Developing Pilot Tuneable Microwave Receiver for Axion Detection

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Introduction

Feebly-coupled, very light, hypothetical particles such as axions may form all of part of the dark matter in the Universe. The UKRI funded project Quantum Sensing for the Hidden Sector (QSHS) is searching for axion dark matter in the mass range from $20\mu eV/c^2$ to $40\mu eV/c^2$.

We report on the development of a pilot tuneable microwave receiver to detect the microwave photons predicted to arise from axion decay inside a strong magnetic field. The experiment will use a high quality factor (Q) normal metal cavity resonator situated in a large stable magnetic field. Ultimately the receiver will be enhanced by a first stage amplification stage based on a quantum-limited superconducting amplifier operating at mK temperatures.

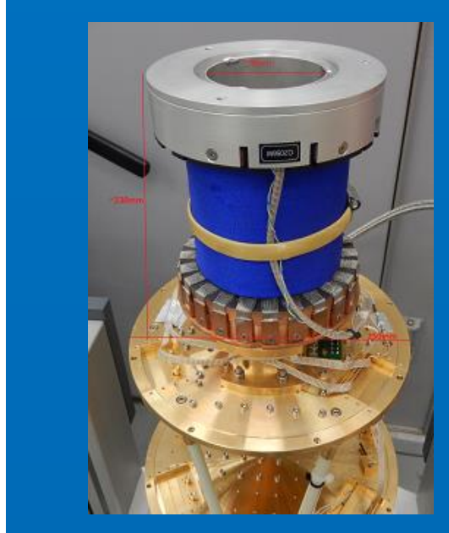
This poster describes the development of the current amplification and detection schemes, employing a cryogenic (3K) high electron mobility transistor (HEMT) microwave amplifier. Further amplification at room temperature, followed by a double heterodyne down-conversion process leads to signal capture, digitisation and processing, aimed at detecting the expected narrow band low level microwave signal expected from the axion decay. The critical coupling of a high Q copper cavity to the HEMT amplifier is implemented, together with the measurement of the system noise temperature of the HEMT amplifier using a variable temperature microwave noise source.

This allows estimation of the overall sensitivity of this pilot base-line receiver. Combined with the signal capture and software processing, the receiver sensitivity allows estimation of the measurement time required to observe the predicted theoretical levels of axion decay. We speculate on the expected final system noise temperature and the issue of efficient and reliable tuning of the high Q cavity.

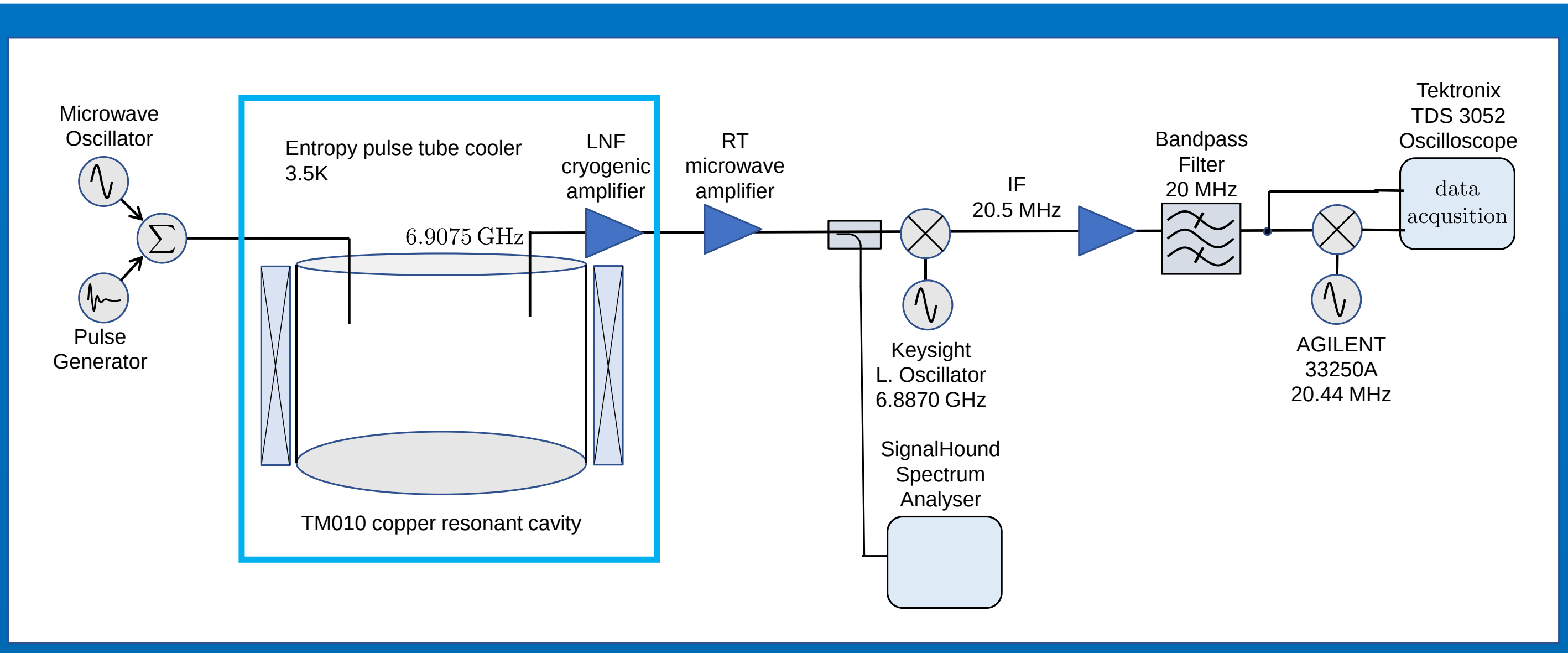
Experimental set up

- The copper resonant cavity is contained at the centre of a 5T superconducting solenoid within a 3.5K pulse tube cooler. The resonator is critically coupled to a cryogenic HEMT microwave amplifier, gain 37dB, whose output is further amplified at room temperature by another microwave amplifier, gain 35dB.
- A small fraction (-10dB) of the signal is fed to a microwave spectrum analyser for monitoring purposes.
- The main signal enters a mixer, the local oscillator input provided by a spectrally pure synthesised signal, tuneable over a wide range (100kHz to 40GHz).
- The intermediate frequency (IF) from the first mixer is passed through a bandpass filter centred on 20.5MHz with ~ 2MHz bandwidth before entering one input of a 500MHz digital oscilloscope (DSO) with amplifying up to 5GS/s but only 10,000 data point storage.
- An alternative path for the 20MHz IF signal goes to a second mixer with LO at ~ 1MHz. Low pass filtering of this signal is then fed to the second input of the DSO.
- When using both down-conversion stages the acquisition time on the oscilloscope is 4ms/division, or 4μs/pt. This sets the Nyquist frequency at 125kHz, equivalent to 5000 points on the Labview plot. This results in a bandwidth of 25Hz for each frequency bin.
- Data acquisition and signal processing is carried out by a laptop pc running National Instruments Labview software. The data is written to a central file store for subsequent off-line processing.
- A narrow-band microwave test signal at power levels as low as 10^{-22} W can be fed into a second port on the cavity resonator, to simulate an axion signal.

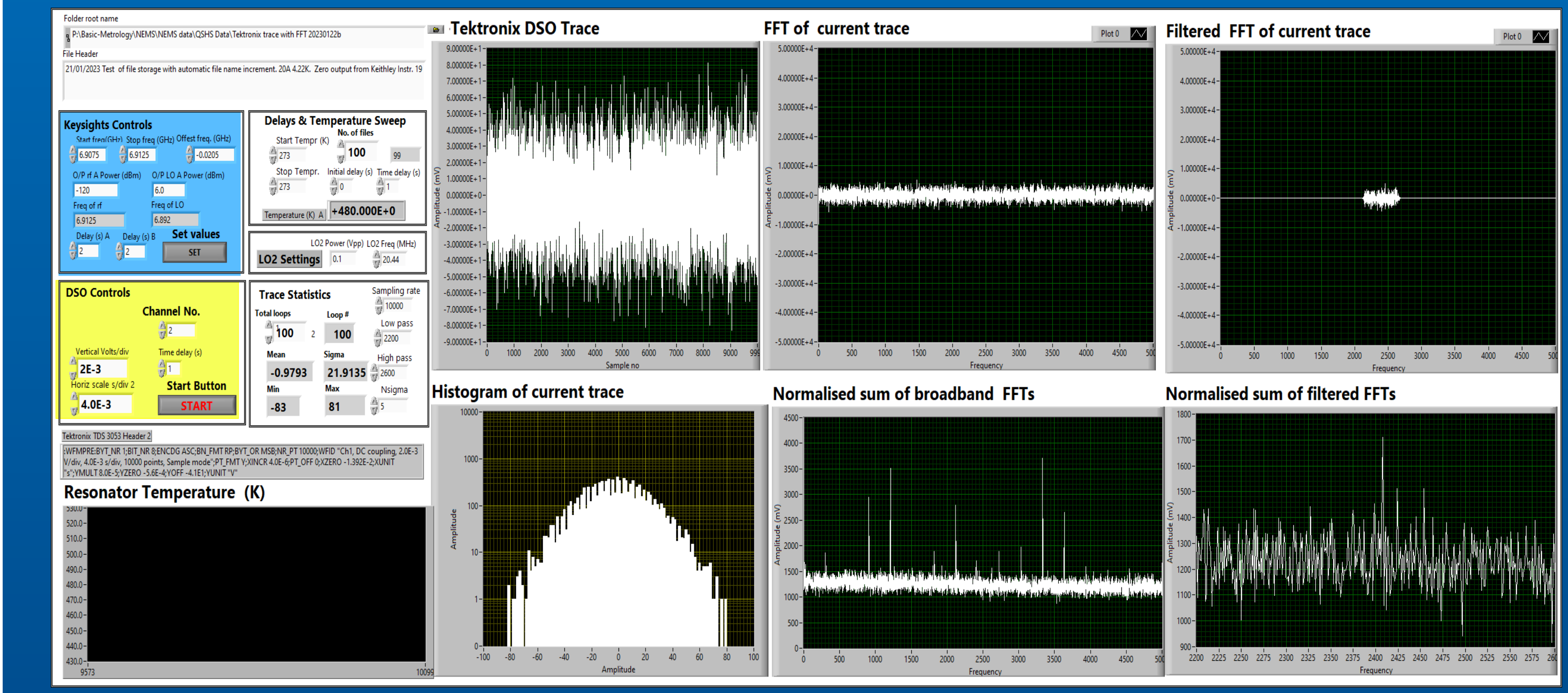
Right: copper TM010 cavity resonator.



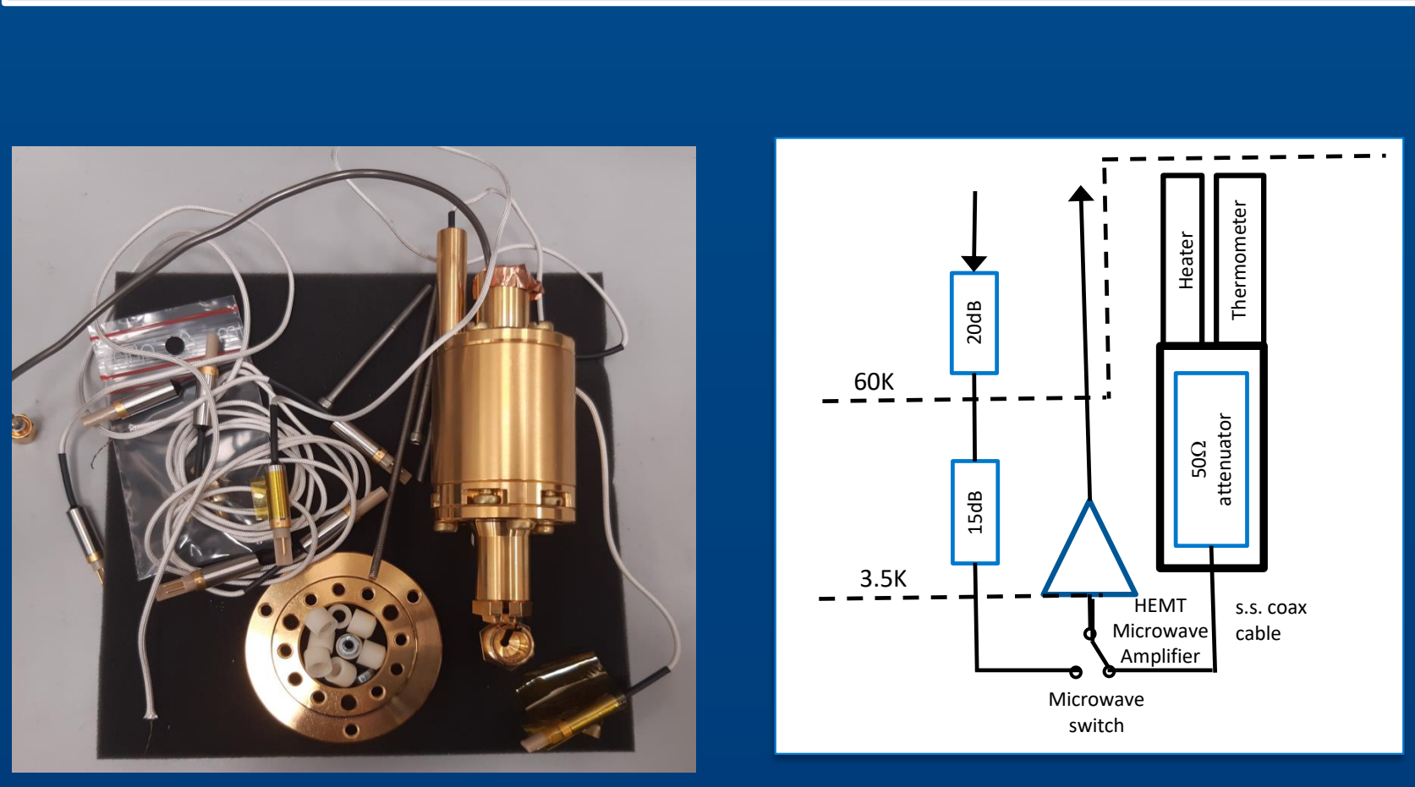
Left: 5T solenoid magnet



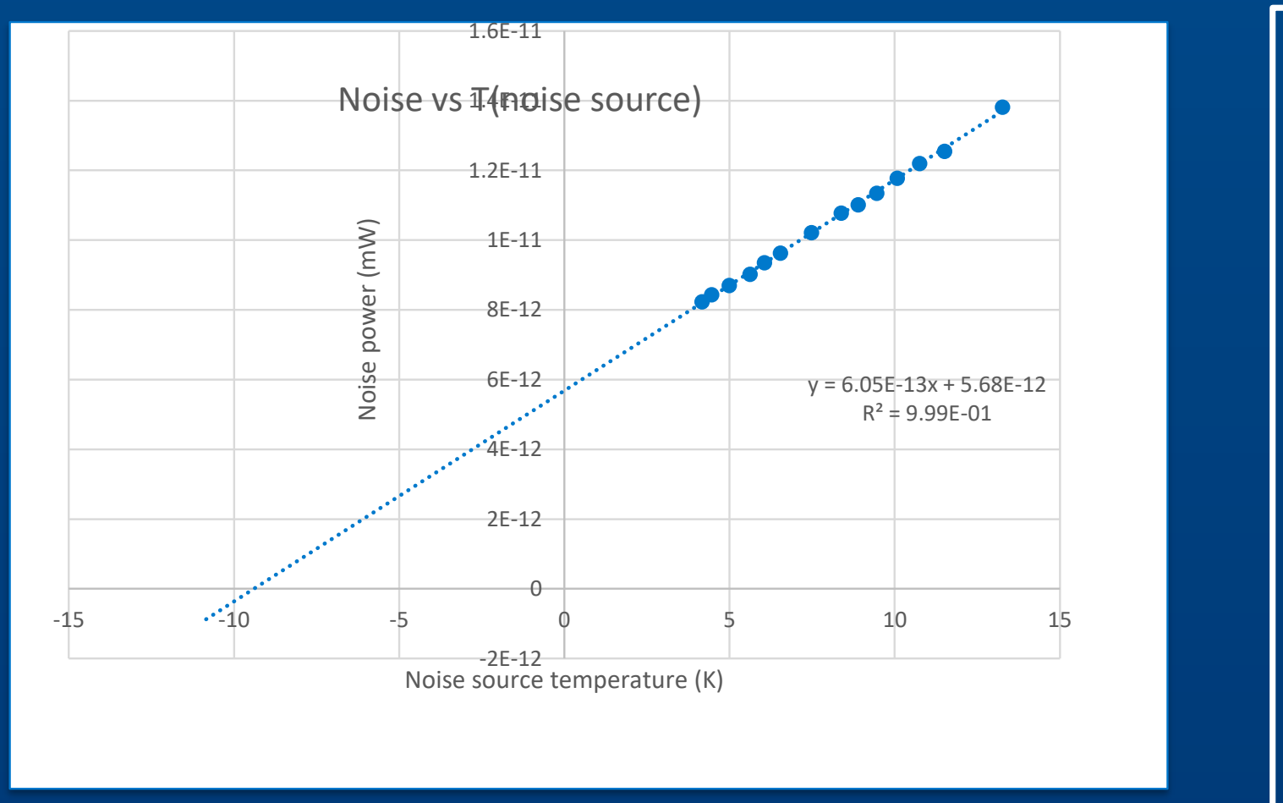
Schematic diagram of tuneable microwave receiver with double heterodyne down-conversion.



Screenshot of Labview data capture software showing trace of real-time data, histogram of this trace, followed by FFT of this trace, including a digitally filtered spectrum. Typically 100 traces are stored to a single data file and the software adds the spectrum of each trace.



Variable noise source and schematic of system.



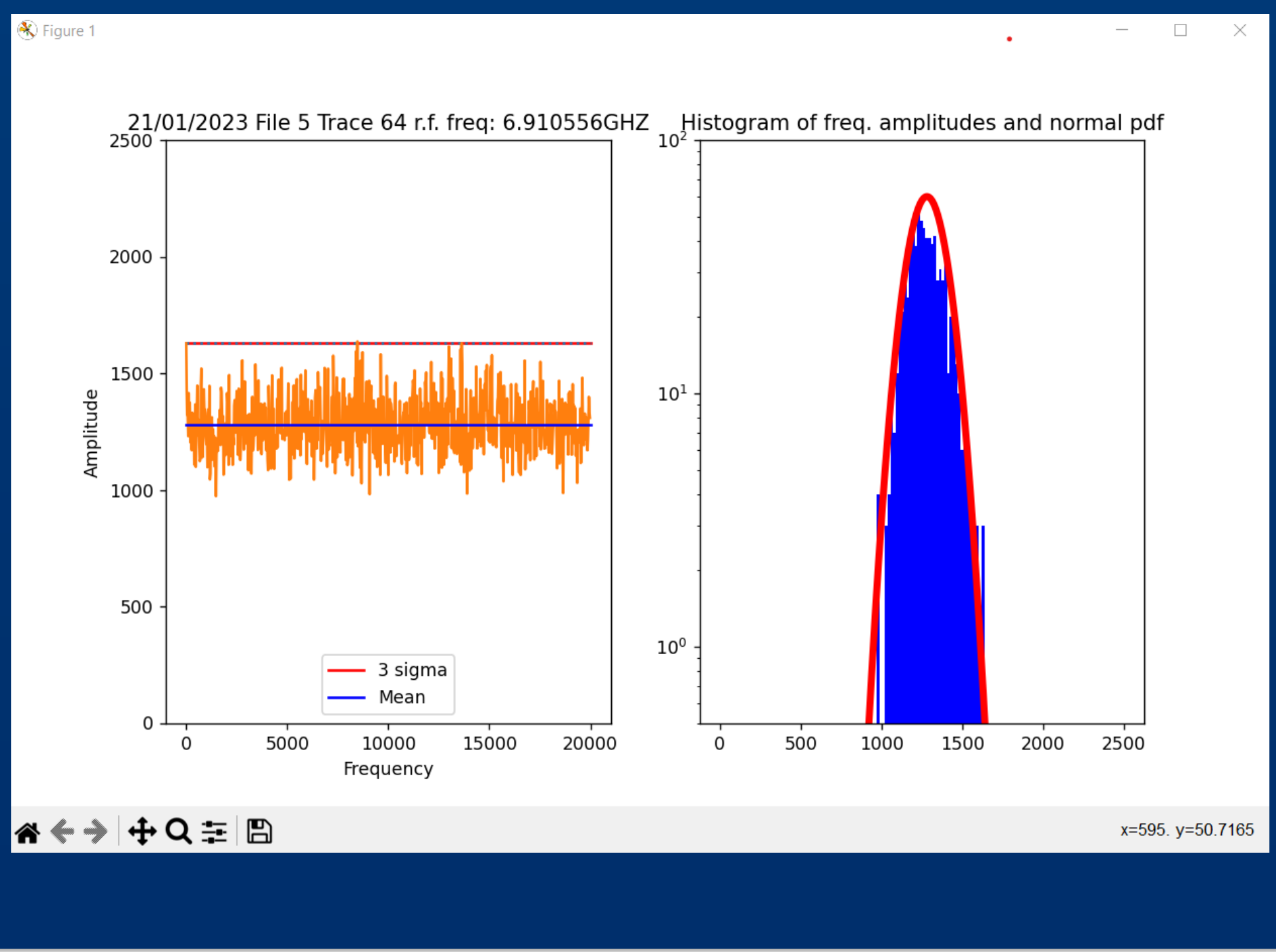
Noise as function of resistor temperature, predicting $T_N = 9.3K$.

Receiver Calibration

- To measure the sensitivity of the tuneable microwave receiver we inject a known signal at the test port of the resonator. A more reliable method to measure the system noise temperature involves connecting ***a variable temperature 50 ohm resistor*** at this port and then varying its temperature while maintaining resonator and HEMT amplifier at the bath temperature.
- The output noise from the receiver is measured as function of resistor temperature T. A plot of noise vs. T extrapolates to yield the system noise temperature ~ 9.3K.

Signal Post-Processing

- The summed FFT data for a set of traces (~100) within a specific file is displayed.
- The mean μ of this data (~1000 points) is plotted & the standard deviation σ is calculated.
- A threshold line representing a threshold at $\mu+3\sigma$ is plotted.
- A histogram of the data is shown on the right, compared with a normal distribution generated from μ and σ.
- At the end of a sequence of traces, if any channel is above the threshold its frequency is written to the data summary file as ***a signal of interest***.
- The process is repeated for all the files in a folder (typically 100).
- ***Signals as low as 10^{-23} W are detectable with this receiver. This is still some 13dB above the predicted theoretical level for KSVZ axions***.
- The next steps include addition at the input of *a mK noise temperature SLUG amplifier* and *a tuneable resonant cavity.*
- These changes should allow preliminary axion searches over a wider range at the predicted theoretical levels.



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