CRYOCOOLERS DEVELOPMENT AND INTEGRATION FOR SPACE APPLICATIONS AT AIR LIQUIDE

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ABSTRACT

Air Liquide Division Techniques Avancées (AL/DTA) has developed cryorefrigerators for space applications and is integrating those in different payloads to be launched in the next coming years. The covered cooling technologies include Brayton, Joule Thomson, Stirling, Pulse Tube and Dilution cycles. The main characteristics and performances of these coolers are presented in this paper as well as some specific features related to their integration.

INTRODUCTION

AL/DTA has been involved in space cryogenics since several decades in the framework of the European ARIANE program mainly for the launcher liquid cryogens (LH2 and LOx) tanks development, qualification and manufacturing but also for the design and implementation of the liquefaction, storage and distribution infrastructures on the launching pad at Kourou, Guyana.

More recently AL/DTA has extended its space related business by developing and integrating cryocoolers for use onboard the International Space Station (ISS) or to be flown on scientific or commercial satellites payloads.

AL/DTA offer covers a very large panel of technologies (Brayton, Joule Thomson, Stirling, Pulse Tube, Dilution) and a very large range of temperature and cooling power (from a few microwatt at 100 mK till hundred watt at 190K). This new line of products has been developed taking advantage of both the heritage of AL/DTA experience in commercial cryorefrigeration and a strong partnership with National Research Laboratories (CNRS, CEA) and industrial partners (THALES Cryogenics). The main efforts have been dedicated to performance and reliability improvements which are the most critical parameters for space applications.

A special attention has also been paid to the thermal and mechanical integration of these coolers in payloads which is a major concern for systems overall efficiency and reliability.

CRYOCOOLERS DEVELOPMENTS

Brayton Cycle Coolers

At the end of the 80's, AL/DTA has initiated, under an ESA Technological Research Program (TRP), the development of a Brayton Cycle Cooler. A major feature was the use of high isentropic efficiency centrifugal compressor and expender implemented on a common shaft suspended with hydrodynamic gas bearings and driven by a high speed permanent magnets central motor integrated on the shaft between compression and expansion wheels. An other key point to be addressed was the miniature counter flow heat exchanger design which strongly influence the cooler overall efficiency. A cooler prototype has been successfully designed and tested and consequently this technology has been later selected by ESA for the development of a flight system: the Minus Eighty degrees Laboratory Freezer for International space station (MELFI).

The MELFI cooler is based on a reverse Brayton cycle using a very high speed turbo-machine (shown on Fig.1) located inside a toroïdal heat exchanger. It provides up to 90 W of net cooling power at 190 K. The radial compressor and expander wheels of the machine are mounted at both ends of the shaft running up to 100.000 rpm on herringbone groove bearings made in Tungsten Carbide (WC). The DC brushless and sensorless synchronous motor is located in the center between the two journal bearings. The compressor uses a smooth inlet and diffuser while the expander uses a bladed diffuser. The heat from the motor and the bearings is removed by a water heat exchanger wounded around the motor coil. The radial gap in the journal is 10 µm, radius. Herringbones are grooved in the WC using an Argon Ion beam bombardment techniques, using masks. The results is a 14 µm depth groove with an accuracy of ± 1 µm. A two pole permanent magnet is shrunk fitted into the hollow shaft. The thrust bearing is a WC spiral groove runner rotating between two static WC plates with an axial gap of 20µm on both sides. Our shafts are balanced on a dedicated bench using hydrostatic pressurized bearings with large gaps. This provides a very low stiffness allowing a very precise balancing. Displacements of the shaft are measured with capacitance probes with an accuracy better than one micron. Thus, the design of hydrodynamic bearings, the use of a brushless DC synchronous motor, the very low level of induced vibration generated thanks to the high level of balancing, allow to provide high reliable coolers (10 years lifetime without maintenance) and able to support several thousands of start/stop cycles. Presently, more than 17000 hours of operation have been achieved with 2700 start/stop cycles.

The first Flight Unit of the MELFI has been delivered to NASA. Initially planned on STS-114, this payload will be launched in November 2004 or early in 2005.

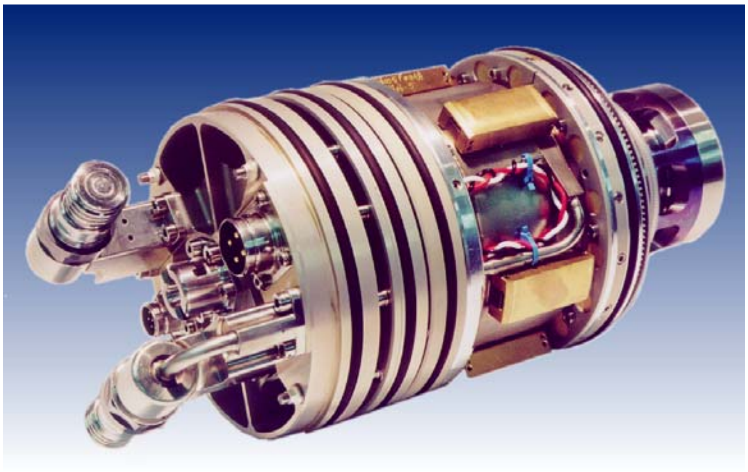

Figure 1: AL/DTA high speed Turbo-Machine for ISS.

Interesting characteristics of Brayton coolers using centrifugal compression and expansion at high speed is their low level of exported vibrations. Future Astrophysics mission will require cooling in the temperature range of 2 K to 6 K with extremely strong specifications on exported vibrations level. A multistage Brayton cooler could be a solution to fulfill these requirements. AL/DTA has been awarded a TRP by ESA to perform a cooler optimization and preliminary design, to identify critical items and to initiate feasibly demonstrations with the aim of 50 mW net cooling power at 5 K. To fulfill the vibration specification, a high rotational speed (1000 Hz) is mandatory, leading to very small wheel diameters for the compressor and expenders which is a challenging issue. In Fig.2 is shown the selected cycle architecture implementing a two staged centrifugal compressor, radiative precooling at 150K and three stages of expansion (60K, 15K and 5K) with centrifugal turbines. The compressor and the expenders are rotating on hydrodynamic gas bearings. The calculated compression work is 95 Watt for a 305 mg/sec 4He mass flow rate, with estimated isentropic efficiencies for the compressor (67 %) and the expansion turbines (50 %). The identified critical components are obviously the compressor and its high speed motor, the compact heat exchangers and the turbines. In a first step of the TRP it has been decided to demonstrate the feasibility of the compressor. Figure 3 shows a compressor wheel before brazing. The compressor is presently under assembly to be tested by the end of this year.

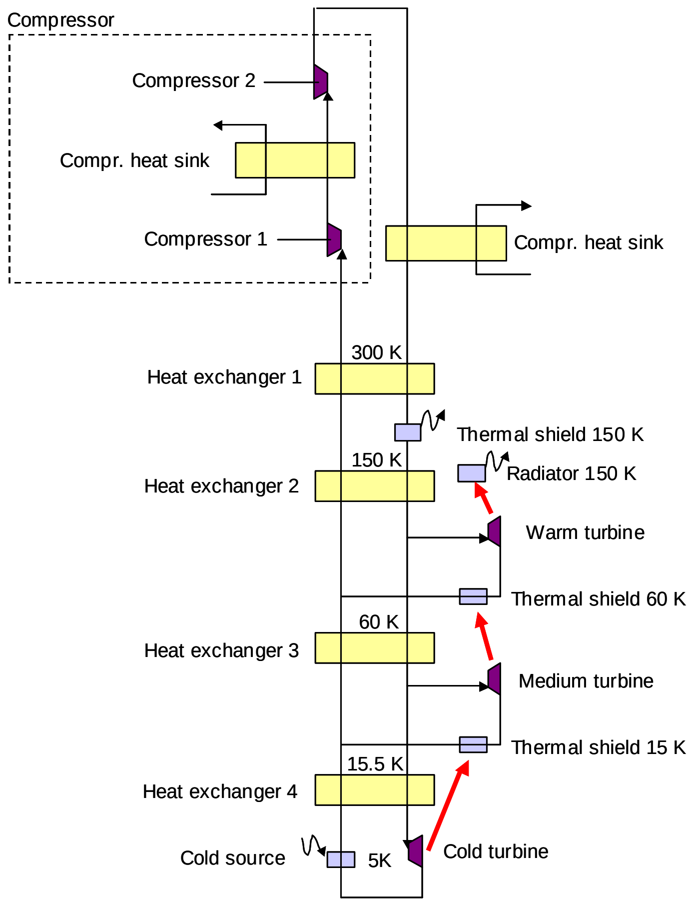

Figure 2: ^{4}He Brayton cycle process flow diagram.

Figure 3: Compressor wheel before brazing (∅ 50 mm)

Stirling Cycle Cooler

To achieve the reliability required for space applications, it is now commonly agreed that the flexure bearing technology developed by Oxford University is a unique feature to ensure frictionless operation and clearance sealing in linear Stirling coolers. Several companies in the US (Ball Aerospace, Lockheed Martin, NGST formerly TRW) have developed, space qualified and flown specific coolers generally associating a two back to back pistons compressor with an actively driven cold finger, implementing flexure bearings, linear motors with moving magnets and phase shift control electronics.

In partnership with THALES, AL/DTA has undertaken the development and qualification of a Stirling cooler introducing a new manufacturing approach combining high reliability and reduced development costs by using as much as possible commercial coolers subassemblies. The basic characteristics of commercial THALES coolers are preserved: high reliability flexure bearings twin pistons linear compressor with moving magnet motor (reducing risks of cycle gas pollution by motor coil out-gazing and of flying wires and feed-through failures), pneumatically driven cold finger (reduced complexity: no motor, no active phase shift control electronics). Major improvements have been to adapt the external shelves architecture and materials to the specific mechanical and thermal constraints of space applications and to implement also flexure bearings for the cold finger displacer.

The performances and characteristics of the developed cooler [1] are summarized in Table 1 and a picture of a prototype is shown in Figure 4. This cooler has been selected by EADS for integration in Cryosystem, a deep-freezer to be flown by ESA/NASA on board the ISS (see further information in Integration section of this paper). Several Engineering Models (EM) have been characterized: thermal performances, launch and landing vibration and thermal environment tests. 2 EM coolers are currently run under lifetime test, with 5200 operating hours already achieved without any performance degradation.

Performance	9.3 W @ 80 K
Input Power	150 W
Frequency	50 Hz
Mass	7,3 kg
Compressor OD	90 mm
Compressor length	189 mm
Cold finger OD	110 mm
Cold finger length	162 mm

Table 1: Cooler characteristics.

Figure 4: Cryosystem EM Stirling cooler.

Pulse Tube Coolers

The main drawback of the Stirling coolers in terms of reliability and integration easiness is their cold finger: the moving displacer technology and the associated linear motor are a potential source of failure and exported vibrations, the reduced clearance between the moving regenerator/displacer and its shelve induces strict mechanical load restrictions on the cold finger cold tip to avoid any internal friction which generally results in very complicated thermal link design, the active phase shift control loop complicates the drive and control electronics.

The Pulse Tube cooler (PTC) technology with no moving part in the cold finger and passive pneumatic phase shift control is recognized as an attractive alternative to Stirling coolers. Recent developments, such as phase shift control by inertance, have greatly improved the PTCs temperature stability and overall efficiency which is now comparable with Stirling coolers.

AL/DTA, in partnership with CEA/SBT and THALES has undertaken since several years the development of PTC technology either on its own funding or through ESA TRP.

A TRP for a Miniature Pulse Tube Cooler (MPTC) has been recently successfully completed [2, 3]. A U-shaped Engineering Model, with 21 cm transfer line between compressor and cold finger has been designed, manufactured and tested (thermal performances in different orientations and thermal environments) and preliminary qualified for space application (thermal and mechanical environment). Typical performances of this MPTC are reported in Table 2 and a picture is shown in Figure 5. The integration of this MPTC in future space missions is under consideration.

Performance	1 W @ 80 K
Input Power	35 W
Frequency	50 Hz
Mass	2.8 kg
Compressor OD	63 mm
Compressor length	157 mm
Cold finger OD	100 mm
Cold finger length	179 mm

Table 2: MPTC characteristics.

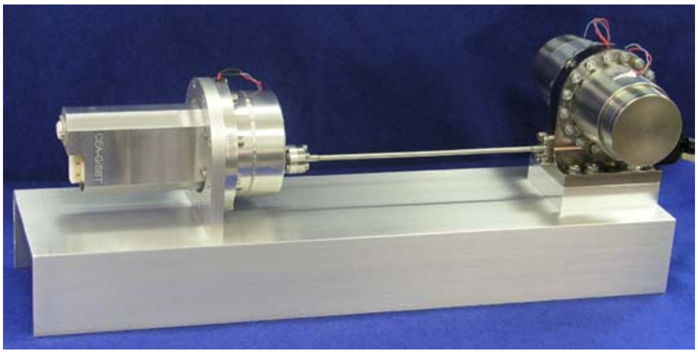

Figure 5: MPTC EM cooler.

The need for a larger cooling capacity PTC has been clearly identified, first for ground based commercial applications (i.e. superconducting filters for telecom) but also for future earth observation or other space applications. AL/DTA and its partners have already completed the development of such a large heat lift capacity PTC demonstrator in the frame work of a PhD work and with the support of French program [4]. The performances achieved with an in-line and a U-shape configuration are reported in Table 3 and a prototype picture of the U-shape is shown on Figure 6. A coaxial version is under industrialization at THALES for ground applications.

In –line Pulse Tube: • 7,7 W @ 80 K • 200 W input power • 50 Hz
U-shape Pulse Tube: • 5,5 W @ 80 K • 189 W input power • 50 Hz

Table 3: PTC characteristics.

Figure 6: U-shape pulse tube cooler.

In the framework of the European SuperADC program, a two staged PTC is also under development with the aim to produce simultaneous cooling power at 80K and 20K-30K.

Preliminary results have been presented recently elsewhere [5]. It is also foreseen to develop a space version of this PTC in the near future.

3He / 4He Dilution Refrigerator

Planck is a European infrared space observatory dedicated to the mapping of the temperature anisotropies of the cosmic background radiation. AL/DTA and the Centre de Recherches à Trés Basses Températures du Centre National de Recherche Scientifique (CNRS/CRTBT) are involved since 1994 in the design and realization of a dilution refrigerator for the cooling from 4 K down to 0,1 K in microgravity environment of the bolometers array of HFI (one of the Planck mission instruments). Several teams in the world have tried to develop closed cycle dilution refrigerators for space operation. They have generally not been able to solve satisfactorily the phase separation in microgravity and the compressor operation. The CNRS/CRTBT has patented a unique design using 3He and 4He isotopes stored in high pressure vessels to feed a continuous mixing/separation process in a capillary pipe and rejecting the mixture (after a Joule Thomson expansion providing extra cooling at 1.6K) in space. This original process has been already demonstrated on ground against gravity (up side down cryostat) and in the Archeops stratospheric balloon mission. This proven technology is presently implemented by AL/DTA for Planck mission. Some specific features have been especially added for this mission: passive mechanical locking of the cooler during launch with specific memory shape alloy releasing the cooler locking during cooling in orbit, large heat capacity magnetic alloys for focal plane thermal stabilization. The qualification model performances [6] are summarized in Table 4 and a dilution fridge picture is shown in Figure 7. This qualification model is presently going through thermal and mechanical environment tests. The flight model is under assembly to be flow in 2007. A nominal continuous operation in orbit of 18 months is foreseen with a margin for 6 extra months.

<table>
<tr><th>Helium 3 flow</th><th>Helium 4 flow</th><th>Cold end temperature</th><th>Cooling power at the cold end</th><th>Temperature stability of the focal plane</th></tr>
<tr><td>6.3 µmol/s</td><td>21.8 µmol/s</td><td>79.9mK</td><td>No power applied</td><td rowspan="3">15 µK/Hz$^{1/2}$ at 0.02 Hz without large heat capacity magnetic alloy</td></tr>
<tr><td>6.3 µmol/s</td><td>17 µmol/s</td><td>101.9 mK</td><td>100nW</td></tr>
<tr><td>7 µmol/s</td><td>19.5 µmol/s</td><td>92.55 mK</td><td>100nW</td></tr>
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Table 4: Dilution plate temperature versus ^{3}He and ^{4}He flows and cooling power

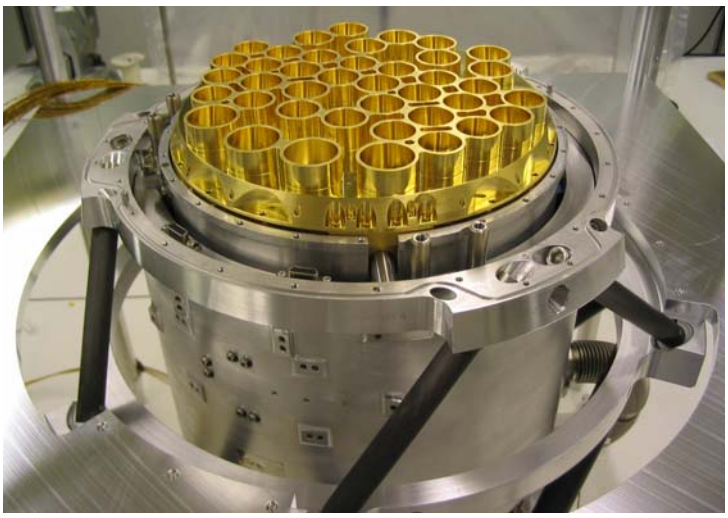

Figure 7: The Focal Plane Unit with the bolometer plate

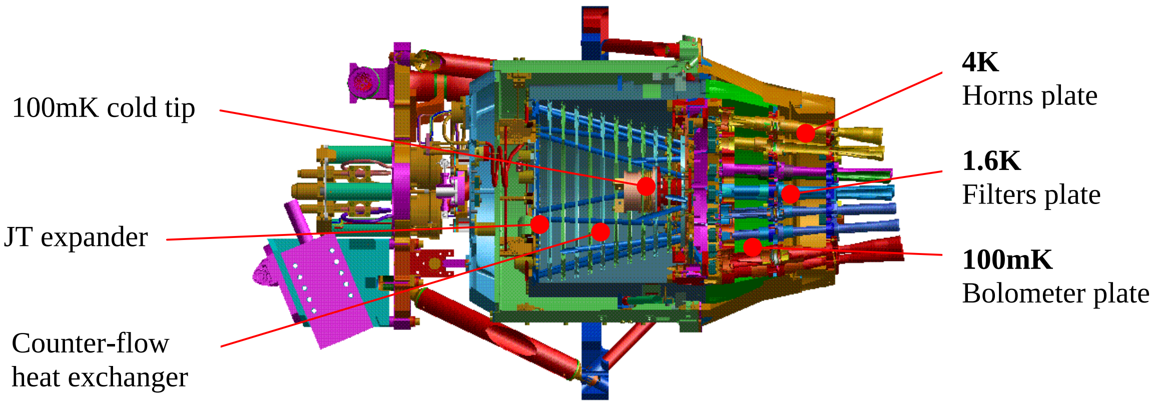

Figure 8. The Focal Plane Unit.

CRYOCOOLERS INTEGRATION

Thermal and mechanical integration of cryocoolers in payloads for space applications is often a complicated and cost effective problem. The best way to solve efficiently this problem is to have a strong collaboration from the initial phases of design between the cryocooler manufacturer and the payload architect. Aware of this important aspect, AL/DTA is not only involved in cryocoolers design and manufacturing but also intents to be involved in integration activities and to develop innovative and performing solutions. The following are some example of payload integration for the above described coolers.

MELFI freezer

As already mentioned, MELFI is a freezer to be operated in a laboratory on board the ISS for biological samples preservation (at –80 °C). The cooling is provided by a Brayton cycle refrigerator previously described. The Brayton cycle is a continuous flow cycle with dedicated components: compressor, compressor aftercooler, counter flow heat exchanger, expander, cold heat exchanger.

Figure 9. MELFI Rack (courtesy of Astrium).

These components can be integrated independently and connected with appropriate piping. This has allowed a particular integration architecture and manufacturing tasks sharing in MELFI project. AL/DTA has developed and manufactured a compact subsystem including all the cycle active parts (turbo compressor, motor and turbo expander on a common shaft) including the compressor aftercooler. The passive parts, the counter flow heat exchanger and the cold heat exchanger, have been directly integrated by the partner in charge of the MELFI dewars and their rack integration: a single compression-expansion unit is able to cool up to three dewars. Both sub assemblies are linked through quick-tight connectors, allowing for easy integration. Figure 9 shows a picture of the MELFI rack.

CRYOSYSTEM freezer

CRYOSYSTEM is also a freezer to be operated in the ISS for biological samples quick/snap freezing and preservation. A Stirling cooler previously described is used to cool a dewar including a rotating massive vials storage vessel. Strict specifications are required by the scientists such has minimal vials freezing time, storage vessel thermal inertia for minimal storage temperature increase during vials loading, capability to survive (minimal temperature) ISS current shut down,… AL/DTA has designed, manufactured and tested a Development Model of this specific dewar and developed simulation tools to reproduce all the potential scientist operations and ISS operation conditions and predict the storage temperature evolution. Thermal performance tests have been successfully performed and reported elsewhere [7]. Due to the challenging cooling performances and electrical consumption specifications and to mechanical integration issues, the thermal link between the Stirling cooler cold finger and the storage vessel has been identified as a key technological point of this project. To combine high thermal conductance with minimal mechanical load on the cold finger, a specific thermal link assembly (TLA) has been designed and tested [8]. Basically a heat pipe like operation is established in a small gap (few millimeters) between a thin walled well mechanically and thermally anchored to the storage vessel and the cooler cold finger: condensation occurs at cold tip surface and evaporation on storage vessel side. The gap is filled with a soft porous media and a heat transfer fluid (nitrogen or argon): the porous media allows for micro gravity operation and liquid draining of the fluid by capillary effect. Figure 10 shows a schematic of the TLA and of CRYOSYSTEM overall assembly.

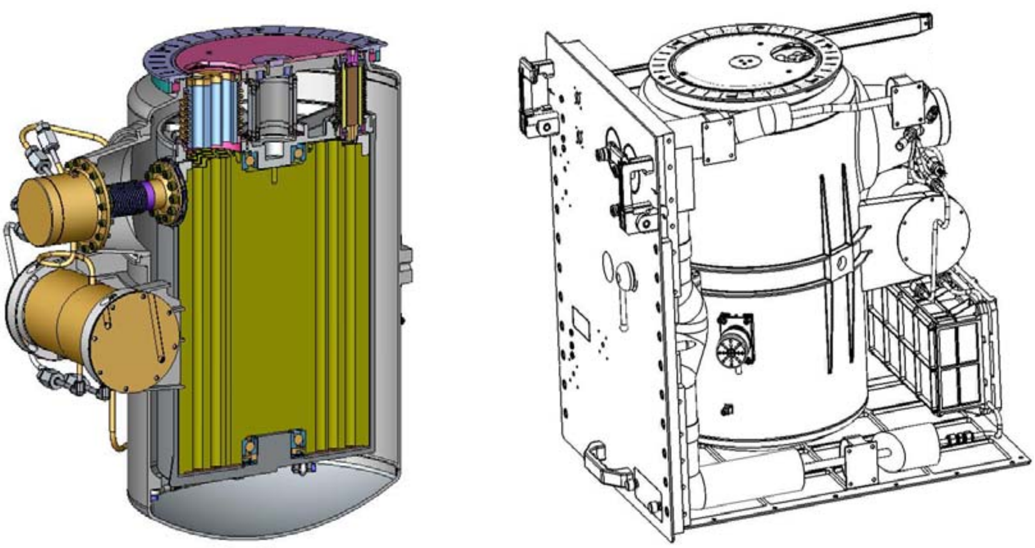

Figure 10: Views of the CRYOSYSTEM Dewar under design (PDR level).

PLANCK HFI Dilution refrigerator integration

The HFI instrument of the Planck mission cooling architecture is of a “cascade” type with four stages. From ambient temperature down to 100 mK, the following different cooling techniques are associated, each one being used as a precooling stage for the next one: a three stages groove type radiator (140 K, 80 K, 50 K), a 20 K Hydrogen sorption compression Joule Thomson cooler (developed by JPL), a 4 K mechanical compression 4He Joule Thomson cooler (developed by RAL) and finally the AL/DTA dilution refrigerator down to 100 mK. A part from the mechanical and thermal interfacing with the upper precooling stages, AL/DTA has faced a specific integration problem with the 1.6 K – 100 mK heat exchanger. This heat exchanger, the efficiency of which is crucial for the dilution refrigerator efficiency, is generally made for ground applications of a tube in tube technology with stainless steel low diameter pipes. To survive launch vibrations, a stiff structure with low thermal conductivity should be used to support this counter flow heat exchanger. NbTi pipes are used as stiffening rods due to their favorable mechanical resistance to thermal conductance ratio in this temperature range. Another point is the minimization of the parasitic conductive heat load transferred down to 100 mK by the bolometers reading electrical wires (64 twisted shielded pair wires) which has been obtained by a continuous thermal anchoring of the wires braid along the counter flow heat exchanger. The resulting hardware, shown on Figure 11, has been mechanically and thermally qualified, fulfilling all the expected specifications and allowing for a smart integration in the instrument with preserved cooling performances.

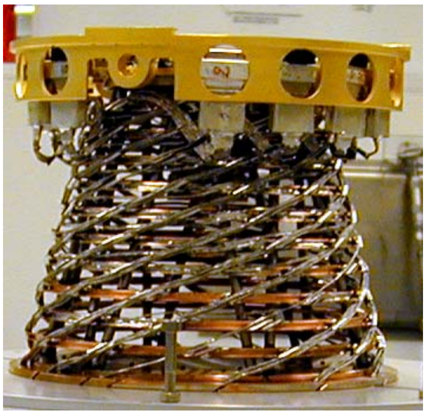

Figure 11: 0.1K-1.6K dilution heat-exchanger.

CONCLUSION

AL/DTA has put in concrete form its objective to develop an offer for cryocoolers design, manufacturing and integration for space applications. Several technologies, including Brayton, Joule Thomson, Stirling, Pulse Tube and Dilution refrigeration cycles, have been demonstrated. Some of these coolers have been specifically designed and developed to be integrated within ESA or NASA scientific missions (MELFI, CRYOSYSTEM, PLANCK/HFI) to be flown during the next coming years. Space qualification of these coolers has been already achieved or is going on. Development of miniature Brayton and large cooling capacity Pulse Tube coolers have also been initiated to prepare the next generation of AL/DTA space coolers.

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