Accelerator Shielding Design for Active Interrogation Methods Development

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INTRODUCTION

A Varian 9-MV [1], 1 kW linear accelerator is being installed at the University of Michigan to enable investigation into the feasibility of using organic scintillators for active interrogation signature detection. The accelerator was previously used at Rapiscan Systems, and is housed in a shielding enclosure tailored to homeland security applications. Special nuclear material (SNM) proxies will be interrogated by 9 MeV endpoint bremsstrahlung photons to induce photonuclear reactions. The challenge in this investigation is to discriminate these neutrons from the large photon flux scattered by the target, and those directly from the accelerator. Shielding of the accelerator will limit the extraneous dose to operators and detectors, while allowing for optimal flux on the target.

The linear accelerator is housed in the basement floor of the Nuclear Engineering Laboratory at the University of Michigan, which formerly housed the Ford Nuclear Reactor. While the reactor building walls provide significant shielding to the public from the accelerator, there are certain spatial constraints that provide challenges for shielding in the laboratory. The beamline is directed towards a separate laboratory space, and must be fully attenuated to less than occupational limits. A door to this separate laboratory is also in the down-beam direction, and must be shielded. The overall goal of this shielding study is to fully cover a 30 cm×30 cm square target of material with the full, unfiltered flux of the beam, while keeping dose rates below safety limits. It is also ideal to limit the amount of shielding in the target area to reduce the probability of non-signal particles being created near or scattering into the detectors.

Dose rates are simulated with MCNPX 2.7.0 [2] and MCNPX-PoliMi [3] These simulations support the safety certification process and pre-installation experiment planning. Once the accelerator has been installed, dose rates will be evaluated with standard dose rate survey meters and organic scintillator detection systems to complete safety certification.

METHODS

Model Development

The model for the accelerator laboratory was designed in MCNP using measurements of the space along with construction documents. The shielding enclosure for the accelerator was modeled using exterior measurements and Rapiscan-provided interior diagrams. The largest unknown aspect of the accelerator model is the dimensions of the conversion target itself, as it is a proprietary Varian design.

The known design value for this accelerator is that the dose rate at 1 m from the target is 2700 Rad/min. It is also known from correspondence with Varex Imaging Corporation that the cylindrical conversion target is tungsten with a copper layer on the downstream side. The target dimensions were estimated to be 23 mm of tungsten backed with 15 mm of copper. This tested target dimension results in a simulated dose rate 16% greater than the specified value. With uncertainties in dose rate measurement techniques, we are assuming that this design offers a conservative estimate to the true target dimensions.

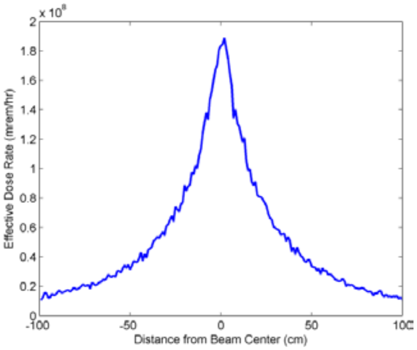

Fig. 1. Simulated photon dose rate beam profile 1 m from bare electron conversion target.

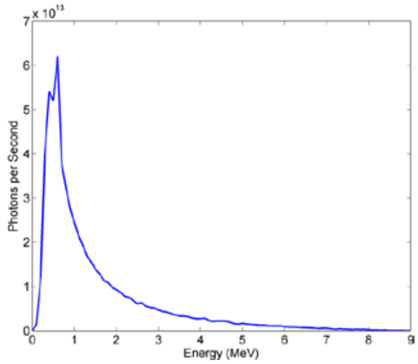

Fig. 2. Simulated photon spectrum, 100 µA 9 MeV electron beam on copper-backed tungsten target. Sampled 1 m from conversion target in forward beam direction.

Fig. 1 shows that the photon flux is forward directed without any additional shielding, reducing the need for transverse shielding of the conversion target. Fig. 2 shows the expected 9 MeV endpoint bremsstrahlung target resulting from 9 MV electrons imparted on a heavy metal target. Along with the inherent forward directedness of the source the custom shielding enclosure cuts the beam to a 16.7° half-angle cone.

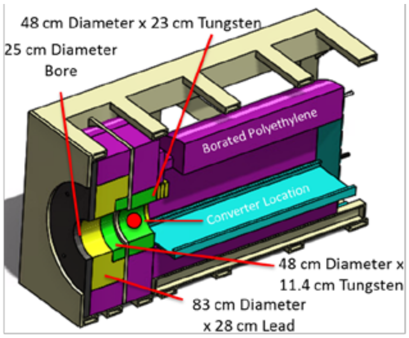

Fig. 3. Shielding enclosure for linear accelerator.

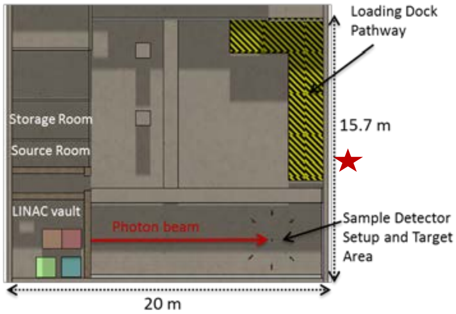

Fig. 4. Laboratory setup with linac location and beamline orientation.

The accelerator in its shielding enclosure shown in Fig. 3 is placed in a shielded room within the laboratory. The placement of the linac is shown in Fig. 4. The cone of the beam will be further reduced by secondary collimators in the linac vault. With this arrangement fully modeled in MCNP, operational parameters can be optimized against dose rate.

Simulation Methods

To obtain accurate simulation results while minimizing the necessary computation time, multiple approaches must be taken depending on the goal of the simulation. These goals can be split into two main categories: dose rate assessment and detector response to an irradiated target.

Dose Rate Mapping

To simulate dose rates, a dose-converted [4] flux mesh tally is used in MCNPX. Full spatial and source profile integrity is required. Because dose rates must be shown for the entire lab space, the entire geometry must be simulated. The source has a spatial dependence as well (shown in Fig. 1), and any simplifications would lead to inaccuracies in the dose rates. Therefore, the source must be modeled directly from the electron beam to preserve spatial integrity and maximize statistical sampling. The complication with this modeling is that charged particle transport is very slow in MCNPX, since each atomic interaction must be sampled.

A large simulated detector volume can be used to generate statistically sound results in a reasonable computation time. In this case, a mesh tally was defined using 50 cm cube voxels. This size was chosen based on the size of a human, and the fact that minute spatial variations in the dose rate map are not expected to affect the overall results in such a large space. Therefore, the calculated dose rate can be averaged over these relatively large voxels.

Detector Response

Detector response simulations require acquisition of a simulated energy spectrum, so a more detailed estimator is required. In these cases, photons from the accelerator are incident on a target material, and a detector is facing the interrogation target. This detector is 50 cm away from the target perpendicular to the beam direction. Because the signature produced by the source photons interacting in the target is of interest here, effects from other particles scattered around the laboratory can be ignored. The flux due to these particles is many orders of magnitude below the flux resulting from the main beam. The target will be placed ~12 m from the source, so the photons are assumed to be a parallel beam. These assumptions allow for simplifying the model to a parallel beam of photons over the face of the target, with nothing in the model but detector and target. The results can be scaled appropriately based on the known geometry and source parameters.

RESULTS

Experimental Optimization

The immediate goal of this experiment is to develop methods for using organic scintillators in an active interrogation system. The design of the shielding for the laboratory must therefore allow for adequate flux on the target to produce the relevant signatures.

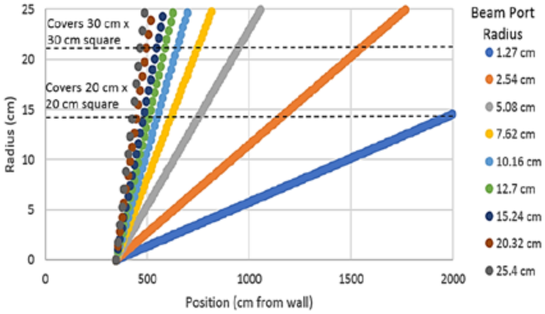

Fig. 5. Square target coverage with different size beam ports in linac vault.

Fig. 5 shows that the beam is capable of fully covering a 30 cm square target 12 m from the photon source if the bore is at least 5 cm in diameter.

To observe the trend of the target size effect, cube targets of increasing size were simulated. These targets were tested with 4 possible target materials: lead, tungsten, heavy water (D_2O) and depleted uranium (DU). Since induced neutron emission is very indicative of special nuclear material, detection of neutrons is treated as a valuable signal for detecting SNM. The best proxy material for SNM will produce the highest ratio of neutrons per photon.

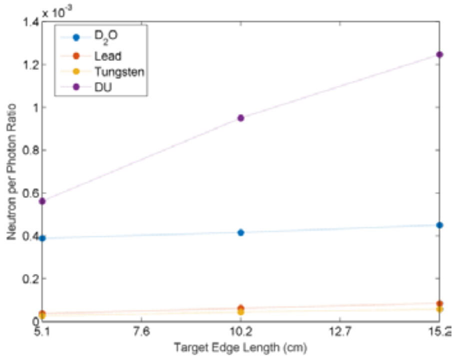

Fig. 6. Signal-to-noise ratio for different size targets of possible SNM proxy materials.

While DU and D_2O have the highest ratio of neutrons to photons as shown in Fig. 6, these ratios are fairly low. This demonstrates the challenge of detecting neutrons in a large photon flux. With this accelerator installation, detection methods will be developed to overcome this challenge.

Dose Calculations

While a large beam would be ideal for maximum target coverage, dose rates must be considered. The location of the star in Fig. 4 is where there is a loading dock door, which the beamline is directed towards. Although the laboratory on the other side of the door is not a public space, this is the limiting location for dose rate, and should be kept under 5 mrem/hr[5] while the beam is on.

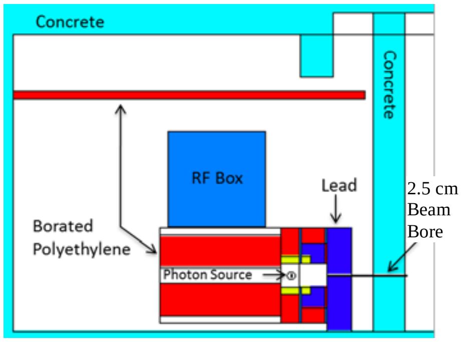

Fig. 7. Elevation view of base shielding for linac enclosure, bore constricts beam to desired size.

With the shielding arrangement shown in Fig. 7, the dose rate was simulated at the limiting position with different size beam bores. For initial certification, the accelerator will be tested at its lowest available current, 10 μA. The dose rate with these parameters is estimated to be 4.5 mrem/hr for the 2.5 cm bore and 18.6 mrem/hr for the 5 cm bore. Because at least a 5 cm bore is desired for target coverage, additional shielding is required to meet the dose rate goal of 5 mrem/hr.

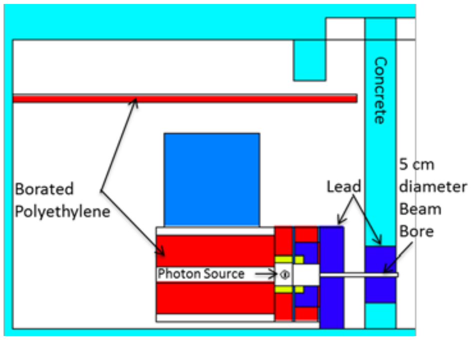

Fig. 8. Elevation view of shielding for linac enclosure, with additional secondary lead collimator.

Fig. 8 shows the additional lead collimator, which is a 74 cm square, 41 cm inches thick. This size collimator covers the full profile of the beam at that location. The dose rates simulated with this secondary collimator in the model are shown in Fig. 9 and Fig. 10.

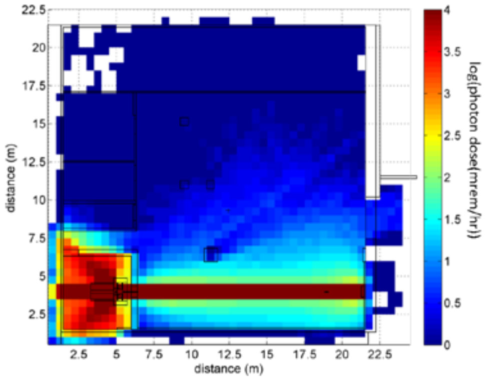

Fig. 9. Photon dose rate map of accelerator laboratory space.

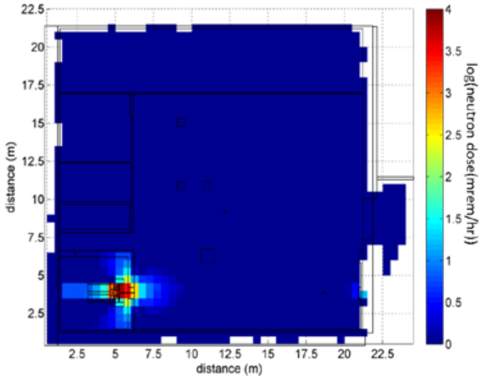

Fig. 10. Neutron dose rate map of accelerator laboratory space.

The full photon dose rate map is shown in Fig. 9, and the dose rate at the limiting location is below the target dose rate at 4.2 mrem/hr. Fig. 10 also shows that neutron dose is not a concern outside of the linac vault itself.

CONCLUSIONS

The simulated shielding design provides a plan to suppress dose rates below targeted limits. The concrete linac vault is sufficient to shield the photoneutrons produced in the shielding enclosure. While additional photon shielding is required to meet the dose rate goals, it can be incorporated into the linac vault area, leaving the beamline open for experiments. This shielding configuration allows for full-flux coverage of a 30 cm square target. Complete target coverage maximizes photoneutron production in a large target, enabling practical experimental design for the testing of organic scintillators

While the limited space and orientation of this laboratory space provides challenges for developing a shielding design, it was possible to develop a practical shielding plan. Full charged-particle simulation with large detector voxels allowed for accurate simulation of the entire lab space. For the detector response simulations, constraining the problem allowed for accurate characterization of detected spectra with practical computation time.

REFERENCES

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