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A NEW MONTE CARLO – GEANT4 SIMULATION TOOL FOR THE DEVELOPMENT OF A PROTON THERAPY BEAM LINE AND VERIFICATION OF THE RELATED DOSE DISTRIBUTIONS

G.A.P. Cirrone[1], G. Cuttone[1], S. Guatelli[3], S. Lo Nigro[2], B. Mascialino[3], M.G. Pia[3], L. Raffaele[1], G. Russo[1], M.G. Sabini[1]

1) *INFN, Laboratori Nazionali del Sud, I-95100 Catania, Italy*
2) *INFN, Dipartimento di Fisica ed Astronomia, Univ. di Catania, I-95100 Catania, Italy*
3) *INFN, Sezione di Genova, I-16100 Genova, Italy*

Abstract

Using the Monte Carlo simulation tool GEANT4 we simulated the hadron-therapy beam line of the CATANA (Centro di AdroTerapia ed Applicazioni Nucleari Avanzate) center. This is the unique italian hadron-therapy facility in which *62 MeV* proton beams are used for the radiotherapeutic treatment of choroidal and iris melanomas. All the elements, such as diffusers, range shifters, collimators and detectors, typical of a proton-therapy line were modelled. The beam line provides an ideal environment for the experimental testing and validation of the software developed. The software architecture was developed, and the validation of the software is in its final stage. Simulated ranges, energy distribution, depth and lateral dose distributions for full energy proton beams will be compared tothe experimental results obtained at LNS (Laboratori Nazionali del Sud) with different detectors.

1 Introduction

At the Laboratori Nazionali del Sud, a high energy and nuclear physics laboratory, in Catania, the first Italian hadron-therapy facility named CATANA (Centro di AdroTerapia ed Applicazioni Nucleari Avanzate) has been realized [1]. Here $62\ MeV$ proton beams accelerated by a superconducting cyclotron are used for the radiotherapeutic treatment of some kinds of ocular tumours, **like choroidal and iris melanoma**. Therapy with hadron beams still represents a pioneer technique, and only a few centres 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 (like Rinecker, Munich, Germany; Heidelberg/GSI Darmstadt, Germany; PSI, Villigen, Switzerland; Centro di Adroterapia, Catania ,Italy in Europe and Wanjie Zibo, China; NCC, Seoul, Korea outside Europe) in the next years, a R&D program has been started in the framework of the INFN (Istituto Nazionale di Fisica Nucleare)-GEANT4 collaboration, having as its main goal the development of a Monte Carlo tool, based on the GEANT4 (version 6.0) [3] simulation toolkit, for the design of proton-therapy beam lines and for the testing of treatment planning systems. This study reports the first results of our simulation work.

2 The CATANA Facility

2.1 The Transport Beam line

The CATANA facility is the first italian center dedicated to the treatment of ocular lesions with proton beams. CATANA uses $62\ MeV$ protons accelerated by the superconducting cyclotron installed at LNS, in Catania.

The increasing interest in the use of ions, and particulary protons, in external radiotherapy arises from the improvement in their absorbed dose distribution, as compared to conventional techniques using photon and electron beams. As well known, protons release most of their energy at the end of their path (Bragg peak) permitting of the irradiation of the tumoral mass sparing surrounding healthy tissues. The accelerated proton beam, exits in air through a $50\ \mu m$ kapton window placed at about 3 meters from the isocenter [1]. The first scattering foil, made of a $15\ \mu m$ tantalum, is positioned before the exit window, under vacuum. The first element of the beam in air is a second tantalum foil of $25\ \mu m$ thickness, provided with a central brass stopper of $4\ mm$ in diameter. The double foils scattering system is optimized to achieve a good homogeneity in terms of lateral dose distributions, minimizing the energy loss. To obtain a specific proton beam energy with

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[1]point in the space located at the intersection of two perpendicular laser beams where, ideally, the tumoral mass is centered.

a correct energy modulation two devices are requested: range shifter and range modulator. The former degrades the energy of the primary beam of a fixed quantity while the latter (a rotating wheel with various steps of increasing thickness) produces a spread out in the energy of the Bragg peak. Two diode lasers, placed orthogonally, provide a system for the isocenter identification and for the patient centering during the treatment. A key element of the treatment line is represented by two transmission monitor chambers and a four-sector chamber, permitting an on-line control of the dose delivered patients dose and beam symmetry. The last element before the isocenter is the patient collimator located $8\,cm$ upstream of the isocenter. Experimental measurements are carried out placing detectors inside a PMMA (PolyMethylMethAchrylate) phantom filled with water, and placed $8\,cm$ after the final collimator. Finally two back and lateral X-rays tubes are mounted for the verification of the treatment fields. Patients, during the treatment phases, are immobilized on a special chair fully computer controlled. In Figure 1 the complete layout of the CATANA proton-therapy beam line is shown. So far, since March 2002, fifty-two

Figure 1: *The CATANA treatment room installed at Laboratori Nazionali del Sud.*

patients coming from different Italian regions have been successfully treated. Follow-up

data upon 30 patients after one year from the treatment confirm the usefulness of proton treatment.

2.2 Detectors for Dose Measurements

Inside the CATANA *facility* particular care is going to be devoted to the development of dosimetric techniques for the determination of the absorbed dose (absolute dosimetry) in the clinical proton beam and 2D and 3D dose distribution reconstruction (relative dosimetry) [2]. A parallel plate *Markus* ionization chamber has been chosen as reference detector for the absolute dose measurements, while *gafchromic* and *radiographic* films, *termoluminescence detectors, diamond* and *silicon diode detectors* are the choices for the relative ones.

3 GEANT4 for Medical Application

The development of an hadron-therapy facility requires a long experimental work, due to the lack of adequate simulation tools. This work concerns mainly the realization of the passive scattering system (to obtain an homogeneous lateral distribution of the beam), of the modulation (to perform a correct energy modulation) and of the collimators system. On the basis of this we decided to start a simulation work using the Monte Carlo tool GEANT4 [3]. GEANT4 is a toolkit developed to simulate the passage of particles through matter. It contains a large variety of physics models covering the interaction of electrons, muons, hadrons and ions with matter from $250 \ eV$ up to several PeV. Specifically for our applications, of particular interest is the *LowEnergy* package developed to extend electromagnetic interaction of particles with matter down to very low energy: $250eV$ 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. GEANT4 provides various features suitable for medical applications; in particular its Object Oriented design permits to achieve the transparency of the physics, therefore contributing to the validation of the experimental results: that is of fundamental importance on such sensitive applications as the medical ones. Moreover it can be interfaced to a variety of commercial and free tools, such as graphic drivers, object databases, histogramming and analysis packages, CAD, etc.

4 Simulation of Treatment Beam Line

We started our work developing a GEANT4 application, named *hadronTherapy*, that simulates entirely the proton therapy beam line starting from the scattering system up to the

diagnostic monitor chambers and the final collimators placed just before the patient. In figure 2 the proton therapy beam line is show, as it is simulated and dispalayed by our application. Moreover we introduced two sensitive detectors that exactly reproduce the
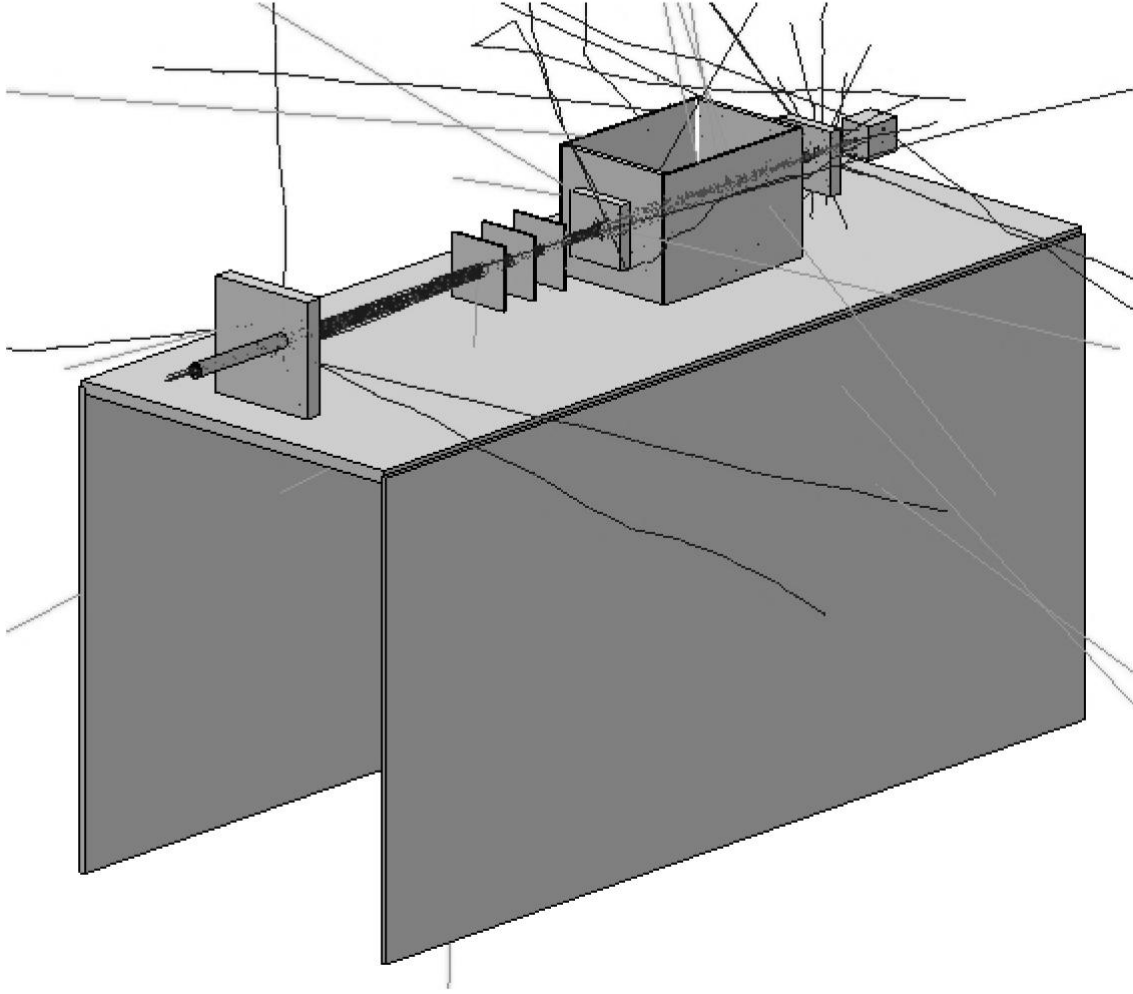

Figure 2: *The proton therapy beam line as it is simulated and dispalayed by hadronTher-apy application.*

experimental ones; these are the Markus chamber (for the Bragg curve reconstruction) and the radiochromic film (for the lateral dose distributions measurements).

For the simulation of the sensitive detectors we implemented the *cut by region* modality: we fixed the cut for the beam transport along the beam line to $10 \ mm$ and the cut inside the detectors to $200 \ \mu m$. In this way *cut by region* permitted us to speed up the simulation process more than a factor ten.

For the simulation we implemented the LowEnergy package and the hadronic processes, activating for these the precompound model.

5 Results and Conclusion

The first step was the validation of the simulated detectors. In particular we compared the Bragg curves obtained with simulation, for interaction of protons of energies between, $10\ AMeV$ up to $62\ AMeV$ with different materials (water, Aluminum, Copper and PMMA), to data from ICRU [4] (fig.3). The agreement obtained between the two distributions (below 0.2 % for all materials and energies) demonstrates the goodness of the simulation of the sensitive detectors from a software point of view. Moreover an
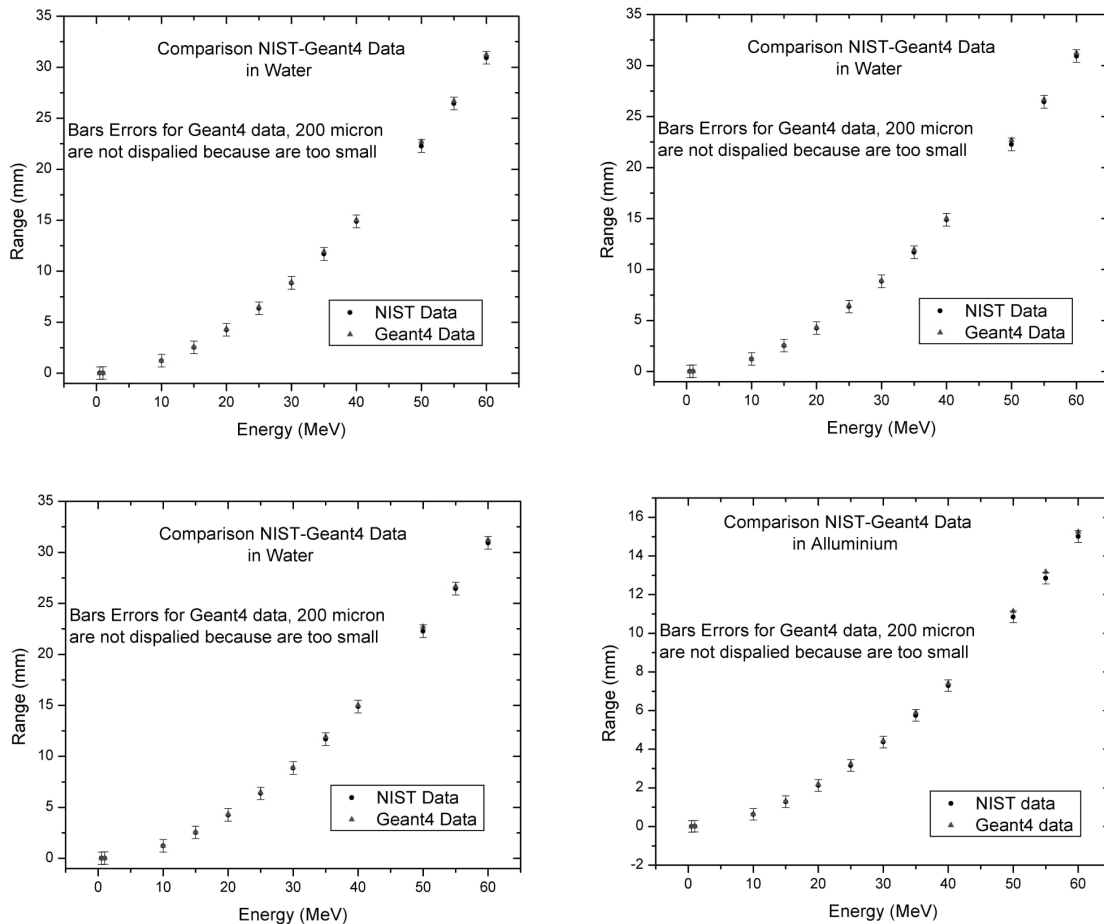
Figure 3: *Comparison between simulated and tabulated by NIST range of proton beams.*

accurate reconstruction of the beam characteristics (its initial energy, energy and fluence distribution, etc.) was performed on the basis of the experimental available data. Then the reconstruction of Bragg curves was carried out for various energies and materials (water, PMMA and aluminum). Figure 4 shows the Bragg peak, in water, for the simulated beam compared with the experimental one measured with the Markus chamber.
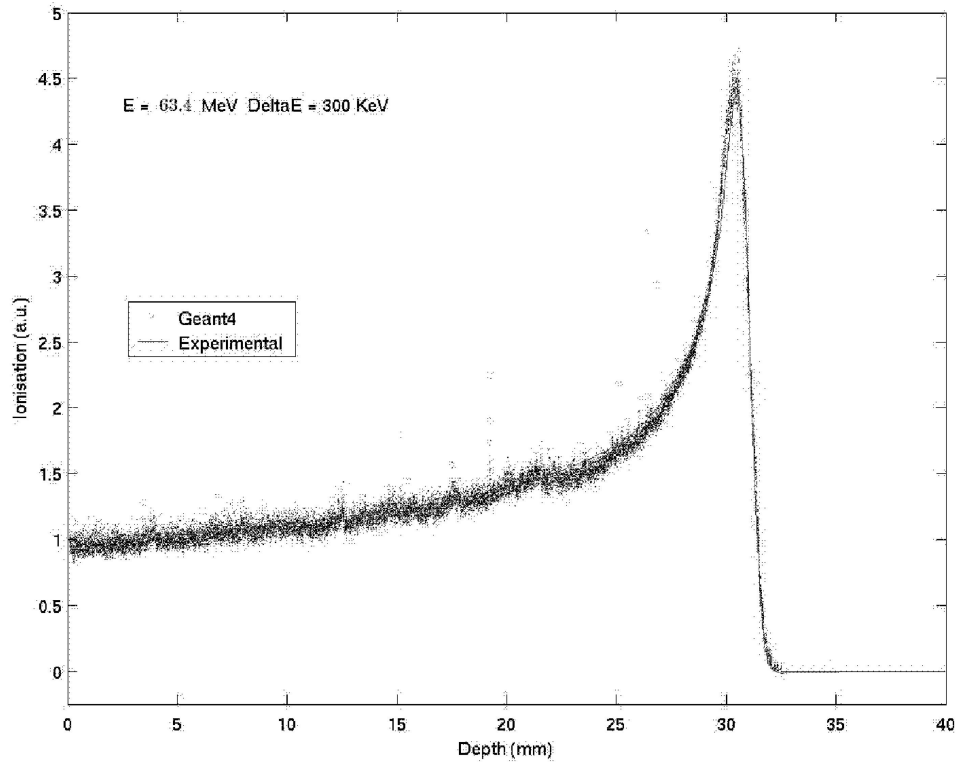
Figure 4: *Comparison between simulated and experimental Bragg curve in water of* $62\ AMeV\ proton\ beams.$

Starting from Bragg distributions, proton ranges values were derived and compared with the experimental ones, the agreement resulting better than 1.4%.
The reconstruction of the lateral distributions of the therapeutic proton beam at isocenter and at various depth in water was performed, too. Simulated results are in agreement with experimental ones. (Figure 5).

Results obtained encourage us to continue our work. The simulation developed permits us to optimize positions and shapes of the beam line elements, to know depth and lateral dose distributions also in situations where the experimental measure is very difficult. This will provide an improvement in the dose distributions released to the patients. Results from simulation can represent a test for the routine-used treatment planning systems. Our work represents also a general tool that can be used by other users to start the design and construction of a new hadron-therapy facility. Future steps will be the simulation of the rotating modulator wheel, the insertion of the DICOM images (i.e. those coming from a Computed Tomography examination) and the possibility to run the appli-
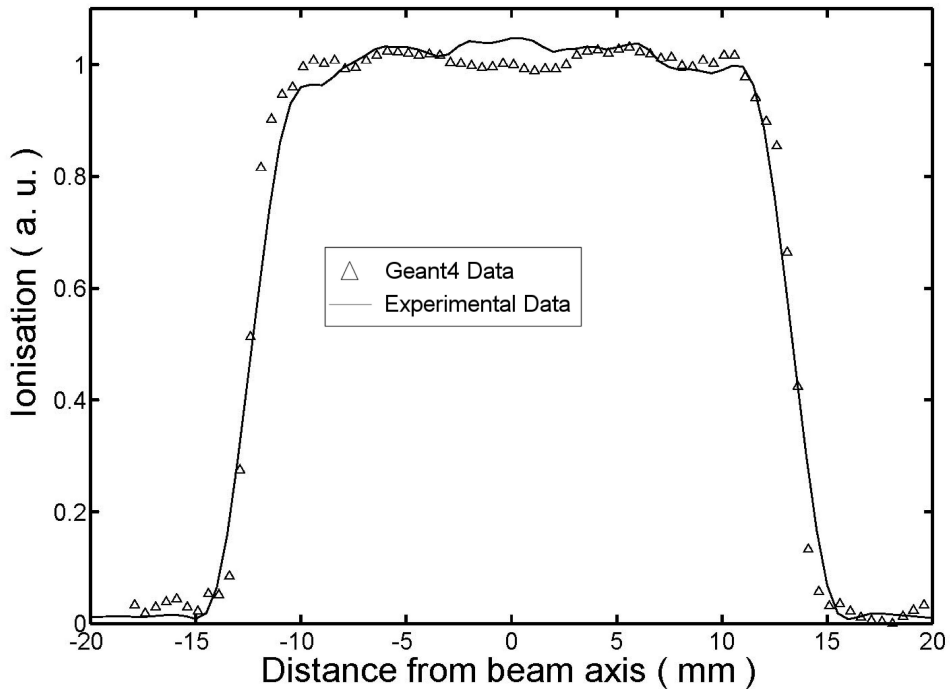
Figure 5: *Simulated and experimental lateral dose distribution for proton beams at the patient position.*

cation on the Grid to reduce the simulation times: we think this will contribute to draw up the Monte Carlo-based medical applicatitons with respect to the analytical-based ones, like those conventionally used for treatment planning systems.

6 Acknowledgements

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