7K - 15K Pulse Tube Cooler for Space

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ABSTRACT

Highly sensitive bolometers as used for X-ray (e.g. XMS on Athena) or Far-IR (e.g. SAFARI on SPICA) observations require cooling down to 50 mK. To achieve this in a closed cycle cooling chain offering a long mission life, a 15 K pre-cooler for the Joule-Thomson (JT) cooler is required. One solution currently under development and partly funded by European Space Agency (ESA) is the 15 K Pulse Tube cooler. This cooler is a 3-stage cooler providing cooling power at 15, 50 and 120 K.

This project includes a breadboard phase to demonstrate the feasibility of our concept, followed by the design and manufacture of an engineering model. We present here the experimental results for a breadboard pulse tube cold finger providing cooling capacity from 7 K to 15 K. In a laboratory configuration, the specification of 400 mW of cooling power at 40 K has been exceeded. The configuration selected for the engineering model cooler is presented.

This configuration is based on a coaxial two-stage pulse tube cooler providing precooling to a low temperature pulse tube cooler. Details on the trade-off and experimental results are presented.

INTRODUCTION

Future astrophysical space missions are aiming at long duration, over 3 years, ruling out the possibility of relying on cryogenic fluid as was the case for Herschel mission. Currently, temperatures down to 50 mK are necessary to provide the sensitivity required for the mission. Such cooling requirements are commonly based on full cryogenic chains including a sub-Kelvin cooler, a JT cooler and a precooler. The technology presented in this paper deals with such an objective, originally identified as a need for the International X-ray Observatory (IXO) mission. The IXO mission, which evolved into the Access on Theaters for European Allied Forces Nations (ATHENA) satellite, has not been selected by ESA. However the need for such coolers is still identified as being critical, either as a precooler or even as a stand-alone cooler. For example, the design for the Space Infrared Telescope for Cosmology and Astrophics (SPICA)/SpicA FAR-infrared Instrument (SAFARI) instruments[1] or of the PIXIE satellite[2] is based on the same philosophy of cryogenic chain. To be efficient, JT loop needs to be precooled down to a temperature of 15 to 20 K[3,4].

For precooling at 15 or 20 K, several technologies can be used. For the Planck satellite a H_2 sorption cooler[5] was developed. This solution with no moving parts offers cooling at about 20 K using 3 precooling stages obtained by a passive radiator. Stirling coolers could be used and in Europe, a 10 K two-stage Stirling cooler is being developed[6]. Pulse tube coolers, which are discussed in this

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paper, are another alternative. The absence of cold moving parts for pulse tube cooler has many advantages discussed elsewhere (vibrations, integration, reliability). Such cryocoolers have demonstrated the ability to achieve temperature below 10 K for space[7] applications or on the ground[8]. Finally, some developments have been done on the coupling[9] of a Stirling cooler and a pulse tube for 10 K operation.

In the previous years, we developed and presented[10] a pulse tube cooler optimized for 20 K operation. An engineering model (EM) model for space application has been manufactured and tested and 300 mW of cooling power at 17.7 K has been measured[11]. By design this cooler took advantage of a pre-cooling stage at around 80 Kelvin, compatible with a radiation panel. We call further "intercepted pulse tube", such cold finger taking advantage of possible precooling. The new program described here is partly funded under an ESA grant. Our objective is the development of a fully autonomous cryocooler able to provide 400 mW of cooling power at 15 K with additional cooling capability at two intermediate temperatures (50 and 120 K). An EM of the cooler will be manufactured and will follow an environmental test campaign. Also, in parallel to this contract a 2-stage pulse tube cooler has been developed at CEA/SBT. It is partly funded by CNES. Performances obtained[12] on a U-tube demonstration model have shown high cooling power available at 2 levels of temperature. A coaxial EM has been manufactured and is currently being tested.

DEVELOPMENT STATUS

As a preliminary approach to the design and realization of this three stage cooler, a series of measurements and tests on a demonstration model was undertaken. Experimental results on a cold stage have been presented[13] showing 8.9 K no load temperature of cooling power exceeding 650 mW at 15 K. These developments have continued toward a more integrated design. Most of the measurements have been done using a secondary compressor used for active phase shift control as previously described[14]. Based on these preliminary measurements, the proposed configuration for this 15 K cryocooler is the coupling of a two-stage pulse tube with an intercepted pulse tube as presented in Figure 1. The two thermal links are used to precool the 15 K cold finger using cooling power available from the two stage pulse tube working in parallel. This two-stage cold finger is also used to provide additional heat lift capacity at intermediate temperatures. This modular configuration is advantageous as the different stages can be optimized separately. In this paper, experimental results on the cold finger studies are presented. Compressor development, which is also part of this project, is undertaken by Thales Cryogenics B.V.

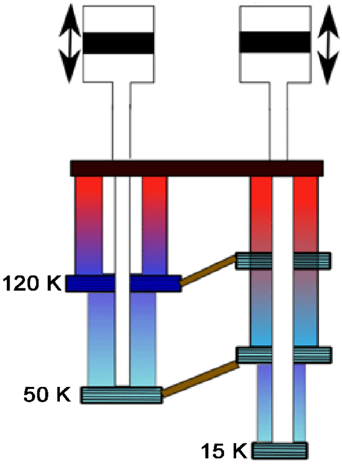

Figure 1. Configuration for a 3 temperature stage coolers based on one two-stage cold finger and a one stage cold-finger with heat intercept.

FOUR PROTOTYPING CONFIGURATIONS

Experimental work on intercepted cold finger is presented here. Four configurations were used and are described below. For all these configurations, optimization of cooling power as a function of input power and frequency has been completed. Heat flow measurements have also been performed for all prototypes as described below.

Configuration A: Test Cryostat with Active Phase Shifter

This configuration, which is not planned to be used on an integrated prototype, let us study various cold finger parameters such as tube and regenerator geometry, type of regenerator material and so on. The two intercepts gave also information on heat fluxes on the intercept. This configuration is presented in Figure 2. Previous work has been described earlier[13]. The lowest temperature reported in this configuration was 8.9 K.

Configuration B: Coaxial Pulse Tube with Intercept with Active Phase Shifter

The coaxial configuration is compact and provides easy integration as seen in Figure 3. Using dedicated materials developed and tested in configuration A led to improved performance: a low temperature of 6.5 K with precooling at 50 K and power in excess of 500 mW at 15 K.

For some practical reasons, the regenerator used in this configuration had larger pressure loss than in the configuration A (longer length for a similar cross section). It could be seen in Figure 4 that the slope of the power versus temperature plot has decreased, which we attribute to a longer regenerator. Depending on the nominal operating point (lower temperature or larger cooling power), it is advantageous to aim for lower temperature or for a steeper slope. Also, to take into account

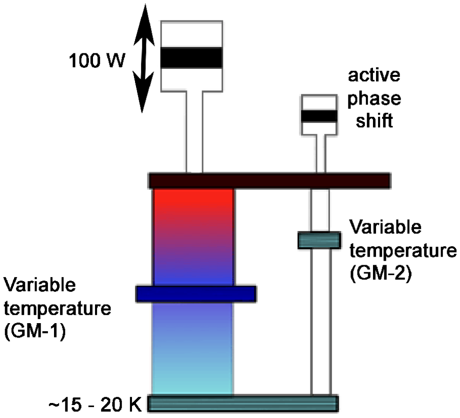

Figure 2. Configuration A: Pulse tube with intercept on tube and regenerator and active phase shift.

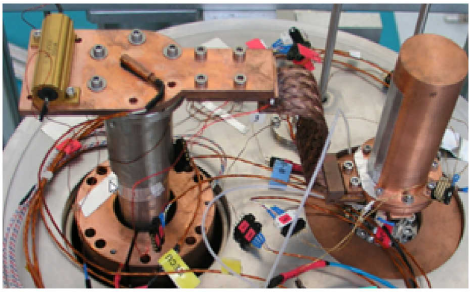

Figure 3. Configuration B Test bench of the coaxial pulse tube with one heat intercept

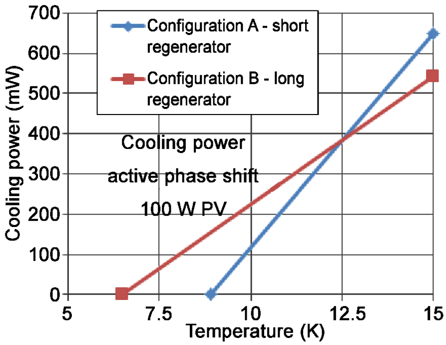

Figure 4. Comparison of cooling powers measured in configuration A and B

compressor design constraints and limit swept volume, it has been decided to use an operating frequency of 35 Hz. With this constraint, the available cooling power at 15 K is reduced by about 150 mW to 400 mW.

Configuration C: Coaxial Pulse Tube with Two Intercepts and Active Phase Shifter

The heat lift on the intercept has been measured to be in the order of 4 to 5 Watts.The required heat lift would be too costly to implement if lifted at 50 or even 80 K. By using two heat intercepts, a much more efficient way of precooling the regenerator is achieved: the main part of the load is extracted at a higher temperature, around 120 K, while precooling at a temperature around 50 K is achieved at a smaller thermal cost. To validate this possibility and to measure heat fluxes, a new configuration has been tested and is described in Figure 5. In this configuration, measurements of

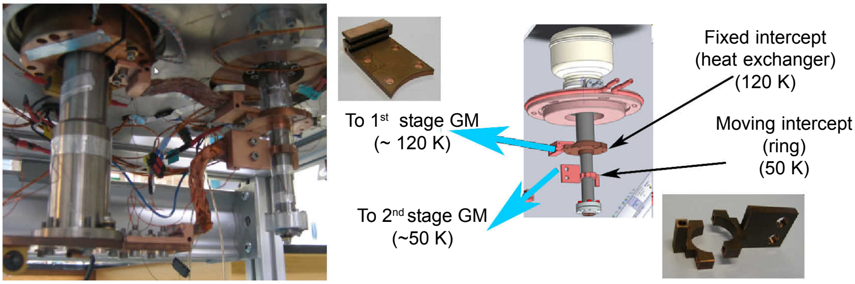

Figure 5. Configuration C and D. Coaxial pulse tube with two heat intercept. Left is picture of experimental setup with precooling using GM cooler.

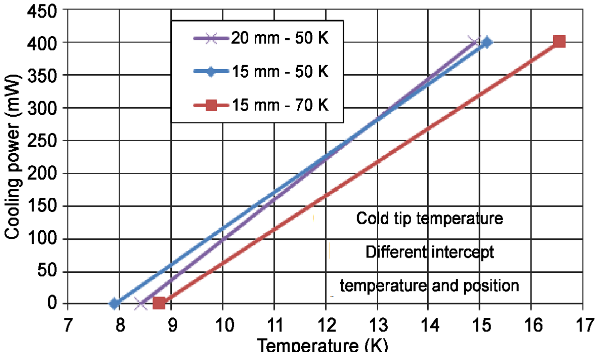

Figure 6. Cooling power measured with different position and temperature of second heat intercept for Configuration C

heat intercept power on the order of 1 to 3 W have been achieved as is discussed below. Cooling power of 400 mW at less than 15 K has been measured as seen in Figure 6. In this figure, the impact on cooling power of a variation of the intercept temperature can be extrapolated from the measurements presented.

Configuration D: Coaxial Pulse Tube with Two Intercepts and Inertances

The configuration C gives very promising results, with cooling power in excess of 400 mW and heat requirements at the intercept compatible with a two-stage pulse tube. The active phase shift configuration is a very efficient solution but add complexity to the system. Using inertance would reduce the number of moving parts and could improve the integration. The difference between inertance and inertance and double inlet and active phase shifter has been evaluated and is presented in Figure 7.

The different phase shifter mechanisms can be compared in Figure 7. It is apparent that the use of an active phase shifter has a significant impact on the cooling power at 15 K. However, for simplification and easier integration, we favor the use of an inertance with or without double inlet.

HEAT FLOW AT INTERCEPT

Heat flow measurements have been done for all prototypes. The test configuration is seen in Figure 8. In principle, these measurements are straightforward: a copper braid between the cold source, the GM cooler and the pulse tube is used. The copper braid acts both as a thermal link and

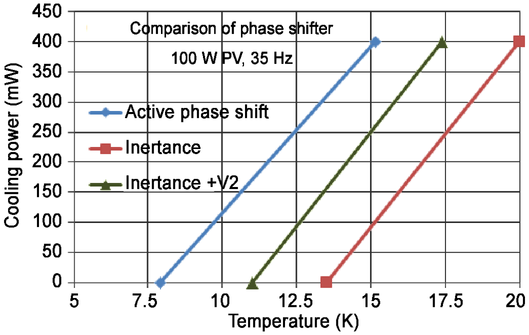

Figure 7. Comparison of cooling power measured with different phase shifters

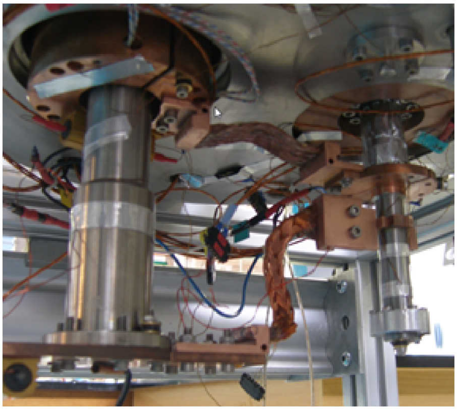

Figure 8. Test bench with two copper braids for measurements of heat flows at intercepts.

as heat flow measuring device. The copper braid is first calibrated, when not connected to the pulse tube and with heaters and then by measurements of temperature on both side and interpolation of the calibration data, the measurements are done. Despite the simplicity of the method, this is rather indirect and imprecision comes from the radiative background for example. We estimate that the precision is on the order of 10 to 20% of the measurements. Typical measurements are on the order of 4 to 5 Watts of cooling power when only one intercept is used. The results of the measurements are found in Figure 9. Using two heat intercepts, the power measured to be of the order of 4 W on the first stage and 1.4 W on the second stage as can be seen in Figure 9. We verified that the flow in the second stage can be decreased by adjusting the position of the moving heat intercept visible on Figure 5.

DEVELOPMENT

Based on the measurements in the various configuration described above, a fully autonomous pulse tube tube cooler is being designed. As presented in Figure 1, this cooler will be based on the coupling of a two-stage pulse tube developed separately and an intercepted cold finger similar to the configuration 4 described above. A possible integration of these two cold fingers is presented in Figure 10. Two compressors will be used to power the cold fingers with a total electrical power of 460 Watts. The compressors are being designed by Thales Cryogenics B.V. An EM of this full assembly will be realized at Air Liquide Advandced Technology.

CONCLUSION

Work on low temperature high frequency pulse tube cooler for space implies development on special regenerator materials for one part and on the choice of an optimum configuration. This

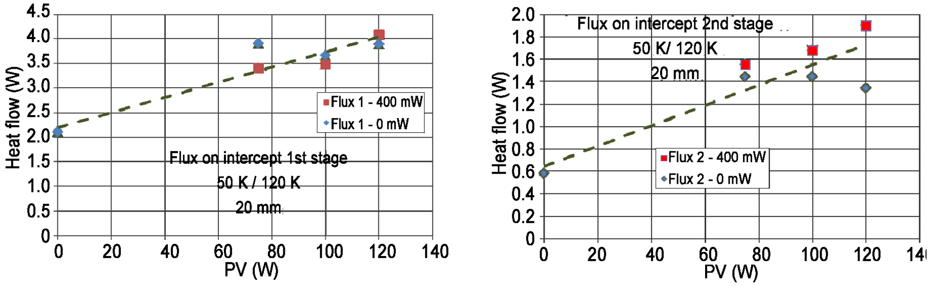

Figure 9. Heat flow measurements on two intercepts in configuration C with active phase shift.

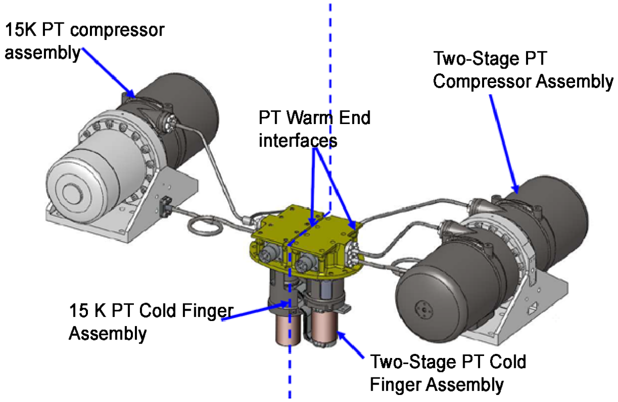

Figure 10. Schematic of a possible version for an integrated EM pulse tube

configuration should guarantee an efficient operation of the cooler leading to an optimization in mass and power consumption. The design should also take into account short development time which leads us to favor a modular conception with two independent cold fingers. We designed a pulse tube cooler aimed at providing 400 mW of cooling power at 15 K. During the experimental phase, we measured an ultimate temperature of 6.5 K and a cooling power of more than 650 mW at 15 K on a coaxial low temperature pulse tube. Such performance is suitable for JT precooling or for the cooling of low temperature detectors down to 7 or 8 K.

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REFERENCES

1. Sugita, H., Y. Sato, T. Nakagawa, T. Yamawaki, H. Murakami, H. Matsuhara, M. Murakami, et al., " Cryogenic system design of the next generation infrared space telescope SPICA," *Cryogenics,* Vol. 50 (2010), pp 566–571.
2. Di Pirro, M., Fixsen, D., Kogut, A., Li, X., Marquardt, J. and Shirron, P.. "Design of the PIXIE cryogenic system," *Cryogenics,* Vol 52, (2012), pp.134–139.
3. Sato, Y. et al., "Development of mechanical cryocoolers for Astro-H/SXS," *Cryogenics.* Vol 50, (2010), pp. 500-506.
4. Bradshaw, T.W., and Orlowska, A.H., "Technology developments on the 4 K cooling system for Planck and FIRST," S*ixth European Symposium on Space Environmental Control Systems,* Vol. 400 (1997), pp. 465-470.
5. Morgante, G, Pearson, D., Melot, F., Stassi, P., Terenzi, L., Wilson, P., Hernandez, B., et. al., "Cryogenic characterization of the Planck sorption cooler system flight model," *Journal of Instrumentation,* Vol. 4 (2009), pp. 12016.
6. Orlowska, A.H., Bradshaw, T.W., Scull,S. and Tomlinson, B.J.. « Progress Towards the Development of a 10K Closed Cycle Cooler for Space Use». *Cryocoolers* 10, Kluwer Academic/Plenum Publishers, New York (2002), pp 67-76.
7. Jaco et al "10 K Pulse Tube cooler Performance Data", *Cryocooler* 15 Kluwer Academic/Plenum Publishers, New York (2009), pp143-148.
8. Qiu, L.M., Cao, Q., Zhi, X.Q., Gan, Z.H., Yu, Y.B., and Liu, Y., "A three-stage Stirling pulse tube cryocooler operating below the critical point of helium-4," *Cryogenics,* Vol. 51 (2011), pp 609–612.
9. Kirkconnell, C.S., Hon, R.C. and Roberts, T. "Raytheon Stirling/Pulse Tube Cryocooler Maturation Program," *Cryocooler 15,* Kluwer Academic/Plenum Publishers, New York (2009), pp31-37.
10. Duval J-M et al. « Experimental results of 20 K Pulse Tube Cold fingers for Space Applications, *Cryocoolers 15*, ICC Press, Boulder, CO (2009), pp 71-77.
11. Trollier, T, Tanchon, J., Duval, J.M., and Charles, I., "GSTP 20-50 K Pulse Tube Cooler – Final results" ESA report.
12. Charles, I., Ercolani, E. and Christophe, D. "Preliminary thermal testing of a high frequency two-stage coaxial pulse tube for earth observation mission," ICEC 2012 (to be published).
13. Duval J.M. and Charles, I., "Development and experimental results on 15 K pulse tube," *Adv. in Cryogenic Engineering*, Vol. 57, Amer. Institute of Physics, Melville, NY (2012), pp. 1040-1050.
14. Charles, I., Golanski, L., Gauthier, A., Coynel, A. and Duval, J.M., "20 K coaxial pulse tube using passive precooling," *Adv. in Cryogenic Engineering*, Vol. 53, Amer. Institute of Physics, Melville, NY (2008), pp. 887–894.