SIMULATION OF RADIATION MONITORS FOR FUTURE SPACE MISSIONS

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A GEANT4 based simulation of a compact lightweight radiation monitor to be included in the payload of future space missions is presented. The instrument must meet severe mass and power constrains, satisfy mission safety requirements and it is also required to perform as a scientific instrument. GEANT4 is a powerful tool for developing and optimising such detector concept thanks to its capabilities for describing the complex detector geometries and simulating the passage of particles through matter. Moreover, the presence of an optical physics process category in GEANT4 is of the utmost importance in the development of a scintillation based detector concept.

1. Introduction

Radiation monitors are becoming an essential component in space missions, providing crucial radiation environment information for the in-flight protection of the spacecraft and instruments onboard. In addition, the data acquired during the mission are a valuable input for space environment models; in particular data gathered in missions to other planets (e.g. particle fluxes and spectral distributions as a function of the distance to the Sun) are essential for models describing the injection and propagation of particles from the Sun. Several of the future space missions (e.g. LISA, Gaia, JWST, BepiColombo) are planned to carry radiation monitors. Given the limited resources on mass, power and accommodation onboard a spacecraft, a new generation of compact and lightweight general purpose energetic particle detectors are being explored.

Monte Carlo simulation tools are essential to develop and optimize a given detector concept and to explore alternative detector concepts. The ability to predict the detector performance in realistic radiation environments is also crucial. This requires the implementation of software models in order to perform an end-to-end simulation, including particle propagation from the source to the spacecraft location, followed by a detailed simulation of the detector response.

The GEANT4 toolkit is an ideal framework for simulating particle interactions with detector materials in complex geometries. A GEANT4 based

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[†] This work was supported through FCT grants SFRH/BPD/11500/2002 and SFRH/BPD/11547/2002.

simulation of a compact lightweight radiation monitor concept for future space missions is presented.

2. Space Radiation Environment

The high energy ionizing radiation[†] environment in the solar system consists of three main sources: the radiation belts, galactic cosmic rays and solar energetic particles.

The radiation belts are composed of electrons and protons trapped in the magnetosphere of the planets. In Earth's radiation belts (Van Allen belts), electrons have energies smaller than about 6-10 MeV and protons have energies up to 250 MeV [1]. Earth's radiation belts are mostly relevant for low earth orbit (LEO) missions.

The galactic cosmic rays (GCR) component consists of a continuous flux of electrons, protons and ions, arriving from beyond the solar system, which are originated mainly in the supernovae. The GCR flux is maximal at energies around 1 GeV/n, decreasing as a power law for higher energies. Lower energy particles are strongly affected by the 11-year solar cycle. Although the GCR flux is comparatively low, energetic heavy ions can locally produce significant energy depositions originating single-event upsets.

Solar energetic particle events (SPE) consist of a sudden and dramatic increase in the flux of particles from the sun, including electrons, protons and heavier ions. SPE are associated with impulsive solar flares and Coronal Mass Ejections and occur with higher probability during the solar cycle maxima. Although the energies of SPE rarely exceed few hundred MeV they give rise to potential risks for space missions due to the high fluxes attained. On the other hand their study is relevant for developing and testing solar particle propagation models [**Error! Reference source not found.**

3. The GEANT4 toolkit

GEANT4 [3,4] is a Monte Carlo radiation transport simulation toolkit, with applications in areas as high energy physics, nuclear physics, astrophysics or medical physics research. It follows an Object-Oriented design which allows for the development of flexible simulation applications.

[†] In the context of space radiation effects, particles are considered energetic if their energy is high enough to penetrate the outer skin of the spacecraft. This means electrons with energies above 100 keV and protons and ions with energies above 1 MeV.

GEANT4 includes an extensive set of electromagnetic, hadronic and optics physics processes and tracking capabilities in 3D geometries of arbitrary complexity. The electromagnetic physics category covers the energy range from 250 eV to 10 TeV (up to 1000 PeV for muons) while hadronic physics models span over 15 orders of magnitude in energy, starting from neutron thermal energies. The optical physics process category allows the simulation of scintillation, Cherenkov or transition radiation based detectors. A distinct class of particles, the *optical photons*, is associated to this process category. The tracking of *optical photons* includes refraction and reflection at medium boundaries, Rayleigh scattering and bulk absorption. The optical properties of a medium, such as refractive index, absorption length and reflectivity coefficients, can be expressed as functions of the photon's wavelength. The characteristics of the interfaces between different media can be defined using the UNIFIED optical model [5]. Full characterisation of scintillators include emission spectra, light yields, fast and slow scintillation components and associated decay time constants.

3. Simulation of a generic space radiation concept

The simulation of a simple space radiation monitor concept [6] was implemented using the GEANT4 toolkit. The detector consists of a tracker made of two position sensitive silicon planes followed by a scintillating crystal surrounded by photodetectors (Fig.1.). An aluminium foil placed on the backside of the crystal is used to tune the energy range of the detector.

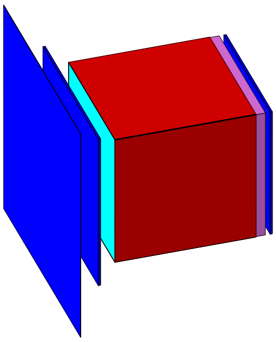

Figure 1. View of the simulated particle detector. From left to right: the two silicon planes, the scintillating crystal surrounded by photodetectors, the aluminum plane followed by a charged particle sensitive detector.

In the present simulation the silicon tracker planes were 0.065 mm and 0.5 mm thick, the crystal size was 3x3x3 cm^3 and the aluminium absorber was 2 mm thick. The scintillation properties of the CsI(Tl) crystal were used. These included a light yield of 65000 photons per MeV of deposited energy and two scintillation components with decay time constants of 0.68 μs (64%) and 3.34 μs (36%). The scintillation light is readout by large area silicon PIN photodiodes, with a spectral sensitivity matching the CsI(Tl) emission spectrum. Since the silicon photodiodes are sensitive both to photons and charged particles, this makes them suitable to be used also as anti-coincidence shield.

Figure 1 displays the fraction of the initial particle energy deposited in the crystal for protons with energies ranging between 25 MeV and 125 MeV.

Protons with energy amounting to 25 MeV or 50 MeV are absorbed in the crystal. For 100 MeV protons the effect of straggling is visible.

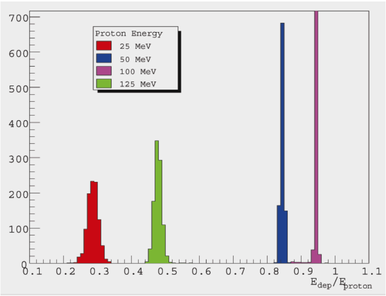

Figure 2. Total energy deposited in the crystal by incident protons expresses as a fraction of the incident particle energy.

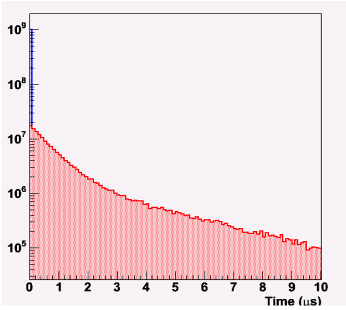

Figure 3. Simulated distribution of the photodetectors’ hits time spectrum.

The principle of the anti-coincidence operation mode is illustrated in Fig.2. where the timing of the simulated hits in the photodiodes, produced by a 100 MeV proton that is not stopped inside the crystal is shown. The fast signal at t=0 is due to the direct ionization produced by the proton in the photodetector, while the slower signal comes from the scintillation light emitted by the crystal. Thus, by a suitable signal processing it is possible to disentangle the direct ionisation from the scintillation. This allows the identification of events where particles entered the detector from the sides or were not fully absorbed in the crystal.

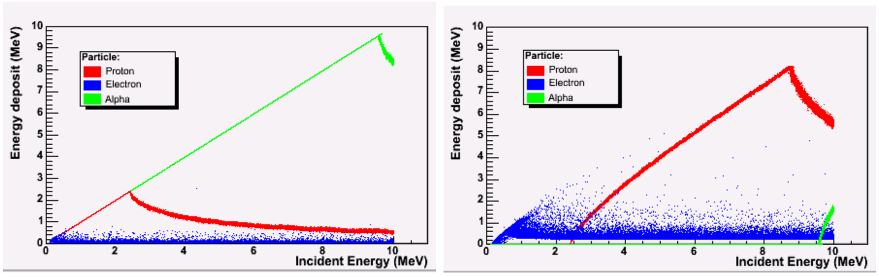

Figure 4. Energy deposited in the first (left) and second (right) silicon planes by electrons, protons and alphas as a function of the energy of the incident particle.

Particle identification is performed by measuring the energy loss in the thin silicon trackers. Figure 4 shows the simulated energy loss in the first (left) and second (right) silicon planes, as a function of the initial particle energy, for electrons, protons and alphas.

4. Conclusions

A new generation of compact, lightweight, general purpose radiation monitors needed for future space missions (e.g. BepiColombo) is under study. A simple concept based on a scintillating crystal was presented. LIP will be responsible for implementing the required Geant4 based detector simulations for the described setup in the context of a contract with EFACEC/Portugal.

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