TRIUMF CYCLOTRON VACUUM SYSTEM UPGRADE AND OPERATIONAL EXPERIENCE

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Abstract

The replacement of the 30-year-old Philips cryogenerator with a modern LINDE-1630 helium refrigerator is an important component of TRIUMF's ongoing 500 MeV cyclotron refurbishing program. Two 10.7 m long cryopanels are cooled with liquid helium rather than with 17 K helium gas, as was the case with the cryogenerator. This has increased the pumping speed and, respectively, improved the vacuum in the approximately 100 m^3 cyclotron tank. Additionally, the thermal shield, previously cooled with helium gas, is now cooled with liquid nitrogen. These changes have resulted in increased reliability of the cyclotron vacuum system and, consequently, longer operation periods without maintenance. The new refrigeration unit was commissioned in September 2007. The results from over one year of operational experience are discussed. Also, data on hydrogen cryopumping is presented.

INTRODUCTION

The prior cryogenerator [1] used for TRIUMF's cyclotron was replaced with a modern helium refrigerator. The helium refrigerator liquefies helium for use in cooling the cryopanels, essential for maintaining adequate vacuum in the cyclotron. Figure 1 depicts the cryogenic systems and transfer lines in their current state.

Installation of this new helium refrigerator has resulted in improvements in cyclotron vacuum, since the cryopanels can now be cooled with liquid helium, compared to the prior system which used cold helium gas. This has also improved the cyclotron reliability and increased the time between cryopanel defrosts.

The new system has undergone several tests to quantify the resulting improvements as well as to confirm continued performance. Tests have included measurements of the pumping speed of the cyclotron cryopanels and measurements of the helium refrigerator's cooling power and liquefaction rate. The results from these tests are presented below.

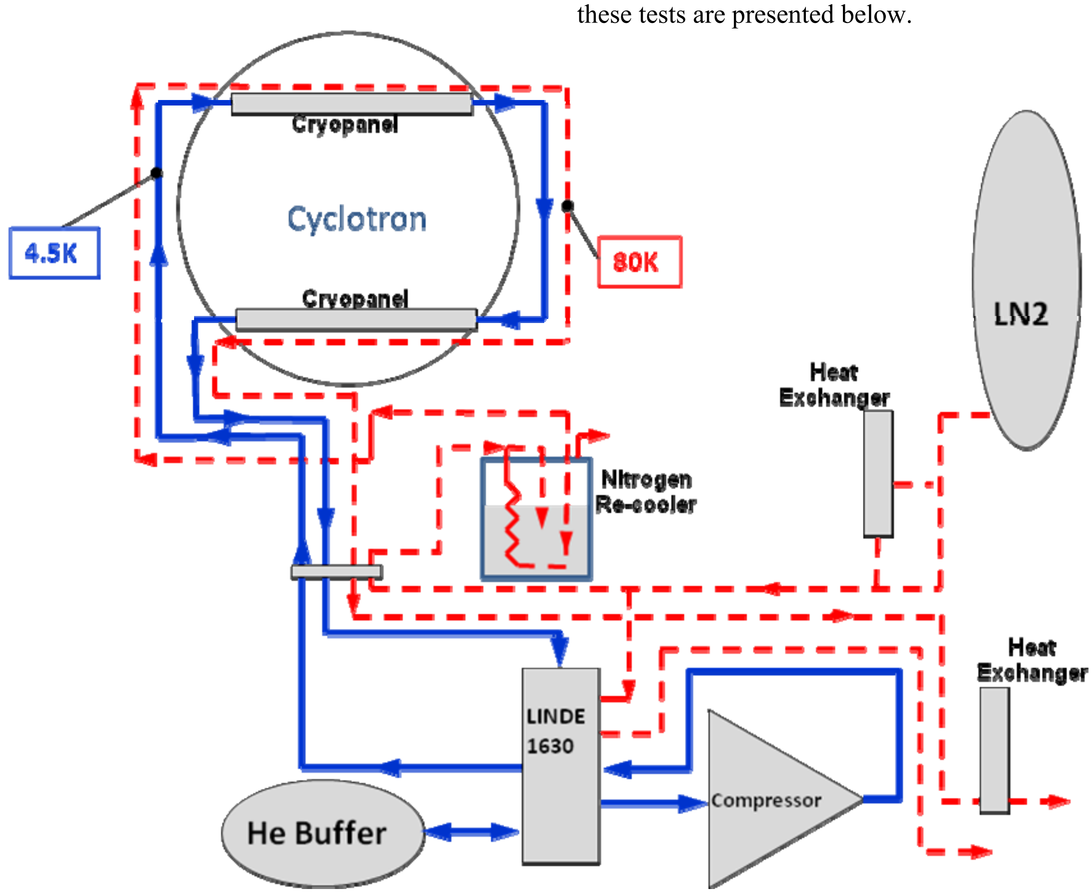

Figure 1: Cyclotron Cryogenic System Diagram.

SYSTEM DESCRIPTION

The 500 MeV cyclotron at TRIUMF is maintained at a low pressure through the use of several types of pumps, including two large cryopanels. These cryopanels, each 10.7 m long, are cooled to a temperature of about 4.5 K with helium liquefied by a LINDE-1630 helium refrigerator located approximately 40 m away from the cyclotron and connected to it with an all-welded transfer line. When gas particles in the cyclotron's vacuum space impact upon the cryopanels' surface, the low temperature causes them to stick rather than bounce off, decreasing the pressure in the cyclotron. The effectiveness of the cryopanels varies for different gases and is related to how low of a temperature can be achieved. As a result, the liquid helium cooled cryopanels are significantly more effective for H_2 compared to being cooled with 17 K helium gas prior to the upgrade.

The new cyclotron cryogenic system was commissioned in September 2007 and has operated successfully since then. The helium refrigerator has a rated cooling power of 151 W at a temperature of 4.5 K or can liquefy 57 ℓ of helium per hour when nitrogen precooling is used. The RSX compressor supplies 22.2 g/s of helium circulation.

Figure 1 shows the 4.5 K and 80 K plumbing for the cyclotron's cryogenic system. As can be seen, nitrogen enters from a large external nitrogen tank, passes through a nitrogen re-cooler (described later) and then enters the cyclotron. It is used to provide thermal shielding for the liquid helium transfer lines. After passing through the cyclotron, the nitrogen is vented to atmosphere through an ambient heat exchanger.

Unlike nitrogen, helium flows in a closed circuit. Helium is liquefied by the LINDE-1630 refrigerator and is transferred to the cyclotron. Some of the helium evaporates during the transport and the resulting dual-phase mixture cools the cryopanels. Next, the helium returns from the cyclotron through the refrigerator and is pressurized by the RSX compressor, before going to the refrigerator for the next cycle.

Furthermore, the new helium refrigerator utilizes the same interface as the previous Philips B-20 cryogenerator, which was retained. Its performance is tested regularly so that it can be used as a backup if needed.

THERMOMETRY

Temperatures throughout the system are measured at several locations. Lakeshore DT-470 silicon diode thermometers are installed on the cryoline. In addition, there are thermocouples located on the nitrogen shields as well as on the helium supply and return lines inside the cyclotron. There are also temperature sensors located on the helium refrigerator's inlet and outlet.

NITROGEN SYSTEM

Nitrogen lines cool the shields for the helium lines to the cyclotron. The nitrogen flow is controlled by a single manual proportional valve. As a result, the liquid nitrogen flow through the system varies with the tank pressure, causing some operational inconvenience. This will be improved by installing an electronic temperature-controlled proportional valve.

To alleviate this issue, a nitrogen re-cooling system, shown in Figure 2, was implemented. The nitrogen re-cooler consists of a dewar flask partially filled with liquid nitrogen. A pipe containing a mixture of liquid and gaseous nitrogen passes through a heat exchanger in the nitrogen tank, causing the gaseous nitrogen to condense. The use of this arrangement allows circulation of liquid nitrogen only, rather than a mixture of liquid and gaseous nitrogen. A pure liquid has a lower temperature and has better thermal conductivity than a liquid-gas mixture, resulting in improved thermal shielding for the helium lines as well as reduced frictional losses in the nitrogen flow.

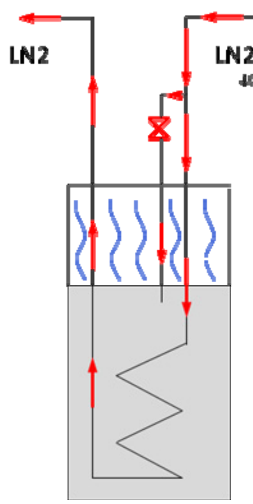

Figure 2: Nitrogen re-cooler.

The nitrogen system can also be used to rapidly defrost the cyclotron when needed, by passing nitrogen gas at ambient temperature from the external nitrogen buffer tank through the system.

Overall, average liquid nitrogen usage has increased from 78,000 ℓ/month with the previous system to 94,000 ℓ/month with the current system. This 20% increase is considered acceptable given the advantages of the new system.

VACUUM IMPROVEMENTS AND HYDROGEN CRYOPUMPING

To quantify the improvement provided by reducing the cryopanel temperature, tests of the pumping speed of the cryopanels were carried out. In 1981, pumping speed tests were performed [2] with a combination of cryopanels, diffusion and turbo pumps. In the 1981 tests, the total pumping speed for hydrogen was 5,700 ℓ/s, measured using ion gauges inside the cyclotron. The pumping speed was determined by measuring the pressure as a function of time after valves to the pumps were opened. By modeling the decline in pressure as an exponential, a characteristic time can be obtained which, along with the chamber volume, determines the pumping speed.

In the 2008 tests, valves to all pumps were closed during the measurement, so pumping was provided only by the cryopanels. The same characteristic time method was employed to calculate the pumping speed, based on measurements from a residual gas analyzer (RGA) located at the end of a pipe some distance away from the cyclotron. The RGA has the advantage of removing the uncertainty due to ion gauge calibration for hydrogen, which was a significant issue in the 1981 measurements. Since the pipe has a limited conductance, pressure changes at the RGA would be slowed compared to pressure changes in the cyclotron, so the results from the 2008 tests are conservative. According to these tests, the pumping speed of hydrogen using the cryopanels was 26,000 ℓ/s, an increase of over four times compared to the 1981 value.

The cryopanel surface area is 3.4 m^2, however, the inlet area to the cryopanels is only 1.9 m^2, and so the pumping speed per unit area was calculated to be 1.4 $\ell \cdot s^{-1} \cdot cm^{-2}$. As expected, this is about an order of magnitude lower than the ideal pumping speed, which is 12.9 $\ell \cdot s^{-1} \cdot cm^{-2}$ when calculated for a sticking coefficient of 1.0, using the formula given in [3]. It is believed that the predominant H_2 pumping mechanism is cryosorption onto other condensed gases on the cryopanels. Our value compares well with the results obtained with TIMO [4], a test platform for a cryopumping system at ITER. There, a pumping speed of 1.2 $\ell \cdot s^{-1} \cdot cm^{-2}$ is achieved by cryosorption onto a surface coated with activated charcoal and cooled to a temperature of 5 K. On the other hand, a cryopump at CERN [5] with a silver coated surface cooled to 4.2 K achieves a significantly higher pumping speed of 9.2 $\ell \cdot s^{-1} \cdot cm^{-2}$.

HELIUM REFRIGERATOR TESTS

As mentioned before, the LINDE-1630 helium refrigerator is rated to provide a cooling power of 151 W and a liquefaction rate of 57 ℓ/h in the operating mode used at TRIUMF. These values were confirmed (or exceeded) in tests conducted at Tulsa, Oklahoma, prior to the device being installed at TRIUMF. Following over one year of operation, tests were conducted on the performance of the refrigerator once again. The tests showed an average cooling power of 130 W and a liquefaction rate of 48 ℓ/h, representing a performance drop of approximately 15%. However, these tests were conducted with long, nonstandard vacuum-jacketed transfer lines, as well as a different set of bayonets and stingers. It was concluded that the decreased cooling and liquefaction rates could be attributed to thermal losses in these transfer lines, rather than a deterioration of the refrigerator's performance.

UPGRADED VACUUM SYSTEM EXPERIENCE

Since the installation of the new helium refrigerator, there have been no significant issues with the vacuum system. Due to various reasons, the B-20 was shut down on average every 400 hours of operation over a two year timeframe to maintain performance, while the LINDE-1630 was only restarted once every 620 hours on average. In fact, the majority of defrosts of the new system have occurred as a result of power outages or scheduled tests rather than as a result of the LINDE-1630 requiring shutdown or maintenance. The longest continuous period of operation of the new machine was over 1400 hours, compared with 840 for the prior one. It should be noted that the data for the new machine come from just over one year of experience, and even longer periods of continuous operation are expected in the future.

CONCLUSIONS

The new helium refrigerator for the 500 MeV cyclotron is performing well. It provides improved vacuum in the cyclotron tank by cooling the cryopanels to a lower temperature than the prior system. H_2 cryopumping rates of up to 26,000 ℓ/s have been measured. Tests after over one year of operation have not shown any significant deterioration in performance. The system is also capable of continuous operation for periods of at least three months. The majority of defrosts and losses of helium have resulted from power outages rather than a necessity to shut down the system. The refrigerator's first annual overhaul was recently completed.

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