Radiation effects analysis tools

Introduction

The radiation effects analysis tools available within the SEPEM software toolset allow the calculation of the effects of shielding against solar energetic particles, and single event upset rates for shielded conditions. The calculations are performed using the Geant4-based MULASSIS shielding analysis tool [1][2][3][4], and a combination of the Integral Right Parallelepiped (IRPP) technique the Geant4-based GEMAT microdosimetry tool [5]. In addition, facilities are provided for the estimation of LET spectra based on proton and heavier ion stopping powers in silicon.

A key requirement for the effects tools was that they should be able to calculate the time-dependence of the effects. To avoid performing a Monte Carlo simulation at each time-step in the spectrum (which would require excessive computer power) the calculation is instead initially performed for particles in each of the relatively coarse energy bins in the input spectrum. The result is a series of response functions relating to particle secondary flux, dose, and SEU rate which can be normalised to the time-dependent spectrum from other SEPEM tools to provide predictions of effects at each time-step.

The following sections provide background on the underlying software tools and calculation methodology.

Background

Multi-Layered Shielding Simulations Software - MULASSIS

MULASSIS is a Geant4-based Monte Carlo simulation tool for simplified shielding conditions, which initially was developed by QinetiQ for the European Space Agency as part of the REAT Project[1][1][2][3][4]. The standard release of the program allows calculation of particle fluence spectra, ionising and non-ionising dose, and pulse-height energy deposition analysis. Users can define the shielding and detector geometry as planar or spherical layers, with the material in each layer defined by its density and elemental/isotopic composition. The standard version of MULASSIS simulates any Geant4 particles including protons, neutrons, electrons, γ-rays, α-particles, and light ions. Furthermore, there is a wide choice of options for their initial energy and angular distribution. Being based on the Geant4 toolkit, MULASSIS allows comprehensive simulation of the physical processes, including:

- Standard and low-energy electromagnetic interactions for leptons and photons;
- Electromagnetic processes for hadrons and ions, including δ-ray electron production;
- Intranuclear cascades for hadrons and ions in the non-relativistic to relativistic regimes;
- Nuclear de-excitation, including processes such as light-particle evaporation, fission and photo-nuclear de-excitation.
- Simulation of low-energy neutrons down to thermal energies.

Results are tabulated as particle spectra and dose-depth information in SPENVIS-compatible comma separated value (CSV) format, and can be used with visualisation tools within SPENVIS and standard applications such as Microsoft Excel. The user can also make full use of the Geant4 visualisation facilities for the shielding geometry and the particle interaction tracks.

Geant4 Microdosimetry Analysis Tool - GEMAT

The standard version of the Geant4 Microdosimetry Analysis Tool (GEMAT) allows detailed simulation of the complex energy-deposition processes from direct ionisation and nuclear interactions of particles in micro-geometries. Using such a tool, the user is able to determine the energy deposition spectra from different particle species and energies, allowing him/her to translate single event susceptibility data from one species (*e.g.* SEU cross-sections measured under ion beam irradiation) to another species (such as protons or neutrons). It is relevant to microdosimetry effects of space radiation on microelectronics and micro-sensors

[1] Radiation Effects on Advance Technologies, ESA Contract 14968/00/NL/EC (ESA Technology Research Programme, Space Environment and Effects Major Axis)

(*e.g.* CCD and APS devices) and the standard version of the software can be used as a standalone tool or run through the SPENVIS web-page interface.

The simple command interface allows definition of different layers within a microelectronics device, and sensitive volumes comprising parallelepipeds, cylinders or more complex shapes embedded into the active semiconductor layers. A similar approach for treating analysis in MULASSIS has been achieved with GEMAT, with the user able to calculate the fluence of primaries and any secondaries incident upon sensitive volumes, energy deposition spectra and path-length distributions, and to tally coincident events in different sensitive volumes (relevant to multiple-cell upsets in microelectronics). As with MULASSIS, the results are generated as SPENVIS-compatible CSV files.

Implementation of MULASSIS and GEMAT in SEPEM

As mentioned above, there is a restricted implementation of MULASSIS and GEMAT within the SEPEM toolset to generate response functions over each of the energy channels of the spectrum defined by a set of energy channels in a data table. Within the SEPEM-MULASSIS web-page “mulassis geometry” the user is able to select whether the shield geometry if planar (“slab”) or spherical, and to identify the thickness and composition of each of the layers (maximum ten layers) from a pre-defined list of materials. The “mulassis response function” web-page allows the user to select which input spectrum dataset to simulate, and the specific particle source and instrument channels to treat.

If the input spectrum selected comprises N channels with the energy of the i^{th} bin between E_i to E_{i+1}, a series of N MULASSIS simulations is performed assuming a flat particle spectrum between these energy limits. The particles are assumed to be incident upon the shield as a cosine-law angular distribution, representative of a shield within an isotropic particle flux. The response functions for each energy channel include calculations of total-ionising dose, non-ionising dose (based on the NIEL function selected by the user), particle fluence and pulse-height spectrum per unit incident particle fluence. Therefore, if the input energy spectrum as a function of energy bin i and time t is $\psi_i(t)$ in units of particles/((MeV/nucleon)·cm^2·s·steradian), then the total ionising dose or total non-ionising dose rates at shield layer l due to the incident particles is:

$$D_l(t_n) = \sum_{i=0}^{N-1} d_{il} C_i(t_n)$$

where d_{il} are the dose-depth data from the MULASSIS CSV file for layer l and incident particles between E_i and E_{i+1}, and $C_i(t)$ is the fluence per energy channel:

$$C_i(t_n) = \psi_i(t_n)\left[E_{i+1} - E_i\right]$$

Similarly for particle flux, one defines from the MULASSIS simulations a series of response functions, ϕ_{ijlk} which corresponds to the flux of particles of species j at layer l and between energy ε_k to ε_{k+1} per unit incident flux between energy E_i to E_{i+1}. Based on an input spectrum of $\psi_i(t_n)$, the output spectrum for species j at layer l is:

$$\Phi_{jlk}(t_n) = \sum_{i=0}^{N-1} \phi_{ijlk} C_i(t_n)$$

The version of GEMAT implemented within the SEPEM toolset is used to calculate the path-length distribution for particles incident upon a sensitive volume. Within this restricted version of the software, the angular distribution of the particles is simulated as isotropic, and the sensitive volume is a rectangular parallelepiped (box) or cylinder with dimensions defined by the user. The geometry can be treated as shielded, with the number of layers, thicknesses and materials defining the shield specified by the user in a similar manner to the MULASSIS simulation (see web-page “seu geometry”).

For incident α-particles and heavier ions, the path-length distribution is used in combination with the shielded particle LET spectrum, and the SEU cross-section based on the Integrated Rectangular Parallelepiped (IRPP) approach for calculating SEE rates as a function of time. For protons and ions, the SEU rate as a function of time is determined from the integration of the SEU cross-section over the proton or ion energy spectrum after the shield (as calculated by MULASSIS). The cross-sections for protons and ions can take the form of Weibull, log-normal or Bendel functions.

Weibull:

$$\sigma(E)=\begin{cases}\sigma_{norm}\left\{1-\exp\left[-\left(\frac{E-x_0}{\lambda}\right)^k\right]\right\} & E>x_0\\ 0 & E\le x_0\end{cases}$$

Log-normal:

$$F_{\log norm}(E)=\begin{cases}\frac{1}{E\sigma\sqrt{2\pi}}\exp\left[-\frac{(\ln(E)-\mu)^2}{2\sigma^2}\right] & E>0\\ 0 & E\le 0\end{cases}$$

$$\sigma(E)=\sigma_{norm}\int_0^E F_{\log norm}(E')dE'$$

Bendel:

$$\sigma(E)=\sigma_{norm}\left\{1-\exp\left[-0.18\sqrt{\sqrt{\frac{18}{A}}(E-A)}\right]\right\}^4$$

LET spectra are approximated based on stopping power information. In the first instance, the stopping power values for ions of protons to uranium nuclei, incident upon silicon, come from the work of Sigmund *et al* (ICRU-73) [6] and Ziegler and co-workers (SRIM2008) [7] where data are not available in reference [6]. A cubic-spline fit will be made to estimate the particle stopping power at the user-defined energy.

Although GEMAT is run only once to determine the path-length distribution within the sensitive volume, response functions for SEU rates are determined for each channel of the input particle spectrum, taking into consideration shielding effects and the averaging of the cross-section over channels. The response functions are then used in combination with the coefficients $C_i(t)$ is the fluence per energy channel to determine the total SEU rate as a function of time.

References

[1] Geant4 web-site: http://geant4.cern.ch, 2008.

[2] S Agostinelli *et al*, “Geant4 – a simulation toolkit,” *Nucl Instrum Meth Phys Res*, **A506**, p250-303, 2003.

[3] MULASSIS web-site: http://reat.space.qinetiq.com/mulassis

[4] F. Lei et al, “MULASSIS: A Geant4-based Multilayered Shielding Simulation Tool,” IEEE Trans. Nucl. Sci. ,vol 49, pp 2788-2793, 2002.

[5] Fan Lei, “REAT-MS Project: Implementation of a simple charge collection mechanism in the GEMAT code,” QinetiQ Technical Report QinetiQ/S&DU/Space/TR0700301, 2007.

[6] “Stopping of ions heavier than helium,” International Commission on Radiation Units and Measurements (ICRU) Report 73, 2005.

[7] SRIM web-site, including SRIM2008 releases: http://www.srim.org.