IOP Conference Series: Materials Science and Engineering

A study of mK cooling system for space application

To cite this article: Chen Liubiao *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **502** 012063

IOP Conf. Series: Materials Science and Engineering **502** (2019) 012063 doi:10.1088/1757-899X/502/1/012063

A study of mK cooling system for space application

Chen Liubiao[1], Jin Hai[3], Wang Jue[1, 2], Pan Changzhao[1], Wu Xianlin[1, 2], Cui Wei[3], Zhou Yuan[1, 2], Wang Junjie[1, 2, *]

[1] Chinese Academy of Sciences Key Laboratory of Cryogenics, Technical Institute of Physics and Chemistry, Beijing 100190, China;
[2] University of Chinese Academy of Sciences, Beijing 100049, China
[3] Department of Physics and Center for Astrophysics, Tsinghua University, Beijing, 100084, China

The corresponding author's e-mail address: wangjunjie@mail.ipc.ac.cn

Abstract. Hot Universe Baryon Surveyor (HUBS) is being conceptualized in China as a major X-ray mission for the next decade to look for "missing baryons". The superconducting transition-edge sensor is a key technology in HUBS, which needs to be worked at temperatures below 100 mK. In this paper, the HUBS cooling system will be designed and discussed. A 4 K mechanical cryocooler combined with adiabatic demagnetization refrigerator (ADR) will be employed in the preliminary design. Some test performance of two candidate models for precooling stage, the self-developed pulse tube cryocooler driven by linear compressor or thermal compressor, will be presented.

1. Introduction

Hot Universe Baryon Surveyor (HUBS) is being conceptualized in China as a major X-ray mission for the next decade [1]. Its primary scientific objective is to conduct a census of baryons in the warm-hot circumgalactic and intergalactic media and thus to directly address the issue of "missing baryons" in the local universe. An instrument with high spectral resolution, large effective area and large field of view would be required for such a purpose. HUBS will couple a TES-based (transition edge sensor) X-ray imaging spectrometer to the optical system to satisfy these requirements. The principle of high-resolution X-ray imaging and spectrometers in the HUBS satellite program is to use the superconducting TES to measure the temperature change of the micro-energy to sense the energy of the incident X-rays. In order to achieve the required high resolution detection target of 2eV@0.6keV, TES detectors need to operate at temperature below 100 mK.

2. Design concept

At present, there is no refrigeration technology that can be directly reduced from room temperature to such a low temperature. Usually, mK temperature can be obtained only by coupling a variety of refrigeration technology. For example: ASTRO-H satellite's mK refrigeration system consists of adiabatic demagnetization refrigerator (ADR), liquid helium (LHe), Joule-Thomson (JT) cryocoolers and Stirling cryocoolers [2-4]. The potential Athena X-ray Integral Field Unit (X-IFU) cryogenic chain will consists of the precooling stages (pulse tube cryocoolers and JT cryocoolers) and the sub-kelvin stages (ADR and sorption cryocooler) [5, 6]. In general, the space mK refrigeration system can be summarized into two parts: one is the sub-kelvin system, and the other is the pre-cooling system that provides cooling power for the sub-kelvin system, such as the pulse tube cryocooler (PTC), stirling cryocooler and the JT cryocooler.

For sub-kelvin system, there are usually three technologies: dilution refrigerator, sorption cryocooler and ADR. Dilution cryocooler technology usually requires a gravity environment, but as there is no gravity in the space environment, a more complicated structure is needed to realize the separation of liquid helium 3 and liquid helium 4 [7]. The lowest temperature that sorption cryocooler can obtain is relatively high. For example, the lowest temperature that can be achieved by helium 3 is about 300 mK [8]. Compared with the above mentioned two refrigeration technologies, ADR is an ideal mK refrigeration technology, which has great advantages in the available lowest temperature, stability and recycle time requirement. In fact, ADR refrigeration technology is also the choice of most of the space mK refrigeration systems such as ASTRO-H, SPICA and ATHENA. Therefore, ADR refrigeration technology will be chosen for mK refrigeration systems of HUBS.

For pre-cooling systems, mechanical cryocooler and liquid helium can usually be used. Compared with liquid helium, the mechanical cryocooler has the advantages of small size, light weight and long life, and it has become the first choice for space applications. Therefore, the precooling stage of the HUBS cooling system will use a mechanical refrigerator.

The design concept of the HUBS cooling system is shown in figure 1. The cooling chain from room temperature to the mK temperature is composed of the ADR and a 4 K mechanical cryocooler. The three radiation shields, working in the liquid nitrogen temperature region, the liquid hydrogen temperature region and the liquid helium temperature region, will be cooled by the three-stage mechanical cryocooler. For ADR, single-stage or two-stage structure will be employed (the ADR structure showen in Figure 2 is a single-stage), which will mainly depend on the lowest temperature that can be obtained by the pre-cooling mechanical cryocooler. For the precooled mechanical cryocooler, we currently have two potential options (VM-type pulse tube cryocooler or Stirling pulse tube cryocooler), which will be described in more detail later. In addition, as also can be seen from Figure 2, this mK refrigeration system designed for HUBS is relatively simple in structure compared to other mK refrigeration systems that have been launched or will be launched in the future. For example, for the pre-cooling stage, we will directly use a VM-type pulse tube cryocooler or a Stirling pulse tube cryocooler to directly obtain a temperature of about 2 K, so the structure is very simple. In general, the conventional pre-cooling systems usually require a Stirling cryocooler or pulse tube cryocooler to obtain a cooling temperature of 10-20 K firstly, and then further use JT cooler to obtain a temperature of about 2 K. In addition to the complicated structure, JT cooler is easily blocked by the condensed impurity gases [9].

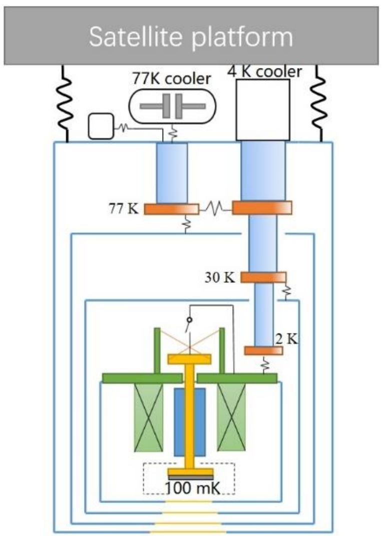

Figure 1. Design concept of the HUBS cooling system.

3. Potential options for pre-cooling

IOP Conf. Series: Materials Science and Engineering **502** (2019) 012063 doi:10.1088/1757-899X/502/1/012063

3.1. Stirling type pulse tube cryocooler

At present, the lowest temperature of the Stirling pulse tube refrigerator developed by Technical Institute of Physics and Chemistry of Chinese Academy of Sciences (TIPC) has been able to reach below 4 K [10, 11]. The structural diagram and prototype photos of this refrigerator are shown in Figure 2. It can be seen that this is a coupling structure of thermal-coupled and gas-coupled. The connection between the first and second stages is a thermal coupling structure. In the current prototype, the first stage uses liquid nitrogen, which will be replaced by the 77 K cryocooler for space application. The connection between the second and the third stage is a gas-coupled structure, which is characterized by a very compact structure.

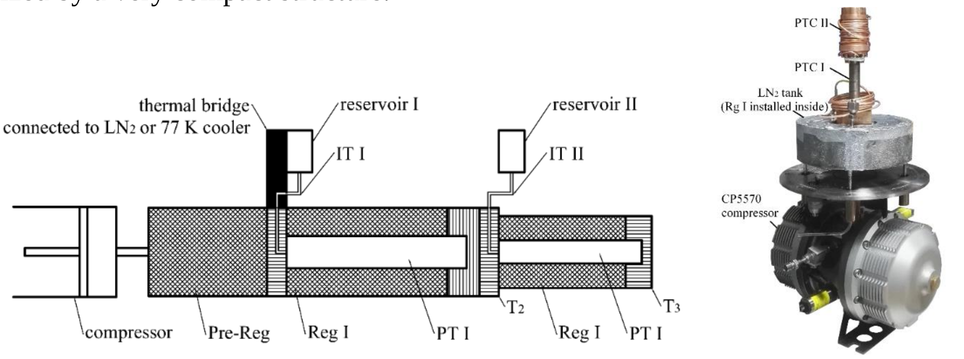

Figure 2. The schematic and photo of the developed three-stage stirling type pulse tube cryocooler.

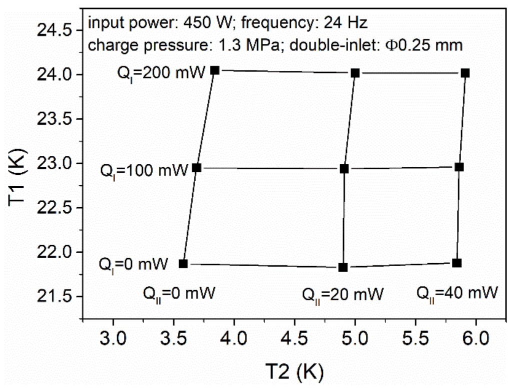

Figure 3. Cooling performance of the developed three-stage stirling type pulse tube cryocooler.

Figure 3 shows the ability of the second and the third stage to output the cooling power simultaneously [11]. It can be seen that the second and the third stage are capable of providing cooling power in the liquid hydrogen temperature region and the liquid helium temperature region, respectively. For example, the second and the third stage are capable of providing 100 mW and 20 mW of cooling power at 22.9 K and 4.9 K, respectively. In fact, through a brief estimation, the needed cooling power of the radiation shields working at the liquid hydrogen and the liquid helium temperature region is very small, which is about 20 mW at 25 K and about 5 mW at 4.2 K (When the cooling capacity of the pre-cooling cooler can meet the heat leakage requirement, then only a little excess cooling capacity is needed to provide pre-cool the mK cooler, such as 1 mW. Of course, the larger the cooling capacity, the more the initial cooling time is reduced.). Therefore, the power consumption of the refrigerator can be reduced to a certain extent. For example, when the input electrical power of the refrigerator is 250 W and the liquid nitrogen provides a pre-cooling power of 12.1 W, the required cooling power of the radiation shields working at liquid hydrogen and liquid helium temperature region can be satisfied. At present, the efficiency of the 77 K refrigerator developed by TIPC can reach 24.2% [12]. Therefore, if this refrigerator is used instead of liquid nitrogen, the power consumption of the whole cryocooler is expected to be controlled within 385 W. In addition, considering that the first-stage radiation shield working at liquid nitrogen temperature region also needs to provide a certain amount of cooling power (the estimated value is 6 W), then the total input electrical power consumption value is about 450 W.

3.2. Vuilleumier (VM) type pulse tube cryocooler

VM type cryocooler is driven by a thermal compressor and its operating frequency is usually below 5 Hz. The pressure wave is generated when the working gas is shifted to different temperature zone by the periodic displacer motion. As the two ends of the displacer are isobaric, the force required to drive the displacer is small, and its power consumption is negligible. Therefore, the power consumption of the VM type cryocooler is mainly concentrated on the two different temperature heat sources.

TIPC has developed a VM and PTC gas coupling type cryocooler, as shown in figure 4 [13]. For this prototype, the hot end temperature of the thermal compressor was room temperature, and the cold end temperature was controlled at 77 K by using liquid nitrogen, and then a lowest temperature of 2.5 K and a cooling power of 35.9 mW/4.2K can be achieved [13]. In addition, this cryocooler can also provide cooling power to different radiation shields in the liquid nitrogen temperature region, the liquid hydrogen temperature region and the liquid helium temperature region.

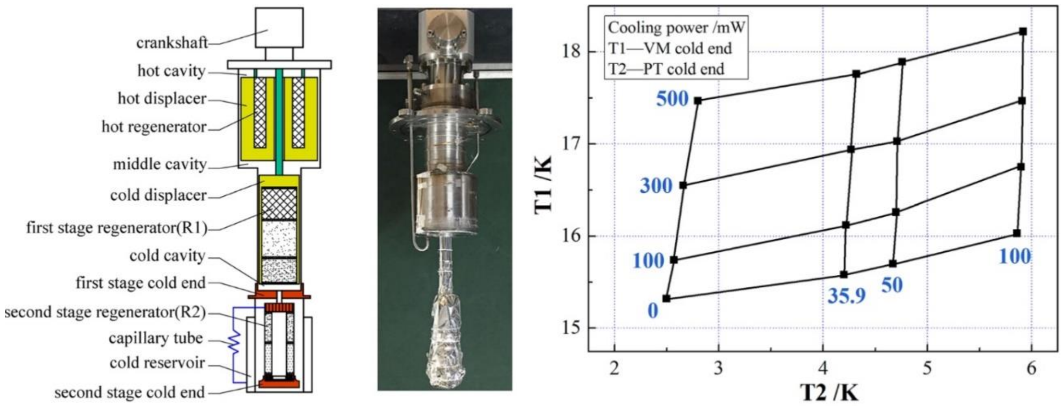

Figure 4. The schematic, photo and cooling power of the developed VM-PTC cryocooler.

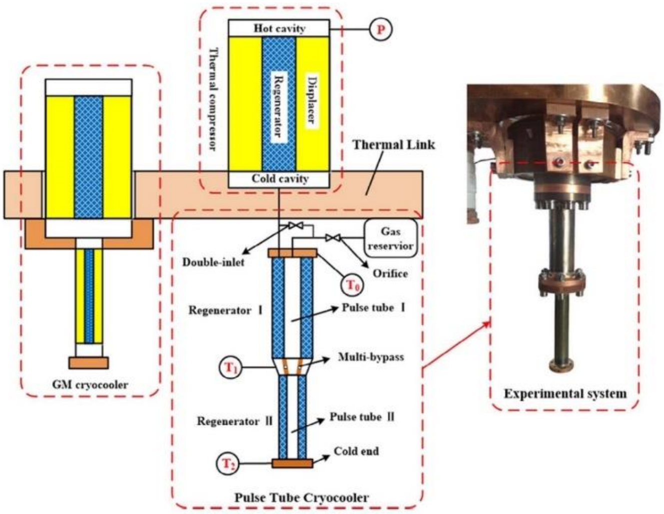

Figure 5. The structure schematic and photo of the developed VM type pulse tube cryocooler.

Based on the above VM-PTC cryocooler, our group made some further improvements: a. Directly use the multi-pass bypass PTC without moving parts to replace the original second-stage displacer to further enhance the reliability of the cooling system; b. A Gifford-McMahon cryocooler (GM) was used instead of liquid nitrogen to further facilitate experimental testing. Figure 5 is the structure schematic and photo of the developed cryocooler [14]. At present, a no-load temperature of 4.9 K and a cooling power of 30 mW/5.6 K can be achieved with a precooling power of 46 W/90K (the total input electrical power of this cryocooler would be below 450W if a high-efficiency 77 K PTC was used to replace the GM cryocooler). In addition, this cryocooler can also provide cooling power to different radiation shields at the temperature around 80 K, 40 K and 4 K simultaneously. By further optimizing the phase shifters such as multi-bypass, double-inlet and inertance tube, the cooling performance of this cryocooler is expected to be further improved. Another point to note is that the current sealing method for our VM cooler displacer and thermal compressor is to use spring energized seal. Next we will use the labyrinth seal method to further improve the reliability and ensure the long life of the chiller (≥5 years).

4. Summary

The design concept of mK cooling system for HUBS has been described. The cooling chain from room temperature to the mK temperature is composed of ADR and 4 K mechanical cryocooler. For sub-kelvin cooling system, single-stage or two-stage ADR will be employed, which will mainly depend on the lowest temperature that can be obtained by the pre-cooling mechanical cryocooler. For the precooling system, there are two potential options, Stirling pulse tube cryocooler and VM type cryocooler. Currently, the two solutions can basically meet the requirements, but the cooling performance needs to be further improved. For the selection of the final scheme of the pre-cooling system, in addition to the cooling power requirements of the three radiation shields working in the liquid nitrogen temperature region, the liquid hydrogen temperature region and the liquid helium temperature region, the power consumption, weight and reliability will be further considered.

5. References

[1] Wei Cui, Taotao Fang, Bo Gao, Li Ji, Hai Jin, Congzhan Liu, Fangjun Lu, Houjun Mo, Changzhao Pan, …and Shuo Zhang. 2018 *Space Telescopes and Instrumentation 2018: Ultraviolet to Gamma Ray* (SPIE) Conference 10699 p 233

[2] Sato Y, Sugita H, Mitsuda K, Nakagawa T, Fujimoto R, Murakami M, ... and Narasaki K 2010 *Cryogenics* **50(9)** 500-506.

[3] Fujimoto R, Mitsuda K, Yamasaki N, Takei Y, Tsujimoto M, Sugita H, ... and Ezoe, Y 2010 *Cryogenic*s **50(9)** 488-493.

[4] Fujimoto R, Takei Y, Mitsuda K, Yamasaki N Y, Tsujimoto M, Koyama S, ... and Okamoto A 2016 *In Space Telescopes and Instrumentation 2016: Ultraviolet to Gamma Ray* International Society for Optics and Photonics (Vol. 9905) p 99053S

[5] Duband L, Charles I., and Duval J M. 2014 *In Space Telescopes and Instrumentation 2014: Ultraviolet to Gamma Ray* International Society for Optics and Photonics (Vol. 9144) p 91445W

[6] Branco M C, Charles I, and Butterworth J 2014 *In Space Telescopes and Instrumentation 2014: Ultraviolet to Gamma Ray* International Society for Optics and Photonics (Vol. 9144) p 91445V.

[7] Mandolesi N, Villa F, and Valenziano L 2002 *Advances in Space Research* **30(9)** 2123-2128

[8] Bhatia R S, Chase S T, Edgington S F, Glenn,J, Jones W C, Lange A E, ... and Rownd B K 2000. *Cryogenics* **40(11)** 685-691

[9] Sato Y, Shinozaki K, Sawada K, Sugita H, Mitsuda K, Yamasaki N Y, ... and Yoshida S 2017 *Cryogenics* **88** 70-77

[10] Liubiao C, Xianlin W, Xuming L, Changzhao P, Yuan Z & Junjie W 2018 *International Journal of Refrigeration* **88** 204-210.

[11] Liubiao C, Xianlin W, Jue W, Xuming L, Changzhao P, Hai J, Wei C, Yuan Z and Junjie W 2018 *Cryogenics*.

[12] Wang X., Zhang Y., Li H., Dai W., Chen S., Lei G and Luo E 2015 *AIP Advances* **5(3)** 037127.

[13] Wang J, Pan C, Zhang T, Luo K, Zhou Y and Wang J 2018 *Journal of Applied Physics* **123(6)** 063901

[14] Pan C, Wang J, Luo K, Wang J and Zhou Y 2017 *Cryogenics* **88** 66-69

Acknowledgments

This research is supported by National Key R&D Program of China (No. 2018YFB0504603), the National Natural Science Foundation of China (No. 51706233, 51427806, U1831203), Strategic Pilot Projects in Space Science of China (No. XDA15010400), and Supported by Key Research Program of Frontier Sciences, CAS, Grant No. QYZDY-SSW-JSC028.