Qualification Program of the Engineering Model of the 50 mK Hybrid Sorption-ADR Cooler

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ABSTRACT

For several years, we have been working on a sub-kelvin hybrid cooler concept based on the combination of a 300 mK sorption stage and a small adiabatic demagnetization stage. A first prototype of this hybrid 50 mK cooler has been developed with ESA support to demonstrate its feasibility for the IXO (International X-ray Observatory) mission, which is now the European-led mission called ATHENA. Based on this successful development and upon the knowledge gained during this work and funding support from CNES, an advanced hybrid cooler has been designed and built to fulfill the requirements of the SAFARI instrument on-board the SPICA mission as of 2014. This compact 5 kg hybrid cooler provides has a net heat lift of 0.4 μW and 14 μW, respectively at 50 mK and 300 mK, for an overall cycle duration of 48 hours and a measured duty cycle of over 78%. This result has been obtained with limited resources, 5 and 10 mW, respectively at 1.8 K and 4.9 K. The cooler successfully went through its qualification program, which includes thermal and vibration tests, and has now reached a TRL 6 level.

INTRODUCTION

The need for sub-kelvin cooling has been voiced for several years and several solutions have been successfully developed and flown. Based on our heritage on sorption coolers for several projects[1, 2] we have developed a so-called hybrid cooler, which is a combination of a 300 mK helium three sorption stage and a miniature adiabatic demagnetization stage. Several prototypes and models have been built and tested[3, 4]. We focus here on the engineering model (EM) specifically developed for the SAFARI instrument onboard the SPICA satellite. The definition of this mission is currently being reworked and will be submitted at the M5 selection of the European Space Agency. During the years 2011-2016, extensive work on the sub-kelvin cooler has been carried out and a first EM unit was designed, built and tested[5]. This EM has been sized to operate from two interface temperatures, 1.8 K and 4.9 K, and most importantly using very limited resources, respectively 5 and 10 mW. In fact during the course of the project the 5 mW specification was reduced to 3.5 mW at 1.8 K.

This one shot system provides simultaneously net heat lift of 0.4 μW at 50 mK and 14 μW at 300 mK, with a duty cycle of 80% and an overall cycle duration of 48 hours. The whole cooler has a low weight of 5.1 kg and is 312 x 182 x 156 mm in size. A schematic along with 2 photos are displayed in Figure 1.

Cryocoolers 19, edited by S.D. Miller and R.G. Ross, Jr.

QUALIFICATION PROGRAM

The experimental qualification campaign of the cooler comprises a test sequence, which contributes, together with analysis and other verification methods, to qualification. This test program covers the functional performance and environmental verifications required to provide confidence in the ability of the cooler to meet the specified requirements. Performance measurements have been made before and after the environmental tests, designed to detect changes in performance parameters, which may indicate a potential failure. Prior to this campaign, the heat switches undergo their own selection process.

The cooler features 3 gas gap heat switches, a proven technology already flown on several systems but has also been identified as single point failure. The redundancy solution has been extensively discussed in the past and shows that a complete redundancy architecture against the ON and OFF position of the switches would require a set of 4 heat switches for any single switch. Thus these items are not redundant, a general conclusion made for ultra low temperature coolers. Yet in order to gain confidence on the performance of the EM, additional switches are built and undergo a dedicated test campaign featuring geometrical, thermal and vibration tests. A tool has been developed to check whether or not the interlocked copper parts in the switch are centered. The tool comprises two sensors, which measure respectively the force and the displacement on a moving part. This moving part is used to push gently on the switch end in all four directions (perpendicular to the switch axis). From the recording of the force versus displacement, the position of the inner copper part is obtained and the switches are ranked.

The switches are then thermally and mechanically tested. An example of the results is reported in Figure 2. The best set is then integrated in the cooler. In practice, the vibration tests very rarely affect the performance of the switches; most of the time, degraded switches, if any, are identified during the first thermal tests and the cause is, in general, due to the brazing process (misalignment of the internal copper parts).

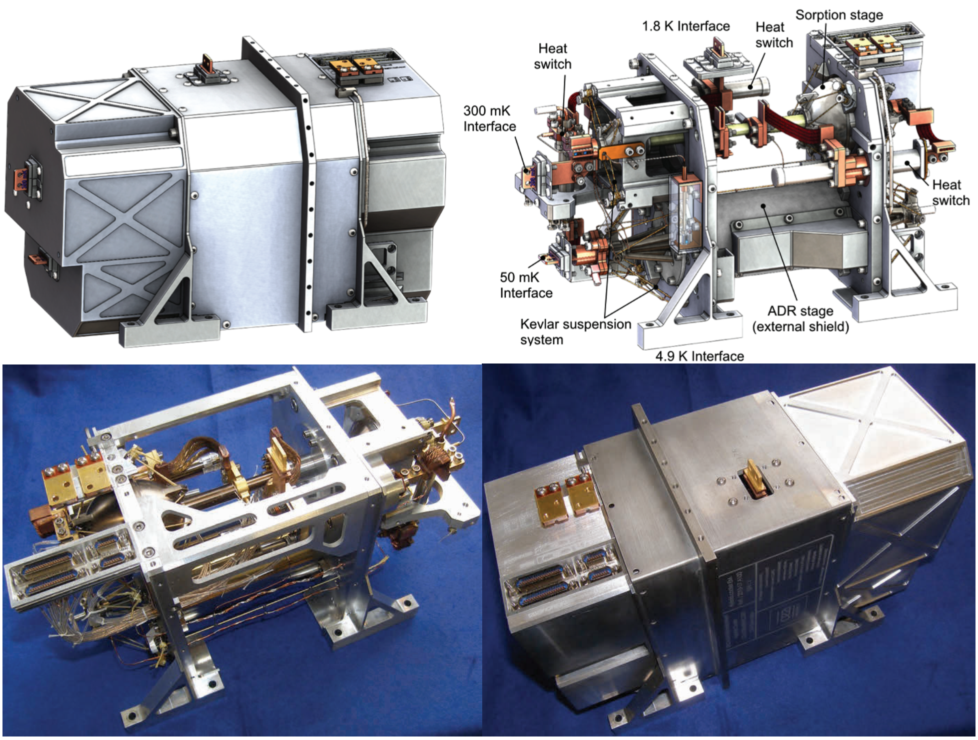

Figure 1. Schematic and pictures of the SPICA SAFARI engineering model

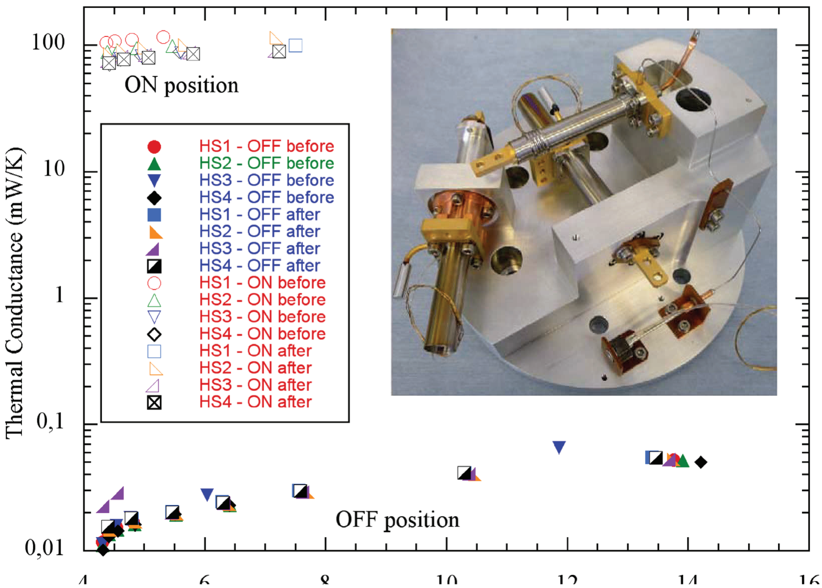

Figure 2. Heat switches thermal conductance before and after vibration tests. The picture depicts the set-up used for the vibration tests

The sorption stage is also thermally tested prior to integration, mostly to verify that the amount of helium-3 gas matches the expected performance. The cooler is charged under a cold condition. The pressure at room temperature is close to 8.4 MPa. By essence this step is straightforward assuming the sizing has been done properly. To qualify as a leak before burst, the pumping line of the cooler is designed with a calculated burst pressure of 35 MPa. This is the weakest point with respect to the internal pressure. The system was proof pressure tested at 18 MPa with ^{4}He (and kept at this level of pressure for 2 minutes). During this test, the recorded leak level was 2.6×10^{-11} Pa m^3 s^{-1}.

Integration in the test cryostat

A specific test cryostat featuring a nitrogen tank and two helium reservoirs has been designed to provide an extended autonomy of about 10 days at a temperature as low as 1.2 K. In this arrangement most heat inputs to the last reservoir are heat intercepted by the 4.2 K tank. Thus with a limited liquid helium volume and once pumped down, the coldest reservoir can last for one to two weeks without the need for refilling which would disturb the cooler operation. On the other hand, the 77 K and 4.2 K reservoirs, both under atmospheric pressure, can be refilled as necessary. The cryostat is fitted with two interfaces that can be temperature regulated respectively at 1.8 K and 4.9 K for the present campaign. The objective of this system is to measure (and control) the heat flows while the cooler is recycled. Thus each thermal interface is thermally connected to the helium cryostat cold plate by a calibrated copper link, which acts as a fluxmeter. Pictures of the EM cooler mounted in the test cryostat are displayed in Figure 3.

Initial thermal tests campaign

The fully assembled cooler is thermally tested under the nominal conditions, i.e., with the interfaces regulated at 1.8 K and 4.9 K. A typical result is provided in Figure 4. A duty cycle of 80% is reached, slightly in excess of the predicted performance (78%). Several scenarios are possible for the recycling of the cooler, and in the case reported a double magnetization (see Figure 5) was used. The ADR stage is first magnetized at about 2 K while the sorption stage is recycled. Then as the sorption stage is cooled down by evaporative process to 300 mK, the ADR is demagnetized so that the cost of cooling this stage is not supported by the ^{3}He stage. Once at 400 mK, the remaining

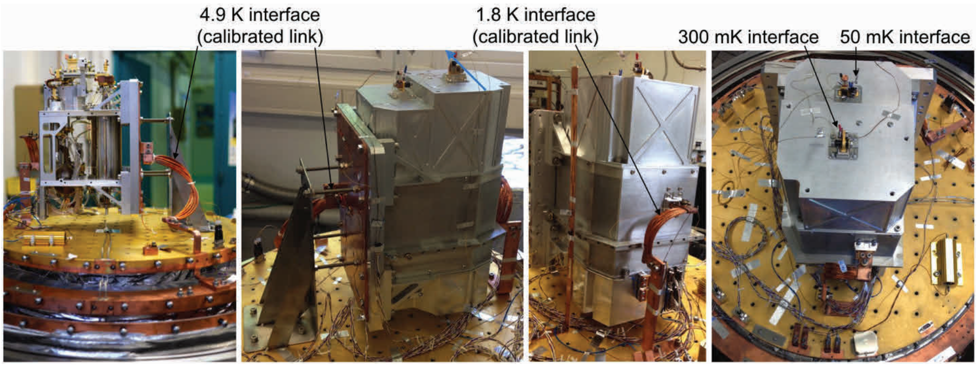

Figure 3. EM cooler mounted in the test cryostat

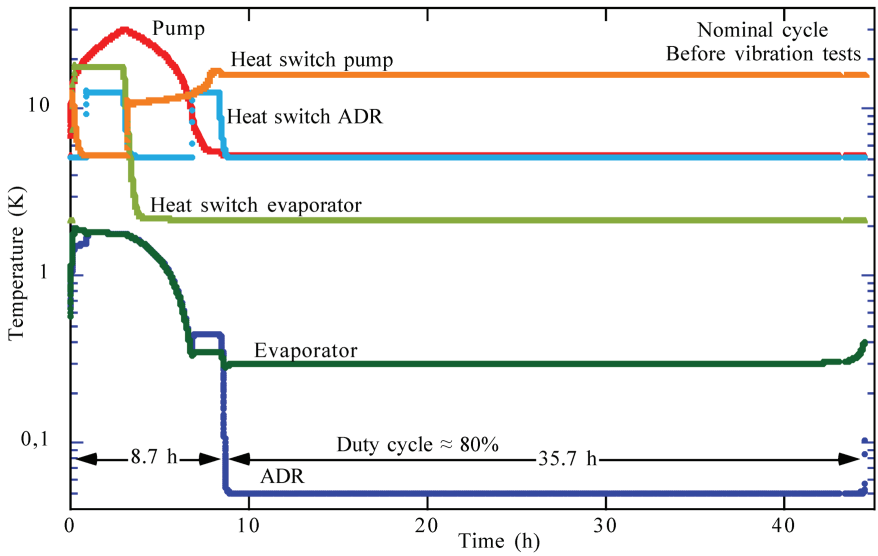

Figure 4. Typical cooler cycle, with 0.4 ∝W @ 50 mK and 14 ∝W @ 300 mK.

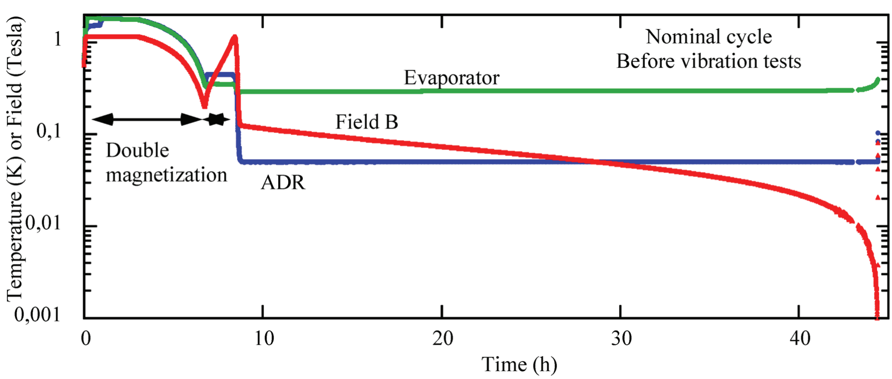

Figure 5. Typical cooler cycle: time evolution of the magnetic field

field is ramped up to about 1.1 T and the ADR is then demagnetized again to bring the salt pill to 50 mK, at which point the field is slowly reduced to keep 50 mK until the salt runs out of magnetic entropy. A few percent of the duty cycle are gained due to this recycling mode.

During the operation of the cooler, the dissipation on the two interfaces (1.8 K and 4.9 K) is monitored and controlled using a Labview® based homemade software. As mentioned the dissipations are measured in real time and the heat switch conductances are tuned accordingly. This method is very efficient but can only be used if the heat flows are measured. An alternative, previously tested on a single sorption cooler, is to produce a "thermal map" of the dissipation for heat switch conductance and sorption pump temperature. This information can then be used as an input by the drive electronic. This technique works equally well as long as the performance of the various thermal links remains the same.

As seen in Fig. 6, the dissipated powers never exceed the specified limits, i.e., 5 mW at 1.8 K and 10 mW at 4.9 K during the recycling phase, and 0.5 and 1.5 mW, respectively, during the operating phase. Additional work on the software and control electronics is currently being carried out to smooth out the behavior and to suppress the slight overshoot on the 1.8 K interface. In fact on this interface, the average dissipated power during recycling falls below the 5 mW limit.

Vibration tests campaign

The EM cooler was mounted on a vibration pot (Figure 7) and tested for each axis following:

- low sine sweep 0.5 g, 20 to 2000 Hz, 2 Oct./min
- high sine 20 g, 30 to 100 Hz, 2 Oct./min
- low sine sweep 0.5 g, 20 to 2000 Hz, 2 Oct./min
- random 13.1 g rms, 20 to 2000 Hz, 2 mn
- low sine sweep 0.5 g, 20 to 2000 Hz, 2 Oct./min

The vibration tests were successfully conducted and can be seen in Figure 8. The signatures recorded before and after each test remain fairly identical. The slight shift seen on the 50 mK interface is attributed to the accelerometer which had to be glued back. In any case no visual defect was spotted and the coil resistance of the ADR superconducting magnet was unaffected. Prior to the

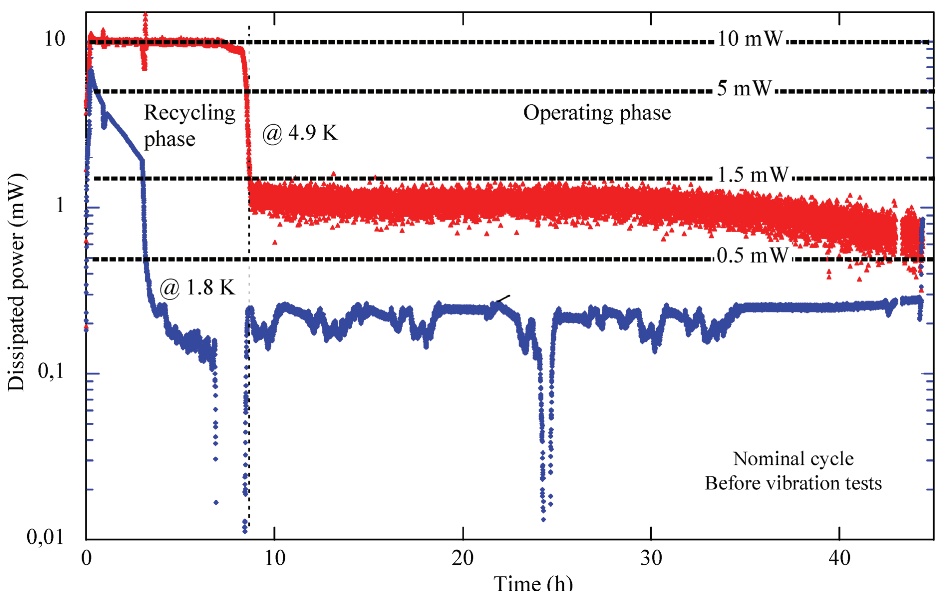

Figure 6. Dissipation of the cooler during operation

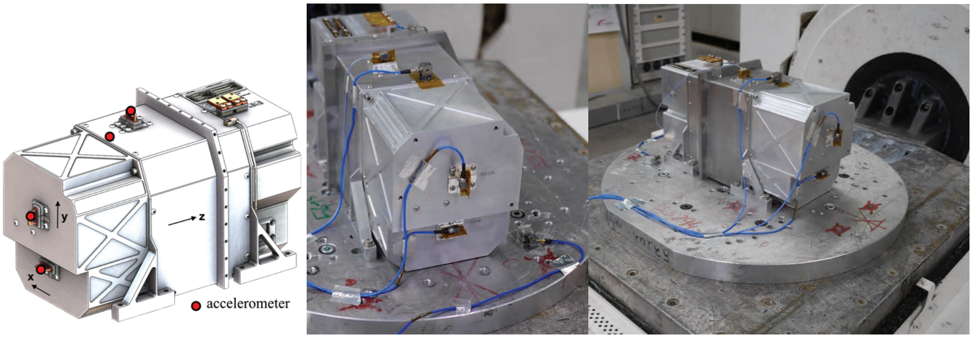

Figure 7. EM cooler ready for the vibration tests

tests, several photographic records of the interfaces and particularly of the way they were centered in their tight opening of the cover allowed us to verify that indeed the suspended masses (sorption stage and salt pill) and the thermal interfaces did not change in position. The cooler was successfully leak checked before integration in the test cryostat.

Final thermal tests campaign

In order to verify the performance of the cooler and check for any internal damage, the unit was tested again under the same operating conditions. The results did not reveal any significant differences between each set of tests.

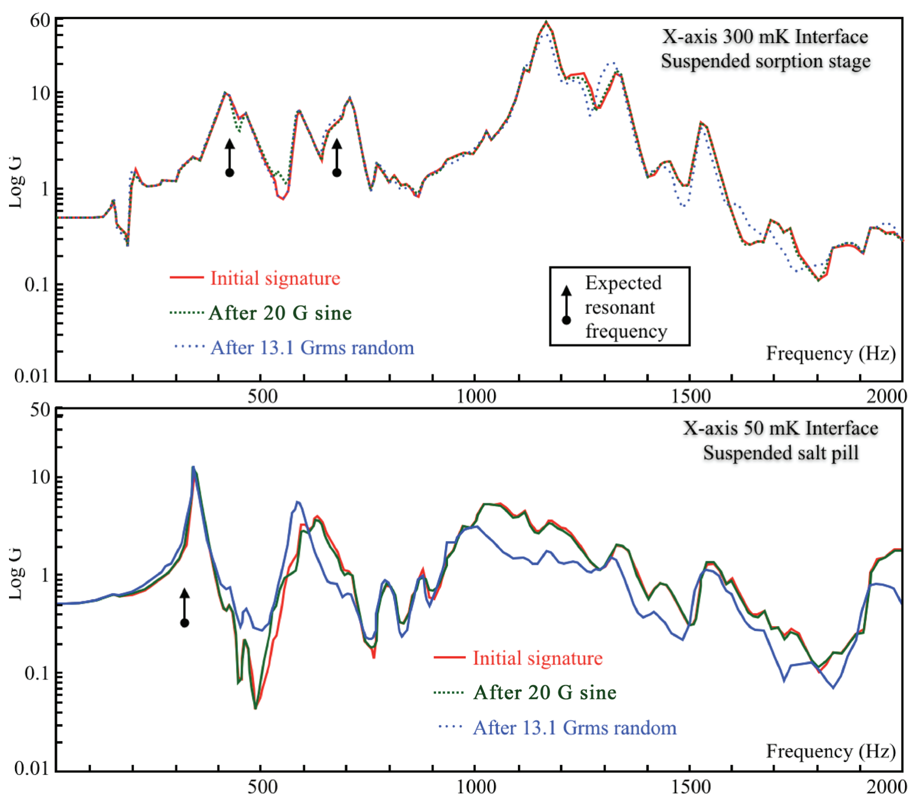

Figure 8. Example of mechanical signatures along the various vibration tests carried out

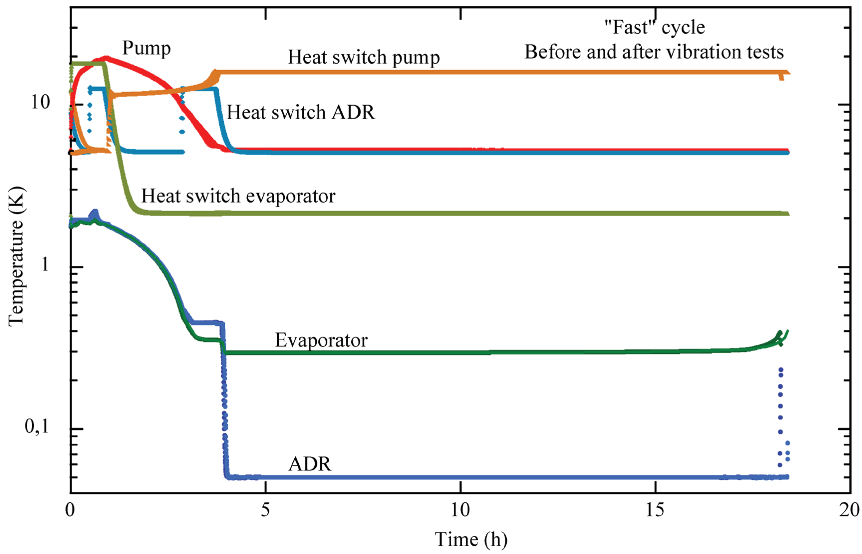

Figure 9. "Fast" cycle. Results of tests before and after the vibration tests; almost perfect superimposition

In Figure 9, we have reported what we called the fast cycle. Rather than doing a nominal test which requires 48 hours (see Figure 4), we set up a faster test which could be done overnight. In fact the cooler is flexible and can be operated over a wide range of conditions. In this case the main sorption pump is heated to 20 K instead of 30 K, and the magnetic field is ramped up to 0.6 T for the second magnetization. Note that the nominal test was done also and lead to identical results. In the results reported in Figure 9, no differences can be distinguished between the cycles obtained before and after the vibration tests. They perfectly superimpose leading to the conclusion that the vibration tests did not affect the performance of the cooler.

The cooler is currently tested under various conditions for which the interface temperatures and available resources are varied. These results will be reported in a subsequent publication. One of the goals is to improve our modeling of the cooler and to be able to better predict its performance. The current model is already reliable to better than 90%, and it can be perfected to provide a better predictions.

CONCLUSION

We have designed, built and tested an engineering model hybrid cooler comprising a 300 mK stage and a 50 mK miniature adiabatic demagnetization. This cooler was originally designed for the SPICA SAFARI instrument to provide cooling powers of 0.4 µW and 14 µW, respectively at 50 and 300 mK. This mission is under redefinition and will presented at the ESA M5 selection. The cooler went through its qualification program and has now reached TRL 6 level.

In the meantime, the X-Rays mission ATHENA (ESA Class L) has been confirmed and the sub-kelvin requirements in terms of temperature match those of SAFARI. The net heat lifts to be provided are not clearly defined at this stage but the SAFARI EM cooler is currently identified as a baseline. Due to its flexibility of operation, it can cover an extended range of operating conditions. If needed, the same design could be scaled up or scaled down to produce and qualify the new cooler to a high TRL within limited time.

ACKNOWLEDGMENT

We thank the French Space Agency (CNES) for the funding of these works. We thank Florian Bancel, Laurent Clerc and Jean Louis Durand for their expert technical work on this project.

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