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CRYOGENIC SYSTEMS FOR OPTICAL ELEMENTS COOLING AT SIRIUS/LNLS

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Abstract

This work presents the in-house solution for cryogenic cooling of beamline optics subject to low to moderate thermal loads at Sirius at the Brazilian Synchrotron Light Laboratory (LNLS). The main requirements regarding extracted power and coolant consumption are detailed. We also discuss discoveries and improvements deployed during the commissioning of the CATERETÊ and the CARNAÚBA beamlines, such as the prevention of ice formation, stabilization of both thermal load and flow-rate, and auto-filling parameters, among others.

INTRODUCTION

Sirius, the Brazilian 4th-generation light source at the Brazilian Synchrotron Light Laboratory (LNLS), presents high-performance requirements in terms of preserving photon-beam quality, particularly regarding wavefront integrity and position stability. In this context, it is imperative that many silicon optical elements are effectively cooled, so that temperatures and their control-related parameters can be precisely handled to the point in which thermal effects are acceptable concerning figure distortions and drifts at different timescales. Keeping in mind the class of precision equipment, the required performance can only be achieved with robust thermal modelling [1-3]. For this, relevant aspects related to the implementation of liquid nitrogen cooling systems need to be emphasized. Currently, two solutions are present in the first-phase beamlines, according to the component thermal load: (1) a commercial cryocooler for high-heat-load applications (50 – 3000 W), such as the double-crystal monochromators; and (2) an in-house low-cost system for components under moderate loads such as the mirror systems and the four-bounce monochromators (4CM). This work describes the in-house solution, with examples from the CARNAÚBA (CNB) and CATERETÊ (CAT) beamlines.

OPEN LN2 CRYOSTAT SYSTEMS

Figure 1 illustrates the cooling circuit of a 4CM at CNB. Inside the vacuum chamber (a), the crystals are connected through thermal braids [4] to a commercial cryostat (b), which is fed with liquid nitrogen (LN2) by an instrumented cylinder (c). Level and pressure are controlled by standard beamline automation system that automatically feed it from a dedicated transfer line (d) connected to a secondary service unit external to the hutch (e) or to the LN2 line of the building. Gaseous nitrogen leaves the first vessel by an exhaust line (f) during filling, whereas the gas in the cryostat outlet is released inside the hutch at a significantly lower rate at normal operation. The LN2 flow in the cryostats is adjustable by regulating its flow regulating valve and the pressure of the liquid cylinder.

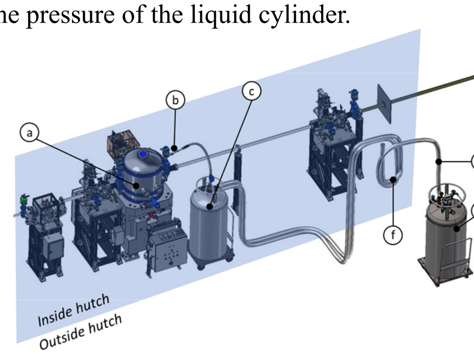

Figure 1: Third optical hutch of the CARNAÚBA beamline, highlighting the liquid nitrogen supply system of the 4CM, which comprises the vacuum chamber (a), the cryostat (b), the primary (c) and secondary (e) LN2 cylinders, the transfer line (d) and the exhaust line (f).

Figure 2 shows the top view of a primary vessel. Besides the standard items, custom stems were added to supply extra handles and solenoid valves for liquid and gas and to monitor pressure and level data.

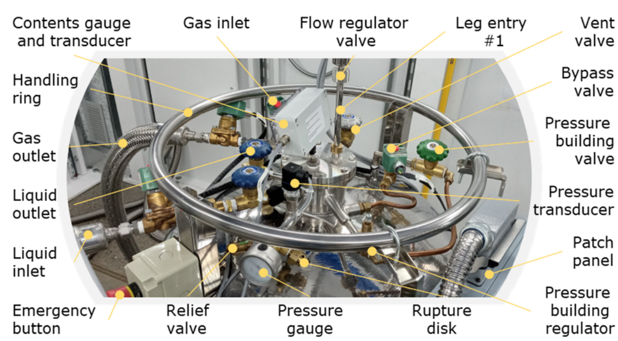

Figure 2: Top of primary LN2 cylinder and description of the connected elements.

The vessel inside the first optical hutch of CNB is connected to two cryostats, which cool the first mirror (M1) and an internal diagnostics (XDU), present in the same vacuum chamber. The same structure appears in its second optical hutch for the chamber enclosing the second mirror (M2) and the secondary source aperture (SSA). For all other optics, only one cryostat is assembled at each vessel.

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FILLING CONTROL

The PLC (Siemens S7-1512SP-1) was configured to keep the level of the primary LN2 cylinder between minimum and maximum setpoints by actuating the solenoid valves mounted at both ends of the transfer line. For CNB:4CM, for example, the setpoint was chosen as 80-95%, in which the temperature of the optics and the flow rate were considered stable even during filling. Those filling events took in average 18 minutes (2.5 L/min). During the offline tests, the speed for a 0-100% fill achieved 5.5 L/min with a 3 bar pressure gradient between vessels.

Figure 3 shows the history in the EPICS Archiver for the level of the primary and secondary LN2 cylinders of CNB and CAT during fifteen days. In average, the secondary cylinder is filled when its level decreases to 10%. The frequency of the filling events changes depending on the optics, since the theoretical heat load may vary from about 16 W (CAT: M1) to 60 W (CNB: M1+XDU). It can be used to estimate the consumption and, consequently, to calculate the losses of the systems.

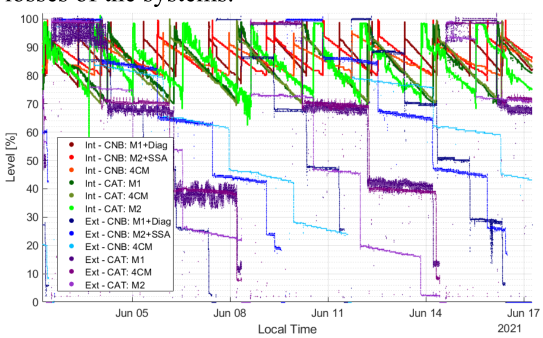

Figure 3: Levels of primary and secondary LN2 cylinders of CARNAÚBA and CATERETÊ beamlines.

Table 1 compares the consumption of the primary and secondary vessels to theoretical values, which are calculated from the estimated total heat load predicted in the thermal models. In addition, it is important to highlight that the cryostat consumes more nitrogen than the theoretical needs to avoid the drying of its internal reservoir in an event of power load increase or temporary liquid flow decrease (filling transfers). This event could lead to a binary gas-liquid flow with the increase of the cold finger temperature due to poor heat transfer or even increase the vibration disturbs, both noticed multiple times during the commissioning.

Table 1: Consumption of the Systems During Jun/2021

Optics	Load [W]	Consumption [L/h]		
		Theor.	Primary	Second.
CNB – M1+XDU	60	1.4	1.6	2.0
CNB – M2+SSA	20	0.5	1.1	1.4
CNB – 4CM	26	0.6	0.7	1.1
CAT – M1	16	0.4	1.55	1.64
CAT – 4CM	50	1.1	1.55	1.60
CAT – M2	20	0.5	1.66	1.71

In the considered time, the efficiency of the system oscillated between 22 and 73%. Furthermore, by comparing the contents of the primary and secondary vessels of CAT optics, it was verified that the losses during the transfer of the LN2 could be reduced to 3%. Investigations are being performed during the beamlines commissioning for optimizing the efficiencies by adjusting parameters such as level and pressure setpoints and opening of the flow regulator valves.

PRESSURE CONTROL

The pressure of the primary vessel is directly associated to the LN2 flow through the cryostat and, consequently to the temperature and dynamic stability of the optical elements. The pressure of the vessel naturally changes because of the outflow, the evaporation of LN2 inside it, and the filling process, which is accompanied by evaporation and the entrance of gas present in the transfer line. Thus, two methods (an active and a passive) were foreseen to keep the pressure of the receiver vessel constant and below the pressure of the provider vessel, which is also controlled.

In the active method, a solenoid valve is opened to vent gaseous nitrogen and decrease the pressure in the primary cylinder, while a second solenoid valve is opened to increase the pressure in the secondary cylinder by allowing a bypass of the vaporizer circuit. For high demanding systems, a third solenoid valve can be used to allow the entrance of gaseous nitrogen from a dedicated line. This solution should eliminate any possibility of condensate formation around the LN2 cylinder, which can occur in the traditional systems (pressure building valve) and would allow for a quick correction against filling events performed with a high gradient between the vessels. However, the on/off method was found to cause pressure variations as high as 0.2 bar in a 40-minute time span at the primary vessel. This variation is detrimental to the optical systems stability as it leads to a change in the LN2 flow, thus causing a change in the heat extraction capacity of the cryostats. For the so-far most sensitive system CNB:M1, considering the constant input power for the referred timespan, it generates a change in temperature as high as 0.42K at the mirror braids, leading to unacceptable thermal drifts. Furthermore, the pressure variation in the circuit was also found to actively move the cryostat, causing disturbances in a shorter timeframe as compared to thermal drifts. This could be solved with a proportional cryogenic gas flow valve for finer pressure control, but higher costs and integration complexity led to the search of a simpler passive solution

As a simpler passive alternative, the use of the already built-in thermal relief valve was found to largely solve the pressure variation issues. At this operation mode, the solenoids of the PLC pressure control are turned off, thus making the pressure rise by passive evaporation until it hits the nominal relief valve rating of 3.6 bar. At this stage, the referred spring-loaded valve proportionally relieves the gas until the equilibrium is archived between evaporation and gas scape. Despite this method being prone to a pressure hysteresis of tenths of a bar, the long-term drift was found

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to be as low as 18,3 mbar during a 12h test. Combined with the heaters PID control, this method led to a temperature variation of 50,2mK and 20,6mK in the M1 cooling braid and silicon substrate, respectively, Fig. 4. In this case, the solenoids are used during the transfer only when the primary vessel pressure is actively lowered back to 2.5 bar to generate the needed differential pressure for the liquid to flow.

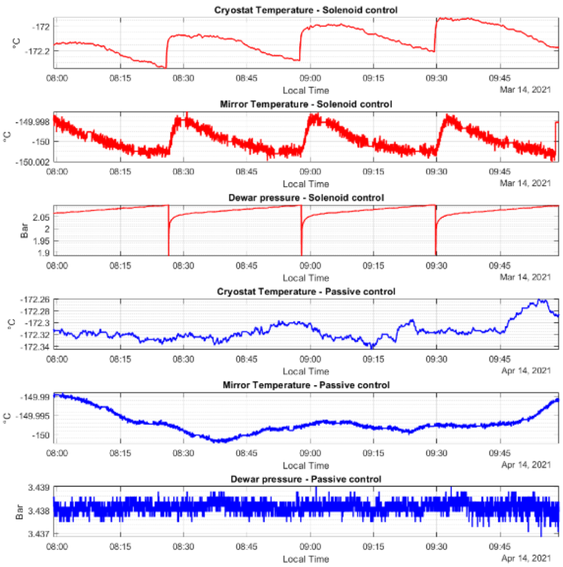

Figure 4: Temperature and vessel pressure when using the active solenoid control or the passive valve at the CNB:M1 systems.

EXHAUSTION

The gas released by the primary liquid cylinder during filling or automatic pressure control is directed out of the hutch through a vacuum-insulated exhaust line. However, the flow discharged by the cryostat is directly released into the hutches, since the flow rate is much lower. Indeed, Fig. 5 demonstrates that the oxygen ratio inside these hutches is comparable to those of the EMA beamline, in which there is no gaseous nitrogen release in the considered period, and even above the levels in experimental hutches of MANACÁ, CAT, and CNB beamlines, where cryojets for sample conditioning are commonly used.

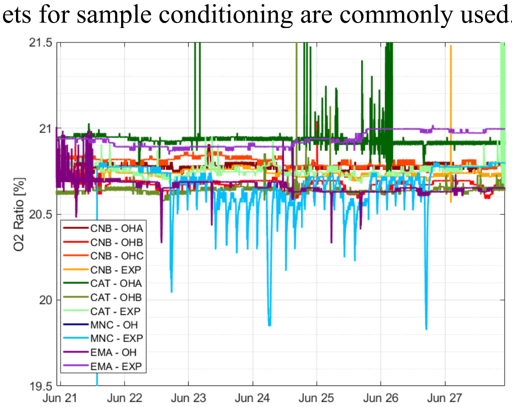

Figure 5: O2 ratio in several optical (OH) and experimental (EXP) hutches of CARNAÚBA, CATERETÊ, MANACÁ and EMA beamlines.

Yet, in addition to occasional ejection of LN2 from the cryostat outlet, the output gas itself is frosty. Consequently, its necessary to avoid the formation of ice and water around the cryostat outlets. Initially, it was observed that the use of an insulator would just offset the ice formation and that warming the residual gas required a noteworthy amount of energy, with additional safety concerns. Indeed, even when heating only the enclosure, significant power was also necessary, so that a fourth solution was developed. As shown in Fig. 6, it consists of a 3D printed PLA part in which the nitrogen flow is surrounded by a cylindrical channel through which there is a laminar flow of compressed air that act as an insulator.

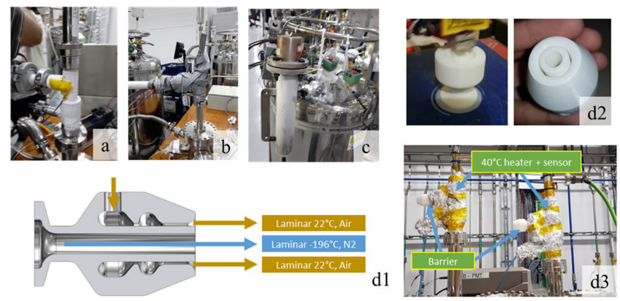

Figure 6: Options against condensate formation: nothing (a), blanket with heaters (b), gas heater (c), and custom part with air barrier (d).

INTERLOCK

The system is considered to have failed when the emergency button is pressed or when the control interface of the primary vessel is disconnected. It is also directly connected to the Equipment Protection System (EPS) such that unwanted events (as vacuum incident or overtemperature) trigger the actuation of valves and shutters as preventive measures.

CONCLUSION

A low-cost solution was developed for the cryogenic cooling of optics under moderate thermal loads at Sirius beamlines through the combination of commercial systems and ad hoc additions. The proposition aimed at solving the challenges associated with nitrogen supply and exhaust and to ensure temperature stability in the optics. Several systems are already operational while refined optimization proceeds. Performance limits could already be observed, and level and pressure controls have been effectively running for several months, endorsed by a robust interlock control.

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