Monte Carlo simulation and analysis of soil activation in and around the Brookhaven Linac Isotope Producer

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Abstract

The Brookhaven Linac Isotope Producer (BLIP) uses proton beams coming from Brookhaven's linac to create radionuclides used for medical and research purposes by guiding the beams into target disks made of different isotopes. Incident protons, however, have enough energy to interact with nearby equipment (e.g. magnets, beam pipes, etc.) and create a cascade of radioactive particles. Some of these particles can pass through the concrete walls and become embedded in the surrounding soil leaving a chance for rainwater to carry the radioactive particles away into the water table below. Our project was geared towards evaluating the extent at which radiation and particles travel after such interactions. We focused our attention on two parts of BLIP: the target arrays and a rastering magnet in the Linac to BLIP transfer line. Using the Monte Carlo N-Particle eXtended (MCNPX) transport code we modelled the target arrays, beam pipes, magnets, and other machinery found in the beam line and ran simulations that bombarded the target arrays and collimator in front of the rastering magnet with billions of protons while tracking the movements and energies of every particle that traveled through the target area or was created by a spallation reaction. The simulations produced contour diagrams that correspond to neutron flux and show the extent and danger of particle interactions in the soil. These simulations will contribute to Brookhaven's and the Department of Energy's goal of engaging future generations in scientific research and providing evidence of their strong stance on the issue of environmental conservation. This opportunity has provided me with a chance to build on my knowledge of computational physics—since I got to use MCNPX and navigate Linux/UNIX shells—and put me right in the middle of accelerator and collider design and engineering, which further prepares me for my future career in particle physics.

I. Background

Soil activation occurs as a result of high-energy particles leaving the vacuum chambers that contain them and interacting with the materials along their flight paths. Particles only leave the vacuum chambers when the beams are being absorbed by beam dumps and they are no longer needed. The materials that the particles interact with include those used for beam dumps, magnets, cooling pipes, accelerator walls, and such equipment found within the collider-accelerator complex. While the list of different materials is lengthy, we can approximate particle interactions with some common core materials: steel, aluminum, copper, rubidium chloride, concrete, earth, and air.

The Brookhaven Linac Isotope Producer (BLIP) uses beams of protons and heavy ions at energies of approximately 200 MeV; energies large enough to cause fragmenting of material nuclei in processes known as *spallation reactions* (Figure 1).[1] An analogous collision would be that of a cue ball striking a racked set of balls in pool. The energy of a single proton or nucleus is large enough, at velocities approaching the speed of light, to break other nuclei down into smaller parts which are usually unstable and begin a cascade of radioactive particles.[2]

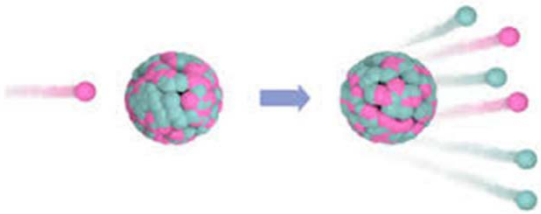

Figure 1: A spallation reaction involving a proton and heavy nucleus. The incident proton carries enough energy to make the nucleus fragment into smaller products. http://myrrha.sckcen.be/en/Engineering/Spallation_target

After these spallation reactions occur between high energy protons and accelerator materials, the products are ejected throughout the collision area and the more energetic

particles pass through the concrete walls and into the soil shielding around the tunnel. [3] Most of these products are relatively short lived and decay into stable counterparts; however, some isotopes such as ^{3}H and ^{22}Na can remain intact in the soil as they have very long half-lives and are easily leachable. The soil used for shielding that contains these radioisotopes is termed *activated soil*.[1]

For this project we simulated the interactions between high energy protons and two areas within BLIP using Monte Carlo calculations. These calculations produced distributions of the activation around the areas of high intensity beam collisions, which we will refer to as *hotspots*. Monte Carlo methods involve the transport of particles through materials in large numbers of steps. In each step different physical processes occur with a given probability. This leads to either a particle continuing along a given path or interacting with material causing other particles to spawn. The end results were given as a file containing a mesh tally used for contour diagrams with peaks where the tally numbers were highest, corresponding to larger amounts of free neutrons released from collisions. This data was taken for both the target array and rastering magnet in BLIP.

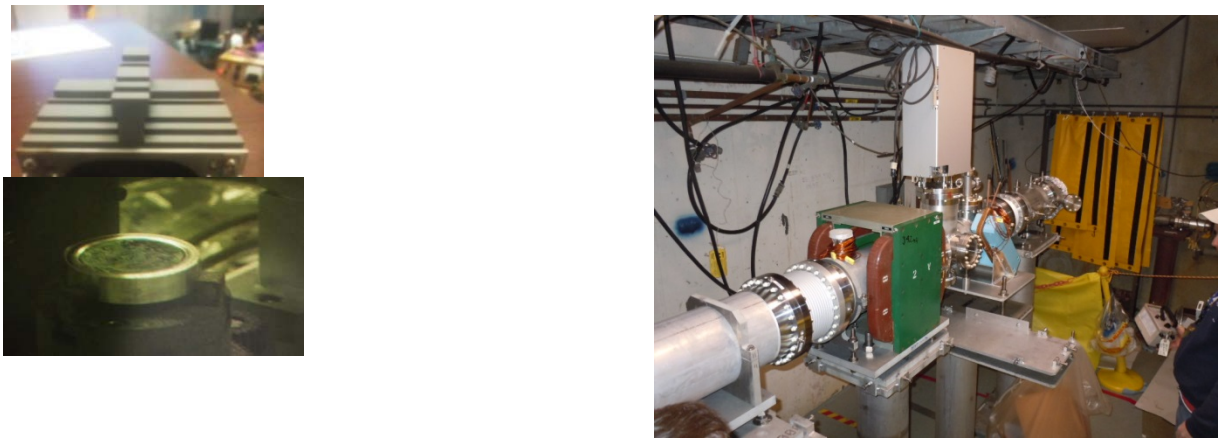

Figure 2: To the left is a picture of the target array holder and a rubidium chloride target. This area is a high radiation hotspot due to the high intensity beams that hit the different materials within. To the right is the rastering magnet upgrade that has a collimator within.

II. Methods

A. MCNPX Modelling

The first part of this project involved the target array in BLIP. This beam dump was recently replaced by a cold snake and is no longer in use, but its simulation will serve as a historical account of soil activation on which future examinations can be based. The plans we used for the modelling came from a collection of three decades worth of material. Some of the old mechanical drawings were contradictory, which resulted in us having to rely on our informed judgment; however, we did have the actual beam dump to look at since it is currently being used in a very high radiation zone. Using copies of the plans for the BLIP target array we made digital models of BLIP in a cube of space 762 cm (25 feet) on each side centered on the array.

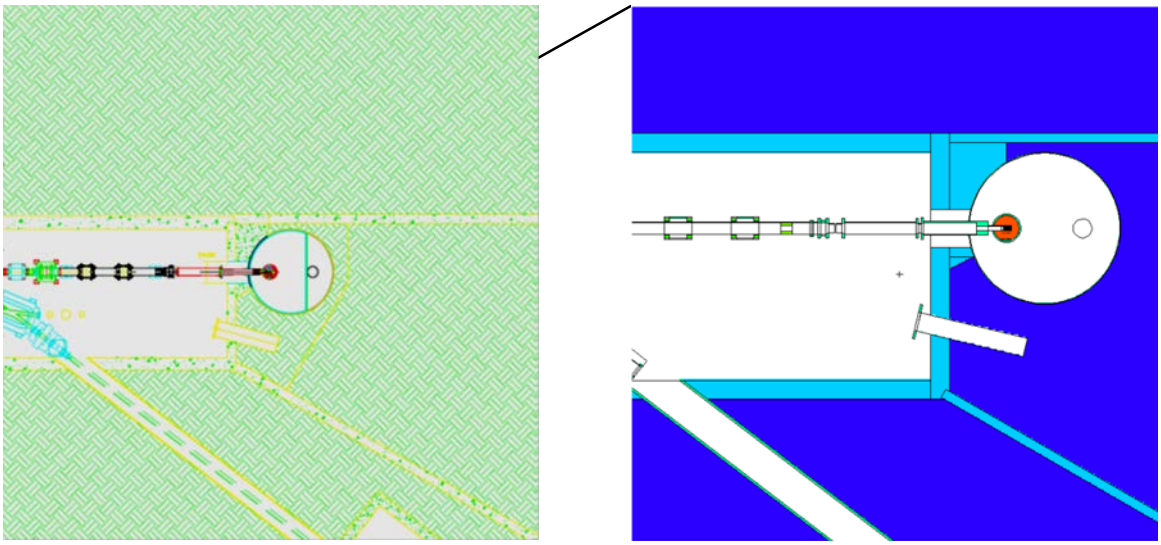

Figure 3: The picture on the left is an AutoCAD drawing of BLIP centered on the target array. The picture on the right is an MCNPX model of the same section that we coded. We can only view one plane at a time with MCNPX, so some details are not shown in the above MCNPX model as they do not exist at the particular horizontal coordinate.

We constructed these components, the stands they sit on, the concrete walls, and surrounding soil using the Monte Carlo N-Particle eXtended Transport Code (MCNPX).[(4)] MCNPX is a specialized program developed at Los Alamos National Laboratory that can simulate high energy interactions between 34 different elementary particles and over 2000 heavy ions based on experimental data files collected for nearly all elements.[(4)] Programming and running simulations involves various logical arguments to develop cells for which components are defined, rather than having a drawing interface like certain computer-aided design programs (e.g. AutoCAD); so modelling can be quite difficult for more complicated shapes like the rotated cylinders of the beam pipes in BLIP. Errors in the code are not obvious at first and only come to light after running the code using the MCNPX graphical interface. The version of the interface we used is rather limited; there is no 3D/isometric view, so we had to see what we created in 2D one plane at a time. This made it difficult to immediately find faults, which appear as red dashed lines with a “cookie-cutter cell” warning displayed to the left of the plot. We ended up checking the model after coding each cell to make sure no contradictions would be left uncorrected.

We followed the same process for the BLIP’s upgraded rastering magnet. The dimensions for the space were the same as the previous model, but there were a few major differences. Instead of centering on the target array, we centered on the face of the collimator in front of the rastering magnet. This means that we had to code the beamline that exists within the space. This beamline

contains multitudes of multipole magnets, meaning there are magnets with cores that are rotated at angles contained in the solution to the unitary roots problem. This required making rotated pole pieces for quadrupole and octupole magnets. For this we took advantage of one of MCNPX's construction abilities that involves using translational and rotational matrices to orient an already constructed cell whichever way we chose. This, however, required some more advanced coordinate geometry methods than usual and took some time to figure out. But from then on the modelling became fairly easy.

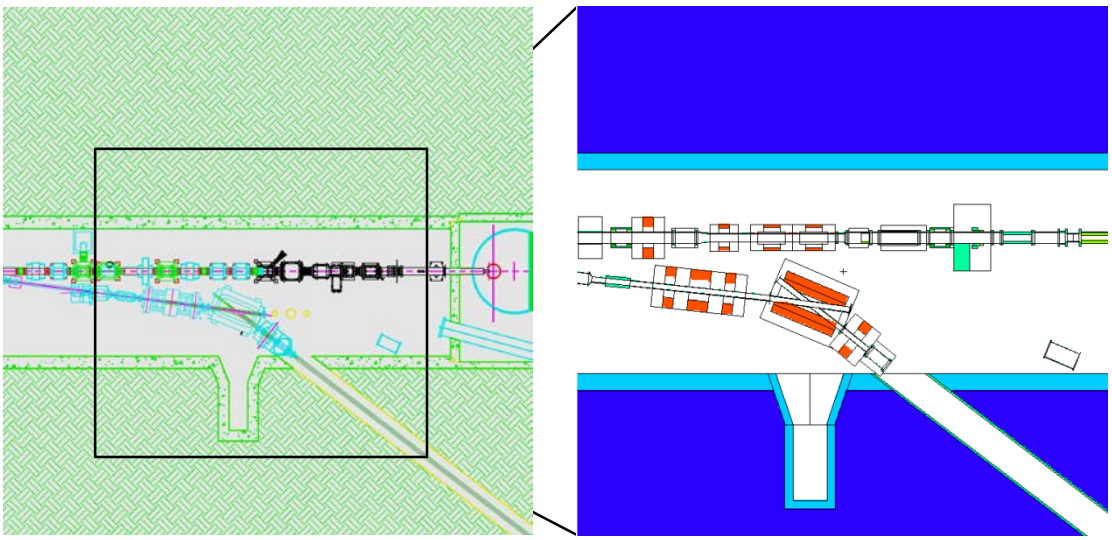

Figure 4: To the left is an AutoCAD drawing of BLIP centered on the new rastering magnet. The picture to the right is an MCNPX model of the same section. Note the relative complexity in modelling between the target array section and the rastering magnet section; there are now two beam lines instead of one.

B. Running Simulations

After the modelling was completed, we submitted the files to various supercomputers across the nation. Using a UNIX based Secure Shell (SSH) between various laboratories, we then chose the three best computers for our work.[5] We used a computer here on site in the Brookhaven Linux Cluster (BLC) as well as two others owned by the National Energy Research Scientific Computing Center (NERSC) called Edison and Hopper, both of which are currently operated by

Lawrence Berkeley National Laboratory (LBNL).[6] Transferring the files involved file format conversions so that the format for the code could adhere to the UNIX operating system rather than Microsoft Windows.

We ran the simulations over multiple times until we reached totals of 2 billion incident protons. This was a large enough sample to sharpen the output file contour diagrams and serve as an appropriate statistical representation of the interactions within the beam pipe. We then extracted the output files of the simulation (we will refer to these as ".o", pronounced "dot-O" and ".m", pronounced "dot-M" files). The .o files contained particle logs, monitoring the particle count, the energies, travel paths, and flight times for each; the .m files contains a mesh tally that can be used for calculations in the MCNPX command line interface producing contour diagrams of particle flux that can be overlaid with the input models.

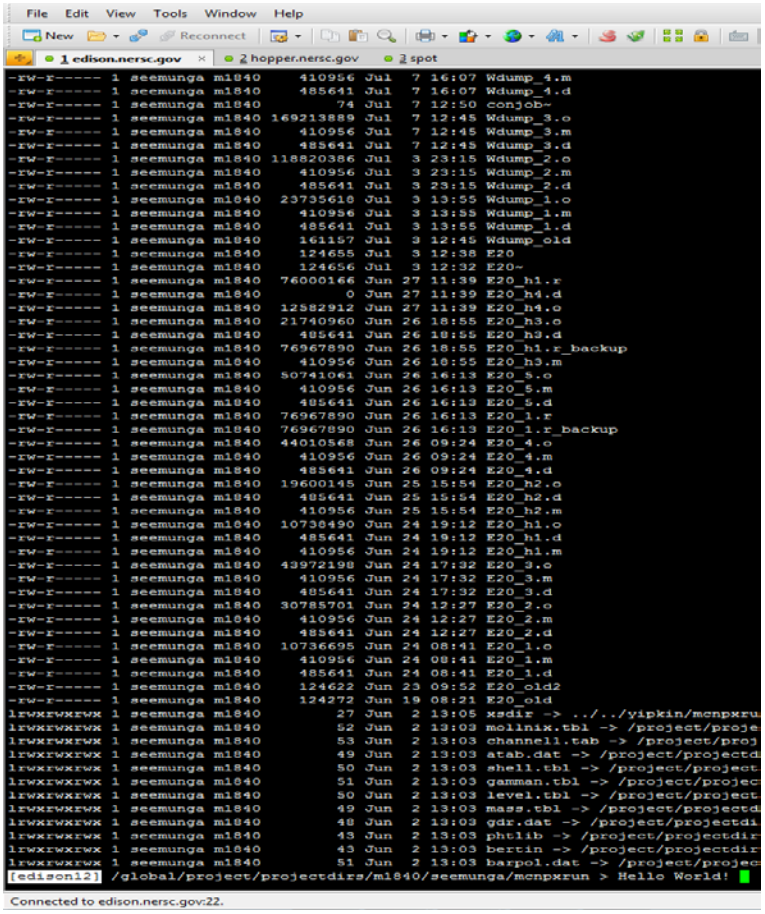

Figure 5: The X shell 4 UNIX Secure Shell (SSH) program for Windows allows secure file transfer between laboratories. The picture to the left is a screenshot of the command-line interfaced used to share data and submit jobs to be executed in laboratory supercomputers. Lists of several .o and .m files are visible for past projects.

III. Data and Results

The raw data was taken from the .m files, which is plotted using the MCNPX command line interface to form contour diagrams corresponding to the neutron flux for each contour line per incident proton. We are able to vary the minimum and maximum contours as well as the size of the steps between them and the scale. We were able to extract the true maxima from the .m file itself using a program in the UNIX shell and chose minima that resulted in the fullest graphs. We opted for base ten logarithmic scales divided in to 8 or 9 main contours for each graph. Contours were produced in the ZY and ZX planes, which correspond to the AutoCAD drawings provided for the modelling task.

After making the appropriately sized contours, we then overlaid the AutoCAD versions of the mechanical drawings with the contour diagrams to make it clear how the contour regions corresponded to the actual space around the target and collimator. We colored and labeled the lines appropriately and fitted the graphs over their respective hotspots. This method will make it clear how the radiation permeates the material around the target array and collimator and in what concentration the particles remain after each beam run.

The following figures are the recolored and fitted contours with their respective AutoCAD drawings underneath. The contours are given in units of neutrons per cm^2 for every incident proton. The graphs are plotted on 762 cm by 762 cm planes corresponding to the

physical dimensions of the hotspots. We took the positive Z direction as the incident beam direction, with YZ plots centered at X = 0 and ZX plots centered 10 cm below the plane where the concrete and soil meet.

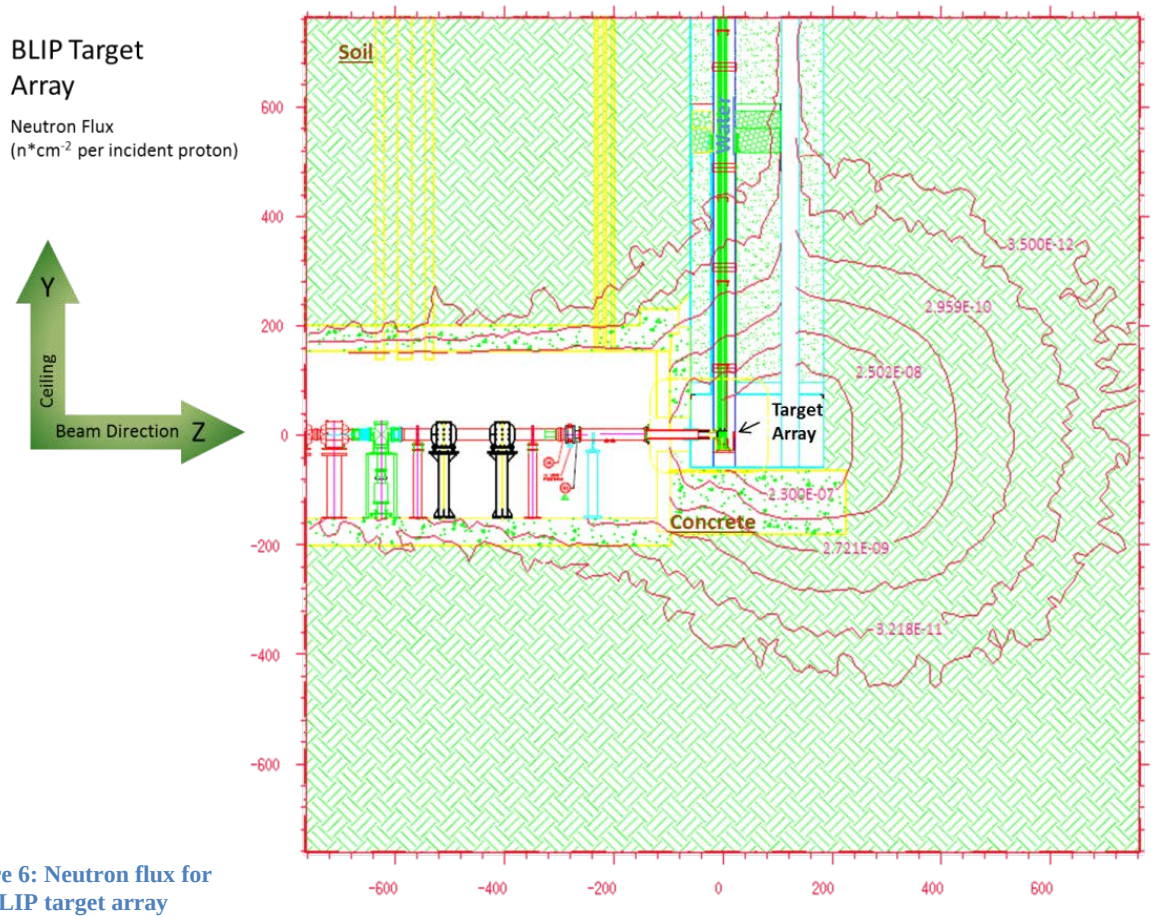

Figure 6: Neutron flux for the BLIP target array plotted in the ZY plane.

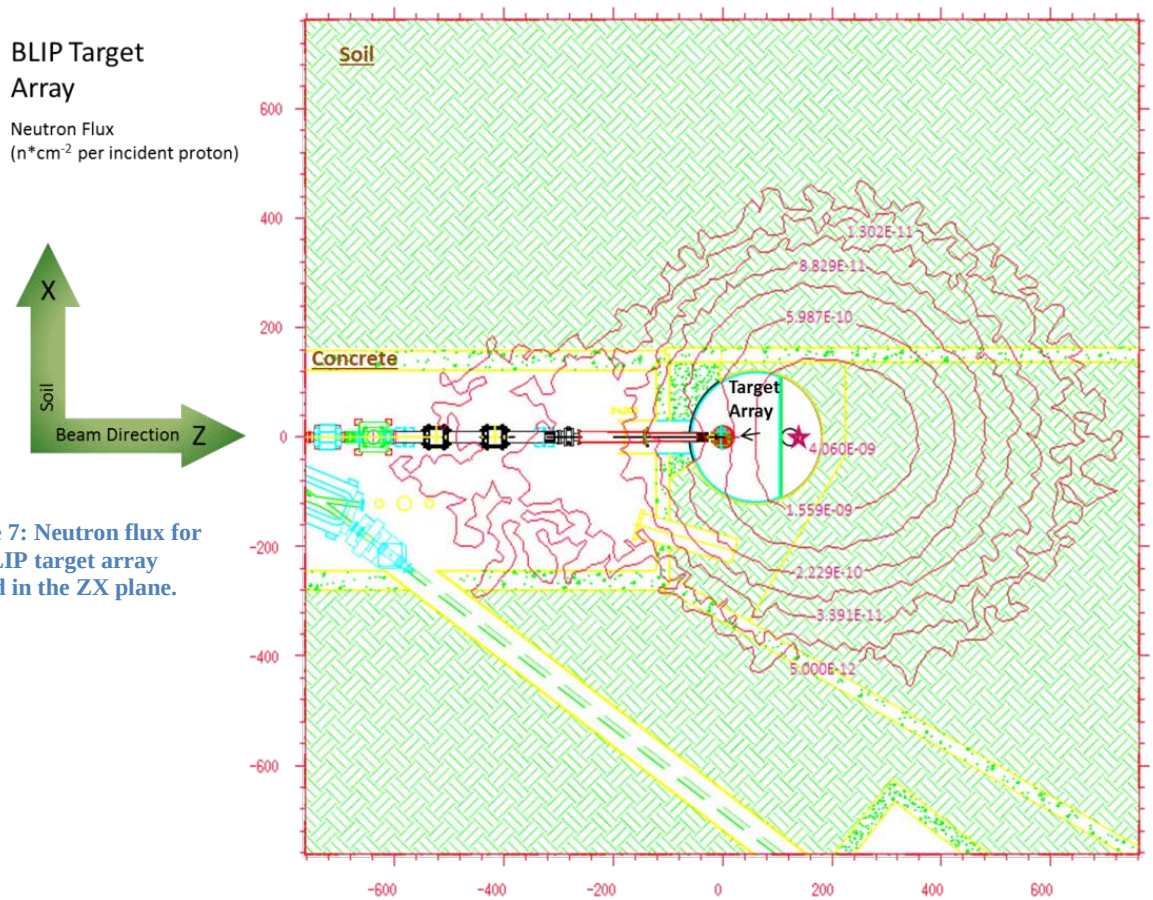

Figure 7: Neutron flux for the BLIP target array plotted in the ZX plane.

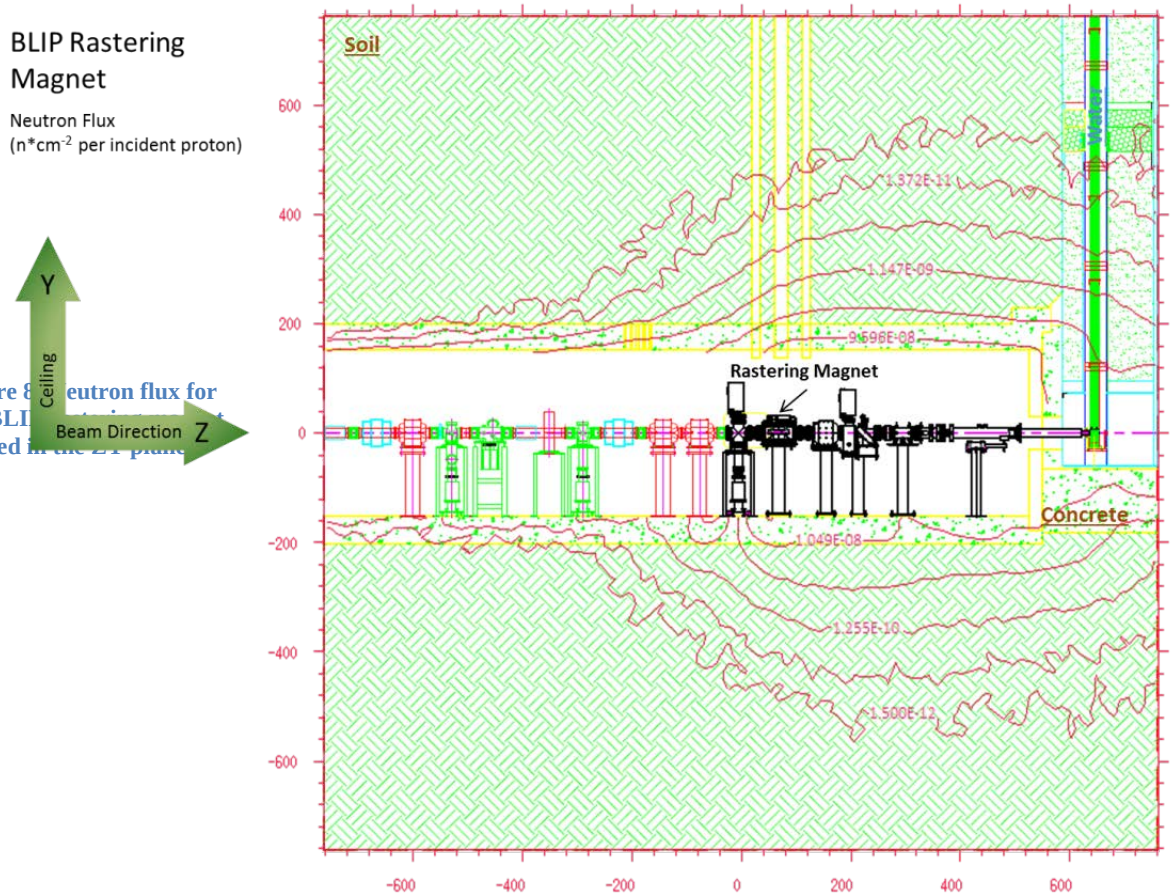

Figure 8: Neutron flux for the BLIP rastering magnet plotted in the ZY plane

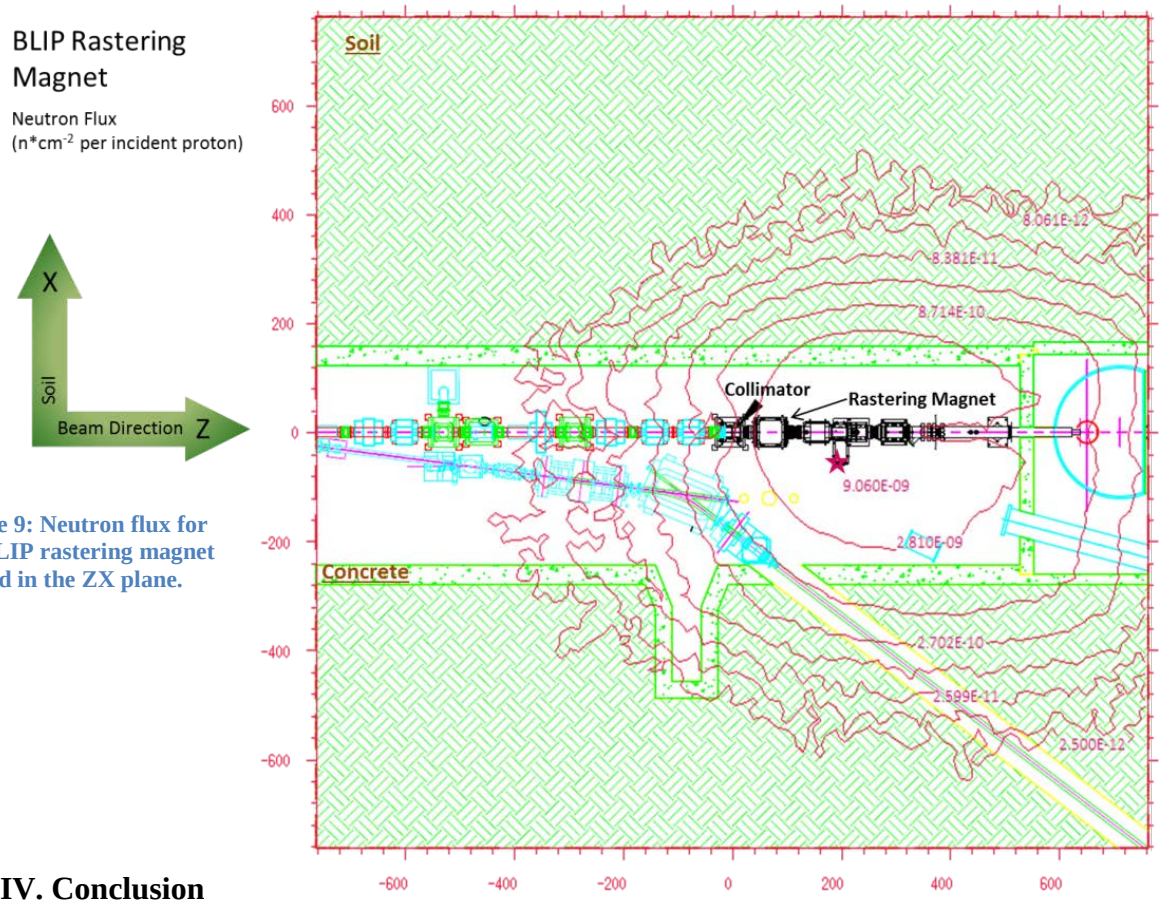

Figure 9: Neutron flux for the BLIP rastering magnet plotted in the ZX plane.

IV. Conclusion

The mesh tallies and contour diagrams produced from these simulations will be added to a collection of such simulations in the Collider-Accelerator Department. Knowledge of the concentration of radioisotopes around the hotspots will guide further research on soil activation and future projects geared towards shielding and decommissioning. This project will also provide evidence in support of Brookhaven National Laboratory's and the Department of Energy's effort to maintain a safe work environment and to protect the environment around national laboratories from radiological harm.

Through this project I have gained knowledge of the MCNPX code and UNIX shell use, which will be valuable should I continue within the field of high energy physics. This project required me to read engineering plans for dipole magnets, beam dumps, and such equipment found in accelerators and colliders, leaving me with a deeper understanding of how they work. All of this only adds more to my background in physics; giving me more of an advantage should competition ever arise.

V. References

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VI. Acknowledgements

This project was supported in part by the U.S. Department of Energy, Office of Science, Office of Workforce Development for Teachers and Scientists (WDTS) under the Science Undergraduate Laboratory Internships Program (SULI).