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Contributions of secondary fragmentation by carbon ion beams in water phantom: Monte Carlo simulation

Abstract

Heavy-particle therapy such as carbon ion therapy is currently very popular because of its superior conformality in terms of dose distribution and higher Relative Biological Effectiveness (RBE). However, carbon ion beams produce a complex mixed radiation field, which needs to be fully characterised. In this study, the fragmentation of a 290 MeV/u primary carbon ion beam was studied using the Geant4 Monte Carlo Toolkit. When the primary carbon ion beam interacts with water, secondary light charged particles (H, He, Li, Be, B) and fast neutrons are produced, contributing to the dose, especially after the distal edge of the Bragg peak.

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Contributions of secondary fragmentation by carbon ion beams in water phantom: Monte Carlo simulation

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Abstract. Heavy-particle therapy such as carbon ion therapy is currently very popular because of its superior conformality in terms of dose distribution and higher Relative Biological Effectiveness (RBE). However, carbon ion beams produce a complex mixed radiation field, which needs to be fully characterised. In this study, the fragmentation of a 290 MeV/u primary carbon ion beam was studied using the Geant4 Monte Carlo Toolkit. When the primary carbon ion beam interacts with water, secondary light charged particles (H, He, Li, Be, B) and fast neutrons are produced, contributing to the dose, especially after the distal edge of the Bragg peak.

1. Introduction

Heavy Ion Therapy (HIT) consists of the use of carbon ions to destroy cancer. The main advantage of HIT with respect to proton therapy and X-ray radiotherapy is better conformality to the target, capability to treat deep-seated tumors and a higher Relative Biological Effectiveness (RBE) [1].

When a primary carbon ion is passing through the medium with energy of several hundred of MeV/u, the radiation field is affected by nuclear fragmentation. Nuclear fragments contribute to the dose deposition and are responsible for the dose tail observed after the distal edge of the Bragg Peak [2-3]. Therefore it is crucial to characterise the components of the radiation field produced by the incident carbon ion, in terms of both spatial distribution and LET, as particles with higher LET have a higher probability to kill cancerous cells.

When the primary nuclei are in tissue-like media such as water or PMMA phantom at several hundred MeV, peripheral collisions are the most frequently occurring nuclear reactions. These reactions result in fragmentation of both target and projectile nuclei. This can be described by abrasion-ablation model with two step processes [4-5]. In the first step of peripheral collisions, the incident beam particle may lose one or several nucleons along the penetration depth and the nucleons in the overlapping zone of the incident projectile and target nuclei are abraded, resulting in the formation of a hot zone (fireball). In this process, outer nucleons called “spectators” are only slightly affected.

In the second step (ablation), the remaining projectile and target fragments as well as fireball de-excite with the evaporation of nucleons and light clusters. The produced fragments



from the projectile move in the direction of the incident projectile with equal or higher velocity to that of the incident projectile, contribute to the dose deposition until they are completely slowed down. The target fragments have velocities much smaller than that of the projectile velocity, fragments from the fireball have a velocity in the range between target emission and projectile fragments. Nuclear fragmentation reactions lead to an attenuation of the primary beam flux and build-up of low mass fragments which have longer ranges than the primary ions and carry large fractions of the original ion's energy enabling the produced fragments to travel a longer distance of the Bragg peak position. Therefore, the depth dose profile of carbon ion beams shows the characteristic fragment tail beyond the Bragg peak.

1.1 Geant4 Simulation toolkit

GEANT4 (GEometry ANd Tracking) Monte Carlo code [6-7] is a toolkit for the simulation of the passage of particles through matter. Geant4 is used because of its powerful abilities to simulate all type of particles, greater flexibility, can simulating various geometric variations and different types of physical interactions process and it became the powerful tools for the study of interaction in the fields of medical physics, radiation protection, high energy physics and nuclear physics etc. Many literatures show the Geant4 studies based on Geant4 simulations had good agreement with the experimental results [8-11].

2. Materials and Methods

2.1. The Geant4 simulation application

An ad-hoc Geant4 simulation was used to model the radiation field produced by a 290 MeV/u carbon ion beam in a Polymethyl Methacrylate (PMMA) phantom. The beam lateral size was 50 mm. The ion beam line was generated at a distance of 30 cm from the surface of the phantom. The sketch of the beam line is shown in the Figure 1(a). The dose along the phantom depth for each type of nuclear fragment was calculated. The characteristics of the radiation field produced by incident carbon ions were studied as well.

The Geant4 QGSP_BIC_EMY Reference Physics List was adopted. The production of secondary particles was governed by a range cut which was set to 0.1 mm. A total number of $5 \cdot 10^5$ events was simulated in order to obtain an adequate statistics. Figure 1(b) shows a snapshot of the simulation. The incident carbon ions (blue tracks) are incident on the phantom and produce gamma and neutrons (green tracks), positively charged nuclear fragments (blue tracks) and electrons (red tracks). Geant4 version 4.9.6.p01 was used.

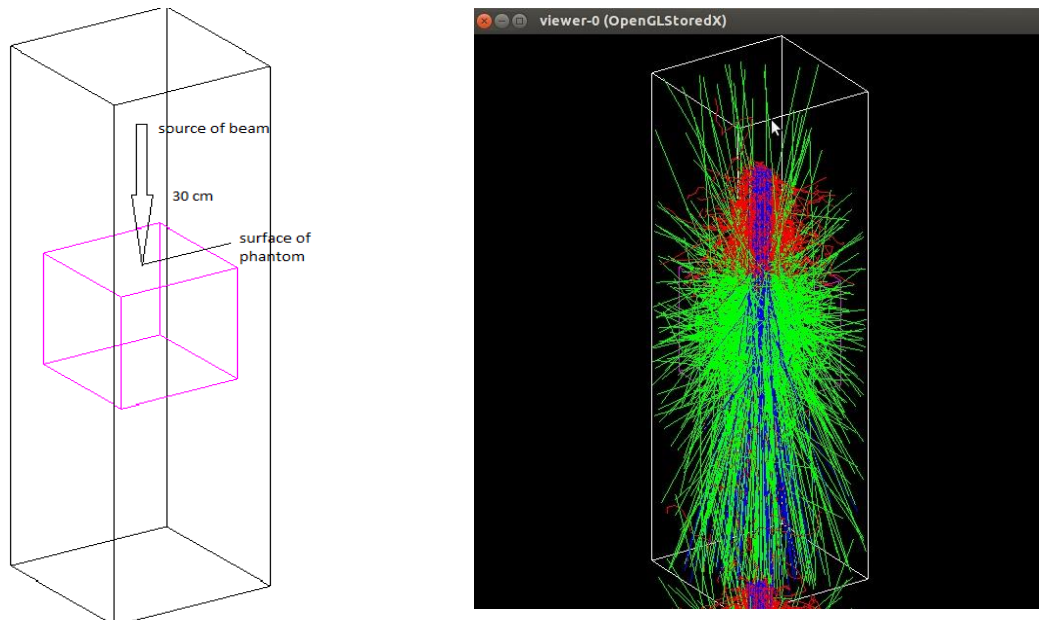


Figure 1. (a) Sketch of the simulation experimental set-up and (b) snapshot of the Geant4 simulation. The carbon ion beam (blue tracks) coming from the top interacts with the PMMA target, producing secondary particles. Red and blue tracks are negative and positive charged particles, respectively. Green tracks are neutral particles.

The characteristics of the radiation field produced by the incident carbon ions were studied in the PMMA phantom. The output of the simulation consisted of the energy deposition in the PMMA phantom as well as the position of secondary particles generated within the phantom. The energy deposition derived from the incident beam and from the secondary nuclear fragments was tallied separately. The Bragg peak was calculated along the direction of the incident beam with 0.1 mm spatial resolution. The deposited energy at a given depth and lateral position was stored in the 2D histogram which had 1 mm² pixels.

3. Results and Discussion

3.1. Contributions of charged fragments & LET calculations

Figure 2 (a) shows the Bragg Peak. The energy deposition contributions deriving from incident carbons and secondary fragments, such as Hydrogen, Helium, Lithium, Beryllium, Boron, secondary Carbon ions, Nitrogen and Oxygen, are shown as well. The Bragg peak was observed to occur at (126.2 ± 0.1) mm in the PMMA phantom which is in good agreement with the expected results calculated by SRIM [12]. Figure 2 (b) shows the depth dose distribution deriving from secondary fragments only and the Figure is close up of Figure 2 (a).

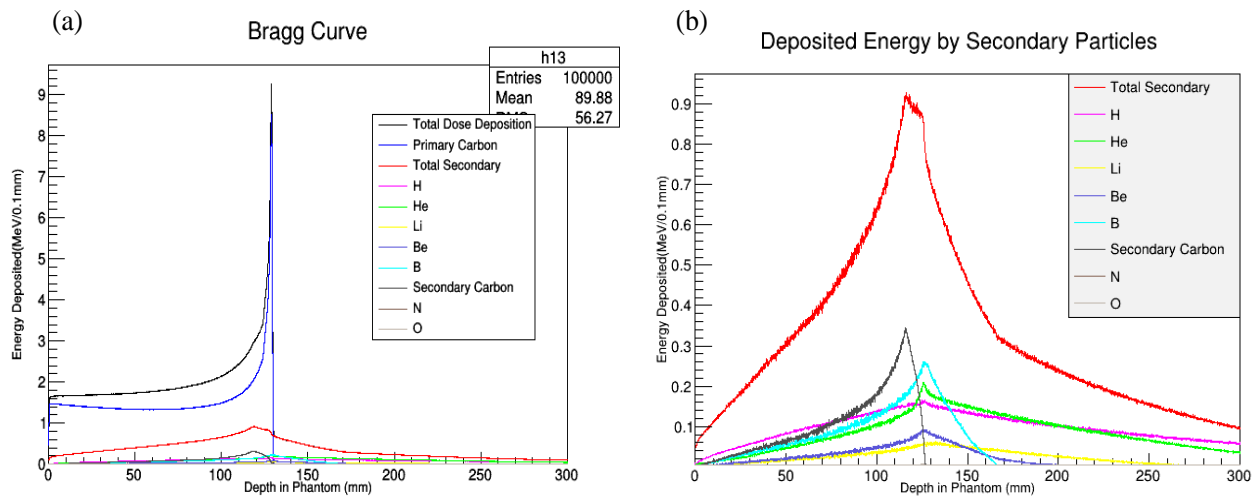


Figure 2. (a) Depth dose distribution deriving from the entire radiation field (Bragg curve) in black, and (b) energy deposition deriving from different components of secondary fragments only

Figure 2 (a) clearly shows that the main contribution in the energy deposition is mainly due to the primary carbon ions. Secondary carbon ions result mostly from neutron scattering in PMMA, although the contributions of the total secondary particles become more evident beyond the distal part of the Bragg peak. In the overall plateau region, the total dose of secondary particles contributed less than 1-3% on the total deposited dose registered at the same position and about 0.5% at the peak position. Therefore, the total depth dose deposition (Bragg curve, in black) and primary carbon (in light blue) almost coincide up to the peak position. The contribution of total depth dose deposition just behind the Bragg peak is only due to the secondary particle (100%). This is because the primary carbon beam energy drops to zero drastically.

As shown in Figure 2(b), B fragments are the main contributors to the dose at 0.1 – 10 mm behind Bragg peak, followed by He and H fragments. He and H fragments have the longest range and therefore they contribute to the long energy deposition tail, while heavier fragments contribute to the dose more locally. Secondary neutrons scatter protons in the phantom which again contribute to the dose beyond the Bragg Peak and laterally. The energy deposition peak of the secondary carbon and B ions are evidently larger than the other fragments. Contributions of other fragments, such as N and O ions, are not significant. The lower-Z fragments, Hydrogen (H), Helium (He) and Lithium (Li) have longer ranges than the primary particles. This is the reason of the depth dose profile of heavy ion beams have characteristic fragment tail beyond the Bragg peak.

The fragment tail clearly indicates that the largest fraction of fragmentation reactions result in a small number of nucleons from either the target or projectile nucleus being ejected in “abrasion-ablation” reactions. It is confirmed that this is the origin of the characteristic fragment tail beyond the distal edge of the Bragg peak when heavy ions such as carbon ions are used [13]. This work also shows the similar output with the other literatures for the secondary fragmentation study [14-15].

Figure 3 shows the 2D lateral dose distribution of a set of different fragments. It can be observed that the lighter ions undergo greater lateral scattering and therefore deposit more energy out of the primary radiation field, while the heavier nuclear fragments contribute more substantially to the energy deposition at the distal edge of the Bragg peak.

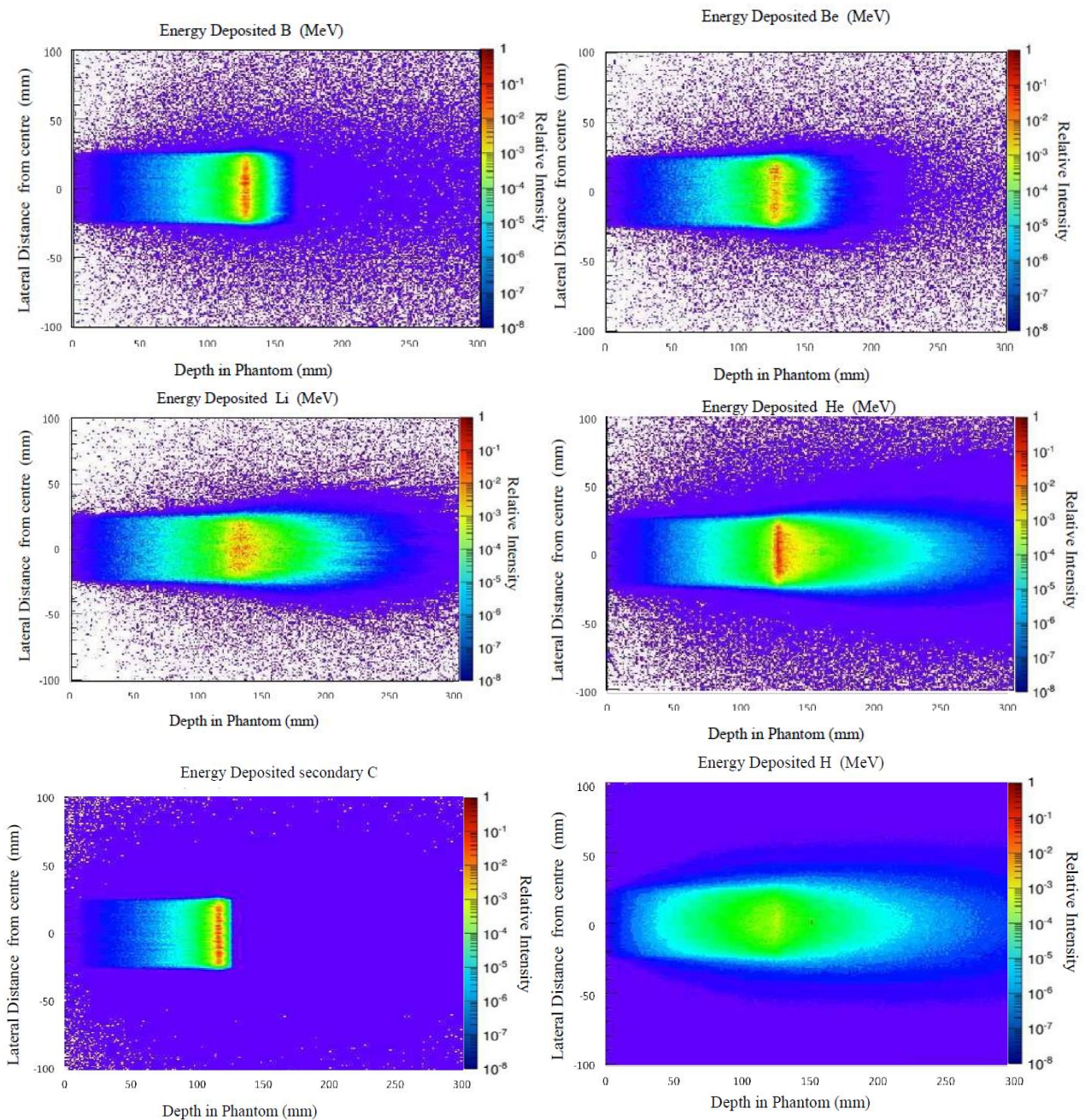


Figure 3. 2D histogram of the energy deposited in the phantom different fragments.

4. Conclusion

The contribution of total depth dose deposition just behind Bragg peak is 100% due to the secondary particle field. Such energy deposition tail cannot be neglected as organs at risk may be located in this position behind the Bragg Peak. For further study, higher therapeutic beam energies are planned to investigate the secondary fragments especially in the regions outside of the field.

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