An Algorithm for Calculating Residual Doses

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Background

The future Mu2e experiment at Fermilab will attempt to observe the neutrinoless conversion of muons into electrons, which, if discovered, would reveal physics beyond the Standard Model. In order to generate the quantity of muons necessary for the experiment, a high-intensity proton beam will be required [1].

In addition to the radiological hazards posed by such a particle beam during operation, beams can activate the structures enclosing them. Collisions between beam particles and nucleons in surrounding structures transmute these nucleons and create radioisotopes.

Quantifying this hazard is essential for personnel safety and compliance with Fermilab radiological standards. Our project aims to develop a reasonably general and accurate procedure for estimation of residual doses. Such an algorithm would have use not only for Mu2e but for other radiological calculations as well.

Algorithm

1. Run a Monte Carlo simulation of the incident particle beam to calculate the radionuclides produced for each region of interest (Figure 1). For large regions, construct a histogram to estimate where these nuclides are produced (Figure 2).
2. Solve the differential equations for nuclear production and decay to determine the quantity of all nuclides after irradiation and cooling.
3. Perform a second Monte Carlo simulation to track the gamma rays emitted by the nuclides present after cooling (Figure 3). Calculate the dose these gamma rays deposit throughout the area of interest.

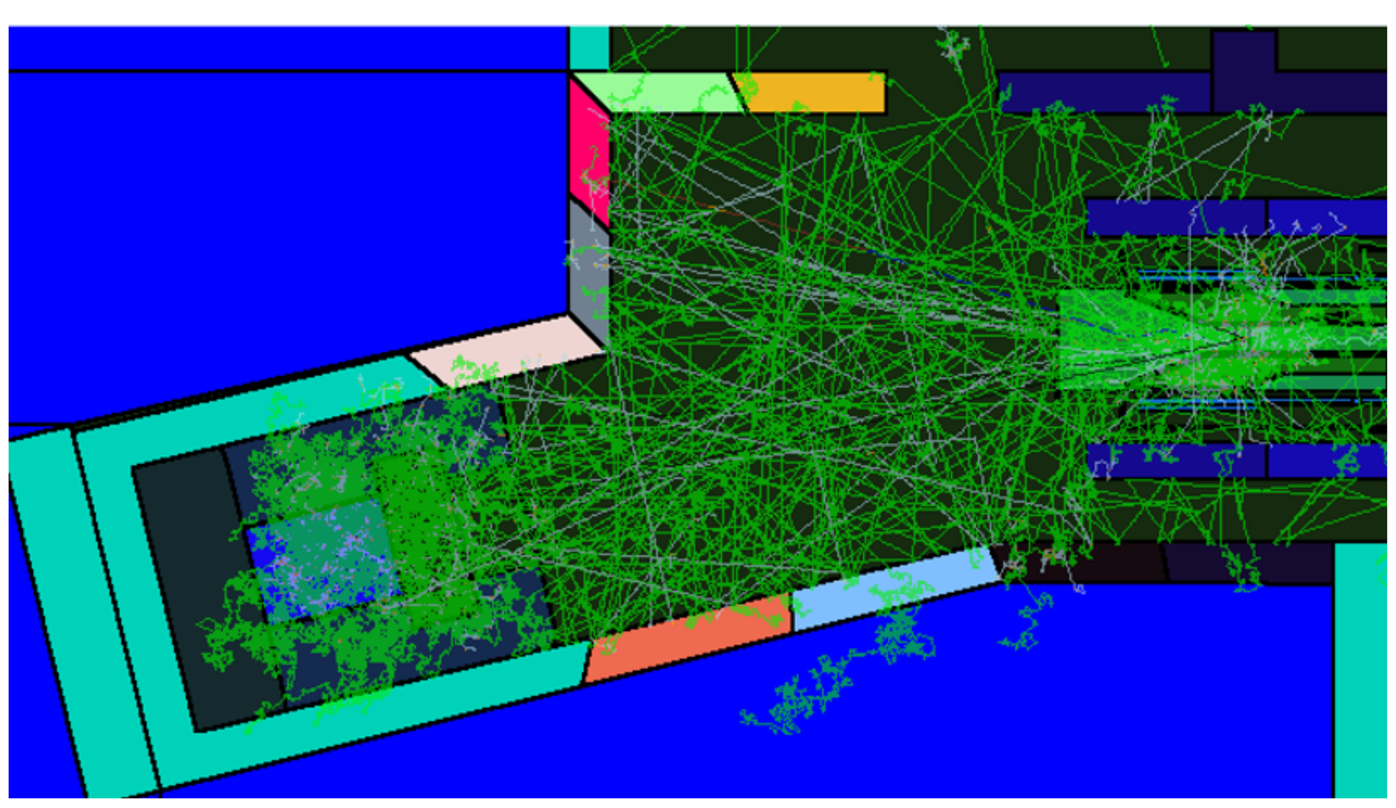

Figure 1 (top left): A sampling of neutrons (green) and gamma-ray photons (white) emitted during the first stage as a particle beam strikes the target and beam dump.

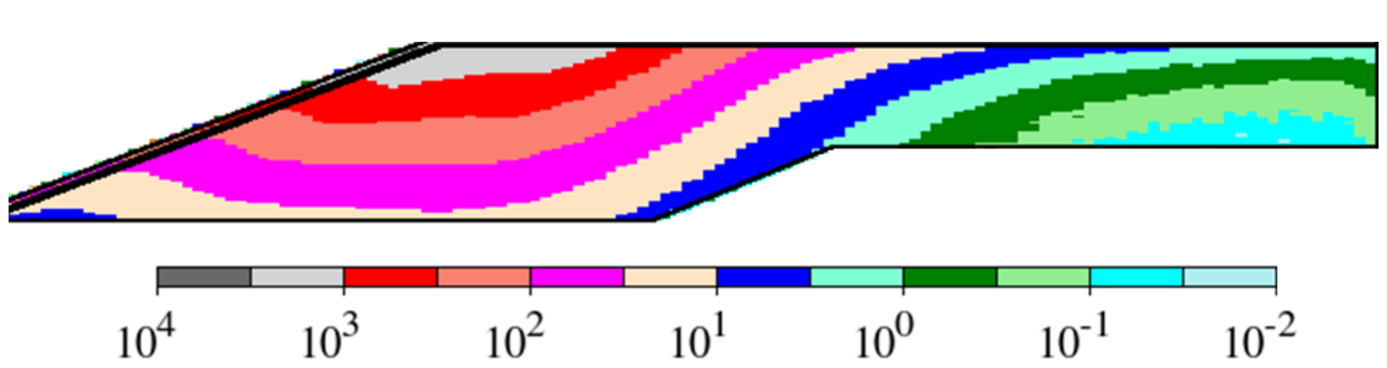

Figure 2 (middle left): A histogram of the relative activities of various areas of the Heat and Radiation Shield of the future Mu2e experiment following activation. Units for this purpose are arbitrary.

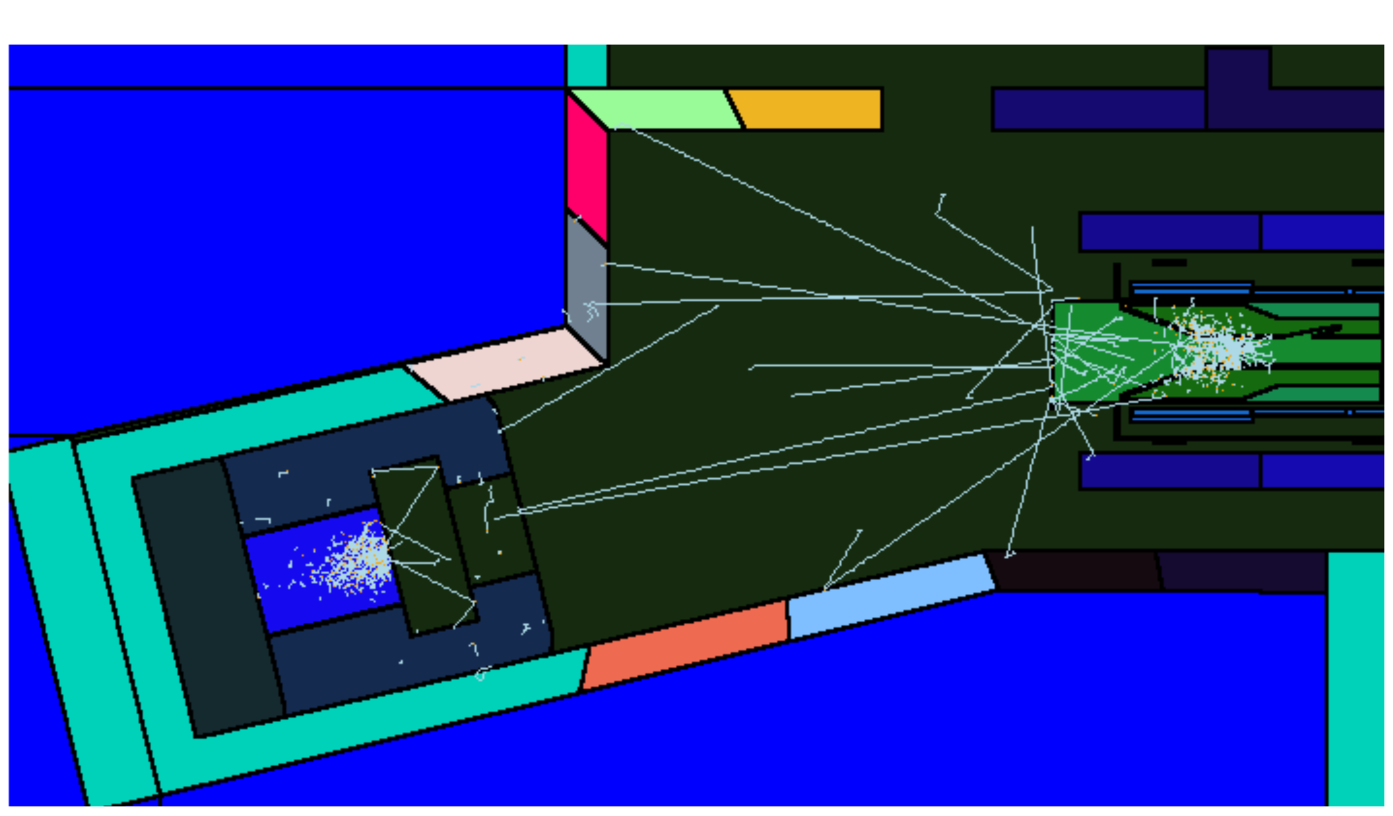

Figure 3 (bottom left): A small sampling of photons emitted during the final stage of the simulation. These photons determine the residual dose.

Results

We benchmarked our programs against the DORIAN code, developed by R. Froeschl, to calculate residual doses. As described in Froeschl's paper [2], we measured the residual dose from a proton beam striking a copper target. The agreement is good for cooling times on the order of days to months but worse for shorter or longer timescales (Figure 4).

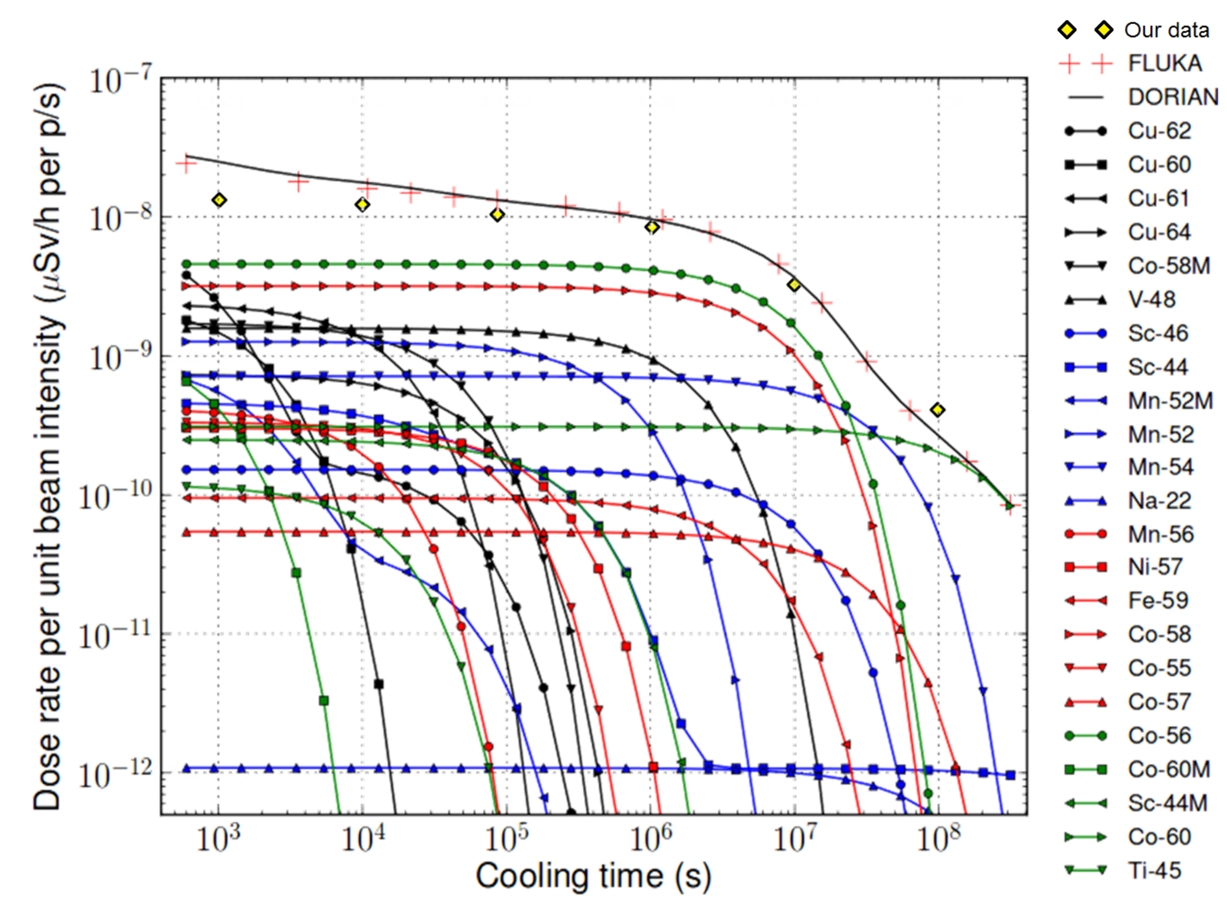

Figure 4: The residual dose from a Cu target calculated by our method (yellow diamonds) compared to results from the codes FLUKA (crosses) and DORIAN (black line). The relative contributions of the various isotopes were calculated from the DORIAN code. Graph taken from [2].

We also used our method to estimate residual doses in the structure housing the production solenoid for the future Mu2e experiment. The residual dose was calculated based on one year of irradiation and one week of cooling (Figure 5).

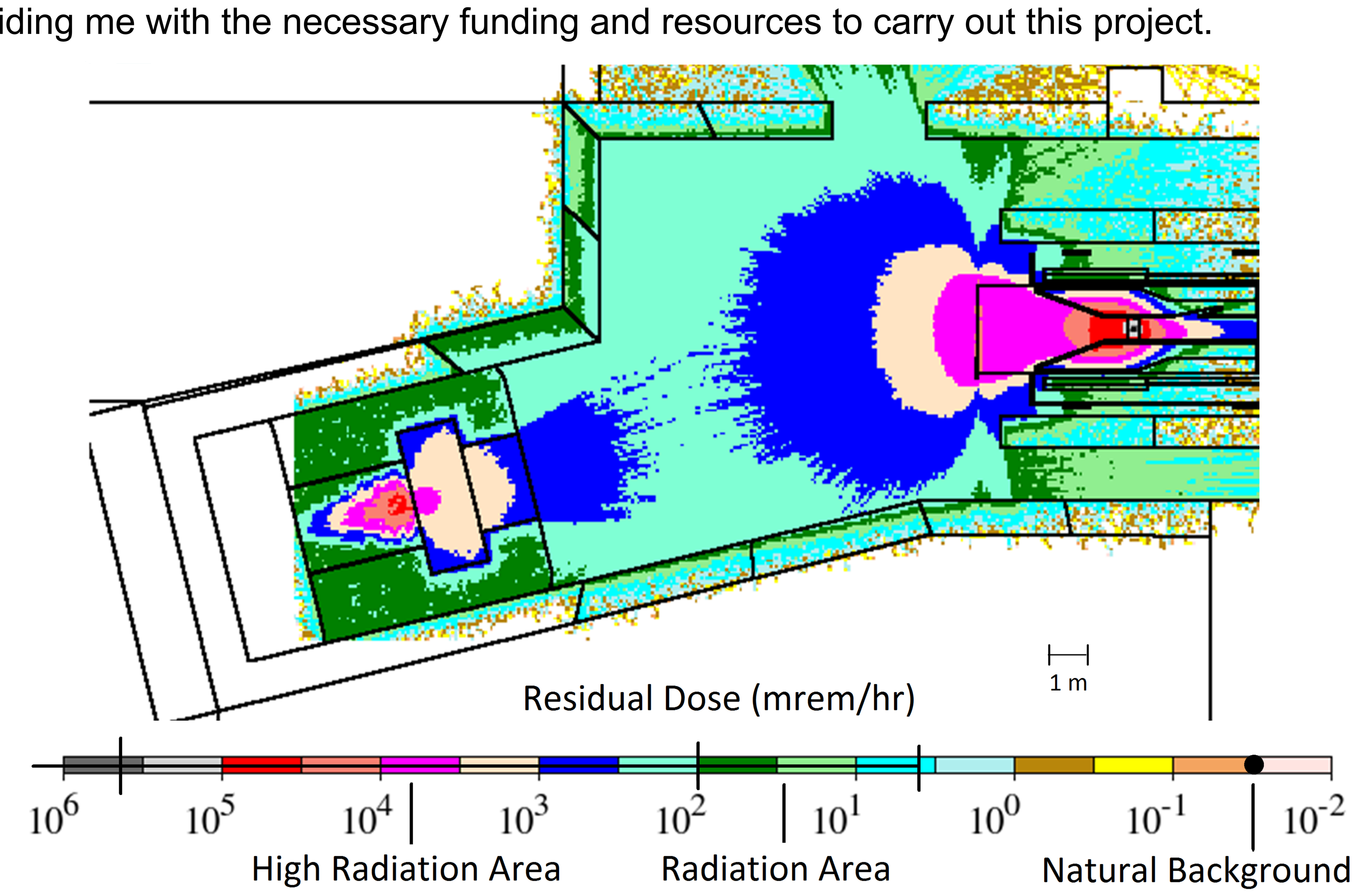

Figure 5 (right): Calculation of the residual dose after one year of irradiation and one week of cooling in the Production Solenoid hall of the Mu2e experiment.

References

[1] Bartoszek, L., et al. “Mu2e Technical Design Report.” Fermilab-TM-2594. Oct. 2014.
[2] Froeschl, R. “The DORIAN code for the prediction and analysis of residual dose rates due to accelerator radiation induced activation.” Eleventh International Topical Meeting on Nuclear Applications of Accelerators. Studiecentrum Voor Kernenergie and Centre d'Etude de l'Energie Nucleaire, Aug. 6, 2013. Web. June 17, 2015.
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[4] Mokhov, N. V., Rakhno E. I., and Rakhno, I. L. “Residual Activation of Thin Accelerator Components.” Fermilab-FN-0788-AD. May 2006.

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