Design, Fabrication, Installation and Commissioning of the Helium Refrigeration system Supporting Superconducting Radio Frequency Testing at Facility for Rare Isotope Beams at Michigan State University

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Abstract
The Facility for Rare Isotope Beams (FRIB) will be a scientific user facility for the Office of Nuclear Physics in the U.S. Department of Energy Office of Science (DOE-SC). The FRIB linear accelerator (LINAC) will be comprised of cryomodules each with multiple Superconducting Radio Frequency (SRF) cavities operating at 2 K. A helium refrigeration system was designed, fabricated, installed and commissioned in the SRF high bay building to test and certify these cavities and cryomodules before installation in the FRIB LINAC tunnel. The helium refrigeration system includes a helium refrigerator which has nominal capacity of 900 W at 4 K, 5000 L liquid helium storage Dewar, helium gas storage, two room temperature vacuum pumps capable of 2.5 g/s each for 2 K testing, purifier, purifier recovery compressor, and the distribution system for liquid nitrogen and helium. The helium refrigeration system is now operational supporting three below grade cavity testing Dewars and one cryomodule testing bunker meeting the required throughput of 1 cavity per day.

Keywords: helium refrigeration, helium liquefier, cryogenic distribution, cryogenic transfer line

1. Introduction
The Facility for Rare Isotope Beams (FRIB) at Michigan State University (MSU), a world class user facility for the U.S. Department of Energy Office of Science (DOE-SC) will be home to a heavy-ion linear accelerator (LINAC). The LINAC utilizes Superconducting Radio Frequency (SRF) cavities operating at 2 K housed in modules (cryomodules) divided among 3 segments [1, 2, 3]. To test and certify these cavities and cryomodules (CMs) before installing them in the FRIB LINAC tunnel, MSU built a test facility called the SRF high bay [4]. In this facility the MSU cryogenics team designed, built, and commissioned a complete cryogenic system capable of producing a cavity testing throughput of 1 cavity per day and 1.5 cryomodules per month. The cryogenic system includes rooftop helium gas storage, a helium liquefier/refrigerator, a liquid helium storage Dewar, a cryogenic distribution system, a sub-atmospheric testing system, a helium recovery compressor, a helium purifier and a contamination monitoring system. The SRF high bay also serves as a test-bed for many components in the FRIB cryogenic system and cryogen distribution system.

2. Design Requirements
The SRF high bay cryogenic system is designed to meet or exceed requirements to support testing of the cavities and cryomodules in the test bunker. The basic performance requirements are to provide 4 K liquid helium up to 5 g/s, 2 K refrigeration at minimum 1 g/s, liquid nitrogen up to 4 g/s and utility 3 atm. gaseous helium and dry gaseous nitrogen for cleaning and preparations. Mechanical requirements are quick disconnects at interfaces between the cryogenic system and cavity test dewars and the cryomodules. Safety
requirements include permissive control logic, safety interlocks and safety reliefs. Other unspecified requirements are reliability, maintainability, operational availability and future scale-ability.

3. Helium Gas Storage System

Helium gas for the cryogenic system is stored on the roof where 7 tanks with 30,000 gallon capacity reside. One of the tanks is dedicated to serving the cryogenic system in the SRF high bay. The other 6 tanks are currently being cleaned and prepared for the main FRIB plant commissioning. Helium gas can be loaded and unloaded from the plant via a dedicated header, while 2 separate headers deliver gas to the purifier system and take clean gas back to the tank. These headers are isolated from the FRIB plant gas distribution piping by flanges during the FRIB plant construction. Figure 1 shows the helium gas storage tanks on the SRF high bay building roof.

![Figure 1. Helium gas storage tanks and distribution piping headers.](image)

4. Helium Refrigerator

The helium plant at the center of the cryogenic system is a custom Linde LR280 specified and procured by MSU. The plant utilizes the reversed Brayton cycle, which can operate between 8 and 13 atm. depending on the load. The helium refrigeration system consists of four major components: the compressor, oil removal skid, main vessel, and subcooler vessel. A single stage water cooled Kaeser compressor modified for pumping helium and driven with a variable frequency drive (VFD) is located inside the compressor room to reduce the noise level. On top of the compressor room sits the oil removal system which consists of 2 coalescing units and 2 parallel charcoal beds. The plant features 3 gas bearing turbo expanders and can support many modes, but has a nominal capacity of 900 W at 4 K. Next to the plant sits a subcooler with a 1,000 L bath that operates at 1.2 atm. saturated pressure. A coil passing through the bath supplies 4.5 K, 3 atm. supercritical helium to the test bunker and the liquid storage dewar. Figure 2 shows the Kaeser compressor, oil removal skid, plant, subcooler and storage dewar.
5. Liquid Helium Storage Dewar
Helium liquefied by the plant is stored in a 5 kL dewar, which serves as a buffer between the plant and cavity testing dewars. While the plant operates continuously, cavity testing is cyclical, typically vaporizing large amounts of helium in the morning of each work day allowing for speedy testing on a convenient schedule. Perched on top of the storage dewar is a vacuum insulated valve and bayonet assembly specified by MSU and fabricated by PHPK Technologies. The valve and bayonet assembly is integrated with the neck of the dewar and facilitates fill, withdrawal, return, and safety relief functions. Liquid level in the dewar is measured using a superconducting probe as well as a differential pressure level gauge. A 1 kW electrical heater submerged in liquid provides the dewar additional pressure control as needed. The dewar is manufactured by Wessington Cryogenics Ltd. Figure 3 shows the liquid helium dewar with the neck can and connecting piping.

6. Cryogen Distribution System
The cryogenic distribution system consists of transfer lines for liquid nitrogen, supercritical helium and the return gases. Saturated liquid helium from the storage dewar is transferred to the below grade cavity testing dewars through a vacuum jacketed transfer line fabricated by Meyer Tool, Inc. per MSU specification. Liquid nitrogen from the LN2 distribution system shields the helium circuit in the transfer line as it flows to the cavity testing dewars. To handle distribution to the test dewars there are valve and bayonet cans fabricated by Ability Engineering per MSU specification.

An LN2 shielded VJ transfer line encloses the super critical helium supply and vapor return from the test bunker allowing it and the cryomodules to operate as refrigeration loads when operating at 4 K. Figure 3 shows transfer lines and distribution valve boxes.
7. Subatmospheric Testing

A large room temperature vacuum pump system with a spare was installed to support testing of cavities and cryomodules with superfluid liquid helium. The vacuum pump system pumps helium from the cavity test dewars or cryomodule bunker. Cold helium gas from the cavity test dewars and cryomodule is warmed up to ambient temperature through an inline 20 kW low power density electric heater. The vacuum pump system was specified by MSU and built by Leybold. It features a rotary vane pump with a roots type booster nominally capable of 2.5 g/s helium at 26.6 mbar and 300K. All helium from subatmospheric testing is discharged from the pump system into the helium purifier recovery system. To prevent over pressurizing the recovery compressor suction, the vacuum system features an internal bypass that can recirculate 100% of the flow during startup. The bypass slowly closes during pump down allowing the recovery system’s internal control loops to adjust. Figure 4 shows the pump system inside the compressor room.

8. Recovery Compressor and Purifier

Given that new untested cavities and cryomodules are regularly connected and disconnected to an otherwise clean helium refrigeration system, all warm return and subatmospheric flows are directed to a recovery compressor instead of the main cryo plant compressor. The recovery compressor is a hermetically sealed oil flooded single stage screw compressor, specified by MSU and built by CryoNova. The compressor has a nominal flow capacity of 20 g/s at 265 psig discharge pressure that can be fully bypassed or discharged to a single-bed helium purifier with capacity of more than 40 g/s, at 260 psig operating pressure. The helium purifier was specified by MSU and built by Ability Engineering. The purifier uses LN2 to cool the helium to 80 K before passing it through an activated charcoal bed to remove trace nitrogen. The charcoal bed is heated up from jacket with an external inline electric heater and a gaseous nitrogen coil during regeneration. Purity of the helium gas at the inlet and the discharge of the purifier can be constantly monitored by a Linde Multi Component Detector (MCD). Figure 4 shows the recovery system and contamination detector rack.
9. Cryogenic Controls
The cryogenic system can be controlled by local and remote desktops using Control System Studio (CSS—shown in Figure 5), and Rockwell Automation Factorytalk through the Experimental Physics and Industrial Control System (EPICS) to Allen-Bradley programmable logic controllers (PLCs) on the hardware. The system allows almost all process variables to be monitored and gives operators control of all pneumatic and electric valves. Operators use the system to tune and implement valve control loops and alarm set points. Process variable alarms allow the control system to notify operations personnel through an automatic dialer and text messaging.

Figure 5. Cryogenic system CSS screen, and control rack with contamination detector.

10. Safety
The Linde LR280 came with standard safety features such as permissives, interlocks, safety pressure relief valves and rupture disks. Standard safety practices such as relief valves were implemented during the design, fabrication and installation of the cryogenic system in the facility. Venting from reliefs on the 5 kL dewar and the cryomodule are directed outside the SRF high bay and test bunker to prevent Oxygen Deficiency Hazard (ODH). ODH sensors, audible alarms and lights are located properly along the transfer line, inside the test bunker, inside the compressor room and throughout the facility to monitor the oxygen concentration. Safety is further enhanced through air ventilation, building controlled access, trained personnel, controlled procedures, and strict adherence to process piping design to code.

11. Test Dewars and Cryomodule Test Bunker
The test dewars are in below grade pits used to test and certify the cavities. The two valve boxes in each pit handle all supply and return flows from test dewars. The connections between the valve boxes and the
test dewar are through bayonets and U-tubes. A thick concrete block cover for radiation protection is placed over the top of the pit during RF testing so all the cryogenic, electrical, controls and utility penetrations enter through a trench.

The cryomodule bunker is a thick concrete structure locate above grade, but all the transfer lines enter through a trench before penetrating up to the distribution valve box above grade. All connections from the cryogenic distribution valve box to the cryomodule are through bayonet and u-tubes except the warm return helium gas which is connected through a jacketed metal hose for ease of installation. Figure 6 shows a test dewar pit and a cryomodule inside the test bunker.

Figure 6. Cavity test dewar (left) and cryomodule in the test bunker (right).

12. Current Status
The design, fabrication, installation and commissioning of the cryogenic system has been a great success. The system is currently in operation supporting all SRF cavity testing at a rate 1 cavity per day and 1.5 cryomodules per month with very little down time. The system was designed, fabricated, installed and delivered on time and budget while meeting MSU’s specifications. Critical long lead spare parts have been procured to help guarantee operations. The system is in continuous operation for the last 24 months. Major upgrades such as adding a second test bunker, a secondary purifier, recovery compressor, and helium vacuum pump have been approved and will be executed when time permits.

13. References
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