IMPACT OF RADIATION ON THE MU2E PRODUCTION SOLENOID PERFORMANCE*

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Abstract

The Muon-to-Electron conversion experiment (Mu2e) is under development at Fermilab to detect direct muon to electron conversion and provide evidence for processes violating muon and electron lepton number conservation not explained by the Standard Model of particle physics.

The Mu2e magnet system consists of three large superconducting solenoids. One of the magnets is the Production Solenoid (PS) named after the production target installed in the magnet bore. The superconducting coils are protected from the secondary particle radiation by a massive Heat and Radiation Shield (HRS) made of bronze, which was optimized for the energy absorption and cost. This paper describes the impact of radiation on the magnet cooling, stability and quench protection.

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], which collects and focuses pions and muons generated in interactions of an 8-GeV proton beam with a tilted high-Z target, by supplying a peak axial field of 4.6-5.0 T and ~1 T/m gradient 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 50-cm thick 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 radiation heat reaching the coils must be extracted to the cryogenic system to maintain the necessary operating margin. It is achieved using a system of thermal bridges made of pure Al connected to the cooling tubes [4]. Electrical and thermal properties of the thermal bridges and the cable stabilizer are significantly degraded under the irradiation that impacts the cooling efficiency, magnet stability and quench performance.

RADIATION ANALYSIS

Simulations were performed using MARS15 code on the model shown in Fig. 1. LAQGSM generator was employed for high-energy particle interactions. The neutrons were propagated down to 0.001 eV. The full set of critical radiation quantities was calculated. The superconducting coil material was described using homogeneous approach (the material was represented as a mix of all elements with appropriate weight factors).

The peak calculated DPA was ~$2.5\cdot10^{-5}$ yr^{-1} and the peak power density was 12 μW/g. Corresponding peak absorbed dose for the insulation in coils is 240 kGy/yr; total dynamic heat load in the cold mass is 28 W. While the total dynamic heat load is relatively small, the power density distribution in the cold mass is strongly non-uniform, as shown in Fig. 2 that creates a localized hot spot in the middle of the coil.

Taking conservative safety factors into account, the calculated DPA translates into the degradation of RRR in Al and Cu from the initial values of 600 and 80 to 100 and 50 respectively in one year of experiment's operation [5]. These numbers are regarded as the minimum allowable values. The magnet will be equipped with RRR gauges that monitor property changes during the operation. Once the critical resistivity degradation is detected, the magnet will be thermo-cycled to the room temperature that restores the original resistivity in Al and ~87% of that in Cu [6]-[7].

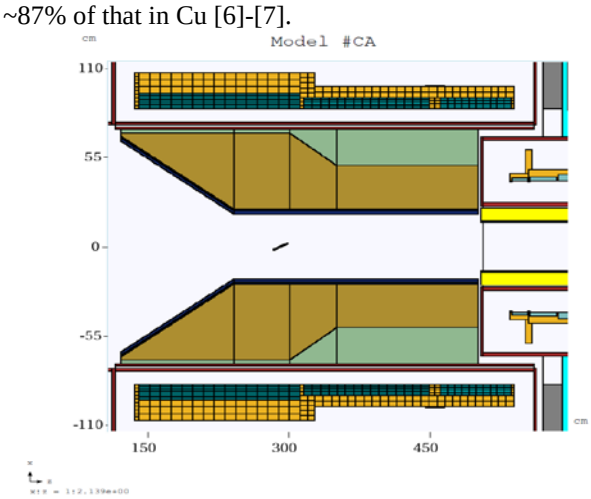

Figure 1: MARS model.

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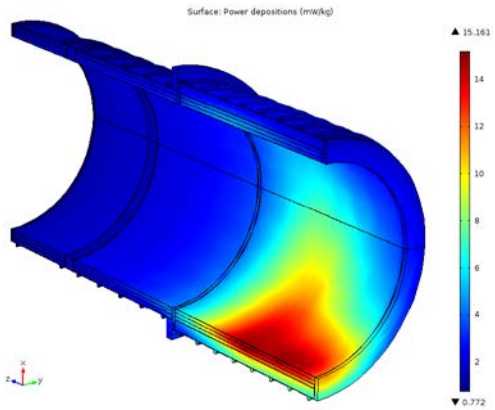

Figure 2: Radiation power distribution in the cold mass.

THERMAL ANALYSIS

The 3D FEM model of the cold mass has been created using COMSOL Multiphysics code. It contained all the relevant features, including the individual coil layers, interlayer and ground insulation, thermal bridges, structural support shells and the cooling tubes with the corresponding material properties. The cold mass is cooled using a thermo-siphon system that maintains the LHe temperature of 4.7 K.

The radiation heat is extracted from the coils using a system of thermal bridges made of pure (5N) Al attached to the inner and outer coil surfaces and connected to the cooling tubes on the outer cold mass surface [8]. The thermal bridge RRR will degrade under the irradiation.

Fig. 3 shows the temperature distribution in the coil when the material RRR's are reduced to the minimum allowable values defined earlier. The local hot spot coincides with the magnet peak field location and therefore affects the operating margin.

The peak coil temperature shall not exceed 5.1 K in order to maintain the required thermal margin of 1.5 K with respect to the current-sharing temperature of 6.6 K at the peak field location. Fig. 4 shows the coil temperature increment as a function of Al RRR. The peak coil temperature rises by ~100 mK during the operating cycle that is accounted for in the magnet design.

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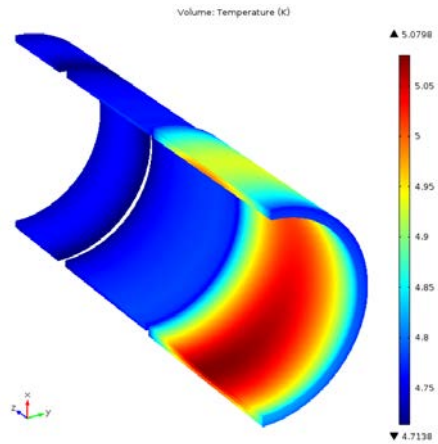

Figure 3: Temperature distribution in the coil.

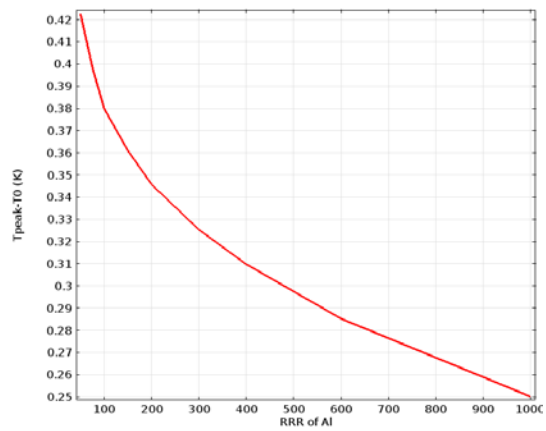

Figure 4: Temperature increment in the coil vs. RRR.

MINIMUM QUENCH ENERGY

Stability of the superconducting state is characterized by the Minimum Quench Energy (MQE) that is the minimum energy released in the superconducting cable that triggers quench. Both the electrical and thermal conductivities of stabilizer material play an important role in the magnet stability.

MQE of PS magnet has been analyzed using COMSOL code for the stack of cables shown in Fig. 5, which included coupled thermal and current sharing models. The analysis has been performed for the coil peak field location that has the smallest margin and consequently the lowest MQE.

The results of simulations are presented in Fig. 6. It is expected that most of the heat perturbations in the coils associated with cracks in the insulation and in the strand-stabilizer interface will occur during the commissioning without the beam. The relatively high initial MQE value of ~175 mJ, comparable to MQE in other large solenoids, will help to stabilize the magnet during that period.

The MQE degrades by ~25% due to higher temperature when the beam is on and gets progressively lower during the operation, reaching ~40 mJ at the end of the operating cycle. Thus the magnet becomes a factor of 4.4 less stable than during the commissioning, however, it is not expected to cause problems for DC operation.

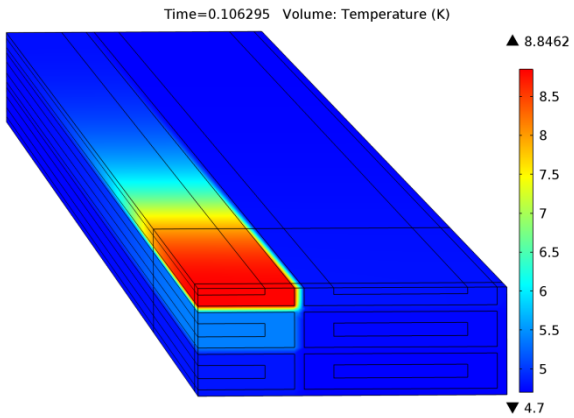

Figure 5: Cable stack model with the temperature distribution at 0.1 s after the initial perturbation.

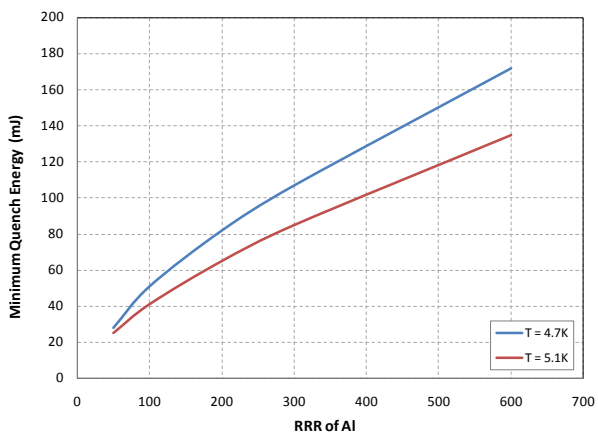

Figure 6: MQE vs. RRR of cable stabilizer.

QUENCH PROTECTION

The purpose of the quench protection system (QPS) is to limit the peak coil temperature to 130 K and the 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.

The 3D FEM model of the PS magnet, created within the COMSOL Multiphysics code, contained 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 energy dissipation due to eddy currents induced in the support shells and the HRS was included. Extensive simulations of different normal and fault scenarios have been performed [9].

It was found that irrespective of the RRR value, the highest coil temperatures during the normally protected quenches occur at the peak field location. Propagation of the quench originated at the peak field location is shown in Fig. 7 at the time when the resistive zones are induced at multiple locations due to quench-back from the support structure and the peak temperature as a function of Al RRR is shown in Fig. 8. The peak coil temperature goes up by ~23 K as the result of RRR degradation in the operating cycle; however, it remains well below the limit.

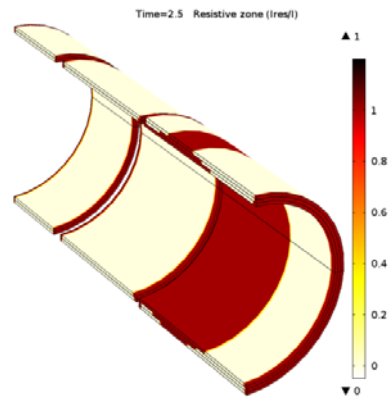

Figure 7: Resistive zone (dark region) from the quench originating at the peak field location.

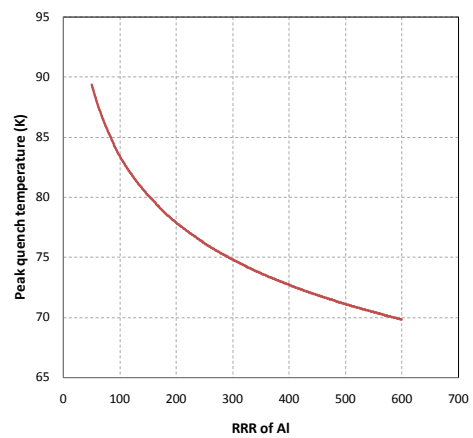

Figure 8: Peak quench temperature vs. RRR of Al.

Protecting the magnet from radiation has indirect structural effect on the magnet design due to the field interaction with eddy currents induced in the HRS during magnet quench. HRS is made from high-resistivity bronze to minimize the eddy currents; however because of the large HRS volume, the peak dynamic force on the cold mass is 115 kN, which nearly equals to the cold mass weight. It is normally subtracted from the much larger PS-TS attractive force, but leads to force reversal when TS is off. The cold mass has a 2-way axial support system designed to counteract the force in either direction [10].

SUMMARY

Radiation coming from the fixed target has a significant impact on the PS magnet performance. In addition to the highly localized heat dissipations in the cold mass, the electrical and thermal properties of stabilizer and thermal bridges are considerably degraded. As a result, the peak coil temperature raises by ~100 mK, the MQE reduces by a factor of 4.4, and the peak quench temperature increases by ~23 K during the operating cycle. Once the critical degradation is detected, the magnet will be thermo-cycled

to the room temperature that will largely restore the original performance.

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