

# Qualification campaign of the 50 mK hybrid sorption-ADR cooler for SPICA/SAFARI

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**Abstract.** SAFARI (Spica FAR-infrared Instrument) is an infrared instrument planned to be part of the SPICA (SPace Infrared telescope for Cosmology and Astrophysics) Satellite. It will offer high spectral resolution in the 30 – 210  $\mu\text{m}$  frequency range. SAFARI will benefit from the cold telescope of SPICA and to obtain the required detectors sensitivity, a temperature of 50 mK is required. This temperature is reached thanks to the use of a hybrid sorption – ADR (Adiabatic Demagnetization Refrigerator) cooler presented here. This cooler provides respectively 14  $\mu\text{W}$  and 0.4  $\mu\text{W}$  of cooling power at 300 mK and 50 mK. The cooler is planned to advantageously use two thermal interfaces of the instrument at 1.8 and 4.9 K. One of the challenges discussed in this paper is the low power available at each intercept. A dedicated laboratory electronic is being designed based on previous development with a particular focus on the 50 mK readout. Temperature regulation at 50 mK is also discussed. This cooler has been designed following flight constraints and will reach a high TRL, including mechanical and environmental tests at the end of the on-going qualification campaign.

## 1. Introduction : 50 mK cooling for space applications

Following the ESA mission Herschel and Planck, both launched in 2009 and with detector temperatures respectively of 300 and 100 mK, future missions have been discussed with detector temperature requirements as low as 50 mK. These low detector temperatures are necessary to reach the targeted sensibility for astrophysics observations both in the infrared and X-ray domain. In particular two space satellites are currently being designed with instruments requiring 50 mK cooling.

First, SAFARI (Spica FAR-infrared Instrument) [1] is an instrument planned for the observation in the far-infrared (30 to 210  $\mu\text{m}$ ) in space on-board the SPICA (SPace Infrared telescope for Cosmology and Astrophysics) satellite. As part of the development of this instrument, a cooler has been designed and is being tested. The SPICA satellite and SAFARI instrument will go through high level review and proposal in the coming years.

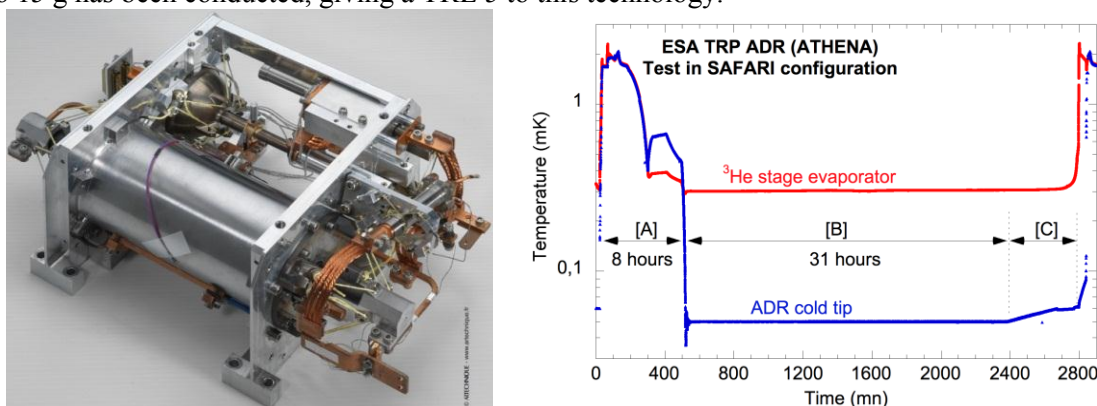
Secondly, an ambitious X-Ray Observatory satellite [2] has been selected as part of the L3 cosmic vision from ESA. For this mission, the X-IFU (X-Ray Integral Field Unit) instrument uses TES (Transition Edge Sensors) microcalorimeter with an ambitious goal of high spectral resolution (2.5 eV for  $E < 7$  keV). The detectors for the X-IFU instrument are based on the same technology as for the SAFARI instrument, and these two missions will have similar cooling needs. The cooler developed and described in this paper is therefore a valuable demonstration for the X-IFU program. Furthermore, it could be used for the demonstration model of the X-IFU instrument to validate technical choices.



Several techniques have been proposed to achieve 50 mK cooling in space, including closed cycle dilution [3], cascade of adiabatic demagnetization refrigerators (ADR) [4],[5] or the hybrid cooler described in this paper. This hybrid concept, based on the coupling of sorption cooler and ADR technology, was proposed in our laboratory several years ago and has been the object of several successful development programs. Two stages comprise this hybrid cooler: the first stage is based on our sorption coolers, heritage from the Herschel satellites [6]. Sorption cooling is extremely light and has demonstrated more than 4 years of operation in space. Because of the very fast pressure decrease with temperature of the  $^3\text{He}$  saturation curve and pressure loss in the pumping line, this technology is limited to a low temperature of about 200 mK. It is therefore completed here by a low temperature stage based on ADR. The size of this ADR stage is kept small because it is used only for the 300 mK to 50 mK cooling and therefore requires only relatively low magnetic field, on the order of 1 T. ADR can reach 50 mK or lower and is particularly well adapted for space because of the absence of fluid and moving parts, making it gravity independent. The coupling of these two technologies leads to the development of a lightweight and reliable 50 mK cooler perfectly adapted for space instrument integration.

Sorption cooler operates with a succession of cold – or operating – phase and a recycling phase during which helium is condensed. This type of operation is called one-shot, as opposed to continuous cooler which provides a constant cold temperature. The hybrid cooler operates also in a one-shot mode. During the recycling phase, in addition to the condensation in the sorption cooler, the ADR is magnetized and its heat dumped to the sorption or higher temperature interface. The duration ratio of the cold phase to the total time is called duty-cycle. This duty cycle is a function of the efficiency of the cooler, of the available heat lift at the interface and of the nominal cooling power. It is on the order of 75% for our current design, allowing for a cold phase of more than 36 hours with a recycling time below 12 hours. Continuous cooling with this technology is possible but requires more complex design and is not preferred in the project described here.

A first prototype of this hybrid 50 mK cooler based on the combination of sorption and ADR 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 (Figure 1). This prototype with a weight of 5.8 kg demonstrated a cooling of  $1\ \mu\text{W}$  at 50 mK and  $10\ \mu\text{W}$  at 300 mK. The cooler successfully reached the targeted specification of 24 hours cold for less than 8 hours recycling, i.e. a 75 % duty cycle. Following thermal tests, a mechanical validation with acceleration of up to 15 g has been conducted, giving a TRL 5 to this technology.



**Figure 1.** Pictures of the IXO hybrid cooler for 50 mK cooling and experimental results

Based on this successful development and on the knowledge gained during this work, an advanced hybrid cooler depicted in Figure 2 and Figure 3 has been designed to fulfill the requirements of the SAFARI instrument. This paper summarizes the specification and performances of this cooler including experimental results. Thermal stability is a crucial parameter for sensitive detectors requiring notably low noise and low temperature measurements for which a dedicated work on the design of the read-out electronic is described in this paper.

## 2. Specification and design

The specifications of this hybrid cooler have been elaborated based on the requirement for the SAFARI instrument. The cooling power is  $0.4 \mu\text{W}$  at 50 mK and  $14 \mu\text{W}$  at 300 mK. Heat rejected at the interface (maximum during peak) must be below 5 mW at 1.8 K and 10 mW at 4.9 K. A duty cycle above 70% was demanded for the SAFARI design and our calculation estimated that over 75% could be reached. The mechanical design has been done to support vibration level of 21 g RMS and 120 g static. A more detailed description of the cooler design parameters including mechanical and magnetic calculation can be found in [7]. The total mass of the cooler is by design 5.1 kg, including 0.6 kg of covers. These covers, visible on Figure 4, are used for electromagnetic shielding and mechanical protection.

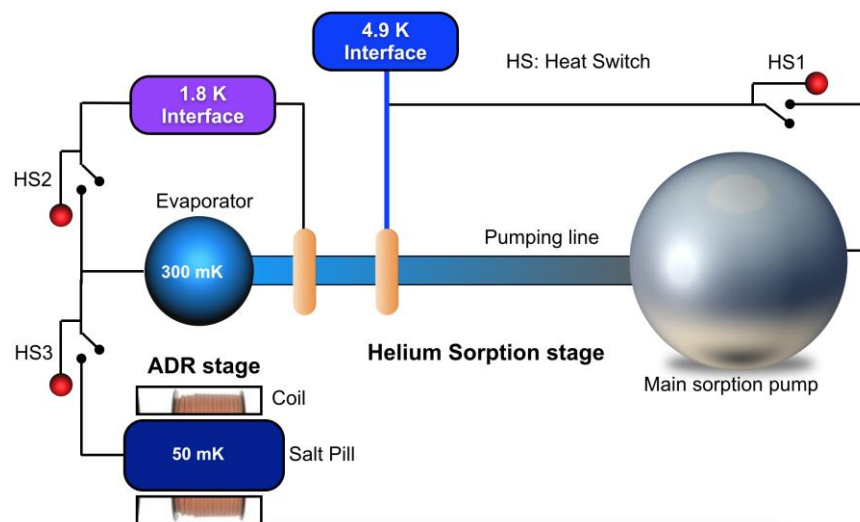


Figure 2. Safari hybrid cooler thermal design

## 3. Full cooler assembly

During manufacturing and assembly preliminary validations have been conducted to ensure the performances of the final prototype. These validations which include for example heat switch performances, coil operation and individual components vibration tests, are not detailed here. The results presented thereafter focus on the final performances of the cooler shown in Figure 4.

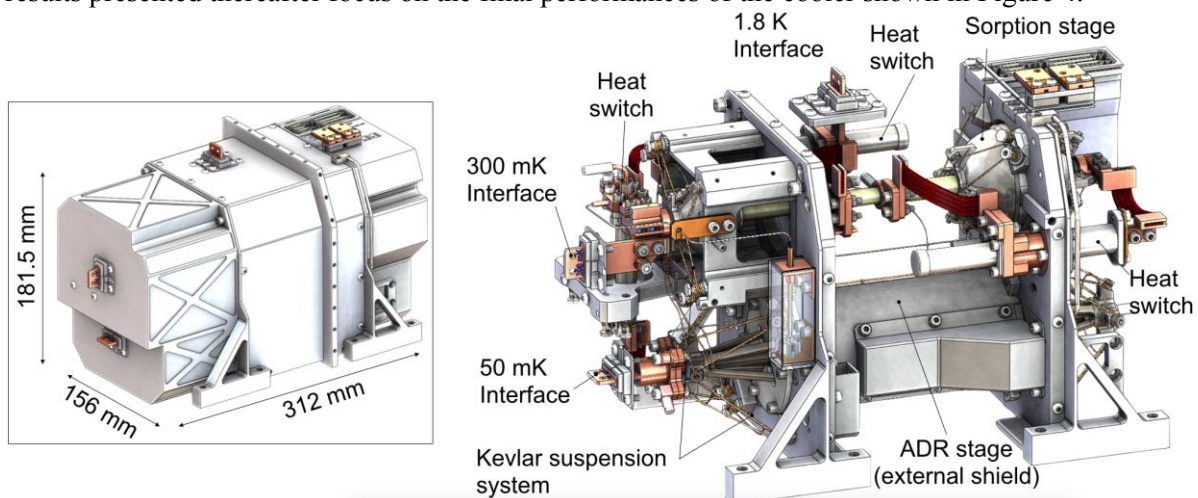
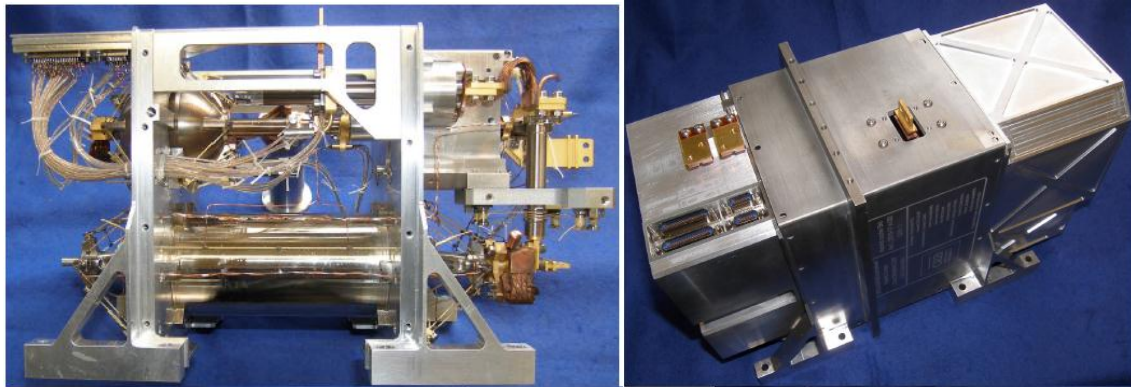


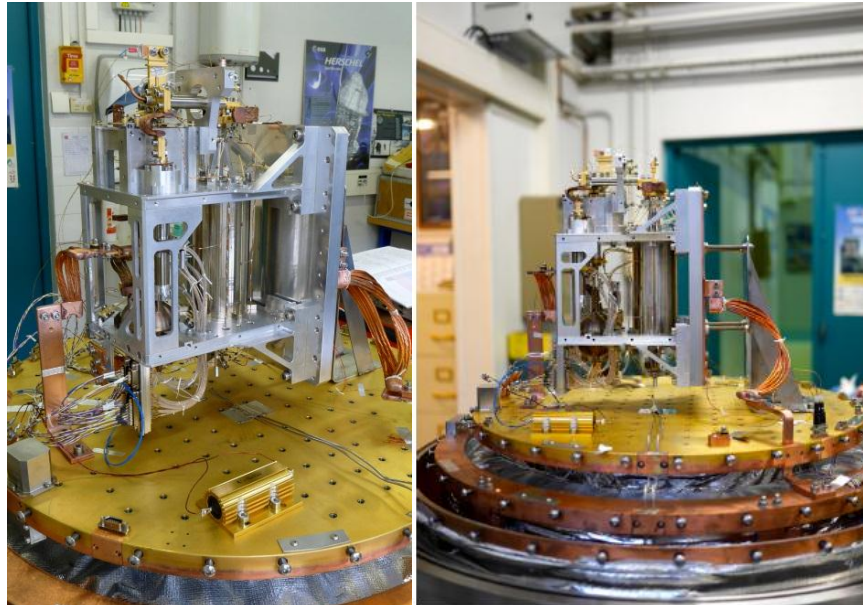
Figure 3. Safari cooler design





**Figure 4.** Cooler with cover off and on

A dedicated test cryostat has been previously designed for this test campaign. It includes two levels of temperature (1.5 and 4.2 K) and gives a possibility to operate for close to 10 days at 1.5 K as has been described in [7]. This long duration is of great interest to demonstrate duty cycle over repeated number of cycles.



**Figure 5.** Testing of the cooler in the cryostat

### 3.1. Cooler operation

As discussed earlier, the operation of the cooler comprises a recycling phase and an operating phase. The succession of these phases is clearly visible in

Figure 6. During recycling, the pump of the sorption cooler is heated to 30 K during which the helium is condensed in the evaporator. The ADR is magnetized and the magnetization heat is evacuated through the evaporator. During the cycle visible below, the ADR is magnetized twice to slightly improve the duty cycle. The gain of this double magnetization in this configuration is only of about 10 minutes as was experimentally verified and therefore could be simplified. The recycling phase and operating phase can happen successively with no limitation. Depending on the operation of the instrument on the satellite, a pause could also occur between each full cycle.

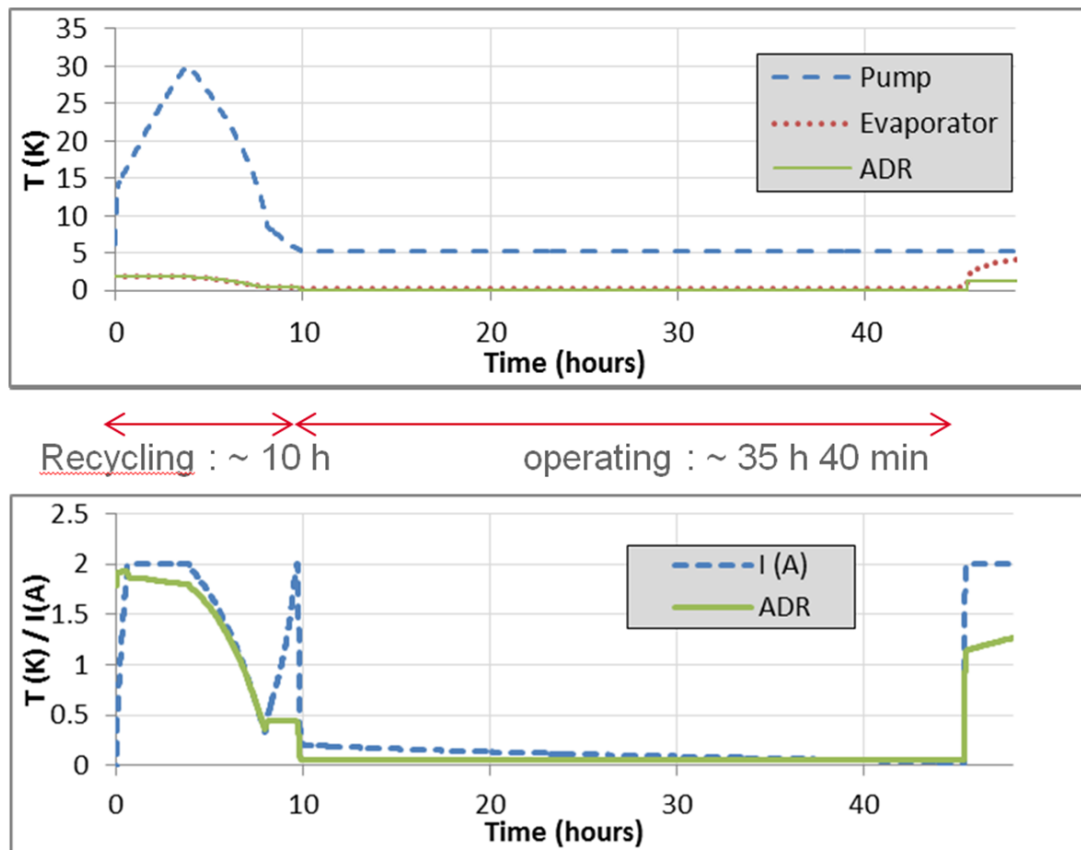


Figure 6. Recycling and operating phase of the cooler in a standard cycle

### 3.2. Recycling and control operation

The cooler is operating simulating a space environment where the warm interfaces (1.8 K and 4.9 K) are in fact cold points of Joule-Thomson coolers. More details on the potential architecture of satellites are discussed in [9]. The power available at each of these interfaces is therefore strictly limited. Depending on the Joule Thomson designs, peak loads for short duration of time might be acceptable, but we chose to demonstrate that operation is possible without peak load and with power below the nominal power at all time (Figure 7). For this demonstration, the heat loads rejected at the two interfaces are measured continuously using calibrated copper braid and regulation loop. The control software regulates the various heaters of the sorption cooler or the ramp of the ADR to insure targeted values are not exceeded.

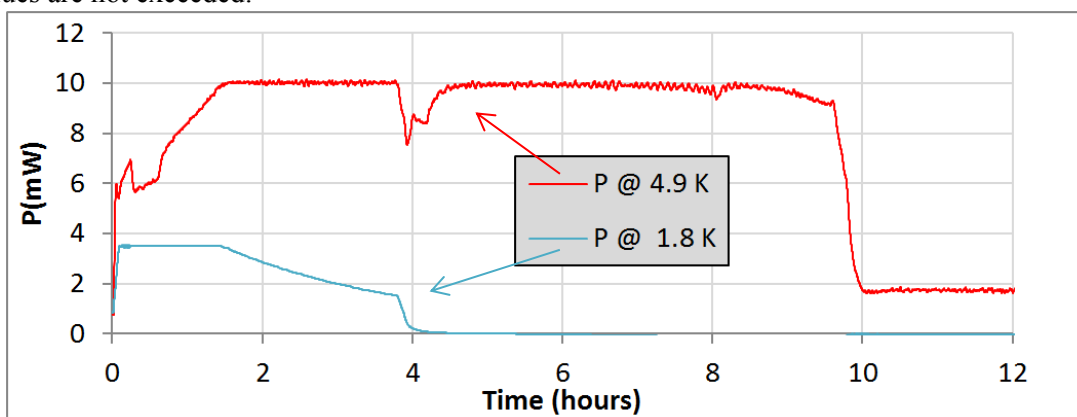


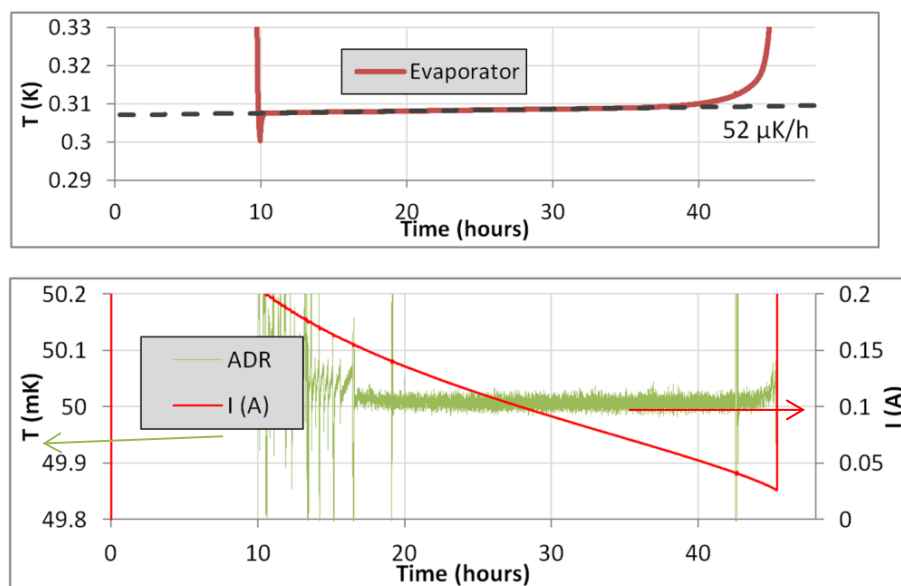
Figure 7. Heat load on both interfaces during a standard recycling phase

#### 4. Thermal stability and thermometers read-out

An important parameter for achieving high sensitivity of astrophysics operation is the thermal stability of the focal plane array. Stability depends on the stability of the cooler itself, on the thermal link between the cooler and the focal plane, on the heat capacity and on the origin of the perturbation. A study will be done for both the SAFARI instrument and the X-IFU instrument to best optimize the operation. The thermal stability is obtained thanks to a precise control of the ADR field demagnetization. The thermal stability depends on the resolution of the control of the ramp of the ADR current supply and on the stability of the thermometers read-out. At first order, for a thermal stability of  $1 \mu\text{K}$ , the ADR power supply must have a ramp rate resolution of  $1 \mu\text{T/s}$  which can be translated in a voltage resolution of  $80 \mu\text{V}$  (coil  $L = 40 \text{ H}$ ,  $2 \text{ Amps/Tesla}$ ). In the short term, our goal is to have temperature stability better than  $0.8 \mu\text{K}/\sqrt{\text{Hz}}$  at a frequency on the order of  $1 \text{ Hz}$ .

##### 4.1. Cold phase temperature stability

During the cold phase, the evaporator temperature drifts at a rate of about  $50 \mu\text{K} / \text{hour}$  which is comparable to the  $20 \mu\text{K}/\text{hour}$  measured on the Herschel coolers. The noise measured on the evaporator temperature is below  $\pm 1 \mu\text{K}$  and depends on our temperature read-out system which has not been optimized for these measurements. By controlling the current, the ADR temperature is regulated at  $50 \text{ mK}$  with no measurable drift. Using a Keithley 2440 power supply with resolution of  $5 \mu\text{V}$ , thermal stability better than  $30 \text{ nK rms}$  is theoretically possible. Experimentally, the noise is limited by the temperature read-out system to about  $4 \mu\text{K RMS}$ . To improve this value and fit with space constraints, we are developing a very low noise lab electronic dedicated to this measurement.



**Figure 8.** Evaporator temperature and ADR current and temperature during the cold phase

##### 4.2. Specifications of read-out electronics

The development of the  $50 \text{ mK}$  electronic read out started with the SAFARI project to guarantee a high thermal stability of about  $0.8 \mu\text{K}/\sqrt{\text{Hz}}$  required for the instrument. A goal of a noise below  $0.1 \mu\text{K}$  is chosen for the temperature measurements electronics. RuOX sensors are used for temperature measurement at about  $50 \text{ mK}$  because of their low sensitivity to magnetic field and ability to withstand vibration as well as their good sensitivity in this temperature range. A typical resistance of  $70 \text{ k}\Omega$  (and a maximum of  $100 \text{ k}\Omega$ ) at  $50 \text{ mK}$  and a sensitivity of  $5 \Omega/\mu\text{K}$  is considered for the electronic development. A self-heating of the sensor limited to  $100 \mu\text{K}$  (about  $0.2 \text{ pW}$ ) sets the current source to  $2 \text{ nA}$ . With all these parameters the noise of the entry preamplifier must stay below about  $2 \text{ nVrms}$  that will be the goal of these developments.

### 4.3. Analog architecture

To minimize the noise, a synchronous detection is used with a sinusoidal modulation centered at 120 Hz and a bandwidth setting of 1 Hz. The bandwidth of the read out electronic will be defined later. The global circuit includes a high gain, very low noise and high impedance (at least 10 M $\Omega$ ) amplifier. The amplifier is divided into 2 stages.

The first, called the preamplifier based on IF3602 and OP270, is the most sensitive. The gain, around 100, is realized thanks to transistors which have a big dispersion on the gate source cutoff voltage. To compensate the dispersion, the preamplifier is designed to be self-biasing. The second, with a gain of about 200, must include an offset compensation due to the preamplifier and must limit the bandwidth down to 200 Hz.

For the current source, a FPGA and a DAC are used to synthesize a sinusoidal waveform from a table of points. A symmetric structure is used to avoid common mode disturbances.

The baseline for the analog to digital conversion is done by the ADS7809 (16 bits). Demodulation is realized by a FPGA (Xilinx Spartan 6 for lab tests). This ADC doesn't permit us to reach specification due to an insufficient number of bits. To achieve the desired sensibility of the electronics, an ADC with at least 18 bits must be used. To our knowledge, no such space qualified components are available. To demonstrate the operation of our electronics, a 24 bit ADC will be used during the initial phase.

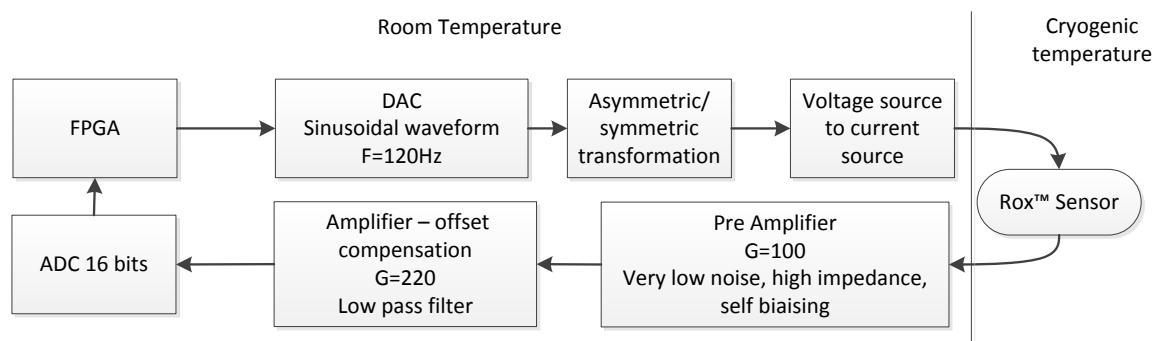


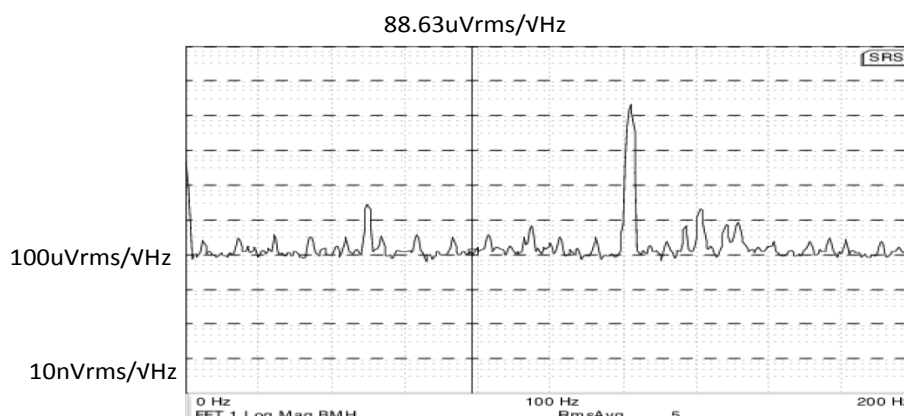
Figure 9. Analog architecture

### 4.4. Experimental results

The noise of the signal from the entry of the ADC when a short circuit is applied is about  $28 \mu\text{V}/\sqrt{\text{Hz}}$ , i.e.  $1.4 \text{ nV}/\sqrt{\text{Hz}}$  at the entry of the preamplifier which is lower than the goal of  $2 \text{ nV}$  and equivalent to a temperature noise of about  $0.15 \mu\text{K}/\sqrt{\text{Hz}}$ . This noise in the short circuit configuration is the intrinsic noise of the electronic chain. Measurements at 300 K and 4 K with a resistance of  $61.9 \text{ k}\Omega$  and 15 ppm have also been done at the entry of the ADC. As expected, the thermal noise (Johnson noise) was dominating all the measurements. Figure 10 shows a noise about  $75 \mu\text{K}/\sqrt{\text{Hz}}$  i.e. about  $3.7 \text{ nV}/\sqrt{\text{Hz}}$  corresponding to the thermal noise at 4 K. The analog chain has been validated thanks to short circuit measurements which demonstrated its compatibility with the specifications. Measurements at 50mK are necessary to confirm these results and to test the numeric chain (demodulation and filtering). They will be conducted in the coming month.

## 5. Conclusion : ready for operation

The engineering model of a hybrid sorption-ADR cooler has been thermally tested. Performances are in close agreement with our previous prediction and well above the specification for this cryostat. Operation with various operating conditions (nominal power, interface temperatures ...) have been measured which validate our thermal numerical model. In the coming month, a vibration campaign is planned which will bring to 6 the TRL of this cooler. Two EM coolers are now available allowing for a validation of operation over a wide range of operating parameters. Our modelling and simulation have been confirmed allowing for a reliable prediction of performances.



**Figure 10.4** K  
measurements FFT

Thermal stability at the 50 mK interface has been demonstrated with a noise of around 4  $\mu$ K RMS limited by the stability of the temperature read-out electronics. To improve this, we are developing an in-house and space compatible electronic for which the noise of the analog chain will contribute to less than 0.4  $\mu$ K RMS. The numerical conversion will be implemented in the coming month to reduce the noise level to below 0.8  $\mu$ K RMS.

## 6. Acknowledgement

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