Stable temperature regulation for TES testing below 200mK employing improved Cohen-Coon method

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Stable temperature regulation for TES testing below 200mK employing improved Cohen-Coon method

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Abstract. Transition Edge Sensor (TES) is a promising low-temperature detector technology for high-resolution X-ray spectroscopy. Hot Universe Baryon Surveyor (HUBS) is a satellite concept proposed in China to address so-called “missing baryon problem”, which has serious implications on the formation and evolution of galaxies. At the heart of HUBS is a soft X Ray spectrometer based on TES operating below 100 mK. In the developing phase, the characterization of TES requires high accuracy and stable temperature regulation. Typically, 10 μK temperature fluctuation would be needed over the temperature range of 50 mK to 200 mK. To achieve this accuracy, we designed and built a cold plate in a dilution refrigerator, which regulates temperature on the cold plate with a PID controller. To improve the stability of temperature regulation, Cohen-Coon method is employed and optimized experimentally. Over the desired temperature range, the temperature of the cold plate can be regulated stably and accurately. At typical transition temperatures of our TES devices, temperature fluctuation is well controlled, e.g., within 8 μK (rms) fluctuation at 100 and 200 mK.

1. Introduction

HUBS, Hot University Baryons Surveyor, is a space X-ray observation project proposed in China to address so-called “missing baryon problem”. It aims to significantly advance the study of formation and evolution of galaxies [1]. Important technologies such as detector, SQUID, refrigerator are under development.

Among all technologies micro-calorimeter is the heart of HUBS. Micro-calorimeter on HUBS will be optimized with a very high energy resolution (2e V@ 0.6 keV). Transition edge sensor (TES) makes such high energy resolution possible. TES generally works at its super conducting transition point, which is below 100 mK for HUBS. Incident photon generates a small raise of TES temperature. In order to distinguish the signal from background noise which is the temperature fluctuation of cryostat in this case, it is necessary to keep temperature of cryostat very stable and precise at the transition point during characterization of TES. Since the transition region is very narrow (1~2 mK), less than 10 μK temperature fluctuation is allowed below 200 mK. Since the whole transition region of TES is necessarily covered, regarding HUBS project the cryostat should cover a temperature range from nearly 4K down to 50mK and stable temperature regulation is a priority for us before characterization of TES.

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Dilution Refrigerator (DR) is a powerful tool for physics experiments, which is able to obtain ultra-low temperature down to 10 mK. It has a larger cooling power below 100 mK compared with adiabatic demagnetization refrigerator, therefore, it is the ideal choice for experiments on the ground. The only drawback of DR is that the temperature of DR is constrained below 1 K due to its principle. TES for HUBS will be made of Mo/Cu bilayer and therefore superconducting transition will happen twice at about 1 K and 100 mK. A commercial DR cannot raise its temperature up to 1 K by directly heating mixing chamber plate. Based on this situation, a cold plate was designed and built on the mixing chamber plate in our DR. On this cold plate temperature is capable to ramp up to 3 K and down to 50 mK. At 100 mK, the temperature can be regulated stably and precisely with experimentally improved Cohn-Coon method (CC method), typically less than 10 μK (rms) temperature fluctuation can be maintained at least one hour.

2. Experiment Details

2.1. Cold plate

A common method for stable temperature regulation is to combine of thermal resistance and heat capacity [2]. We didn't add additional heat capacity because a large heat capacity will prolong the cool down time and slow down temperature ramp rate significantly. The cold plate with only a large thermal resistance was designed. This cold plate is made of stainless steel (SST) and high-purity oxygen-free copper (HOFC). Thermal conduction of SST is weak at this temperature, which provides enough thermal resistance [3]. HOFC can provide a good thermal conduction on the plate, is mainly used for TES mounting [4].

The details of designed cold plate are shown in Fig.1. It was gold plated to reduce thermal resistance. Extra thermal anchors were built for better thermal equivalences between thermometers' wires and the cold plate.

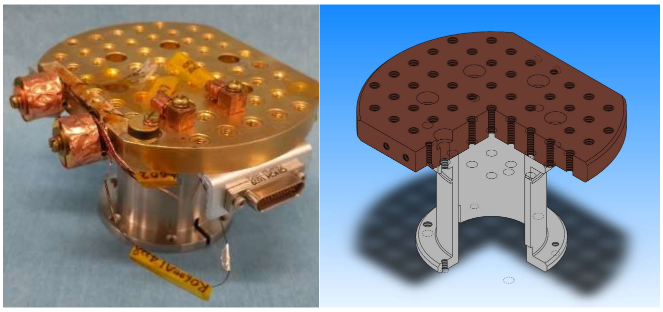

Figure 1. Cold plate design

2.2. Experiment schematics

The experiment schematics is shown below in Fig.2. The designed cold plate was mounted on the mixing chamber plate in DR. Built-in thermometers and heater were used for temperature readout. More than one thermometer were used for controlling and monitoring reasons. A commercial bridge was used for temperature readout, it had two synchronized channels for the controlling and monitoring thermometers. Current for heater can be provided either from commercial bridge or high-accuracy source meter. All of these instruments were controlled by Labview program on a PC.

2.3. Temperature readout

Commercial calibrated RuO thermometers were employed in both temperature regulation and monitor. A typical curve is manifested in Fig.3. RuO is a typical negative temperature coefficient resistance thermometer. The resistance changes dramatically below 1 K and its sensitivity is ideal for temperature regulation at this range. The calibration accuracy for this kind of thermometer is usually within mK range. The values of temperature fluctuation were interpolated from thermometer's resistance. Resistances of thermometers were recorded in this experiment to reflect the temperature fluctuation.

RuO thermometers are not so sensitive above 2 K, so it becomes difficult to get stable temperature regulation with RuO above 2 K. The molybdenum film transition happens around 1 K, for this reason temperature regulation above 2 K is not a main concern of this experiment.

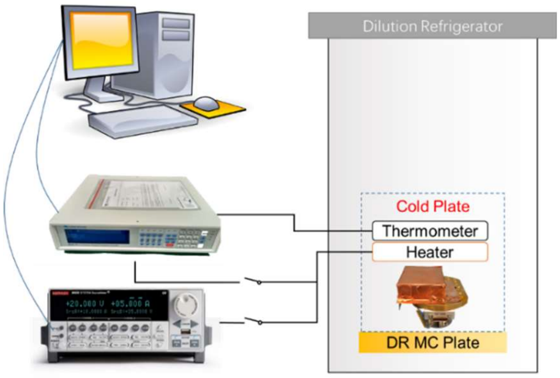

Figure 2. Schematic of experiment

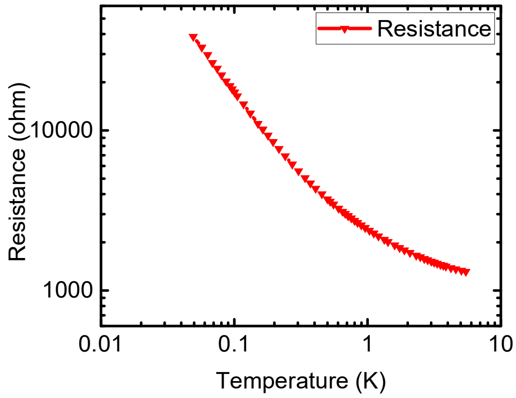

Figure 3. Calibrate curve of Thermometer

3. Results and discussion

Manual PID tuning method is still widely used in cryogenics experiments. In this way, a group of PID parameters could be obtained by several experiments, nevertheless, manual PID tuning method is time-consuming and not satisfying in some cases. In this experiment, Cohen-Coon method, widely used in industry [5], was implemented and optimized experimentally to achieve a fast and stable regulation result.

3.1. Step response

Firstly, we introduced a step change of current, which caused a temperature change, seen in Fig.4. 100mA current caused the temperature raise from 52 mK to 142 mK. Points of t1 and t2 in Fig.4 were used to calculate the regulation parameters by standard CC method [6]. Standard CC PID parameters were calculated as follow: P=34.05, I=16.4.

Since heating current was constant, temperature fluctuation was an indication of temperature oscillation of DR itself. Temperature fluctuation of 36.5 μK@142mK, and 64.2μK@ 355mK(rms) could be seen in this case. Regulation temperatures were set by thermometer's resistance in the following experiment, we rounded resistance and actual temperature setpoint were 100.15 mK and 199.99mK.

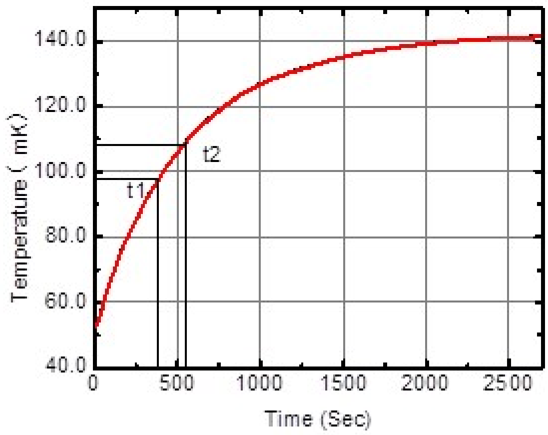

Figure 4. Step response of the cold plate

3.2. Regulation with standard CC method

After calculation of PID parameters, temperature regulations were tested around 100 mK and 200 mK, which can be seen in Fig.5 below. There was a large overshoot at 100 mK and it took quite a while to converge to the target temperature. After the temperature became stable, the temperature fluctuation was 13.2 μK (rms), which is lower than DR's oscillation. The low frequency interference existed and the noise level was high, which had an adverse effect to the regulation result. At 200mK there was a reasonable overshot, and the temperature converged to the target temperature rapidly and then stayed still. Fluctuation of the temperature was less than 6μK in the following 7000 seconds. The noise from environment could still be seen in the temperature reading, however, it was relatively small, the main noise in domain seemed to be random noise.

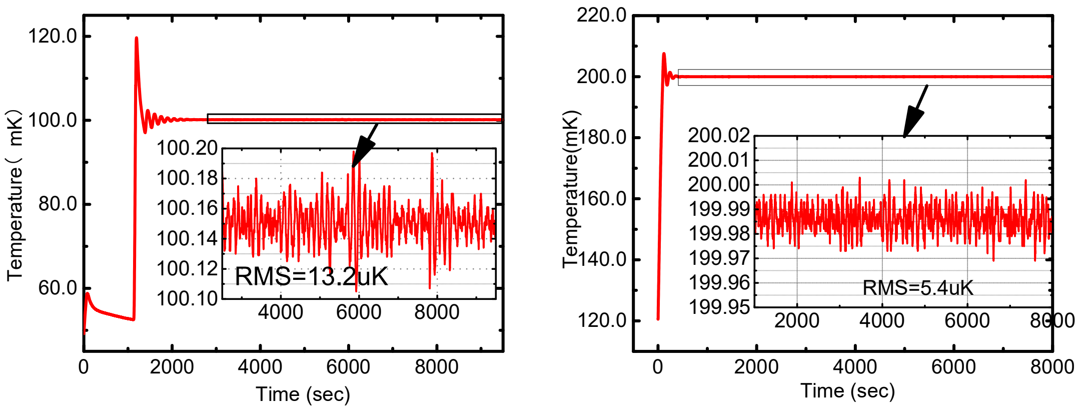

Figure 5 Regulation Result with standard CC method

3.3. Regulation with improved CC Method

Regulation with standard CC method was not satisfying in two aspect: the converging time and overshoot. Correction was made experimentally based on this group of PID parameters. Parameter I was multiplied by 1.3 and parameter P was multiplied by 0.8. Improvement were seen in Fig.6. Overshoots were reduced and converging times were shortened at 100 mK. The improvement in temperature fluctuation was obvious. 7.5 μK and 4.7 μK temperature fluctuation in rms can be achieved at 100mK and 200mK respectively.

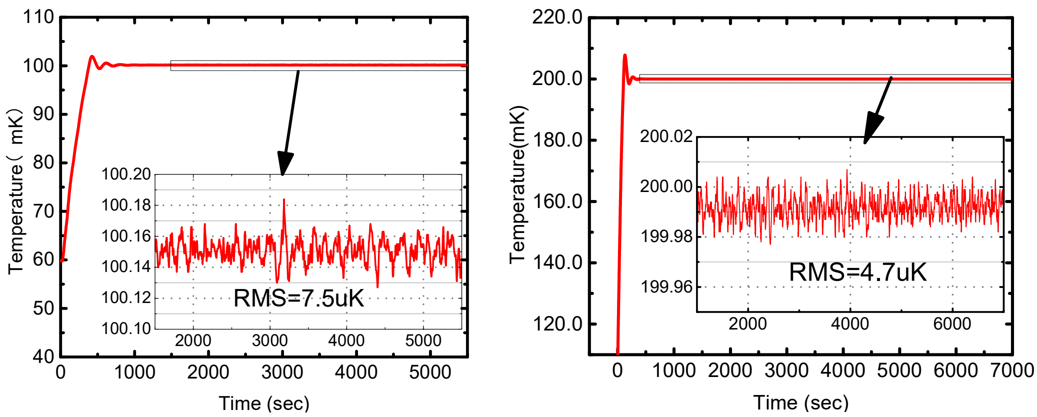

Figure 6 Regulation Result with standard CC method

3.4. Upper temperature of cold plate

This cold plate could be heated up to 3.06K with 1500 uW heating power. In this case, the mixing chamber plate of DR could stay 208mK, which was far away from phase separation point of He^3 and

He^4. This cold plate is able to test TES from 50mK to 3K which covers the transition range of molybdenum and bilayer film.

4. Conclusion

A cold plate was designed and tested in DR. The temperature of the cold plate could be regulated stably and precisely. In this experiment, it was found that parameter I shall be increased and parameter P shall be reduced to obtain a better regulation. Temperature fluctuation can be maintained below 7.5μK and 4.7μK (rms) at 100mK and 200mK with improved CC method, which fulfilled the requirement of stability in TES characterization test. Temperature of this cold plate could change from 3K down to 50mK. It is enough for HUBS development at this stage.

Acknowledgement

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Reference

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