ON THE PERFORMANCE OF CRYOGENIC COOLING SYSTEMS FOR OPTICAL ELEMENTS AT SIRIUS/LNLS

B. A. Francisco†, M. P. Calcanha, L. M. Volpe, G. P. Lima, L. M. Kofukuda,
R. R. Geraldes, M. Saveri Silva
Brazilian Synchrotron Light Laboratory, Campinas, Brazil

Abstract

Several of Sirius' beamlines employ cryogenically cooled optics to take advantage of the silicon properties at low temperatures. A series of improvements has been evaluated based on our early operational experience focusing on the prevention of thermal instabilities of the optics. This work discusses the performance of the systems after optimizing the pressure of the vessels and their control logics, the effectiveness of occasional purges, and the cooldown techniques, and presents the monitoring interface. Furthermore, we introduce solutions (commercial and in-house) for achieving better beam stability, featuring active control of liquid nitrogen flow. We also propose the approach for the future 350 mA operation, including different cooling mechanisms.

INTRODUCTION

Sirius light source demands high performance instruments for ensuring photon-beam quality, especially in terms of wavefront integrity and position stability. Effective cooling of numerous silicon optical elements is essential to precisely control temperatures and related parameters, ensuring acceptable thermal effects regarding figure distortions and drifts at various timescales. Achieving the necessary precision equipment standards relies on robust thermal design. An alternative for cooling optical instrumentation in CATERETÊ [1] and CARNAÚBA [2] beamlines was described by Saveri Silva, et al [3]. This solution used open-cycle cryostats and continuous 24/7 functioning according to the diagram in Fig. 1. This approach was selected as a cost-effective alternative to closed-cycle cryocoolers for handling low-to-medium thermal loads with low vibration. Some of the adopted strategies continue to be integrated into the ongoing operation. However, during the working phase, it became evident that various instabilities occurred, posing significant hurdles to the reliable performance of the system.

The current research delves into an analysis of these instabilities and the series of tests undertaken to develop effective strategies for their mitigation. Three instances of instability were observed: temperature drifts (I) at the optics initiated after gradual variations in the temperature of the cold fingers at the end of the cryostats, variations associated with changes in the pressure (II) of the liquid nitrogen (LN2) vessels, and significant temperature spikes (III) during their refilling, as illustrated in Fig. 2.

It is believed that the explanation for all cases is related to the formation of vapor films at the cold fingers, Fig. 1. In the first case, there may be a gradual growth of the vapor film until the cold finger reaches a critical temperature, beyond which the current of the heaters that control the temperatures of the parts reaches zero and temperature variations in the optics start. In the other cases, the forced entry of vapor into the transfer line is the primary trigger for these variations [4].

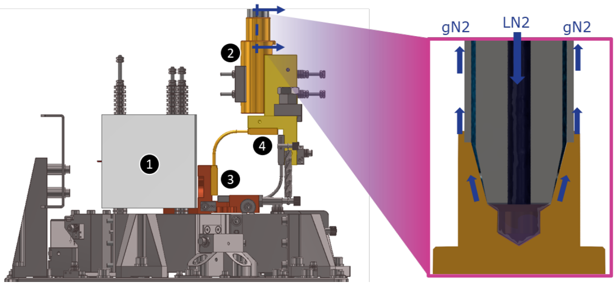

Figure 1: The second mirror (1) of CATERETE beamline is thermally connected to a cryostat (2) by a copper braid (3-4). In detail, the operation of the coupled open flow cryostat.

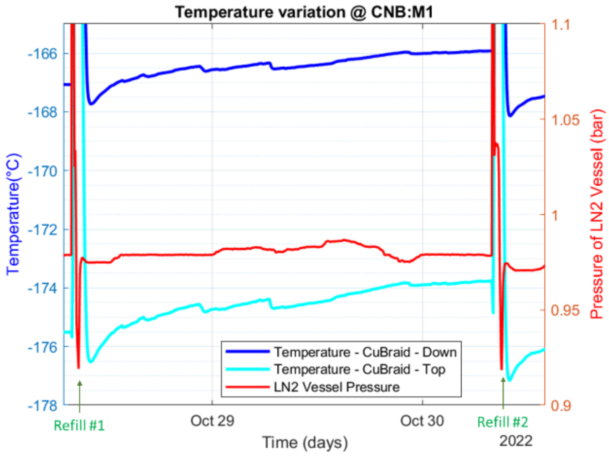

Figure 2: Temperature of a copper braid between first mirror and cold finger at CARNAÚBA beamline presenting drifts (case I), pressure-dependent variation (case II) and spikes (case III) during the refill.

It was noted that agitating the transfer line, whether through manual shaking or temporarily adjusting the flow (by a manual needle valve) and then returning it to its previous state, was sufficient to make temperatures decrease. However, this approach would require the operator to be systematically monitoring the graphs. Consequently, a general solution to these challenges could be achieved by implementing a closed-loop automatic control that adjusts the flow of liquid nitrogen based on the cold finger temperature, or, for the second and third cases, by implementing a solution that effectively prevents vapor from entering the transfer line, which motivated a test with a Phase Separator prototype.

INITIAL UPGRADES

The active pressure control approach for the primary vessels (that are connected directly to the cryostats) using solenoids induced mechanical impulses contributing to temperature fluctuations at the cryostat's end. Initially, passive relief valves were used as an alternative, resulting in clearance and non-repetitive oscillations, particularly during refilling. Subsequently, a passive control strategy was implemented by introducing nitrogen gas to a vent valve connected to a regulating valve, which exhibited periodic fluctuations.

In addition, the setpoint for this pressure control was decreased to enhance the system's flow adjustment sensitivity. Furthermore, the setpoint of maximum level was decreased to 90 % to prevent ice formation near the needle valve. The pressure of the secondary vessels (those located outside the hutch, which supply the primary ones.) was also reduced to minimize the pressure gradient during refilling.

Additionally, a purging process was standardized to eliminate water of the circuit. The purging process involved introducing heated N2 gas at 100 °C into the vessels and transfer lines until the gas emerged hot, followed by 12 additional hours of purging. After that, the transfer line needle valve is closed, and the transfer line is introduced into the cryostat. The dewar is then filled with liquid nitrogen, and the cooldown process is initiated with the cryostat being pumped by a vacuum pump. Finally, the vacuum pump is disconnected, and once the temperature stabilizes, the needle valve is adjusted.

An updated user-interface enables scheduling (date and time) for LN2 refills. Furthermore, the system incorporates a safety feature that, regardless of the time, triggers a forced filling if the level of the vessel falls below 30 %. A timeout ensures that no filling takes longer than 2h30 min, which prevents excessive interference of the process with the beamline time and contributes to operational safety. Additionally, if a timeout occurs during the filling process or if the system experiences faults, an email notification will be automatically sent to the individuals responsible for the subsystem, allowing for a quicker response to any potential issues. All variables are archived in EPICS [5] and shown by the human-machine interface (HMI) whereas a supervisory system centralizes information from all cryogenic systems in Sirius, allowing a quick check of levels, pressures, status, and alerts.

AUTOMATIC FLOW CONTROL

As mentioned in the previous section, at times, the needle valve needed to be manually adjusted. In order to make these sets at all times without the need to open the hutch and consequently shut down the beamline, the installation of a motorized bayonet was proposed. A transfer line between primary LN2 vessel and cryostat was replaced by a commercial transfer line with automatic needle valve (Fig. 3(a)), that receives a 0–10 V signal from the same CompactRio [6] that is already associated to the optics. The PID control loop is closed by reading the temperature of the mirror.

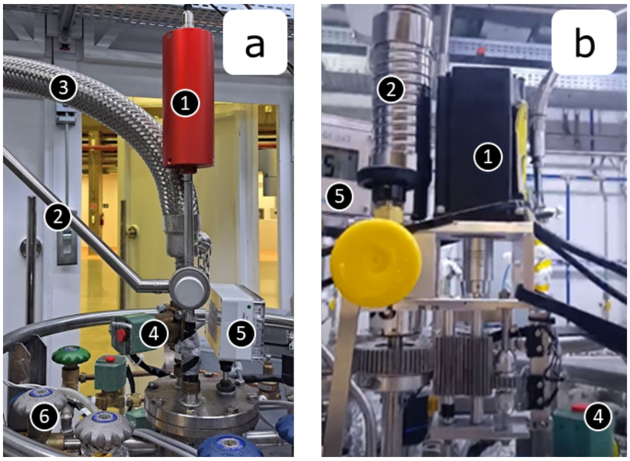

Figure 3: Commercial (a) and in-house (b) actuators (1). Also highlighted: transfer lines between primary vessel and cryostat (2), transfer line between vessels (3), valves for automatic filling (4), level gauge (5) and vent valve (6).

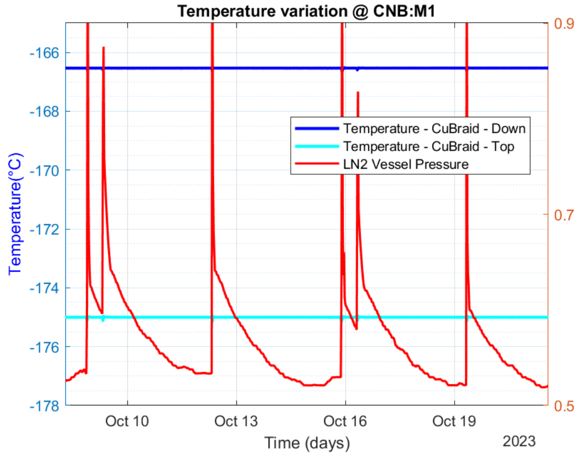

Figure 4: Temperature versus time for M1 Carnauba after introducing the commercial flow control valve. The red curve shows pressure fluctuation when operating with passive control.

This approach resulted in a 95 % reduction in the amplitude of temperature variations over 10 days (Fig. 4) even during refills as well as an 80 % reduction in beam movement.

A prototype was developed to motorize the needle valves currently in use, as shown in Fig. 3(b). This prototype featured a stepper motor coupled to the needle valve through gears in a ratio of 2.8:1. The control loop uses signals from temperature and from a rotary encoder, whereas mechanical limit switches were applied for homing and safety. The result of the bench test confirmed that the solution can eliminate drifts. The temperature was controlled within ±0.9 °C during 16 hours (Fig. 5(a)), which is expected to be fur-

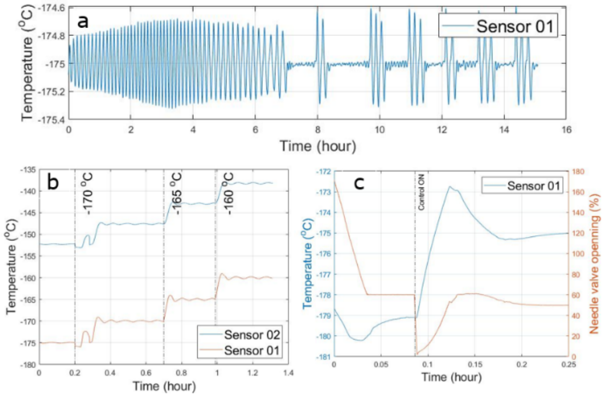

Figure 5: Temperature controlled for 16 hours during bench testing with unoptimized PID (a); setpoint selection for cryostat tip (b); activation of the PID control of the prototype when assembled at CARNAUBA 2^{nd} Mirror.

Figure 6: PS setup. A transfer line (1) connects the cryostat (2) to the PS (3) above the hutch. A manual valve (4) regulates the LN2 flow between them and an automatic valve (5) controls the LN2 level inside the PS, that is supplied by the secondary LN2 vessel by the 2^{nd} transfer line (6).

ther improved after PID optimization. Other improvements aimed at field application are the replacement of the mechanical limit switch by inductive ones aiming to reduce backlash and improve the homing procedure. Figure 5(b) illustrates that the flow control mechanism prototype allows for setpoint adjustment. Figure 5(c) displays the moment when the flow control prototype is active in CARNAUBA second mirror.

PHASE SEPARATOR

A customized setup was assembled (Fig. 6) wherein a phase separator (PS) replaced the primary vessel. The PS was positioned atop of the optical hutch containing the first mirror of the CARNAÚBA beamline and fed the cryostat by gravity. A manual valve was introduced to regulate the flow between them. As this setup was a prototype using in-house equipment, its length was notably extended due to the need for adaptations among various vacuum-isolated connections.

Significant temperature fluctuations were observed in this setup, as seen in Fig. 7, which were not reduced by increasing the flow rate. Such oscillations were not related to variations in the pressure of the LN2 vessel or to the opening of the PS valve. The working hypothesis is that the fluid undergoes a phase change along the path between PS and cryostat. For future applications, it would be beneficial to build a more compact circuit to ensure effective thermal insulation and stability of the transfer line.

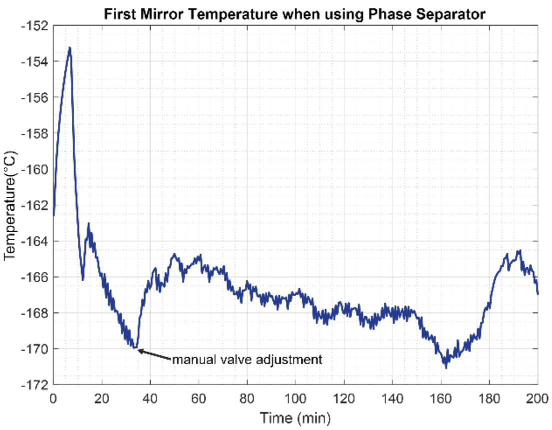

Figure 7: Temperature fluctuations of first mirror of CARNAUBA along 4 hours of cooling using the PS.

In comparison to the motorized bayonet, the mirror supplied by PS exhibited more vibration at both high and low frequencies, suggesting that switching to the PS is not advisable for the current system.

NON-CRYOGENIC SOLUTIONS

The flow control approach presented good perspectives and the in-house actuator tends to be economically advantageous. Despite of this, sporadic instability events persist related to the cryogenic circuit or even mechanical vibration transmitted by the thermal path between large mirrors and cryostats.

Preliminary simulations assuming higher temperatures indicate the possibility of keeping acceptable deformation rates on the surfaces of some mirrors currently cryogenically cooled. Therefore, three new designs have been considered using Peltiers with 0.5–9 W range and ±0.01 °C resolution.

CONCLUSIONS

This study focused on the actions taken to improve the performance of open-circuit cryogenically cooled systems at Sirius/LNLS, addressing temperature drifts, pressure variations, and temperature spikes during refilling. We implemented automatic flow control, enhancing system stability. The use of a Phase Separator was explored, but further investigation is needed. Now, even looking ahead to 350 mA operation, non-cryogenic solutions like Peltiers have been contemplated as viable options for some mirrors. In the other hand, motorizing transfer lines emerge as a promising solution for the optical instruments that will remain cryogenic.

REFERENCES

[1] F. Meneau, *et al.*, “Cateretê: the coherent X-ray scattering beamline at the fourth-generation synchrotron facility SIRIUS”, *Acta Crystallogr., Sect. A: Found.*, vol. A77, p. C283, 2021. `doi:10.1107/S0108767321093995`

[2] H. C. N. Tolentino, *et al.*, “Innovative instruments based on cryogenically cooled silicon crystals for the CARNAÚBA beamline at Sirius-LNLS”, *AIP Conf. Proc.*, vol. 2054, no. 1, p. 060026, Jan. 2019. `doi:10.1063/1.5084657`

[3] M. Saveri Silva *et al.*, “Cryogenic systems for optical elements cooling at Sirius/LNLS”, in *Proc. MEDSI'20*, Chicago, USA, Jul. 2021, pp. 21. `doi:10.18429/JACoW-MEDSI2020-MOPB02`

[4] M. Kida *et al.*, “Pool-Boiling Heat Transfer in Liquid Nitrogen”, *J. Nucl. Sci. Technol.*, vol. 18, no. 7, pp. 501–513, 1981. `doi:10.1080/18811248.1981.9733284`

[5] EPICS - Experimental Physics and Industrial Control System, `https://epics-controls.org/`

[6] CompactRIO Systems (22 August 2023), NI, `https://www.ni.com/en/shop/compactrio.html`