# Implementation of a New Monte Carlo—GEANT4 Simulation Tool for the Development of a Proton Therapy Beam Line and Verification of the Related Dose Distributions

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***Abstract*—Using the Monte Carlo simulation tool GEANT4, we simulated the hadron-therapy beam line of the Centro di AdroTerapia ed Applicazioni Nucleari Avanzate (CATANA) 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 modeled. 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 to the experimental results obtained at Laboratori Nazionali del Sud (LNS) with different detectors.**

***Index Terms*—GEANT4, hadron-therapy, Monte Carlo, simulation.**

## I. Introduction

At THE Laboratori Nazionali del Sud (LNS), a high-energy and nuclear physics laboratory, in Catania, the first Italian hadron-therapy facility named Centro di AdroTerapia ed Applicazioni Nucleari Avanzate (CATANA) 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 Istituto Nazionale di Fisica Nucleare (INFN)-GEANT4 collaboration, having as its main goal the development of a Monte Carlo tool, based on the GEANT4 (ver. 6.0) [3] simulation toolkit, designing proton-therapy beam lines and testing treatment planning systems. This paper reports the first results of our simulation work.

## II. Catana Facility

### A. 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 particularly 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 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 m 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 in 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 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 online control of the dose delivered to the patients and beam symmetry. The last element before the isocenter is the patient collimator located 8 cm upstream of the isocenter. Experimental measurements are

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

Fig. 1. CATANA treatment room installed at LNS, Catania (Sicily), Italy.

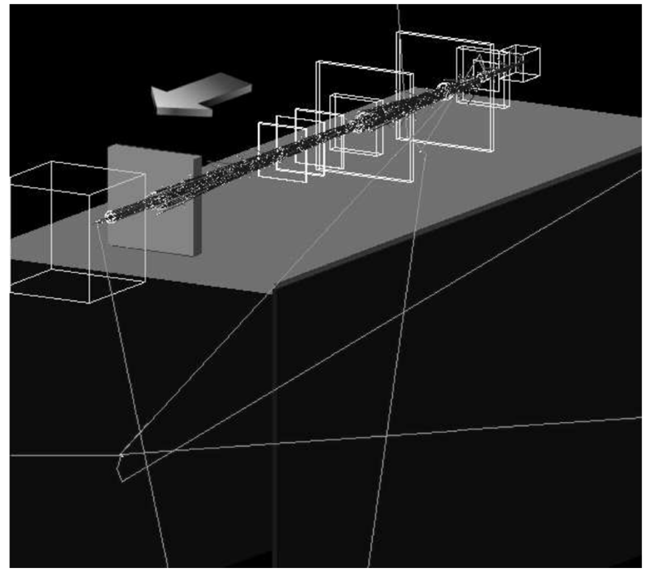

Fig. 2. Proton therapy beam line as it is simulated and displayed by the hadron-therapy application. The beam direction is indicated by the arrow. Secondaries are delta rays and neutrons produced in the interaction with the beam line elements.

carried out placing detectors inside a polymethylmethachrylate (PMMA) 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 Fig. 1, the complete layout of the CATANA proton-therapy beam line is shown.

So far, since March 2002, sixty-six patients coming from different Italian regions have been successfully treated. Follow-up data at 30 patients after at least one year from their treatment confirm the usefulness of proton therapy.

### *B. 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 two- and three-dimensional dose distribution reconstruction (relative dosimetry) [2]. A parallel plate ionization Markus chamber has been chosen as a reference detector for the absolute dose measurements, while gafchromic and radiographic films, thermoluminescence detectors, diamond, and silicon diode detectors are the detectors chosen for the relative ones.

## III. GEANT4 FOR MEDICAL APPLICATIONS

The development of a 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 collimator systems.

On the basis of these, we decided to start a simulation work using the Monte Carlo tool GEANT4 [3]. It 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, the *LowEnergy* [4] package is the main element. It 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 unique to GEANT4 among Monte Carlo codes on the market and is of relevance for several medical physics applications.

GEANT4 provides various features suitable for medical applications. Specifically, the GEANT4 object oriented design allows a transparent implentation and, hence a careful check, of the physics models. This contributes to an accurate validation of the experimental results that is particularly important for such sensitive application 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.

## IV. SIMULATION OF THE TREATMENT BEAM LINE

We started our work developing a GEANT4 application, named *hadronTherapy*, simulating 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 Fig. 2, the proton therapy beam line, as it is simulated and displayed by our application, is shown.

Moreover, we introduced in the simulation two sensitive detectors that exactly reproduce the experimental ones; these are the Markus chamber (for the Bragg peak reconstruction) and the radiochromic film (for the lateral dose distribution 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 by more than a factor of ten reducing the total time for a complete simulation to ten hours.

We used the LowEnergy package, (with the ICRU [5] stopping power tables) taking into account both fluorescence and

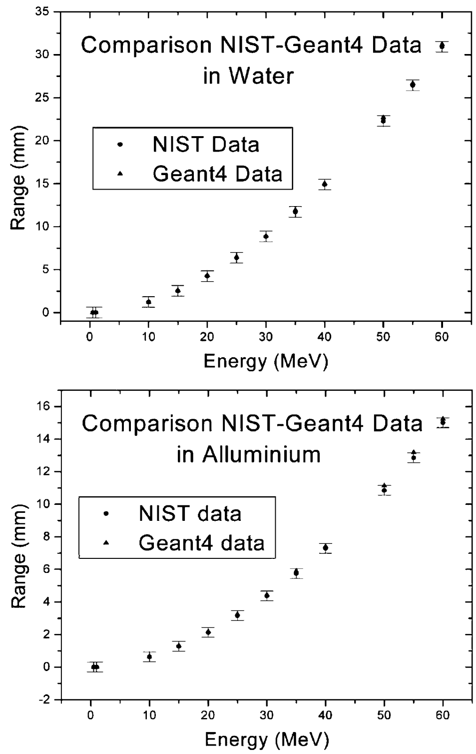


Fig. 3. Comparison between simulated (GEANT4) and tabulated (ICRU) data of the range of proton beams in water and aluminum. Error bars, for the GEANT4 data, are not displayed because too small.

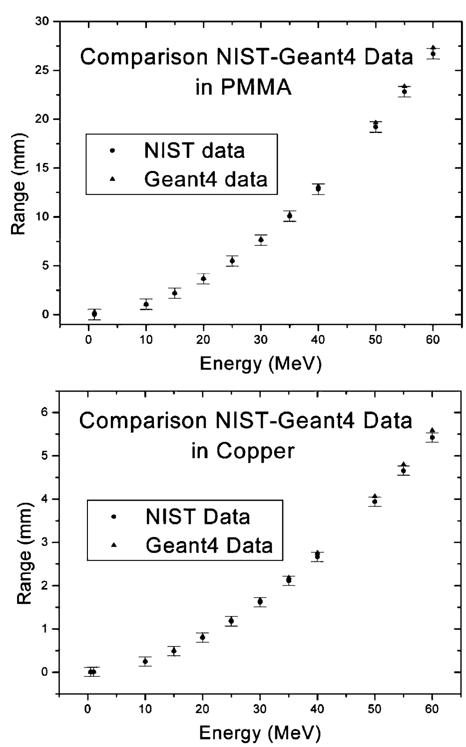


Fig. 4. Comparison between simulated (GEANT4) and tabulated (ICRU) data of the range of proton beams in PMMA and copper. Error bars, for the GEANT4 data, are not displayed because too small.

Auger emmission, in order to perform a complete and very precise calculation. The hadronic processes were considered activating the GEANT4 precompound model.

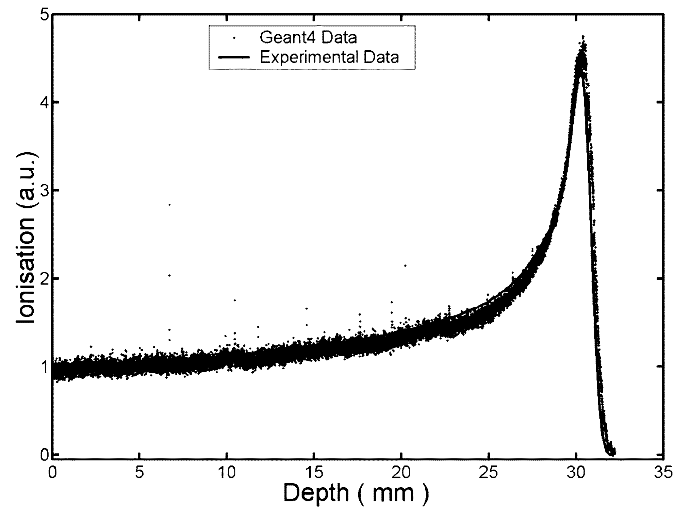


Fig. 5. Comparison between simulated and experimental Bragg peaks in water of 62 MeV proton beams.

## V. Results and Conclusion

The first step was the validation of the simulated detectors. In particular, we compared the simulated proton ranges obtained, in the energy range of 10–62 MeV and with different materials (water, aluminum, copper, and PMMA), to data from ICRU [5] (Figs. 3 and 4). The agreement obtained between the two distributions (below 0.2% for all materials and energies) demonstrates the accuracy of the simulation of the sensitive detectors from a software point of view. We found, for the Geant4 data, an error of 200 $\mu$m. It was statistically estimated performing ten, repeated simulations under the same conditions. Errors for the tabulated ranges are estimated by the ICRU authors: they assume an error of 2% for range values [5].

Moreover, an accurate reconstruction of the beam characteristics was performed on the basis of the experimental available data: in this way, we defined the beam initial energy ($E = 63.4$ MeV), energy spread ($\Delta E = 300$ keV) and beam spot size ($\delta = 5$ mm). Then, the reconstruction of Bragg peaks was carried out for various energies and materials (water, PMMA, and aluminum). Fig. 5 shows the Bragg peak, in water, for the simulated beam compared to the experimental one measured with the Markus chamber.

Starting from Bragg distributions, proton range values were derived and compared with the experimental ones: the resulting agreement is better than 1.4%.

The reconstruction of the lateral distributions of the therapeutic proton beam at the isocenter and at various depths in water was performed. Simulated results are in agreement with experimental ones as shown in Fig. 6.

Results obtained encourage us to continue our work. The simulation application 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 measurements are very difficult. This will provide an improvement in the dose distributions given 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

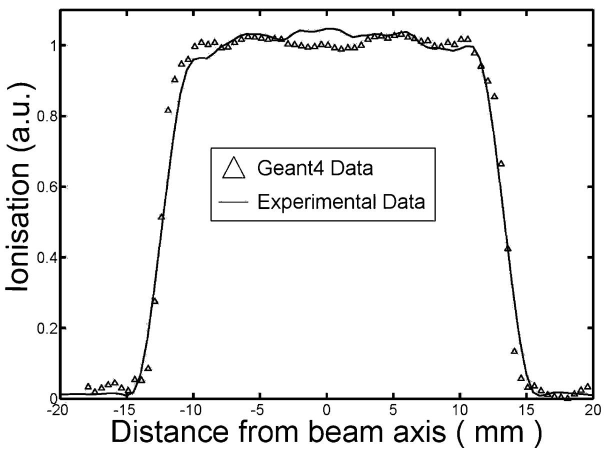


Fig. 6. Simulated and experimental lateral dose distribution for proton beams at the patient position.

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 [6] (i.e., those coming from a computed tomography examination) and the possibility to run the application on the Grid [7] to reduce the simulation times: we think this will contribute to draw up the Monte Carlo-based medical applications (that are intrinsically very precise as they permit to follow the behavior of each particle inside matter) with respect to the analytical-based ones, like those conventionally used for treatment planning systems.

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