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<b>Instructor:</b>	Victor Yang
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<i>Assignment/Lab Title:</i>	LINAC Design

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<b>Student LAST Name</b>	<b>Student FIRST Name</b>	<b>Student Number</b>	<b>Section</b>	<b>Signature*</b>
Walters	Jermaine	xxxx8764	02	J.W
Van Greuning	Aiden	xxxx40587	02	A.V

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# BME Lab 4: 704 LINAC Design

## I. OBJECTIVE

This lab aims to investigate the function of the target and flattening filter in a linear accelerator. It also evaluates how variations in the size and material of linac components influence the characteristics of the treatment beam, utilizing the EGSnrc Monte Carlo simulation software for analysis [1].

## II. INTRODUCTION

Linear accelerators (linacs) are complex machines used in radiation therapy to treat cancer by delivering high-energy X-rays to tumors while minimizing exposure to healthy tissues. These devices accelerate electrons to high speeds using microwave amplifiers, a technology derived from radar development during the mid-20th century. After acceleration, the electrons are directed towards a metal target, typically tungsten, where X-rays are produced through a process known as bremsstrahlung. This occurs when the high-speed electrons collide with the atomic nuclei in the target material, rapidly decelerating and releasing their energy as X-ray photons. The efficiency and energy of the X-rays produced are influenced by both the electron energy and the atomic number of the target material. Tungsten, with its high atomic number and high melting point, is commonly used because it optimizes X-ray production.

The efficiency of X-ray generation can be represented by the equation:

$$Y = k * Z * E \quad (1)$$

where Y is the X-ray yield, k is a constant based on the efficiency of bremsstrahlung, Z is the atomic number, and E is the electron's kinetic energy. The energy delivered by the target is determined by:

$$\text{energy delivered} = \text{peak fluence} \times \text{peak energy} \quad (2)$$

The overall beam efficiency is expressed as the ratio of photons generated to total electrons, multiplied by 100:

$$\text{efficiency (\%)} = \frac{\text{Number of photon}}{\text{Total Number of Particles}} \times 100 \quad (3)$$

Once X-rays are generated, the beam-shaping system, including the flattening filter, collimators, and sometimes a multileaf collimator (MLC), adjusts the beam's intensity profile. The flattening filter converts the initially peaked X-ray beam into a more uniform distribution to ensure consistent therapeutic doses across the treatment area, reducing risks to healthy tissue. The photon fluence modified by the filter can be described by:

$$\Phi(d) = \Phi_0 / 1 + [(d - d_0)/D]^2 \quad (4)$$

where  $\Phi(d)$  is the photon fluence at depth d,  $\Phi_0$  is the initial fluence,  $d_0$  is the reference depth, and D is a constant related to the filter's effectiveness. Collimators and MLCs further refine the beam, ensuring it conforms to the tumor's shape. This precision is vital for modern radiation techniques such as intensity-modulated radiation therapy (IMRT) and stereotactic radiosurgery (SRS), which require the ability to deliver high doses to irregularly shaped tumors while minimizing damage to nearby healthy tissues. Furthermore, linacs are equipped with imaging and control systems that allow for real-time monitoring during treatment, a technique known as image-guided radiation therapy (IGRT). IGRT improves the precision of beam targeting by compensating for patient movements and changes in tumor position between sessions.

This lab uses EGSnrc Monte Carlo simulation software to examine two key components of linac operation: the X-ray target and the flattening filter. In Part A, X-ray production was studied by simulating the interaction of electrons with different metal targets. Part B explored the role of the flattening filter in achieving uniform radiation distribution across the tumor [2].

## III. MATERIALS

The primary tools used in this experiment were Beamnrc and Beamdp. Beamnrc, which employs Monte Carlo methods, was used to generate phase-space data. The Monte Carlo method is commonly used for

radiation therapy planning due to its ability to model complex interactions in dosimetry [3]. By using random sampling techniques, the Monte Carlo method provides reliable estimates for systems with complex behaviors, such as particle interactions involving scattering and absorption [4]. Beamnrc specifically simulates electron-photon transport in a linac, producing phase-space (PHSP) files that contain information about the beam's angle and spatial distribution [3]. These files are useful for modeling photon and electron beams for therapeutic purposes.

Beamdp, or Beam Data Processor, is a tool used to read, visualize, and analyze phase-space data generated by Beamnrc [5]. Written in MORTRAN, a scientific computing language based on FORTRAN, Beamdp is designed for data processing and visualization, producing plots and graphs of beam energy by fluence [6].

#### IV. METHODS

##### A. Part A: X-ray Target

The first part of the experiment involved generating X-ray spectra for tungsten and aluminum targets with different thicknesses. The procedure followed these steps:

1. Launch the EGSnrc GUI.
2. Load the 'target.module' accelerator model.
3. Select the file '521icru.pegs4dat' under HEN\_HOUSE.
4. Choose the input file for a tungsten target of 2 cm thickness.
5. Modify the target thickness to 2 cm.
6. Save the parameters and execute the program.
7. Open the Beamdp GUI.
8. Select 'Derive spectral distribution from ph-sp data.'
9. Set the particle type to photons.
10. Select 'None' for latch type.
11. Assign a name to the output file.
12. Choose a histogram graph type.
13. Set the fluence type to 'estimated real fluence.'
14. Execute the Beamdp file.
15. Save the resulting graph.

16. Repeat steps 1 through 15 for a tungsten target of 0.2 cm and aluminum targets of 2 cm and 0.2 cm thicknesses.
17. Create a table summarizing energy delivered and efficiency for each trial using the output from the phase-space file.

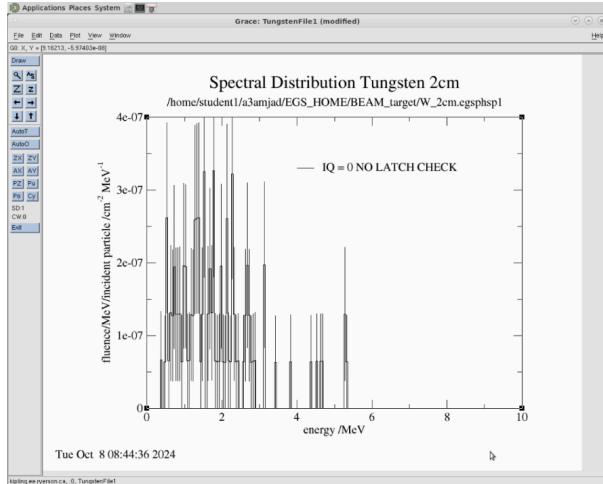
##### B. Part B: Flattening Filter

The second part of the lab focused on analyzing the impact of various flattening filters used in the linear accelerator. The following steps outline the procedure used to assess the effect of the different filters:

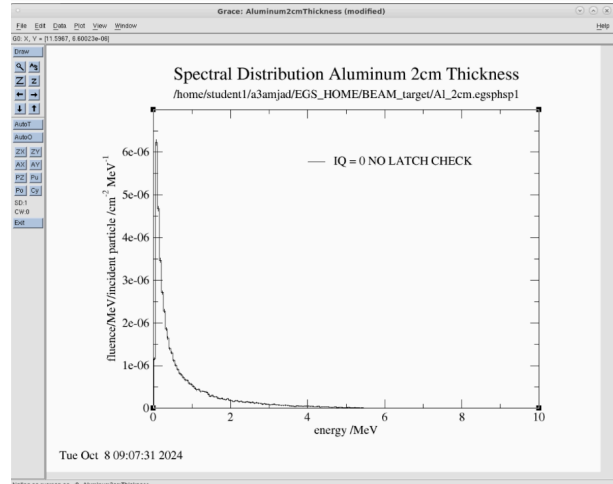
1. Launch the EGSnrc GUI.
2. Select the 'target\_ff' module.
3. Choose the '521icru.pegs4dat' file from HEN\_HOUSE.
4. Load the input file 'Test2\_no\_slab\_ff.egsinp.'
5. Run the EGSnrc GUI.
6. Open the Beamdp GUI.
7. Select 'Derive energy fluence vs. position.'
8. Set the field type to rectangular.
9. Set the Y-direction to downward.
10. Set the number of bins to 200.
11. Assign zero to both X\_min and Y\_min.
12. Set X\_max and Y\_max to 100.
13. Repeat steps 5 through 12 for the input file 'Test2\_with\_slab\_ff.egsinp.'
14. Repeat steps 5 through 12 for the input file 'Test2\_cone\_ff.egsinp,' changing the field type to cone in step 8.

#### V. RESULTS AND DISCUSSION

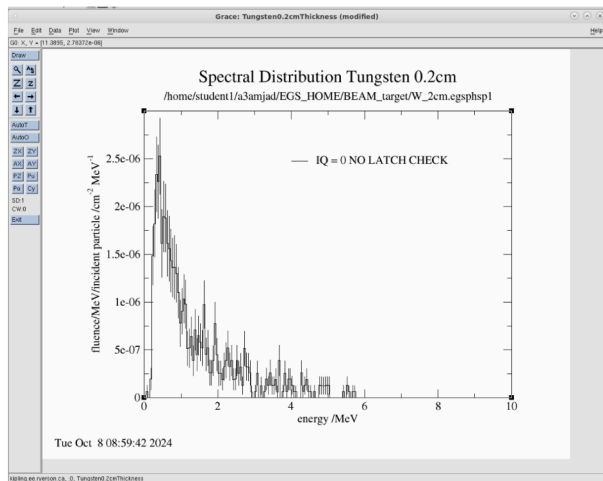
##### A. Part A: X-ray Target



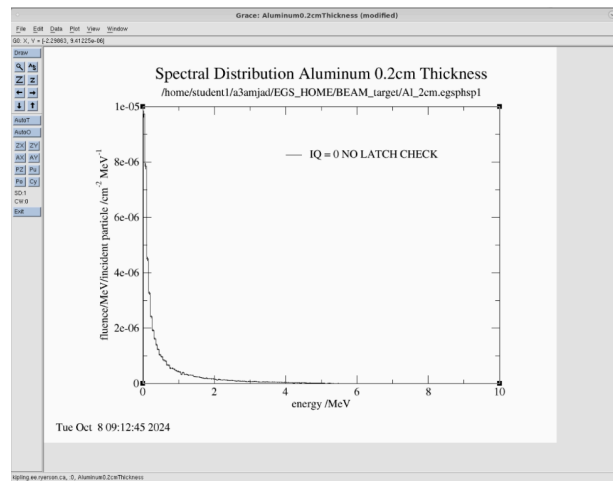
**Figure 1** illustrates the spectral distribution for a tungsten target with a thickness of 2 cm.



**Figure 3** demonstrates the spectral distribution for an aluminum target with a thickness of 2 cm.



**Figure 2** depicts the spectral distribution for a tungsten target with a thickness of 0.2 cm.



**Figure 4** presents the spectral distribution for an aluminum target with a thickness of 0.2 cm.

Upon analyzing the fluence data, it can be observed that the fluence for the tungsten target with a thickness of 2.0 cm is lower compared to that of the tungsten target with 0.2 cm and the aluminum targets. Among these, the aluminum target with a thickness of 0.2 cm exhibits the highest peak fluence. All targets have peak energy levels that remain constant at approximately 5.3 MeV. Tungsten targets, particularly the one with a thickness of 2.0 cm, display more variation in their spectral distribution curve, as shown in **Figure 1**. The fluence per incident particle declines exponentially with increasing energy, a trend that is more pronounced in aluminum targets than in tungsten.

The energy delivered and the target efficiency are summarized in **Table 1**. The energy delivered is calculated using equation (2), while the beam efficiency is computed using equation (3). Below is an example calculation for the energy delivered by a tungsten target with a thickness of 2.0 cm:

$$\begin{aligned} \text{Energy delivered} &= \text{peak fluence} \times \text{peak energy} \\ \text{Energy delivered} &= (4 \times 10^{-7})(5.339) \\ \text{Energy delivered} &= 2.1356 \text{eV} \end{aligned}$$

TABLE 1  
X-RAY TARGET SIMULATION

Material	Thickness (cm)	Energy Delivered	Efficiency
Tungsten (W)	2.0	2.1356	111
Tungsten (W)	0.2	16.0328	99.6
Aluminum (Al)	2.0	38.623	99.7
Aluminum (Al)	0.2	59.63	68.5

Comparing the efficiencies of the four X-ray target cases, the tungsten target with a thickness of 2.0 cm is the most efficient. This is because Bremsstrahlung interactions are influenced by the electron interactions with atoms in the material, and tungsten, with its high atomic number, has more electrons, protons, and neutrons per atom. Additionally, tungsten has a high melting point, which further enhances its suitability for X-ray generation [7]. The dose of X-rays produced in the Bremsstrahlung interaction is determined by factors such as the material used, its thickness, and the energy of the X-ray beam [8].

For deep-seated tumors, the aluminum target with a thickness of 0.2 cm is the most effective, as it delivers the highest energy, enabling deeper penetration. Other important considerations when selecting a target material include a high melting point, cleanliness and purity, and the ability to produce high-quality photon beams [9].

B. Part B: Flattening Filter

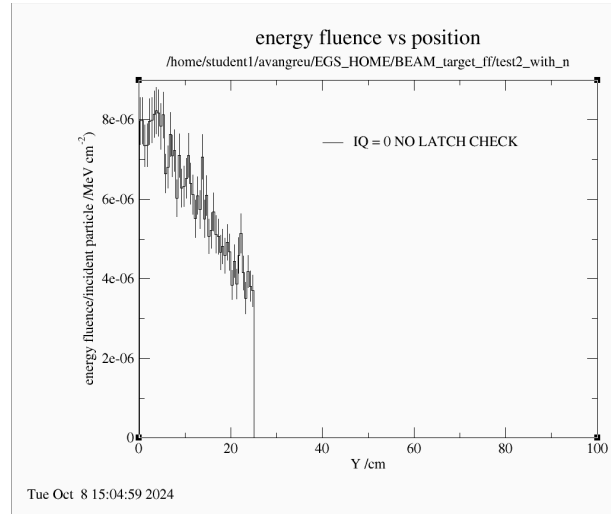


Figure 5: Flattening Filter Rectangular Field With No Slab

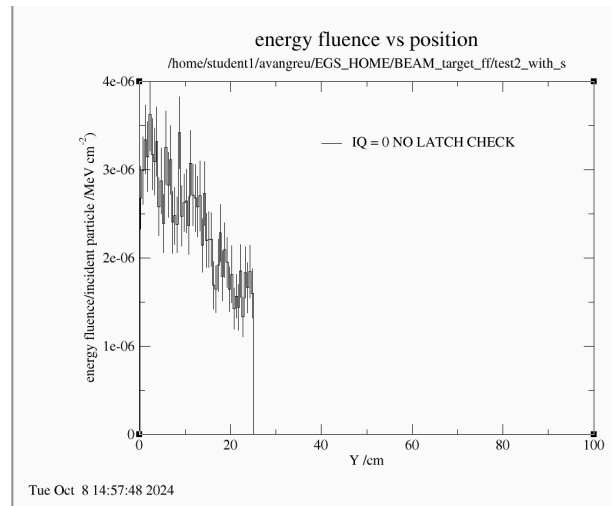


Figure 6: Flattening Filter Rectangular Field With Slab

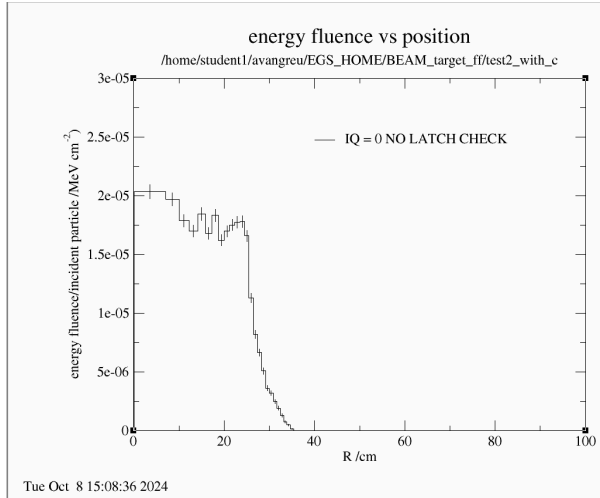


Figure 7: Flattening Filter Cone Field

The “No Slab” plot where the photon beam energy fluence has no flattening filter is represented in Figure 5. A highly non-uniform distribution is displayed, primarily concentrated at the beginning. Due to this uneven energy distribution, it is less suitable for any type of radiation therapy. The “Slab” plot is represented in Figure 6, displaying a more uniform distribution compared to no flattening filter. Therefore it is more suitable for radiation therapy treatments that require a consistent dose across a wider area. The “cone” plot is represented in Figure 7, demonstrating a gradual decrease in energy fluence and offers focused energy distribution. Thus it is ideal for radiation therapy treatment where smaller areas are targeted with high precision.

Overall if one filter were to be chosen as most suitable for radiation therapy based on the energy fluence profile, the slab filter would be best because of its uniform distribution. This type of distribution is integral to treat larger tumour volumes without exceeding dose limits on surrounding tissue. It also assists in minimizing hotspots and provides better coverage, also essential for safe and effective radiation therapy.

The typically linear and uniform shape of the slab filter moderates the intensity of the beam more evenly across its entire depth and width. In turn the energy of the beam is scattered more uniformly, reducing the beam center intensity compared to its edges. This is known as the “peaking effect” demonstrated with no filter. With the beam going through more even diffusion, the slab

filter assists in achieving a more homogeneous dose distribution across the treatment field. For radiation therapy this uniformity is essential because it guarantees the entire tumour is irradiated enough while healthy tissue is spared from excessive radiation exposure [10].

One disadvantage from using a flattening filter is the overall increase in complexity and treatment time. Flattening filters absorb and scatter a portion of the beam photons, in turn decreasing overall beam efficiency. Thus higher beam intensities or longer exposure times required for absorption and to achieve desired dose levels at the target. Furthermore, the flattening filter can increase dose outside of the target area due to scattering, leading to healthy tissue receiving higher doses. The filter itself will also require precise positioning and maintenance which adds further complexity to calibration and treatment [11].

## VI. CONCLUSION

The critical role and impact of varying target and flattening filters within a linear accelerator using EGSnrc Monte Carlo simulation software were successfully demonstrated in this lab. The first set of experiments validated how the spectrum and efficiency of X-ray production are influenced by different materials and target thickness. The superior properties of tungsten were highlighted, specifically its higher energy yield and efficient radiation due to high atomic number and melting point. The second set of experiments clarified the influence of no filter, slab and cone flattening filters on photon energy fluence distribution with the slab filter best suited for uniform dose radiation treatment. Together the two sets of experiments underscore the importance of both carefully selecting the target material and filter type in linear accelerator setups for specific objectives in radiation therapy. In turn, radiation therapy techniques can be advanced with these insights and effective treatment can be ensured while ensuring minimal healthy surrounding tissue exposure.

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