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An extremely high stability cooling system for planet hunter

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Abstract. The detection of exoplanets is done by measuring very tiny periodical variations of the radial velocity of the parent star. Extremely stable spectrographs are required in order to enhance the wavelength variations of the spectral lines due to Doppler effect. CARMENES is the new high-resolution, high-stability spectrograph built for the 3.5 m telescope at the Calar Alto Observatory (CAHA, Almería, Spain) by a consortium formed by German and Spanish institutions. This instrument is composed of two separated spectrographs: VIS channel (550-1050 nm) and NIR channel (950-1700 nm). The NIR-channel spectrograph's has been built under the responsibility of the Instituto de Astrofísica de Andalucía (IAA-CSIC). It has been manufactured, assembled, integrated and verified in the last two years, delivered in fall 2015 and commissioned in December 2015.

Beside the various opto-mechanical challenges, the cooling system was one of the most demanding sub-systems of the NIR channel. Due to the highly demanding requirements applicable in terms of stability, this system arises as one of the core systems to provide outstanding stability to the channel at an operating temperature finally fixed at 140 K. Really at the edge of the state-of-the-art, the Cooling System is able to provide to the cold mass (~1 Ton) better thermal stability than few hundredths of a degree over 24 hours (goal: 0.01K/day). The present paper describes the main technical approach, which has been taken in order to reach this very ambitious performance.

1. Historic, technical proposal

The technique for detecting exo-planet by measuring variation of wavelength lines has existed for more than a decade. CARMENES was one of the first attempts to extend the wavelength range further in the InfraRed. The original idea was simply to extend to the closest Near Infrared band, a domain where an operating temperature of 240 K would have been enough. For this reason the original plan was considering using a sort of large climate chamber in order to refrigerate the complete instrument including its vacuum chamber. Such technology would not have been very efficient, as the mass to be cooled would be much larger. Moreover, it would have been very difficult to cool the core of the instrument that is partially insulated in the vacuum chamber. In addition, a number of technical problems were appearing with the freezing of the O-ring seals. For all of these reasons, this technique was rapidly rejected. Another alternative could have been cooling of the instrument with a liquid nitrogen bath. This might have allowed a more compact design of the spectrograph. However a complex control mechanism and adjustable connection might have been required in order to select and tune the operation temperature. A temperature stabilisation control loop would have been necessary in order to compensate for the natural fluctuation of the LN2 boiling temperature linked with the variation of atmospheric pressure. A deep analysis of these various aspect leads us to select a cooling technique using a Continuous Flow Circulation of Nitrogen (CFC). A long and solid experience has been gained over many years of use of LN2 continuous flow cooling systems. This is used in a high number of small cryostats to operate scientific detectors and also in large infrared instruments in order to pre-cool them down to the final operating temperature.

The following section explaining the various aspects which ensure the success of this technique which, until now, was never used for an experiment requiring a high level of stability.

2. Design of the spectrograph, thermal analysis

The spectrograph is basically a massive and heavy optical bench on which the various optical components are rigidly positioned. This optical assembly has to be attached in a vacuum chamber for the purpose of thermal insulation and also in order to minimize optical instabilities which could be caused by fluctuations of the refractive index of the atmospheric medium. The main thermal requirements of the instrument are listed in Table 1, the most challenging one being the thermal stability. It is to be noted the looser requirement on the final operating temperature. The most important is that temperature, which is clearly defined by the upper limit of the wavelength range of operation, is low enough in order not to be affected by thermal emissions from the instrument itself.

Table 1. Thermal requirements.

Requirement	Value
Working temperature	~140 K
Temperature stability	±0.07 K (±0.01 K goal) in the timescale of 1 day
Pre-cooling time	48 h (goal)
Cooldown and warm-up rate for the optics	<10 K/h
Liquid nitrogen consumption	<90 l/day
Environment temperature	285±0.5 K
Vacuum level	~10^{-6} mbar

Looking onto the optical design of the instrument: the light is fed through a limited number of optical fibres. This suppresses any high thermal load linked with the thermal radiation of an optical window which would directly impact the cold part of the instrument. In such a case, a thermo-mechanical analysis of the instrument shows that the thermal load is clearly dominated by the radiation exchange between the cold part and warm vacuum vessel. In addition to radiations, thermal loads are coming from conduction through the various connection between the two extreme temperatures: the supporting structures (A number of G10 plates), the wiring of the thermal temperature and heaters, the LN2 tubes of the pre-cooling system and finally the vacuum jacket of the detector cryostat.

This analysis demonstrates the importance of a well-designed radiation shield which surrounds the sensitive cold part of the instrument. Taking these considerations into account we understand that after original cool-down only very little cooling power (< 150 W) is required to keep the instrument at operational steady state temperature.

3. Design of the cooling system

Figure 1 below shows the schematic of the system used for cooling of the spectrograph. We can see two different circuits: the pre-cooling circuit which is directly attached to the optical bench and the temperature stabilisation circuit which is attached to the radiation shield. As described before, during operation, the Optical Bench is exposed to the only thermal load via the few conducting points. These conduction points are all thermally linked to the radiation shield which in this case provides a real thermal barrier. Then the only remaining impact on the Optical Bench is via radiation from the radiation shield. The extremely high mass of the bench (700 Kg) and the very low temperature difference make this effect fully negligible. Therefore for operation mode, the strategy consists in an indirect cooling via the radiation shield.

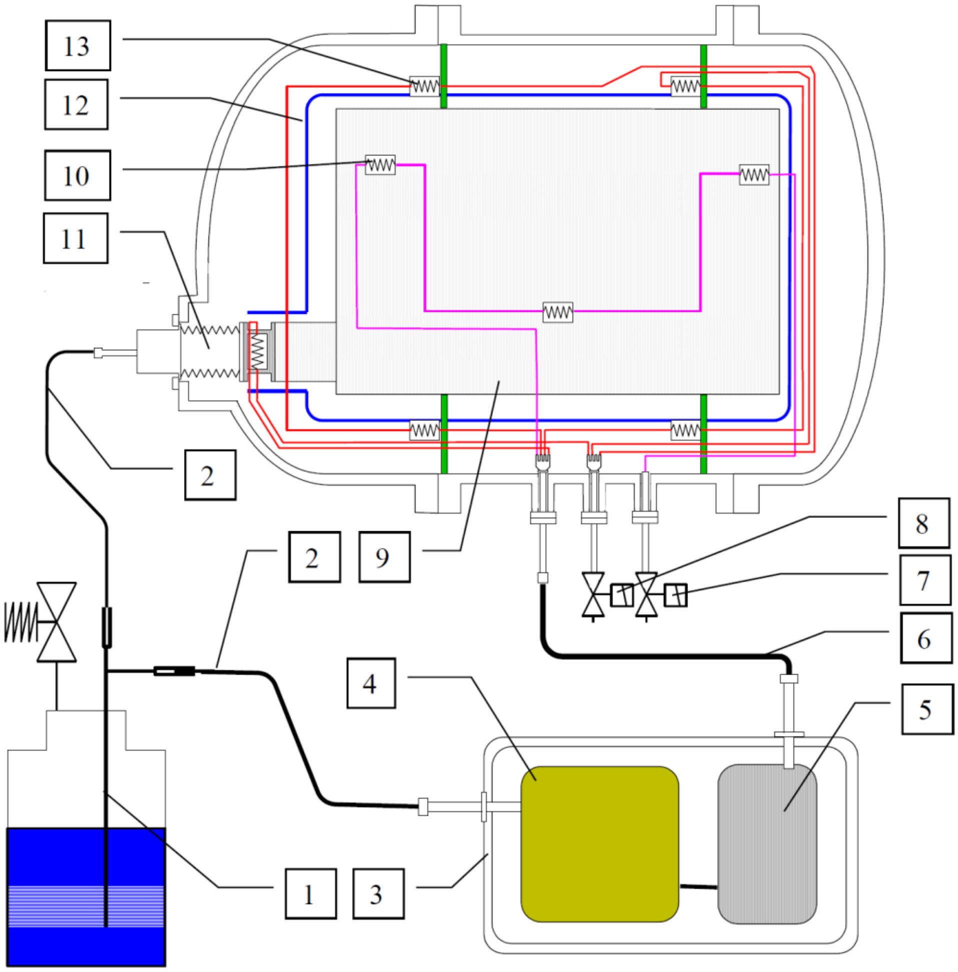

Figure 1. Schematic of the cooling system. 1: LN2 storage tank; 2: LN2 transfer line; 3: Gas Preparation Unit; 4: Evaporator; 5: Gas stabilisation chamber; 6: N2 gas transfer line; 7: Pre-cooling valve; 8: Steady state valve; 9: Cold Optical Bench; 10: Pre-cooling circuit; 11: Detector cryostat; 12: Radiation shield; 13: Temperature stabilisation circuit

The CFC System is based on a series of cooling lines that dissipate the power from the radiation shielding by means of heat exchangers (see Figure 2). In a cooling arm, obviously, the first heat exchanger will be cooler than the second one, which means that a temperature gradient is produced by having both heat exchangers at different temperature. Therefore, a large amount of heat exchangers connected in series will generate a large gradient between the first one and the last one. On the opposite case, all the cooling lines could include only one heat exchanger but the amount of cooling ports and hardware necessary makes this option quite unpractical. As compromise, the amount of heat exchangers connected in series in a cooling line has been limited to two units. In order to reduce in any case the gradient the lines have been inverted (exchanger 1 of line 1 is in the vicinity of exchanger 2 of line 2 and the same for the other lines).

The heat exchangers are built from small blocks out copper in which a labyrinth channel is milled. A number of copper beryllium springs are inserted in the channel in order to create turbulence and force the thermal exchange. A copper cover welded on the body is used to seal the circulation channel. Two stainless steel tubes brazed on the copper body ensure a reliable interface for the connection using Swagelock connectors. All internal connections are provided via cooling lines made from stainless steel wave tubes.

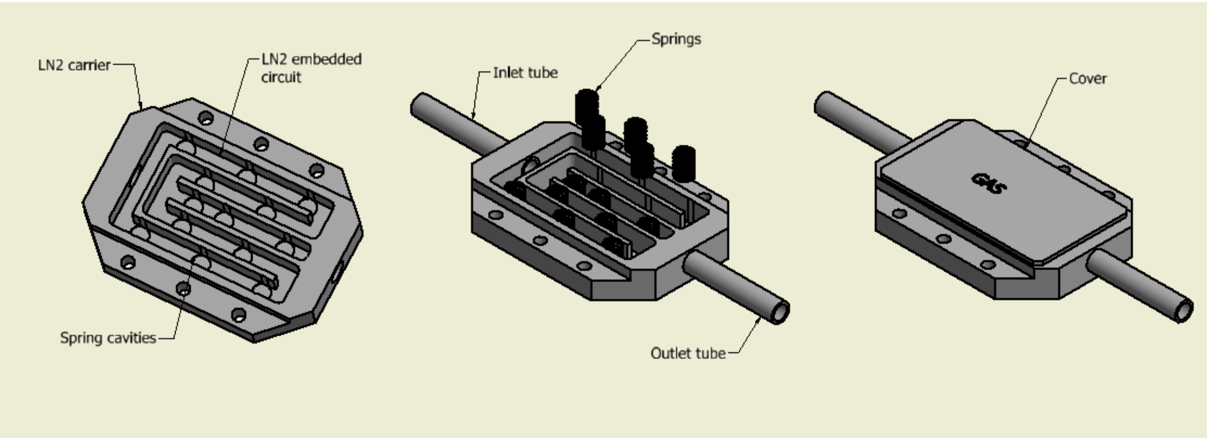

Figure 2. Heat exchangers

The radiation shield is composed of a main body and two end covers. The radiation shield is made from 2 mm thick aluminium plates, which are polished outside in order to reduce the heat load. The various components are connected by screws. The main body includes 12 heat exchangers distributed among 6 cooling lines while each cover includes one heat exchanger. Therefore, the present design includes 8 cooling lines. Figure 3 shows a general view of the NIR spectrograph enclosed in the radiation shielding envelope. We can also see the various heat exchangers as well as the distribution heads used for splitting and collecting the cooling lines.

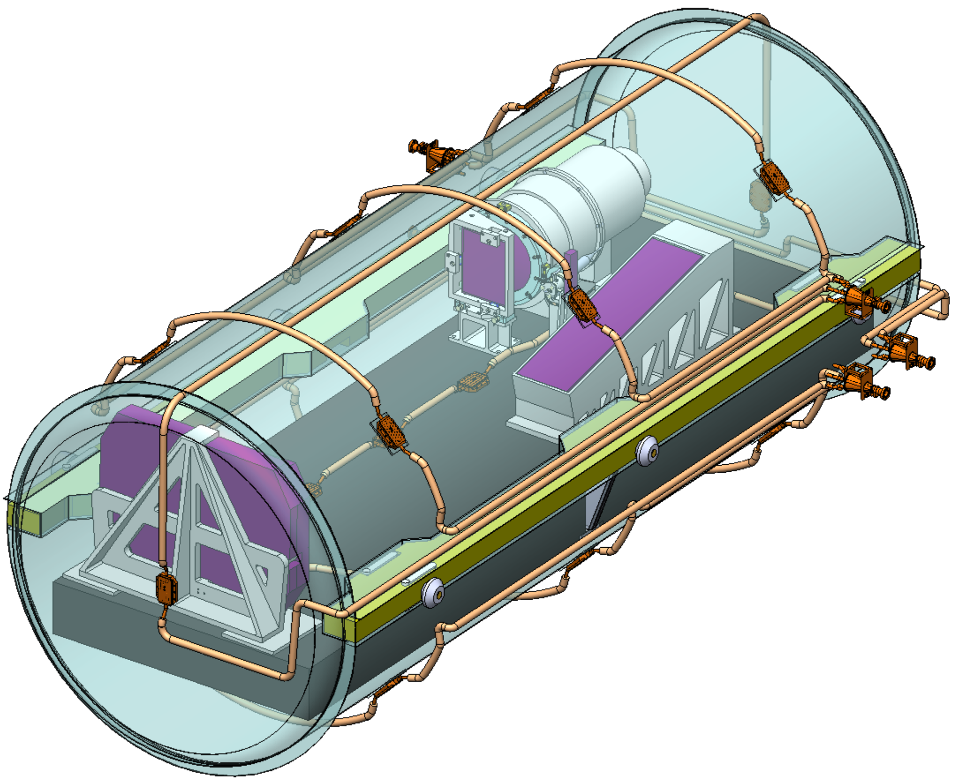

Figure 3. Optical Bench enclosed in the radiation shield

4. The gas preparation unit

The Gas Preparation Unit consists of a vacuum tank where several systems are enclosed: the Evaporator Unit, the Intermediate Exchanger and the Final Heat Exchanger. All of them are equipped with heaters in order to supply the power required for the GN2 flow to reach the desired temperature. Once the LN2 comes into the Preparation Unit, the flow passes first through the Evaporator Unit. The power here supplied allows not only changing the phase of the flow from liquid to gas but also providing a temperature level close to the desired temperature. The Evaporator Unit includes different cross sections for the channel where nitrogen flows through. At the entrance to the Evaporator Unit, the cross section is small compared to the cross section at the exit. This compensates for the natural expansion due to phase change. The flow exiting the Evaporator Unit may not be very stable due to the turbulence produced in the phase change. At the exit from the Evaporator Unit, there is the Intermediate Exchanger, which consists of a long coil whose large cross section allows the flow to become even more stable in terms of pressure and temperature. This stage can be used to provide an additional temperature step to the flow. After the Intermediate Exchanger, the flow comes into the Final Heat Exchanger. This stage provides a huge exchange area with the gas. Note that the incoming flow is close to the working conditions. Therefore, this big heat exchanger provides the last and small temperature step. Due to the high mass of the Final Heat Exchanger, the temperature reached by the flow will be very stable. The shape of this massive component has also been adapted such that its capacity is very close to the quantity of gas that the complete instrument circuit can accommodate. This allows while regulating to have a full charge of stable gas when the steady state regulation valve opens.

After the exit from the Final Heat Exchanger, the flow leaves the Preparation Unit and comes into the cooling circuit of the instrument. In order to minimize the losses in between, the pipe linking the Preparation Unit and the Instrument must be vacuum insulated, its length being not more than 2m.
Note that the electrical hardware prone to maintenance (e.g. the heaters) are inside the Preparation Unit, the Vacuum Vessel being undisturbed if a heater needs to be replaced. Eventually, all the systems of the Preparation Unit are enclosed inside a radiation shielding not shown on Fig.4.

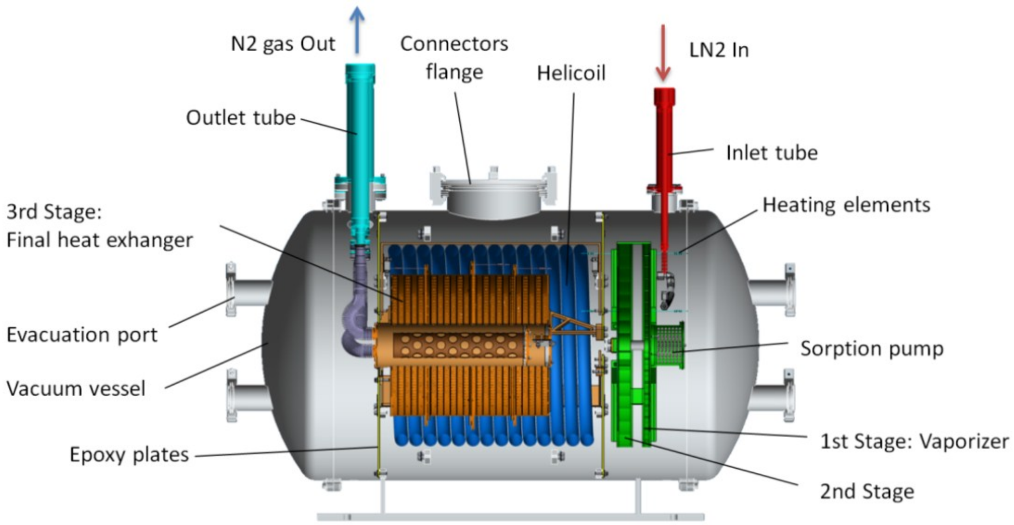

Figure 4. Gas preparation Unit

5. Conclusion and results

The instrument has been fully designed and has undergone all integration and testing phases in the laboratory of the IAA (Instituto de Astrofísica de Andalucía). The most challenging thermal stability has been meet, the final stability is better than 0.02 K over a period of 5 hours is Actually within a few weeks of commissioning on the Telescope of Calar Alto Observatory in Spain, CARMENES has been providing science since the end of 2015.

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