Evaluation of the Beam Line Activation Levels during the 12 GeV GMn Experiment

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***Abstract*— The report presents results of the beam line activation studies for the 12 GeV GMn experiment to be run in the experimental Hall A at JLab in 2021. The activation was expected to be significant, and the need for the detailed ALARA studies was justified to achieve better planning of the personal accesses and manual operations in the vicinity of the beam line, required during the experiment. A detailed FLUKA simulation model for the beam line was created, and the simulations performed. The results show the expected dose rate levels after the run. The model is available for more evaluations, adjusted to the "as-is" experimental schedule during the experiment.**

***Index Terms*— ALARA concept, FLUKA Monte Carlo Simulations, Material Activation.**

I. Introduction

ALARA (As Low As Reasonably Achievable) concept plays an important role in planning experiments and during accelerator operations when delivering beams to the experimental halls at JLab. Typical experimental setup at JLab includes experimental target and the beam line containing the spent electron beam, and safely delivering it to the beam dump. Depending on the experimental conditions, such as beam energy and current, target material and thickness, special features limiting the exit line aperture, magnetic fields present, etc., the target and the beam line elements may become activated during the run. Such activation determines the radiation environment in the vicinity of the target and the beam line, and thus may impose limitations on the accessibility of the beam line elements during and after the run. Minimizing such activation by design is one of the activities helping to optimize operations, consistent with the ALARA principle. Beam line for the upcoming 12 GeV GMn experiment was designed with ALARA concept in mind, utilizing a novel type of conical exit beam pipe, protected from the stray magnetic fields.

II. GMn Beam Line Design

Fig. 1 presents one of the engineering drawings showing the vicinity of the experimental target, Interaction Chamber, the exit beam line and other equipment. The beam line contains a conical section with a series of elements providing magnetic shielding around it. The big experimental magnets are movable and have special provisions to allow partial overlapping with the beam line. Critical elements along the beam line are also the two corrector magnets helping to balance beam position at the dump shifted by the fringe magnetic fields. The target (15 cm length of liquid deuterium) is in the middle of the evacuated Interaction Chamber in the middle.

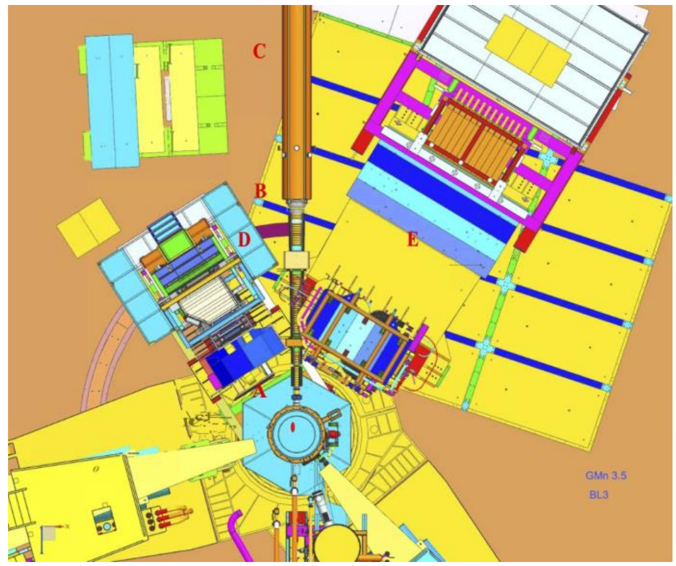

Fig. 1. Illustration to the general layout of the GMn beam line and other equipment in the vicinity. The capital letters (A, B, C, D, E) indicate the regions of interest for the calculations of residual radioactivity during and after the run.

III. FLUKA Simulation Model

Detailed FLUKA ([1], [2]) Monte Carlo simulation model was created based on the simplified engineering drawings of the setup, omitting multiple non-critical design elements, leaving in the model most of the volumes close to the beam, and approximating the surrounding objects using volumes made of proper materials with less detail. Such an approach improves performance of the simulation without compromising accuracy.

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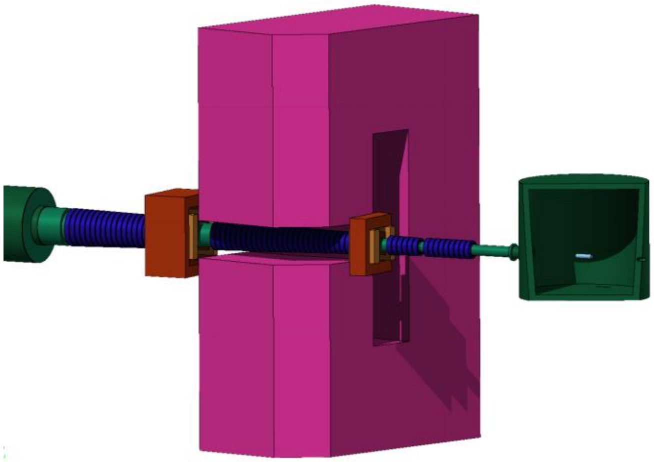

Fig. 2. 3D view of the FLUKA model for the GMn beam line. Cylindrical volume of the Interaction Chamber is cut out to show the location of the target inside. The beam exit line is modeled as a pipe with flanges, then conical volume with a set of iron magnetic shielding rings around it, exiting into a large-diameter exit pipe leading to beam dump. The beam displacement control quadrupole magnets, as well as the movable big experimental magnet surround the beam line.

The map of the magnetic field was introduced inside of the beam line, using the tabulated calculations by Bogdan Wojtsekhowski. All the simulations were performed using the magnetic field in the line. However, its influence on the activation results was not significant. Figs. 2 and 3 show the model geometry in 3D and as a cut in horizontal plane.

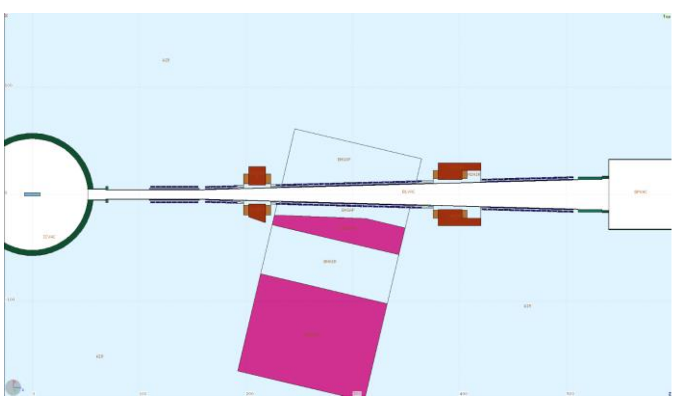

Fig. 3. Horizontal plane cut view of the FLUKA model for the GMn beam line. Cylindrical volume of the Interaction Chamber contains the target inside. The beam exit line is modeled as a pipe with flanges, then conical volume with a set of iron magnetic shielding rings around it, exiting into a large-diameter exit pipe leading to beam dump. The beam control quadrupole magnets, as well as the movable big magnet surround the beam line.

IV. Simulation Results

The FLUKA model was run for the planned beamline configuration and planned experimental conditions, to evaluate the prompt radiation fields during the run, and the dose rates from the activated beam line components after the run. The approximate running conditions for the basic simulation were selected to consist of two parts, first running at the beam energy of 4.4 GeV for 724 hours at an average beam current of 22 μA, then at 8.8 GeV for 64 hours, as per B. Wojtsekhowski. Prompt

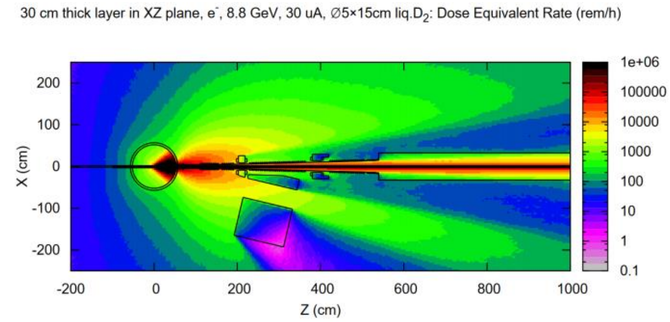

Fig. 4. Prompt total dose equivalent rates in the horizontal layer 30 cm thick during the run at 8.8 GeV beam energy and 30 μA beam current.

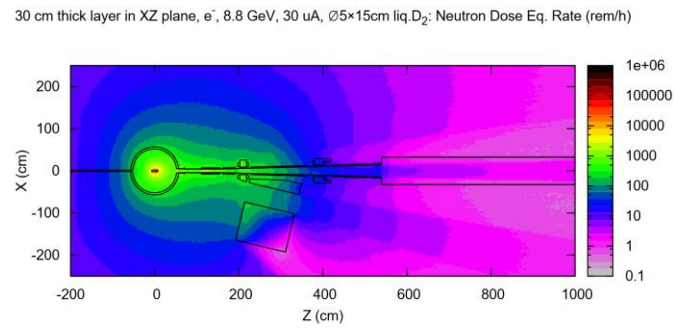

Fig. 5. Prompt neutron dose equivalent rates in the horizontal layer 30 cm thick during the run at 8.8 GeV beam energy and 30 μA beam current.

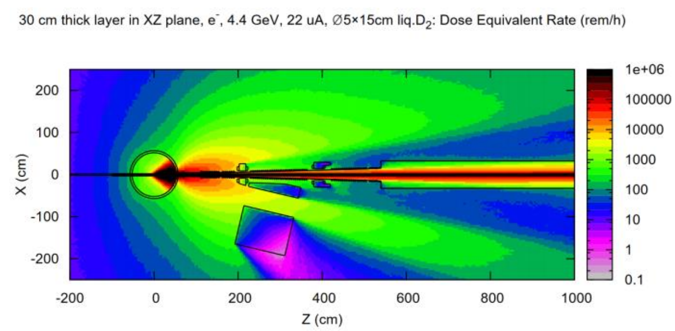

Fig. 6. Prompt total dose equivalent rates in the horizontal layer 30 cm thick during the run at 4.4 GeV beam energy and 22 μA beam current.

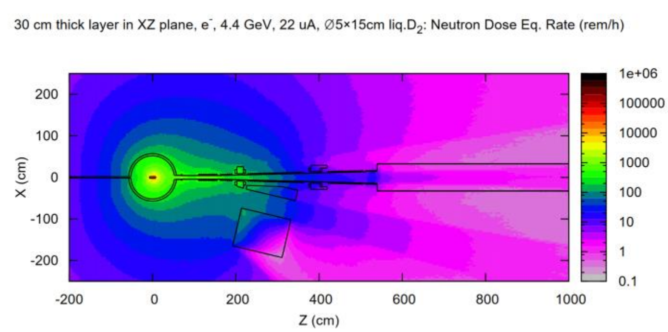

Fig. 7. Prompt neutron dose equivalent rates in the horizontal layer 30 cm thick during the run at 4.4 GeV beam energy and 22 μA beam current.

dose rates around the target during these runs are illustrated in Figs. 4 through 7, both for the total, and for the neutron dose equivalent rates. The dose rates in the immediate vicinity of the beam line are expected to be significant, as it is expected in such experiments. Measures should be undertaken to avoid radiation damages to the equipment nearby, by moving it out of the way, by shielding, or using radiation hard components.

During the run high energy electrons and photons interact with materials, inducing nuclear reactions. They lead to the production of radioactive nuclear isotopes and cascading products, including neutrons, capable of further nuclear interactions. As a result, multiple radioactive nuclides are produced, each characterized by its characteristic live time and the emitted radiation spectra. The beam line components become activated, exhibiting complex time-dependent radiation fields around them. FLUKA simulation is capable of handling all this complexity, producing the radiation field maps, function of the irradiation history, time after the irradiation end, and location.

The examples of such dose maps are given in Figs. 8-10. The task was to evaluate the radiation environment around the beam line after the set of runs at different energies, first at 4.4 Gev, and the second at 8.8 GeV. The calculations had to be performed separately, assuming that the radiation field from the first irradiation is decaying gradually during the second part of the experiment. The dose rates at 30 minutes after end of the second part will be the sum of the rates produced in the second par, with 30 minutes delay, and the rates from the first part, decayed during the 64-hour second run. Fig. 8 shows the contribution from the first portion of the run at the time of the second run stop. Figs. 9 and 10 show the contributions from the second part at the decay times of 30 minutes (approximately the time of first opportunity for someone to access the beam line), and 24 hours, a day after the experiment end. The contribution from the second portion of the run decays relatively quickly, but for the total dose rate evaluation it needs to be added to the remaining contribution from the first part of the experiment. The resulting total dose rate evaluated in the five characteristic locations as a function of time is presented in Fig. 11. The statistical and systematic error of the calculations may be estimated as approximately 30%. At this point the major factor that would contribute to the uncertainty, is the uncertainty in the running schedule, which may include beam delivery interruptions. All interruptions in the run will decrease the activation levels at the end of the experiment due to decays, so these estimates may be considered as conservative. After experiment the levels of activation can be verified using the radiation dose rate measurements, which may help evaluate the

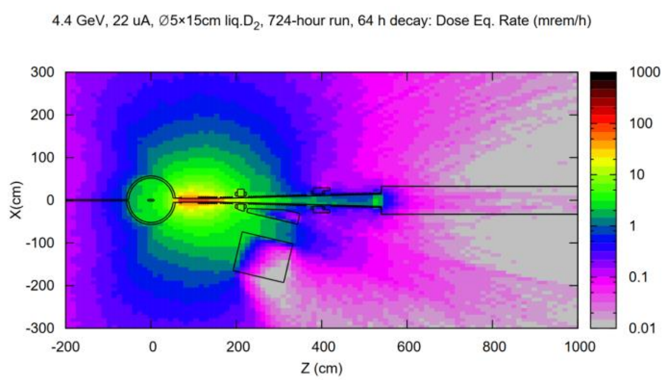

Fig. 8. Dose equivalent rates in the horizontal layer 30 cm thick, 64 hours after the end of 724-hour continuous irradiation during the run at 4.4 GeV beam energy and 22 μA average beam current.

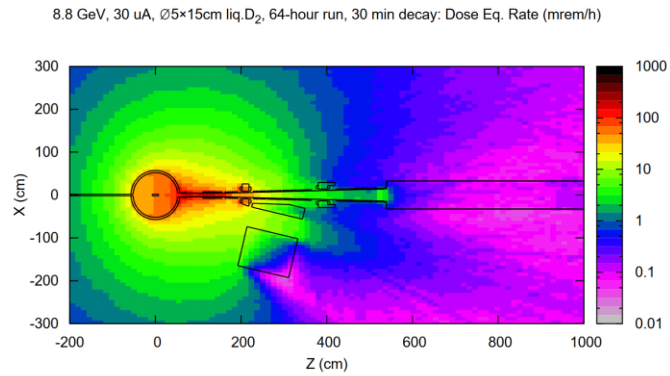

Fig. 9. Total dose equivalent rates in the horizontal layer 30 cm thick, 30 min after the end of 64-hour continuous irradiation during the run at 8.8 GeV beam energy and 30 μA beam current.

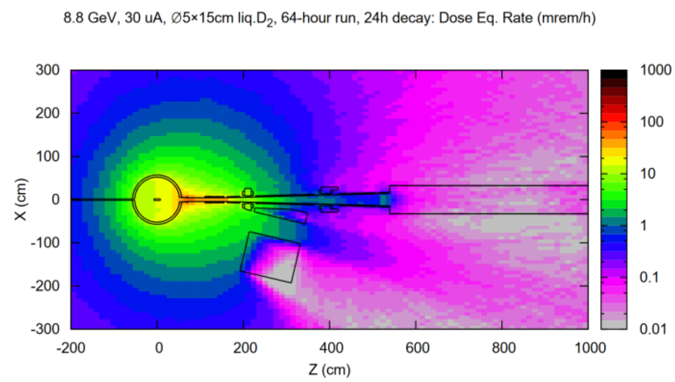

Fig. 10. Total dose equivalent rates in the horizontal layer 30 cm thick, 24 hours after the end of 64-hour continuous irradiation during the run at 8.8 GeV beam energy and 30 μA beam current.

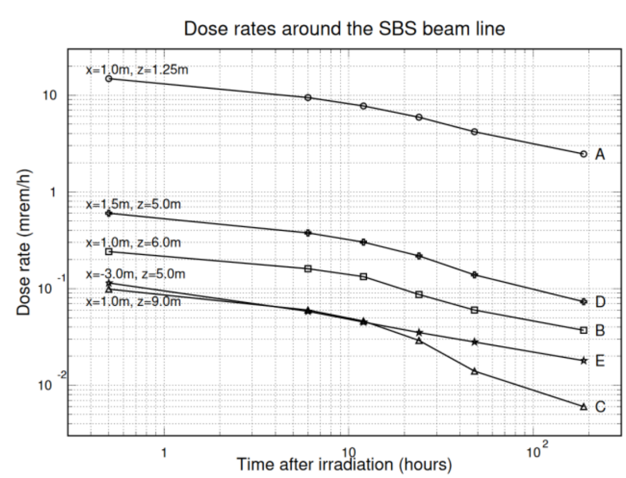

Fig. 11. Evaluated dose rates in the five locations around the beam line (A, B, C, D, E as referenced in Fig. 1), function of time after irradiation, from 30 minutes to 1 week. The locations are within +/- 15 cm of the horizontal plane, in the vicinity of the (x,z) coordinates indicated next to each series.

reliability of FLUKA model simulations.

V. CONCLUSION

Beam line activation studies for the 12 GeV GMn experiment to be run in the experimental Hall A at JLab in 2021 were performed using the FLUKA Monte Carlo simulation tool. A detailed FLUKA simulation model for the beam line was created, and the simulations performed. The results show the expected dose rate levels after the run. The model is available for more evaluations, adjusted to the "as-is" experimental schedule during the experiment, and also open for evaluation of extra radiation protection measures if necessary.

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