Improvements and Performance of the Fermilab Solenoid Test Facility

Darryl Orris[6], Don Arnold[1], Jeffrey Brandt[1], Sergey Cheban[3], Daniel Evbota[1], Sandor Feher[1], Artur Galt[2], Steven Hays[5], Ali Hemmati[2], Charles Hess[2], James A. Hocker[1], Min Jeong Kim[4], Lidija Kokoska[2], Sergey Koshelev[2], Sergey Kotelnikov[2], Michael Lamm[1], Mauricio L. Lopes[1], Jerzy Nogiec[2], Thomas M. Page[1], Roman Pilipenko[3], Roger Rabehl[2], Cosmore Sylvester[2], Michael Tartaglia[2], Antonios Vouris[2]

***Abstract*— The Solenoid Test Facility at Fermilab was built using a large vacuum vessel for testing of conduction-cooled superconducting solenoid magnets, and was first used to determine the performance of the MICE Coupling Coil [1], [2]. The facility was modified recently to enable testing of solenoid magnets for the Mu2e experiment, which operate at much higher current than the Coupling Coil. One pair of low current conduction-cooled copper and NbTi leads was replaced with two pairs of 10 kA HTS leads cooled by heat exchange with liquid nitrogen and liquid helium. The new design, with additional control and monitoring capability, also provides helium cooling of the superconducting magnet leads by conduction. A high current power supply with energy extraction was added, and several improvements to the quench protection and characterization system were made. Here we present details of these changes and report on performance results from a test of the Mu2e prototype Transport Solenoid (TS) module. Progress on additional improvements in preparation for production TS module testing will be presented.**

***Index Terms*— Magnet, Mu2e, Solenoid, Test Stand.**

I. Introduction

THE Solenoid Test Facility (SolTF) [3] was selected for testing the superconducting prototype Transport Solenoid (TS) for the Muon-to-Electron (Mu2e) Experiment at Fermilab [4]. This facility was originally designed to test the superconducting Coupling Coil solenoid for the Muon Ionization Cooling Experiment (MICE) [2]. SolTF was well suited to support the testing of Mu2e Transport Solenoid coil modules [5] since its vacuum cryostat was large enough to accommodate the magnets and the facility could provide the required cryogens for cooling the magnet and superconducting leads to their cryogenic operating temperatures (~5 K). SolTF included a cryogenic monitoring and controls system, a quench protection system, and fast data logging for magnet quench characterization. This facility was also designed to accommodate the large magnetic fringe fields of these solenoids. There were, however, several necessary upgrades in order to meet the new requirements for carrying out the TS magnet tests. These upgrades include a new mechanical support structure, a higher current power system with energy extraction (the MICE coupling coil required 220 A), a new set of high current power leads, and DAQ modifications for the additional instrumentation and controls required for cooling leads and testing the TS magnet. In addition, this test facility also provided the opportunity to implement the quench protection and power system interface, which was being developed for the Mu2e experiment.

II. Test Stand Modifications

A. Magnet Test Objectives

The primary purpose of the prototype TS test was to establish verification of the coil module design as early as possible to allow procurement of production coil modules to begin. This would be carried out via the following test objectives [6]:

- Verify coils can hold a test current up to 2100 A with coils powered in the same magnetic polarity
- Reverse the magnetic polarity of one of the coils and power to 1040 A
- Characterize the thermal performance of the conduction cooled magnet with and without the use of heaters to simulate the heat flow expected from the Transport Solenoid mechanical supports.
- Perform quench propagation studies using heaters located in the coils and acoustic sensors [7] located in the support shell.

B. Magnet Test Stand Requirements

The prototype Transport Solenoid magnet consists of two superconducting coils integrated into an aluminum shell for structural support and precise coil positioning [5]. Coil cooling is achieved by conduction from forced flow of liquid helium through tubing welded to the aluminum shell. The coil to ground hi-pot requirement with the shell grounded is 2 kV with a leak rate < 10 μA. The following list summarizes the most important test stand requirements necessary to meet the TS magnet test objectives:

- The coil assembly must be sufficiently supported

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1. Magnet Systems, Fermilab, Batavia, IL, United States.
2. Test & Instrumentation, Fermilab, Batavia, IL, United States.
3. SRF Development, Fermilab, Batavia, IL, United States.
4. ND Technical Support, Fermilab, Batavia, IL, United States.
5. AD EE Support, Fermilab, Batavia, IL, United States.
6. Darryl Orris is with Test & Instrumentation, Fermilab, Batavia, IL, United States (email: orris@fnal.gov).

within the test cryostat to sustain lateral and vertical forces when ramping and quenching the coils.

- The cold mass assembly is conduction cooled by forced helium flow through the cooling tube. The test facility must provide helium supply and return lines to connect to the cooling tube.
- The maximum temperature difference between any coil and the aluminum shell must be controlled to limit it to 23 K during cool-down and warm-up.
- The test facility must provide a 1 psig two-phase helium supply up to 10 g/s (200 W conduction cooling capacity), sufficient to overcome the system heat loads, the test cryostat heat loads, and AC losses during coil charging and discharging.
- Two pairs of high temperature superconducting (HTS) current leads will be used to power the magnet. The test stand must supply a regulated flow of liquid nitrogen and liquid helium to the HTS leads. Each HTS lead will transition with a splice joint to one of the Prototype Transport Solenoid coil leads.
- Two pairs of low temperature superconducting (LTS) magnet leads (one pair per coil) to be conduction cooled by thermal contact with tubing carrying a flow of liquid helium and must remain superconducting at the maximum operating current of 2100 A.
- The quench protection system must monitor voltages across the coil and coil leads and trigger the power supply to shut down and initiate the energy extraction system when the voltage threshold limit is exceeded.
- A power system is required that can deliver up to 2.1 kA DC.
- A 500 kJ energy extraction (dump) circuit is required.

C. Test Stand Cryogenics and Cryogenic Modifications

The cryogenic system [1], [8] used to test the first coupling coil solenoid of the Muon Ionization Cooling Experiment (MICE) was modified to test the Mu2e prototype Transport Solenoid (TS) module. A pair of conduction-cooled copper current leads was replaced with two pairs of HTS power leads. The HTS power leads were previously purchased from American Superconductor (ASC) for the Fermilab Tevatron [9], [10]. A second helium circuit was added to the test stand piping to cool the LTS bus connecting the HTS power leads to the magnet. A liquid nitrogen (LN2) circuit was added to the test stand to cool the upper sections of the HTS power leads. The LN2 was supplied from a 189,000 liter (50,000 gallon) storage dewar.

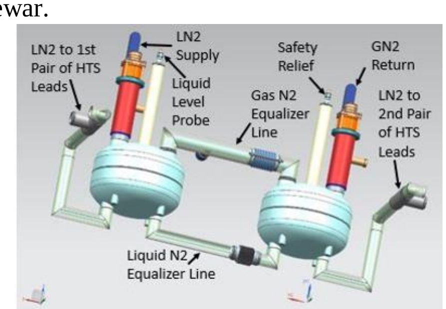

Fig. 1. Phase separators used to supply LN2 to the HTS power leads.

Two small phase separators were placed at the test stand, close to the HTS power leads, to ensure that good quality LN2 was supplied to the power leads. The phase separators were operated with a supply valve controlling the liquid level and a backpressure regulator controlling the pressure so that the HTS sections of the power leads were no warmer than 85 K. A model of the phase separators assembly is shown in Fig. 1. Each phase separator consists of a 0.273 m (10.75 in) diameter LN2 vessel inside a 0.324 m (12.75 in) diameter vacuum vessel. The LN2 volume per vessel is 4.8 l.

The cryostat did not have a thermal shield, so a custom thermal shield was built around the magnet. The shield consisted of an aluminum rib cage around the magnet and aluminum shield boxes around the magnet supports. Forty layers of multilayer insulation (MLI) were then applied in five-layer blankets. Cooling was provided by the helium gas returning from the magnet. This approach is identical to what was successfully used for testing the MICE coupling coil [8]. A model of the installed thermal shield is shown in Fig. 2.

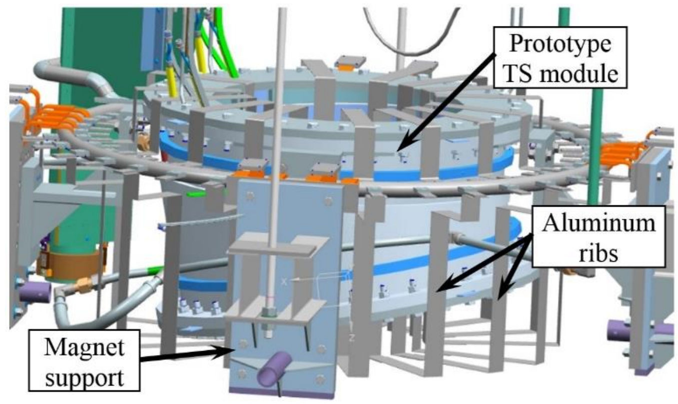

Fig. 2. A 3-D model of the Mu2e prototype TS module with custom thermal shield components.

D. Cryogenic Monitoring and Controls

The Cryogenic Controls and Monitoring system used to test the Mu2e prototype TS module was based on National Instruments' CompactRIO with LabVIEW operator interfaces. Precision measurements of cryogenic sensors such as RTDs, HTS lead voltage, and magnet current were performed by a Keithley 3706A high performance DMM/Switch system, which is controlled by the CompactRIO over USB. Separate interface screens were used for the magnet helium circuit and the power leads circuits (helium and nitrogen). Functionalities included process monitoring, PID control loop interfaces, valve control, and alarm and interlock indications. A screen capture of a typical operator interface can be found elsewhere [1].

E. Quench Protection and Data Acquisition

The quench protection system architecture [11] is based on National Instruments' CompactRIO and includes both primary and redundant quench detection components. The primary Digital Quench detection component is implemented on the C-RIO's FPGA backplane and the redundant Analog Quench detection component is implemented via discrete hardware modules. The quench protection system was upgraded to include redundant analog quench detection for the coils since the original system used to test the MICE magnet relied on passive diode protection as the redundant system. This system protects the coil, the HTS leads, the low temperature SC power leads, and the copper lead sections of the HTS power leads. Software Quench Detection (SQD), which measures the HTS leads voltage with a DMM (1 LC of integration), was implemented in the Cryo Monitoring and Controls system to provide redundant protection for the HTS leads. Some signals are bucked to improve quench signal sensitivity. For instance, the magnet whole coil voltage is bucked against the derivative of the current (Whole Coil – dI/dt), which increases the sensitivity to resistive voltage growth. In addition, the number of quench characterization channels were increased and the slow logging capability was disabled. The quench detection threshold voltages are listed in TABLE I.

TABLE I

COIL AND LEAD QUENCH DETECTION THRESHOLDS

Quench Signal	Threshold Voltage
Whole Coil	1.0 V
Whole Coil – dI/dt	500 mV
Bucked Half Coils	400 mV
Copper Leads	40m V
Bucked HTS Leads	1.5 mV
LTS Leads	10 mV
HTS Leads (SQD)*	1 mV

F. Power System and Current Bus

The power supply system consists of two elements, the power converter and an energy extraction system. The power supply is a 50 kW current source that is capable of providing 0-20 V @ 0-2500 A as needed. This power supply system was used on the Tevatron Electron Lens system and is a good match for the Mu2e experiment Transport Solenoid Magnets. The only power system changes between Mu2e TS prototype test stand and the Mu2e TS power system for the experiment is an increase in the required power level of the dump resistor. In operation of the Mu2e experiment this system is expected to operate for an extended period of time at 1730 A DC with a repeatability of 100 ppm. In the test stand the power system is being used to verify each element of the magnet system before being assembled into a magnet. During these tests the magnet system is expected to be tested beyond the normal operating current and may be ramped many more times than in normal operation.

G. Power Supply

The power supply was constructed by Inverpower Controls Ltd. Toronto in 1990 and used for 22 years. It is constructed using a Type 31 transformer with two full-wave bridges connected in parallel using an interphase transformer. The Electron Lens needed a higher level of control and regulation, so the voltage regulation electronics were replaced with a Fermilab design used in many other applications. The output filter was also replaced with a damped resonate filter that allows for higher speed ramping while still attenuating the 720 Hz output structure to -40 db. The power supply control circuits were replaced with a PLC to improve maintainability. The current regulation system was replaced with a newer analog system for use in the test stand. The Mu2e magnet system will use a new digital current regulation system during the experiment operation. The power supply and energy extraction circuit are shown in Fig. 3.

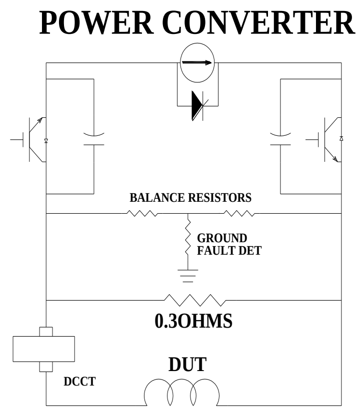

Fig. 3. Power Supply and Energy Extraction (Dump) circuit

H. Dump Switch

Redundant energy extraction (dump) switches (Fig. 4) are required for all superconducting magnet systems. There are two semiconductor switches installed in series with the power supply output terminals. This allows for a complete disconnect between the power supply and the magnet. The dump resistor is connected to the magnet at all times and because this is a static DC system the current conducted into the resistor is minimal. The magnet system is ramped very slowly during operation so the LdI/dt voltage is small and therefore the current in the resistor is also small. The magnet current is monitored by a DCCT that is connected between the dump resistor and the magnet so that the current in the magnet is always monitored. This signal provides the current feedback to the current regulator and is also sent to the quench protection system. Independent hardware over-current detection is provided in the power supply to back up the DCCT.

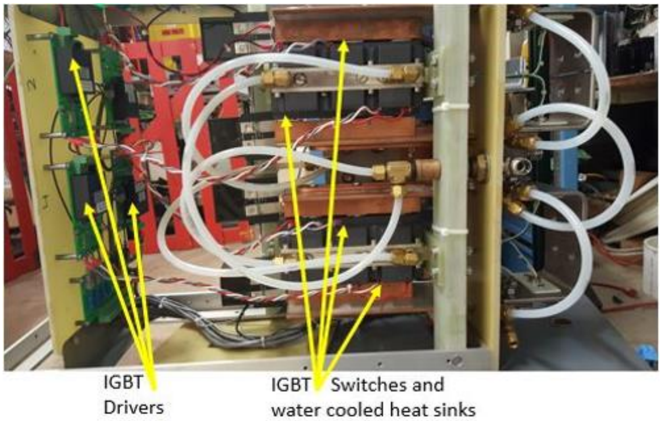

Fig. 4. Energy Extraction (Dump) switch

The dump resistor is set to a value that represents the LdI/dt voltage expected by the magnet elements in the full TS production magnet. The nominal dump resistance for the Transport Solenoid is 0.3 Ohms; however, 0.019 Ohms was used for the two module test. The magnet circuit is hi-potted to verify isolation to ground. The current is carried in parallel cables between the power system and magnets. A 4800 µF capacitor is connected in parallel to the dump resistor near the magnet. The capacitor filters voltage spikes caused by the inductance of the resistor and cable during energy extraction.

Each dump switch is capable of disconnecting the power supply from the magnet load. In order to verify the correct operation of the dump switches we turn off one switch and verify that the voltage rises across the switch then 30 msec later we turn off the other switch. On the next dump we turn off the other switch first to verify that both switches are operational. To prevent a single point failure in the dump system the dump resistor is divided into four elements and cabled with four cable pairs. This is so that a single element or cable connection cannot cause an open circuit that would cause excessive voltage on the magnet elements.

The junction temperatures in the semiconducting devices are held at 80 ^{0}C in order to maintain high reliability. This requires that two IGBTs are operated in parallel to manage the temperature. The IGBTs also have an emitter resistor to help force shared current in the parallel devices. The temperatures of these resistors are monitored for reliability; if the temperature in each resistor is not hot enough then it is assumed that only one IgBT is conducting.

III. Test Stand Performance

A. Cryogenic Operations

Fig. 5 shows maximum coil temperature and minimum shell temperature vs. elapsed time for a typical controlled cool-down of the Mu2e prototype TS module. This was achieved by mixing liquid helium and helium gas to maintain a constant 23 K ΔT between the maximum coil temperature and the helium supply temperature to the magnet.

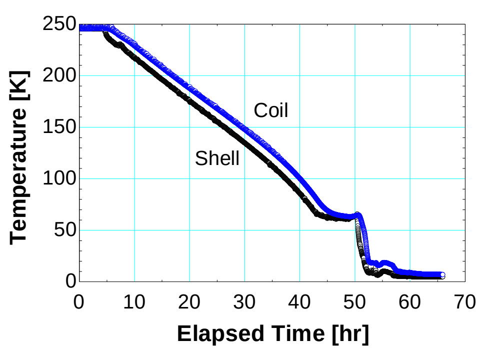

Fig. 5. Maximum coil temperature and minimum shell temperature vs. elapsed time during a controlled cool-down of the Mu2e prototype TS module.

The static heat load to the magnet was determined using the rate of temperature rise of the magnet shell and the magnet coils after the cooling flow was turned off. The resulting calculation showed a 4.5 W static heat load as shown in Fig. 6.

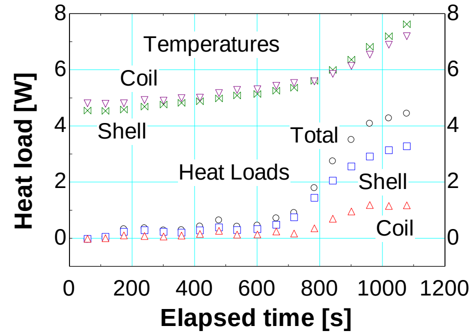

Fig. 6. Temperatures and calculated heat loads vs. elapsed time during a static heat load test of the Mu2e prototype TS module.

B. HTS Power Leads and LTS Current Bus

The HTS and copper sections of the HTS power leads were cooled by LN2 only. Although the power lead design included a He cooling path, it was found to be not vacuum-tight as required for a conduction-cooled operations mode and was therefore left open to the insulating vacuum space.

The HTS-LTS junctions as well as the LTS buswork connecting the four power leads to the magnet were cooled by a LHe series flow. Each HTS-LTS junction was cooled by a copper block soldered onto the bottom of the power lead. The copper block had a machined internal flow passage for LHe cooling. The LTS bus sections were cooled by mechanically clamping them to the flat surface of D-tubing.

All four of the HTS power leads and three of the four LTS bus sections were sufficiently cooled to allow power testing up to the 2,200 A power supply limit. One of the LTS sections was only marginally cooled and limited the test current to 1.9 kA. The coil without the lead limitation was powered independently to 2.2 kA. Possible reasons were insufficient thermal conductance of the LTS/D-tube clamped joint or insufficient stabilizer continuity between the etched LTS cable and the copper block mounted on the end of the HTS power lead. Note that the longest section of uncooled lead was 1 m.

The HTS leads were previously tested in a 0.3 T field at 10 kA without performance degradation. The stray field in this application was much less; no HTS lead quenches occurred.

C. Magnet Test Performance

The magnet was successfully cooled down and power tested up to 2200 A. Details of the Mu2e prototype TS magnet tests are published in another paper [6].

IV. Conclusion

The Fermilab Solenoid Test Facility was upgraded to meet the requirements for testing a Mu2e prototype Transport Solenoid. A 2.2 kA power supply and an energy extraction circuit were installed with two pairs of high current HTS leads. The coils and LTS leads were conductively cooled. The TS magnet was successfully tested and met all of the test objectives.

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