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OVERVIEW OF GEANT4 APPLICATION IN MEDICAL PHYSICS

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Abstract

We present a series of achievements associated with Geant4-based applications in medical physics and, in particular, in radiotherapy (external beams and brachytherapy), protontherapy, PEM, PET, MRT, metabolic therapy, IORT; projects in microdosimetry and radiobiology are beginning. The Geant4 CT-interface allows to reproduce realistically the patient anatomy, the integration to the GRID allows to run the applications sharing distributed computing resources. The Geant4 Medical Physics Group has born from the collaboration of Geant4 with several research and medical physics institutes in Europe.

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1 Introduction

Several applications in medical physics require a Monte Carlo approach. In particular, the Monte Carlo method allows the study of new strategies and methodologies both in diagnostic and therapy, to evaluate available techniques and to plan therapy treatments that require accurate dose mapping. The fundamental requirements for the application of a Monte Carlo tool in medical physics are: flexibility to model complex geometries and define homogeneous or heterogeneous media of biological interest; property of simulating a wide variety of physics processes over an extended energy range; ability to steer run, event, track within any geometry with the possibility of a full simulation. Other relevant points to take into account are the capability of experimental set-up visualisation, a simple user interface. The development of the Monte Carlo tool must follow a rigorous software process in order to guarantee its reliability, a fundamental issue for applications in medical physics. All these items are offered by Geant4 Simulation Toolkit and, as a consequence, Geant4 is a powerful tool for medical physics. Several Geant4 medical physics applications have been developed from diagnostic to radiotherapy and dosimetry at the cellular level.

2 Geant4 Simulation Toolkit

The Geant4 Simulation Toolkit [1] kernel handles the management of runs, events and tracks. Figure 1 shows the structure of the Geant4 kernel. 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 the track, determined by the physics interactions. The Hits and Digi domains provide the functionality to reproduce the read-out structure of the detector and its electronic response. Geant4 Geometry provides the user with the ability to model experimental set-ups in a detailed way. Multiple solid representations, such as Constructive Solid Geometry, Boundary Represented Solids, Boolean Operations, are supported according to the ISOSTEP standard. Thanks to the power and flexibility of Geant4 geometry, beam lines, radioactive sources and the patient anatomy can be described in the same framework. Geant4 Electromagnetic Physics manages leptons, 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, Compton effect (also with polarization); it handles annihilation, pair conversion, synchrotron and transition radiation, scintillation, refraction, reflection, absorption, Raleigh Effect, Auger effect and fluorescence. Low Energy processes down to 250 eV for photons and electrons as well as for

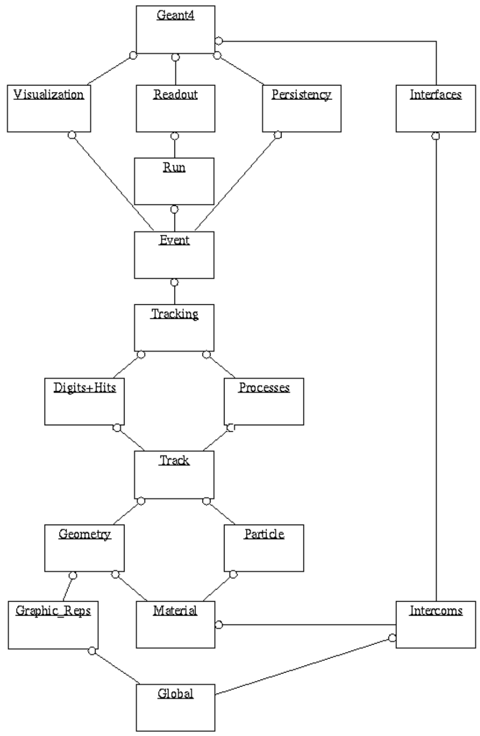

Figure 1: Geant4 kernel

hadrons and ions, are implemented, with multiple models. Thanks to its low energy extensions, Geant4 Electromagnetic Physics is especially suitable for accurate physics studies in bio-medical domain. Geant4 Hadronic Physics offers both parameterisation-driven models and a variety of theory-driven models, as well as treatment of low energy neutron transport. Particle Data Group compliant particle definitions, including hundreds of baryonic and mesonic resonances and ions, with their decay processes and models are available in the Toolkit.

3 Geant4 medical physics applications

Because of its advanced functionality Geant4 is used as a simulation toolkit in various domains by medical physics communities. A sample of applications is presented in the following sections.

3.1 Geant4 radiotherapy applications

Geant4 is used in radiotherapy in external beam treatment, brachytherapy and hadrontherapy. Geant4 is a powerful tool in bio-medical physics because it unifies accurate physics models and accurate experimental set-up modelisation. Geant4 allows the modelling of complex geometries such as, for example, accelerators, radioactive sources, patient anatomy. Thanks to the Geant4 DICOM Interface it is possible to model treatment target area in terms of geometries and tissues involved. Both physics models and geometry management contribute to the accuracy of calculation of dosimetric quantities of medical physics interest. Geant4 applications have been developed for external beam radiotherapy. One example is modelling of a compact treatment head preformed at Karolinska Institutet [2]. The vital components of the beam production have been modeled. Geant4 is advantageous for this simulation as it allows simulation of particle transport through matter and magnetic fields simultaneously. Geant4 has been used also for studies in brachytherapy. A dosimetric system has been developed in order to calculate dose distributions in patient's treatment target for all the brachytherapic sources [3], in contrast with available commercial software; the last ones are addressed to singular brachytherapic techniques and perform approximations at the dose calculation level. The brachytherapy application is a prototype of a Geant4 application able to run in parallel mode, sharing distributed computing resources [4]. A hadrontherapy beam line has been simulated with Geant4 [5]. In this case Geant4 is a suitable and powerful Monte Carlo tool because it handles both electromagnetic and hadronic physics processes for ions and hadrons. Both the physics models and the proton beam line modelisation contribute to the accurate dosimetric calculation in the patient's treatment area. Geant4 is used also in studies concerning Metabolic Therapy of Thyroid Diseases; this technique takes adavantage of the radioactive properties of ^{131}I and of the metabolic capability of the thyroid. Geant4 is used to model the geometrical structure of the experimental set-up, to define physics processes of photons and electrons. The application calculates the dose delivered in the ill lobe of the thyroid [1]. Radiotherapy treatments are in continous evolution; one of the most advanced techiniques is IMRT. A Geant4 application has also been developed in this domain at INFN, Torino, Italy, in collaboration with Ordine Mauriziano-IRCC [6].

3.2 Other dosimetric studies

A Geant4 application is under development for dosimetric studies at cellular level [7]. Dosimetry has always been performed at the macroscopic level but studies have never been done at cellular level; this application is meant to fill this gap. Geant4 is a suitable tool for such an application because it offers the possibility to model the structure of a cell in terms of geometries and materials.

3.3 Radiodiagnostic

Geant4 is a powerful tool addressed to radiodiagnostic because it also offers the possibility to reproduce geometries moving in time and source decay; the management of timedependent phenomena is an original feature of Geant4 important for the development of radiodiagnostic applications. GATE is a Geant4 Application for Tomographic Emission, general purpose simulation for PET and SPECT applications [8]. A PEM application has been developed at LIP, Lisbon, Portugal [9].

4 Geant4 new projects in bio-medicine

4.1 Geant4 DNA

Estimating cancer risk for human exposure to space radiation is a challange which involves a wide range of knowledge in physics, chemistry, biology and medicine. The future activities on the International Space Station impose a greater attention to such effects. Traditionally, the biological effects are studied in top-to-bottom order. A novel approach that proceeds in a reverse order, bottom-to-top mode, by analysing nano-scales effects of energetic particles at the DNA level has been launched by the European Space Agency (ESA). The project involves an international collaboration among biologists, physicians, physicists, space scientists and software engineers.

4.2 Shielding in space missions

In 2001 the European Space Agency (ESA) set up the AURORA Programme whose primary objective is to create, and then implement, a European long-term plan for the robotic and human exploration of the solar system, with Mars, the Moon and the asteroids as the most likely targets. A new project has born at INFN, Genova, Italy in order to perform studies of radiation shielding in space missions with Geant4 Simulation Toolkit. The project involves specialists in different domains: space scientists, physicists, software specialists. Such a study is a fundamental issue in order to guarantee astronauts health, and the safety of crafts (detectors, electronics, etc.) in interplanetary space missions.

5 Technology Transfer

The application of Geant4 in the bio-medical domain is a successful example of technology transfer project [10]. Thanks to the adoption of Objected Oriented Techology it has been possible to develop physics models for a wide range of particle energies, permitting Geant4 use in other domains such as medical physics. HEP offers the most modern technologies to medical physics, the latter providing feedback about the quality of the provided tools. This collaboration with medical and biological domains is fruitful to HEP software, providing contributions such as testing and validation of simulation software, user requirements stimulating new models and developments also relevant to HEP applications.

6 Conclusions

Geant4 Simulation Toolkit is a powerful and versatile Monte Carlo tool addressed to biomedical applications, open to extensions and evolution. Geant4 allows accurate modelling of experimental set-ups such as, for example, radiotherapy beam lines,brachytherapic sources, detectors used in radiodiagnostic and patient's anatomy. Geant4 provides a wide set of complementary and alternative physics models both in elctromagnetic and hadronic physics. The transparency of the physics is guaranteed -as a consequence any user can understand the models adopted in his/her specific application. The extensibility and flexibity of Geant4, given by the adoption of Object Oriented Technology, allows the development of applications in different research domains as radiodiagnostic, external beam radiotherapy, brachytherapy, hadrontherapy, microscopic dosimetry and studies of shielding in space missions.

Acknowledgment

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