A NEW FACILITY FOR TESTING SUPERCONDUCTING SOLENOID MAGNETS WITH LARGE FRINGE FIELDS AT FERMILAB

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Abstract

Testing superconducting solenoid magnets with no iron flux return can be problematic for a magnet test facility due to the large magnetic fringe fields generated. These large external fields can interfere with the operation of equipment while precautions must be taken for personnel supporting the test. The magnetic forces between the solenoid under test and the external infrastructure must also be taken under consideration. A new test facility has been designed and built at Fermilab specifically for testing superconducting magnets with large external fringe fields. This paper discusses the test stand design, capabilities, and details of the instrumentation and controls with data from the first solenoid tested in this facility: the Muon Ionization Cooling Experiment (MICE) coupling coil.

INTRODUCTION

There has recently been a need to test solenoid magnets at Fermilab that have no iron flux return so the fringe magnetic fields could be relatively large. The Muon Ionization Cooling Experiment (MICE) Coupling Coil (CC) solenoid is the first such solenoid intended to be tested.

Since the existing dewars at Fermilab's Magnet Test Facility (MTF) are not large enough to test a MICE CC solenoid a new cryostat would be required. In addition, the large fringe field that would be produced by the solenoid would interfere with operations at MTF. At full operating current (210A) the 600 Gauss line would be at a radius of 3m and the 5 Gauss line would be at a radius of 15m. The 5 Gauss level is the limit for personnel with pacemakers and the 600 Gauss level impacts both personnel safety as well as the operation of equipment.

Several options were researched and the final decision was to build the solenoid test facility (SolTF) at the Fermilab Central Helium Liquefier (CHL) [1]. This location was selected because it had adequate space for the large test cryostat and the large fringe magnetic fields would not impact personnel and equipment operations: Personnel access could be managed to meet safety requirements. In addition, there was a sufficient source of liquid helium available to operate the new test facility.

SOLENOID TEST FACILITY

The new solenoid test facility (SolTF) would have to meet the cryogenic cooling, mechanical support, powering, quench protection, and data acquisition requirements for testing the MICE coupling coil at Fermilab. Table 1 lists some of the MICE CC specifications that SolTF must accommodate.

Table 1: MICE Coupling Coil Specifications for Testing

Parameter	Specification
Coil Design	96 Layers, 166 Turns in Series
Superconductor Strand	Cu/NbTi (MRI) 1.0 mm x 1.65 mm
Magnet Outer Structure Diameter	1860 mm
Magnet Weight	2.2 Tons
Cryogenic Cooling	Conduction Cooled
Helium Flow Rate	10 g/s
Cool Down Delta-T Limit	50 K Across the Magnet
Magnet Inductance	596 H
Maximum Current (4.5 K)	220 A
Stored Energy @220A	14.4 MJ
Peak Field (on axis)	2.6 T
Peak Field (on coil)	7.5 T
5G, 100 G, & 600 G Lines	15 m, 5m, 3m

Solenoid Test Cryostat

The cryostat used for the solenoid test facility was transferred to Fermilab from the National High Magnetic Field Laboratory (NHMFL) at Florida State University. The stainless steel vacuum vessel is 3.34m outer diameter, 3.32m inner diameter, and 2.7m high. The MICE CC coil would be tested in this cryostat using liquid helium conduction cooling.

The MICE CC solenoid is supported by a dished head assembly and four stainless steel rods each connected to a support bracket. The four support brackets are attached to the magnet with a G-10 block sandwiched between them to minimize heat conduction to the coil. G-10 rods between the support brackets and the cryostat wall prevent the magnet from moving horizontally. Although the cryostat was located as far as practical from the building's support columns and other fixed ferromagnetic material, tilt switches and displacement sensors were installed to monitor the magnet's vertical motion, if any,

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due to forces generated between the magnet and external magnetic material. Figure 1 is shows a 3-D model of the cryostat with the MICE CC solenoid.

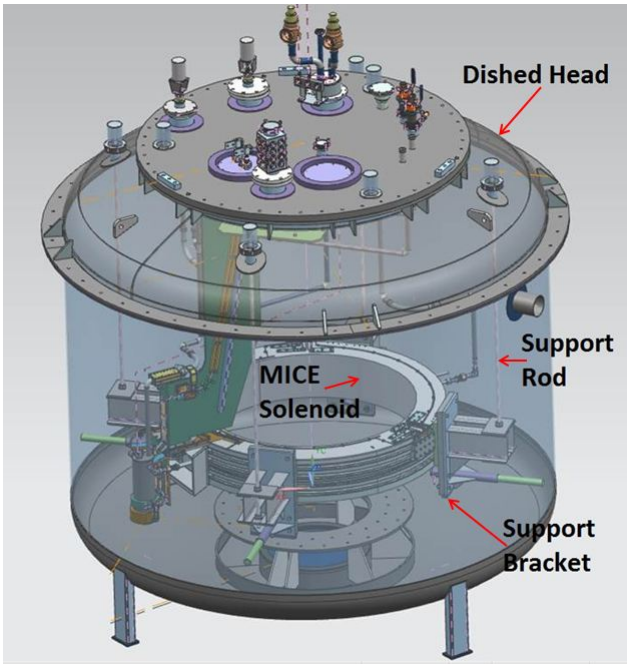

Figure 1: 3D model view of the SolTF Cryostat with the MICE Coupling Coil Supported from the Dished Head

Floor Layout

The solenoid test facility is located in the east annex of Fermilab's Central Helium Liquefier facility. The cryostat is located in the middle of the open floor space to optimize distance from magnetic materials, power panels, etc. A staging area with a support structure for the dished head is east of the cryostat for readying the solenoid for testing and the data acquisition and controls racks are located against the south wall where the maximum field is expected to be less than 20 Gauss.

The floor layout of the solenoid test facility is shown in Figure 2.

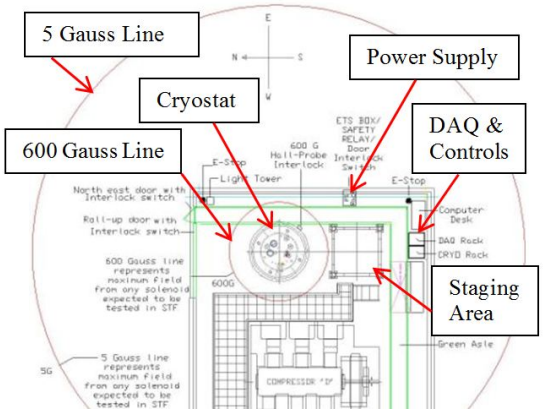

Figure 2: SolTF Floor Layout at CHL

DATA ACQUISITION & CONTROLS

The DAQ and controls systems includes quench protection, fast and slow data logging for quench characterization, and cryo monitoring and controls. The quench protection and cryo controls are based on National Instrument's Compact-RIO (C-RIO), which uses a real-time operating system and FPGA. The data logging is based on National Instrument's PXI. The computer system consists of two operator stations, one devoted to managing the quench subsystem and another to monitoring and controlling of the cryogenic subsystem and the magnet. Each operator station is equipped with two monitors. Hardwired interlocks for equipment and personnel are also monitoring by this system.

Cryogenic Monitoring & Controls

The monitoring and control system is capable of both monitoring various process variables (temperatures, pressures, levels, flows, etc.) and controlling process variables (valves, levels, power, etc.) using PID regulators. The process interlock logic is a separate process that monitors vacuum, quench status and temperatures; it responds immediately to assigned events by closing or opening valves. The data archiver as well as all user interface programs resides in the top layer, the monitoring and control software resides in the real-time system layer, and the interlock logic and I/O in the FPGA part of the system [2]. Figure 3 shows the cryo monitoring and control display panel.

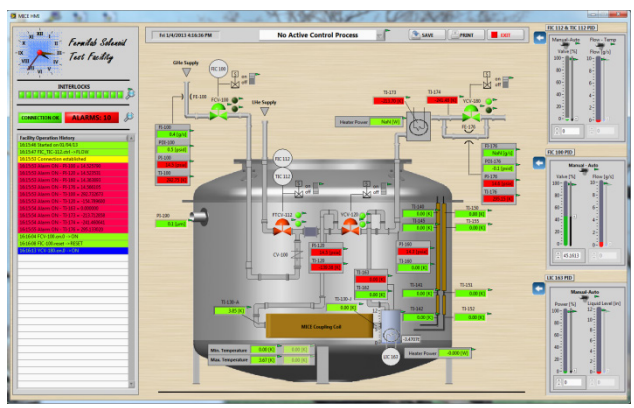

Figure 3: Cryo Monitoring and Control Display Panel. An Image of the cryostat with interactive parameters, such as temperature and pressure, are included in the Display.

Power System & Personnel Interlocks

The MICE power supply system was provided by Lawrence Berkeley National Laboratory (LBNL). This system includes a CryogenicLimited 240 Amp +10/-8.5 V power supply and energy absorber, and a circuit for

disconnecting the power supply and enabling the passive diodes in the MICE solenoid. This system is also interfaced to the test stand quench detection system and hardwired personnel interlocks. A hardwired interlock "Electrical Trip System" (ETS) was built to enable or disable power to the bus based on several interlocks. These include the power supply access door, several "Emergency Off" buttons, etc. This system was installed in the power supply rack.

Quench Protection

The quench protection system uses an FPGA based digital quench detection (DQD) system [3]. Since the MICE CC magnet uses passive diodes for primary quench detection, the digital system provides redundant coil quench protection. The low temperature superconducting leads, however, are protected by the DQD for primary protection and an Analog Quench Detection (AQD) circuit for redundant protection. The quench detection system also provides the trigger to open the relays that connecting the power system to the magnet bus and ramps down the supply. A resistor in parallel with the output of the power system will generate enough voltage to turn on the cold diodes if the relays are opened at currents above ~25 A at 4.5K. Spot heaters were installed on the inner bore of the MICE CC to initiate a quench for verifying the operation of the quench protection system at low current. Figure 4 shows a heater induced quench at 46A while ramping at 0.010A/s.

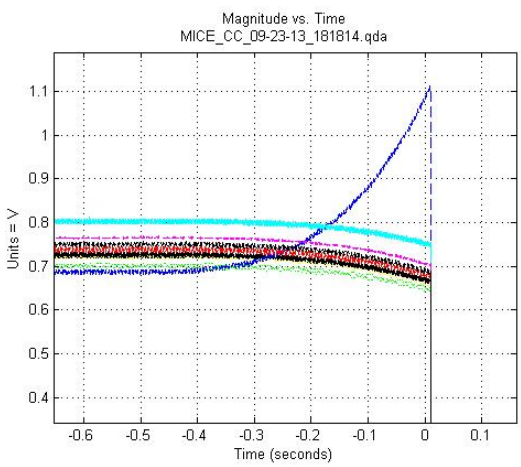

Figure 4: Heater Induced Quench of MICE CC at 46A. Coil 1, closest to the heater, quenched.

COOL DOWN AND TEST RESULTS

The MICE CC cool down is restricted to a 50K difference between the coldest and warmest coils. Since there are no temperature sensors on the coils, the resistance of the coils was monitored during cool down. This was accomplished by exciting the magnet with a trickle current of 10mA to 100mA while all eight coil voltages were monitored by the cryo monitoring scans. The calculated resistances were converted to temperatures based on resistance to temperature calculations provided by LBNL. Figure 5 shows all eighth coils transitioning to the superconducting state.

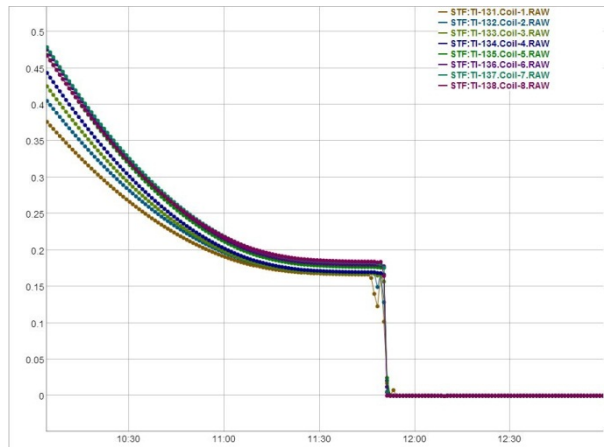

Figure 5: Plot of all MICE CC eighth coil voltages with 100mA current excitation during final cool down. The transition to the superconducting state is clearly seen.

The first ramp to quench occurred at 63A. Further analysis showed that the eighth coil #1 voltage signal rose to the threshold level in ~0.25ms. This was not a slow resistive growth but rather a voltage spike indicative of some coil motion.

SUMMARY

A new Solenoid Test Facility (SolTF) was built at Fermilab for testing conduction cooled superconducting magnets with large fringe magnetic fields. The facility was built in the Fermilab's Central Helium Liquefier (CHL) building since it had adequate space, liquid helium availability, and access to a crane for staging the magnets.

The Muon Ionization Cooling Experiment (MICE) Coupling Coil is the first magnet to be tested in this facility. The coil was recently cooled down and power tests have begun. A prototype capture solenoid coil built by Toshiba Corporation will be tested next. A mu2e prototype transport solenoid is expected to be tested next year.

REFERENCES

[1] R. Rabehl et al. To be published in Advances in Cryogenic Engineering, Volume 59.

[2] Jerzy Nogiec et al. "Software System for Monitoring and Control at the Solenoid Test Facility", submitted at the 14th International Conference on Accelerator & Large Experimental Physics Control Systems, ICALEPCS 2013, San Francisco, October 2013.

[3] R. Pilipenko et al., "An FPGA-Based Quench Detection and Continuous Logging System for Testing Superconducting Magnets", FERMILAB-PUB-12-546-TD, Oct 2012.