Demonstration of an Ultra-Stable Temperature Platform

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ABSTRACT

We report on a new precision heater controller and thermometer design for use in cryogenic experiments. The heater controller uses a series array of Josephson junctions to precisely control the voltage drop across a heater resistor. The thermometer design reduces the thermal resistance between the thermometer and the liquid ^{4}He sample to the point where the noise is limited by thermally driven current fluctuation in the PdMn.

1 Introduction

Existing paramagnetic susceptibility thermometers used in fundamental physics experiments near 2.2 K are capable of measuring temperature changes with a precision of about 100 pK in a one-hertz measurement bandwidth, with a drift stability of about a nK per day. Commercial electrical heater controllers are only able to control power dissipation to a precision of about ten parts per million (ppm), with an open loop drift of about 50 ppm per day. We have developed an ultra-stable temperature platform with a noise of 25 pK in a one-hertz bandwidth, and we have identified the physical source of this residual noise.
We used an array of rf-biased Josephson junctions to precisely control the electrical power dissipation in a heater resistor mounted on this thermally isolated cryogenic platform to well beyond our ability to measure, which we estimate is stable to better than a part in 10^{12}. This Josephson heater controller may be used in a new synchronous demodulation circuit to maintain absolute temperature stability of the stage to about the same level as the demonstrated noise, provided that the ^{4}He superfluid transition temperature is fundamentally stable at this level.

2 Experimental Setup

2.1 Overall Design

The overall design of the experiment is sketched in figure 1. There are five independent, temperature controlled stages, each with a commercial germanium resistance thermometer (GRT) and a heater. A radiation shield/cooling stage with a high resolution PdMn paramagnetic susceptibility thermometer [1] [2] a backup GRT and a heater surrounds the experimental cell. The PdMn helium cell is mounted inside the shield, supported by stainless steel posts. A novel new cell construction, consisting of a cell made with the PdMn thermometric material and inserted in a superconducting flux tube, was used in this work. A cryogenic valve that connects to the cell is mounted on the shield. The shield is controlled using its HRT to better than 1 μK. The Josephson array is mounted outside the vacuum space in the helium bath, and superconducting wires are routed through a hermetic seal to connect the Josephson array voltage to the heater resistor on the cell.

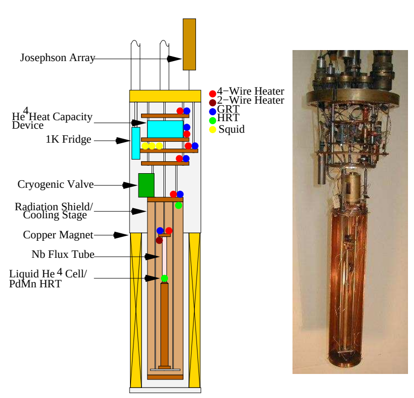

Figure 1. The overall experimental design. Photograph shown with vacuum can removed.

2.2 Josephson Array

The setup for the Josephson array is shown in figure 2. The Josephson array is attached to a series of filters for the voltage and current leads. The array is biased with a frequency of 94.100000000 GHz. The state is selected by varying the current through the array using the attached oscilloscope. The array is directly attached to a 1015 Ω surface mount resistor using a twisted pair of superconducting wires. This ensures that the voltage difference across the array is the same as the voltage drop across the resistor. This voltage drop is also measured using the pair of voltage leads connected to the oscilloscope.

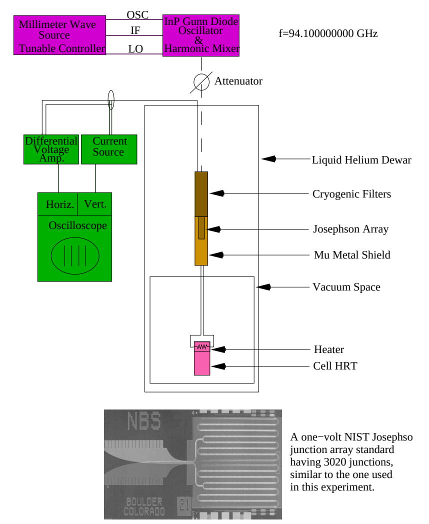

Figure 2. The Josephson array setup.

2.3 PdMn Cell

A schematic for the PdMn cell is shown in figure 3. The cell body is made of PdMn rolled to a thickness of 0.076 cm and formed into a cylinder around a 0.483 cm rod. A small gap was left in the cell wall. Cigarette paper was wrapped around the PdMn and coated with epoxy to create a hermetic seal. The SQUID pickup loop was wrapped on top of the epoxy. A GRT and two heaters (a two wire heater connected to the Josephson array and a four wire heater that can be independently controlled) are thermally connected to the cell through a 0.089 cm ID Cu capillary that also functions as the fill line. A .013 cm ID CuNi capillary is connected to this Cu capillary and runs between the cell and the valve on the radiation shield. This small capillary forms the major component of the thermal link between the cell and the shield.

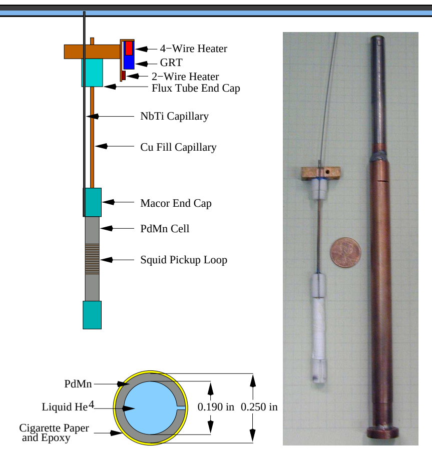

Figure 3. The design of the PdMn cell.

3 Cell Noise Limitations

3.1 Results

With the cell in thermal equilibrium with the surrounding shield, stabilized at a given temperature, the squid output is recorded at a rate of 20 kHz. This data is then analyzed to find the power spectral density (PSD) of the cell thermometer. Figure 4 shows the PSD for a typical data set taken at 1.6 K. This data clearly shows that the noise levels out to around 25 pk/$\sqrt{\text{Hz}}$ = 52 $\phi_0/\sqrt{\text{Hz}}$. Although the PSD computed using a large number of windows averaged together seems to show a rise in the noise around 300 Hz, this is just a byproduct of the averaging (done using Welch's method). In addition higher frequencies only show moderate drops in noise with no apparent roll off at the available frequencies, limited by the SQUID controller's 50 kHz bandwidth.

3.2 Anaysis

The cell noise was analyzed at a number of different temperatures and that data is summarized in figure 5. This data indicates that the noise is a non-linear function of temperature that is independent of temperature sensitivity, see figure 6.
In previous experiments the lower bound on noise in PdMn thermometers was due to fluctuation dissipation energy which is directly proportional to thermal resistance [1] [3]. In this design the thermal resistance has been greatly reduced, we estimate it at 0.25 K/W, which should lower this noise to around 5 pK/$\sqrt{\text{Hz}}$. This is well below the noise we have seen indicating that fluctuation dissipation energy is no longer the limiting factor. This is supported by the data showing that the noise is independent of cell sensitivity. If thermal fluctuations were the root cause of the noise then the noise in figure 5 should have corresponded to the sensitivity in figure 6. In addition, the noise seen here is significantly larger than typical SQUID flux noise of about <5 $\mu\phi_0/\sqrt{\text{Hz}}$.
This indicates that this noise is caused by thermally driven current fluctuations due to Johnson noise. These current fluctuations are given by equation 1:

$$\langle(\Delta I)^2\rangle_{\Delta f} = 4k\tau T/R_{el} \quad \text{(Eq. 1)}$$

Where k is the Boltzmann constant, τ is the time constant of the system, estimated to be 1ms, T is the temperature, and R_{el} is the electrical resistance, estimated to be 4 $\mu\Omega$. The expected flux noise for a different PdMn thermometer system was found to be $7x10^{-5}$ $\phi_0/\sqrt{\text{Hz}}$ [1], which is very close to the noise seen here.

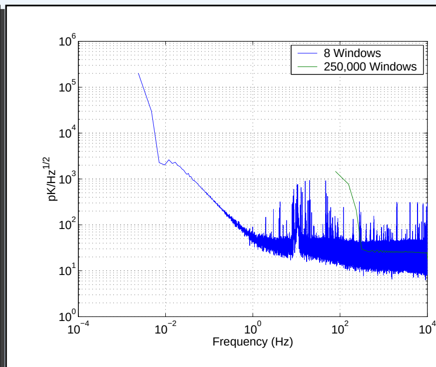

Figure 4. Temperature noise at 1.6K

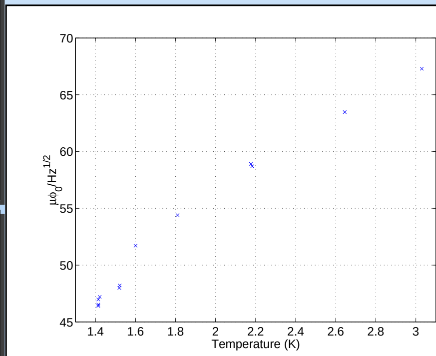

Figure 5. Flux noise on cell at 1kHz.

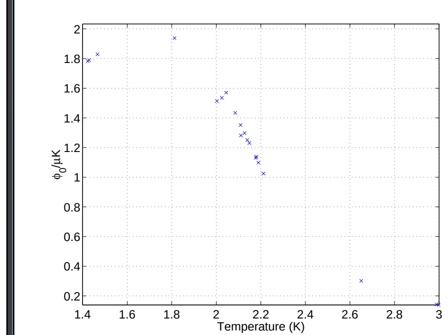

Figure 6. Sensitivity of cell as a function of temperature.

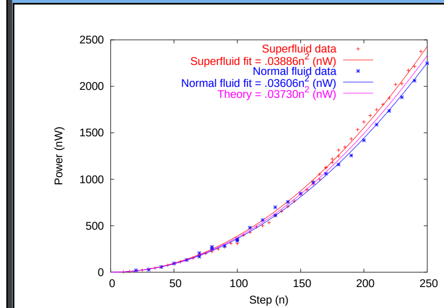

Figure 7. The power dissipation on the cell as a function of Josephson state n.

4 Josephson Heater Controller

Using an array of Josephson junctions it is possible to control the heat dissipated in a heater resistor with great precision, we estimate that it should be better than a part in 10^{12}. Experimental evidence of this is show in figure 7. Since the uncertainty in this power is so low, it is possible to apply a square wave power function to a helium filled cell. An example of this is shown in figure 8. In this case the array is changing between state 0 and state 10 every 60 seconds. Based on the slope of the triangle wave temperature that results from the applied power, it is a simple task to calculate the heat capacity, 2.2 J/K in this case.
Using this type of power supply, it should be possible to take advantage of the heat capacity peak that occurs in ^{4}He at the superfluid transition. By adjusting the temperature of the cooling stage to maximize the heat capacity of the helium it should be possible to maintain the temperature of the helium at the transition to about the same level as the thermometer noise.

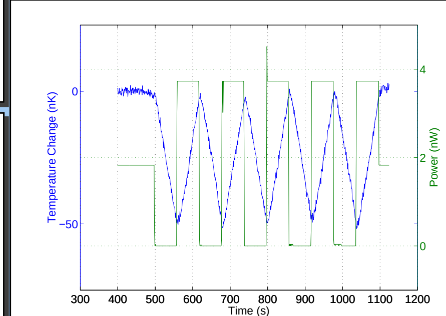

Figure 8. Square wave biasing of the cell heater using Josephon array.

Acknowledgments

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