Importance of nuclear models and Monte Carlo tools for radiation effects simulations

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Importance and use of Monte Carlo codes for accelerator R2E applications

- Simulation of the radiation environment
- Simulation of the radiation effects on electronics
  - Semi-empiric approach though SEE models combining technological information and free parameter(s) fitted to experimental data
  - Convolution of energy deposition distribution and response function, through RPP, nested RPP or IRPP
  - Main motivation of radiation effects simulation: very broad range of particles and energies present in the accelerator mixed-field environment
High-energy hadron environment in accelerators

Figure 1: FLUKA model of the IR7 warm section.


- Importance of Monte Carlo codes (and radiation detectors) to assess radiation levels in high-energy accelerators
High-energy hadron environment in accelerators


- Broad range of particle species (protons, pions, neutrons) and energies (from meV to GeV) that can cause disruption in electronic components and systems, notably through Single Event Effects

Fig. 1. Example of the simulated particle energy spectra (lethargy) representative for tunnel areas in the LHC. The radiation is due to particle debris induced by the colliding beams in one of the experiment points at CERN. The spectra is therefore normalized to one proton–proton collision (referred to as a primary in the y-axis label).
Typical SEE experimental data for R2E applications

- (Quasi-)Monoenergetic:
  - High-energy (20-200 MeV) protons at PSI
  - Intermediate energy (0.2-20 MeV) neutrons at PTB
  - Thermal neutrons (~25 meV) at ILL

- Spectra/mixed-field:
  - Spallation neutrons at ChipIr (from 800 MeV protons)
  - Mixed hadron field at CHARM (from 24 GeV protons)

- Mainly on SRAMs of different technology nodes (40-400nm), for both SEU and SEL
Introduction to slides on simulated and experimental SEE cross sections

- Taken directly from referenced publications
- Short comments related the main observations are included, but please check the papers for more details
- Comparisons between simulated and experimental SEE data should *not* be considered as physical benchmarks, as simulated SEE response depends on a variety of input parameters subject to large levels of uncertainty (e.g. component geometry and materials, SEE response function, etc.)
- However, these comparisons can be useful to spot significant deviations from experimental data for well calibrated semi-empirical models, as well as to compare results from different Monte Carlo codes and/or nuclear models
High-energy (>20 MeV) hadrons (protons, neutrons and pions)

- Fairly constant proton SEU cross section in 50-230 MeV range, and rapid fall off at lower energies (strong dependence on package, lid, etc.)
- Neutron and proton equivalence above ~50 MeV
- Pion resonance at ~200 MeV
- Factor ~2 increase in SEU cross section between tens of MeV and hundreds of GeV, i.e. relatively constant with energy over many decades

More on pions


• More recent pion resonance SEU study, including also simulations for kaons
More on pions


- SEE cross section excess for pions also observed for SEL, extending down to lower energies
• Direct ionization from low energy protons meant that SEU cross section fall off at several tens of MeV no longer applies.
Proton SEU contribution


- Elastic scattering (Coulomb + nuclear) suppressed by direct ionization at low energies, and inelastic reactions at high energies

Figure 5.12: Proton SEU cross-section of various interaction mechanisms as a function of the primary proton energy for the ISSI SRAM. Obtained with G4SEE.
When high-Z materials are present near the sensitive volume of the components, effects with relatively large LET threshold will have a strong cross section increase with energy, between ~100 MeV and ~3 GeV.

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Fig. 8. Measured and simulated proton SEU cross section for Device B as a function of energy. More information about the rest of the mono-energetic data shown can be found in [14].

High-Z materials


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Intermediate (0.2-20 MeV) energy neutrons


- Importance of soft error contribution from intermediate (0.1-20 MeV) energy neutrons, particularly for components with low critical charges, and sensitive to proton direct ionization (i.e. (n,p) reactions, hydrogen recoils)

Fig. 11. ISSI 40 nm proton (p) and neutron (n) simulations and experimental data comparison. Proton simulations derive from FLUKA and GEANT4 tools, while the neutron ones from the latter.
High-Energy Electrons


- High-energy electrons (up to 200 MeV) can cause SEU and SEL even in relatively large LET threshold components, through photo-nuclear and electro-nuclear reactions, and with SEE cross sections that are a few orders of magnitude lower than for hadrons.
High-Energy Heavy Ions


• Very High Energy (VHE, 100 MeV/n – 5 GeV/n) and Ultra High Energy (UHE, 5 GeV/n-150 GeV/n) ions will undergo nuclear reactions, undergoing fragmentation (high-energy projectile-like and fission products) and generating low-energy target-like recoils.
Heavy ion SEE cross section in 10-100 MeV/n range


- Monte Carlo codes predict relatively constant or decreasing heavy ion nuclear (i.e. sub-LET) SEE cross sections
- They also underestimate the experimental results, perhaps due to fragments generated in elements not considered in the simulation (e.g. collimators, vacuum windows)

- Heavy ion nuclear SEE cross sections can be orders of magnitude larger than proton ones at low energy, but at high energy, they are only a factor a few larger.

Fig. 12. FLUKA simulated sub-LET for heavy ions and proton SEL cross section as a function of ion energy for a SRAM memory up to 150 GeV/c compared to experimental data.
Solid state detector for energy deposition measurements


- Solid-state detector coupled to fast readout electronics, and calibrated through triple alpha source (and higher energy heavy ions, in cyclotron facilities)

Fig. 5. Pulse area spectrum measured with a calibration triple-alpha source of $^{239}$Pu, $^{241}$Am and $^{244}$Cm (top). Linear calibration of deposited energy as a function of pulse area (bottom).
Intermediate energy neutrons


- Energy deposition distribution in silicon for intermediate (0.2-20 MeV) energy neutrons

- Energy deposition distribution in silicon for high (20-200 MeV) energy neutrons

Figure 5. Fast neutron response functions as measured at nTOF (left). The right-hand panels show a subset of those measured response functions compared to FLUKA simulations. The upper panels are for the silicon detector and the lower panels are for the diamond detector.
K. Bilko et al, “Silicon solid-state detectors for monitoring high-energy accelerator mixed field radiation environments”, RADECS 2021

Fig. 4. Measured and simulated energy deposition spectra normalized with the proton fluence (for 1000 µm thick diode). Considered proton beam energies: 30, 51, 101, 151, 200 MeV, whereas 70 MeV is presented in Fig. 5.

- Energy deposition distribution in silicon for high (50-200 MeV) energy protons
Spallation neutron and mixed field


- Mixed-field energy deposition measurements, and dominance of pions for high deposited energies
High-energy proton energy deposition distribution as a function of Monte Carlo code and nuclear model

Spikes in energy deposition distribution are due to biasing – when integrated with the response function, their contribution to the total statistical error of the simulated SEU cross section is still within a few percent
Conclusions and further thoughts

- Importance of benchmarking radiation effects simulations across different models and Monte Carlo codes, and against experimental data (*note: often not a direct comparison, due to uncertainties in SEE model parameters*)

- Solid state detectors provide a very useful means of directly comparing measured and simulated energy deposition distributions, but involve sensitive volumes that are much larger than those representative of SEEs (i.e. light, energetic secondaries dominate over heavy, high-LET, short-ranged)

- Comparison between FLUKA and different hadronic physics models in Geant4 for high-energy protons show differences that are relatively small (few tens of percent) when compared to other SEE model uncertainty sources (sensitive volume dimensions, surrounding materials, critical charge, etc.) but not completely negligible

- Differences in heavy ion nuclear reactions, both for the target-like and projectile/fission-like fragments, are expected to be larger and would require further assessment.
Thank you for your attention!