Small Scale 80K Pulse Tube Cooler for RAPID e-APD Infrared Camera

J. Tanchon[1], T. Trollier[1], Y. Icart[1], A. Ravex[1], P. Feautrier[2], E. Stadler[2]

[1]Absolut System SAS
Meylan 38240 FRANCE
[2]Institut de Planétologie et Astrophysique de Grenoble, IPAG
Saint Martin d'Hères 38400 FRANCE

ABSTRACT

The RAPID project (Revolutionary Avalanche Photodiode Infrared Detector) aims to develop a highly-sensitive HgCdTe avalanche diode matrices (e-APD), typically 320x256 pixels in size, operating at cryogenic temperatures. This next generation detector will target applications such as medical imaging, scientific instrumentation, spectroscopy for gas analysis, and military applications like hyperspectral detection and active imaging. The first demonstrations of the RAPID project will concern the astronomical applications of such detector with a high performances infrared wavefront sensor and an infrared fringe sensor for interferometric light combination of several ground based telescopes.

A high efficiency 1.5W @ 77K coaxial pulse tube cooler has been developed, manufactured and tested for this project. An LSF91xx type commercial compressor from Thales Cryogenics BV has been modified to enhance the overall efficiency of the cooler.

The paper presents the optimization and the successful test results of the small scale cooler. The integration constraints of the cooler inside the RAPID cryostat and RAPID camera are also presented.

INTRODUCTION

The RAPID program is a 4 years R&D project funded by the French "Fonds Unique Interministériel" in 2009. It includes several industrial and academic partners in the field of advanced infrared focal plane arrays fabrication (SOFRADIR, CEA-LETI) and of astronomical/defense institutes (IPAG, LAM, ONERA). The goal of this program is to develop a fast and low noise infrared focal plane array of moderate format for astronomical application like adaptive optics wavefront sensing and fringe tracking for astronomical interferometers[1].

RAPID is a 320x256 infrared focal plane array based on the e-APD HgCdTe technology. The APD applies moderate multiplication gain without adding noise, therefore lowering the readout noise with almost no penalty. This is the only way to reach the fast frame rates required by wavefront sensing with readout noise lower than 5 e. This kind of performance can not been achieved by classical HgCdTe arrays, the APD technology is absolutely necessary.

A First Light Imaging[2] RAPID camera system based on the developments described in this paper will be commercially available in 2014.

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OBJECTIVES OF THE RAPID PROJECT

The ultimate objective of the RAPID development is to demonstrate operation of the 320x256 pixels 30 microns pitch infrared array at 2000 fps with 2 e- readout noise. To achieve such readout noise and fast frame rate, APDs technology and intra-pixel Correlated Double Sampling were both needed. The focal plan of the device is shown in the Figure 1. It includes 8 parallel outputs clocked at a 20 MHz pixel rate defining 8 stripes of 40x256 pixels with one amplifier per stripe.

The multiplication gain of the APD depends on the cutoff wavelength and the reverse bias voltage of the photodiode, and also, with less sensitivity, depends on the detector temperature. The gain increases with the bias voltage, the cutoff wavelength and decreases with the temperature. Increasing the cutoff wavelength increases the gain and the dark signal, and the requirement for a colder operating temperature.

SSC80 PULSE TUBE CRYOCOOLER DESIGN

In order to provide cryogenic cooling of the ADP detector, a Small Scale 80K Cooler has been designed and manufactured for RAPID project. This cooler is based on the Pulse Tube technology and has been fully customized to answer RAPID performance requirements. Several commercial cryocoolers exist in the 1.5W @ 80K cooling power range. These cryocoolers are commercially available at low cost and reduced lead time, but with reduced efficiency, basic interfaces definition and with low level of integration with cryostat. For the RAPID project, the cooling power capability, the power consumption and thermal interface management are particularly critical.

It was then required to produce a technical solution able to exceed the existing commercial products performance while offering a customized product definition to optimize integration within the cryostat. The results of this work with IPAG project team is presented in the following sections.

Cold Finger Design

A split coaxial architecture using a double diameter inertance mode has been selected due to high relevant experience gained in previous 50-80K cryocooler developments[3]. The SSC80 Pulse Tube cold finger is found in Figure 2.

The hot flange is made with an aluminum 6061T6 alloy, selected to optimize the thermal performances of aftercooler heat exchanger EDM cut inside the flange and mechanical aspects, including stress corrosion resistance. The warm-end flange integrates the heat rejection area for heat sinking and vacuum flange interface with cryostat.

The cold finger is made with Ti-6Al-4V thin tube filled with a regenerator matrix and pulse tube. The Ti-6Al-4V material has been selected for its good thermal performances and machinability. The cold heat exchanger is made in OFHC copper which is high vacuum brazed on the Ti-6Al-4V regenerator tube. This kind of process can be implemented on low volume production, like it is the case in RAPID project.

In order to reduce the radiative heat exchange between the cold tip and the surroundings at ambient temperature, the cold heat exchanger is gold coated. This coating enhances the conductance of the thermal contact for high conductive heat transfer with the attached thermal link. In

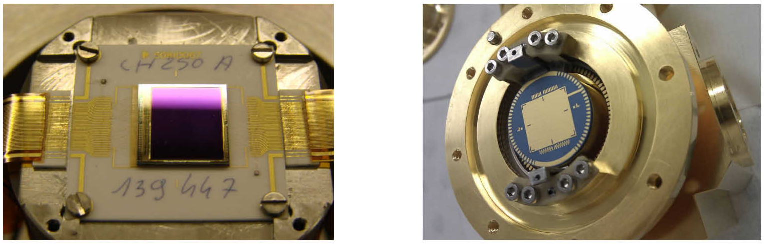

Figure 1. The 320x256 pixels RAPID infrared e-APD in the SOFRADIR detector test cryostat (left) and the RAPID cryostat with the cold ceramic before integration of the detector (right)

Figure 2. SSC80 Pulse Tube cold head during assembling (left) and after assembling (right)

order to reduce the parasitic heat losses on the cold tip, a heat intercepted cold shield has been placed at an intermediate position along regenerator length. This cold shield drastically reduces the radiative heat losses in the overall budget. The load absorbed on the cold shield is injected inside the regenerator with minor impact on the cryogenic performance of the cooler. This solution allows completely removing the multilayer insulation which is a source of outgassing and contamination risks close to the focal plane area.

Compressor Custom Design for the SCC80 Cooler

The compressor used for the SSC80 cooler is manufactured by our partner Thales Cryogenics BV (see Figure 3). The LSF91XX series has been selected to fit the cold finger design. This compressor is a flexure bearing compressor with a moving magnet design. In order to improve the performance of the LSF91XX compressor, some design improvements have been done on the compressor standard definition. In order to increase the filling pressure, the material used for the outer casing of the compressor has been changed from 304SS to Inconel which offers a higher mechanical margin.

The piston diameters have been also decreased in order to match the compressor characteristics with the damping of the cold head estimated with internal modeling performed during the design phase. The modification of the piston diameter allows also an increase of the compressor efficiency by a few percents.

The compressor is controlled using a standard HPCDE (High Power Cooler Drive Electronic) developed and manufactured by Thales Cryogenics BV. The Cooler Drive Electronics (CDE) converts a DC voltage into a regulated AC output voltage to the cryocooler in order to achieve a constant temperature at sensor level. The CDE insures the control of the cryocooler during the cool down phase and the regulated mode. The CDE also provides the bias current required for temperature sensing diode used for the temperature regulation loop.

(a)

(b)

Figure 3: (a) Thales SSC80 Cooler. (b) High Power Drive Electronics

SCC80 Cooler Performance

The SCC80 Pulse tube cooler has been tested and optimized to meet the performance requirements (see Figure 4). The allowed input power for the cooler is in the range of 60Wac for a cooling capacity above 1.5W @ 80K and for a warm end temperature controlled at 20 °C. These performances are not inaccessible, particularly for high-rel space cryocoolers class which are very efficient but with a cost which is not affordable for the ground applications like RAPID camera. The challenge was to obtain the required efficiency with an intermediate class and cost range cooler.

After several optimizations of the phase shifter, the optimal performances of the SSC80 cooler has been reached. The best configuration selected for the phase shifter is a two diameters inertance mode wound on a large diameter. The inertance has been placed in a mechanical support to maintain the tubes and to protect them during integration and future utilization of the system.

The double inertance mode demonstrated a significant improvement for the cryogenic performances of pulse tube coolers. For the SSC80 cooler, this mode increases the cooling power by about 15% after frequency tuning at a constant input power. The second aspect optimized during the test was the geometry of the inertance assembly. The shape of the inertance tube is very important for the performance optimization. For a straight inertance, the gain compared to a wounded inertance within the buffer volume is in the range of 14% and when we combine the double diameter and the shape optimization, we can improve the cooler performances by 24%.

Table 1 describes the cooling power measured at 80K for different phase shifter configurations. The "single diameter" corresponds to simple capillary with a constant diameter along the length while for the "double diameter" mode, the inertance is made with two different capillary diameters. The inertance shape corresponds to the straight or wounded inertance configurations. The cooling power at 80K is reported for constant input power and warm-end temperature. Finally, the last column reports the percentage of improvement of the cooling capacity compared to the reference point which is the single diameter tube in wounded configuration.

Based on the optimization test campaign, the configuration selected for the RAPID SSC80 cooler is the double diameter inertance in the wounded configuration. The characterization of the SCC80 cooler in its final configuration is found in Figure 5. The SSC80 cooler is able to provide more than 1.56W @ 80K with 60Wac at compressor interface for a warm-end temperature regulated at 20 °C.

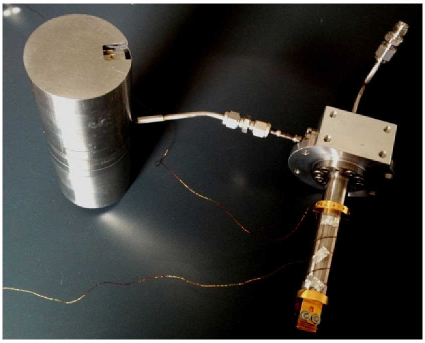

Figure 4. SSC80 Pulse Tube cooler during performance optimization tests (without cold shield)

Table 1. Impact of the phase shifter configuration on the cooler performances at 80K

Inertance mode	Inertance shape	Cooling power @80K	% / reference
Single diameter	wounded	1.33	-
Single diameter	straight	1.54	14%
Double diameter	Wounded	1.56	15%
Double diameter	Straight	1.75	24%

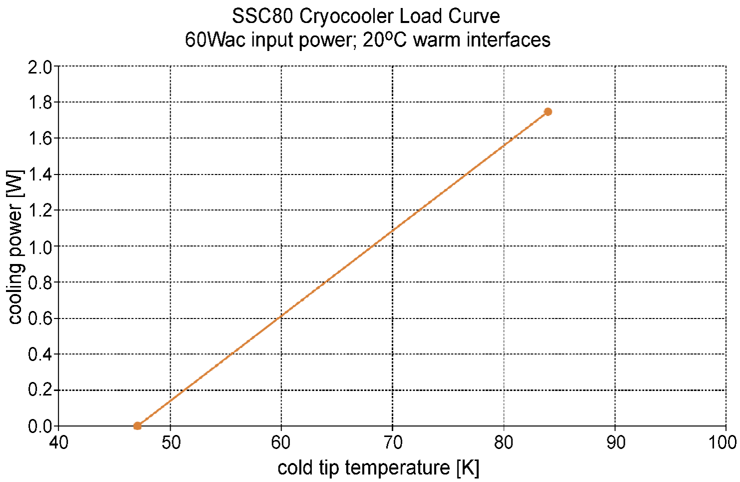

Figure 5. SSC80 cryocooler load curve

RAPID CRYOSTAT AND CRYOCOOLER INTEGRATION

For operation of the RAPID device on astronomical sites, a nitrogen free cryostat has been designed and manufactured to be connected to the SCC80 miniature vibration free pulse tube. As described previously, this pulse tube cooler is a customized Absolut System SAS development that provides more than 1.5W of cooling power at 80K with almost no vibrations. This allows for an extremely compact design of the cryostat in order to shorten the electrical wiring between the detector and the front end electronics to less than 5 cm. Figure 6 describes the different components of the RAPID cryostat. The focal plane assembly of the cryostat is cooled directly by the pulse tube cooler.

In order to reject the high wavelengths from background, low pass cold filters are implemented between the APD detector and the sapphire window. The low pass filters, with 1.9 µm cutoff capability, are cooled at 80K by conduction. An additional floating screen, see Figure 7 (right), is also

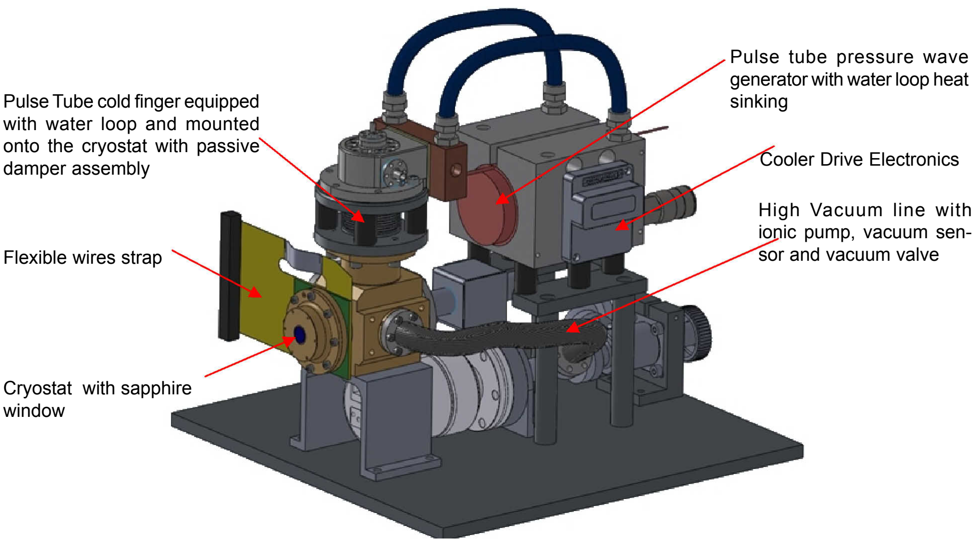

Figure 6. RAPID cryostat general overview

used to shield the cryostat background. It is anticipated that the short distances between the detector and the front end electronics will decrease the readout noise and will allow detector operation a 2 kHz frame rate with no penalty on the other performances.

The cryostat used for this application requires dimensional stability to suppress the relative displacements between components. For this reason, the cryostat, as seen in Figure 8, has been machined in a massive piece of Kovar material which offers a comparable Differential Thermal Expansion (DTE) to ceramics, sapphire and borosilicate materials used for the internal components and cryostat sealing. The cryostat has been gold coated internally and externally to reduce emissivity and to remove potential stress corrosion. To insure the thermal coupling between the APD detector and the SCC80 cold finger, a flexible copper strap thermal link has been manufactured.

Thermal Control Management

In order to insure the thermal control of the system, a water loop has been integrated onto the cryocooler with copper and aluminium heat exchangers. The compressor is directly mounted on its aluminium heat exchanger and is conduction cooled. The same heat exchanger is used to heat sink the CDE insuring the temperature regulation of the focal plane.

On the cold finger side, a copper heat exchanger is mounted on the warm-end interface. This thermal interface is particularly critical for the thermal efficiency of the Pulse Tube thermodynamic cycle and has to be managed carefully. In this application where the cryogenic operating temperature has to be as low as possible, a Thermo Electric Cooler (TEC) is implemented between the copper block and the warm-end cooler interface (see Figure 9).

This TEC module is used to transfer the rejected heat load from the warm-end to the water loop with an amplified temperature gradient compared to simple conduction cooling heat sinking mode. The warm-end temperature will then be 10K to 15K lower than the water loop temperature. This

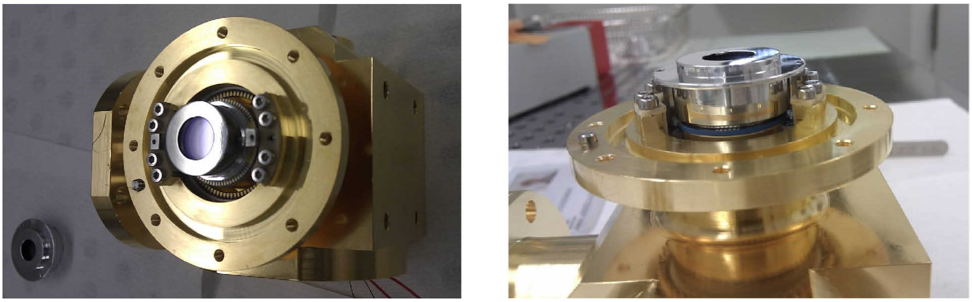

Figure 7. The RAPID cryostat with the cold filter (left) and with the additional floating shield (right).

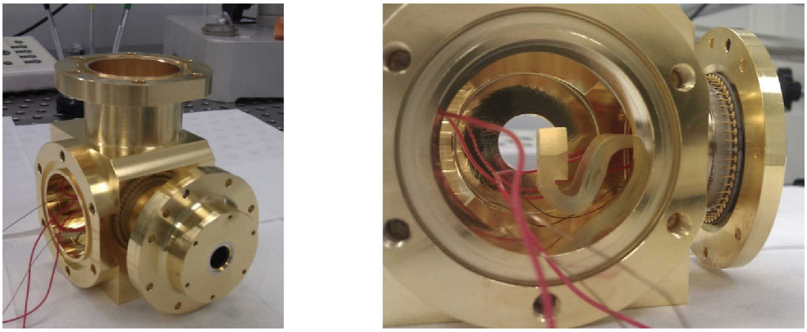

Figure 8. the RAPID cryostat in KOVAR gold coated (Left) and internal view of the RAPID cryostat with copper thermal link (Right)

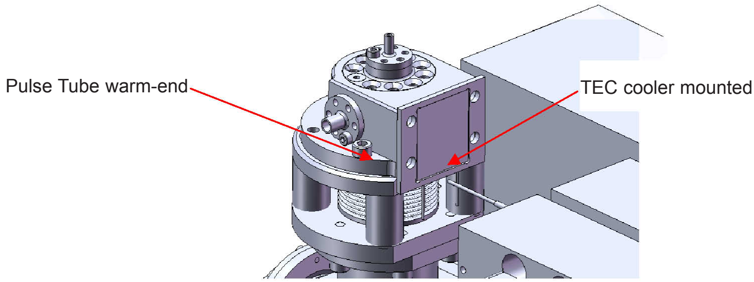

Figure 9. Peltier cooler integrated on the pulse tube warm-end

integration results in about 200mW additional heat lift capacity on the cryocooler performances at 80K.

To decrease the operating temperature of the cooler, it is necessary to minimize the parasitic heat losses of the cryostat. The dissipation of the APD detector is limited (in the range of 200mW). The main parasitic heat losses come from environment radiation and from the conduction through the electrical wiring between the detector and the front end electronics. The electrical wiring is very short (<5 cm) due to the constraints of noise and high speed operation of the camera. It is then not possible to reduce the contribution of the wiring on the overall losses budget. Main efforts remaining to optimize the performances shall be placed on the reduction of radiative heat losses. Several cold shields have then been implemented around the cold parts and components of the cryostat. The focal plan and the low pass filter have been shielded with a polished aluminium screen (see Figure 7) and the cold finger has been shielded with a gold coated copper screen fixed onto the cold finger's regenerator (Figure 2). The use of the intercepted cold shield allows to increase the cooling capacity of the cooler of about 180mW @ 80K compared to the naked regenerator with a standard cold heat exchanger low-emissivity coating.

Vibration Management

The objective of this camera is to perform adaptive optics wavefront sensing and fringe tracking for astronomical interferometers and both applications are very critical in term of displacements. It is then not possible to submit the APD detector to important induced vibrations.

For this reason, the Pulse Tube technology has been preferred to Stirling technology. But even if the residual vibration level of Pulse Tube cryocoolers is generally small, particular attention has been taken to disconnect mechanically the cryocooler from the RAPID camera. Passive dampers have been implemented to damp the residual vibrations both at cold finger and compressor mechanical interfaces (see Figure 10). On the cold finger side, a low stiffness metallic below is inserted between the vacuum flange of the cold finger and the cryostat to insure vacuum tightness of the assembly.

Vacuum Management

In nominal operation, the RAPID cryostat will operate in sealed mode. The dynamic pumping will be implemented for system testing phase but will be finally removed. For this reason a particular care has been taken on the material selection (reduction of outgassing) and on the sealing interfaces. Metallic spring energized seals have been selected for all the vacuum flange assemblies. A ionic pump could be implemented in the cryostat in order to re-pump during operation if the vacuum level is degraded. However, with the performance measured on the cryocooler, the operating temperature should decrease compared to the initial figures and then cryopumping should insure the required vacuum level with no need of additional pumping. Just below the focal plan, a zeolite volume has been implemented to increase the cryopumping capacity of the cooler. This volume is also equipped with a heater and a temperature sensor to insure periodic regeneration.

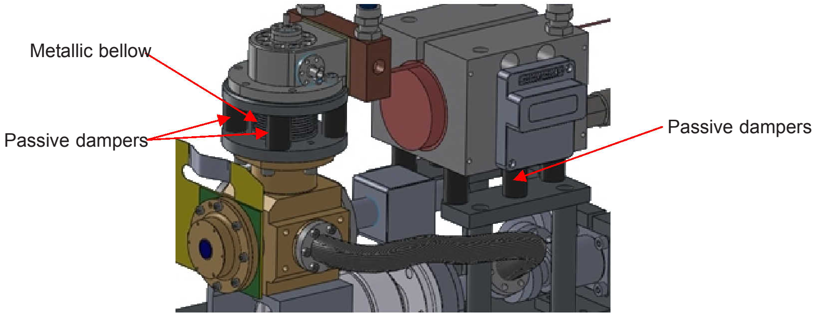

Figure 10. Residual vibration management of the pulse tube cooler

CONCLUSIONS

A 1.5W capacity Pulse Tube cooler has been designed and optimized for RAPID application. This cooler uses a commercial compressor but adapted to the Pulse Tube cold finger damping requirements. The compressor housing material has been changed from 304SS to Inconel and the piston diameters have been modified to reduce the compressor damping. The phase shifter of the cooler has been particularly optimized with double diameter inertance and several shapes have been tested. Significant performances improvements have been reported in this paper. Four cryocoolers have been manufactured based on the SCC80 cooler design. These coolers will be integrated soon on the cryostat assembly and delivered to IPAG to complete RAPID camera testing.

Finally a high performances cryostat has been designed for the RAPID application. The materials, the coatings or the components used have been selected carefully for their high performances. The result is a cryostat very similar to space systems with high-quality materials and high reliability components (detector, cryocooler, electronic).

REFERENCES

1. Feautrier, P., et al, "Advance in Detector Technologies for Visible and Infrared Wavefront Sensing," *Proc. of SPIE Astronomical Telescopes + Instrumentation 2012*, vol. 8447 (submitted for publication).

2. First Light Imaging, http://www.firstlight.fr

3. Trollier, T., Tanchon, J., Buquet, J. and Ravex, A., "Status of Air Liquide Space Pulse Tube Cryocoolers," *Cryocoolers 15*, ICC Press, Boulder, CO (2009), pp. 115-123.