CARMENES ultra-stable cooling system: very promising results

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ABSTRACT

CARMENES is a high resolution spectrograph to detect planets through the variation of radial velocity, destined for the Calar Alto Observatory in Almeria, Spain. The optical bench has a working temperature of 140K with a 24 hours stability of ±0,1K; goal ±0,01K. It is enclosed with a radiation shield actively cooled with thermalized nitrogen gas that flows through strategically positioned heat exchangers to remove its radiative load. The cooling system has an external preparation unit (N2GPU), which provides the nitrogen gas through actively vaporizing liquid nitrogen with heating resistances and a three stage circuit flow, each one controlled by an independent PID.

Since CARMENES is still in the construction phase, a dedicated test facility has been built in order to simulate the instrument and correctly establish the N2GPU parameters. Furthermore, the test facility allows a wide range of configurations set-ups, which enables a full characterization of the N2GPU and the cooling system.

The N2GPU has been designed to offer a wide temperature range of thermally stabilized nitrogen gas flow, which apart from CARMENES could also be used to provide ultra-high thermal stability in other cryogenic instruments. The present paper shows the testing of the cooling performance, the hardware used and the very promising results obtained.

Keywords: nitrogen circulation, cryogenics, cooling, thermal stability, large instrument, extrasolar planets, near-infrared instrumentation

1. INTRODUCTION

The CARMENES instrument is in the construction phase, some of the components are already built but some others, such as the vacuum vessel, the optical bench and the radiation shield, are on their way. These are key components for the active cooling of the near-infrared channel. To ensure that the cooling will accomplish the thermal specifications when the AIV phase arrives, a test facility was built in order to simulate the instrument.

An external nitrogen gas preparation unit (N2GPU) has been built, tested and set up to provide the right amount of nitrogen gas flow necessary to fulfil the thermal cooling requirements. A full description of the cooling system for the NIR channel of CARMENES can be found in a paper presented at SPIE 2012**.

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** Becerril, S., "CARMENES. III: an innovative and challenging cooling system for an ultra-stable NIR spectrograph", Proc. SPIE Volume 8450, article id. 84504L, 12 pp. (2012)

The present paper shows the promising results obtained during the testing of the N2GPU with the test facility. It also describes the hardware used, the set-up configuration parameters and finishes with the conclusions and improvements to be done next.

2. COOLING REQUIREMENTS

The following list shows the working conditions of the CARMENES instrument. As the test facility simulates CARMENES, the same conditions have been applied. From the list below, the working temperature stability is the most challenging one:

- Working temperature around 140K.
- Temperature stability of ±0.07 K (±0.01 K goal) in the timescale of 1 day.
- Pre-cooling time of 48h (goal), in this case, as there weren't any optics in the test facility this specification was reached in a few hours.
- Cool-down and warm-up rate for the optics <10 K/h. Again, as there weren't any optics in the test facility this specification was reached in a few hours.
- Liquid nitrogen consumption <150 l/day.
- Environment temperature 285±0.5 K, for the test we worked with a room temperature around 294K.
- Vacuum level ~10^{-6} mbar.

3. COOLING SYSTEM

The following sections describe the cooling system and the pieces of hardware used for the tests. Section 3.1 shows the final design of the NIR channel of CARMENES where all the cooling hardware is represented, making it easier to identify all these parts later on in the test facility. The test facility, section 3.3, has been built to simulate the CARMENES instrument. The cooling system is a new concept design and it was necessary to know whether this method was the right one as well as the liquid nitrogen consumption before the instrument was fully assembled.

The cooling system uses thermally stabilized nitrogen gas. To obtain this gas from liquid nitrogen a preparation unit has been built (N2GPU) (see section 3.2). The connections between the liquid nitrogen storage tank, the N2GPU and the test facility have been made using either liquid or gas transfer lines, all of them vacuum isolated in order to minimize the heat load to the coolant in the ducts.

3.1. CARMENES NIR channel overview

The cooling hardware is shown on the final design of the NIR channel of the CARMENES instrument. As mentioned before the same hardware is also simulated on the test facility. As can be seen on figures 1 and 2, the optical bench (in grey) and all the opto-mechanics (in pink) are enclosed in a radiation shield (in light blue). Both the optical bench and the radiation shield have cooling lines with strategically placed heat exchangers (in violet). The heat exchangers are connected between them with flexible and solid pipes. The cooling lines on the optical bench are only used for the pre-cooling of the opto-mechanics, with liquid nitrogen, until the steady-state temperature is reached; on the contrary, the cooling lines on the radiation shield are permanently actively cooled with the thermalized nitrogen gas coming from the N2GPU. Each cooling line has two heat exchangers. This number has been extracted from the previous paper presented at SPIE 2012** where the thermal analysis of the NIR channel of CARMENES was modelled. The flow of nitrogen gas enters through the inlet gas bayonets (in blue) and returns to the outlet gas bayonets (in red) and finally through the on/off valve. All the pipes and the radiation shield are wrapped in a multi-layer insulator.

Three epoxy fiberglass legs (in yellow) support and isolate the in-vacuum cooling hardware. The support legs and the cooling lines from the inlet/outlet gas bayonets to the flow splitters/collectors are the only path with heat load conduction. Figure 2 shows the bottom part of the instrument with the pre-cooling lines that go to the optical bench (in blue) and return (in red). The insulation support legs can also be clearly seen.

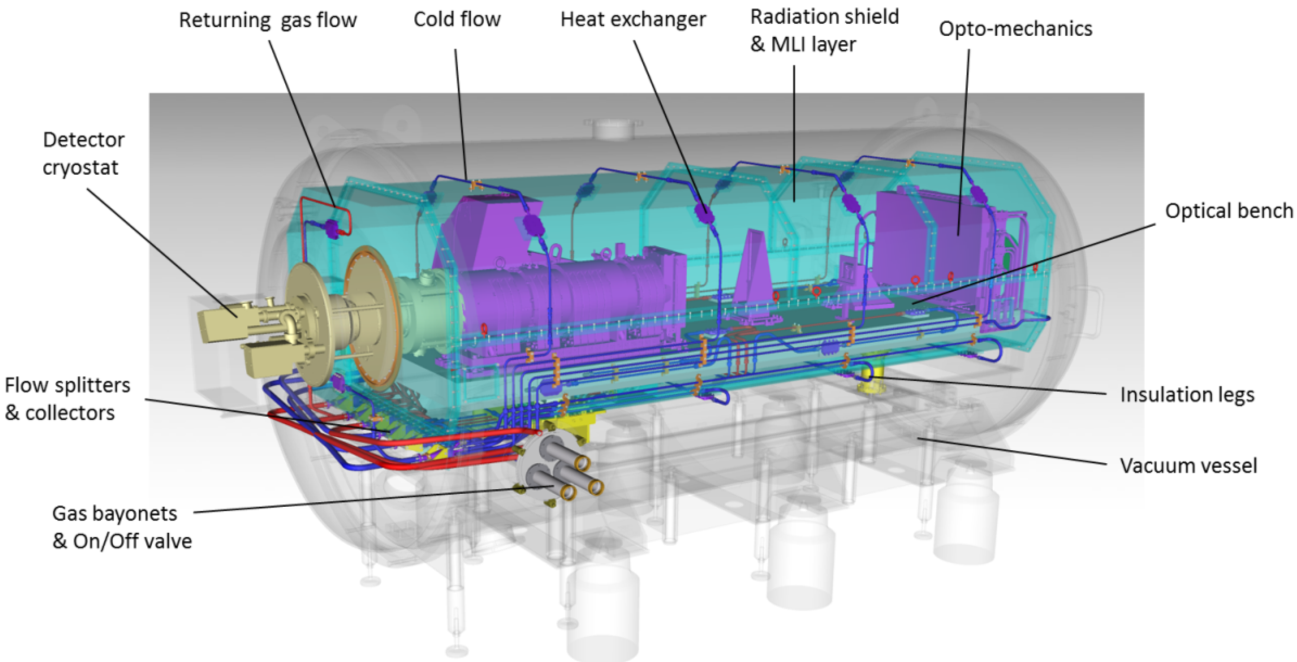

Figure 1. Final design of the NIR channel of CARMENES

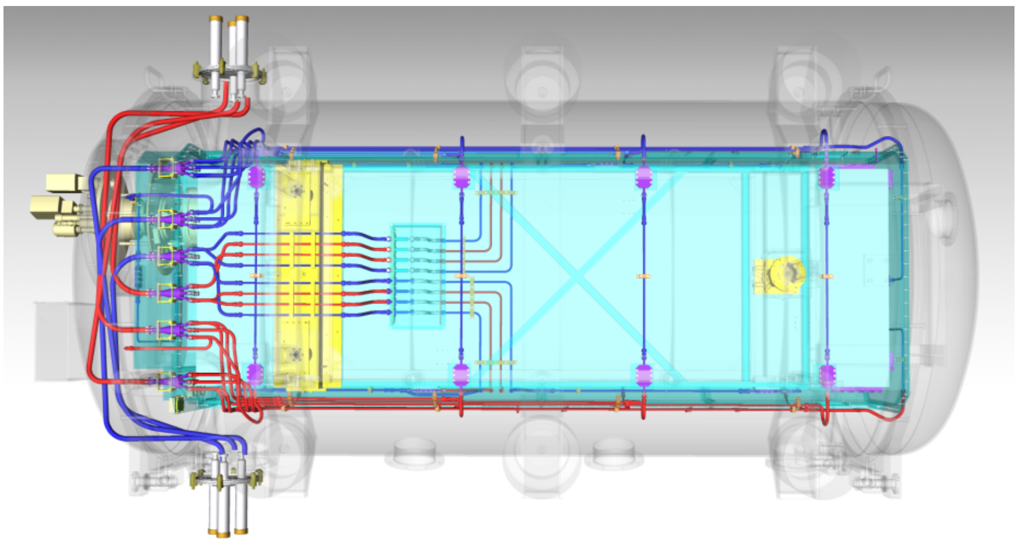

Figure 2. Bottom part of the instrument design

3.2. N2GPU

The nitrogen gas preparation unit has been designed to use liquid nitrogen stored in a tank to produce nitrogen gas at a stable and controlled temperature. The main reason why liquid nitrogen is not used instead is because the working temperature of CARMENES is 140K. This unit has been developed by ESO (Garching) within the collaboration frame of the CARMENES project. The aim of this development is to extend the use of these devices to the new generation of cryogenic instruments led by ESO.

A set of 3 PID controls the three stages of the gasification process, each one has a 240W power supplier for the heating elements of each stage. The liquid nitrogen enters the circuit through the inlet tube until the first stage: the vaporizer. This part is warmed up by heaters which convert the liquid nitrogen to gas. This flow enters the second stage, the cross section of this stage increases to accommodate the nitrogen gas as its volume compared to liquid is much higher. Next, it is distributed along the helicoil, until the final heat exchanger where the gas is thermally stabilized. Finally, it comes out through up to three outlet tubes. The system is isolated from the outside with a vacuum vessel. There are some ports installed for the electronic connectors and the vacuum pump. All main components are thermally isolated from the vacuum vessel using epoxy glass fingers.

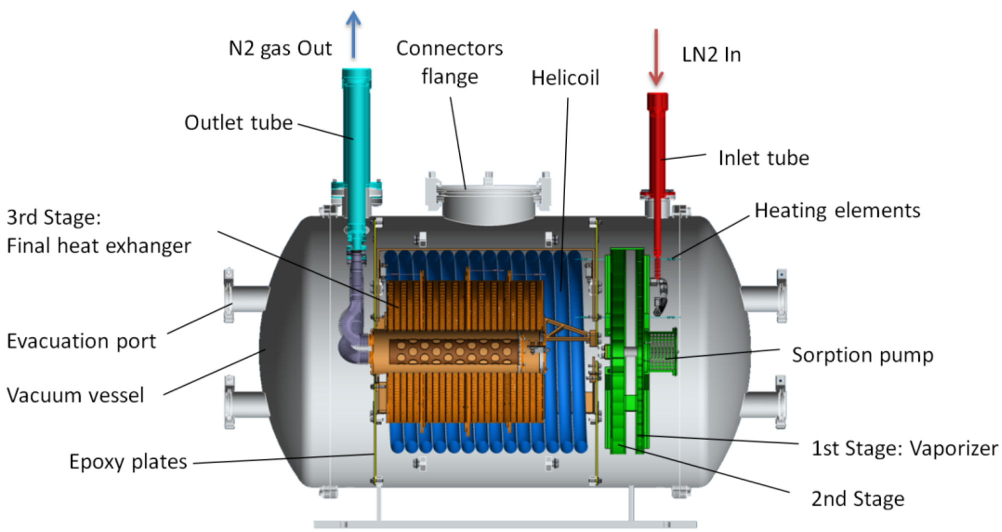

Figure 3. Nitrogen gas preparation unit N2GPU design

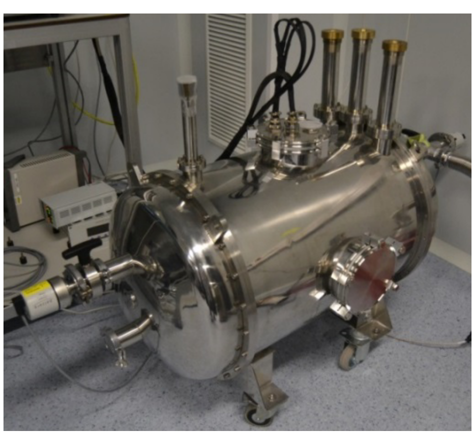

Figure 4. N2GPU assembled

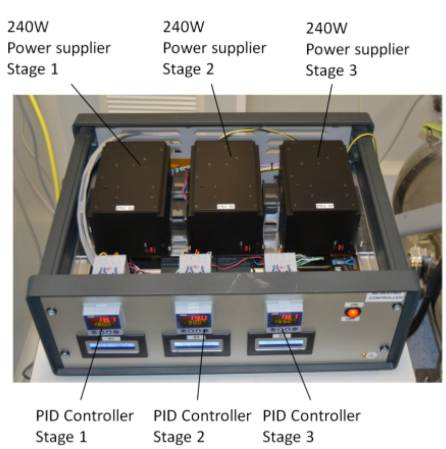

Figure 5. N2GPU PID's controller

3.2.1. Working modes

The N2GPU itself can only work in a continuous flow mode. However, with an independent cryogenic on/off valve at the end of the circuit with its own PID controller, it can be converted to a non-continuous flow. There are three active control inputs:

One is the overpressure of the liquid nitrogen storage tank that makes the nitrogen circulate. If this overpressure is too high, then the third stage is flooded with liquid nitrogen as the power of the heating elements is not enough to gasify all the accumulated nitrogen. To reduce the flow of liquid nitrogen at the entrance of the N2GPU and to be able to use a higher overpressure, a diaphragm placed at the end of the transfer line has been used. It reduces the section of the line and has the function of decreasing the amount of nitrogen flow. The overpressure parameter is adjusted in order to evacuate the heat load required while keeping the LN2 consumption within the requirements. Once the overpressure value is adjusted, it will be fixed permanently.

The second main control input is the power applied to the heating elements controlled by their own PID. As previously described, each stage has its own role, and the first stage is the one that sets the amount of nitrogen gas flow produced. If the first stage is at its maximum power it will gasify much more than at low power.

The third control input is the on/off valve, this mode allows the N2GPU to work with a higher overpressure, and therefore the cooling power is higher. This is because the on/off valve helps the third stage of the N2GPU not to flood. Indeed, when the valve is off the flow is stopped and the heating elements have time to gasify and thermalize all the nitrogen before the valve opens again.

3.3. TEST Facility

The test facility has been designed and built to simulate the CARMENES instrument. It is composed of a vacuum chamber of 500mm in diameter and 1000mm in height that simulates the vacuum vessel and contains an aluminum dummy mass of 34kg that simulates the optical bench. The dummy block has two heat exchangers made of copper attached to it and it is held from the top cover via a set of epoxy plates providing thermal insulation. These plates simulate the insulation support legs on the instrument.

A radiation shield encloses the dummy mass and has six heat exchangers made of copper connected in parallel attached to its external side. A set of copper foils are attached from the pre-cooling flow splitters to the radiation shield in order to simulate the link between them on the instrument. To reduce the heat loss everything is wrapped in multi-layer insulation, except the top and bottom covers of the radiation shield cylinder that are not covered with MLI because of the design. A set of temperature sensors is placed on the main in-vacuum hardware parts: the inlet and outlet gas bayonets, the aluminum block, the radiation shield and the pre-cooling inlet bayonet

Both the aluminum block and the radiation shield have independent cooling circuits: the cooling circuit for the aluminum block is shown on figure 8 and it is only used for its pre-cooling to reach the temperature of the steady state. Once this temperature is reached, the pre-cooling circuit is closed and the aluminum block then only receives radiation coming from the radiation shield and heat transfer through the insulation plates. On the contrary, the cooling circuit of the radiation shield, shown on figure 7, is always actively cooled with the cooling power of the thermalized nitrogen gas coming from the N2GPU. The cryogenic on/off valve at the end of this circuit allows it to work in with a non-continuous flow mode.

The cryogenic on/off valve opens and closes depending on the temperature of the gas collector at the end of the in-vacuum circuit. The valve is controlled by a PID module, that combined with the PIDs on the N2GPU, it allows a fast warm up of the gas when the valve is closed and a generous flow of nitrogen gas when the valve opens. An interesting subject of study would be the relation between both groups of PIDs.

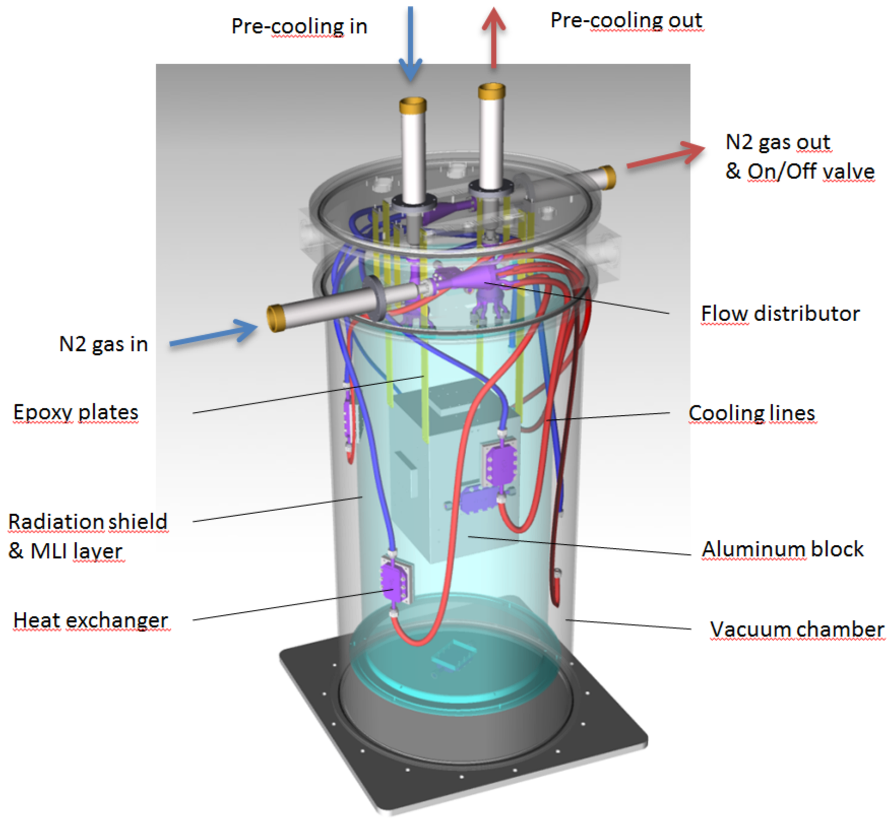

Figure 6. Test facility design

Figure 7. Test facility assembly with the radiation shield

Figure 8. Aluminum block of the test facility

4. TESTS IMPLEMENTED

4.1. TEST layout 1: N2GPU working alone

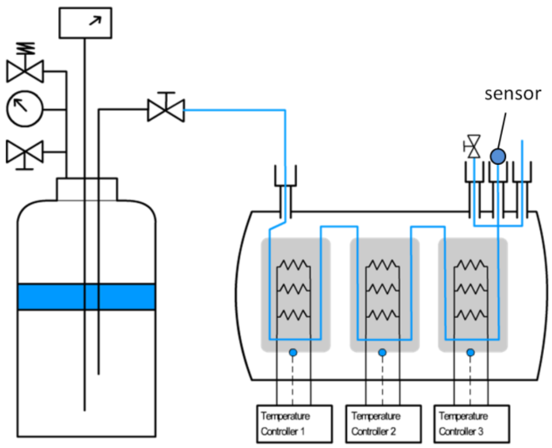

Figure 9. Test layout for the N2GPU working alone

These tests were carried out to establish the limits of the N2GPU working alone in different conditions. As explained before, the thermal conditions were reached through varying the overpressure on the nitrogen storage tank, the power supplied to the heating elements or the temperature set point. All these tests were done with two outlet bayonets opened to simulate how CARMENES will work.

To measure the outgoing thermally stabilized nitrogen gas temperature a diode sensor was attached to the end of one of the outlet bayonets, see figures 10 and 11. The set-up of the PID parameters was adjusted properly during the tests. Figure 9 shows the test layout of the N2GPU working alone with the liquid nitrogen.

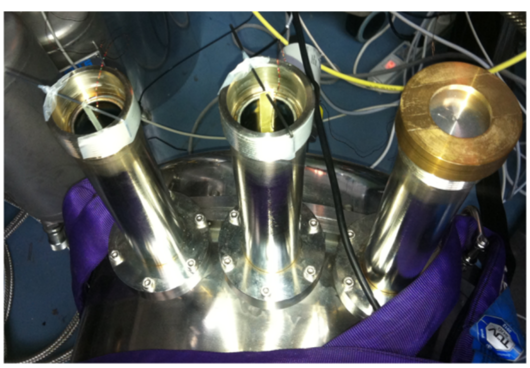

Figure 10. Two outlet bayonets opened

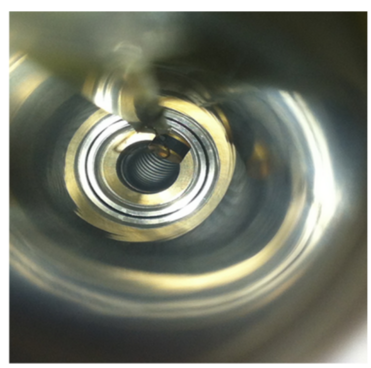

Figure 11. Diode sensor inside the bayonet

4.1.1. Test 1: Very low consumption rate at 140K

The objective of this first test was to obtain a stabilized temperature of the outlet gas at 140K with very low consumption of liquid nitrogen. To do so the heaters of the first stage were turned off to gasify less and the gasification process was mainly done at the second stage. As can be seen on the following list of the test configuration parameters, the temperature target of the second stage is significantly higher than the test target temperature, this is because the second stage responds very well to the PID control and therefore the third stage, which have a slower time response, would only need to adjust the thermal stabilization of the nitrogen gas.

- Power of the heaters of each stage:
    - 1st stage power fixed at 0W
    - 2nd stage power auto regulated by the PID with an average value of 67 W
    - 3rd stage power auto regulated by the PID with an average value of 216 W

- Temperature set point of the PID for each stage:
    - 1st stage temperature set point at 70 K
    - 2nd stage temperature set point at 153K
    - 3rd stage temperature set point at 133K

- Nitrogen storage tank overpressure at 0.2 bars
- Continuous flow mode
- Outlet gas temperature of 140K

4.1.2. Test 2: The highest stabilized gas flow at 140K

The objective of this second test was to obtain a stabilized temperature measurement at around 140K of the outlet gas producing the maximum amount of flow. Next list shows the tests configuration parameters:

- Power of the heaters of each stage:
    - 1st stage power fixed for the whole test at 223W
    - 2nd stage power fixed for the whole test at 67 W
    - 3rd stage power fixed for the whole test at 216 W

- Nitrogen storage tank overpressure of 0.12 bars
- Continuous flow mode
- Outlet gas temperature of 140K

4.1.3. Test 3: The coolest outlet gas flow

The objective of the third test was to establish the minimum temperature of the outlet gas that the N2GPU could produce with the maximum amount of flow. To do so the same parameters as the test 2 were taken but increasing the overpressure to 0.25 bars. The following list shows the test configuration parameters:

- Power of the heaters of each stage:
    - 1st stage power fixed for the whole test at 223W
    - 2nd stage power fixed for the whole test at 67 W
    - 3rd stage power fixed for the whole test at 216 W

- Nitrogen storage tank overpressure of 0.25 bars
- Continuous flow mode

4.2. TEST layout 2: CARMENES-like test

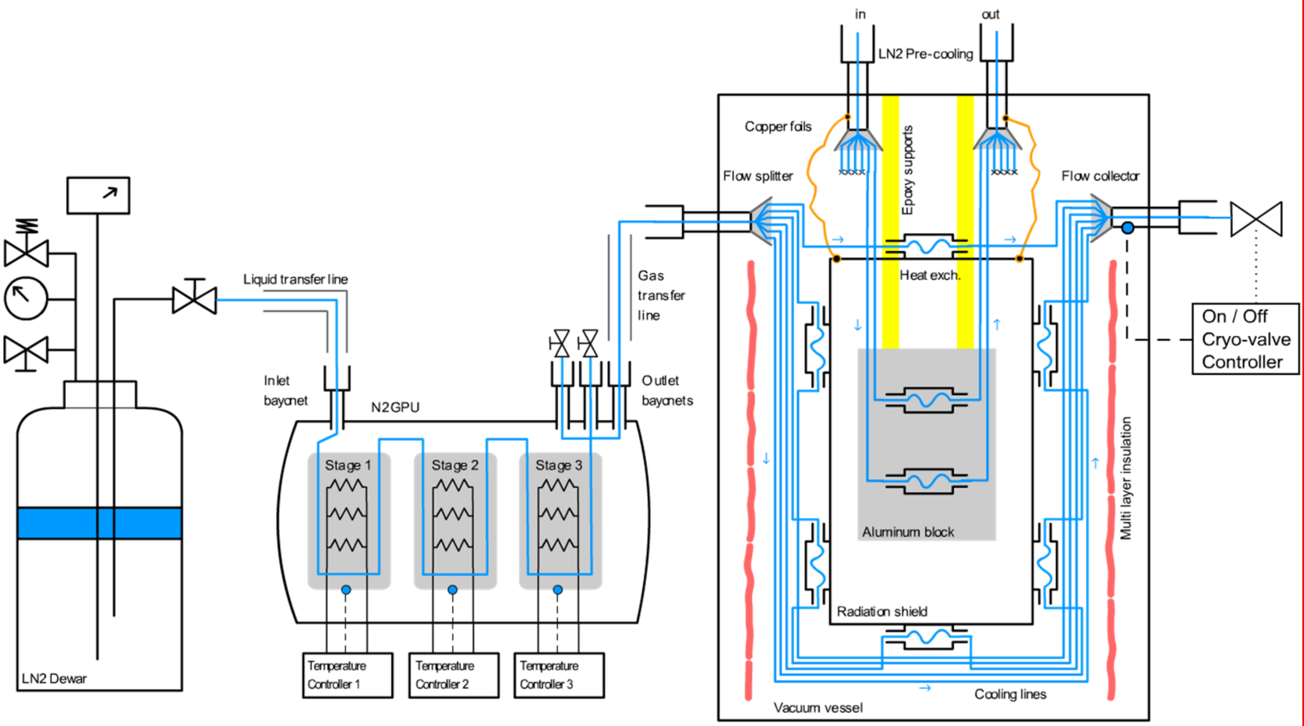

Figure 12. Test layout for the CARMENES-like configuration

The main objective of this test was to simulate the cooling system of the CARMENES instrument to confirm that the method and hardware chosen were appropriate.

By establishing the temperature of the radiation shield and the dummy block close to 140K and then measuring the temperature evolution of the radiation shield and the aluminum block over time, it is possible to analyze the thermal amplitude response that the optical bench receives when it is cooled only through the radiation of the radiation shield.

The test facility layout configured to simulate the CARMENES instrument is shown on figure 12: the aluminum block is represented in grey, the radiation shield is the black rectangle with the heat exchangers attached to it. The multi-layer blanket is represented with a red outline, the epoxy plates are represented by the yellow rectangles and the copper foils that go from the flow splitters to the radiation shield are shown as orange lines. On the left of the figure 12 the nitrogen dewar is shown. This is from where the liquid nitrogen flows to the N2GPU, then the thermally stabilized nitrogen gas goes out and enters to the test facility. Into the test facility the flow is divided into six parallel lines (in blue), each one feeding only one heat exchanger. At the end of the circuit, the six lines rejoin in the flow collector and the flow finally goes out through the cryogenic on/off valve placed outside the test facility. Figure 14 shows the sensor attached to the flow collector.

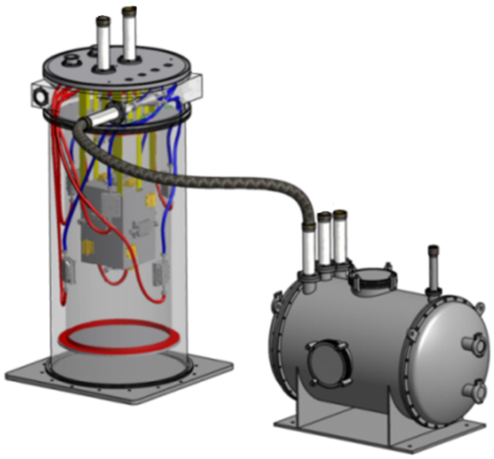

Figure 13. CARMENES test representation

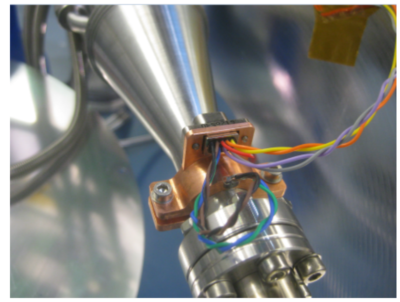

Figure 14. PT100 sensor of the on/off valve

The following list shows the test configuration parameters:

- Power of the heaters of each stage:
  - 1st stage power fixed at 230W
  - 2nd stage power auto regulated by the PID varying with a range from 0 to 235W
  - 3rd stage power auto regulated by the PID varying with a range from 0 to 216W

- Temperature set point of the PID for each stage:
  - 1st stage temperature set point at 70 K
  - 2nd stage temperature set point at 123K
  - 3rd stage temperature set point at 108K

- Nitrogen storage tank overpressure of 0.35 bars
- Non-continuous flow mode
- Temperature set point of the cryogenic on/off valve at 138K

5. RESULTS

5.1. N2GPU working alone

5.1.1. Results test 1

The following list shows the results from test 1:

- Consumption of 2.74 liters of LN2 per hour.
- Temperature average of the steady state of 142K, it is 9 kelvins higher than the temperature target of the third stage of the N2GPU.
- Temperature amplitude of ±2.5K.
- Temperature period of 3hours.
- Test length of 44h including the cool down of the N2GPU itself.

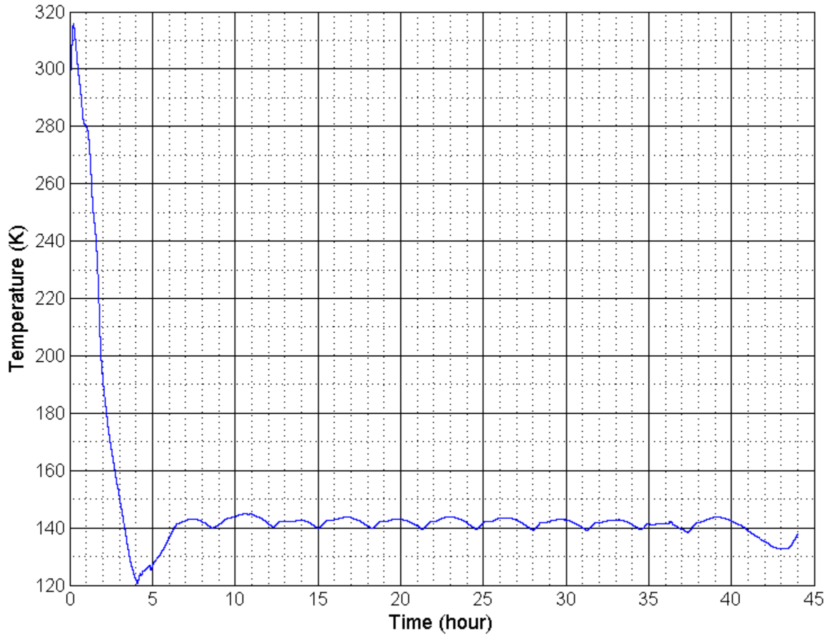

Figure 15. Evolution of the nitrogen gas temperature for test 1

5.1.2. Results test 2

The following list shows the results from the test 2:

- Consumption of 10.3 liters of LN2 per hour.
- Temperature average, even though no clear steady state was reached, of 140K.
- The temperature amplitude and period are not significant as no clear steady state was reached.
- Test length of 11h.

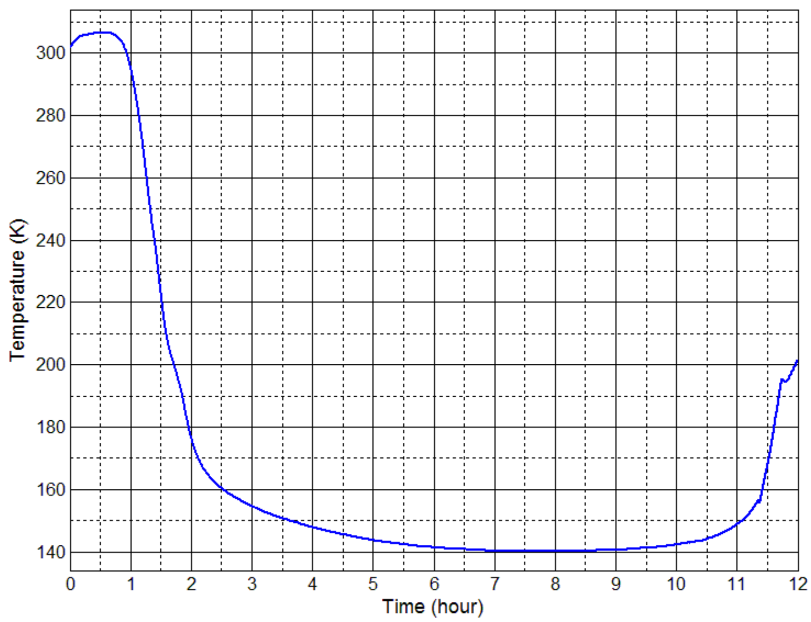

Figure 16. Evolution of the nitrogen gas temperature for test 2

5.1.3. Results tests 3

The following list shows the results from the test 3:

- Consumption of 13.5 liters of LN2 per hour.
- Temperature average, even though no clear steady state was reached, of 97.5K.
- The temperature period and amplitude are not significant as no clear steady state was reached.
- Test length 9h.

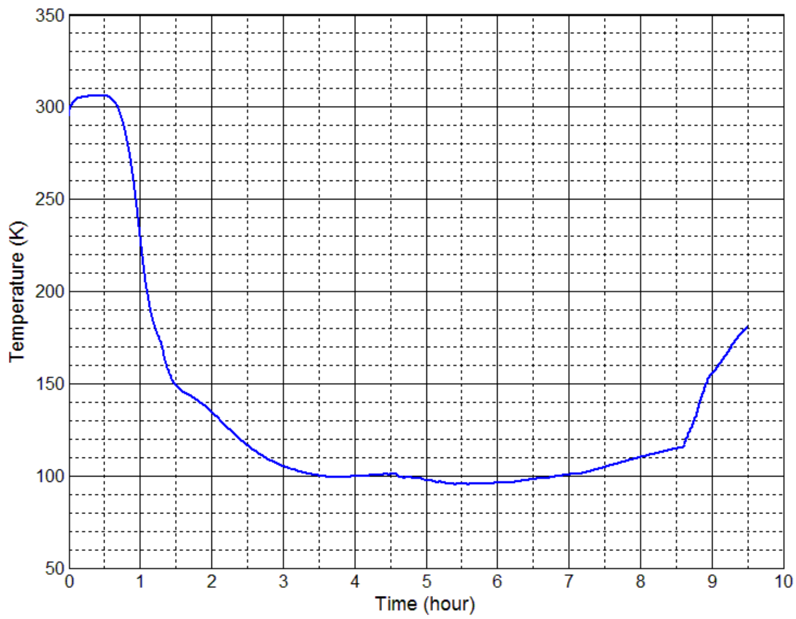

Figure 17. Evolution of the nitrogen gas temperature for test 3

5.2. CARMENES-like test

The following list shows the results from the CARMENES set up test:

- Overall test:
  - Test length after pre-cooling of 12.5 hours.
  - Liquid nitrogen consumption of 9.5 liters per hour.

- Radiation shield temperatures:
  - Temperature average of the radiation shield of 134K.
  - Temperature amplitude of the radiation shield of ±0.75K.
  - Temperature period of the radiation shield of 45 minutes.

- Aluminum block temperatures:
  - Temperature average of 136.1K with no steady state reached.
  - Temperature increased 1.7K.

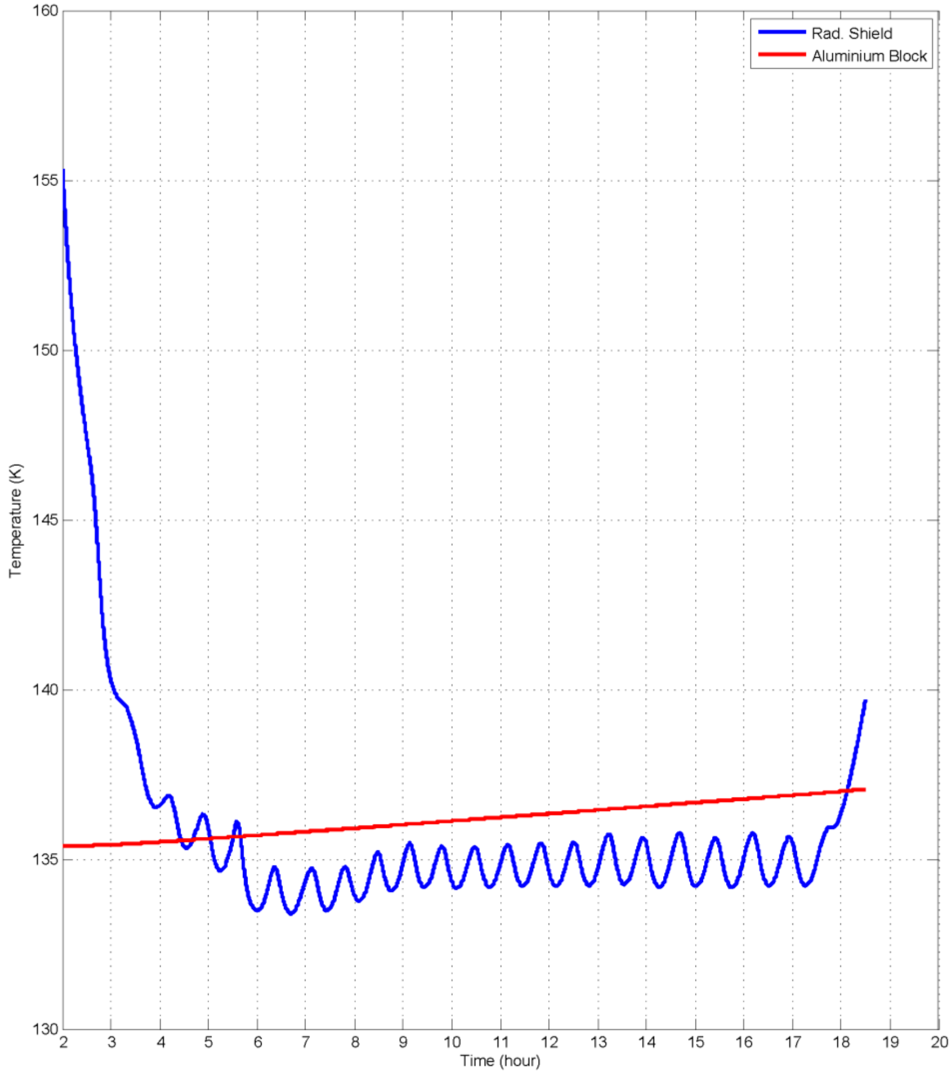

Figure 18. Evolution of the radiation shield and the aluminum block temperature

Figure 18 shows the temperature evolution of the radiation shield over time, represented with a blue line, and the aluminum block, represented with a red line. As can be seen, the radiation shield has a quite regular sinusoidal behavior with an almost constant period and amplitude. The temperature of the aluminum block increases looking for an equilibrium between the cooling power of the radiation shield and the source of heat load. During this test the equilibrium was not found because the duration of the test was not long enough.

If the aluminum mass was very well isolated, the gap between the mean line of the temperature wave of the radiation shield and the temperature of the aluminum block would be relatively small. In the present test, the temperature evolution of the aluminum block shows an increasing drift from the equilibrium phase due to the contamination through conductive heat transfer. This arises from the fact that, at the test facility, the LN2 pre-cooling lines used to pre-cool the aluminum block, including the inlet and outlet bayonets and the lines connected to the heat exchangers, link the system to room temperature. Afterwards they are not used and begin warming up immediately after the pre-cooling stops. The design of the instrument is much different and it is expected avoiding this head load transfer contamination.

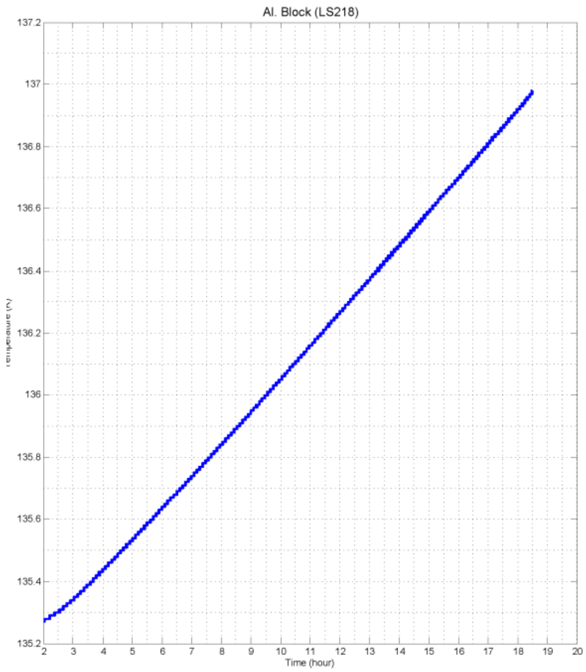

Figure 19. Evolution of the aluminum block temperature

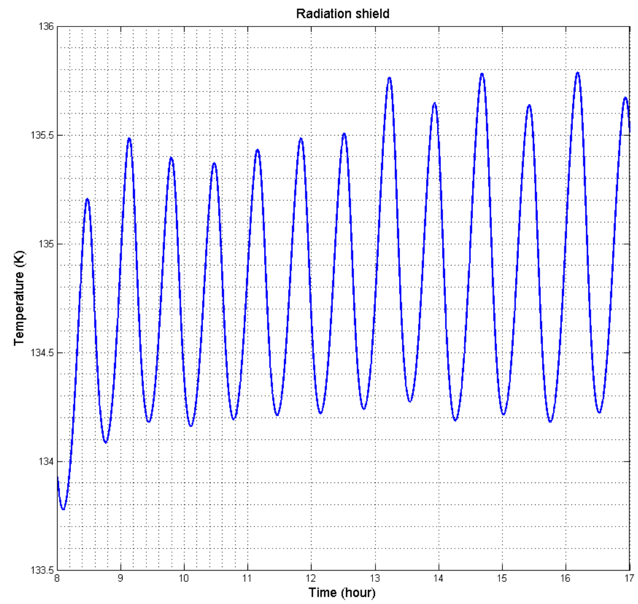

Figure 20. Evolution of the radiation shield temperature

The graph below shows the temperature gap between the inlet bayonet used to pre-cool the aluminum mass and the radiation shield. This shows the effect of the heat load contamination that is conducted from the vacuum vessel through the inlet bayonet to the radiation shield. The curve tends to become horizontal; at that point the temperature of the aluminum block would reach the steady state.

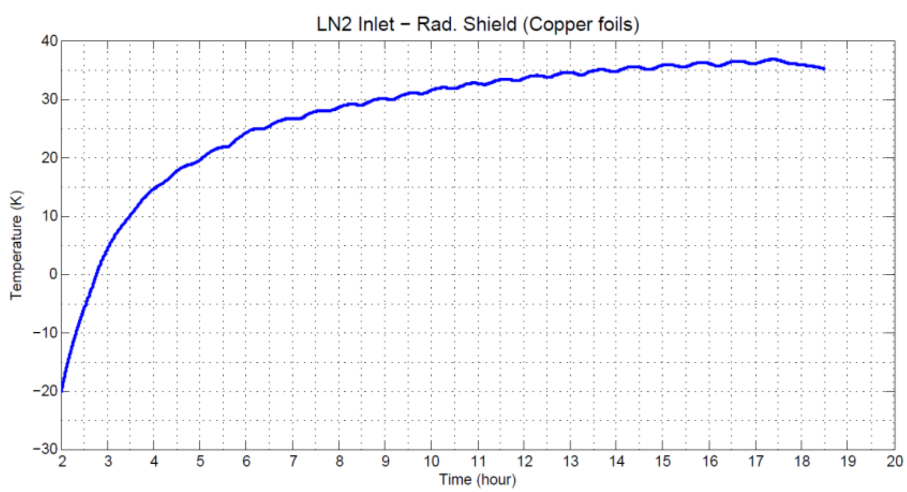

Figure 21. Gap evolution between the temperature of the radiation shield and the pre-cooling inlet bayonet

Figure 22 shows the temperature evolution of the flow collector that regulates the on/off valve. It has the same period of the radiation shield temperature evolution and amplitude of ±3 kelvins. Note that, due to its higher mass, the wave of the radiation shield has a damped amplitude compared to the one of the flow collector.

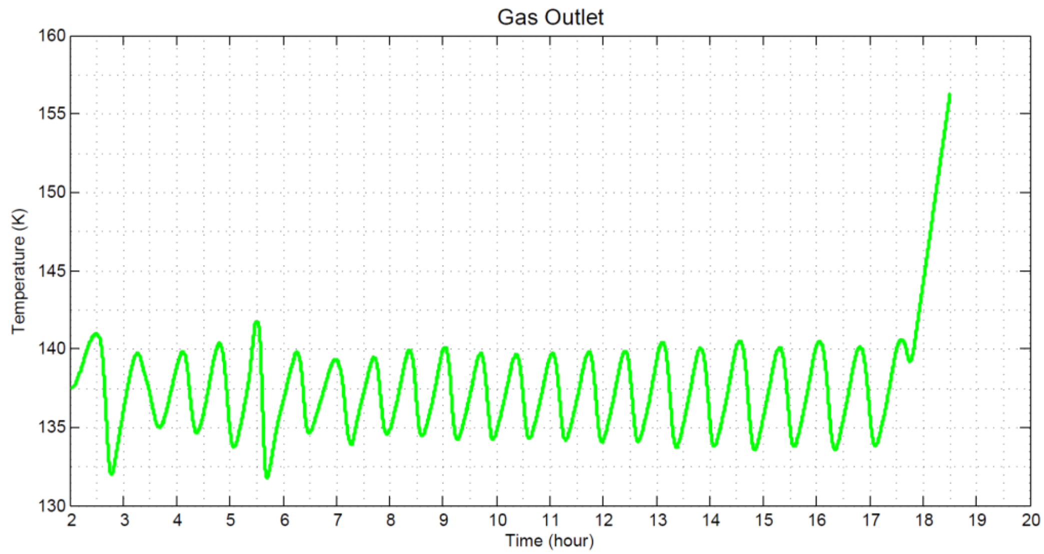

Figure 22. Evolution of the temperature of the on/off valve sensor

5.2.1. Drift-removed temperature fluctuation analysis

As shown in figure 19, there is a drift caused by the flow of conductive heat to the aluminum block. In order to analyze the temperature evolution of the aluminum block in more detail and check its interaction with the whole system, a drift-removed curve has been calculated, fitting a polynomial curve to the original temperature, and subtracting it afterwards. The result is shown in figure 24. It can be clearly seen how the aluminum block interacts with the temperature fluctuations of the whole system and has a similar period as the radiation shield temperature evolution but with much smaller amplitude. The magnitude of the oscillations shown in the aluminum block is around ±0.002K, which is almost one order of magnitude below the initial goal (±0.01K). This results show that the cooling concept here applied is really appropriate to reach ultra-stable conditions. In figure 23, on the left, the correlation between the temperature cycles of the radiation shield (in blue), and the aluminum block (in red), can also be clearly seen.

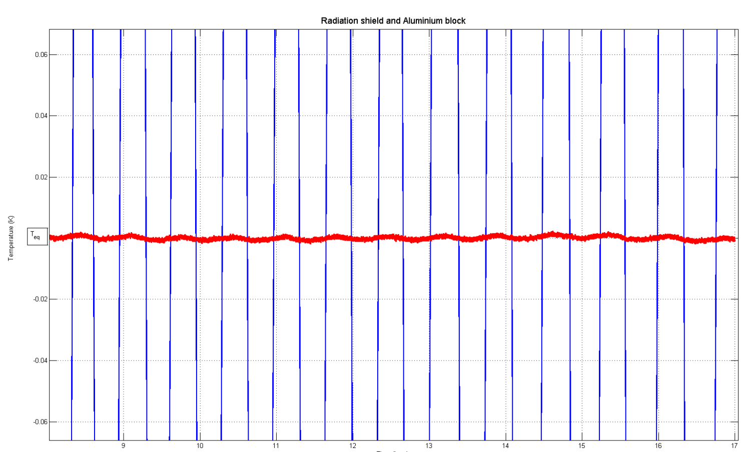

Figure 23. Temperature of the radiation shield and the drift-removed curve of the aluminum block

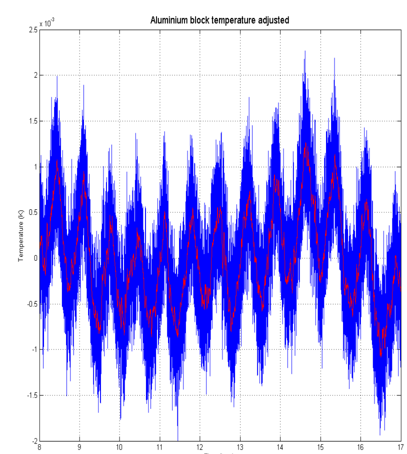

Figure 24. Drift-removed curve of the aluminum block temperature

6. CONCLUSIONS

It has been shown that the N2GPU can provide a long-term stabilized nitrogen gas flow at the working temperature range of the NIR channel of the CARMENES instrument.

The non-continuous flow through a cryogenic on/off valve at the end of the circuit has been shown to be more reliable and efficient in terms of temperature stability control, as well as covering a wide range of temperatures and being able to provide a high amount of flow. The more power supplied to the heating elements mainly on phases 1 and 2, the more consumption and nitrogen gas flow would be produced.

The cooling system has been proven to be the right one to fulfill the instrument requirements: the temperature amplitude on the drift-removed graph of the aluminum block is ±0.002K, much more precise than the goal requirement of ±0.01K. The same test is going to be repeated but with a longer duration until the temperature of the aluminum block achieves the steady-state. Then it will be possible to obtain the real gap produced by the warm heat transfer.

On the instrument, all the elements placed inside the vacuum vessel, including the cooling hardware, have been carefully designed to be very well thermally insulated to avoid sources of heat load transfer. Furthermore, due to the 285K thermally stabilized Coudé room at the Calar Alto Observatory, where the instrument will be placed, it is expected that the liquid nitrogen consumption will be lower as less heat will needed to be mitigated.

The integration of the NIR channel of CARMENES at the Instituto de Astrofísica de Andalucía is due to start by the end of May 2014, this is the biggest project the institute has participated in to date in a multi-disciplinary approach, with the AIV phase at system level being included. The cooling system is an advanced and innovative method, which will contribute to the success of the instrument and to position IAA as a trustful partner of ESO for future cryogenic instruments.

7. REFERENCES

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