Enabling Ambitious Space Science Missions Thanks to 10 K-20 K Cryocooling

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ABSTRACT

In the past years, Air Liquide Advanced Technologies has developed a HiPTC, standing for Heat intercepted Pulse Tube Cooler, for space science missions. This cooler is a dual stage Pulse Tube cooler developed by a consortium led by Air Liquide with CEA, TCbv and SITAEL. It includes a compressor designed and built by Thales Cryogenics b.v and a driving electronics developed by SITAEL. This work has been funded by the European Space Agency (ESA).

Tests performed on one engineering model showed that the cooler reached 6.9 K zero load temperature. This makes it suitable for a large number of science missions requiring cooling in the 10 K-20 K temperature range.

This is the case for the ATHENA mission, for which the cryocooler is developed and purposed to supply thermal shielding around 80 K-100 K, and precooling at 15 K for lower temperature coolers aimed at detector cooling.

Recent activities on this cooler include:

- Development of a TRL 6 engineering model
- Study and testing of several cooler architectures, passive phase shifting or active phase shifting at the low temperature stage
- Improvement of overall efficiency
- Development of a new driving electronics with damping of µvibration
- Preliminary studies for integration of the cooler on several space science mission projects

The results show the availability of a compact, efficient and low vibration cryocooler for space science applications. The power consumption of the cooler is less than 500 W including electronics. Total cooler mass is around 36 kg (including margins) including drive electronics and the cooler fits in a reduced volume. Recently, ALAT has been awarded a new ESA contract centered on the overall cooler system including the development of Cryocooler Control Electronics realized by SITAEL. This project aims to increase the maturity of the cooler to reach Technological Readiness Level 6 at the Cooler Mechanical Assembly level and be able to go to lifetime test in support of a future qualification program.

Cryocoolers 21, edited by R.G. Ross, Jr., J.R. Raab and S.D. Miller

INTRODUCTION

Previous developments provided European Space programs with single stage Pulse Tube coolers. They offer reliable, powerful and efficient cooling down to 45 K. An example of such a cooler is the Air Liquide Advanced Technology (ALAT) Large Pulse Tube Cooler (LPTC) offering up to 3 W at 50 K. Looking forward, Future Earth Observation missions will require cooling down well below the 20 K mark to either extend the wavelength range of MCT Infrared detectors or other THz detectors. In this frame, ATHENA mission requires cooling sensitive detectors down to the 50 mK range or below [1]. In this context, ESA funded the development of a high-power low temperature Pulse Tube cooler to reach such performance. This contract has been carried out with a consortium made with CEA SBT and TCBV [2,3].

Indeed, in the current ATHENA cryochain, HiPTC constitutes the first active cooling stage.

It realizes two functions:

- supplying primary cooling to cryogenic shields
- providing precooling for helium Joule Thomson coolers.

A JT cryocooler is needed for the second cooling stage, and performance is extremely sensitive to the injection temperature as the Joule Thomson coefficient improves significantly from to 20 K down to 15 K.

HISTORY

Development of HiPTC under ESA contract started in 2011. The objective was to develop a low temperature multi stage Pulse Tube cooler for answering needs of science missions. Air Liquide and CEA relied on their experience on Pulse Tube (using LPTC program for Air Liquide and low temperature R&D for CEA) to analyze different architectures. Trade-off and test results led to a focus on a 2-stage cooler.

In parallel, TCBV developed a dedicated compressor to provide the needed pressure wave. This mechanical device is based on the compressors already developed for the LPTC program but is around two times more powerful.

In 2014/2015 a first TLR 4 breadboard (15 K BB) of a 2 stage CFA (Cold Finger Assembly) and a maxi-CPA (Compressor Part Assembly) has been manufactured and tested. The results were very encouraging since it provided around 500 mW at 15 K and 2 W at 80 K. Moreover, CFA and CPA supported mechanical and environmental tests with success.

This CFA and CPA has been delivered to CEA in order to be coupled with a 2K JT and measure the final performance reached at 2K. These data have been used for refining the specification of the ATHENA cooling chain.

Following this first contract and the need for ATHENA mission, ESA awarded to Air Liquide a second contract to continue the development of this cooler (15 K EM). This project focused on the following points:

- Improving overall efficiency
- Increasing cooling power at 15 K by improving the cold regenerators [4].
- Reducing exported μvibrations
- Reaching TRL 6 for CFA and CPA
- Start developing the driving electronics (TRL3)
- Test of passive phase shift device

The development of a new driving electronics (CCE) is carried out by SITAEL who has already developed one of the LPTC driving electronics.

In parallel to ESA contracts and to answer to external opportunities, Air Liquide manufactured a CFA Breadboard (CFA BB) based on the first CFA (first ESA contract). This CFA was used to increase the understanding of the CFA by adjusting different parameters. In particular, Air Liquide optimized the settings for reaching very low no-load temperatures (down to ~8 K). Air Liquide has also tested different kinds of Active Phase Shift compressors and compared their overall performance.

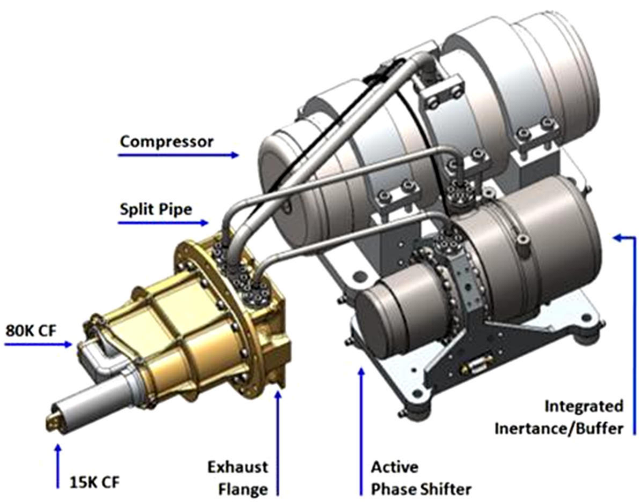

Figure 1. Cryocooler architecture: A common high-power compressor supplies the assembly of one intermediate single stage cold finger and one low temperature cold finger. The inertance tube of the intermediate stage (conceptual view) is integrated around the active phase shifting miniature compressor for the low temperature coldfinger

MATERIAL & METHODS

Thanks to the development of the 15K Pulse Tube Cooler (Fig. 1), under ESA contract from 2011 to 2015, ALAT uses the same architecture for the future contract, but also adds a Cryocooler Electronics (CCE) to drive the compressors, monitor the sensors, do the thermal regulation, reduce the induced microvibration, and help the CMA to sustain the mechanical test with a launch lock system. The aims of the CCU are then to:

- Provide cold power to the cold tip
- Ensure temperature regulation at both cold tips
- Ensure exported micro vibration reduction of both compressors
- Report operating data
- Sustain launch mechanical loads

The CCU is composed of one maxi compressor delivering the mechanical power to the CFA and one mini compressor which realizes the phase shift for the 15 K pulse tube. These two compressors are powered and driven by the CCE. An EGSE is developed by ALAT to monitor and drive the CCE. The CFA transforms the mechanical power of the compressor to cold power. The gas (He) is compressed and expanded by the compressor linked to the CFA by the split pipe. The pressure wave goes then through the two pulse tubes:

- 1 pulse tube 80 K-100 K
- 1 pulse tube 15 K intercepted by the 80 K-100 K pulse tube

These two cold fingers generate the cold power (at 80 K-100 K and 15 K). The warm power is recovered at the warm end of the cold finger. In addition, temperature sensors and heaters are fixed at the end of the cold finger to monitor and drive the temperature. The information is gathered by the CCE which could be able to regulate the temperature by using heaters. The two cold tips are equipped with other heaters to simulate the DC Heat load which cannot be ensured by the heater driven by the CCE.

The 80 K-100 K pulse tube (LPTC one) integrated with an inertance tube and buffer to realize the phase shifting (passive phase shift). On the other side, the 15 K pulse tube is integrated with the mini compressor to realize the active phase shifting.

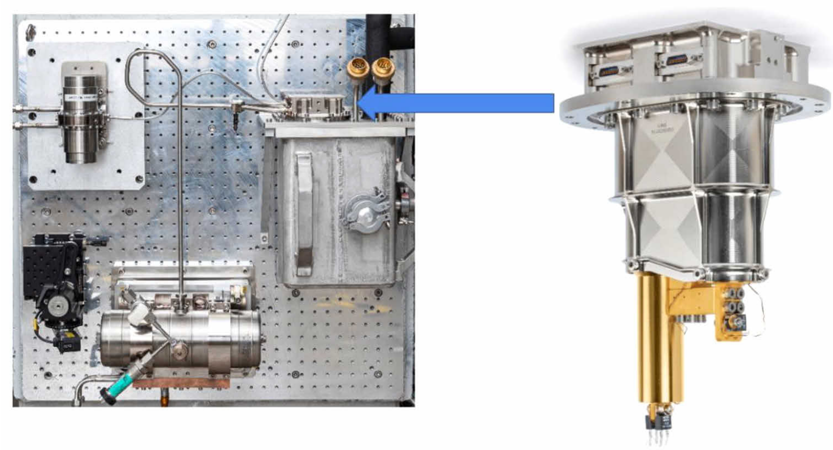

Figure 2. EM PT15K CFA mounted on the test bench.

15K EM RESULTS

Tests are still ongoing for the EM PT15K, shown in Fig. 2. The first results have shown a good reproducibility of the cryogenic performance with respect to the previous PT15K. The cryogenic performance obtained at 450 W input power with EGSE are presented in the list below:

- 100 mW at 10 K
- 450 mW at 15 K & 2.5 W at 80 K (BOL)
- >0.8 W at 20 K
- Tmin: cold finger < 7 K, middle stage <70 K

The lowest temperature reached was 6.94 K on the cold tip (with no load). As discussed, the emphasis was on the overall efficiency of the CCU, especially on the matching between the main compressor and the CFA.

First measurement of the micro vibration on the maxi compressor at full power without a vibration reduction algorithm provided encouraging results. The microvibration measured at the driving frequency on the piston axis was only 7 N without the reduction algorithm. The algorithm will be handled by the CCE. ALAT and TCBV aim to reach less than 200 mN peak piston axis / 1 N peak off axis at the compressor mechanical interface.

A dedicated test campaign is ongoing in order to improve the overall efficiency by adjusting parameters such as inertance-tube length, drive frequency, and fill pressure.

Emphasis is also focused on CCU accommodation, especially the length between the compressors and the CFA, in order to investigate its influence for Athena accommodation.

The next step will be to couple the Cryocooler with the CCE and perform measurement of cryogenic performance (stability, cooling power, …) and validate expectations on µvibration reduction.

Finally, the mechanical and thermal environment test will be carried out according to the levels shown in Table 1. In addition, a 25 g (all axis) constant acceleration will be performed on CFA and CPA. This model will then go to a first lifetime test for at least 6 months.

Table 1. Thermal environment and Random vibration requirements

T° (°C)at TRP	Operating temperatures		Non - operating temperatures	
	Min	Max	Min	Max
TRP CCE	-30	+50	-40	+60
TRP CPA	-30	+50	-40	+60
TRP APS	-30	+50	-40	+60
TRP CFA^WF	-30	+50	-40	+60

For CMA (Axial/lateral)	
Frequency Range	Qualification Levels
20 – 100 Hz	+ 3 dB/ Oct.
100 – 300 Hz	0.3 g^2/Hz
300 – 2000 Hz	- 5 dB / Oct.
GLOBAL	13.7 grms

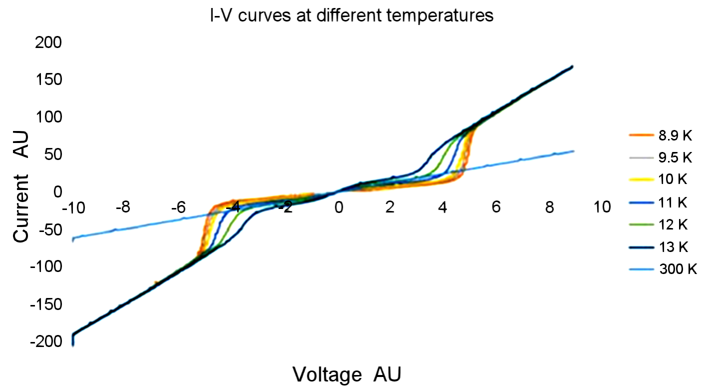

Figure 3. SIS mixer I-V curves at different temperature (arbitrary units)

TERAHERTZ SENSOR COUPLING TO A PT15K CFA

The objective of this test was to couple a Terahertz sensor (SIS mixer) to an ALAT 15K CFA breadboard to cool it to its transition temperature.

The compressor used for this test was a ground compressor similar to one of the EM versions. ALAT has been able to reproduce for a third time the cryogenic performance of the PT15K. It demonstrates the robustness of the PT15K design and the manufacturing capabilities of Air Liquide for sensitive products.

The sensor has been directly connected to the cold tip of the PT15K. The mass of the ground sensors was around 150 g. The superconductor transition of the sensor is characterized thanks to an I-V curve. The results obtained at different temperatures are shown in Figure 3. The PT15K easily cools down the SIS mixer below its transition temperature.

PERSPECTIVES

This last HiPTC model (15K EM) is still on test campaign until the end of 2020. However, initial performance measurements demonstrate a very robust design (third model that provides the same cooling power). In addition, improvements implemented in the last model increased the reliability and performance of this cryocooler.

The next step will be to validate the stability of the performance during a long duration period (at least 6 months) and continue increasing the maturity of CFA, CPA and CCE.

As a preliminary development plan, we can expect a first FM to be delivered by 2027/2028

CONCLUSION

An efficient and mature 15 K pulse tube have been extensively tested and qualified. It is based on an intercepted low temperature cold finger precooled by a space flown 50 – 100 K pulse tube and using a common compressor. Three models have been tested showing a high level of reproducibility and efficient performance. SIS sensors have been tested when cooled by a HiPTC showing the expected performance and thus demonstrating the compatibility of the cooler with sensitive instruments.

This cooler is ready for the Athena mission with current steps focusing on efficient integration in the instrument.

ACKNOWLEDGMENT

We acknowledge the financial and technical support of the European Space Research and Technology Centre (European Space Agency/ESTEC Contract No. 4000121042/17/NL/HB)

AirLiquide would like to acknowledge Purple Mountain observatory and Sheng-Cai Shi and his team for the SIS mixer detector and the interpretation of the data.

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