LOW-ENERGY ELECTROMAGNETIC PROCESSES IN GEANT4 IN THE CONTEXT OF SPACECRAFT CHARGING

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Abstract

A set of physics processes is implemented in the Geant4 Monte Carlo particle transport toolkit to extend the validity range of electromagnetic interactions down to lower energy than in the standard Geant4 electromagnetic processes. Corresponding low-energy extensions for protons and ions have also been developed in Geant4. These implementations, together with the ability of Geant4 to track particles down to zero range, thanks to the absence of any tracking cuts, can be highly useful for studies of electrostatic charging both in electronic components and in space science instrumentation. Both the electron-photon and proton-ion extensions, together with a number of other relevant capabilities of Geant4, are described in this paper.

1. Introduction

Simulation of deep charging in spacecraft benefits from accurate geometrical modelling of the spacecraft and of detailed tracking of the incident particles. To that end, Monte Carlo methods are a suitable and powerful tool to be applied. Geant4 [1] is a toolkit for full and fast 3D Monte Carlo simulation intended for a wide range of fields including space physics and cosmic ray studies, nuclear and radiation computations, and also medical applications. Geant4 provides functionality for all typical domains of simulation: geometry, tracking, detector response, run, event and track management, visualisation and user interface, as well as a large variety of physics processes and models. The code is designed using Object-Oriented technology and implemented in C++. Geant4 is publicly distributed from the WWW [2], together with ample documentation.

Geant4 has been used in a number of critical space instrumentation radiation analyses. These include a study of low-angle, low-energy protons scattering of the mirror structures of XMM-Newton and Chandra X-ray telescopes [3] and simulation of gamma ray detector characteristics of the GLAST and AGILE gamma ray observatories [4,5]. In the context of the ESA Bepi Colombo mission, Geant4 is used both for detector optimisation and for the evaluation of the physics reach. The mass model of the ESA INTEGRAL gamma ray mission is also being translated from Geant3 to Geant4. Additionally, the ESA Standard Radiation Environment Monitor (SREM) geometry is currently implemented in Geant4 [6] and simulations of that and other future ESA radiation-monitoring devices such as the Charged Particle Telescope (CPT, [7]) will be carried out using Geant4.

2. Geant4 electromagnetic physics

Geant4 electromagnetic physics manages the electromagnetic interactions of leptons, photons, hadrons and ions. There are two associated class categories: the *standard* electromagnetic physics that handles the basic processes of these particles, and the *low-energy* category [8] that provides alternative models extended down to lower energies than in the standard category. The currently available extensions cover processes for electrons, photons, positive and negative charged hadrons and positive ions. Further extensions to cover positron and negative ion interactions are in progress.

Possibility for tracking to lower energies ultimately enables a more accurate tallying of charged particle propagation in and out of the sensitive volumes within the spacecraft geometrical model, leading to improved charging simulation. An algorithm is also available to optimise the generation of δ-rays only where they are needed, i.e. near the boundaries [9]. The result can be a drastic improvement of the performance of the simulation, while maintaining the quality of physics. The main features of the Geant4 low-energy electromagnetic extensions are described below.

3. Geant4 low-energy extensions for electron and ion electromagnetic processes

The current implementation of Geant4 Low Energy electron and photon electromagnetic processes covers the energy range from 250 eV up to 100 GeV for elements with atomic number between 1 and 99, and for arbitrary compounds of these [10]. It includes the processes of photoelectric effect, Compton scattering, Rayleigh effect, Bremsstrahlung and ionization. For completeness, a photon conversion process has also been implemented based on the same data sources as the other low energy ones. The implementation is based on the exploitation of evaluated data libraries (EPDL97 [11], EEDL [12] and EADL [13]) that provide data for the determination of cross-sections and the sampling of the final state. Shell effects and treatment of atomic relaxation are also taken into account. Implementation of the Auger effect is in progress, and further extensions in the energy range coverage are foreseen. In Figure 1, an example comparison between Geant4 simulation and experimental data [14] on photon transmission through 1 μm thick Aluminum foil is shown, with evidence of atomic shell effects.

4. Geant4 low-energy extensions for hadron and ion electromagnetic processes

In certain applications, such as fundamental physics missions in the interplanetary space utilising free-floating proof masses, charging due to incident cosmic ray ions and solar event protons — rather than due to electrons — is the primary source of interference and needs to be taken into account.

The Geant4 low-energy extensions for hadrons and ions provide a variety of energy loss models depending on the energy range [15,16]. The charge dependence effect is taken into account by specialised models for negatively charged hadrons. In the high-energy domain (E>2 MeV) the standard Bethe-Bloch formula is applied, while in the low-energy one (E<1 keV for protons) the free electron gas model is used. In the intermediate energy range parameterised models based on experimental data from Ziegler [17] and ICRU [18] reviews are implemented. Corrections due to the molecular structure of materials [19] and due to the effect of the nuclear stopping power [20] are taken into account.

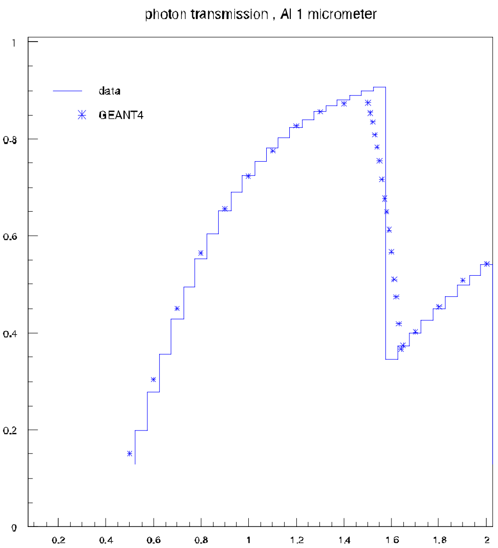

Figure 1. Geant4 simulation (crosses) and experimental data (histogram) on photon transmission through 1 μm of Aluminum, with evidence of the atomic shell effects. Data are from [14].

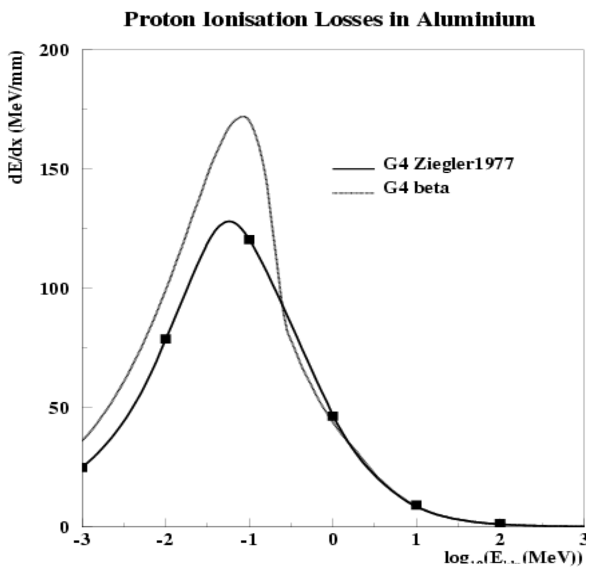

Figure 2. Proton ionisation energy loss as a function of incident energy as predicted by Geant4 beta version (thin line), Geant4 low-energy electromagnetic extensions (thick line), together with experimental data (dots).

5. Supporting capabilities and features

In addition to the detailed physics processes treatment, the Geant4 toolkit offers various possibilities to facilitate charging simulations. The most relevant of these are briefly outlined in the following.

Tracking of particles

In Geant4, there are no tracking cuts, but only production thresholds. Each physics process has its intrinsic limits to produce secondary particles, which can be tracked down to zero range; the cut associated to each particle represents only a recommended production threshold. In Geant4 the thresholds for producing secondaries are expressed in range, universal for all media. This range is converted in energy for each type of particle and each material. The cuts in range allows determination of energy release at the correct space position, limiting the approximation within a given distance, while cuts in energy would imply accuracy of the energy depositions, which depend on the material. This leads to an inherently more precise treatment of particle propagation and hence more accurate charging analysis.

As a user action it is possible to tally the charge deposition within the sensitive volume either by registering the track end positions together with the particle charge, or alternatively by observing charged particle crossings at the volume boundaries. In the first case, the user has to recall to separate the possible stopping charged secondary particles from the primary particles (such secondaries may originate from the sensitive volume itself, thus in reality not affecting the net charge balance in that volume). The second case, on the other hand, can be implemented in the user code as a straightforward charge addition and/or reduction algorithm.

General Particle Source

The Geant4 General Particle Source module or GPS [21] allows the user to apply various simulation scenarios with a desired incident particle energy spectrum (power or exponential law, linear spectrum, bremsstrahlung, black-body, cosmic ray diffuse, interpolation of user-given values) and directional distribution (isotropic, cosine law, user-defined). Both 3-D and 2-D particle entry point distributions can be invoked.
The GPS also includes variance reduction methods to bias the sampling distribution. This feature can permit, for example, more particles to be sampled from higher energies in a cosmic ray spectrum, which produce larger number of secondary particles.

Electric and magnetic fields

Both electric and magnetic fields can be implemented in Geant4, enabling detailed tracking of incident and secondary charged particles in the setup in the presence of such fields. The default method for propagating the particle is by using a fourth-order Runge-Kutta method, while lower order methods are available for fields that are not smooth enough and higher order methods are available for fields that are smooth and do not vary greatly [1]. To intersect volume boundaries, the particle paths are split into sections and each section is approximated by its chord. By placing a constraint on the sections it is ensured that the user-defined accuracy is maintained.

Front-end for CAD software

This add-on software module [21] uses the AP-203 protocol of STEP (ISO 10303 Standard for the Exchange of Product model data) to provide an interface to standard computer-aided design tools which facilitates the transfer of instrument engineering designs to Geant4 simulations and vice versa. In addition to geometrical and visualisation data, materials information may also be included.

6. Discussion and conclusions

By virtue of its detailed physics treatment and a number of auxiliary tools and capabilities, Geant4 offers a robust platform for simulation of deep charging in fundamental physics space missions and in other spacecraft. The former category includes, for instance, free-floating test masses to be used in future fundamental physics missions such as LISA and STEP; see the analysis in [22] that utilised Geant3.21 interfaced to the ITS Monte Carlo package. A clear advantage of Geant4 in this type of studies is that the whole charging analysis can be done in one coherent framework, rather than resorting to complex interfacing between various different codes that each have different software architectures, physics models, energy ranges, and geometry and materials definitions.

The models and capabilities of the Geant4 toolkit can be easily extended thanks to the transparent Object-Oriented approach. Further developments and extensions of the electro-magnetic physics in the low-energy regime, and refereed publications of these, are in preparation.

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