TORUS CLAS12 - Superconducting Magnet Quench Analysis

V. S. Kashikhin, L. Elouadhiri, P. K. Ghoshal, D. Kashy, A. Makarov, O. Pastor, L. Quettier, G. Velev, M. Wiseman

Abstract— **The JLAB TORUS magnet system consists of six superconducting trapezoidal racetrack-type coils assembled in a toroidal configuration. These coils are wound with SSC-36~~an~~ NbTi superconductor and have the superconductor peak field of 3.6 T. The first coil manufacturing based on the JLAB design began at FNAL. The large magnet system dimensions (8 m diameter and 14 MJ of stored energy) dictate the need for ~~careful~~ quench protection. Each coil is placed in an aluminum case mounted inside a cryostat and cooled by 4.6K supercritical Helium gas flowing through a copper tube attached to the coil ID. The large coil dimensions and small cryostat thickness drove the design to challenging technical solutions, suggesting that Lorentz and Eddy current forces during quench and various failure scenarios are analyzed. The report covers the magnet system quench analysis using the OPERA3d™ Quench code.**

Index Terms— **Superconducting magnet, Magnetic field, Quench, 3D simulations, Lorentz forces, Failure analysis, eddy current.**

I. INTRODUCTION

THE TORUS magnet system is a part of the JLAB CLAS12 experiment [1]-[2]. The detailed analysis of the magnet design suggested having a robust protection circuit and supporting structure for the magnet with reference to the electromagnetic (EM), eddy current forces and thermal loading. It is critical to investigate possible fault scenarios: coil shorts (turn to turn and turn to ground), quench without an adequate protection system, etc. During this work, the Vector Field (COBHAM) Quench code was used, that combines ELEKTRA 3D code for transient EM simulations and TEMPO 3D thermal analysis which was also employed for quench analysis of MICE [3-4] [6]. The simulation results include: currents, voltages, magnetic field and temperature distribution, eddy currents, Lorentz forces, and power losses. The main reason for using these codes is the complicated response of a multi-coil magnet system where the quench propagation depends on the coupled thermal-EM effects. The superconductor and non-linear material properties used in the simulations are obtained from tests done at the Fermi National Accelerator Laboratory (FNAL) Superconductor Test Facility.

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V. S. Kashikhin#, A. Makarov, G. Velev are with the Fermi National Accelerator Laboratory, Batavia, IL 60510, USA (corresponding author# phone: 630-840-2899; fax: 630-840-6766; e-mail: kash@fnal.gov).

L. Elouadhiri, D. Kashy, P. K. Ghoshal, O. Pastor, L. Quettier,, M. Wiseman are with the Jefferson National Accelerator Laboratory, Newport News, VA 23606.

II. SUPERCONDUCTING MAGNET SYSTEM

The TORUS magnet system consists of six superconducting coils forming the toroidal magnetic field [1]. The schematic arrangements of the coils that are mounted inside a common cryostat are shown in Fig. 1. Coils are made from double pancakes of 117 turns each and are vacuum impregnated with epoxy and placed into an aluminum case with indirect supercritical helium gas cooling to form the coil cold mass (CCM). The coil inside the CCM is in thermal communication with the cooling tubes through OHFC shroud around the pancake at 4.7 K. Each CCM is surrounded by a nitrogen shield that is placed between vacuum vessel walls and coil cases shown in Fig. 2.

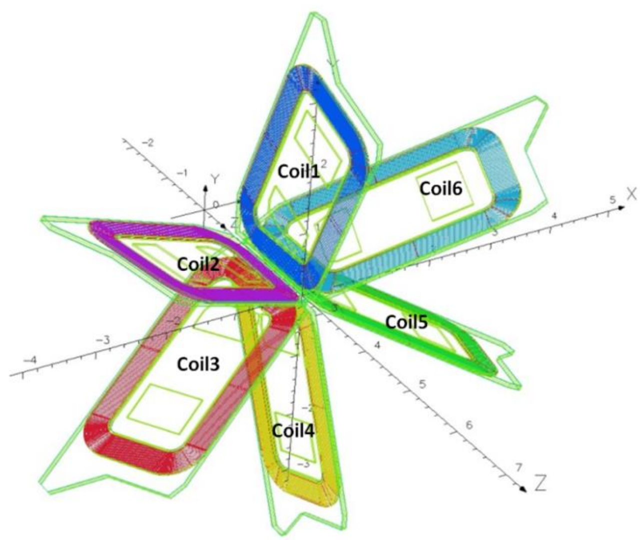


Fig. 1. Superconducting magnet system (dimensions in m).

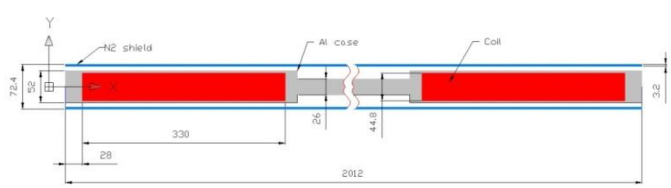


Fig. 2. Coil assembly cross-section (dimensions in mm)

The TORUS magnet electrical parameters that were used in the quench simulations are shown in Table 1.

TABLE I TORUS COIL PARAMETERS

Parameter	Unit	Value
Peak operating current	A	3770
Coil peak field	T	3.6

Number of coils		6
Total number of turns/coil		2 x 117
Superconducting cable dimensions	mm	2.5 x 20
NbTi strand bare diameter	mm	0.648
Number of strands in the cable		36
Cu:Sc ratio (strand)		1.8
Cu:Sc ratio Cu stabilizer (20mmx2.5mm) 12mm wide channel and RRR		10.3/70
Critical current at 5.6 T, 4.2 K	kA	10.2
Total stored energy	MJ	14.2
Inductance	H	2.0

III. Superconducting Cable and Parameters

The NbTi Rutherford type (SSC outer) superconductor is selected for the superconducting coil winding that is soldered into a copper channel. The SSC superconductor properties were measured at University of Twente and at FNAL. Table 1 shows the superconductor parameters, and Fig. 3 shows the measured superconductor data with the magnet system load line.

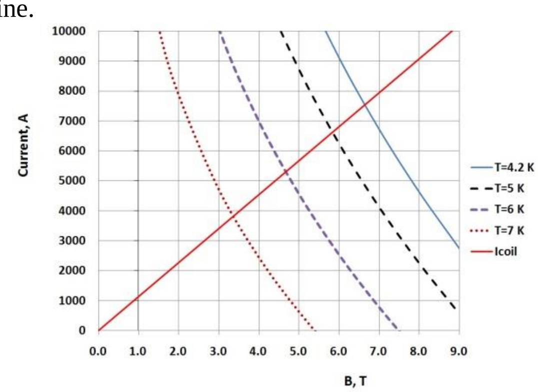


Fig. 3. Cable critical current and magnet load line (solid).

At a 3770 A nominal operating current, there is a 3 kA margin at 4.2 K and a zero current margin at 7 K. With large coil dimensions it is advisable to have large short sample performance (SSP) limit and temperature margin >1.5 K. Often in large magnet systems, the quench happens around 50% of the SSP limit.

IV. Electromagnetic and Thermal Models

For the TORUS magnet system, quench simulations are =built using 3D electromagnetic and thermal models. The combination of two generally different geometries is a challenge, especially for the FEM analysis. It is difficult to combine very thin shells, spacers, and electrical insulation having various electromagnetic and thermal properties with the same mesh.

The electromagnetic transient analysis was based on the ELEKTRA 3D code. During a quench initiated by a film heater, the magnet discharged on the external dump resistor. The relatively fast current decay in each coil generates eddy currents in the aluminum case and the nitrogen shield. So, part of magnet stored energy is dissipated in coil cases and shields. Using currents during quench, Lorentz forces are calculated that are experienced by coils, coil cases, and shields.

The thermal transient analysis was based on the TEMPO 3D code. In normal conditions, during the coil quench, a heat wave propagates along the conductor length and across the coil and transfers to the superconductor. Eddy currents heats up cases and coils, causing the "quench back" effect, this extra heat quenches coils more rapidly. This effect may also quench the coil during the fast discharge of the magnet system, even without an initial coil quench.

The QUENCH code provides the interface between electromagnetic and thermal codes at each time step during differential equations integration. It also combines all material properties, a superconductor, and an electrical schematic diagram. The code also provides output for most electromagnetic parameters: currents, voltages, losses, resistances, and other user defined parameters.

Two general models were investigated: 30° and 360° models. The 30° model with proper boundary conditions extremely reduces the simulation time, and with a reasonable finite element mesh may give more accurate results.

V. Quench Simulation of the 30° Model

The quench analysis for most superconducting magnet systems follows the simplified approach described in [5]. The role of the "quench back" effect for the MICE solenoids was investigated in [3], [4]. The 3D QUENCH code is capable of simulating a realistic quench propagation and the influence of eddy currents on the "quench back" effect.

The TORUS magnet system generates a toroidal magnetic field. The magnetic field value is critical for the superconductor choice and quench performance. Fig. 4 shows the magnetic field distribution on the coil surface. The peak field 3.6 T is evaluated at the coil inner surface and low radius. The magnetic flux density is about two times lower at the coil's outer radius. The probability of quench will be greater in a high magnetic field area. Of course, it also will depend on the cooling conditions and coil temperature.

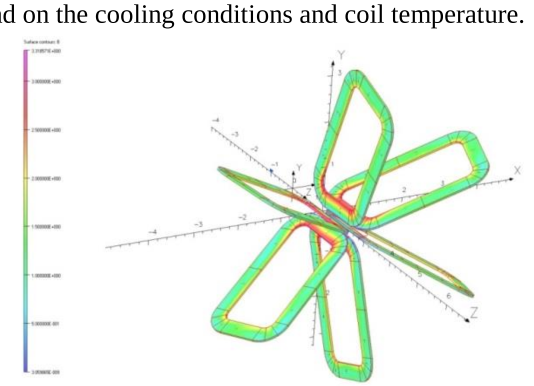


Fig. 4. Magnetic flux density map (Bmod) at 3770 A (nominal).

The stored magnetic field energy is 14.2 MJ at the operating coil current 3770 A. So, the total magnet system inductance (L) is 2.0 H. The magnet system discharge on the 0.12 Ω dump resistor (R) without a quench will be with the time constant 16.7 s (L/R). It should be noted that non-linear superconductor normal zone growth and induced eddy currents in the aluminum cases and shields will decrease the effective discharge time due to the increase in effective resistance in the magnet circuit.

The 30° model with proper boundary conditions reduces 12 times the number of finite elements and the time for calculations. The electric circuit was modeled by the coil and dump resistor connected in a series. The model included the superconducting coil, aluminum case, and aluminum radiation shield with dimensions shown in Fig. 1, Fig. 2. The model with the finite element mesh is shown in Fig. 5. It is supposed that the initial nominal current 3770 A is flowing through 117 turns of COIL1 (half coil). After the quench initiated by the COIL1 heater, the magnet discharges on the external dump resistor of 0.12 Ω. This current decays with the initial time constant ~ 10 s to zero after 40 s.

It should be noted that because of 12-fold symmetry, the 30° model represents the solution when all six coils are quenched simultaneously by the film heater in the model in order to initiate a quench.

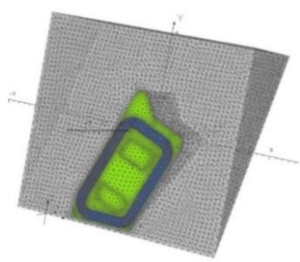


Fig. 5. 30° model geometry with the mesh.

Quenches propagate symmetrically in all coils starting from the peak magnetic field area (inner coil surface at low radius), propagating through the whole coil to the outer radius in the model as the point of quench initiation represented in Fig. 6.

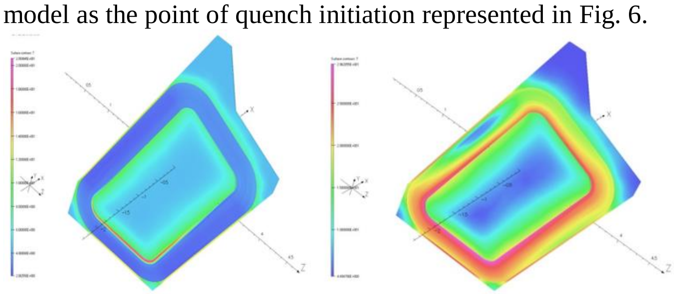


Fig. 6. Cold mass temperature at 0.25 s, Tmax = 21 K (left), 1.0 s, Tmax = 30 K (right) after the quench.

During coil current decay large eddy currents are in induced Al cases and N_2 shields shown in Fig. 7. The worst effect is on 3.2 mm thick Al shields, which would be loaded by 38 kN transverse to their surface force shown in Fig. 8.

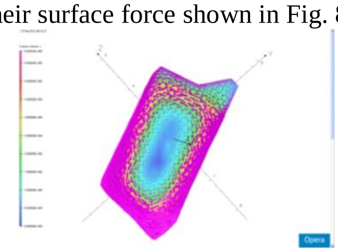


Fig. 7. Eddy currents in the shield at time 1 s after the quench.

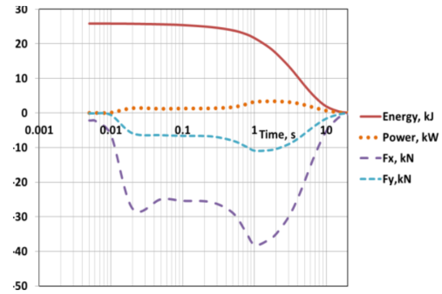


Fig. 8. N_2 shield parameters vs. time.

The peak forces on the shield after ~1 s of the magnet quench are the following: Ft = -38 kN (transverse direction), Fr = -11 kN (radial direction). So, the transverse force was directed to the coil mid-plane. In the case of the toroidal field, the transverse forces on all shields are balanced and equal zero for any coil cold mass assembly. In order to reduce the force on shields, slits are introduced that will interrupt the eddy currents' paths and increase the resistance. A variant was investigated with shield cuts forming four electrically isolated areas for the single shield, reduced the force to 19 kN. The total half coil force components are much larger at the initial current than for the shield: Ft/2 = -2.7 MN, Fr = -1.5 MN. Ft/2 will be applied to the coil interlayer spacer and Fr to the inner support cylinder.

VI. Quench Simulation of the 360° Model

The whole 360° model shown in Fig. 9 was simulated to investigate a "quench back" effect and coil failure scenarios.

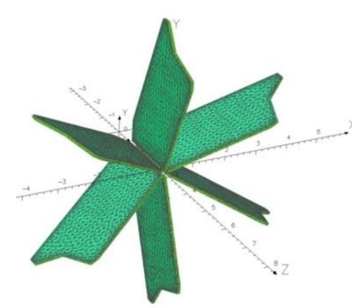


Fig. 9. The 360° model geometry with the mesh

Initially investigated were variants with the quench only in Coil1, and the variant of system discharge on the dump resistor without the quench initiated by a heater. Both variants showed about identical parameters because the "quench back" effect caused by the Al case heating initiated the fast transfer of all coils in the normal condition just after 0.3 s.

The complicated scenario of coil short circuit with single coil failure that might result in high current arc has a complex non-linear physics. A simple model [7] is employed to investigate electrical characteristics of arcs and the arc resistance is calculated as:

$$R = \frac{20+0.534z}{I^{0.88}} ,$$

where R is arc resistance, I is arc current, and z is the gap between short-circuited conductors.

At 1 kA arc current and with the gap between conductors at 0.3 mm (turn to turn insulation), the arc resistance will be only 6 mΩ. The real resistance in worst case might be even lower for the arc plasma channel with evaporated copper and electrical insulation. It is supposed that the initial breakdown is caused by defective electrical insulation, electrical contact due to the presence of an unwanted matter. The equivalent circuit diagram is represented in Fig. 10.

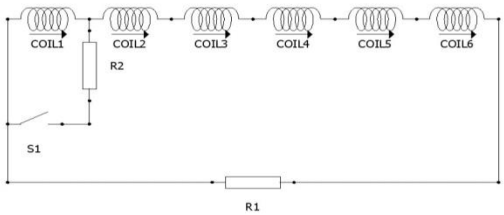


Fig. 10. The single coil short diagram.

During such scenario, Coil1 will be short circuited by the S1 switch and represented with the short resistance, R2. Several variants with different R2 were investigated. The system discharge through R1 (dump resistor) and R2 causes the quench. Additionally, some part of the stored energy will be dissipated R2. The currents circulating in coils #2-6 along with current in coil1 and R2 are shown in Fig. 11.

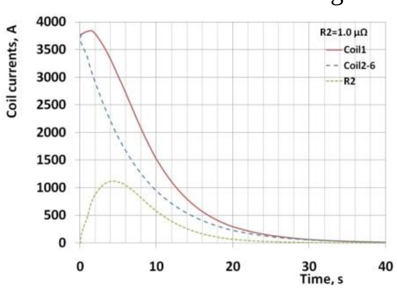
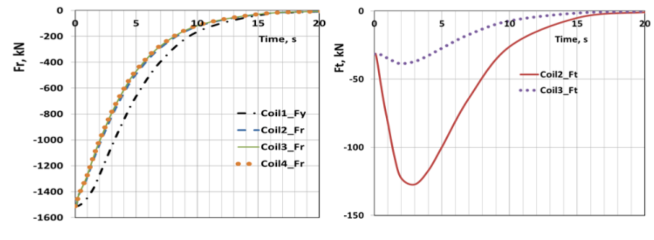


Fig. 11. The single coil short currents. R1 = 0.124 Ω, R2 = 1.0 μΩ.

Initially, the Coil1 current will rise for 1.5 s, and the short circuit current will also rise to 1100 A after 4 s, defined by the unbalanced currents between Coil1 and the other coils: Coil2–Coil6. This effect breaks the toroidal magnetic field symmetry, causing the redistribution of the initially axial symmetric Lorentz forces on the coils. Because of the extra energy dissipated in Coil1, it has a higher hot spot temperature rise to 73 K, relative to the other coils heated to about 47 K. For any magnetic field distortions, the total magnet system under Lorentz forces will be in equilibrium. But there will be uneven pressure on the central support cylinder from the radial force components with the difference of 270 kN, and large transverse forces will appear (Ft-perpendicular to the coil mid-plane). The maximum transverse force will be applied in opposite directions to Coil2 and Coil6: Ft = 115 kN. The increase of R2 from 1 μΩ to 10 mΩ will not substantially change the current redistribution because R2 is still less than the total resistance of all quenched coils. The power losses in R2 at 1 μΩ are negligible, and at 10 mΩ they are quite large, with the peak of 10 kW at 4 s and with the peak Ft = 127 kN shown in Fig. 12.



(a) (b)

Fig. 12. Fr (a) and Ft (b) coil force components after Coil1 short.

VII. Conclusion

A quench analysis was performed for various scenarios and main conclusions:

1. The quench during normal magnet system operation will heat the coil only to 53 K. But after 1 s of the quench, the radiation shield will experience 38 kN of transverse force.
2. The magnet system discharge on the dump resistor without initial quench will initiate the "quench back" after 0.3 s with about all the same parameters as in the forced quench scenario.
3. A single coil short followed by a quench, breaks the magnetic field symmetry. After 4 s, the short circuit current rises to 1100 A, which increases this coil temperature to 73 K. The difference in coil radial forces reaches 270 kN. The transverse force in Coil2 and Coil6 rises to ~130 kN. The change of short circuit resistance in the range of 0–10 mΩ did not substantially change the current redistribution. But at 10 mΩ of short resistance, the power losses in the arc rise to ~10 kW.
4. The shield force and deflection analysis shows the requirement of slits in the shield to reduce eddy currents and large transverse forces on shields during the coil(s) short, stoppers/bumpers are introduced in the shield-case design.
5. Large non-symmetric Lorentz forces on coils in any type of failure should be intercepted by "coil-case-vacuum vessel" stoppers to avoid cold mass damage. The vacuum vessel should be capable of withstanding these forces also. The peak forces will be with the short across three coils. The probability of such failure has the highest risk for the magnet system and should be carefully avoided.

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