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A BEAM LINE SETUP FOR FLASH RADIATION THERAPY WITH FOCUSED ELECTRON BEAMS AT THE PITZ FACILITY AT DESY IN ZEUTHEN: BASIC CONCEPT AND DOSIMETRY SIMULATIONS

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Abstract

The objective of this study is demonstration of the principal possibility to increase the electron beam dose deposition at the certain depth of the sample for radiation therapy purposes. Electron bunches of 22 MeV within train generated at PITZ are focused inside the sample using a dedicated fast deflector and a solenoid magnet. To explore the capabilities of the proposed setup, dose distributions are calculated for multiple electron bunches focused in a single point inside a water phantom. Electron beam focusing produces dose peaks with a tunable maximal dose depth which is interesting for healthy tissue sparing at the surface and enhancing treatment quality. The duration of the full bunch train is 1 ms. During this time interval, the FLASH effect could be efficiently triggered inside the irradiated target volume. Monte Carlo simulations based on the FLUKA code were performed to evaluate the depth dose curves distributions in a water phantom. Using the PITZ electron beam parameters, simulations have shown the possibility to produce a peak dose in water seven times higher than compared to the dose at the surface. Moreover, the RMS size homogeneous area around the maximal dose is approximately 25 mm.

INTRODUCTION

Radiation therapy is an effective method of treating cancer by directing high-energy radiation at a tumor to kill cancer cells. However, healthy tissue surrounding the tumor can also be affected by radiation, leading to unwanted side effects [1, 2]. Ion and proton therapies have been developed to increase the effectiveness of radiation therapy because they concentrate the dose within the Bragg peak, thus minimizing radiation damage to surrounding healthy tissue [3, 4]. Unfortunately, these methods are often costly, and their limited availability due to the size and complexity of the equipment required has prevented their wider application [5]. Consequently, there is a growing demand for more affordable and accurate radiotherapy solutions, electron accelerators could therefore be an interesting alternative to generate Bragg peak like dose distributions.

This work aims to demonstrate the possibility of increasing the electron beam dose deposition at a tune able maximum depth inside a water phantom for radiotherapy purposes. A special fast deflector ("kicker" – also called "sweeper") and a solenoid magnet were used to focus the electron beams, and produce dose peaks at the desired depth. Monte Carlo simulations based on the FLUKA code were performed to estimate the dose distribution in water [6, 7]. The calculations have shown that peak doses up to seven times higher could be obtained w-r-t the dose at the surface. By presenting the basic concept of the proposed dosimetry setup and simulation, this article highlights the potential of the presented approach as a more cost-effective, accurate solution and as an original concept for electron beam-based radiotherapy.

FOCUSED HIGH-ENERGY ELECTRON BEAMS IN WATER PHANTOM

Recent studies have demonstrated the possibility of focusing very high energy electron beams to obtain high energy deposit penetration inside a water phantom the maximal dose depth is controlled by changing the configuration of the quadrupole settings [8-10].

The main purpose of this study was to investigate the peak energy deposition in water at various depths resulting from the crossing of several electron bunches with an energy of 22 MeV. To achieve the intersection of several bunches at one point in the water, we used a kicker and solenoid magnets. The kicker magnet allowed each bunch to deviate in different directions with a duration of a complete train of bunches of 1 ms. Subsequently, a solenoid magnet was used to bring several bunches into one point at different depths (10 mm, 20 mm, 30 mm, and 40 mm) in water. The strength and length of the required solenoid magnets were determined using the ASTRA code [11].

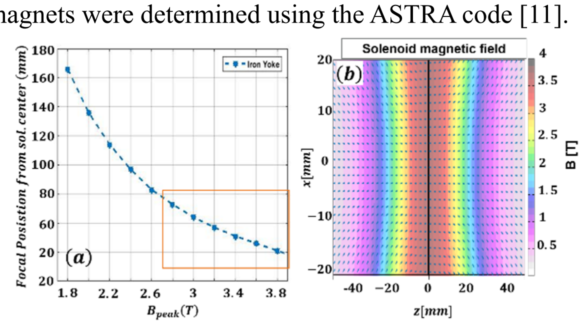

Figure 1: (a) Relation between the strength of the magnetic field and its focus position relative to the centre of the solenoid and (b) the distribution of the solenoid magnetic field used in the simulation.

Figure 1 (a) shows the relation between the strength of the magnetic field of the solenoid and the position of its focus with respect to the centre of the solenoid. The peak values of the magnetic field strength were in the range from

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2.8 T to 3.8 T, while the electron beam with an energy of 22 MeV was focused in vacuum at a distance of 80 mm to 40 mm from the center of the solenoid. To simulate the transfer and interaction of charged particles in the magnetic field of a solenoid, we used the FLUKA Monte Carlo simulation program. The distribution of the magnetic field of the solenoid used in the simulation is shown in Figure 1(b). Electron beam vacuum extraction was taken into account by including accelerator exit window made of titanium with a thickness of 50 µm and a diameter of 34 mm. The simulated setup consisted of an exit window, followed by an air box of 30 mm, and a water phantom with dimensions of 60×60×60 cm^3. In our simulation model, we placed the kicker magnet system 1000 mm away from the exit window, which was surrounded by a solenoid magnet, as shown in Figure 2.

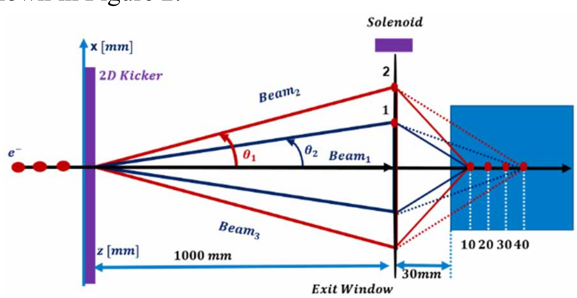

Figure 2: A schematic representation of the electron bunches for the simulation model in the FLUKA code.

Our analysis included two cases where we considered displacement angles of θ_2= 6 mrad and θ_1=10 mrad, which led to bunch displacements on the exit window by dr_2=6.0 mm and dr_1=10 mm away from the center, respectively. In addition, we used a solenoid magnet to combine several bunches at one point in the water at different depths (10 mm, 20 mm, 30 mm and 40 mm). We also investigated the effect of beam spot size on dose distribution over depth in the range of 0.2-3 mm. Figure 3 shows nine beam profiles on the window surface, each corresponding to a different offset angle of 6 mrad or 10 mrad.

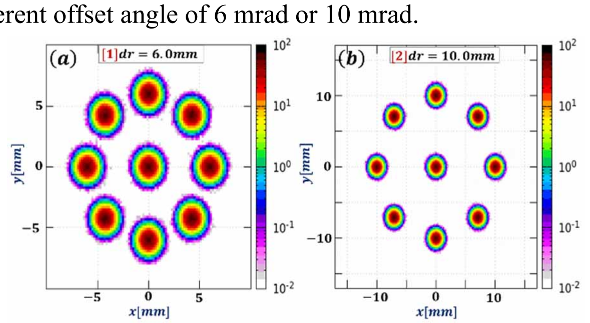

Figure 3: Beam profiles on the window surface for different displacement angles of 6 mrad and 10 mrad in (a) and (b), respectively, resulting in the bunches shifting from the center by 6 mm and 10 mm.

MONTE CARLO MODELING FOR DEPTH DOSE CALCULATIONS

The ASTRA particle physics code is a widely used and efficient tool for designing particle orbits in a vacuum, commonly used in accelerator physics. However, it cannot accurately predict the scattering effects in air and water. Therefore, Monte Carlo simulations using FLUKA are necessary to accurately simulate the behaviour of focused electron beams in a water phantom. For our simulations, we used a 1×1×1 cm^3 voxel size was used for dose estimation, and each simulation included all-particle interactions such as triplet formation, photonuclear decay, Compton radiation correction, electron ionization, and Rayleigh scattering. We set the number of primary electrons used for each simulation to 6.25×10^6, and tracked the electrons and photons to a kinetic energy of 30 keV to accurately reflect their behaviour in the water phantom.

Figure 4 shows the results of energy deposition along the beam axis, where the two transverse dimensions are integrated for a central space of 1×1 mm^2.

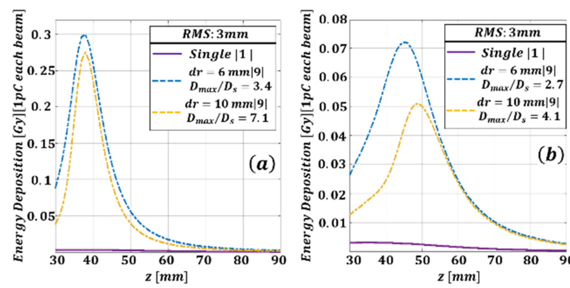

Figure 4: Energy deposition distributions along the beam axis where two transverse distributions are integrated for the central 1×1 mm^2 area. Dashed line colors correspond for different position of bunches displacement (a) dr_2 = 6.0 mm and (b) dr_1 = 10 mm. Solid line corresponds to a single bunch without displacement.

The curves correspond to two cases: (a) at a depth of 10 mm behind the water surface, where the bunches intersect, and (b) at a depth of 30 mm with an incident beam spot size of 3 mm. It can be seen from the figures that introducing different offset angles of 6 mrad and 10 mrad with a kicker magnet (as shown in Fig. 4(a)) can increase the ratio between peak dose and maximum dose at the water surface by up to seven times. This results in a higher dose at maximum depth compared to the dose at the water surface. In addition, in fig. Figure 4 (b) shows that at shift angles of 10 mrad and a focusing depth of 30 mm in the water surface, the depth of the dose peak is 18 mm. The symbols |1| and |9| in Fig. 4 represent the number of simulated bunches, and the energy deposition calculation takes into account the charge of each 1 pC bunch.

The axial dose distributions for various beam spot sizes are shown in Figure 5. The results show that the position of the dose peak remains constant for various beam spot sizes, regardless of the offset angles of 6 mrad and 10 mrad. The results demonstrate that the position of the dose peak remains constant for different beam spot sizes, indicating that the beam spot size does not affect the depth of the dose peak in the water. However, the figure also shows that increasing the beam spot size leads to an increase in the ratio of the peak dose to the maximum dose at the water surface.

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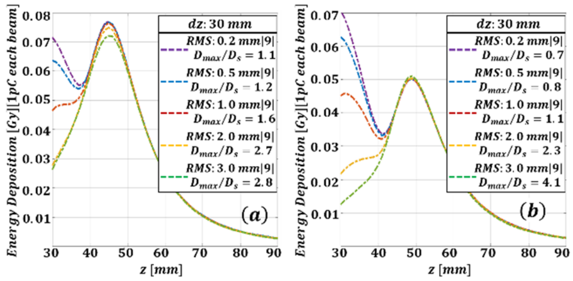

Figure 5: The axial dose distributions for different beam spot sizes. Dashed line colours correspond for different position of bunches displacement (a) $dr_2 = 6.0$ mm and (b) $dr_1 = 10$ mm.

The dose peak on-axis change as a function of various focal points in the water is shown in Figure 6. The graph demonstrates that the magnetic force generated by the solenoid can effectively control the depth position of the dose in water by shifting the focal point towards deeper regions. Specifically, the results demonstrate that setting the focal point at deep locations leads to a decrease in the dose depth position, while setting the focal point closer to the surface increases the dose depth position.

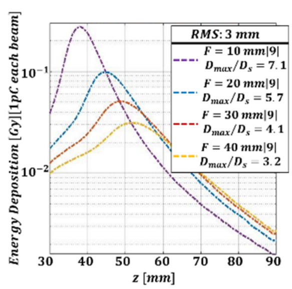

Figure 6: Behaviour of on-axis dose peak as a function of focal point position in water for different solenoid magnetic strengths. The line colours correspond to different focal point positions, while the incident beam spot size is 3 mm.

Figure 7 shows the dose distribution in the YZ plane along the incident electrons. The integral dose is taken over the vertical axis of a 1 mm central slice. From the figure, we can observe how changing the position of the bunches intersecting in the water affects the area of homogeneous dose. The results demonstrate that increasing the depth of the bunches intersecting at the focal point in the water can lead to a more homogeneous dose distribution at 25 mm depth approximately. This key result is particularly useful for optimizing radiotherapy treatment planning with electron beams, where precise control of dose depth is critical to maximizing therapeutic effect while minimizing the risk of healthy tissue damage.

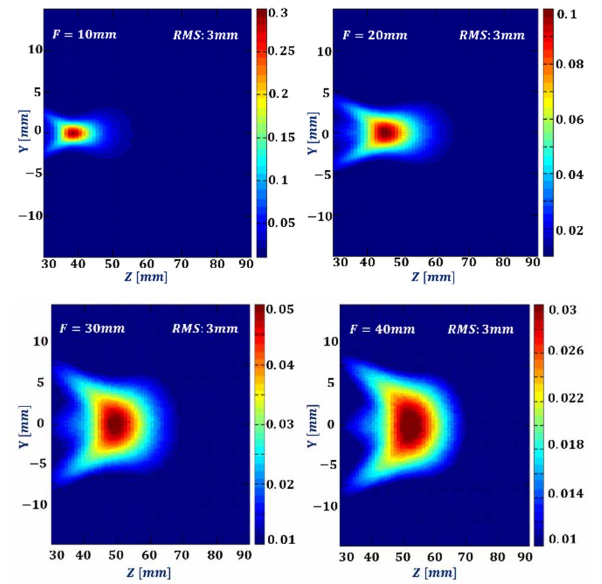

Figure 7: The dose distribution in the YZ plane along the incident electrons for an initial beam spot size of 3 mm. The plots correspond to different bunch intersect points in the water, where combine several bunches at one point in the water at different depths F = 10 mm, F = 20 mm, F = 30 mm, and F = 40 mm.

CONCLUSION

The study shows that 22 MeV electron beams can be focused in a water phantom to produce Bragg peal like dose distribution, using a special fast deflector and solenoid magnets. By adjusting the offset angles of the kicker magnet, the peak-to-maximum dose ratio can be increased by up to seven times, resulting in a higher maximum depth dose. The position of the peak dose remains constant for different beam spot sizes, indicating that the beam spot size does not affect the dose depth in water. However, increasing the beam spot size increases the ratio of peak to maximum dose at the water surface. By adjusting the focus point with solenoid magnets, the position of the dose depth in the water can be controlled, providing more control over dose distribution and improving radiotherapy treatment. Increasing the depth of the beam intersection points in water can lead to a more uniform dose distribution at around 25 mm depth. Electron beam focusing produces dose peaks with a tunable maximal dose depth which is interesting for healthy tissue sparing at the surface and enhancing treatment quality.

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