

# International Conference on Space Optics—ICSO 2008

Toulouse, France

14–17 October 2008

*Edited by Josiane Costeraste, Errico Armandillo, and Nikos Karafolas*



## *Space cryogenics at CEA-SBT*

*Lionel Duband*

*Ivan Charles*

*Jean-Marc Duval*

*Eric Ercolani*

*et al.*



International Conference on Space Optics — ICSO 2008, edited by Josiane Costeraste, Errico Armandillo, Nikos Karafolas, Proc. of SPIE Vol. 10566, 105660A · © 2008 ESA and CNES  
CCC code: 0277-786X/17/\$18 · doi: 10.1117/12.2308267

## SPACE CRYOGENICS AT CEA-SBT

Lionel DUBAND, Ivan CHARLES, Jean-Marc DUVAL, Eric ERCOLANI, Philippe GULLY, Nicolas LUCHIER, Thomas PROUVE and Pierre THIBAUT\*

*Service des Basses Températures – Institut Nanosciences et Cryogénie - CEA Grenoble, 17 rue des Martyrs 38054 Grenoble FRANCE. E-mail: lionel.duband@cea.fr.*

*\* Université Joseph Fourier, Grenoble FR*

### ABSTRACT

The “Service des Basses Températures” (SBT) of CEA Grenoble has been involved in space cryogenics for over 20 years now. In fact a dedicated laboratory was created within SBT to carry out these developments, the “Cryocoolers and Space Cryogenics” group, which comprises about 20 persons as of today. Various cryocoolers have been developed in the past and our fields of activity focus now on four main technologies: sorption coolers, multistage pulse tubes, adiabatic demagnetization refrigerators (ADR), and cryogenic loop heat pipes. In addition work on two new concepts for ground based dilution refrigerators is also ongoing. Finally developments on various key technologies such as the heat switches, the suspension or structural systems are also carried out. These developments are mainly funded by the European Space Agency (ESA) or by the Centre National d’Etudes Spatiales (CNES).

For most of these systems the common feature is the absence of any moving parts or any friction, which guarantees a very good reliability and make them very good candidates for space borne instruments requiring cryogenic temperatures.

In this paper we give an overview of these developments with a particular focus on the sub Kelvin coolers. Based on the HERSCHEL heritage for which we developed the flight sorption coolers, we are now proposing an original concept featuring the association of a 300 mK sorption unit with a miniature adiabatic demagnetization refrigerator. This combination will allow to provide temperature as low as 50 mK with a system weighting less than 5 kg. This development may have direct application for the XEUS and SPICA missions.

### 1. INTRODUCTION

The current trend in space cryogenic is the suppression of liquid cryogen cryostat. Indeed this very simple technique leads to heavy reservoirs and structures and by essence limits the mission duration. Thus in the range from ambient down to liquid helium temperature, liquid cryogenics are now replaced by long life mechanical coolers. However this new philosophy comes with a number of technical challenges.

In the first place multistage cryocoolers must be available whenever temperature below typically 50 K

are required since single stage system are roughly limited to 50 K. Not only it is more efficient from a thermodynamic point of view, but several level of temperatures will in general benefit the thermal architecture. They can be used to shield the radiative loading, to thermally ground the wires, pipes and/or to cool various equipments at the desired temperature. They need to be robust, reliable with user friendly interfaces. It also allows to use a heat intercept (when available) on the first stage to extract part of the heat generated by the second stage.

Secondly for mechanical coolers the interface is usually a gold plated copper block with limited surface area, which can pose the problem of the heat transport whenever the component to be cooled is not in a close location. In the case of a liquid cryostat the low temperature interface is in general large and if necessary liquid can be extracted to provide cooling at remote locations. In addition the cold vapor can easily be routed through pipes and a large fraction of this enthalpy can be used for cooling.

Thirdly the mechanical coolers feature a limited cooling power and in certain case cannot accept large peak powers. In general this is not the case for the liquid cryostat for which a large number of cold joules are available (latent heat) and thus can accommodate for peak power (at the cost of autonomy reduction of course). Consequently it is necessary to come up with clever thermal architectures in which all available cooling sources are used in order to optimize the heat dissipation at each temperature stage.

The developments carried out at SBT cover most of these aspects. There are a number of other constraints (induced vibrations, drive electronic, ...) that will not be developed in this paper.

### 2. MECHANICAL CRYOCOOLERS

Development work on mechanical coolers for space application began at CEA-SBT in 1987 with the design and test of a Vuilleumier and double stage Stirling coolers [1]. The cold fingers as well as the pressure oscillators were using hydrodynamic gas bearings for the sustentation of the moving parts.

In the meantime in the early nineties a significant breakthrough was achieved in the cryocoolers development by the emergence of the pulse tube (PT) concept. Similarly to Stirling coolers, this technology

requires a pressure oscillator to generate a pressure wave, but it allows for the design of a cold finger with no moving parts. This is obviously a very attractive feature, which allows for easier manufacturing and integration, lower level of induced vibrations and higher reliability. Both theoretical and experimental aspects have been studied at SBT and our area of investigation in pulse tube technology is widely extended. Indeed, we have acquired a good knowledge in modeling and a large experience in designing either through internal developments or through industrial partnership.

For the low frequency pulse tube "Gifford-MacMahon like" operating at maximum frequencies of a few hertz, SBT has developed a large number of coolers, single or multi-staged, with ultimate temperature and cooling power ranging from 2.5 K - 600 mW at 4.2 K to over 100 W at 80 K. Although some developments are still ongoing, the team is focusing on the small, high frequency "Stirling like" pulse tube suitable for space or ground applications.

SBT was awarded several ESA contracts on pulse tube to develop the so called "second generation" space cryocooler. These contracts have lead to some major improvements and as a result to the production of very efficient systems [2,3]. As a matter of fact one of the latest pulse tube developed with Air Liquide under an ESA contract, the so called LPTC: Large Heat Lift Pulse Tube Cooler [4], is currently the baseline solution for the Meteosat third generation satellite. In addition two pulse tube cold fingers have been transferred to industry for ground applications (Thales BV) [5]. Some of the cold fingers developed in the 50-80 K temperature range are depicted on Fig.1, 2 and 3.



Fig.1. Miniature PT (ESA). U shape and in-line version (1.2W@80K)

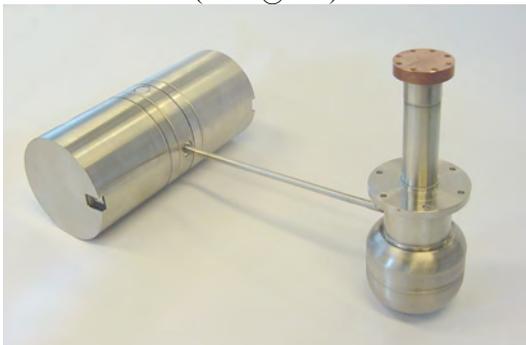


Fig. 2. Technology transfer to Thales BV (NL)  
Two systems: 4 W @ 80 K / 1 W @ 80K



Fig.3. LPTC (2.3W@50K) (ESA contract)

Several recent developments are focusing on multistage pulse tube. This architecture offers advantages both for high temperature cooling (50-80 K) and for low temperatures (~15 – 50 K). At high temperature where single stage pulse tubes are also available, multistage ones offer the advantage inherent to the availability of two levels of temperature. These can be used for cooling detectors at different temperatures as it is foreseen on SIFTI for example. It could also be used to cool optics for missions requiring LWIR detectors. Multistage cold sources can also be benefic for clever cryostat design. It is possible to strongly reduce the thermal loads on the coldest stage by intercepting them on the first stage. This leads to a strong reduction of cryocoolers power consumption at system level and as a consequence to mass saving (batteries / solar panel). To fit these objectives, CNES is funding the development of a two stage temperature pulse tube cold finger able to remove 2 W at 70 K plus 6 W at 140 K simultaneously with less than 160 W of electrical power. This level of performance has already been achieved at SBT[6].

Multi stage architecture is also used to extend the operating temperature toward lower temperature. For missions requiring temperature lower than 4 K and an extended autonomy – forbidding the use of helium bath -, the use of several cryocoolers in cascade to pre-cool the latest stages is necessary (see Planck mission). Multistage pulse tube is a good candidate to provide cooling power in the 15K-20 K to pre-cool the next stage (Joule Thomson cooler).

The missions requiring very low temperature are usually set in the deep space and can benefit of efficient passive cooling with radiation shields. Multistage pulse tube using passive cooling has been developed in the framework of an ESA contract (GSTP with Air Liquide in partnership with SBT). Recently, temperature lower than 15 K and a cooling power of 300 mW at 20 K have been achieved with a laboratory prototype pulse tube using a precooling stage at 80 K and supplied with 100 W of mechanical power [7]. Internal development

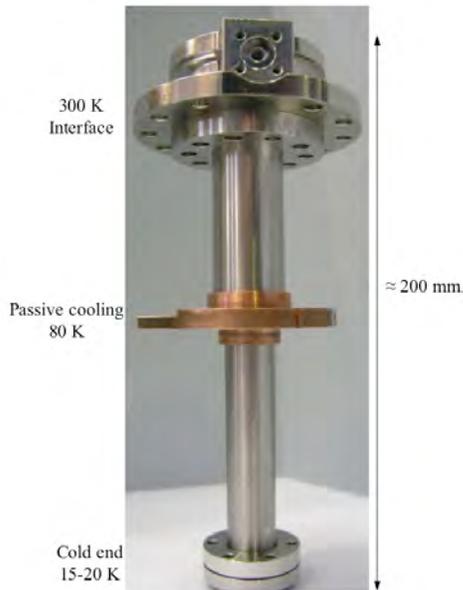


Fig. 4. Low temperature coaxial pulse tube

### 3. SUBKELVIN COOLERS

#### 3.1 Sorption coolers

For low temperature cooling (sub-Kelvin), SBT has developed numerous adsorption Helium coolers. Several of them featuring specific design for zero-g operation have been flown. These coolers achieve sub-Kelvin temperature (300 mK and 800 mK respectively for helium 3 and 4) with autonomies ranging from 1 day to 2 weeks for typical net cooling power ranging from 10 to few hundred of micro-watts [9].

In addition we have designed and space qualified gas thermal switches suited for the cyclic operation of this type of adsorption cooler. Multistage sorption coolers for ground based applications have also been developed. A double stage sorption unit has been coupled to our 4.2 K pulse tube cooler to be the first 300 K – 300 mK cryogen free system.

Several feasibility studies have also been undertaken for CNES on cooling applications for space. These studies include for instance a closed cycle Joule Thomson cooler using Nitrogen as cycle gas and adsorption/desorption compressors.

Finally SBT was selected to supply the flight models (sorption coolers) for two instruments, SPIRE and PACS, onboard the HERSCHEL satellite. Both instruments feature detectors operating at 300 mK. This program included the design, fabrication and

characterization of eight models, two structural, two qualification, two flight and two spare models. The flight models successfully went through the acceptance program and were delivered in 2004 and 2005 [10]. The table hereafter summarizes the performance of the SPIRE flight model cooler as Fig. 5 displays the PACS flight model of this sorption cooler

Table 1: Performance versus requirements for the SPIRE flight model cooler

Main Requirements	Results
Proof pressure test and leaktightness	2 mn at 20.3 MPa $10^{-10}$ mB.l.s <sup>-1</sup>
Recycling time < 2h	OK
Autonomy under 10 $\mu$ W applied load : no less than 46 hours	69 h 5 mn
5 J of gross cooling at 300 mK	5.3
12/14 $\mu$ W maximum parasitic load	11.3
10 $\mu$ W net heat lift at 290 mK	277 mK
Energy per cycle $\leq$ 860 J	927*
Mechanical stiffness (vibration tests)	Passed
Cleanliness 300-400 ppm range	150.4
Mass $\leq$ 1800 grams	1748 gr
Size $\leq$ 230 x 100 x 100 mm	OK

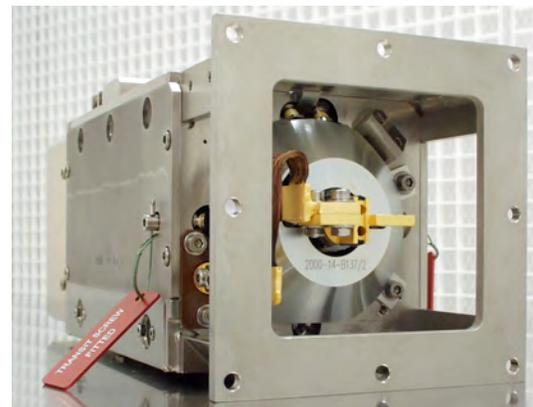


Fig. 5. Flight model sorption cooler of the HERSCHEL Satellite

Additionally SBT was also in charge of the development and supplying of a flight model gas gap heat switch for the HFI instrument onboard the Planck Satellite (Fig. 6).

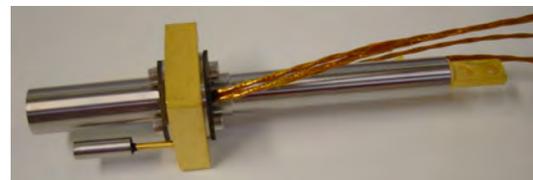


Fig. 6. Gas Gap Heat switches( PLANCK Satellite)

Helium multistage systems allow to operate from a 5 K heat sink. In this case a first <sup>4</sup>He sorption stage is used to condense the second stage (<sup>3</sup>He). A space compatible version of a double stage unit (Fig. 7) was actually

demonstrated in the framework of an ESA contract. It should be noted that we could propose now a more clever design to gain on the integration aspect. Another interest of the multistage systems is the improvement of the ultimate temperature. Indeed the upper stages can be used as heat intercept and as a matter of fact we have demonstrated temperature as low as 204 mK.

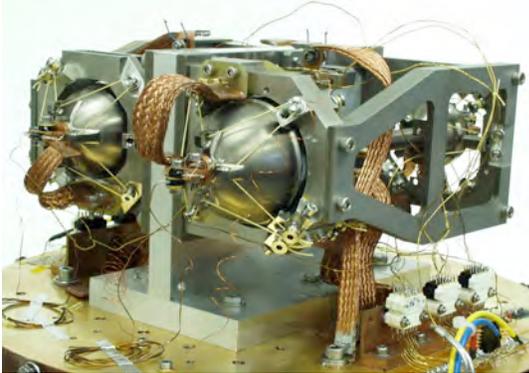


Fig. 7. Prototype of a space borne double stage helium sorption cooler

In summary sorption technology offers attractive features for space applications in the Sub-Kelvin temperature range. Among the current technologies down to 200 mK, adiabatic demagnetisation or dilution refrigerator, it is certainly the simplest in terms of interface and operations, and has the smallest mass and volume. Concerning the drawbacks relatively poor thermodynamic efficiency with regards to Carnot due to the heat of adsorption, and one shot operations can be noted.

Two lines are currently followed on this technology. The first one deals with the operation of helium sorption coolers with mechanical coolers. Indeed as mentioned it is expected that for several future space missions the liquid cryogen tank that lead by essence to lifetime-limited mission will be replaced by a combination of active coolers. In this case the challenge is to make use of all heat sinks available to deal with the peak powers generated during the sorption cooler recycling. Although there is no major showstopper this operating mode has to be demonstrated.

The second objective is to lower the operating temperature. Indeed a practical limit for these systems is 200 mK. Thus we are proposing a simple concept featuring the association of a miniature ADR with a sorption unit. This will allow to lower this temperature down to 50 mK or below. The main benefit of this concept in comparison with multistage ADR is the fact that this ADR stage is magnetized at 300 mK and thus requires only a limited field which directly impact the mass, size, energy stored, current leads, etc... This concept can also be used to provide continuous cooling at 300 mK by using the ADR stage as a thermal buffer while the sorption cooler is recycled. This shall be

demonstrated in the near future in the framework of a CNES funded development.

### 3.2 Adiabatic Demagnetization Refrigerator

Several future scientific space missions are asking for very low temperatures outside the range of helium sorption cooler (for instance the XEUS or SPICA missions currently feature temperature down to 50 mK). Consequently SBT decided to put efforts on the design and the building of refrigerators able to cool down below 100 mK. In that respect a program on Adiabatic Demagnetization Refrigerator (ADR) was initiated. ADR is a very efficient technology able to cool down to a few milliKelvin. Moreover, it is gravity independent and has no moving part. It fulfils the main reliability requirements of space missions.

Several ADR can then be chained to cover an extended temperature range. As a rule of thumb, one can assume a ratio  $T_{hot}/T_{cold}$  of 5 for each ADR stage at low temperature. However one of the drawbacks is that the higher the magnetization (heat sink) temperature, the higher the magnetic field needed for a given autonomy for a given salt quantity. These high fields will in turn mean heavy coils and/or high current, shielding, high current DC power supply in the warm electronics and large current capacity within the cryoharness. This is further aggravated when considering the support structure: a heavier component to be mechanically held certainly requires a substantial support structure. And the support structure has a direct impact on the parasitic thermal loads and thus on the performance. For starting temperature in the 2 K range or above, these constraints can be very penalizing for this solution.

In order to overcome these “problems” and to save up mass an alternative approach to the multistage ADR system is proposed by CEA-SBT. In this approach the most demanding stage in terms of mass (first ADR stage) is replaced by a  $^3\text{He}$  sorption cooler that is substantially lighter than the ADR. As an example the HERSCHEL sorption cooler heart weights less than 300 grams. Then from this 300 mK stage, only one ADR stage is required to achieve temperature lower than 50 mK.

A first prototype has been build (see Fig. 8). For laboratory purpose it uses a double stage sorption cooler and the whole system can be operated from 4.2 K.

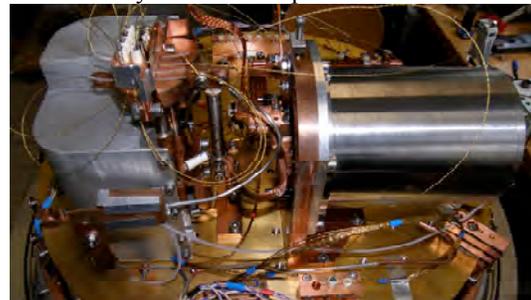


Fig. 8. Miniature ADR prototype

The ADR stage features an active compound made of Chromium Potassium Alum (CPA) encapsulated in a pill, and a dry superconducting coil made of Niobium titanium wires. The pill prevents the dehydration of the CPA salt. It is suspended within the coil mandrel using Kevlar cords, and is thermally connected to the 300 mK upper stage via a Helium three gas-gap heat switch. This prototype has demonstrated temperatures below 20 mK [11]. Obviously by using two ADR stages in serie it is also possible to provide continuous cooling at 50 mK for instance.

### 3.3 Application to future space missions

As mentioned this concept can have direct application for the XEUS and SPICA/SAFARI mission. In preparation of the XEUS mission CEA-SBT has been awarded an ESA contract to develop an engineering model of a 50 mK continuous system operated on two heat sinks, 2.5 K and 15 K. Recently ESA, JAXA and NASA joined together and decided to merge the ongoing XEUS and Constellation-X efforts to develop an international X-ray Observatory (IXO). The requirements on the cooling solutions and the selected technologies are not clear at this stage.

SPICA, a Japanese led mission, is part of the JAXA future science program and is planned for launch in the horizon 2015-2020. SPICA will perform imaging and spectroscopic observations in the 5 to 210 mm waveband. The SPICA payload features three instruments, including SAFARI which will be developed by a European based consortium. As already mentioned SPICA's distinctive feature in comparison with HERSCHEL for instance is to use an actively cooled telescope down to 4K. In addition SPICA is a liquid cryogen free satellite and all the cooling will be provided by radiative cooling (L2 orbit) down to 30 K and by mechanical coolers for lower temperatures. The satellite will be launched warm and slowly brought to its operating temperatures once in orbit. This warm launch approach allows to suppress any large liquid cryogen tank and to use the mass saved to launch a large diameter telescope (3.5 meters). This 4K cooled telescope allows to significantly reduce its own thermal radiation, offering superior sensitivity in the infrared region.

The cryogenic system that enables this warm launch/cooled telescope concept is a key issue of the mission. Three of the detector options currently considered for SAFARI need to operate from a heat sink temperature of around 50 mK in order to achieve the required Noise Equivalent Power (NEP) dictated by the science requirements. The cryogenic chain foreseen for SPICA features a number of cooling stages comprising passive radiators, Stirling coolers and several Joule Thomson loops. These stages will provide cooling at 20, 4.5, 2.5 and 1.7 K. The sub Kelvin cooler will be operated from these various heat sinks.

The main challenge with the sorption cooler is that it requires to thermally cycle the sorption pump between few K and 45 K. This cycling implies to remove a given amount of energy: if this is done quickly, large peak powers are to be dealt with. In the case of HERSCHEL this is not a problem since the superfluid tank contains about 2500 litres of superfluid helium. For mission such as XEUS or SPICA, the limited cooling powers available require that 1) the thermal architecture takes advantage of all available cooling resources and 2) the timing of the cycle is set such that the instant loads never exceed these cooling powers.

For SPICA/SAFARI we are proposing the concept described previously in a single shot version. In this case the cooler is recycled and then provides cooling powers at two temperatures ( $\approx 300$  and 50 mK) for a given time. Once the system is out of "cold joules" it can be recycled again (and indefinitely as long as the upper heat sinks are available). They are a number of technical challenges that needs to be addressed and part of these developments are supported by CNES.

### 3.4 Pocket Dilution Refrigerator

We have developed a compact, self-contained dilution cooler that can be operated from a 2.5 K or lower heat sink [12]. This cooler is gravity dependent and can only be operated on ground or on a spin satellite. However it is mentioned here as a fairly simple tool to provide temperature down to 50 mK, and thus can be used to characterize flight detectors. The system is made of a helium sorption cooler coupled to a closed loop in which the helium mixture flows (see Fig. 9). The dilution loop operates continuously and is only limited by the autonomy of the sorption unit that needs to be recycled on a regular basis. This first prototype has been designed to provide temperatures below 100 mK for a typical day work. The system can be scaled up within certain limits. Temperatures down to 35 mK and typical cooling power of 1  $\mu$ W at 50 mK and 6 at 100 mK have already been achieved. We expect to reach a nominal useful power of 2.5  $\mu$ W at 50 mK with mixing chamber improvements.

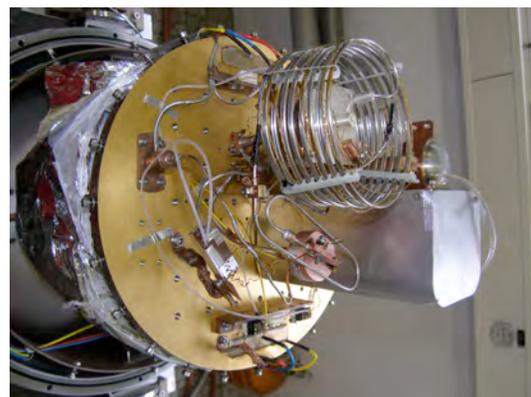


Fig. 9. Pocket dilution in the test cryostat

#### 4. CRYOGENIC LOOP HEAT PIPES – MULTIPHASE SYSTEM

SBT has recently decided to initiate a development program on cryogenic two phase thermal links. Indeed in numerous applications the position of the active cooling device (cold finger) is fixed and thus there is a need for solutions able to extract the heat at location not necessarily close to the cold finger. In a first step we are working on a liquid nitrogen cryogenic loop heat pipe (CLHP) driven by capillary forces (see Fig. 10). This first prototype allows 19 W heat transportation around 80 K with a limited temperature difference of 5 K across 0.46 m distance [13]. The general objective is to develop a helium loop within the next 4 years.

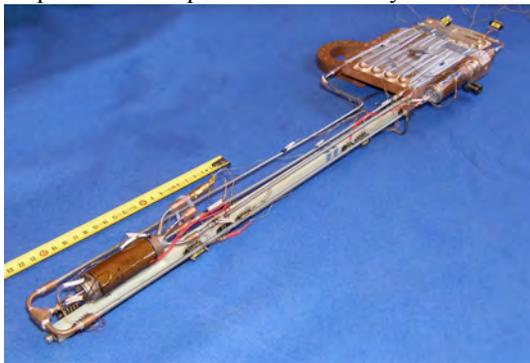


Fig. 10. Nitrogen loop heat pipe

Although not directly linked to CLHP we have been awarded an ESA contract to study a high density collection process of CO<sub>2</sub> on Mars owing the condensation of CO<sub>2</sub> gas on a cold surface inside of a collection tank. Once collected this CO<sub>2</sub> is used to deliver a continuous high pressure CO<sub>2</sub> flow in a discharge line to generate a thrust. This device could be used for ballistic jumps.

Both of these developments involve the use of porous media and the thermohydraulic control of biphasic systems.

#### 5. ANCILLARY EQUIPMENTS

##### 5.1 Heat Switches

Cryogenic heat switches are one of the key technologies in many space cryogenic systems. Indeed the ability to make or break a thermal contact finds direct applications in numerous devices. It can be used to produce adiabatic environments, to couple/decouple a redundant cryocooler from the operating one, to decrease the cooling time in a transient operation, to control the temperature gradient and thereby allow to manage the liquid phase in specific closed cycles, to control Energy Storage Units, etc. Many cryogenic heat switches based upon different physical mechanisms have been developed in the past. To the exception of the ultra low temperature range for which specific

techniques must be employed (see further), two types of switches are mostly used. The mechanical switches whereby the thermal conductance is directly linked to the quality of contact between two surfaces, and the gas gap heat switch whereby the conductance is due to the absence or presence of gas between two interlocked parts. In this latter case a miniature sorption pump manages the gas. In most cases, particularly at liquid helium temperature, the gas gap heat switch is selected for its high reliability (no moving parts) and excellent ON thermal conductance. We have built literally several dozens of helium gas gap heat switches with a very high success rate. Two developments, both funded by CNES, are currently carried out.

First most of the switches we have designed and built operates at liquid helium temperature and are limited to temperature below 20 K because a physisorption process is used to control the gas. Thus a program is ongoing to extend this range to ambient temperature. A generic prototype has been assembled and is used to test various gases and in particular to verify or actually measure the gas adsorption properties. This program was initially carried out in collaboration with the physics department of the University of Lisboa (Portugal) and results with neon, hydrogen and nitrogen have already been obtained.

The second program deals with an innovative concept. The standard gas gap switch works pending precautions are taken; in particular during integration the mechanical constraints on the switch free end must be limited. To address this last point a highly flexible high purity copper braid can be used for the link between the switch end and whatever it is connected to. Thus we came up with an alternative design to improve the integration aspects, the so called thermomechanical heat switch (Fig. 11). In addition this design can allow for a control of the ON conductance and features extremely fast switching time. The switch features a thermally active moving part which can be displaced using a magnetic engine made of a dry niobium titanium coil and a permanent magnet.

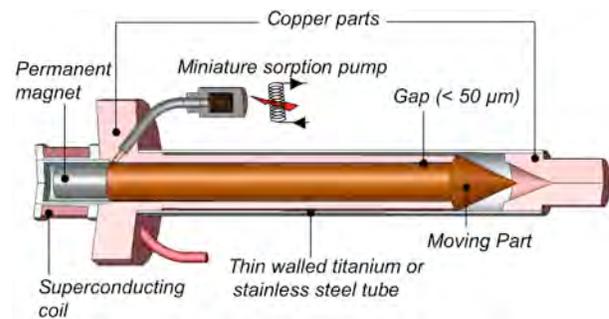


Fig. 11. Schematic of the thermomechanical switch

Several prototypes have already been tested and Table 2 summarizes a typical performance [14].

Table 2 : Thermal performance

	Specif. CNES	Experimental result
Fully ON @ 4.2 K	> 20 mW/K	≈ 50 mW/K
OFF @ 4.2 K	< 20 μW/K	≈ 20 μW/K
Partly ON	0.1 < spec < 1 mW/K	0.5 mW/K
Switching time : partly ON to ON	-	5 seconds

Down to 300 mK <sup>3</sup>He gas-gap heat switches are a very good choice for thermal links between the ADR and the sorption cooler. But they are of limited use under 250-300 mK because they naturally go in the OFF position below these temperatures (switch internal pressure driven by saturated vapor pressure). In case of a continuous cooling design, heat switches able to operate at very low temperature, 50 mK for the present concern, are needed. Superconducting switches are the classical solution and SBT investigated this field recently. The first results are already fulfilling our expectations and we will go into this subject more deeply in the future. In parallel, we are looking for alternate solutions. A possibility may be to extend the range of use of the thermomechanical heat switch and a new program also funded by CNES will be initiated soon on heat switches development for ultra low temperature.

## 6. CONCLUSION

A quick overview of the developments carried out in the Space Cryogenics Group of CEA-SBT has been presented. Our activities range from 80 K high frequency pulse tube coolers to 20 mK miniature ADR. The team features a strong know-how in helium sorption coolers and for instance has been responsible for the production and characterization of the coolers for the HERSCHEL satellite. Recent developments include a nitrogen cryogenic loop heat pipes and a new concept for the thermal switches. We are currently involved in the development of possible solutions for the future XEUS and SPICA missions. In that respect we are proposing an original thermal architecture featuring the association of a 300 mK sorption unit with a 50 mK miniature ADR.

## 7. REFERENCES

1. Duband L., Ravex A. and Rolland P., *Development of a Stirling cryocooler using hydrodynamic gas bearings*, Proc. 8th ICC, Vail CO USA (1995 Plenum Press, NY USA) p. 47-53
2. Duband L., Ravex A., Bradshaw T., Orlowska A., Jewell C. and Jones B., *50-80 K Pulse Tube cryocooler development*, Proc. 9th ICC, Waterville Valley NH USA (1997 Plenum Press, NY USA) 213-22

3. Charles I., Duband L. and Ravex A., *Permanent flow in low and high frequency pulse tube coolers – Experimental results*, Cryogenics Vol. 39, 777-782, 1999
4. Trollier T., Tanchon J., Buquet J., Aigouy G., Ravex A., Charles I., Coynel A., Duband L., Ercolani E., Guillemet L., Mullié J., Benschop T., Linder M., *Performance testing of a large heat lift 40 to 80K pulse tube cooler for space applications*, Proc. of SPIE, Vol. 6542, Infrared Technology and Applications, 2007
5. Charles I., Duband L., Martin J.Y., Mullié J.C. and Bruins P.C., *Experimental characterisation of a pulse tube cryocooler for ground applications*, Adv. in Cryo. Eng., Vol 49B, 1373-1379, 2004
6. Charles I., Coynel A., Duval J.M., Daniel C., Briet R., *Development of a Two Stage High Temperature Pulse Tube Cooler for Space Applications*, to be published in Proc. of 15<sup>th</sup> ICC
7. Duval J.M., Charles I., Gauthier A., Trollier T., Tanchon J., Linder M. and Briet R., *Experimental Results of 20 K Pulse Tube Cold Fingers for Space Applications*, to be published in Proc. of 15<sup>th</sup> ICC
8. Charles I., Golanski L., Gauthier A., Coynel A., Duval J.M., *20 K coaxial pulse tube using passive precooling*, Adv. in Cryo. Eng., Vol B, 887-894, 2008
9. Duband L. and Collaudin B., *Sorption coolers development at CEA-SBT*, Cryogenics Vol. 39, 659-663, 1999
10. Duband L., Clerc L., Ercolani E., Guillemet L. and Vallcorba R., *Herschel Flight Models Sorption Coolers*, Cryogenics Vol. 48, 95-105, 2008
11. Duval J.M., Luchier N. and Duband L., *50 mK continuous cooling with ADRs coupled to helium 3 sorption cooler*, to be published in Proc. of 15<sup>th</sup> ICC
12. Prouvé T., Luchier N. and Duband L., *Pocket dilution cooler*, to be published in Proc. of 15<sup>th</sup> ICC
13. Gully Ph., Qing M., Seyfert P., Thibault P. and Guillemet L., *Nitrogen cryogenic loop heat pipe : results of a first prototype*, to be published in Proc. of 15<sup>th</sup> ICC
14. Duband L., *a thermomechanical heat switch*, to be published in Proc. of 15<sup>th</sup> ICC