The GEANT4 toolkit capability in the hadron therapy field: simulation of a transport beam line

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At Laboratori Nazionali del Sud of the Instituto Nazionale di Fisica Nucleare of Catania (Sicily, Italy), the first Italian hadron therapy facility named CATANA (Centro di AdroTerapia ed Applicazioni Nucleari Avanzate) has been realized. Inside CATANA 62 MeV proton beams, accelerated by a superconducting cyclotron, are used for the radiotherapeutic treatments of some types of ocular tumours. Therapy with hadron beams still represents a pioneer technique, and only a few centers worldwide can provide this advanced specialized cancer treatment. On the basis of the experience so far gained, and considering the future hadron-therapy facilities to be developed (Rinecker, Munich Germany, Heidelberg/GSI, Darmstadt, Germany, PSI Villigen, Switzerland, CNAO, Pavia, Italy, Centro di Adroterapia, Catania, Italy) we decided to develop a Monte Carlo application based on the GEANT4 toolkit, for the design, the realization and the optimization of a proton-therapy beam line. Another feature of our project is to provide a general tool able to study the interactions of hadrons with the human tissue and to test the analytical-based treatment planning systems actually used in the routine practice. All the typical elements of a hadron-therapy line, such as diffusers, range shifters, collimators and detectors were modelled. In particular, we simulated the Markus type ionization chamber and a Gaf Chromic film as dosimeters to reconstruct the depth (Bragg peak and Spread Out Bragg Peak) and lateral dose distributions, respectively. We validated our simulated detectors comparing the results with the experimental data available in our facility..

1. Introduction

An increasing number of radiotherapy facilities around the world use charged particles beams, namely protons or carbon ions to treat tumours [1]. Yet nowadays, radiotherapy with charged ions represents an innovative and pioneering technique in the area of the battle against cancer. Ions have physical and radiobiological characteristics that differ from those of conventional radiotherapy beams (high energy photons and electrons) and offer a number of advantages. They have a depth dose curve completely different from those of conventional beams, with a finite range of penetration in a tissue, negligible scattering and a high amount of energy released at the end of their track, giving rise to the so-called Bragg Peak. The depth and width of the Bragg peak depend respectively on the initial beam energy and energy spread of the beam. Therefore varying the energy in a controlled way it is possible to superimpose many narrow Bragg peaks to achieve a large Spread Out Bragg Peak (SOBP) that can tailor a highly conformal dose distribution, able to irradiate selectively tumour volumes sparing the adjacent critical normal tissues. Charged ions combine the advantage of a high physical selectivity with that of high-LET radiations providing a higher Relative Biological Effectiveness (RBE). For protons RBE is assumed to be 1.1 in clinical practice, although there is an evidence for an increased RBE that varies with depth [2]. All these considerations led, in the last twenty years, a large number of medical physicists, radiotherapists and oncologists, to consider with more and more interest ions with respect to electron and photon beams. Today more than 25 centres, which use proton and carbon ions for radiotherapeutic purposes, are active. Beside this, a huge number of studies is still necessary to improve the quality of an ion therapy treatment. These studies regard both a better understanding of the dose distributions inside patients (also taking into account the contribution due to the nuclear non-elastic interactions) as well as the possibility to improve the design of the transport beam line dedicated to the ion therapeutic treatments. On the basis of the experience we gained in the last years in the realization of the CATANA facility [3] [4], dedicated to the treatment of ocular melanoma using 62 MeV proton beams, and considering the future proton therapy facilities being planned in the world, we decided to start the development of a Monte Carlo application dedicated to proton therapy and based on the GEANT4 toolkit [5].

2. Simulation of the experimental setup

2.1. GEANT4: a Monte Carlo simulation toolkit

GEANT4 is a Monte Carlo simulation tool [5]. It is not a stand-alone executable but a toolkit of libraries; it was designed and developed by an international collaboration, formed by individuals from a number of cooperating institutes involved with High Energy Physics, space and medical experiments. It builds on the accumulated experience of many contributors to the fields of Monte Carlo simulation and of the physics of particle detectors. The transparency of its physics implementation permits a rigorous procedure in validating the physics results. On the other hand the flexibility of its design permits the simulation of physical processes in such different fields as high energy physics, space and cosmic ray applications, nuclear and radiation computations, as well as heavy ion and medical applications. In the past a large number of Monte Carlo codes have been developed for application in physics, particularly for the nuclear/high energy processes. In the previous version of GEANT the physical processes at low energy were not treated in sufficient detail. Only in the fourth version, a specific library for low energy processes was inserted. It provides a dedicated set of libraries for the electromagnetic processes which extends the applicable energy range of electromagnetic interactions down to 250 eV for photons and electrons and down to 1 keV for protons, ions and antiprotons. These energy ranges are now ideal for medical applications. Moreover hadronic processes for the specific medical range can also be implemented.

2.2. GEANT4 set up: simulation of the beam line

In the application we developed all the elements of a generic proton-therapy beam line can be precisely reconstructed. The application permits to define all the typical elements of a transport beam line for proton therapy, from the point in which beam exits in air (typically three meters before the patient) up to the isocenter. Such elements are the scattering and collimator system, the monitor chambers, the range shifter (to degrade the beam energy), the final collimator; the geometrical and physical characteristics of these elements can be easily defined and changed. Moreover it is possible to choose the characteristics of the incident beam: beam energy, energy spread, beam spot size and angular spread. Two different detector can be simulated: a Markus chamber (for the depth dose curves reconstruction) and a GafChromic (for the lateral dose distributions). As far as the physics processes are concerned, we activated inside our simulation the Low Energy electromagnetic package coupled with the PreCompound hadronic model. We tested our application simulating the CATANA [4] proton beam installed at Laboratori Nazionali del Sud (Figure 1).

Figure 2 shows the simulation output of the proton beam line we obtained using the developed application. The arrow indicates the proton beam direction.

2.3. Experimental set up

We have available two types of experimental data: depth dose (Bragg curves) and lateral dose distributions acquired using a Markus type ionisation chamber and GafChromic films, respectively. The Markus is a plane parallel ionisation chamber with an electrode spacing of 2 mm, a sensitive air-volume of $0.05 cm^3$ and a collector electrode diameter of 5.4 mm. We measured the

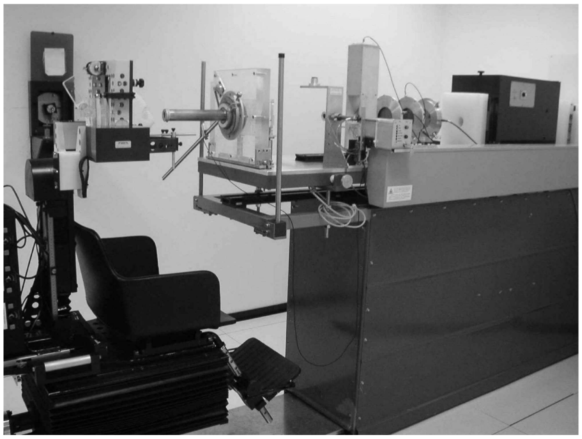

Figure 1. The proton therapy beam line for the treatment of ocular melanoma, installed at Laboratori Nazionali del Sud - INFN in Catania, Italy.

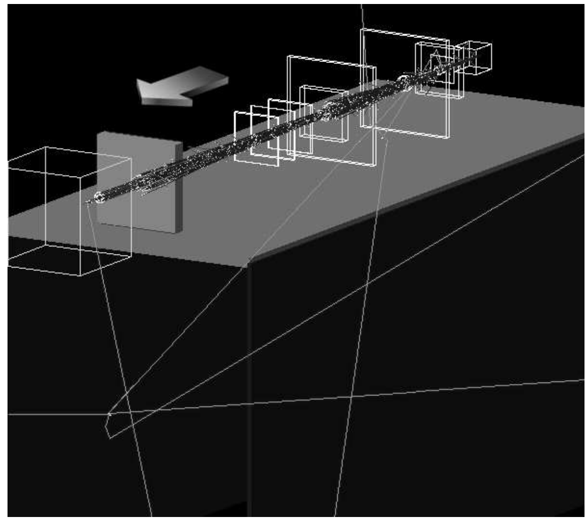

Figure 2. The CATANA proton therapy beam line simulated using our GEANT4 application. The arrow indicates the proton beam direcion.

depth dose distributions in different solid materials (aluminium, copper, polymethyl methacrylate) and in liquid water. In the first case the chamber is positioned inside a phantom of that material and layers of the same are placed in front of it in order to degrade beam energy until the Bragg curve is reconstructed. In these cases the spatial resolution of the measurement was 100 μm. For the measurement in water, the chamber is placed inside a water phantom and its movements are performed using an high-precision stepping motor, fully controlled by a software developed by us. The spatial resolution achieved for the in-water measurements is 200 μm. In both cases (for in-solid and in-water measurements) the ionisation charge produced between the inter-electrode space is collected using a Keithley 7517 electrometer. GafChromic (ISP-HS model) films, used for the lateral dose distributions reconstruction, are self-developing film media. The films develop a distinctive and characteristic colour upon exposure to ionising radiation and become progressively darker in proportion to the absorbed dose. The advantages of GafChromic for the determination of the lateral dose distributions include a high spatial resolution and tissue equivalence. Experimental lateral dose distribution measurements were carried out placing the films in a polymethyl methacrylate (PMMA) holder at isocenter. A non-modulated 62 MeV proton beam, 25 mm in diameter, was used for the irradiation.

3. Results and Conclusions

We simulated the Bragg curve distribution using different combinations of the available GEANT4 physic models: the *Standard* electromagnetic model, and the *Low Energy* one. Each of these was coupled to the *Pre Compound* hadronic model. The activation of the hadronic model produces a decrease of the height of the Bragg peak of about 8%. The best results were obtained using the *Low Energy* package togheter with the *Pre Compound* hadronic model, as shown in Figure 3; here the simulation result is compared with an experimental Bragg curve acquired using the Markus ionisation chamber.

In order to fully exploit the potentialities of the

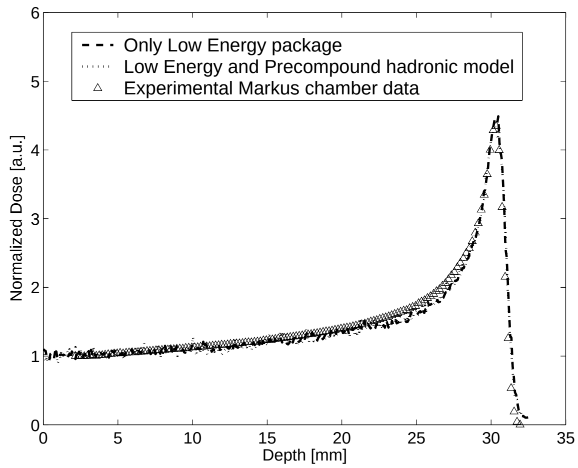

Figure 3. Experimental and calculated Bragg peaks comparison. The results from simulation are obtained using only the *Low Energy* package and coupling it with the *Pre Compound* hadronic model.

Bragg peak in the clinical practice of the cancer treatment, it is necessary to "spread" its width so that the entire tumour can be irradiated with the same dose. This is done inserting along the beam path a PMMA rotating wheel of varying thickness. The result is the so-called *Spread Out Bragg Peak* (SOBP). Our application permits to an user to simulate such modulation and to reconstruct the corresponding dose distribution. Figure 4 shows a comparison between a simulated and an experimental SOBP. It is a very preliminary result but that demostrates the ability of the application to simulate also time-dependent beam line elemnts.

The results obtained permit us to conclude that the Monte Carlo GEANT4 toolkit can be powerfully applied in the hadron therapy field for the simulation of a complete treatment beam line. We validated the outputs of the simulations comparing them with the experimental data available

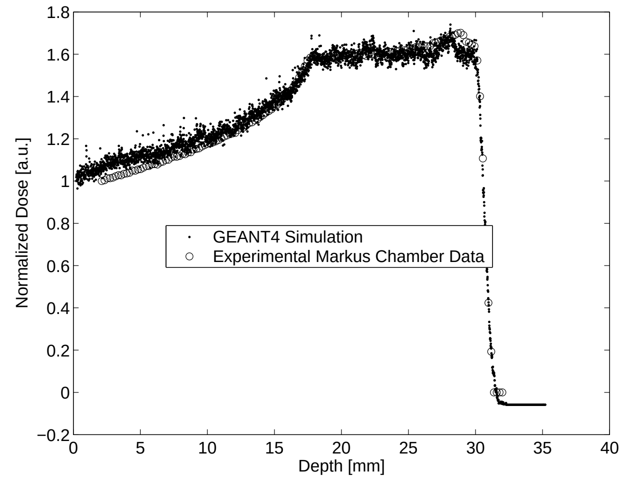

Figure 4. Experimental and calculated Spread Out Bragg Peak (SOBP). The experimental result was acquired with a Markus type Ionisation chamber

in the CATANA facility and the results encourage us to continue and refine our work in the next months.

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