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SIMULATION OF RADIATION QUANTITIES FOR ACCELERATER-BASED EXPERIMENTS*

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Abstract

Simulations of secondary particle fluxes, energy deposition, radiation damage, doses and other radiation quantities are necessary means of apparatus designing and understanding results of accelerator-based experiments. Taking as an example target stations of two experiments – a muon-to-electron conversion experiment Mu2e and the prospective multi-purpose ProjectX Energy Station at Fermilab, results of MARS15 application to their design are presented.

In the Mu2e experiment, the 8 GeV 8 kW proton beam will be delivered to the tungsten target, placed at the center of the superconducting Production Solenoid (PS) bore during the lifetime of the apparatus (~5 years). Being in the vicinity of the target, PS magnets are most subjected to the radiation damage. A ProjectX Energy Station is proposed at Fermilab to carry out studies on radiation damage and other aspects of material science, as well as ADS-related research. It will be using a spallation target irradiated by a GeV-range 1 MW proton beam. An alternative solid tungsten target is considered here.

Detailed MARS15 analysis has been carried out focusing on the most important radiation quantities such as displacements per atom, peak temperature and power density in the coils, absorbed dose in the insulation, and dynamic heat load.

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Simulation of radiation quantities for accelerator-based experiments

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Simulations of secondary particle fluxes, energy deposition, radiation damage, doses and other radiation quantities are necessary means of apparatus designing and understanding results of accelerator-based experiments. Taking as an example target stations of two experiments – a muon-to-electron conversion experiment Mu2e and the prospective multi-purpose ProjectX Energy Station at Fermilab, results of MARS15 application to their design are presented.

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I. INTRODUCTION

Impact of radiation on targets, structures of accelerators and experimental facilities in accelerator-based experiments is manyfold. Interacting with targets, high-intensity beams induce radiation damage, energy deposition, leading to a high heat loads as well as structural changes in the targets. Secondary particles created in the targets, γ-quanta and neutrons being the most penetrating, cause high backgrounds in the vicinity of the target, magnets and detectors.

Superconducting magnets, specific for particle physics experiments, their coils and supporting structures, are sensitive to even small radiation impact, which can lead to loss of their superconducting properties and quench. On the contrary, reaching high secondary neutron fluxes and radiation damage in and near targets is the goal in facilities intended to studies, for example, in material science and ADS-related research.

The MARS15(2012) [1] is the latest version of a multi-purpose Monte-Carlo code developed since 1974 for detailed simulation of hadronic and electromagnetic cascades in an arbitrary 3-D geometry of shielding, accelerator, detector and spacecraft components with energy ranging from a fraction of an electronvolt to 100 TeV [2].

The Quark-Gluon String Model code LAQGSM [3] is used in MARS15 for photon, hadron and heavy-ion projectiles at a few MeV/A to 1 TeV/A. This provides a power of full theoretically consistent modeling of exclusive and inclusive distributions of secondary particles, spallation, fission, and fragmentation products. This code, very suitable for solving a wide range of problems concerning interactions of high-energy particles, is used in this work. For sake of a better agreement with the data, in simulations of interactions of several-GeV protons with high-Z materials we use LAQGSM generator above ~3 GeV and Cascade-Exciton Model CEM [3] below that energy and above tens of MeV.

The Mu2e experiment 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 [4]. 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 sophisticated absorber, 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 ProjectX Energy Station is proposed at Fermilab to carry out studies on radiation damage and other aspects of material science, as well as ADS-related research, using a spallation target irradiated by a GeV-range 1 MW proton beam. Despite the design has not yet been made, an option was recently considered [5] with a liquid lead or lead-bismuth target surrounded by a test matrix for ma-

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terial tests. In this work we are considering an alternative design with a solid tungsten target capable also to serve a test matrix. MARS15 calculations are performed to estimate energy deposition and radiation damage in the target, determine maximum attainable secondary particle fluxes and volumes of high neutron flux and DPA.

II. DPA MODEL IN MARS15

New MARS15(2012) DPA model for low-energy neutrons makes use of defect production cross sections calculated using the industry standard NRT [7] model for a database of 393 nuclides with the use of the NJOY99 code [8]. Cross section calculations are based on the ENDF-VII [9] data base of neutron-induced reactions on isotopes in the range from 10^{-5} eV to 20 (150) MeV.

After calculating NRT-type DPA for the particular elements in the problem, they are corrected for the defect production efficiency η [10]. This factor represents the ratio of the number of single defects produced in a material to that calculated by the NRT model, and scales the DPA to the experiment. Efficiencies are measured experimentally for a number of low-energy neutron spectra on a number of practically important materials, and agree well for different kinds of spectra.

III. MU2E PRODUCTION SOLENOID

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

The following quantities were calculated: dynamic heat load, peak power density, number of displacements per atom (DPA) in the helium-cooled solenoid coils, peak absorbed dose and peak neutron flux in the superconducting 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 is attained and also to determine requirements to the cooling system.

Spectra of neutrons and γ-quanta in the first, most heavily irradiated PS coil, are shown in Figure 2. Neutrons in the simulation had thresoulds 170 keV for γ-quanta and 0.001 eV for neutrons. Neutrons with energies <14.5 MeV contribute less than 1% to the total neutron flux in the coil.

DPA and power density levels in the PS coils are shown in Figure 3. These quantities are given in bands limiting the innermost ~6 cm of the coils near the beam exit (note similar longitudinal profiles).

The constraints in the Mu2e PS absorber design are quench stability of the superconducting coils, low dynamic heat loads to the cryogenic system, a reasonable lifetime of the coil components, acceptable hands-

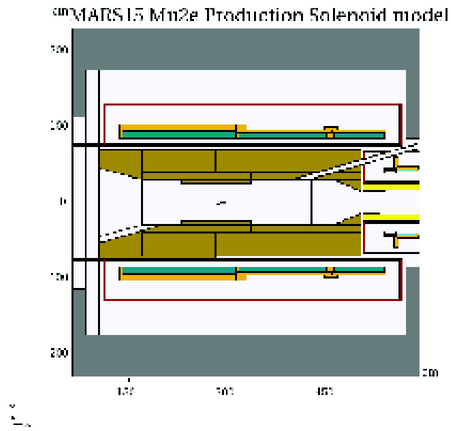

FIG. 1. MARS15 Mu2e PS model. Parts are: brown – Heat and Radiation Shield (bronze), green – NbTi/Al superconducting coils, orange – Al support structure, gray – concrete shield, yellow – Cu collimator leading to the muon transport system.

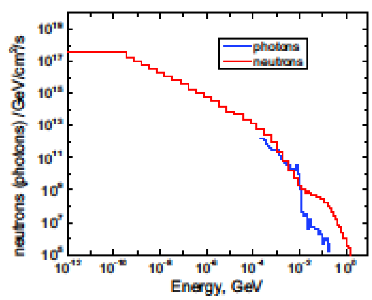

FIG. 2. Neutron and photon spectra in the first PS coil.

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 constraints [6]. Comparison to the requirements reveals that peak DPA is the most critical parameter as it is within the limit of $4-6\cdot10^{-5}$ DPA/yr, while peak power density, peak absorbed dose, and dynamic heat load are all well under the limits.

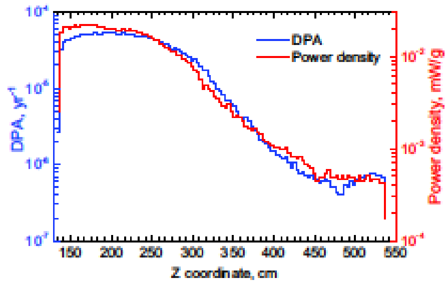

FIG. 3. Displacement per atom and power density levels in PS superconducting coils.

IV. AN OPTION FOR ENERGY STATION TARGET

In the framework of the prospective ProjectX at Fermilab, an Energy Station is considered as a facility intended for material and energy application studies. At the first stage of that project, 1 MW proton beam of 1 GeV energy could be delivered to the station. Recently, a proposal of a liquid lead or lead-bismuth target, surrounded by a matrix was simulated [5]. In this work we are studying with MARS15(2012) an alternative solid tungsten target option.

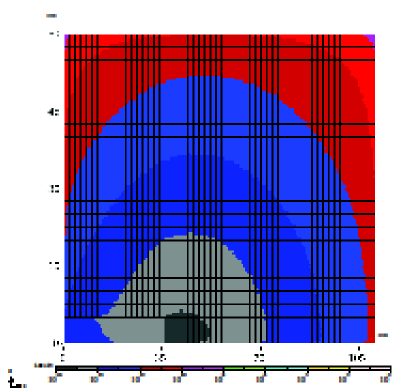

FIG. 4. Neutron flux R-Z isocontours in the tungsten target, $cm^{-2}s^{-1}$.

Target represents itself a cylinder of tungsten, 60 cm in radius and 110 cm in length. In the front of the target a 10 cm in diameter hole is made, 35 cm in length, for the beam entrance. Simulated proton beam intensity was $6.25{\cdot}10^{15}$ protons per second. The depth of the hole as well as the overall dimensions of the target are chosen to keep the neutron leakage below 2%.

Distribution of the total neutron flux in the target is given in Figure 4. The highest neutron flux within the target reaches the level of $2 \cdot 10^{15}$ n/cm^2/s, near surfaces it falls off down to 10^{12} n/cm^2/s. The peak instantaneous temperature rise does not exceed 220 K, which is far from the critical values for the target local meltdown.

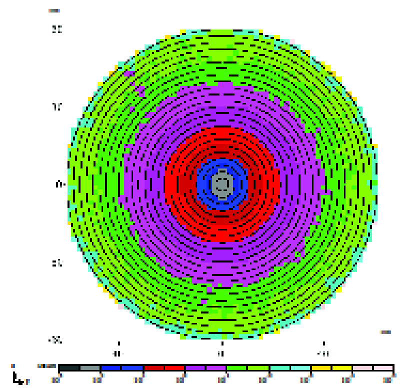

FIG. 5. Displacement per atom transverse isocontours at longitudinal peak in the tungsten target, yr^{-1}.

The peak DPA in the target (calculated as average within 10 cm from the end of the beam hole, in the shower maximum) (see Figure 5) amounts to $\sim$ 200 DPA/yr (year for fixed target experiments is assumed to be $2{\cdot}10^7$ seconds. This quantity near target surfaces is as low as 0.003 DPA/yr. Neutrons were found to be not the largest contributor to DPA, as pions and protons induce most part of the radiation damage.

Calculation of neutron flux (see Figure 6) test volumes allows a comparison with [5]. In addition we calculated also DPA test volume. Test volume with the flux within $3{\cdot}10^{14}$ and $5{\cdot}10^{14}$ $cm^{-2}s^{-1}$ is ∼8 liters as in the case of the lead target (13 liters for $> 3 \cdot 10^{14}$ $cm^{-2}s^{-1}$). Available DPA test volume is 0.8 liters (> 100 DPA/yr) or 3.3 liters (> 20 DPA/yr).

Spectra of particles produced in the target are given in Figure 7. Gamma flux becomes comparable to that of neutrons at 1-3 MeV. Secondary proton spectrum has a peak near the incident proton energy and falls off by an order of magnitude rapidly. Maximum of the neutron spectrum corresponds to ∼10 keV.

Agerage concentrations of hydrogen, helium and tritium in the volume of the target as a function of the distance along the beam are shown in Figure 8. For all the gases, peak values are at 35 cm from the front of the target (end of the beam hole, where the beam strikes the target).

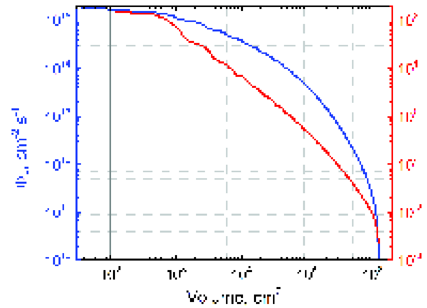

FIG. 6. Test volumes for the total neutron flux and DPA in the target.

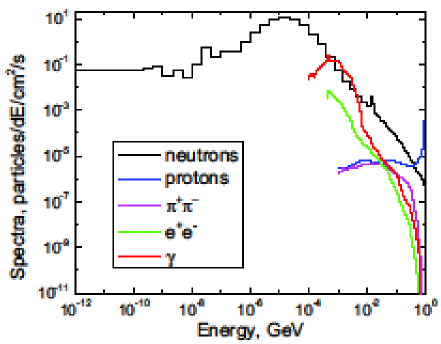

FIG. 7. Spectra of particles created in the target.

As a possible next step in the target design, a target from a fissile material, like the depleted uranium, can be considered. Preliminary MARS15 simulations showed that the recently obtained in integral experiments [11] axial distributions of fission rates in a 0.5 tonnes ^{238}U target as well as the integral fission rates in the incident deutron 1-8 GeV energy range (which is also suitable for ProjectX Energy Station) are well reproduced by the code (within experimental errors).

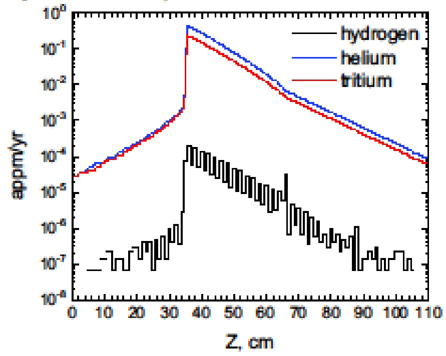

FIG. 8. Average gas production in the target volume.

V. CONCLUSIONS

Extensive MARS15 simulations for the design of two future experimental facilities proposed at Fermilab have been performed. Radiation damage (DPA), power densities, absorbed doses, gas production rates and other energy deposition related quantities have been calculated for the Mu2e Target Station and ProjectX Energy Station.

Radiation damage (DPA) appeared to be the most critical parameter for both Mu2e superconducting magnet coils, where it should be minimized and a level of 10^{-5} can be limiting, and Energy Station, where attaining large test volumes with a high DPA is the goal. Both target stations look promising and feasible from the point of view of the radiation quantities simulated.

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