Proton Cancer Therapy: Using Laser Accelerate Protons for Radiation Therapy

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Graduation with Research Distinction in Engineering Physics

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Abstract

High intensity lasers have been shown to accelerate protons to high energies. These protons are energetic enough to be used in treating cancers and tumors up to three centimeters deep. Protons are advantageous to use because they do not cause as much damage to healthy cells in the body then other radiation sources, e.g. photons. Simulations using MCNP show the radiation dose received by an intraocular melanoma would require 10^6 protons to deliver a dose of 1.2 Gy to the tumor. The simulations also show that protons do a better job of giving less dosage to healthy cells compared to the same dose delivered using x-rays. Further research needs to be done to find ways to accelerate protons to higher energies.

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I. Introduction

Radiation therapy is a proven method of killing cancers and tumors inside of the body. Radiation therapy can be achieved through the use of x-rays, photons, protons, as well as heavy ions. Radiation therapy works by external particles (or protons) interacting with cell structure in the body, causing excitation and ionization. The released charged particles have the ability to destroy the cancer cell's DNA. If the DNA has been significantly altered, so the cell can no longer replicate, it is considered to be destroyed. Since the applied radiation will irradiate all cells, for therapy to be effective, the risk of irradiating healthy cells must be minimized while maximizing the damage done to the cancerous cells [1].

Wilson, in 1946, first proposed using protons as an effective method of radiation therapy. The first medical case treated with protons was a pituitary tumor in 1954. There are many advantages for using protons for therapy: unlike x-rays and photons each of which will give a large dose of radiation to the healthy cells on its path to the tumor, the dose deposited by the proton while traveling through healthy tissue is smaller. The protons give off the majority of their energy at the end of their path. This is denoted by the Bragg Peak (see figure. 1). The distance the protons travel is determined by their initial energy. By using a modified Bragg Peak, one can select a range of proton energy and a range of distance by which to deposit dosage. Another reason for using proton therapy is protons are deflected less than electrons. Because the protons are more massive in size, the momentum transfer from hitting cells is less likely to cause a change in direction. This means when the protons are traveling through tissue the protons will stay collimated and will not diverge and deposit their energy into healthy cells. Using protons for radiation therapy gives great control so energy can be deposited into exact locations within the tumor. [2].

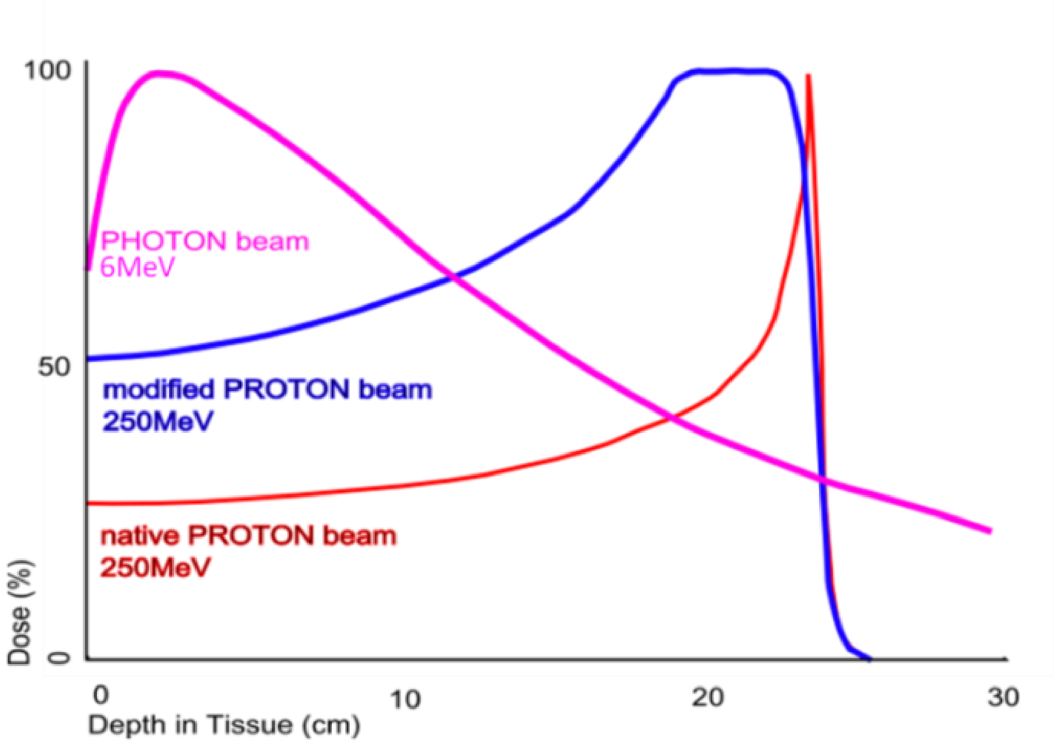

Figure 1 Plot of dose deposited in water as a function of distance for 6 MeV photons and 150 MeV protons. For example, if the tumor was located 20 to 25 cm into tissue, the dosage at the tumor would be maximized with protons while decreasing the dosage to healthy cells that the photon beam would distribute.

II. Proton Energy Requirements

Basic requirements for using protons include control of the proton energy, control over energy selection, collimation of the beam, and control of the number of protons delivered with requirements for steering the protons to the patient. In order for protons to reach tumors deep inside the body, the proton energies must reach 230-250 MeV. One eV is the amount of energy it takes for one proton to travel across an electric potential of 1 volt. Therefore, 230-250 MeV is equivalent to 3.7×10^{-11} to 4×10^{-11} J. The beam requirement for selecting specific energy ranges is necessary to control the depth at which the protons deposit their energy. The range of protons delivered should be enough to reach the depth of the tumor without excessive radiation dosages being received by the healthy cells surrounding the tumor. The collimation of the beam allows for precise placement of energy into the patient, avoiding healthy cells around the tumor. The number of protons delivered must be controlled in order to control the radiation dosage received to the tumor cells. Other requirements for radiation therapy delivery systems are steering the protons to the patient while minimizing patient discomfort, and providing the proper shielding from other radiation products produced [3] [4].

Research in physics recently discovered that proton beams can be generated by a high intensity laser hitting a metal target. High intensity lasers are less expensive, costing tens of millions of dollars as opposed to over $100 million. High intensity lasers also are more compact. The lasers would have the ability to fit into a hospital wing, as opposed to needing a whole building dedicated to proton therapy treatment [5]. The savings in cost and space would make proton therapy more affordable to medical facilities, ultimately increasing the availability of radiation therapy treatment for those with cancer.

III. Accelerating Protons: Target Normal Sheath Acceleration

One method to accelerate protons from a laser source is Target Normal Sheath Acceleration (TNSA) (Figure 2). In this process, an intense laser (10^{18} W/cm^2) hits a target. The energy of the laser is transferred to the target. Because the electrons in the target are less massive than protons, the electrons will accelerate faster than the protons in the target and will achieve greater speeds than the protons. Some of the electrons escape off the back of the target. As this occurs, the target will become positively charged and the electrons that escape will stay on the back target, creating a layer called the Debye Sheath. The electric force attracts protons and accelerates the protons off of the back of the target. The protons accelerating off the back of the target are collimated because of the electric force created by the electrons [6].

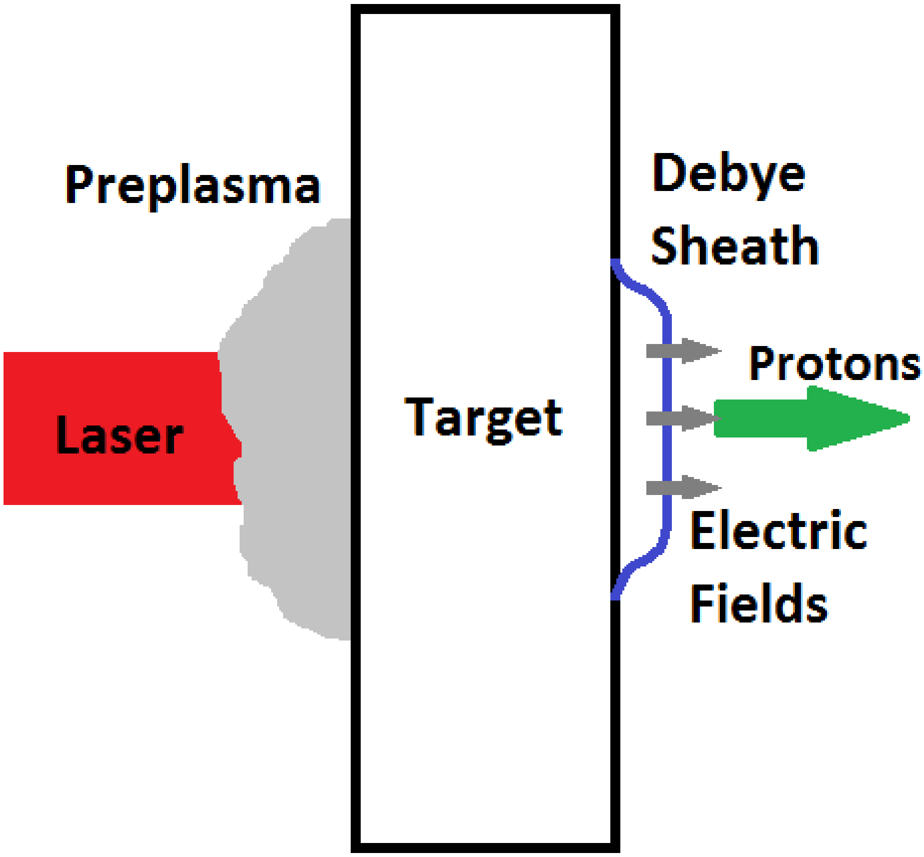

Figure 2 The laser pulse hits the front of the target creating the preplasma and the hot electrons. The hot electrons are driven out of the target setting up a Debye Sheath, which creates electric fields. The electric fields accelerate the protons. This is not to scale.

Obstacles for the immediate construction of this instrument include the need to increase the number of protons generated at higher energies. Currently lasers in operation are able to achieve proton energies of up to 60 MeV [7]. This energy would not be great enough to treat most types of tumors or cancers which require 50-250 MeV. As proton energy is increased the number of protons produced will also have to increase so that the tumor will receive a high enough dose to destroy tumor cells.

IV. Relevance

The proton energy needed to treat an eye tumor 2 cm deep is 50 MeV. This converts to 8 x 10^{-12} Joules. An eye tumor with mass of 1 gram requires a dose of 60 Gray which would be a total of 10^{10} MeV. The dose deposited per minute is 1-2 Gy, which translates to 2 x 10^{8} protons per shot of 50 MeV, or 8 x 10^{-12} J, protons [7]. This estimate uses approximations including that all of the protons are deposited at the Bragg Peak and that all of the protons are monoenergetic. According to Snavely's paper [8] on experiments from the NOVA pettawatt-laser, which has since been dismantled, one shot from the laser can produce as many as 7 x 10^9 protons of 50 MeV for a single laser shot [8]. Therefore, with current laser technologies it is feasible to deliver a dosage that could treat cancers just a few cm under the skin.

Laser acceleration of protons would be a cost effective solution to proton therapy treatment. The successful results of this research would increase the fiscal opportunity for more facilities to be able to provide radiation therapy to patients with cancer.

V. Goals

The goal of this research is primarily to show through simulations using the particle transport code Monte Carlo N-Particle, code optimized for protons (MCNPX), that a proton source can target and treat a tumor a few cm into the eye. The proton source in the simulation will resemble the size and amount of protons generated from a laser shot. The eye will initially be modeled as a body of water with its surrounding bone and tissue in order to accurately calculate the dosage deposited in the tumorous region and the collateral damage that will occur to healthy material surrounding the tissues. The bone, skin, and tissue modeled have the correct molecular ratios and stoichiometry in the MCNP simulation.

MCNP is a Monte Carlo code that is able to simulate particle interactions. The user must input the source particles including what type and what energies, and the material that the source particles interact with. The code will send in one source particle at a time and determine different aspects of it behavior in the material including the path of the source particle, flux through user defined surfaces, and energy deposited in different areas. After running many source particles through the material the Monte Carlo code is able to determine the average behavior of the particles and give a distribution of the behavior per particle.

VI. Results

A simulation was run using MCNPX with a 50 MeV uniform disc source, radius 0.5 cm, generating 100,000 protons shot into a cylinder of water. The protons generated were all traveling normal to the plane of the source. The cylinder of water had a radius of 5 cm and was broken into section every tenth of a cm for a total of 4 cm of water (see figure 3). The simulation calculated the amount of energy deposited in each tenth cm of water in MeV/gram.

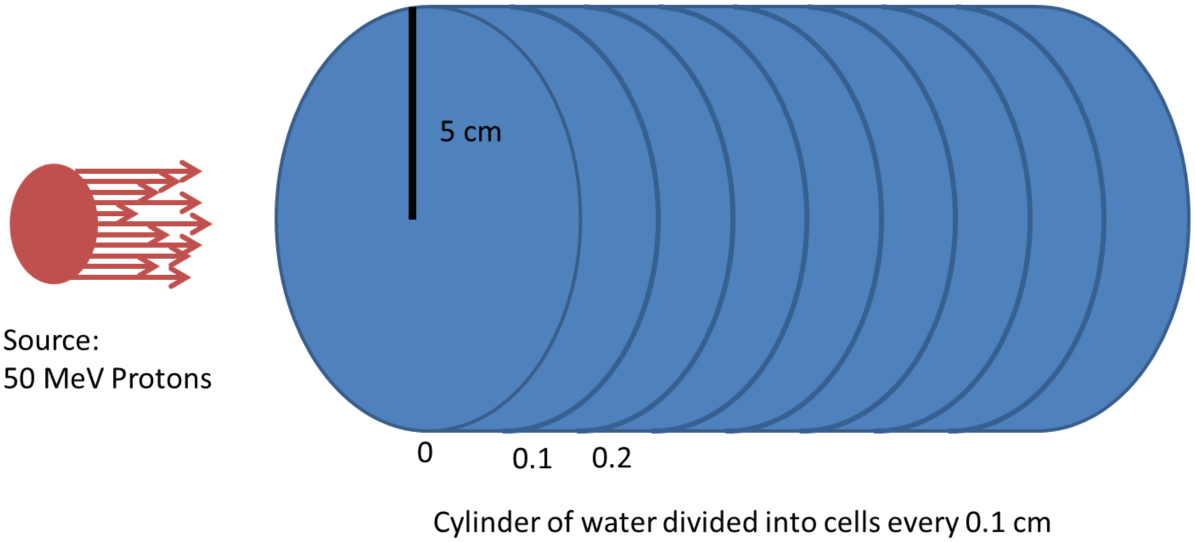

Figure 3 Simulation set up in MCNPX of a 50 MeV proton disc source and a cylinder of water partitioned every tenth of a centimeter.

The simulation results were graphed and the results are shown below in figure 4. The peak of the protons occurs in the volume from 2.1 to 2.2 cm deep into the cylinder. This agrees with the results of Konefal for 50 MeV protons [9].

For 10,000 protons at 50 MeV a dose of 0.00017 Gy will be deposited to the tumor. This means for the $7x10^9$ protons at 50 MeV seen in Snavely's paper there would be a dose of 200 Gy to a tumor which would be one hundred times bigger than the dose needed to treat it.

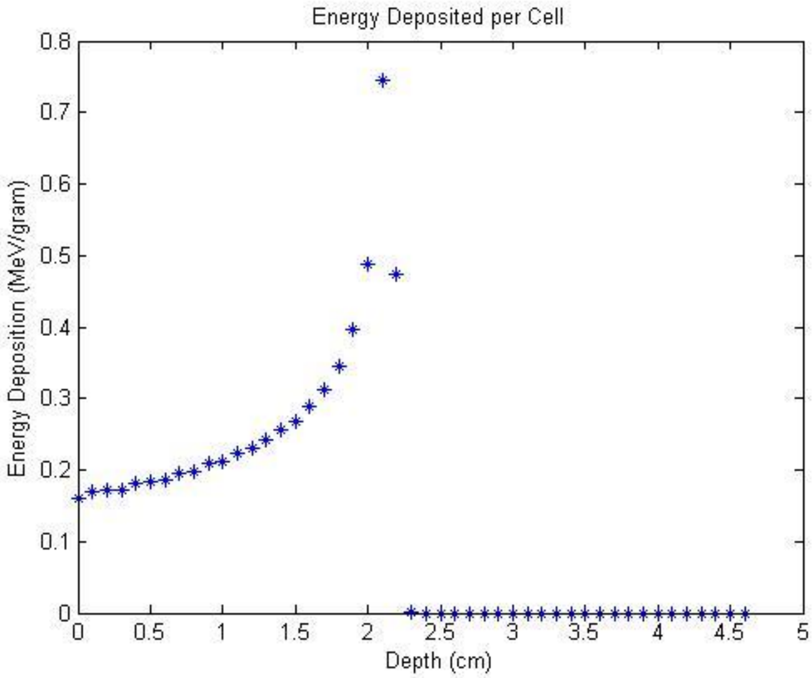

Figure 4 Simulation result of MCNPX showing the Bragg peak in water with depth of 2.1 to 2.2 cm

The next simulation used a crude model of a head to find the dosage a 58 MeV source would input into an intraocular tumor (see figure 5). The intraocular tumor was modeled for the dimensions of a large intraocular melanoma [10]. The density and atomic makeup of the materials in the simulation were found in the thesis "Medical Physics Calculations with MCNP^{TM}: A Primer" [11] with the exception of the eye and tumor. The eye was estimated to be water and the tumor to be soft tissue [12]. The eye is 4.8 cm in diameter and the tumor is estimated to be a cylinder with a diameter of 2 mm and 5 mm in depth.

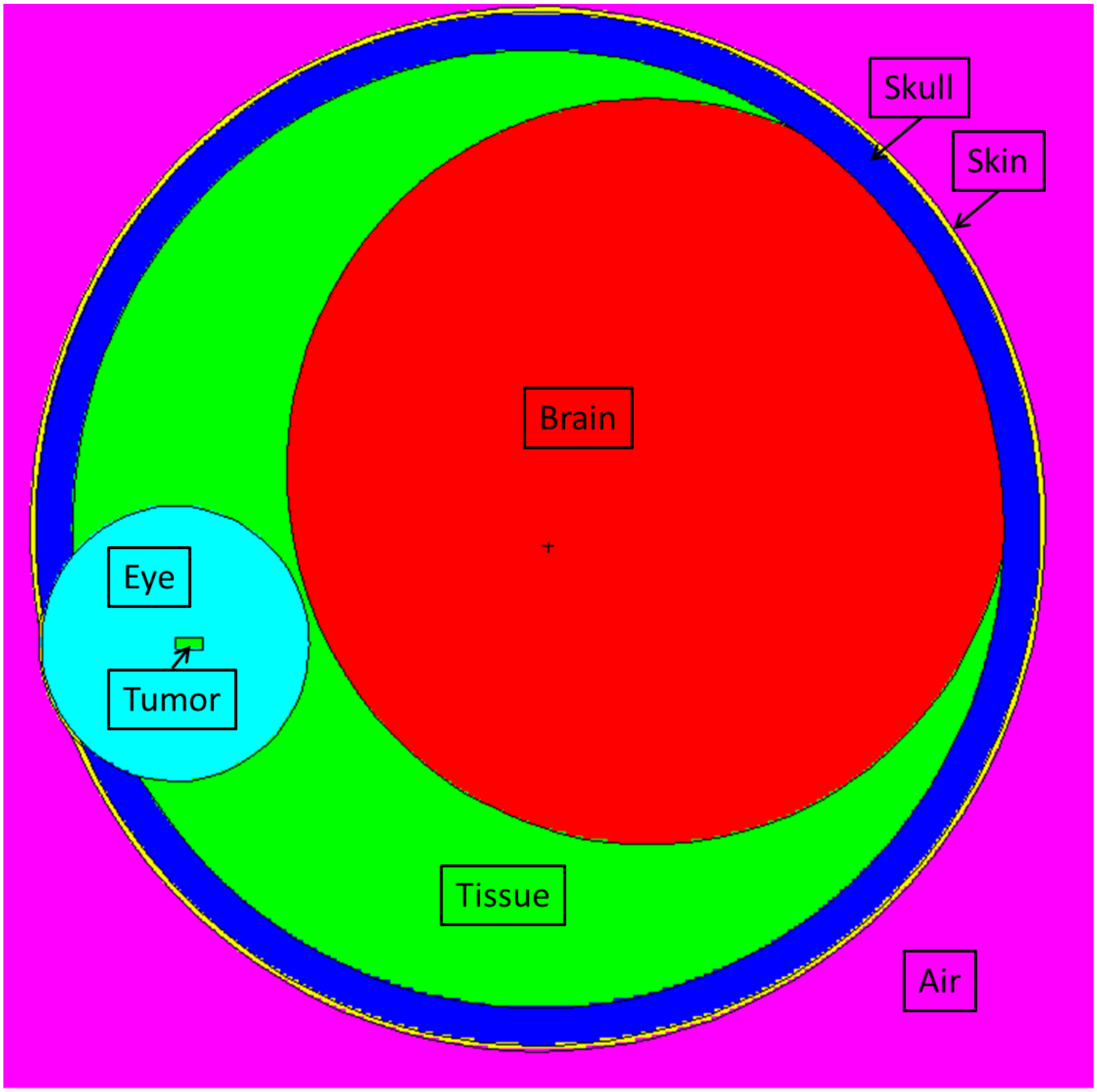

Figure 5 Geometry of the simulation. The light blue is the eye with the green tumor inside. Blue is skull, yellow is skin, red brain, green is soft tissue, pink is air.

The source was 5 cm to the left of the eye and collimated with a single energy of 58 MeV. The diameter of the source is 10 microns which is the approximate size of the proton beam accelerated from the laser TNSA interaction.

The simulation ran for 1x10^6 protons and the resulted in 1.2 Gy deposited into the tumor. The next highest dose deposited was the region directly in front of the tumor which received a dosage of 0.13 Gy. Overall there was a total dose of less than 2 Gy deposited in the whole structure. The dosage for most of the areas including the skull, skin, and parts of the eye that was not in a direct line from the source received doses of less than a microGray. The brain received no dose from the protons.

This can compare to a simulation done with 20 MeV photons. For the same amount of dose to be received by the tumor the dose to the eye, skin, and skull all increase by a factor of three. In the photon simulation the brain will receive a dose of 0.3 mGy. However, this dose is for the whole brain and most of the energy will be deposited in the line of the photon beam therefore a dose of higher than 0.4 mGy should be expected for that area.

Plots of the particles going through the head are shown below the points that appear on the plot are the places where the particles, either the protons or the photons, deposit energy into the head. Figures 6 and 7 show the particle tracks for 1000 protons going into the eye. It can be seen that there is some dispersion but the majority of the energy is indeed deposited into the tumor. Figure 8 shows the particle tracks for 1000 photons entering the skull. The figure clearly shows that the photons will go through the brain deposit energy throughout it.

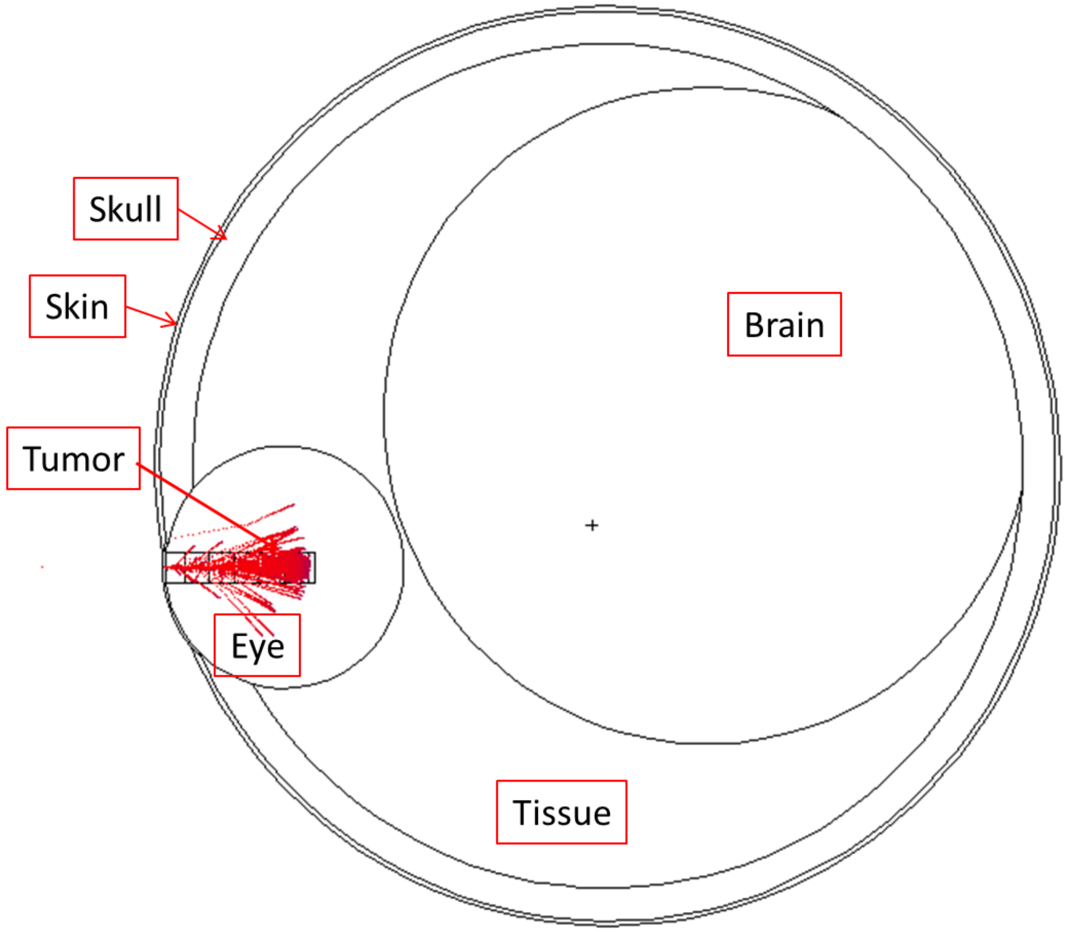

Figure 6 Particle tracks of 1000 protons through the skull.

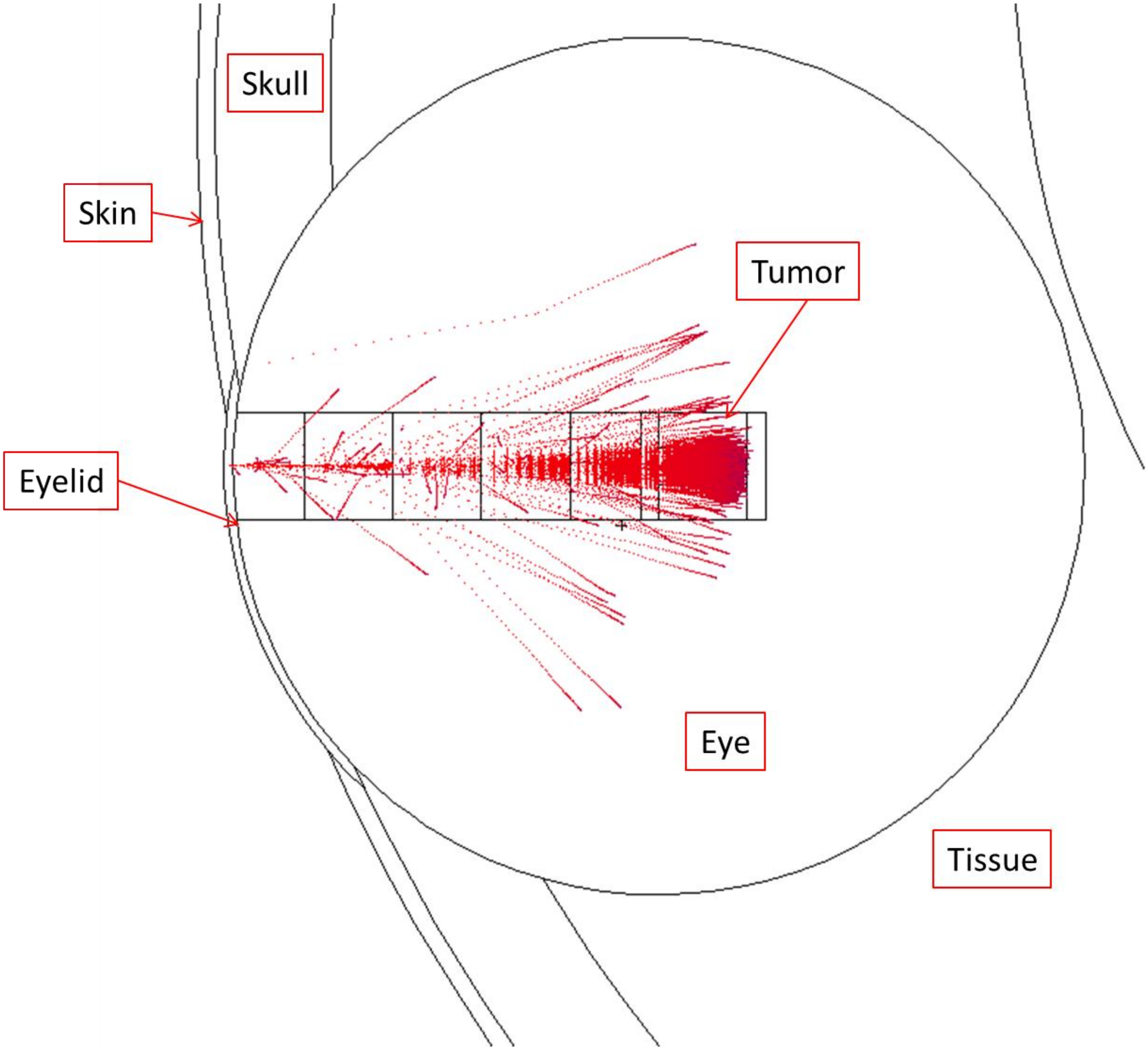

Figure 7 Close up picture of proton particle energy deposited in the eye.

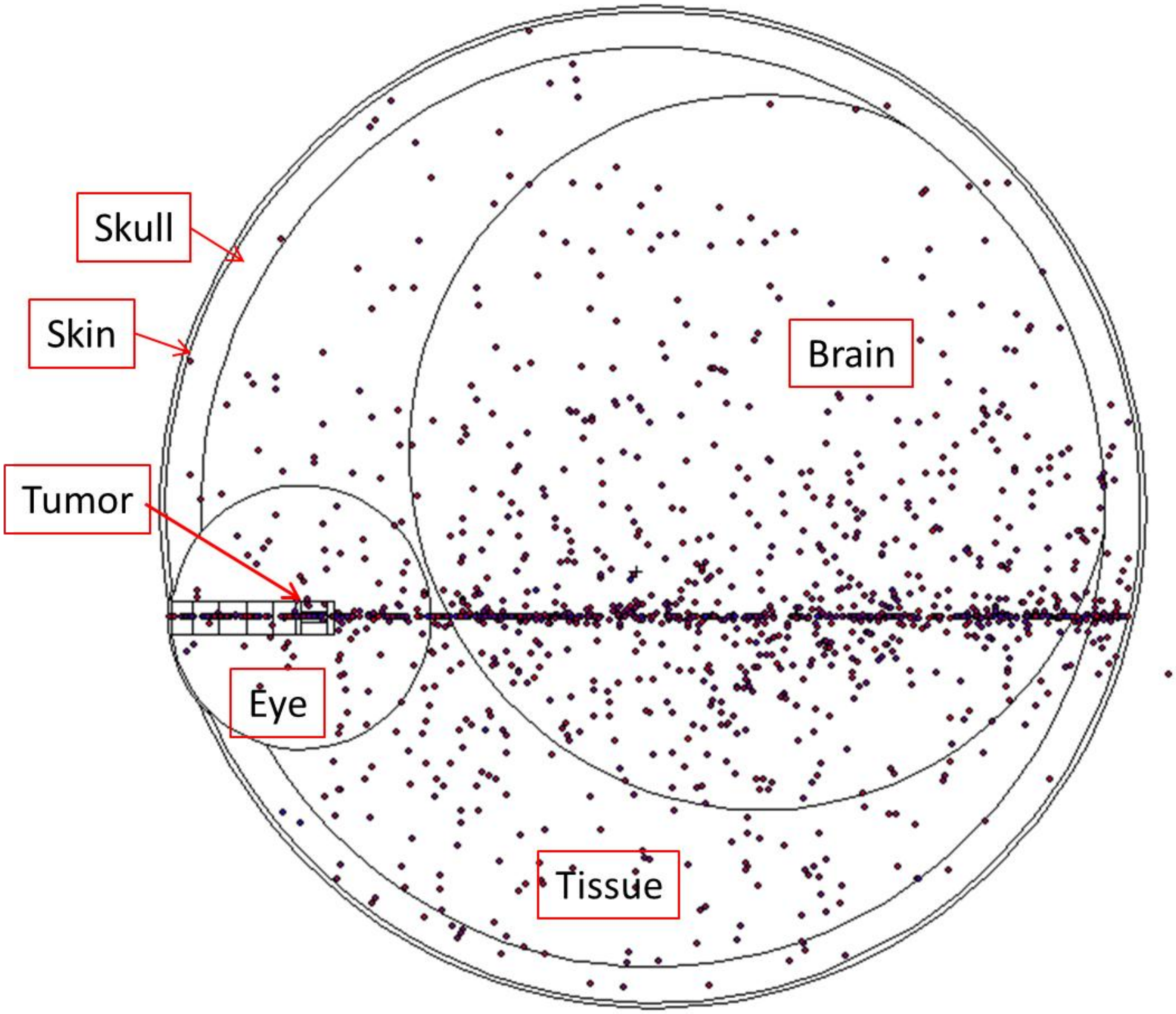

Figure 8 Locations of energy deposited by 1000 x-rays through the skull.

Another simulation was run in MCNP to determine the distribution of dose through the skull in line with the source. For this simulation a cylinder with a diameter of 2 mm was inserted through the skull with in line with the path of source particles. This cylinder was partitioned every millimeter and the dose of each millimeter partition was determined for both the proton and x-ray cases. This plot is shown in figure 9. In this figure both the proton and s-rays will give a total tumor dose of 1.2 Gy. The figure clearly shows that protons will give a smaller dose to all areas surrounding the tumor and that protons are much more effective at protecting the brain, and in fact the protons give the brain no dose.

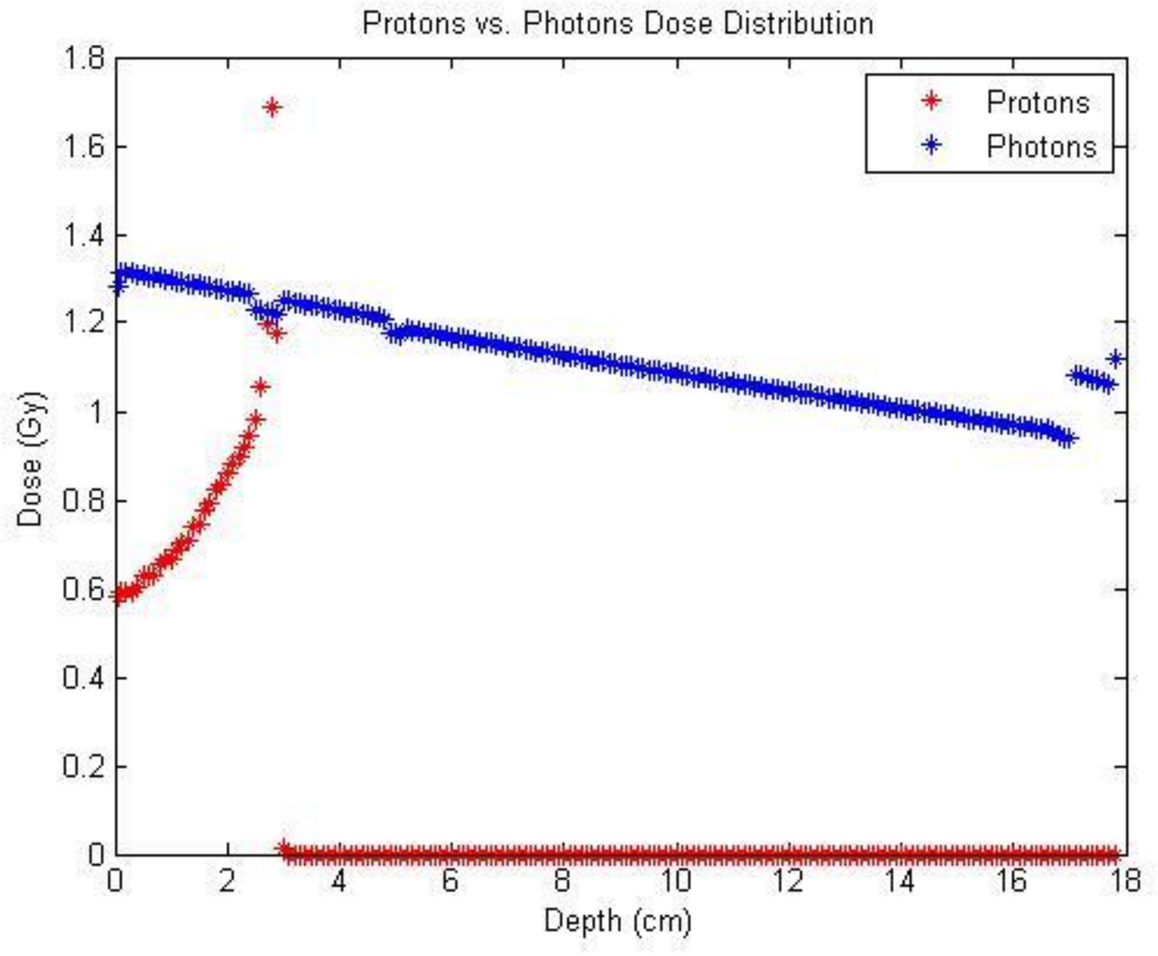

Figure 9 Dose deposited by both protons and photons that give a whole tumor dose of 1.2 Gy.

VII. Conclusion

Having a means to treat cancers and tumors up to 3 cm deep in the body without causing much damage to surrounding areas, and more importantly causing almost no damage to cells behind the tumor has major implications to treating tumors.

It has been shown that protons accelerated by lasers can create a dosage of 1.2 Gy with 10^6 protons. The amount of 58 MeV protons seen in one laser shot by Snavely was 1 x

10^9. This means that one laser shot could conceivably deliver a dosage of much greater than the 60 Gy required to treat an eye tumor so patients will need fewer radiation treatments.

The next step in the study is to have the source come in at multiple angles to try and find the smallest dosage possible to the surrounding structures for a maximum dose to the tumor. Another simulation to be done is the have a larger tumor and have a proton source of multiple energies so that an even dosage will be deposited throughout the tumor.

Other scientists have considered different systems to separate single energies from the protons created by the laser and for the gantry systems that would deliver the protons to the patients.

An example of separating different proton energies was developed Ma at Fox Chase Cancer Center [13]. The protons from the laser target interaction would go enter a collimator and enter a series of magnets. The amount that the protons would bend can be determined knowing the magnetic field of the magnets. The protons would enter an energy selector where only the specific energies needed for treating the tumor would be selected and the rest of the proton energies would be absorbed. The protons would then return through a series a magnets and exit through a second collimator and then would be used for treatment. This configuration is shown in figure 8.

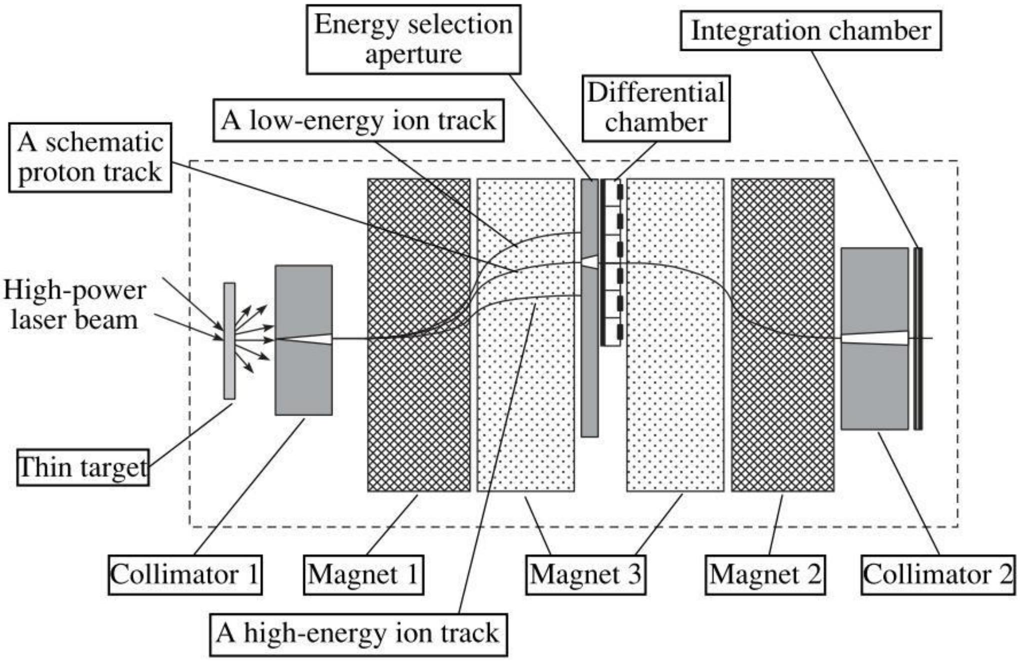

Figure 10 An example of a proton energy selector by Ma from Fox Chase Cancer Center.

Different gantry systems have been modeled to show how a patient would be orientated during treatment [14]. The systems have a laser with light steered to the patient. Very near the patient is the target interaction. By having the patient close to the laser it minimizes the cost of having to steer the protons with large magnets. After the laser target interaction it the protons will enter into an energy selector and then be delivered to the patient (see figure 9). With this system one laser can treat multiple patients in different rooms. The laser light could be steered to different target areas for each patient room with mirrors, again minimizing the cost of the facility.

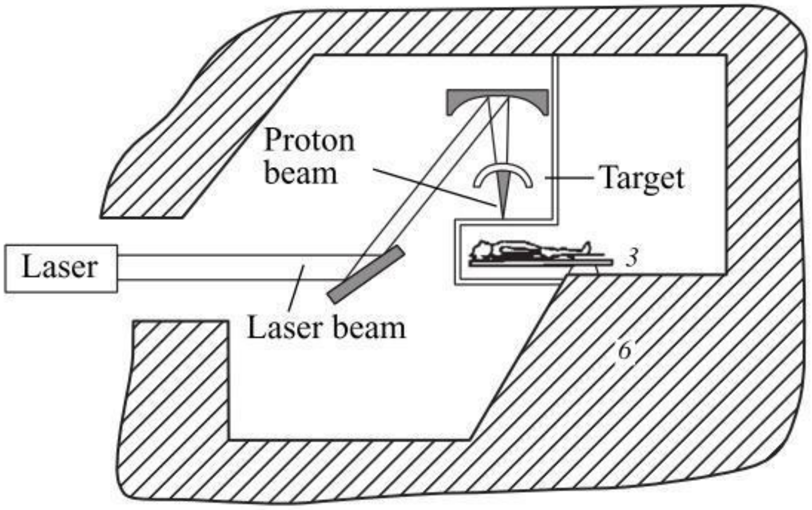

Figure 11 Possible gantry system showing the laser light steered to the patient treatment room

For laser accelerated protons to be a viable option for treating all types of cancers and tumors further research needs to be done to find ways to increase the proton energies up to at least 250 MeV. However, it is shown that for cancers up to 3.5 cm deep in the eye protons current laser accelerated protons energies would be sufficient for the treatment of those tumors.

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