Quench Protection Analysis of the Mu2e Production Solenoid

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Abstract. The Muon-to-Electron conversion experiment (Mu2e), under development at Fermilab, seeks to detect direct muon to electron conversion to provide evidence for a process violating muon and electron lepton number conservation that cannot be explained by the Standard Model of particle physics. The Mu2e magnet system consists of three large superconducting solenoids. In case of quench, the stored magnetic energy is extracted to an external dump circuit. However, because of the fast current decay, a significant fraction of the energy dissipates inside of the cryostat in the coil support shells made of structural aluminum, and in the radiation shield. A 3D finite-element model of the complete cold-mass was created in order to simulate the quench development and understand the role of the quench-back. The simulation results are reported at the normal and non-standard operating conditions.

Keywords: Superconducting magnet, solenoid, quench, cryostat.

INTRODUCTION

The Mu2e magnet system consists of three large superconducting solenoids [1]. The first in the chain of magnets is the Production Solenoid (PS) [2], shown in Fig. 1 whose role is to collect and focus pions and muons generated in interactions of an 8-GeV proton beam with a tilted high-Z target, by supplying a peak axial field between 4.6 T and 5.0 T and an axial gradient of ~1 T/m within a 1.5 m warm bore.

The PS is a challenging magnet because of the relatively high magnetic field and a harsh radiation environment that requires the state-of-the-art conductor both in terms of the current-carrying capacity and structural strength. The PS coils are protected by a massive Heat and Radiation Shield (HRS) made of bronze, placed within the warm magnet bore. An extensive simulation effort has been carried out to optimize the shield parameters and get the radiation load below the tolerable levels with a sufficient safety margin [3]. The HRS volume (and cost) was minimized while keeping the absorbed dose, peak power density, total power dissipation and the number of displacements per atom (DPA) within the acceptable limits.

FIGURE 1. Cross-section through the PS cryostat with a part of the Transport Solenoid (TS) cryostat shown. HRS is not shown.
It was calculated that due to the radiation damage, the RRR of Al and Cu stabilizers degrade from the initial values of 600 and 80 to the minimum acceptable values of 100 and 50 in about one year of operation [4]. The magnet will be equipped with the witness samples made of Al and Cu, placed at the strategic locations on the inner cold mass surface. Once the critical degradation is detected, the magnet will be thermo-cycled by warming up to the room temperature that restores 100% of the original resistivity in Al and ~87% of that in Cu [5]-[6].

A careful analysis of the quench protection system has been performed to determine the peak temperatures and voltages during quench. The large variation of the stabilizer’s electrical and thermal properties within the operating cycle imposes the additional challenges for determining the worst-case condition. Presence of the massive, electrically-conductive HRS within the magnet bore affects the rate of the current decay during quench and creates an additional force on the cold mass that must be taken into account in the design of the support system.

**MAGNET DESIGN**

The PS cold mass consists of three separate coil modules with 3, 2 and 2 layers of Al-stabilized NbTi cable shown in Fig. 2(a), wound in the hard-way around the aperture. A precipitation-hardened Al-0.1wt%Ni alloy is used for the stabilizer that in conjunction with 15-20% of the cold work achieves the target 0.2% yield strength of >80 MPa at 4.2 K and the RRR of >600 [7]. The final cable has a small keystoning that compensates the trapezoidal deformation acquired during the hard-way bending.

The heat extraction scheme based on the heat conduction through a system of thermal bridges connected to the thermal siphon tubes has been proposed and numerically evaluated [8] for the actual distribution of the heat depositions inside of the cold mass. The most recent iteration of the cooling scheme design includes the detailed interface between the thermal bridges and the cooling tubes as well as the heat map for the updated HRS design [9]. It was found that the required thermal margin of 1.5 K is preserved at the nominal operating loads.

The field distribution in the PS magnet is shown in Fig. 2(b) and the main magnet parameters are listed in Table 1. The coil support shells are included in the model along with the HRS made from C63200 bronze with the nominal relative magnetic permeability of 1.04 and resistivity of 2.46×10^-7 Ω·m. That specific material has been selected after industry studies and a cost optimization as a compromise between large resistivity, low magnetic permeability and forge-ability in sufficiently large pieces [10].

Each coil module is equipped with its own support shell made of Al 5083-O. The shells are bolted together to form the cold mass assembly. The details related to the cold mass structural analysis are discussed elsewhere [2].

**FIGURE 2.** Cold cable cross-section (a) and the magnet model (b) with the flux density at the maximum current. HRS and the coil support structures are shown.
TABLE 1. Magnet parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Design</th>
<th>Nominal</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strand diameter</td>
<td>mm</td>
<td>1.30</td>
<td></td>
<td></td>
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<tr>
<td>Number of strands</td>
<td></td>
<td>32</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cu/nonCu ratio in the strand</td>
<td></td>
<td>0.95</td>
<td></td>
<td></td>
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<tr>
<td>Initial RRR of Cu matrix</td>
<td></td>
<td>&gt;80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al-stabilized cable width</td>
<td>mm</td>
<td>30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al-stabilized cable thickness</td>
<td>mm</td>
<td>5.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial RRR of Al stabilizer</td>
<td></td>
<td>&gt;600</td>
<td></td>
<td></td>
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<tr>
<td>Liquid helium temperature</td>
<td>K</td>
<td>4.70</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum allowable coil temperature (T_peak)</td>
<td>K</td>
<td>5.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cable critical current at 5 T, 4.2 K</td>
<td>A</td>
<td>&gt;50700</td>
<td></td>
<td></td>
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<tr>
<td>Magnet quench current at T_peak (I_q)</td>
<td>A</td>
<td>13610</td>
<td></td>
<td></td>
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<tr>
<td>Peak coil quench field at I_q</td>
<td>T</td>
<td>7.34</td>
<td></td>
<td></td>
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<tr>
<td>Magnet inductance</td>
<td>H</td>
<td>1.58</td>
<td></td>
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<tr>
<td>Operating current</td>
<td>A</td>
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<td>10150</td>
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<td>Peak bore field</td>
<td>T</td>
<td>4.56</td>
<td>5.02</td>
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<tr>
<td>Peak coil field (B_peak)</td>
<td>T</td>
<td>4.97</td>
<td>5.48</td>
<td></td>
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<tr>
<td>Critical current fraction at B_peak, T_peak</td>
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<td>0.676</td>
<td>0.746</td>
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<tr>
<td>Thermal margin at B_peak, T_peak</td>
<td>K</td>
<td>1.50</td>
<td>1.20</td>
<td></td>
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<tr>
<td>Stored energy</td>
<td>MJ</td>
<td>66.8</td>
<td>79.7</td>
<td></td>
</tr>
</tbody>
</table>

The cold mass is supported inside of the cryostat using a system of the radial and axial support rods. The axial load on the cold mass during the normal operation of the Mu2e magnet system acts towards the TS. However, if a quench occurs during the stand-alone PS operation, the axial load on the cold mass reverses the direction because of interaction with the eddy currents induced in the HRS. To address this problem, the axial support system employs the 2-way support rods that are able to intercept the load in either direction while staying always under tension [11].

All PS coils are powered in series from a single power converter. In order to guarantee meeting the nominal operating parameters, the magnet is electrically and structurally designed for ~10% higher field and current. A 1-kA trim power supply connected across the coil module adjacent to the TS is used to compensate the field variation and provide a smooth matching between the PS and TS fields in case of adjusting the PS current.

**QUENCH PROTECTION SYSTEM**

The purpose of the quench protection system (QPS) is to limit the peak coil temperature to 130 K and peak coil to ground voltage to 600 V during any normally protected quench. It is achieved by detecting the resistive voltage rise associated with the quench development and extracting the stored energy to an external dump resistor.

Schematic of the magnet electrical circuit is shown in Fig. 3. The magnet is powered by a two-quadrant thyristor-based power converter with the maximum voltage of 20 V. The power converter has the internal DC current transformer (DCCT) for current regulation. In case of quench, the energy is extracted to the fast dump resistor permanently connected between the magnet leads, with the resistance of 59 mΩ chosen to limit the voltage across the magnet leads to 600 V at the maximum design current. When the slow ramp-down is requested, the power converter reverses the voltage.

Each leg of the two buses leading to the power converter has an independent, electronically controlled solid-state breaker. The bus-bars are made of copper and air-cooled. Their total resistance is significantly less than the resistance of the circuit in case of slow dump, but sufficient for converter regulation. The grounding circuit symmetrically divides the voltage across the magnet terminals through a 1 kΩ resistance. The leakage current to ground is continuously monitored and triggers a magnet discharge if a preset limit is reached.

Each coil layer is equipped with redundant voltage taps connected to the QPS. The QPS continuously monitors the magnet voltages during operation. If the resistive voltage exceeding the detection threshold of 0.5 V is detected, the QPS waits for 1 s to eliminate false signals and to give the magnet a chance to recover if the perturbation energy was less than the minimum quench energy (MQE). If the resistive voltage remains above the detection threshold, the QPS activates the main breaker to disconnect the power converter from the magnet and the current decays through the fast dump resistor.
The goal of the quench analysis was to determine the peak temperatures and voltages in the magnet at different operating conditions. The primary tool for modeling the quench development in the PS magnet was COMSOL Multiphysics code that was benchmarked against QLASA code [12] at an early stage of the analysis.

It is safe to assume that the quench may occur at any location of the magnet and at any stage of the operation. Because of the potentially time consuming nature of the quench analysis, several representative cases have been carefully selected. Two strategic quench locations have been chosen for the analysis: high-field (HF) region in the inner layer of the 3-layer coil and the low-field (LF) region at the magnet end adjacent to the TS. All simulations were performed at the maximum design current shown in Table 1.

Model description and verification

The 3D FEM model of PS magnet, shown in Fig. 3(b), created within the COMSOL Multiphysics code included all the relevant features, including the individual coil layers, interlayer and ground insulation, thermal bridges on the inner and outer surfaces of the coils, coil support structures and the HRS. The thermal conductivity, specific heat and electrical resistivity of different components were parameterized in 4-300 K range. The orthotropic thermal properties of the individual coil layers were calculated from the properties of constituent materials using the law of mixtures.

The time-dependent thermal model was directly coupled to the time-dependent magnetic model, shown in Fig 2(b), and the differential circuit equation representing the electrical schematic in Fig 3(a). The quench was initiated by delivering a 10 ms heat pulse with the energy exceeding the MQE at a given location to the length of ~0.3 m of a single cable. The resistive coil voltage was monitored by the code. During the normal operation of QPS, the code followed the detection/protection logic described in the previous chapter.

Several test cases were run on the previous iteration of the magnet design [2], in order to benchmark it against the available results from the QLASA analysis at the HF location, gradually adding the quench-related components: the thermal bridges on the inner and outer coil surfaces and the power depositions due to eddy currents in the coil support structures. The RRR for Al and Cu have been set to intermediate values of 200 and 73. The peak coil temperatures and resistances calculated by these two codes are shown in Fig 4.
FIGURE 4. Peak coil temperatures (a) and coil resistances (b) for different thermal bridge (TB) and eddy current (EC) cases.

The maximum temperature calculated by QLASA is 108 K and the maximum temperature calculated by COMSOL is 100 K for the case without the thermal bridges and eddy currents in the support structure. It gives the closest comparison between the two codes since the QLASA simulation did not include these features. The higher temperature in QLASA simulation is due to absence of the coil-to-coil quench propagation, which results in lower coil resistance and therefore longer current decay, and no cooling of the hot-spot by heat conduction to the surrounding media, which is evident from no temperature reduction after reaching the peak at ~50 s. Adding the thermal bridges and the eddy currents in the COMSOL model reduces the peak temperature to 90 K and 78 K respectively. All the following simulation results in this paper included these integral features of the magnet design.

Magnet commissioning stage

During the commissioning stage, the magnet will be tested in the stand-alone mode before and after the HRS is installed and then as part of the Mu2e magnet system. In all cases, the RRR of the cable stabilizer will be at its maximum value. Figure 5 shows the resistive zone at the beginning of the quenches in the HF and LF locations and at 2.5 s and 3 s - when the quenches are induced at multiple locations due to heating of the coil support structure by the eddy currents (quench-back). The peak coil temperatures and voltages corresponding to quenches during different test conditions are shown in Fig. 6.

FIGURE 5. Resistive zone (dark region) from the quenches originating at the HF (a) and LF (b) locations.
The maximum peak temperature of 69 K occurs during the quench at HF location without the HRS. Adding the HRS reduces the peak quench temperature by 0.9 K. Although a part of the stored energy dissipates in the HRS volume, the effect on the peak temperature is small because this energy dissipates outside of the cryostat and does not contribute to heating the coil and accelerating the quench development. In case of quenches at LF location, the peak quench temperature is further reduced to 58 K and 0.5 K less when HRS is installed. The peak resistive voltages of 100-112 V are generated in the coil depending on the location, which are offset by a factor of six higher inductive voltage.

**Normal operation stage**

The HRS will always be present during the normal operation stage, and the cable RRR will gradually decrease from the maximum to the minimum allowed value in about one year. The RRR degradation will not be uniform because of the non-uniform distribution of the radiation flux in the cold mass. However, for the purpose of this study, it was assumed that the RRR will degrade to the minimum allowed value uniformly in the coil volume.

The case of the maximum RRR has already been considered in the previous paragraph. Figure 7 shows the peak coil temperatures and voltages when the stabilizer’s RRR is degraded to the minimum allowed value. The peak coil temperatures are 82 K and 78 K for the quenches at the HF and LF location respectively. While the absolute temperatures increased by 14-20 K with respect to the maximum RRR case, the temperature difference between the HF and LF quenches reduced by more than a factor of two. The peak resistive voltages increased by almost a factor of three, but are still a factor of two less than the peak inductive voltage component.

Despite the practically negligible effect on the peak quench temperature, presence of the HRS during quench creates an additional force on the cold mass due to interaction of the induced eddy currents with the magnetic field. The force evolution on the cold mass due to interaction with the HRS is shown in Fig. 8 (a). Since the considered HRS material is a general purpose bronze with no control over the magnetic and electrical properties, its nominal magnetic permeability was increased to 1.1 and the electrical resistivity reduced to $1 \times 10^{-7} \, \Omega \cdot m$ to account for the possible property variation. The maximum dynamic force of 115 kN in the direction away from the TS is reached at 3.5 s after the beginning of the quench. The 2-way cold mass axial support system is designed to counteract this additional force [11].

There is a strong dependence of the initial quench propagation speed and coil voltages on the quench location and material properties. Figure 8 (b) presents the resistive coil voltages before the dump activation for different quench cases. The slowest voltage growth is for the quench at the LF location with the maximum RRR, where it takes ~1s to reach the quench detection threshold. The fastest voltage growth is for the quench at HF location with the minimum RRR, where it takes 0.2 s to reach the same threshold.
QPS failure

It has been shown that the proper operation of QPS limits the peak coil temperatures and voltages well below the limiting values at all stages of the magnet operation. A catastrophic failure of the QPS has been considered as part of the risk assessment. It was assumed that the energy extraction circuit fails completely and all the stored energy is dissipated in the cold mass. In reality, it represents a simultaneous failure of both dump switches or a short between the bus-bars and the subsequent arc with nearly zero resistance. The only mechanism of the energy dissipation is the normal zone propagation and the quench-back from the structure when the field change becomes sufficiently high.

The peak coil temperatures and voltages are shown in Fig. 9. Opposite to the protected quench behavior, the maximum temperature of 240 K is at the maximum RRR quench at the LF location. The minimum temperature of 130 K is at the minimum RRR quench at the HF location. Clearly, the most dangerous unprotected quenches are those originating at the low field because of the slow quench propagation, which have low probability to occur.
The resistive coil voltage gets to a maximum of 800 V during the minimum RRR quench at the HF location. However, the voltage across magnet leads is zero, meaning the inductive voltage is the mirror copy of the resistive voltage, which mostly cancel each other inside of the coil.

ACKNOWLEDGMENTS

This work was supported in part by Fermi Research Alliance under the U.S. Department of Energy Contract DE-AC02-07CH11359.

REFERENCES