

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 Production Solenoid (PS) named after the pion 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.

INTRODUCTION

The Mu2e magnet system consists of three large superconducting solenoids [1]. PS is the first magnet in the chain [2], which collects and focuses pions and muons generated in interactions of an 8-GeV proton beam with a tilted high-Z target and directs them towards Transport Solenoid (TS), by supplying a peak axial field of 4.6-5.0 T and ~1 T/m gradient within a 1.5 m warm bore.

It is a challenging magnet because of the relatively high magnetic field and a harsh radiation environment. The PS coils are protected from radiation by 50-cm thick water-cooled HRS made of high-resistivity 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 with the MARS15 code [5] on the model shown in Fig. 1. 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).

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The peak calculated Displacement Per Atom (DPA), which characterizes the radiation damage in metals, was $\sim 2.5 \cdot 10^{-5} \text{ yr}^{-1}$ and the peak power density was $12.6 \mu\text{W/g}$ [3]. Corresponding peak absorbed dose for the coil insulation 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 first 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 about one year of experiment's operation [6]. These numbers are regarded as the minimum allowable values. The magnet will be equipped with RRR gauges that monitor the material 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 [7]-[8].

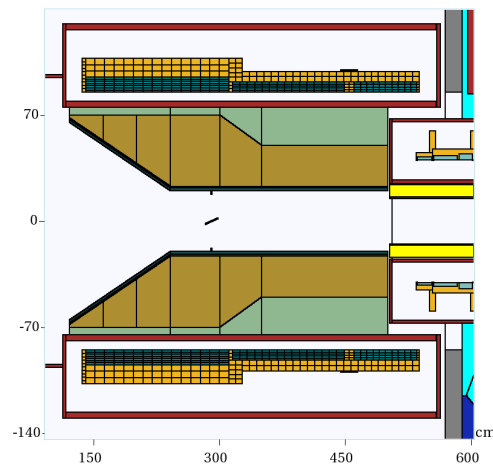


Figure 1: MARS model.

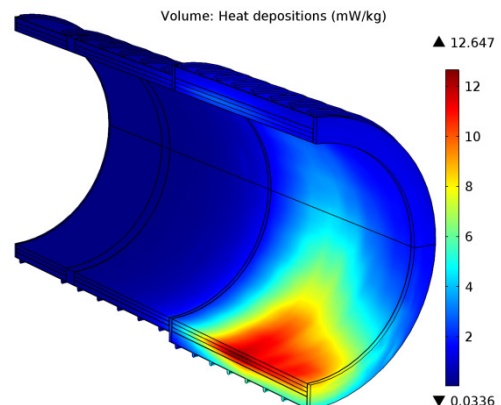


Figure 2: Radiation power distribution in the cold mass.

THERMAL ANALYSIS

The 3D FEM model of the cold mass has been created using ANSYS code [9]. It contained all the relevant features, including the 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 [10]. The thermal bridge RRR will degrade under the irradiation.

Fig. 3 shows the temperature distribution in the coil when the material RRR is 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 peak coil temperature as a function of Al RRR for the static (beam is off) and total (beam is on) heat loads. The peak coil temperature rises by ~200 mK after turning the beam on and gains another ~70 mK due to RRR degradation in the operating cycle that is accounted for in the magnet design.

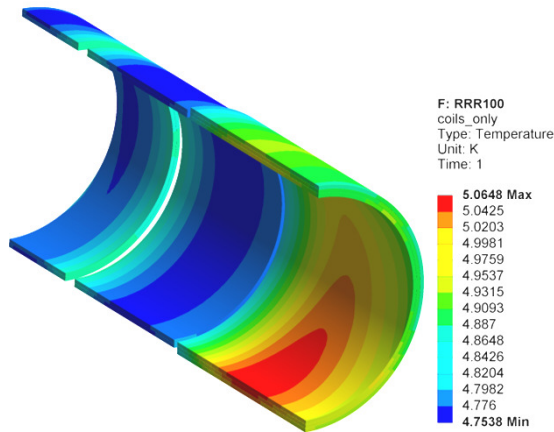


Figure 3: Temperature distribution in the coil.

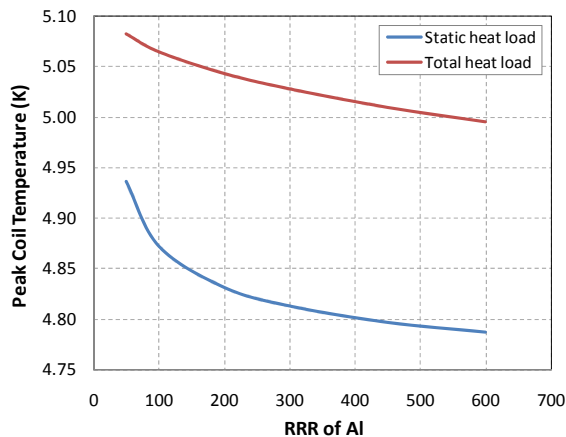


Figure 4: Peak coil temperature vs. RRR of Al.

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 a quench. Both the electrical and thermal conductivities of the stabilizer material play an important role in the magnet stability.

MQE of the PS magnet has been analyzed using COMSOL Multiphysics code [11] for the stack of cables shown in Fig. 5, which included coupled thermal and electrical transient 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 coil temperature rise 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.

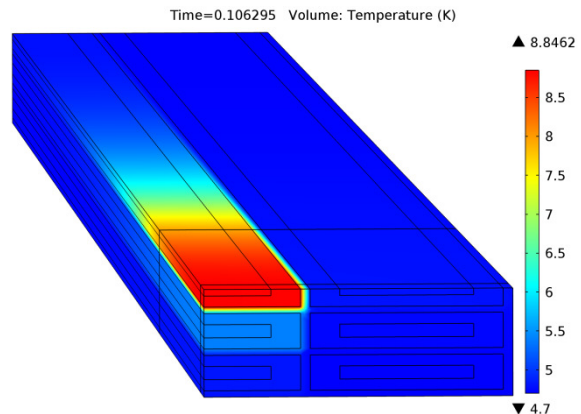


Figure 5: 1/8 of the cable stack model with the temperature distribution 0.1 s after the initial perturbation.

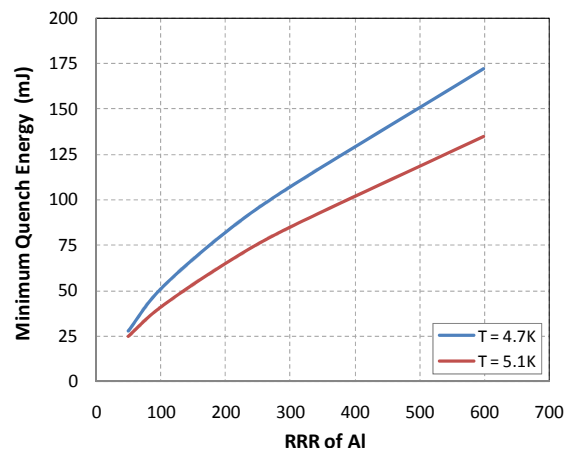


Figure 6: MQE vs. RRR of cable stabilizer.

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 also included. Extensive simulations of different normal and fault scenarios have been performed [12].

It was found that irrespective of the RRR, the highest coil temperatures during the normally protected quenches occur at the peak field quench location. Propagation of a quench originated at the peak field location is shown in Fig. 7 at the time when the multiple resistive zones are induced due to quench-back from the support structure. The peak coil temperature and the resistive voltage go up by ~23 K and ~510 V respectively as the result of RRR degradation in the operating cycle as shown in Fig. 8; however, they remain below the limits.

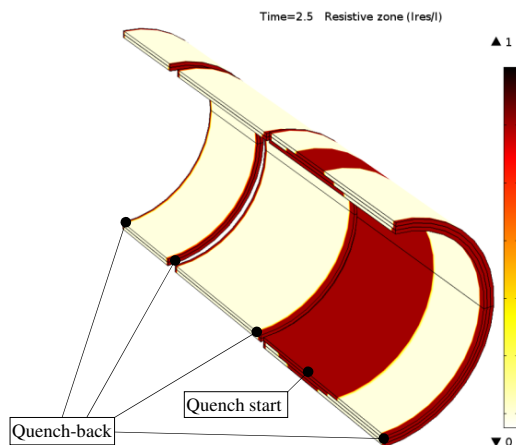


Figure 7: Resistive zone propagation (dark region).

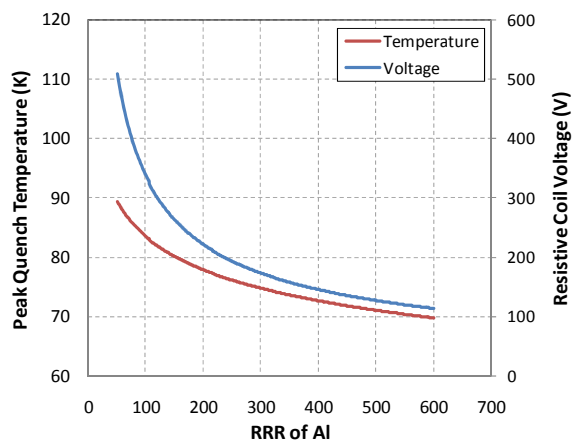


Figure 8: Quench temperature and voltage vs. RRR of Al.

Protection from the radiation has indirect structural effect on the magnet design due to field interaction with eddy currents induced in the HRS during 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 the TS is off. To address this issue, the cold mass has a 2-way axial support system designed to counteract the force in either direction [13].

SUMMARY

Radiation from the pion production target has a significant impact on the PS performance. In addition to the highly localized heat dissipation in the cold mass, the electrical and thermal properties of the stabilizer and the thermal bridges are considerably degraded, which is taken into account in the magnet design. Once the critical degradation is detected, the magnet will be thermo-cycled that will largely restore the original performance.

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