Properties of a two stage adiabatic demagnetization refrigerator

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Abstract. Currently, many space missions using cryogenic temperatures are being planned. In particular, high resolution sensors such as Transition Edge Sensors need very low temperatures, below 100 mK. It is well known that the adiabatic demagnetization refrigerator (ADR) is one of most useful tools for producing ultra-low temperatures in space because it is gravity independent. We studied a continuous ADR system consisting of 4 stages and demonstrated it could provide continuous temperatures around 100 mK. However, there was some heat leakage from the power leads which resulted in reduced the cooling power. Our efforts to upgrade our ADR system are presented. We show the effect of using the HTS power leads and discuss a cascaded Carnot cycle consisting of 2 ADR units.

1. Introduction

Many scientific measurements have been taken using a microgravity environment in recent years. In the study of X-ray astrophysics observations, the most active research is on the polarimetry of cosmic microwave background (CMB). By measuring CMB in fine detail, it is considered that it should be possible to establish the cause of the wide bandwidth of the cosmic microwave background.

The X-ray detector used in the polarimetry of CMB is the transition edge sensor (TES) X-ray microcalorimeter [1]. The microcalorimeter is shown in Figure 1. This sensor consists of an absorber, thermometer and heat sink, and measures the X-ray energy from the temperature-increase of the absorber caused by the detected X-rays. However, the temperature-increase of the absorber caused by the detected X-rays is the result of very low energy levels, typically 1.0*10-15 J. Therefore, by operating the element below 100 mK and using a highly sensitive sensor, the temperature-increase can be measureable in this condition.

The energy resolution of the TES X-ray microcalorimeter depends on the fluctuation of phonon numbers, as shown in Equation (1), using the temperature of the system T, sensitivity of the thermometer α and heat capacity of the element C.

$$E_{FWHM} \propto \sqrt{KT^2C/\alpha} \tag{1}$$

The thermometer of the TES X-Ray Microcalorimeter uses a superconducting material and measures the temperature increase of the absorber by rapidly changing the superconduction to normal conduction at the phase transition edge. The sensitivity of thermometer α is shown Equation (2) using a resistance R and temperature T.

$$\alpha = \frac{\partial \ln R}{\partial \mathrm{Ln} T} \tag{2}$$

The TES X-Ray Microcalorimeter used in the polarimetry of CMB is needed to operate in an ultra-low temperature environment less than 100 mK [1]. It is ideal for installation in a scientific satellite to measure the polarimetry of CMB without being affected by the debris and water in the atmosphere. With this background, it is necessary to develop a refrigerator that operates under 100 mK and can be used in space. Therefore, we studied a continuous ADR system (CADR) consisting of 4 stages. However, the 4-stage-CADR cannot operate under 100 mK because of heat leakage from power leads, which reduces the cooling power, and the problems associated with the switching temperature of the 4-3 stage heat switch. In this study, several approaches to upgrading our ADR system are presented. First, we show the effect of using the HTS power leads that reduce heat penetration. We then conducted experiments on adiabatic demagnetization to improve the switching temperature of the 4-3 stage heat switch by using a cascaded Carnot cycle consisting of 2 ADR units.

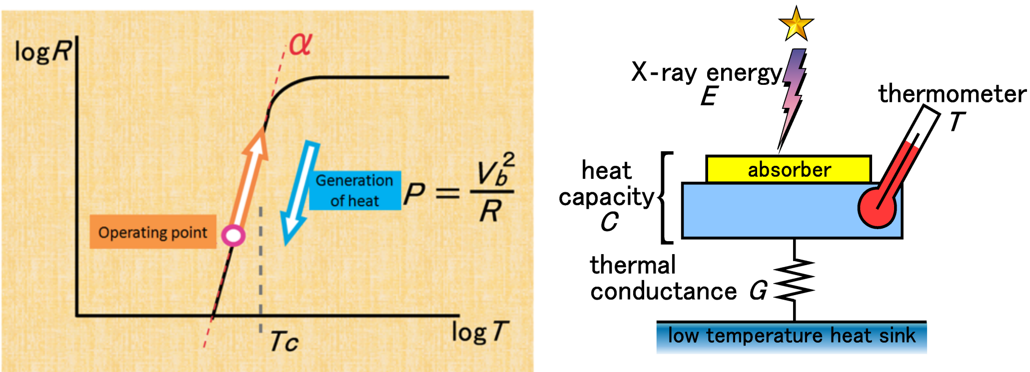

Figure 1. The schema of TES X-Ray Microcalorimeter.

2. Adiabatic demagnetization refrigerator

The adiabatic demagnetization refrigerator (ADR) uses the magnetocaloric effect caused by changing the external magnetic fields to change the entropy of the magnetic material. The structure of the ADR and an example of the Carnot cycle is shown in Figure 2. The operation of this refrigerator is not affected by gravity. Moreover, the ADR has the ideal properties for a cosmic refrigerator because it has high refrigeration efficiency and it is possible to miniaturize and reduce its weight. However, the ADR cannot continue to cool and prevent the rising temperature in the magnetization process because it must operate with a repeated magnetization and demagnetization process. Because the experiments must be stopped when the temperature rises in the magnetization process, the ADR cannot be used in experiments that take a long time. Therefore, it is necessary to solve this problem of cooling intermittency in the ADR when using it as an ultra-low temperature refrigerator.

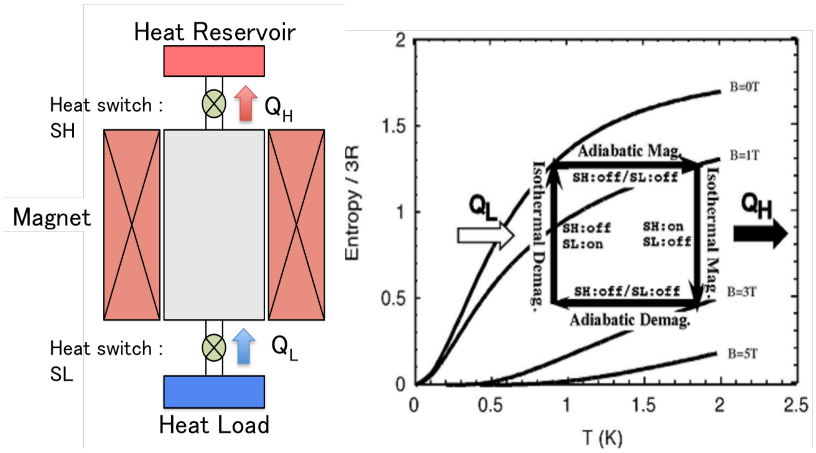

Figure 2. The Structure of ADR and Constitution example of carnot cycle.

3. Continuous adiabatic demagnetization refrigerator

To solve the refrigeration intermittence of the ADR, Peter Shirron et al. devised the continuous adiabatic demagnetization refrigerator (CADR) [2] [3]. The structure of the 2-stage CADR and the 2-stage Carnot cycle as the simplest example is shown in Figure 3. The CADR consists of two refrigeration units (a magnetic material and superconducting magnet) and a heat switch. As shown in Figure 3, two refrigeration units are connected in series using a heat switch. The CADR operating property is that the temperature rise of the cold stage is prevented by demagnetization of the other refrigeration. Figure 4 shows the cycle of a 2-stage CADR. In step 1, stage 1 is cooled by demagnetization. In step 2, stage 1 is magnetized, but the cold stage can be kept at a constant low temperature because stage 2 is starting to demagnetize and absorb the heat generation of stage 1 when heat switch 1 is turned on instantaneously. Notice stage 2 needed to be designed so that it has more than twice the cooling power of stage 1 to absorb the heat load of the cooling object and heat generation of stage 1 by magnetization. In step 3, stage 1 is demagnetized after magnetization of stage 1 is complete, and heat switch 1 is again turned off. At this point, heat switch 2 is turned on and stage 2 starts magnetizing to dissipate the heat as an exhaust heat stage. Therefore, the CADR is able to refrigerate continuously by conducting this cycle repeatedly.

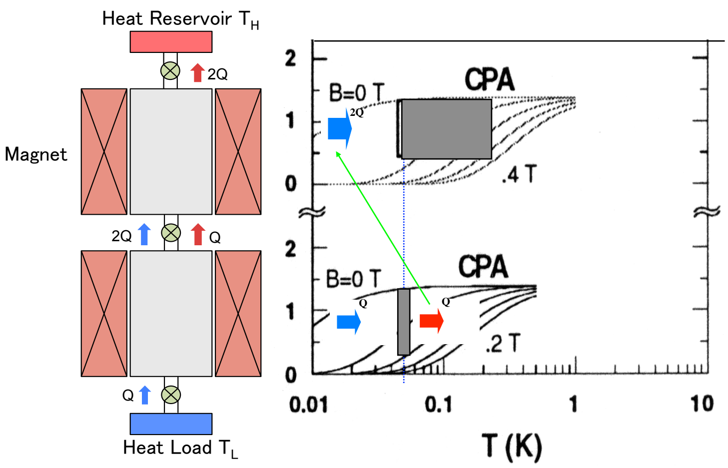

Figure 3. The structure of 2-stage CADR and Constitution example of 2-stage carnot cycle.

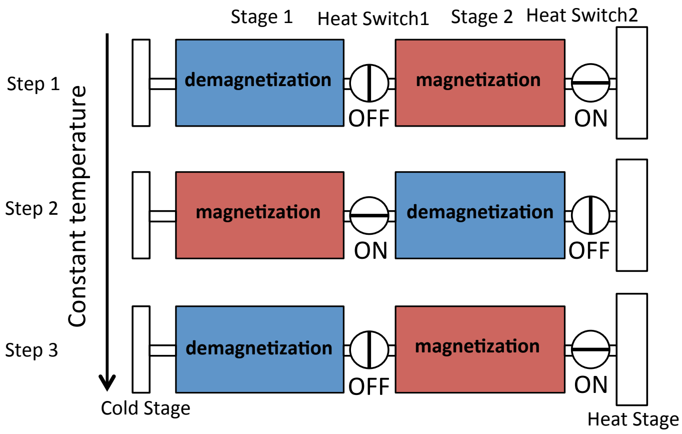

Figure 4. Cycle of the 2-stage CADR.

4. 4-stage continuous adiabatic demagnetization refrigerator

The CADR is able to operate if it consists of only two refrigeration units (a magnetic material and superconducting magnet) and a heat switch. However, if the operating temperature is between 4.2 K and 100 mK and the CADR is a two-stage unit, the mass of magnetic material must be increased and the 2-stage CADR needs a very large magnetic field. Therefore, if we want to operate the CADR in this temperature range, such as between 4.2 K and 100 mK, the CADR must become a multi-stage unit and each stage needs to share the temperature range. Moreover, it is important to choose a magnetic material that has a large entropy change in the temperature range, because it is difficult to obtain a large entropy change if the same magnetic material is used in each stage of the CADR. In this study, to operate the CADR in the temperature range between 4.2 K and 100 mK, we designed the CADR to consist of 4 stages. The conceptual design and cycle of a 4-stage CADR are shown in Figure 5 and the specification for each stage is shown in Table 1. Stage 1 is operated continuously at under 100 mK, and connected to stages 2, 3, and 4, and the baseplate as the exhaust heat stage. The baseplate is cooled to 4.2 K using a GM refrigerator. In this cycle of the 4-stage CADR, the stage on the heat side starts magnetization and demagnetization, and the cold stage is then cooled. The heat generated in the magnetization process is absorbed by the demagnetization of the contiguous stage when the heat switch is turned on. Finally, the cold stage is kept under 100 mK because steps 4 and 5 are repeated.

The stages are connected to each other by heat switches. The heat switch between stages 1 and 2 is a superconducting heat switch, and between stage 2 and the baseplate a passive Gas-Gap Heat Switch (PGGHS) is used [4].

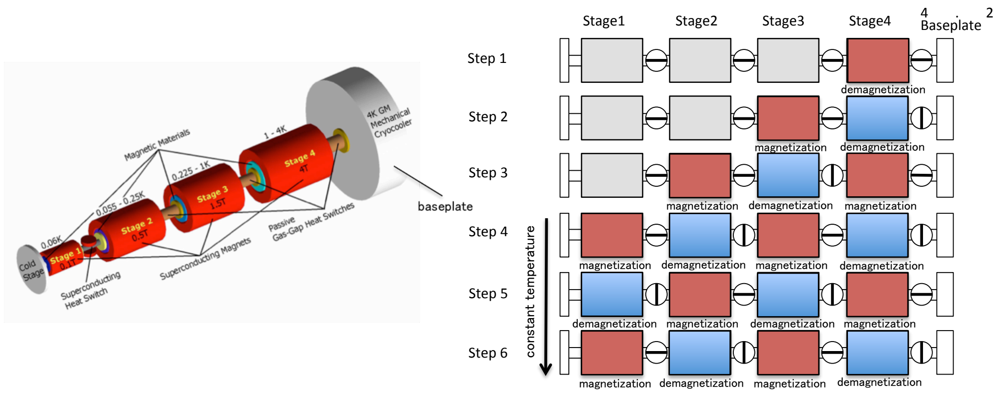

Figure 5. Conceptual design and cycle of a 4-stage CADR.

TABLE 1. Specification for each stage.

Stage	Operating Temperature	Refrigerant	Field	Mass (Magnet + Refrigerant)
1	60 mK	CPA	0.1 T	0.57 kg
2	55 - 280 mK	CPA	0.5 T	0.57 kg
3	250 mK - 1.0 K	CPA	1.5 T	0.57 kg
4	0.9 K - 4.5 K	GLF	4 T	0.83 kg

*Refrigerant:CPA =$CrK(SO_4)_2 \cdot 12H_2O$, GLF=$GLiF_4$

5. Structure of the CADR cryostat

In this study, the structure of the CADR cryostat consists of a vacuum vessel, 60 K shield and 4 K shield on the outside. The structure and a picture of the CADR cryostat are shown in Figure 6. The inside of the vacuum vessel is kept in a high vacuum state by a vacuum pump, so that heat loads from the room temperature are avoided. The 60 K shield is cooled by the first stage of the GM refrigerator, and the 4 K shield is cooled to 4.2 K by the second stage of the GM refrigerator. The baseplate of the CADR is the exhaust heat stage, and made of oxygen-free copper to provide a large heat capacity. Conversely, the 4 K shield, 60 K shield, and vacuum vessel are made out of aluminum to minimize any increase in mass.

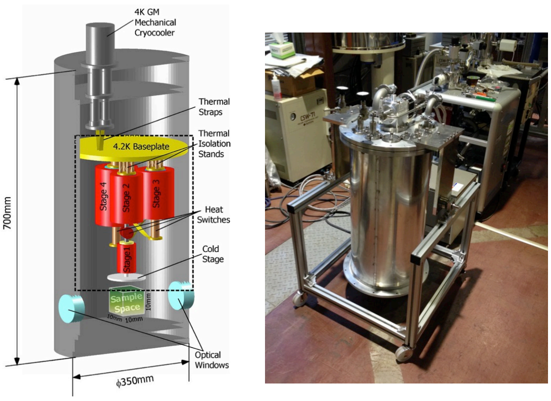

Figure 6. Structure and picture of the CADR cryostat.

6. Experiment for cooling the 4.2 K baseplate

The baseplate temperature is influenced by various heat loads and internal heat generation. The heat loads consist of conductive heat, radiant heat and joule heat generation. These heat loads are absorbed by a 0.1 W model 4 K GM refrigerator before influencing the baseplate. The cooling power of the 4 K GM refrigerator is 0.15 W at 4.2 K, and the value that heat loads subtract from 0.15 W is the cooling power that can absorb the exhaust heat of the CADR. In this study, to reduce these heat loads, REBCO superconducting tapes were chosen for the power leads of the superconducting magnet between the 60 K shield and 4.2 K baseplate, because the heat energy (joules) into the 4.2 K baseplate had a zero value. A picture of the 1st - 2nd stages, and the REBCO tapes and their structure, are shown Figure 7.

We measured the heat load from the 1st stage to the 4.2 K baseplate by wiring the REBCO current leads and compared the two minimum temperatures that the 2nd stage reached when eight REBCO tapes were connected and when none were connected. The REBCO superconducting tapes were 0.1 mm thick, 2.5 mm wide and 140 mm long and eight of them were connected between the 60 K shield and 4.2 K baseplate.

The two temperature variations when eight REBCO tapes, and none, were connected are shown in Figure 8. With no REBCO tapes connected, the minimum temperature was 2.6 K, and with the REBCO tapes, it was 2.76 K. With this result, the heat load into the baseplate was 14 mW with a temperature difference of 0.16 K. In addition, all the heat loads for each stage of the cryostat are shown in Figure 9. The total heat load into the CADR system, including the supporting material, pre-cooling line using liquid nitrogen, power leads of the superconducting magnet, superconducting leads of the thermometer, energy heat generation and radiant heat of the shield, was calculated at 0.116 W. This value is about 77% of the cooling power of 0.150 W of the GM refrigerator at 4.2 K, and the remaining 0.034 W could then be used as the exhaust heat for the CADR. Therefore, the heat load into the CADR system can be lower than the cooling power of the GM refrigerator using the REBCO superconducting tapes. In contrast, the total amount of heat load into the 60 K shield was calculated at 2.70 W and the cooling power of the GM refrigerator at 60 K was 3.0 W. Consequently, the GM refrigerator could adequately absorb the heat load of the 60 K shield.

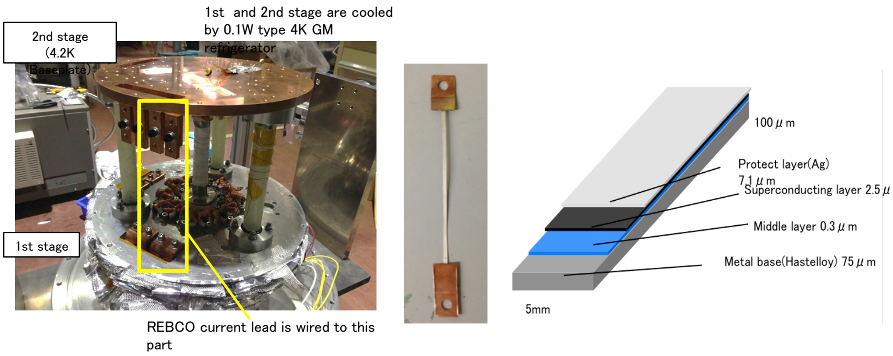

Figure 7. Pictures of the 1st - 2nd stages, REBCO tape and structure of REBCO tape.

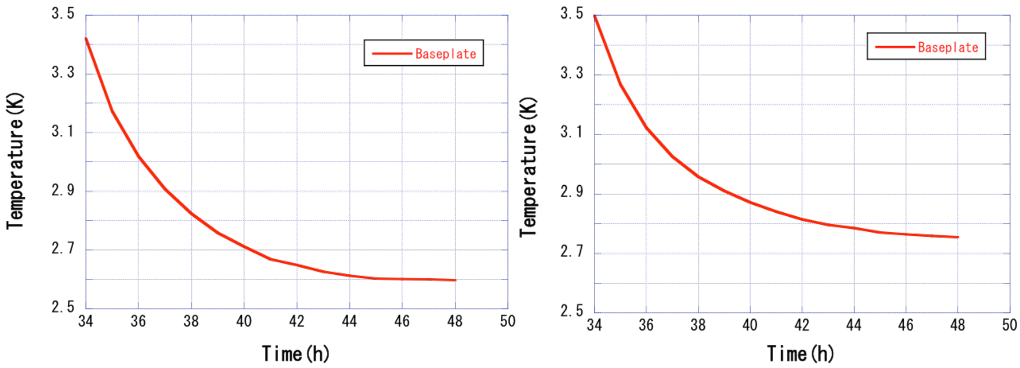

Figure 8. Temperature variation without the REBCO tape (left) and with the REBCO tape (right).

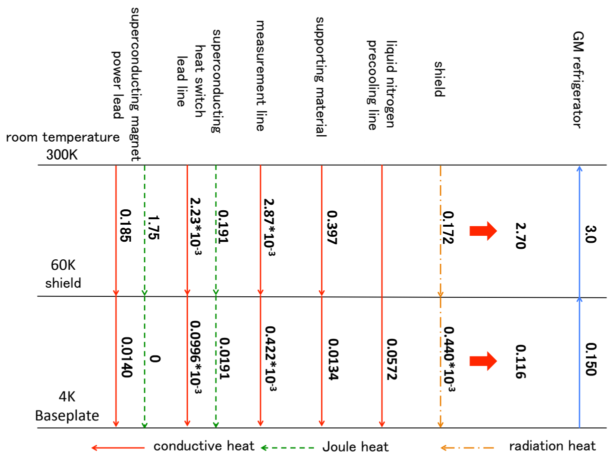

Figure 9. Total heat loads for each stages of the cryostat (Unit:W).

7. Experiment on adiabatic demagnetization in 2-ADR units

The previous 4-stage CADR could reach only 120 mK continuously on the ground environment. Because of this, we found there was a problem with the switching temperature of the heat switch between stages 4 and 3. To improve the switching temperature of this heat, we charged the heat switch with ^4He at 6 torr and conducted adiabatic demagnetization experiments on the 2-stage ADR.

In this 2-stage ADR, we used the ADR of stages 4 and 3 of the previous CADR. The structure and picture of the 2-stage ADR are shown in Figure 11. Stages 4 and 3 were set on the baseplate, which, however, exchanged heat only with stage 4 because stage 3 was kept adiabatically isolated from it. In other words the baseplate was the exhaust heat stage and stage 3 was the cold stage. The heat switch between the baseplate and stage 4 was incorporated in stage 4, which, in turn, was connected to stage 3 by the heat switch and a thermal strap of oxygen free copper. The experimental procedure follows:

1. Magnetize stage 4 to 3.99 T (3 A).
2. Demagnetize stage 4 and magnetize stage 3 to 1.5 T (3.75 A).
3. Demagnetize stage 3.
4. Re-magnetize stage 4 to 3.99 T.

The temperature and tesla variation for the 2-stage adiabatic demagnetization experiment are shown in Figure 11s. From around 2700 s, we found the heat switch turned off at about 2.7 K and the temperature of stage 3 was then constant at 0.67 K. From this result, we confirmed the switching temperature of the heat switch between stages 4 and 3, and stage 3 reached 0.67 K.

Next, we attempted to re-magnetize stage 4, although the temperature of stage 3 rose at around 4700 s, and the adiabatic state of stages 3 and 4 was broken because, it was believed, there was a temperature difference of 5 K at 4700 s.

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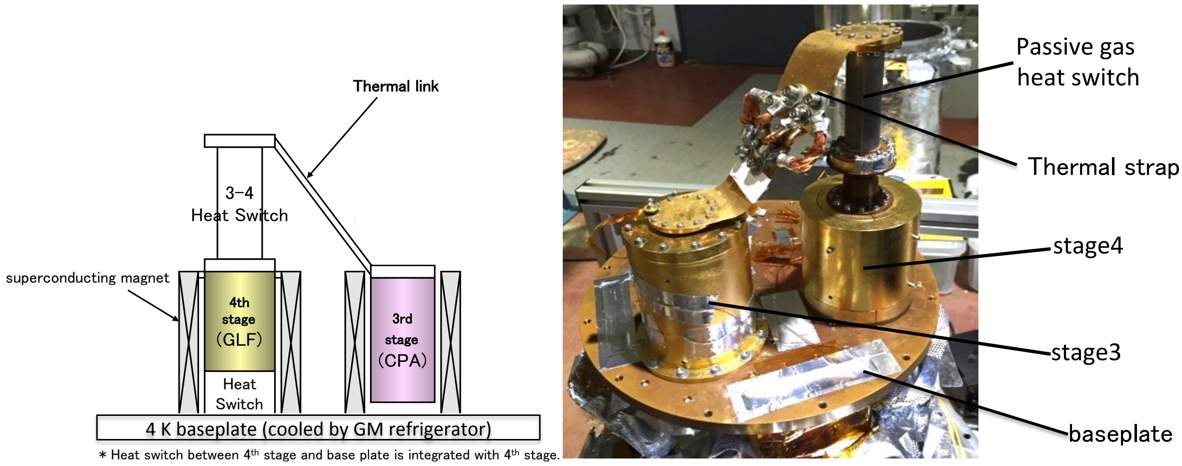

Figure 11. Structure and picture of the 2-stage ADR.

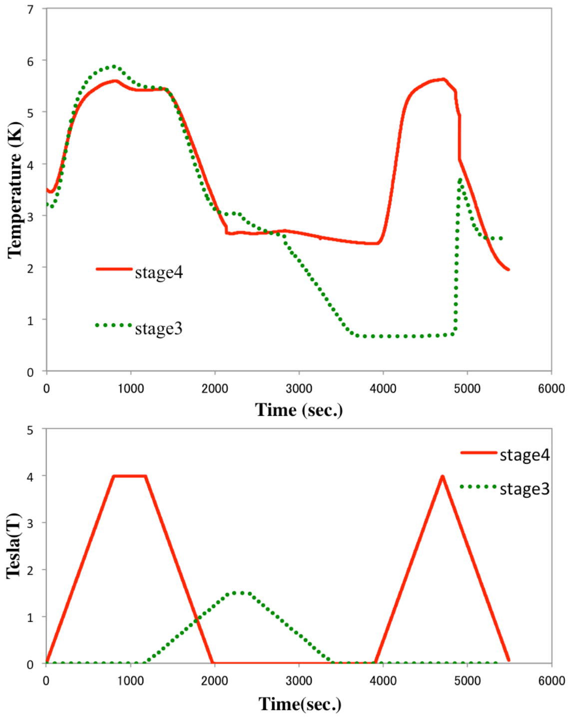

Figure 11. Structure and picture of the 2-stage ADR.

8. Conclusion

We succeeded in enabling the 4.2 K baseplate to reduce the heat load by adopting REBCO current leads between the 1st stage and the baseplate, and the total heat loads into the baseplate were absorbed by the GM refrigerator.

We confirmed that the heat switch between stages 4 and 3 turned off at 2.7 K and achieved a minimum temperature in stage 3 at 0.67 K. However, when we re-magnetized stage 4, the adiabatic state between stages 4 and 3 broke down, because a temperature difference of 5 K was generated between the two stages. Accordingly, we need to reduce this temperature difference. For example, we could consider increasing the amount of heat transferred between stages by increasing the sectional area of the thermal strap and improving the performance of the heat switch between stages when the heat switch is turned on.

References

[1] H.Akamatsu et al 2008 J. Phys. Soc. Jpn **63** 90 22pSH-11
[2] Shirron P J et al 2000 Adv. Cryo. Eng. **45B** 1629
[3] Shirron P et al 2002 Cryogenics **41** 789
[4] Shirron P J et al 2002 Adv. Cryo. Eng. **47B** 1175