Experimental results of ADR cooling tuned for operation at 50 mK or higher temperature

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Abstract. Several astrophysics missions are currently planned, with significant European participations. To reach their targeted performances, cooling down to temperature of 50 or 100 mK, depending on the instrument design is required. Multi stage Adiabatic Demagnetization Refrigerator (ADR) cooling can provide such performances and is well adapted for space. At the early stage of the mission definition various cryogenics design are considered implying different cooling requirements. A 3-stage ADR cooler demonstration model for space has been used to demonstrate and validate several operation modes. Results will be presented for a 100 mK cooling including a continuous 400 mK stage as well as for 300 mK continuous cooler. A specific focus has also been put on 50 mK temperature measurements demonstrating the tight thermal stability, well below 1 µK that can be reached with this technology.

1. Introduction
For several astrophysics mission currently in the selection (SPICA, LiteBIRD) or design phase (Athena), high sensitivity detectors are required to reach the ambitious scientific goals. To reach their target, cooling detectors to 50 or 100 mK temperature is required. For such low temperature cooling, dedicated coolers are developed to provide cooling for interface at around 2 K to 5 K. For this purpose, a three stage adiabatic demagnetization refrigerator (ADR) have been extensively qualified in the laboratory [1]. A novel material, Ytterbium Gallium Garnett (YbGG), had been proposed [2] and a new pill has been manufactured based on this material Initial experimental results have been previously described. This paper describes additional results, and especially measurements of temperature stability that demonstrates our capabilities to reach high values. In the last part a description of potential cooling cycle well adapted for astrophysics mission currently discussed is presented.

2. Design
The design of the system is based on a 3 stage ADR system, schematized on figure 1. It includes a succession of ADR stage in series and connected with thermal heat switches.
Experimentally the setup is visible on figure 2. It uses a cryostat cooled by a 4 K commercial mechanical cooler: a Cryomech PT415. The mechanical and thermal interface of the demonstrator is mounted on the main plate of the cryostat which can be thermally controlled at temperature from 2.7 K to 4.0 K or higher.

3. Recycling and thermal cycling

A measurement of a cycle is presented on the plot figure 3. The thermal recycling scheme has been well discussed in [1]. New measurements are improved over results previously presented by the author because parasitic losses likely due to microvibration in the cryostat had been drastically reduced. The interface temperature was regulated at 3.5 K. A 24 hours operation has been demonstrated with 25 µW cooling power at 1.2 K, 2 µW at 400 mK and 0.5 µW at 50 mK. The losses at this temperature stages have been measured independently with values of respectively 20 µW, 5.5 µW and 0.1 µW on the 1.2 K, 0.4 K and 0.05 K stage. Losses on the 50 mK stage are very sensitive to the cryostat supporting structure and special care has been taken to reduce this value.

Similar measurements with an interface temperature of 4.0 K and 10 µW at 1.3 K, 2 µW at 400 mK and 0.5 µW at 50 mK has been measured and are presented on figure 3.
The first phase of the cycle correspond to the remagnetization of the ADR when heat is dumped to the interface. This heat is dumped in several phases, because the first stage size is limited to reduce the total mass of the demonstrator. Measurements of power dumped on the warm interface (3.5 K) is important to plan for the integration in a full instrument. To perform these measurements, a heater has been placed on the 3.5 K to 4.0 K interface and the thermal gradient with respect to the heat applied has been measured. It is then possible to retrieve instantaneously the heat flow at the interface as function of time. The results of these measurements is presented on figure 4. The maximum heat flow is of 40 mW for a period of less than 5 minutes. The maximum heat flow can be controlled and limited if needed. The total flow through the interface, calculated with the integration of the plot has been measured with a heat rejected of 63 J or an average of 5.9 mW over 3 hours. Similar measurements has been made with a 3.5 K interface and 25 µW at 1.2 K, 2 µW at 400 mK and 0.5 µW at 50 mK with a heat rejected of 46 J which is equivalent to an average flow of 4.2 mW over the 3 hours period. The heat dissipated by the magnets and the heat switches is not measured and account to less than 1 mW. No optimization of this cycle has been made leaving room for improvements.
4. Temperature stability measurements and regulations

Great care have been put to temperature stability measurements. A new card developed in house, the ULTM50 (Ultra Low Temperature Measurement 50 mK) have been used. This card has 4 dedicated channels. The basic measuring principle is to use a synchronous detection with a 2 nA current excitation. The bandwidth can be changed from 0.5 Hz to 6 Hz allowing to observe fast thermal phenomena. Others current excitation ranges are available up to 150 nA.

The analog architecture is designed to be space compatible with a self-noise less than 2 nV/√Hz (about 0.8 µK/√Hz for thermal noise based on typical Rx-102A sensibility from Lakeshore). The cryostat has not been conceived with so sensitive measurements in mind and for some measurements the addition of a filter at cold temperature drastically reduced the noise, indicating that the main source of noise is from the RF heating on the sensor. This is also hinted by the fact that measurements on a resistor of similar value lead in this case to much lower noise than on the thermometer itself.

Measurements have been made by the ULTM50 with a bandwidth of over 1 Hz. The signal has been recorded with a sampling rate of 10 Hz and is displayed on figure 5. It is shown on this figure that the temperature is very stable, at 50.012 mK with variation of around 0.4 µK RMS.
An FFT of the signal has been computed and presented on figure 6. It shows clearly the 1 Hz bandwidth of the acquisition. The noise appears to be close to white noise lower than 1 Hz and is dominated to our understanding by noise on the sensors itself and not by the actual temperature of the device.

This temperature stability is well below the requirements for the X-IFU instruments and these results demonstrates that this level can be achieved with well mastered components.

5. Alternative demonstration for 300 mK cooling
This configuration with 3 stages is well adapted to various operation for different need. While the sizing of the demonstrator is not optimized, it makes possible to demonstrate alternative operating mode. For example, operation with 300 mK continuous cycle is possible with this configuration.
While the cycle presented on figure 7 is not well optimized, first because the stages are oversized, second because the heat switches were not optimized and finally because the algorithm has not been fully adapted to this operation, the results from these measurements is very interesting. It shows that the margin in current as seen on figure 8 is very large, demonstrating that this cooling scheme could be achieved with a much smaller cooler. Typically, the size of all the stages could be reduced to propose a prototype of less than 2.5 kg for 2 µW operation.

For some projects in discussion, high cooling power, typically over 20 µW could be requested on the intermediate stage at about 300 mK. Providing these high power with a cycle as discussed on chapter 2 and 3 has a large cost in mass. An alternative, is to use a continuous stage at 300 mK, using 2 stages for this temperature. This continuous schemas has been previously described by [3]. Operating the detectors themselves at continuous temperature of 50 or 100 mK has inherent difficulties. First, this require the use of a heat switch operating at this low temperature. Gas gap switches cannot be used because of the low vapour pressure at this temperature and therefore superconducting heat switches are usually used [4] which is less efficient and robust. Another difficulty is the strong requirements in temperature stability which is difficult to obtain during the switching operation. Typical values of over 10 µK are obtained. To overcome these limitations, we propose to use the same 3 stages design, but using 2 stages for the continuous intermediate temperature– based on YbGG and a last stage providing cooling power for several hours (typically 24 to 48). The temperature and magnetic field profiles is schematized on figure 9, but in practice the number of cycles on the first stage is much higher.
Figure 9. Schematic temperature and magnetic field variations of a 3 stage cooler with continuous 300 mK stage

Because the 2 stage operates continuously at 300 mK it can store a large amount of energy for a long period. It is therefore advantageous to design this stage to store the heat of the last stage and dump it to higher temperature over several cycles.

While not experimentally demonstrated, this solution benefits from the high maturity of single stage ADR from our previous work on hybrid cooler developments combining a sorption stage with an ADR stage[5]. This hybrid cooler has reached TRL 6. The heat switch technology is also very similar and only the use of the YbGG material, presented previously will require a mechanical validation which is not seen today as a major difficulty.

7. Conclusion and perspectives
In this paper, experimental results of a 3 stage ADR has been detailed, with in particular, 0.4 µW of cooling power at 50 mK. Based on these results, alternative cooling scheme have been devised for future space missions. To our eye, one of the most promising one is the combination of a 300 mK continuous stage with a one shot low temperature (50 mK or 100 mK) cooler stage. This gives the possibility to reach high cooling power (several 10s of µW) at 300 mK with a relatively small cooler. It is based on a 300 mK continuous stage, which is oversized to store the energy dumped from the previous stage cooler.

The noise level is well compatible with most of the mission requirements, with measurements of 0.4 µK RMS in the 1 Hz frequency range.

8. References
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Acknowledgments
This work is financially supported by CNES and CEA. We wish to thank Jean-Louis Durand for the experimental work and his expertise in the design, set up and experimental measurements. Thanks to Florian Bancel for the design of the full model and Thierry Jourdan for expertise in temperature measurements and acquisitions.