FERMILAB-CONF-13-406-APC-PPD-TD
September 2013

Optimization of Mu2e Production Solenoid Heat and Radiation Shield*

V.S. Pronskikh§, R. Coleman, D. Glenzinski, V.V. Kashikhin, N.V. Mokhov

Fermi National Accelerator Laboratory, Batavia IL 60510-5011, USA

Abstract

The Mu2e experiment at Fermilab is designed to study the conversion of a negative muon to electron in the field of a nucleus without emission of neutrinos. Observation of this process would provide unambiguous evidence for physics beyond the Standard Model, and can point to new physics beyond the reach of the LHC. The main parts of the Mu2e apparatus are its superconducting solenoids: Production Solenoid (PS), Transport Solenoid (TS), and Detector Solenoid (DS).

Being in the vicinity of the beam, PS magnets are most subjected to the radiation damage. In order for the PS superconducting magnet to operate reliably, the peak neutron flux in the PS coils must be reduced by 3 orders of magnitude by means of sophisticatedly designed massive Heat and Radiation Shield (HRS), optimized for the performance and cost. An issue with radiation damage is related to large residual electrical resistivity degradation in the superconducting coils, especially its Al stabilizer.

A detailed MARS15 analysis and optimization of the HRS has been carried out both to satisfy the Mu2e requirements to the radiation quantities (such as displacements per atom, peak temperature and power density in the coils, absorbed dose in the insulation, and dynamic heat load) and cost. Results of MARS15 simulations of these radiation quantities are reported and optimized HRS models are presented; it is shown that design levels satisfy all requirements.

---

*Work supported by Fermi Research Alliance, LLC under contract No. DE-AC02-07CH11359 with the U.S. Department of Energy.
§ Corresponding author. Email: vspron@fnal.gov

ELSEVIER

Available online at www.sciencedirect.com

ScienceDirect

Nuclear Physics B Proceedings Supplement 00 (2013) 1–3

Nuclear Physics B Proceedings Supplement

Optimization of Mu2e Production Solenoid Heat and Radiation Shield

V.S. Pronskikh*, R. Coleman, D. Glenzinski, V.V. Kashikhin, N.V. Mokhov

Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, 60510 IL, USA

Abstract

The Mu2e experiment at Fermilab is designed to study the conversion of a negative muon to electron in the field of a nucleus without emission of neutrinos. Observation of this process would provide unambiguous evidence for physics beyond the Standard Model, and can point to new physics beyond the reach of the LHC. The main parts of the Mu2e apparatus are its superconducting solenoids: Production Solenoid (PS), Transport Solenoid (TS), and Detector Solenoid (DS).

Being in the vicinity of the beam, PS magnets are most subjected to the radiation damage. In order for the PS superconducting magnet to operate reliably, the peak neutron flux in the PS coils must be reduced by 3 orders of magnitude by means of sophisticatedly designed massive Heat and Radiation Shield (HRS), optimized for the performance and cost. An issue with radiation damage is related to large residual electrical resistivity degradation in the superconducting coils, especially its Al stabilizer.

A detailed MARS15 analysis and optimization of the HRS has been carried out both to satisfy the Mu2e requirements to the radiation quantities (such as displacements per atom, peak temperature and power density in the coils, absorbed dose in the insulation, and dynamic heat load) and cost. Results of MARS15 simulations of these radiation quantities are reported and optimized HRS models are presented; it is shown that design levels satisfy all requirements.

Keywords: muon-to-electron conversion, secondary neutrons, energy deposition, radiation damage

1. HRS MARS15 model

The MARS15 [1, 2] model of the optimized HRS (see Fig. 1) is a bronze cylinder with 20 cm inner and 70 cm outer radii tapered to the left to provide the exit to the spent beam. A tungsten target 16 cm in length and 0.315 cm in diameter is positioned at the center of the HRS bore. The peak magnetic field on the PS axis is 4.6 T; the field is graded. The HRS has a 2 cm stainless steel liner around the bronze shield (brown) and the water (green) shown in Fig 1.

Simulations have been performed using the MARS15 code with 0.001 eV thresholds for neutrons (MCNP mode using ENDFB-VI library), 200 keV for γ-quanta, and 100 keV for charged hadrons, electrons, muons, and heavy ions. To describe the interactions of particles above few MeV the exclusive hadron-nucleus model employing LAQGSM [3] model above 3 GeV, and CEM [4] below was used. Proton beam intensity was $6 \cdot 10^{12}$ p/s, which corresponds to 8 kW. PS was surrounded by a 0.5 m thick concrete shield, which partly reflects neutrons.

2. Simulation of radiation quantities

Longitudinal distribution of power density calculated in the innermost 64-mm thick layer of the PS coils is shown in Fig. 2 (red histogram, right scale). Besides, heat maps for the thermal analysis are always produced in the course of simulations. Thermal maps help determine temperature rise in the coils for particular cooling schemes and simulate the quench propagation conditions. The figure shows that the peak power density

*Corresponding author

Email address: vspron@fnal.gov (V.S. Pronskikh)

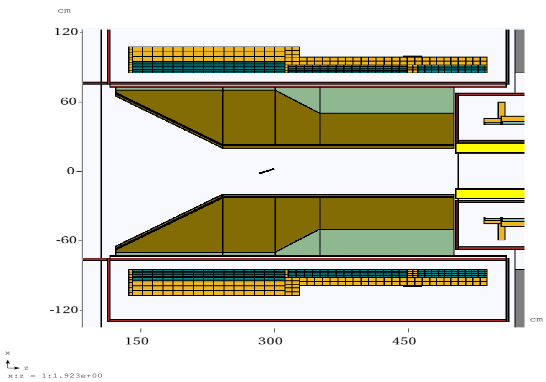

Figure 1: MARS15 model of the Mu2e HRS.

in the coils is 12 μW/g, which is below the reference 30 μW/g, however, the heat map analysis can impose additional constrains on design. Power density drops from the peak down by more than an order of magnitude thus suggesting a reduction of material upstream the target in the vicinity of the second and third coils. However, such a reduction requires further thermal analysis of trade-off with the quench propagation in the coils, which is affected by not only the peak value of the power density, but also its 3D distribution in the entire cold mass. The total dynamic heat load in all the coils was found to be 28 W.

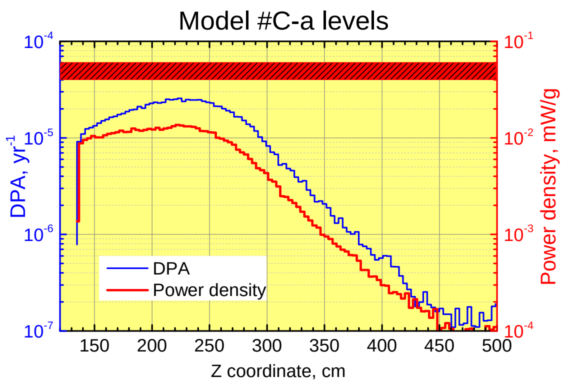

Figure 2: DPA and power density levels in HRS coils.

The simplest accidental mode modeled is the beam mis-steering at the upstream edge of the HRS near the beam pipe entrance location at the rightmost HRS edge(see Fig. 1). The peak values attained in such a mode are $1 \cdot 10^{-14}$ DPA (per 1 ms, which was assumed to be a characteristic time scale for an accidental mode), peak energy deposition – 0.1 μJ/g for the same time. These values are considered to be far from the potentially dangerous levels. Similar simulations performed for the beam mis-steered within the beam pipe near the TS1 coils showed that in the case of such kind of accidental mode the coils are still safe within that time scale.

Residual dose simulations for production solenoid parts show that the dose on contact with PS coils and Al stabilizer will be $\sim$ 0.7 mSv/hr after a year of irradiation and a week of cooling, and $\sim$ 80 μSv/hr after 30 days of irradiation and a week of cooling, which is rather high and requires particular safety measures for personnel performing PS maintenance during the lifetime of the experiment.

Distribution of the absorbed dose in the hottest strip of the HRS magnet coils and structures resembles that of the power density shown in Fig. 2, however, requires a unit conversion from mW/g to Gy/s. For $2 \cdot 10^7$ s, representing a working year for fixed target experiments, such scaling gives 240 kGy/yr for 12 μW/g as the peak absorbed dose. Assuming the lifetime of the Mu2e experiment to be 5 years, we obtain the design value of 1.2 MGy, which is under the limit of 7 MGy with a good safety margin.

Radiation damage to the atomic lattice of a superconducting cable, and its quench stabilizing matrix made from normal conductor takes the form of the accumulation of such lattice defects as atomic displacements (formation of pairs of vacancies and interstitial atoms as well as defect clusters). Damage to a metal sample exposed to a flux of penetrating particles can be characterized by the average number of displacements per atom (DPA). The DPA damage effect is directly related to electron transport in metals, leading to Residual Resistivity Ratio (RRR) degradation. RRR is defined as the ratio of the electrical resistance at room temperature of a conductor to that at 4.5 K, which decreases after an irradiation. However, warming such a sample to room temperature (annealing) leads to recovery of the RRR but the degree of recovery is different for metals with different crystalline latices. Aluminum is a material that shows complete recovery at 300 K. The annealing time has a time scale of minutes. This time scale needs to be compared to cryogenic heat capacity as well as expected thermal stresses for the PS during warm-up or cool-down cycles, which can take days.

RRR affects the magnet performance during operation in superconducting mode and its transition to the normal state (also called quench). Magnet stability is the ability of coils to recover the superconducting state after a short time-scale transition into the normal state without the quench. The superconductor transition to the normal state occurs when either the magnetic field, temperature or current exceed the critical values. When quenches, the electric current in the superconductor is removed into the surrounding Cu and Al stabilizers that have much lower resistivity than the superconductor in its normal conductor state. If the stabilizer resistivity is low enough (that corresponds to a high RRR), the temperature can return to the operating temperature after an excursion. Otherwise, the normal conductivity zone can propagate and eventually transit to the normal state entirely, i.e. quench.

The final magnet design will be optimized to work at the minimum RRR of 100 for aluminum and 50 for copper set forth in the PS requirements document [9] with sufficient operating margins. These margins, governed by the practices applicable to the design of superconducting magnets, however, do not account for the errors in determining DPA and RRR. Therefore, it is important that the HRS design requirement includes an appropriate safety margin in the maximum acceptable value of DPA to account for these errors, in order to guarantee meeting the minimum RRR requirements with a 5% accuracy. DPA distribution in the coil strip near the beam exit (under the same assumptions as for the peak power density) is shown in Fig. 2 (blue line, left scale). The peak DPA rate, which is about $2.3{\cdot}10^{-5}$ yr^{-1}, corresponds to approximately the first third of the first coil, and then falls off in the upstream direction (along Z axis) by the same factor as in the case of the power density. For more discussion on the new DPA model see [10].

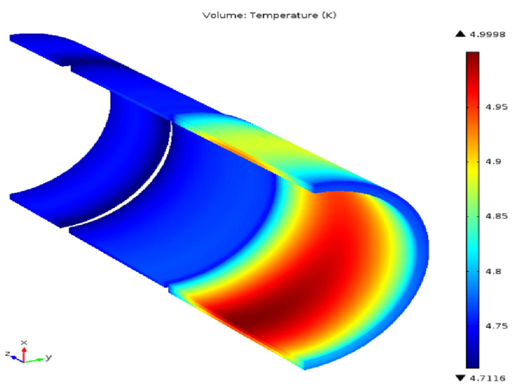

Figure 3: Temperature distribution in the HRS coils.

The 3D thermal analysis is performed for the radiation heat load at all stages of the HRS optimization. The FEM model created by COMSOL Multiphysics was discretized to the level of individual layers and the interlayer insulation/conducting sheets. The thermal conductivity of each layer in the axial direction is modeled by the equivalent thermal conductivity of the insulated cable in that direction. The coil layers were separated from each other by two layers of insulation with a layer of Al in between that was 1-2 mm thick, depending on the location within the coil. The Al layers formed thermal bridges by connecting to the Al plates placed between the coil ends and the end flanges. Analysis shows that the peak temperature in the coils is 5 K (see Figure 3).

3. Conclusion

Calculations using the MARS15 code have been performed to optimize Mu2e HRS according to the requirements [9] that were set based on: quench protection requiring that peak coil temperature does not violate allowable value of 5 K with 1.5 K thermal margin for peak power density, 10% degradation of ultimate tensile strength for absorbed dose, RRR (residual resistivity ratio) degradation from 600 to 100 in Al stabilizer, and requirements from the particular cooling system designed for dynamic heat load. In the current design peak power density is limited to 30 μW/g, peak DPA is $4 \div 6 \cdot 10^{-5}$, peak absorbed dose over the experiment lifetime is 7 MGy, and total (dynamic and static) heat load is 100 W. Simulations show that all quantities satisfy the requirements.

The design of the HRS also affects the neutron backgrounds in the Mu2e Detectors located in the Transport and Detector Solenoid areas. The minimization of these backgrounds exerted influence on the design of the HRS as well, particularly in the section downstream with respect to the muon beam, where PS coil irradiation is minimal but the effects of the HRS on Detector background are significant. This has lead to the larger water volume and a relatively small aperture beam pipe.

References

[1] N.V. Mokhov *et al.*, Technical Report FERMILAB-CONF-12-635-APC, 2012.
[2] N.V. Mokhov *et al.*, Fermilab Report Fermilab-FN-628 (1995); N.V. Mokhov *et al.*, AIP Conf. Proc. 896, pp. 50-60 (2007); http://www-ap.fnal.gov/MARS/.
[3] S.G. Mashnik *et al.*, LANL Report LA-UR-08-2931, (2008); arXiv:0805.0751 v1 [nucl-th] 6 May 2008.
[4] S. G. Mashnik *et al.*, LANL Technical Report LA-UR-05-7321, (2005).
[5] M.B. Chadwick *et al.*, Nuclear Data Sheets **107**, 2931 (2006).
[6] R. E. MacFarlane *et al.*, LANL Preprint LA-12740-M, (1994).
[7] C.H.M. Broeders, A.Yu. Konobeev, Journal of Nuclear Materials, **328**, 197 (2004).
[8] M.J. Norgett *et al.*, Nuclear Engineering and Design, **33**, 50 (1975).
[9] G. Ambrosio *et al.*, Fermilab Report Fermilab-FN-0954-AD-APC-TD (2013).
[10] V.S. Pronskikh, Modern Physics Letters A, **28**, 1330014 (2013).