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Frédéric Wrobel

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An introduction to natural radiations and their detrimental effects on electronic devices

Une introduction aux effets des radiations naturelles et leurs effets indésirables sur les dispositifs électroniques

Frédéric Wrobel[a]

[a] Montpellier University, IES UMR-CNRS5214, France

E-mail: frederic.wrobel@umontpellier.fr

Abstract. Modern electronic devices are naturally exposed to radiative environments, particularly in aerospace and avionics applications. This radiation is a major challenge, as it can lead to breakdowns and long-term degradation of electronic components. It comes from galactic cosmic rays (GCRs), the Sun and the Earth's radiation belts. They give rise to three main families of malfunctions: Total Ionizing Dose (TID), Displacement Damage (DD) and Single Event Effects (SEEs).

SEEs, in particular Single Event Upsets (SEUs), are of particular concern, as a single particle can alter the information in a memory bit, leading to critical errors. Monte Carlo simulations are widely used to predict and mitigate these effects. These probabilistic methods can be used to estimate SEU rates and develop hardening strategies. Monte Carlo predictive tools simulate the interaction of particles with electronic devices to assess their vulnerability.

Although Monte Carlo simulations have their limitations, particularly in modeling sensitive volumes and nuclear interactions, they remain essential for the aerospace and automotive industries. With the miniaturization of components, susceptibility to SEUs is increasing, underlining the need to improve these prediction tools and to pursue research into the reliability of components exposed to radiation.

Résumé. Les dispositifs électroniques modernes sont naturellement exposés à des environnements radiatifs, notamment dans l'aérospatial et les applications avioniques. Ces radiations constituent un défi majeur, car elles peuvent provoquer des pannes et une dégradation à long terme des composants électroniques. Elles proviennent des rayons cosmiques galactiques (GCRs), du Soleil et les ceintures de radiations terrestres. Elles engendrent trois familles de dysfonctionnements principaux : la dose ionisante totale (TID), les effets de déplacement (DD) et les effets singuliers (SEEs).

Les SEEs, en particulier les Single Event Upsets (SEUs), sont préoccupants, car une seule particule peut modifier l'information d'un bit de mémoire, entraînant des erreurs critiques. Pour prédire et atténuer ces effets, les simulations de type Monte Carlo sont largement utilisées. Ces méthodes probabilistes permettent d'estimer les taux de SEU et d'élaborer des stratégies de durcissement. Les outils, dits de prédiction, simulent l'interaction des particules avec les dispositifs électroniques afin d'évaluer leur vulnérabilité.

Bien que les simulations Monte Carlo présentent des limites, notamment dans la modélisation des volumes sensibles et des interactions nucléaires, elles restent essentielles pour l'industrie aérospatiale et automobile. Avec la miniaturisation des composants, la susceptibilité aux SEUs augmente, soulignant la nécessité d'améliorer ces outils de prédiction et de poursuivre les recherches sur la fiabilité des composants exposés aux radiations.

Keywords. Radiations, Single Event Upset, Monte Carlo simulations, Electronic reliability.

Mots-clés. Radiations, Evénement Singulier, Simulations Monte Carlo, Fiabilité électronique.

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1. Introduction

Electronic devices are increasingly being used in environments where they are exposed to extreme conditions, such as vacuum, intense vibrations, wide temperature variations, and high levels of radiation. While the effects of vacuum and temperature are well understood and often mitigated using traditional engineering approaches, radiations are still a crucial challenge, particularly in aerospace, nuclear, and high-altitude applications. Radiations are not limited to artificial sources like nuclear reactors or particle accelerators. They are indeed present in a natural environment such as Space and the atmosphere. In these environments, electronic components are likely to undergo failures and long-term degradation [1].

This paper explores these environments, which impact electronic systems. Natural environment radiations include galactic cosmic rays (GCRs), solar energetic particles (SEPs) and Earth's radiation belts. The particles that compose these environments interact with electronic materials, leading to various effects such as Total Ionizing Dose (TID), Displacement Damage (DD), and Single Event Effects (SEEs). Among SEE, Single Event Upsets (SEUs) are of the main concern since they are due to a unique particle that deposits enough energy in the device to flip a memory bit [2].

Predicting and mitigating SEU-induced failures is of crucial interest and must be deeply investigated. Monte Carlo simulations tools are widely used in this field as they allow to assess SEU rates and develop hardening techniques. This paper discusses the use of these Monte Carlo tools, including their advantages and limitations.

2. The natural radiative environment

Radiations are everywhere around us, from space down to our planet. Radiations have a major impact on both living organisms and electronic systems. In this part, we present the origin of these radiations that include galactic cosmic rays, solar radiations and the terrestrial environment.

2.1. *Galactic cosmic rays*

Galactic cosmic rays (GCRs) are composed of high-energy particles present in Space. They are mainly composed of protons, electrons, and heavy ions. These particles come from astrophysical events, such as supernova explosions that can accelerate particles [3].

2.2. *Solar radiative environment*

The Sun emits unpredictable and powerful bursts of radiation. This emission follows an 11-year activity cycle, during which the flux of particles varies. Solar flares and coronal mass ejections (CMEs) release large amounts of high-energy particles such as protons and helium nuclei [4]. These solar energetic particles (SEPs) can induce failures in electronic devices onboard our satellites. In addition to these bursts of radiation, the Sun emits a continuous flux of particles, which is called solar wind and mainly composed of protons and electrons.

2.3. *Terrestrial space environment*

The Earth's magnetic field traps some of the charged particles that comes from space, creating the Van Allen radiation belts. These belts contain high flux of protons and electrons, which is an additional risk for embedded electronics that fly through these regions. The Van Allen radiation belts, or radiation belts, are composed of two belts: the inner belt is composed of energetic protons and electrons, while the outer belt is mainly composed of electrons. During solar storms, radiation belts can expand, exposing then satellites to higher radiation levels [5,6].

2.4. *Radiative environment in the atmosphere*

When cosmic rays reach the top of the atmosphere, they interact with the nuclei of the atoms and produce secondary particles, which can penetrate deep into the atmosphere and even reach the ground level. While many kinds of particles are produced during these interactions (protons, electrons, muons, neutrons...), neutrons represent the main risk for electronic devices. Their flux varies with altitude. For example, the flux at ground level is known to be around 20 $n/cm^2/h$ and is 300 times higher at avionic altitude (typically 12 km).

3. Radiation effects on electronic devices

Radiation effects on electronic devices can be divided into three major categories: Total Ionizing Dose (TID), Displacement Damage (DD), and Single Event Effects (SEEs). Each type of damage impacts electronic devices differently.

3.1. *Total Ionizing Dose (TID) effects*

Prolonged exposure to radiation leads to a progressive degradation of the functionality of electronic components. This phenomenon, known as total ionizing dose (TID), results in an accumulation of charges in insulating materials such as silicon dioxide. As a result, transistors and electronic circuits lose performance and can become unusable [7].

To decrease the effects of TID, it is possible to use specific materials, hardening techniques and circuit designs that minimize the impact of radiation. For example, space electronics are manufactured using radiation-hardened transistors [8].

3.2. *Displacement Damage (DD) effects*

When particles interact with semiconductor material, they can knock atoms out of their sites, modifying the structure of the crystal and affecting the properties of the semiconductor. This process, known as Displacement Damage (DD), reduces the efficiency of semiconductor devices such as solar cells and image sensors [9].

Optoelectronic components, such as infrared detectors and fiber-optic communication systems, are particularly vulnerable to DD effects. To mitigate this damage more resistant semiconductors may be used such as silicon carbide (SiC) and gallium nitride (GaN) [10].

3.3. *Single Event Effects (SEEs)*

Unlike Total Ionizing Dose (TID) and Displacement Damage (DD), which result from cumulative exposure over time, Single Event Effects (SEEs) occur when a single particle strikes a sensitive region of a transistor [1,2,11]. This may lead to data corruption but also to catastrophic failures.

One of the most common SEEs is the Single Event Upset (SEU), when a charged particle deposits energy in a memory cell, leading to a bit flip (data corruption). For critical systems, this necessitates mitigation techniques such as error correction codes (ECC) and redundant memory architectures. Another type of SEE is the Single Event Latchup (SEL) [12], in which an ionizing particle triggers a parasitic thyristor, which creates a low-resistance path that can lead to a destructive short circuit. To prevent SEL, it is possible to use current-limiting circuitry and radiation-hardened design strategies.

Other catastrophic SEEs include Single Event Burnout (SEB) [13] and Single Event Gate Rupture (SEGR) [14] which affect power devices. SEB occurs when a high-energy particle induces excessive current in a power transistor, causing thermal runaway and permanent failure. SEGR, on the other hand, is the rupture of an insulating gate oxide layer due to excessive electric fields, leading to a non-recoverable breakdown of the component.

To improve electronic reliability in radiation-exposed applications, space agencies and industry conduct extensive testing under beam of particles. Techniques such as triple modular redundancy (TMR) and real-time error detection further enhance system robustness against SEEs. The continuous advancement in radiation-hardened materials and circuit design plays a crucial role in mitigating these effects.

4. The special case of single event effects

4.1. *Monte Carlo simulations for SEU analysis*

Single Event Upsets (SEUs) are one of the most concerning radiation effects in modern technologies, particularly in space and avionics applications. Because SEUs occur randomly when a particle ionizes a sensitive region of a semiconductor device, their prediction requires probabilistic methods. Monte Carlo simulations are widely used for estimating the SEU cross-section (a quantity that assess the sensitivity of the device) and predicting the Soft Error Rate (SER) of a given technology.

Monte Carlo methods are based on random numbers to model the interactions between radiation and matter of electronic devices. Instead of using deterministic equations to calculate SEU probabilities, these simulations generate thousands of millions of random particle interactions based on physical probability distributions. We can then obtain statistically significant estimates of SEU rates under a given radiation environment.

4.2. *Typical Monte Carlo steps for SEU prediction*

Many companies have developed their own Prediction tool in order to assess the reliability of a given device in a given environment. The good metric for such an assessment is the SEU cross section which gives the equivalent area of the device that is sensitive to radiation. These tools are always proprietary, and it is thus difficult to know exactly all the key ingredients that are inside. Very often, these tools are based on Monte Carlo approach, which basically includes the following steps:

(1) Circuit definition: The user defines the circuit to be studied. It is composed of NMOS and PMOS transistors for which the parameters must be defined (gate length, gate width, supply voltage). Figure 1 shows an example of circuit definition for a 4-transistor SRAM cell.

(2) Layout definition: The user defines the location of each transistor as well as its size (drains and sources width). Average doping may also be accounted for. Figure 2 shows an example of the layout associated with the SRAM cell (4 transistors).

(3) Geometry definition: A basic structure is made of a bulk of silicon and a BEOL in silicon dioxide. The thickness of the bulk and that of the BEOL must be defined. In addition, the user must choose the direction of the beam of particles that will irradiate the device. Figure 3 shows an example of geometry in which the irradiated layout is embedded.

(4) Parameters: The user chooses the type of particles between ions, neutrons and protons as well as the criteria for stopping the simulations (based on the accuracy and the fluence of particles simulated). Figure 4 shows a typical user interface for the beam parameters.

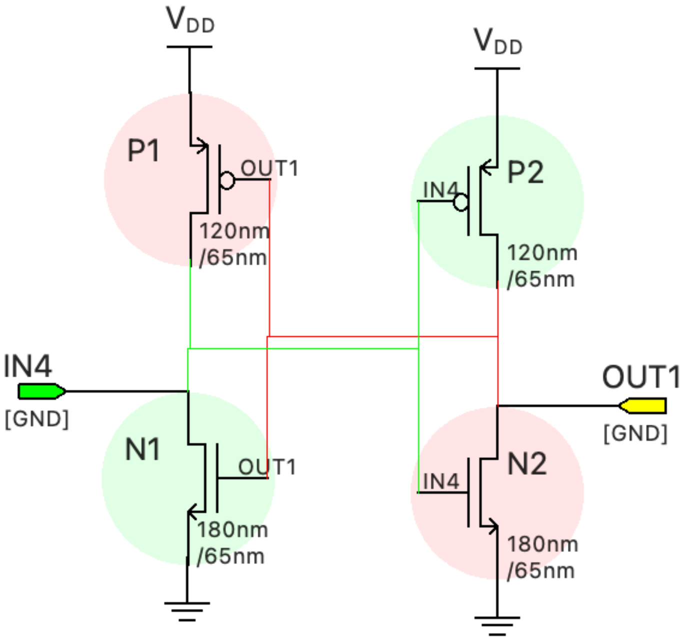

Figure 1. Example of circuit definition of an SRAM Cell with no access transistors. Green disks indicate the ON transistors (no sensitivity to SEU). Red disks indicate the OFF transistors (sensitivity to SEU).

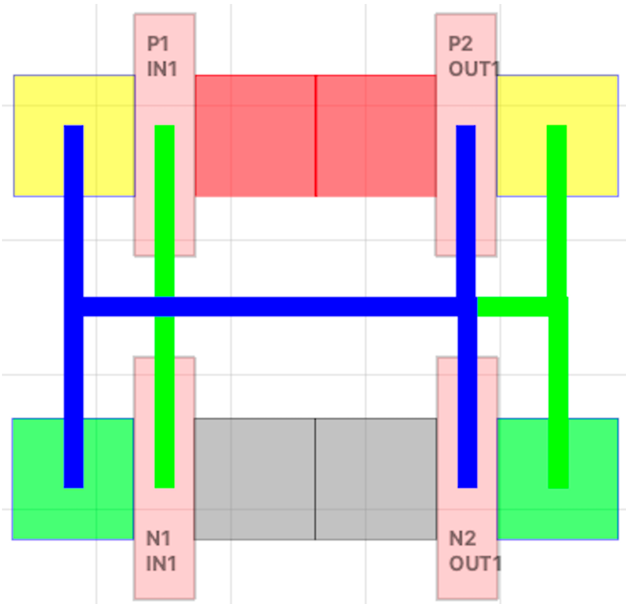

Figure 2. Example of layout definition of an SRAM Cell with no access transistors. Pink boxes indicate the gates. Red boxes are electrodes connected with power supply (V_{DD}). Grey boxes indicate electrodes connected to ground. Yellow boxes are other PMOS electrodes. Green boxes are other NMOS electrodes.

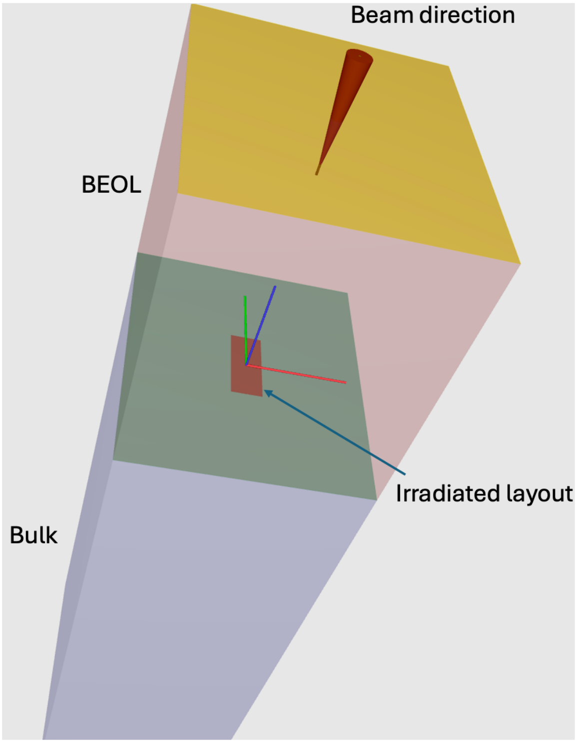

Figure 3. Example of geometry definition indicating the irradiated layout and the beam direction.

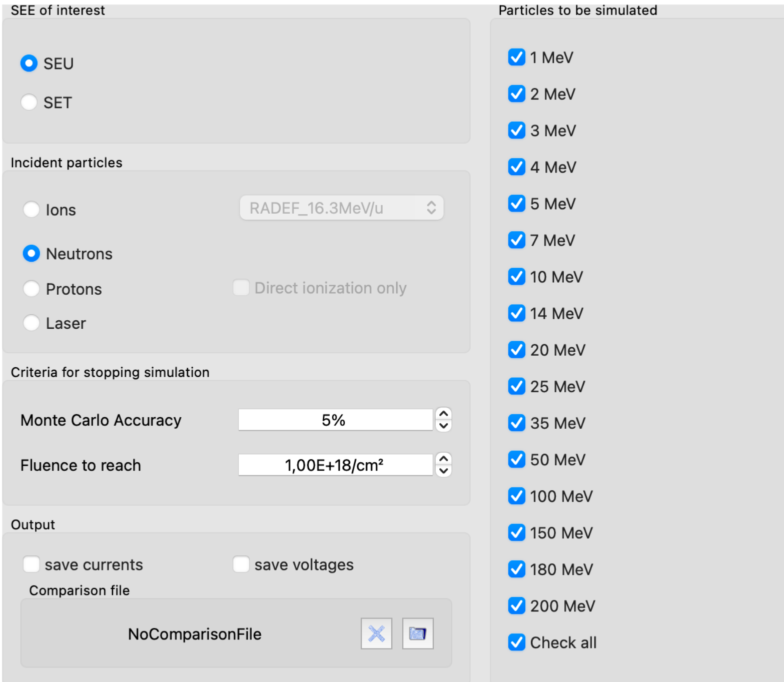

Figure 4. Typical parameter interface of a predictive Monte Carlo tool.

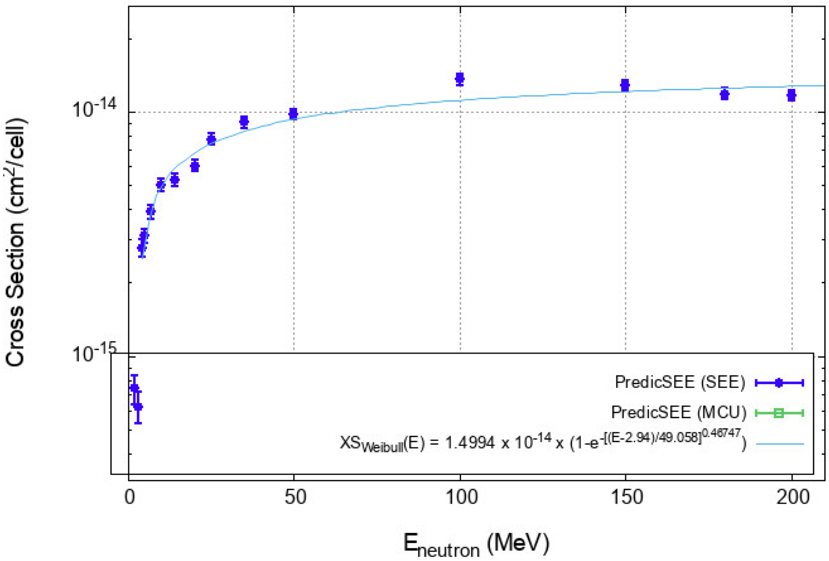

Figure 5. Typical results obtained with a Monte Carlo predictive tool. The cross section represents the sensitivity of the device to particles (here neutrons). Dots are simulation points, and the line is a fit with a Weibull shape, generally used to this purpose.

(5) Running: Once all previous steps are achieved, the simulation may be run. The tool graphically shows the cross section of SEU as a function of stopping power (for ions) or energy (for neutrons and protons). At the beginning of the simulation, due to poor statistic, results do not seem consistent. Then, with the increasing number of events that are simulated, the curve converges toward a result (an example is provided in Figure 5). It shows an increase in the cross section, which indicates that the sensitivity of the device increases with neutron energy and reaches a plateau above a few tens of MeV. The cross-section value is in the order of 10^{-14} cm^2/bit. It means that the SEU will be triggered if the neutron reaches this area. The probability of such an event seems to be very low, and it is. Indeed, knowing that the flux of neutrons at ground level is around 20 n/cm^2/h, we should expect 2×10^{-13} SEU per hour. However, this is the sensitivity associated with a single bit, while memories are often composed of Gbit. Additionally, if we consider avionics applications, the number of SEU is multiplied by a factor of 300 compared to ground level. For example, a 1 GBytes memories in a commercial flight will undergo 1 SEU every 2 h of flight at 12 km of altitude.

4.3. *Key assumptions and limitations of Monte Carlo methods*

Monte Carlo simulations, while highly useful for predicting Single Event Upsets (SEUs), rely on certain assumptions that can impact their accuracy. For example, in some tools, one key assumption is the modeling of the sensitive region within the semiconductor device. In many simulations, the volume of this region is approximated using simplified geometric shapes, such as rectangular parallelepipeds, which may not fully represent the actual charge collection and does not provide any information about the time dependence of the process. Another critical factor is the choice of nuclear reaction models, which determine how incident particles interact with semiconductor. The accuracy of SEU predictions strongly depends on the nuclear physics used. Additionally, modern semiconductor devices exhibit charge sharing between neighboring transistors, leading to multiple cell upsets (MCUs). While some Monte Carlo methods attempt to incorporate charge-sharing effects, accurately capturing these phenomena remains a challenge due to the complexity of semiconductor physics. Despite these limitations, Monte Carlo simulations remain one of the most effective tools for understanding SEU behavior, provided that their assumptions are well-calibrated against experimental data.

4.4. *Advantages of Monte Carlo SEU simulations*

Monte Carlo-based simulations have become indispensable for assessing the vulnerability of electronic components to radiation-induced SEUs. One of their major advantages is cost reduction, as they lower the need for extensive physical testing in radiation facilities, which are expensive and time-consuming. Additionally, Monte Carlo methods allow to simulate different conditions without requiring physical hardware modifications. This is particularly useful for space applications, where predicting SEU rates under varying solar and galactic cosmic ray conditions is essential. Another key benefit is scalability: as semiconductor technology advances, device structures become increasingly complex, making traditional testing methods less practical. Also, Monte Carlo simulations enable to analyze new materials and transistor architectures efficiently. The continued refinement of these simulation tools, combined with experimental validation, makes them an essential tool for space agencies, semiconductor manufacturers, and avionics engineers working on radiation-hardened electronics.

5. Conclusion

The study of radiation effects on electronic devices is critical for ensuring the reliability of modern technology, particularly in space, avionics, and high-altitude applications. The natural radiative environment, composed of galactic cosmic rays, solar radiation, and trapped particles in the Earth's magnetosphere, presents significant challenges for electronic components. These radiation sources can induce a range of failures, such as Total Ionizing Dose (TID), Displacement Damage (DD) and Single Event Effects (SEEs).

Among SEEs, Single Event Upsets (SEUs) pose a unique challenge due to their stochastic nature. Understanding and predicting SEUs require sophisticated modeling techniques, and Monte Carlo-based simulations have emerged as powerful tools in this domain. These simulations allow to assess the probability of SEUs under various radiation conditions, evaluate the sensitivity of devices, and optimize mitigation techniques. Despite certain assumptions and limitations, Monte Carlo methods provide a complementary tool to extensive radiation testing, making them a crucial resource for industries.

As technology advances and transistor sizes continue to shrink, the susceptibility of electronic devices to radiation-induced failures is expected to increase. This trend underscores the importance of continued research in radiation effects modeling, error correction techniques, and hardened circuit design. Future developments in Monte Carlo-based prediction tools, coupled with experimental validation, will be crucial for developing next-generation electronics capable of withstanding the ever-present challenges of radiation exposure in critical applications.

Declaration of interests

The author does not work for, advise, own shares in, or receive funds from any organization that could benefit from this article, and has declared no affiliations other than their research organization.

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