Geant4 Monte Carlo simulations and applications in medical physics

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Abstract – Monte Carlo (MC) methods are currently considered the most powerful approaches in the medical physics field, from the absolute and relative dose calculation to the verification of the Treatment Planning Systems. MC approaches are also useful for the simulation of transport beam lines, in order to predict the output beam characteristics also for non-conventional accelerated input. In this report, MC applications developed at LNS with the GEANT4 toolkit are presented.

INTRODUCTION

The GEANT4 (GEometry ANd Tracking) MC toolkit is one of the most versatile and widespread codes used today for particle tracking and largely employed in many kinds of applications [1, 2]. It is a C++ object-oriented toolkit permitting the simulation of particle interactions with matter and providing advanced functionalities for all typical domains of simulation. Initially developed for High Energy Physics Experiments simulation, it is now widely used also for low-energy medical physics applications. Some of the authors of this work are currently members of the official GEANT4 collaboration, contributing to the maintenance of the advanced examples, and developing two examples currently distributed in the public release of the code, named hadrontherapy and gammaknife.

GEANT4 APPLICATIONS IN THE MEDICAL FIELD

Several applications in the medical physics domain have been developed using the GEANT4 toolkit. An advanced example simulating a Gamma Knife device for Stereotactastic Radiosurgery has been recently included in the public release. It reproduces in details the cobalt sources displacement inside the unit and allows a comparison with the Treatment Planning System used for the dose computation. The PRIMA (Proton IMaging) prototype for proton Computer Tomography (pCT) has been also fully simulated to investigate the reconstruction methods and study the path of the proton beams. Moreover, the fragmentation of carbon ion beams on thick and thin targets (FRATT and FRAG experiments) has been studied in order to validate the GEANT4 nuclear for beams of interest in hadrontherapy. As concern the use of proton and ion beams for therapeutic purposes, the hadrontherapy advanced example is developed and maintained for several years. In the application, the CATANA beam line for eye melanoma treatment is fully simulated and, recently, a module dedicated to the computation of the dose-average linear energy transfer has been included [3, 4]. During the last year, a new module has been also implemented, reproducing a typical beam line for the transport and handling of laser-driven beams.

The CATANA beam line and the average linear energy transfer calculation

The Hadrontherapy example simulates a typical proton/ion therapy beam line, including all the necessary elements, from the diffusion and modulation system to the detectors for relative and absolute dosimetry. The application offers also the possibility to change many beam line parameters without modifying the source code, i. e. run-time by means of several idle commands. Moreover, a module dedicated to the calculation of the average 3-dimentional Linear Energy Transfer (LET) for proton and carbon ion beams has been recently added. For instance in Figure 1 the total and primary LET-dose distributions for a 62 MeV proton beam in PMMA are shown. The dose curve is compared with experimental data, normalized at the entrance [5].

Figure 1. LET-dose distributions for a 62 MeV proton beam in PMMA. The relative dose distributions and primary protons fluence are given in arbitrary units.
The laser-driven beam line

During the last years, the interest in particle acceleration driven from ultra intense lasers is strongly growing, thanks to the huge number of potential applications and to the possibility to investigate new physics regimes. It could bring to more compact and less expensive acceleration systems and, consequently, to a larger availability of radiation beams around the world. However, current available laser-driven charged particle beams are characterised by non-conventional and sometimes extreme features, such as a wide divergence and a 100% energy spread. In this framework the capability to accelerate laser-driven beams in a controlled and reproducible manner for their use in any potential downstream applications, like linac injection, isotope production, imaging or radiobiology, represents one of the main objective for many worldwide researchers. In this background, the ELIMED (MEDical and multidisciplinary application at ELI-beamlines) project was born and a transport beam line dedicated to laser-driven beams has been recently realized. This beamline has been simulated with Geant4 and it has been also added as optional choice to the hadrontherapy example. The Monte Carlo approach has allowed, indeed, to optimize the beam line elements design and to study the output beam features modifying the input characteristics. As shown in figure 2 two main devices compose the beam line: a collecting focusing system and an energy selector. The first element, placed few cm downstream the source point, collects, focuses and pre-selects in angle and energy the accelerated particles. The final beam energy refinement is obtained by means of the energy selection system (ESS), composed of two collimators, four permanent dipole magnets with alternating polarity and a central slit [6,7]. Each element has been simulated in details, and several idle commands have been implemented in order to change run-time some geometrical parameters, as necessary [8]. Regarding the magnetic fields, they have been treated using a grid map with a 2 mm step and a linear interpolation. The grids have been obtained by OPERA simulations and read by a dedicated new class.

The new dosimetric detector

There are many suitable applications for the optically accelerated beams, but we have focused our attention on the possibility to irradiate cell samples with controlled dose distributions. However the ultra-short duration of laser-driven multi-MeV ion bursts offers dose rates of about $10^5$ Gy/min, very far from the conventional values. In this background and considering the saturation effects of dosimetric detectors typically used for conventional beams, an alternative detector has been proposed: a Faraday Cup, well know dose rate independent detector, has been recently realized at LNS at this aim. Several preliminary studies have been performed in order to optimise shape, dimensions, materials and electric field features, by means of COMSOL, Simion and Geant4 simulations. The final configuration, reported in figure 3 and described in [9], represents the final prototype and it has been implemented in the public hadrontherapy application. 

CONCLUSIONS

MC methods can be considered one of the most powerful approaches in the medical field. Geant4 is an open source MC toolkit, widely used for several applications. Our group is part of the official collaboration and has gained a long and consolidated experience. Beyond the daily working on physics model validation and advanced example development, a constant activity of dissemination is carried out, with the organization of national and international courses.

REFERENCES