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Quench Analysis of MICE Spectrometer Superconducting Solenoid

Vladimir Kashikhin, Alan Bross, Soren Prestemon

Abstract— **MICE superconducting spectrometer solenoids fabrication and tests are in progress now. First tests of the Spectrometer Solenoid discovered some issues which could be related to the chosen passive quench protection system. Both solenoids do not have heaters and quench propagation relied on the "quench back" effect, cold diodes, and shunt resistors. The solenoids have very large inductances and stored energy which is 100% dissipated in the cold mass during a quench. This makes their protection a challenging task. The paper presents the quench analysis of these solenoids based on 3D FEA solution of coupled transient electromagnetic and thermal problems. The simulations used the Vector Fields QUENCH code. It is shown that in some quench scenarios, the quench propagation is relatively slow and some areas can be overheated. We describe ways of improving the solenoids' quench protection in order to reduce the risk of possible failure.**

***Index Terms*— Superconducting solenoid, Magnetic field, Thermal analysis, Quench, 3D simulations.**

I. INTRODUCTION

THE MICE experiment [1] magnet system is based on superconducting solenoids. Two Superconducting Spectrometers [2] should be fabricated and tested in US before the delivery to RAL.

The solenoid design explores technical solutions widely used for MRI solenoids: cooling by cryocoolers, HTS current leads, passive quench protection system, efficient cold mass supports, etc. Nevertheless, large magnetic field and stored energy push these magnets close to critical parameters. Several issues were observed during Spectrometer tests [3-5]. The analysis was complicated because voltage taps signals were not monitored during the solenoid training. To reduce the risk of possible future failures, it was decided to make the solenoid quench performance analysis with 3D simulations by OPERA3D QUENCH code [6]. This code calculates the 3D transient magnetic field (code ELEKTRA) coupled with the 3D thermal analysis (code TEMPO). The main reason of using these codes is the complicated electromagnetic response of multi-coil magnet system where the quench propagation entirely relies on the "quench back" effect.

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II. SPECTROMETER SOLENOID

The Spectrometer solenoid consists of six coils wound on the slotted aluminum 6061 bobbin (See Fig. 1). Each coil has 1 mm thick ground insulation on the inner surface, and 3.2 mm on both sides. To avoid coil separation from the mandrel under Lorentz forces, the Al bandage is wound on top of each coil under tension. Solenoid assembly is mounted inside of the LHe vessel used for the solenoid bath type cooling.

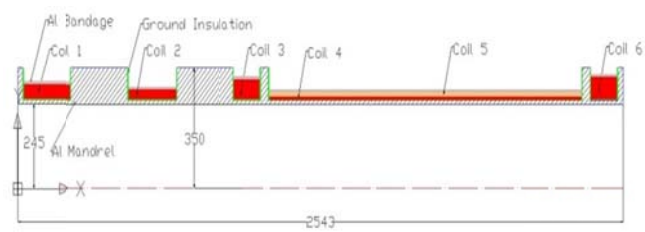

Fig. 1. Solenoid cross-section. All dimensions are in mm.

A. Solenoid Geometry and Parameters

Two superconducting solenoids were fabricated and tested by WANG NMR [2-5]. Spectrometer solenoid parameters which were used in the simulations are shown in Fig. 2 and Table 1.

TABLE I SPECTROMETER SOLENOID

Parameter	Unit	Value
Peak operating current	A	275
Coil peak field	T	5.8
Solenoid length	mm	2544
Bore radius	mm	257
Number of coils		6
Total number of turns		30934
NbTi superconductor dimensions	mm	0.955x1.6
Cu:Sc ratio		4.0
Critical current at 5 T, 4.2 K	A	760
Cu RRR		70
Number of filaments		222
Filament diameter	μm	41
Inductance (all coils in series)	H	78
Total stored energy	MJ	3.0

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B. Solenoid Model for Quench Simulations

Quench analysis of most superconducting magnet system followed approach described in [7] by M.N. Wilson. The role of "quench back" effect for the MICE solenoid was investigated in [8]. The simulations were based on predetermined from other solenoids experimental data on the quench propagation velocity. This velocity is strongly correlated with the Al mandrel heating by the currents induced during quench. The 3D QUENCH code [6] is capable to simulate the more realistic quench propagation, and the influence of eddy currents on the "quench back" effect. The electrical circuit used in the simulations is shown in Fig. 2.

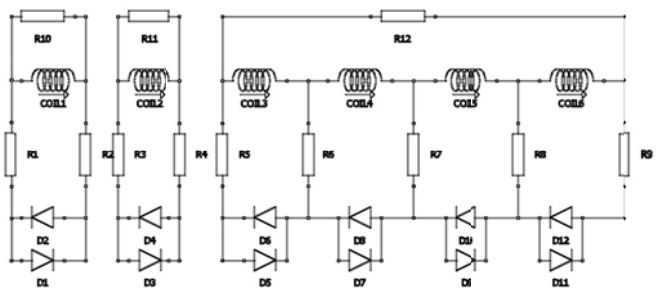

Fig. 2. Solenoid electrical circuits. D1-D12 – cold diodes, R10-R12 – 1 Ω external resistors, R1-R9 – 15 mΩ shunt resistors.

The solenoid is protected by a passive quench protection system formed by 12 cold diodes, and 9 shunt resistors. During quench, for example, in the Coil 1, the normal zone propagates in this coil with the corresponding resistance grows. As soon as the coil voltage reaches 4 V the cold diodes open, and the Coil1 current decays, flowing through R1-R2 shunt resistors. These resistors limit the coil voltage and partly reduce the losses dissipated in the coil. Because all six coils are mounted close to each other, there is a strong magnetic coupling through mutual inductances. Because of the current decay in the mandrel, the induced eddy currents heat the Al mandrel causing quench in the closest coil. The situation with Coil3-Coil6 circuit, which has overlapping currents in five loops, is more complicated.

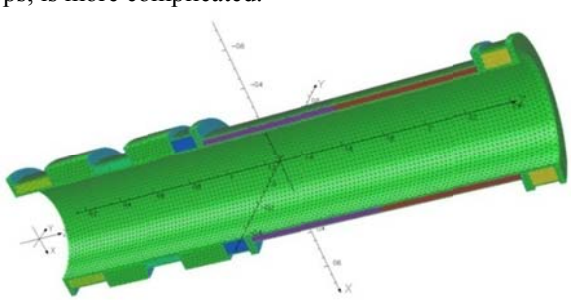

Fig. 3. Solenoid geometry used in simulations.

C. Quench Simulation at 275 A Current

The circuit shown in Fig. 2 was used for the quench simulations. Each coil in this circuit is protected by cold diodes and shunt resistors. External circuits are presented by 1 Ω resistors. Many quench scenarios were investigated and it was found that the most dangerous scenario is when the quench started in the left corner of Coil 1. The quench in this corner during simulation was initiated by a spot heater energized for only 0.2 s. In this case, the quench propagates during 2 s along 2.5 m long Al mandrel. In 7 s all currents decay to 10 % of the initial 275 A current (See Fig. 4). At the same time, the coil normal zone voltages rises in 2.5 s up to 1.4 kV (See Fig. 5), and the peak coil hot spot temperature reaches 77 K (See Fig. 6).

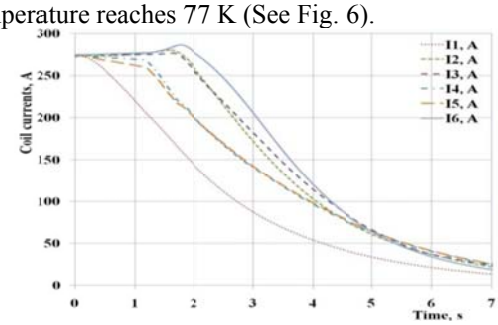

Fig. 4. Coil currents at the 275 A initial quench current.

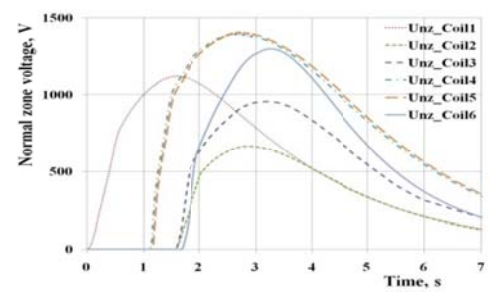

Fig. 5. Coil normal zone voltages at the 275 A initial quench current.

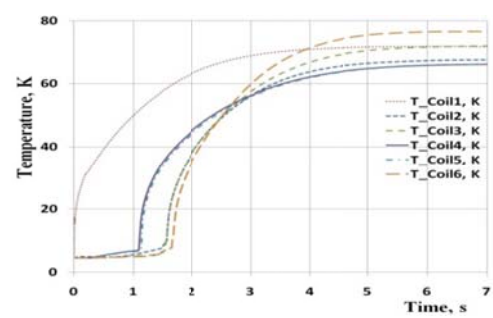

Fig. 6. Coil hot spot temperatures at the 275 A initial quench current.

All the above parameters look reasonable. It confirms that at peak currents, the passive quench protection system works in an agreement with the expected performance. Nevertheless, after the Solenoid 2B test, there was noticed a substantial shunt resistor overheating [5] shown in Fig. 7.

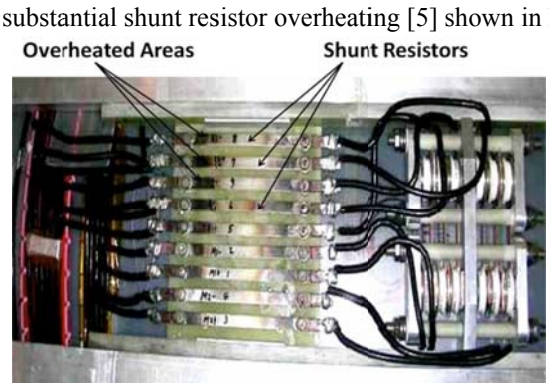

Fig. 7. Shunt resistors assembly.

G10 spacers were dark burned indicating that the shunt resistor temperature reached several hundred degrees

Celsius. This could not be explained by ~7 s currents decay in shunt resistors shown in Fig. 8.

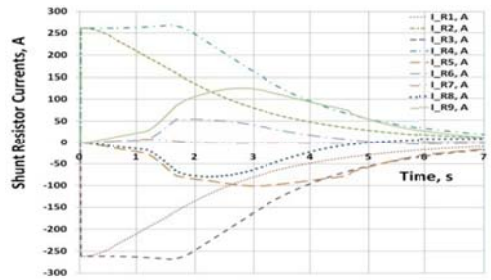

Fig. 8. Shunt resistor currents at the 275 A initial quench current.

One of the possible explanations is that during the solenoid training at low current quenches, the shunt resistor currents circulated longer than expected because of slower quench propagation, and a delayed "quench back" effect. It should also be noted that for the first tests of the solenoid, all coils were connected in series and powered from the single 300 A, 10 V power supply. It is proposed to reduce the shunt resistors heating in the future by attaching to them heat sinks.

D. Quench Simulation at 100 A Current

A number of quench scenarios was investigated in the range of 100 A - 275 A currents. The longest quench time was observed for the lowest 100 A current (See Fig. 9, Fig. 10). Quenches of this type might happened even during the normal operation of a trained magnet because of an unexpected temperature rise, leaks, shorts, etc.

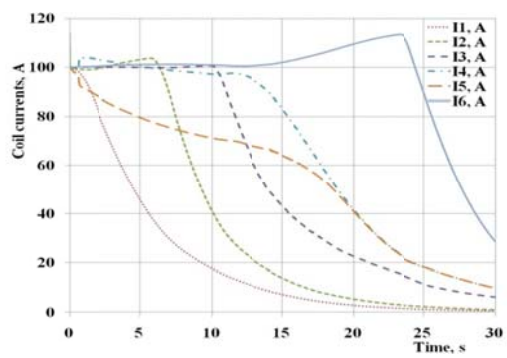

Fig. 9. Coil currents at the 100 A initial quench current.

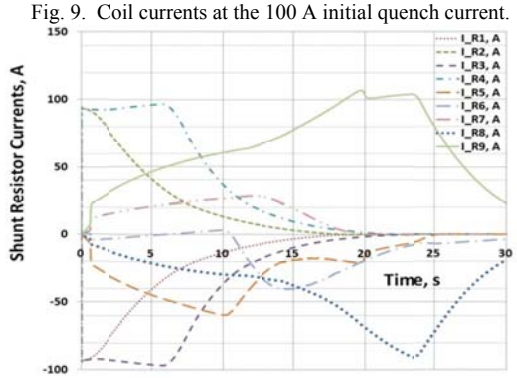

Fig. 10. Shunt resistor currents at the 100 A initial quench current.

It is obvious, that the lower quench current, results in the lower energy dissipated in the mandrel, the slower quench propagation along the solenoid, and the longer current decay in the coils far away from the quenched one. The things become even more complicated if there is any coil separation from the mandrel under Lorentz forces causing the loss of a good thermal contact.

E. Strand Adiabatic Heating

Another critical situation might be in the coil lead areas which are not heavily stabilized by a copper stabilizer. If these areas have a single strand conductor with copper cross-section 1.2 mm^2, then they might be overheated. The copper strand melting temperature is 1084 °C. Using the adiabatic approach, we can estimate the strand heating time up to specified temperature as function of current (See Fig. 11). A permanent degradation of NbTi superconductor may be caused by overheating. NbTi strand degradation was observed in [9] after heating up to 600 °C for varied magnetic field levels. The test results for the 10 s and 30 s heating time at 3 T field shown in Table 2.

TABLE II Normalized Critical Current at B=3 T

Annealing temperature	Time, 10 s	Time, 30 s
No annealing	1.0	1.0
400 °C	0.95	0.9
500 °C	0.91	0.79
550 °C	0.55	0.33
600 °C	0.22	0.08

Thus, up to 45 % of the permanent NbTi superconductor degradation is possible only after 10 s of heating time at 550 °C.

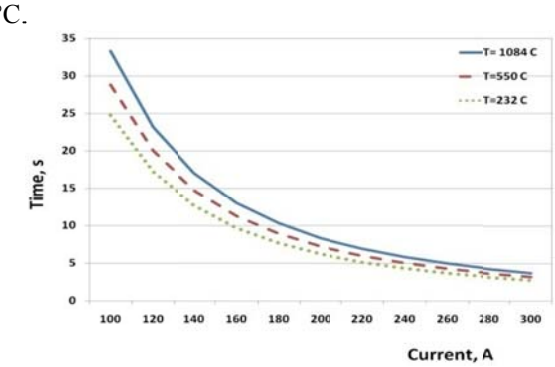

Fig. 11. The strand heating time vs. current.

At the 100 A quench, the Coil 6 current will circulate for ~ 30 s (See Fig. 9). In this case, the strand heating will be close to the 550 °C (See Fig. 11) causing the superconductor degradation. This estimation does not take into an account the coil quench from the external lead because of its heating from a nearby shunt resistor.

III. The Active Quench Protection System

It is possible to reduce the risk of solenoid damage by implementing an active quench protection system. The case of an active quench protection system was investigated with heaters incorporated in the Al mandrel body. The key issue for such system is to initiate quenches simultaneously in all coils during a reasonable period of time and the dissipated power. The electrical scheme shown in Fig. 2 was used for the quench simulation. The initial current was 150 A, which is well below the nominal operating current of 275 A. At this current, more power is needed to initiate the coil quenches which will be much lower at larger currents. All cartridge heaters [10] are mounted in the 14 mm diameter holes drilled in the Al mandrel. Each spot heater generates 400 W during 1 s, or 400 J of thermal energy.

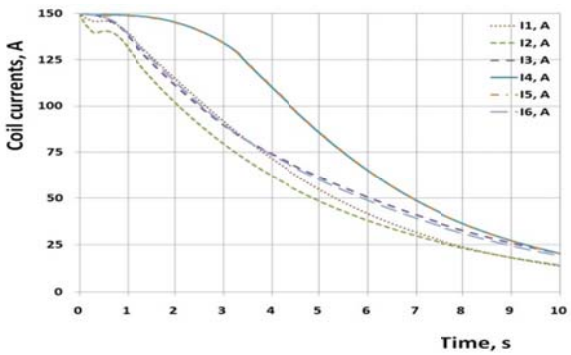

Fig. 11. Coil currents after firing heaters at the 150 A initial quench current.

The peak temperature during quench will be in the aluminum around spot heaters. The proper optimization of heating power will equalize the temperatures around heaters, and the quench time of all coils.

Nevertheless, even for this not optimized scenario, all coils quenched in 1 s (See Fig. 12). There is no effect of long circulating current in the far away coil.

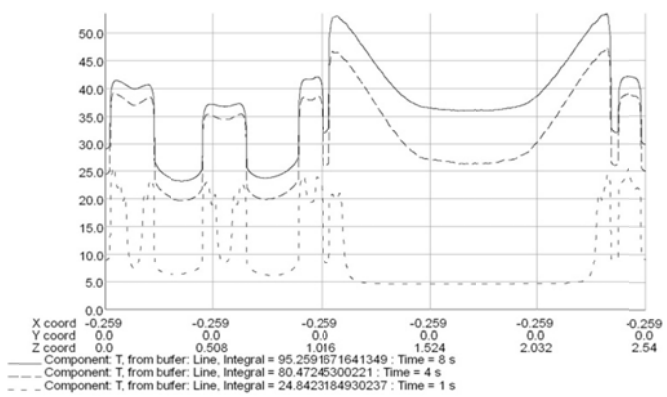

Fig. 12. Temperature distribution along the solenoid at the inner coil radius r = 259 mm for: 1 s, 4 s, and 8 s time.

The shown system performance confirms the efficiency of the proposed active quench protection system. The implementation of this system strongly correlates with the probability of quenches at relatively low coil currents. These quenches may be initiated during the solenoid charge/discharge, unexpected temperature rise, magnet training. It is also supposed to investigate a muon cooling at different energies with a corresponding field and the solenoid current variations during the experiment [1].

IV. Conclusion

The main conclusions from the presented quench simulation results are:

1. The lower quench current is, the longer delay time in the "quench back".
2. The coil current decay time for the solenoid final configuration is in the range of 10÷30 s, and depends on the initial current and material properties.
3. The coil hot spot temperature at the 275 A quench current is 75 K.
4. The coil leads attached to the heavily stabilized by copper leads (inside the cold mass) might be overheated.
5. The active quench protection system with cartridge heaters into Al mandrel can reduce the risk of the cold mass failure.
6. Low current quenches are possible during the magnet system operation.
7. The presented simulation results should be verified by using: the more fine mesh, measured superconductor critical current density at varies temperatures and flux densities, measured nonlinear cold diode V-A characteristics.
8. The final Spectrometer solenoid test results should be compared with the presented results for better understanding the performance of this complicated passive quench protection system.

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