Noise Temperature measurements for Axion Haloscope Experiments at IBS/CAPP

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Introduction

The axion was first introduced as a consequence of the Peccei-Quinn solution to the strong CP problem in QCD[1] and is a well motivated cold dark matter candidate[2].

This particle is is expected to interact extremely weakly with matter and its mass is expected to be in the μeV - meV range (corresponding frequency range roughly from 1 to 100 GHz).

In 1983 P. Sikivie proposed a detection scheme, so called axion haloscope, where axions resonantly convert to photons in a microwave tunable cavity permeated by a strong magnetic field[3].

A major source of the noise component is attributed to added noise by RF amplifiers, thus precision measurements and understanding of amplifiers' noise are of importance in dark matter axion search.

In this poster, we present the measurements of various HEMT amplifiers planned to be used for experiments at IBS/CAPP.

Haloscope Parameters

$$P_{a\to\gamma\gamma} = g^2_{a\gamma\gamma}\frac{\rho_a}{m_a}B^2 VCmin(Q_L, Q_a) \sim 10^{-24}W$$

$$SNR \equiv \frac{P_{signal}}{P_{noise}} = \frac{P_{a\to\gamma\gamma}}{k_B T_{syst}}\sqrt{\frac{t_{int}}{\Delta f_a}}$$

$g_{a\gamma\gamma}$: Axion-photon coupling constant
ρ_a, m_a: local halo density and axion mass
Q_a: Axion quality factor
C: mode-dependent form factor

Scan Rate

$$\frac{df}{dt} \sim \frac{B^4 V^2 C^2 Q_L}{T^2_{syst}}$$

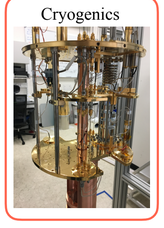
B: external magnetic field
V: cavity volume
$\mathbf{Q_L}$: cavity quality factor

$\mathbf{T_{syst}}$: $T_{cavity} + T_{receiver}$

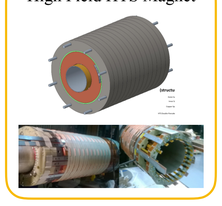
It is **critical to minimize** Temperature of the system $\mathbf{T_{syst}}$ **(Noise Temperature)**:

Low Temperature (Cryogenics)
Low noise Amplifier

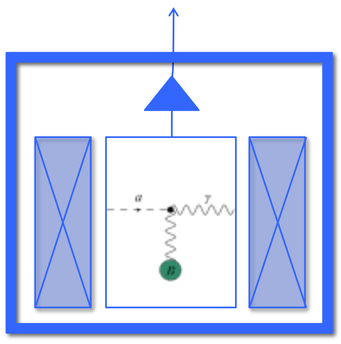
Cryogenics



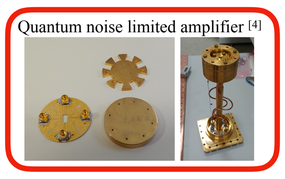
High Field HTS Magnet



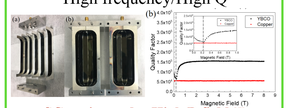
RF readout chain



Quantum noise limited amplifier [4]



Microwave resonator (V,C,Q)
High frequency/High Q



SC cavity under High B field [5]

Pizza cavity for high frequency [6]

Searching for Axion @ IBS/CAPP

Center for Axion and Precision Physics Research (CAPP)

established in Oct. 2013

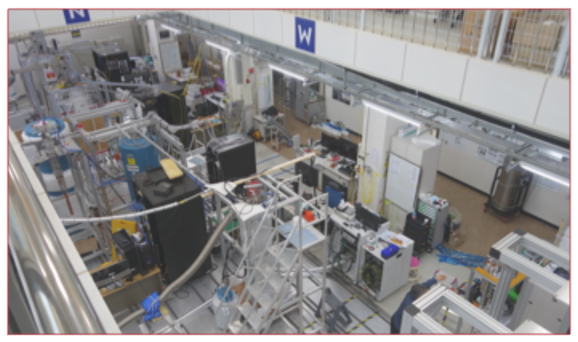
Infrastructure

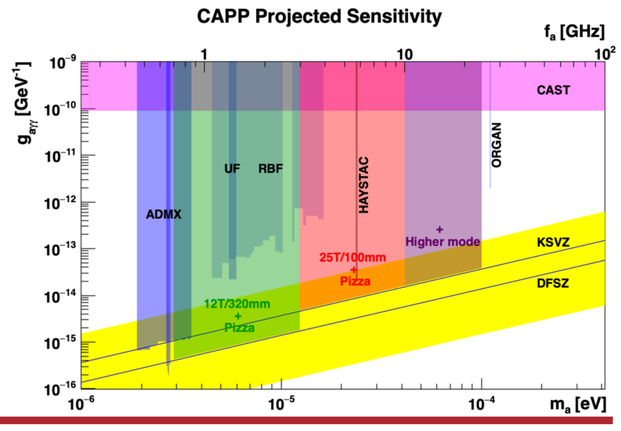
Refrigerators and SC magnets
7 low vibration pads for parallel experiments

Status of the experiments

3 under data taking in 2019

Refrigerator		Magnet		Experiment
Model	T [mK]	Manufacturer	B_{max} [T] - Bore [mm]	Name
BlueFors LD400	10	Parallel experiments targeting different mass ranges		
BlueFors LD400	10			
Janis HE-3-SSV	300	Cryo Magnetics	9 - 125	CAPP-9T MC
BlueFors LD400	10	AMI	8 - 125	CAPP-8T (PACE)
BlueFors LD400	10	AMI	8 - 125	CAPP-8T
Oxford Kelvinox*	30	SuNAM	18 - 70	CAPP-18T
Leiden DRS1000	100	Oxford	12 - 320	CAPP-12T
Oxford Kelvinox	30	IBS/BNL	25 - 100	CAPP-25T





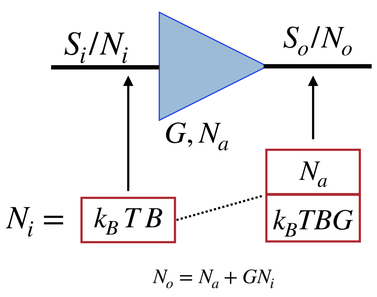
Noise Temperature Measurements

The temperature of the system is one of the most dominant factors that affect the experimental sensitivity:
physical temperature lowered cooling the system at mK temperatures
low noise-high gain amplifier reduce the noise temperature

Amplifiers → additional noise ⇒ important to evaluate the device noise temperature

Y factor method

Ratio of noise power levels corresponding to different noise source/temperature input



$N_o = N_a + GN_i$

$$\frac{S_i/N_i}{S_o/N_o} = \frac{S_i/N_i}{GS_i/(N_a+GN_i)} = \frac{N_a+GN_i}{GN_i}$$

i, o : $input, output$
$S/N = signal/noise$
$G = Gain = S_o/S_i$
$N_a = noise\ added\ by\ amplifier$

$$T_e = \frac{N_a}{k_B B}$$

Equivalent Temperature corresponding to noise $\mathbf{N_a}$ with B = Bandwidth

Measurements:

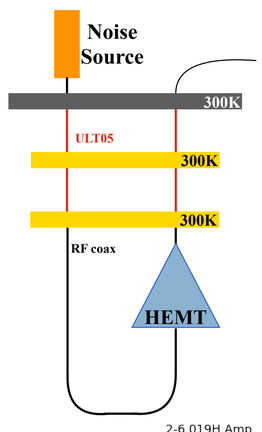
2 SOURCES:
Noise Source → $ENR = \frac{T_{hot} - T_{cold}}{T_0}$
Hot Load → several temperatures

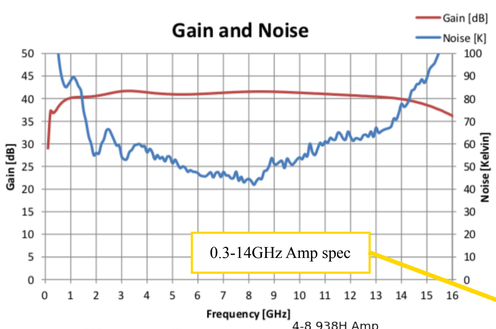
3 High-Electron-Mobility-Transistor (HEMT) Amplifier
different frequency ranges:
2 - 6 GHZ, 4-8GHZ, 0.3-14GHz

Room Temperature
Low Temperature (4K)

Noise Source @ Room Temperature

$$ENR = \frac{T_{hot} - T_{cold}}{T_0} \sim 15dB$$

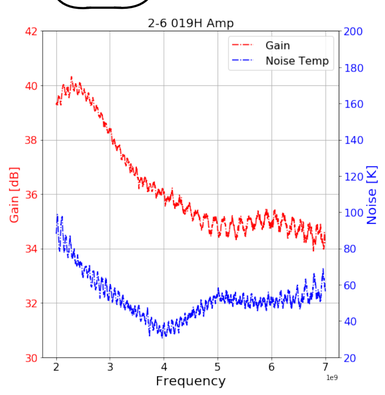


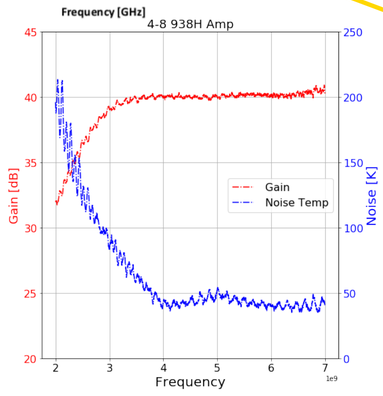


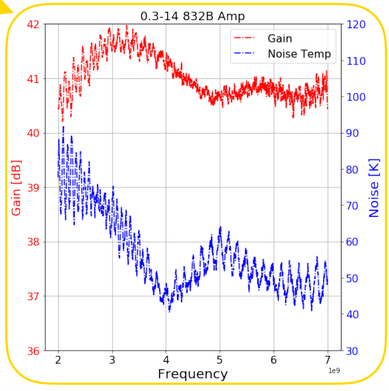
2 Temperature measurement:
Source ON & OFF

T_{hot}
T_{cold} → line attenuation → T_{hot} @ Amp, T_{cold} @ Amp

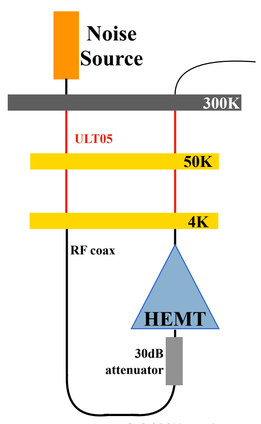
Good agreement with the Gain and Noise Temperature from the specification provided by the manufacturer

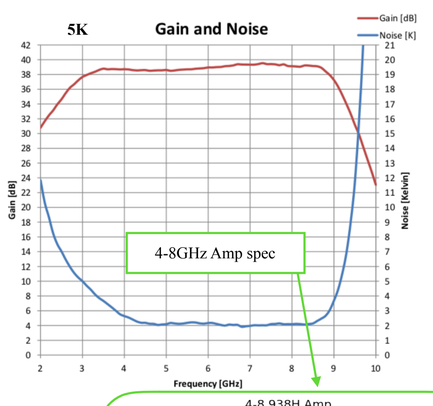






Noise Source @ 4K





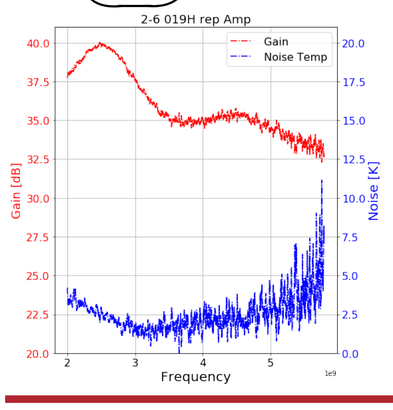
$$ENR = \frac{T_{hot} - T_{cold}}{T_0} \sim 15dB$$

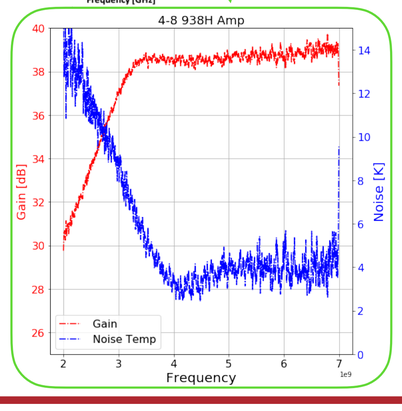
T_{hot}
T_{cold} → temperature gradient line attenuation 30dB attenuation → T_{hot} @ Amp, T_{cold} @ Amp

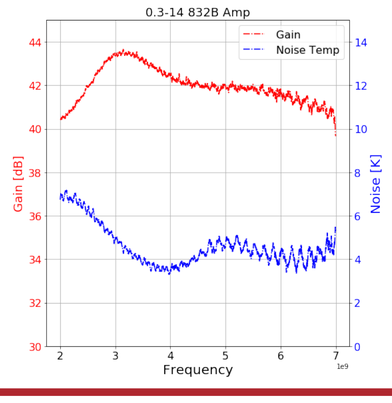
Monitor attenuator and Amplifier temperature

same configuration as Room Temp measurements

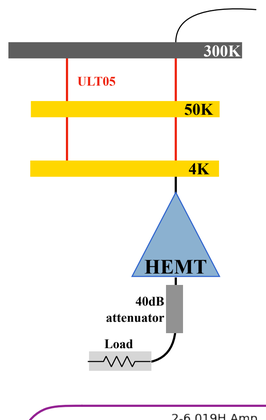
Good agreement for both noise temperature & gain @ 4K

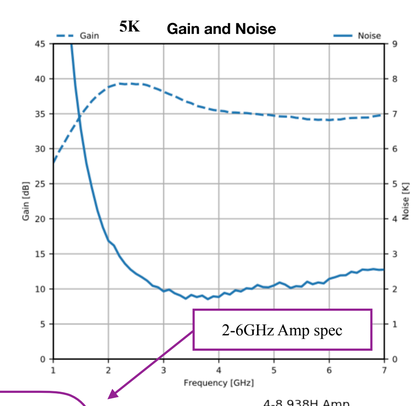






Hot Load @ 4K

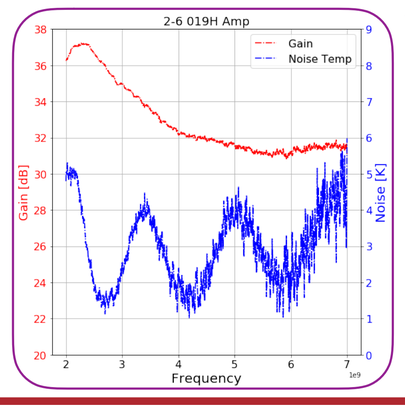


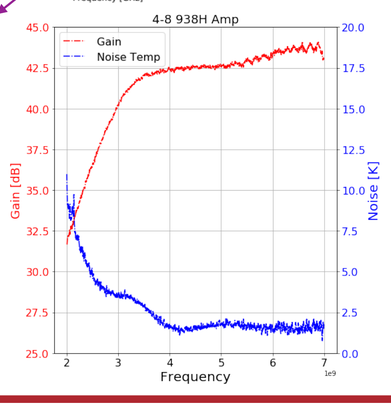


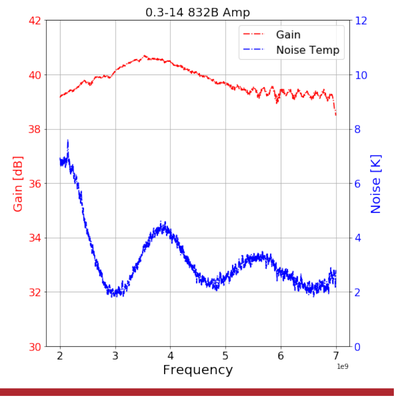
Monitor attenuator and Amplifier temperature

Several temperatures
controlling current
↓
Recording Attenuator physical temperature
↓
Acquisition of Noise Power spectrum

Good agreement with specification & comparison with Noise Source measurements







Conclusion & Plan

The measurements of noise temperature and gain of several HEMT amplifiers used in Axion Haloscope in IBS/CAPP show a good agreement with the amplifier specification given by the manufacturer.
Furthermore two different types of source were used at low temperature both showing that the noise temperature of the device at 4K is about 2K in the working frequency range.
Measurements of the complete electronic chain noise temperature are currently ongoing. As a future plan, given the relation between noise temperature and scan rate,
the development of high gain low noise amplifier is crucial to improve the experimental sensitivity.

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[6]J. Jeong et al., Phys. Lett. B 777 412-419 (2018)