A 1K ^{4}He Close Cycle Loop Precooled Using a PT415 Pulse Tube for the BLISS Test Bed Cryostat

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ABSTRACT

The Background Limited Infrared Submillimeter Spectrometer (BLISS) is an instrument proposed for the Japanese space borne telescope mission SPICA. The BLISS cryogenic chain is a hybrid solution, coupling a continuous 300 mK ^{3}He sorption cooler with a single-shot 50 mK adiabatic demagnetization refrigerator (ADR). On SPICA, the instrument and cooler operate from thermal stages at 4.5 K and 1.7 K. The peak power dissipation to these stages must meet the SPICA allocations of <10 mW and <5 mW, respectively. To test the BLISS cryogenic chain prototype, a large pulse tube cryostat has been built that replicates the SPICA cryogenic interface. The 4.5 K and 1.7 K interfaces are regulated at constant temperature and cooled by the cold head from a Cryomech PT415 pulse tube and a 1K ^{4}He close cycle loop respectively. The ^{4}He gas for the 1 K cooling loop is circulated by a room temperature dry pump, precooled by a heat exchanger soldered onto the pulse tube, and passed through a Joule-Thomson expander before it flows back to the dry pump. Passive graphite heat switches are used to expedite the initial cool down of the BLISS cooler from room temperature as an alternative solution to exchange gas. In this paper, we describe in detail the design and performance of the ^{4}He close cycle 1K loop and graphite heat switches.

INTRODUCTION

SPICA is a Japanese led spaceborne telescope mission that consists of a 3.5 m aperture telescope actively cooled to <5 K to provide background limited measurement in the far infrared and submillimeter [1] over the 5 year mission. The cryochain in SPICA consists entirely of mechanical cryocoolers that cool the telescope and provide cold fingers at 4.5 K and 1.7 K to cool instruments and detectors. The Background Limited Infrared Submillimeter Spectrometer (BLISS) is a grating spectrometer that utilizes the lowest sensitivity range available from the cold telescope on SPICA to probe galaxies as early as 1 billion years after the Big Bang [1]. To achieve this sensitivity, the bolometric detectors in BLISS are cooled to 50 mK. A variety of sub-K cooling architectures were considered for BLISS [2]. The two driving requirements for the cooler for BLISS are to operate the sub-Kelvin cooler within heat lift allocations at 4.5 K and 1.7 K of <10 mW and <5 mW, respectively, and to have the highest technology readiness level (TRL). The architecture chosen for BLISS is a two-stage ^{3}He cooler that provides continuous cooling at 300 mK and a single shot ADR [3].
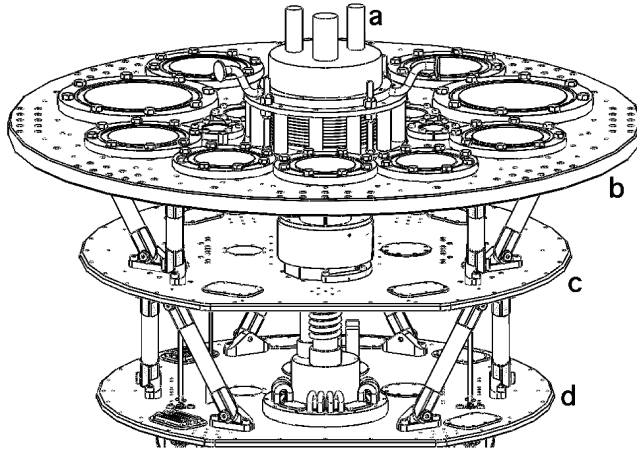
Figure 1. a: pulse tube, b: 300K flange, c: 60K flange, d: 3.5K flange

In order to test the BLISS sub Kelvin cooler in a SPICA-like environment, a dedicated cryostat has been developed with thermally regulated stages at 4.5 K and 1.7 K used to test the cryocooler and ~0.15m³ instrument volume capable of testing BLISS spectrometers. The cryostat, shown in Figure 1, is a commercial cryogen-free model [4], cooled by a Cryomech pulse tube PT415 [5] with an integrated ⁴He liquefier tube. The room temperature vacuum shell has a diameter of 70 cm and a length of 110 cm. The first stage of the pulse tube [4] provides 40W of lift at 45 K to cool a 65 cm diameter aluminum flange and 89 cm long aluminum shield wrapped with MLI. The flange cools to 60 K and the farthest end of the shield cools to 75 K. The second stage PT provides 0.3 W of lift at 3 K to cool to 3.5 K a 60 cm diameter copper plate with 66 cm long aluminum radiation shield. The 3.5 K enclosure is nearly isothermal with gradients measured to be no larger than 0.01 K.

1K ⁴HE STAGE

Continuous cooling to 1.7 K is commonly provided in cryostats with liquid cryogens using a so-called 1 K pot [6,7]. In a 1 K pot, liquid helium is siphoned from the cryogen bath through a capillary into a pot (or still) where it is pumped to low pressure, using a low impedance line and room temperature pump, causing cooling to ~1K. These 1K pots have been integrated into a commercially available 'dry' dilution cooler [8,9,10], but are not available commercially as a stand-alone option. One approach to a 1K pot in a pulse tube system is to inject a high pressure stream of ⁴He gas from a K-bottle [11]. We have designed a closed cycle 1 K pot into our pulse tube system to provide continuous cooling at <1.7 K to a third cryogenic stage as shown in Figure 2. The third stage is a 6061 aluminum plate, 55 cm in diameter and 12.27 mm thick, with a 50cm long TIG welded aluminum radiation shield cooled to ~1.1 K. The plate is supported by 3 bipods made of stainless steel tubes that conduct a parasitic load of 1.5 mW from 3.5 K. A copper tong connected directly to the 1 K cold finger goes through the plate in order to provide a high conductivity cold finger for the sub Kelvin cooler and instrument.

Injection Line

The 4He liquefier tube is integrated with the pulse tube. The injection capillary coiled and brazed around the second stage regenerator. This precools the helium in stream enthalpy without degrading the second stage PT cooling power [12,13,14,15,16]. The injection stream is then passed into a heat exchanger at the 3.5 K flange, where the helium is liquefied. Helium condensation flow rates as high as 6.5 milliMoles/sec are possible.
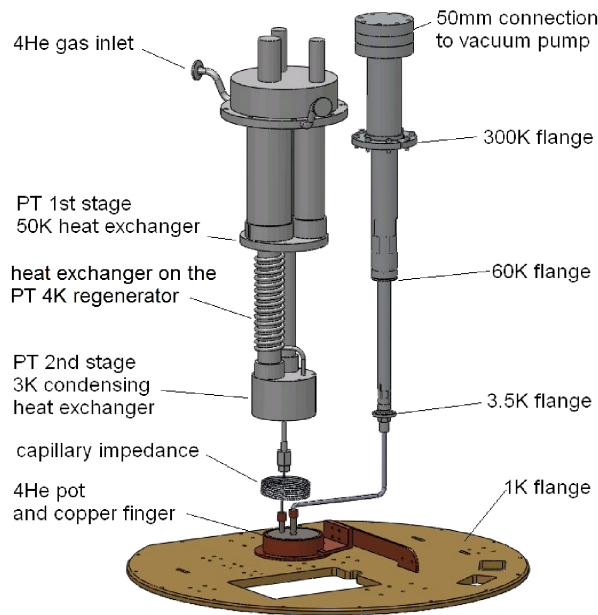
Figure 2. Cold part view of the 1K ^{4}He loop.

The capillary impedance, $Z= 3.88 \, 10^{15}$ m^{-3}, has been chosen in order to get temperatures of 1 K with a cooling power up to 15mW, or three times the initial BLISS allocated power at 1.7 K. Many publications describe how to calculate capillary impedances [6,7,11]. We chose a 60" long stainless steel capillary with an ID (OD) of 0.007" (0.0625") [17]. The helium pot consists of a copper body with inside dimensions of 7.4 cm in diameter by 2 cm in height. Copper fins are machined in it to increase the surface to 130 cm^2 of exchange surface area for a 30 cm^3 volume. A stainless steel cap is silver soldered on top of it. The injection capillary and the pumping tube are soft soldered to copper end connections. A 3 mm diaphragm is placed at the outlet of the pot in order to reduce the parasitic flow due to the Rollin film evaporation [6,7], which sets the base temperature of the 1 K pot to ~0.96 K.

Pumping Line, Pump

The low impedance pumping line is designed, Table 1, to have a base pressure of 0.1 mbar at a flow rate up to ~0.5 milliMole/sec and low parasitic load on the pulse tube cryochain. The warmer section of the cold pumping tube is insulated from the room temperature flange by a 160 mm length of 48-50 mm SS tube. Radiation shields were placed into the pumping line to avoid direct radiation from 300 K to 3.5 K.

The room temperature circulation pump is a dry ADIXEN [18] ACP40. At the high pressure output of the pump is a 50 L ballast tank and injection line manifold. During operation, the tank acts as a low pass filter for the injection line pressure. Between cryogenic runs, the tank is used to store the helium gas. The manifold is used to control injection pressure.

Table 1. Dimensions of the pumping line.

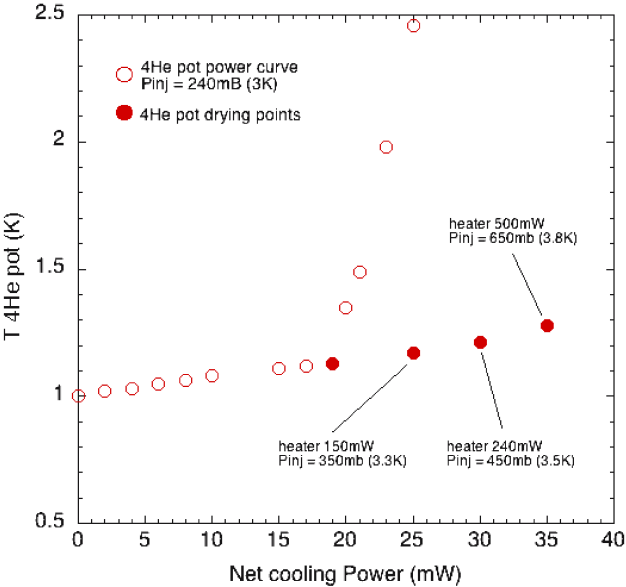| Temperatures of tubes sections	ID and OD in mm	Length in mm
1K-3.5K	5-5.5	20
3.5K-60K	18.5-19	207
60K-300K	37-38	365
300K	50	1000

Figure 3. Temperature of the 1K pot as a function of applied power and temperature of the PT 2nd stage.

1K Pot Operating Performance

The heat lift performance as a function of 1 K pot temperature and pulse tube head temperature is shown in Figure 3. The open circles show the 1 K pot performance when the PT second stage is in normal operation at a base temperature of 3.0 K. The pot temperature, T, is a very weak function of applied power, P, up to 19 mW. For applied powers higher than 19 mW, the slope, dT/dP increases dramatically from ~7 mK/mW to ~300 mK/mW. This corresponds to when the applied heat immediately evaporates all superfluid helium in the pot and it becomes 'dry'. This is the so-called drying point [11] and is noted by the filled circles in Figure 3. Our design of the 1 K pot behaves this way since both the volume of the heat exchanger at the second PT stage is greater than the 1 K pot volume and the heat lift and heat exchange at the second PT stage is sufficiently high that under flow rates at the drying point, the heat exchanger remains still not full of liquid. Since the flow impedance of the capillary is constant, helium flow is increased only by increasing the (saturated) vapor pressure of the liquid helium in the heat exchanger at the input to the capillary. We raised the capillary input pressure by increasing the temperature of the second stage pulse tube with applied heat as shown by the series of filled circles in Figure 3. We demonstrated P = 35 mW at T < 1.3 K by increasing the 1 K pot flow in this manner.

SYSTEM PRECOOLING FROM ROOM TEMPERATURE

The cryogenic testbed was sized to cool down exceptionally large instruments, ~25 kg, to sub Kelvin temperatures. For instruments cooled with liquid cryogens, this is done by immersing the instrument vacuum can in the liquid and filling the can with an exchange gas. For actively cooled systems, special liquid precooling lines have been used [19]. We have adopted a pair of novel approaches. The first, described in the previous section, is running the 1 K pot at a high pressure during cooldown. This expedites cool down to the point the PT head and the injection capillary are cold enough to condense helium. The second is the use of passive heat switches (HS) made of POCO graphite. The thermal conductivity decreases dramatically with temperature as shown in the plot to the left in Figure 4. At room temperature it has a thermal conductivity close to 1W/cm-K which is near that for aluminum. At 1 K, the thermal conductivity falls to 10^{-5} W/cm-K yielding a
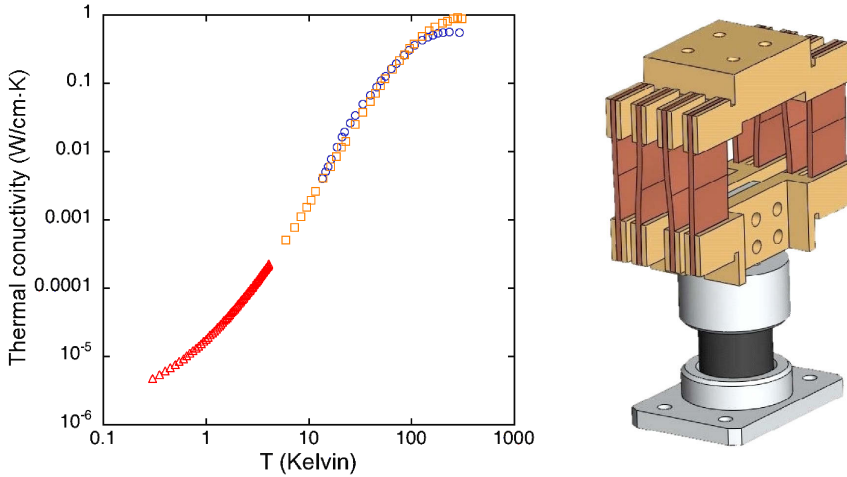
Figure 4. POCO graphite thermal conductivity (triangles (20), squares (21) circles (22) and drawing of the HS with copper straps.

very high on-off ratio of 10^5. The switches are fabricated, as shown to the right in Figure 4, using pitch bounded polycrystalline graphite with a particle size of 0.01 mm available from McMaster Carr [17] press fit into aluminum end fittings. The graphite rod is purchased 25.4 mm in diameter and cut to 50 mm length. Bottom and top aluminum end fittings are made with a through hole 0.05 mm (0.02%) smaller in diameter than the graphite rod diameter and 12.5 mm and 17.5 mm long, respectively. The graphite rod is pressed into the aluminum parts using a press. This produces a clean and high force interface between the graphite and aluminum for high boundary conductance. Since aluminum has a higher coefficient of thermal contraction that graphite, the boundary contact force increases with decreasing temperature. Each heat switch was dunked in liquid nitrogen to ensure that the thermal contraction force did not exceed strength limits for graphite. No sign of mechanical fatigue was apparent after the dunk test and ~a dozen cryogenic cycles. The two heat switches are screwed on the 3.5 K plate and linked to the 1 K plate using two 4 mm S/L copper braids straps. At operational temperatures, between 1 K and 3.5 K (4.2 K) — the operating temperature of the stages — the total contribution to the parasitic heat load from the two HS used in our cryostat is estimated to be less than <0.8 mW (1.5 mW).

Thermal Test of the Heat Switch

The thermal conductance of one of the two heat switches was measured between 50 K and 250 K as shown in Figure 5. For the measurement, temperatures were measured using DT670 diodes read out with a Lakeshore 218 temperature monitor [23]. Both sides of the HS, the side bolted to the cold stage through a copper thermal link and the free end, are regulated at fixed temperatures, Tf and Tc respectively, using a PID loop and 5 ohm resistive heaters. The heaters current leads were two pairs of 0.5mm^2 copper wires with resistance <<5 Ohms. The heater leads were heat sunk on the cold stage away from the end of the HS. Load curves of applied heater power to the free side Pf(Tf) for fixed Tc were measured. The thermal conductance is the slope G(Tc) = dPf/dTf(Tc), shown as the filled dots in Figure 5, determined from a linear fit to the heat load curve. The offset obtained from this fit is the parasitic power conducted by the heater wire to the free end. The parasitic power for each value of conductance is in good agreement with the estimated value computed including the measured cold stage temperature. We estimate the accuracy of the measurement as <10%. The measured thermal conductance of the HS assembly is >70% of the value for a 50 mm long piece of graphite without end fittings. The HS conductance was modeled, numerically [24], as a function of temperature for T > 50 K as shown by the open symbols in the plot in Figure 5. In our model, we find thermal spreading in the graphite from the contact region with the aluminum
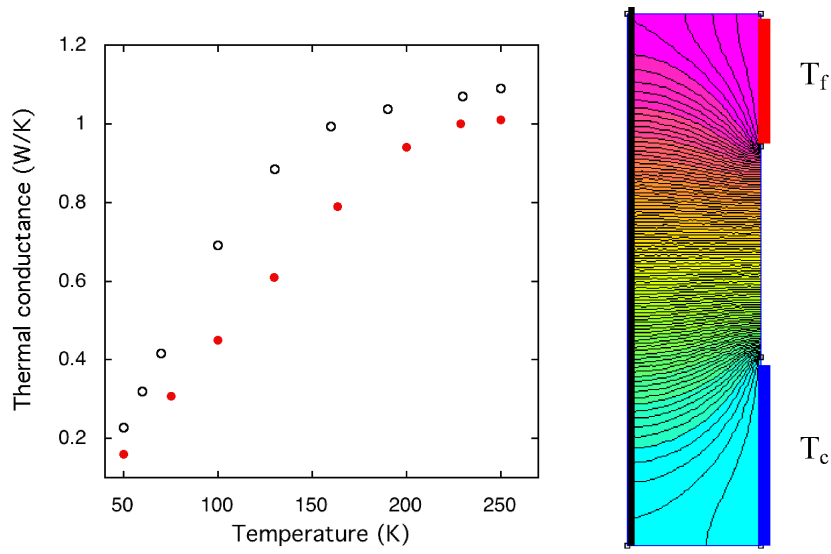
Figure 5. Left: full dots: HS measurements, empty dots: thermal model Right: Calculation of T profile into graphite (axisymmetric calculation with fixed T simulating perfect thermalization).

to be a significant factor limiting heat flow. An example of the temperature profile, showing just the isothermal contours from the spreading is given to the right in Figure 5. From this model, we estimate the contributions from the aluminum end fittings and interface conductance between the graphite and aluminum to be > 10W/K. If we assume all of this is due to the interface, we find a lower bound of 1W/K-cm^2 from the interface conductance for the press fit graphite aluminum interface.

An actual cool down profile is shown in Figure 6 when the prototype BLISS cooling chain is mounted on the 1 K stage, Figure 7. The cool down of the 1K stage is expedited from 300 K to <30 K before the HS conductance is small compared to the thermally isolating stainless steel supports. At ~22 hours, once the temperature of the second stage of the PT is less than the critical point
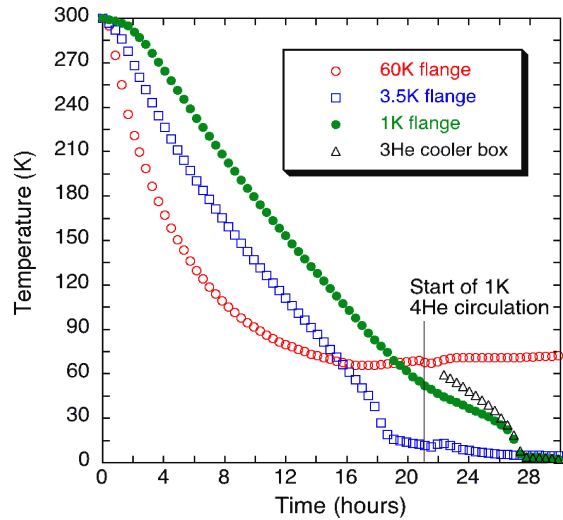

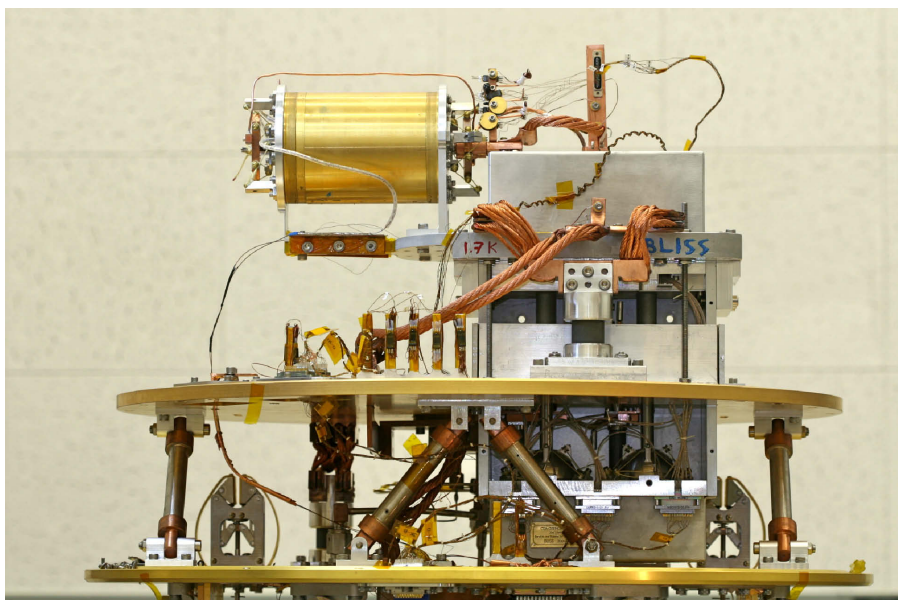**Figure 6.** Precooling of the cryostat with the 1K plate.

Figure 7. The bliss cryochain demonstrator installed on the 1K plate**.**

of ^{4}He (<5.3 K), the ^{4}He is circulated to expedite the remainder of cooling to ~1 K. To estimate the effectiveness of the HS, we compared the measured cooling rate, shown in Figure 6, with passive radiative cooling. Using an emissivity of 0.1, typical of machined aluminum, the heat transfer rate is ~10 W when the instrument stage temperature is between 300 K and 200 K. When the instrument stage is below 100 K, the radiative heat transfer rate is <1W. The heat transfer rate through the graphite heat switches, including the copper heat straps, for these two temperature ranges is 70 W and 20W, respectively. Thus, the expected cool down time of the instrument without the graphite HS would increase from 1 day to 1 week.

CONCLUSION

We have developed a cryogenic system using a commercial PT415 pulse tube and an integrated 1 K pot capable of cooling a 1 K stage with 55 cm in diameter and 50 cm long instrument volume for testing a prototype sub Kelvin cooler and spectroscopic instrument for BLISS. The 1 K pot stage has a base temperature of 0.96 K and a maximum cooling power of 19 mW at 1.1 K. When the second stage of the pulse tube is heated from 3 K to 3.8 K, the cooling power of the 1 K stage is increased to 35 mW at 1.3K. Passive heat switches (HS) made of graphite thermally pressed fit into aluminum end fitting were made to expedite the cooldown of the 1 K stage. The measured thermal conductance of the graphite HS from 50 K to 300 K is within 80% of the ideal value of a graphite switch with no end fittings. We estimate the boundary conductance between aluminum and graphite for our switch is >1W/K-cm^2 between 50 and 300 K. Cool down times for instruments on the 1 K stage are ~1 day.

ACKNOWLEDGMENT

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