Continuous 350 mK Stage ADR Cooling for Space and Ground Application

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ABSTRACT

LiteBIRD is a planned JAXA-led mission aimed at measurement of the polarization of the cosmic microwave background. To reach the desired sensitivity, its detectors must be cooled to 100 mK. The proposed cooler, based on a succession of Adiabatic Demagnetization Refrigerator (ADR) stages, includes a 350 mK continuous stage driving the overall mass. This cooler will use a 1.75 K interface and must be optimized with mass as a strong driver. In this paper the overall design of the *LiteBIRD* 100 mK cooler is presented with a focus on the 350 mK intermediate stage. A demonstrator for this intermediate stage has been manufactured and is ready for testing.

This type of cooler operation, providing continuous cooling at 350 mK, is also well suited for ground applications and benefits from space optimization: the mass and size reduction necessary for space design can translate into cost reduction for a dedicated ground design. For this application, a higher interface temperature would be used. Experimental demonstration of 350 mK cooling, using an existing assembly, has been achieved based on a 2.7 K interface from a laboratory pulse tube and is presented as an initial experimental result.

INTRODUCTION

In standard cosmological models, the cosmic inflation is a time of extremely fast expansion of the size of the universe happening in the first fractions of seconds of the Big Bang Expansion. Its existence is postulated to reconcile observations with a consistent theory. This inflation would have left a key signature in the polarization of the cosmic microwave background. Observing this signal, the primordial B-mode, would support – or discredit – the most popular underlying models, and the level of this primordial B-mode would help in understanding of the physics in play. Several experiments based on ground observation, such as BICEP [1], are focusing on this objective. A space instrument would give access to wider angular measurements as well as measurements on a large bandwidth, not limited by the earth's atmosphere. Hence, a space observation would bring valuable detailed measurements of this B-mode.

The Japan Aerospace Exploration Agency (JAXA), together, with an international collaboration team is designing a space observatory dedicated to the measurements of the CMB polarization. The observatory is called *LiteBIRD* (see [2] for a full description of the project). Two instruments are installed on the *LiteBIRD* payload: the low frequency telescope (LFT) designed under JAXA leadership, and the medium and high frequency telescopes (MHFT) designed under European leadership. For both these instruments, sensitive TES detectors (transition edge sensors) are being developed in North America. To reach the required sensitivity, the TES must be cooled to 100 mK. The principle of CMB observation consists in a full sky map, and thus benefits from continuous cooling.

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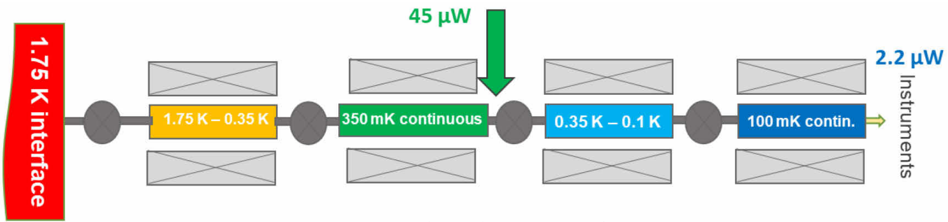

Figure 1. ADR configuration for the *LiteBIRD* cooler

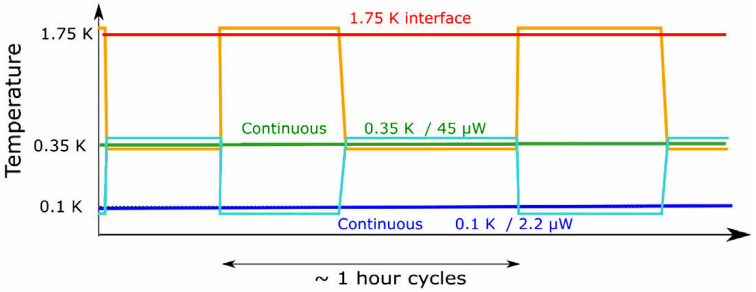

Figure 2. *LiteBIRD* ADR simplified temperature variation of the four stages; each color line is representative of the temperature of the stages presented in Figure 1.

The low temperature cooler, providing 100 mK cooling, and an intermediate temperature stage of about 350 mK are both based on adiabatic demagnetization refrigerators (ADRs) that provide continuous cooling at their respective stage temperatures. Warm interfaces at 1.75 K and 4.8 K, are derived from a cryogenic chain using two types of Joule Thomson coolers provided by JAXA. More details on the cryogenics chains are described in [3]. This paper will focus on the intermediate temperature cooling at 350 mK with a required cooling power of 45 µW. A demonstrator for this intermediate stage is described. It has been built and is ready for testing. Additionally, the paper will also present preliminary experimental results of its operation using existing ADR stages and based on a 2.7 K interface.

KEY DESIGN REQUIREMENTS FOR ADR CONTINUOUS COOLING

General Configuration for the *LiteBIRD* Cooler

As previously proposed by Shirron et al. [4], a series configuration of ADR stages is a very efficient way to provide continuous cooling and to deal with a large delta temperature. The design proposed here is a succession of four stages (see Figure 1). Each group of two ADR stages provides continuous cooling at 350 mK and at 100 mK, respectively (see Figure 2).

As a crude approximation, the required magnetic field of each ADR stage is proportional to the value of the warmer temperature of its cycle. This maximum magnetic field also drives the mass and volume of the stage. Consequently, the larger ADR stage of this setup is the first stage, which operates at up to 1.75 K; of course, cooling power and cold time come into play as well in the sizing. For this typical cooler, the two stages providing 350 mK (in orange and green on Figure 1) will drive most of the mass requirement. Our focus is therefore on the optimization of this 350 mK cooler.

In addition to this promising space application, 350 mK continuous cooling based on small size coolers can be extremely useful for many ground based applications, such as Kinetic Inductance Detectors (KIDS) based systems.

Overall Design of the *LiteBIRD* Cooler

A first preliminary design has been proposed and is represented in Figure 3 in an in-line configuration. The four ADR stages, the vertical cylinder shapes, account for most of the mass. This overall cooler is estimated at 8.0 kg. The mass estimated for the two first stages is 4.6 kg, and the mass for the two last stages is 3.4 kg. In this design, the last two stages are oversized, providing margin and space for further optimization.

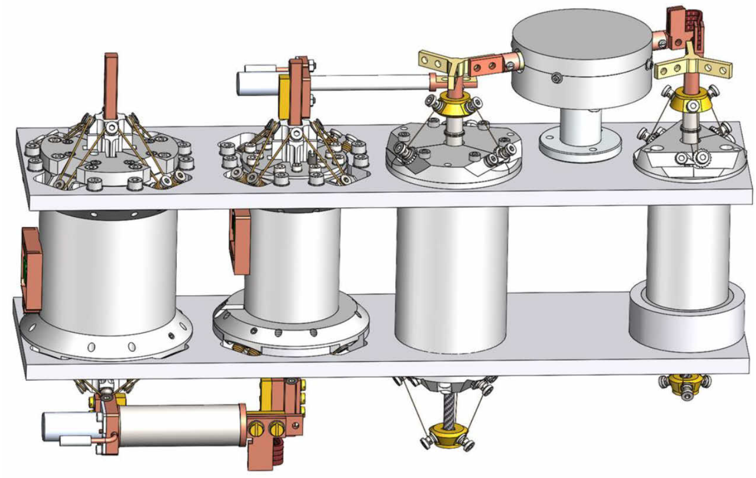

Figure 3. In-line ADR configuration for the *LiteBIRD* cooler

Magnetic shielding is another key to compatibility with detector operation and is linked to mass optimization. Further study will focus on this optimization.

The cooler mechanical interface is linked to a 4 K stage of the payload provided by a JAXA JT cooler. In addition to the mechanical support, the dissipation of the heat switches (sorption pumps) and of the magnetic stage (eddy current and hysteresis losses) will be passed to this 4 K stage. The thermal interface for the ADR itself, however, is connected to a 1.75 K interface from a 2K JT. The four stages are connected on the same support and will be tested and qualified as a single unit. However, the operation of the 350mK stage and the 100mK stage are almost independent. As a first phase of this development, our work is focusing on the optimization and demonstration of the 350 mK-stage. Therefore, the continuation of this paper will focus solely on the 350 mK operation.

Key Design Choices for 350 mK Continuous Cooling. Ytterbium Gallium Garnet (YbGG) material is well suited for 350 mK cooling from an interface ranging from 3 K to 1 K. The properties of this material, which offer good magnetocaloric properties and mechanical integration, have been presented previously [5].

Gas-gap heat switches are used between the two stages and to the heat sink at 1.75 K. While the design is based on a flight proven technology [6], the sizing had to be adapted. For continuous operation, indeed, large heat transfer must be favored, and large ON conductivity are necessary. The size (diameter notably) of the switch has therefore been increased compared to our standard design. The operation of the gas-gap heat switch requires careful timing management to reduce temperature fluctuations during transition.

General Configuration for 350 mK Continuous Cooling. We designed and constructed a compact 350 mK ADR cooler. This design is well adapted to the specific *LiteBIRD* demonstration. The nominal interface temperature is 1.75 K, well below the interface discussed in our preliminary demonstration, giving the possibility to reduce drastically the size of the ADR stages. The demonstrator is also based on Ytterbium Gallium Garnet (YbGG) material. The compact design can be seen in Figure 4.

EXPERIMENTAL RESULTS

Manufacturing and Test Bench

Manufacturing is finalized, and particular attention has been paid to providing a space compatible design. For example, the process for coil manufacturing has been improved to be compatible with space constraints. The coil of the second stage has been tested functionally, and then followed a mechanical environment campaign and its operation validated. A current twice the nominal current without any training

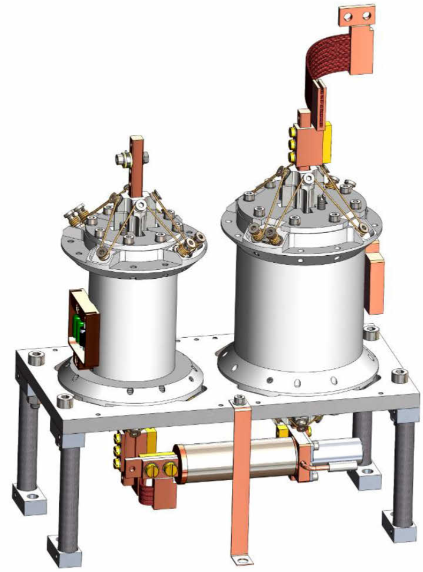

Figure 4. Design of the 350 mK ADR cooler for *LiteBIRD* (total mass of 4.6 kg)

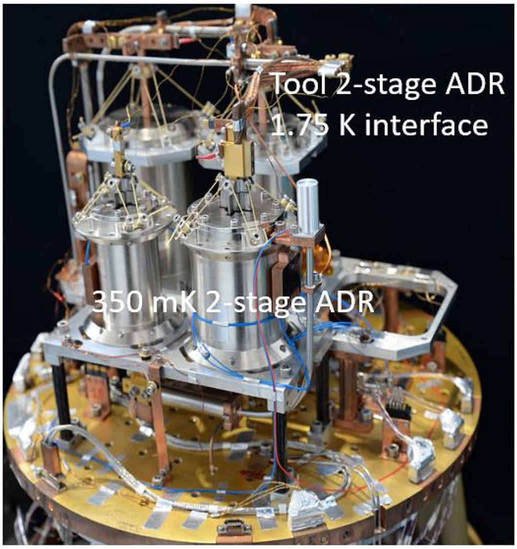

Figure 5. 350 mK ADR cooler in the test bench

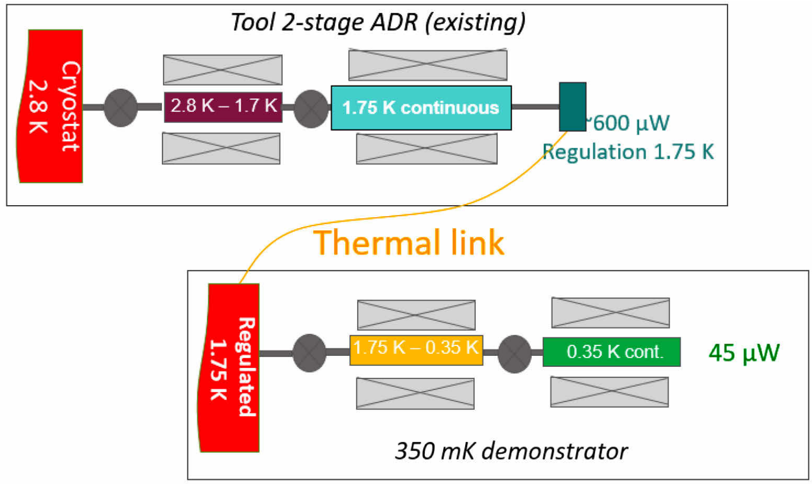

Figure 6. Setup scheme for the *LiteBIRD* demonstration of 350 mK operation

quench was verified in the two functional sequences. The cooler was mounted in a cryostat (Figure 5 and scheme Figure 6). The two-stage ADR in the background (blurry) was used to provide the intermediate temperature; it can provide a continuous interface at 1.75 K, representative of the mission requirement. In addition, this setup will give us the possibility to characterize the prototype with different interface temperatures. This experimental campaign will be pursued in the following month.

Experimental Validation of 350 mK Continuous Cooling from a 2.7 K Interface

We used the "tool" ADR, introduced above and built from existing ADR blocks, for another purpose. Prior to the validation of the performance of the *LiteBIRD* prototype, we characterized the tool as a preliminary demonstration of 350 mK cooling using a 2.7 K interface. This demonstration is detailed in the following sections.

Figure 7. Two stage ADR cooler

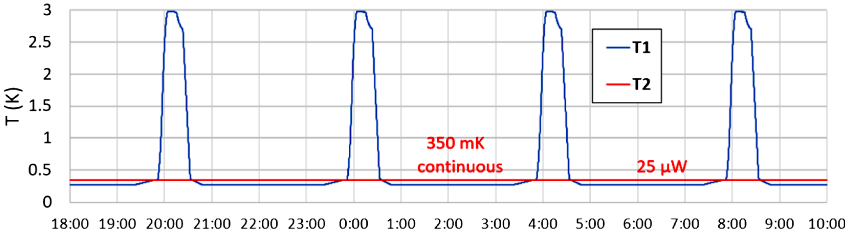

Figure 8. Experimental measurements of temperature during several cycles with 25 µW net heat lift at 350 mK.

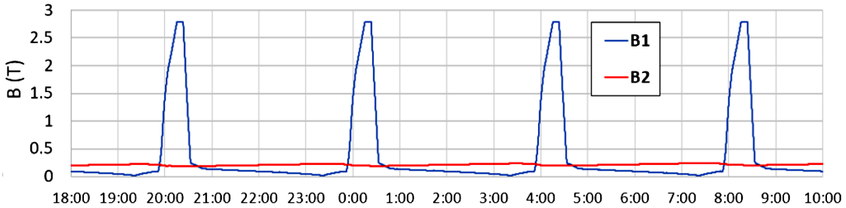

Figure 9. Variation of magnetic field during the experimental 350 mK continuous operation

This demonstration serves two purposes. Practically, this model will be used in this project to serve as a continuous cooler interface that can be regulated anywhere between 350 mK and 2.7 K. For instance, for *LiteBIRD*, it will operate at 1.75 K. More fundamentally, this demonstration is a first step to validate our prediction and the efficiency of this operation. In itself, this cooler, seen in Figure 7, is also a good candidate for ground-based cooling for various applications.

The experimental results are presented in Figure 8. Measurements T1 and T2 are based on Cernox censor placed directly on the copper tip of the ADR stage. A continuous cooling of 25 µW was measured at 350 mK from a 2.7 K interface. This type of operation, based on a commercial pulse tube cooler and a simple to operate two-stage ADR can have many laboratory applications. For instance, cooling detectors (such as KIDS) can be optimized for this temperature range. The period is 4 hours with less than 30 minutes taken to recycle the T1 stage.

The variation of magnetic field is presented as well in Figure 9. The first stage variations are large due to the large temperature gradient that needs to be compensated. The small variations of the second stage magnetic field are an indication that, as anticipated, the second stage is largely oversized for this type of

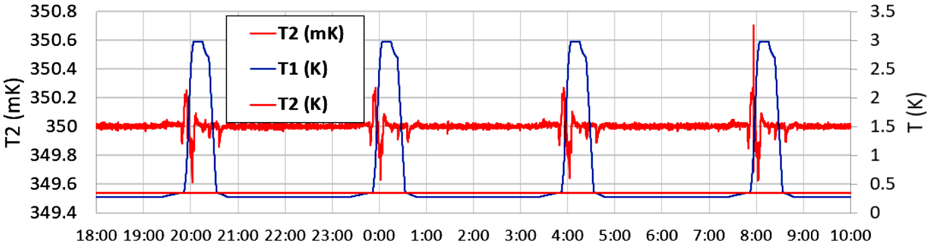

Figure 10. Variation of temperature during the experimental 350 mK continuous operation

operation. The mass of the prototype here was 8 kg, but if the design were to be made for this specific operation, we estimate it would be 6 kg or less.

The temperature stability measured was lower than 1 mK (see Figure 10). The instability is driven by switching of the first stage temperatures. To reduce these variations before each heat switch opening on the cold phase, the temperature and therefore magnetic field (B1) increased slightly before the main magnetization. The thermal mass of the stage is negligible (only few grams of copper) compared to the paramagnetic material, and the temperature is measured directly at the cold tip, leading to a worst-case measurement of thermal fluctuations. The addition of a thermal link decoupling (typically few mK/µW) and a realistic thermal mass (several 10s gram of copper as would be in an application) would drastically reduce these temperature variations.

The size and operation of this stage were not optimized for this application. Based on our analysis, more than 50 µW could be obtained in a more optimized design, especially focusing on heat switch design. In any case, this experimental demonstration with a 2.7 K interface validates the principles of our design and operations.

This demonstrator is also perfectly suitable to serve for precooling of an optimized "*LiteBIRD*" cooler as described in Figure 6. While it can operate at a low temperature, as low as 350 mK, the flexibility of the ADR operation makes it possible to operate at a warmer interface temperature with a much higher cooling power. In this case, providing 600 mW of cooling at a 1.75 K interface is well within the capability of this demonstrator.

PERSPECTIVES AND CONCLUSION

The 350 mK cooler designed and manufactured will be extensively characterized and optimized. Based on the results and of the evolution of the *LiteBIRD* specification, an iteration of the design will be proposed to fit the mission needs. Already, a design with a 6.5 kg cooler has been proposed with expected cooling at 100 mK and at 350 mK. The optimization of the intermediate temperature will be made.

Experimentally, 350 mK cooling from a 2.7 K interface with a two stage ADR cooler has been demonstrated providing more than 25 µW cooling. Because the demonstrator has not been specifically designed for this use, this performance could be achieved with a cooler of less than 7 kg.

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