RADIATION SHIELDING FOR THE 100 keV ELECTRON GUN OF THE HAMPTON UNIVERSITY LOW ENERGY LINEAR ACCELERATOR

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Introduction

The research conducted under the guidance of Dr. Paul Guèye involved the construction of a Low Energy Electron Accelerator (LELIA) spearheaded by the Physics Department at Hampton University\(^1\). The aim of this research has been to reactivate a thermionic gun previously used by Jefferson Lab in Newport News, VA\(^2\) during its early years of operation.

The system delivers a 100 keV electron beam and will be expanded to 500 keV over the course of two years. The goal will be to eventually expand the electron beam up to 5 MeV and beyond. The accelerator will be used for low energy beam physics studies, open new opportunities for research, and provide training for students and faculty in new and exciting multi-disciplinary areas.

Some of the work required includes the development of a full realistic simulation of the electron beam gun using the Geant4 Monte Carlo simulation toolkit\(^3\)\(^4\), along with the associated preliminary radiation budget for the system. There is currently a study of the optical transport design for the gun and the accelerating sections being conducted through the use of accelerator physics transport codes. The latter permits researchers to assess the beam parameters. The simulated data will be benchmarked against experimental data previously obtained at Jefferson Lab. Furthermore, the development and construction of diagnostic tools necessary to identify the definite profiles and currents of the beam exiting the gun allow access to dedicated data to be compared to the Geant4 simulation.

The present work focuses on the preliminary implementation of the development of the full realistic simulation of the thermionic gun using the Geant4 Monte Carlo simulation toolkit, version 4.9.6\(^3\)\(^4\).

Main Body

Overview

A new accelerator physics track is being implemented within the Physics Department at Hampton University\(^1\). The possession of an accelerator physics track on Hampton’s campus will have a significant impact on the University and be a distinguishingly notable experience for those involved, specifically those in associated multi-disciplinary research.

Accelerators have previously been used in a copious number of areas of study in which many of Hampton’s physics faculty are heavily involved. For example, some faculty are involved in nuclear and high energy physics, and the nearby Department of Energy (DoE) funded Jefferson Lab has the most powerful super-conducting machine in the intermediate energy regime. Hampton University’s Physics Department has been active in studying nuclear matter since the late 1980s, and is also operational in neutrino-based research.

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\(^2\) Retrieved from Jefferson Lab: Exploring the Nature of Matter website: https://www.jlab.org/

\(^3\) S. Agostinelli et al., Geant4 – A Simulation Toolkit, Nuclear Instruments and Methods in Physics Research, A 506 (2003) 250-303


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experiments at Fermi National Accelerator Laboratory in Batavia, IL.\(^5\)

The accelerator physics track will also impact scientists dedicated to medical physics. X-ray machines are classified as small-scale accelerators and have been used by students during clinical rotations; cyclotrons are accelerators as well and are used for proton therapy research. Some students will have the opportunity to work in radiation biology once the accelerator has been installed on the university campus. The NASA Langley Research Center has a long-standing space radiation program and primarily utilizes the facility at the Brookhaven National Laboratory in Upton, NY; jointly sponsored by the DoE.

NASA recently started a validation program of their codes with faculty from the Physics Department at Hampton University that requires dedicated measurements of data at very low energies. During the summer of 2011, I was involved in performing a comparison between Geant4 and deterministic transport codes from NASA Langley\(^6\) through the Langley Aerospace Research Summer Scholars Program. The work was aimed at understanding the interaction of particles in geosynchronous earth orbit, specifically electrons with energies up to 5 MeV with given materials for shielding purposes.

The exposure to the Geant4 Monte Carlo simulation toolkit gave me the necessary foundation and knowledge to work on the LELIA project as it serves as an extension of my previous research experience. The primary difference between the two research projects is in the implementation of a more complex geometry. When working with the deterministic transport codes the geometry was less complex than what has been required for LELIA, where the aim is to apply a realistic implementation of the full electron gun with its components in Geant4.

**LELIA Accelerator System**

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5 MINERvA: Bringing neutrinos into sharp focus. Retrieved from MINERvA at Fermilab website: http://minerva.fnal.gov/
The proximity to and long-term partnership with Jefferson Lab has been a tremendous asset for Hampton University. Working closely with Jefferson Lab has previously granted Hampton University students and faculty the ability to provide alternate venues for research in nuclear physics. The LELIA system consists of a 100 keV DC electron gun with a gridded thermionic cathode. Electron guns like this are fabricated from highly durable materials, dense ceramics and high quality stainless steels. They are assembled by quality methods, high temperature brazing and TIG welding, and the internal electrodes are highly polished by hand with diamond paste to eliminate field emission as an issue.

This system has been transferred to a dedicated laboratory space of 10x15x17 cubic feet on Hampton University’s campus. The dedicated room encompasses the required power of 144 kW and possesses an existing water-cooling system. Some of the accelerator components; including the thermionic gun, isolating cage, high power RF system, and the three ion pumps that have been obtained are presented below in Figure 2.
While the focus of LELIA will exclusively focus on the 100 keV electron gun, there is a plan of action dedicated to extending the capability of this device to increase the energy. These expansions of the system will be developed based on the Jefferson Lab injector region displayed in Figure 3.

Figure 3: The proposed 100 keV and 500 keV expansion beamlines for LELIA\textsuperscript{2}. [2]

\textsuperscript{2} Retrieved from Jefferson Lab: Exploring the Nature of Matter website: https://www.jlab.org/
thermionic gun, the expected electric and magnetic fields, and evaluating the electron and secondary produced ion beam parameters; as well as the energy and angular distributions at various locations, fluency, and additional factors.

The present research was essentially limited to estimate the associated preliminary radiation budget of the LELIA system. Because of delays that resulted from relocation of some equipment stored within the laboratory space, performing small-scale experiments to benchmark simulation data was not feasible seeing as the assembly of the LELIA system could not be completed. Moreover, the physical dimensions of the expected assembled gun could not be obtained, as this information requires the various components to be physically in place to extract the appropriate positions, angles, and geometrical offsets. Therefore, only a basic simulation of LELIA was performed that included estimates of lead shielding thicknesses to stop 100 keV, 500 keV, and 5 MeV electrons and photons. This information could serve as a foundation to validate the current radiation safety of the designated laboratory space.

Conclusion

Geant4 Monte Carlo Simulation

In conducting the research for the LELIA project we utilized the readily available “radioprotection” example from the Geant4 toolkit. “Radioprotection” enables evaluating the shielding needed to protect an astronaut from Galactic Cosmic Rays. The generated particles travel through a simplified inflatable habitat (SIH), a shielding material—made of lead for this experiment, and a solar particle events (SPE) shelter before reaching a phantom—the astronaut model. The geometry of the setup is displayed in Figure 4.

![Figure 4: Schematic of the “radioprotection” example of Geant4.](image)

Experimental Setup

The “radioprotection” example was modified to solely portray the lead shielding wall with varying thicknesses ranging from 0.5 cm to 10 cm, and the human phantom as a water-filled box with dimensions of 30 cm x 200 cm x 30 cm. The phantom is voxelised in 300 slices along the beam direction, which follows the z-axis. The data attained from the dose deposited by the primary and secondary particles in each voxel was recorded. Table 1 lists the various configurations simulated with the space surrounding the lead shielding and water phantom being composed of air material.

<table>
<thead>
<tr>
<th>Particle</th>
<th>Strength of Beam</th>
<th>Shielding Thicknesses Tested [cm]</th>
</tr>
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<tbody>
<tr>
<td>Electrons</td>
<td>100 keV</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>500 keV</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>5 MeV</td>
<td>0.5 3.0 5.0</td>
</tr>
<tr>
<td>Gammas</td>
<td>100 keV</td>
<td>0.5 1.0 1.5 3.0</td>
</tr>
<tr>
<td></td>
<td>500 keV</td>
<td>0.5 1.0 2.0 3.0 4.0</td>
</tr>
<tr>
<td></td>
<td>5 MeV</td>
<td>0.5 1.0 2.0 3.0 4.0 5.0 10.0</td>
</tr>
</tbody>
</table>

Table 1: The different configurations for the Geant4 Monte Carlo simulation work.
Figures 5 and 6 show 3-dimensional views of the particles’ tracks for incident electrons and incident gamma particles, respectively. The tracks are the colored lines: green signifies gamma, red represents electrons or photons, and yellow denotes the interaction points of the particles in a material. The shielding wall is the red rectangle and the phantom is the blue rectangle.

<table>
<thead>
<tr>
<th>Particle</th>
<th>Physics Process</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gamma</td>
<td>Photoelectric Effect</td>
<td>G4PhotoElectricEffect</td>
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<tr>
<td></td>
<td>Compton Scattering</td>
<td>G4ComptonScattering</td>
</tr>
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<td></td>
<td>Gamma Conversion</td>
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<td>Electrons</td>
<td>Multiple Scattering</td>
<td>G4eMultipleScattering</td>
</tr>
<tr>
<td></td>
<td>Ionization</td>
<td>G4eIonisation</td>
</tr>
<tr>
<td></td>
<td>Bremsstrahlung</td>
<td>G4eBremsstrahlung</td>
</tr>
</tbody>
</table>

Table 2: A description of the particles analyzed, their physics processes, and models.

In this model, particles travel from the left to the right along the z-axis. The simulation was setup where the beam is located one meter to the left of the lead shielding wall and the wall is located one meter to the left of the water phantom. Because of the low energies used in our work, only electromagnetic interactions were taken into account. Table 2 lists the particles analyzed, their physics processes, and models. It is only when electrons have sufficiently large energies, in the 5 MeV range, that thicker shielding walls are required to stop the particles. 100 keV electrons are already stopped in air before they were even able to reach the shielding wall. However, the scenario changes when analyzing gamma particles: they can pass through 0.5 cm of lead with energies of 500 keV. One conclusion is that it is crucial to wholly surround LELIA with walls to prevent such particles from presenting a clear and present danger to unwitting personnel.

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Results and Discussion

Figures 7 through 10 display the results obtained from the LELIA simulation, they also display a physical representation of Table 1. The data presented corresponds to the dose recorded along the beam direction within the water phantom. For each run, the data collected consisted of 10,000 individual events generated.

Figure 6 contains the shielding plot of 100 keV electron and gamma rays. The electron particles at this energy level are blocked at a shielding thickness of 0.5 cm. When examining gamma particles, a thickness of 0.5 cm proved to be sufficient as well, preventing the gamma from reaching the phantom. For both cases, the absorbed dose by the phantom is zero.
Figure 7: The shielding plot of 100 keV electron and gamma rays (top). 3-D view of 100 keV incident electrons impinging on a 0.5 cm lead wall (bottom left). 3-D view of 100 keV incident gamma particles impinging on a 0.5 cm lead wall (bottom right).

Figure 8 displays the graph of the data obtained for 500 keV electron and gamma particles. The electrons at this energy level are blocked with a lead shielding thickness of 0.5 cm. The gamma particles, however, required a shielding thickness of 3.0 cm to block the particles from reaching the simulated water phantom. The dose level is still very low, at the pGy level, and therefore not of concern for humans. The peaks observed are due to statistical fluctuation (a larger number of events is required to smooth the distribution and is being performed beyond the VSGC funding period).
Figures 9 and 10 display the shielding necessary for protection against electron and gamma rays of 5 MeV respectively. Figure 9 specifically shows that protection against electrons at energy 5 MeV needs to be at least 5.0 cm thick when the shielding is made of lead. For the gamma particles at 5 MeV, Figure 10, the shielding thickness needs to be around 10.0 cm for the same material to prevent the particles from reaching and harming the phantom. It is worth noting that the absorbed dose is still very low and at the pGy level.

Ultimately, in building LELIA, the shielding must be at least 10.0 cm thick for the system to accelerate electrons to 5 MeV. Further investigations must be conducted to compare the use of different and cheaper materials such as concrete, in order to minimize the overall cost of the building.
Acknowledgements

In completion of this research, I would like to thank the Virginia Space Grant Consortium for funding this work allowing me to have successfully completed such a project. My advisor Dr. Guèye for offering a mode of study that aligns with my personal interests and future in science. I would like to thank the Thomas Jefferson National Accelerator Facility for donating the thermionic electron gun that will consists of the front-end of the low energy linear accelerator, the basis behind the entire research project. I would like to thank Hampton University for providing a location for LELIA and for me to conduct my research. The Hampton University Physics Department for supporting me in my endeavors, and everyone else who has had a hand in this research project.
REFERENCES