ISTITUTO NAZIONALE DI FISICA NUCLEARE

Sezione di Genova

INFN/AE-2000/??

12 September 2000

MEDICAL APPLICATIONS OF THE GEANT4 TOOLKIT

S. Agostinelli[1], S. Chauvie[2,5], F. Foppiano[1], S. Garelli[1],
F. Marchetto[2], P. Nieminen[3], M.G. Pia[4,6], V. Rolando[2], Ada Solano[2]

[1] *Istituto Nazionale per la Ricerca sul Cancro, I-16132 Genova, Italy*

[2] *INFN, Sezione di Torino and University of Torino, I-10125 Torino, Italy*

[2] *ESA/ESTEC, Keplerlaan 1, 2200 AG Noordwjik, The Netherlands*

[4] *INFN, Sezione di Genova, I-16146 Genova, Italy*

[5] *IRCC, Institute for Cancer Research and Treatment, I-10060 Candiolo, Italy*

[6] *CERN, CH-1211 Geneva 23, Switzerland*

Abstract

A powerful and suitable tool for attacking the problem of the production and transport of different beams in biological matter is offered by the Geant4 Simulation Toolkit. Various activities in progress in the domain of medical applications are presented: studies on calibration of brachytherapy sources and thermoluminescent dosimeters, studies of a complete 3-D inline dosimeter, development of general tools for CT interface for treatment planning, studies involving neutron transport, etc. A novel approach, based on the Geant4 Toolkit, for the study of radiation damage at the cellular and DNA level, is also presented.

To be published in the
Proceedings of Monte Carlo 2000, International Conference on Advanced Monte Carlo for Radiation Physics, Particle Transport Simulation and Applications,
23-26 October 2000, Lisbon, Portugal

Published by **SIS-Pubblicazioni**
Laboratori Nazionali di Frascati

1 The Geant4 Object Oriented Simulation Toolkit

Geant4 [1] is a general purpose code which provides a complete set of tools for the simulation of particle passage in matter. It provides tools for Tracking, Geometry, Detector Response, Run, Event and Track management, Visualisation and User Interface. A variety of physical processes describes interactions of hadrons, leptons and bosons in a wide energy range. In particular, new low energy extensions of electromagnetic interactions [3] are relevant in the domain of medical simulations. A fundamental requirement for physics validation of the Geant4 simulation results is to make transparent how the software produces the results. This is one of the major requirements and achievements of Geant4 and it is exploited through advanced Software Engineering and Object Oriented Technology. The OO technology allows fast and easy implementation of new features without modifying the preexistent code. Geant4 is supported for both UNIX and Windows platforms. The source code of Geant4 is freely available [1] and distributed by the Geant4 Collaboration. A User Support service is also available. The Geant4 software has been developed by a world-wide collaboration of over 100 scientists from Europe, Canada, Russia, Japan and USA.

2 Geant4 features relevant for Medical Applications

The capabilities of the Geant4 Toolkit include a very powerful kernel, transparency and evidence of physics model and several auxiliary tools. The latter include the ability to visualise the detector, particle trajectories and hits, and the creation of a persistent geometry and persistent events.

The kernel of Geant4 handles the management of Run, Event and Track to perform the act of simulation. Geant4 Run encapsulates the possibility to create different geometry configurations and/or several beam types within a single computer job. Geant4 does not apply tracking cuts but only secondary production cuts, so that the validity range of physical models can be fully exploited and all particles are tracked down to 0 range. Cuts can be given in energy or in range so that the accuracy of spatial energy deposition becomes independent of the material. The Geant4 framework allows Fast Monte Carlo simulation that co-works with the full event simulation, for example, by plugging-in a user's parameterization. This feature is interesting, for example, to simulate treatment planning: full simulation is needed in case of inhomogenous parts, while fast simulation can be applied to homogeneous media. In this way it is easy to describe local energy deposition in small volumes with great density differences.

The role of geometry in Geant4 consists of providing tools to describe the complete environment. This can result in interesting medical applications in which beam sources and the patient can be described in the same frame. Geant4 handles the equation of motion solver in an electromagnetic field. An object geometry can be described in several different ways: via the geometrical definition of solid with Constructive Solid Geometry module, describing a solid as an intersection of surfaces with Boundary REPresented Solid (BREPS), or using geometry definition from commercial tools such as CAD via an ISO STEP compliant solid modeller. Geant4 itself treats the response of the object hit by the beam, including readout and digitisation. 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 Electromagetic Physics manages electrons, positrons, γ-rays, X-rays, optical photons and muon interactions, as well as hadrons and ions interactions. A complete set of electromagnetic processes has been created and specialized processes extend the treatment of photons and electrons down to 250 eV [3] as well as for hadrons and ions. Hadronic processes are implemented for all hadrons in a variety of models over a wide energy range. For the neutron transport all databases available are used. These features are relevant for particle cancer treatments such as Boron Neutron Capture Therapy or Hadrontherapy, in which a precise description of the energy deposition is needed.

The visualisation and Graphical User Interface design is based on an object oriented abstract interface that makes Geant4 independent from any particular graphics system. At the same time, this interface allows multiple implementation of drivers for graphical libraries; the implemented visualisation drivers support the use of X11, PostScript, OpenGL, OpenInventor, RayTracer, DAWN and VRML. A friendly user interface offers batch or command line approaches and also fully graphical user interface such as OPACS, Momo, GPE and VRML. Due to the versatility of Object Oriented Technology, it is possible to add modules for interfacing Geant4 with different tools or graphical systems in an easy and powerful way. The ability to store relevant data in a persistent object storage has been developed in Geant4 for event data, hits and geometry description.

3 Brachytherapy applications

The role of Monte Carlo simulation in Brachytherapy is mainly to obtain complex physical parameters used in treatment planning which are not directly available by experimental measurements. The task described here [4] 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 and the accuracy required, the new features contained in Low-Energy Electromagetic 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 literature experimental values available at NIST [5] are shown in Fig. 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 value (see Fig. 2).

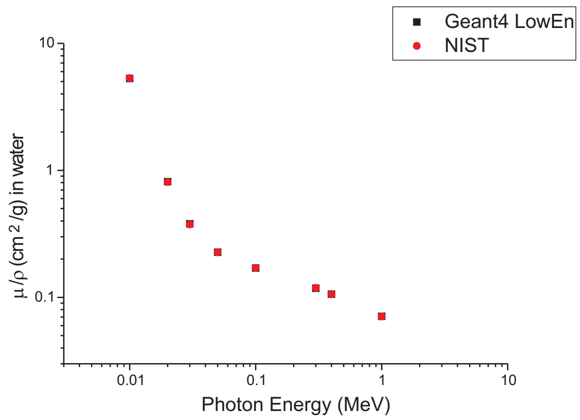

Figure 1: μ/ρ simulation results, with GEANT4 versus NIST tabulated values

The Geant4 simulated energy absorption in 20 cm water phantom (Fig. 2) of 10 millions of photons of energy equal to ^{192}Ir mean energy (356 keV) was also simulated.

The picture shown in Fig. 3 describes the anisotropy function obtained at 6 cm distance from the axis by sampling in polar coordinates the available data with nearest neighbour interpolation.

4 Dosimeter studies

Thanks to its physics performance and easy geometry management, Geant4 is suitable for electron and photon beam studies. At INFN Torino, within the TERA project, a simulation of a pixel ionization chamber to measure the relative dose with therapeutical photon beam

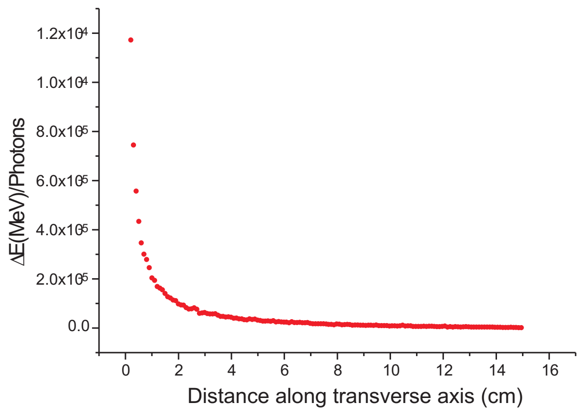

Figure 2: Simulation results for ΔE as a function of axial distance.

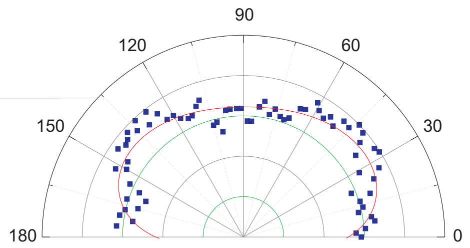

Figure 3: Simulated anisotropy function at 6 cm axial distance.

is under development. The energy of the photon beam follows a typical Bremsstrahlung spectrum extended through 6 MeV. A very preliminary comparison between experimental data and simulation is shown in Fig. 4, where the profile of the deposited energy for a middle section of the chamber is shown. The agreement is fairly good; further attempts to shape the beam tranverse profile are under way. The CPU time measured on a 500 MHz PC Linux platform is about 5 ms/photon.

Studies have already been performed for proton beams; the Bragg peak reconstructed from experimental data taken at PSI compared with simulation (Fig. 5) show a good agreement [6].

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

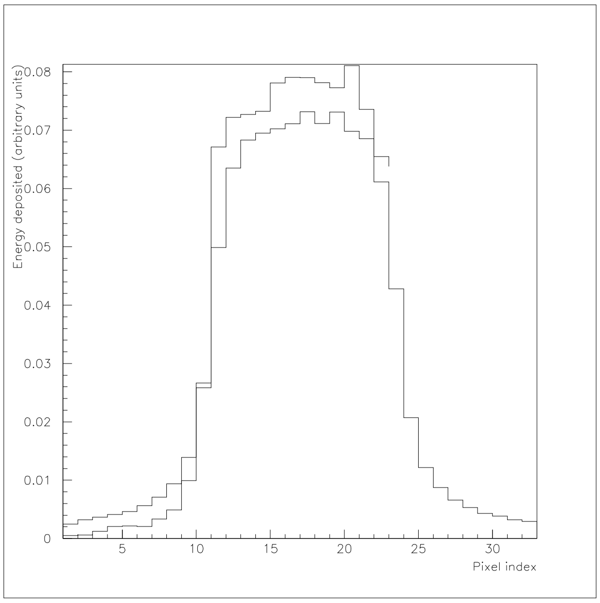

Figure 4: Comparison between experimental data (full line) and simulation (dashed line). The histograms are normalised according to their areas. The results are preliminary.

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 pprogress to interface Geant4 with DICOM CT scan images 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 Particle interaction with DNA

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 [2]. In the framework of this project, nanodosimetric studies are in progress, involving the application of the Low Energy elec-

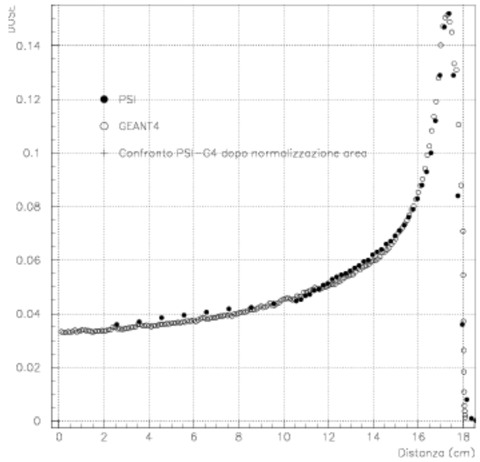

Figure 5: Simulated versus experimental energy deposition in function of the depth in water

tromagnetic processes. In Fig. 6 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 is shown. The particle is followed in steps of 1 nanometer in water and with δ emission. A definition of tissue and cell within the framework of Geant4 using the Object Oriented approach, as well as a detailed modelling of the DNA double helix, are in progress.

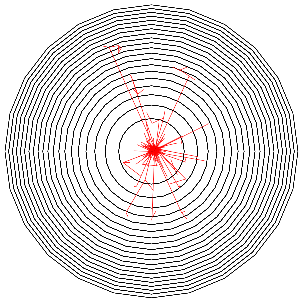

Figure 6: 5.3 MeV α particle in a cylindrical volume inside the cell nucleus. The inner cylinder has radius 50 nm.

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.

References

[1] The Geant4 Collaboration, http://wwwinfo.cern.ch/asd/geant4/geant4.html

[2] The Geant4-DNA Collaboration, http://www.ge.infn.it/geant4/dna/index.html

[3] M.G. Pia et al. MC2000 Proceedings. Lisbon, Portugal, 16-20 October 2000

[4] F. Foppiano *et al.*, The application of GEANT4 simulation code to the verification of a Brachytherapy calibration procedure, in Proc. of the XIII International Conference on the Use of Computers in Radiation Therapy, Heidelberg, Germany 22-26 May 2000.

[5] National Institute of Standards and Technology, http://physics.nist.gov

[6] R. Gotta, Monte Carlo Simulation with Geant4 of a 3D dosimeter for therapeutical proton beams, Thesis, University of Torino, 1999