FERMILAB-CONF-05-637-AD

SCRF CRYOGENIC OPERATING EXPERIENCE AT FNPL

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ABSTRACT

The Fermilab-NICADD Photoinjector Laboratory (FNPL), a photoelectron research and development beam line, has been operational since 1998. A single TESLA 9-cell superconducting RF cavity is operated in support of this accelerator system. The superfluid cryogenic system consists of a dewar-fed liquid helium supply with up to 2 g/s vacuum pumping capacity. Helium gas is recovered to the Tevatron cryogenic system. The photoinjector static load is about 2.5 W to 1.8 K, with a typical dynamic component of about 0.5 W. The capabilities, performance, operating experience, and reliability of this superfluid cryogenic system will be discussed. An auxiliary cryogenic system for testing bare superconducting RF cavities in a vertical dewar is also available, providing a steady state capacity of about 12 W at 1.8 K for testing.

KEYWORDS: Cryostat, RF cavity; Test facilities, superfluid; Heat load measurements, RF cavities.
PACS: 07.20.Mc

INTRODUCTION

The Fermilab NICADD (Northern Illinois Center for Accelerator and Detector Development) Photoinjector Laboratory is an 18 MeV electron linac located in the South Cave next to the Tevatron A0 building. It produces a high-intensity, low emittance beam. The principal components of the facility are a pulsed UV laser, a normal conducting 4 MeV RF gun, a 1.3 GHz 9-cell superconducting cavity, a magnetic chicane, and a beam transport line. The accelerator is used for studies in accelerator science, plasma wake-field acceleration, and channeling radiation. [1]

The cryogenic system is an important component of the accelerator, providing superfluid He cooling of the SCRF cavity. Cryogens are supplied from dewars of liquid helium and liquid nitrogen. Roots blower vacuum pumps are used to pump down the SCRF

FIGURE 1. Fermilab-NICADD Photoinjector Laboratory beam line.

cavity to 1.8 K. The pressure and the liquid level in the superfluid He vessel are regulated with control loops which actuate variable flow valves on the He supply and exhaust lines. Liquid helium is also used for 5 K thermal shielding. The cryogenic system and the SCRF cavity initial performance have been previously described [2]. Since 2002, helium gas from the vacuum pumps and 5 K shield has been recovered to Tevatron helium gas storage. This system is sometimes referred to as the A0 SCRF cryogenic system, based on its location.

Typical SCRF cavity operating parameters are 12 MV/m accelerating gradient at 1 hz repetition rate with 170 μsec at flattop. The accelerator system's initial cryogenic, RF, and beam tests have also been described [3]. FIGURE 1 shows the testing section of the A0 beamline located downstream of the accelerating SCRF cavity. FIGURE 2 shows the CRYOCAP Cryostat which contains the superfluid Helium and the SCRF cavity. The cryogenic connections to the vessel are fed through the top of the vessel with the cryogenic transferline located overhead. The beamline passes through the center of the CRYOCAP vessel.

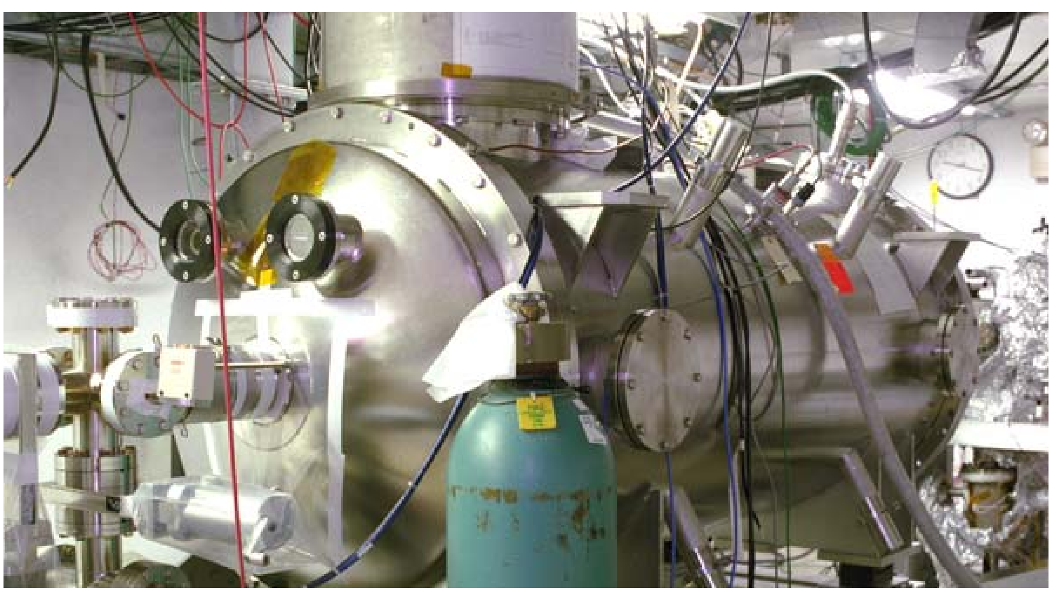

FIGURE 2. The 9-cell SRF Cryomodule for the Fermilab-NICADD Photoinjector Laboratory.

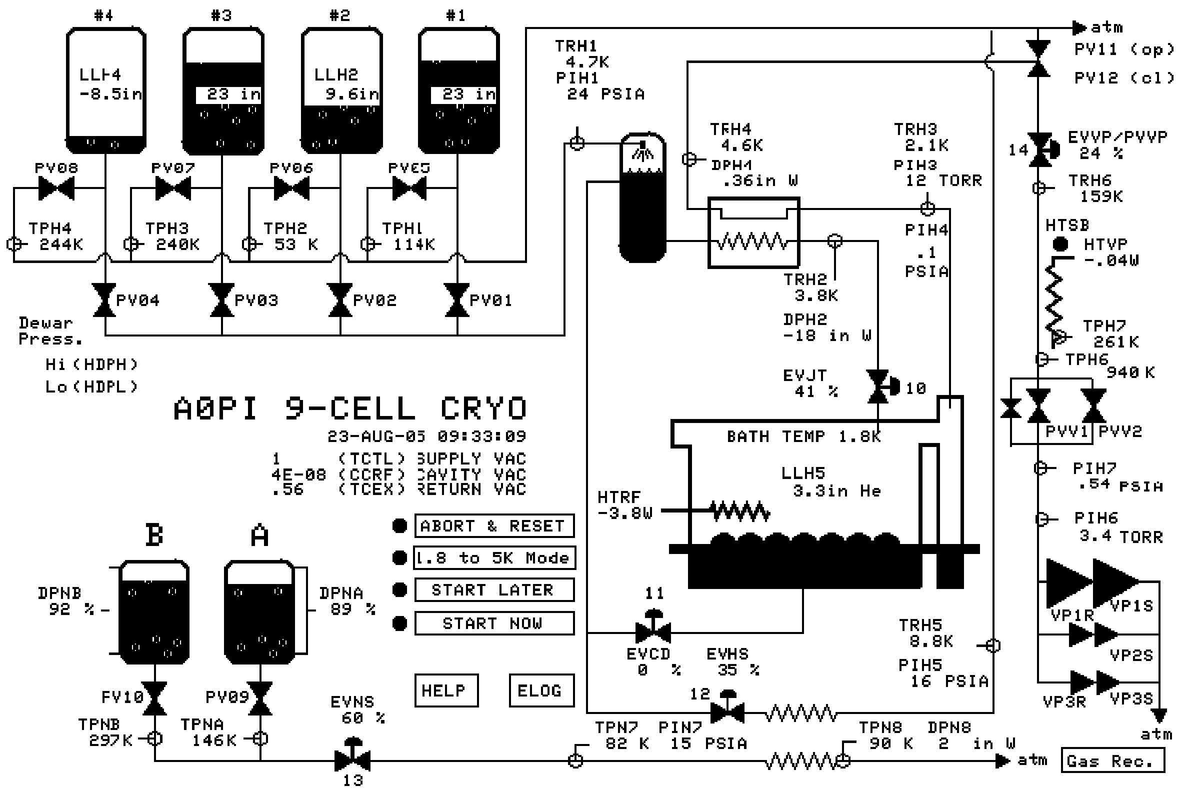

FIGURE 3. ACNET graphic depicting typical operating conditions. ACNET device names and measurements shown.

TYPICAL SOUTH CAVE OPERATIONS

The South Cave SCRF Cryomodule operates continuously at or below 5 K. Tevatron ACNET controls are responsible for controlling the A0 cryogenic system. The SCRF vessel is periodically filled with either LHe or superfluid by a supply valve (EVJT), which is then closed. At appropriate liquid level, the valve is reopened to batch-fill the vessel, making up for losses. Typical conditions during a superfluid refill cycle are shown in FIGURE 3.

The operating schedule for the A0PI 9-cell cavity is designed to conserve helium. At 0400 on Monday through Friday, the ACNET controls will initiate a pumpdown routine to lower the helium bath pressure from 103 kPa to 1.60 kPa thus achieving the necessary 1.8 K cavity operating temperature. This pumpdown routine exposes the helium vessel to the vacuum pumps located in the A0 facility by opening a series of three vacuum valves sized

TABLE 1. Heat loads to FNPL Cryogenic System.

Description	Temp [K]	Heat Load [W]	SRF accel [MV/m]	usage [g/s]
Cavity, normal static	1.8	2.4 +/- 0.3	0	0.10
Cavity, low RF	1.8	2.4 +/- 0.3	10	0.10
Cavity, normal operating	1.8	3.0 +/- 0.3	12	0.13
Cavity, without 5K shield	1.8	3.6 +/- 0.4	0	0.16
LHe supply and shield	5	12	n/a	0.4
N2 with 2-phase at vent	80	<300	n/a	1.5

so that the inlet pressure to the vacuum pumps does not exceed 4.00 kPa. When operation and testing is completed by the physicists at night, the system is transitioned back to 4.5 K by closing the vacuum pump valves. By employing this cycling schedule, the life of a 500 L dewar is extended from 20 hours to almost 22 hours.

Experimentally determined heat loads for various conditions are shown in TABLE 1. Superfluid loads were determined by transient boil-off of a known volume of liquid. Normal liquid helium loads were based on known gas recovery flow rate, minus superfluid boil-off, and known superheated vapor temperature at the shield exit. Nitrogen flow rate is not throttled; it has on-off control.

GAS RECOVERY

The helium gas from vacuum pump exhaust and 5 K shielding is recovered by raising the pressure of the helium with a booster compressor and sending it through a pipeline to the Central Helium Liquefier (CHL) where it can be reclaimed into the Tevatron cryogenic system. The vacuum pump exhaust contains some residual oil from the vacuum pumps, which is removed by a coalescer that separates, collects, and periodically drains the oil. Then, the pressure is raised by a Corken Model D490 single-stage two cylinder vertical reciprocating compressor driven by a 5.6 kW motor. Since gas flow to this compressor can vary a great deal depending on the operational modes, an electrically actuated bypass valve is installed to bypass gas from the discharge to suction to maintain a suitable suction pressure. The booster compressor discharge has a final filter to remove any particulates and remaining residual oil from the helium stream before being sent to CHL. A 76 mm diameter, 750 m long header runs to CHL where it joins the CHL purification system.

The maximum compressor flow rate is 2.8 g/s. Automatic shutdown of the compressor will occur via a pressure switch and PLC control if the compressor suction runs sub-atmospheric due to He gas supply interruption. Oxygen contamination is measured on the recovery compressor discharge using an Illinois Instruments Series 810 Oxygen Monitor with a set range of 0 to 1,000 ppm. Oxygen contamination is also measured at CHL with a similar instrument. If oxygen contamination rises above 1000 ppm for two minutes, the recovery helium is vented to atmosphere before reaching the CHL purifier.

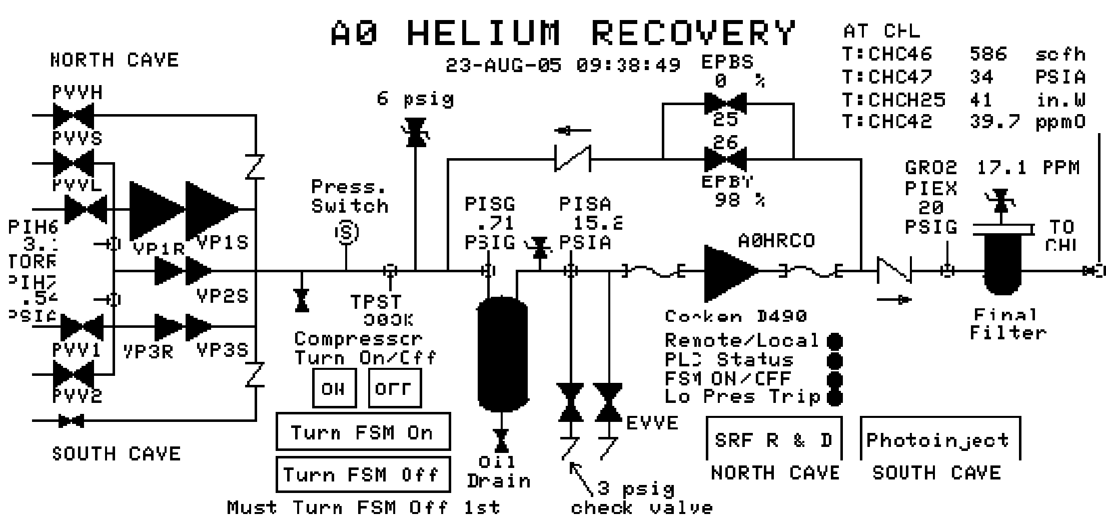

FIGURE 4. ACNET graphic depicting A0 Gas Recovery System. ACNET device names and measurements shown.

Representative bulk system helium usage is approximately 0.65 g/s (400 standard m^3 per day). The recovery of this gas results in major cost savings. The recovered gas makes up for a large fraction of Tevatron helium system losses, which historically are about 1.5 g/s or 740 standard m^3 per day.

PROBLEMS AND TROUBLESHOOTING

The largest problem experienced by the South Cave Cryogenic System is the small buildup of contamination due to the use of commercial 500 L dewars. The process of changing dewar tops allows a small amount of air to condense in the liquid bath. Since these dewars are rarely warmed to room temperature, this small buildup can grow at the bottom of these supply dewars. A0 has experienced several instrumentation plugs as a result of dewar contamination propagating into the system.

The most severe of these incidents occurred in June 2004 when the cavity pressure capillary line plugged. This pressure line is used to regulate the bath pressure to 1600. +/- 33 Pa. Accurate regulation with thermometry was not possible since only an approximate fluid temperature measurement was available at the return to the feedcan. This device (TRH3) is a carbon resistor that is beyond its calibration range during superfluid operation. The ultimate solution was to use the heat exchanger differential pressure tap located on the shell side exhaust. There is a known pressure drop at 1600. Pa of 27 Pa which was accounted for in the loop regulation set point. This pressure location exhibited much more sluggish readbacks of the cavity pressure, probably due to the distance from the cavity. However, eventual tuning of the ACNET controls loop gains achieved the same pressure tolerance of 1600. +/- 33 Pa as before the plug. The concern over losing this last pressure line ultimately prompted the November 2004 warm-up of the CRYOCAP vessel to room temperature. The subsequent cooldown revealed that the previously plugged instrumentation lines were again clear and useable.

It is very important to avoid unnecessary thermal cycling of the SCRF cavity. The cavity tuner inside the CRYOCAP module has been broken since March 2002 and thermal cycling the cavity could result in a critical de-tuning that would prevent operation of the cavity. Since 2002, there has only been one week, noted above, where the cryogenic system was warmed up to 300 K for purification. Several supply helium dewar problems have caused the cavity to warm to around 40 K over the years. The duration of these warming events varied, but typically the time required to re-establish the liquid helium supply to the system was under 4 hours.

HEAT EXCHANGER LESSONS

One reason we tend to operate in batch fill mode is that the exchanger is not fully efficient at the lower flows required for the one cavity load. The feedcan heat exchanger for subcooling 4.3 K LHe with 2 K return vapor is oversized. This exchanger uses Fermilab's Magnet Test Facility subcooler design: a shell and tube exchanger, 10 mm tube, 22 mm fins, 5.95 m long, wrapped on 8.6 cm mandrel. The MTF exchanger is optimized for a design point of 4 g/s, where test data indicates heat transfer effectiveness, the ratio of actual heat transfer to ideal heat transfer, of 80-90% [4].

A general goal for heat exchangers is to operate the gas side in the transition-to-low turbulent region, $10^3 < Re < 10^4$, for the best balance of good heat transfer with acceptable pressure drop. The Reynolds number characteristic length is taken as the hydraulic diameter, as shown in equation (1), where L_{shell} is the flow length of the exchanger, A_{cs} is the flow cross-sectional area, and A_{ht} is the total heat transfer area [5].

$$D_{hyd} = 4r_{hydr} = 4L_{shell}\frac{A_{cs}}{A_{ht}} \tag{1}$$

For this exchanger at typical MTF superfluid supply flow rates of 4 g/s, $\mathrm{Re} \approx 10^4$. But at a FNPL representative flow rate of 0.2 g/s, $\mathrm{Re} \approx 400$, indicating the exchanger is operating in the less efficient laminar flow regime. This penalizes the effectiveness at lower flow, which was measured at 40%. A more appropriately sized heat exchanger will be used for future system with similar loads and flow rates.

R & D TEST AREA

The FNPL SRF cryogenic system was upgraded in 2000 to add a superconducting RF Research and Development Test Area. This is a versatile, dewar-fed superfluid helium system for testing superconducting RF cavities inside a cave. Cryogens are supplied via one 500 L helium dewar and two 250 L nitrogen dewars. It shares vacuum pumping with the photoinjector cryogenic system, so they cannot be simultaneously operated with superfluid. This R & D Area is usually is configured for superfluid testing of bare RF cavities inside a Vertical Test Dewar (VTD). See FIGURE 5 for ACNET schematic of the North Cave SCRF test facility.

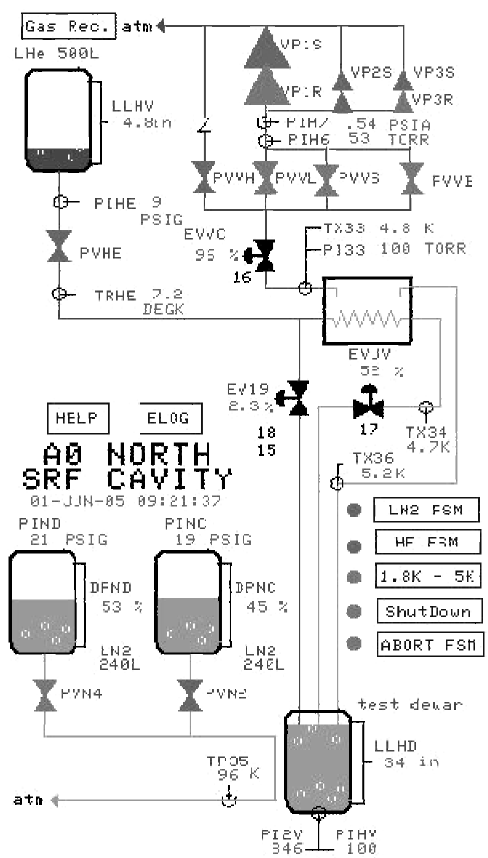

FIGURE 5. ACNET Graphic Depicting A0 R & D Cryogenic System with normal LHe. ACNET device names and measurements shown.

The VTD was fabricated from an existing 3.7 m in-ground dewar used for the Tevatron dipole coil test program. It was shortened to reuse the upper flanges and the vacuum vessel. The VTD provides a 0.46 m diameter, 1.66 m deep helium space for superfluid bathed cell testing [6]. It has a static heat leak of 1.7 W to 2K. Typically, the VTD operates in batch-fill mode due to superheat of the 2K vapor return, which is somewhat close to the 80K shield and underneath a top plate that is not vacuum insulated. The VTD operates on a four day schedule. The first 24 hours are allotted for cooling down the Nitrogen TL and shield. The second 24 hours allows for a slow cooldown to 30 K ensuring that the entire system achieves thermal equilibrium. The morning of the third day starts the actual testing of the vessel. It is promptly filled with 86 cm of liquid helium and pumped down to 1600. Pa for testing. The fourth day allows for the system to quickly warm up past 80K and eventually to 300 K.

The geography of the A0 facility places the VTD and the North Cave much closer to the vacuum pump skid than the South Cave. This resulted in high levels of vibrations propagated into the test area. Extensive testing revealed vibrations were traveling through the concrete floor to the VTD. The solution was to use Newport XL-A Laser Table pneumatic damping vibration legs. These legs are used typically used on experimental tables for physics laser applications, which need to be free from background vibrations. Each leg provides a cushion of air for the cryostat to rest on. A position sensing arm on each leg holds the cryostat height to within 0.25 mm.

The use of these legs has significantly reduced the level of vibrations seen by the cavity inside the VTD and thus has allowed for more accurate reading. FIGURE 6 shows a comparison of accelerometer readings on the VTD and on the cave floor right next to the vessel.

The Test Area system capacity was measured with a calorimetry heater connected as the superfluid helium load. Results are shown if FIGURE 7. This curve shows a gain in system capacity resulting from a heat exchanger upgrade in 2003. The original tube and shell heat exchanger had too large of a pressure drop from limited flow cross sectional area, which was limiting the pumping capacity. Another operational improvement was the addition of a transfer line shutoff valve (PVHE in FIGURE 5) to avoid a failure mode in which an empty supply dewar can inadvertently reach sub-atmospheric conditions.

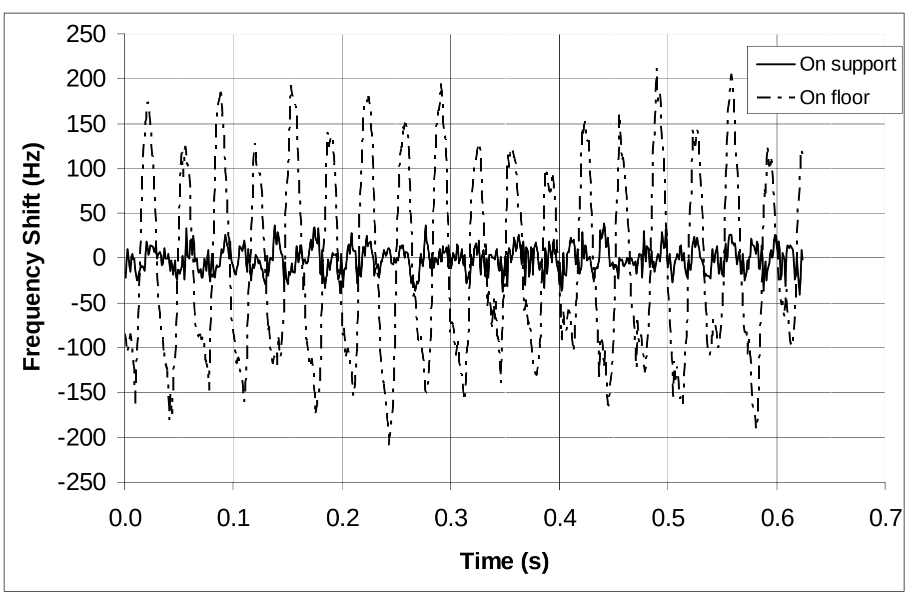

FIGURE 6. Vibration damping results for the VTD.

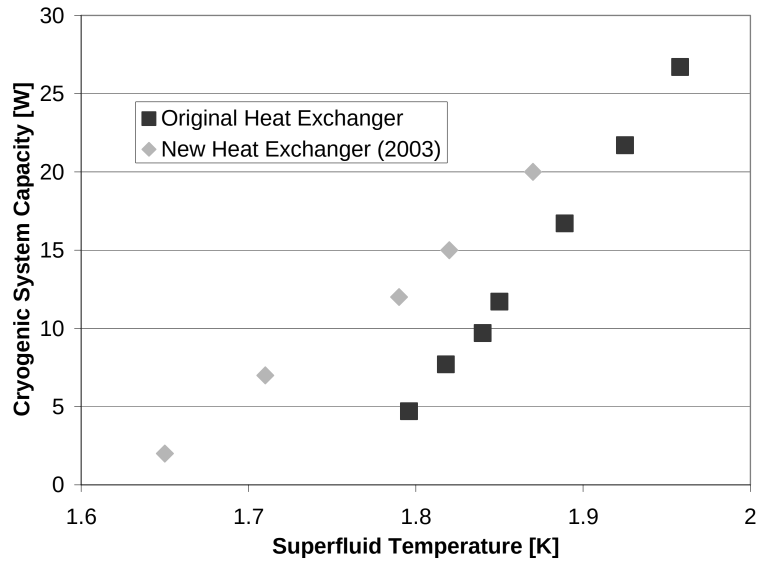

FIGURE 7. A0 R & D Test Area cryogenic system capacity tests.

CONCLUSIONS

Recent Fermilab experience with a superfluid helium cryogenic system that supports SRF cavity beam line operations and research has been discussed. This has allowed Fermilab to gain valuable experience in a field of great interest to the high energy physics accelerator community. The cryogenic experience gained and lessons learned will be applied to future SRF cryogenic systems at Fermilab, such as the High Brightness Test Facility and an upgraded photoinjector.

ACKNOWLEDGEMENTS

This work is supported by the U. S. Department of Energy under contract No. DE AC02 76CH03000. The authors wish to acknowledge the dedicated effort of the Accelerator Mechanical Support Department technicians who handle the daily cryogenic operation of this system. We recognize the vast contribution made by Joel Fuest, who led the original engineering, design, installation, and commissioning of this system.

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