MEDICAL APPLICATIONS OF THE GEANT4 SIMULATION TOOLKIT

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15 March 2001

ABSTRACT

The main features of the Geant4 Simulation Toolkit of interest for biomedical studies are illustrated. A few significant applications and results are presented, including simulations for brachytherapy, dosimetric studies and the study of radiation damage at cellular and DNA level.

KEYWORDS

Simulation, Geant4, medical.

1 INTRODUCTION

A powerful and suitable tool for studies of particle production and transport in biological matter is offered by the simulation with Monte Carlo procedures. The Geant4 Simulation Toolkit (4) is a general purpose Monte Carlo code for the simulation of the passage of particles through matter. It provides a wide set of tools to address the domain of medical physics applications: geometry and material description, particles tracing within any geometry, material and field, run, event and track management, an ample variety of physics processes over an extended energy range, response to particle interactions, visualisation and user interface. In particular, it provides various features relevant for medical applications:

- the Object Oriented design allows to achieve the transparency of the physics, contributing therefore to the validation of experimental results, that is of fundamental importance on such sensitive applications as the medical ones;
- the code is freely available and is publicly distributed from a unique source;
- a large international Collaboration is responsible for the maintenance, further developments of the code and for the user support;

- the toolkit relies on the use of standards - both ISO and de facto ones - wherever available;
- the code is independent from any system of units;
- the toolkit does not depend on any external software packages, but can be interfaced to a variety of commercial and free tools, such as graphic drivers, object databases, histogramming and analysis packages, CAD etc.;
- the physics packages make use of evaluated databases, acknowledged as the state of the art in their domain, available from a large number of international distribution centres;
- powerful and unique physics functionalities of medical interest are provided.

A sample of applications in the bio-medical domain is presented in the following sections.

2 THE GEANT4 SIMULATION TOOLKIT

Geant4 (4) is a simulation toolkit designed for a variety of applications, including HEP, astrophysics and nuclear physics experiments, space science and medical physics.

The Geant4 kernel handles the management of runs, events and tracks. The Run, Event and Track management allows the simulation of the event kinematics, together with primary and secondary tracks. The Tracking handles the propagation of a track, determined by the physics interactions. The tracking system manages various kinds of interactions, leading to a generalisation of the traditional classification into discrete and continuous physics processes. In order to fully exploit the validity ranges of the physics models, Geant4 does not apply any tracking cuts, but relies only on production thresholds: thus all particles are tracked down to zero range. In addition, Geant4 can ensure a consistent and material-independent accuracy of the simulation, as the production cuts are set in range, rather than in energy. The Tracking performs a correct treatment of near-boundary regions, based on the capability of processes to produce secondaries below threshold. The user can optionally define cuts in energy, path length and time-of-flight for special treatment of selected areas in the experimental set-up.

The Hits and Digi domains provide the functionality to reproduce the read-out structure of the detector and its electronic response, independently from the geometry used for the tracking.

A fast parameterisation framework is integrated with the full simulation, allowing independent and simplified descriptions of the set-up and direct production of hits. The fast simulation can be triggered according to various options, such as particle type, volume etc. This feature is interesting, for example, to simulate treatment planning: full simulation is needed for inhomogenous parts, while fast simulation can be applied to homogeneous media.

Geant4 Geometry provides the user the ability to describe the detailed geometrical structure of a set-up; it also handles the equation of motion solvers in different fields and geometrical boundaries conditions for the propagation of particles. Geant4 Geometry provides an ISO STEP compliant solid modeller, allowing the exchange of models from CAD systems. Multiple solid representations, such as Constructive Solid Geometry, Boundary Represented Solids (including NonUniformRationalBSplines), Swept Solids, Boolean Operations, are supported according to the ISO STEP standard. Thanks to the power and flexibility of Geant4 geometry, beam sources and the patient can be described in the same framework. Geometry can be modified at run-time, for example by a particle interaction with a volume of the geometry itself. This can be useful, for example, in the simulation of cell survival after irradiation, in which cells which have been hit, can send biochemical signals to neighbouring cells and modify their structure.

Geant4 Electromagnetic Physics (9) manages lepton, photon and muon interactions, as well as the electromagnetic interactions of hadrons and ions. It provides multiple implementations of ionization, Bremsstrahlung, multiple scattering, photoelectric effect (also with fluorescence), and

Compton effect (also with polarization); it handles annihilation, pair conversion, synchrotron and transition radiation, scintillation, refraction, reflection, absorption and Raleigh effect. Low energy processes - down to 250 eV for photons and electrons (1) - as well as for hadrons (5) and ions (6), are implemented, with multiple models. Thanks to its low energy extensions, Geant4 Electromagnetic Physics is especially suitable for accurate medical physics studies.

Geant4 Hadronic Physics offers both parameterisation-driven models and a variety of theory-driven models, as well as treatment of low energy neutron transport. These features are relevant for particle cancer treatments such as Boron Neutron Capture Therapy or Hadrontherapy. Event biasing options are also provided.

Particle Data Group compliant particle definitions - including hundreds of baryonic and mesonic resonances and ions, with their decay processes and modes - are available in the Toolkit.

A wide set of utilities, including a powerful set of random number generators, physics units and constants, as well as isotopes, elements, compounds definitions, interface to event generators and to ODBMS complete the Toolkit.

Extensive possibilities of interaction with the Geant4 system are offered to the user via a set of dedicated user-action classes.

Geant4 Visualisation and User Interface design, based on object oriented abstract interfaces, makes Geant4 independent from any particular graphics system; at the same time it allows multiple implementations of drivers for graphics systems and interaction with sophisticated GUIs or command line and batch systems.

The ability to store relevant data in a persistent object store has been designed, developed and demonstrated in Geant4 for event data, hits and geometry descriptions.

3 BRACHYTHERAPY APPLICATIONS

Monte Carlo simulation in Brachytherapy is devoted mainly to obtain complex physical parameters used in treatment planning which are not directly available by experimental measurements. The task described here (2) is to simulate a commercial ^{192}Ir source in order to:

- verify the anisotropy function,
- verify the dose distribution in a tissue equivalent phantom,
- compare the simulated air kerma strength with the measured value.

As a first test of Geant4 capabilities in Brachytherapy, the attenuation coefficient μ/ρ in different materials of interest has been simulated. Because of the energy range involved and the accuracy required, the new Geant4 Low Energy Electromagnetic processes have been used. The tests involved one million photons of various energies passing through a thin layer of material and detected by a long-distance sensitive detector. Each test took approximately 2 minutes on a Windows Intel PC running at 300 MHz. Simulation results for water versus NIST (8) reference experimental data are shown in Figure 1; Geant4 is able to simulate with great accuracy the attenuation for photons with a difference of less than 1% with respect to the experimental values.

Figure 2 shows the anisotropy function obtained at 6 cm distance from the axis by sampling in polar coordinates the available data with nearest neighbour interpolation.

4 DOSIMETRIC STUDIES

Thanks to its physics performance and the flexibility to manage complex geometries, Geant4 is suitable for electron and photon beam studies. At INFN Torino, within the TERA project, a

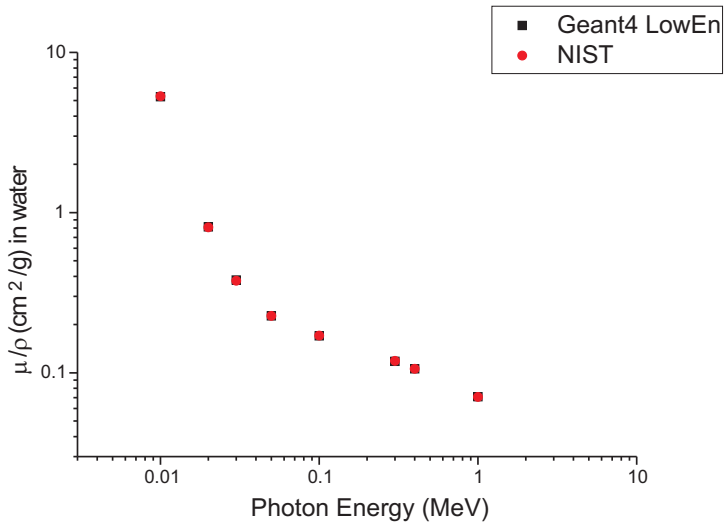

Figure 1. μ/ρ simulation results: Geant4 versus NIST tabulated values

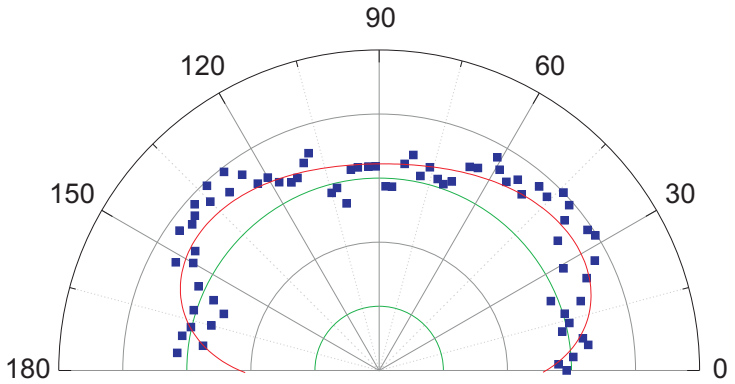

Figure 2. Anisotropy function

simulation of a pixel ionization chamber to measure the relative dose with therapeutical photon beams has been developed. The energy of the photon beam follows a typical Bremsstrahlung spectrum extended up to 6 MeV. A preliminary comparison between experimental data and simulation is shown in Fig. 3.

Studies have been performed for proton beams as well; the Bragg peak reconstructed from experimental data taken at PSI shows a good agreement with the simulation (7).

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Characterisation of Termoluminescent Detectors, used in in-vivo dose estimation in radiological examinations, is also in progress in collaboration with the Institute for Cancer Research and Treatment.

5 CT IMAGE INTERFACE

To simulate a full radiotreatment planning it is necessary to have the complete geometrical description of the patient; this is done trough a CT scan image. An activity is in progress to

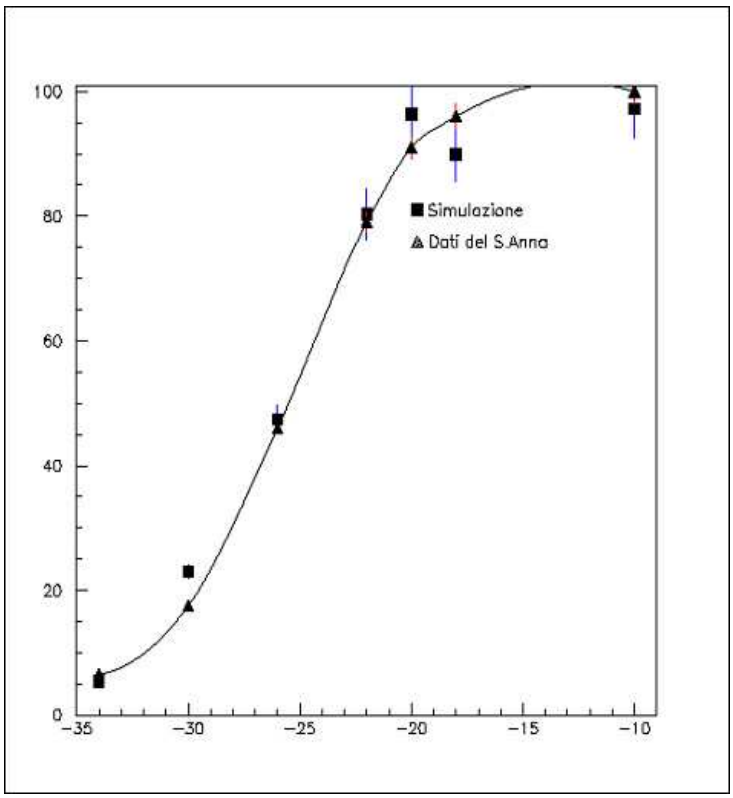

Figure 3. Deposited energy versus depth in water: comparison of experimental data and simulation.

interface Geant4 with the DICOM CT scan image format in order to perform direct simulation in an *ad hoc* described tissue, with the definition of organs at risk and target tumor volume.

6 RADIATION INTERACTIONS AT THE CELLULAR AND DNA LEVEL

Estimating cancer risk for human exposure to space radiation is a challenge which involves a wide range of knowledge in physics, chemistry, biology and medicine. Traditionally, the biological effects of radiation are analyzed in top-bottom order, i.e. the evaluation of the absorbed macroscopic radiation dose at a given location in the biological tissue is translated to the degree of danger it presents, and dose limits are consequently set that are considered to be acceptable. A novel approach that proceeds in a reverse order, from bottom to top, by analyzing the nano-scale effects of energetic particles at the cellular and DNA molecule level, has been started (3). User requirements for a Geant4-based simulation tool for such studies have been collected, analysed and specified.

In the framework of this project, nanodosimetric studies are in progress, involving the application of Geant4 Low Energy Electromagnetic processes. Figure 4 shows an α particle of 5.3 MeV from an ordinary Po^{210} source producing δ electrons traversing a cylindrical volume inside a modelled cell nucleus. The particle is followed in steps of 1 nanometer in water and with δ-ray emission.

The Geant4-DNA project is sponsored by the European Space Agency (ESA) and the Italian National Institute of Nuclear Physics (INFN) and is pursued by a multidisciplinary European Collaboration of biologists, physicians, physicists, space scientists and software engineers.

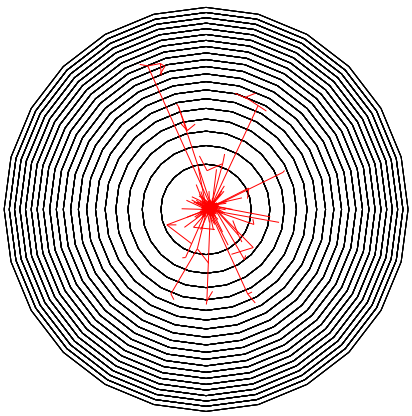

Figure 4. 5.3 MeV α particle in a cylindrical volume inside the cell nucleus. The inner cylinder has radius 50 nm.

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