Operational Experience with the MICE Spectrometer Solenoid System

S. Feher, A. Bross, P. Hanlet

Abstract—**The Muon Ionization Cooling Experiment located at Rutherford Appleton Laboratory in England utilizes a superconducting solenoid system for the muon cooling channel that also holds particle tracking detectors and muon absorbers inside their bores. The solenoid system installation was completed in summer of 2015 and after commissioning the system it has been running successfully. This paper summarizes the commissioning results and operational experience with the magnets focusing on the performance of the two Spectrometer Solenoids built by the US.**

Index Terms— **Spectrometer Solenoid Magnet, Superconducting, Commissioning, Operation**

I. Introduction

THE primary goal of the Muon Ionization Cooling Experiment (MICE) [1] located at Rutherford Appleton Laboratory (RAL) is to demonstrate muon cooling, the key element for accelerating and storing s muon beam for high energy muon accelerators [2]. The cooling channel of the muon beamline utilizes a superconducting solenoid system that also holds particle tracking detectors and muon absorbers inside their bores. MICE is planned to be operated in stages. Each stage has a different number of magnet modules. Stage 4 is the current configuration of MICE, shown in Fig. 1. It contains two Spectrometer Solenoid (SS) modules – upstream (SSU) and downstream (SSU) – and a single Absorber Focus Coil (AFC) module.

The solenoid system installation was completed in the summer of 2015 and, after commissioning, the system has been running successfully. This paper summarizes the commissioning results and operational experience of the US built SS magnets focusing on quench performance and the description of the magnet protection system that was upgraded during the commissioning phase.

II. Preparing a Manuscript

The Spectrometer Solenoid [3] cold mass contains five coils wound from heavily stabilized (Cu/Su 4:1) NbTi strand on a single aluminum bobbin: two coils (M1 and M2) in the matching section and three coils (E1, C, E2) in the spectrometer section, as shown in Fig. 2.

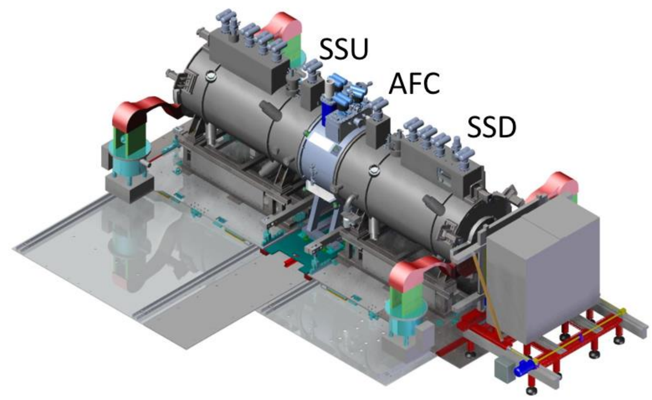

Fig. 1. MICE Stage 4 configuration.

The spectrometer solenoid vacuum vessel is 2735 mm long with a 1404 mm outside diameter. On top of the round vacuum chamber is a service turret that contains 5 two stages PT-415 pulse tube coolers. Each cooler develops 50 W at 55 K on the 1st stage and 1.5 W at 4.2 K on the 2nd stage. The current leads are bi-functional leads: 600 A and 60 A copper and HTS leads. As built parameters of the spectrometer Solenoids are summarized in Table I. For Cryostat details see [6].

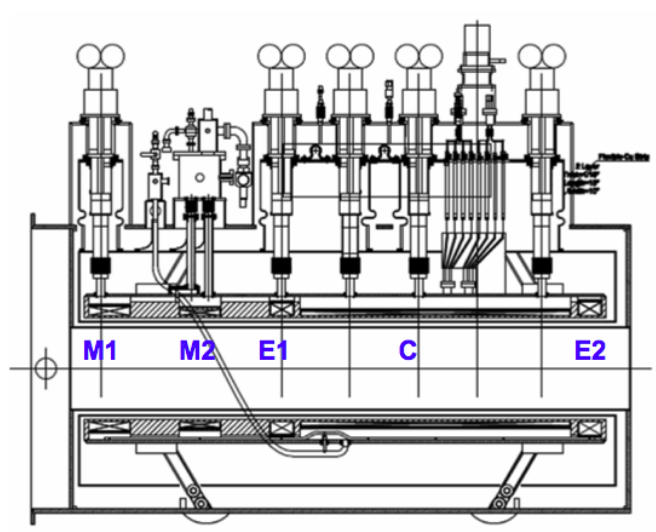

Fig. 2. Spectrometer Solenoid.

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The powering scheme that was utilized at the beginning of the commissioning phase is shown in Fig. 3. Three circuits are driven with five power supplies. M1 and M2 are powered separately. E1, C, and E2 are powered in series with a main power supply and there are two trim power supplies across the two end coils. Since the chosen TDK Lambda and Lake Shore power supplies are two quadrant designs, absorber diodes are used to control the current ramp at both up and down ramp current directions.

Initially the magnet protection was based on an internal dump circuit (diode pack - cold diodes - and internal dump resistors). The coils are self-protected, meaning once the quench starts the coils dissipate their stored energy. The primary purpose of the Quench Protection System (QPS) [4] was to detect the quench and open the contactors to force the current into the internal dump system. Since the coils are on the same aluminum mandrel, if one coil quenches eventually all the other coils will quench through the mandrel. The QPS also protects the HTS leads and a good fraction of the superconducting buses (LTS). Once the quench is detected in the LTS or HTS sections, the QPS will open the contactors which re-directs the current from the quenched sections into the internal dump circuit. Due to the heating of the internal dump resistor, eventually the coils will quench and the stored energy is dissipated. A symmetric voltage based Active Ground Fault Detection (AGFD) system was also used to indicate a ground fault in the circuit.

TABLE I
SPECTROMETER SOLENOID PARAMETERS

	M1	M2	E1	C	E2
Inner Coil Radius (mm)	258	258	258	258	258
Coil Thickness (mm)	46	31	61	22	68
Coil Length (mm)	201	199	110	1314	111
Coil Average J (A/mm^2)	137	148	124	147	127
Number of Layers per coil	42	28	56	20	62
Number of turns per coil	115	114	64	768	64
Design Current (A)	265	285	234	275	240
Coil Self Inductance (H)	12	5	9	40	11
Coil Stored Energy (MJ)	0.42	0.20	0.26	1.55	0.32
Peak Field in Coil (T)	5.30	4.30	5.68	4.24	5.86
Temperature Margin at 4.2 K (K)	-1.6	-1.8	-1.5	-2.0	-1.5

Inductance of the two end coils and the center coil in series is about 74 H.

III. COMMISSIONING OF SSU AND SSD

Initial commissioning of SSU and SSD was done in summer and fall of 2015 at RAL. Cool down related experience and the mechanical behavior of the magnets due to electromagnetic forces among the magnets and the iron yoke are described elsewhere [5,6].

A. Cold Electrical Checkout

Prior to powering the magnets, the power supplies were disconnected, and high voltage withstand tests were performed. Both SSU and SSD coils were not able to withstand higher than 250 V. Since the peak coil to ground voltage inside the coil during a high current quench is close to 1600 V, it was obvious that we could not fully qualify the magnets for safe operation with respect to possible ground fault at higher than 250 V.

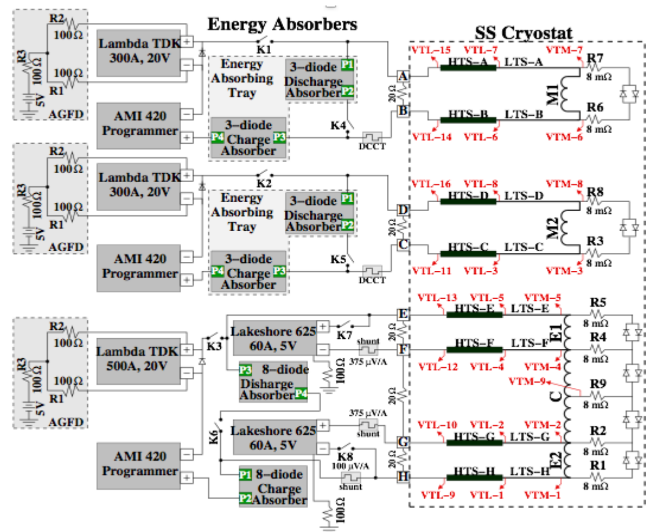

Fig. 3. Spectrometer Solenoid Powering Circuit.

Voltage taps continuity checks were also performed. It was found that one of the SSD M2 coil voltage taps (VTM-5) and the SSD C coil center tap (VTM-9) were not connected. These V-taps were marked as already missing at the manufacturing site and shown in the traveler of the magnet.

B. Quench Training

At the initial powering of SSU M1 coil we observed a strange oscillation of the power supply. Further investigation revealed that the power supply was short circuited. In the vacuum space below the feedthroughs each HTS lead is connected with two copper leads. Accidently, one of the cables was connected to the opposite polarity. This repair work delayed the quench test by about a month. After the repair work, full warm electrical checkout was performed, and we found no performance issues with the magnet. Cold HV to ground test results remained the same as before, stable until ~250 V.

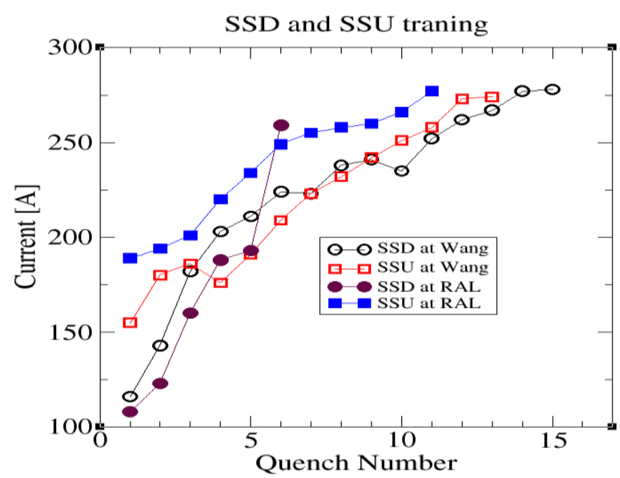

Fig. 4. Quench Training of SSU and SSD. After the last quench of SSD the M1 circuit was opened.

The SSD and SSU quench training procedure was the same as their training procedure at Wang NMR. By refilling the cold mass with liquid helium right after the quench it was possible to quench the magnets twice a day, thus reducing the training time significantly.

The quench training history is shown in Fig. 4 with the quench history of the magnets from previous quench training campaigns done at Wang NMR. SSU trained similarly as before. SSD training history up to the 5th quench was also similar to that at Wang NMR. The 6th ramp to quench ended up with a spurious noise related trip that also eventually quenched the magnet. Before the 6th spontaneous quench we decided not to power M2. Due to a missing M2 coil V-tap it was considered that the protection of the LTS section was not safe, since we were not able to lower the detection voltage threshold value to the desired 20 mV range.

The 6th quench of SSD occurred at a much higher current value than expected. This could have been related to the lower external forces on E1, C, E2 coils since the adjacent M2 coil was not powered. After this quench we observed a strange smell in the MICE experimental hall, an indication that plastic was burned.

Further investigation revealed (see Fig. 5): i) That the M1 circuit was open ii) one of the M1 lead was shorted to ground and between the two M1 leads the resistance was 5.7 kΩ iii) between the M2 and M1 lead the lowest resistance was 2.6 kΩ.

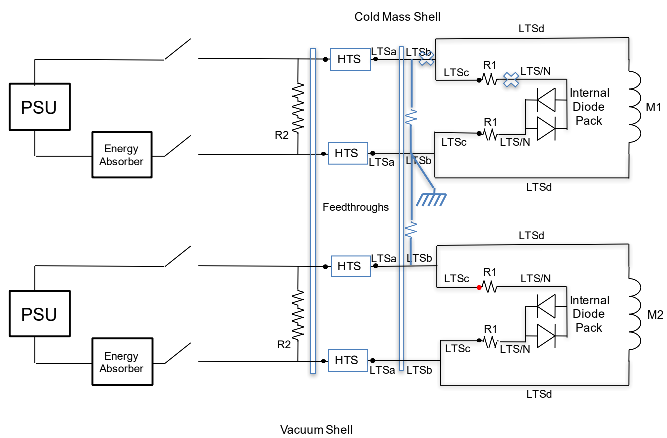

Fig. 5. M1 and M2 circuits after quench number 6.

C. *Failure Analysis*

In Fig. 6 a regular quench event with M1, M2 and EC coil voltage signal development is shown after a quench occurred at 280 A. The polarity was chosen, so that the coil voltages prior to the quench during current up-ramp are all positive. Once the quench triggered the opening of the contactors, the current was forced inside the internal dump circuit, consequently the polarity of the voltage signal has reversed. The voltage spikes right after the opening of the contactors are due to the higher opening voltage of the cold diodes, that are estimated to open between 4-6 V. The cold diode junction warms up very rapidly so the absolute value of the voltage will experience a sudden decrease and if one compares the voltage difference between the M1/M2 and EC voltage signals at this stage, one can estimate the diode voltage value and the resistance value of the cold dump and any additional circuit resistances. The diodes voltage values were estimated to be ~1.2 V.

Following the evolution of the voltage signals, it can be seen that the EC coil has quenched first (we already knew this by analyzing the pre-quench part of the voltage traces), since the

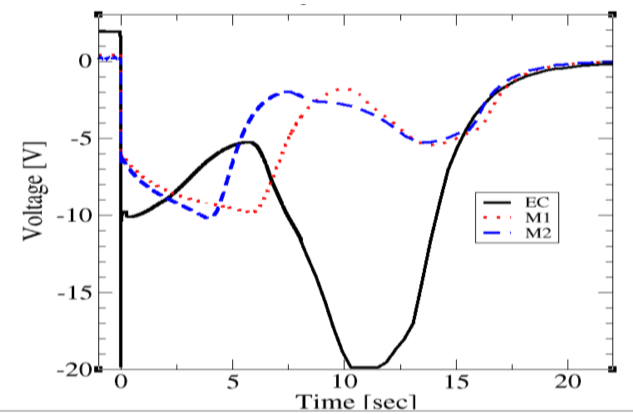

Fig. 6. SSU Training quench at 280 A taken at RAL.

absolute value of the voltage decrease almost instantly related to the fact that the current value is decreasing, and the measured voltage is driven by the dump resistors. On the other hand, if the current is not decreasing, the dump resistor starts to warm up so the absolute value of the voltage will increase, as it can be seen by M1 and M2 coil voltage evolution. When M1 and M2 voltage values start to decrease, it means that the coil has quenched, and the current started to decrease rapidly; faster than the resistor is warming up.

Additional rise of the absolute value of the coil voltages before the final decrease to zero volt is related to low current values flowing through the diodes, allowing the diode to cool back

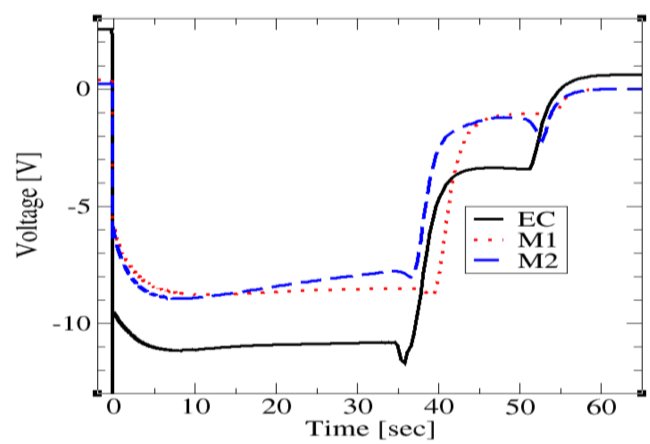

Fig. 7. SSU trip event at 250 A.

to low temperatures.

Fig 7 shows voltage traces for a current ramp that ended up with the trip at 250 A. M1, M2 and EC did not experience spontaneous quenches, their voltages rose after the quench, that is a clear indication of dump resistor heating until eventually all three coils quenched. The estimated peak temperature of the dump resistor was ~600 K.

On Fig. 8 two SSD high current ramp voltage signal traces are shown: a spontaneous and a trip related quench event. q5 occurred first, followed by the trip event. The two event current values were similar: M1 current for q5 was 198 A and for the trip event it was 195 A. It can be seen that q5 was a regular quench but the trip event was completely different: the absolute value of the M1 voltage rose to 14 V, 6 V higher than q5 M1 voltage and EC circuit quenched about the same time as M2.

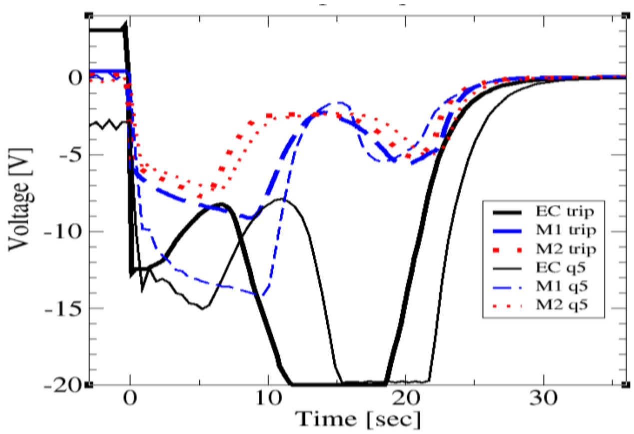

Fig. 8. SSD coil voltage signal evolution for quench number 5 and the trip event that occurred after q5. Current value for M1 for q5 event was 198 A and for the trip event was 195 A.

Interestingly, M1 quench delay was about the same for the two events. M1 trip event voltage rise clearly shows that there was an extra resistance in the circuit besides the dump resistor. This extra resistance has increased the power dissipation significantly.

This trip event was a precursor to a possible coil failure, however, it was not noticed, since at the time, only a pre-quench analysis was performed after each quench to determine which coil quenched or to find out that it was only a trip event.

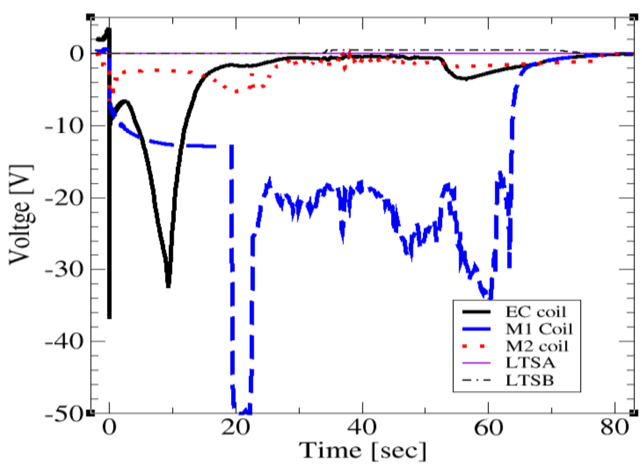

Fig. 9. q6 coil voltage signal evolution is shown.

In Fig. 9 q6 coil voltage signal evolution is shown. In this current ramp M2 was disconnected. First EC quenched and 20 seconds later M1 experienced a very high voltage (50 V is the data logger maximum voltage) rise. The most plausible explanation: first the internal dump circuit opened, and the voltage drop on the external $R_2 = 20\ \Omega$ resistance across the current lead terminals would have been too high (~5 kV) and an arc started between the leads at the vacuum end flange side. This arc evaporated a small section of the lead and at about 30 seconds after the quench, connection to ground appeared. This can be shown by the voltage signal occurring on LTSB lead voltage segment; the LTSB voltage segment is between the lower end of the HTS lead and at the resistor side of the dump circuit. This hypothesis requires an additional ground connection being developed at the dump circuit region where the M1 circuit first opened.

This analysis points strongly to a lack of manufacturing quality control during the fabrication of the internal dump circuit. A possible weak point was too resistive, and it overheated beyond the melting point of the metal.

IV. Upgrade of the Quench Protection System

To avoid additional failure, the QPS has been upgraded (see Fig 10 for the general concept of the upgrade). The following changes has been implemented:

- External Dump Circuit has been added to avoid using the internal dump. The dump resistor (R_2) value was lowered to limit the dump voltage below 150 V.
- U_{coil} - k*dI/dt detection based protection system for M1 and M2 has been added.

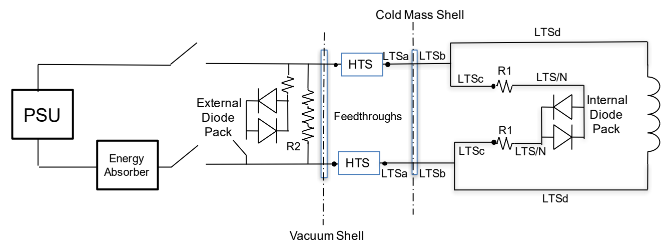

Fig. 10. Upgrade of QPS.

This new protection scheme allowed us to optimize the protection of the coil circuits to all the scenarios that can occur: i) normal quench – main contactor opens, ii) HTS or LTS quench – main contactor opens and additionally the External Dump contactor opens redirecting the current to the internal loop to protect the leads, iii) ground fault failure treated as regular quench event, iv) emergency trip is treated as normal quench event.

We have also implemented additional adjustable quench validation time constraints to detect the quench to avoid spurious trips that occurred during the initial operation of the magnets. Since these changes have been introduced the MICE experiment was running successfully collecting lot of useful data. SSD was running with reduced current (less than the last quench current the magnet experienced) and without operating SSD M1 coil.

V. Conclusions

Operational experience of the MICE Spectrometer Solenoid System operated at RAL was described focusing on quench performance. Failure of the SSD M1 coil was analyzed and shown that the most likely scenario for the failure was due to poor manufacturing quality control. To avoid a similar failure, the QPS has been upgraded.

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