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Simulation of Radiation Quantities for Accelerator-based Experiments

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Results of the MARS15 code application to the design of target stations for two experiments – a muon-to-electron conversion experiment Mu2e and the prospective multi-purpose ProjectX Energy Station at Fermilab – are presented. A detailed MARS15 analysis has been carried out focusing on the most important radiation quantities such as displacements per atom (DPA), peak temperature and power density in the coils, absorbed dose in the insulation, dynamic heat load; DPA and neutron volumes, tritium production are also simulated for the ProjectX target, a benchmark of the neutron fission model is presented.

I. INTRODUCTION

The impact of radiation on targets, accelerator structures, and experimental facilities in accelerator-based experiments has many aspects. Interacting with targets, high-intensity beams induce radiation damage, lead to high heat loads as well as structural changes in the target systems. Secondary particles created in targets, especially the most penetrating γ-quanta and neutrons, cause high background rates in the vicinity of targets, in magnets and detectors.

Structural components of superconducting magnets, which are widely used in particle physics experiments – coils and stabilizers – are sensitive to radiation that can induce a loss of their superconducting properties and a quench. On the other hand, attaining high secondary neutron fluxes and radiation damage in and around targets is desirable, for example, in material science experiments and the Accelerator-Driven System (ADS) research.

The MARS15 code [1, 2] employs the Quark-Gluon String Model code LAQGSM [3] for photon, hadron and heavy-ion projectiles in the energy range from a few MeV/A to 1 TeV/A. It provides the power of a full theoretically consistent modeling of exclusive and inclusive distributions of secondary particles, spallation, fission, and fragmentation products. This code, is widely used for solving a wide range of problems concerning interactions of high-energy particles. The best agreement with data is attained when in simulations of interactions of several-GeV protons with high-Z materials the LAQGSM generator above ∼3 GeV and the Cascade-Exciton Model CEM [3] below that energy but above tens of MeV; this mode is employed in this work.

The Mu2e experiment [4] will be seeking for the charged lepton flavor violation, which can manifest itself as the conversion of μ^- to e^- in the field of a nucleus without emission of neutrinos. The 8 GeV proton beam will deliver $6 \cdot 10^{12}$ protons per second to the tungsten target, placed at the center of the Production Solenoid (PS) bore during the lifetime of the apparatus. Being in the vicinity of the target, PS superconducting magnets are most subjected to the radiation damage.

In order for the PS magnet to operate reliably, the peak neutron flux in the PS coils must be reduced by ∼3 orders of magnitude by means of a bronze absorber, optimized for the performance and cost. An issue with radiation damage is related to a large residual electrical resistivity (RRR) degradation in the superconducting coils and especially their Al stabilizer.

A ProjectX Energy Station is considered at Fermilab to carry out studies on radiation damage and other aspects of material science, as well as ADS-related research, employing a spallation target irradiated by the GeV-range 1 MW proton beam. In the recently considered option [5], a liquid lead or lead-bismuth target is surrounded by a test matrix for material tests. In this work we propose an alternative design with a solid tungsten target capable also of serving as a test matrix. MARS15 calculations were performed to estimate energy deposition and radiation damage in the target, determine maximum attainable secondary particle fluxes, volumes of high neutron flux, and DPA.

II. DPA MODEL IN MARS15

The new MARS15(2012) DPA model for low-energy neutrons makes use of defect production cross sections calculated using the industry standard NRT [6] model for a database of 395 nuclides with the use of the NJOY99

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code [7]. Cross section calculations are based on the ENDF-VII [8] data base of neutron-induced reactions in the energy range from 10^{-5} eV to 20 (150) MeV; the cross section library `FermiDPA 1.0` [9] is used with the MARS15 code.

The NRT DPA cross sections are corrected for experimental defect production efficiencies η tabulated by [10] for many important materials for a number of neutron spectra in the reactor energy range (below 14.5 MeV). The defect production efficiency η, are the ratios of a number of single interstitial atom vacancy pairs (Frenkel pairs) produced in a material to the number of defects calculated using NRT model ($\eta = N_d/N_{NRT}$). NRT DPA rates are corrected with η for materials at low temperatures ($\leq$ 4.2 K), like the superconducting coil material (Al, Nb, Ti, Cu); for higher temperatures it is assumed to be 1.

III. MU2E PRODUCTION SOLENOID

The Mu2e Production Solenoid (PS) MARS15 model view is given in Figure 1. A pencil-like tungsten target (16 cm long, 6 mm in diameter), which is placed at the center of the PS bore, will be irradiated by 8 GeV protons at the intensity of $6{\cdot}10^{12}$ protons per second.

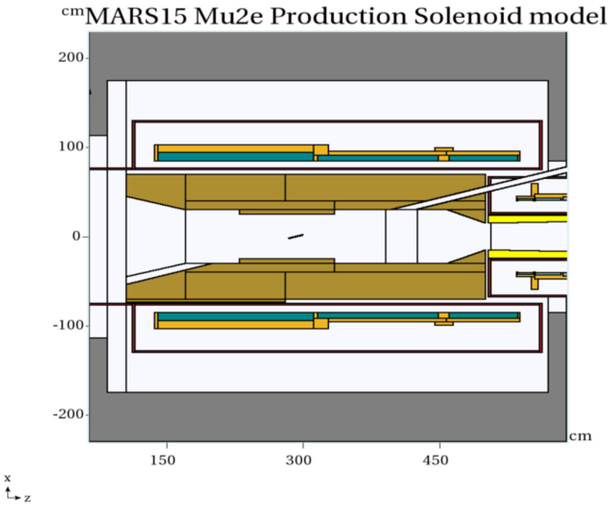

FIG. 1. MARS15 Mu2e PS model. Parts are: brown – Heat and Radiation Shield (bronze), green – NbTi/Al superconducting coils, orange – Al support structure, gray – concrete shield, yellow – Cu collimator leading to the muon transport system.

The following quantities were simulated: the dynamic heat load, the peak power density, the DPA in the helium-cooled solenoid coils, the peak absorbed dose and the peak neutron flux in the Al stabilizer of superconducting magnet coils. As one of the primary functions of the absorber is to protect the coils from heating and consequential quench, first two parameters serve to determine if the critical heating level is reached as well as to define requirements to the cooling system.

Neutron and γ-quanta spectra in the first, most heavily irradiated PS coil, are shown in Figure 2. The thresholds used in the simulations were 100 keV for γ-quanta and 0.001 eV for neutrons. Neutrons with energies $\geq$14.5 MeV were found to contribute to the total neutron flux in coils less than 1% .

DPA and power density levels in the PS coils are shown in Figure 3. These quantities are given for the region that limits the innermost $\sim$6 cm of coils in the azimuthally hottest region (note similar longitudinal profiles).

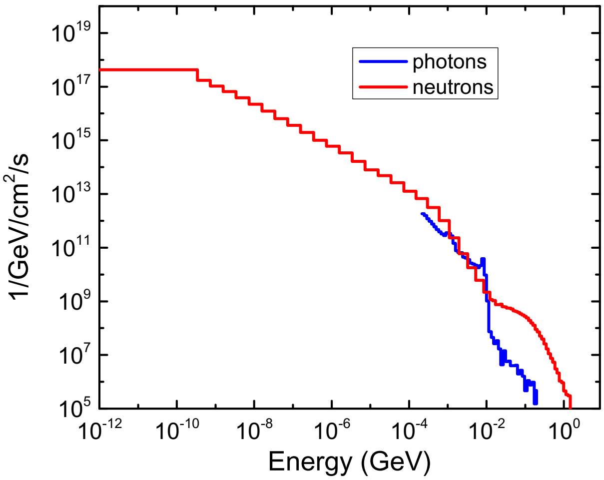

FIG. 2. Neutron and photon spectra at the first PS coil.

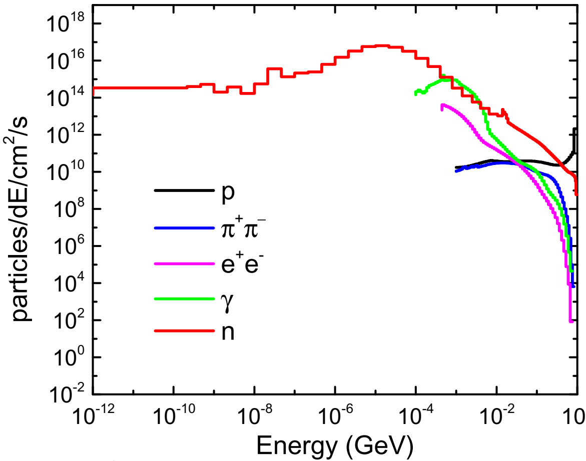

FIG. 3. DPA and power density levels in the innermost layer of PS superconducting coils.

The main constraints in the Mu2e PS absorber design are the following : quench stability of the superconducting coils, low dynamic heat loads to the cryogenic system, a reasonable lifetime of the coil components, acceptable hands-on maintenance conditions, compactness of the absorber that should fit into the PS bore and provide an aperture large enough to not compromise pion collection efficiency, cost, weight and other engineering requirements [11]. A comparison of simulated quanti-