Simulation of cosmic radiation spectra for personal microdosimetry at the International Space Station's altitude

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Abstract
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Simulation of cosmic radiation spectra for personal microdosimetry at the International Space Station’s altitude

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Abstract. Latest researches predict the cosmic rays exposure during long space missions outside the Earth’s geomagnetic sphere, as to the Moon and Mars, can double the cancer risk. The minimization of risk associated with radiation exposure in the Low Earth Orbit (LEO) is of great interest for astronauts of the International Space Station (ISS). This risk is due to radiation hazard and can be predicted by measurement of the dose equivalent produced by the radiation environment inside of the spacecraft. Since more than 15 years ago, the Centre For Medical Radiation Physics (CMRP), University of Wollongong, is developing silicon based microdosimeters as alternative solution to Tissue Equivalence Proportional Counters, for dose equivalent determination in the context of astronauts radiation protection. This work describes a Geant4-based study characterising the radiation environment encountered by astronauts inside the ISS. In particular, the energy spectra of different components of the cosmic radiation field, as Galactic Cosmic Rays (GCR), trapped protons and electrons and Solar Proton Event (SPE), has been simulated outside and inside the Columbus module where astronauts live. The simulated radiation environment inside of the ISS will be used to model the response of the 3D Mushroom Silicon On Insulator (SOI) microdosimeter recently developed at CMRP.

1. Introduction

Latest researches predict the cosmic rays exposure during long space missions outside the Earth’s geomagnetic sphere, as to the Moon and Mars, can double the cancer risk. The need to characterize cosmic radiation and its effects on astronauts’ health motivated the development of new sensible instruments capable to evaluate the dose at the cellular level, strongly damaged by radiation. The Centre for Medical Radiation Physics (CMRP) developed several generations of Silicon On Insulator (SOI) microdosimeters and the response of the first generation of microdosimeter was tested before when exposed to solar protons within a spacecraft [1]. In this study, the cosmic radiation field inside the International Space Station (ISS) has been characterized in detail. The calculated radiation field will then be used to fully characterize the response of the detector for personal microdosimetry in cosmic radiation, in the context of astronauts’ radiation protection.

The Earth is surrounded by a harsh radiation environment, composed of three main sources: Galactic Cosmic Rays (GCR), coming from sources outside the Solar System, Solar Energetic Particles (SEP), emitted by the Sun during flares and coronal mass ejections, and the trapped radiation belts. The fluxes of particles change with the 11-years cycle of the Sun and depend strongly on the trajectory and altitude.

The environment scenario subject of this study is the Earth Orbit (LEO), where the International Space Station (ISS) is currently orbiting. It consists of three main components which are Galactic Cosmic Rays (GCR), Solar Proton Events (SPEs) and trapped protons and electrons. GCRs are mainly
composed of 87% of protons, 12% of alpha particles and 1% of heavy ions, whose energy can be up to 100 GeV/n. SPEs are emitted by the Sun during solar flares and coronal mass ejections (CMEs) where it included electrons, protons and heavier charged particles of GeV [3, 4] energy range. The geomagnetic field of the Earth partially shields our planet from GCR and SPE, but also traps charged particles creating the so-called Van Allen belts. Energies are usually up to tents of MeV for electrons and hundreds of MeV for protons. Particles fluxes are influenced by the Sun activity as well the presence of the Earth’s magnetic field: the first one is ruled by a cycle of 11 years of maximum and minimum peaks, whereas the second is linked to the cut-off rigidity, a quantity depending on geographical coordinates [2].

GCRs, SPEs and trapped particles hit the ISS and can traverse the shielding walls reaching astronauts’ habitat, eventually producing nuclear products, e.g. neutrons, protons, pions, heavy ions deriving from fragmentation.

In this study the radiation field has been characterised in the ISS Columbus module as it is the astronauts’ workspace. The type of the orbit and the altitude of ISS determinate the radiation environment, so real-time orbit details have been collected to simulate particles spectra at the present time of this study.

2. Materials and Methods

In the Geant4 simulation the Columbus module has been modelled based on specifications of the real Columbus structure and materials [3]. It is a cylinder with walls consisting of layers of different materials (multilayer). The wall thickness is approximately 7.9 cm. Main materials are Aluminium, Kevlar and Nextel. The material of the outer space and of the inner habitable space of the Columbus is vacuum.

The particles of the radiation field, incident on the Columbus module, have been modelled as generated from a random position on a sphere S of radius 1km. The Columbus module is at the center of S. The direction of the particles follows a cosine distribution. Such configuration has been demonstrated to model the isotropic radiation field typical of open space [4]. In order to speed up the simulation times, the particles are generated towards the center of the sphere within a cone investing the Columbus.

The particles fluxes and energy spectra outside the ISS have been derived from SPENVIS, an online tool to model space environment and its effects developed by a consortium led by the Royal Belgian Institute for Space Aeronomy (BIRA-IASB) for ESA’s Space Environments and Effects Section [5]. Considering a typical orbit of the ISS at the variable altitude between 401 and 408 km (perigee and apogee, respectively), with an inclination of 51°, we selected the following models in the solar minimum condition which corresponds to the maximum particles flux intensity:

- The NASA AP8/AE8 models for trapped protons and electrons in a range of energy up to 400 MeV and 7 MeV, respectively
- The CREME96 model for GCRs up to 100 GeV/n
- The JPL-91 model for SPE protons with energy up to 500 MeV

The differential fluxes of each radiation component have been used as input to the Geant4 simulation. The Geant4 GeneratorParticleSource has been used to model the radiation field investing the Columbus.

Both electromagnetic and hadronic physics interactions were modelled in the simulation with the following Geant4 Physics list G4EmStandardPhysics_option3 and the G4HadronPhysicsQGSP_BIC_HP, respectively.

The output of the simulation is the fluxes and energy spectra of the particles emerging from the multilayer, inside the Columbus.
3. Results

Figure 1-5 show how particles spectra change behind the multilayer, when considering incident trapped protons and electrons, GCR protons and alpha particles and SPE protons, respectively.

In Figure 1 trapped protons are shown to survive mostly at energy above 10 MeV, accompanied by a significant production of secondary low energy neutrons. Because of their low kinetic energy (up to 7 MeV), trapped electrons get stopped inside the multilayer (Figure 2). Incident GCR protons with energy up to 100 GeV are attenuated in the lower energy range (they are fully absorbed up to 5 MeV). Indeed, Figure 3 shows a significant flux of neutrons from spallation reactions and a not negligible flux of alpha particles due to disintegrations of the light and heavy nuclei of walls materials. Similarly, incident GCR alpha particles with 2.6 MeV are completely shielded. Indeed, they produce a significant flux of secondary neutrons and protons of hundreds MeV (Figure 4). Finally, SPEs protons interacted with wall’s material and produced a high fluence of secondary neutrons as shown in Figure 5.

![Figure 1](image1.png)

**Figure 1.** Kinetic energy spectra of incident trapped protons outside the ISS (grey), incident and secondary protons inside the ISS (black) and secondary neutrons entering the ISS (dashed line).

![Figure 2](image2.png)

**Figure 2.** Kinetic energy spectra of incident trapped electrons outside the ISS. All of these have been stopped by the ISS’s wall.

![Figure 3](image3.png)

**Figure 3.** Kinetic energy spectra of incident GCR protons outside the ISS (grey), incident and secondary protons inside the ISS (black) and secondary neutrons and protons (dashed line).

![Figure 4](image4.png)

**Figure 4.** Kinetic energy spectra of incident GCR alpha outside the ISS (grey), incident and secondary alpha (black) and secondary neutrons and protons (dashed line).
protons inside the ISS (black) and secondary neutrons
(big dashed line) and alpha particles (small dashed
line) entering the ISS.

alpha particles inside the ISS (small dashed line) and
secondary neutrons (big dashed line) and protons
(black) entering the ISS.

Figure 5. Kinetic energy spectra of incident SPEs protons outside the ISS (grey), incident and secondary protons inside the ISS (black) and secondary neutrons (big dashed line) entering the ISS.

4. Conclusions
The characterization of the LEO radiation environment where the ISS is orbiting and hosting several astronauts has been performed with the simulation of particles spectra coming from main radiation sources as trapped protons and electrons, GCR, and SPEs.

Particle spectra outside the Columbus module have been derived from SPENVIS showing high energy fluxes of protons and alpha particle, up to 100GeV/n, which represent a high risk for astronauts health. By means of Geant4, we simulated energy spectra inside the spacecraft behind a multi-layer shielding wall. The results show that only the low energy component of the incident radiation is stopped in the ISS’s wall, but high energy particles survive during the propagation through the ISS’s wall, reaching the astronauts’ habitat. Significant fluxes of secondary neutrons are produced, e.g. by spallation from protons. GCRs and SPEs seem to be the most dangerous source of radiation because of high energy particles.

In the next future simulations will be done to model the response of the 3D Mushroom microdosimeter, set inside the Columbus module, at different distances from the wall, using as input the mixed radiation field inside the ISS, calculated in this work. Based on the microdosimeter response, the dose equivalent for astronauts will be calculated.

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