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Cooling performance of Joule Thomson coolers in 300 K -50 mK cryochain demonstration for ATHENA X-IFU

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Abstract. The cooler system for the ESA X-ray astronomical mission ATHENA X-IFU instrument is being studied, and a demonstration cooling test has been performed by integrating the mechanical coolers (double-stage Stirling cooler = 2ST, 4K-class and 1K-class Joule Thomson coolers = 4K-JT and 2K-JT) provided by JAXA with the coolers (15K-class pulse tube cooler = PT15K and 50mK hybrid cooler) provided by CEA into the cryostat. This paper describes the measured cooling performances of these Joule Thomson coolers under successful integration with the 50mK hybrid cooler and the pulse tube cooler. The demonstration test is proceeded under the international framework of ESA Core Technology Program (CTP) for a detector cooling system demonstration for ATHENA, and should provide valuable insight for other future space missions such as SPICA and LiteBIRD.

1. Introduction

The X-ray Integral Field Unit (X-IFU) is the cryogenic micro-calorimeter of the Athena space X-ray observatory [1], and ESA CTP program was started in 2016 to build a flight like cryostat demonstrator in parallel with the X-IFU phase A studies. As the intermediated step in the CTP, a 300 K - 50 mK cryochain demonstration called "cryostat1" with the dedicated cryostat in France (CEA Grenoble) was planned and space-qualified mechanical coolers have been coupled.

The 50 mK hybrid cooler (300 mK sorption cooler and 50 mK single stage adiabatic demagnetization refrigerator) was developed by CNES / CEA in the framework of SPICA SAFARI instruments project [2], and PT15K was developed by ESA / CEA /Air Liquide /

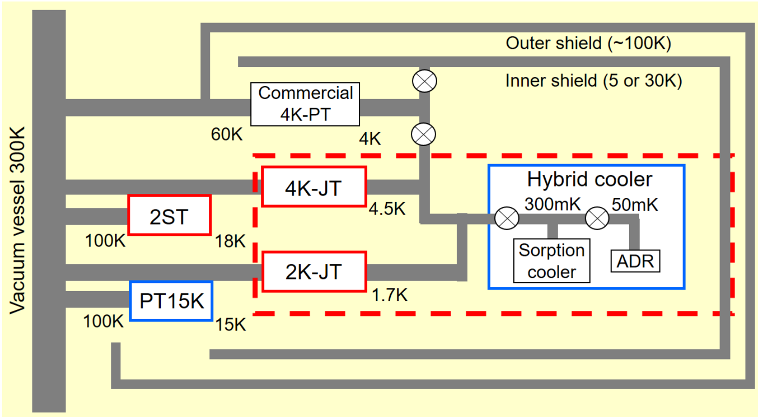

Figure 1. The cooling chain of the cryostat1 [7]. The red dotted area shows the same interface part for cooler systems in Athena, SPICA and LiteBIRD.

Thales Alenia Space [3]. The 4K-JT and 2K-JT were developed by JAXA and SHI (Sumitomo Heavy Industries, Ltd.)[4]. Since the cooler system with the hybrid cooler in combination with the 4K-JT and 2K-JT is also proposed for the space infrared telescope SPICA [5] and the CMB B-mode polarization detection satelite LiteBIRD [6]. Therefore, the 50 mK validation by coupling the hybrid cooler and JT coolers in the cryostat1 test also presents a good opportunity to verify the cooler system for other missions.

2. CTP cryostat1 cooling chain

The vacuum vessel, radiative shields and interface for all coolers for cryostat1 were designed by CEA Grenoble [7]. Figure 1 shows the cooling chain of cryostat1. The 2K-JT and 4K-JT were connected to the hybrid cooler with thermal straps (70 mW/K for 2K-JT and 75∼100 mW/K for 4K-JT) and used as precoolers of the hybrid cooler. The PT15K was used for the 2K-JT's precooler, while the 2ST was used as the precooler for the 4K-JT. The commercial 4K PT cooler was integrated to cool the two radiative shields, and was also used to cool the 4K-JT interface point through the gas gap heat switch if necessary.

The JT cooler performances are influenced not only by parasitic heat loads into the coldtip but also by the precooling temperature, which depends on the parasitic heat load from a higher temperature region. Therefore, the variance in temperature of the JT cooler coldtips and precooling stages with a different inner shield temperature (5 K or 30 K) was measured, and the parasitic heat load from the inner shield to each cooler was confirmed as being very small compared with each cooling power [7].

3. JT coolers test sequence and test items

The 4K-JT cooling performance, particularly the specified cooling power (40 mW at 4.5 K) with the 2ST precooler was verified in each sequence (before and after transport from Japan to France, and after integration into cryostat1). Conversely, no cooling verification was made prior to the 2K-JT transport due to the feasibility, schedule and enough margin in the design. Then the 2K-JT compressors performance without the cold part was verified before and after transport. Then the 2K-JT was transported with a PT15K dummy.

The most important test item for JT coolers is to verify the operation method during the 50 mK hybrid cooler recycle. Figure 2 (a) shows the typical temperature behavior of the sorption pump in the hybrid cooler, 4K-JT coldtip temperature and heat load during the hybrid cooler

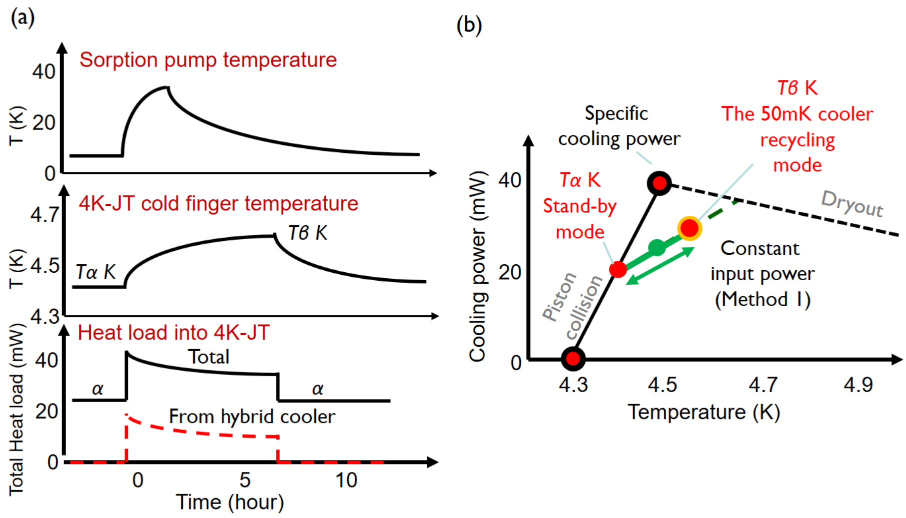

Figure 2. (a) Temperature behavior of the 50mK hybrid cooler and JT coolers during the hybrid cooler recycle. (b) JT coldtip temperature depends on total heat load.

recycle. The heat load from the hybrid cooler is rejected into the 4K-JT and 2K-JT during this phase. As a targeted interface condition, the peak heat loads are 10 mW and 3.5 mW for the 4K-JT and 2K-JT, respectively [2]. The schematic relation between the JT cooling power and coldtip temperature is shown in Figure 2 (b). The cooling power is determined by the input driving power of the compressors. The JT cooler raises a concerns of about possible dryout and a rapid rise in temperature in case of a heat load higher than the cooling power. Such a situation would also raise concerns about piston collision in the JT compressors when the heat load is too low.

Followings are the three main methods of operation.

(i) Method 1 : Constant JT driving power.
- A : Recycling regulation to ensure constant heat load into JT.
- B : Higher heat load in the early phase and constant heat load (Figure 2(a)).

(ii) Method 2 : Changing JT input power to approximate the JT interface temperature.

(iii) Method 3 : Heater regulation to maintain almost the same JT interface temperature.

The first target is method 1B due to its ease of operation in orbit and in determining the interface condition. Method 3 is the alternative method for safe operation of the JT coolers.

4. Test results

The 4K-JT and 2K-JT were transported on March 2017. The performance test for each cooler was performed in each integration phase, and the integration of all coolers was completed by September 2017 without any severe discrepancies.

Figure 3 shows the temperature behavior in cryostat1 when cooling down from 300 K to 1.7 K after the integration of all coolers. At first, the 2ST is started with low driving power (20 W) to confirm that it can cool as usual, and then the PT15K and 4K-PT are started 2 hours later. Both JT coolers are started with low driving power (1∼2 W) to circulate the working gas through the bypass valves before starting the precoolers. The PT15K can cool down faster than the 2ST due to its higher cooling power. Then, both JT coolers can initiate circulation through the orifices when the precooling temperature reaches 18 K for the 4K-JT and 15 K for

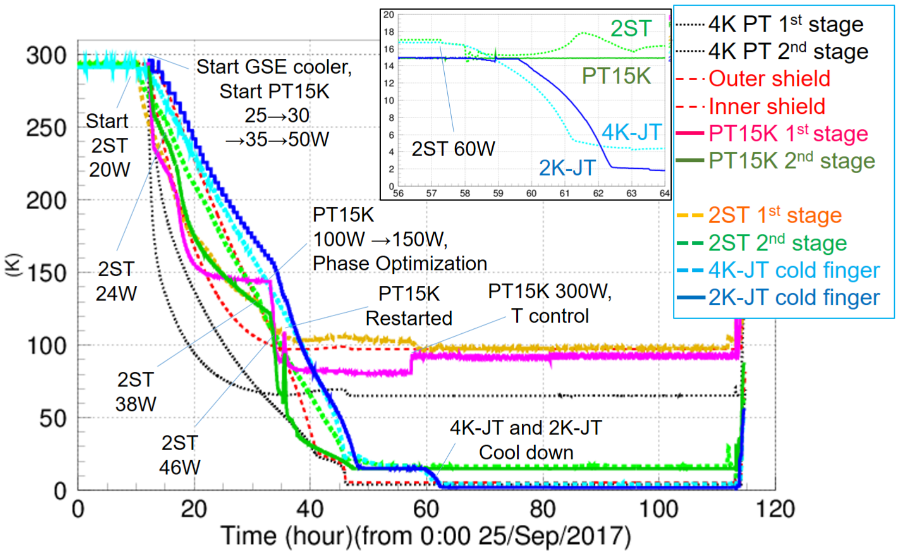

Figure 3. Temperature behavior in cryostat1 when cooling down from 300K to 1.7K (1st cooling down after the integration of all coolers).

Table 1. 2K-JT typical performance result.

Heat load	PT15K 1st stage	PT15K 2nd stage	JT coldtip	Inlet pressure	Outlet pressure	JT flow rate	PT15K power	JTC power
10 mW	92.2 K	14.9 K	1.72 K	7.8 kPa	540 kPa	1.3 NL/min	300 W	40 W
19 mW	92.2 K	9.9 K	1.77 K	7.2 kPa	480 kPa	1.3 NL/min	300 W	37 W

the 2K-JT. Figure 3 shows that the 2K-JT smoothly reached lower than 2 K within three hours after starting the circulation (62.5 hrs).

It has been confirmed that the 4K-JT could provide the specified cooling power (40 mW at 4.5 K) with driving power of <63 W (corresponding to <90 W at EOL) after its integration into cryostat1. The 2K-JT also obtained the specified cooling power (10 mW at 1.7 K) by coupling the PT15K with the 2nd stage of 15 K (same as the prior condition of the 3rd heat exchanger precooling temperature in the 2K-JT design). Table 1 lists the experimental result. Since the PT15K can reach 10 K with appropriate cooling power, the 2K-JT cooling power with a different precooling temperature was also measured, with a maximum cooling power of 19 mW being obtained.

In the cryostat1 test, 17 recycles of the hybrid cooler were performed with different interface conditions including the heat load applied to the JT coolers and JT coldtip temperature. As a result, 50 mK was successfully obtained in all recycles. Prior to these, the maximum interface temperature must be known in order to operate the JT coolers with method 1B. As a nominal condition, the maximum hybrid cooler interface was determined to be 1.86 K for the 2K-JT and 4.75 K for the 4K-JT, at which the heat load from the hybrid cooler through the interface were 10 mW and 3.5 mW for each cooler, respectively. Then the heaters of 30 mW for the 4K-JT and 3.5 mW for the 2K-JT were added to simulate other heat load including the main truss. As

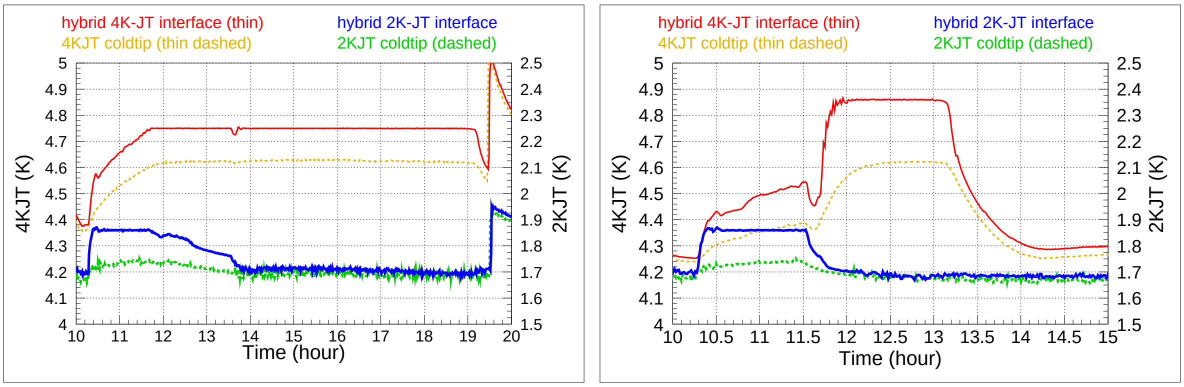

Figure 4. Temperature behavior of the JT coolers and 50mK hybrid cooler interface during the nominal recycle (left) and the accelerated cycle (right).

shown on the left side of Figure 4, both JT coolers were successfully operated without any piston collision or dryout, and each variance in temperature was 0.33 K for the 4K-JT and 0.047 K for the 2K-JT during the recycle. The recycling time was about nine hours.

The temperature behavior during the accelerated cycle is shown on the right side of Figure 4. In this test, the heat load from the hybrid cooler to the 4K-JT was 20 mW, two times higher than in the nominal condition to accelerate the recycle and thus reaches 50 mK faster for ToO (Time to Opportunity) observation. Additionally, the test was a demonstration to obtain a better duty cycle (observation time / full time including recycle time). As a result, the 4K-JT could be operated successfully with a temperature variance of 0.38 K, and the recycling time was about three hours. In the four kinds of trials, a duty cycle of 85 % was measured.

5. Conclusion

The 4K-JT and 2K-JT have been transported, integrated and measured to cool down without any severe problems, and 50 mK was obtained in all 17 cooling cycles in the cryostat1 test. Both JT coolers were also successfully operated with the proposed interface conditions, including the variance in coldtip temperature without any piston collision or dryout during the hybrid cooler recycle. These results in the cryostat1 test enhance the feasibility of the cooler system for SPICA, LiteBIRD and the Athena X-IFU.

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