Development Status of 50 mK Hybrid Coolers for Space Applications at CEA-SBT

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ABSTRACT

For several years, CEA-SBT has been developing a concept to produce temperatures down to 20 mK. This concept is based on the combination of a 300 mK sorption stage and a small adiabatic demagnetization stage. This hybrid architecture allows for low weight design and a compact cooler. Because the sorption cooler is probably the lightest solution to produce sub-Kelvin temperatures, it permits the stringent mass budget of space missions to be met. Several systems have been built from prototypes to engineering model. Different combinations are possible and the cooler can be designed as a one shot unit providing cooling power at 50 and 300 mK, or a mix of continuous stages, either at 50 mK or 300 mK, or both. Most future space missions will be designed as cryogen free satellites and will use mechanical coolers to provide temperatures down to 1.5 K. Solutions to couple our sub-Kelvin unit to these intermediate stages with limited resources have been demonstrated. Advanced solutions are being developed to maximize the duty cycle efficiency. A fully integrated engineering model intended for the Advanced Telescope for High ENergy Astrophysics (ATHENA) mission has been produced. Mechanical analysis and measurements validate a high Technology Readiness level (TRL). A second engineering model dedicated to the Space Infrared Telescope for Cosmology and Astrophysics (SPICA) FAR-infrared (SAFARI) instrument on board the SAFARI satellite is currently being produced. In parallel, work has also been carried out on a slightly different configuration which includes a continuous 300 mK stage. This cooler could be used in the Background Limited Infrared Submillimeter Spectrograph (BLISS) instrument, a US candidate for SPICA.

INTRODUCTION

Within the last decade, several space missions have been flown with cryogenic instruments on board featuring detectors cooled to sub Kelvin temperatures. This is the case for HERSCHEL, the largest space observatory ever flown, with bolometric detectors operated at 290 mK, PLANCK with detectors cooled to 100 mK and Suzaku which had a limited lifetime due to a cryostat problem[1], yet was able to demonstrate cooling down to 60 mK.

The foreseen large cryogenic missions for the next decades share at least two requirements: the use of mechanical coolers instead of liquid cryogen, and a temperature objective of 50 mK. One can mention Astro-H, SPICA, ATHENA, CORE and Polar Ionospheric X-ray Imaging Experiment (PIXIE) for instance. The ATHENA and CORE missions were not selected for the next ESA space missions, but they may be proposed in the future.

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The benefit of the mechanical coolers is to provide an extended lifetime for the missions. As a matter of fact, durations over 3 years are now planned. In addition, the volume of the coolers is substantially smaller than a HERSCHEL-type helium cryostat, which allows optimizing the number of instruments and their packing. Yet there are several drawbacks; such as the induced vibrations, the interfacing, heat distribution and limitation of the instant loads on the cooler cold tips. These constraints must be considered carefully when selecting and designing sub Kelvin stages

DESCRIPTION OF THE THERMAL ARCHITECTURE

The possible choices for active coolers providing temperatures below 1 K are currently limited to three technologies for space applications: evaporative cooling (mostly with ^{3}He), ^{3}He/^{4}He mixture dilution cooling and adiabatic demagnetization refrigerator (ADR). These are developed in several laboratories and a high TRL has already been demonstrated for all of them[2, 3, 4]. Of course, a combination of these techniques is also possible and this is indeed the route we are following. One of our initial drivers was to propose a system as light as possible and be able to provide temperatures down to 50 mK. Taking advantage of our heritage[2] for the HERSCHEL program was also considered. The requirements of several years of operation exclude, for the time being, the dilution cooler which is not yet fully operational in its continuous version[5], and set the ADR as the only possible option for the final stage. Evaporative cooling and ADR are one-shot system in essence; they are recycled and then provide a net heat lift at the required temperature for a limited time. However, if necessary, continuous operation can be obtained by combining stages in series or in parallel.

Stacking up several ADR stages to cover the required temperature range from 50 mK to a few K is one option, but our approach is to combine a last ADR stage with a noticeably light ^{3}He stage. This architecture requires an interface temperature below the critical temperature of ^{3}He, i.e. 3.2 K. One could argue that a ^{4}He sorption stage could be used to extend this upper limit to 5.2 K. Although feasible in theory, this would lead to adding a ^{3}He sorption stage in series or at least a double stage ADR to cover the remaining range from typically 800 mK down to 50 mK. In this case, the complexity and efficiency of the system does not justify the mass advantage in our opinion.

The two stages, sorption and ADR, can be arranged in a number of configurations whether the objective is to have a one shot system and limit the complexity, or continuous cooling at any of the two temperatures (few tens and few hundreds of milliKelvin, respectively). The configurations will also differ depending on the available resources, i.e. interface temperature and associated cooling power. Indeed the limitations on the instant loads at the upper interfaces require dissipating in a controlled manner the energy associated with the recycling of the sub Kelvin stages. This is particularly true for the sorption stage for which at some point during the recycling the dissipation can be very large. In order to limit this dissipation to an acceptable value, one needs to control the heat flow to dump the energy over a longer time. This is done by using heat switches with an adjustable conductance. Three architectures have developed, respectively, for the IXO/ATHENA[6], SPICA/SAFARI[7] and SPICA/BLISS[7] missions. These arrangements are depicted in Fig. 1.

For each of these architectures, prototypes have been designed, built and tested. More detailed information is given in the following paragraphs. For each of them the issue of the peak power has been solved and experimentally demonstrated. As mentioned before, the energy related with the cooldown of the main sorption pump is dumped slowly through the heat switch, which conductance is controlled, either on a single interface stage (SAFARI and BLISS cases) or first on a high temperature stage and then on a low temperature one (IXO/ATHENA case). Typical results are displayed on Fig. 2. For these tests the requirements on the various interfaces were a maximum dissipated power of 10 and 100 mW respectively at 2.5 and 15 K for the IXO/ATHENA cooler prototype, and 5 and 10 mW respectively at 1.7 and 4.5 K for the SPICA/SAFARI prototype.

For the IXO/ATHENA cooler, the dissipations at the two interfaces are measured in real time and the heat switch conductance is tuned accordingly. This method is very efficient but can only be

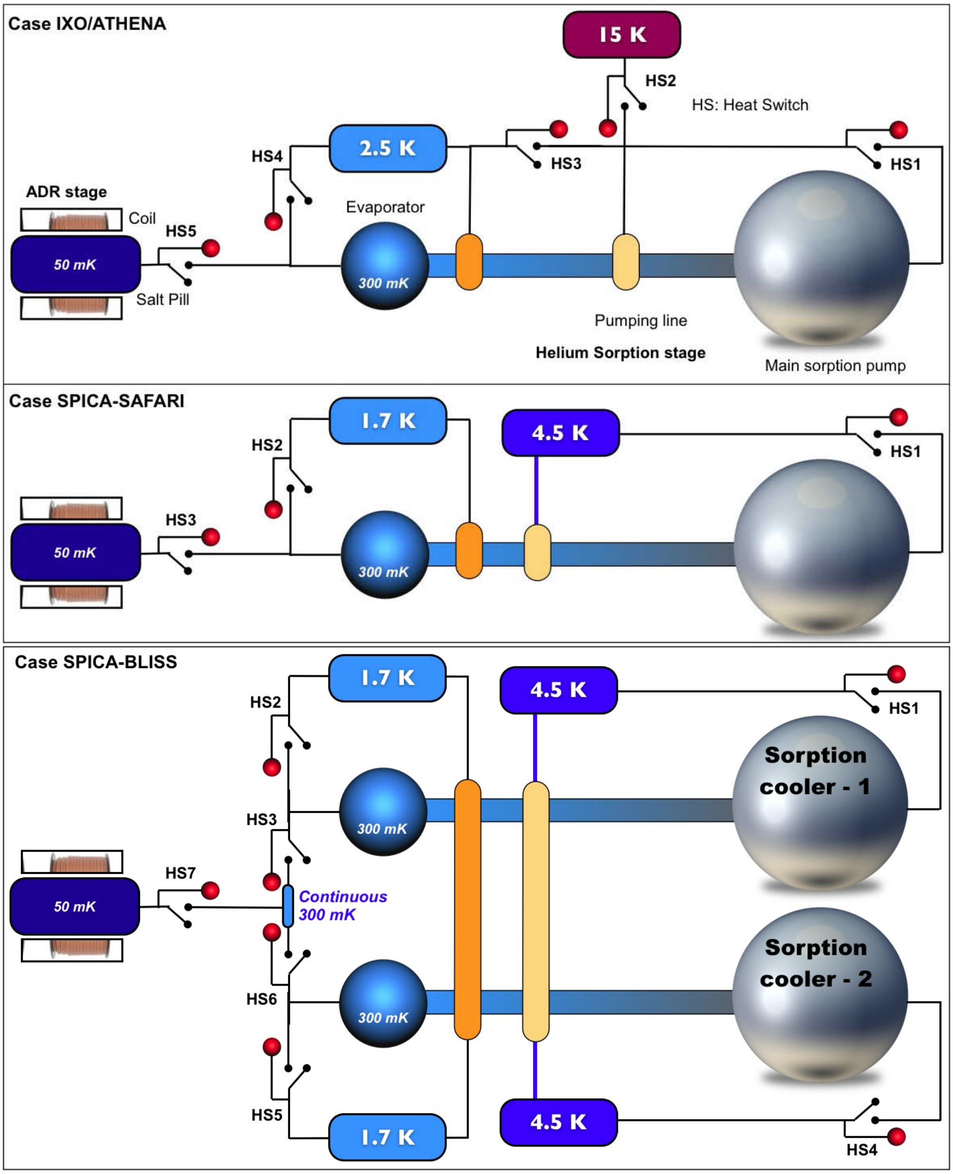

Figure 1. Example of thermal architecture for the hybrid sorption/ADR cooler

used if the heat flows are measured. For the SPICA/SAFARI case, a "thermal map" of the dissipation for various heat switch conductances and sorption pump temperatures has been produced. This information is then used as an input by the drive electronics. This technique works equally well as long as the performance of the various thermal links remains the same.

IXO/ATHENA COOLER PROTOTYPE

In 2007, CEA-SBT was awarded an ESA contract to develop a 50 mK cooler for the IXO mission, an x-ray satellite formerly called XEUS, renamed IXO in 2009 and then ATHENA in 2011. This mission was part of the last round of selection for the large (L-class) candidates in the framework of the ESA cosmic vision program. When the Technical Research Program (TRP) was

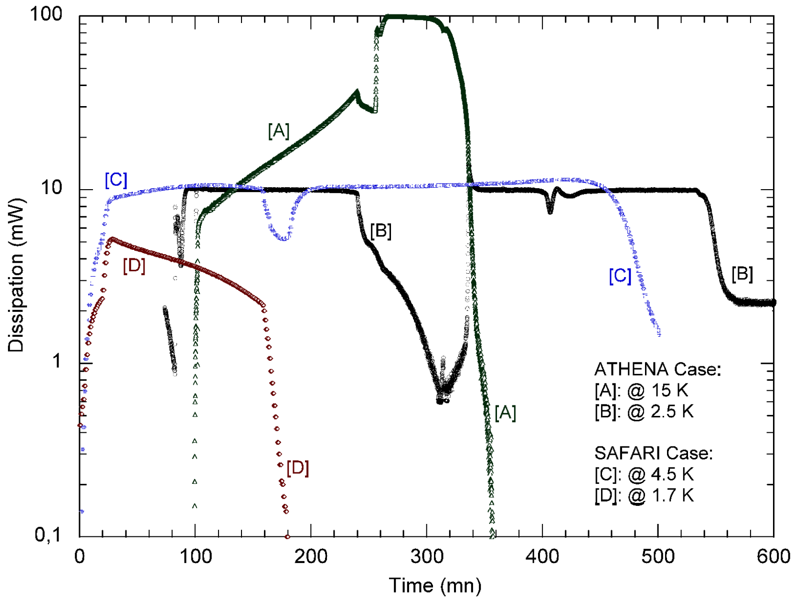

Figure 2. Dissipation of the IXO/ATHENA and SPICA/SAFARI prototype coolers during the recycling phase. SAFARI case: sorption stage only. ATHENA case: sorption stage and ADR stage included.

released, the specification for the cooler was a low temperature stage at 2.5 K and an intermediate stage at 15 K, providing 10 mW and 100 mW of cooling power, respectively. This program has been successfully carried out and has led to the first fully integrated engineering model cooler. Yet in this TRP, high level vibration tests were not required and the cooler only went through a low sine sweep to identify the resonant frequencies. In order to increase the TRL level, we decided to perform a standard vibration test (high sine and random).

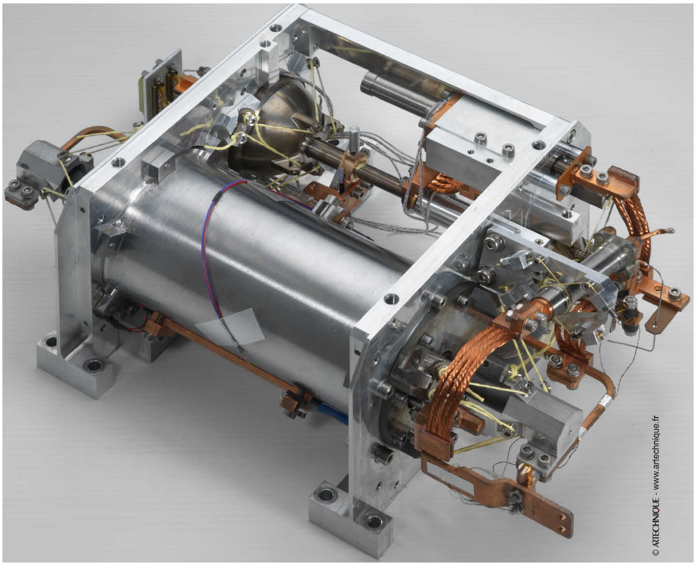

Figure 3. 50 mK cooler developed for IXO/ATHENA (ESA Technical Research Program)

In the meantime, the interface temperatures for the IXO mission, now ATHENA, were discussed again and could evolve toward the interfaces currently used for the SPICA/SAFARI mission, i.e. 1.7 K and 4.5 K. It was thus decided to modify the TRP cooler and set it in a SAFARI type configuration. The cooler is shown in Fig. 3. It should be noted that the cooler was not originally sized for SAFARI and is not optimized for these operating conditions. A first thermal test campaign has been carried out to validate the performance of the cooler and obtain a reference set of values. These results are displayed in Fig. 4. For this test the applied load on the cold tips were 1 and 10 µW, respectively at 50 and 300 mK, and the dissipated powers at the 1.7 and 4.5 K interfaces were limited to 5 and 10 mW, respectively. This reference set will be used to detect any change in performance after the vibration tests.

For this project the laboratory drive electronics are based on a LabVIEW environment. The test cryostat features calibrated thermal shunts to the cooler interfaces, and the dissipation is measured and controlled in real time. The control is performed through the tuning of the thermal switch conductances as described earlier[6].

The cooler recently went through a vibration tests campaign. The levels applied for each axis were 15 G sine between 20 and 100 Hz, and 12 Grms random test in a 20-2000 Hz bandwidth. No visible deterioration nor peculiar behavior (consistency of the resonant frequencies throughout the tests) has been detected. The cooler will now be thermally tested to check for any internal damage.

SAFARI COOLER ENGINEERING MODEL

As for any project in its early phases, the SPICA payload and in particular the SAFARI instrument design are evolving over time. In this context the sub-Kelvin cooler specifications have been recently reviewed. The progress made in the detector design, on the instrument thermal architecture and on the various suspension structures, allow reducing the demand at the two target temperatures, 300 and 50 mK. The net heat lifts required are now 10 and 0.2 µW respectively (was 12 and 1 before). These new contributions must be added to the previous numbers leading to a grand total of 25 and 0.5 µW,

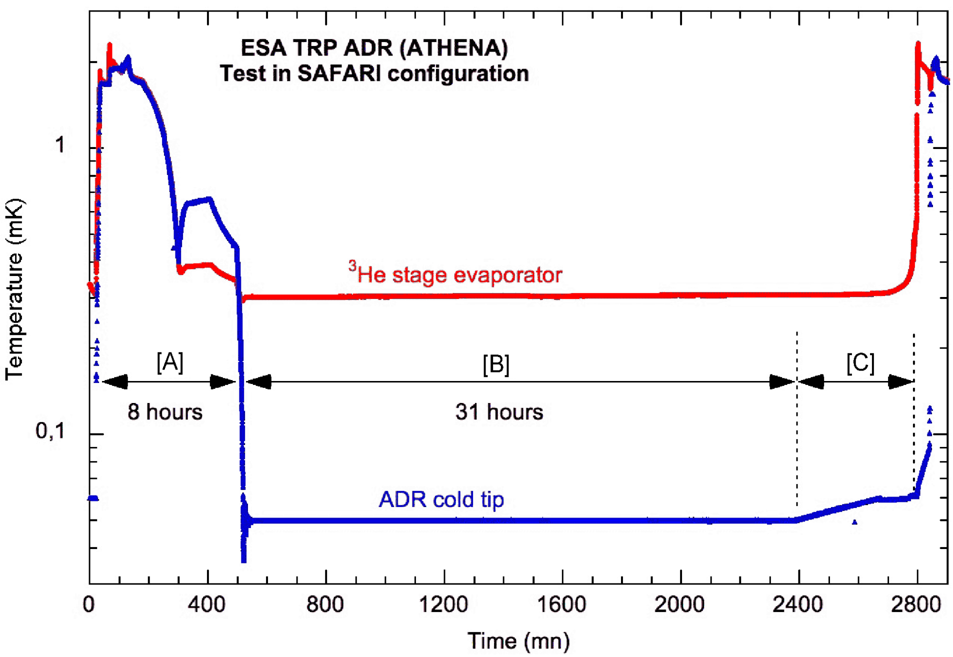

Figure 4. Performance of the ESA TRP cooler in the SAFARI configuration (not optimized). [A]: recycling phase, [B]: operating phase, [C]: ADR reaches zero field (300 mK stage still operating).

respectively at 300 and 50 mK, parasitics included. The hold time has also been revisited and is now 37 hours to be compatible with a 48 hours overall cycle (see next paragraph on the duty cycle efficiency). Finally, the available thermal resources have been lowered to 3.5 mW @ 1.8 K with simultaneously 10 mW @ 4.9 K. The design of the cooler is currently being updated, and the overall mass is expected to be about 5.5 Kg. A preliminary view of the new unit is depicted in Fig. 5. The mechanical and thermal interfaces are yet to be defined and for the time being the cooler is mounted on an aluminum plate (4.9 K interface) using 8 M5 screws located on the foot of the two aluminum flanges (see Fig. 5), while the 1.8 K is provided by a flexible copper strap.

DUTY CYCLE EFFICIENCY

Since the energy associated with the recycling of the sorption stage has to be dissipated over an extended period to limit the instant load, the duty cycle of the cooler is impacted. The duty cycle is defined as the ratio of the operational phase (low temperature phase) to the sum of the low temperature and recycling phase. Apart from any other considerations, maximizing this parameter is a reasonable objective and the cooler is designed accordingly. Yet it is not clear if the duty cycle is an issue as it depends on the observing strategy. Indeed for these L2 missions, in most cases the observatory has inherently a 24 hour rhythm. The cooler is used during the observation and is sized to provide the associated hold time, but once this phase is out, the satellite is set in a transmission mode during which operation of the detectors and thus observation is usually no longer possible. Depending on the available storage capacity on board and on the transmission performance, the downlink phase can last up to 10-12 hours (limited by satellite visibility). Consequently as a first approximation, duty cycle of the order of 70% or more are targeted, and the current SAFARI cooler is expected to provide a duty cycle in excess of 75%. A development program has been initiated to investigate solutions to further increase this number.

Since the energy to be removed cannot be reduced for a given cooler and that the resources available to extract this energy are provided by the upper stages, the only alternative is to use a thermal buffer to store this energy over a short duration and release it at the slower pace. From the cooler point of view (SAFARI case), it is acceptable to operate the sorption pump at a temperature of the order of 5 K without degrading the performance of the 300 mK stage. Thus we have assumed the thermal interface of the buffer will vary from 4.5 K to 5.1 K. For that matter, material with a specific heat anomaly are sought. Several candidates have been evaluated, and two solutions have selected. The first and most evident one is to use the latent heat of helium and design a sphere holding the required amount. This sphere must be sized to hold helium at room temperature and thus must be able to withstand pressure of 50 MPa. This is certainly the main point that questions

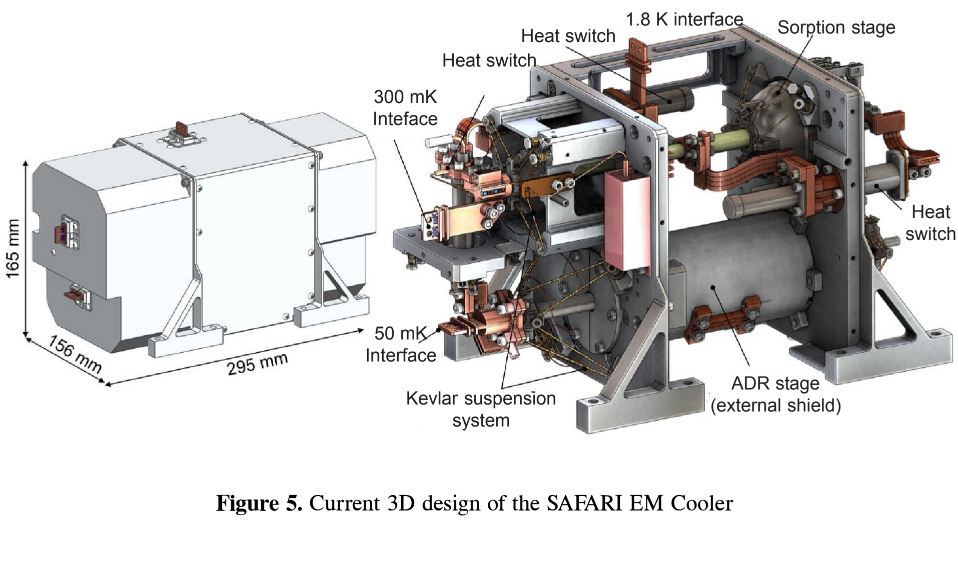

Figure 5. Current 3D design of the SAFARI EM Cooler

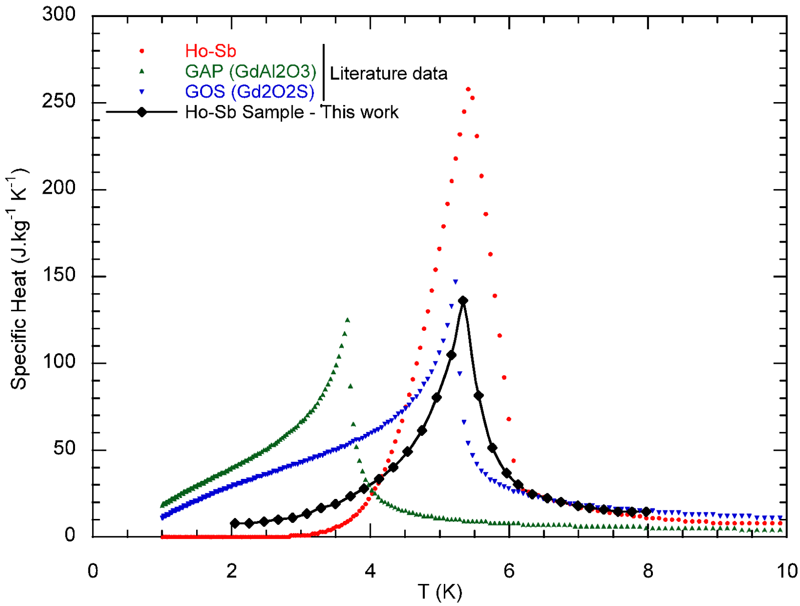

Figure 6. Specific heat measurement on Holmium antimony (HoSb) sample

this solution. There are a number of technological challenges in particular on how to provide a good thermal path between the liquid and the external interface, and also on how to test the device on the ground, under gravity. These points are under investigation. The second solution is to use a holmium antimony energy storage unit. As seen on Fig. 6, its specific heat exhibits a peak anomaly around 5.5 K. The production of this alloy is not straightforward, and a teaming agreement with the neighboring Neel Institute (CNRS) has been arranged to develop this technique. Several samples have been made and characterized[8]. Although the peak is indeed found at the expected temperature, its amplitude is significantly below the reported value (see Fig. 6). Work is ongoing to establish the correct fabrication method and also increase the density.

Another alternative to increase the duty cycle efficiency is to minimize the parasitic loads internal to the cooler. A development program is currently ongoing on the possible use of the titanium alloy Ti 15V-3Cr-3Sn-3Al (Ti15333). Its thermal conductivity is extremely low as measured again recently by others[9] and us, and features a superconducting transition at 3.89 K. Its mechanical properties at room temperature are better than that of the widely used Ti 6Al-4V (Ti6V), however Ti15333 exhibits a brittle behavior. For instance we have done chirpy v-notch tests at room and liquid nitrogen temperatures and found values of respectively 12 and 4 Joules. For comparison purpose samples were also made in Ti6V (from the HERSCHEL program) and led to 39 and 17 for the same conditions. Additional tests will follow to further investigate this aspect. At this point it is not clear whether or not we can use this material as a structural material. The SPICA mission will be launched warm and thus what matters is the behavior at room temperature; however, the system will be submitted to a large number of cryogenic cycles, and it is crucial to demonstrate that no failure propagation due to fatigue occurs. This is still under investigation but at this stage, Ti6V remains the material of choice for us.

CONCLUSION

Several prototype coolers able to provide cooling power at 50 mK have been developed and experimentally tested including engineering model coolers that have now demonstrated high TRL.

These hybrid coolers, made of a combination of small ADR and sorption stages, are attractive for the next generation space missions where compactness, mass and self-contained system are strong issues. Although there are solutions to make them continuous, these are one-shot systems in essence. When integrated in a cryogenic chain featuring cryocoolers with limited heat lifts, typical duty cycles of 75% or more are feasible. If necessary, the duty cycle can be substantially increased by using a thermal storage unit able to store a large amount of energy with limited temperature increase. Several candidates are currently under investigation in the 4 to 6 K range.

The design of the engineering model dedicated to the SAFARI instrument on board the SPICA satellite is currently being updated. Manufacturing of this model is expected in Fall 2012.

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