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Simulation by Geant4 of Hadrontherapy Beam Line

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Abstract: Hadrontherapy represents a pioneer technique, and only few centers worldwide can provide this advanced and specialized cancer treatment. Geant4 (GEometry ANd Tracking 4) is a C++, free and open toolkit that used to simulate the interaction of particles in matter. It is employed in various fields from high-energy physics, nuclear physics to medicine. By means of Monte Carlo simulation tool Geant4, we have simulated the hadrontherapy beam line typical of a proton-therapy line modeled in the category of the advanced examples with all its elements: the diffusers, range shifters, collimators and detectors. This Simulation has permited the calculation of dose and Linear Energy Transfer (LET). In this context, this study reports the first results of our simulation realized by means of Geant4 10.2 version and their comparizon with those obteined by Cironne.

***Keywords*:** Monte Carlo simulation, Hadrontherapy, Geant4

Hadronterapi Işın Hattı için Geant4 Benzetimi

Özet: Hadrontherapy öncü bir tekniktir ve dünya çapında sadece birkaç merkez bu ileri ve uzmanlaşmış kanser tedavisini sağlayabilir. Geant4 (GEometry ANd Tracking 4), parçacıkların madde içindeki etkileşimini simüle etmek için kullanılan C ++, ücretsiz ve açık bir araç kitidir. Yüksek enerji fiziği, nükleer fizik ve tıbbın çeşitli alanlarında kullanılmaktadır. Çalışmada, Monte Carlo simülasyon aracı Geant4 ile, gelişmiş unsurlar kategorisinde modellenen bir proton-tedavi hattının tipik tüm unsurları olan difüzörler, aralık değiştiriciler, kolimatörler ve detektörler ile simronterapi ışın hattınının benzetimi yapıldı. Bu benzetim, doz ve Çizgisel Enerji Transferi (LET) hesaplamasına izin vermiştir. Bu bağlamda bu çalışmada, Geant4 10.2 sürümü ile gerçekleştirilen benzetimlerimizin ilk sonuçları ve bunların Cironne tarafından belirlenenlerle karşılaştırılması verilmiştir.

***Anahtar Kelimeler*:** Monte Carlo benzetimi, Hadronterapi, Geant4

1. INTRODUCTION

The history of radiation treatment started in 1895 when Roentgen discovers the X-ray [1]. In 1932 Lawrence developed the first cyclotron and Wilson proposed proton therapy and began exploiting the proprieties of the Bragg Peak [2, 3]. The main asset of proton lies in its particular ballistic. In contrast to the photon beams, where maximum energy deposition is in the first centimeters at the patient's inlet and decreases with depth, charged ions such as protons deposit

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their maximum energy at the end of the path while maintaining a minimum dose deposited at the inlet. In 1954 Tobias treats the first patient and starts extensive studies with various ions in the Berkley Laboratory (LBL) [4]. In 1957 Uppsala center has constructed the first Synchrotron, and has produced the first proton beam of 185 MeV energy dedicated to stereotactic treatment into account physico-biological consequences to treating produced on the first patient in European center [5]. Then in 1974, the first patient with pelvic sarcoma was treated with fractional proton therapy 2Gy/fraction [6].In 1983 Tsukuba university (Japan) treated their first patient and in 1985 the PTGOG. [7]

Extensively, the improvement of this theory by Chen and Quivey resulted in fractionation of the dose per 2Gy treatment session. They showed the importance of relative biological efficiency and oxygenation rate in the target volume [8]. In the ninetieth, the evolution was exceptional with the first hospital based proton facility at LLUMC and the beginning of the treatment of patients at Loma Linda [9]. Then, the first installations dedicated to carbon ions became operational at HIMAC Japan [10] in 1994. While, the first treatments with carbon ions began in 1997 at the GSI [11]. Then in 2009, the first European carbon facility started processing in Heidelberg. Currently, 27 facilities worldwide treat patients with more than 67000 patients with proton [12].

The popularity of Monte Carlo (MC) techniques in the field of medical physics has increased rapidly over the last decade and specifically for proton therapy. MC simulations are an essential tool for the design and commissioning of clinical facilities allowing a detailed description of the beamline and delivery system. These are a valuable tool for commissioning Treatment Planning Systems (TPSs). In addition, MC codes can be a unique instrument for validation, and possibly improving, analytical TPSs. In situations where experimental validation is unavailable and/or analytical methods are inadequate; MC simulation allows a patient-specific dose calculation by more realistically taking into account the composition of the human body, with a possible advantage over the equivalent water approach typically used in analytical TPS. These methods naturally include mixed field description and three-dimensional spread of the particle fluency, reliably describing the transport, and the interaction of the primary and secondary beams [13].

Nowadays the mixture of protontherapy and MC methods is the most important evolutionary process. It underwent a revolution, as long as current practices differ from the first established bases. Computerization is the main source since it is found in all phases of diagnosis, imaging, preparation, processing and validation.

Geometry description and simulation of treatment beam line

The development of Hadrontherapy facility requires a long experimental work, due to the lack of adequate simulation tools. The geometry of Hadrontherapy is used from P. Cironne [14] to perform specific validation of the implemented nuclear models, in order to test the actual capability of Geant4 in the framework of the protontherapy applications [15-19].

The Hadrontherapy module is divided in two main independent blocks, the first block delegated to the simulation of the geometry and the second reserved to the simulation of detection region, it permits the scoring of the specific quantities of interest (dose deposited, particle fluencies, LET distribution, etc.).The beam delivering system has to be simulated in detail and the beam initial parameters have to be known as accurate as possible [15, 16-19].

To acquire full advantage of the Monte Carlo approaches, in principle a very accurate prediction of the proton treatment beams takes into account all the physics processes involved, including electromagnetic energy loss, energy straggling, multiple Coulomb scattering, elastic and non-elastic nuclear interactions as well as the transport of any generated secondary particle even if it is negligible in proton case.

For a physic approach, we have chosen to add the elastic and binary p-p interaction. In the recent reference physic lists QGSP_BIC, they reproduce real experimental apparatus and detectors QGSP (Quark Gluon String Precompound) defines the hadronic models for nucleons; BIC (Binary Ion Cascade) defines the inelastic models for ions, It has been specifically created to address simulation problems for which high level of accuracy is requested but only with the G4EMStandardPhysics Opt3. In Medical simulations, it is better to use QGSP_BIC_EMY Reference Physics List. It is less resent but it was tested many times by some papers [14-19], QGSP_BIC_EMY is an acronym that briefly explain all the physics models activated when it is called: QGSP BIC as it was explained before and EMY (Electro Magnetic Y) defines the electromagnetic models used for all particles (Y indicates a particular EM physics) [16,17].

All the results presented in this paper and that are relativeto the simulation of the proton beams have been obtainedusing the QGSP_BIC_EMY as the Reference Physics List.

We used in our work the version 10.2 (Patch1) of Geant4. We started by importing all the macros existing in the 'EXAMPLES' file of Geant4 named "*hadrontherapy*". This entirely simulates the CATANA (Centro di Adro Terapia ed Applicazioni Nucleari Avanzate) Center's [19] a passive proton therapy beam line from the scattering system up to the diagnostic monitor chambers and the final collimators which is placed just before the patient [16].

This work mainly concerns dose and LET evaluations as first step. These quantities are performed on a voxelized 3D water phantom placed at the end of the beam line, exactly at the point where the patient is located in the real treatment. The phantom of 40 × 40 × 40 centimetersis positioning orthogonal to the beam direction, inside which the total dose is retrieved. It is divided into cubic voxels, each dimension of 10 × 10 × 10micrometers [17-19].The simulation is realized in order to have a reasonable statistical fluctuation (less than 3%) without huge calculation times [16].

In **Figure 1,** we can observe the Hadrontherapy beam line as simulated and displayed by application of the example. The proton energy of 62 MeV is used.

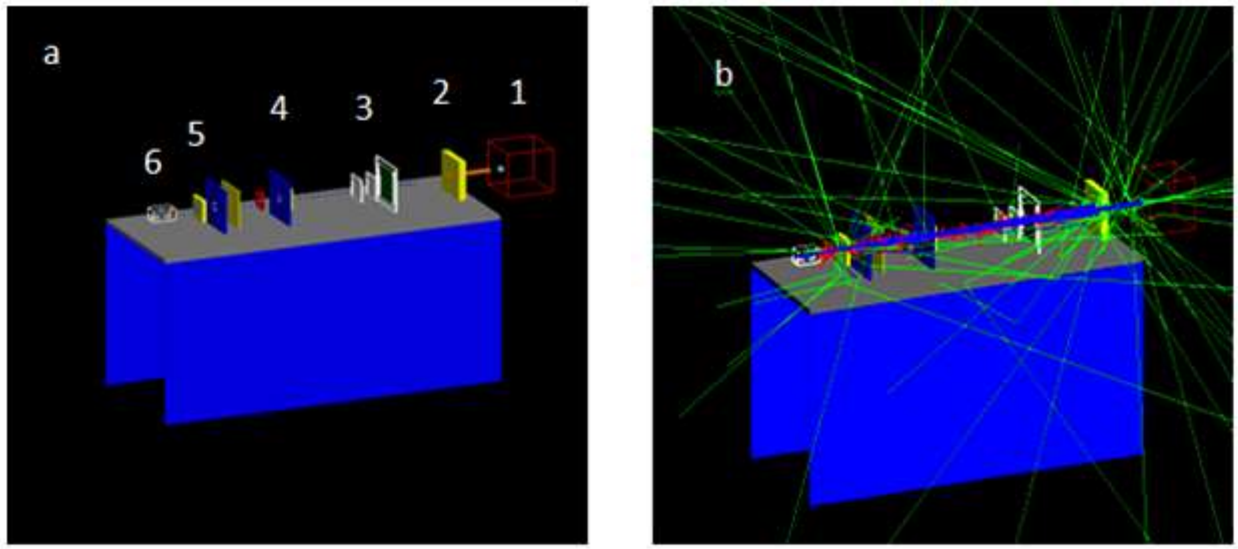

Figure 1. The proton therapy beam line as it is simulated and displayed by hadrontherapy example in Geant4version 10.2 **(a)** 1. Voxelized 3D water phantom. 2. Final collimator and Positioning laser. 3. Light field simulator. 4. Monitor chambers. 5. Intermediate collimator. 6. Box for the location of modulator wheel and range shifter.**(b)** irradiation of proton therapy beam line in simulation.

RESULTS and DISCUSSION

Figure 1 Shows the Geant4 simulation output of the proton irradiation beam line. The blue tracks represent the protons traversing the beam line and reaching the phantom (red cube). Inside the phantom, a smaller cubic volume (in cyan) is the sensible voxelized detector.

Comparisons between experimental and simulated depth dose distributions (Bragg peak) are necessary in order to verify trustworthiness. The experimental apparatus has been simulated with Geant4 as well as the initial parameters of the incident beam and represented in ROOT analysis program [20].

From **Figure 2**, we can observe that a noticeable difference between the two peaks. It is improved by a larger number of events. The simulation results obtained for the 10000 events (10000 is minimum number of events allowed in real treatment) are compared with those of the experimental data file provided by the 62 MeV Bragg Peak in water, acquired in the CATANA proton therapy facility at INFN-LNS (Laboratori Nazionali del Sud of the Instituto Nazionale di Fisica Nucleare) [16, 19].Monte Carlo simulations were not used to perform this estimation due to the CPU time needed. It is acknowledged that simulations are more accurate but the interest for this estimation is the variation yielded by changing the number of events to have acceptable curve with good quality which can used in comparison rather than best curve obtained by a huge number of events and important calculated time. The experimental apparatus was simulated with Geant4 as well as the initial parameters of the incident beam using a plat ion chamber Markus[19].

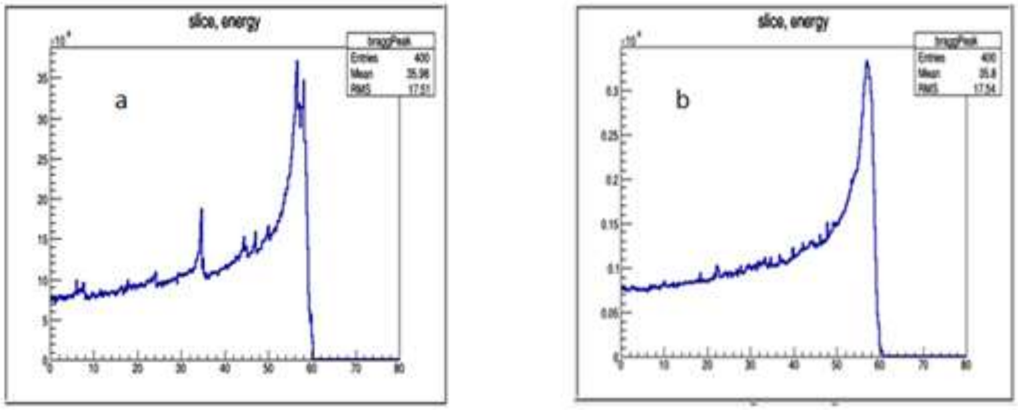

Figure 2. Proton Bragg Peaks obtained by ROOT for **(a)**1000 events **(b)**10000 events and 62 MeV protons energy.

LET, generally used to quantify the effects of ionizing radiation on biological specimens or an electronic device and expressed as the stopping power (in keV/µm), was calculated for the proton beam and compared to the experimental data. **Figure 3** shows the comparison between the simulation and the experimental data [21, 22].

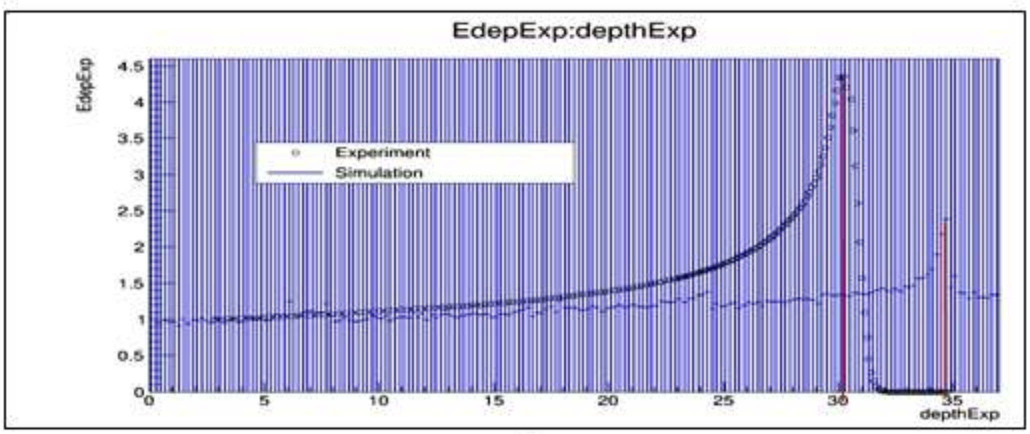

Figure 3. Simulated and experimental depth dose profiles of a 62 MeV proton beam in water for 10 000 events. The dept h in water (expressed in millimeter) and the energy deposited (expressed in arbitrary units).

It is observed that the simulation and experiment curves are shifted and not superposed, and they are different from those obtained in Ref. [20, 23]. We can distinguish that the maximum range of experiment proton beam was 30 mm in water. The range of the simulated beam is shifted instead of 35 mm.

In the proton incident beams, the production of secondary particles is not really significant in terms of fluency contribution. Therefore, in this case only the average proton LET and the LET dose were calculated. As described in Ref [14], we can explain the difference of 0.5 % between the two results by implementation of the Low Energy package and the hadronic processes that we neglected in our simulation (the optimizations were done without applying the low energy process).The *Low Energy* package was developed to extend electromagnetic interaction of particles with matter down to very low energy: 250 eV for electrons and photons, 1 keV for hadrons and ions. This package is the unique tool among Monte Carlo codes on market and of relevance for several medical physics applications. The possibility of new version Geant4 2.10 may also be the cause of these results.

CONCLUSION

These preliminary results of simulated beam lineshowaquasi similar result of Cironne [16]. The first step was to accurate design of proton transport beam line with all the elements with 3D voxelized water phantom, using Proton physics process and inclusion of Reference Physics list for 3D output to obtain calculated results of LET. The resulting curves were reconstructed with ROOT analysis program. In particular; we compared simulated and measured Bragg curves, for protons interaction of 62 MeV energy.

The agreement obtained between the two distributions (up 0.2 % for water and energy) demonstrates the goodness of the simulation of the sensitive detectors from a software point of view. But finally, results obtained encourage us to continue our work.

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