

A Cryogenic Test Stand for Large Superconducting Solenoid Magnets

R. Rabehl^a, R. Carcagno^a, J. Nogiec^a, D. Orris^a, W. Soyars^b, and C. Sylvester^a

^a*Technical Division, Fermilab, P.O. Box 500, Batavia, IL 60510 USA*

^b*Accelerator Division, Fermilab, P.O. Box 500, Batavia, IL 60510 USA*

Abstract. A new test stand for testing large superconducting solenoid magnets at the Fermilab Central Helium Liquefier (CHL) has been designed, installed, and operated. This test stand is being used to test a coupling coil for the Muon Ionization Cooling Experiment (MICE), and future uses include solenoids for the Fermilab μ 2e experiment. This paper describes the test stand design and operation including controlled cool-down and warm-up. Overviews of the process controls system and the quench management system are also included.

Keywords: Magnet, test stand.

PACS: 07.20.Mc

INTRODUCTION

A new test facility has been constructed at Fermilab to support testing of large superconducting solenoid magnets. The initial use is to test a Muon Ionization Cooling Experiment (MICE) coupling coil solenoid. Four MICE coupling coils will be tested: three (including one spare) for the MICE experiment to be operated at Rutherford Appleton Laboratory, and one for the Fermilab Mucool Test Area. Details of the MICE coupling coils can be found elsewhere [1,2,3]. Future uses include testing solenoids for the Fermilab μ 2e project.

A new test stand was required for cooling and powering these 1.86 m diameter, 2.2 ton MICE solenoids. The test stand provides the capability to provide 10 g/s of helium at temperatures ranging from 300 K to 4.5 K. This is accomplished by mixing liquid helium with gaseous helium in the cryostat piping. The MICE magnet is conductively cooled as the temperature-controlled helium is split between two cooling paths, each following half of the magnet circumference on the outer mandrel.

Once at 4.5 K, the MICE magnet will be powered and quench trained to hold a minimum test current of 210 A. Due to the high inductance of the magnet (596 H), there is a significant stored energy of 13 MJ at 210 A. The limited helium inventory in the test stand due to conduction cooling rather than bath cooling will limit the cryostat piping pressure rise upon quenching. The magnet is protected by a passive quench protection system using cold diodes.

TEST FACILITY

Unlike other test stands designed, constructed, and operated by the Fermilab Technical Division's Test and Instrumentation Department [4,5], the Solenoid Test Facility is located away from the Industrial Building 1 CTI-1500 refrigerator and associated cryogenic infrastructure. While the IB1 cryogenic system has sufficient capacity, this capacity would be shared with other test stands. The significant fringe magnetic field of a fully-powered MICE coupling coil was also a consideration. It would affect power supplies, other test stands, the main control room, and offices. Finally, the availability of floor space to locate the test cryostat also was a concern.

A second location considered was the Collider Detector at Fermilab (CDF) Hall. In addition to issues related to the solenoid fringe magnetic field, this location has the additional disadvantages of coincident construction at the CDF Hall, and possibly inadequate cryogenic capacity for future uses of this cryostat.

Ultimately, the Fermilab Central Liquefier (CHL) [6] was selected as the site for the Solenoid Test Facility, where both space for the large test cryostat and a sufficient source of liquid helium are available. The CHL plant, which had been out of service since the end of Fermilab's Tevatron operation in 2011, was brought back into service to support this test stand. The cryostat has been placed in the CHL South Annex, away from operating equipment.

Physical barriers and signage have been posted to deal with fringe magnetic fields that extend beyond the building walls.

TEST CRYOSTAT AND MECHANICAL DESIGN

The test cryostat is a re-purposed cryostat originally designed and fabricated by Meyer Tool & Manufacturing, Inc. (Oak Lawn, IL) in 1997 for a superconducting magnetic energy storage (SMES) application [7]. The cryostat was unused at the National High Magnetic Field Laboratory (NHMFL) at Florida State University and transferred to Fermilab for this use. The cryostat was disassembled and for the testing of MICE coils, only the vacuum vessel and the top plate are being used. The stainless steel cryostat vacuum vessel has an outer diameter of 131.5 in, an inside diameter of 130.75 in, and a height to the vacuum vessel flange of 105 in.

A liquid helium vessel, a liquid nitrogen-cooled thermal shield, and a vacuum vessel welded cover assembly were removed from the cryostat and stored for possible future use. A new vacuum vessel cover assembly using a dished head transition piece was designed to cover the transition between the top plate and the vacuum vessel, and to provide four points for supporting the magnet weight. This new cover consists primarily of an ASME Flanged and Dished head, an 82-inch diameter pipe section, and two flanges – one welded to the outside diameter of the dished head and the other flange is welded to one end of the 82-inch diameter pipe section. This all-welded assembly is manufactured from type 304 stainless steel.

For the MICE coupling coil, a support bracket assembly is installed at each of the four support locations for this magnet and these brackets are connected via stainless steel rods to the dished head cover. To provide thermal isolation between the coil and the stainless steel support brackets, a machined G-10 block is clamped between the coil and the support bracket. Also, to minimize coil movement due to magnetic forces, G-10 rods are installed in each of the support brackets. These rods limit the horizontal displacement of the assembly and also provide some thermal insulation between the vacuum vessel and the cold coil. Modifications to this suspension and support scheme to facilitate the assembly and testing of $\mu 2e$ magnets is underway.

The cryostat and the new vacuum vessel cover assembly are shown in FIGURE 1.



(a)



(b)

FIGURE 1. (a) shows the cryostat as it was stored outside at the NHMFL, and (b) shows the new vacuum vessel cover assembly placed on the staging area framework with the magnet mounted underneath. Support brackets can also be seen on the periphery of the magnet.

TEST STAND CRYOGENIC SYSTEM

Liquid helium is produced by the CHL cryoplant into its 38,000 liter storage dewar and fed to the test cryostat by a new 16 m long cryogenic transfer line. This dewar-fed system allows the CHL cryoplant to function independently of solenoid testing to refill the 38,000 liter dewar. The CHL cold box is operated in a reduced capacity mode with no nitrogen pre-cooling to meet the test stand requirements of up to 10 g/s of two-phase helium flow. Theoretical design performance for the cold box without liquid nitrogen with original full compressor discharge and full turbine output estimates 22 g/s of helium liquefaction. Further capacity reduction is achieved by lower cold box inlet pressure, adjusting turboexpander speeds, and finally by tuning a storage dewar trim heater to match the test stand load.

FIGURE 2 shows a simplified flow schematic for the test stand. Cool-downs and warm-ups of the magnet are controlled to limit thermal stress. However, there were no temperature sensors installed in the magnet coils and as a result, the temperature of each of the eight coil segments must be calculated using temperature-dependent properties and measured resistances. The temperature of the helium supplied to the magnet is controlled during cool-down to be 50 K colder than the maximum one-eighth coil segment temperature and during warm-up to be 50 K warmer than the minimum one-eighth coil segment temperature. Room temperature high-pressure helium gas is provided from the CHL buffer tanks and supplied to the cryostat at a maximum rate of 10 g/s through a pressure-reducing regulator and a warm control valve V1. The flow rate is measured by a V-cone flowmeter upstream of the cryostat. Liquid helium flow from the storage dewar and through the transfer line and bayonet can is controlled by a cold control valve V2 integrated into the cryostat. All helium returning from the cryostat is warmed to room temperature by an 18 kW immersion heater.

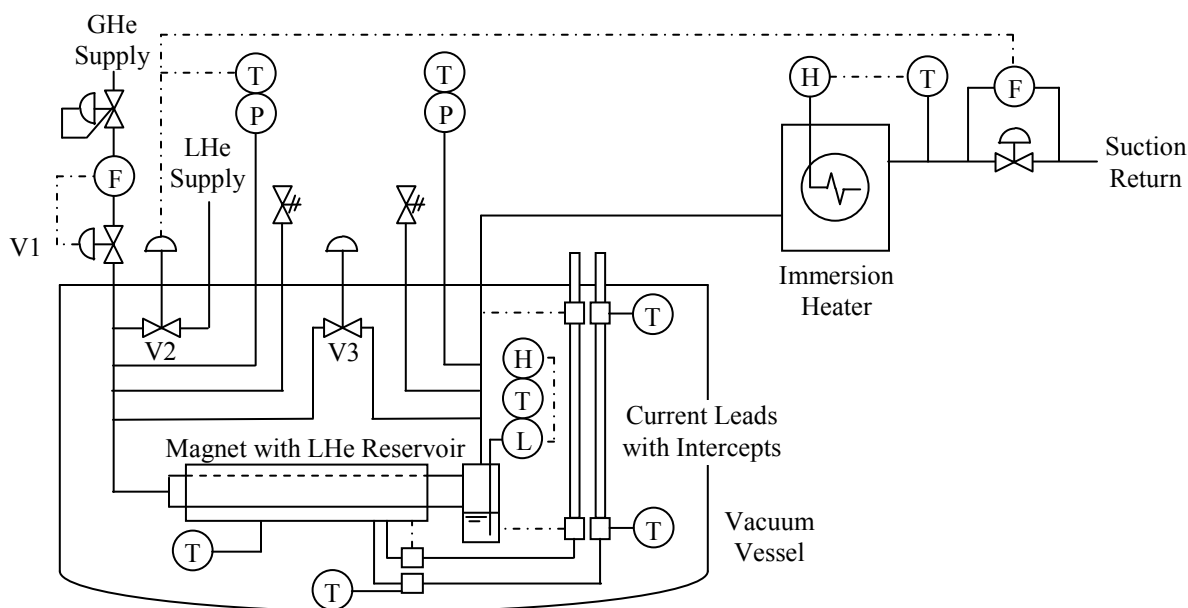


FIGURE 2. Simplified flow schematic for the cryogenic test stand.

During normal operations, liquid helium is supplied to the magnet by cold control valve V2 at a rate such that liquid spills out of the magnet cooling tubes into a liquid helium reservoir vessel where it is vaporized by a 25 W cartridge heater. The liquid helium flow rate supplied to the cryostat is measured warm, downstream of the 18 kW immersion heater described above.

Cold isolation valve V3 opens upon a magnet quench, providing a parallel path for helium to leave the cryostat piping.

FIGURE 3 shows some of the cryogenic system elements described above.

The magnet and cryostat piping are protected by two 55 psig spring-operated relief valves. These valves were sized to accommodate venting rates for magnet quenching, loss of insulating vacuum, and fire.

The magnet is powered by conduction-cooled current leads optimized for 220 A of current. The upper part of the lead is optimized to operate between 300 K and 60 K. It consists of 000 AWG copper electrical cable, 1.6 m long.

The heat load to the 60 K intercept is 10W, which is removed by thermally sinking the intercept to the 4.5 K GHe return piping. The lower section of the lead is optimized to operate between 60 K and 4.5 K. It consists of 4.7 mm copper cable, 1 m long. The heat load to 4.5 K is 1.5 W, which is removed by thermally sinking the intercept to the liquid helium reservoir vessel. Finally, stabilized LTS buswork connecting the current lead to the magnet buswork is cooled at one end by this same 4.5 K intercept and at the other end by being thermally sunk to the magnet mandrel. The 4.5 K intercepts include assemblies of Kapton-insulated copper fingers. The assemblies are produced by Wang NMR (Livermore, CA). FIGURE 4 shows the 60 K and 4.5 K intercepts of the conduction-cooled current leads.

The magnet and cryostat internal piping are both insulated with multi-layer insulation (MLI). The cryostat interior walls and bottom head have 60 layers. All other surfaces inside the cryostat have 25 layers of MLI.

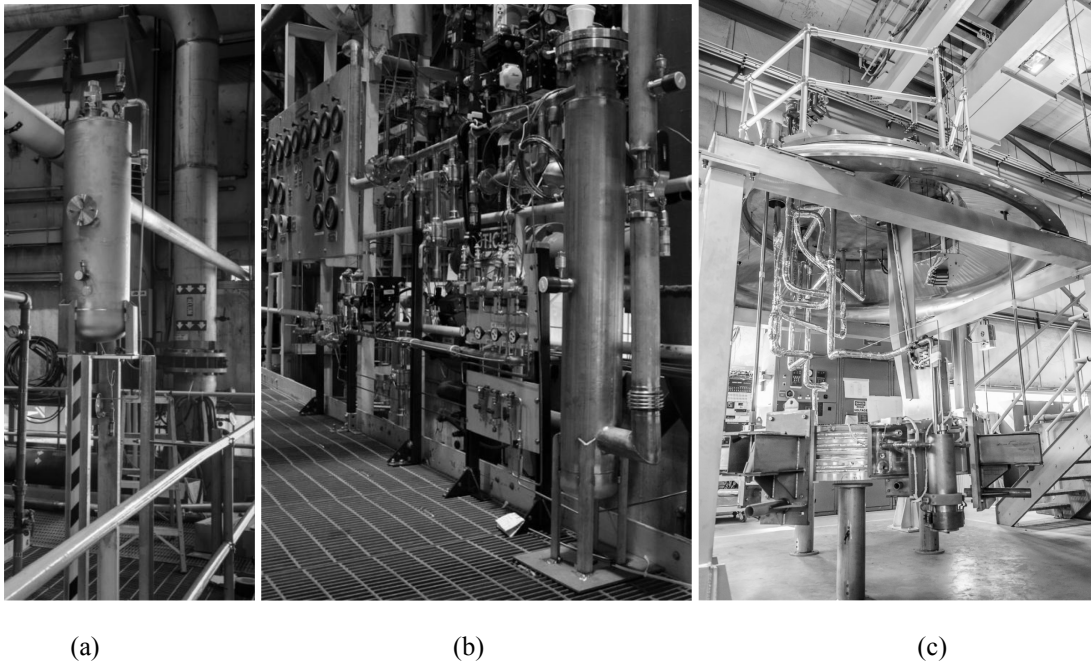


FIGURE 3. (a) shows the bayonet can with the transfer line supply at right of center, (b) shows the 18 kW immersion heater vessel, and (c) shows the vacuum cover assembly on the staging area framework, internal cryogenic piping, and LHe reservoir vessel at bottom center.

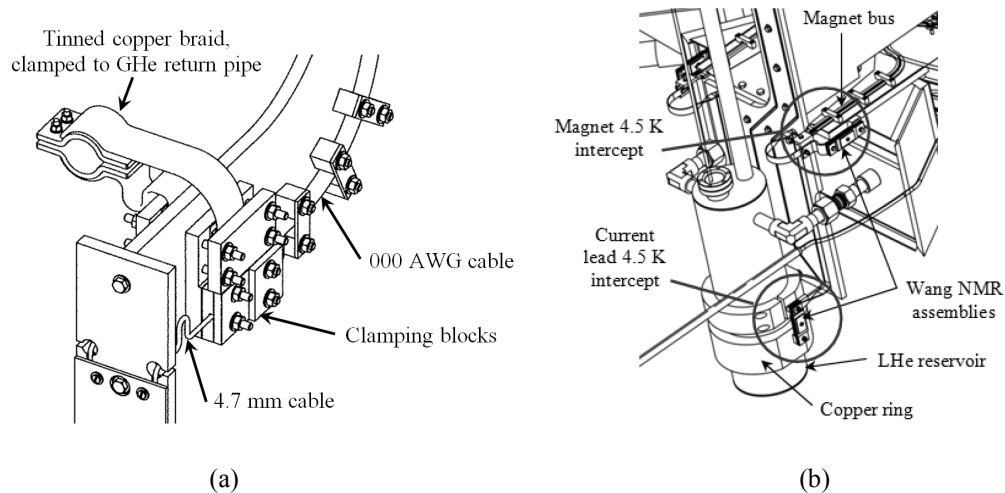


FIGURE 4. (a) shows the 60 K intercept assembly, and (b) shows the 4.5 K intercept assembly of the conduction-cooled current leads.

TEST STAND PROCESS CONTROLS SYSTEM

The test stand process controls system is based on National Instruments' Compact-RIO (C-RIO), which uses a real-time operating system and FPGA. A Labview operator interface runs on a host computer and communicates to the C-RIO cryogenics computer via a protected network. The operator interface, as shown in FIGURE 5, includes instrumentation monitoring, PID control loop faceplates, valve control, and alarm and interlock notifications.

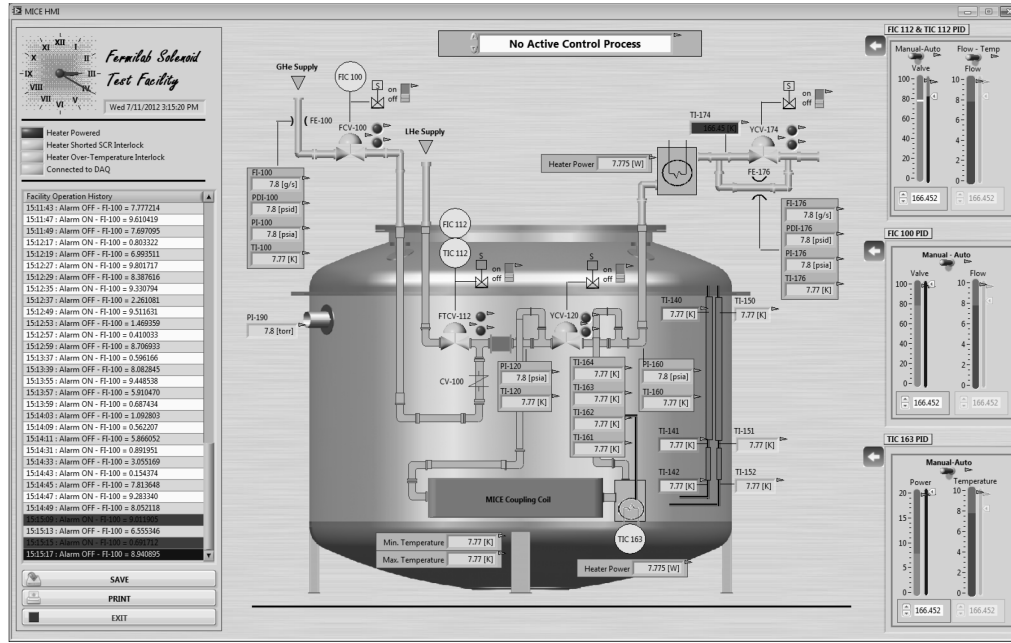


FIGURE 5. Labview cryogenic operator interface for the new test stand.

TEST STAND QUENCH MANAGEMENT SYSTEM

The test stand quench management system software has several components, including a quench detection module, a quench characterization module, a quench monitoring data viewer, an isolation amplifier configurator, and power supply control. The quench detection module monitors all signals pertaining to the detection of a quench in order to protect the magnet and to capture the quench-related data. The quench characterization module allows for capturing all quench signals and observing those signals at run-time. The quench data are also exported to a MATLAB quench analysis application for further analysis and viewing. The isolation amplifier configurator allows gains and offsets to be examined and changed.

INITIAL OPERATING EXPERIENCE

FIGURE 6 shows the cryostat just prior to starting commissioning. At the upper left are the gaseous helium supply line, the liquid helium supply U-tube, and the gaseous helium return U-tube.

Mounted on the side of the cryostat is a magnetic field sensor. Once a field of 600 Gauss reaches the cryostat surface during magnet powering, all entrances to the area become interlocked as a high magnetic field hazard. Entering the area by opening a door, for example, will trip the power supply and de-energize the magnet.



FIGURE 6. The cryostat ready for commissioning.

Cool-down of the first MICE coupling coil was started on May 6, 2013. Approximately 53 hours was required for the calculated coil temperatures to go from 300 K to approximately 10 K. The cool-down rate temporarily slowed after 24 hours due to an issue with the I-P transducer range on the LHe supply valve. Once this problem was resolved, the cool-down rate increased.

FIGURE 7 provides the cool-down curves for each of the eight coil segments.

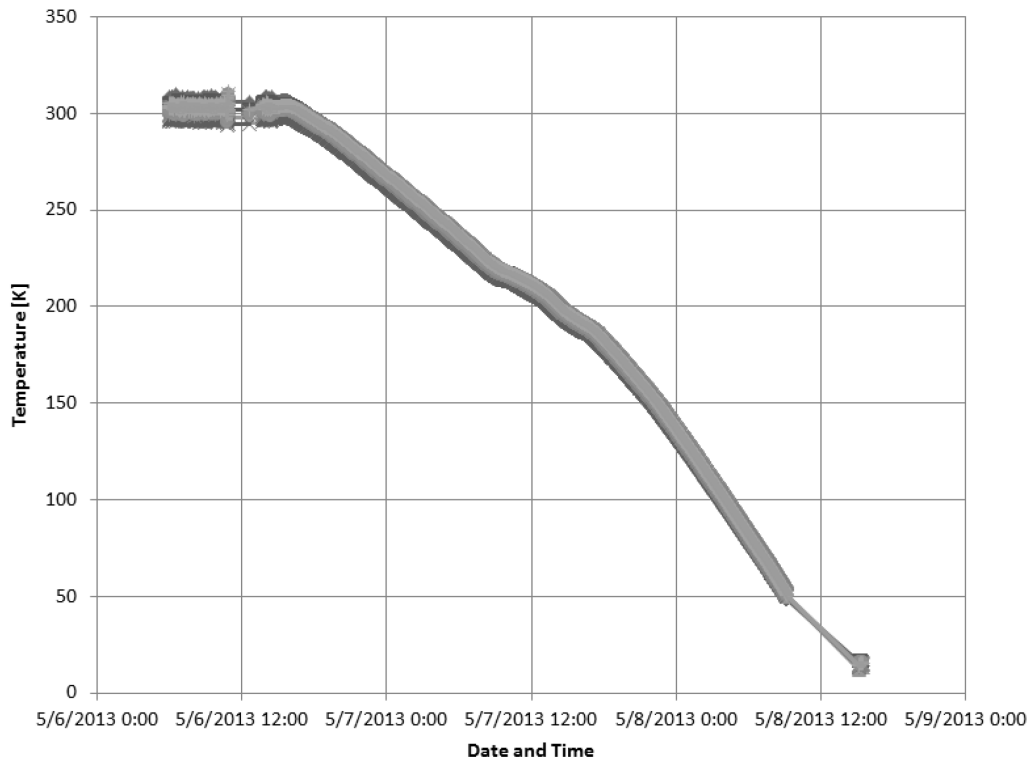


FIGURE 7. Cool-down curves for each of the eight coil segments for the first cool-down of the new test stand.

Soon after two-phase helium began reaching the magnet cooling tube, insulating vacuum problems appeared. The vacuum level was already poor at 3-5 milliTorr until 9:00 on the morning of May 8 when the vacuum quickly worsened to 15 milliTorr. Increasing the liquid helium flow rate from 5 g/s to 10 g/s to try to overcome the associated heat load only worsened the situation as the increased pressure in the piping increased the leak rate until an insulating vacuum interlock was tripped, shutting the LHe supply valve. The insulating vacuum then quickly recovered to the previous level of 3-5 milliTorr.

These events are illustrated by FIGURE 8.

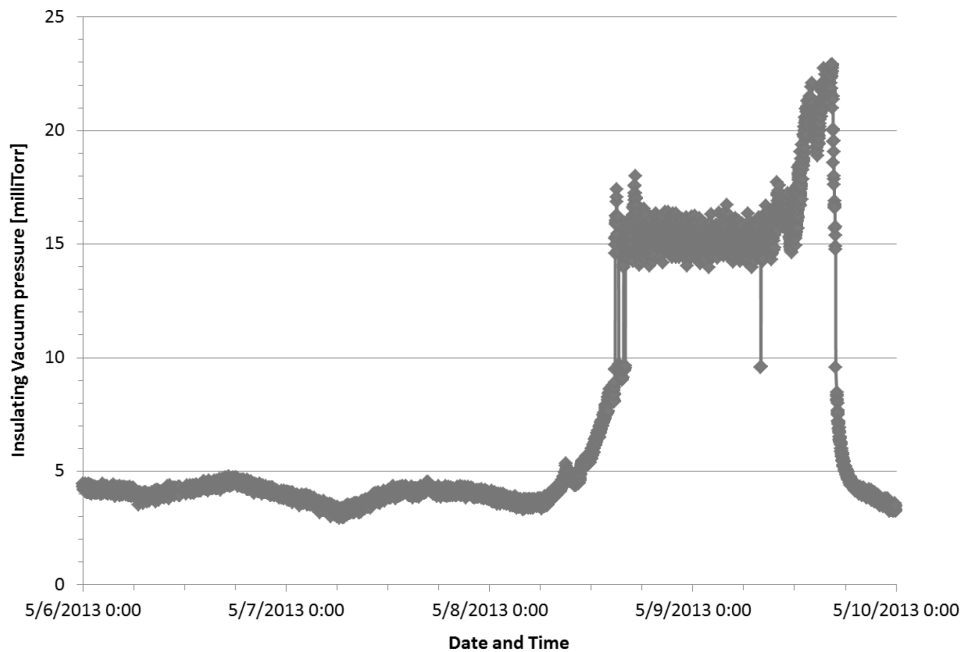


FIGURE 8. Illustration of the insulating vacuum problems experienced during the first cool-down of the new test stand.

During the subsequent warm-up, efforts were made to quantify the leak by isolating the vacuum pumping system and measuring the rate of rise of the vacuum pressure. At 5 K, the leak rate was calculated to be 0.2 atm-cc/s. At 40 K, the leak rate was calculated to be 0.009 atm-cc/s. Finally, at 100 K the leak rate was calculated to be 0.0016 atm-cc/s. The leak was not detectable by this method at 200 K.

Also during cold commissioning, the current lead intercepts which are expected to operate at 60 K and 4.5 K with the magnet powered only reached 85 K and 20 K, respectively, with no magnet powering. Subsequent analysis has indicated this is due to increased heat load (gas conduction and radiation) resulting from poor insulating vacuum as well as improper accounting for thermal contact resistances.

Ultimately, the coil never became fully superconducting during the initial commissioning and therefore the magnet was not powered. A warm-up was started on May 16, and leak hunting and repair are in progress.

CONCLUSIONS

A new test stand for large conductively-cooled solenoids magnets has been designed and installed at the Fermilab Central Helium Liquefier. An initial commissioning run has been completed. A number of issues are being addressed in preparation for continued commissioning and operations later this summer.

It is expected that this test stand will have a steady throughput of test objects. In addition to the four MICE coupling coils, this test stand will also test conductively-cooled magnets for the Fermilab $\mu 2e$ project. A prototype Production Solenoid (PS) [8] from Toshiba has already been delivered to Fermilab and is expected to be tested after the first MICE coupling coil. This coil is shown in FIGURE 9.

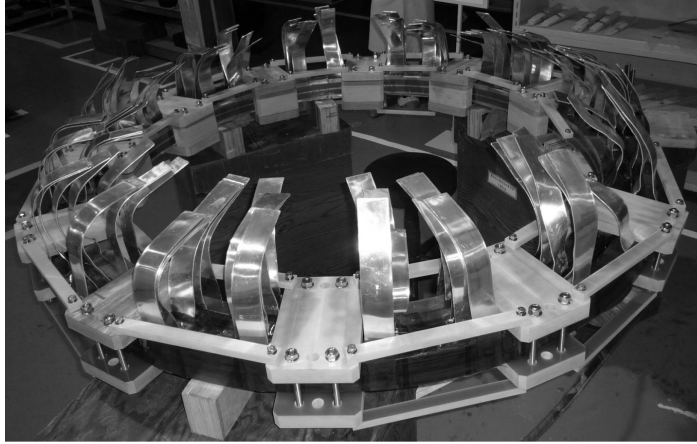


FIGURE 9. The $\mu 2e$ prototype PS from Toshiba.

ACKNOWLEDGMENTS

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

REFERENCES

1. M. A. Green et al., "The Mechanical and Thermal Design for the MICE Coupling Solenoid Magnet," ASC 2004.
2. L. Wang et al., "The Helium Cooling System and Cold Mass Support System for the MICE Coupling Solenoid," MT-20.
3. M. A. Green et al., "Progress on the Coupling Coil for the MICE Channel," 2005 PAC.
4. T. J. Peterson et al., "A 1400 Liter 1.8 K Test Facility," in *Advances in Cryogenic Engineering* 43A, edited by P. Kittel, Plenum, New York, 1998, pp. 541-548.
5. R. Carcagno et al., "Cryogenic Infrastructure for Fermilab's ILC Vertical Cavity Test Facility," in *Advances in Cryogenic Engineering* 53A, edited by J. Weisend II et al., Plenum, New York, 2008, pp. 1594-1601.
6. W. M. Toscano and F. J. Kudirka, "Thermodynamic and Mechanical Design of the FNAL Central Helium Liquefier," in *Advances in Cryogenic Engineering* 23, edited by K. Timmerhaus, Springer, New York, 1978, pp. 456-466.
7. R. D. Luther, "Design and Fabrication of a Large Cryostat for Testing SMES Apparatus," in *Advances in Cryogenic Engineering* 45, edited by Shu et al., Kluwer Academic/Plenum, New York, 2000, pp. 1699-1705.
8. M. Yoshida et al., "Development of a Radiation Resistant Superconducting Solenoid Magnet for mu-e Conversion Experiments," *IEEE Transactions on Applied Superconductivity*, Vol. 23, Issue 3.