Radiation Therapy Simulations

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Abstract

This labs main purpose was to run through varying simulations of radiation treatment plans and how to observe those plans by looking at data output files of the main dose profile, transverse and longitudinal viewpoints. This report will establish what radiation therapy physics is, and the problems it tries to solve. Then by running through different beam sources and energies, (photon, proton and carbon) properties of these sources will be seen in the output files. Within each simulation run the strengths and weakness of how it could be applied to treatment plans will also be shown and established [1]. [Counts: 98]

Introduction/Theory

For this lab the field of interest is radiation therapy physics, specifically simulation of running cancer treatments using virtual phantoms. To understand the concepts used I will outline what radiation therapy is, the types of beams (lepton and hadron). Radiation Therapy is a medical treatment plan that uses high energy ionized electromagnetic radiation (gamma rays, X-rays, hadron beams, etc.) to target cancerous tumors by releasing energy deposits on the tumor with the goal of destroying it without damaging healthy organs. For treatment plans most of the time the beams that are used are gamma rays or x-rays but there has been a shift to transition to hadron beams like protons. Both radiation beams are governed by the Bethe-Bloch equation (Equation 1) which described the physical principles of stopping power of how much energy can be released based on particles going through cross-sections of matter. This governing equation is what makes hadron beams superior to proton. For treatment plans a phantom is made to model a tissue of the cancer area, density, and orientation. The Bethe-Bloch equation makes the proton be in favor as treatment beam because since it's heavier than photon and electron it'll move slower and can be easier to plan out when to release the energy because stopping power can be modeled to release energy as specific orientation deep within the tumor [1]. In figure 1, it describes the process of what a treatment plan could look like. In sub-caption 1a as described earlier it is shown of hitting the cancerous tumour at different orientations and beam intensity so it can alleviate overdoing treatment at one specific cross section of the tumour so healthy tumors don't become susceptible to toxicity effect. This is very crucial especially in photon treatments since they don't have a sharp Bragg peak. In sub-caption 1b you have an example of Bragg peaks of different sources. A Bragg peak is a curve that describes sharp energy loss of a beam source at a specific depth within the phantom. In comparing between photon and proton beams it shows how a treatment plan can be modeled for one and not the other at a specific depth. Proton, beam and as shown later even ion beams can be modeled to give as much dose within the tumor at a specific depth as needed. In photon sources most the Dose profile peaks that are seen are one's that have maximum dose at small depth and a dose distribution curve that slightly decreases as you go along in depth which is what explains how healthy organ can be affected [2]. [Counts: 429]

$$\frac{-dE}{dx} = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} [\ln(\frac{2m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2}) - \beta^2 - \frac{\delta(\beta\gamma)}{2}] \tag{1}$$

1 Equipment/Procedure

To evaluate different sources and their suitability for varying treatment plans, multiple trial runs using simulations provide the necessary information. The key metrics derived from these simulations are described by Equations 2, 3, and 4, which represent the quantities being tested and analyzed to observe how they vary across scenarios. Before delving into the simulation procedures and the specific data being sought, it is essential to first establish the concepts of absorbed dose, equivalent dose, and TNR. The absorbed dose, defined in Equation 2, represents the radiation energy from a beam source that is absorbed by a mass, organ, tumor (critical in this lab), or any other object capable of absorbing radiation. Its units are Grays (Gy = J/kg). The equivalent dose, defined in Equation 3, adjusts the absorbed dose by a radiation weighting factor,w.The w-factor serves as a scale that accounts for the biological effectiveness of the radiation type, which depends on the beam source being used. Equivalent dose is a critical metric in treatment plans because it aligns with safety protocols established by the International Committee for Radiation Protection (ICRP) [3]. These w-values ensure the safety of the treatment plan and help determine the energy of the beam source required. The values of w for various radiation sources are shown in Figure 1d. The units of equivalent dose are Sieverts (Sv). Another important metric in treatment plans is the Tumor-to-Normal Tissue Ratio (TNR), defined in Equation 4. TNR quantifies the ratio of the dose absorbed by the tumor to the dose absorbed by healthy tissue. The goal in treatment planning is to maximize the TNR, as a higher TNR indicates that the tumor is receiving the majority of the radiation dose while sparing healthy organs. As stated earlier, it is crucial to minimize radiation absorbed by healthy organs to ensure their safety and functionality [1]. Now to test a treatment plan it's crucial to do pre-planning and run and test it using simulations. We do that in this lab. In this lab we have a virtual phantom that is being used and targeted by beam source and this phantom will absorb the beam at certain orientations and the effect of matter interaction of the beam and phantom will be displayed. The simulations that are being used are attributed to University of Glasgow [4]. The simulation has multiple features worth mentioning; ROOT and GEANT 4 are being used for the plotting, analysis and model/treatment plan design of this experiment. To give an example of a simulation run it goes like this: initialize the Runsim script by giving source and energy, generate beam script is processed and information to be used for simulation (physics properties/models) gets accessed by Geant 4, if this stage passes it processes the Dose profile P,L, and T scripts. The P-script is essentially a script that outputs an energy dose distribution histogram per treatment plan as a specific count. L, and T scripts are plots of energy per depth in lateral/transverse directions of the phantom. L and T plots are what allows access to see how a source hits the phantom per lateral and transverse slice. Bragg peaks can also be seen in the L and T plots. In the analysis section multiple source and energy runs based on their display P,L, and T plots are what we'll be shown to display the viability of this source in a treatment plan. Another side note is the vis, batch and detector setup Mac files are what allow for adjustments to see tumour effects turned on and to allow assumption of hadronic interactions as well. Units of energy are in Mev, and depth in mm [1]. [Counts: 607]

1.1 List of Equipment

Here is a list of the equipment used in this lab:

1. Geant 4 Software
2. Root Data Analysis Framework
3. Generate Beam Script
4. Dose Profile P,L, and T Scripts
5. Laptop/Desktop
6. Runsim Script
7. vis/batch/Detector-Setup Mac Scripts

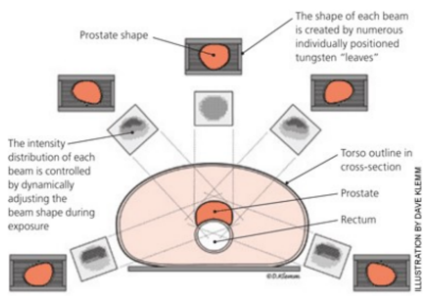
1.2 Equations used For Simulations

$$D = \frac{E_d}{m} \tag{2}$$

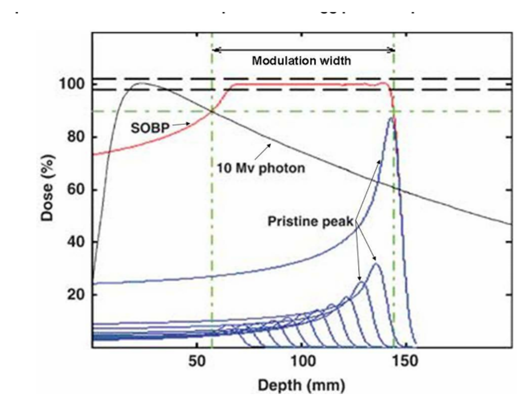
$$H = \sum_R W_R D_R \tag{3}$$

$$TNR = \frac{D_{\text{tumour}}}{D_{\text{healthy}}} \tag{4}$$

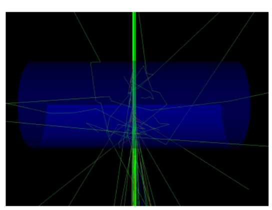
1.3 Treatment Plan Overview and Properties



(a) Beam orientation of the treatment delivery system. Shows how orientation of the beam and target minimizes hitting healthy tissue.



(b) Graphical representation of treatment plans and their Bragg peaks. Picture sourced from [2].



(c) Simulation view of a photon beam source passing through a water phantom.

Radiation Type	W_R
lepton	1.0
meson	2.0
baryon	2.0
ion	20.0

(d) Table displaying radiation weighting values for safety in treatment plans [1].

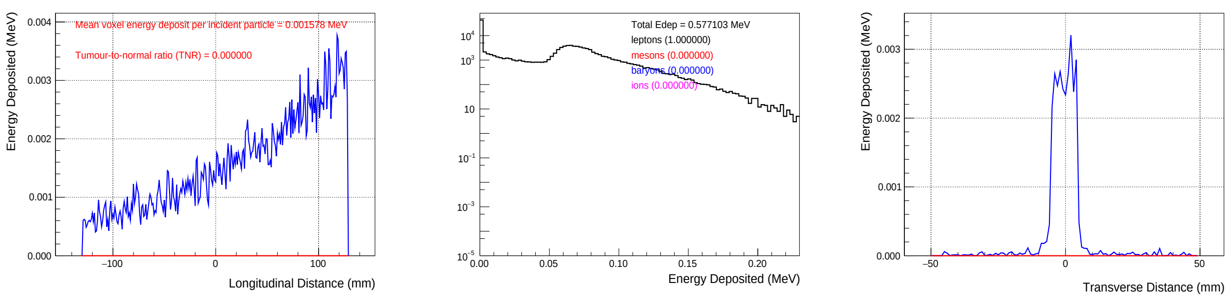
Figure 1: These figures describe 3 treatment stages: how a beam source interacts with a phantom, dose profiles from Bragg peaks, delivery system behavior at cross-sections, and radiation weighting factors in treatment plans. The rest of these picture were taken from the manual [1].

2 Analysis/Results

2.1 Question 1.

- Discuss the magnitude and distribution of energy deposited in the phantom for a beam 1 MeV gamma-rays, using the output PDF files from your simulation. How do these observations relate to the underlying gamma-ray interactions [1]?

Gamma 1 Mev



(a) Longitudinal Dose Profile. (b) Dose Profile. (c) Transverse Dose Profile.

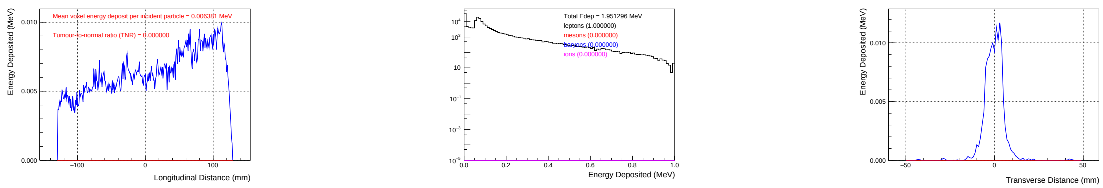
Figure 2: These plots display the main energy dose profile, longitudinal and transverse dose profile for the 1 Mev gamma.

- Each simulation run outputs 3-plot results: dose profile per particle, longitudinal profile, and transversal profile. Dose profile per particle plot (histogram), represents each beam treatment as a counting event per energy deposition. It also displays total energy deposition and fractional contributions based on each particle type. Longitudinal plot represents a trend of energy per particle depositing as the treatment beam travels alongside parallel to the phantom phantom. Mean voxel just the energy being deposited per longitudinal volume slice. The transverse plot is a representation of the energy being deposited per transversal slice. So that means the beam is perpendicular to the phantom and goes through it. A 1 Mev gamma beam has a total energy deposited of (E_{dep} = 0.577 MeV) with about 100 % lepton contribution. This makes since because of scattering and electromagnetic interactions a photon can have with any lepton. For the longitudinal its clear to see as the beam travels parallel through the phantom it deposition decreases indicating a negative slope trend. This is what makes optimal photon beam to use in certain treatment plan because it decreases risk of hitting healthy cells longitudinally. the mean voxel energy was about 0.001578 MeV. For the transverse direction it deposits mostly through the center of the phantom but certain excess electrons deposit very little to the top and bottom of the phantom. You can see the effect of excess electrons by energy fluctuations as you go farther from the center. [Counts: 242]

2.2 Question 2.

- Simulate photon beams with kinetic energies of 1, 5, 10 and 50 MeV to compare how the energy transferred to the phantom varies. How do the nature of the underlying interactions change as the beam energy is increased [1]?

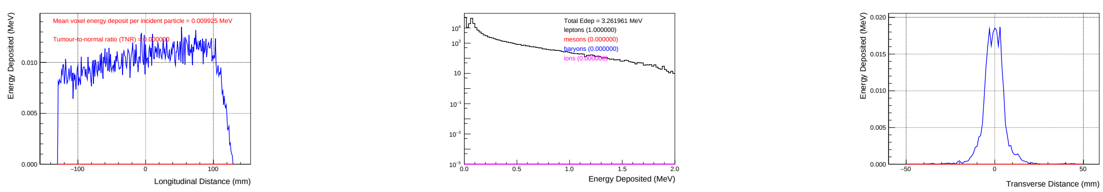
Gamma 5 MeV



(a) Longitudinal Dose Profile. (b) Dose Profile. (c) Transverse Dose Profile

Figure 3: Dose Profiles for Gamma 5 MeV.

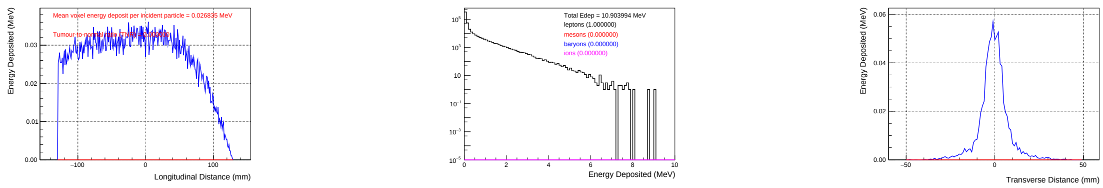
Gamma 10 MeV



(a) Longitudinal Dose Profile. (b) Dose Profile. (c) Transverse Dose Profile.

Figure 4: Dose Profiles for Gamma 10 MeV.

Gamma 50 MeV



(a) Longitudinal Dose Profile. (b) Dose Profile. (c) Transverse Dose Profile.

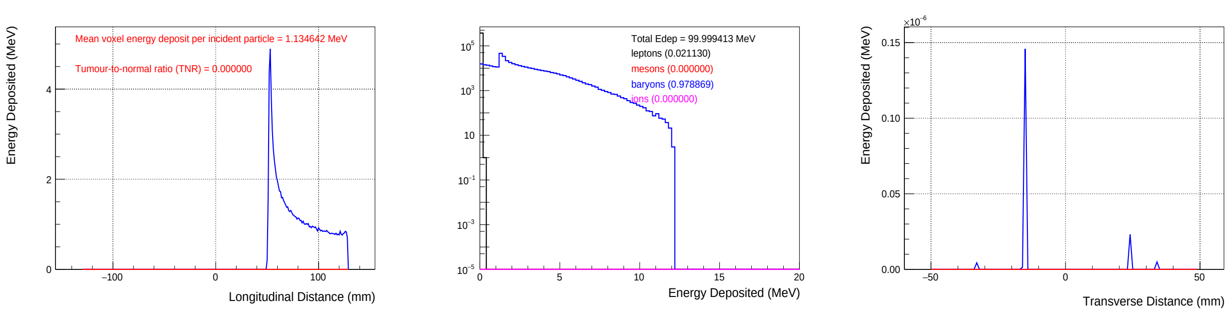
Figure 5: Dose Profiles for Gamma 50 MeV

- For gammas of 10,50, and 100 MeV the first thing that is noticeable is total deposition increase from 1.95, 3.26 and 10.90 MeV. The most important changes arise in the longitudinal plot. Here's what happens, as you increase beam energy of gammas Deposition trend-line increases as the beam travels longitudinally through the phantom and the transversal plot become more broader. This supports the underlying physics that the longitudinal profile curve of higher gammas gradually increase dose while traveling through the phantom. This shows how healthy organs can be hit with radiated beams. [Counts: 92]

2.3 Question 3.

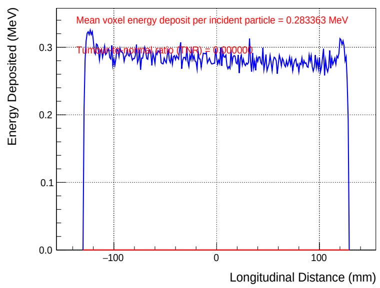
- Simulate and extract the dose distributions for proton beams with kinetic energies of 100, 500 and 1000 MeV. Do the same for carbon ion beams of 500, 1000 and 2000 MeV.What can you conclude about the nature of the energy deposit for hadron beams? Discuss the range of the charged particles in the water phantom, and how this might be exploited in cancer treatment. Comment on the typical length scale (i.e. FWHM) associated with the Bragg peaks for protons and ions of the same energy. What implications does this latter observation have in terms of treatment planning [1]?

Proton: 100 MeV

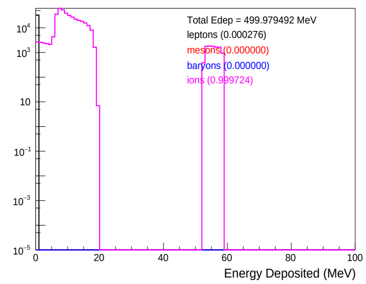


(a) Longitudinal Dose Profile. (b) Dose Profile. (c) Transverse Dose Profile.

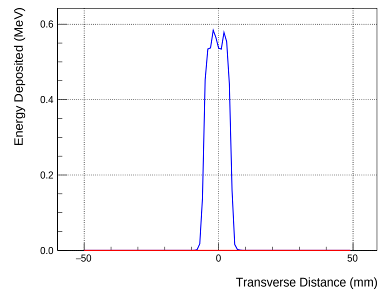
Proton: 500 MeV



(a) Longitudinal Dose Profile.

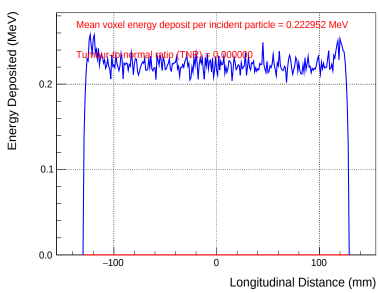


(b) Dose Profile.

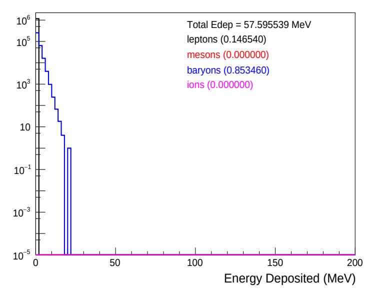


(c) Transverse Dose Profile.

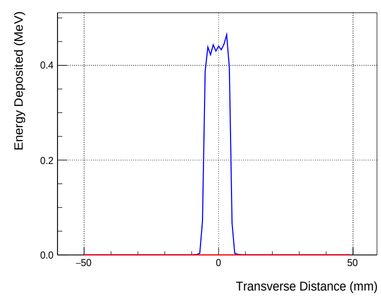
Proton: 1000 MeV



(a) Longitudinal Dose Profile.

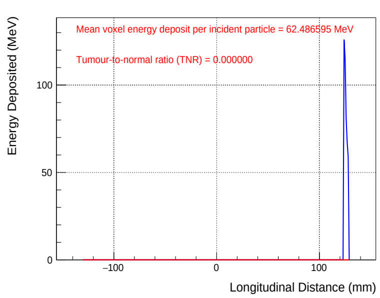


(b) Dose Profile.

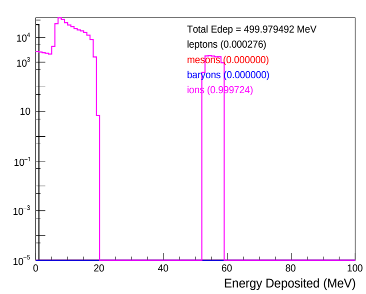


(c) Transverse Dose Profile.

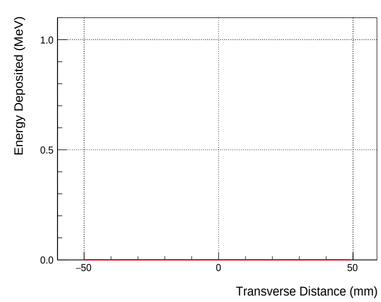
Carbon: 500 MeV



(a) Longitudinal Dose Profile.

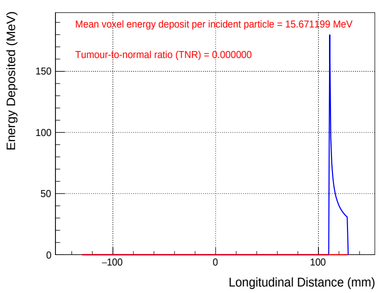


(b) Dose Profile.

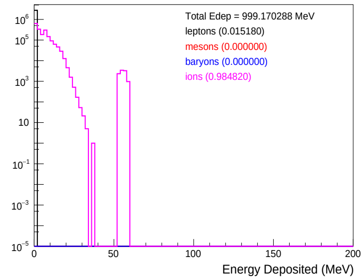


(c) Transverse Dose Profile.

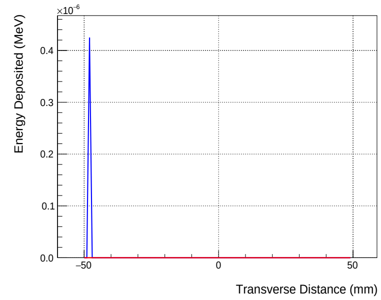
Carbon: 1000 MeV



(a) Longitudinal Dose Profile.

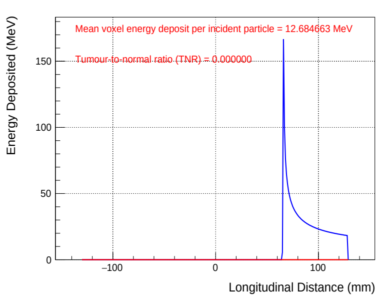


(b) Dose Profile.

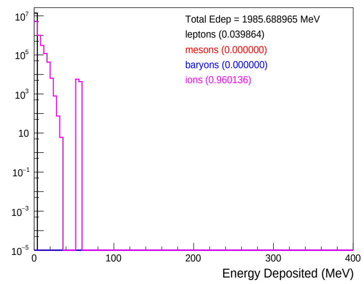


(c) Transverse Dose Profile.

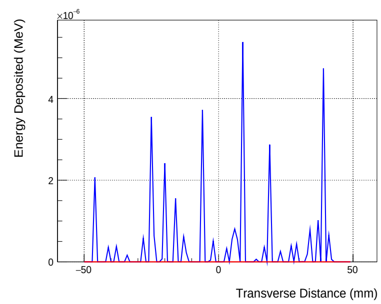
Carbon: 2000 MeV



(a) Longitudinal Dose Profile.



(b) Dose Profile.



(c) Transverse Dose Profile.

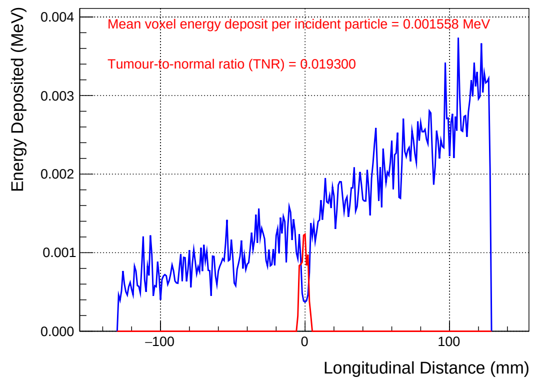
Figure 5: Profile plots for proton and carbon beams that span 100-1000 Mev for proton beams and for carbon 500-2000 Mev.

- In this part were using the data/plots of high energy proton and carbon ion beams to understand range of penetration in phantom, nature of energy deposit for hadron beams, length scales of Bragg peaks, and to answer when its possible use these specific beams for cancer treatment. For proton beams at lower MeV (100 MeV) exhibit Bragg peaks that rapidly deposit at a certain penetration distance and then deposit rapidly drop. For the 100 Mev plot it can be shown when beam is traveling 100-50 mm distance the deposit rapidly up to 6 Mev then rapidly decreases. This gives important principle for protons at lower Mev they the energy deposition is concentration at a certain longitudinal depth of a phantom. Even at this energy range the beam is barely crossing through certain surfaces laterally of the phantom. As you go into higher MeV like for 500 and 1000 Mev you see a longitudinal dose profile that has constant energy deposit at all longitudinal penetration of about 0.2-0.3 MeV per voxel. Even at the transverse direction the beam is very concentrated at the center of the phantom. For protons beams as beam energy increases the FWHM is more broad in terms of desribing the dose profile. The Bragg peak for proton has rapid energy deposit around 50-100 mm longitudinal depth of the phantom. So it means either the source doesn't really reach the phantom at this energy or it barely goes through. It does mean it releases most dosage around the thickness. for the 100 Mev source and it can be seen For carbon ions it exhibit more sharp like Bragg peaks. As you increase beam energy to 500-2000 MeV. At 500 MeV the Bragg Peak exhibits more voxel energy deposit compared to the 1000 and 2000 MeV, at around 62.49 MeV. These peaks also obtain higher FWHM as the energy of source is increased. This beam barely penetrates longitudinally. As you increase Carbon beams energy they exhibit Dose profile with constant dose deposit for full penetration. For Carbons beams of 500-2000 Mev they have more narrow FWHM compared to proton especially at 500 Mev of both sources. This means these beams are good at depositing large amounts of energy abruptly at a specific penetration For treatment plans protons are better and take less beam energy input to get constant dose deposit per whole penetration as in comparison with Carbon ions it takes higher Mev close 5000-7000 Mev. For lower MeV (500-1000 Mev) Carbon ion can have higher deposit if a tumor needs to be hit a specific confined region of penetration. [Counts: 431]

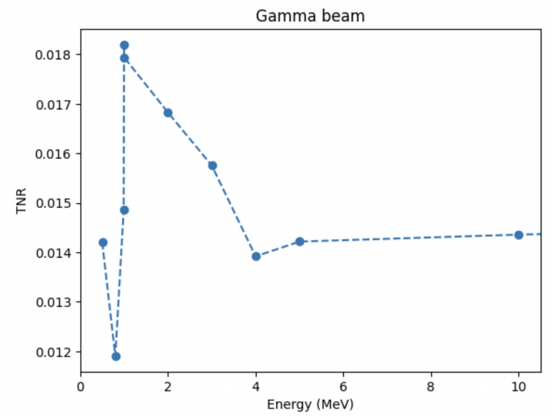
2.4 Question 4.

- Use the data that you analyzed in the first part of the experiment to identify the optimum energy for targeting this tumour as described in Section 5.2.6 (i.e. maximizing the TNR) for the photon, proton, and carbon ion beam types. This will require a bit of trial and error. Once you are happy that you have optimized the beam energies, run the simulations and take note of the results. Pay particular attention to the fraction of energy deposited by different particle types [1].

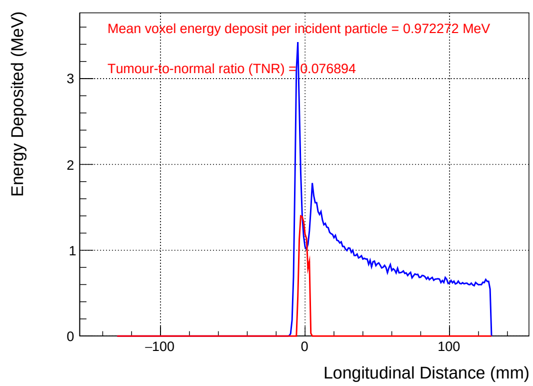
Longitudinal and TNR plots of Gamma, Proton, and Carbon



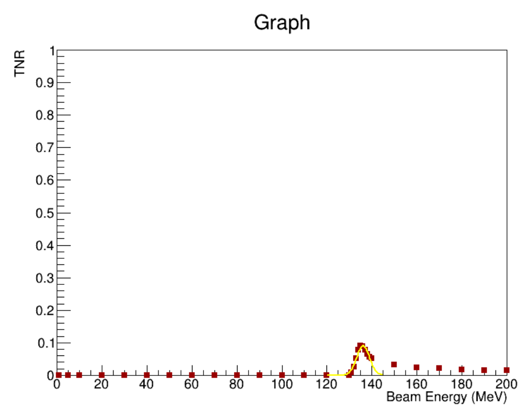
(a) Gamma longitudinal dose profile.



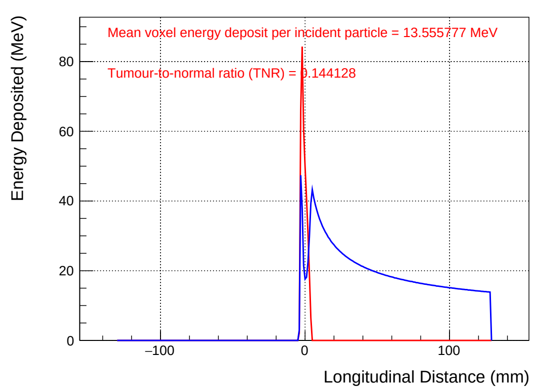
(b) Gamma TNR plot.



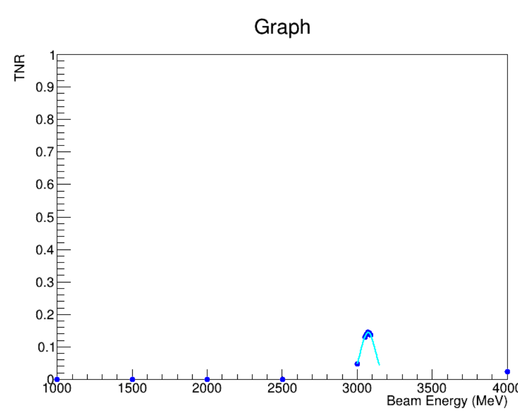
(c) Proton longitudinal dose profile.



(d) Proton TNR plot.



(e) Carbon longitudinal dose profile.



(f) Carbon TNR plot.

Figure 6: Longitudinal profiles and TNR plots of gamma, proton and carbon to demonstrate the optimum TNR.

Sources TNR Values/Energies

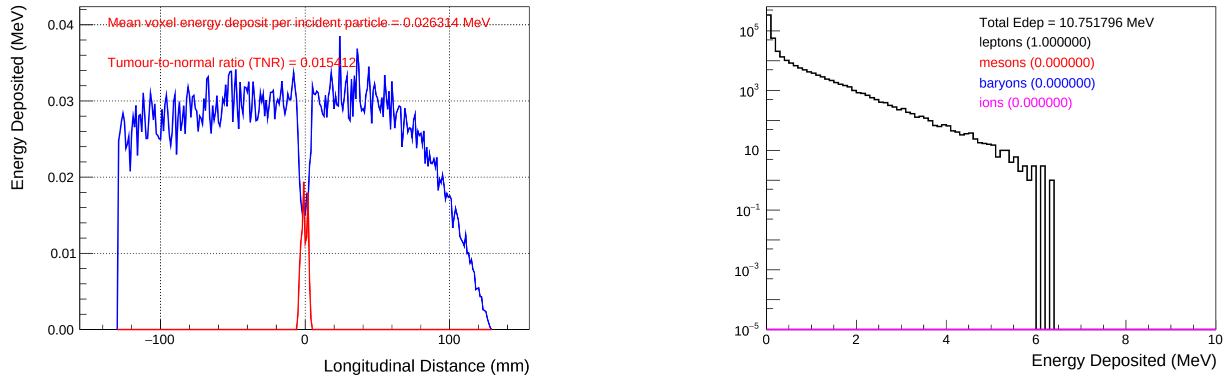
Beam	Energy (MeV)	TNR value
Gamma beam	0.999	0.019300
Proton beam	137	0.076894
Carbon ion beam	3070	0.144128

Table 1: Maximized TNR values for respective sources/energies.

- The tumor was activated by modifying the line in macros/DetectorSetup.mac to set the spherical tumor volume to 1. The objective was to determine the energy that maximizes the TNR ratio. This was achieved by analyzing the variation in TNR values across different energies and performing multiple runs to identify the optimal TNR value. The analysis plot and longitudinal profile above illustrate the maximized TNR ratio for gamma rays, protons, and carbon ions. Here's a quick reason these particular sources at the energies listed above give the maximum TNR, because for gamma the higher the energy of beam source the longitudinal energy deposit curve will show rapid rise then continuous increase the higher it goes, and for carbon/proton you see the Bragg peak at the 137/3070 Mev beam energy the higher the source the deposit curve will just show profile of rapid rise and constant deposit. Either way with any variation the Bragg peak becomes less notable to find. [Counts: 158]

2.5 Question 5.

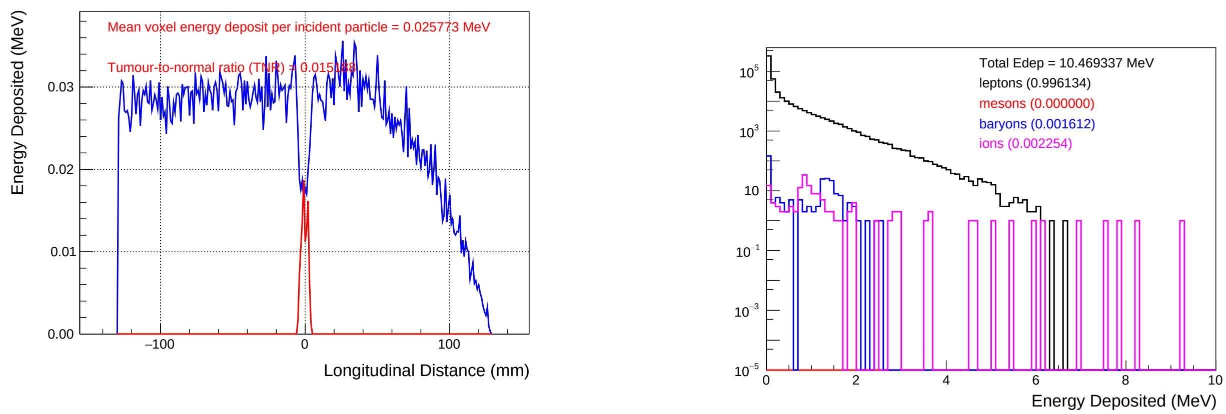
- Comment on the differences in dose distribution with and without hadronic interactions turned on in the simulation as described at the end of Section 5.2.6. Which beam type is affected most by this change and why? The addition of hadronic interactions means that you should see more secondary particle production. How do these secondary particles contribute to the dose magnitudes and distributions [1]?



(a) Longitudinal profile for Gamma 50 MeV (Non-Hadronic).

(b) Dose profile for Gamma 50 MeV (Non-Hadronic).

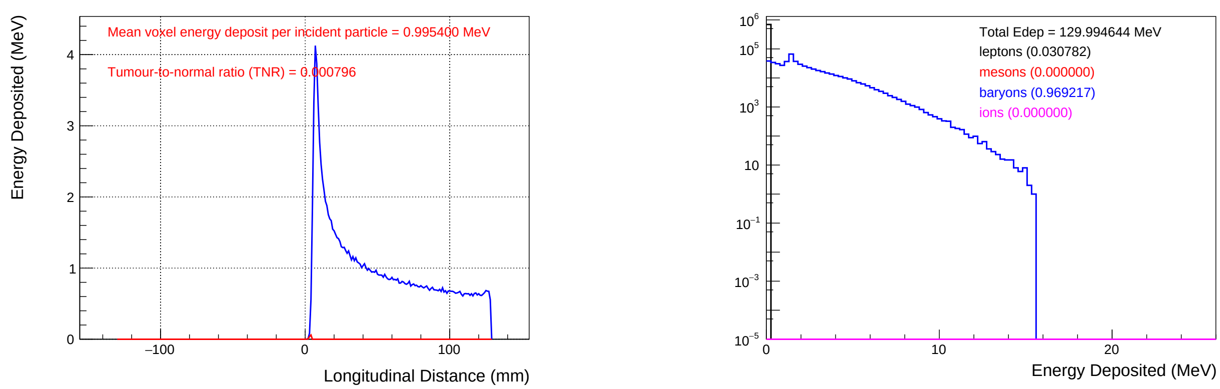
Figure 7: Gamma 50 MeV: Non-Hadronic Interaction profiles.



(a) Longitudinal profile for Gamma 50 MeV (Hadronic).

(b) Dose profile for Gamma 50 MeV (Hadronic).

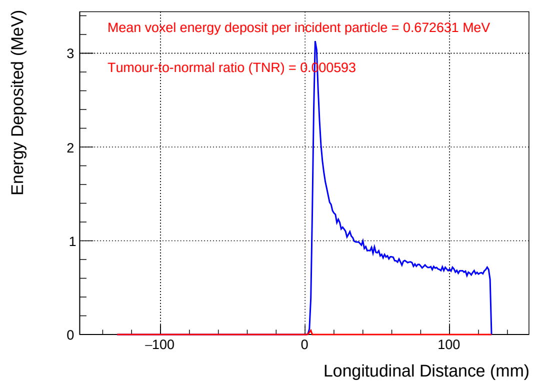
Figure 8: Gamma 50 MeV: Hadronic Interaction profiles.



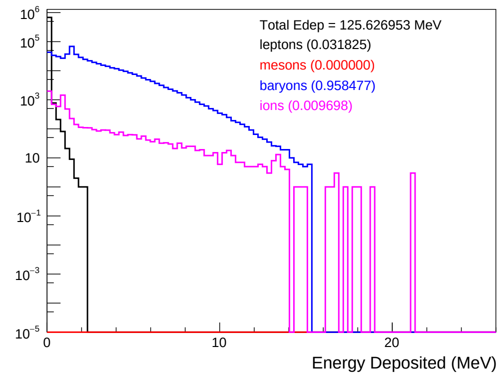
(a) Longitudinal profile for Proton 130 MeV (Non-Hadronic).

(b) Dose profile for Proton 130 MeV (Non-Hadronic).

Figure 9: Proton 130 MeV: Non-Hadronic Interaction profiles.

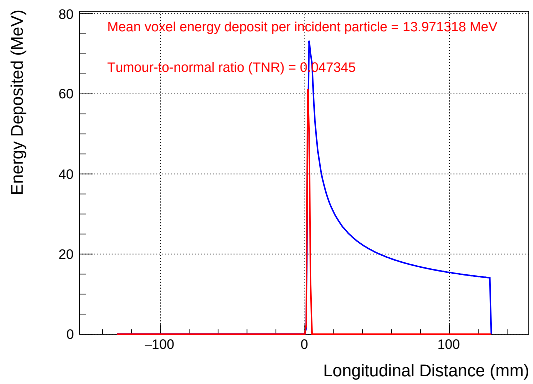


(a) Longitudinal profile for Proton 130 MeV (Hadronic).

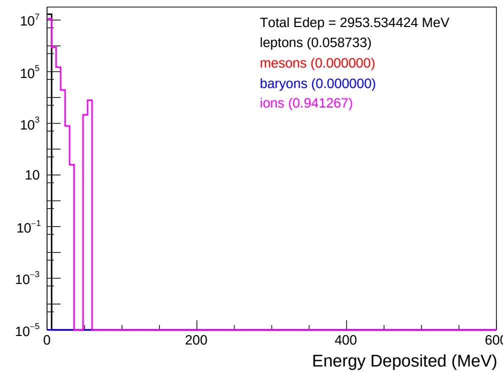


(b) Dose profile for Proton 130 MeV (Hadronic).

Figure 10: Proton 130 MeV: Hadronic Interaction profiles.

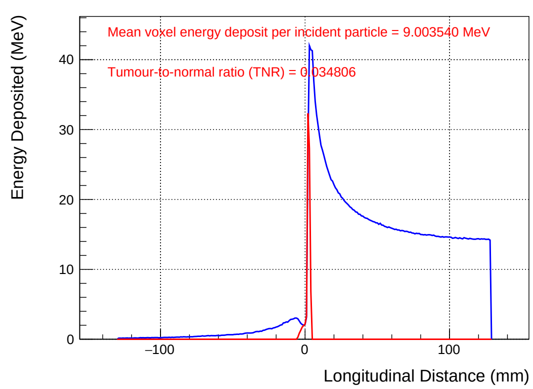


(a) Longitudinal profile for Carbon 3000 MeV (Non-Hadronic).

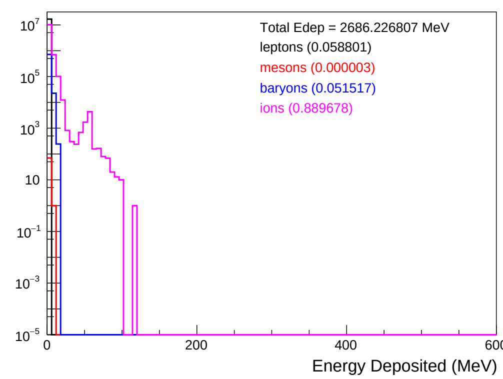


(b) Dose profile for Carbon 3000 MeV (Non-Hadronic).

Figure 11: Carbon 3000 MeV: Non-Hadronic Interaction profiles.



(a) Longitudinal profile for Carbon 3000 MeV (Hadronic).



(b) Dose profile for Carbon 3000 MeV (Hadronic).

Figure 12: Carbon 3000 MeV: Hadronic Interaction profiles.

Table 2: Gamma beams: 50 (MeV)

Particles	Energy %: Non-Hadron Int	Energy %: Hadron Int
Leptons	1.0000	0.9961
Mesons	0.000	0.000
Baryons	0.0000	0.0016
ions	0.0000	0.0022
Total energy deposited (Mev)	10.7518	10.4693

Table 3: Proton beams: 130 (MeV)

Particles	Energy %: Non-Hadron Int	Energy %: Hadron Int
Leptons	0.031	0.032
Mesons	0.000	0.000
Baryons	0.969	0.958
ions	0.000	0.097
Total energy deposited (Mev)	129.9946	125.6270

Table 4: Carbon ion beams: 3000 (MeV)

Particles	Energy %: Non-Hadron Int	Energy %: Hadron Int
Leptons	0.0587	0.05880
Mesons	0.0000	0.0000
Baryons	0.0000	0.0515
ions	0.9413	0.8897
Total energy deposited (Mev)	2953.5344	2686.2268

- It can be observed that the energy percentage per composition that contributes to the total deposition is more spread. This increase of composition of the particles is due to the strong force that governs hadronic interactions which results in the creation of new particles. With the hadronic considerations particle that compose the beam and phantom have to consider electromagnetic , strong force and scattering interactions. These interactions are what give arise to kinetic energy transfer and secondary particle creation. At tables 2-4 the heavier mass of the composites that make the beam a larger difference of non hadronic vs hadronic energy deposition is observed. For example gamma data from table 2, E_{dep} = 10.75 Mev, and for no hadronic interaction, and E_{dep} = 10.47 Mev for hadronic. For carbon data from table 4, E_{dep} = 2953.5 Mev, and for no hadronic interaction, and E_{dep} = 2686.2 Mev for hadronic. Discrepancies here demonstrate that when hadronic interactions a carbon beam will greatly scatter more that a photon and proton because it's heavier mass and scattering and strong process are prominent. Carbon ion beams produce more secondary particles in comparison. This is due to the fact that carbon beams are more heavier and possess a higher charge and are most likely to undergo nuclear fragmentation. Protons have a much smaller mass and therefore has less probability of nuclear fragmentation in comparison to carbon ions. The secondary particles created contains less energy. Finally photon beams have lowest impact when considering the creation of secondary particles as the primary mode of particle production is through Compton scattering and photoelectric absorption and they do not produce secondary particles as heavy ions do. It can be seen in Table 2 that the energy distribution is extremely similar and is not as significant as heavy ions. Last comparison that can be noted is that the heavier the beam source the TNR values will decrease as shown in the longitudinal plots as shown in figures 7-12. [Counts: 328]

3 Conclusion

To summarize the lab goals; This reports main objective was demonstrate through simulations of how a gamma, proton and carbon beam interact with a phantom and how these properties can be utilized through treatment plans. The simulation did find that for gamma beams it's better utilized under 1 Mev for safe utilization without hitting healthy tumors, and that proton can give higher doses around 100-200 Mev that can hit a phantom and have a rapid Bragg peak. For carbon beams they're better utilized for beams with high energy dosage to give at a defined depth. As shown longitudinally the carbon beams of 3000 Mev have large energy deposit that has more sharp Bragg peak than proton that can hit tumour at specific depth without the issue of hitting healthy cells. The only recommendation that can optimize the simulation would be for it to have a specific treatment design part to where more specific details like tumour area and orientation are more known. [Counts: 162]

Works Cited

[1] Dr. Paul King. *Physics 6751: Nuclear Lab Manual*. Version 24.5. Athens, Ohio, 2024.

[2] Thomas A. Trikalinos et al. *Introduction. Particle Beam Radiation Therapies for Cancer*. NCBI Bookshelf, Nov. 2009. URL: `https://www.ncbi.nlm.nih.gov/books/NBK44535/`.

[3] International Committee for Radiation Protection (ICRP). *International Committee for Radiation Protection Reports*. Accessed: 2024-11-13. 2024. URL: `https://www.icrp.org/`.

[4] PHYS5036. *Simulation Software and Setup*. Accessed: 2024-11-13. 2021. URL: `https://github.com/PHYS5036/Sim`.