OPERATING EXPERIENCE WITH THE MICHIGAN STATE UNIVERSITY SUPERCONDUCTING CYCLOTRON CRYOGENIC SYSTEM*

M.L. Mallory
Cyclotron Laboratory, Michigan State University
East Lansing, Michigan 48824

Abstract

The MSU superconducting cyclotron cryogenic system has been operating for about one year and many cryogenic parameters have been measured. Data for cryostat cool-down, liquid helium consumption, liquid nitrogen consumption, cryostat warmup, and vacuum jacket pressure as a function of temperature have been taken. In addition, methods have been developed for handling of contaminants in the helium system (air), for filling liquid helium in the cryostat, and for various cryogenic failure modes. Finally, a leak detection method was developed that is applicable at liquid helium temperature and has been used to find ultra-small leaks in the cryostat. This method utilizes the density and viscosity variations of cold helium gas as a function of temperature and may ultimately provide three orders of magnitude sensitivity improvement beyond presently achieved room temperature leak rates.

Introduction

A superconducting heavy ion cyclotron magnet[1] is now successfully operating at Michigan State University. The major effort at turning this magnet on and its subsequent operation has been predominately the task of understanding various cryogenic problems. The majority of these problems can be classified as understanding the practical knowledge of operating a cryogenic system, i.e., versus some fundamental or new aspects of cryogenics.

In acquiring the necessary knowledge to run the cryogenic system, the invaluable advice of various cryogenic experts has been obtained, but, as to be expected, problems have been encountered that were not considered. The characteristics of the Michigan State University cryogenic system and various operating experiences are reported in the following sections with the expectation that future superconducting cyclotrons will profit from these results.

Cryogenic System Characteristics

The cryogenic system of the superconducting cyclotron is a closed helium loop. The major components of the system are 1) the magnet cryostat, 2) a 9733 gallon helium gas reservoir tank, 3) a 500ℓ liquid helium dewar, 4) a CTI 1400 refrigerator-liquifier with dual charcoal filter traps at 60 K and variable engine speed control, 5) two 55 cu ft/min helium compressors, and 6) all interconnecting helium transfer lines. An existing liquid nitrogen system was used and required construction of transfer lines to the appropriate ports. Fig. 1 is a block diagram of the superconducting cyclotron helium system.

An important part of the system is the instrumentation used to monitor the cryogenic parameters. Shown in Fig. 2, it includes four platinum thermometers, twelve tophel-cupron thermocouple junctions, and eight helium level sensors. Various temperature and pressure gauges are included on the refrigerator.

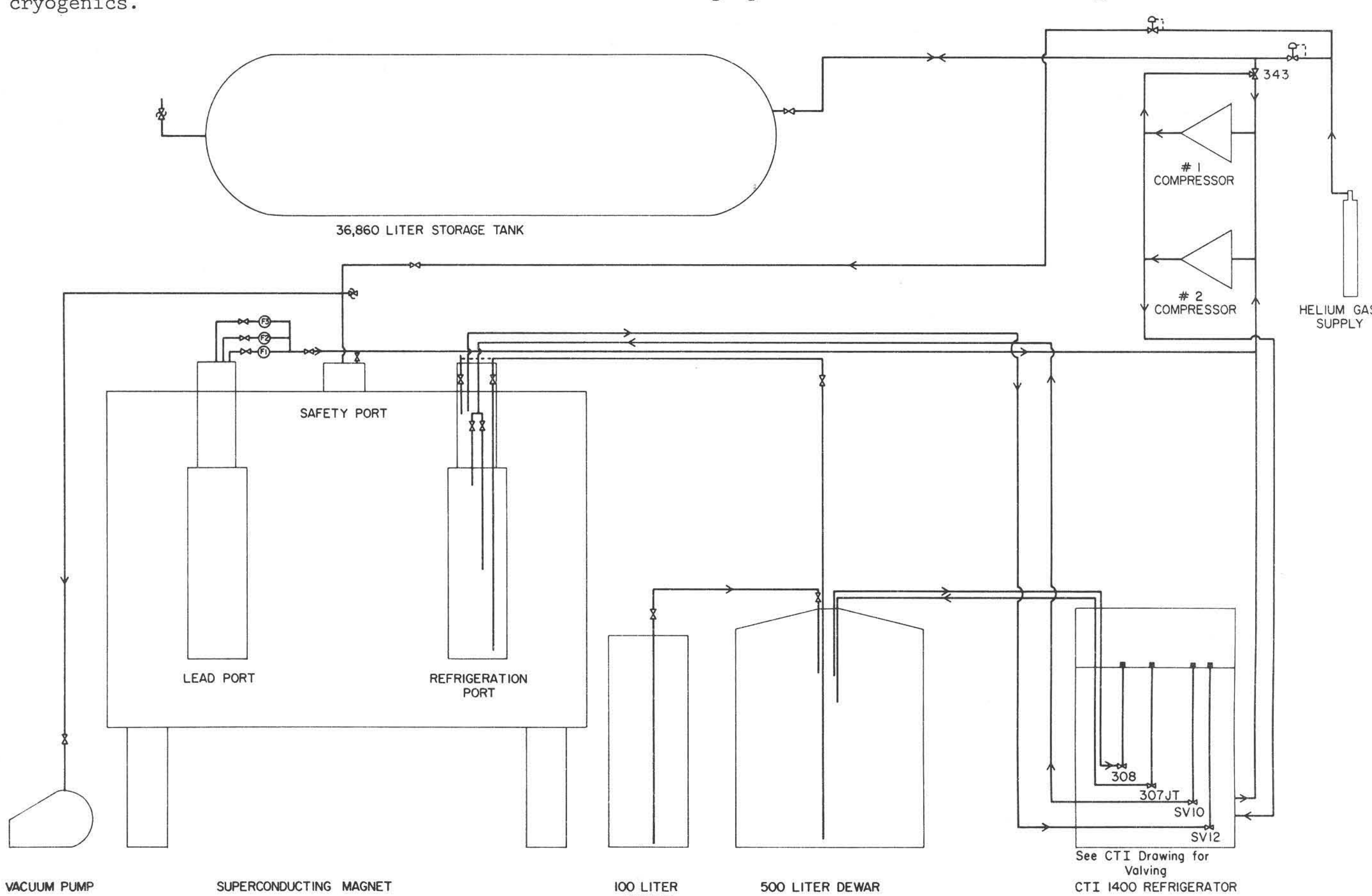

Fig. 1. The helium system block diagram for the 500 MeV superconducting cyclotron. The system is a closed helium loop and has a liquid helium production capacity of 26 ℓ/hr.

*This material is based upon work supported by the National Science Foundation under Grant No. Phy 78-01684.

0018-9499/79/0400-2138$00.75 ©1979 IEEE

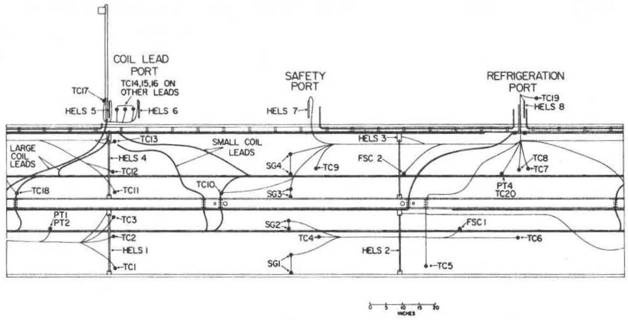

Fig. 2. Side view of coil surface showing sensors and lead locations inside the helium chamber. This representation is as if the coil surface were unrolled to show the entire circumference. TC are thermocouples, HELS are helium levels sensors, and PT are platinum thermometers.

Operational Parameters

Magnet Cooldown

The cooldown of the superconducting magnet from room temperature to 20 K was accomplished on May 22, 1977. Fig. 3 is the cooling curve for the two extreme thermocouple sensors and shows a cooling time of 130 hrs. The theoretical valve, based on cooling of 4,171 lbs. of stainless steel and 9,747 lbs. of copper with a mass flow of 9.2 g/sec of helium, is 60 hrs. Measurements of the refrigerator throughput indicated that approximately 1/2 of the refrigerator mass flow was being bypassed. The decreased mass flow is attributed to a conductance problem.

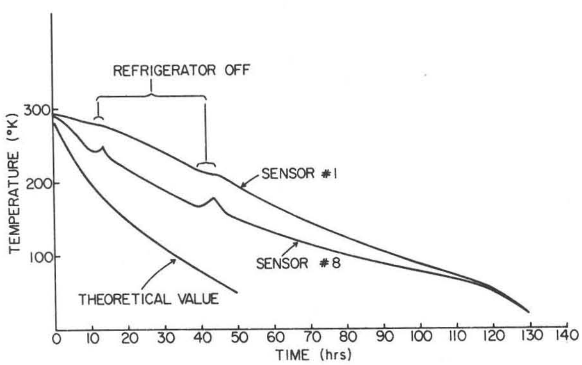

Fig. 3. The cooling curves for the superconducting magnet are shown. Sensor #8 is located near the entrance of the cold helium gas from the refrigerator. Sensor #1 is located the furthest from the entrance of the cold helium gas and represents the warmest coil temperature. The predicted cooling rate is also included.

In cooling the magnet all the gas is initially passed through a liquid nitrogen cooled charcoal trap which traps water vapor. At 250 K this trap is then removed. The internal traps in the refrigerator are then used to catch any containments. These traps are regenerated several times during the cooldown.

Liquid Helium Operations

The mode for filling the magnet cryostat with liquid helium utilizes the 500ℓ liquid helium dewar as the source of liquid helium. The pressure in the dewar is increased (≃ 8 psi) beyond the pressure in the magnet cryostat (≃ 5 psi), causing liquid helium to transfer. The refrigerator is valved for making liquid helium in the 500ℓ dewar, and the magnet cryostat boil-off gas is returned to the low temperature heat exchanger in the refrigerator. The transfer rate is limited by the maximum liquid helium production rate of the refrigerator (≃ 26 ℓ/hr.). If the boil-off gas rate exceeds the refrigerator production rate, the pressure in the cryostat causes the pressure in the pump suction side of the refrigerator to increase beyond its pop off limit. Two methods of handling excess boil-off gas have been developed. The first method is to restrict the transfer rate by closing a valve in the liquid helium transfer line and thereby ultimately matching the refrigerator load. The method now used is to valve off the boil-off gas to the refrigerator until gas venting is stopped. The pressure in the magnet cryostat then increases, thereby approaching the pressure in the 500ℓ dewar, causing the transfer rate to decrease. Transfer rates as high as 70 ℓ/hr. have been achieved.

The magnet cryostat has the option of transferring the liquid helium to the bottom or to the top of the cryostat—there is a distinct difference in the time required for liquid helium to accumulate. Namely, if the top fill is used, the magnet must be completely cold from top to bottom before liquid helium will appear on the level sensors. We have tried to fill the cryostat for time periods of ≃ 24 hrs. from the top and have not succeeded. Filling the cryostat from the bottom requires only the complete cooling of a small section of the magnet coil before liquid is detected. Secondly, the boil-off gas establishes a temperature gradient in the coil that allows rapid liquid helium accumulation. Complete filling times of less than 8 hrs. have been achieved.

The phenomenon of heat pulses was encountered. A heat pulse (a warm quantity of helium gas) occurs when liquid helium is first transferred through the warm transfer line. If the warm gas enters the low temperature exchanger, the liquid production rate drops to zero and over-pressurization occurs. The refrigerator has the option of valving the boil-off return gas to the proper temperature range in its heat exchanger, thereby allowing the refrigerator to stay tuned to maximum liquid production rate. Heat pulses are also encountered at various level heights in the initial filling of the magnet cryostat, and these level heights are associated with coil sections.

A 40ℓ reservoir of liquid helium covers the top of the magnet coil. Difficulties in filling this reservoir have been encountered from initial cooldown. In one reservoir filling attempt, the refrigerator was sending large quantities of liquid helium into the 500ℓ dewar but a factor of two change in pressure on the dewar did not change the helium height in the cryostat reservoir. Changing the transfer line to the top fill port of the cryostat resulted in immediate filling of the reservoir. This "chocking mode" in the liquid transfer appears to be produced by the heat load at the top of the cryostat. The current leads, safety port, refrigerator port, and the mechanical link to room temperature are sources of heat located at the top of the helium cryostat. In addition, the main coil section is shielded from this heat load by a stainless steel partition until the liquid helium enters the reservoir. This hypothesis is supported by the observation that the reservoir has been successfully refilled from the bottom port after initial filling.

A thermal short at the median plane penetration of the magnet coil occurred after an incident in adjusting the centering of the magnet coil in the yoke. The refrigerator could not handle the boil-off gas until the liquid helium height dropped several inches below the thermal short. Evidence of frost also appeared at the short. A temporary solution was achieved by evacuating this cryostat penetration, thereby increasing the path length of the thermal short to room temperature.

The helium level sensor in the refrigerator port of the cryostat has responded differently than the other level sensors when liquid helium was introduced into the cryostat through the top liquid helium fill. Namely, the level sensor indicates that liquid helium is filling that port up to the 80% level, when all other data indicated no liquid helium in the top of the cryostat. It was found that the helium splash baffle, located directly under the liquid helium top fill entrance, appears in close proximity to the level sensor at its 80% mark. It is postulated that liquid helium forms a pool on top of the splash baffle and then flows from this pool down the level sensor and into the cryostat, making it appear to the level sensor that it is under liquid helium.

Steady state cryostat helium level operation has been achieved. As the liquid helium fills the top port of the cryostat, the thermal load increases. This results in a pressure increase in the magnet cryostat, which changes the pressure differential between it and the 500ℓ dewar, producing a decreased transfer rate which then lowers the helium height and hence the pressure, resulting in an equilibrium level operation. The other part of steady state operation requires matching the refrigerator to the helium consumption. This is done by adjusting the amount of warm helium gas that flows by the liquid nitrogen heat exchanger. The whole system has operated for periods of 48 hrs., without any adjustment, where the adjustments then made were not needed.

Two methods have been used to measure the cryostat liquid helium boil-off rate. The first method measures the excess liquid helium production rate where it is assumed that the refrigerator is tuned to maximum production. This method yields a boil-off rate of ≈ 12 ℓ/hr. The second method measures the cryostat helium height as a function of time with the liquid helium transfer valve closed. Eight ℓ/hr. have been obtained by this method. The transfer line loss may account for the difference. The best value is expected to be 5 ℓ/hr. and the cryostat heat load, due to poor vacuum insulation, may account for the boil-off rate above this value.

Liquid Nitrogen Usage

Liquid nitrogen is used to cool the radiation shield surrounding the magnet cryostat and in the refrigerator first heat exchanger. The usage rate depends on the cryostat temperature. At initial cooldown, all the warm helium gas is heat exchanged with the liquid nitrogen and the rate is ≈ 93 ℓ/hr. At 100 K the rate decreases to ≈ 50 ℓ/hr. and finally when the magnet is full of liquid helium, the rate is ≈ 30 ℓ/hr. Improvements in the liquid nitrogen transport system, the radiation shield of the magnet, and the heat load of the cryostat are expected to decrease this further.

Cryostat Warmup

The cryostat warmup procedure is still in the development stage. The first stage in warmup involves transferring the liquid helium from the cryostat to the 500ℓ dewar. A slow method is to close the transfer line valve and let the heat load boil off the liquid. A fast method is to close the boil-off gas valve, thereby causing the cryostat pressure to exceed the 500ℓ dewar pressure and reversing the flow through the transfer line.

The cryostat diffusion pump is also closed while it contains liquid. The cryostat is warmed to 60 K in ≈ 24 hrs., then the vacuum jacket is released to atmosphere with dry nitrogen gas. The cryostat takes ≈ 5 days to warm to 270 K. A very small temperature differential in the coil is measured during the entire warmup process. Heat tapes have been attached to the outside of the cryostat and do shorten the warmup time. Flowing current through the coil has not been attempted.

Cryostat Vacuum

The cryostat vacuum jacket is evacuated by a 6" diffusion pump. The jacket contains 27 layers of super insulation and 27 layers of paper. Outgassing from this material and the metal of the cryostat results in a vacuum of > 1 micron at room temperature. Two distinct steps in the vacuum pressure are observed during cooldown. At a temperature of ≈ 260 K (where water freezes out) the pressure drops to ≈ 8×10^{-4} Torr. At 60 K (where nitrogen and oxygen freeze out) the pressure drops to 2×10^{-5} Torr.

Contaminants

Care about keeping contaminants (i.e., air) out of the helium system is a major concern expressed by experienced cryogenic people. At MSU, a major effort was made to assure that the helium system was leak tight. In addition, the system was vacuum pumped and backfilled many times with clean helium gas. Secondly, the refrigerator contains dual charcoal traps that are regenerated while operating.

Two partial freeze-ups (blockage within the refrigerator heat exchanger) have been encountered during the two years of operation. The first occurred after initial cooldown of the cryostat. The cryostat was warmed to 270 K and all the helium gas was recovered into the reservior tank. A partial freeze up occurred at the next cooldown.

It is hypothesized that the contaminants came from the magnet cryostat, and entered the pure helium during warm up. The procedure used now disconnects the magnet cryostat from the helium system at 60 K, and the helium pressure increase in the cryostat, as it warms, is vented to atmosphere.

The second partial freeze-up occurred in a similar situation involving the 500ℓ dewar. The dewar was warmed to room temperature after ≈ 1 year of containing liquid helium. A partial freeze up occurred at the cooldown of this dewar. It is hypothesized that the dewar collected contaminants, since the transfer lines are frequently inserted and removed and are potential contamination sources. It is proposed that the 500ℓ dewar be treated in the same manner as the magnet cryostat in its next warmup.

A contaminant problem has been encountered in the long term operation of the magnet cryostat. After several weeks of liquid in the cryostat the heat load or refrigeration cooling capacity changes. It was found that regenerating the charcoal filter traps restored the refrigerator to its original capacity.

Leak Detection Method

Investigation into the causes of the liquid helium boil-off rate revealed that helium gas was leaking into the vacuum jacket. A method has been developed for finding this helium leak while the cryostat contains liquid helium.

The method utilizes the temperature variation of the viscosity and density[2] of cold helium gas as shown in Fig. 4. Changes in the temperature of the helium gas at the leak location change the leak rate into the vacuum jacket. Several ways of temperature variation of the cryostat are possible. The method used has utilized the ten different connections to the helium refrigerator by returning the boil-off gas from the liquid (≈ 5°K) through any one of these connections for short times. The change of the boil-off

0018-9499/79/0400-2140$00.75

return gas path causes a temperature shift in the cryostat and corresponding variation in the vacuum jacket pressure, which then can be used as indications of leak locations. Fig. 5 is an example of the effect when cold helium gas was allowed to flow through current lead number one and clearly shows a helium leak. Three additional helium leaks have now been found by this technique. As the helium leaks of the cryostat were fixed, the helium boil-off rate decreased. This leak detection technique[3] offers the potential of finding leak rates at liquid helium temperatures that are three magnitudes smaller than presently achieved at room temperature.

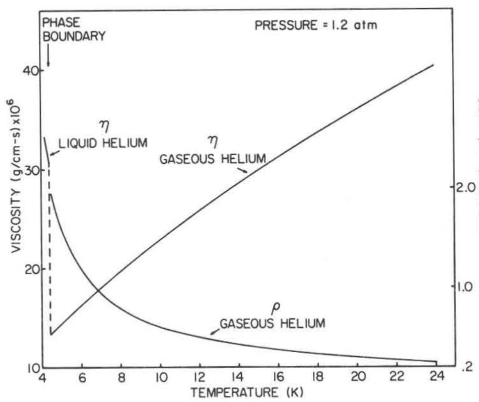

Fig. 4. The viscosity and density of helium from 24 K to 4 K at a pressure of 1.2 atm, the operating pressure of the superconducting cyclotron cryostat, are shown. A temperature change from 24 K to 4 K causes a change in the helium viscosity of ≃ 3 and hence a corresponding change in the leak rate through a crack.

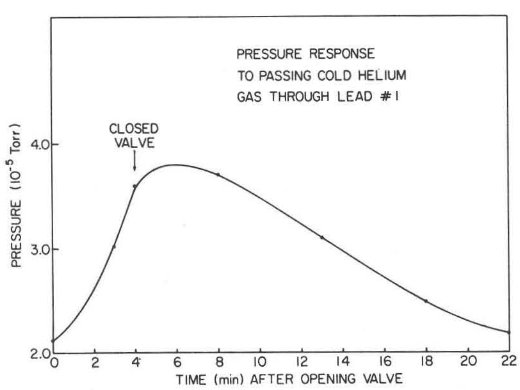

Fig. 5. Measurement of the pressure in the cryostat vacuum jacket when cold helium gas is passed through the cryostat area containing the crack. Additional leaks have now been found with leak rate five times smaller than the one shown above.

The helium leak in the cryostat has allowed measurements of the "hold-up" time at room temperature of helium atoms in the super insulation layers. The helium leak detector is used to monitor the cryostat vacuum jacket and it detects a helium leak rate of $\simeq 1 \times 10^{-9}$ Torr ℓ/sec., while the pressure in the vacuum jacket is held at 1 micron by a 6" diffusion pump. The warm helium gas is then evacuated from the liquid helium can, thereby removing the helium leak source. After approximately 60 minutes, the leak detector sees no helium atoms (sensitivity of $\simeq 5 \times 10^{-10}$ Torr ℓ/sec.) indicating that they have been completely pumped from the super insulation layers.

Conclusion

During the past year, a large lore of experience in operating the MSU cryogenic system has been gained and verifies the cryogenic feasibility of the MSU superconducting cyclotron magnet.

References

[1] H.G. Blosser et al., Seventh International Conference on Cyclotrons and their Applications, Birkhäuser, 584 (1975).

[2] R.D. McCarty, NBS Technical Note 631 (1972).

[3] M.L. Mallory and H.G. Blosser, Nucl. Instr. and Methods, to be published.

** DISCUSSION **

K. ERDMAN: How do you find leaks in long welds at the bottom of your cryostat where you don't have boil-off circuits you can shut off?

M. MALLORY: The fourth leak that we have now located is indeed in the lower half of the coil. It was found by monitoring the concentration of helium atoms in the vacuum jacket with the helium leak detector mass spectrometer and by varying the helium height in the coil. As the helium level in the coil approaches the crack, we detect a slight increase in the number of helium atoms in the vacuum jacket. After the liquid helium is above the crack, a magnitude change in the helium concentration is detected. In lowering the helium level, we detect the inverse process.

E. HUDSON: Can you elaborate a little more on your ion source tests at 52 KG?

M. MALLORY: We have successfully extracted a nitrogen ion beam into our 180° mass analyzer that is located in the superconducting magnet, and have resolved the following peaks: $^{14}N_2^{1+}$, $^{14}N^{1+}$, $^{14}N^{2+}$, $^{14}N^{3+}$, and $^{16}O^{1+}$. We plan to use argon gas in the source and hope to detect the peaks up to Ar^{8+}.

0018-9499/79/0400-2141$00.75 ©1979 IEEE