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A VACUUM ASPIRATED CRYO COOLING SYSTEM (VACCS)

G. Duller, B. Olafsson, M. Nagy, Diamond Light Source, Didcot, United Kingdom
D. Magrath*, Brompton Bicycles, Greenford, United Kingdom

Abstract

The use of liquid nitrogen for cooling of synchrotron equipment is widespread. The cryogenic sub-coolers commonly employed come with some significant drawbacks such as cost, complexity, stiffness of distribution lines, and vibration induced by pressure variations. The typical sub-cooler is capable of handling 2 to 3 kW of absorbed power whilst many optics require no more than 50 to 150 W of cooling. We present a Vacuum Aspirated Cryo-cooling System (VACCS) which overcomes many of these disadvantages and which allows cryo-cooling to be implemented more widely. The VACCS system uses a vacuum, generated with no moving parts, to draw LN2 through a heat exchanger. Thus the system does not have to be pressure rated. We describe our designs for highly flexible distribution lines. A simple control system offers variable temperature at the heat exchanger by varying the flow rate of LN2. A system is installed at Diamond which allows the independent control of three zones. A test rig has demonstrated cooling capacity in excess of 100 W for a monochromator crystal assembly and controlled temperatures −194 to −120 °C.

INTRODUCTION

Many synchrotron optics require some sort of cooling. Cryogenic cooling is often an attractive choice due to, for instance, the enhanced properties of silicon and copper which can be accessed. Equally, scientific goals commonly demand that sample environments are held at cryogenic temperatures (77 K and above).

As a result closed-cycle cryogenic cooling systems are frequently employed where the high cost of implementation can be warranted. Unfortunately these systems come with some significant drawbacks, including high capital and running costs, take up a substantial footprint, have a tendency to excite vibrations due to pressure fluctuations, and require high stiffness distribution lines. These sub-coolers circulate liquid nitrogen (LN2) at elevated pressures to increase the boiling point of the fluid, thus allowing the coolant to extract power from the heat exchanger without inducing local boiling. Commonly rated at 5 to 10 bar, these pressures demand that all distribution lines are constructed to withstand these pressures whilst having minimal thermal losses, and vacuum vessels equipped with these systems require safety assessment and protection (burst disc or similar). These sub-cooler systems are typically rated at 2 to 3 kW cooling power, significantly in excess of the requirements of a typical beamline. In our tests the majority of monochromators require cooling of less than 100 W.

We have developed a novel cryocooling system, the Vacuum Aspirated Cryo-Cooling System (VACCS), with the goal of addressing many of the issues associated with sub-cooler systems and have demonstrated its cooling ability up to 100 W. This has been implemented at the Diamond Light Source (DLS) beamline, VMXm, to control three independent end-station zones and will shortly be implemented in a monochromator.

DESIGN

Principles of Operation

The VACCS system is designed with a focus on simplicity and cost-effectiveness, aiming to cool assemblies down to cryogenic temperatures using basic components. As the name implies, flow of LN2 is induced by generating partial vacuum at the exhaust. This is achieved by using an ejector pump and the basic function of it is shown in Fig. 1, where suction is generated by a motive fluid (pressurised air in our case), entering from the left side. The converging/diverging nozzle increases the velocity of the motive fluid and the kinetic energy is balanced by a drop in pressure, thereby generating suction at the bottom inlet [1].

A schematic of the VACCS system is shown in Fig. 2 which illustrates its principle components. The dewar supplying the LN2 to the system is vented to atmosphere. By placing a temperature sensor on the heat exchanger (device to be cooled), flow of LN2 can be adjusted via a PID controller by varying the pressure of the compressed air entering the ejector pump to achieve a desired temperature. Alternatively, the flowmeter in front if the ejector pump can used as a set point for control.

Taking advantage of the latent heat of vaporisation to cool the device, most of the LN2 is expected to have transformed to gaseous form (GN2) as it exits the heat exchanger. The purpose of having an exhaust heater after the heat exchanger is to heat the nitrogen to ambient temperature, allowing for uninsulated pipework to be used beyond this point, and thereby increasing the system's flexibility and ease of installation. Additionally, a standard calibrated flowmeter for air can be used, making it more cost-effective.

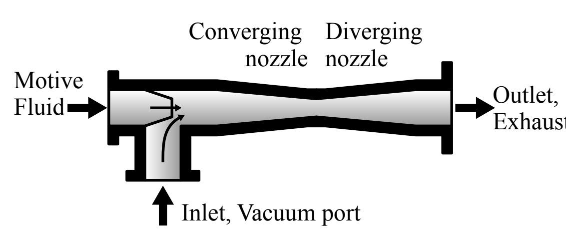

Figure 1: An illustration of an ejector pump (Figure based on a diagram from the product sheet in [2]).

* daniel.magrath@brompton.co.uk

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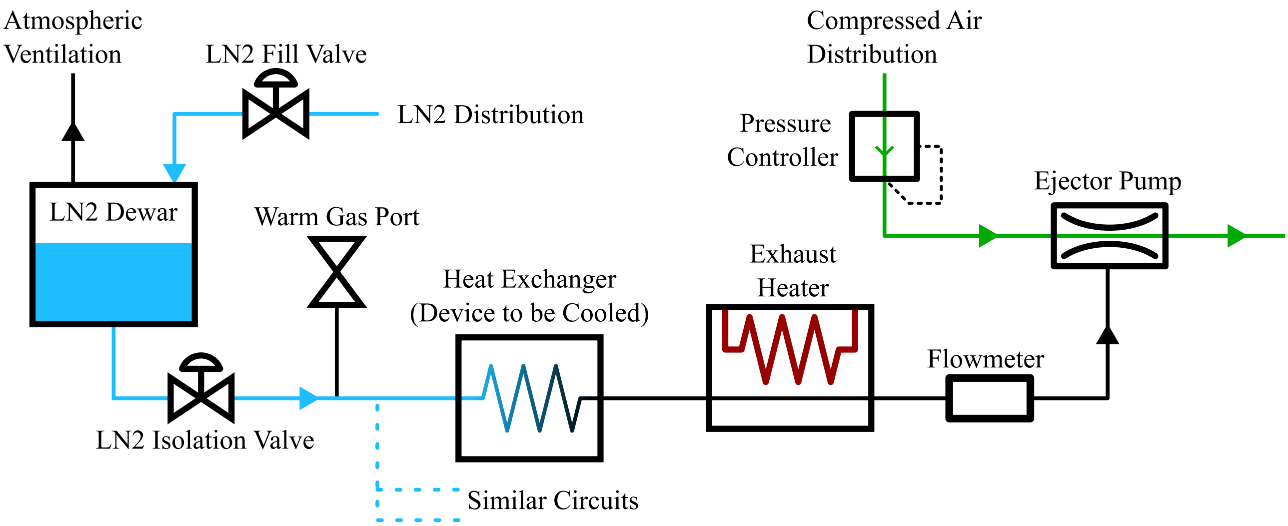

Figure 2: A diagram of the VACCS system. Liquid nitrogen is represented with blue lines, gaseous nitrogen with black lines, and air with green lines.

Flexible LN2 Distribution Lines

Having the dewar vented is one of the system's standout advantages. No specific pressure rating downstream of the LN2 fill valve is required. Rigid lines with flexible joints have been designed for this system and are shown in Fig. 3. In this design, edge-welded bellows are used as joints for both internal and external pipework, resulting in a highly flexible joint. A gimbal with limits was designed to prevent the joints from exceeding their maximum bending angle, which can also be used to restrict the motion of the joint if needed.

VACCS ON VMXM

As previously mentioned, VACCS has already been successfully implemented on VMXm, a beamline at DLS, on three individually controlled zones, all interconnected to in vacuo sample cooling. The three zones are as follows:

- **Sample hotel** A closed vessel above the goniometer that stores up to 5 samples.
- **Anti-contaminator** Aimed to be the coldest object inside the sample environment.
- **Sample gripper** A vertical arm that transfers a selected sample from the hotel and places it on the goniometer.

The control system for the three zones are depicted in Fig. 4. The compressed air distribution enters through the blue pneumatic tubes on the left side of the figure and is then subdivided into three distinct paths to three separate pressure controllers, one for each zone [3]. Each of these paths corresponds to a specific zone and is indicated by varying colors of pneumatic tubing: yellow for the sample hotel, green for the anti-contaminator, and red for the sample gripper. Gaseous nitrogen, emerging from the heater, enters from the right side of the diagram, passing through a flowmeter before continuing on to the ejector pump [2, 4].

The cool down process from room temperature for the sample gripper is illustrated in Fig. 5, where the gripper's temperature is depicted in blue on the left y-axis and the nitrogen flow rate is shown in orange on the right y-axis. It

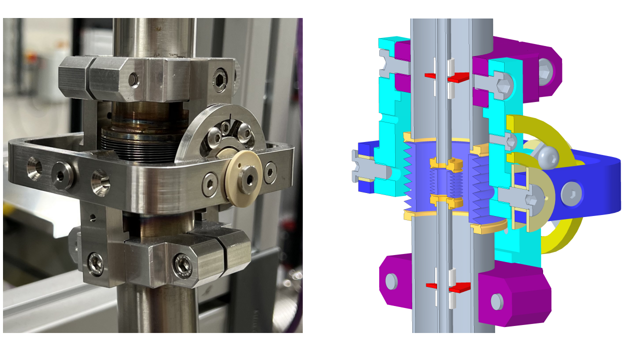
(a) (b)

Figure 3: Joint of a flexible LN2 distribution line. (a) a picture of a joint on VMXm, (b) a section view of the CAD model.

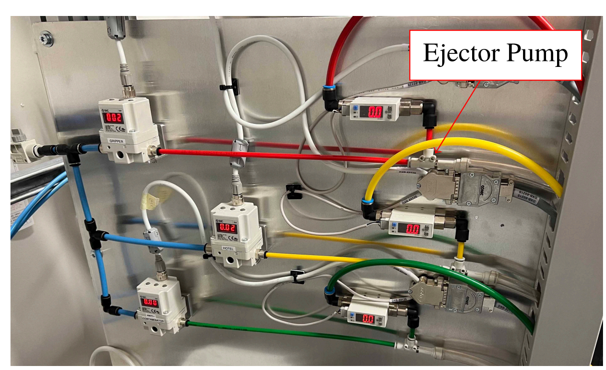

Figure 4: The pneumatic control system for the three zones on VMXm. Sample gripper zone (red tubing) on top, the sample hotel zone (yellow tubing) in the middle, and the anti-contaminator zone (green tubing) at the bottom.

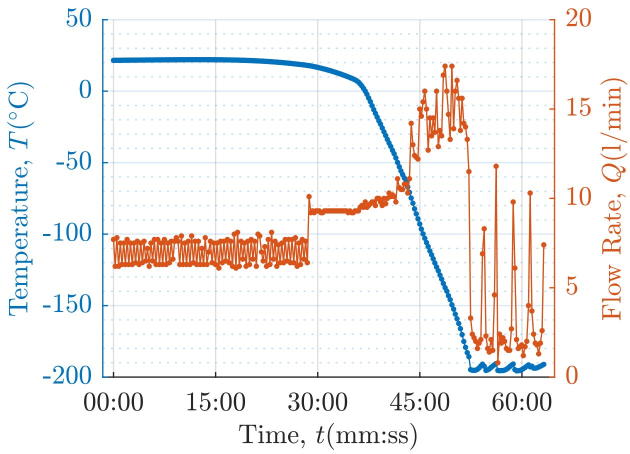

Figure 5: Cool down of the sample gripper. The left axis depicts the temperature of the gripper, while the right axis depicts the flow rate of GN2.

takes the gripper approximately 50 min to reach cryogenic temperatures and the flow rate of GN2 peaks at 17 l/min. It should be noted that liquid-to-gas expansion ratio of nitrogen is approximately 1:700 at 20 °C, making the LN2 usage only about 25 ml/min [5]. As it stabilises, the flow rate of GN2 oscillates between 2 to 10 l/min keeping an average temperature of −193.6 °C with a standard deviation of 1.3 °C.

The Sample Gripper is intermittently used to re-cool samples, and hence experiences variations in heat loads. The moment the sample is positioned on the goniometer, it starts warming up due to conduction. Typically, within 7 min the temperature of the sample rises to approximately −140 °C and needs to be re-cooled. Figure 6 depicts results from the sample gripper's interaction with a sample as it is lowered to cool the sample back to cryogenic temperatures. The lower plot on Fig. 6 shows the gripper's position, starting 23.5 mm above the sample and then lowered to 0 mm when it engages with the sample on the goniometer, and then subsequently released and raised back to 23.5 mm. Meanwhile, the upper plot displays the gripper's temperature and flow rate, mirroring the format seen in Fig. 5. These plots effectively illustrate the system's rapid response to temperature changes in the gripper. As a result, prior to lowering the gripper, it maintains a temperature of −195 °C and as it grips the sample it increases to −175 °C and the control system increases the flow to reduce the temperature of the sample and within a mere 3 min it has descended to −193 °C at which point it reduces the flow again.

MONOCHROMATOR TEST RIG

The previous section demonstrated the applicability of the system for sample environments. To assess the potential extension of the VACCS system to cool monochromators with relatively modest heat loads, an offline monochromator test rig was designed and manufactured. The designed test rig is illustrated in Fig. 7.

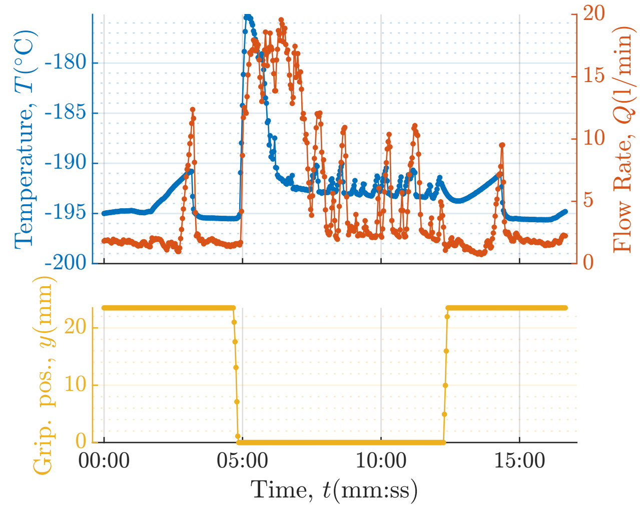

Figure 6: Cooling performance of the sample gripper. The upper plot depicts sample gripper and flow rate of GN2, on the left and right axis respectively, while the lower plot depicts the vertical position of the sample gripper.

The crystal assembly is presented in Fig. 8a, it consisting of a single dummy crystal block (made from aluminium), dimensions 30 (W) × 100 (L) × 70 (T) mm and two heat exchangers mounted on each side of the block with a 0.5 mm indium sheet in between. A more comprehensive depiction of the assembly is illustrated in Fig. 8b which shows an exploded view of the CAD model.

In order to replicate the heat absorbed from the beam, two Lake Shore cartridge heaters (HTR-50) [6] were mounted inside the dummy crystal. These heaters are both compatible with UHV and cryogenic conditions. To minimize the thermal resistance between the components, thermal grease, Apiezon N, was applied between the dummy crystal and the heaters [7]. Two PT100 temperature sensors were placed on the dummy crystal. Both of them were attached on the end of the crystal, where one was clamped and the other glued. Based on our experience, the glued sensor provides more

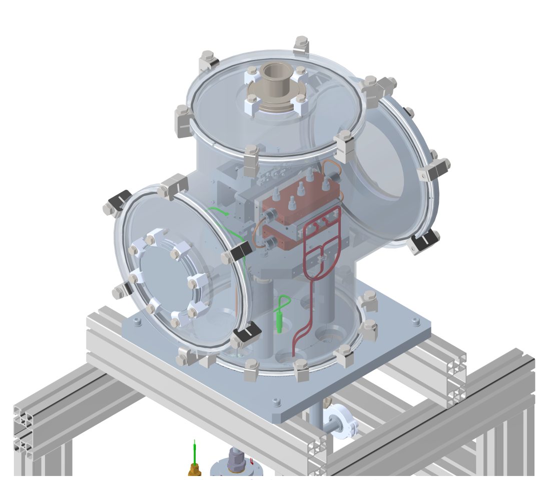

Figure 7: A CAD model of the monochromator test rig for validating the application of the VACCS system.

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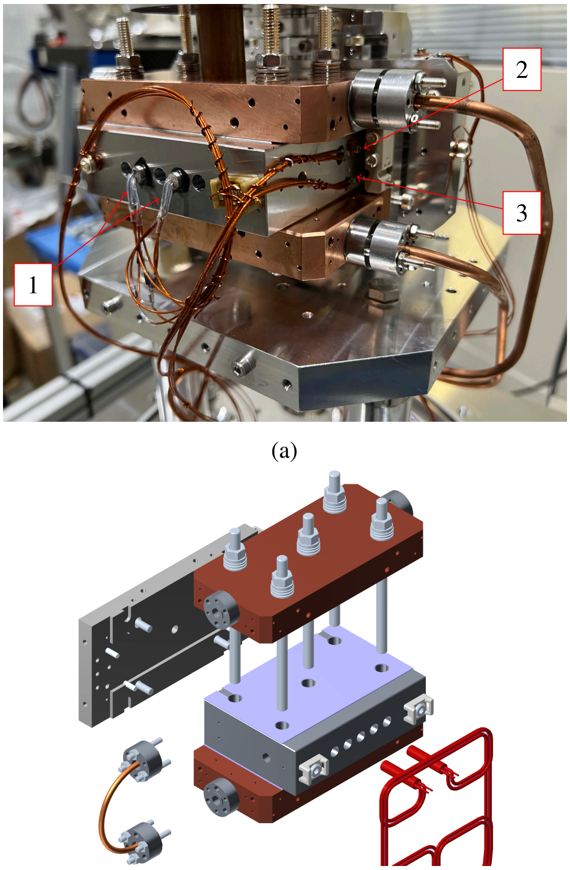

(a)

(b)

Figure 8: Dummy crystal assembly on the monochromator test rig. (a) A picture of the assembly (1) heaters, (2) clamped PT100, (3) glued PT100, and (b) an exploded view of the CAD model.

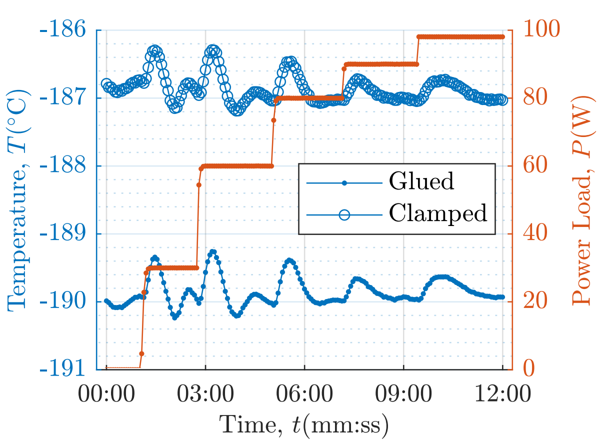

Figure 9: Power load variation on the test rig. The glued PT100 is depicted with pointed markers and the clamped PT100 circle markers.

precise results, but the clamped one has been included as a reference. To measure the power applied to the dummy crystal, the voltage and current were data-logged.

Figure 9 shows the results of varying the power load on the dummy crystal. The figure shows the temperature measured on the dummy crystal represented on the left y-axis and the power load applied to the heaters on the right y-axis. In this case, the temperature was set to −190 °C and the power load on the heaters was incrementally increased to 100 W.

As anticipated, a minor discrepancy is evident between the two PT100 readings, but both readings exhibit remarkable stability. Throughout this test, the glued PT100 yielded an average temperature of −189.9 °C with a standard deviation of 0.2 °C, while the clamped yielded an average of −186.9 °C with a corresponding standard deviation of 0.2 °C.

CONCLUSION

This paper has introduced an innovative and cost-effective approach to cryogenic cooling by using basic components and does not require pressure rated distribution lines. The system has been successfully implemented on an existing beamline at DLS to facilitate sample environment cooling. A thorough performance evaluation of the system has been carried out.

Moreover, the potential suitability for cooling a monochromator has been investigated on a dedicated test rig. Notably, the results were highly promising demonstrating to consistently maintain the target temperature, exhibiting merely 0.2 °C of standard deviation when subjected to a varying heat load of up to 100 W.

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