Demonstration of an Ultra-Stable Temperature Platform

C. J. Green[*], D. A. Sergatskov[*], and R. V. Duncan[*,†]

[*] *University of New Mexico, Albuquerque, NM 87131, USA*
[†] *California Institute of Technology, Pasadena, CA 91125, USA*

We report on a new thermometer design and precision heater controller for use in cryogenic experiments. 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 electrical current fluctuations in the PdMn. The heater controller uses a series array of rf-biased Josephson junctions on a constant voltage state to precisely control the voltage drop across the heater resistor. This technology may be used to create a blackbody reference device with unprecedented stability.

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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[1,2]. We have developed a new 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.

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. In order to improve on this stability level, 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} per day. 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

The overall design of the experiment is sketched in Fig. 1(a). 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 (HRT)[1,3] a backup GRT, and a heater surrounds the experimental cell. The PdMn helium cell is mounted inside the shield, supported by Vespel posts, giving a thermal resistance between the cell and the cooling stage of approximately 4 kK/W. 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. 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 across the heater resistor on the cell.

A schematic for the PdMn cell is shown in Fig. 1(b). The cell body is made of PdMn rolled to a thickness of 0.076 cm and formed into a cylinder with a 0.483 cm inner diameter. A small gap was left in the cell wall to reduce the mutual inductance of thermally induced eddy currents to the SQUID pickup loop. Cigarette paper was wrapped around the PdMn and this gap and coated with epoxy to create a hermetic seal. Since the epoxy seal was only made between the paper and the ceramic end caps, the area between the paper and the cell body should be filled with helium. The SQUID pickup loop was wrapped on top of the epoxy and cigarette paper. A GRT and two heaters (a 1 kΩ heater connected to the Josephson array and a 5 kΩ heater that can be independently controlled by a commercial current source) are thermally connected to the cell through four Cu braids and a 0.089 cm ID Cu capillary that also functions as the fill line.

3. NOISE MEASUREMENTS

With the cell in thermal equilibrium with the surrounding shield, stabilized at a given temperature, the SQUID output is recorded with 16-bit precision at a rate of 20,000 samples per seconds. This data is then analyzed to find the power spectral density (PSD) of the cell thermometer. At all temperature the PSD's showed higher noise at lower frequencies and flattened out above 1 Hz. Data was also taken at much lower (10^{-5} Hz) and

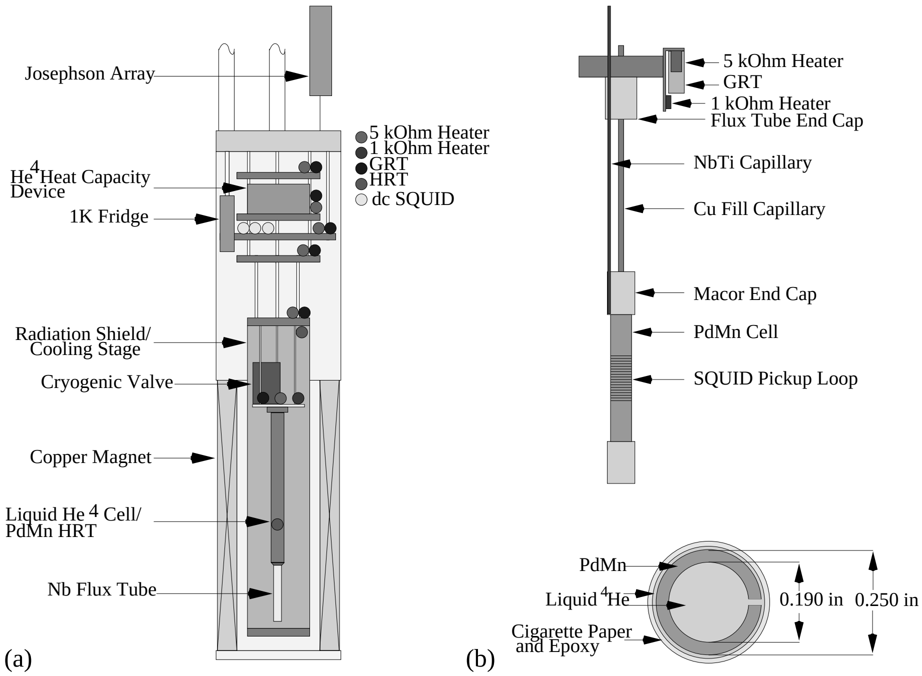

Fig. 1. (a) Cryostat setup for noise measurements. (b) Design of PdMn cell.

higher (50 kHz) frequencies with no apparent changes. The lower frequency data showed continually higher noise, due to long term instabilities of the platform in part due to energy fluctuations through the 4 kK/W thermal resistance of the cooling path from the cell. The higher frequency data remained flat at the available frequencies, limited by the SQUID controller's 50 kHz bandwidth. A summary of the data taken is shown in Fig. 2. The data in this figure represents the noise at 1 kHz, disregarding lower frequency data. The sensitivity of this paramagnetic susceptibility thermometer peaks at about 1.6 K, and drops rapidly in either direction from this point. Using the measured sensitivity and noise at this temperature, the temperature noise figure was 25 pK/$\sqrt{\mathrm{Hz}}$ at 1.6 K, and the temperature noise was a minimum at this temperature.

In previous experiments the lower bound on noise in PdMn thermometers was due to spontaneous thermal fluctuations (ΔT), given by[1,4]

$$\langle(\Delta T)^2\rangle_{\Delta f} = 4RkT^2 \tag{1}$$

where R is the thermal resistance to the heat bath, k is the Boltzmann constant, and T is the temperature of the system. In earlier experiments[2,5] $R \cong 50$ K/W, which resulted in thermal fluctuations of about 100 pK/$\sqrt{\mathrm{Hz}}$. In this cell design the helium heat bath is in direct contact with the PdMn.

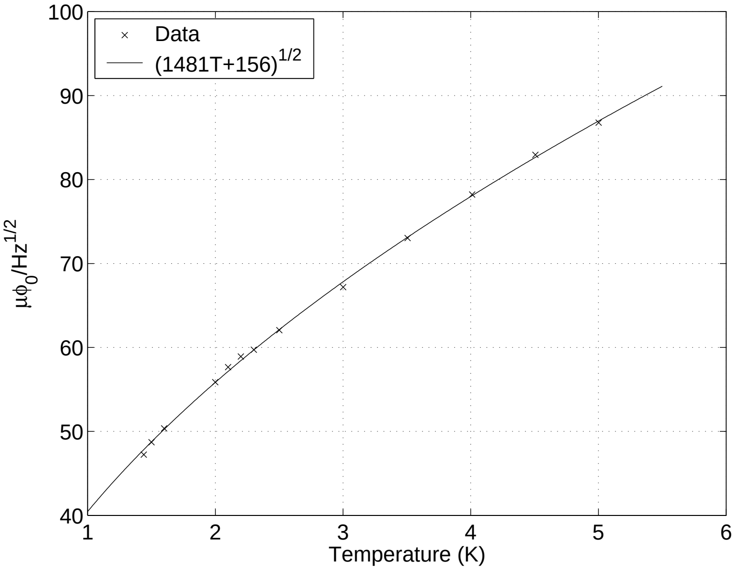

Fig. 2. Cell flux noise at 1 kHz as a function of temperature. Here the noise is expressed as flux noise coupled to the SQUID, where $\phi_0 = \frac{h}{2e}$ Wb $= 2.07\text{x}10^{-15}$ Wb.

This greatly reduces R, we estimate it at 0.25 K/W, which reduces the noise contribution to around 8 pK/$\sqrt{\text{Hz}}$. This is lower than the noise seen here, indicating that thermal fluctuations are no longer the limiting contribution to the noise. Furthermore, the flux noise shown in Fig. 2 does not have any correlation with the temperature variation of our sensitivity measurements, which it certainly would if the root cause of the noise were actual thermal fluctuations.

In this design the noise appears to primarily caused by thermally driven electrical current fluctuations in the metallic PdMn caused by Johnson noise. This magnetic flux noise induced by thermal fluctuations for a solenoid wound around a simple cylindrical sample with radius R, length l, and electrical conductivity σ, is[6]

$$\langle(\Delta\Phi)^2\rangle_{\Delta f} = \frac{2\pi\mu_0^2 kTN^2\sigma R^4}{l} \tag{2}$$

where N is the number of turns in the SQUID pickup loop, and k is the Boltzmann constant. For our geometry, the amplitude will be significantly reduced, but the dependence on σ and T will remain the same. Temperature change, ΔT, is related to flux change through the calibrated thermal sensitivity of the thermometer. We measured the electrical resistivity of the PdMn that was used in our cell construction using a standard 4-wire technique and found the residual resistivity ratio, RRR, to be 6.9 with less than a 1% variation in the resistivity over the range of interest. As expected from equation 2, the flux noise in Fig. 2 follows a $\sqrt{T}$ curve. The 12 $\mu\phi_0/\sqrt{\text{Hz}}$ noise that is independent of temperature may be due to the intrinsic noise of the superconducting SQUID circuit.

4. JOSEPHSON ARRAY HEATER CONTROLLER

Using an array of rf-biased Josephson junctions locked to a constant voltage state, $V_n = n\phi_0 f$, it is possible to control the heat dissipated in a heater resistor, $P_n = V_n^2/R$, with great precision, which we estimate to be better than a part in 10^{12}. Here n is an integer quantum number and f is the drive frequency. We have verified that the power dissipated through a resistor by an array of Josephson junctions does follow an n^2 curve as expected. Since the uncertainty in this applied heating power is so low, it is possible to apply a square wave power function to a helium filled cell and very accurately measure the heat capacity. An example of this is shown in Fig. 3. In this case the total heat to the cell is nulled with n=7 and f = 94.1 GHz by lowering the cooling stage temperature until the cell achieves steady-state. Then n is switched to $n = 0$ and then to $n = 10$, and back again, with one switch in n per 60 seconds. This is fast compared to the 50,000 s time required for the cell to reach steady state, so the time rate of change of the cell can be used to calculate its 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. Resulting in an ultra-stable temperature platform for an indefinite period of time.

Hence we predict that the temperature of this platform may be held stable to within better than 50 pK at the superfluid transition for an indefinite length of time. If the “Big Bang” theory of the origin of the cosmic microwave background radiation (CMB) is correct, then the temperature of the CMB should be cooling at about 250 pK/year. A measurement of this CMB cooling rate would be exceptionally difficult to make, but at least now we have demonstrated a technology which may be used to stabilize a reference blackbody temperature to better than the predicted stability of the CMB radiation temperature, provided that the superfluid transition temperature does not vary with the cosmic expansion.

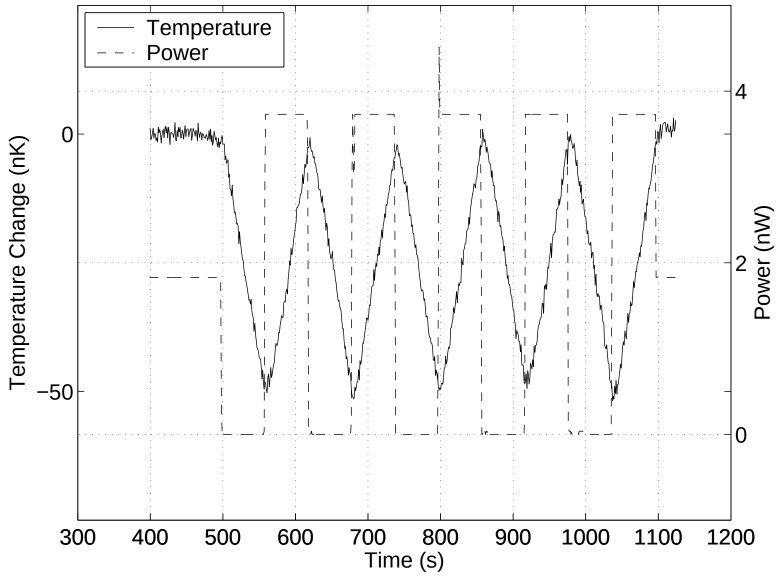

Fig. 3. Square wave biasing of the cell using Josephson array heater. These measurements were made with zero temperature change corresponding to 120μK below the superfluid transition temperature.

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