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Monte Carlo Geant4 Simulations of Protons Lateral Deviation in Liquid Water

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Abstract

Proton therapy is an advanced treatment technique for cancer cells leading to promising results compared to conventional photon radiotherapy. The protons deposit a large portion of their energy by inelastic (coulomb) interactions with the outer shell electrons of medium molecules causing the ionization or excitation processes, specially near the end of their range and weakly by elastic interaction with the nucleus. The last process seems to be responsible for the lateral deflection of the protons in the medium. This work presents the determination of the stopping power (SP), range (R), and radial deviation (r) of protons with impact energies 180 - 215 Me, by using the Monte Carlo Geant4 toolkit. In this contribution, we focus on the interaction of energetic proton beams with liquid water. We studied the correlation between the radial deviation lateral (r) and the incident kinetic energy (E), and the range (R). The results are compared to the available experimental and other simulation results. Good agreements are generally observed especially for the radial deviation. We find that the ratio between lateral deviation and range does not exceed 3- 4 %.

Keywords: *Monte Carlo, Geant4, proton, liquid water, lateral deviation, stopping power.*

I. INTRODUCTION

The proton therapy is a form of radio- therapy more efficient than other types of cancer treatments such as chemotherapy, X-rays [1]. This technique has seen continuous gradual improvements due to advantages of protons to kill tumors cells while sparing the surrounding non-cancer cells [2]. In the physical process, protons deposit their maximum energy in the tumor volume. Unlike, the photons and X-rays loss gradually their energy as they travel through a medium. Most of the protons energy is transferred to electrons by inelastic (coulomb) interactions [3] which cause the maximum of deposit energy by protons around region called Bragg peak [4] and weakly by elastic interaction with the nucleus [3], so the last process is responsible for the lateral deflection of the protons in the medium. In fact, in the region called Bragg pick, all protons have the same energy and are stopped in the same position, which depends on the medium and the protons energy. Monte Carlo calculations have shown good capabilities in the treatment optimization and can also increase the accuracy of dose calculation. The aim of the present investigation was to simulate protons lateral deviation (r) in water with impact energy 180 – 215 MeV and study the correlation between the lateral deviation (r) and the proton range (R) by Geant4Monte Carlo simulations. To validate the Geant4 simulations, the results will be compared with experimental results and with other simulation results. It should be noted that this is a primarily the first study simulation of protons lateral deviation in medium with Geant4 Monte Carlo software.

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II. MATERIALS AND METHODS

A. Simulation Monte Carlo Geant4

In this work, all simulations were performed with Geant4. Geant4 [5] is a toolkit for the simulation of the passage of particles through matter using an Object-Oriented environment (C++), developed by the European Center For Nuclear Research CERN. It's an area of applications including high-energy physics, astrophysics, space science, medical physics and radiation protection. Mono-energetic proton beam with the therapeutic energies of 180 MeV - 215 MeV are used to irradiate a (40 * 40 *40) cm3 box filled with liquid water with an equivalent density of 1g/cm3. For each configuration in the study, 15 millions primary protons have been generated. Indeed, water is chosen as phantom material to simulate the protons interaction with soft tissues [6].

The simulations accuracy depends principally on the knowledge of the physical processes responsible of protons interaction in the medium. This could be fixed in Geant4 by choosing the adequate physics list including a list of processes and associated models that will be used in the simulations.

III. SIMULATION RESULTS and DISCUSSION

Our results from GEANT4 simulations are shown in figure 1 and Figure 2.

Figure 1 represents the obtained stopping power and lateral deviation as a function of the depth at incident energies of 180 MeV (top) and 215 MeV (bottom). The plots illustrate two mechanisms by which protons loss their energy via coulomb interactions. The first one represents protons energy loss with atomic electrons, which results in a maximum of energy deposit around the Bragg peak. This physical process leads to a limited range of protons in water. The proton ranges extracted from the Bragg curve are 29.5 cm and 21.74 cm for incident energies of 215 and 180 MeV respectively. It is commonly accepted that Monte Carlo codes, such as Geant4, PHITS [7], and FLUKA [8], give precise estimation of protons dose distribution along the beam entrance axis.

The second corresponds to multiple elastic scattering of protons with atomic nucleus, which gives a proton deviation from a straight line. The multiple scattering effect grows as the depth increases, the maximum of lateral deviation is then naturally reached around the Bragg peak.

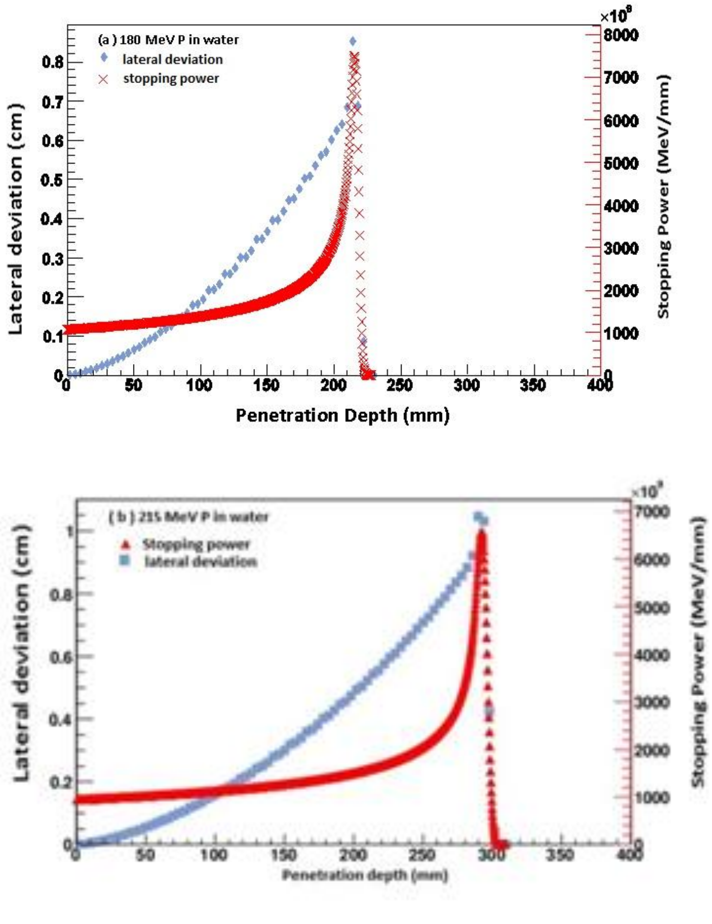

Figure 1. Geant4 simulation of lateral deviation r and stopping power in liquid water, as a function of penetration depth, at incident energies of (a) 180 MeV and (b) 215 MeV

Lateral beam deviation is an important factor to be taken into account for the treatment efficiency. Indeed, it is interesting to study its distribution along beam path.

The powerful of the Monte Carlo Geant4 simulations is the possibility to take into account the space deviation of the incident particle at each step of its interaction with the medium targets. So, it is possible to calculate the root mean square radius r of the beam particles as a function of the depth:

$$\left(\overline{r^2}\right)^{1/2} = \sqrt{\overline{x^2} + \overline{y^2}}$$

In figure 2, we compare our results (red line) to the results of Monte Carlo simulations using SEICS code (blue line) [9], experimental data (rectangle symbols) [10] and the predictions of the analytical model [11] (circle). Comparisons are done at incident energies of 180 (top) and 215 MeV (bottom). A good agreement between Geant4 simulations and experimental data is observed.

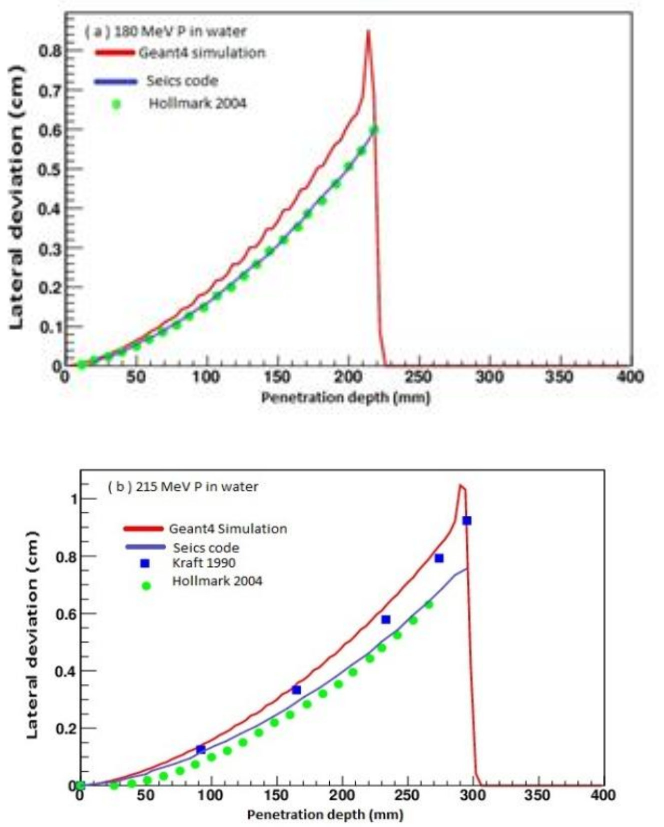

Figure 2. Lateral deviation of a proton beam in water as a penetration depth at incident energies of (a) 180 MeV and (b) 215 MeV

The ratio between the maximum lateral deviation r_{max} and the protons range in water R, extracted from simulation results, does not exceed 3-4%. It could be interesting to predict the dependence of such a ratio on the target, the energy of the incident particles and the atomic weight of the target.

IV. CONCLUSIONS

The aim of this work was to study the le influence of radial distribution of particles along the beam path represented by the root mean square radius of the beam particles. This parameter is crucial since it influences the lateral dose distribution. The lateral deviation of the proton beam given by our simulations is very small and does not exceed 3-4 % of the proton range.

A good agreement has been found between the radial deviation extracted from Geant4 simulations, the experimental results and the results given by other simulation codes.

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