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Experimental and numerical investigations of operational parameters of TRIUMF's cyclotron cryogenic system

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Abstract. TRIUMF houses the world's largest cyclotron built in 1972. The cyclotron accelerates H⁻ ions up to 520 MeV. Proton beams are extracted from the cyclotron by using stripping foils converting H⁻ ions to H⁺ ions. High availability of the 520 MeV proton beams is a vital part of TRIUMF's scientific program. Vacuum tank of the cyclotron is $\approx 100 \text{ m}^3$ chamber operating at 1×10^{-8} Torr pressure during beam production. The vacuum is achieved through the use of turbo pumps, cryopumps and cryopanels. The cryopanels are a form of a distributed cryopump that does the major portion of pumping. The cryogenic system of cryopanels went through an extensive upgrade from B-20 Stirling cycle cryo-refrigerators to Linde-1630 helium liquefier. Open-loop liquid nitrogen circulation was introduced for cryopanels 80 K shield. Operational costs associated with procurement of liquid nitrogen triggered the search for alternative configurations of cryogenic support for cryopanels. This paper presents the results of TRIUMF's evaluation for possible upgrades of the existing cryogenic system, as well as experimental and numerical investigations of its operational parameters.

1. Introduction

TRIUMF's cyclotron vacuum tank is $\approx 100 \text{ m}^3$ chamber operating at 1×10^{-8} Torr pressure. The cyclotron with its elevated lid is shown in figure 1.

The cryopanels are a form of a distributed cryopump that does the major portion of the pumping, especially of hydrogen, water vapour, oxygen, and nitrogen. They are cooled to low temperatures using 4.5 K liquid helium and 80 K liquid nitrogen. The cryopanels' layout and cross-section are shown in figure 3 and figure 4.

The initial setup of the cyclotron cryopumping system included B-20 Stirling cycle cryogenerator, which supplied helium gas at 16 K and 70 K to the cryopanels in the tank. The decreasing stability of the Stirling cryogenerator over time triggered the decision for a complete replacement of B-20 installation. A Linde-1630 helium refrigerator was chosen to become a main source of low temperature cryogenic supply, providing 4 K liquid helium to the helium circuit. A gravity driven open loop liquid nitrogen supply from the storage tank has replaced a cooling agent for 80 K cryopanel circuit [1, 2].

At the current configuration of the cyclotron cryogenic system, both liquid helium and liquid nitrogen circuits are connected to the cyclotron tank through a vacuum insulated transfer line, accommodating four tubes for supply and return of helium and nitrogen correspondingly. Cold gaseous helium stream is returned to Linde-1630 helium refrigerator, forming a closed loop



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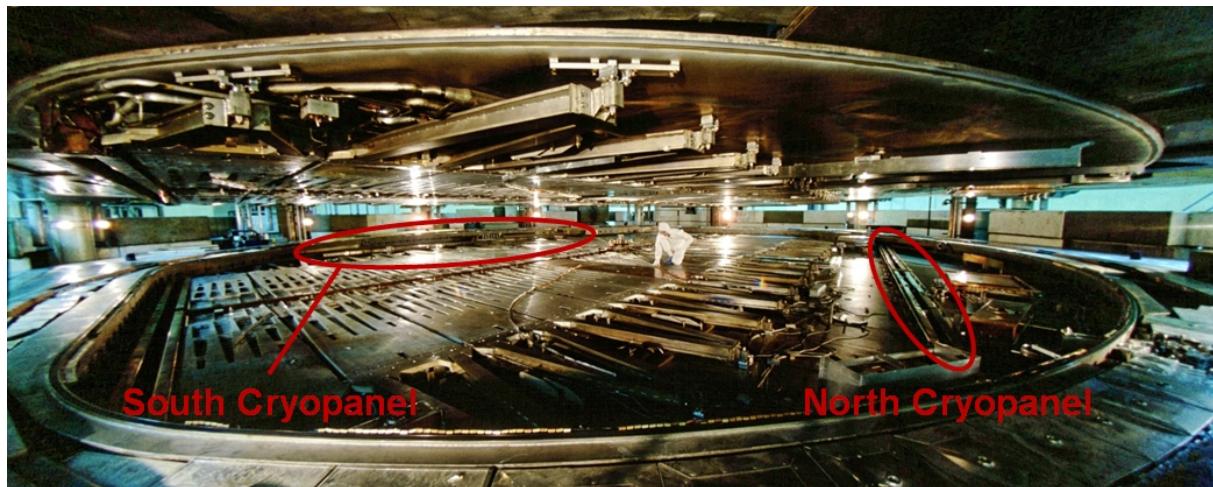


Figure 1. The cyclotron with its lid elevated

helium process system. Cold gaseous return of nitrogen stream is warmed up and vented to the atmosphere, forming an open loop nitrogen cooling system.

2. Analysis of liquid nitrogen consumption

The use of liquid nitrogen as a cryogen for the first stage of cryopanels introduces the drawback on limitation of the lowest achievable temperature, limited by boiling temperature of nitrogen at a given pressure. To achieve this temperature over the entire length of the cryopanel, two-phase flow of liquid nitrogen at the outlet of the south cryopanel is required. The temperature of nitrogen outlet from the cryopanel is controlled by a proportional control valve located downstream of the cryopanel utilizing dedicated PID control loop. The valve is controlled by the cryopanel nitrogen outlet temperature.

During cyclotron operation, the temperature at the outlet from the south cryopanel fluctuates with low-amplitude, low-frequency oscillations (figure 2). These oscillations might be created by nitrogen vapor pockets passing by the temperature sensor due to the slug pattern of two-phase nitrogen flow. Associated with the temperature spikes are spikes in the vacuum pressure in the cyclotron, indicating that there is some localized warming or flow induced vibration of the shield

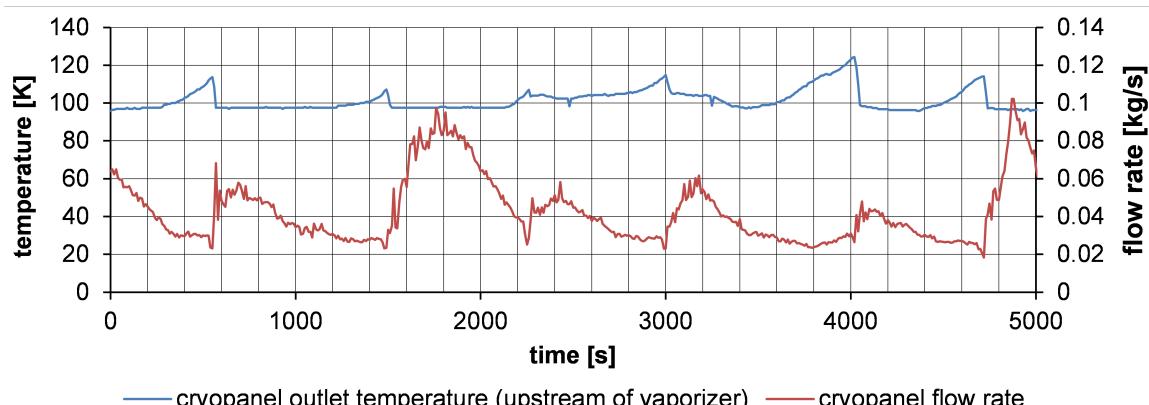


Figure 2. Example of flow and temperature oscillations at the outlet of the cyclotron cryopanels

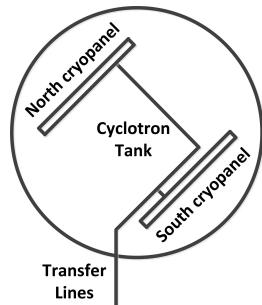


Figure 3. Layout of cryopanels in the cyclotron

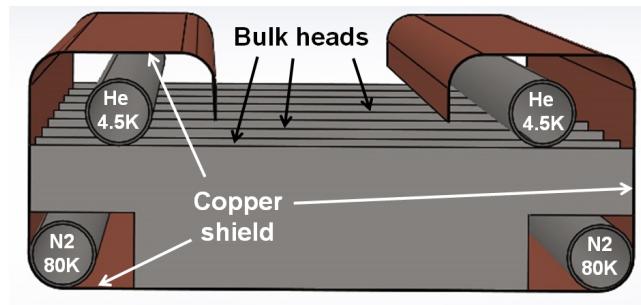


Figure 4. Cyclotron cryopanels cross-section shown with multiple bulkheads

causing some of the cryo-pumped material to escape the surface of the panels.

Since the current design of the liquid nitrogen cooling circuit requires two-phase nitrogen condition at the outlet from the cryopanel, it results in excessive use of liquid nitrogen. A fraction of the latent heat of the two-phase liquid nitrogen flow and the entire sensible heat within the range from 80 K to 300 K is lost during the warm-up of two-phase nitrogen flow in vacuum-insulated flexible lines and ambient vaporizer. Only a fraction of usable heat is used in the heat-exchange process between liquid nitrogen flow and 80 K stage of the cryopanel shield, reducing the efficiency of liquid nitrogen use and increasing the total amount of consumed product.

A number of studies were performed to analyze the consumption rate of liquid nitrogen, as well as the quality of two-phase nitrogen exhaust, or equivalent heat load to liquid nitrogen circuit. A number of challenges are associated with the process of measurement of the heat load due to periodic pressure and temperature (quality) oscillations of the exhaust nitrogen flow (figure 2).

2.1. Total consumption study based on level sensors of liquid nitrogen storage tank

Calculations were performed based on retrieved archives of data from level sensors of liquid nitrogen storage tank. Archives for four consecutive years of operation (2010, 2011, 2012, and 2013) were used (figure 5). TRIUMF's e-linac cryogenic system first became operational in Q4 of 2013 [3], therefore, operational data was affected by e-linac consumers in consecutive years.

2.2. Total consumption studies based on orifice and Venturi-type flow meters

A few measurements were performed by using a custom built calibrated orifice flow meter connected downstream of the nitrogen vaporizer and a standard Venturi type flow meter connected upstream of the nitrogen vaporizer. For the measurement at the upstream of vaporizer, an electric heater was used to provide a calibrated heat load into a return flow of nitrogen in order to define the enthalpy and quality of the two-phase nitrogen flow. The e-linac cryogenic system and the Linde-1630 refrigerator are equipped with dedicated nitrogen exhaust lines, not affecting cyclotron consumption measurements.

2.3. Liquid phase return flow rate study

A multiple flow rate measurements of the liquid phase of nitrogen were performed at the outlet of cyclotron cryopanels using a portable dewar as phase separator. The gaseous nitrogen phase was vented. The accumulation rate of liquid nitrogen over time indicated the rate of liquid nitrogen exhaust.

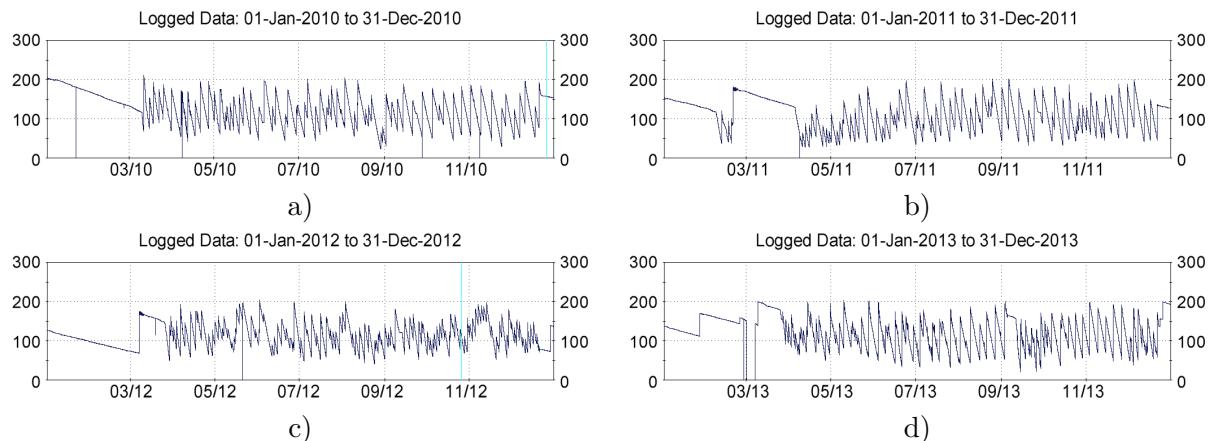


Figure 5. Liquid nitrogen storage tank levels over 2010, 2011, 2012, and 2013

The results of all the measurements performed are shown on table 1. The highly unstable character of liquid phase exhaust rate triggered a numerical study of liquid nitrogen and liquid helium flows within cyclotron cryopanels.

3. Mathematical model of cryogen flows in cyclotron cryopanels

A dynamic time-dependent mathematical model of cryogenic flows in cyclotron cryopanels was developed using MATLAB®. The model provides the temperature, quality (liquid/vapor phase ratio) and pressure distributions as functions of time for each part of the cryopanel (liquid helium and nitrogen lines, walls, fins and bulk heads). The model accounts for conductive and radiative heat transfer, phase change in the liquid helium and nitrogen streams, includes pressure drop in the liquid helium and nitrogen streams and considers variations in convective heat transfer coefficients due to temperature, pressure, viscosity, etc.

Figure 6 illustrates an example of the temperature distributions found in the cryopanel's walls, shields and bulk heads. The plots are constructed for the cross-section slice taken at the mid-point of the north cryopanel.

Comparison of simulation data with operational data of the cyclotron cryogenic system lead to a possible conclusion, that there are significant heat losses in the nitrogen supply lines leading in

Table 1. Results of liquid nitrogen flow rate measurements.

Measurement	Total nitrogen consumption [l/hr]	Liquid phase exhaust flow rate [l/hr]
Storage tank level (2010)	154.2	-
Storage tank level (2011)	156.2	-
Storage tank level (2012)	164.1	-
Orifice type flow meter	122.9	-
Venturi type flow meter	198.4	35.32
Liquid phase return (1)	-	143.3
Liquid phase return (2)	-	64.01
Liquid phase return (3)	-	36.88
Liquid phase return (4)	-	39.91
Liquid phase return (5)	-	49.54

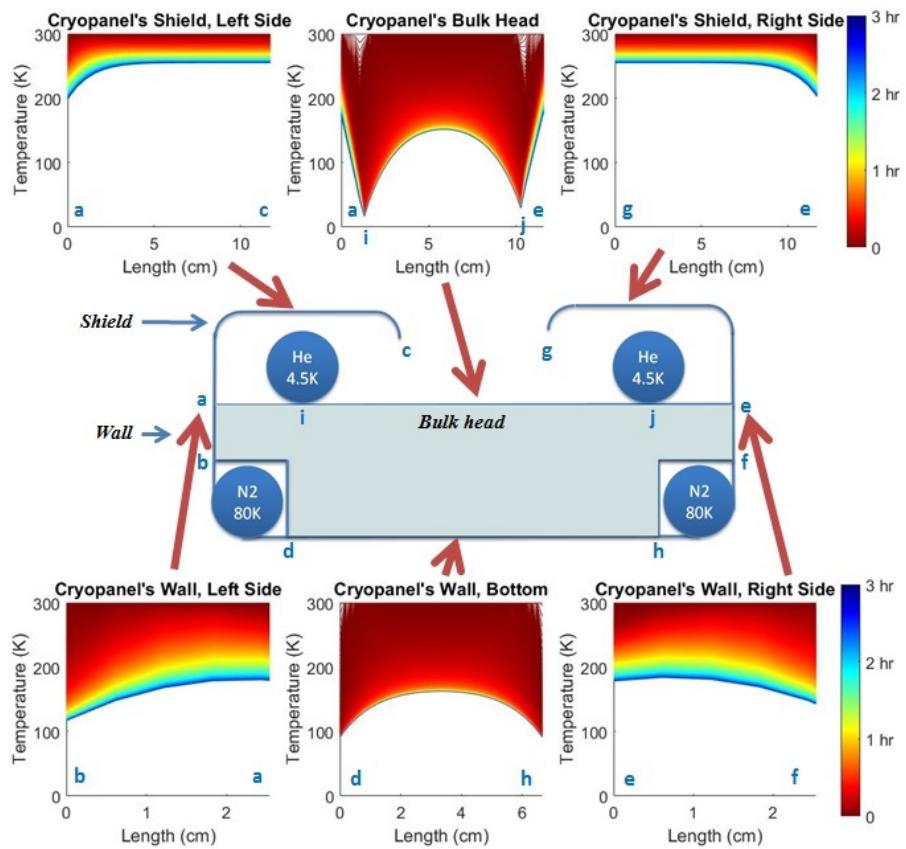


Figure 6. Example of the temperature distributions found in cryopanels cross-section [4]

and out of the cryopanels. The model was used to determine that cryopanel's surface emissivity is $\epsilon \approx 0.115$, which would be otherwise impractical to determine experimentally.

4. Conclusion and future work

Low repeatability of the nitrogen flow measurements leads to a conclusion of an unstable character of nitrogen flow in the cryopanels. Results of the mathematical model suggest that significant amount of heat load might be introduced by degraded over time multi-layered insulation of distribution lines. TRIUMF's search for reliable alternatives to the existing installation is currently underway. Such alternatives, as replacement of liquid helium and liquid nitrogen circuits with gaseous helium flows from a dedicated helium refrigerator, use of turbo Brayton cycle refrigerator and recirculation of liquid nitrogen using cryogenic circulator are being considered.

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