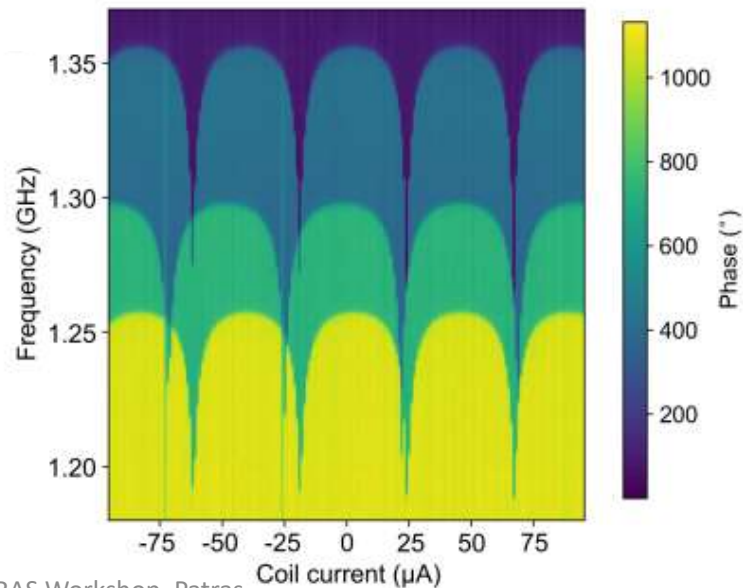
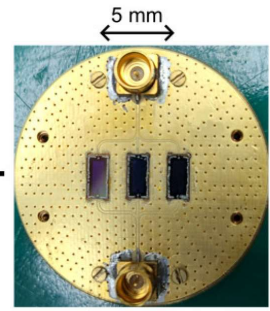
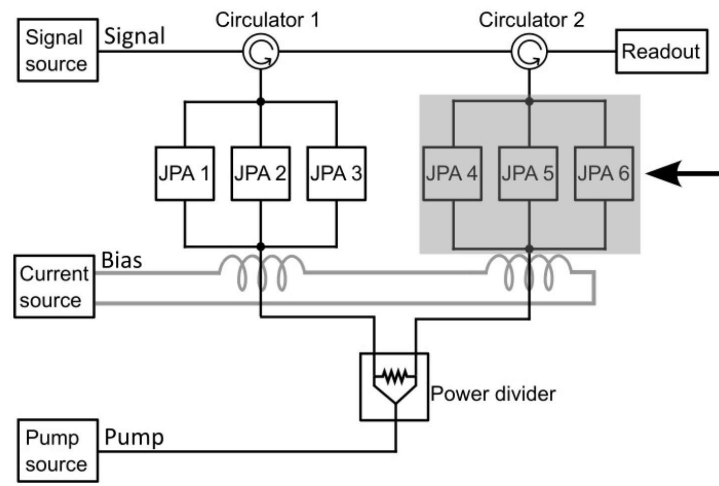
This problem also appears in other situations:

- Programming of RSFQ and other quantum circuits
- Reset of magnetic sensors

# Extension of the axion scanning frequency range

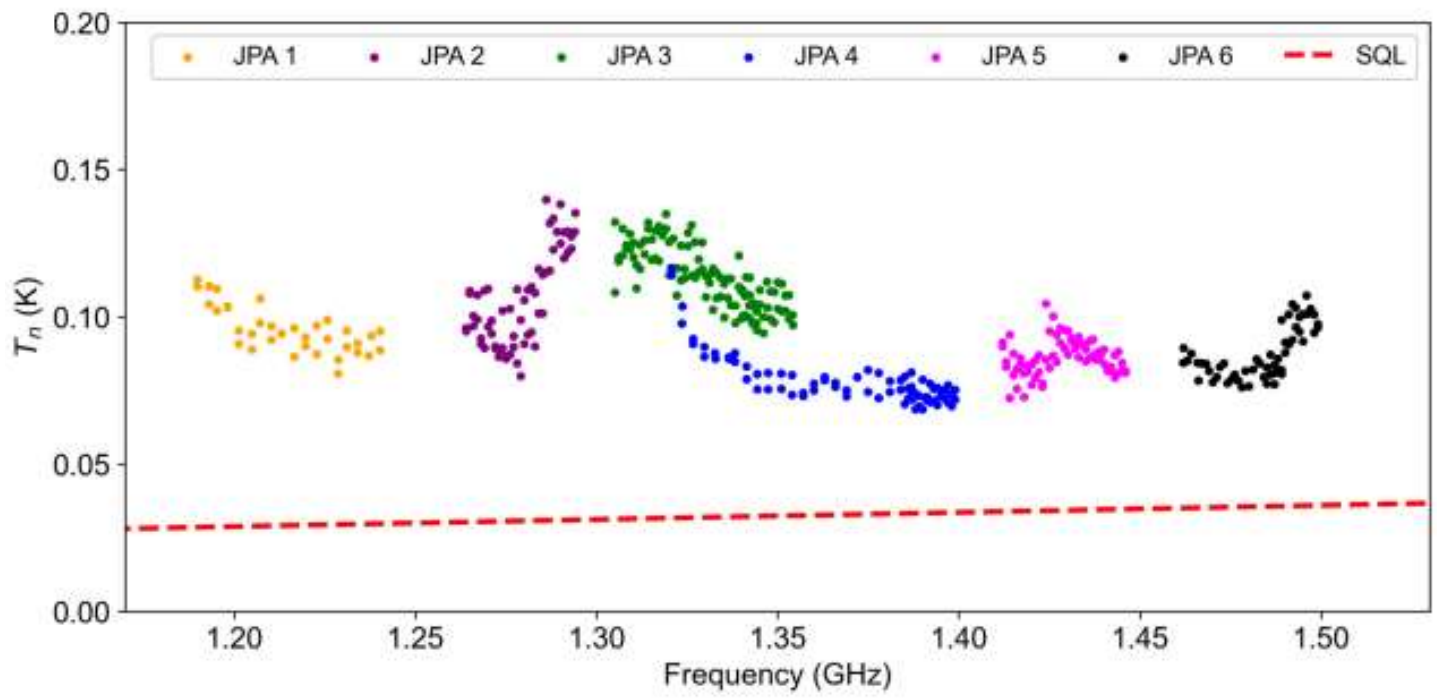
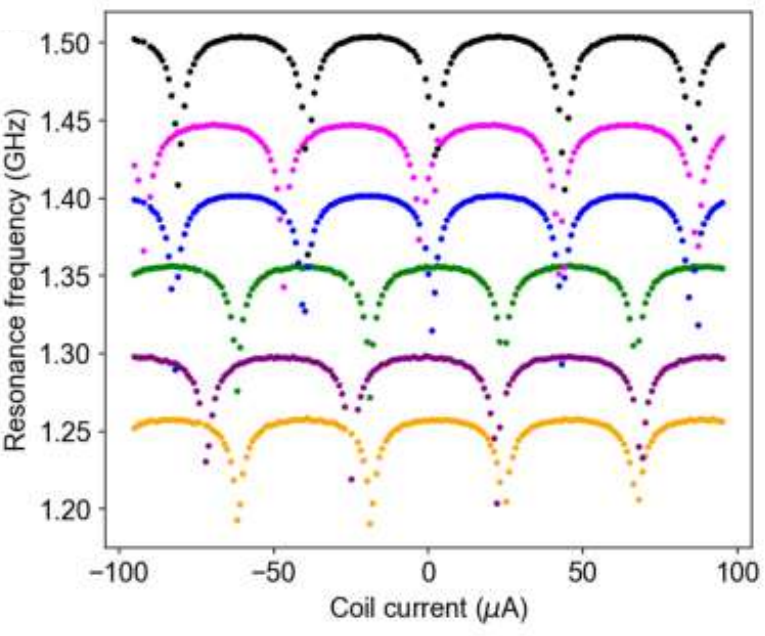
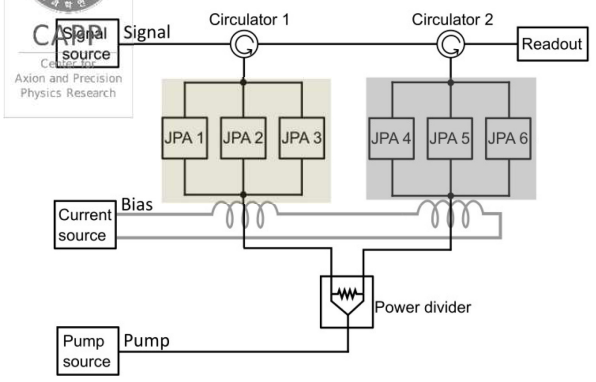
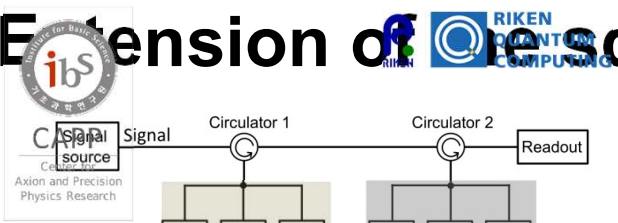


Three JPA phase response  
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Three JPA flux sweep curve

# Extension of QCS scanning frequency range



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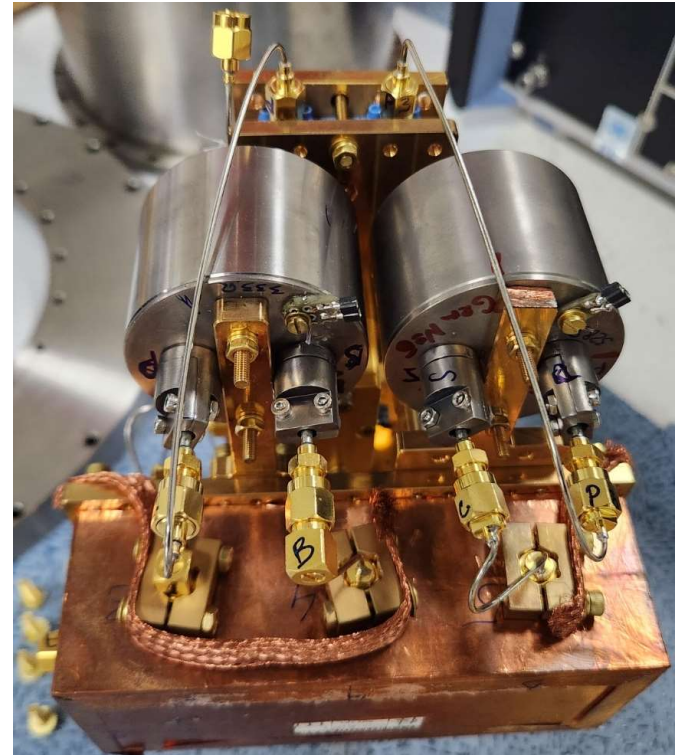
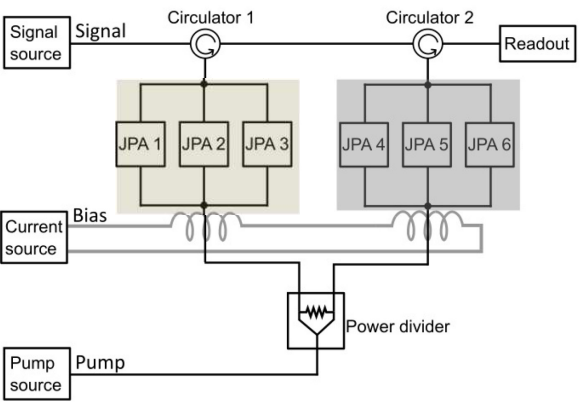
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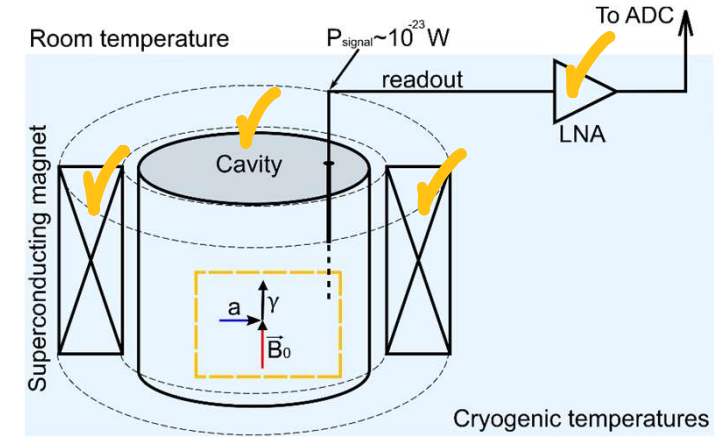
## Multiple JPA readout within data taken RUN6

### The features and challenges of the JPA operation:

- operation of low-noise amplifiers under strong magnetic field is one of the crucial challenges in haloscope experiments,
- the working frequency range of a single JPA around 1~2 GHz is usually limited by < 60 MHz;
- extended scanning frequency in axion search experiment of JPAs based on multiple connection of JPAs is applied.



Final JPA assembly



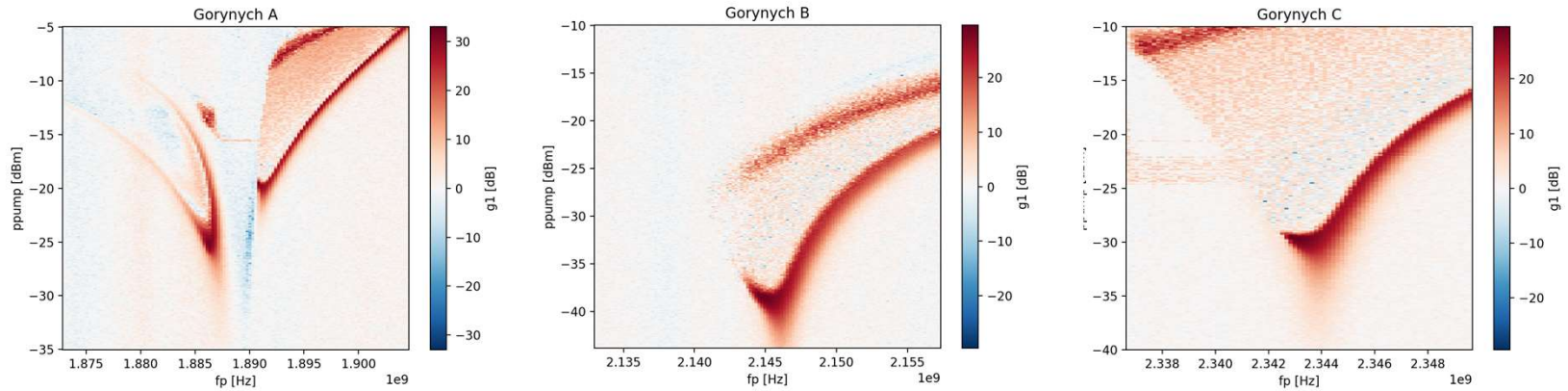
Currently installed to the CAPP-MAX.

LOOKING FORWARD FOR A NEW DATA

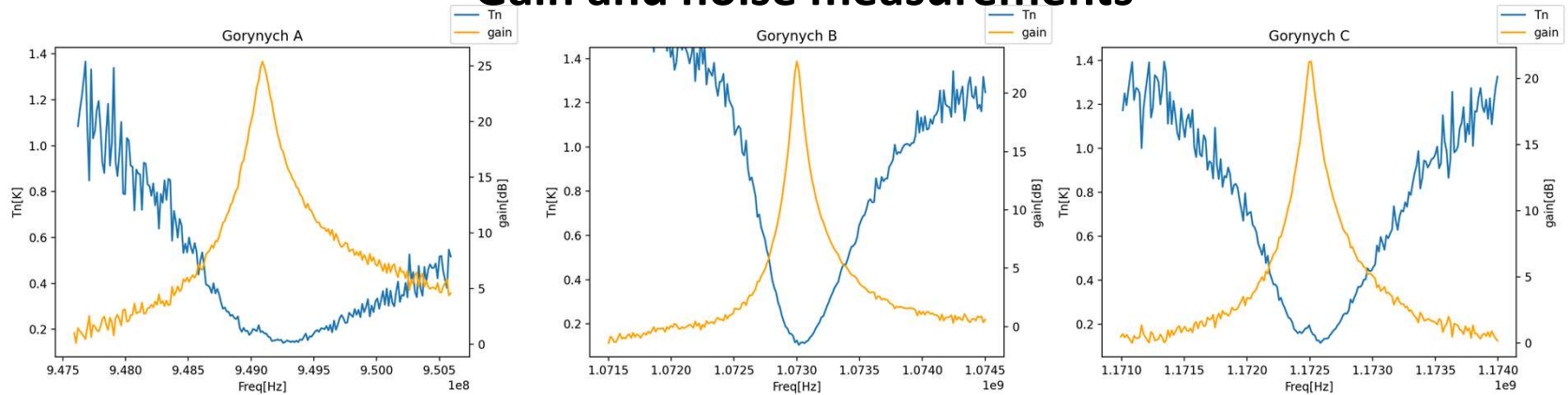
IN CAPP-MAX RUN 9

# Challenge III: Gorynych test results

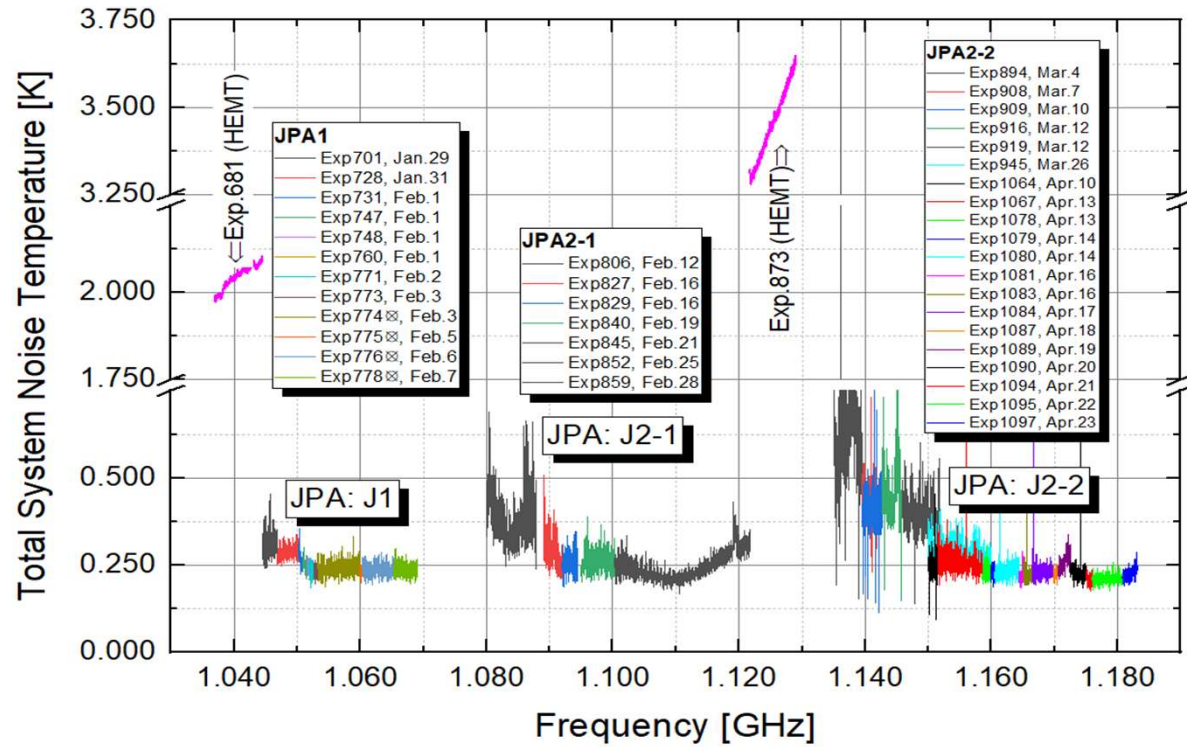
## Gain paramaps



## Gain and noise measurements



# Leo assembly in Run 6



Plot prepared by S.Ahn