III. An innovative and challenging cooling system for an ultra-stable NIR spectrograph

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Abstract. The present paper describes and summarizes the cooling system designed for CARMENES NIR as well as the complex analyses implemented to ensure the high thermal stability requirement (0.07K in 24 hours; ±0.01K (goal)). The radiation shield enveloping the Optical Bench is actively cooled, thus the instability there produced being further damped on the Optical Bench due to its high mass of the latter and thermal decoupling with respect to the shield, the main heat exchange being produced by radiation. The radiative heat load to the shield is removed by a previously prepared flow of N2 going through some properly dimensioned heat exchangers.

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	48h (goal)
Cooldown and warm-up rate for the optics	<10 K/h
Liquid nitrogen consumption	<90l/day
Environment temperature	285±0.5 K
Vacuum level	~10-6 mbar

Main design guidelines and drivers

- The complete spectrograph supported on an in-vacuum optical bench.
- Optical bench thermally stabilized by radiation.
  - Optical bench enclosed inside a radiation shield (with 20-layered MLI).
  - Radiation shield kept at working temperature by heat exchangers that dissipate the radiative load coming from the vessel.
  - Any temperature instability on the shield is highly damped on the optical bench.
- Highly homogeneous temperature distribution on the bench.
  - Coupled view factors of the shield w.r.t. the bench provide smoother gradients on the latter.
- Cooling sequence
  - Cooldown of the optical bench and the radiation shield → the latter will be much faster due to its relatively low mass.
  - Once it is at working temperature, the circuit cooling the optical bench is closed.
  - The circuit cooling the radiation shield keeps working while the optical bench is left until the temperature gradients on the latter get to the steady-state.
  - Once the instrument starts working, temperature conditions are kept permanently.
- Dedicated temperature-controlled rooms (±0.5K) for housing the instrument.
- CFC system (ESO standards) chosen to provide the cooling performance.

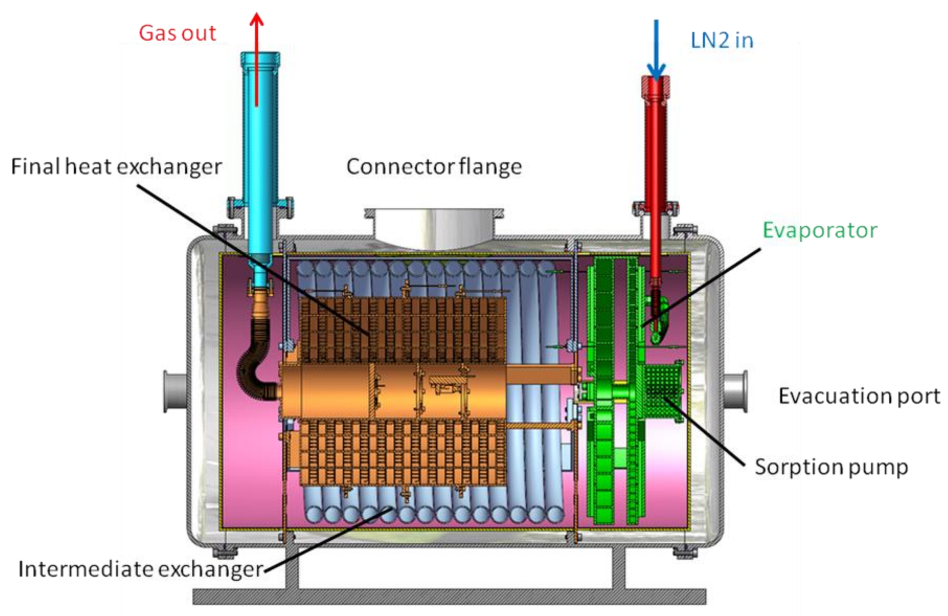

Figure 1. General cut view of the Preparation Unit.

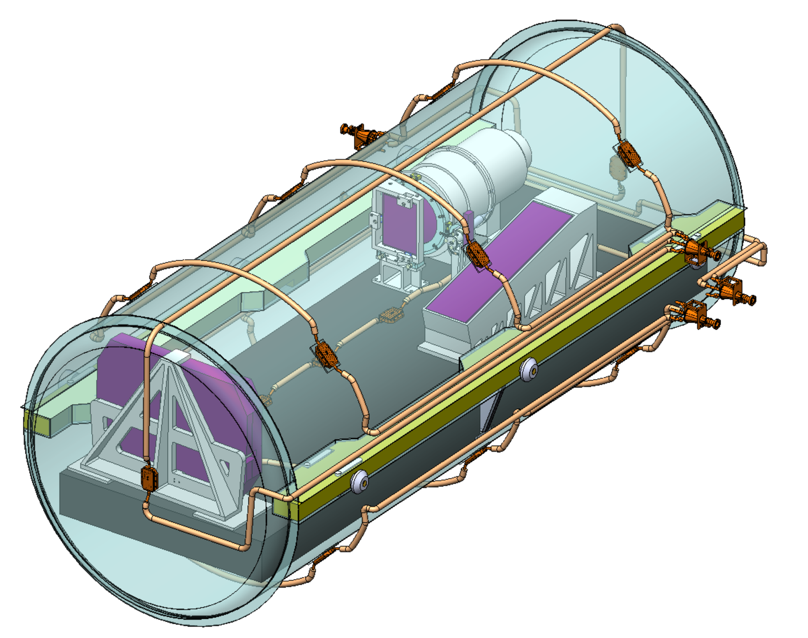

Figure 2. General view of the enclosure of the radiation shield. Optical bench is shown whereas the vacuum vessel is not.

Description of the CFC system

- Radiation shield composed by a main cylindrical body and two end covers.
- 8 cooling lines for the radiation shield.
  - 1 line for each cover (with 1 heat exchanger).
  - 6 lines for the main body of the shield (2 heat exchangers per line)
- Coolant flow prepared through an external, dedicated unit (Preparation Unit).
- CFC system allows for pre-cooling (fed with LN2) and for warming-up (fed with nitrogen gas at room temperature).

PREPARATION UNIT

- 3 systems equipped with heaters and temperature sensors in order to control the gas temperature at the exit.
  - Evaporator Unit
    - LN2 flow is evaporated and heated up to certain temperature.
    - 1st stage for flow stabilization.
  - Intermediate Heat Exchanger.
    - Further stabilization and heating up to a level close to working temperature.
  - Final Heat Exchanger.
    - Huge exchange area.
    - Slight heating for the gas flow to reach the working temperature.
- Hardware prone to maintenance (heaters,...) inside the Preparation Unit (not inside the spectrograph's vessel).

Thermal analyses

THERMAL STABILITY ANALYSIS

- Input → sinusoidal temperature signal on the radiation shield (140±0.5 K; 2 h period)
- Output : damped temperature signal obtained for the optical bench.
- Optical bench and radiation shield made of aluminium
- Optical bench mass → 800 kg
- Emissivity of surfaces involved → 0.95 (to avoid unwanted reflections inside the shield)

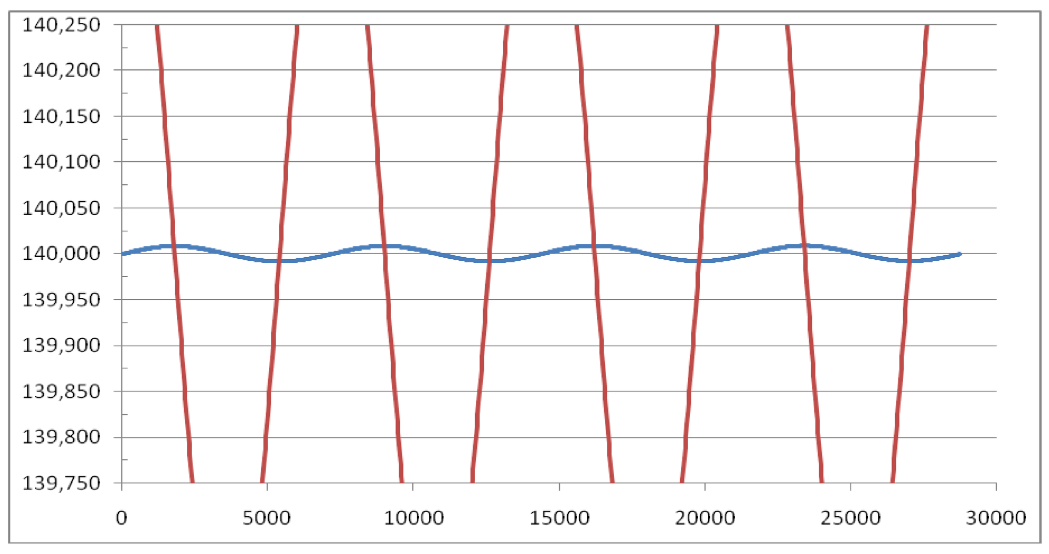

Figure 3. Graph showing the temperature (K) in time (sec) of the radiation shield (red colour) and the optical bench (blue colour).

FEA STEADY-STATE ANALYSIS

1. Radiative load

- Model includes vacuum vessel and optical bench.
- Boundary Conditions
  - Ambient temperature → 285K.
  - Emissivity → 0.03 (inner surface of vacuum vessel) // 0.002 (outer surface of radiation shield with 20-layer mLI).
- Radiative load to the different surfaces of the Radiation Shield is found (see Figure 5).

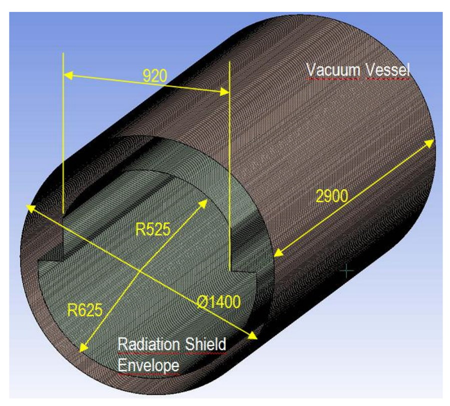

Figure 4. Model showing vessel's inner envelope and radiation shield (with main dimensions applicable)

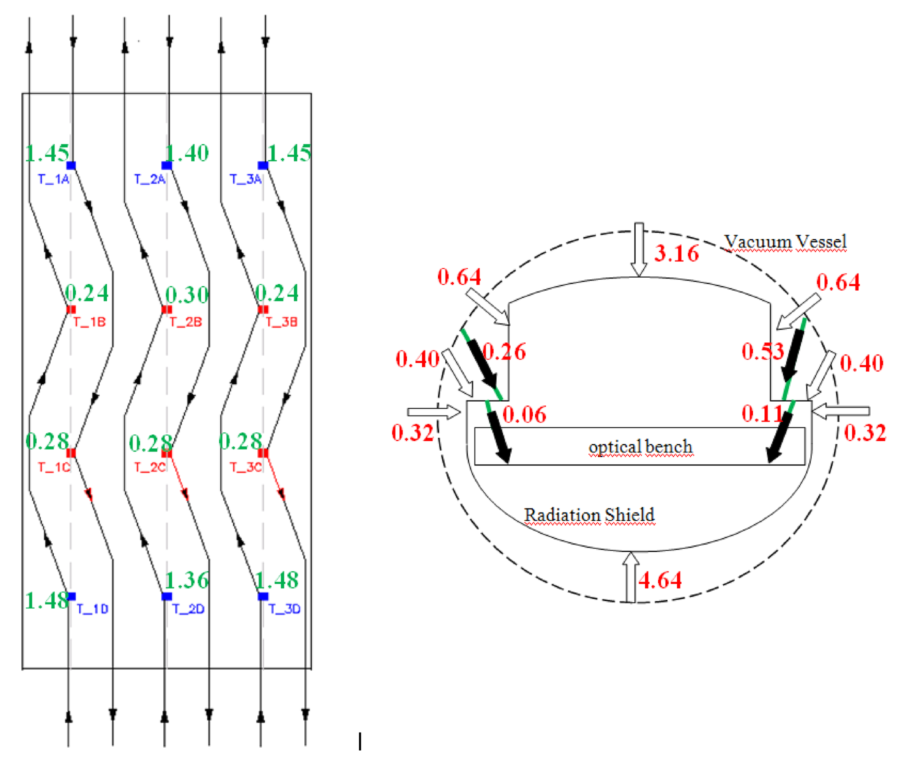

Figure 5. *Right.* Steady-state net heat flows (in watts) within the system composed by the optical bench, the radiation shield and the Vacuum Vessel. The radiative load to each cover (not shown) is 0.96W. Conductive losses (black arrows); radiative flows (white arrows). *Left.* Heat flows drained through heat exchangers on the main body of the radiation shield.

2. Temperature distribution on the radiation shield and the optical bench

- Model includes radiation shield, optical bench and their links to the vacuum vessel.
- Boundary Conditions
  - Radiative loads found above
  - Emissivity of surfaces involved → 0.95
  - Temperature on heat exchangers.
    - 135 K (1st unit); 138 K (2nd unit)

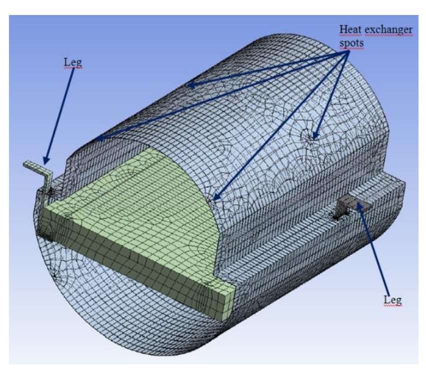

Figure 6. As-meshed model showing the radiation shield, optical bench and respective links.

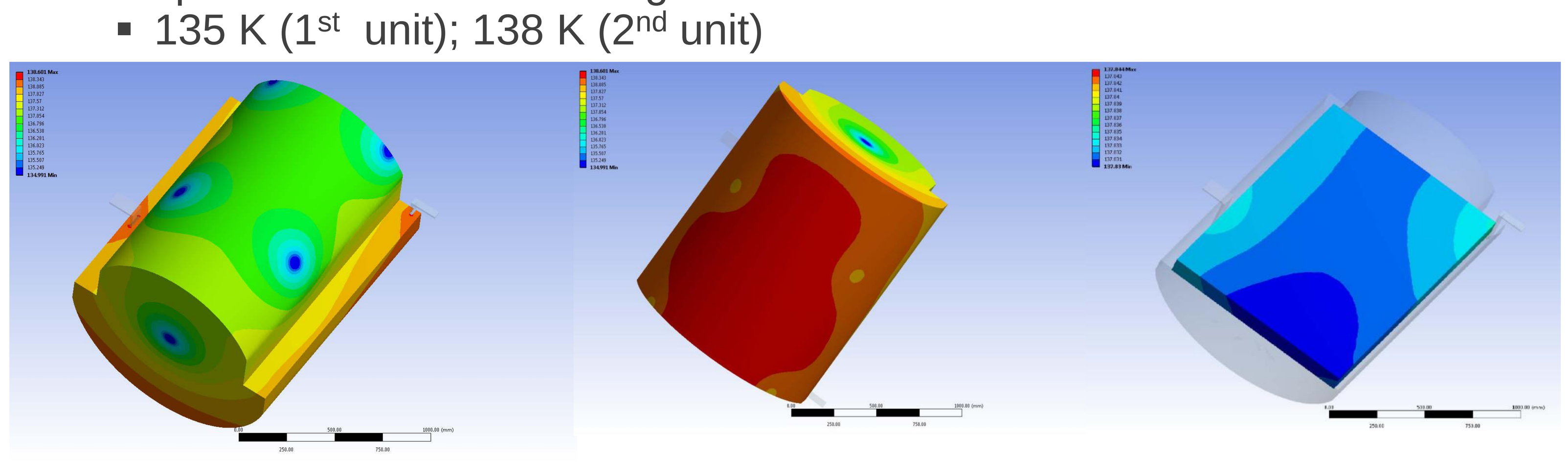

Figure 7. Temperature distribution across the radiation shield and the optical bench.

Conclusions and results

- Total radiative load from vessel to radiation shield is 13.4 W.
- Conductive losses are very low:
  - 0.79 W between vessel and shield; 0.17 W between shield and bench.
- Temperature stability on the bench fulfils the requirement (~ ±0.01) K (see Figure 3).
- Very smooth steady-state gradient on the bench (~ 0.02 K) whereas the gradient on the shield is relatively high (~ 4.6 K)
- **The current concept and design provides very high thermal damping on the bench in terms of stability and gradients.**

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Some of the models here shown have been made with CATIA v6

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