FERMILAB-CONF-13-206-AD

Cryogenic System for the Cryomodule Test Facility at Fermilab

Michael White, Alex Martinez, Rick Bossert, Andrew Dalesandro, Michael Geynisman, Benjamin Hansen, Arkadiy Klebaner, Jerry Makara, Liujin Pei, Dave Richardson, William Soyars, Jay Theilacker

Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510 USA

Abstract. This paper provides an overview of the current progress and near-future plans for the cryogenic system at the new Cryomodule Test Facility (CMTF) at Fermilab, which includes the helium compressors, refrigerators, warm vacuum compressors, gas and liquid storage, and a distribution system. CMTF will house the Project X Injector Experiment (PXIE), which is the front end of the proposed Project X. PXIE includes one 162.5 MHz half wave resonator (HWR) cryomodule and one 325 MHz single spoke resonator (SSR) cryomodule. Both cryomodules contain superconducting radio-frequency (SRF) cavities and superconducting magnets operated at 2.0 K. CMTF will also support the Advanced Superconducting Test Accelerator (ASTA), which is located in the adjacent New Muon Lab (NML) building. A cryomodule test stand (CMTS1) located at CMTF will be used to test 1.3 GHz cryomodules before they are installed in the ASTA cryomodule string. A liquid helium pump and transfer line will be used to provide supplemental liquid helium to ASTA.

Keywords: Cryomodule, Helium Refrigerator, Compressor, Cryomodule Test Facility

INTRODUCTION

Fermilab is in the process of installing cryogenic equipment in the new Cryomodule Test Facility (CMTF), which is shown in Fig. 1 and Fig. 2. CMTF will initially house two test caves. The first test cave is for the Project X Injector Experiment (PXIE), which is the front end of the proposed Project X. PXIE includes one 162.5 MHz Half-Wave Resonator (HWR) cryomodule and one 325 MHz Single-Spoke Resonator (SSR) cryomodule, as well as room temperature accelerator components. Both cryomodules contain superconducting radio-frequency (SRF) cavities and superconducting magnets operated at 2.0 K. The second test cave is Cryomodule Test Stand 1 (CMTS1), which will test 1.3 GHz cryomodules. Future plans include running a transfer line over to an adjacent building to support the Advanced Superconducting Test Accelerator (ASTA) accelerator.

Two cryogenic plants are being installed at CMTF. The Superfluid Cryogenic Plant (SCP) is being purchased from industry and will be able to maintain loads at the nominal temperatures of 2K, 4.5 K, and 40 K while operating in a pure refrigeration mode. The SCP includes 3 cold compressors in series, which allows the plant to recover refrigeration from 2K return flow. The discharge of the cold compressors is routed to a warm vacuum compressor system (WVCS). The other plant is a refurbished CTI-4000, which was previously used at Stanford Linear Accelerator Laboratory (SLAC) [1]. This plant will be primarily used as a liquefier for the CMTS1 2K circuit. In the future the CTI-4000 will also supply supplemental liquid helium to ASTA via a transfer line between CMTF and New Muon Lab (NML).

FIGURE 1. Photograph of the CMTF Building (left) and the NML Building (right)

Operated by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the United States Department of Energy

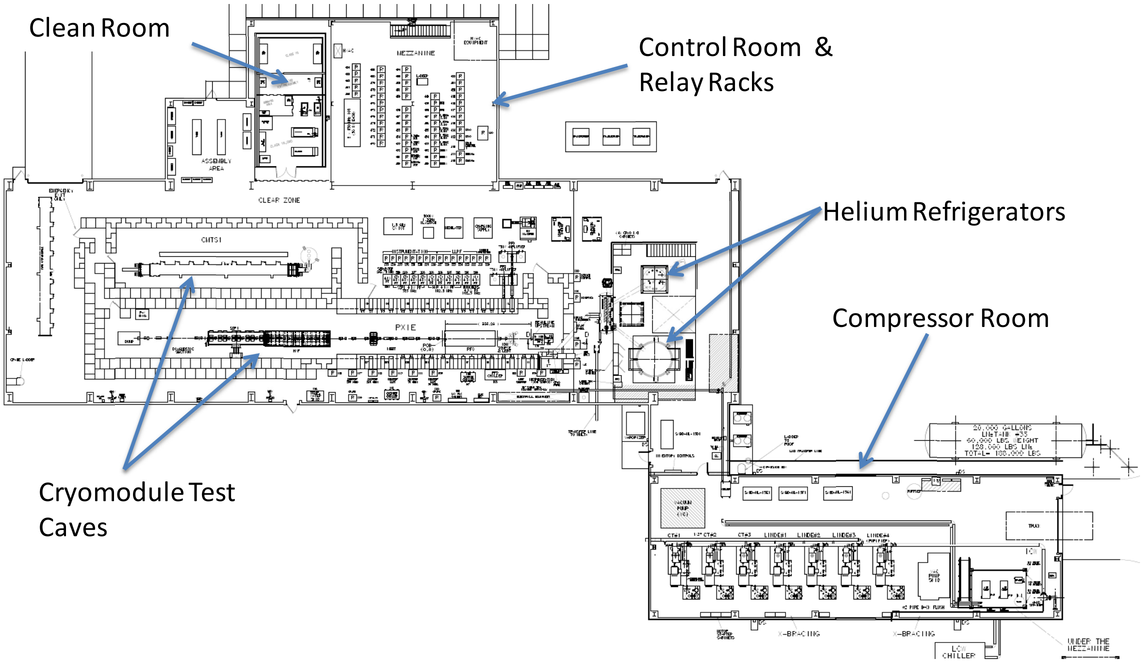

FIGURE 2. Layout view of the CMTF Building. Detail views of the compressor room and the refrigerator pit can be found in Fig. 4 and Fig. 5 respectively.

HELIUM COMPRESSOR SYSTEM

The CMTF helium compressor system consists of seven Mycom compressor skids, which are all located in a building annex, shown in Fig. 3 and Fig. 4, to reduce the noise in the rest of the CMTF building. Three skids are dedicated to the SCP, three skids are dedicated to the CTI-4000, and one is used as a purifier compressor. All helium that might be contaminated is routed to the purifier compressor and then to a stand-alone LN_2-cooled charcoal adsorber vessel. The Mycom compressor skids were previously used at Fermilab for the Tevatron satellite refrigerators. All of the compressor skids were refurbished before being installed at CMTF. No major modifications were required since the compressors have had 30 years of successful service. The primary components of the skid include a Mycom 2016C compressor, an oil pump, an oil reservoir, three oil coalescers, a charcoal adsorber, a molecular sieve, and a final filter [2]. Each compressor has a 300 kW (400 hp) motor and delivers up to 60 g/s with a suction pressure of approximately 1 bar and a discharge pressure of up to 20 bar. Experimental tests at Fermilab have shown that the Mycom compressors have an approximately constant isothermal efficiency across a broad range of discharge pressures ($\approx$ 10 bar to 18 bar), so the discharge pressure will be regulated based on the cryogenic heat load. The cooling produced by expansion through the turbines is directly related to the compressor discharge pressure, so during time periods when the cryogenic loads are small the compressor discharge pressure will be reduced to conserve electricity. Further long term testing is required to determine the lowest discharge pressure at which the coalescers in the oil removal system remain effective.

HELIUM REFRIGERATORS

The original T-S diagram supplied by CTI estimated that the CTI-4000 plant was capable of delivering 1,176 W of refrigeration at 4.4 K. The plant was designed to operate with an inlet of 13.8 bar and exhaust of 1.2 bar. Further details on the capacity of the plant are included in another paper at this conference [3]. Several modifications have been made since the plant was moved to Fermilab. First, the old bearing cartridges were rehoused and modified to magnetically levitated bearings for both of the turbines. The turbine brake and water cooling system was also replaced. The control logic for safely and efficiently operating the turbines was developed in conjunction with Linde and will be consistent with the operation of turbines in the SCP. The two 80K adsorbers were recertified to a higher pressure to take advantage of the higher discharge pressure from the Mycom compressors. The last major improvement to the CTI-4000 was to add a reciprocating expansion engine by installing two new bayonets. The

FIGURE 3. Photograph of the CMTF Compressor Room (left) and the SCP Pit and Instrument Panel (right)

expansion engine is located in parallel with the Joule-Thomson (JT) valve and is used to improve liquefaction capacity.

The SCP is scheduled to be delivered to Fermilab in June 2013. The SCP will be installed in a pit, as shown in Fig. 3 and Fig. 5, so that control valves and instrumentation on the top plate are easy to access. There are three primary modes of operation for the plant, as shown in Table 1. Mode 1 and Mode 2 have 1.8 K and 2.0 K liquid helium leaving the SCP, respectively, while having the cold subatmospheric vapor from the cavity bath returning to the plant. The temperature difference of 0.2 K between the two modes is quite significant, since the SCP will have twice the capacity at 2.0 K that it does at 1.8 K. The BCS resistance of the cavities increases with temperature, so the expected cavity heat load increases with bath temperature. One of the functions of CMTF is to search for the optimal tradeoff between plant efficiency and cavity temperature. Mode 3 is running the plant with a liquefier load, as would be the case during a cooldown or while filling a dewar. During Mode 3 the helium would be routed from the cavity bath circuit directly to the Mycom compressor suction header without passing through any of the SCP heat exchangers or cold compressors. Valves internal to the SCP allow refrigeration to be recovered once the return helium temperature drops below 80 K. The SCP acts almost as a pure liquefier at the start of a cryomodule cooldown (with some refrigeration used on distribution system thermal shields), moves into a mixed refrigeration/liquefier mode once the return temperature(s) drop below 80K, and operates in a pure refrigeration mode (Mode 1 or Mode 2) during normal cryomodule operation.

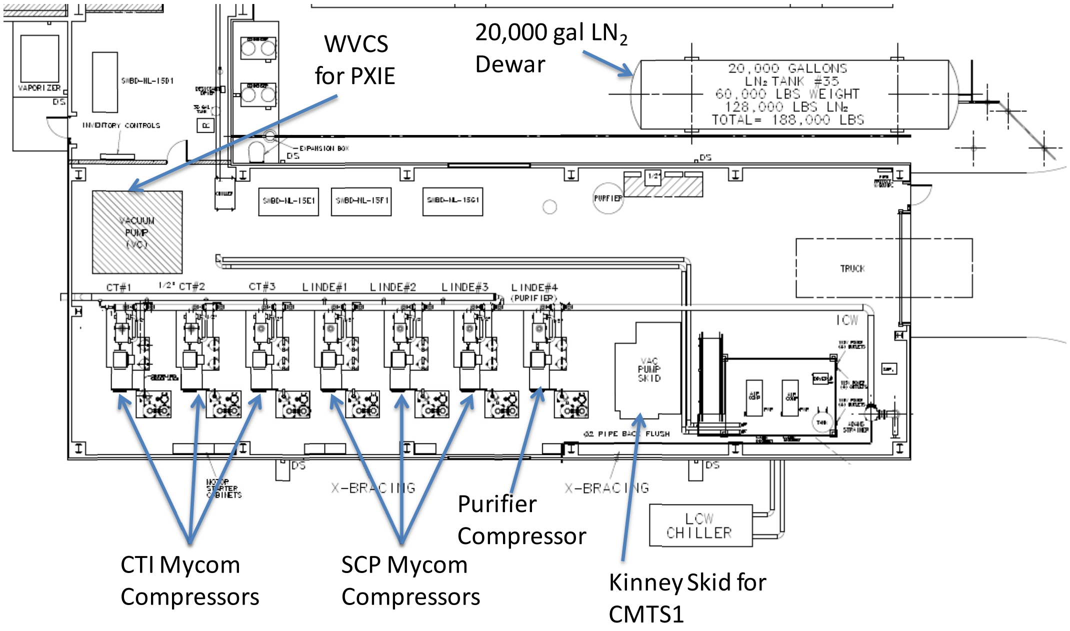

FIGURE 4. Layout of the CMTF Compressor Room

Table 1. Calculated capacity of the CMTF Superfluid Cryogenic Plant

Nominal Temperature	Units	Mode 1	Mode 2	Mode 3
1.8 K	[W]	250	N/A	N/A
2.0 K	[W]	N/A	500	N/A
5 K to 8 K	[W]	600	600	100
40 K to 80 K	[W]	5000	5000	700
Liquefaction	[g/s]	N/A	N/A	16

A total of 5 turbines with dynamic gas bearings are used to generate refrigeration with the SCP. The design of the vendor's dynamic gas bearing turbines has been previously described and compared to other turbine types [4]. The SCP turbines are rated to a pressure of 21 barg, so the turbines can safely utilize the maximum discharge pressure from the Mycom compressors. The turbine speed is regulated by a control valve on a warm helium gas brake circuit. The helium brake gas passes through a chilled water heat exchanger to reduce the heat load through the turbine shaft to the cold impeller. The turbines are interlocked based on the follow criteria: low turbine speed, high turbine speed, low discharge temperature, loss of brake circuit cooling water, high temperature in the brake circuit, high differential in the brake circuit. A trip of the interlock results in the inlet valve closing to protect the turbine. All turbine inlet valves have an accumulator volume that prevents the pneumatic actuators from closing at a rate greater than 1 %/s.

The SCP has two charcoal adsorbers that are nominally at 80 K and located just downstream of the liquid nitrogen pre-cooler. Each 80 K adsorber is designed for the full flow of the high pressure stream so that plant is protected from contamination even if one adsorber is being regenerated or serviced. There is also a single adsorber nominally at 20 K that is used for adsorbing any neon or hydrogen entering the plant. The 20 K adsorber has a bypass valve that will be used during regeneration. All heating of the adsorbers is done through band heaters located on the outside of the adsorber vessel and inside the insulating vacuum space. Each adsorber has a temperature interlock to protect against high temperature conditions and each adsorber also has a backup heater element.

The SCP also has a three stage cold compressor system that allows the plant to recover refrigeration from subatmospheric circuits. The SCP vendor has previously built cold compressor strings at the LHC and elsewhere [5]. The nominal design parameters for the three compressor stages are shown in Table 2. Note that the first stage inlet parameters account for the both the pressure drop and the heat gain between the SRF cavity bath and the plant. The cold compressor string is expected to operate at greater than 51% isentropic efficiency at the full load capacity of 26.8 g/s when operating the cavities at 2.0 K. The cold compressor string is also expected to be able to compress

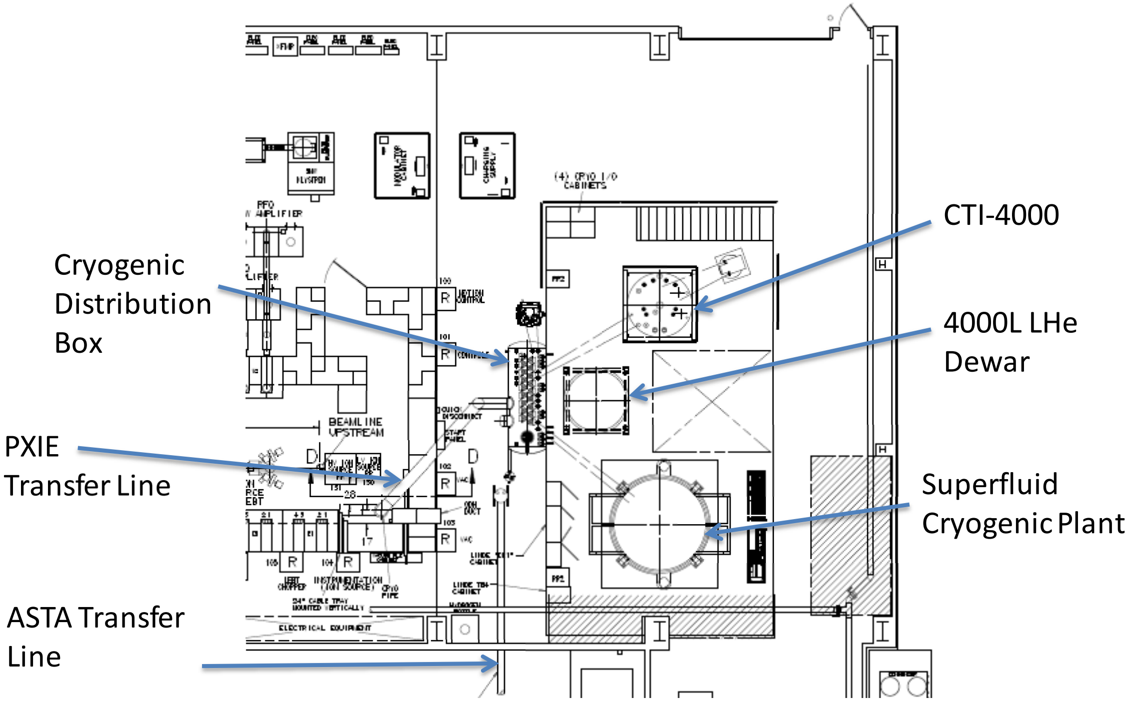

FIGURE 5. Layout of the CMTF Refrigerator Pit

Table 2. Estimated pressures and temperatures in the SCP cold compressor string

	Cavity 2.0 K Operation		Cavity 1.8 K Operation	
Location	Pressure [mbar a]	Temperature [K]	Pressure [mbar a]	Temperature [K]
1st Stage Inlet	23.7	4.05	12.4	4.05
1st Stage Outlet	97.3	9.26	50.8	9.90
2nd Stage Outlet	221	14.8	109	15.9
3rd Stage Outlet	382	20.4	180	21.8

up to 14.0 g/s when operating the cavities at 1.8 K. The cold compressors can operate at speeds up to 800 rps. The cold compressors utilize a bypass valve that opens when necessary to prevent the cold compressor string from operating at surge conditions. There are multiple 2.5 barg relief valves upstream from the cold compressor string to protect against cryomodule failure scenarios. Each cold compressor is intercepted at approximately 60 K to reduce the heat load on the subatmospheric flow. The cold compressor motors, pressure sensors, and temperature sensors are all supplied with guard gas to prevent air contamination during subatmospheric operation.

HELIUM WARM VACUUM COMPRESSOR SYSTEM

A warm vacuum compressor skid (WVCS) is located downstream of the cold compressor string. The WVCS consists of five compressors with space for a sixth. Each vacuum compressor is a modified Busch® COBRA NS 600. The WVCS is cable of compressing 13.8 g/s of helium with suction pressure of 154 mbara and suction temperature of 10 °C. The WVCS discharges into the suction of the Mycom compressor used for purification, which is typically at 0.086 bar (1.25 psi) above atmospheric pressure. The WVCS is interlocked based on the follow criteria: high discharge temperature, high discharge pressure, high suction temperature, low suction temperature, loss of cooling water, high motor temperature, high oil temperature, high internal coolant temperature, and high vibration amplitude. A trip of the interlock results in closing the skid common inlet and outlet valves, while also cutting off the electrical power to the WVCS motors.

The CTI-4000 will function primarily as a liquefier during normal operation to support 2K operation. The CMTS1 test stand does not have provisions to return 2K helium to either refrigeration plant at CMTF. Instead, the 2K return is routed directly to a warm vacuum pump after passing through a J-T heat exchanger. Fermilab previously acquired and refurbished two large vacuum pump skids from Thomas Jefferson National Accelerator Facility [6,7] for use in testing SRF cavities at 2.0 K. Fermilab has acquired and is currently refurbishing two more identical vacuum pumps skids, one for use at CMTF and one for Oak Ridge National Laboratory. The primary components of the skid are a Kinney® roots blower (Model KMBD 10,000) and a Kinney® liquid ring pump (Model KLRC 2100). The vacuum pumps were originally designed for air service, so some modifications were required to prevent contamination of subatmospheric helium. The main modification made by Fermilab is to add a helium guard gas system to the dynamic seals. Other modifications included replacing fittings and flanges, adding additional instrumentation, adding safety interlock switches, and upgrading the oil distribution/reclamation system.

FIGURE 6. Photograph of the CMTF Distribution Box

INVENTORY STORAGE AND DISTRIBUTION

Both helium refrigerators at CMTF deliver helium to a distribution box, which is shown in Fig. 6. The SCP is connected to the distribution box by a multi-circuit transfer line and the CTI-4000 is connected by two U-tubes. The distribution box was designed at Fermilab and fabricated by PHPK Technologies®. Control valves and instrumentation within the distribution box control flow to three planned cryogenic loads for the CMTF plants: PXIE, CMTS1, and the ASTA transfer line. There are two multi-circuit transfer line supply stubs, one dedicated for PXIE and one spare for future test stands. CMTS1 and the ASTA transfer line are connected via U-tubes. There is a cooldown supply circuit from the SCP that supplies helium between 40K and 300K to each supply line leaving the distribution box, which allows loads to be cooled down at precise rates. In addition, flow from the return lines to the distribution box can be diverted to the cooldown return line. The cooldown return line has control valves at several locations within the SCP that allows refrigeration in the cooldown return flow to be recovered. There is also a 4000L LHe dewar that is connected to the distribution box via U-tubes. The 4000L dewar acts as a buffer for operational upsets and is also used to provide temporary additional cooling capacity during cryomodule cooldowns.

Parasitic heat loads in the distribution box are intercepted with a liquid nitrogen cooled radiation shield, but the liquid nitrogen is not distributed to any of the loads from the distribution box. No liquid nitrogen is used in either the CMTS1 or PXIE test caves. The ASTA transfer line is supplied with liquid nitrogen via a separate bayonet can. The CMTF liquid nitrogen storage consists of single horizontal 76,000L unit operating at 4 bar, again being reutilized from the Tevatron's Central Helium Liquefier.

Warm helium gas storage capacity was increased with an addition of a storage tank (114 m^3 at 17 bar or 2000 liters LHe equivalent) from Tevatron's Central Helium Liquefier facility, nearly doubling the available warm helium gas storage capacity. The common helium storage can be utilized by either the CMTF SCP or CTI-4000 plants, as well as the NML ASTA refrigeration system. Helium inventory makeup from high pressure tube trailers are provided for nearby.

PXIE TEST CAVE

The PXIE test cave will initially be used for testing the front end of the proposed Project X. The cryogenic temperature section of the PXIE linac includes a single 162.5 MHz half wave resonator (HWR) cryomodule and a single 325 MHz single spoke resonator (SSR) cryomodule. Each cryomodule type contains multiple superconducting radio-frequency (SRF) cavities and superconducting magnet packages that are operated nominally at 2.0 K. A J-T heat exchanger is included in both cryomodules. The cavity bath pressure is regulated through a series of three cold compressors in the refrigeration plant and a warm vacuum compressor system. Each cryomodule has a thermal intercept nominally at 5 K and a radiation shield operated between 40 K and 80K. All cryomodule circuits use helium as the working fluid. HWR and SSR cryomodules have bayonets mounted on a side port to facilitate u-tube connections. The PXIE linac will be capable of accelerating 1 mA of beam to 15 MeV [8].

The cryogenic distribution system for PXIE will stay at CMTF when the PXIE accelerator components are moved to their permanent Project X location. In the future, the PXIE Test Cave will be used for commissioning SSR cryomodules before installation into Project X. The current design for Project X calls for only one HWR cryomodule, so the HWR valve box might be reconfigured for testing other cryomodule types in the future.

CMTS1 TEST CAVE

The CMTS1 test cave is designed for testing 1.3 GHz cryomodules that are derivatives of the cryomodule design for the TeV Energy Superconducting Linear Accelerator (TESLA) collaboration [9]. CMTS1 will be used for commissioning cryomodule assemblies before they are installed into a working accelerator, such as ASTA or the proposed Project X. Several international projects such as X-Ray Free Electron Laser (XFEL) under construction at Deutsches Elektronon-Synchrotron (DESY) and the proposed International Linear Collider (ILC) also call for TESLA style 1.3 GHz cryomodules. CMTS1 will be designed for ease of cryomodule installation, cooldown, warmup, and removal to accommodate the expected large number of 1.3 GHz cryomodules that will be used at Fermilab and in international collaborations.

The cryogenic distribution system for CMTS1 is based on the original design for the Cryomodule Test Bench (CMTB) at DESY [10]. Fermilab has used the CMTB design concept for several years to operate the ASTA accelerator at the NML building adjacent to CMTF. Current plans for the ASTA accelerator call for as many as six 1.3 GHz cryomodules in series. Since the TESLA type cryomodules have supply and return piping at the end of the cryomodule, all cryomodules in series have to warm up and cool down together. Due to temperature rate of change restrictions, the warmup and cooldown of 1.3 GHz cryomodule strings takes several days. In order to reduce the down time for a working accelerator a new dedicated test facility must be built for commissioning cryomodules.

CMTS1 will have three major components: a Feedbox, a Feedcap, and an Endcap. The Feedbox contains the subcooler, the J-T heat exchanger, the control valves, most of the relief valves, and most of the instrumentation. The Feedbox also has connections to the supply transfer line, the 2K vacuum pumping line, and the relief headers. The Feedcap is connected to the Feedbox by a short (<1 m) right angle transfer line. The Feedcap distributes the supply and return helium between the transfer line and the pipe stub at the end of the cryomodule. One of the other major drawbacks to using the ASTA cryogenic distribution system as a test facility is that all connections are welded. Welded connections provide reliable leak tight seals, but also require a lot of time and labor to install and remove. CMTS1 will incorporate flexhose assemblies with Conflat® flanges to reduce installation time. The final major component of the distribution system is the Endcap, which contains a reservoir for maintaining liquid level. The Endcap also contains some instrumentation and returns flow to the return side of the cryomodule.

ASTA TRANSFER LINE

The ASTA accelerator is located in a building adjacent to the new CMTF building. The ASTA linac is comprised of two capture cavity cryostats and up to six 1.3 GHz TESLA style cryomodules. ASTA uses two Tevatron satellite style refrigerators to deliver liquid helium to the inner radiation shield and cavity bath circuits of the cryostats and cryomodules. Liquid nitrogen is used on the outer radiation shield circuit of the cryostats and cryomodules. Each satellite style refrigerator can produce up to 600 W of refrigeration or up to 4 g/s of liquefaction. There are no cold compressors in the satellite refrigerators, so any heat load on the cavity bath circuit acts as liquefier load on the plant. The combined capacity of the two plants is too small to be able to maintain 6 cryomodules with full RF power. In addition, the nitrogen dewar that supplies ASTA is undersized at 23,000 liters. During normal operation the nitrogen dewar needs to be filled every two days, which can be problematic over long holiday weekends or during inclement weather. Running out of liquid nitrogen is a serious operational issue. There are many restraints on the rate at which the 1.3 GHz cryomodules temperatures can be warmed up or cooled down, so operators must carefully observe and control the cryogenic distribution system over the span of several days.

The current plans call for running a two-circuit transfer line from CMTF to ASTA that is approximately 125 m in length. The transfer line will use a liquid nitrogen cooled radiation shield. At the end of the transfer line the nitrogen can be vented or can be used to supplement liquid nitrogen flow to the ASTA cryomodule string. Even if the ASTA liquid nitrogen dewar runs dry operators will be able to avoid thermally cycling the ASTA string by using liquid nitrogen from CMTF. Running out of liquid nitrogen should be much less of an issue once the ASTA transfer line is installed.

The CTI-4000 at CMTF is primarily used as a liquifier to fill the 4000 L external LHe dewar. The SCP is also capable of filling the 4000L dewar, but the SCP is expected to function primarily as a refrigerator for PXIE. Two loads are able to draw liquid out of this dewar, CMTS1 and ASTA. Flow to CMTS1 is expected to be intermittent due to the frequent installation and removal of cryomodules. During the CMTS1 downtime the full capacity of the CTI-4000 can be used to support ASTA.

CONCLUSION

The new CMTF building is quickly filling up with equipment for the cryogenic system and other cryomodule support systems. The summer of 2013 will be an exciting time as the new SCP refrigerator is being commissioned. The next couple years will see a lot of activity within the CMTF building as the CTI-4000 refrigerator, distribution box, and cryomodule test stand transfer lines are installed and commissioned. CMTF will be a critical test facility for Project X components.

ACKNOWLEDGMENTS

Fermilab is operated by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the United States Department of Energy. The authors wish to thank the technical staff at Fermilab for all the work that has been performed at CMTF.

REFERENCES

1. J. Weisend, R. Boyce, W. Burgess, A. Candia, R. Carr, J. Gao, K Gustafsson, C. Jones, W. Kaminskas, G. Oxoby, R. McKeown, H. Quack, A. Scott, T. Weber, "The Cryogenic System for the SLAC E158 Experiment" in *Advances in Cryogenic Engineering, Vol. 47*, Madison, Wisconsin, USA, edited by S. Breon, American Institute of Physics, Melville, New York, 2012, pp. 1123-1129.
2. J. Satti, R. Andrews, "Fermilab Satellite Refrigerator Compressors with Oil and Moisture Removal Systems" in *Advances in Cryogenic Engineering, Vol. 30*, Colorado Springs, Colorado, USA, edited by R.W. Fast, Plenum Press, New York, New York, 1984, pp. 453-459.
3. B. Hansen, H. Quack, A. Klebaner, "Process Model and Capacity Upgrades of the CTI-4000 Liquid Helium Coldbox", to be published in *Advances in Cryogenic Engineering, Vol. 59*, Anchorage Alaska, USA, edited by J.G. Weisend, American Institute of Physics, Melville, New York, 2014
4. K. Ohlig, S. Bischoff, "Dynamic Gas Bearing Turbine Technology in Hydrogen Plants", in *Advances in Cryogenic Engineering, Vol. 57B*, Spokane, Washington, USA, edited by J.G. Weisend, American Institute of Physics, Melville, New York, 2012, pp. 814-819.
5. F. Millet, S. Claudet, G. Ferlin, "Performance Assessment of 35 Cold Hydrodnamic Compressors for the 1.8 K Refrigeration Units of the LHC", in *Advances in Cryogenic Engineering, Vol. 55B*, Keystone, Colorado, USA, edited by J.G. Weisend, American Institute of Physics, Melville, New York, 2006, pp. 1837-1844
6. A. Martinez, A. Klebaner, J. Theilacker, B. DeGraff, M. White, and G. Johnson, "Fermilab SRF Cryomodule Operating Experience" in *Advances in Cryogenic Engineering, Vol. 57B*, Spokane, Washington, USA, edited by J.G. Weisend, American Institute of Physics, Melville, New York, 2012, pp. 1123-1129.
7. A. Martinez, A. Klebaner, J. Theilacker, B. DeGraff, and J. Leibfritz, "Design and Testing of the New Muon Lab Cryogenic System at Fermilab" in *Advances in Cryogenic Engineering, Vol. 55B*, Tuscon, Arizona, USA, edited by J.G. Weisend, American Institute of Physics, Melville, New York, 2010, pp. 488-495
8. S. Nagaitsev, PXIE (Project X Injector Experiment) Functional Requirements Specification, *Internal Fermilab Document*, 2012
9. TESLA Technical Design Report, Edited by F. Richard, J. Schneider, D. Trines, and A. Wagner, Deutsches Elektronon-Synchrotron (DESY) Report 2001-011, Hamburg, Germany, March 2001, http://tesla.desy.de/new_pages/TDR_CD/start.html
10. Y. Bozhko, C. Engling, E. Gadwinkel, K. Jensch, B. Peterson, D. Sellman, A. Zolotov, "XFEL Cryomodule Test Bench" in Proceedings of the 21st International Cryogenic Engineering Conference, edited by G. Baguer, R. Safrata, and V. Chrz, Prague, Czech Republic, 2006, pp. 125-128.