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Design and performance testing of the 3-stage ADR

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Abstract. As an important sub-Kelvin refrigeration technology, the adiabatic demagnetization refrigeration (ADR) is used for space detector cooling and ground-based experiments because of its wide temperature coverage, high efficiency and gravity-independence. We design a 3-stage adiabatic demagnetization refrigerator pre-cooled by a GM-type pulse tube cooler and operating from 4 K to 50 mK. Gadolinium Gallium Garnet (GGG) is used for high temperature stage and chromium potassium alum (CPA) is used for low temperature stage. All the salt pills are supported by polyether ether ketone (PEEK) suspensions. The active/passive air-gap heat switches are used to control heat transfer between stages. The system has achieved a lowest temperature of 35mK in a single-shot mode as well as 100mK intermittent cooling. This paper introduces the refrigeration performance of the 3-stage ADR as well as details of critical components. An interesting configuration for realizing an ADR with multiple continuous cooling stages will also be discussed.

1. Introduction

Sub-Kelvin refrigeration used to achieve temperatures below 1 K plays an indispensable role in space detector cooling and frontier scientific research. Adiabatic demagnetization refrigeration (ADR), as one of primary sub-Kelvin refrigeration technologies, is preferred choice for space missions because of its wide temperature coverage, high efficiency and gravity-free operation.

Many space detectors require ultra-low temperatures (tens to hundreds of millikelvin). It needs muti-stage ADR to achieve these significant cooling. Over the past decades, international space agencies, including NASA (U.S.), ESA (Europe) and JAXA (Japan), have conducted researches on ADR for space missions. A 3-stage ADR was developed for the Japanese Astro-H mission to cool the SXS instrument to 50 mK[1–4]. Subsequently, a 5-stage continuous ADR (cADR) was designed by NASA for the Constellation-X mission, meeting the cooling requirements of the XMS instrument[5]. This system achieved a minimum continuous cooling temperature of 35 mK and provided 20 μW of continuous cooling power at 100 mK. To study B-mode polarization of the cosmic microwave background, a 7-stage ADR is being collaboratively investigated for LiteBIRD program to achieve cooling for different instruments[6]. In the program, JAXA provides 4 K precooling for ADR, NASA develops 3-stage ADR subsystem maintaining 1.75 K continuous cooling, and CEA designs 4-stage ADR subsystem for dual continuous cooling at 300 mK and 100 mK.

The 3-stage ADR developed in our laboratory has achieved a minimum cooling temperature of 38 mK in 2023[7]. At 100 mK, it demonstrated an experimental cooling capacity of 71 mJ and a temperature fluctuation of 10.6 μK. We have upgraded the 3-stage ADR by replacing traditional Kevlar suspensions with PEEK suspensions and using a large mass gadolinium gallium garnet (GGG) salt pill in high temperature stage and the schematic of the cryogenic system is shown in Fig. 1. Section 2 presents the design details. Section 3 presents the cooling performance test, including both the single-shot mode and the intermittent cooling mode. In section 4, we propose a multiple continuous cooling stage configuration using 3-stage ADR and the conclusions are stated in Section 5.

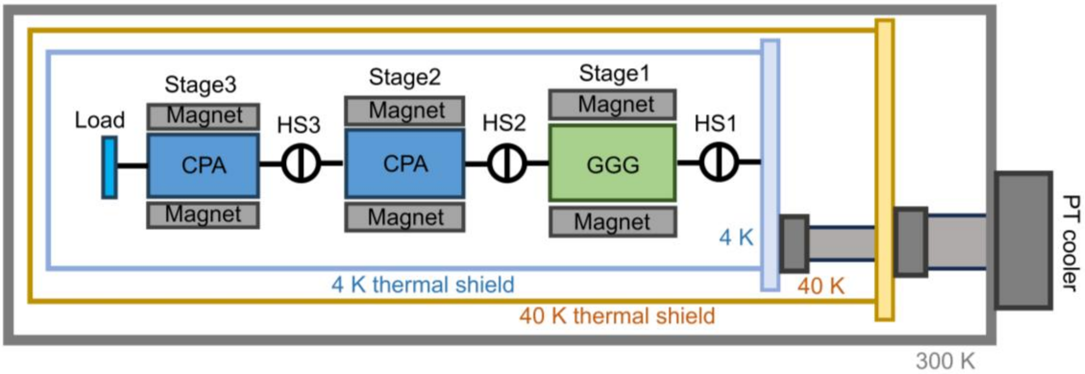

Figure 1. Schematic of 3-stage ADR system.

2. Design of 3-stage ADR

A 2-stage GM-type pulse tube cryocooler provides the 4 K heat sink to ADR subsystem while simultaneously providing the cooling for the two-stage thermal shields. The first and second stage cold heads of PT cooler are connected to their respective cold plates via multi-layered flexible copper foil, while all three magnets of ADR are thermally anchored to the 4 K cold plate. The detailed description of some components is presented below with Table 1 summarizing the design details.

2.1 Salt pills

The salt pill comprises magnetocaloric materials and thermal transfer structures. In our ADR system, the high temperature stage (S1) operates near 1 K, so gadolinium gallium garnet (GGG) is chosen for high magnetic entropy density. For GGG, a single-crystal material, as shown in Fig. 2(a), it is encapsulated with copper fins and hermetically sealed within a stainless steels canister filled with ^{3}He to achieving high-efficiency heat transfer. A 1078g GGG is intentionally selected to provide a long-time stabilization of the 1 K thermal interface for stage 2 and 3, so the performance testing could focus on stage 2 and 3.

Since the lower temperature stage cools below 100 mK, chromium potassium alum (CPA) is chosen for stage 2 and stage 3, which exhibits a magnetic ordering transition temperature of 9 mK. The CPA salt pill, shown in Fig.2(b), consists of thermal buses and CPA crystals, which are both sealed inside a G10 canister. Thermal buses with 0.2 mm diameter are passed through two stainless steel spacers and pressure welded to copper rod. CPA crystals are grown on the thermal buses by circulating solution technique and can be filled over 95%.

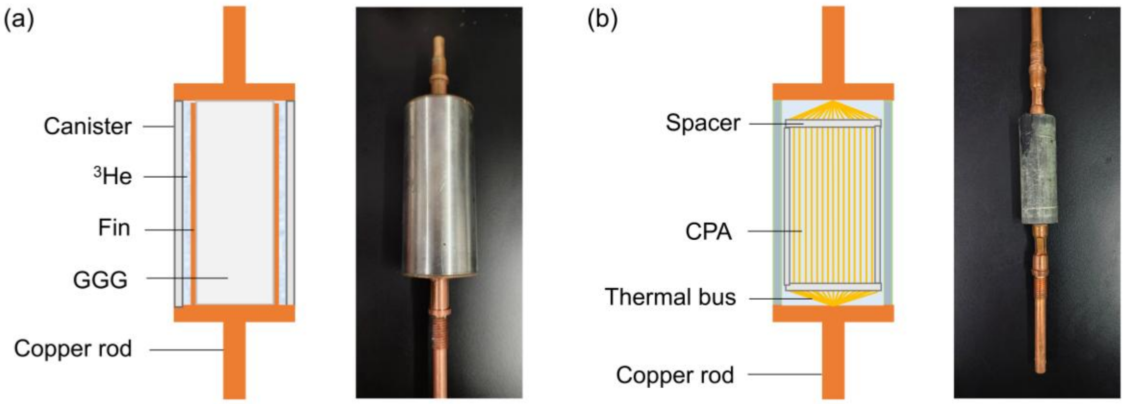

Figure 2. Schematics and photos of salt pills: (a) GGG salt pill; (b) CPA salt pill.

2.2 Heat switches

Heat switch used for heat transfer between each stage is the critical components to achieve the refrigeration cycle. Gas-gap heat switches are chosen because of simple design and easy control.

Active gas-gap heat switches are used both in stage 1 and stage 2. Short-tailed HS1, as shown in Fig.3(a) is used for stage 1. When heating the adsorption bed, ^{3}He is released and HS1 is at ON state; After heating is stopped and the adsorption bed is cooled by heat sink through weak thermal link, ^{3}He is adsorbed back and HS1 is at OFF state. The long-tailed HS2 presented in Fig.3(b) is designed for stage 2, which is based on the same working principle as the short-tailed one. The difference is that there is a stainless-steel capillary tube about 15 cm long between the adsorption bed and the hot end, and this design reduces the parasitic heat towards the upper stage.

For stage 3 cooling below 100 mK, the passive gas-gap heat switch seen in Fig. 3(c) is used and internal fin works as adsorption surface. This design realizes ^{3}He condensation and vaporization with the help of salt pill temperature variation, thereby autonomously switching between OFF and ON state without extra heating[8]. In our system, concentric sleeve fins and triple folded stainless-steel enclosure are designed. Testing revealed that the cold end requires approximately 15 minutes at 120 mK to enter full OFF state, which significantly limits the ADR cycle time. Alternative constructions are under development and evaluation, including interweaved fins, Vespel enclosure and Ti15-3-3-3 enclosure.

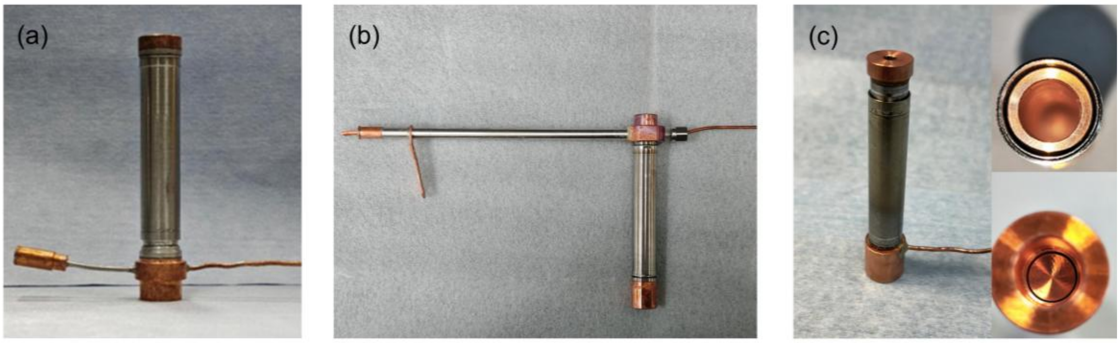

Figure 3. Photos of heat switches: (a) Active gas-gap heat switch with a short tail; (b) Active gas-gap heat switch with a long tail; (c) Passive gas-gap heat switch.

2.3 PEEK suspensions

The suspension system is to physically support the salt pill in the bore of superconducting magnet with minimal thermal conduction. Instead of Kevlar suspension, PEEK suspensions are installed at each stage as shown in Fig. 4, which is 3D printed with 10% glass fibre reinforced[9]. As the outer ring is fixed on 4 K heat sink, the muti-ring configuration reduces the heat leak towards the salt pill. For low-mass CPA salt pills, a square cross section design is implemented. To accommodate the first-stage GGG salt pill with a mass exceeding 1000 g, we develop a T-shaped cross section suspension with the same cross-sectional area to enhance structural stiffness. For stage 3 holding at 50 mK, the calculated heat leak from two PEEK suspensions with an intermediate heat sink on the ring is 0.25 μW, which is the dominant source for low temperature stage. This value can be further reduced by muti-stage intermediate heat sink. The PEEK suspension has represented a lightweight solution for laboratory ADR systems, while its mechanical resonance behaviour needs further investigation.

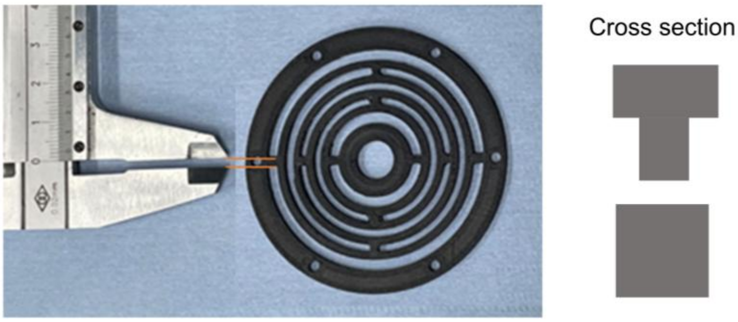

Figure 4. Photo of suspension and its cross-section shapes.

Table 1. Design details of 3-stage ADR.

	Stage 1	Stage 2	Stage 3
Refrigerant	GGG	CPA	CPA
Mass	1078 g	54 g	45 g
High temperature	4 K	1.2 K	500 mK
Lowest temperature	1 K	200 mK	100 mK
Heat switch type	Active gas-gap	Active gas-gap	Passive gas-gap
Suspensions	PEEK (T-shape)	PEEK	PEEK
Magnetic field	4 T	2 T	2 T
Magnet current	14.1 A	17.7 A	11 A

3. Performance testing

3.1 Single-shot mode

In the single-shot mode, the three stages are first magnetized to a slightly higher temperature than the cryocooler cold plate (about 4 K). After the heat is fully released, the cooling process begins as depicted in Fig. 5(a). HS1 is firstly turned off and stage 1 is demagnetized to pre-cool stage 2 and stage 3 to an initial temperature of 0.8 K. Then HS2 is turned off, and stage 2 is demagnetized to cool down stage 3 to expected temperature of 200 mK. After this point, Stage 3 begins to demagnetize. When reaching about 150 mK, passive gas-gap heat switch HS3 is automatically OFF. A minimum temperature of 35 mK is achieved at the end of demagnetization. A surprising fact is that it could hold for 1.5 hours and then warms up by only 1.4 mK with an estimated parasitic heat loss of 0.31 μW. One possible guess is that CPA crystal itself may have reached a much lower temperature at which it has a large heat capacity. It implies that the thermal bus may need to be improved to reduce the influence of quickly increased temperature-related Kapitza resistance between it and CPA crystal.

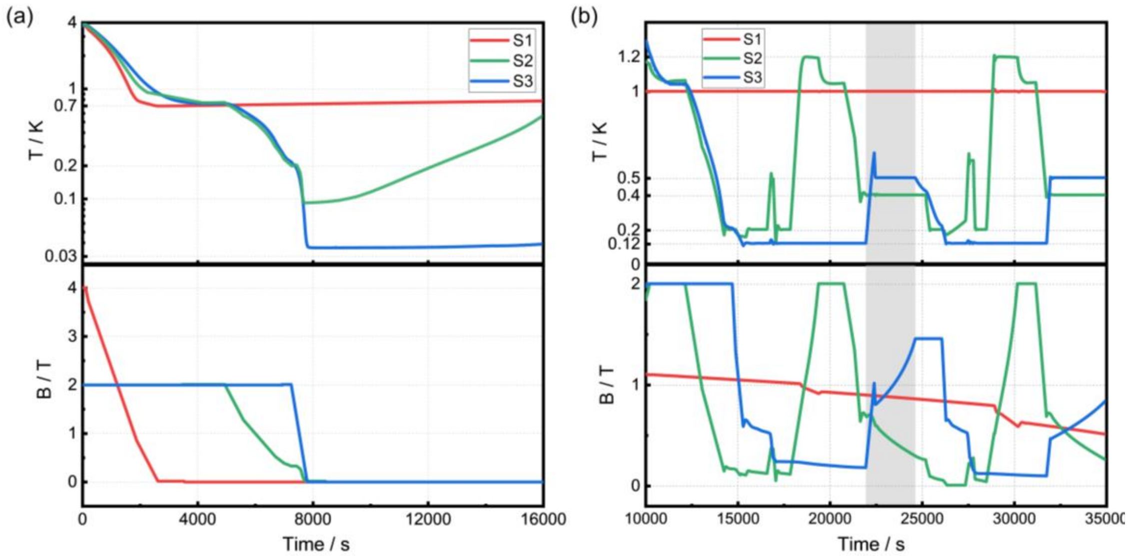

Figure 5. Temperature and magnetic field in (a) single-shot mode cooling process and (b) intermittent cooling process. The red lines represent stage 1 (S1), the green lines represent stage 2 (S2) and the blue lines represent stage 3 (S3).

At a cooling temperature of 50 mK, 3-stage ADR maintain a load-free operation for over 3 hours, shown in Fig. 6. Based on the theoretical isothermal entropy change of CPA, the total cooling capacity is 31 mJ. The temperature stability under a typical PID control within 20 minutes (gray shading in Fig. 6) is 26.63 μK RMSE, which could be reduced by a more precise control and careful shielding of external noises.

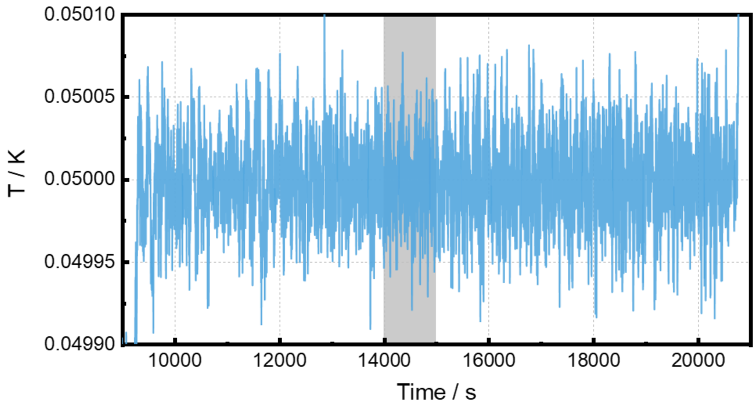

Figure 6. Temperature fluctuation at 50 mK.

3.2 Intermittent cooling

To address future continuous cooling requirements, we also conducted tests on intermittent cooling as explained below. Fig. 5(b) illustrates the temperature and magnetic field profiles during the cooling process. In this cycle, stage 1 maintains isothermal demagnetization at 1 K; stage 2 operates between 200 mK and 1.2 K; and stage 3 functions between 120 mK and 500 mK. During the 1.5-hour load-free hold at 120 mK in Stage 3, stage 2 completes magnetization at 1.2 K. Subsequently, stage 2 cools to the intermediate hold temperature of 400 mK, while stage 3 undergoes magnetization at 500 mK. The magnetization heat from stage 3 is transferred via HS3 with an estimated thermal conductance of 0.52 mW/K. This value is much lower than the standalone test result of HS3, raising suspicions of the quality of related thermal interfaces.

The curves in Fig. 5(b) are not ideal, particularly for the green and blue lines. For the blue line (stage 3), the minor fluctuations and overshoot arise from the challenges of manual control during transitions. For green lines (stage 2), in addition to this issue, two magnetization attempts within one cycle can be observed. The first unsuccessful magnetization occurs near 17,000 seconds, which failed due to the behaviour of HS3. As stage 2 cooled to 200 mK, a portion of ^{3}He may condense on stage 2 side of HS3; subsequent warming up resulted in rapid vaporization of the condensed ^{3}He, which may not be timely adsorbed/re-condensed on the colder side of HS3; this leads to an unintended thermal bridging and related temperature fluctuations on the blue lines. During the second magnetization attempt, this phenomenon did not occur and this is due to, as we guess, a stabilized ^{3}He distribution.

4. Multiple continuous cooling stages ADR

As we continue to improve our setup, we have also proposed a new configuration [10]. Actually, in space missions, detectors and associated electronics requires distinct operating temperatures, sometimes necessitating multiple isothermal stages, as exemplified by the aforementioned LiteBIRD program. While extra stages are needed in these designs, we have proposed a novel 3-stage ADR configuration to enable, e.g. 1 K and 300 mK continuous cooling, simultaneously as show in Fig. 7(a). Stage 1 and HS2 collaborate with stage 2 and HS3 to achieve continuous cooling at 1 K. Stage 3, being at 300 mK costant temperature, operates under conventional continuous refrigeration principles [5] and thus will not be elaborated here. Fig. 7(b) depicts the expected operational sequence within a typical cycle:

(1) First half-cycle (t_0-t_4), dominant by stage 1:

At point t_0-t_1, HS2 is ON, while HS3 is OFF. Stage 1 stablizes at 1 K and stage 2 stablizes at 250 mK through isothermal demagnetization. Form t_1 to t_2, stage 2 magnetizes and then at point t_2, HS3 is also turned on, enabling stage 2 to complete regeneration at 1.2 K. In between t_2 and t_3, stage 1 cools both load 1 and stage 2.

(2) Second half-cycle (t_4-t_8), dominant by stage 2:

At point t_4, HS2 changes to OFF state and HS3 keeps ON state. Then stage 2 demagnetizes to 1 K and maintains isothermal demagnatization, while stage 1 undergoes magnetization to regenerate. Then at point t_7, stage 1 demagnetizes back to 1 K, and stage 2 demagnetizes to 250 mK, ending the cycle.

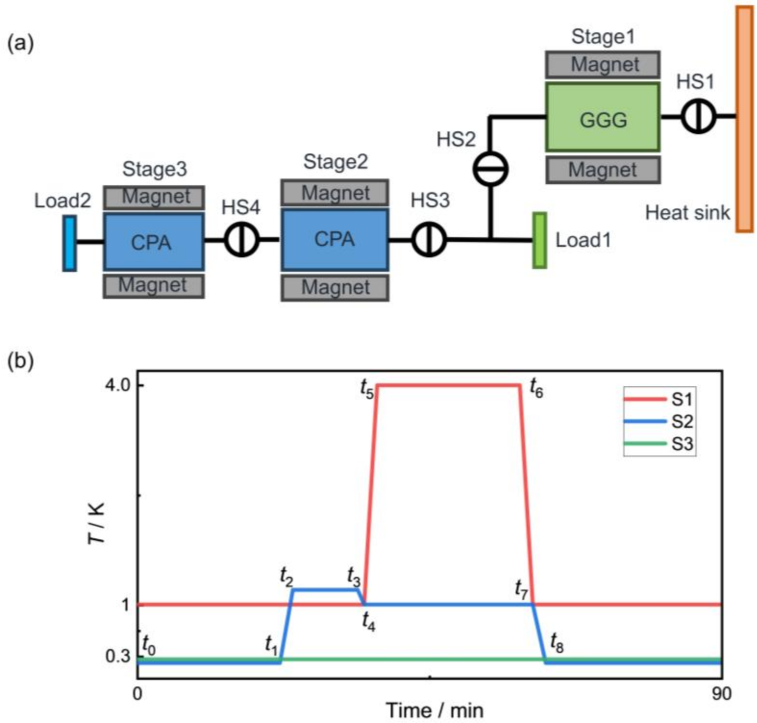

Figure 7. (a) Schematic of 3-stage ADR with continuous cooling at 1 K and 300 mK; (b) Temperature curves in one cooling cycle.

5. Conclusion

A-3 stage ADR operating from 4 K to 50 mK has been developed, with key components and performance test results presented. The system achieved a single-shot minimum temperature of 35 mK, a load-free operation exceeding 3 hours at 50 mK. Preliminary intermittent cooling tests at 120 mK were conducted, revealing shortcomings in our current design, particularly in salt pills and heat switchs. Based on these investigations, optimization of both components, thermal interface and cycle control are undergoing. Finally, we propose a configuration with multiple continuous cooling stages. This design requires only one additional heat switch to enable simultaneous continuous cooling at both 1 K and 300 mK using a three-stage configuration.

Acknowledgments

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