Radiation Fields in High Energy
Accelerators and their impact on Single
Event Effects

Champs ionisants dans un accélérateur à
haute énergie et leur impact sur les Effets Singuliers

Soutenue le 15/12/2014 devant le jury composé de

Mme. Lorena ANGHEL, Professeur, Laboratoire TIMA - Equipe
Examinateur
Mr. Markus BRUGGER, Directeur de Recherche, CERN
Co-directeur de thèse
Mr. Véronique FERLET-CAVROIS, Directeur de Recherche, Agence Spatial Européen (ESA)
Examinateur
Mr. Alessandro PACCAGNELLA, Professeur, Université Degli Studi di Padova
Rapporteur
Mr. Frédéric SAIGNE, Professeur, Institut d’Électronique du Sud
Directeur de thèse
Mr. Ari VIRTANEN, Directeur de Recherche, Radiation Effects Facility (RADEF)
Rapporteur
Mr. Frédéric WROBEL, Professeur, Institut d’Électronique du Sud
Co-directeur de thèse
A Verónica, por su cariño y apoyo.
A mis padres, por su amor y dedicación; por haberme transmitido la pasión por aprender.
A mi hermano, por acompañarme siempre.
Including calculation models and measurements for a variety of electronic components and their concerned radiation environments, this thesis describes the complex radiation field present in the surrounding of a high-energy hadron accelerator and assesses the risks related to it in terms of Single Event Effects (SEE). It is shown that this poses not only a serious threat to the respective operation of modern accelerators but also highlights the impact on other high-energy radiation environments such as those for ground and avionics applications.

Different LHC-like radiation environments are described in terms of their hadron composition and energy spectra. They are compared with other environments relevant for electronic component operation such as the ground-level, avionics or proton belt. The main characteristic of the high-energy accelerator radiation field is its mixed nature, both in terms of hadron types and energy interval. The threat to electronics ranges from neutrons of thermal energies to GeV hadrons.

Moreover, an overview is provided of the standard test approach used to characterize components to be utilized in a high-energy accelerator environment. A set of commercial microelectronic components are tested in a broad range of radiation environments and modeled in the scope of the FLUKA Monte Carlo code leading to the conclusion that, when applying standard test results to the estimation of the high-energy accelerator SEE rate, significant safety margins (quantified in the thesis) need to be applied to account for the risk of the very high-energy particles in the environment.

**Keywords:** Radiation damage, Single Event Effects, High-Energy Accelerator, Monte Carlo studies, Test requirements, Monitoring requirements
RéSUMÉ

Basée sur des modèles de calculs ainsi que sur des séries de mesures pour différents composants électroniques et leurs environnements de radiation, cette thèse décrit le champ ionisant complexe présent à proximité d’un accélérateur d’hadrons et évalue les risques associés en terme d’effets singuliers (SEE). Il y est démontré que cela cré une menace sérieuse non seulement pour les opérations respectives des accélérateurs modernes mais également pour d’autres environnements de rayonnement à haute énergie comme par exemple les applications au sol ou avionique.

Différents environnements similaires au LHC sont décrits en termes de composition d’hadrons et de spectres d’énergie. Ils sont comparés à d’autres environnements tels que ceux utilisés au niveau du sol ou encore pour l’avionique et le spatial. La principale caractéristique d’un champ de rayonnement d’un accélérateur à haute énergie est son caractère mixte, à la fois en termes de hadrons et de gamme d’énergie. La menace sur l’électronique s’étend de l’énergie thermique des neutrons jusqu’à l’énergie en GeV des hadrons.

De plus, la thèse donne un aperçu de l’approche du test standard employé pour caractériser les composants à utiliser dans un environnement d’accélérateur à haute énergie. Un ensemble de composants microélectroniques commerciaux sont testés dans de nombreux environnements radiants et modélisés avec le code Monte Carlo FLUKA. Cela conduit à la conclusion que, lorsque les résultats du test standard sont appliqués à l’estimation du taux SEE de l’accélérateur à haute énergie, des marges de sécurités significatives (quantifiées dans la thèse) doivent être respectées pour tenir compte du risque lié à la très haute énergie des particules.

Mots clés: Dégâts de radiation, Effets Singuliers, Accélérateur à haute énergie, Etudes Monte-Carlo, Conditions de test, Conditions de mesure
# CONTENTS

## 1 INTRODUCTION
- 1.1 | Context and Overview 11
- 1.2 | SEEs in the High-Energy Accelerator Environment 14

## 2 LHC MIXED RADIATION ENVIRONMENT AND OTHER CONTEXTS OF INTEREST 25
- 2.1 | Introduction 25
- 2.2 | LHC Environment Description and SEE Rate Calculation 28
  - 2.2.1 | HEH, intermediate and thermal neutrons 28
  - 2.2.2 | Other contributions and dependencies of interest 29
- 2.3 | Mixed-Field Environment Parametrization 33
  - 2.3.1 | LHC Accelerator environment 33
  - 2.3.2 | LHC Experiment environment 35
  - 2.3.3 | Atmospheric environment 36
  - 2.3.4 | Proton-belt Space environment 39
- 2.4 | Volume-Equivalent LET Environment Representation 40
- 2.5 | Summary 44

## 3 SEE TEST APPROACH AND FACILITIES 47
- 3.1 | Introduction 47
- 3.2 | Monoenergetic Hadron Facilities 49
  - 3.2.1 | PSI: protons in the 30-230 MeV range 50
  - 3.2.2 | TRIUMF: protons up to 480 MeV 53
  - 3.2.3 | PTB: Quasi-monoenergetic neutrons at 5, 8 and 14.8 MeV 55
  - 3.2.4 | H4IRRAD and CERF: several hundred GeV hadrons 56
- 3.3 | Mixed-field hadron facilities 58
  - 3.3.1 | The VESUVIO neutron spectrum at ISIS 58
  - 3.3.2 | The H4IRRAD mixed-field test area 61
  - 3.3.3 | The future CHARM facility at CERN 63
- 3.4 | Summary 69

## 4 SEE SIMULATIONS USING FLUKA 73
- 4.1 | Introduction 73
- 4.2 | Nuclear Interactions in Silicon 75
- 4.3 | High-Energy Accelerator Mixed-Field Simulation and Benchmark 83
## SEU Measurements and Simulations

### 5.1 Introduction

### 5.2 ESA SEU Monitor Test Results
- 5.2.1 PSI: 30-230 MeV protons
- 5.2.2 TRIUMF: 230-480 MeV protons
- 5.2.3 PTB: 5-15 MeV neutrons
- 5.2.4 VESUVIO: Atmospheric-like neutron spectrum
- 5.2.5 H4IRRAD and CERF: 120 and 400 GeV hadrons
- 5.2.6 H4IRRAD: Accelerator-like mixed-field

### 5.3 SEU modeling and simulation for the ESA SEU Monitor
- 5.3.1 RPP model and calibration to the PSI data
- 5.3.2 Application of the RPP model to mixed-field particles and energies

### 5.4 Summary

## SEL Measurements and Simulations

### 6.1 Introduction

### 6.2 SRAM and ADC Test Results
- 6.2.1 DUTs and test description
- 6.2.2 Heavy Ion test data
- 6.2.3 PSI and TRIUMF: 30-480 MeV protons
- 6.2.4 VESUVIO: Atmospheric-like neutron spectrum
- 6.2.5 H4IRRAD: Accelerator-like mixed-field

### 6.3 Semi-Empirical Monte Carlo SEL Model for SRAMs
- 6.3.1 Tungsten fission in FLUKA
- 6.3.2 SEL model: definition and calibration
- 6.3.3 Using the model as a predictive tool
- 6.3.4 Comparison with previous approaches
- 6.3.5 Application of the model to GeV energies
- 6.3.6 Construction analysis and implications on the model

### 6.4 High-Z Impact on Hardened SEU Cross Section

### 6.5 Summary

## Implications on the High-Energy Environment SEE Rate

### 7.1 Introduction

### 7.2 Mixed-Field Environment Description

---

Radiation Fields at High-Energy Accelerators and their impact on Single Event Effects
1

FIRST CHAPTER

INTRODUCTION

1.1 Context and Overview

The Large Hadron Collider (LHC) is the world’s largest and most powerful particle collider, built by the European Organization for Nuclear Research (CERN) between 1998 and 2008. Its main research domain is that of high-energy physics, and more specifically the discovery and study of new particles such as the theorized Higgs boson: the missing piece of the Standard Model puzzle. In addition, the unprecedented energy and luminosity levels achieved in the machine will also enable the progress in other high-energy particle physics research subjects such as supersymmetry, which predicts heavier particle counterparts of those already known in the Standard Model, or dark matter studies.

The goal of the LHC is to accelerate and collide two proton beams, producing interactions that generate particles that can be (directly or indirectly) measured in the experiments. Because the interaction products that are of interest to high-energy particle physicists are extremely rare, a vast quantity of interactions needs to be generated in order to produce them. The number of interactions per unit surface and time is known as luminosity, which in the case of the LHC is in the order of $10^{34} \text{cm}^{-2}\text{s}^{-1}$. The integral of the delivered luminosity over time is called the integral luminosity, and can be considered as the final product of the collider. This value has units of an inverse surface, and is typically expressed in $f\text{b}^{-1}$, where $1\ f\text{b} = 10^{-43}\ m^2$ and corresponds to approximately $10^{12}$ proton-proton collisions. The integral luminosity in the LHC in 2012 was roughly $23\ f\text{b}^{-1}$. Therefore, the performance of a collider can be quantified by its ability to deliver integral luminosity, and there are two ways of increasing this figure-of-merit: (i) by increasing the luminosity (as will be done in the High Luminosity
Chapter 1. Introduction

LHC upgrade, involving technological enhancements such as more powerful magnets or high-power superconducting links) and (ii) by increasing the operational time (also referred to as availability) of the machine.

The availability of the machine is limited by its operation cycle. The protons need to be injected in the two vacuum pipes (in what is known as a fill) and accelerated until reaching their maximum energy (up to 4 TeV in 2012, nominally 7 TeV). Once this energy is reached, the two beams circulating in opposite senses will cross in the collision points, generating data for the experiments. This phase is known as stable beam, and during it, the number of protons available for collision will decrease, due to both the (wanted) losses in the collision points and the (unwanted) ones in other locations of the accelerator. The duration of an uninterrupted stable beam cycle is roughly 10 to 15 hours. Once the LHC operators decide to interrupt the run due to the degraded quality of the beam, the fill is ended through a controlled dump. However, it is often the case that the fill is prematurely terminated by a fault (in 2012, \(~70\%\) of the dumps were of this nature) yielding an average stable beam duration of \(~6\) hours.

Once the beam is interrupted, certain operations need to take place before the beam is again injected and accelerated, reaching its stable conditions and ready to resume luminosity production. This process is known as turnaround and can theoretically be achieved in just above 2 hours. In practice however, the average turnaround time in 2012 was 5.5 hours, mainly due to the fact that most beams were prematurely dumped and therefore related to a fault which typically required some sort of intervention.

Therefore, from what was introduced above, the two ways of optimizing the integral luminosity from an availability point of view are (i) reducing the number of premature dumps and (ii) reducing the average fault time. As will be detailed in the following section, a significant proportion of the premature dumps are due to radiation induced errors in the LHC electronic systems. In 2012, over 70 out of 409 dumps were attributed to such effects, with a total associated downtime of more than 300 hours. If we consider the 2012 integral luminosity, this corresponds to \(~3\) radiation induced dumps per \(fb^{-1}\). This is already a significant improvement with respect to 2011, where \(~12\) dumps per \(fb^{-1}\) were attributed to radiation effects. Ultimately, the goal for an acceptable High Luminosity LHC operation will be that less than 0.1 dumps per \(fb^{-1}\) are due to radiation. As will be detailed in the following section, the type of radiation effect analyzed in this thesis are Single Event Effects (SEEs) which are induced by a single particle in the radiation environment. For reasons that will be discussed later, SEEs are the radiation effect with a strongest impact in the high-energy accelerator context.

The significant improvement between 2011 and 2012 in terms of the number of radiation induced dumps per unit integrated luminosity as well as the task of further optimizing this performance in the future is a responsibility of the Radiation to Electronics (R2E) project [1] at CERN. The short-term, most direct measures that can be applied once an LHC system in place is experiencing radiation induced failures are (i) its relocation (ii) increasing the amount of shielding protecting it and ultimately (iii) replacing it for a more robust system. These
solutions are only partially feasible and are subject to limitations such as the connection distance between the system and the accelerator, the amount of space available for shielding or the capability of developing a more resistant system. In the mid and long-terms however, prevention is more desirable and efficient than mitigation, and therefore radiation tolerance is at the present stage generally taken into consideration by the different groups designing and developing electronic systems for the LHC. Starting from a component level, its radiation hardness assurance can be guaranteed in two ways:

(i) using or developing radiation hardened components

(ii) using commercial components and qualifying them against radiation

In the case of the LHC systems, involving a vast quantity of electronic components, option (i) is typically not viable due to its overcost. In fact, option (ii) is the standard approach, therefore involving the radiation testing of commercial components in order to determine if they are compliant with the application requirements, which in the case of the LHC is related with its availability.

The action of testing can be generally defined as that of taking measures to check the quality, performance, or reliability of something, especially before putting it into widespread use or practice. This means that the test has to be conceived in such a way that it reproduces the practical application before it is used. Therefore, similar conditions to those of the application need to be achieved. When considering radiation tests, one of the main characteristics is that these are accelerated, in the sense that they are intended to mimic the operational case in a much smaller time frame. In addition, they will take place in a certain radiation field, which will in principle not be the same as that present in the operational case. A radiation field is defined by the particles composing it and their energy distributions, and in the case of the high-energy accelerator environment, the range of particles species and energies concerned is extensive. Such is the case that standard radiation tests are typically performed in a much more reduced particle species and energy range than what is present during operation. Therefore, it is essential to correlate the radiation effects expected in the (generally broader) operational environment to those measured under experimental conditions in order to predict realistic failure rates for the critical electronic components.

Notably, one of the key characteristics of the LHC environments is its very high energy levels, typically exceeding those achieved in standard radiation test facilities. Therefore, two of the basic questions that motivated this thesis work are: is there a risk related to the higher particle energies present in operational context with respect to those used at test facilities? If so, is it possible to quantify this risk?

The structure of the thesis further motivating, analyzing and extracting conclusions from the correlation between the effects in the test and operational radiation environments is as follows:
• Chapter 2 describes the high-energy accelerator environment and compares it with other operational contexts of interest.

• Chapter 3 introduces the test methodology for electronic components to be used in the high-energy accelerator context and compares the test environments with their operational counterparts.

• Chapter 4 describes the computational simulation tool used to extract information about both the environment and effects relevant to SEE induction.

• Chapter 5 introduces a specific electronic component and effect, analyzing its occurrence probability in different radiation fields by means of measurements and simulations.

• Chapter 6 extends this analysis to a broader range of components and a more relevant effect in terms of radiation hardness assurance.

• Chapter 7 studies the implications of the radiation effect probability analysis on the high-energy accelerator test and failure rate estimation procedures.

• Chapter 8 provides a brief summary of the main results and conclusions.

A schematic overview of the context of the thesis summarizing and structuring the different elements introduced above is shown in Fig. 1.1. The cornerstone of the structure is the progress in the SEE failure rate calculation approach, ultimately aimed at improving the availability for LHC operation.

1.2 SEEs in the High-Energy Accelerator Environment

As was introduced above for the LHC, modern high-energy particle accelerators are extremely elaborate machines, making use of evermore complex electronics for control, steering, powering and monitoring. Cable length or timing issues often limit the maximum possible distance from the electronic equipment to the accelerator, with the former therefore partially operating in areas exposed to high levels of prompt radiation. Examples of such systems for the LHC at CERN are the power converter units, providing currents up to 13 kA to superconducting magnets, the pumps for creating the required vacuum conditions in the beam pipe or cryogenic systems to reach temperatures as low as 4 K.

Moreover, most of these electronic systems are (at least partially) based on Commercial-Off-The-Shelf (COTS) components, as the use of radiation hardened devices is limited due to their cost and sometimes reduced electronic performance as trade-off of their radiation robustness. However, the enhanced performance and reduced purchase price of state-of-the-art COTS come at the expense of the need to evaluate the failure rate and impact of the potential radiation effects in the operational environment. The support and coordination of
1.2. **SEE in the High-Energy Accelerator Environment**

The failure rate linked to the use of COTS-based systems in radiation environments can be expressed in terms of failures per unit time, or mean time between failures, the estimation of which requires a detailed knowledge of (i) the radiation environment and (ii) the response of the component to it. The first is typically derived through measurements and calculations, whereas the second requires the characterization of the component through dedicated radiation tests. In the present thesis, the high-energy accelerator radiation environments are described in Chapter 2, whereas different test facilities and approaches are introduced in Chapter 3. Results from the characterization of a broad range of commercial electronic components in a wide variety of test environments are shown in Chapters 5 and 6 together with models based on the FLUKA Monte Carlo tool (presented in Chapter 4). These results are used to estimate the response of the components to particles and energies typically not accessible in standard test facilities but still highly relevant to the accelerator environment. The implications of these results on the test and failure rate estimation approaches are treated in Chapter 7.

In addition to the failure rate evaluation, it is essential to evaluate the impact the former would have on LHC operation. This critical analysis is not treated in this thesis, however it is worth mentioning that four general levels of impact are defined in decreasing order of importance:

---

Radiation Fields at High-Energy Accelerators and their impact on Single Event Effects

---

**Fig. 1.1.** Schematic representation of the context of the thesis in terms of increasing the LHC physics data production (light green) as well as the building blocks used in this work to progress in the SEE failure rate calculation domain (bright green).
(i) Safety of the personnel and machine

(ii) Beam stop

(iii) Down time

(iv) Loss of monitoring

Evidently, the first of the requirements is based on protecting the personnel and the permanent damage of core elements of the machine, which could potentially lead to weeks or even months of operation interruption. Secondly, it is important to reduce the number of beam losses due to radiation effects, as they involve the ramping down of the current of the magnets, the re-initialization of the machine and the preparation of a new run until reaching a stable beam condition and being able to resume the production of data for the physics experiments. This full cycle typically takes a few hours, and the time can be incremented if the failure leading to the beam dump was related to the damage of an equipment that needs to be repaired or replaced. This might also be the case for failures not directly resulting in a beam dump but requiring an intervention in the next potential access slot. Finally, radiation-induced failures which cause the loss of monitoring data which is not vital for the operation are considered of minor impact.

As to what regards the type of radiation induced failures, these can be categorized as those induced through Displacement Damage (DD), Total Ionizing Dose (TID) and Single Event Effects (SEE). The first is related to the non-ionizing energy loss of the radiation field particles in a certain material, leading to the displacement of its atoms and potentially limiting its performance (such as for example the efficiency loss in a solar cell). The quantity to which these effects are in general assumed to be proportional to is the 1 MeV equivalent neutron fluence. The second category is related to the ionization of the radiation field particles and the trapped charge generated by it in the oxides of the electronic components, which can cause serious degradation in MOS and bipolar devices. The quantity used to describe the TID degradation is the total dose (deposited energy per unit mass) typically expressed in units of Gray (Gy, \(1\, Gy = 1\, J/kg\)).

Single Event effects (SEEs) are the third type of radiation damage on electronics, and as indicated by their name, are caused by the interaction of a single particle with the component’s sensitive region. In the context of a high-energy accelerator radiation field, these effects are typically caused by high energy hadrons (HEH, defined as hadrons above 20 MeV), intermediate energy neutrons (in the 0.2-20 MeV range) or thermal neutrons (with energies around 0.025 eV). The physical mechanisms through which SEEs are induced will be detailed in Chapters 2, 4 and 6, however it is worth noting at this stage that in the context of the mixed-field characteristic of the high-energy accelerator environment, these are generated through indirect energy deposition events, meaning that a discrete interaction between the environmental hadron and a nucleus in (or near) the device’s sensitive region needs to occur to trigger the event.
This situation differs from an environment dominated by Galactic Cosmic Rays (GCR) for which direct ionization (i.e. through Coulomb interaction, typically described as a continuous phenomenon) from heavy ions will dominate the error rate. As will be described in Chapter 2, the standard quantities monitored and calculated in order to evaluate the SEE rates in the LHC context are (i) the equivalent High Energy Hadron flux (sum of all hadrons above 20 MeV and a weighted contribution of the intermediate energy neutrons) and the R factor (ration between the equivalent hadron flux and the High Energy Hadron flux).

Before further categorizing SEEs, it is relevant to note several important differences with respect to the cumulative effects (DD and TID) that render SEEs a generally more severe threat in a high-energy accelerator environment:

(a) DD and TID are typically only an issue for areas with significant radiation levels (i.e. the LHC tunnel) with annual levels above $10^{10}$ $1\text{ MeV n. eq.}/\text{cm}^2/\text{yr}$ and 1 Gy/yr whereas SEEs can also be of concern for zones with significantly lower levels (shielded areas with a HEH flux of $\sim 10^7/\text{cm}^2/\text{yr}$ are already regarded as critical zones due to the relatively high number of exposed systems).

(b) DD and TID effects normally manifest in the form of the drift of a certain electrical parameter, which depending on the system design can still be within the specifications for a correct operation. SEEs on the other hand are discrete errors or failures in the component.

(c) Cumulative effects can be mitigated through replacement and rotation protocols, whereas for SEEs this is not an option due to their stochastic nature.

(d) As long as the maximum total dose and 1 MeV neutron equivalent levels are well below the limit for which a component is no longer operational, an increased number of components of this type used will not increase the failure risk. For SEEs however, the Mean Time Between Failures (MTBF) will be inversely proportional to the total number of components used (which in the case of LHC systems can be of several thousands).

(e) Whereas the TID sensitivity tends to decrease with the technology scaling owing to the smaller oxides and consequently lower trapped charge levels, the SEE cross section per component typically increases with technology scaling (at least in the case of SEU). This is mainly due to the reduced capacitances and voltages used in transistors in order to reduce the size and increase the access speed of the components. A clear example of how technology scaling can significantly impact the error rate is the SEU sensitivity to singly charged particles as discussed in [2].

(f) More related to the radiation field monitoring and calculations, TID and DD are proportional quantities that have a relatively linear dependency with values such as the voltage drift in a RadFET or a PIN diode [3]. However, the relationship between the SEE rate and the thermal and (notably) HEH fluxes is less straight-forward and can significantly depend on the specific radiation field and component.
Chapter 1. Introduction

The research work presented in this thesis is closely related to point (f), as it aims at evaluating the potential effect of the high-energy accelerator environment on the SEE rate with respect to what is derived using the standard qualification approach that will be introduced in Chapter 3.

Coming back to the classification of radiation effects in electronic components, we will now briefly list several of the most important SEE types taken from the European Cooperation for Space Standardization (ECSS) handbook of radiation effects [4], distinguishing between destructive (hard) and non-destructive (soft) effects:

- **Destructive (hard) SEEs:**
  - Single Event Latchup (SEL): potentially destructive triggering of a parasitic $pnpn$ thyristor structure in a device. When a latchup occurs, the current increases and if the power supply is maintained, the device can be destroyed by thermal effects. The use of a current monitoring and a power control circuit allows the power to be shut down quickly after the latchup is detected in order to protect the device against thermal destruction.
  - Single Event Gate Rupture (SEGR): formation of a conducting path in the gate oxide due to a high field generated by high current. The charges created by the heavy ion crossing the semiconductor are collected and propagate up to the insulator interface making the electric field across the dielectric exceed a critical value (breakdown voltage). Unlike SEL, there is no way to avoid a SEGR becoming destructive. The only way to protect a component against single event gate or dielectric rupture is to use it with electrical conditions that do not allow the SEGR to occur (i.e. derating).
  - Single Event Burnout (SEB): destructive triggering of a vertical n-channel transistor accompanied by a regenerative feedback. This occurs in power MOSFETs biased in the OFF state (i.e., blocking a high drain-source voltage) when a heavy ion passing through deposits enough charge to turn the device on.

- **Non-destructive (soft) SEEs:**
  - Single Event Upsets (SEUs): single bit flip induced in a digital element either by direct ionization from a traversing particle or by a recoiling nucleus emitted from a nuclear reaction. This event induces no damage to the basic element which can be rewritten with the right value.
  - Multiple Cell Upset (MCU) and Multiple Bit Upset (MBU): MCUs occur when two or more bits (physically adjacent or not) become corrupted by a single particle, or its secondary particles from nuclear interactions. If the two or more bits corrupted by the same event are in the same logical word, the effect is known as a Multiple Bit Upset (MBU).
Single Event Transient (SET): momentary voltage excursion (voltage spike) at a node in semiconductors, originally formed by the electric field separation of the charge generated by an ion passing through or near a circuit junction. The signal perturbation is very short but can in some cases propagate through the whole system depending on where and when it occurs.

Single Event Functional Interrupt (SEFI): caused by a single ion strike or nuclear interaction that leads to a temporary non-functionality (or interruption of normal operation) of the affected device. A SEFI is not accompanied by a high current condition and can last as long as the power is maintained (persistent SEFI) or a reset is sent to resume the normal operation.

Because the test results, calculation models and SEE rate estimation approaches that will be shown in this thesis concern SEU (Chapter 5) and SEL (Chapter 6) we will provide further description and references of these effects in the following paragraphs.

A state-of-the-art summary of SEU mechanisms and modeling can be found in [2]. In order to describe the SEU process at a circuit level, the referenced work uses the example of a six-transistor (6T) SRAM cell, which has a layout as that shown in Fig. 1.2. The logic value associated to the cell is maintained by a pair of coupled inverters, with transistors M1, M2, M3 and M4 acting to reinforce the stable logic state. In each inverter there will be a transistor in the OFF state, which will be sensitive to SEU. Fig. 1.3 shows a cross section at device level for the M1-M2 inverter. Let us imagine the PMOS transistor (M2) is ON and the NMOS transistor (M1) is off. Therefore, the full supply voltage is dropped across the drain depletion region setting up an electric field. Free charge carriers generated from an ionizing particle will be collected through the drift of the electric field, altering the potential on NQ, which was initially maintained high, driving the M3-M4 inverter. As current flows through the M1 drain-to-body junction, an equal current must flow the drain from M2 and the M3 and M4 gates. The capacitive loads of the cell will help maintain its logic state, however if the current is sufficiently high and maintained for a long enough time, the capacitors will not be able to hold the potential at NQ and it will drop to ground, switching the M3-M4 inverter and leaving the cell in a stable but errant state.

There are several techniques that can be applied to mitigate SEUs. Many of these are based on correction codes (Error Correcting Codes, ECCs) and redundancies (Triple Modular Redundancy, TMR) implemented at component or system level, typically at the cost of some area or memory size penalty.

Moreover, it is also worth noting that, despite originally an adverse effect, SEUs can also be used to monitor the radiation level through the linear correlation between the HEH fluence and the number of upsets. This is the purpose of the ESA SEU Monitor, calibrated in a wide range of facilities and used as a detector for a polar orbit space mission [5–8]. In the LHC context, a similar approach has been used integrated in the RadMon system [3, 9, 10].
Chapter 1. Introduction

Figure 1: Circuit level schematic diagram of a six transistor SRAM. Transistor M2 is on and the NMOS transistor M1 is off. The shared circuit node NQ is maintained high and drives the M3–M4 inverter. Because M1 is off, the full supply voltage is dropped across the drain depletion region setting up an electric field. Carriers generated from an ionizing particle are swept up by the electric field and alter the potential on NQ.

Figure 2: Cross sectional device level view of an inverter fabricated in a bulk CMOS process and illustrating single event photocurrent.

For the purposes of explaining the circuit response, consider that the cell may be represented by an equivalent RC circuit in Figure 3. Here, M2 is represented by a resistor with resistance $R_{M2}$. Capacitive loads are attached to the NQ contact representing the total gate capacitance of M3 and M4. In addition, resistors are

Figure 1.2. Circuit level schematic diagram of a six transistor SRAM (from [2]).

Figure 1.3. Cross sectional device level view of an inverter fabricated in a bulk CMOS process and illustrating the free change induced by an ionizing particle (from [2]).

monitor, equipped with detectors for all three axes of radiation damage (TID, DD and SEEs) uses an SRAM memory to measure the flux of high energy hadrons. In an earlier version of the RadMon, a Toshiba memory was used for this purpose. By using it at two different supply voltages, the thermal neutron and HEH fluxes can be measured separately [10]. We will refer to this memory as the Toshiba RadMon in the context of this thesis. In addition, a new version of the RadMon based on a more modern SRAM is currently available [11] and deployed in the LHC tunnel and surroundings. It will be referred to as the Cypress RadMon in the following, according to its manufacturer.

A detailed description of SEL hardening strategies, triggering mechanisms, testing considerations and technology scaling can be found in the doctoral thesis works [12] and [13] and references therein. SEL is a well known hard error as it can potentially occur anywhere where CMOS technology is present owing to the $pnpn$ structures, also known as thyristors or

———

Radiation Fields at High-Energy Accelerators and their impact on Single Event Effects
silicon controlled rectifiers. This structure is shown in Fig. 1.4, where PMOS and NMOS are placed side-by-side (characteristic of the CMOS architecture). The $pnp$ and $npn$ can be seen as two coupled parasitic transistors in feedback loop, such that the output (collector) of each transistor is connected to the input (base) of the other. If a transient current is introduced in the device (such as that generated by an ionizing particle) the feedback loop can amplify this current and cause it to sustain itself. The resulting high current state, known as latchup, persists until power is removed or until the device is destroyed by the high current density.

![Fig. 1.4. Cross section of an n-well CMOS technology showing parasitic resistors and bipolar transistors. Taken from [13].](image)

The SEL sensitivity of a device strongly depends on the layout of the component, and as will be shown in Chapter 6, can vary several orders of magnitude for SRAMs of the same technology and similar electronic performance. Also, larger supply voltages promote SEL as they lead to larger collector currents making it easier for one of the Bipolar Junction Transistors (BJT) to trigger the other into the forward active mode, which enables the SEL. Likewise, a larger supply voltage is also more likely to exceed the value needed to sustain the high current state (i.e. the hold voltage). In addition, an increase in the operating temperature also promotes latchup, mainly due to the increased resistances that shunt the emitter/base junctions.

As to what regards the trend in the SEL sensitivity with the scaling of the technology, two dominant and opposing effects were identified in [12]:

(i) the amount of charge necessary to induce SEL decreases due to the fact that devices become smaller and more closely spaced.

(ii) the supply voltage decreases and can eventually reach values that are unable to sustain the voltage necessary for SEL.

Radiation Fields at High-Energy Accelerators and their impact on Single Event Effects
Chapter 1. Introduction

The overall effect of these two contributions is that, for technology nodes as low as 65 nm, SEL is unlikely at room temperature but still possible at increased temperatures.

Having introduced the effects, it is worth noting that a wide variety of electronic components are sensitive to SEEs. For instance, SEB and SEGR typically affect power components such as power MOSFETs and IGBTs. SEL can in principle occur in any device with an npnp structure and SEUs affect logic electronics such as DRAMs or SRAMs. We will provide a brief introduction to the applications and structure of the latter, as they are components broadly tested by the radiation effects community in general and in the scope of this thesis in particular.

SRAMs are mainly designed to fulfill two needs: that of providing direct interfaces at speeds not attainable by DRAMs and that of replacing DRAMs in systems that require a very low power consumption. For instance, in a typical microprocessor, the SRAM can provide the interface between the DRAM and the CPU. The flip-flop bit cell needs a power supply to keep the information, therefore SRAMs are volatile memories. However, data is not lost through charge leakage as in the DRAM case. Consequently SRAMs do not require a refresh cycle.

The SRAM market is therefore driven by reduced power consumption and size requirements. For this reason, successive technologies are characterized by their technology node, defined as the minimum half-pitch of the metal interconnect and considered as the most representative parameter of the process capability of enabling high-density integrated circuits. According to Moore’s law (postulated in 1965 as a technological observation and since then proven to be very accurate in terms of predicting the scaling trend [14]) this parameter (also known as the feature size) is reduced by a factor 0.7 every two years, allowing for roughly twice as many transistors per chip. According to the International Technology Roadmap for Semiconductors (ITRS, [15]), the most advanced delivered technology (as of April 2012) is the 22 nm node.

Finally, as to what regards the general SEE test and rate estimation approaches and tools, provided the latter are induced through the energy deposition of ionizing particles, the description of the sensitivity of a component is typically expressed as the probability per unit fluence (i.e. cross section) that an SEE occurs for a given incident beam. The latter is characterized by its energy in the case of (hadron-induced) indirect energy deposition and by its Linear Energy Transfer (LET) for heavy ions. This quantity is also referred to as the Stopping Power or \( \frac{dE}{dx} \). The LET of a particle in a certain material is defined as its energy loss per unit length and density (Eq. 1.1, where \( dE_{dep} \) is the deposited energy, \( \rho \) is the material density and \( dx \) is the distance), and is tabulated for a wide range of ions and materials [16]. The behavior of LET for energies above 1 MeV/amu is very well described by the Bethe formula [17], based on two parameters: the mean-ionization potentials and the shell corrections. Moreover, it is to be noted that the total LET includes both the electronic (due to Coulomb collisions that result in the ionization and excitation of atoms) and nuclear (due to transfer of energy to recoiling atoms in elastic collisions) contributions. For energetic charged particles, the electronic contribution clearly dominates, however this is not the case for stopping heavy ions.
1.2. **SEE in the High-Energy Accelerator Environment**

\[ LET = \frac{1}{\rho} \cdot \frac{dE_{dep}}{dx} \]  

(1.1)

An example of the electronic and nuclear LET of silicon in silicon is plotted in Fig. 1.5 using data extracted for the SRIM tool [16] in the 10 keV - 1 GeV total kinetic energy range. As can be seen, the standard units are \( MeV cm^2/mg \), which means that the energy deposition per unit length is divided by the material density. For SEE applications, it is often useful to express this quantity in units of generated charge (in fC) per micron. In silicon, the conversion factor to be applied is shown in Eq. 1.2, which is obtained by multiplying times the silicon density (2.33 g/cm\(^3\)) and converting energy to charge considering that the ionization energy in silicon is 3.6 eV. As a basic approximation, one can assume that an SEE will occur when a particle deposits an amount of charge larger than a certain critical value in the sensitive volume of the component. Because the deposited charge is proportional to the LET, the occurrence of an SEE will also be defined by a certain critical LET, therefore experimental SEE tests are typically expressed as a function of this value.

\[ 1 MeV cm^2/mg = 10.35 fC/\mu m \]  

(1.2)

![Fig. 1.5. Electronic and nuclear LET of silicon in silicon as extracted using the SRIM online tool [16].](image-url)
SECOND CHAPTER

LHC MIXED RADIATION ENVIRONMENT AND OTHER CONTEXTS OF INTEREST

The accurate knowledge of the radiation environment is essential when evaluating the expected SEE impact on a specific component or system for a given application. For this reason, the LHC mixed radiation field is parametrized in this chapter in order to quantify its potential impact in terms of SEE effects and compare it with other operational environments of interest such as in the atmospheric and space contexts.

2.1 Introduction

When evaluating the use of commercial electronic components in high-intensity radiation areas, an SEE rate estimation is needed in order to accept or reject the candidate parts. Indeed, this final decision will strongly depend on the criticality of the concerned SEE and component application, however the environment and device response from which the SEE rate is extracted can be described in a relatively independent way. This chapter focuses on the study of the SEE-relevant high-energy accelerator environment in terms of several quantities here defined, as well as its comparison with other well known radiation contexts such as ground level, avionics or space.

The main sources of radiation in the LHC environment are (i) distributed beam losses around the machine (collimator and collimator-like objects, beam-gas interaction) and (ii) beam-beam collisions in the CERN experiments [18]. The resulting radiation field is composed of a wide range of particles and energies and is therefore referred to as a mixed-field environment. The particle proportion and intensity of the field in a given location will depend on (i) the accelerator operation conditions (ii) the distance and angle with respect to the interaction
point and (iii) the amount of shielding (if any) between the interaction point and the location. The characterization of the radiation field in the LHC context is generally performed using the FLUKA Monte Carlo transport code [19–21] which is validated for a wide range of applications including proton and electron accelerator shielding, target design, calorimetry, activation and dosimetry, cosmic ray studies and radiotherapy. The radiation field simulations have been benchmarked against the RadMon monitoring system [3, 9, 10] used to measure the environment in real time, showing a very good agreement for different accelerator locations [22]. A detailed description of the use of FLUKA to characterize the radiation fields in the accelerator context is provided in Chapter 4.

Moreover, many of the systems controlling, monitoring and protecting the accelerator (and which are by design constraints located close to it) are built with Commercial Off-The-Shelf (COTS) components, and are therefore potentially sensitive to radiation effects that can negatively affect the operation of the accelerator [23–25]. For this reason, radiation testing of the candidate parts for a given system to be operated in the accelerator mixed-field is essential in order to decide whether they are suitable or not for such a purpose. A detailed knowledge of the radiation environment (integral levels and particle energy spectra) in which the system is to be operated is therefore essential in order to define the radiation test to be performed (particle type, energy, total fluence) and the resulting acceptance or rejection of the part.

In the LHC and its surroundings, the mixed radiation field is composed of a wide variety of particle species. Those capable of inducing SEEs are hadrons (i.e. those by definition capable of undergoing nuclear interactions and therefore of depositing large amounts of energy through indirect ionization\(^1\)). The most relevant hadrons present in the LHC radiation field are protons, neutrons, charged pions and (to a lesser extent) kaons. In the case of charged hadrons, they are normally only found in a significant proportion above several hundred keVs, with their flux peaking at several hundred MeVs. Neutrons on the other hand extend down to thermal energies owing to their neutral character. A typical LHC particle energy spectra can be seen in Fig. 2.1 expressed in lethargy form\(^2\) thus highlighting the different SEE-relevant energy intervals that will later be defined in this chapter.

In first approximation, and owing to theoretical and empirical arguments that will be introduced later, the SEE rate is proportional to the High Energy Hadron (HEH) flux\(^3\), defined as the integral hadron flux above 20 MeV. As a consequence, the annual HEH flux is employed to

---

\(^1\)As will be detailed in subsection 2.2.2 state-of-the-art deep sub-micron technologies are also sensitive to direct ionization from singly charged particles.

\(^2\)Lethargy is defined as the differential flux times the geometrical mean of the bin energy and is often used to represent neutron energy spectra [26]. Because the flux decreases with energy following a power law of index near one in a wide energy range, the respective lethargy representation is almost constant in this interval. In addition, because \(\frac{d\phi}{dE} \cdot E = \frac{d\phi}{d(logE)}\), when plotting the lethargy in log-lin representation, the surface below the differential flux curve is proportional to the integral flux.

\(^3\)In general, the flux (here represented as \(\Phi_{HEH}\)) is defined as the number of particles per unit surface and time, whereas fluence (here represented as \(\Phi_{HEH}\)) corresponds to a time-integrated flux. In both cases, the quantities can be expressed in differential form with respect to energy or integrated over an energy interval.
Fig. 2.1. FLUKA simulated lethargy spectra for the SEE-relevant hadrons at an LHC-like test location at the CHARM test facility (to be described in detail in Chapter 3). The different shaded regions represent, in an approximate manner, the thermal neutron (gray), intermediate neutron (blue) and HEH fluxes (red), defined formally in Table 2.3.

![FLUKA simulated lethargy spectra](image)

Table 2.1. HEH annual fluxes for different radiation environments.

<table>
<thead>
<tr>
<th>Spectrum</th>
<th>$\Phi_{HEH} (/cm^2/yr)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground level</td>
<td>$1 \sim 2 \cdot 10^5$</td>
</tr>
<tr>
<td>Avionics</td>
<td>$\sim 2 \cdot 10^7$</td>
</tr>
<tr>
<td>ISS Orbit</td>
<td>$\sim 7 \cdot 10^8$</td>
</tr>
<tr>
<td>Polar LEO orbit (800 km)</td>
<td>$\sim 3 \cdot 10^9$</td>
</tr>
<tr>
<td>LHC</td>
<td>$\sim 10^6 \sim 10^{12}$</td>
</tr>
</tbody>
</table>

characterize the SEE-relevant radiation level for a certain LHC location. As a first introduction to these levels, Table 2.1 shows a summary of the approximate annual HEH flux values both at the LHC and other contexts of interest. As an initial observation, it can be noted that levels in the LHC have a very wide range, extending from values just above the natural ground level flux to quantities several orders of magnitude larger than those obtained for typical Low Earth Orbit (LEO) missions.
Chapter 2. LHC Mixed Radiation Environment and other Contexts of Interest

2.2 LHC Environment Description and SEE Rate Calculation

2.2.1 | HEH, intermediate and thermal neutrons

Provided it is the most sensitive and broadly studied SEE, the environment description presented here is first based on the SEU response. A generalization to other (destructive) SEEs will be introduced in Chapter 6, however the environments relevant to effects requiring larger energy deposition quantities than SEUs can be considered as a subset of the SEU-relevant description.

As was introduced above, the main representative value for SEE rate quantification is taken as the integral hadron flux above 20 MeV on the basis that the inelastic interaction probability of hadrons is fairly constant above this value [27, 28] and that below it, charged particles (i) lose a significant amount of energy in their passage through the component package, thus not reaching the SV or (ii) reach the SV but do not have enough energy to produce inelastic events leading to an SEU [22]. This physical feature is supported by a wide variety of proton SEU data showing a significant cross section fall-off below this energy. Therefore, in a first simplified approach all hadron species above this energy are considered equally efficient in inducing SEUs whereas all charged hadrons below it are regarded as incapable of triggering an SEU.

In contrast, neutrons below 20 MeV need to be treated differently owing to their neutral character and significant proportion in the LHC context. Therefore, two further neutron energy intervals are included in the SEU-relevant environment description:

(i) neutrons below 20 MeV have proven capable of inducing SEUs in different SRAM technologies [29, 30]. Therefore, a weighed contribution of the neutrons in the 0.2 - 20 MeV range 4 is considered according to the Toshiba RadMon response (reference TC554001AF-70L [32]) and referred to as intermediate energy neutron equivalent flux ($\phi_{n_{int}}$). When added to the HEH flux, the total value is referred to as HEH equivalent flux ($\phi_{HEH_{eq}}$). The respective mathematical expressions are shown in Eq. 2.1 where the Weibull fit function is of the form shown in Eq. 2.2. The corresponding fit parameters can be found in Table 2.2.

\[
\phi_{HEH_{eq}} = \int_{0.2 \text{ MeV}}^{20 \text{ MeV}} w_{int}(E) \phi_n(E) dE + \int_{20 \text{ MeV}}^{\infty} \phi_{HEH}(E) dE = \phi_{n_{int}} + \phi_{HEH} \quad (2.1)
\]

\[
w_{int}(E) = 1 - e^{-(E-E_o)/W} \quad (2.2)
\]

(ii) thermal neutrons (defined with a kinetic energy of 0.025 eV) can induce SEUs through their capture by $^{10}B$ nuclei and the production of energetic $^7Li$ (0.84 MeV) and $^4He$ (1.47 MeV) ions [33,34] with a probability decreasing as the inverse of the neutron velocity, $v$. The $^{10}B$

\footnote{The lower limit of 0.2 MeV corresponds to the minimum ($n$, $\alpha$) reaction energy for materials typically present in electronic components; in this case, nitrogen [31].}
2.2. LHC Environment Description and SEE Rate Calculation

Table 2.2. Weibull fit parameters for the Toshiba SRAM neutron SEU cross section implemented in FLUKA and used to extract the equivalent HEH flux [22].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_o$ (MeV)</td>
<td>0.2 MeV</td>
</tr>
<tr>
<td>$W$ (MeV)</td>
<td>9.25</td>
</tr>
<tr>
<td>$s$</td>
<td>3.02</td>
</tr>
</tbody>
</table>

neutron capture cross section at 0.025 eV is measured to be 3855 ± 26 b in [35]. Therefore, the equivalent thermal neutron flux ($\phi_{th}$) is defined as the neutron flux weighted by a $1/v$ function as shown in Eq 2.3, which considers non-relativistic energies. Likewise, the thermal neutron risk factor (here referred to as the R factor, $R^5$) is introduced as the ratio between the equivalent thermal neutron and the HEH fluxes [18]. An LHC tunnel neutron energy spectrum is shown in Fig. 2.2 with the different contributions (thermal, HEH equivalent and HEH) represented as well.

$$\phi_{th} = \int_0^\infty w_{th}(E)\phi_n(E)dE$$

$$w_{th}(E) = \left(\frac{0.25 \text{ eV}}{E \text{ (eV)}}\right)^{1/2}$$

Provided the knowledge of the thermal neutron and HEH equivalent fluxes for a specific location, the SEU rate (also referred to as Soft Error Rate, SER) can be extracted by multiplying each value by the respective sensitivity, represented through the cross sections. By definition of the corresponding equivalent fluxes, the cross sections to be considered are the thermal neutron cross section ($\sigma_{th}$, at 0.025 eV) and the HEH cross section ($\sigma_{HEH}$, at a saturated energy, regarded in the present work as protons at 230 MeV$^6$ unless stated otherwise.). These quantities, together with the fluxes defined above and other related values are summarized in Table 2.3. Moreover, the expression relating these values to the expected SEU rate can be found in Eq. 2.4. We will refer to the calculation of SEU rates using this expression and the definitions introduced above at the HEH approach.

$$SER = \phi_{th}\sigma_{th} + \phi_{HEH_{eq}}\sigma_{HEH}$$

2.2.2 | Other contributions and dependencies of interest

In addition to the HEH description of the mixed-field radiation environment introduced in subsection 2.2.1 (considering the thermal neutron, intermediate energy neutron and HEH contributions), the R stands for risk, as both the thermal neutron flux and component sensitivity are often unknown or subject to large uncertainties.

$^5$Maximum energy available at the PSI PIF facility where standard CERN radiation tests are carried out (as detailed in Chapter 3).
fluxes), there are at least three further potentially relevant contributions not directly accounted for in this approach that therefore deserve a separate analysis:

(i) the HEH cross section energy dependence.

(ii) the HEH cross section dependence on the hadron type.

(iii) the contribution from low energy charged particles.

The first point is related to the assumption that the hadron SEE cross section is saturated at (at least) 230 MeV [28]. Whereas this is generally the case for silicon-dominated SEEs, cross sections driven by high-Z fission fragments have been shown to have a very strong dependency with energy, even at several hundred MeVs [36–38]. In these cases, considering a constant cross section value at an energy lower than the actual saturation can lead to an underestimation of the error rate (or equivalently, overestimation of time to failure) that can be especially significant in environments with hard particle energy spectra.

7The terms hard and soft used for describing energy spectra are traditionally employed in the astrophysics context for EM radiation, however in the scope of the current thesis they are also used for the particle energy spectra relevant to SEEs.
### Table 2.3. SEU-relevant quantities defined to characterize a mixed-field radiation environment.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Notation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Energy Hadron (HEH) flux</td>
<td>$\Phi_{HEH}$</td>
<td>Hadron flux above 20 MeV. For LHC environments, often referred to in units of $\text{HEH/cm}^2/\text{yr}$ and nominal operational conditions. Available as a generalized particle in FLUKA under the name HADGT20M.</td>
</tr>
<tr>
<td>Intermediate neutron flux</td>
<td>$\Phi_{n_{int}}$</td>
<td>Weighed neutron contribution in the 0.2 - 20 MeV energy range according to the Toshiba RadMon response [22].</td>
</tr>
<tr>
<td>Equivalent High Energy Hadron flux</td>
<td>$\Phi_{HEH_{eq}}$</td>
<td>Hadron flux above 20 MeV plus the intermediate neutron fluence. Available as a generalized particle in FLUKA under the name HEHAD-EQ.</td>
</tr>
<tr>
<td>Equivalent Thermal Neutron flux</td>
<td>$\Phi_{th}$</td>
<td>Neutron flux weighed by the $^{10}\text{B}(n,\alpha)^7\text{Li}$ cross section normalized to the value at thermal energy ($0.025$ eV). Available as a generalized particle in FLUKA under the name THNEU-EQ.</td>
</tr>
<tr>
<td>Differential HEH flux</td>
<td>$\phi_{HEH}(E)$</td>
<td>Differential flux of HEH as a function of energy, typically in units of $\text{HEH/cm}^2/\text{s}/\text{GeV}$</td>
</tr>
<tr>
<td>Differential neutron flux</td>
<td>$\phi_{n}(E)$</td>
<td>Differential neutron flux as a function of energy, typically in units of $\text{HEH/cm}^2/\text{s}/\text{GeV}$</td>
</tr>
<tr>
<td>R factor</td>
<td>$R$</td>
<td>Ratio between the equivalent thermal neutron flux and the HEH flux.</td>
</tr>
<tr>
<td>HEH cross section</td>
<td>$\sigma_{HEH}$</td>
<td>SEU cross section at a saturated hadron energy (taken as 230 MeV protons unless stated otherwise).</td>
</tr>
<tr>
<td>Thermal neutron cross section</td>
<td>$\sigma_{th}$</td>
<td>SEU thermal (0.025 eV) neutron cross section.</td>
</tr>
</tbody>
</table>

A possible way of representing the potential impact of a strong cross section energy dependency on the operational error rate is to quantify the hardness of the respective radiation field. In order to do so, two hardness energies are introduced as those at which 50% ($H_{50\%}$) and 10% ($H_{10\%}$) of the total HEH flux lie above. For instance, it is clear that the HEH error rate in an environment with an $H_{10\%}$ value of ~100 MeV is not expected to be larger than that extracted from the experimental $\sigma_{HEH}$ value (defined at 230 MeV) however in a mixed-field with a $H_{50\%}$ value equal to 800 MeV, an increasing cross section with energy above the measured $\sigma_{HEH}$ could lead to a significant SEE rate underestimation. Moreover, the normalized reverse integral of the HEH flux as a function of energy (here defined as $NRI_{HEH}(E)$) can be used to provide a graphical representation of the relative hardness of a certain spectrum. Through it, different environments can be compared in terms of their energy dependence regardless of the absolute intensity value. $NRI_{HEH}(E)$ is defined as a function that takes the value of the relative HEH proportion above a certain energy as shown in Eq. 2.5 together with the respective hardness energy definitions.

---

Radiation Fields at High-Energy Accelerators and their impact on Single Event Effects
Concerning the second point, while protons and neutrons have been shown to have an experimentally equivalent SEE cross section above \( \sim 50 \text{ MeV} \) (as expected by their analogous hadronic character \([39]\)), charged pions have been reported in the past as having a different behavior, with a factor \( \sim 3 \) cross section increase with respect to protons at around 150 MeV for different DRAM components \([40]\)\(^8\). Because charged pions can have a significant contribution to the total HEH flux in the accelerator context, their relative proportion will be considered in the description of the mixed field environments, along with protons and neutrons \(^9\). Moreover, the potential effects of charged pions on the different SEE processes is considered from a simulation perspective in Chapters 5 and 7.

As to what regards the third point, it is now well established that low energy singly-charged particles such as protons or muons are capable of inducing SEUs through direct ionization in deep sub-micron SRAM technologies \([42–46]\). In addition, low energy negative muons are expected to be more efficient in inducing SEUs than their positive counter-parts owing to the negative muon capture probability \([47]\). Likewise, negative pions are also capable of depositing large amounts of localized energy though their capture by the positive nuclei. All these particles, while considered capable of inducing SEUs in modern SRAM technologies, are not included in the HEH approach introduced in subsection 2.2.1. In this case, there is to our best knowledge no study quantifying the potential effect of such a contribution to the mixed-accelerator error rate for highly integrated technologies. This point, though regarded as relevant from a research and application perspective, is beyond the scope of this thesis.

Finally, heavy ions, though accelerated in the LHC during lead-lead or lead-proton collision experiments are not considered a part of the LHC radiation environments as they do not reach the electronic equipment owing to their fragmentation and absorption. Heavy ions produced in the vicinity of the sensitive volume through nuclear interactions are ultimately responsible for the SEE induction, however from a radiation environment point of view these are considered as events induced indirectly by the incoming hadron.

\(^8\)In contrast, in \([41]\) no measurable difference could be identified in the 60-250 MeV interval for a set of SRAMs and DRAMs.

\(^9\)Kaons are in general not considered explicitly as they typically have fluxes at least one order of magnitude lower than the three dominating hadrons (see Fig. 2.1).
2.3 Mixed-Field Environment Parametrization

In the following subsections, different mixed-field radiation environments are introduced and quantified according to the parameters defined in Section 2.2.

2.3.1 LHC Accelerator environment

The LHC and its surroundings are critical zones for electronic component operation, and therefore their respective radiation environments need to be carefully considered. In this context, three main subcategories can be further defined according to the distance of the areas to the concerned radiation source and the amount of shielding between them:

(i) the tunnel, in which the amount of electronics is minimized and if present, was initially tested for and validated against SEE, TID and DD effects for the relevant fluences.

(ii) the heavily-shielded areas (known as UJs), close to the interaction points.

(iii) the lightly-shielded areas (named RRs) with less intense, harder spectra than their more protected counterparts.

The two shielded areas (UJs and RRs) are often referred to as alcoves in the LHC context and typically host a wide variety of electronic systems controlling the accelerator. An example of a horizontal cut from a FLUKA geometry for the two latter is shown in Fig. 2.3 in order to provide a visual representation of their locations relative to the LHC tunnel.

Using the quantities defined above, and with the objective of providing an overview of the radiation levels and spectra in the different critical LHC areas, Table 2.4 shows the main SEE-relevant characteristics of the radiation fields present for different location categories and nominal operational conditions (50 fb$^{-1}$ of annual integral luminosity at 7 TeV energy). These include the annual HEH flux, their typical particle compositions, the intermediate neutron contribution, the $R$ factor and the hardness energy values. A comparison of the normalized neutron spectra and the reverse HEH integrals are shown in Fig. 2.4. Furthermore, orientational TID and 1 MeV equivalent neutron values are provided in Table 2.5 for the three different zones considered.

As can be noticed, the hardness of the spectra as well as its composition vary significantly depending on the specific location. Generally speaking, the more shielded areas (i.e. the UJs) have softer, more neutron-dominated spectra. In addition, it is worth noting that the thermal neutron flux and respective $R$ factor strongly depends on the exact location and shielding materials. For example, $R$ factors as large as 200 for a UJ and 50 for an RR are reported in [48].

---

10 The examples considered are extracted from calculations performed for the tunnel and UJ76 and RR7 alcoves in the IR7 line of the LHC.
Chapter 2. LHC Mixed Radiation Environment and other Contexts of Interest

Fig. 2.3. Horizontal cut (top view) of the FLUKA geometry example for a UJ (top) and RR (bottom) location. Each plot represents an LHC tunnel 30 m sector in the beam direction with the respective alcove areas on the side. The shielding between the tunnel and the regions typically hosting electronic systems is 40 cm of iron (brown) and 200 cm of concrete (gray) for the UJ and 40 cm of iron plus 40 cm of concrete in the RR.
2.3. Mixed-Field Environment Parametrization

Table 2.4. Expected maximum nominal annual HEH fluence for two different LHC areas [1] together with the respective typical HEH composition, intermediate energy neutron contribution (in HEH percentage), R factor and hardness energies.

<table>
<thead>
<tr>
<th>Critical Area</th>
<th>$\Phi_{HEH}$ ($/cm^2/yr$)</th>
<th>Composition (%)</th>
<th>R</th>
<th>Hardness Energy (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>n</td>
<td>p</td>
<td>$\pi^\pm$</td>
</tr>
<tr>
<td>UJ</td>
<td>$\sim 2.5 \cdot 10^9$</td>
<td>99</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>RR</td>
<td>$\sim 1.0 \cdot 10^9$</td>
<td>71</td>
<td>13</td>
<td>16</td>
</tr>
<tr>
<td>Tunnel</td>
<td>$\sim 6.0 \cdot 10^{11}$</td>
<td>45</td>
<td>18</td>
<td>37</td>
</tr>
</tbody>
</table>

Fig. 2.4. Normalized lethargy neutron (left) and reverse integral spectra (right) for different LHC accelerator radiation environments.

Table 2.5. Expected nominal annual 1 MeV equivalent neutron and TID for the three locations considered and the HEH fluxes reported in Table 2.4. The conversion factors used are $1 \text{HEH/cm}^2 = 4.1 \text{MeV n}_{eq}$ and $10^9 \text{HEH/cm}^2 = 1 \text{Gy}$ and can generally be applied in a mixed-field context in order to obtain a rough estimate of the DD and TID effects.\footnote{\textsuperscript{11}The exact value does not linearly correlate with the HEH flux and depends on the specific composition and energy spectra (including particles not relevant for SEEs such as photons or electrons) therefore requiring a separate study both from a monitoring and simulations point of view.}

<table>
<thead>
<tr>
<th>Critical Area</th>
<th>$1 \text{ MeV n}_{eq}$ ($/cm^2/yr$)</th>
<th>TID ($\text{Gy/yr}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UJ</td>
<td>$\sim 1.0 \cdot 10^{10}$</td>
<td>$\sim 2.5$</td>
</tr>
<tr>
<td>RR</td>
<td>$\sim 4.0 \cdot 10^9$</td>
<td>$\sim 1$</td>
</tr>
<tr>
<td>Tunnel</td>
<td>$\sim 2.4 \cdot 10^{12}$</td>
<td>$\sim 600$</td>
</tr>
</tbody>
</table>

2.3.2 | LHC Experiment environment

The LHC experiments are areas with very large high-energy particle fluxes due to their vicinity to the interaction points. For this reason, most electronic components used in the detector are radiation hardened by design. However, commercial electronics is still used in some detector designs owing to their low relative cost and attractive electrical performance.

\textsuperscript{11}The exact value does not linearly correlate with the HEH flux and depends on the specific composition and energy spectra (including particles not relevant for SEEs such as photons or electrons) therefore requiring a separate study both from a monitoring and simulations point of view.
In this case, the expected SEE rate and subsequent impact at a system level needs to be carefully evaluated in the design study. A good example of this is the case of the FPGA used in the ALICE detector readout electronics [49–51]. Therefore, the need of characterizing the respective environments is essential to extract realistic error rates from the experimental SEE cross section measurements.

An example of a representative LHC experiment spectra is shown here for the ATLAS case\textsuperscript{12}. Table 2.6 summarizes the SEE-relevant parameters for two cylindrical detection surfaces in the ATLAS detector, both centered around the interaction point and with their axis along the beam line. The first surface (labeled as \textit{inner}) has a radius of 20 cm and extends over 3.0 m in the z (beam) direction. The second surface (labeled as \textit{outer}) has a radius of 390 cm and a z dimension of 6.0 m. The respective reverse HEH integral spectra for these locations are shown in Fig. 2.5 compared to the UJ and tunnel cases for the LHC.

<table>
<thead>
<tr>
<th>Critical Area</th>
<th>$\Phi_{HEH}$ ($/cm^2/yr$)</th>
<th>Composition (%)</th>
<th>R</th>
<th>Hardness Energy (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer</td>
<td>$\sim 3.5 \cdot 10^9$</td>
<td>67 5 28 25 1.1</td>
<td>140</td>
<td>460</td>
</tr>
<tr>
<td>Inner</td>
<td>$\sim 1.0 \cdot 10^{12}$</td>
<td>4  7  89 1</td>
<td>2.0</td>
<td>890 3.8 GeV</td>
</tr>
</tbody>
</table>

As expected, the location closest to the interaction point shows a harder HEH spectrum and a composition very rich in charged pions. In terms of absolute values, the annual HEH fluxes for the inner and outer surfaces are similar to those encountered in the LHC tunnel and shielded areas respectively.

2.3.3 | Atmospheric environment

In a similar way as high energy protons interact with elements of the accelerator in the LHC, very energetic charged particles generated and accelerated in outer space and known as Galactic Cosmic Rays (GCR) interact with the Earth’s atmosphere creating showers of secondary particles of which neutrons and muons reach the surface in a largest proportion. The former have been long known to induce SEEs in the terrestrial context [52] whereas recent studies show that the latter are also capable of inducing SEUs though direct ionization [44, 53].

\textsuperscript{12}Raw data was obtained through a private communication with an ATLAS radiation expert.

\textsuperscript{13}The milibarn (mb) is a cross section unit equal to $10^{-27} cm^2$. When performing Monte Carlo simulations of a radiation environment, the proton-proton (pp) interaction is often the starting point, therefore in order to normalize the results, it is necessary to know how many interactions occur for a given time period. This is proportional to both the number of protons crossing each other and their interaction probability given by the respective cross section.
Fig. 2.5. Reverse HEH normalized integral fluxes for the ATLAS experiment and LHC accelerator environments described in the text.

An increasing interest for ground level and avionics radiation induced effects has been evident in the recent years \[33, 54\]. With the scaling of electronic components, the sensitivity per integrated chip can develop significantly, reaching levels that can seriously impact the reliability of systems even for ground level applications. Therefore, comparing the accelerator environment with its atmospheric counterpart is valuable in order to underline the possible similarities and differences between them.

For this purpose, Table 2.7 is introduced showing the main characteristics of the atmospheric spectra at different altitudes. The corresponding HEH reverse integral spectra are shown in Fig. 2.6 and directly compared to the LHC tunnel case. The following general conclusions can be drawn when contrasting these values with the accelerator environment cases:

(i) the ground level and avionics flux levels are generally below those encountered in the critical accelerator zones.

(ii) the neutron and proton HEH fraction is similar to the accelerator environment (with different possible combinations) however the pion contribution is below 1% even at the highest altitude considered\(^{14}\) while being dominant in certain accelerator cases.

(iii) the contribution of intermediate neutrons is similar, however the thermal neutron fraction (represented through the R factor) is much lower than the one in the accelerator

---

\(^{14}\)This analysis only considers pions in the atmospheric environment and not those created through the interaction of high energy hadrons with the aircraft materials.
cases. It is to be noted however that the thermal neutron flux for a given location strongly depends on the materials surrounding it, therefore for components inside buildings or airborne, the R factor can vary significantly.

(iv) the atmospheric and stratospheric spectra are of a hard character, with the hardness energy increasing rapidly with altitude. In fact, the HEH spectrum at 20 km is more energetic than in the LHC-tunnel environment.

Table 2.7. Expected nominal annual HEH for different atmospheric environments extracted using the QARM tool [55] together with the respective typical HEH composition (in HEH percentage), R factor and hardness energies. Different altitudes are included for a latitude of 46°N and a longitude of 6°E (Geneva, Switzerland)

<table>
<thead>
<tr>
<th>Altitude</th>
<th>( \Phi_{HEH} ) (( \text{cm}^2/\text{yr} ))</th>
<th>Composition (%)</th>
<th>R</th>
<th>Hardness Energy (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>( n )</td>
<td>( p )</td>
<td>( \pi^\pm )</td>
</tr>
<tr>
<td>375 m</td>
<td>( \sim 1.7 \cdot 10^5 )</td>
<td>93</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>10 km</td>
<td>( \sim 1.7 \cdot 10^7 )</td>
<td>82</td>
<td>18</td>
<td>0</td>
</tr>
<tr>
<td>20 km</td>
<td>( \sim 3.8 \cdot 10^7 )</td>
<td>68</td>
<td>32</td>
<td>0</td>
</tr>
</tbody>
</table>

Fig. 2.6. Reverse integral normalized HEH fluxes for different atmospheric environments as extracted using the QARM online tool [55]. The ground level location corresponds to that of Geneva (375 m altitude, 46°N, 6°E).
2.3. Mixed-Field Environment Parametrization

2.3.4 | Proton-belt Space environment

The space environment remains the core activity in the SEE analysis domain provided its harsh conditions and very high reliability requirements. For this reason, detailed and accurate models of the space radiation environment are available, as well as a wide range of space-borne detectors (and even full missions) specifically designed to study the radiation effects on electronics.

Of the relevant space environments for electronic component operation, the Earth’s inner proton radiation belt is the context that most resembles that of an accelerator owing to the dominance of singly charged hadrons and thus having indirect ionization as the main source of SEE-induction. This environment is highly relevant for Low-Earth Orbits (LEO), including those of the International Space Station (ISS) and more generally Earth-observation missions.

In order to put this environment in contrast with the high-energy accelerator case, two LEO orbit spectra examples (that of the International Space Station and the sun-synchronous orbit of the Proba-II mission [7]) were extracted using the CREME 96 online tool [56]. The main SEE-relevant characteristics of the particle energy spectra are shown in Table 2.8. The respective normalized reverse integral HEH fluxes are plotted together in Fig. 2.7, including two examples of the high-energy accelerator environment for the shielded locations. It is to be noted that in the case of the latter, protons are typically present together with other hadron species (notably neutrons and charged pions); whereas in the former, heavy ions will also be part of the environment despite the geomagnetic shielding and therefore also contribute to the SEE rate.

Table 2.8. Main characteristics of two examples of trapped proton-belt spectra averaged over the orbit and extracted using the CREME 96 tool [56] with the AP8MIN model (Cosmic-ray maximum). Protons are the only relevant HEH type.

<table>
<thead>
<tr>
<th>Mission</th>
<th>Altitude (km)</th>
<th>Inclination</th>
<th>HEH Fluence ($/cm^2/yr$)</th>
<th>$H_{50%}$ (MeV)</th>
<th>$H_{10%}$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISS</td>
<td>450</td>
<td>51.5°</td>
<td>$\sim 7.3 \cdot 10^8$</td>
<td>110</td>
<td>250</td>
</tr>
<tr>
<td>Proba-II</td>
<td>800</td>
<td>98.3°</td>
<td>$\sim 2.7 \cdot 10^9$</td>
<td>100</td>
<td>280</td>
</tr>
</tbody>
</table>

The following conclusions can be extracted when comparing the proton belt environment with the accelerator context:

(i) HEH fluxes in the proton belt are similar to those in the shielded LHC locations.

(ii) the accelerator field is typically composed of protons, charged pions and neutrons (or of the latter in heavily shielded areas) whereas protons are the only relevant hadron type for the inner belt case inducing SEEs through indirect ionization.

(iii) spectra are generally harder (more energetic) in the accelerator case (except for the negligible contribution from Galactic Cosmic Ray (GCR) protons which correspond to the
tails above ~600 MeV in Fig. 2.7) whereas the low energy interval (~1 MeV, not included in 2.7) potentially relevant for direct ionization effects in deep sub-micron technologies is more prominent in the case of the inner radiation belt.

2.4 Volume-Equivalent LET Environment Representation

A representative (while simplified) manner of visualizing the potential impact of the radiation environment in terms of SEE induction is through the so-called LET spectra. As is typically done for interplanetary space environments, the heavy ion flux of a specific radiation field can be plotted as a function of their individual LET values (defined in Chapter 1), either in a differential or integral form. An example of this is shown in Fig. 2.8 for the interplanetary space environment extracted using the CREME online tool [56]. If a step-function SEE cross section is considered at a certain LET threshold value, the corresponding error rate is proportional to the respective value of the reverse integral LET spectrum.

The main advantage of this representation is that of being able to describe a very complex mixed-field involving a wide range of particles species and energies through a flux as a function of a single variable (LET, in this case). The associated limitations however are also important, and mainly related to the fact that it is actually the collected charge as opposed to the LET that determines the occurrence or not of an SEE, and the relation between both variables is not always straight-forward. Notably, the latter strongly depends on the dimensions of the
regions sensitive to the energy deposition as well as their efficiency in collecting the charge. In addition, nuclear reaction products generated in the vicinity of the SV are not be considered in the LET representation while however still contributing to the SEE rate. Moreover, whereas ground testing with heavy ions is typically performed at normal incidence, the interplanetary GCR flux is isotropic. Again, this introduces a dependency of the deposited energy distribution on the specific SV geometry of a given component.

In analogy to the interplanetary HI case, it is possible to represent the accelerator environment in a similar manner as that depicted in Fig. 2.8. Nevertheless, further considerations (in addition to those applicable to the interplanetary environment) are to be carefully taken into account related to the fact that the particles responsible for the SEE induction in the accelerator (and atmospheric) case are typically not those of the external environment directly but are rather generated through nuclear interactions in the SV material and its surroundings, therefore:

(i) the LET spectra in the accelerator case will strongly depend on the materials surrounding the SV.
(ii) the direction of the secondary fragments with respect to the primary particle is not uniquely defined (for instance, fission fragments are isotropic [37]).
(iii) the secondary heavy ions generated through the interaction of the environment particles with the component materials typically have energies and ranges much smaller than GCR
(and ground test) heavy ions, and therefore the LET can vary significantly within the SV, its initial value being no longer representative of the total energy deposited in the SV.

In order to overcome these important limitations for the LET spectrum representation in the indirect energy deposition case as well as to account for the directionality of the environment, the \emph{volume-equivalent LET} (\(\text{LET}_{\text{vol}}\)) is introduced at the cost of depending on a certain SV (and surroundings) definition. The volume-equivalent LET is defined as the deposited energy in a certain volume divided by its thickness (determined itself by the standard ground test direction used, i.e. normal to the device’s surface). In other words, an indirect energy deposition event (potentially involving stopping ions, non-representative LET values, at-angle incidence and reaction products) is represented though the LET of a penetrating HI that would lead to the same energy deposition in the standard experimental case.

In the general case of having a certain experimental HI cross section \(\sigma(\text{LET})\) (by convention defined for the direction normal to the device’s surface) the error rate would correspond to the convolution of the latter with the differential volume-equivalent LET spectrum, \(\phi_{\text{vol}}(\text{LET})\), as shown in Eq. 2.6, where \(S \text{ [cm}^2\text{]}\) is the total surface of the component exposed to the radiation field and \(\kappa\) is a dimensionless factor related to the geometry of the sensitive volume and the directionality of the radiation field\(^{15}\). Let it be noted that \(\phi_{\text{vol}}(\text{LET})\) corresponds to the product of the differential LET spectrum and the integral path-length distribution in the broadly used RPP expression initially introduced by Bradford [57] and therefore has units of \(\text{[LET/ cm}^2\text{/ s]}\) when expressed per unit time to calculate the SER or \(\text{[LET/ cm}^2\text{]}\) when integrated over a time period (e.g. a space mission lifetime) to calculate the total number of events. In addition, \(\text{LET}_o\) is the minimum LET capable of inducing an error in the component, which will be equal to \(\text{LET}_c \cdot \frac{t}{l_{\text{max}}}\), where \(\text{LET}_c\) is the critical LET in the experimental case (normal incidence), \(t\) is the thickness of the component in the test direction and \(l_{\text{max}}\) is the maximum possible path-length in the SV. An analytic expression of \(\phi_{\text{vol}}(\text{LET})\) is provided in Eq. 2.7, where \(\phi(\text{LET})\) is the differential LET spectrum and \(C\left(\frac{E_c}{\rho \cdot \text{LET}}\right)\) is the reverse integral path-length distribution [4].

A possible interpretation of this expression is the following: for a given LET value from the LET spectrum, the probability of it creating an upset is that of depositing an energy larger that the critical energy, \(E_c\). For this LET, there will be a minimum (critical) path-length traveled by the particle above which it will induce an event, which will be equal to \(\frac{E_c}{\rho \cdot \text{LET}}\), where \(\rho\) is the density of the material. The integral path-length distribution is the probability that the path-length for a specific geometry and radiation field directionality is larger than the critical value. Its product with the LET spectrum yields the volume-equivalent LET spectrum.

\[
\text{SER} = \kappa \cdot S \int_{\text{LET}_o}^{\text{LET}_{\text{max}}} \frac{d\phi_{\text{vol}}(\text{LET})}{d(\text{LET})} \sigma(\text{LET}) d(\text{LET})
\]

\[\text{(2.6)}\]

\(^{15}\)For example, for an isotropic field, \(\kappa = \frac{1}{4}\), and for a monodirectional beam homogeneously covering the sensitive surface, \(\kappa = 1\).
2.4. Volume-Equivalent LET Environment Representation

\[
\phi_{\text{vol}}(\text{LET}) = \phi(\text{LET}) \cdot C \left( \frac{E_c}{\rho \cdot \text{LET}} \right) \tag{2.7}
\]

When extracted through a Monte Carlo simulation as opposed to the analytic expression, the calculation of the volume-equivalent LET (derived from the event-by-event deposited energy distribution) implicitly considers effects such as the LET difference through the passage of the SV, the path-length distributions of both the environmental particles and their fragments, and the fact that only part of the ionization column might be contained in the SV. Notably, another key point of the simulation is that of considering the nuclear reaction probabilities and fragment properties.

With the purpose of illustrating the volume-equivalent LET representation and its application, an RPP volume of dimensions 0.44 x 0.34 x 0.4 \( \mu m^3 \) is considered, consistent with a 150 nm SRAM technology [58]. In order to account for the indirect energy deposition (relevant for hadron-dominated environments such as the atmospheric or the high-energy accelerator) the surroundings of the SV need to be defined so that fragments generated in them can reach the SV. As a basic assumption, 5 \( \mu m \) of SiO\(_2\) are considered directly above the SV as representative of the Back-End-Of-Line (BEOL), which is the set of metalization and insulation layers placed on top of the active transistors, providing access to the SRAM bit cells. As was shown in [59, 60], its thickness and composition can have a strong impact on the SEE rate.

This model can then be used in FLUKA to extract the event-by-event energy deposition distribution for a given incident beam or environment, including the inelastic fragment contribution. The SER as a function of critical LET can then be defined as the normalized reverse integral of the events above the critical value. Details of this approach will be provided in Chapter 4.

The resulting distributions are shown in Fig. 2.9 for different energies and HEH mixed-fields (i.e. only hadrons above 20 MeV are considered) and a pure silicon case. The different cross sections for a given critical \( \text{LET}_{\text{vol}} \) are proportional to the corresponding error probability value per incoming particle. As can be seen, for the monoenergetic proton beams, the error probability tends to one for an LET approaching zero, consistent with the fact that all incoming particles through the sensitive surface will deposit a certain amount of energy. In contrast, the curve for the UJ environment is fully representative of the indirect energy deposition, as only neutrons are involved. In addition, it can be useful to represent the SEE probability (or SEE cross section if normalized to the sensitive surface) as a function of critical charge instead of LET. The relationship between both is based on the fact that 3.6 eV are needed in silicon to produce an electron-hole pair. Therefore, 22.5 MeV are required to generate 1 pC of charge as extracted using the conversion factors in Eq. 2.8 where \( q_e \) is the charge of the electron. A state-of-the-art SRAM component (e.g. 65 nm technology) has a critical charge of around 1 fC [42].
As can be noticed, for values above the maximum direct energy deposition from protons ($LET_{vol} \sim \sim 0.1 \text{ MeV cm}^2 / \text{mg}$) the expected cross section is within a factor $\sim 3$ for all cases considered, despite the wide energy range and hardness of the spectra (from 60 MeV to 3 GeV protons, and UJ and tunnel environment). This result is in line with the experimental observation that the SEE cross section above several tens of MeV is typically saturated, and also supports the use of the HEH flux as being representative of the expected SEE rate for a given environment. However, as has been shown in the past [36–38] and as will be developed in Chapters 5 and 6, this is not necessarily the case for components with materials significantly denser that silicon (or other standard BEOL materials such as $SiO_2$ and aluminum) in the surroundings of the SV.

\[
\frac{3.6 \text{ eV}}{q_e} = \frac{3.6 \cdot 10^{-6} \text{ MeV}}{1.6 \cdot 10^{-7} \text{ pC}} = \frac{22.5 \text{ MeV}}{pC}
\]  

(2.8)

**Fig. 2.9.** Simulated error probability per incident particle on the SV surface for the RPP model introduced in the text as a function of critical charge/volume-equivalent LET for different monoenergetic beams and HEH mixed environments. Only silicon and $SiO_2$ are considered in the sensitive volume and its surroundings.

### 2.5 Summary

In the present chapter, a parametrization of the mixed-field radiation environments was introduced with the purpose of describing and comparing different contexts of interest according to their capability of inducing SEEs. This description includes the annual HEH flux, the
HEH particle composition, the contribution of intermediate and thermal neutrons and the hardness of the HEH spectra.

When analyzing and comparing the LHC radiation fields through this metric, it is found that the HEH levels strongly depend on the distance to the interaction point, the intensity of the beam and its losses and the shielding elements in the particle's trajectories, and therefore extend over a wide range of values. For the more critical areas, these levels are several orders of magnitude larger than other environments such as the atmospheric or inner proton belt contexts. As to what regards their composition, certain LHC spectra have a strong contribution of charged pions, not relevant for any other of the environments analyzed. Finally, the hardness of the LHC HEH spectra also strongly varies among different locations, and in the case of the LHC is comparable to the atmospheric and stratospheric contexts.

Moreover, a representation was introduced in analogy to the LET spectra for heavy ions in space, describing the indirect energy deposition events through their volume-equivalent LET. Through this description and a simple RPP model, we showed that the indirect energy deposition in silicon is fairly constant over a wide range of proton energies and environments, confirming the relevance of the HEH approach in order to describe the expected SEE rate for a given environment and a pure silicon SV and surroundings geometry.
Once the local radiation environment is characterized, the second element needed to evaluate the operational SEE error rate for a specific electronic component or system is its sensitivity to SEEs, represented through the respective cross sections. In the present chapter, the test methodology for LHC components is introduced focusing on both monoenergetic and mixed-field measurements. In addition, the different facilities in which test data have been collected in the scope of this thesis work are introduced. Finally, an insight to the future CHARM radiation facility at CERN is provided, discussing the wide range of possible mixed-fields and their comparison with the operational environments introduced in Chapter 2.

### 3.1 Introduction

As described in Eq. 2.4, the basic approach for SEE rate estimation in the LHC context requires the knowledge of two cross section values: those representing the thermal neutron and HEH sensitivities. For the former, no direct measurements have been performed in the scope of the present work, however available data will be used for different components. For instance, the ESA SEU Monitor was tested for thermal neutrons at the Orphée reactor laboratory [5] whereas the RadMon SRAMs were characterized in the epithermal neutron beam in NRI Rez near Prague [10]. Likewise, indirect thermal neutron sensitivity measurements were performed in the work here presented using an atmospheric-like neutron spectrum, as will be shown in Chapter 5. Otherwise, certain technologies are known to be immune (in practical terms) to thermal neutrons and therefore might not require this type of characterization. This is typically the case for SRAM memories more modern than the 0.25 \( \mu m \) technology node, for

---

1Thermal neutron measurements are performed using neutron spectra in a certain energy interval. However, because the cross section is then calculated using the equivalent thermal neutron flux, these tests are formally considered as monoenergetic in this thesis.
which $^{10}\text{B}$ was removed from the BPSG (Borophosphosilicate glass) used as an insulator in the BEOL\textsuperscript{2}.

As to what regards the HEH cross section, it is typically measured by CERN groups at the Proton Irradiation Facility (PIF) in PSI using a 230 MeV proton beam. Additionally, several correction factors and safety margins might have to be applied to the SEE rate calculations extracted from Eq. 2.4 accounting for the potential energy dependence of the HEH cross section as will be shown in Chapters 5 and 6. For the intermediate neutron sensitivity, the Toshiba RadMon memory fit can be used as an approximate general response [22], as was shown in Chapter 2.

Moreover, SEE tests for LHC error rate estimations can be performed directly in mixed-field environments, reproducing the particle energy spectra present in the actual operational context at an accelerated rate. An example of such a test environment is the future CHARM facility at CERN, which will be introduced in subsection 3.3.3. In order to establish an analogy with the atmospheric testing, an accelerator mixed-field is the equivalent to an experimental neutron spectrum ranging from thermal energies to several hundred MeVs, such as LANSE in Los Álamos [61], NIF at TRIUMF [62, 63], ANITA at TNS [64] or VESUVIO at ISIS [65]. The corresponding error rate is typically expressed in units of FITs (Failures In Time) or FITs per Mbit, which corresponds to the number of errors expected in $10^9$ hours of operation in a given radiation environment and respective neutron flux.

In the case of the LHC approach, and provided that operational locations are described through their yearly HEH fluxes, test results from mixed-field measurements are represented as a cross section, considering the experimental HEH fluence and here defined as the mixed-field HEH cross section ($\sigma^{\ast}_{\text{HEH}}$). If the equivalent HEH fluence is considered instead (i.e. that considering the intermediate energy neutron contribution as introduced in Chapter 2) then the respective cross section is referred to as the mixed-field equivalent HEH cross section ($\sigma^{\ast}_{\text{HEH}_{eq}}$). Let it be noted that, despite using the HEH or HEH equivalent fluences in the cross section definition, other mixed-field contributions such as thermal neutrons are also included in this experimental value, as they too potentially contribute to the measured error rate. The main advantage of mixed-field testing is that, as long as the specific test energy spectra are representative of the operational environment, the mixed-field cross section extracted from the measurements can be directly used to obtain the operational error rate by normalizing it to the annual fluence at the location of use. On the other hand, the different contributions to the mixed-field cross section cannot be separately determined, as is the case when performing monoenergetic characterizations. This can be an important shortcoming when applying mixed-field results to a very different operational environment (e.g. more energetic spectra, significantly different thermal neutron contribution); whereas a complete set of monoenergetic

---

\textsuperscript{2}In fact, as shown in [34] thermal neutrons can still have a limited contribution (several percent) to the ground-level SER due to the presence of $^{10}\text{B}$ in doped silicon.

\textsuperscript{3}Not to be mistaken with the HEH cross section defined in subsection 2.2.1 as that corresponding to the 230 MeV proton value.
results are more generally applicable.

Finally, in addition to the monoenergetic hadron and mixed-field measurements, information about the expected LHC SEE rate can be indirectly estimated through the HI cross section. Because HI are the main contributor to SEEs in the interplanetary and outer radiation belt contexts, and add significantly to the error rate in the inner belt space missions, their cross section as a function of LET can often be found in publications and test reports for many different components. In the case of the high-energy accelerator environments, HI do not directly contribute to the error rate, as they are not a part of the environment. However, as will be shown in Chapter 4 their cross section can be used in combination with Monte Carlo simulations of the energy deposition distributions in order to obtain the expected monoenergetic hadron and mixed-field environment cross sections. Nevertheless, as will be seen this step involves the definition of a model including information about the SV geometry and its surrounding. Provided these parameters are typically not known in an accurate manner and that results are strongly dependent on them, cross sections extracted using this method are subject to an important uncertainty and are therefore only to be used as indicative values. Test facilities providing HI beams used to obtain published test data that will be employed in the scope of this thesis include UCL (Louvain, Belgium) [66, 67], TAMU (Texas, USA) [68] and RADEF (Jyvaskyla, Finland) [69, 70].

The different approaches for obtaining the high-energy accelerator error rate from the various experimental data are shown schematically in Fig. 3.1. As can be seen, the mixed-field SEE rate prediction requires the characterization of the operational field as well as experimental information about the device’s response. The latter can be obtained either through accelerated mixed-field measurements and the scaling of the experimental error rate with the operational flux, or by means of monoenergetic cross section data (extracted experimentally or through models and assumptions) multiplied by the respective flux values (i.e. thermal equivalent and HEH equivalent).

### 3.2 Monoenergetic Hadron Facilities

As has been mentioned in the introduction of this chapter, monoenergetic tests\(^4\) aimed at extracting the LHC error rate are focused on (i) thermal neutron and (ii) 230 MeV proton measurements. In the following subsections, test facilities providing results for the latter are presented, together with other beams used to study the intermediate neutron contribution as well as the dependency of the HEH cross section with energy.

\(^4\)It is to be noted that, in practice, test beams are not purely monoenergetic owing to their degradation or production energy spread. In particular, for thermal neutrons, a peak around 0.025 eV is typically used.
Chapter 3. SEE Test Approach and Facilities

Fig. 3.1. Schematic representation of the different test approaches used to estimate the mixed-field SEE rate.

3.2.1 | PSI: protons in the 30-230 MeV range

The Proton Irradiation Facility (PIF) beam line at the Paul Scherrer Institute (PSI) is the standard facility used by CERN groups to perform radiation tests on electronic components. It was constructed through the cooperation between PSI and ESA and is used extensively by the space community as well as by research groups in other disciplines [71]. Provided one of the most important tasks of PSI is the biomedical research and medical radiation treatment program, PIF uses the same original beam line as the PROSCAN proton therapy facilities. Since 2007, the COMET cyclotron is in operation designed to produce a 1000 nA, 250 MeV proton beam. The cyclotron provides beam to the OPTIS2 instrument, two Gantries and the PIF experimental station as can be seen in Fig. 3.2. A third Gantry will soon be added to the facility.
3.2. Monoenergetic Hadron Facilities

Fig. 3.2. Schematic view of the COMET cyclotron at PSI and the PIF beamline. Figure taken from [72].

Table 3.1. Degrader thickness and energy values at PSI together with the FLUKA calculated average energy \( \langle E \rangle \) and spread, represented by the standard deviation of the distribution \( \sigma_E \).

<table>
<thead>
<tr>
<th>Deg. Thickness (mm)</th>
<th>Facility Energy (MeV)</th>
<th>Calculated ( \langle E \rangle ) (MeV)</th>
<th>Calculated ( \sigma_E ) (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>230</td>
<td>230</td>
<td>0</td>
</tr>
<tr>
<td>11.5</td>
<td>200.1</td>
<td>195.3</td>
<td>24.2 (12%)</td>
</tr>
<tr>
<td>28</td>
<td>151.2</td>
<td>146.9</td>
<td>19.0 (13%)</td>
</tr>
<tr>
<td>41.4</td>
<td>101.4</td>
<td>98.8</td>
<td>11.3 (11%)</td>
</tr>
<tr>
<td>45.9</td>
<td>80.5</td>
<td>78.3</td>
<td>8.5 (11%)</td>
</tr>
<tr>
<td>49.5</td>
<td>60.9</td>
<td>58.1</td>
<td>6.7 (12%)</td>
</tr>
<tr>
<td>51.5</td>
<td>47.2</td>
<td>44.0</td>
<td>6.5 (15%)</td>
</tr>
<tr>
<td>53.5</td>
<td>29.4</td>
<td>25.3</td>
<td>7.9 (31%)</td>
</tr>
</tbody>
</table>

The initial proton energy delivered by the cyclotron to PIF is currently 230 MeV. This energy can be degraded through the use of copper plates of different thicknesses. The degrader system can be seen in Fig. 3.3. Along with the beam energy reduction, this process also introduces a certain energy spread. For example, the FLUKA-simulated beam energy spectrum after the corresponding degradation thickness is shown in Fig. 3.4 for different final energies. Table 3.1 shows the pairs of degrader thickness and energy values extracted from a facility document together with the respective FLUKA calculations of the average energies and spread. Both the full degraded spectrum and a fit of it to a Gaussian function can be used as a source in FLUKA simulations for the energy deposition distribution scoring, as will be detailed in Chapter 4. As will be seen in Chapter 5, the consideration of the degraded beam with its corresponding spread as opposed to a monoenergetic beam with the average energy can have a strong impact on the simulated SEE rate, especially in the 30 MeV case. In addition, as we will later shown for the case of TRIUMF, the contribution of secondary HEH generated in the degraders is negligible at the test location.
Chapter 3. SEE Test Approach and Facilities

**Fig. 3.3.** SRAM SEL test during the April 2014 R2E irradiation campaign at PSI. From left to right, the DUTs can be observed together with the copper collimator (5 cm aperture), second ionization chamber, copper degrader system and first ionization chamber.

**Fig. 3.4.** FLUKA simulated beam energy distributions for different degrader thickness values and respective final energies. The curves are normalized to represent the same total flux and therefore do not consider the flux reduction due to scattering and inelastic interactions in the degrader.

In terms of the flux measurement and calibration, the monitoring system consists of an ionization chamber located downstream the degrader. A plastic scintillator placed in the
location of the test sample is used to measure the flux before the test runs and establish the conversion factors between the counts from the ionization chamber and the actual proton flux. The same scintillators can also be used to extract the beam profile by moving it horizontally and vertically in millimetric steps. The profile is typically flat within \( \sim 10\% \) with a diameter of \( \sim 5 \text{ cm} \). Both the beam intensity and energy can be set from the measurement control room which is also equipped with a PC showing the various dosimetric parameters during a run. In the test area, samples can be centered on the beam using a laser system. As to what regards the beam current and respective fluxes, the maximum value is typically 5 nA, corresponding to a flux of \( \sim 2 \cdot 10^8 \text{ p/cm}^2/\text{s} \) at 230 MeV and \( \sim 4 \cdot 10^7 \text{ p/cm}^2/\text{s} \) at 30 MeV. These values can be reduced linearly with the intensity until a lower stable limit of \( \sim 0.1 \text{ nA} \).

Different test campaigns in the scope of this thesis were performed in the PIF facility between September 2011 and April 2014, including the SEU characterization of the ESA Monitor and the SEL measurements for a wide range of SRAMs and an ADC.

### 3.2.2 TRIUMF: protons up to 480 MeV

The TRIUMF Proton Irradiation Facility (PIF) and Neutron Irradiation Facility (NIF) provide proton and neutron beams for users interested in space and terrestrial environments. The main commercial users include the MDA Corporation, The Boeing Company or Cisco Systems. Moreover, charge-free beam time is also available for academic and research purposes for studies of radiation effects formally approved by the TRIUMF Experiment Evaluation Committee. In addition, one of the proton beam lines is also used for cancer treatment of ocular melanoma in the Proton Therapy Centre (PTC) treating 10 patients per year on average.

The high energy proton beam line (BL1B) reaches energies up to 480 MeV \[63,73\], providing a worst-case scenario for trapped proton belt space missions, as the proton flux drops by about an order of magnitude above this energy \[74\]. Likewise, this maximum energy provides an increase of a factor 2 with respect to the maximum PSI energy, and is therefore very interesting for the study of the energy dependency of SEE cross sections beyond 230 MeV.

In addition, a low energy proton beam line (BL2C) provides extraction energies between 65 and 120 MeV and can be degraded down to 5 MeV with a FWHM of 1 to 2 MeV, which is very convenient for the study of direct proton ionization effects. Likewise, a surface positive muon beam has been used in the past to characterize the response of deep sub-micron SRAMs to this type of particle \[44\]. Finally, the NIF facility yields an atmospheric-like neutron spectrum generated through the interaction of the high-intensity proton beam line BL1A (100-150 \( \mu \text{A} \)) of 400 to 450 MeV with an aluminum target surrounded by a water moderator. The resulting neutron flux above 10 MeV is \( 2 \sim 3 \cdot 10^6 \text{ n/cm}^2/\text{s} \).

In terms of flux monitoring and integration, a small, portable ionization chamber (see Fig. 3.5) is used in place of the DUT for each configuration before the test runs to calibrate...
the counts in the fixed ionization chamber which stays in place during the test. The resulting calibration factors are provided in units of \( \text{p/cm}^2/\text{count} \) and \( \text{Gy/count} \) for fluence and dose respectively. Both the differential and integral count values are displayed in a panel during the runs. As to what regards the flux levels, two different test locations were available in the BL1B line during the R2E test campaign: one in the front and one in the back. For the latter, the beam size was larger (up to 7.5 cm in diameter) and the maximum flux at 480 MeV was \( \sim 7 \cdot 10^7 \text{p/cm}^2/\text{s} \). For the former, the beam is smaller (1-2 cm in diameter) whereas the maximum flux obtainable was \( \sim 3 \cdot 10^8 \text{p/cm}^2/\text{s} \) (and therefore comparable to the PSI value). In addition, a laser alignment system is available for the positioning of the DUTs, and a wire chamber monitor was operated during the runs in order to measure the beam profile.

At the time of the R2E test campaign at TRIUMF, two extraction energies were available in the BL1B line: 355 and 480 MeV; whereas the use of a lower extraction energy (210 MeV) is typically also possible but was not usable at that time. Therefore, in order to obtain a measurement energy overlapping with the PSI range, the 355 MeV beam was degraded down to 230 MeV using a 15.9 cm aluminum degrader, as can be seen in Fig. 3.5. Calculations were performed with FLUKA showing that 20 cm downstream the degrader, the average beam energy is 234.5 MeV with a FWHM of 5.7 MeV. The HEH contribution of secondaries generated in the degrader was just below 1% with a roughly equal presence of protons and neutrons.

![Fig. 3.5. BL1B test configuration at TRIUMF for a front location, 230 MeV degraded beam during the December 2013 R2E test campaign. From left to right, the elements that can be seen are the beam profile monitor, the portable ionization chamber, the 15.9 cm aluminum degrader and the fixed ionization chamber.](image)

Tests were carried out in the scope of this thesis work in the BL1B beam line in December 2013. The components characterized included the ESA SEU Monitor as well as the SRAMs and...
3.2. Monoenergetic Hadron Facilities

ADC devices composing the SEL energy dependence study.

3.2.3 | PTB: Quasi-monoenergetic neutrons at 5, 8 and 14.8 MeV

The PTB Neutron Reference Fields (PIAF) are quasi-monoenergetic neutron reference beams in the energy range from thermal to 200 MeV [75]. The main purpose of such beams is the energy response calibration of instruments used for neutron monitoring and dosimetry. In the case of the R2E project at CERN, measurements are carried out in this facility in order to characterize the response of several SRAM detectors to intermediate energy neutrons [29] which depending on the specific environment can have a significant contribution to the total SEU rate of the monitor. Such tests were performed for the Toshiba and Cypress RadMon detectors, as well as for the ESA SEU Monitor during a test campaign integrated in the present thesis work.

As can be seen in Fig. 3.6, the architecture of the facility is characterized by the very large dimensions of the hall and the grid floor in order to minimize the impact of neutrons scattering off the walls.

![Fig. 3.6. SRAM test setup at PTB during the November 2013 R2E test campaign.](image)

The principle behind the production of intermediate and high energy quasi-monoenergetic fields is that of light ions (protons, deuterium) accelerated in a cyclotron or Van-de-Graaf (VdG) accelerator impinging on gas or solid low-Z targets (deuterium, tritium, $^7$Li). The reactions and field properties for the energies used in the R2E calibration campaign are shown in Table 3.2. In terms of the neutron energy spectra, the energy distribution typically consists of a dominating peak corresponding to the neutron reaction energy and a low energy tail due to scattered neutrons.
Table 3.2. PTB calibration for different energies in the 1-20 MeV range. Flux rates correspond to a distance of 1 m from the source. Ti(T) stands for tritiated titanium. The energy spread is represented by the FWHM.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$&lt; E_n &gt;$ (MeV)</th>
<th>FWHM $E_n$ (MeV)</th>
<th>Target</th>
<th>Flux ($/cm^2/s$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^2\text{H}(d, n)^3\text{He}$</td>
<td>5.0</td>
<td>0.2</td>
<td>$D_2$-gas</td>
<td>$5.2 \cdot 10^4$</td>
</tr>
<tr>
<td>$^2\text{H}(d, n)^3\text{He}$</td>
<td>8.0</td>
<td>0.2</td>
<td>$D_2$-gas</td>
<td>$1.9 \cdot 10^4$</td>
</tr>
<tr>
<td>$^3\text{H}(d, n)^4\text{He}$</td>
<td>14.8</td>
<td>0.4</td>
<td>Ti(T)</td>
<td>$1.3 \cdot 10^4$</td>
</tr>
</tbody>
</table>

At PTB, measurements of the neutron peak fluence are performed relative to the differential n-p scattering cross section by means of a proton recoil proportional counter (PRPC) or a recoil proton telescope (RPT) depending on the energy. Likewise, the measurement of the spectral fluence is carried out using pulsed beams and the Time-Of-Flight (TOF) technique with scintillators and fission ionization chambers. This detection technique cannot be used for low energy neutrons at PTB due to the beam pulse frequency, therefore their spectral characterization is performed through the unfolding of Bonner sphere readings. For a given number of detector counts $N_{det}$ and corresponding detector calibration factor $C_{det}$ the fluence as a function of DUT distance to the source $d$ can be calculated through Eq. 3.1, where $\theta$ corresponds to the subtending angle of a simple cone with a solid angle of one steradian.

$$\Phi(d) = \frac{N_{det} \cdot C_{det}}{\pi \cdot (d \cdot \tan(\theta))^2}$$ (3.1)

Other quasi-monoenergetic neutron test facilities available worldwide include the Quasi-monoenergetic neutron (QMN) beam facility at TSL (Uppsala University) [64, 76] or the iThemba Laboratory for Accelerator-Based Sciences (iTL) (Cape Town, South Africa) [77]. A more complete review of present and future facilities of such type can be found in [78].

3.2.4 | H4IRRAD and CERF: several hundred GeV hadrons

The H4IRRAD and CERF test areas at CERN are typically used to generate a mixed radiation field through the interaction of several hundred GeV energy beams with a target (as will be shown in subsection 3.3.2). However, these beam lines can also be used to interact directly with the DUT, enabling the possibility of performing very high energy SEE measurements and thus studying the energy dependency of the respective cross sections. Tests of this type were carried out in the scope of this thesis and will be shown in Chapter 5.

In the North Experimental Area at the Prevessin site of CERN, a 450 GeV proton beam is extracted from the Super Proton Synchrotron (SPS) and used in different beam lines. The SPS beam is directed to three different primary targets: T2, T4 and T6. These are further divided through secondary targets and magnets, generating up to seven different beam lines. Two of these (H4 and H6) are used for the H4IRRAD [79] and CERF [80] test areas respectively. The former is composed of monoenergetic protons of an energy of 280 or 400 GeV depending on
the specific beam settings, whereas the latter has a mixed composition (60.7% $\pi^+$, 34.8% $p$, 4.5% $K^+$) of an energy of 120 GeV. They are both pulsed beams with $\sim$5 s spills every 44 s. At H4IRRAD, the pulse intensity during the tests performed in the scope of this work was as large as $\sim$$3 \times 10^9$ protons per spill. At CERF, the pulse intensity was approximately an order of magnitude smaller. In both cases, ionization chambers are used to determine the number of protons per spill. The beam profiles were monitored using Multi-Wire Proportion Chambers (MWPC) that provide signals proportional to the projection of the beam intensity in the horizontal and vertical axes of the plane perpendicular to the beam direction at the location of the detector.

The dominating source of uncertainty in the H4IRRAD and CERF SEE measurements is related to the alignment of the DUT relative to the beam, therefore an accurate measurement of the beam profile and DUT position is needed in order to extract a meaningful fluence for the cross section derivation. Wire chamber measurement data and fits of the H4IRRAD and CERF profiles can be found in Figs. 3.7 and 3.8 for two different runs performed in the scope of this thesis. As will be seen in Chapter 5, the uncertainty related to the alignment for the ESA SEU Monitor measurements could be reduced thanks to the graphical display of the physical location of the SEU distribution in the memory which could be used to iterate the component’s position until finding a centered distribution.

In addition, it is to be noted that the 24 GeV proton beam at CHARM will also be suitable for direct SEE measurements, with a maximum beam size significantly larger than those at H4IRRAD and CERF, therefore providing a more homogeneous flux over the components to be tested and reducing the uncertainty associated to the alignment.
3.3 Mixed-field hadron facilities

3.3.1 The VESUVIO neutron spectrum at ISIS

The VESUVIO neutron beam line is part of the ISIS physical and life sciences research centre at the STFC Rutherford Appleton Laboratory near Oxford in the United Kingdom [81]. VESUVIO is a unique neutron spectrometer, which uses the high intensity of neutrons in the eV energy range and the pulsed nature of the ISIS source to measure atomic momentum distributions in a variety of condensed matter systems [82]. Despite its main use as a condensed matter research instrument, provided its relative simplicity with respect to other beam lines in terms of the front-end structure (magnets, choppers, etc.) and its forward direction, it is also suited for SEE measurement purposes.

Benchmark measurements have been performed proving it provides a neutron spectrum similar to the ambient at sea level [65]. Neutrons are generated through the interaction of a 800 MeV, 200 µA proton beam produced in bunches in a synchrotron with a spallation target. The protons are delivered to the spallation target in two 100 ns long pulses with a frequency of 50 Hz. The neutron beam line is at 60° with respect to the initial proton beam line. The neutron flux obtained above 10 MeV is \( \sim 5.8 \times 10^4 \text{ n/cm}^2/\text{s} \) and is therefore over an order of magnitude lower than those available at TRIUMF NIF or LANSCE. The neutron spectrum is calculated using the MCNPX Monte Carlo simulation tool [83] and benchmarked against Time-Of-Flight measurements performed with different detectors including Bonner spheres, activation foils, CCD devices and Thin Film Breakdown Counters (TFBC) [84].

The flux and fluence measurement relies on the benchmarked MCNPX calculations and can be extracted using the beam current (per unit time for flux, integrated for fluence) \( I \) and DUT position \( z \) in Eq. 3.2 where the values with a zero underscore are the reference ones (\( \phi_o = 5.8 \times 10^4 \text{ n/cm}^2/\text{s} \), \( I_o = 180 \mu A \) and \( z_0 = 601 \text{ cm} \)) and \( D \) is the distance from the calibration...
3.3. Mixed-field hadron facilities

Point to the flange (point from which the DUT distance is measured, and equal to 35 cm). In addition to the calculated spectrum, several beam monitoring detectors are used in the facility. A $^{238}$U fission counter and a diamond detector are used to measure the high-energy neutron flux, whereas a lithium fluoride detector is employed to determine the thermal neutron flux. Part of the VESUVIO beamline and R2E experimental setup can be seen in Fig. 3.9

$$\phi = \phi_0 \cdot \frac{I}{I_0} \cdot \frac{z_0^2}{(z_0 + D + z)^2}$$ \hspace{1cm} (3.2)

The main characteristics of the spectrum are shown in Table 3.3 following the structure introduced in Chapter 2. As can be seen, the neutron spectrum is of a soft nature even when compared to the ground level case, which is the least energetic environment of those here analyzed. Moreover, the equivalent thermal neutron flux is considerable, and can however be easily reduced by placing a cadmium slab in front of the DUT. In addition, the contribution
of the intermediate energy neutrons to the SEE rate is estimated to be comparable to that of the HEH. The lethargy neutron spectrum is plotted in Fig. 3.10 as calculated using MCNPX\(^5\) together with the neutron non-elastic cross section in cadmium and the resulting spectrum after a 1.5 mm slab of this material. This thickness reduces the equivalent thermal neutron flux to 16% its initial value while not altering the intermediate and HEH regions.

Table 3.3. Main characteristics of the neutron spectrum in the VESUVIO beamline at ISIS. If a cadmium absorber is used (see Fig. 3.10) the R factor is reduced to 4.7 while the rest of the beam characteristics are not altered. If the ESA SEU Monitor intermediate energy neutron response (to be introduced in Chapter 5) is used instead of the Toshiba one, the respective value is 85% of the HEH flux (as opposed to 132%).

<table>
<thead>
<tr>
<th>Spectrum</th>
<th>HEH/cm(^2)/s</th>
<th>Composition (%)</th>
<th>R</th>
<th>Hardness Energy (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VESUVIO</td>
<td>∼ 3.6 \cdot 10^4</td>
<td>100 - - 132</td>
<td>29</td>
<td>50 150</td>
</tr>
</tbody>
</table>

![Fig. 3.10. MCNPX calculated neutron lethargy spectra at VESUVIO according to the data provided by the facility. The normalization corresponds to a proton beam current 180 \(\mu\)A and a DUT to flange distance of 10 cm. The neutron non-elastic cross section in cadmium is also included, showing a large peak in the thermal region.](image)

Finally, a new neutron facility known as ChipIR [85] and currently under construction will soon be available at ISIS providing a neutron flux above 10 MeV of \(\sim 1 \cdot 10^6\) \(n/cm^2/s\) and a harder spectrum than that at VESUVIO.

\(^5\)Raw data were provided by the VESUVIO beam line contact.
3.3. Mixed-field hadron facilities

Measurements in the scope of the present work were performed in the VESUVIO beamline at ISIS in March 2014 and included the characterization of the ESA SEU Monitor as well as SEL measurements for the high-sensitivity SRAMs.

3.3.2 | The H4IRRAD mixed-field test area

In order to provide the possibility of accelerated testing in mixed radiation fields similar to those encountered in the LHC, the H4IRRAD test area was constructed in the North Experimental Hall at the CERN site in Prevessin. The mixed-field generation principle is that of making the 280 GeV (or 400 GeV during the last operation slots) described in subsection 3.2.4 interact with a 1 m copper target creating a secondary particle environment similar to that found in the LHC [86]. At H4IRRAD, two main irradiation areas are available, one in direct line-of-sight of the particles generated in the target (and known as the internal zone) and one separated from the target area by a 20 cm thick concrete wall (and referred to as the external zone). In both cases, the mixed radiation field covers the full test area, enabling the possibility of testing entire, bulky systems or large boards containing different electronic components such as those shown in Fig. 3.11. This feature however also requires the use of radiation tolerant test set-ups when these need to be in the vicinity of the DUTs (for instance, the FPGAs used to access the SRAM memories during an SEU test).

Similar to the case of the VESUVIO beamline, the fluence and dose values for a specific location and time interval at H4IRRAD are extracted through Monte Carlo simulations normalized by a certain value proportional to the amount of protons interacting with the production target. In the case of the neutron beam line at VESUVIO, this value was the total beam current, whereas at H4IRRAD, the value to which the simulated data are normalized is the total number of protons-on-target, measured though an ionization chamber. For each H4IRRAD run, a dedicated FLUKA simulation is performed with the respective geometry including the specific equipment positions. Generally, an overall scoring of the dose, HEH, thermal equivalent and 1 MeV neutron equivalent fluences is performed with a relatively coarse binning due to the large total scoring volume. Additionally, regions representing the DUTs are defined in which the SEE-relevant values and particle energy spectra are scored. The exact location and size of the components is important, as the field gradients can be very strong, especially in regions directly downstream the target. The FLUKA calculations of the mixed-field are regularly bench-marked against monitor measurements. For instance, the RadMon SEU counts were used to cross-check the simulated HEH and thermal neutron fluxes [22, 48].

An example of the H4IRRAD test configuration and FLUKA scoring regions can be found in the horizontal cut shown in Fig. 3.12. In order to characterize and compare the different environments, the mixed-fields at the positions labeled as H4RAD03, H4RAD04 and ESA are analyzed. These correspond to the locations of SRAM devices who’s SEU results are analyzed in Chapter 5. The coordinates of the three locations in a reference frame centered at the target are shown in Table 3.4, where \( z \) is the beam axis (traveling in the positive direction) and \( y \) is the
vertical direction, perpendicular to the plane shown in the figure. In addition, the radiation environment for H4RAD02 is also included as an example of an external location.

**Table 3.4.** Coordinates of the test locations in which the particle energy spectra are analyzed in a reference frame centered at the downstream end of the target.

<table>
<thead>
<tr>
<th>Location</th>
<th>x (cm)</th>
<th>y (cm)</th>
<th>z (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H4RAD03</td>
<td>30</td>
<td>-46</td>
<td>77</td>
</tr>
<tr>
<td>H4RAD04</td>
<td>0</td>
<td>0</td>
<td>106</td>
</tr>
<tr>
<td>ESA</td>
<td>0</td>
<td>-8</td>
<td>106</td>
</tr>
</tbody>
</table>

In order to compare the different test locations, the corresponding SEE-relevant spectral properties are shown in Table 3.5 considering $10^9$ protons-on-target per spill for spills every 44s. In addition, the neutron spectra are compared for the four cases in Fig. 3.13. From both, the following points can be highlighted:
Fig. 3.12. Horizontal cut (top view) of the spectra scoring positions for the 3rd H4IRRAD slot in 2011 showing both the internal and external areas, separated by 20 cm of concrete shielding. The vertical positions (y axis) can be found in Table 3.4. The beam is in the positive z direction.

- the thermal neutron peak is very similar for all cases.
- the intermediate energy neutron flux is almost identical for all internal cases despite the different angle with respect to the beam, and is reduced by a factor ∼5 for the external case due to the shielding.
- the HEH interval strongly depends on the angle with respect to the beam, and is much harder in the case directly downstream the target. The effect of the shielding also further reduces the HEH flux.

It is important to note the significant difference between the HEH flux and high energy neutron spectra for locations H4RAD04 and ESA while their positions only differ in 8 cm, manifesting the very intense field gradients at this test location. SEU test results for the ESA Monitor at location ESA and the Toshiba RadMon at locations H4RAD03 and H4RAD04 will be presented in Chapter 5 and compared with different calculation methods.

3.3.3 | The future CHARM facility at CERN

The main limitation of the H4IRRAD test area was its restricted availability (typically consisting of two or three 15 to 20 day periods per year) as well as its relatively low intensity due to shielding restrictions. In addition, accesses to the H4IRRAD internal zone required the interruption of a separate beam line, thus limiting intervention possibilities. These drawbacks,
Table 3.5. Main characteristics of the mixed spectra at H4IRRAD considering spills of $10^9$ protons every 44s.

<table>
<thead>
<tr>
<th>Spectrum</th>
<th>$HEH/cm^2/s$</th>
<th>Composition (%)</th>
<th>$R$</th>
<th>Hardness Energy (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$n$</td>
<td>$p$</td>
<td>$\pi^+$</td>
</tr>
<tr>
<td>H4RAD02</td>
<td>$\sim 2.4 \cdot 10^4$</td>
<td>78</td>
<td>8</td>
<td>14</td>
</tr>
<tr>
<td>H4RAD03</td>
<td>$\sim 5.2 \cdot 10^4$</td>
<td>58</td>
<td>14</td>
<td>26</td>
</tr>
<tr>
<td>H4RAD04</td>
<td>$\sim 1.2 \cdot 10^5$</td>
<td>20</td>
<td>13</td>
<td>59</td>
</tr>
<tr>
<td>ESA</td>
<td>$\sim 6.3 \cdot 10^4$</td>
<td>28</td>
<td>11</td>
<td>54</td>
</tr>
</tbody>
</table>

Fig. 3.13. Neutron lethargy plots for the H4IRRAD FLUKA scoring positions shown in Fig. 3.12. The normalization considered was $10^9$ protons per spill every 44s.

added to the increase in the user demand motivated the construction of a dedicated mixed radiation test facility at CERN known as CHARM (CERN High-energy Accelerator Radiation Mixed facility, [87]). The design of this new facility is largely user-oriented and will host radiation experiments both for CERN groups and other external research institutes. The production principle is similar to that at H4IRRAD: in this case, a 24 GeV proton beam from the Proton Synchrotron (PS) will be used to generate the mixed-field through the interaction with a 50 cm copper target. In addition, different shielding configurations will be available through movable iron and concrete blocks, enabling the use of a wide variety of flux levels, particle compositions and energy spectra.

Testing at CHARM will be driven by the need of characterizing the radiation response of components and systems in an environment resembling that of the LHC and other CERN
3.3. Mixed-field hadron facilities

locations of interest. The design of the facility enables the possibility of obtaining higher intensities than at other previous mixed-field test areas such as H4IRRAD, CERF and CNRAD [88]. For this purpose, the shielding around the target zone was carefully designed in order to maintain the prompt dose levels in the surroundings at background levels. In addition, the large volume available in the test area as well as the fact that the mixed radiation field covers the entire space enables the possibility of testing full systems or boards containing a large number of components. Moreover, the movable shielding blocks will provide the possibility of performing measurements in a wide variety of particle energy spectra, ranging from soft to very hard, thus fully covering the phase-space of the operational environments of interest. In addition, as opposed to previous in-house CERN test areas, the CHARM facility is specifically designed for radiation effects testing rather than being parasitic to other experiments or a modification to an existing structure, and is therefore also more user-oriented.

In the scope of the thesis work, FLUKA simulations were performed in order to obtain the radiation levels and particle energy spectra in the different possible test locations at CHARM. In Fig. 3.14, a horizontal cut of the FLUKA geometry is shown, with the movable shielding placed inside and the different scoring volumes used in the simulation. The beam considered has a spread of 2.0 cm FWHM in the vertical and horizontal directions. The target is defined with a diameter of 8.0 cm, and aluminum is also considered as a possible choice in order to evaluate the impact of the material on the HEH levels as well as the particle energy spectra. In the present work, a specific test location and configuration is identified by its rack number and shielding layout, starting from the layer closest to the target. Cn and Fe represent concrete and iron, respectively. For instance, the configuration corresponding to Rack 7 in Fig. 3.14 would be represented as 7, FeFeCnCn. The scoring racks here considered are centered 50 cm below the horizontal beam plane, and have dimensions of 60 x 50 x 40 cm in the case of the lateral ones (1 through 12) or 40 x 50 x 60 cm for the downstream regions (13-18), where the first dimension is the horizontal direction perpendicular to the beam (vertical axis in Fig. 3.14), the second is the vertical direction and the third is in the horizontal plane and in the beam direction (horizontal axis in Fig. 3.14). A second set of racks of the same size was placed directly above the former, however no significant differences in the HEH fluxes and hardness energies could be observed except for the cases directly downstream the target.

Results for the HEH fluxes considering an average proton-on-target intensity of $2.2 \times 10^{10} \, p/\text{s}$ are shown in the 2D plot in Fig. 3.15. As can be observed, the flux gradient is relatively strong, especially in the direction perpendicular to the beam. In addition, the HEH flux levels are represented in Fig. 3.16 for different shielding and target configurations. As can be seen, the aluminum target reduces the flux by a factor 2-3 depending on the location. It was also confirmed that the target material did not affect the shape of the particle energy spectra. Moreover, the HEH flux when considering the different target, shielding and location possibilities ranges from $2 \times 10^3$ to $3 \times 10^6 \, \text{HEH/cm}^2/\text{s}$ considering the above mentioned proton-on-target intensity. The maximum flux obtainable in the racks on the side of the target where the flux is more homogeneous in the direction parallel to the beam is roughly $8 \times 10^5 \, \text{HEH/cm}^2/\text{s}$. 

Radiation Fields at High-Energy Accelerators and their impact on Single Event Effects
Fig. 3.14. Horizontal cut (top view) on the target plane of the FLUKA geometry for the CHARM target area. Racks 1 to 18 are the regions in which the particle energy spectra are scored. The beam comes from the negative z axis (left of the plot) and impinges on the target. In this case the movable shielding is placed inside. Iron is represented in blue whereas concrete is in gray.

The FLUKA study also included an analysis of the impact of the specific shielding configuration on the HEH flux levels and particle energy spectra. As a result, it was interesting to note that, as can be seen in Fig. 3.17, the order of the two concrete and iron layers, while not affecting the HEH part, has a very different impact on the thermal peak and intermediate energy neutron intervals. Whereas the former is more prominent in the case with the iron on the target side, the latter has a higher flux when the concrete is placed first. Additionally, the ambient ground level neutron lethargy spectrum in also included, showing that the configuration CnCnFeFe is more successful in reproducing the HEH part of the spectrum whereas the shielding layout FeFeCnCn better reproduces the intermediate energy neutron interval. The final implementation for the CHARM internal shielding is CnFeFeCn due to activation reduction considerations.

In order to further characterize the SEE-relevant particle energy spectra, Table 3.6 shows the different parameters for a wide range of shielding and location configurations. When comparing the energy distribution of the different CHARM test configurations with the natural or high-energy accelerator environments introduced in Chapter 2, very similar cases can be identified. These are summarized in Table 3.7.

In order to visualize the broad range of possible HEH spectral hardnesses, Fig. 3.18 shows the normalized reverse integral for different CHARM configurations without shielding, fully
3.3. Mixed-field hadron facilities

Fig. 3.15. Horizontal cut on the target plane of the FLUKA HEH scoring for the shielding-out configuration and a proton-on-target intensity of $2.2 \cdot 10^{10}$ protons/s.

Table 3.6. Main characteristics of the mixed spectra at CHARM considering an average of $2.2 \cdot 10^{10}$ protons/s impinging on a copper target.

<table>
<thead>
<tr>
<th>Test config.</th>
<th>$HEH/cm^2/s$</th>
<th>Composition (%)</th>
<th>R</th>
<th>Hardness Energy (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$n$</td>
<td>$p$</td>
<td>$\pi^-$</td>
</tr>
<tr>
<td>1, OOOO</td>
<td>$\sim 2.8 \cdot 10^5$</td>
<td>85</td>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td>4, OOOO</td>
<td>$\sim 6.7 \cdot 10^5$</td>
<td>77</td>
<td>10</td>
<td>13</td>
</tr>
<tr>
<td>7, OOOO</td>
<td>$\sim 1.0 \cdot 10^6$</td>
<td>68</td>
<td>15</td>
<td>17</td>
</tr>
<tr>
<td>10, OOOO</td>
<td>$\sim 9.5 \cdot 10^5$</td>
<td>60</td>
<td>17</td>
<td>23</td>
</tr>
<tr>
<td>13, OOOO</td>
<td>$\sim 1.2 \cdot 10^6$</td>
<td>53</td>
<td>18</td>
<td>29</td>
</tr>
<tr>
<td>16, OOOO</td>
<td>$\sim 2.1 \cdot 10^6$</td>
<td>39</td>
<td>20</td>
<td>41</td>
</tr>
</tbody>
</table>

covering the interval of operational environments introduced in Chapter 2. Similarly to what was suggested in the case of the different monoenergetic and mixed-field environments, the
Chapter 3. SEE Test Approach and Facilities

Fig. 3.16. HEH flux levels for the different scoring locations and several target + shielding combinations considering a proton-on-target intensity of $2.2 \cdot 10^{10} \, p/s$.

Table 3.7. Comparison between the environmental spectra introduced in Chapter 2 and the most representative CHARM test location in terms of spectral hardness.

<table>
<thead>
<tr>
<th>Environment/ Test config.</th>
<th>HEH/cm²/yr</th>
<th>Composition (%)</th>
<th>R</th>
<th>Hardness Energy (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$H_{50%}$</td>
</tr>
<tr>
<td>LHC UJ 4, CnCnFeFe</td>
<td>$\sim 2.5 \cdot 10^9$</td>
<td>99 1 0 14</td>
<td>1.7</td>
<td>80</td>
</tr>
<tr>
<td>LHC RR 11, OOOO</td>
<td>$\sim 1.0 \cdot 10^9$</td>
<td>71 13 16 21</td>
<td>7.2</td>
<td>180</td>
</tr>
<tr>
<td>LHC tunnel 14, OOOO</td>
<td>$\sim 6.0 \cdot 10^{11}$</td>
<td>45 18 37 16</td>
<td>1.2</td>
<td>370</td>
</tr>
<tr>
<td>Atm, 350 m 13, CnCnFeFe</td>
<td>$\sim 1.6 \cdot 10^5$</td>
<td>93 7 0 21</td>
<td>0.12</td>
<td>80</td>
</tr>
<tr>
<td>Atm, 10 km 13, OOOO</td>
<td>$\sim 1.7 \cdot 10^4$</td>
<td>82 18 0 18</td>
<td>0.08</td>
<td>110</td>
</tr>
<tr>
<td>LEO, Proba-II 6, OOOO</td>
<td>$\sim 2.7 \cdot 10^3$</td>
<td>72 13 15 28</td>
<td>2.4</td>
<td>100</td>
</tr>
</tbody>
</table>

A wide collection of spectral hardnesses at CHARM is expected to have a strong impact on the event-by-event energy deposition distribution for devices with a significant proportion of high-Z materials near the SV. If these devices have a relatively large critical charge value, these differences are expected to result in a significant mixed-field cross section dependency on...
3.4 Summary

The general LHC test approach for SEE rate estimation was introduced in the present chapter, distinguishing first of all between monoenergetic and mixed-field characterizations. While the latter provide a direct means of evaluating the expected LHC SEE rate, the former (generally requiring testing in at least two different facilities) identifies the individual contributions of both thermal neutrons and HEH separately, and as will be seen in Chapter 7 can in some occasions require the application of safety margins to compensate for the larger operational energies.

As to what regards the monoenergetic test approach, five different facilities or test areas were introduced in which SEE measurements were performed in the scope of this thesis work. The PIF facility at PSI is used on a regular basis by CERN groups, providing a proton beam up to 230 MeV. The TRIUMF BL1B beam line was employed in order to reach an energy of 480...
MeV, thus evaluating the potential energy dependency of the SEE cross section. Moreover, the PTB quasi-monoenergetic neutron beams were used to characterize the SEU response of the ESA Monitor to intermediate energy neutrons (5-15 MeV). Finally, unprecedented SEU measurements were performed using the several hundred GeV hadron beams at H4IRRAD and CERF.

Concerning the mixed-field facilities, VESUVIO is presented as an example of a neutron spallation spectrum in which the SEU and SEL responses of different electronic components were measured. H4IRRAD is introduced as the past of in-house mixed-field testing at CERN, whereas CHARM is presented as a future test facility for high-energy accelerator, space and atmospheric applications. As was shown, the broad range of test locations, target and shielding configurations available at this new facility will enable the possibility of testing using a wide variety of HEH fluxes and energy spectra, some of which closely resemble environments of crucial interest for electronic component operation.

A summary of the different test beams used and respective measurements campaigns is shown in Table 3.8. The SEE results obtained in the different test campaigns will be shown and analyzed in Chapters 5 and 6.

---

The reported beams and respective characteristics apply only to the tests performed by R2E for data presented in this thesis and are therefore not be regarded as complete, general information.
### Table 3.8. Summary of the main characteristics of the test beams used in the context of this thesis and respective test campaign dates.

<table>
<thead>
<tr>
<th>Facility</th>
<th>Particle Type</th>
<th>Energy Range</th>
<th>Max. Flux ($cm^2/s$)</th>
<th>Test Campaign</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSI</td>
<td>Protons</td>
<td>30-230 MeV</td>
<td>$2 \cdot 10^8$</td>
<td>Sept. 2011 - Apr. 2014</td>
</tr>
<tr>
<td>TRIUMF</td>
<td>Protons</td>
<td>230-480 MeV</td>
<td>$3 \cdot 10^8$</td>
<td>Dec. 2013</td>
</tr>
<tr>
<td>PTB</td>
<td>Neutrons</td>
<td>5-15 MeV</td>
<td>$2 \cdot 10^4$</td>
<td>Nov. 2013</td>
</tr>
<tr>
<td>H4IRRAD (direct beam)</td>
<td>Protons</td>
<td>400 GeV</td>
<td>$\sim 2 \cdot 10^7$</td>
<td>Nov. 2012</td>
</tr>
<tr>
<td>CERF (direct beam)</td>
<td>Protons and pions</td>
<td>120 GeV</td>
<td>$\sim 4 \cdot 10^6$</td>
<td>May, Nov. 2012</td>
</tr>
<tr>
<td>VESUVIO</td>
<td>Neutrons</td>
<td>Thermal - 800 MeV</td>
<td>$\sim 4 \cdot 10^4$</td>
<td>Mar. 2014</td>
</tr>
<tr>
<td>H4IRRAD</td>
<td>Mixed Field</td>
<td>Thermal - 400 GeV</td>
<td>$\sim 7 \cdot 10^4$</td>
<td>Oct. 2011</td>
</tr>
</tbody>
</table>

Radiation Fields at High-Energy Accelerators and their impact on Single Event Effects
FOURTH CHAPTER

SEE SIMULATIONS USING FLUKA

This chapter describes the use of the FLUKA Monte Carlo code to simulated high-energy accelerator radiation environments such as those presented in Chapter 2 and 3 and their SEE-relevant interaction with matter. The corresponding customized scoring routines are presented along with the methodology used to calculate SEE cross sections, to be applied in Chapter 5 for SEU and Chapter 6 for SEL. In addition, an analysis of the cross sections and products of hadron-silicon nuclear reactions is included.

4.1 Introduction

Estimating the SEE rate for a given component in a certain environment requires the knowledge of: (i) the radiation field and (ii) the response of the component to it. Chapter 2 provides a description of the radiation environments of interest in the context of this thesis, whereas in Chapter 3 different test facilities and SEE rate estimation approaches are introduced. These will be used in Chapter 5 for SEU and Chapter 6 for SEL rate calculations.

The present chapter concentrates on the simulation tools used to extract information about both the radiation environment as well as the device response. In particular, it focuses on the FLUKA Monte Carlo code [19–21]. FLUKA is a well benchmarked general purpose tool for calculations of particle transport and interactions with matter, covering an extended range of applications such as proton and electron accelerator shielding, target design, calorimetry, activation and dosimetry, cosmic ray studies and radiotherapy. The version used to obtain the results presented in this thesis is FLUKA 2011.2b.

Therefore, provided the two-fold application of Monte Carlo codes in the SEE study context (i.e. that of simulating the radiation field as well as the interaction of it with the sensitive device),
we will first of all highlight the similarities between both approaches. Starting from the *inside* of the device, simulating and modeling the sensitivity of a component to a radiation field requires the definition of a sensitive volume, its surroundings, the scoring of the event-by-event energy deposition distribution and the device's response to the deposited energy. This point will be treated in detail in Section 4.4, however what is important at this stage is that, in an atmospheric or accelerator environment, the particles present (either neutral or singly charged) typically do not have a large enough LET to induce SEEs directly. The latter are rather triggered through nuclear interactions of the environment particles with the component itself. Thus, understanding the interaction probabilities and fragment properties for the particles and energies present in the radiation field is a reasonable starting point to the analysis. We will refer to this step of the study as the *production* phase in order to differentiate it from the full MC simulation involving both the production and *transport* of the secondary particles.

In the case of the environment study, nuclear interactions are also extremely important. For instance, if we consider the atmospheric or high energy proton accelerator cases, the primary particles are both the same: mainly high energy protons, which will propagate in vacuum (let it be in the interplanetary space or the LHC) until reaching a medium with which they interact (e.g. the atmosphere for the ground level and avionics environments, and another proton beam or a collimator-like object in an accelerator). It is often the case that the primary beam is well known, however the secondary radiation field will strongly depend on local factors (latitude, altitude, angle with respect to the interaction point, shielding elements between the source and the component, etc.) therefore MC tools are extremely useful in describing the local radiation fields.

Moreover, in certain test facilities, the step between the original beam and the secondary radiation field is controlled and tailored in order to produce the desired radiation fields. For instance, thin, light targets are used to convert (high intensity) monoenergetic proton beams into (low intensity) quasi-monoenergetic neutron beams (as explained in subsection 3.2.3, PTB is an example of this facility category) and thick, heavy (spallation) targets are used to produce atmospheric-like neutron spectra (as in VESUVIO, see subsection 3.3.1) and high-energy accelerator like mixed-fields (such as in H4IRRAD or CHARM, see Section 3.3).

Therefore, the present chapter is structured as follows: in Section 4.2, the production of secondary fragments from proton-silicon reactions in a broad energy range (20 MeV - 30 GeV) is described, both through references to previous works and production simulations using FLUKA. Section 4.3 briefly describes the application of FLUKA to the simulation and benchmark of the high-energy accelerator and mixed-field test facility environments. A similar application is described in Chapter 5 for different SEU SRAM detectors in the H4IRRAD field. Finally, Section 4.4 discusses the use of FLUKA as a means of calculating the SEE cross sections. In this way, the underlying methods we will later use in the SEU and SEL calculation approaches in Chapters 5 and 6 are also described.
4.2 Nuclear Interactions in Silicon

As introduced before, the SEE rate in an accelerator environment is typically dominated by indirect energy deposition events produced by nuclear interactions between the mixed-field hadrons and the SV and its surroundings. Therefore, studying the probability of these events occurring for the relevant hadrons and energy range should be the first step of the analysis. In FLUKA, hadron-nucleus interactions below 20 TeV are treated through the Pre-Equilibrium Approach to NUclear Thermalisation (PEANUT) [20, 21] model. PEANUT includes a very detailed Generalized Intra-Nuclear Cascade (GINC) and pre-equilibrium stage. This model can produce excited fragments, which depending on their mass will deexite through Fermi break-up \((A < 17)\) or either evaporation or fission \((A \geq 18)\).

We use the FLUKA production tool available in the developer’s version to extract the inelastic interaction cross sections in silicon for the relevant hadrons in the high-energy accelerator mixed-field. Results are shown in Fig. 4.1(a) in units of mb. First of all, in order to obtain a more intuitive understanding of the cross section values, these can be expressed in terms of the inelastic interaction length \(\lambda\), which is defined as the average length a particle will travel in a certain material before undergoing an inelastic interaction. The relationship between both is shown in Eq. 4.1 where \(N\) is the number of atoms per unit volume (equal to \(5.01 \cdot 10^{22} \text{ cm}^{-3}\) for silicon). Therefore a cross section value of 450 mb (roughly the saturation value for protons and neutrons in silicon as can be seen in Fig. 4.1(a)) corresponds to an inelastic interaction length of 44 cm. Thus the probability of undergoing an inelastic interaction in the characteristic scale of microelectronic SVs \((\sim 1 \mu m)\) is \(\sim 2 \cdot 10^{-6}\) as shown in Eq. 4.2.

\[
\lambda = \frac{1}{N\sigma_{\text{in}} \rightarrow \lambda_{\text{Si}}(\text{cm})} = \frac{20.0}{\sigma_{\text{Si}}(b)}
\]

\[
\lambda = P_{\text{int}}(x) = 1 - e^{-\frac{x}{\lambda}} \rightarrow P_{\text{int}}(1 \mu m) = \frac{x}{\lambda} \sim 2 \cdot 10^{-6}
\]

When comparing the neutron and charged pion inelastic cross sections with that of protons (typically used in monoenergetic SEE characterizations) several differences (see Fig. 4.1(a)) are to be noted:

- below \(\sim 30\) MeV, the neutron cross section is larger than that of protons. The difference at the peak (14 MeV) is \(\sim 20\%\) \(^1\).

- charged pions have different inelastic cross sections than protons in three ways:
  - the cross section above 1 GeV is smaller (by \(\sim 25\%\) at 10 GeV).
  - there is a resonance for pions with a maximum at 140 MeV and a value \(\sim 65\%\) larger for \(\pi^+\) and \(\sim 85\%\) for \(\pi^-\).

\(^1\)The neutron inelastic cross section below 10 MeV is not shown as it is not provided as an output in the FLUKA production tool.
(iii) the fall-off at low energies for $\pi^+$ occurs at a larger energy than for protons, whereas $\pi^-$ still have a cross section of roughly 70 mb down to the lowest energy considered (100 keV). This is due to the negative pion capture probability in silicon, which can lead to large energy deposition events.

In addition, the individual cross sections for the production of different fragments and recoils is shown in Fig. 4.1(b). The main conclusion is that although the total inelastic cross section is practically saturated above 200 MeV (~20% increase up to 2 GeV and constant within ±8% above that until 1 TeV) the $^4He$ production cross sections increases by a factor 2.5 between 200 MeV and 2.5 GeV. A closer look at the $Z$ distribution of the inelastic products at different energies as well as other properties such as the energy, angular and LET distributions is provided in the following paragraphs.

![Graphs](image)

**Fig. 4.1.** Inelastic interaction and production cross sections as calculated using the FLUKA inelastic event generator.

We performed production runs for proton interactions in silicon for different energies in the 20 MeV - 30 GeV range with the objective of highlighting the energy dependency of the generated fragments and recoil properties. A similar study is presented in [28] in the 50-500 MeV range, showing that the secondary particle production in silicon in terms of LET spectra weakly depends on the proton energy. In this thesis we extend the analysis to larger energies still relevant in the high-energy accelerator environment (present section) as well as to other materials (namely tungsten, as will be shown in Chapter 6).

For each energy, $10^5$ inelastic interactions were simulated. All secondary products except photons and other neutral particles other than neutrons ($Z=0$) were scored and histogrammed.

---

\footnote{In the following we will refer to fragments as particles significantly lighter than the nucleus, and recoils (or heavy fragments) as interaction products resembling the nucleus.}

---

Radiation Fields at High-Energy Accelerators and their impact on Single Event Effects
All singly charged hadrons other than protons (e.g. pions, kaons, etc.) are assigned a Z value of -1. We arbitrarily divide the products into three categories according to their Z value: light ($2 \leq Z \leq 4$), intermediate ($5 \leq Z \leq 9$) and heavy ($Z \geq 10$). First of all, we focus on the Z production yield comparison, which is shown in Fig. 4.2. As can be seen, at 20 and 60 MeV the intermediate fragment production is lower, with a slightly larger heavy fragment peak. However, at 230 MeV and above, the production yield of light, intermediate and heavy fragments is similar for all energies (with the light yield slightly increasing and the heavy yield slightly decreasing). The main difference is that, as the projectile energy increases, the production of heavy fragments decrease, with an increase in the production of light fragments, including protons, neutrons and notably other singly charged hadrons.

**Fig. 4.2.** $Z$ distribution of inelastic fragments generated in p-Si interactions for different energies as extracted using FLUKA. All singly charged hadrons other than protons are assigned a Z of -1.

Concerning the energy and range distributions of the fragments, the maximum and average kinetic energies for the three groups defined above are shown in Table 4.1 for the different simulated projectile energies. The kinetic energy and range distributions are shown in Figs. 4.3 to 4.5 for the three different fragment types considered. The main conclusion that can be extracted from the table and plots is that the energy distribution of the fragments and recoils weakly depends on the projectile energy. As can be seen in Table 4.1, for the light and mid weight fragments, the increase in the average production energy between 230 MeV (i.e. maximum energy typically tested for by CERN groups) and 30 GeV is roughly a factor 2 and 30% respectively. For the heavy fragments, no change can be identified at all. Therefore, from the inelastic interaction and the secondary energy and range distribution analyses, it can be
concluded that:

- for light and intermediate products, both the production probability and the transferred energy moderately increase with increasing projectile energy.
- heavy fragments have slightly lower production probabilities and similar energy distributions above 200 MeV.

Table 4.1. Average ($<E>$) and maximum ($E_{\text{max}}$) inelastic product energy in units of MeV for the categories considered in the text and different proton projectile energies as extracted from the distributions obtained using the FLUKA production tool and $10^5$ inelastic interaction events per energy.

<table>
<thead>
<tr>
<th>Projectile Energy (MeV)</th>
<th>Light</th>
<th>Mid</th>
<th>Heavy</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>5.2</td>
<td>15</td>
<td>-</td>
</tr>
<tr>
<td>60</td>
<td>6.3</td>
<td>38</td>
<td>5.4</td>
</tr>
<tr>
<td>100</td>
<td>6.9</td>
<td>78</td>
<td>5.7</td>
</tr>
<tr>
<td>230</td>
<td>7.4</td>
<td>180</td>
<td>6.3</td>
</tr>
<tr>
<td>1 GeV</td>
<td>9.9</td>
<td>590</td>
<td>7.5</td>
</tr>
<tr>
<td>30 GeV</td>
<td>5.1</td>
<td>1.3 GeV</td>
<td>8.1</td>
</tr>
</tbody>
</table>

Fig. 4.3. Differential kinetic energy and range distributions of the light fragments of (p, Si) interactions for different projectile energies.

Another important property of the particles generated in the inelastic interactions is their angular distribution. These are shown for the intermediate and heavy fragments in Figs. 4.6(a) and (b) in the laboratory reference frame. As can be seen, the reaction products are predominantly forwardly directed. For the heavy recoils, as the proton energy increases, the angular distribution tends to become more isotropic.
4.2. Nuclear Interactions in Silicon

Fig. 4.4. Differential kinetic energy and range distributions of the intermediate fragments of (p, Si) interactions at different projectile energies.

Fig. 4.5. Differential kinetic energy and range distributions of the heavy recoils of (p, Si) interactions at different projectile energies.

In addition, a complete analysis of nuclear interactions of hadrons in silicon requires a discussion about the elastic recoils, which can also be explicitly produced in FLUKA. This was performed for $10^5$ elastic events for different incident proton energies. In Table 4.2 we show the elastic interaction cross section for the different energies considered which as can be seen are comparable to their inelastic counterparts. In addition, the average and maximum silicon recoil energies for the number of events produced are included in the same table. The energy distributions of the recoils are shown in Fig. 4.7(a). The recoil energy for elastic interactions can be calculated through simple collision kinematics owing to the conservation of the kinetic energy. The resulting expression is shown in Eq. 4.3, where $T$ is the transferred energy, $m$ is
Chapter 4. SEE Simulations using FLUKA

Fig. 4.6. Angular distribution of the p+Si reaction products in the laboratory reference frame.

the projectile mass, $M$ is the target mass and $\theta$ is the scattering angle in the laboratory frame. Therefore, the maximum possible energy transfer for a proton ($m = 1$) hitting a silicon nucleus ($M = 28$) is 0.133 its kinetic energy for a forwardly directed recoil ($\cos\theta = 1$). As can be seen in Table 4.2, the maximum energy for the 20 MeV case is consistent with this value. This is no longer the case for the larger proton energies due to statistical limitations.

\[
T = \frac{4mM}{(m + M)^2} \cos^2 \theta
\]  

(4.3)

As can be seen in Fig. 4.7(b) for 230 MeV, the production energy of the recoils is significantly lower than the heavy fragments produced in inelastic interactions for the same proton energies (see Table 4.1). The range in silicon of the average energy recoils ($\sim 200$ keV) is 270 nm, therefore if produced within (or very near) the SV (typical dimensions in the $\mu m$ scale), their deposited energy will in general be equal to the initial kinetic energy. However, in this range the nuclear dE/dx for silicon in silicon is comparable to the electronic one (as can be seen in Fig. 1.5), therefore approximately only half its energy will be converted into charge. This means that the average deposited charge by an elastic recoil is expected to be around 4 fC. Provided inelastic events have a similar occurrence probability, and that they yield much larger fragment and recoil energies, they are expected to dominate the SEE induction, at least for critical charges of several fC and hadrons above 20 MeV. This situation changes however for very sensitive components ($Q_{crit} \sim 1$ fC) and lower energy neutrons, for which the elastic cross section has important resonances around 1 MeV and the recoils produced are still capable of depositing charges in the order of $\sim 1$ fC. The evaluation of the impact of such sensitivity on the SEU cross section and rate in a mixed-field is beyond the scope of this thesis.

In order to globally analyze the dependence of the SEE probability induced by indirect energy deposition events on the energy of the incident protons, the production LET distribution
### Table 4.2. Elastic interaction cross section for protons in silicon together with the average \(< E >\) and maximum \(E_{\text{max}}\) energies of the recoils.

<table>
<thead>
<tr>
<th>Projectile Energy (MeV)</th>
<th>(\sigma_{\text{el}}) (mb)</th>
<th>(\sigma_{\text{inel}}) (mb)</th>
<th>(&lt; E &gt;) (MeV)</th>
<th>(E_{\text{max}}) (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>810</td>
<td>855</td>
<td>0.21</td>
<td>2.7</td>
</tr>
<tr>
<td>60</td>
<td>985</td>
<td>552</td>
<td>0.19</td>
<td>8.2</td>
</tr>
<tr>
<td>100</td>
<td>631</td>
<td>460</td>
<td>0.20</td>
<td>12</td>
</tr>
<tr>
<td>230</td>
<td>197</td>
<td>403</td>
<td>0.21</td>
<td>13</td>
</tr>
<tr>
<td>30 GeV</td>
<td>217</td>
<td>453</td>
<td>0.31</td>
<td>15</td>
</tr>
</tbody>
</table>

Fig. 4.7. Recoil kinetic energy distributions as simulated in FLUKA.

of the particles is a relevant figure of merit. The inverse integral of the LET distribution of the inelastic products with \(Z \geq 2\) and \(E_{\text{kin}} > 100\) keV is shown in Fig. 4.8 for the different energies considered. Similarly to what was concluded in [28] up to 500 MeV, the main conclusion is that the LET distribution weakly depend on the proton energy for energies above 50 MeV. From an interaction point of view, this is mainly related to the fact that, as the proton energy increases above 50 MeV, most of the available energy is either carried by the projectile itself or transferred to light fragments (nucleons, pions, etc.) therefore hardly affecting the heavier fragments \((Z \geq 2)\) relevant to SEE induction.

However, it is relevant to note several important caveats associated to the conclusion that results shown in Fig. 4.8 will lead to a saturated SEE cross section above 60 MeV:

(i) for devices sensitive to alpha particles \((LET_{th} < 1.5\) MeV cm\(^2\) / mg\)) already at a production level one can expect a slight increase in the SEE cross section with increasing energy in the 200-3 GeV range owing to the increase in the alpha production cross section (see Fig. 4.1(b)). This increase will be even stronger for deep sub-micron technologies sensitive to...
singly charged particles, as their production yield clearly increases with increasing energy (see Fig. 4.2).

(ii) even if the production LET is very similar for the different energies considered including and above 60 MeV, the Z and energy distributions differ. In general, secondaries from interactions with more energetic protons will have lower Z values and larger energies due to the increased fragmentation of the nucleus\(^3\). This also means they will have longer ranges which, for a similar LET implies that (a) they can reach the SV from longer distances (b) for large SV dimensions in which an average heavy recoil stops, the energy deposition from a lighter, more energetic fragment with a similar LET will be larger (c) the MCU probability will increase.

(iii) whereas this analysis is limited to silicon, other materials with potentially different inelastic cross section behaviors can be present in a significant proportion near the SV. This is particularly true for high-Z materials which can undergo fission thus involving a very different energy dependence.

\(^3\)At 30 GeV, the fragmentation of the nucleus can be extreme. For example, we identified an event producing 6 positive pions, 4 neutral pions, 7 negative pions, 9 protons, 5 neutrons, 2 deuterium atoms, one tritium atom and an alpha particle (thus the heaviest product of the reaction).
These different points are accounted for when running a full FLUKA simulation including the secondary particle transport. The effect of point (i) above is treated in Chapter 5 for an SEU cross section case, whereas points (ii) and (iii) are dealt with in Chapter 6, mainly for SEL.

4.3 High-Energy Accelerator Mixed-Field Simulation and Benchmark

As introduced in Chapter 2, an accurate description of the radiation environment is a key element to estimate the operational SEE rate. Monte Carlo particle transport codes are an essential tool to calculate such environments provided an accurate knowledge of the primary radiation source and the concerned geometry. In addition, benchmarking the calculations against measurements (i.e. through the monitoring of the radiation field) is also highly relevant. This section provides a brief overview of how FLUKA is used to simulate the radiation environment in the CERN LHC context.

A comprehensive description of the use of FLUKA for the simulation of the SEE-relevant fluences and particle energy spectra in the accelerator context can be found in [48]. These results (or similar) were used in Chapter 2 of this thesis as an example for the different LHC environments. Moreover, LHC experiment environment calculations and the respective discussions can be found in [27] for one of the CERN detectors.

As to what regards the accelerator construction in FLUKA, a detailed library of material and geometry descriptions is available for typical elements such as collimators or magnets. Concerning the physics and thresholds of the simulation, for cases in which only SEEs are of interest (as opposed to TID effects) the radiation environment simulation time can be optimized by disabling the transport of electrons and photons, effectively turning off the electromagnetic cascade. Additionally, justified by the rapid decrease in the charged hadron nuclear interaction cross section below 20 MeV and their energy loss in the device package, the transport cut-off for charged hadrons can be set to this energy for simulations aimed at reproducing the radiation environment.

The LHC area treated in [48] is that around the Interaction Point 1 (IP1), corresponding to the ALTAS experiment. Proton-proton collisions are forced at the interaction point and the emerging particles are transported through the geometry. In the order of $10^5$ interactions are needed to achieve sufficient statistics in the scoring regions of interest. Different UJ and RR alcoves are considered, yielding results similar to those used in the environment description in Chapter 2.
Moreover, the environment in the LHC injection points (TI2 and TI8) is also analyzed, as these are locations in which significant radiation fields are expected due to the beam interaction with the injection line. In this case, protons impinging on the collimator jaw are the source of the mixed-field calculation. In particular, the mixed-field in UJ87 is quantified, as this alcove hosts several power converter units. In this case, a benchmark of the simulation was performed through Toshiba RadMon measurements and the HEH approach for the SEU calculation, including neutrons between 5 and 20 MeV (with no weighting applied). Despite the low count statistics, a very good agreement between measurement and simulation was achieved.

Similarly, a further LHC benchmark study is published in [22] for the collimation region at the LHC point 7 (IR7), which is associated to high losses due to the interaction of high energy protons with the collimator jaws, developing into nuclear showers. In this case, the proton loss distribution maps used as an input in FLUKA are based on the particle tracking code SixTrack [89]. SEU calculations for the Toshiba RadMon were performed using the FLUKA simulated environment and the HEH approach with the weighting function for intermediate energy protons. Results are compared to the SEU measurements yielding a satisfactory agreement considering the complexity of the IR7 beam line.

As to what regards the mixed-field test area environment calculation and benchmark, a detailed description is also provided in [48] for CERF [80]. All Toshiba RadMon measurements at CERF were within a factor 2 of the response predicted by FLUKA simulations combined with the measured cross sections. The main uncertainty source for the calculations is attributed to the sensitivity spread of the detectors. In Chapter 5, we will perform a similar approach for the Toshiba RadMon and ESA SEU Monitor at H4IRRAD (mixed-field test area introduced in subsection 3.3.2), including SEU calculations not only extracted from the measurements but also based on the simulation of the component response using FLUKA.

### 4.4 Monte Carlo Approach for SEE Rate Estimation

An exhaustive description of how Monte Carlo codes can be used to estimate the SEU response of a component in an accelerator environment can be found in [27]. The central assumption of this and other similar approaches is that the complex response of the circuit to an energy deposition event can be represented through its experimental heavy ion cross section. Therefore, it is not necessary to know the details about the circuit and charge collection mechanisms and the approach is almost free of adjustable parameters other than a reasonable description of the SV size.

Whereas the method we use in the scope of this thesis is based on the same principle, several important differences and enhancements with respect to [27] need to be carefully considered:
In [27], FLUKA is only used in the production phase as an inelastic event generator. Elastic scattering is considered through an optical model based on the Glauber theory [90] and the transport of the produced fragments is based on the TRIM code [17] with several modifications to make it more suitable for SEU estimation applications. In this thesis, FLUKA is used for all three purposes in a single, full production and transport simulation.

In [27], a pre-equilibrium intranuclear cascade model included in the FLUKA package is used, which at that time had an upper energy limit of several GeV. The present version of FLUKA includes the PEANUT model up to an energy of 20 TeV.

In [27], only silicon is considered as a material, whereas in our analysis we include other materials such as copper, tungsten or gold. As will be shown, the consideration of such elements in the surrounding of the SVs can have a very strong impact on the test approaches and SEE rate estimation methodologies.

The analysis in [27] is limited to SEU, whereas we also consider SEL in our study, which owing to its potentially destructive character is typically more relevant in terms of radiation hardness for LHC components and systems.

Despite these differences, many of the core conclusions of [27] for silicon geometries apply to the results we will present here and are therefore worth underlining:

- recoils \((Z \geq 10)\) from high energy hadron interactions with silicon nuclei have rather low energy, rarely exceeding 10 MeV, and therefore have their range limited to about 10 µm.

- Elastic scattering gives a minor contribution to the SEU rate.

- The upset rate for 10 GeV protons in only slightly higher than for 200 MeV protons.

- For 200 MeV pions, twice the upset rate of protons of the same energy is expected.

- Simulations for isotropic and monodirectional irradiations show negligible impact on the SEU rate.

Therefore, the basic FLUKA output for SEE cross section calculations is the event-by-event energy deposition in a certain volume. Several standard detector cards are available in FLUKA in order to perform such scoring. As can be seen in the FLUKA manual [19], the DETECT card scores the energy deposition on an event-by-event basis, providing also coincidence and anti-coincidence capabilities such as those of a trigger. However, only one DETECT card is permitted per input, with limited detection volumes. In addition, the energy histogramming is fixed to 1024 bins and it is not possible to link the AUXSCORE card to it for filtering purposes. Moreover, it will only provide meaningful results when FLUKA is used in a completely analogue (i.e. non-biased) mode.

---

**Footnote:** The PEANUT model, which had an upper limit of 1.8 GeV in 1996, has been further increased by incorporating into its sophisticated nuclear framework the Glauber cascade and DPM part of the high energy model [91].
Likewise, the EVENTDAT card prints the event-by-event scored stars (inelastic interactions) and/or energy deposition in each region. Its main limitations for SEE use are that it writes a line for each energy deposition event, resulting in very large output files (notably if rare events are of interest) and that, due to its event-by-event nature, the output of a biased run would not be meaningful.

Due to these limitations, a set of user routines in FLUKA were developed by Ketil Røed (formerly an R2E member at CERN, now with the University of Oslo) in order to provide a versatile means of scoring and histogramming the energy deposition on an event-by-event basis. This protocol was used extensively in the scope of this thesis, as well as further developed to include features such as biasing, the use of heavy ions and/or a particle energy spectrum as a source, and defining different charge collection efficiency regions within the sensitive volume.

The core of the event-by-event scoring protocol consists of two standard FLUKA routines: the comscw.f routine, called after every energy deposition step, and the urseou.f routine, called after each primary particle run. The information about the energy deposition steps in the scoring regions is stored in the comscw.f variables and processed in urseou.f from where the event-by-event energy deposition histogram is filled.

As to what regards the FLUKA input, several cards need to be included in order to activate and define the scoring. First of all, the USERDUMP and USERWEIG cards need to be added to enable access to the mgdraw.f and comscw.f routines respectively. Secondly, a USRBIN card needs to be defined with the set of sensitive volumes as region inputs and a name that is then used in the comscw.f routine as a flag to score the energy deposition events in the regions included in the USRBIN card. Additionally, USRICALL cards are used to define the histogram properties (number of bins, minimum and maximum deposited energy value, linear or logarithmic, particle type) for a certain type of energy deposition (either total or associated to a specific particle ID in FLUKA). A blank USROCALL is also required in order to activate the call to the usrout.f routine.

More specifically, a summary of the different routines involved and their role in the event-by-event energy deposition scoring is listed below. A simple schematic representation showing a brief description and their sequential relation is shown in Fig. 4.9. All routines are standard FLUKA scripts, customized in most cases. Their general description can be found in [19]. An exception to this is the histogram.f routine which was specifically developed for this scoring purpose.

- The usrini.f routine, called every time the USRICALL card is found in the input stream, initializes the histogram scoring.
- The histogram.f routine contains the INITHIST (called in the beginning of the run through usrini.f) and FILLHISTOGRAM (called from usrout.f at the end of each primary event) subroutines.
• The `mgdraw.f` routine (activated using the `USRDUMP` card in the input) is called after every nuclear interaction, keeping track of the information related to the particle generating it.

• The `comscw.f` routine (activated by the `USRWEIGH` card in the input) is called every time an energy deposition event takes place. A flag is set indicating if this event has occurred in a scoring region. In this case, the relevant information about the event (deposited energy, collection region, particle type) is stored in tables defined in a certain FORTRAN common (which in our case is called `edepcommon`).

• The `usreou.f` routine is called after each primary event and takes the information from the energy deposition table, processing it and storing it in the respective histogram through the `FILLHISTOGRAM` routine.

• The `ursout.f` routine is called at the end of a complete simulation and loops through all requested histograms, printing them in a file.

---

**Fig. 4.9.** Schematic representation of the input cards (blue background) and user routines (red background) used in the event-by-event energy deposition scoring protocol. In addition, the `USERDUMP`, `USRWEIGH` and `USRICALL` cards need to be included to enable the access to the `mgdraw.f`, `comscw.f` and `usrout.f` routines respectively.

The output of the event-by-event energy deposition scoring is therefore a histogram with the number of events per incident particle and energy bin. An example of this considering a cubic RPP of side 0.625 µm and 230 MeV protons as a beam particle is shown in Fig. 4.10, both
for a case including only the RPP itself, and one considering the surroundings (3 \( \mu m \) of Si and 2 \( \mu m \) of \( SiO_2 \) above the SV, 2.5 \( \mu m \) of substrate below the SV and a 40 \times 40 \( \mu m^2 \) beam and lateral geometry dimensions). As can be seen, a broad energy deposition peak is observed around 0.2 keV. This corresponds to the direct ionization from protons, which at 230 MeV have an LET of \( 3.3 \times 10^{-3} \text{ MeV cm}^2/\text{mg} \) or 0.76 keV/\( \mu m \). For a depth of 0.625 \( \mu m \), this would correspond to a deposited energy of 0.47 keV. The broadness of the peak is mainly due to the statistical spread of the energy deposition (known as energy straggling), with some protons depositing more energy than others through direct ionization in the sensitive volume.

Moreover, above 10 keV, a tail of high deposited energy events is observed, extending up to \( \sim 2 \text{ MeV} \). This is due to the indirect energy deposition through nuclear interactions of the protons with the SV and surrounding materials. A 2 MeV energy deposition in a depth of 0.625 \( \mu m \) corresponds to a volume-equivalent LET of 14 \( \text{ MeV cm}^2/\text{mg} \), consistent with the maximum production LET in silicon. Also, as expected, the direct ionization peak is independent of the material surrounding the SV, however the indirect energy deposition tail is very different, especially at low deposited energy values. This is due to the fragments generated outside the SV but with ranges long enough to reach it, depositing part of their kinetic energy. The contribution of the surrounding materials is more important in the low indirect energy deposition interval, corresponding to lighter, longer-ranged secondary particles. In fact, for very large deposited energy values, the differences are significantly reduced, manifesting the dominance of heavy, short-ranged particles that therefore only contribute when generated inside or very near the SV. As will be shown in Chapter 6 this situation drastically changes when considering high-Z fissile materials in the vicinity of the SV.

Additionally, the CREME MC online Monte Carlo tool from the Vanderbilt University \cite{56,92} was also used to extract the event-by-event energy deposition distribution for the same simulation case as the vacuum surrounding run using FLUKA. As can be seen in Fig. 4.10, the corresponding outputs are in very good agreement, both in the direct and indirect energy deposition intervals.

Once the event-by-event energy deposition histograms are produced, the corresponding SEE cross section can be extracted as a function of the assumed response function of the component. For a given deposited energy \( E_{dep} \), we can assume there is an associated probability \( w(E_{dep}) \) that the event will lead to an SEE. Having defined this, we can regard the simulation as a mathematical experiment in which the fluence \( \Phi \) will be one over the beam surface \( S \) (as FLUKA results are normalized per incident particle) and the number of SEEs \( N \) will be the result of convoluting the differential energy deposition distribution \( h(E_{dep}) \) with the SEE probability function \( w(E_{dep}) \). Therefore, the cross section for a given particle beam can be calculated using Eq. 4.4. If we assume that there is a certain critical energy \( E_{crit} \) above which all SVs will be sensitive and below which no events will occur, \( w(E_{dep}) \) takes the form of a step function and Eq. 4.4 can be simplified to Eq. 4.5 where \( H(E_{crit}) \) is the integral of \( h(E_{dep}) \) above \( E_{crit} \). All variables in Eqs. 4.4 and 4.5 can also be represented as a function of critical charge or volume-equivalent LET, applying the conversions factors shown in Eq. 4.6 and 4.7 for silicon.

---

Radiation Fields at High-Energy Accelerators and their impact on Single Event Effects
Fig. 4.10. Differential energy deposition spectrum for the RPP example introduced in the text, both only considering the SV itself (vacuum) and the surrounding material (surrounding). The normalization considered (pp) is per primary proton reaching the SV though in the case of the surrounding simulation the beam is larger than the SV surface.

where \( t \) is the thickness of the SV and it is assumed that 3.6 eV are required to generate an electron-hole pair in silicon (i.e. the ionization energy, not to be mistaken with the energy gap, which in silicon is 1.12 eV).

\[
\sigma = \frac{N}{\Phi} = \frac{\int_0^\infty h(E_{\text{dep}})w(E_{\text{dep}})dE_{\text{dep}}}{1/S} \tag{4.4}
\]

\[
\sigma = \frac{N}{\Phi} = \frac{H(E_{\text{crit}})}{1/S} \tag{4.5}
\]

\[
Q_{\text{crit}}(fC) = \frac{E_{\text{crit}}(\text{MeV})}{22.5} \tag{4.6}
\]

\[
LE_{\text{vol}}(\text{MeV cm}^2/\text{mg}) = 4.29 \cdot \frac{E_{\text{dep}}(\text{MeV})}{t(\mu m)} \tag{4.7}
\]

Therefore, the SEE cross section for a step function response can be extracted by integrating the differential energy deposition curves shown in Fig. 4.10 and dividing the results by the simulated fluence (i.e. multiplying by the beam surface if results are normalized to one incident particle), resulting in the curves shown in Fig. 4.11. When looking at the plot from left to right, we see there is a plateau at a cross section value equal to the SV surface \(0.625 \times 0.625 = 0.39\)
\( \mu m^2 \)). This means that, for low enough critical energies, all protons reaching the SV induce an error, and the cross section is therefore equal to the SV surface. When moving towards larger energies, the direct ionization fall-off is identified, with the indirect tail dominating the cross section from critical charges above 10 keV (volume-equivalent LET of 0.1 MeV cm\(^2\)/mg). In this range, the cross section changes only moderately between 0.1 and 10 MeV cm\(^2\)/mg (factor \( \sim 10 \) cross section decrease for a factor 100 critical energy increase) and then falls of rapidly above 10 MeV cm\(^2\)/mg, with no events happening above 14 MeV cm\(^2\)/mg.

![Integral energy deposition spectrum](image-url)

**Fig. 4.11.** Integral energy deposition spectrum for the RPP example introduced in the text, both only considering the SV itself (vacuum) and the surrounding material (surrounding). The events per primary particle are divided by the simulated fluence (or equivalently multiplied by the simulated beam surface) therefore the resulting y-axis units are of an SEE cross section per SV.

A key point when considering Monte Carlo simulations is their CPU efficiency. Different biasing techniques can be employed in order to reduce the otherwise unacceptable CPU time without affecting the outcome of the simulation. In other words, biasing can be used to notably increase the simulation precision without negatively impacting its accuracy.

One of the main challenges related to SEE simulations is that they combine very large particle ranges with very small sensitive volumes. If we consider a production target in a mixed-field test area, the distance between the generation point of the hadron inducing the SEE and the SV can be up to several meters, and indeed the transport of the particle through this path needs to be taken into account. Even at a more local level (i.e. device package or lid) alpha particles potentially capable of inducing SEEs can be generated with ranges up to several...
hundred $\mu m$, thus representing a relevant volume much larger than the actual SV. Having geometries much larger than the SV implies spending vast CPU resources in generating and tracking particles that will not reach the SV and will thus not contribute to the scoring statistics. Therefore, a first way to overcome this limitation is through a two-step simulation, the first one concentrating on the generation and transport of the particles, and the second devoted to the production of fragments in the SV and its vicinity and their energy deposition. Indeed, not only the geometry will be very different in both steps, but also some of the physics settings.

For instance, whereas the explicit tracking of delta rays can be neglected in the first step, it is very important to consider them in the second. In FLUKA, this can be done by using the DELTAYRAY card, which has a minimum delta ray kinetic energy threshold value of 1 keV (whereas the default in PRECISION is 100 keV). This value significantly affects the CPU time of the simulation due to the explicit production and transport of the secondary electrons. However, an obvious accuracy loss related to the use of a too large delta ray threshold for event-by-event energy deposition scoring is that derived from considering the total energy of an energetic delta ray as locally deposited, whereas in reality the electron would escape the SV, only depositing a very small fraction of its energy. This effect is increasingly important for low LET, high energy particles (such as charged hadrons in the accelerator environment) for which the maximum energy transferred to a delta ray can be larger than the average deposited energy through $dE/dx$ in the small SV.

Another important source of inefficiency of the analogue (i.e. non-biased) Monte Carlo simulations for SEE calculations is the fact that, for a hadron beam or mixed-field environment, it is the inelastic energy deposition events that can lead to an SEE as opposed to the direct ionization from the environmental particles. As discussed in Section 4.2, the probability of such an event happening in the SV scale ($\sim \mu m$) is in the order of $10^{-6}$. This means that a very large number of primary particles needs to be produced and transported in order to induce a statistically meaningful amount of inelastic interactions near the SV and subsequently simulated SEE counts.

A biasing technique that can compensate for this natural inefficiency is that of enhancing the inelastic interaction probability of the primary particles in the vicinity of the SV. This can be done through the LAM–BIAS card available in FLUKA. When it is used, the inelastic interaction probability is increased by a certain biasing factor $B$, and particles produced in such interactions are assigned a weight equal to the inverse of the factor, $B^{-1}$. The energy deposited by the particles in the standard FLUKA scoring is the physical value times its weight. For cumulative scoring such as dose, an inelastic biasing factor of (for example) 100 would lead to the generation of 100 more inelastic fragments each depositing one hundredth of their physical deposited energy, thus compensating for the interaction probability increase while enhancing the scoring statistics and recovering the physical value. However, if we consider the event-by-event energy deposition distribution, more particles would deposit less energy than in the analogue case, which of course would lead to a very different distribution and consequently meaningless SEE results. This is the reason why the standard event-by-event
scoring options in FLUKA are incompatible with biasing.

Therefore, in order to use the potentially very powerful biasing tool, we need to adapt the customized scoring routines in such a way that the physical energy deposition and interaction probabilities are recovered. This is performed as follows for the scoring routine used in this thesis: when the individual step-by-step energy depositions are added by region in the userou. f routine, they are also added by weight. Therefore, if a biased event has occurred, it will be divided into two histories: one with a weight of \(1 - B^{-1}\) (if the interacting particle is forced to survive as can be determined in the LAM–BIAS card [19]) corresponding to the non-biased case, and one with a weight \(B\) related to the biased case. The energy deposition is then divided by the weight associated to the sum of the energy deposition steps for a given history (thus recovering the physical value), and when included in the histogram, this event is counted as \(B^{-1}\) instead of 1, thus recovering the physical probability of the event occurrence.

In order to benchmark the biasing accuracy and to evaluate its impact on the simulation precision, we run a set of simulations with 230 MeV neutrons and different biasing factors on the same geometry (including the surroundings) used to extract the energy deposition spectrum shown in Fig. 4.10. The quantity considered as a result is the SEE cross section for a component with a critical energy of 225 keV (corresponding to 10 fC). In all cases, the product of the number of primary particles and the biasing factor is constant, thus resulting in the same total number of inelastic events as shown in Table 4.3. The statistical precision is defined as two times the standard deviation between the different statistically independent runs performed in each case divided by the average value and expressed as a percentage. The accuracy is expressed as the ratio between the cross section result for a given biasing factor and the non-biased case. As can be seen, differences with respect to the analogue run are within the statistical precision and therefore no systematic effect of the biasing on the result can be identified.

In order to evaluate the efficiency of the biasing for the different factors, we define the Figure-of-Merit (FOM) as the ratio between the total CPU time for the analogue and biased runs of theoretically equal precision (i.e. same number of inelastic events). As can be seen, for a biasing factor of 5, the total CPU time is reduced by a factor 4.4 with respect to the analogue case, showing that the CPU time improvement is close to linear with the biasing factor. However, for a factor of 20, the FOM is 11, already indicating a clearly sub-linear dependency. Above 200, the FOM is saturated at a value near 20. We attribute this to the relative dominance of the inelastic events in the total CPU time, which will result in the increase of the CPU time per primary particle proportionally to the biasing factor. Anyhow, a factor 20 CPU time gain without affecting the accuracy of the simulation results\(^5\) can be considered as a significant improvement.

\(^5\)It is to be noted that the accuracy of the biased runs was benchmarked for most scenarios in which this technique was used in the scope of this thesis, however there might be specific cases beyond the applications here considered in which the implementation of the biasing in the scoring routines could lead to systematic errors in the results.
### 4.5 Summary

This chapter explains how the FLUKA Monte Carlo code is applied to SEE studies in the high-energy accelerator context. In particular, it describes how available user routines can be used to provide a versatile event-by-event scoring of the deposited energy.

Moreover, the FLUKA inelastic interaction generator available in the developer’s version is used to describe the probability and product properties of hadron-silicon reactions at different energies relevant to the LHC-like environment. The main conclusion is that, as was previously shown for energies up to 500 MeV, the SEE-relevant properties of the fragments and recoils are relatively independent of the incident proton energy, also when extending the considered interval to GeV energies. This fact has important hardness assurance consequences, as tests at energies in the 50-230 MeV range are therefore expected to be representative of what occurs at larger energies still relevant for the high-energy accelerator context. As will be shown in Chapters 5 and 6, this is not necessarily the case when considering the full transport of the secondary products as well as notably materials other than silicon in the vicinity of the SVs.

#### Table 4.3. Characteristics and results for the SEE simulation described in the text and different biasing factors.

<table>
<thead>
<tr>
<th>Biasing Factor</th>
<th>Total Primaries</th>
<th>Total Inel. Events</th>
<th>CPU time per primary (s)</th>
<th>Total CPU time (s)</th>
<th>Accuracy</th>
<th>Statistical Precision (%)</th>
<th>FOM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$2 \cdot 10^{10}$</td>
<td>$5.5 \cdot 10^8$</td>
<td>$3.1 \cdot 10^{-5}$</td>
<td>$6.2 \cdot 10^5$</td>
<td>1.000</td>
<td>3.51</td>
<td>1.0</td>
</tr>
<tr>
<td>5</td>
<td>$4 \cdot 10^9$</td>
<td>$5.5 \cdot 10^6$</td>
<td>$3.6 \cdot 10^{-5}$</td>
<td>$1.4 \cdot 10^5$</td>
<td>0.989</td>
<td>3.63</td>
<td>4.4</td>
</tr>
<tr>
<td>20</td>
<td>$1 \cdot 10^8$</td>
<td>$5.5 \cdot 10^4$</td>
<td>$5.7 \cdot 10^{-5}$</td>
<td>$5.7 \cdot 10^4$</td>
<td>1.008</td>
<td>4.00</td>
<td>11</td>
</tr>
<tr>
<td>200</td>
<td>$1 \cdot 10^6$</td>
<td>$5.5 \cdot 10^2$</td>
<td>$3.0 \cdot 10^{-4}$</td>
<td>$3.0 \cdot 10^4$</td>
<td>1.005</td>
<td>3.47</td>
<td>21</td>
</tr>
<tr>
<td>1000</td>
<td>$2 \cdot 10^7$</td>
<td>$5.5 \cdot 10^0$</td>
<td>$1.4 \cdot 10^{-3}$</td>
<td>$2.8 \cdot 10^4$</td>
<td>0.986</td>
<td>3.67</td>
<td>22</td>
</tr>
</tbody>
</table>
5th Chapter

SEU Measurements and Simulations

This chapter shows the experimental SEU results for the ESA SEU Monitor in a wide range of test beams, including neutrons between 5 and 15 MeV and protons from 30 MeV up to several hundred GeV. In addition, results from different mixed-field environments are also shown and correlated with the HEH approach prediction. Finally, a semi-empirical SEU model is implemented in FLUKA in order to simulate the ESA SEU Monitor cross section and extrapolate it to particle types and energies not obtainable at standard test facilities.

5.1 Introduction

The importance of measuring the SEU cross section and expected error rate of an SRAM to be used in the LHC environment is crucial, especially for critical systems. As was introduced in Chapter 1, SEUs are soft errors that can be corrected and are therefore in principle non-destructive. Nevertheless, SEUs affecting control systems of the LHC accelerator can lead to data corruption and faulty information. Moreover, in the case of SRAM memories containing configuration information (for instance, in an FPGA) an SEU can lead to a malfunction in the system. Therefore, it is compelling to obtain information of (i) the expected error rate in the operational mode and radiation environment and (ii) the criticality of this error rate. If regarded as non-acceptable, measures will need to be carried out in order to reduce the error rate, such as selecting an alternative, more robust component, or implementing radiation hardening techniques at a system level (redundancies, Error Correction Codes, etc.).

Likewise, the development and use of SEU simulation techniques complementary to the experimental measurements is vital in order to individually study the impact of each particle type and energy, something not feasible through monoenergetic measurements, and not possible to extract directly from mixed-field results.
Chapter 5. SEU Measurements and Simulations

Before introducing the SEU cross section results, it is important to clearly define what is meant by this value. In the context of this thesis, the cross section for a certain device, facility, particle type and energy is the best estimate of the average of a cross section distribution of individual components of the same type (i.e. those following the same well-behaved response distribution). Experimentally it is obtained through \( N \) different measurements \( x_1, \ldots, x_N \) of individual components of the same distribution, and can therefore be calculated through Eq. 5.1.

\[
\sigma_{\text{SEE}} = \frac{\sum_{i=1}^{N} x_i}{N} \tag{5.1}
\]

A measurement \( x_i \) applies to the same individual component, facility and particle type and energy, and is extracted by dividing the number of SEE counts \( m \) by the respective particle fluence \( \Phi \) as shown in Eq. 5.2.

\[
x_i = \frac{m_i}{\Phi_i} \tag{5.2}
\]

The distribution of the real individual cross section values (i.e. not the measured values \( x_i \), which are subject to the count statistics error) will be subject to a certain spread (assumed to be of a Gaussian nature) related to the natural deviation in the sensitivity of the devices, \( \sigma_{\text{sens}} \). Estimating its value (associated to the standard deviation of the measurement distribution) is also highly relevant, especially for components to be used as SEE-count based radiation monitors. Related to this, a very important point to be considered in the SEE data analysis are the uncertainty sources of the experimental cross section value and their quantification. As a first approach, two different error types are to be considered: statistical and systematic. The first category is of a random nature and can be reduced by increasing the counts per measurement and total number of measurements per cross section. For a set of \( N \) measurements, the corresponding statistical error \( \epsilon_{\text{stat}} \) is here considered as two times the standard deviation of the mean as shown in Eq. 5.3, where \( \sigma_N \) is the standard deviation\(^1\) of the measurement set \( x_1, \ldots, x_N \). This value \( \sigma_N \) is defined in the standard way in Eq. 5.4 and will converge to the standard deviation associated to the sensitivity spread of the original distribution when the number of counts per measurement and the number of measurements tend to infinite. However, for a finite number of counts per measurements, it will also include the contribution of the uncertainty related to the count statistics, \( \sigma_{\text{count}} \), of the individual measurements, which for a cross section \( x_i \) obtained from \( m > 50 \) counts\(^2\) can be calculated using Eq. 5.5. In addition, for a finite number of measurements \( N \), it will also be subject to the statistical spread of the standard deviation distribution [94].

---

1 The symbol \( \sigma \) in this case represents the standard deviation of the cross sections and not the SEE cross section values \( \sigma_{\text{SEE}} \).

2 In this case, the Poisson distribution characteristic of the SEE events can be approximated to a Gaussian distribution. For count values below 50, the tabulated uncertainty ranges should be employed for the desired confidence level [93].
Moreover, the fluence measurements at a facility from which the cross section values are derived depend on a certain beam dosimetry which relies on a given calibration. As all results will be affected by this calibration in the same manner, this is a source of systematic error \( \epsilon_{sys} \) which unless stated otherwise will be considered as 10% for a 2\( \sigma \) confidence level, in line with what is typically reported by the facilities.

Therefore, cross section values will typically be expressed with their associated statistical and systematic relative errors in percentage, which can be summed in quadrature to obtain the total uncertainty. Results are therefore expressed in the form shown in Eq. 5.6 also including an example. If only one error is shown instead of two, it corresponds to the statistical and systematic contributions expressed together. Moreover, if the error values are not followed by a percentage sign, they are expressed in absolute terms as opposed to relative values.

\[
\sigma_{\text{SEE}} \pm \frac{\epsilon_{\text{stat}}}{\sigma_{\text{SEE}}} \% \pm \frac{\epsilon_{\text{sys}}}{\sigma_{\text{SEE}}} \%
\]

\[
2.63 \times 10^{-14} \text{ cm}^2/\text{bit} \pm 7\% \pm 10\%
\]

5.2 ESA SEU Monitor Test Results

The ESA SEU Monitor is an SRAM-based detector that uses an AT60142F 4Mbit ATMEL memory [95] which is produced on a radiation hardened 0.25 \( \mu \)m CMOS process. The die area of the memory is 6 x 11 mm. The monitor is available both in a 4Mbit version and in a 16Mbit multi-chip module (AT68166F [96]) composed of four AT60142F memories. In both cases, the memory is connected to a motherboard containing a microprocessor that is used to access it. The latter is then connected to a computer via RS232 (4Mbit version) or Ethernet (16Mbit version) from which the memory can be written and read through a dedicated software. The software interface shows the number of SEUs after each memory read operation as well as their physical distribution in the memory. In the 4Mbit version, the error distribution is provided per 512K block, whereas for the 16Mbit it is displayed per 32K block [97]. In each individual 4Mbit memory, the 8 bits of a same word are physically placed in a separate 512K memory block, therefore MCUs (events upsetting more than one bit) do not lead to MBUs (events upsetting more than one bit in the same logical word). Moreover, the memory die is protected with a
Chapter 5. SEU Measurements and Simulations

420 µm Kovar lid. The impact of the latter on the SEU rate will be analyzed in this chapter through both experimental and simulation results.

As mentioned above, it is extremely important to quantify the sensitivity spread of an SRAM memory when planning to use it as a radiation detector. For instance, the ESA SEU Monitor was developed as a means of cross-calibrating the beam fluence at different facilities [5] (i.e. a so-called golden chip). The device was calibrated using different beams and was associated a cross section as a function of energy which can then be used to extract the particle fluence from the number of counts. However, in order to evaluate a possible mismatch between the value provided by the facility and that measured with the monitor, it is essential to accurately know not only the cross section value but also its spread, in order to evaluate if the measured difference is compatible with it. For this reason, SRAM memories selected as monitors should have a relatively small sensitivity spread in order to more accurately measure the fluence.

In the case of the ESA SEU Monitor, the sensitivity spread was assumed to be independent of the particle type and energy, and extracted through 8 measurements (i.e. performed on different components) at 230 MeV in the PSI facility. The retrieved $2\sigma$ sensitivity spread was below 7% at a 95% confidence level. It is to be noted at this stage that, in order to evaluate the sensitivity spread of a component, its distribution (i.e. the standard deviation distribution [94]) was taken into account. In a similar way that the uncertainty in the average number of counts per unit fluence (i.e. the cross section) is evaluated, an analogous treatment needs to be performed on the standard deviation in the case the sensitivity spread evaluation is of interest.

5.2.1 | PSI: 30-230 MeV protons

The ESA Monitor SEU cross section was measured in the 30-230 MeV energy range during different test campaigns at PSI (see subsection 3.2.1 for the facility description) and using different components. A summary of the cross section results can be found in Table 5.1 for the energies tested. As can be seen, the energy dependence in the range analyzed is relatively small, with a peak near 50 MeV and a fall-off at 30 MeV.

Moreover, measurements were also performed exposing the memory die directly to the proton beam by removing the Kovar lid from the ESA SEU Monitor in order to evaluate its impact on the SEU cross section. Results in the same energy range for the component without the lid are included in Table 5.2. When comparing these results with those with the lid it can be noticed that the only statistically meaningful difference is found at 30 MeV, for which the cross section without lid is 16% larger. Both data sets are plotted in Fig. 5.1 together with the fit of the lid case to a Weibull function of the type shown in Eq. 5.7 with the parameters shown in Table 5.3. It is also to be noted that the experimental energies are reported as monoenergetic values, however as was shown in Table 3.1 and Fig. 3.4, the energies below 230 MeV are obtained through a copper degrader system which introduces a spread in the beam energy. The effect of this spread on the SEU cross section will be discussed in Section 5.3.
Table 5.1. SEU cross section summary for the ESA SEU Monitor at PSI. The total memory size is 16 Mbit, therefore the cross section for the full monitor at 230 MeV corresponds to $4.4 \times 10^{-7} \text{cm}^2$.

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Number of Measurements</th>
<th>$\sigma_{SEU}$ $(\times 10^{-14} \text{cm}^2/\text{bit})$</th>
<th>$\pm 2\sigma$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>4</td>
<td>2.12</td>
<td>$\pm 11 \pm 10$</td>
</tr>
<tr>
<td>47</td>
<td>2</td>
<td>2.94</td>
<td>$\pm 12 \pm 10$</td>
</tr>
<tr>
<td>60</td>
<td>3</td>
<td>2.84</td>
<td>$\pm 7 \pm 10$</td>
</tr>
<tr>
<td>80</td>
<td>3</td>
<td>2.66</td>
<td>$\pm 12 \pm 10$</td>
</tr>
<tr>
<td>100</td>
<td>4</td>
<td>2.65</td>
<td>$\pm 9 \pm 10$</td>
</tr>
<tr>
<td>150</td>
<td>3</td>
<td>2.39</td>
<td>$\pm 10 \pm 10$</td>
</tr>
<tr>
<td>200</td>
<td>1</td>
<td>2.37</td>
<td>$\pm 9 \pm 10$</td>
</tr>
<tr>
<td>230</td>
<td>8</td>
<td>2.63</td>
<td>$\pm 7 \pm 10$</td>
</tr>
</tbody>
</table>

Table 5.2. SEU cross section summary for the ESA SEU Monitor (no lid) at PSI.

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Number of Measurements</th>
<th>$\sigma_{SEU}$ $(\times 10^{-14} \text{cm}^2/\text{bit})$</th>
<th>$\pm 2\sigma$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>2</td>
<td>2.48</td>
<td>$\pm 10 \pm 10$</td>
</tr>
<tr>
<td>60</td>
<td>2</td>
<td>2.92</td>
<td>$\pm 9 \pm 10$</td>
</tr>
<tr>
<td>100</td>
<td>2</td>
<td>2.62</td>
<td>$\pm 10 \pm 10$</td>
</tr>
<tr>
<td>150</td>
<td>2</td>
<td>2.42</td>
<td>$\pm 10 \pm 10$</td>
</tr>
<tr>
<td>230</td>
<td>2</td>
<td>2.54</td>
<td>$\pm 10 \pm 10$</td>
</tr>
</tbody>
</table>

$$\sigma_{SEU}(E) = \sigma_{sat} \cdot (1 - \exp(-(E - E_0)/W)^s)$$ (5.7)

Table 5.3. Weibull fit parameters for the ESA Monitor proton SEU cross section. The energy onset is extracted from the proton Coulomb barrier in silicon, however it hardly affects the fit as the fall-off is determined by the 30 MeV point.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{sat}$</td>
<td>$2.6 \times 10^{-14} \text{cm}^2/\text{bit}$</td>
</tr>
<tr>
<td>$E_0$ (MeV)</td>
<td>3.7</td>
</tr>
<tr>
<td>$W$ (MeV)</td>
<td>18.2</td>
</tr>
<tr>
<td>$s$</td>
<td>1.67</td>
</tr>
</tbody>
</table>

In addition to the PSI measurements in the 30-230 MeV range, the ESA Monitor was characterized during a January 2013 test campaign performed by ESA at KVI, Groningen (The Netherlands) covering a similar energy interval. Measurements were carried out on a 16 Mbit version of the monitor, with the lid removed. Results are also plotted in Fig. 5.1 together with those obtained at PSI. As can be seen, both data sets are consistent, with the KVI values in the 50-80 MeV range being slightly larger (by $\sim 10\%$) that those at PSI. This effect could be related to the different initial energies and degrader thicknesses in each case, therefore resulting in a
different beam energy distribution in a region in which the energy dependency of the cross section is significant. Likewise, proton tests were performed on one of the CERN ESA Monitors by a research group from the University of Oslo using a 170 MeV beam at TSL in Uppsala [98] during a May 2014 test campaign. As can be seen in Fig. 5.1, the resulting cross section is compatible with results at PSI and KVI for similar energies.

On the other hand, the initial calibration results from the ESA SEU Monitor also performed at a wide range of proton facilities (PSI, LIF, RADEF and KVI) in measurements performed in 2004 yielded a consistent saturated cross section of $3.4 \cdot 10^{-14}$ cm$^2$/bit [6] and therefore 30% larger than the more recent values retrieved by R2E at PSI (between 2011 and 2014) and ESA at KVI (in 2013). Provided that the total uncertainty of the cross section values was measured to be significantly smaller than this 30% difference, the mismatch cannot be explained by it. Likewise, the consistency between the different facilities almost completely excludes the possibility of the difference arising from the beam dosimetry. Therefore, the focus was set on potential differences in the detector memory. When inquired about this in a private communication, the SRAM memory manufacturer (ATMEL) pointed to a change in the memory core voltage in a revision carried out in 2004 as a possible cause of the sensitivity change. The bias voltage was increased from 2.5V to 2.7V in order to improve the SRAM’s access speed, which could (at least partially) explain the SEU sensitivity decrease. However the change happened in revision F, and both the memories reported in [6] and those more recently tested and here presented were referenced as AT60142F, thus having the same core voltage (2.7V). Therefore, this discrepancy,
while still suspected to be related to a change in the memory composing the monitor, remains unexplained. In any case, it is to be underlined that all monitors used in the work presented in this thesis where performed using the new monitors, i.e. those with a 230 MeV cross section compatible with $2.6 \times 10^{-14} \pm 12\% \text{ cm}^2/\text{bit}$.

### 5.2.2 TRIUMF: 230-480 MeV protons

As was shown in subsection 3.2.2, the TRIUMF facility was used in the scope of this thesis in order to evaluate the dependency of different SEE cross sections for energies beyond the 230 MeV value reached at PSI. One of the tested components was the ESA SEU Monitor for which the energy response in the 30-230 MeV had been previously characterized at PSI. The use of the monitor also enabled the possibility of verifying that the beam was centered on and homogeneous over the DUT’s sensitive surface and to discard test configurations for which this was not the case.

At TRIUMF measurements were performed in the BL1B line using the extraction energies of 480 and 355 MeV as well as the degraded energy of 230 MeV. For the first and the third, both the front and back test locations were used. For the second, measurements were only carried out in the back location. Two different ESA SEU Monitors were characterized for all energies both with and without lid. The respective cross section results are shown in Table 5.4 and plotted in Fig. 5.2 together with those from PSI. The first conclusion to be drawn when comparing the 230 MeV TRIUMF result with that obtained at PSI is that the former is 16% smaller than the latter. In both cases, the measurements have a small statistical uncertainty (~7%) therefore the discrepancy can in principle only be explained through the different calibration values at both facilities. For this reason and in order to be consistent, the TRIUMF fluence values for the different runs (including those for the rest of component types and effects) were scaled in the same manner in order to match the PSI ESA SEU Monitor cross section at 230 MeV.

Furthermore, another important conclusion from the TRIUMF experimental data is that a weak (but measurable) cross section increase with energy is clearly observed above 230 MeV. In fact, the 480 MeV cross section value is ~30% larger than that at 230 MeV. This behavior will be analyzed and disused through an RPP model in FLUKA in Section 5.3. Finally, the cross section value for the ESA Monitor without lid at 480 MeV is smaller than the one with lid by ~5% and could point to a weak contribution from the secondaries generated in the lid at this energy, however both values are still compatible when considering their statistical uncertainty.

---

3 Individual measurements of the cross section for the same component and slightly different positions showed a large spread for the 355 MeV, front test configuration. Moreover, the physical SEU distribution on the monitor was clearly not homogeneous, therefore manifesting that the beam size at this location was not large enough to cover the DUT’s sensitive surface. For this reason, this test configuration was discarded for SEE testing.

4 This selection does not in any way favor the PSI dosimetry with respect to that at TRIUMF, however provided it is the test facility where the vast majority of the R2E radiation tests are performed, it is here considered as the reference.
Table 5.4. SEU cross section summary for the ESA SEU Monitor at TRIUMF

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Number of Measurements</th>
<th>$\sigma_{SEU}$ $(\cdot 10^{-14} \text{ cm}^2/\text{bit})$</th>
<th>$\pm 2\sigma$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>230</td>
<td>2</td>
<td>2.15 (2.63)</td>
<td>$\pm 6 \pm 10$</td>
</tr>
<tr>
<td>355</td>
<td>2</td>
<td>2.44 (2.98)</td>
<td>$\pm 7 \pm 10$</td>
</tr>
<tr>
<td>480</td>
<td>2</td>
<td>2.75 (3.36)</td>
<td>$\pm 6 \pm 10$</td>
</tr>
<tr>
<td>480 (no lid)</td>
<td>2</td>
<td>2.65 (3.24)</td>
<td>$\pm 7 \pm 10$</td>
</tr>
</tbody>
</table>

Fig. 5.2. SEU cross section for the ESA SEU Monitor at TRIUMF including the PSI data. The scaled results (by a factor 1.16) in order to match the 230 MeV PSI result are also shown.

5.2.3 | PTB: 5-15 MeV neutrons

Measurements were performed on the ESA SEU Monitor at PTB (see subsection 3.2.3 for a description of the facility) with the objective of characterizing its SEU response to intermediate energy neutrons. As illustrated in the LHC radiation environments introduced in Chapter 2 these particles can have an important contribution to the total SEE rate for certain locations. In order to further put this calibration into context, a detailed report of the 2011 Toshiba RadMon characterization at PTB for LHC monitoring purposes can be found in [29] whereas the application of the respective Weibull fit response to LHC radiation level measurements is published in [22].

As a rule of thumb, the intermediate energy neutron contribution in the LHC and surrounding areas can be up to 100% that of the HEH.
For the ESA SEU Monitor characterization, three different neutron energies were used: 5.0, 8.0 and 14.8 MeV. For the two latter energies, two different monitors were tested, whereas for the former, only one was characterized. These energy values are used because (i) they are available with reasonably high fluxes (see Table 3.2) and (ii) they provide enough information to perform a statistically meaningful fit of the intermediate energy neutron data to an analytic function. The merged SEU cross section results are presented in Table 5.5 showing a strong fall-off with energy (the cross section decreases by over a factor 10 between 14.8 and 5.0 MeV).

Table 5.5. SEU cross section summary for the ESA SEU Monitor at PTB.

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Number of Measurements</th>
<th>$\sigma_{SEU}$ ($10^{-14}$ cm$^2$/bit)</th>
<th>$\pm 2\sigma$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0</td>
<td>1</td>
<td>0.19</td>
<td>$\pm 25 \pm 10$</td>
</tr>
<tr>
<td>8.0</td>
<td>2</td>
<td>0.51</td>
<td>$\pm 17 \pm 10$</td>
</tr>
<tr>
<td>14.8</td>
<td>2</td>
<td>2.22</td>
<td>$\pm 17 \pm 10$</td>
</tr>
</tbody>
</table>

Following the equivalent HEH formalism introduced in Chapter 2, the intermediate energy neutron cross section values can be used to derive the response function in this energy range. The standard assumption is that the HEH cross section is constant above 20 MeV and equal to the saturation value (i.e. 230 MeV) and falls off below 20 MeV following a Weibull function (see section 2.1 for details). The corresponding Weibull fit parameters extracted from the PTB measurements for the ESA SEU Monitor can be found Table 5.6 and are plotted together with the neutron and proton data in Fig. 5.6. As can be seen, when compared with the intermediate energy neutron data points, the proton cross section measurement at 30 MeV already shows a fall-off at a larger energy, as expected from the positive charge of the particle. Also included in the plot is the fit implemented in FLUKA for the HEH equivalent generalized particle and extracted as described in subsection 2.2.1. As is observed, the fit to the ESA Monitor data exhibits a similar response shape as that used in the HEH equivalent definition, while being slightly shifted towards larger energies. The impact of this difference on the SER estimation will be discussed in the following subsection.

Table 5.6. Weibull fit parameters for the ESA Monitor neutron SEU cross section.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{sat}$ (cm$^2$/bit)</td>
<td>$2.6 \cdot 10^{-14}$</td>
</tr>
<tr>
<td>$E_o$ (MeV)</td>
<td>0.2</td>
</tr>
<tr>
<td>$W$ (MeV)</td>
<td>11.6</td>
</tr>
<tr>
<td>$s$</td>
<td>3.14</td>
</tr>
</tbody>
</table>

In addition, one measurement was performed at 14.8 MeV irradiating the ESA Monitor from the back side and yielding a cross section value of $9.42 \cdot 10^{-15}$ cm$^2$/bit, thus a factor 2.4 smaller that the respective result for irradiation from the front. This effect was also measured for the Toshiba RadMon [29] and cannot in principle be justified through the attenuation of the...
neutron beam in the component substrate. An explanation to this experimental observation is provided in [99]. Recoils from neutron reactions in oxygen have larger average energies than those in silicon for energies below 50 MeV owing to their lower mass (see Eq. 4.3). Because these recoils are predominantly forwardly directed, and provided oxygen is only present above the SV (in the SiO₂ layers), irradiations from the back yield a smaller cross section value.

5.2.4 | VESUVIO: Atmospheric-like neutron spectrum

As introduced in subsection 3.3.1, the VESUVIO beamline provides a neutron spectrum ranging from thermal to several hundred MeV energies. The ESA SEU Monitor was tested in this radiation environment with the purpose of correlating the experimental error rate with that predicted from the proton and neutron monoenergetic measurements. In order to do so, two type of measurements were performed: one exposing the ESA Monitor directly to the neutron beam and one introducing a 1.5 mm cadmium slab in front of it in order to absorb the thermal part of the neutron spectrum. The respective neutron spectra are proportional to those shown in Fig. 3.10.

Once the thermal and HEH equivalent fluxes (fluences) are known along with the respective cross section values, the expected error rate (total error count) can be estimated using Eq. 2.4.
At VESUVIO, the average thermal neutron, HEH and HEH equivalent fluxes on the ESA SEU Monitor during the different runs can be extracted using Eq. 3.2 and the respective nominal values (see Table 3.3). The resulting total fluence values for the two test configurations are reported in Table 5.7 both considering the standard approach to calculate the intermediate energy contribution (dotted green line in Fig 5.3) as well as the actual ESA Monitor response (unbroken green line in Fig 5.3).

Table 5.7. Total fluences for the ESA Monitor runs at VESUVIO in units of cm\(^{-2}\). In both configurations (full spectrum and cadmium absorber) the HEH and HEH equivalent fluxes were the same, therefore differences are only due to the different test times. In the case of the equivalent HEH flux, both the result derived the standard approach (\(\Phi_{HEH_{eq}}^{HEH}\)) and that using the response specific to the ESA Monitor (\(\Phi_{HEH_{eq}}^{ESA}\)) are shown. In the case of the thermal neutron fluence, the R factor is included in brackets.

<table>
<thead>
<tr>
<th>Spectrum</th>
<th>(\Phi_{HEH})</th>
<th>(\Phi_{HEH_{eq}})</th>
<th>(\Phi_{HEH_{eq}}^{ESA})</th>
<th>(\Phi_{th})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Spectrum</td>
<td>4.25 (\times) 10(^8)</td>
<td>9.85 (\times) 10(^8)</td>
<td>7.86 (\times) 10(^8)</td>
<td>1.23 (\times) 10(^{10}) (29)</td>
</tr>
<tr>
<td>Cadmium Absorber</td>
<td>2.10 (\times) 10(^8)</td>
<td>4.86 (\times) 10(^8)</td>
<td>3.88 (\times) 10(^8)</td>
<td>9.73 (\times) 10(^8) (4.6)</td>
</tr>
</tbody>
</table>

Table 5.8 shows the total SEU counts for each test spectrum together with the estimated HEH approach value considering the ESA Monitor response for the intermediate neutrons. The associated uncertainty is derived considering a 40% error in the thermal neutron fluence and cross section. The former is related to the difficulty of accurately describing the exact composition of the materials responsible for the neutron thermalization, which have a very strong impact on the calculated spectrum. The latter is an assumption for the thermal neutron cross section value of 3.3 \(\times\) 10\(^{-15}\) cm\(^2\) / bit reported in [6] without providing an error. The thermal neutron contribution to the total count value is calculated to be 65% for the full spectrum and 23% for the cadmium absorber configuration. The reason for the significant calculated thermal neutron contribution despite the absorber is that, as can be seen in Fig. 3.10, Cd only absorbs neutrons below \(\sim\) 0.5 eV and provided the very intense epithermal\(^6\) part of the neutron spectrum, the equivalent thermal neutron flux is still important.

As can be seen, the predicted value for the spectrum with the cadmium absorber is in excellent agreement with the measurement, whereas in the case of the full spectrum, the calculation overestimates the measurement by 21%. However, the calculation is compatible with the experimental result if we consider its uncertainty, mainly driven by the strong thermal neutron contribution to the total SEU rate. To this regard, we can note two possible sources of systematic overestimation of the calculated number of SEUs:

- the thermal neutron cross section used for the ESA SEU Monitor was that reported in [6] and therefore corresponds to the components that also had a HEH cross section 30% larger than that measured in the more recently tested devices. As is shown in [10], the

---

\(^6\)Epithermal neutrons are those in the energy range immediately above the thermal range, roughly between 1 meV and 10 keV.
relative cross section difference when altering the device sensitivity can significantly differ for the HEH and thermal neutron cases.

- the neutron flux as a function of energy at VESUVIO was measured by means of a scintillator down to energies of 2 meV (therefore below the thermal peak) and the resulting distribution results in an equivalent nominal thermal neutron flux of $8.3 \cdot 10^5 / cm^2 / s$, which is a 30% lower than the value obtained from the calculation.

**Table 5.8.** Measured SEU counts for each test spectrum at VESUVIO including the expected value from the HEH approach (using the ESA SEU Monitor response) and the ratio between the latter and the measured value.

<table>
<thead>
<tr>
<th>Spectrum</th>
<th>Number of Measurements</th>
<th>SEU Counts</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Measured</td>
<td>Estimated</td>
</tr>
<tr>
<td>Full spectrum</td>
<td>3</td>
<td>843</td>
<td>1024 ± 24%</td>
</tr>
<tr>
<td>Cadmium absorber</td>
<td>2</td>
<td>219</td>
<td>223 ± 13%</td>
</tr>
</tbody>
</table>

Moreover, as introduced in Chapter 3, the mixed-field HEH equivalent cross section can be extracted from mixed-field measurements by considering the equivalent HEH fluence. Likewise, the SER can be expressed in units of FITs (introduced in Section 3.1) for a given environment of HEH flux per hour $\phi_{\text{HEH}_{\text{eq}}}$ through the relation shown in Eq. 5.8 where $N_{\text{bit}}$ are the number of bits in the memory and $N_{\text{Mbit}}$ is the memory size in Mbit. Table 5.9 shows the values for these two quantities extracted from the measurement results shown in Table 5.8.

$$
SER \ (\text{FIT/Mbit}) = \frac{10^9 \cdot \sigma_{\text{HEH}_{\text{eq}}} \cdot N_{\text{bit}} \cdot \phi_{\text{HEH}_{\text{eq}}}}{N_{\text{Mbit}}}
$$

**Table 5.9.** Mixed-field equivalent HEH SEU cross section ($\sigma_{\text{HEH}_{\text{eq}}}^*$) and ground-level SER for the two different spectra used in VESUVIO. The considered ground-level radiation environment corresponds to that calculated for Geneva and shown in Table 2.7.

<table>
<thead>
<tr>
<th>Spectrum</th>
<th>$\sigma_{\text{HEH}_{\text{eq}}}^*$</th>
<th>SER</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(-$10^{-15}$ cm²/bit)</td>
<td>(FIT/Mbit)</td>
</tr>
<tr>
<td>Full spectrum</td>
<td>5.10 ± 17%</td>
<td>1037 ± 17%</td>
</tr>
<tr>
<td>Cadmium Absorber</td>
<td>2.69 ± 18%</td>
<td>547 ± 18%</td>
</tr>
</tbody>
</table>

Finally, if we consider the ESA SEU Monitor thermal neutron cross section as unknown, it can be estimated independently to the HEH cross section through the VESUVIO measurements by comparing the SER for a given test configuration, without ($SER_{\text{Full}}$) and with ($SER_{\text{Cd}}$) the

---

[7] In this case, the scaling between the experimental and ground-level error rates is performed based on the equivalent HEH (neutron) flux as opposed to the flux above 10 MeV specified in the standards [100], however the difference between both approaches is small owing to the similar energy spectra.
cadmium slab. Provided the HEH flux will be the same in both cases, the SER expressions can be subtracted and the subsequent equation solved for \( \sigma_{th} \), resulting in Eq. 5.9.

\[
\sigma_{th} = \frac{SER_{full} - SER_{Cd}}{\phi_{th}^{full} - \phi_{th}^{Cd}} = 2.3 \times 10^{-15} \ (\pm 17\% \pm 20\%) \ cm^2/\ bit
\]  

(5.9)

5.2.5 | H4IRRAD and CERF: 120 and 400 GeV hadrons

SEU measurements were performed on the ESA SEU Monitor with a 400 GeV proton beam at H4IRRAD and a 120 GeV mixed pion and proton beam at CERF. Details of the test beams can be found in subsection 3.2.4. The objective of these measurements was to evaluate the energy dependency of the SEU cross section in the several hundred GeV range, still relevant for the high-energy accelerator radiation environment.

As was pointed out in subsection 3.2.4, the assumption that the beam is homogeneous over the DUT is not valid in the case of the H4IRRAD and CERF beams owing to their small size relative to the sensitive surface, therefore it is very important to (i) accurately measure the beam profile and (ii) have the component centered with respect to the beam. The beam profile distributions were measured using proportional wire chambers as was shown in Figs. 3.7 and 3.8 for H4IRRAD and CERF, with a FWHM of \( \sim 30 \times 30 \) and \( \sim 20 \times 10 \ mm^2 \) respectively. As to what regards the alignment, the DUTs were mounted on an xy-table perpendicular to the beam with a 0.1 mm precision. The physical layout of the SEU events was then used to retrieve the position for which the beam was centered on the component through different iterations. Two examples of the SEU distribution for a CERF and H4IRRAD run are shown in Figs. 3.7 and 3.8. Within the sensitive surface limits, the beam distributions can be considered Gaussian and therefore integrated in order to obtain the respective fluences for each run.

Measurements were performed at both facilities, with and without lid. In addition, a tungsten slab of the same thickness as the original lid was also employed at H4IRRAD. Results for the different cross sections are shown in Table 5.10 and consider, in addition to the standard uncertainty sources introduced above, a 0.3 mm error in the horizontal and vertical beam size \( \sigma \) and a 0.5 mm position error in both axis, which are included in the statistical error. Results are also plotted in Fig. 5.6 for the case with lid together with the PSI and TRIUMF proton data. The main conclusion that can be extracted from the measurements is that the cross section increases significantly with respect to the 230 MeV value (by a factor \( \sim 2 \)) in both cases. Despite this measurable effect, considering the 3 orders of magnitude energy change with respect to standard several hundred MeV tests, this result is a confirmation that, for silicon-fragment dominated cases, the SEU cross section value is relatively stable above this energy interval. Furthermore, unlike in the 60-480 MeV range, the lid has an important impact on the SEU cross section, as measurements with it have a cross section \( \sim 50\% \) larger than those without. Also, the tungsten slab (labeled as \( W \ lid \)) has the same effect on the cross section as the Kovar lid from the monitor. In addition, it can be noted that the cross section values at H4IRRAD...
Fig. 5.4. Physical SEU distribution per 512K memory block for the 4Mbit ESA SEU Monitor in H4IRRAD during a November 2012 run. The output shows a centered DUT with respect to the beam, though slightly off in the horizontal axis (note that the right count column is moderately larger than the left). The block labeled "Average" does not correspond to a physical part of the memory, but just shows the average SEU value per block. The difference between the word error and bit error counts displayed in the software interface is due to the fact that, despite the bits in a same word are distributed in different physical blocks of the memory (i.e. no MBUs are possible) there is still a certain probability that more than one error will randomly happen in the same word.

Fig. 5.5. SEU distribution per 4Mbit memory die for the 16Mbit ESA SEU Monitor at CERF during the May 2012 run showing that the DUT was centered in one of the dies (right-bottom in the image) due to the small beam size relative to the entire monitor. The vertical beam direction (in which the beam size is smaller) is horizontal in the figure.

are ~10-15% larger than those at CERF. All these different experimental observations will be compared with the simulation results in Section 5.3. Likewise, the effect of the cross section increase with energy on the accelerator SEU rate for the ESA Monitor and more generally of Radiation Fields at High-Energy Accelerators and their impact on Single Event Effects.
other components and effects will be treated in detail in subsection 5.3.2.

Table 5.10. SEU cross section summary for the ESA SEU Monitor at CERF and H4IRRAD. The ratio to the 230 MeV value is also shown together with its respective absolute 2σ uncertainty.

<table>
<thead>
<tr>
<th>Test conditions</th>
<th>Number of Measurements</th>
<th>$\sigma_{\text{SEU}}$ (10^{-14} cm^2 / bit)</th>
<th>±2σ (%)</th>
<th>Ratio to 230 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>CERF</td>
<td>2</td>
<td>5.10</td>
<td>±21 ± 10</td>
<td>1.96 ± 0.13</td>
</tr>
<tr>
<td>CERF, no lid</td>
<td>1</td>
<td>3.52</td>
<td>±17 ± 10</td>
<td>1.35 ± 0.17</td>
</tr>
<tr>
<td>H4IRRAD</td>
<td>1</td>
<td>6.07</td>
<td>±14 ± 10</td>
<td>2.31 ± 0.09</td>
</tr>
<tr>
<td>H4IRRAD, W lid</td>
<td>1</td>
<td>5.92</td>
<td>±14 ± 10</td>
<td>2.25 ± 0.09</td>
</tr>
<tr>
<td>H4IRRAD, no lid</td>
<td>1</td>
<td>4.00</td>
<td>±14 ± 10</td>
<td>1.54 ± 0.14</td>
</tr>
</tbody>
</table>

Fig. 5.6. SEU cross section for the ESA SEU Monitor at CERF and H4IRRAD including the 30–480 MeV data from PSI and TRIUMF. Note that the CERF point, while here represented together with proton cross section values, was obtained using a mixed pion and proton beam described in subsection 3.2.4.

5.2.6 | H4IRRAD: Accelerator-like mixed-field

SEU measurements were performed on the ESA Monitor in the internal zone of the H4IRRAD mixed-field test area. A detailed description of the radiation environment can be found in subsection 3.3.2. In addition to the ESA Monitor, the SEU response of the two Toshiba RadMons placed in the internal zone during the same test slot is also analyzed.
Similarly to what was performed in the case of the VESUVIO atmospheric-like neutron environment, the expected total SEU count can be extracted from the HEH and thermal neutron responses and the respective equivalent fluences through Eq. 2.4. The former are shown in Table 5.11 for both components whereas the latter are retrieved through the simulated values of the corresponding FLUKA output for the specific run (see Table 3.5) and its associated normalization provided by the total number of protons on target for each measurement.

Table 5.11. HEH and thermal neutron SEU cross section for the Toshiba RadMon (5V operation) and the ESA SEU Monitor including the associated relative total uncertainty in percentage. For the case of the thermal neutron cross section of the ESA Monitor, this value is assumed as no information is provided in the source for the result.

<table>
<thead>
<tr>
<th>Device</th>
<th>$\sigma_{HEH}$</th>
<th>$\sigma_{th}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$(10^{-14} cm^2/bit)$</td>
<td></td>
</tr>
<tr>
<td>Toshiba</td>
<td>2.9 ± 25%</td>
<td>0.31 ± 25%</td>
</tr>
<tr>
<td>ESA Monitor</td>
<td>2.6 ± 12%</td>
<td>0.33 ± 40%</td>
</tr>
</tbody>
</table>

The resulting measured and calculated SEU count values are shown in Table 5.12 together with the respective calculation to measurement ratio. As introduced in Chapter 2, the calculation is based on (i) the HEH and thermal neutron sensitivities and (ii) the FLUKA simulation of the equivalent HEH and equivalent thermal neutron fluxes. As can be seen, all test results are within the calculated count value except for the case of the ESA SEU Monitor for which the upper estimated limit is still marginally below the measured value. Several possible sources of underestimation when using the HEH approach for this particular case will be studied in Section 5.3, including that related to the several hundred GeV cross section increase shown in subsection 5.2.5 and the hard spectrum at the ESA Monitor test location described in subsection 3.3.2.

Table 5.12. Measured SEU counts for each test spectrum at H4IRRAD including the expected value from the HEH approach and the ratio between the latter and the measured value. The ESA Monitor was only running for ~1/3 of the total test campaign intensity in order to protect its peripheral readout circuitry. In the case of the measured value, the uncertainty is associated to the device sensitivity spread.

<table>
<thead>
<tr>
<th>DUT</th>
<th>SEU Count</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measured</td>
<td>Estimated</td>
</tr>
<tr>
<td>RadMon 3</td>
<td>4909 pm 25%</td>
<td>4725 ± 16%</td>
</tr>
<tr>
<td>RadMon 4</td>
<td>8063 pm 25%</td>
<td>9156 ± 17%</td>
</tr>
<tr>
<td>ESA Monitor</td>
<td>1925 pm 7%</td>
<td>1570 ± 16%</td>
</tr>
</tbody>
</table>
5.3 SEU modeling and simulation for the ESA SEU Monitor

Motivated by the natural lack of test data covering the full particle species and energy ranges relevant to the accelerator mixed-field environment, Monte Carlo simulations of the SEU cross sections of interest were performed using the RPP model introduced in Chapter 4. In this case, the sensitive volume dimensions are selected according to the device technology node and the critical charge is empirically extracted through the fit of the calculated cross section to the proton test data in the 30-230 MeV range as will be detailed in the following subsection. Once this semi-empirical model is defined through its sensitive volume dimensions and critical charge it can be used to predict the cross sections for particles and energies relevant to the mixed-field and not available in standard test facilities. Theses simulated cross sections can then be employed in combination with the environment spectra in order to obtain the expected operational error rate.

5.3.1 RPP model and calibration to the PSI data

In the case of the ESA SEU Monitor, a $0.25 \mu m^3$ cubic sensitive volume (RPP model) was assumed, representative of the commercial $0.25 \mu m$ SRAM technology [101]. In addition, a $6.7 \mu m$ BEOL zone consisting of silicon dioxide and aluminum layers was considered above the SV region, according to the information provided by the memory manufacturer. Moreover, the lid of the device (typically not removed for proton tests), with a measured thickness of $420 \mu m$ and composed of Kovar and a gold and nickel plating of $25 \mu m$ of each material on each side, was implemented in the following way:

- for very high energy neutrons ($E > 1 GeV$) the full lid was explicitly simulated due to the effect of the long-ranged light particles produced in the interaction with it and capable of reaching the SV.

- for lower energy hadrons ($E < 100 MeV$) the effect of the lid in terms of fragment generation was determined to be negligible in practical terms for the critical charges of interest owing to their shorter ranges. Therefore its contribution was only accounted for through a first-step simulation with fewer primary particles transported through the lid (only direct energy loss is of interest) resulting in a decrease in the average beam energy and increase in the spread for charged hadrons. The resulting spectra are then used as input for the second-step, full-statistics simulation.

- For neutron energies in the $100 MeV < E < 1 GeV$ range and hadrons above $1 GeV$, an intermediate solution between both cases above was employed, following a compromise between statistical precision, accuracy associated to the geometry and CPU time in each case.
In order to include the effect of the secondary particles arriving from the materials surrounding the SV while preserving a reasonable statistical precision despite the small dimensions of the SV in relation to the lid and the BEOL, 100 different collection volumes were placed on the same plane perpendicular to the beam (z direction) in the center of a $40 \mu m \times 40 \mu m$ surface. In Fig. 5.7, a cut in the yz plane of the simulated geometry is shown.

**Fig. 5.7.** Cut in the yz plane of the RPP model used in the simulations. The beam travels from left to right, in the positive z direction. Not included in the figure, to its left, is the main part of the lid, 420 $\mu m$ long in total. From left to right of the figure part of the nickel (brown) and the complete gold layer (yellow) of the lid can be found. After this, the silicon dioxide (blue) and aluminum (gray) layers can be observed, representing the BEOL. Finally the silicon region in which the SVs are located can be seen. These have a thickness of 0.63 $\mu m$ and are placed in the rectangular region marked in red, adjacent and to the right of the BEOL layers.

With the RPP model defined above, the next step is to determine its critical charge value based on the available PSI experimental data introduced in subsection 5.2.1. Eight proton energies between 30 MeV and 230 MeV were simulated using the considerations mentioned above, together with two additional ones:

- for proton energies below 80 $MeV$, instead of considering a monoenergetic beam in the simulation, the original 230 MeV beam used at PSI was degraded accordingly using different copper thicknesses, mimicking the experimental situation and thus increasing the spread of the beam as shown in Table 3.1 and Fig. 3.4. This effect becomes more important with decreasing energies and has a significant impact on the corresponding energy deposition simulation.
• due to their almost identical interaction with matter above 100 MeV in terms of nuclear reactions [39], neutrons were used for energies larger than this value instead of protons because of their lower CPU cost (owing to the fact they do not lose energy continuously through Coulomb interactions during their transport).

Twenty jobs of $5 \times 10^8$ particles were run for each energy using standard FLUKA physics settings (PRECISIO defaults, COALESCE and EVAPORAT physics cards, and a delta-ray threshold of 10 keV). As shown in detail in Chapter 4, the event-by-event energy deposition distribution was scored for each case using a customized routine, and the integrals of the deposition events above a certain critical charge were calculated and divided by the simulated fluence, yielding the SEU cross section as a function of $Q_{\text{crit}}$ for each tested energy. The corresponding cross section values for the critical charges of interest were obtained with a relative $2\sigma$ statistical error of less than 8%. A reduced $\chi^2$ fit of the critical charge to the experimental data was performed providing a best fit value of 9.8 fC as can be seen in Fig. 5.8, consistent with the 8 fC reported in [101] as typical for a 0.25 µm commercial technology operated at 2.5V. The accuracy of the fit was evaluated through the reduced $\chi^2$ value, which was equal to 1.6. The resulting simulated cross section is represented in Fig. 5.9 together with the test data and the ±2σ curves derived from the fit to the critical charge. As can be observed, the best fit of the critical charge yields a cross section curve in very good agreement with the data in the entire calibration energy range considered.

5.3.2 | Application of the RPP model to mixed-field particles and energies

Once the RPP model is defined and calibrated to the experimental data as explained above, it can be used to perform SEU cross section simulations for the relevant hadrons in the considered environment (p, n, $\pi^\pm$) and energy range of interest. At least 16 points separated logarithmically between 10 MeV and 400 GeV were simulated for each hadron type. In addition to the considerations already introduced, the following optimizations were applied:

• positive and negative pions were considered to have the same SEU cross section above 200 MeV due to their almost equivalent inelastic interaction cross section, and only positive pions were simulated, representing both of them.

• due to their different treatment in FLUKA, the neutron cross section below 20 MeV was not simulated as an average energy deposition is used as opposed to the event-by-event energy deposition distribution.

---

8The data shown in Fig. 5.9 corresponds to that published in Fig. 4 of [102], to which the critical charge was initially fitted to, resulting in the value of 9.8 fC used in this thesis. The data presented in Table 5.1 include a broader measurement set and the resulting cross section values are slightly larger than those to which the original fit is performed, yielding a best fit critical charge value of 9.4 fC.
The resulting simulated cross sections for the different particle types are then derived by integrating the energy deposition events above the critical charge normalized to the simulated fluence, and are plotted in Fig. 5.10 together with the TRIUMF data (see subsection 5.2.2) and the experimental GeV measurements from CERF and H4IRRAD (see subsection 5.2.5). As can be seen, the RPP model calibrated to the PSI experimental results is very successful in reproducing the cross section behavior at larger energies. The simulated and measured values for the respective experimental beams are shown in Table 5.13 together with their ratio. As can be seen, the agreement between measurements and simulations is within ±6% for all cases except those without the lid, for which simulations underestimate the measured value by 20–25%. A possible source of systematic uncertainty is the description of the BEOL through its materials and thicknesses, which have a very strong impact on the simulated cross section for the very high energies considered.

For the π-meson cross section, a clear resonance around 150 MeV is observed, which has previously been identified experimentally [40] and attributed to the pion-nucleus reaction cross section related to the formation of the delta \( \Delta(1232) \) resonance. Alternatively however, it was shown in [41] that for several components tested of 0.5–0.8 \( \mu m \) technologies, no significant
5.3. SEU modeling and simulation for the ESA SEU Monitor

![Proton SEU cross section data for the ESA Monitor as a function of energy together with the corresponding simulated curve for the best fit of the critical charge to the data. Uncertainties for the simulated cross section curve are taken as $2\sigma$ from the fit to the critical charge parameter and represented as dashed lines.](image)

**Fig. 5.9.** Proton SEU cross section data for the ESA Monitor as a function of energy together with the corresponding simulated curve for the best fit of the critical charge to the data. Uncertainties for the simulated cross section curve are taken as $2\sigma$ from the fit to the critical charge parameter and represented as dashed lines.

differences between proton and pion upset cross sections could be measured. Because the typical LHC pion spectra peaks at energies above the resonance region, the potential effect of an increased sensitivity in this interval is not expected to have a crucial impact on the respective upset rates. This point will be treated in detail in Chapter 7.

Moreover, a gradual increase in the SEU cross section with increasing energy is observed for hadrons above $\sim 200$ MeV and until $\sim 3$ GeV, consistent with the behavior of the proton-proton (pp) total cross section in this energy range [103]. As can be seen in an extended version of the work here presented [104], this increase is mainly due to the enhanced production cross section and energy (and thus range) of light and intermediate silicon fragments ($Z < 7$). In contrast, the relative contribution of the heavy fragments ($Z > 8$) decreases significantly between 230 MeV and 3 GeV. Above this energy and until 400 GeV (highest energy simulated) the calculated SEU cross section does not vary significantly. Despite the increase in the available energy for the secondaries in the inelastic processes, other effects such as the slight decrease in the pp cross section, the increased yield of fragments per interaction (notably mesons) and a larger
Fig. 5.10. Simulated proton, neutron and π± cross section for a sensitive volume of 0.25 \( \mu m^3 \) and a critical charge of 9.8 fC, together with the experimental data used for the calibration of the model (also in Fig. 5.9 with a smaller energy range) and the test data from TRIUMF, CERF and H4IRRAD. The 2\( \sigma \) error associated to the fit of the critical charge is not explicitly shown to avoid overloading the graph, but is of \( \sim \pm 15\% \).

The proportion of energy transferred to the electromagnetic part of the nuclear reactions result in an overall saturation of the simulated SEU cross section above \( \sim 3 \) GeV. It is also to be noted that the saturated SEU cross section for pions is lower than that for protons and neutrons, as expected from the respective reaction cross sections shown in Fig. 4.1(a). This could explain the lower SEU cross section measurement in the CERF beam (120 GeV, \( sim2/3 \) pions, \( sim1/3 \) protons) by \( \sim 15\% \) with respect to H4IRRAD (400 GeV protons). However, both results are compatible when considering their respective uncertainty intervals.

In order to obtain an overview of the cross section increase as a function of the critical charge of the model, the energy deposition distribution is shown in a normalized reverse integral form in Fig. 5.11 therefore representing the simulated cross section as a function of critical charge. As can be seen, the effect of the lid for 3 GeV is significant, and therefore the contribution of the thickness and composition of the materials surrounding the SV (BEOL, package, etc.) at this energy is much more relevant than in the case of 230 MeV. Another
Table 5.13. Simulated and measured cross section values in units of $10^{-14} \text{cm}^2/\text{bit}$ for different test beams. The ratio between the simulated and measured cross sections is shown in the last column. The W in the lid column represents the tungsten lid.

<table>
<thead>
<tr>
<th>Test beam</th>
<th>Energy</th>
<th>Lid</th>
<th>$\sigma_{\text{simulated}}$</th>
<th>$\sigma_{\text{measured}}$</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRIUMF</td>
<td>355 MeV</td>
<td>Yes</td>
<td>2.80 ± 15%</td>
<td>2.98 ± 12%</td>
<td>0.94 ± 0.18</td>
</tr>
<tr>
<td></td>
<td>480 MeV</td>
<td></td>
<td>3.18 ± 15%</td>
<td>3.36 ± 12%</td>
<td>0.95 ± 0.18</td>
</tr>
<tr>
<td>CERF</td>
<td>120 GeV</td>
<td>Yes</td>
<td>4.84 ± 15%</td>
<td>5.10 ± 23%</td>
<td>0.95 ± 0.26</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No</td>
<td>2.73 ± 15%</td>
<td>3.52 ± 20%</td>
<td>0.78 ± 0.20</td>
</tr>
<tr>
<td>H4IRRAD</td>
<td>400 GeV</td>
<td>Yes</td>
<td>5.97 ± 15%</td>
<td>6.07 ± 17%</td>
<td>0.98 ± 0.22</td>
</tr>
<tr>
<td></td>
<td>W</td>
<td></td>
<td>5.88 ± 15%</td>
<td>5.92 ± 17%</td>
<td>0.99 ± 0.22</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td></td>
<td>3.11 ± 15%</td>
<td>4.00 ± 17%</td>
<td>0.77 ± 0.17</td>
</tr>
</tbody>
</table>

important conclusion that can be extracted from the figure is that the effect of the cross section increase with energy between 230 MeV and 3 GeV is expected to be more pronounced for lower critical charge components, reaching a factor 5 for a critical charge of 1 fC. This is consistent with the fact that, as was shown in Chapter 4, light particles are produced in a larger proportion and with longer ranges, thus affecting more sensitive components in a more severe way. When moving towards larger critical charges, the difference is reduced (factor 2 for 10 fC) until it increases again above 30 fC. This is due to the fission fragments from the gold layer in the lid, and would not be the case if a non-fissile material was present instead. A detailed discussion about the effect of fission fragments on the SEE cross section is provided in Chapter 6. In addition, it is to be born in mind that whereas protons and neutrons have the same indirect energy deposition behavior in silicon above $\sim 50$ MeV [39], the fission cross section of the latter is larger than that of the former by a factor $\sim 3$ in the 50-200 MeV interval, as can be seen in [105]. The effect of this difference on the mixed-field SEE failure rate will be treated in Chapter 7.

Finally, because the Toshiba RadMon SRAM was tested together with the ESA SEU Monitor in the H4IRRAD mixed-field environment, an RPP model for it was defined in analogy to the one presented above. In this case, in order to obtain a realistic SV size, the values provided in [101] for the 65 nm - 250 nm technology range were fitted to a polynomial function and extrapolated, providing a value of 0.99 $\mu m^3$ for a technological node of 0.4 $\mu m$. Again, a cubic volume was assumed, and in this case, a plastic package was considered instead of a Kovar lid, as well as 2.4 $\mu m$ of BEOL mainly composed of SiO$_2$ and aluminum, following a construction analysis of the memory. After simulating the energy deposition for the experimental values shown in [106] a best fit for the critical charge parameter for the 5V operation was found for a value of 33.7 fC, with a reduced-$\chi^2$ of 2.1 and a ±2σ uncertainty of 1.9 fC. With this model, the expected cross section increase between 200 MeV and 3 GeV calculated in the ESA SEU Monitor case is not observed owing to the larger critical charge, thinner BEOL and plastic as a package material instead of Kovar.
Fig. 5.11. FLUKA simulated SEU cross section as a function of critical charge for the RPP model here used. Neutrons were used instead of protons in order to optimize the CPU time, therefore only indirect energy deposition events are taken into account. The ratio between the 3 GeV and 230 MeV cross sections for the case with lid is also shown as a function of critical charge.

Both cross section sets for the RPP models (ESA Monitor and Toshiba) introduced above can then be used to estimate the SEU rate in a mixed-field environment by convoluting them with the respective particle energy spectra. This was performed for the H4IRRAD locations (see subsection 3.3.2) and the respective SEU rates are shown in Table 5.14 for all three components together with the measured value. As can be seen, the difference between the HEH approach and the simulated cross section values for the Toshiba memories is minor, owing to their larger critical charge, thinner BEOL and less dense package material. In contrast, the prediction for the ESA SEU Monitor when using the calculated cross sections is ∼50% larger than that obtained through the HEH approach. As will be shown in Chapter 7, this is mainly due to the contribution of the hadrons in the 1-10 GeV range, which are present in the environment in a significant proportion and are calculated to have a larger SEU cross section as can be seen in Fig. 5.10. When compared to the measurement, the calculated cross section method for the ESA Monitor overestimates the experimental value in a similar proportion as the HEH approach underestimates it (∼25%). We attribute this result to the uncertainty in the radiation field calculations, mainly associated to the large gradients in the area where the component was placed (i.e. almost directly downstream the target) as the model is very successful in reproducing the hadron data in a very broad energy interval as can be seen in Fig. 5.10.
Table 5.14. Simulated SEU rate per $10^9$ protons on target for the ESA SEU monitor and Toshiba RadMons in the respective operating environment for (i) the HEH approach, (ii) the simulated SEU cross sections and (iii) the measured values. Values include the relative uncertainties in brackets, which are mainly related to the exact positioning of the components and the strong radiation field gradients. Results for the HEH approach differ marginally from those published in [102] due to the different thermal and intermediate neutron treatment.

<table>
<thead>
<tr>
<th>Particle</th>
<th>SEU counts per $10^9$ protons on target using HEH</th>
<th>using simulated $\sigma_{SEU}$</th>
<th>measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toshiba 3</td>
<td>1.40 ($\pm$17%)</td>
<td>1.41 ($\pm$24%)</td>
<td>1.44</td>
</tr>
<tr>
<td>Toshiba 4</td>
<td>2.70 ($\pm$29%)</td>
<td>2.52 ($\pm$32%)</td>
<td>2.36</td>
</tr>
<tr>
<td>ESA SEU Monitor</td>
<td>1.45 ($\pm$29%)</td>
<td>2.17 ($\pm$32%)</td>
<td>1.76</td>
</tr>
</tbody>
</table>

Finally, the study here presented did not include an analysis of the MCU dependency with energy, however provided the increase in the secondary particle multiplicity (i.e. number of fragments generated per nuclear interaction) as well as their range, it is also expected to increase significantly with energy.

5.4 Summary

The SEU cross section measurements for the ESA Monitor were presented in this chapter for a wide range of test facilities. Measurements at PSI and TRIUMF using protons between 30 and 480 MeV showed that (i) the cross section is fairly constant in this range, with a fall-off at 30 MeV, a peak around 50 MeV and a slight increase between 200 and 480 MeV and (ii) the sensitivity spread among the different components is very small.

In addition, neutron measurements at PTB confirmed that the fall-off of the cross section at intermediate energies follows a similar behavior to that of the RadMon Toshiba, while being slightly less sensitive. Moreover, the expected SEU rate from the HEH approach at the VESUVIO neutron spectrum slightly overestimated the measured rate (by 20%) but can be regarded compatible with it when considering the different sources of systematic uncertainty related to the response of the component and the provided fluences.

Likewise, unprecedented very high energy measurements were performed using the CERF and H4IRRAD beams showing that in the several hundred GeV hadron energy range, (i) the cross section increases by a factor $\sim$2 with respect to the several hundred MeV case and (ii) the lid plays an important role in the SEU induction mechanism, with a $\sim$50% cross section increase with respect to the case without lid. At H4IRRAD, SEU measurements were also

---

9While results here shown use the equivalent thermal neutron definition to evaluate the thermal neutron impact on the SEU rate (see subsection 2.2.1 for details), in [102] the integral below 500 meV is considered, yielding slightly different results. In addition, the fit for the intermediate neutrons in the case of the results shown in [102] are based on a different fit than the one to the Toshiba RadMon data implemented in FLUKA.
performed in the mixed-field both for the ESA Monitor and the Toshiba SRAM. For the latter, the expected SEU rate was in very good agreement with the measured value, whereas for the former, the rate based on the HEH approach slightly underestimated the experimental result.

With the objective of applying it to a broad range of particle types and energies, an RPP model was defined for the ESA Monitor and calibrated to the experimental PSI data resulting in a highly compatible fit. The model confirmed the cross section increase above 200 MeV and at several hundred GeV, and determined that it mainly takes place in the 200 MeV - 3 GeV interval owing to the increased light and intermediate silicon fragment production and energy. The calculated increase strongly depends on the materials surrounding the SV, and is expected to be more pronounced for components with a smaller critical charge value. Finally, the simulated cross sections were used to calculate the mixed-field error rate at H4IRRAD, which yielded a result ~50% above that expected using the standard HEH approach and ~25% above the measured value, compatible when considering the respective uncertainties.
This chapter shows a set of SEL proton test data for commercial components focusing on the cross section dependency with energy. A model is defined relating this dependency with the presence of high-Z materials near the SV. The model is then used to calculate the cross sections for a range of particles and energies broader than what is obtainable experimentally.

6.1 Introduction

As introduced in Chapter 1, SEL is a potentially destructive radiation effect that poses a serious threat to the operation of CMOS devices. In the LHC environment, SEL events in the past have lead to system failures seriously compromising the accelerator’s performance [107]. Therefore, characterizing the SEL response of commercial electronic components to be used in LHC and its injector chain control and powering systems is highly important.

With the objective of analyzing the SEL cross section dependence with the proton energy in the 30-480 MeV interval, we tested a set of commercial components including an ADC and eight different types of SRAMs at PSI and/or TRIUMF. In addition to the measurements we performed directly, test results from ESA are also used in the study.

Furthermore, we present an SEL model in FLUKA that is used to estimate the SEL cross section for larger energies and evaluate the impact of the observed energy dependence on the high-energy accelerator failure rate. The model uses the HI and proton test data as an input, as well as information about the typical SRAM SEL sensitive volume geometry based on published laser inspections.
Finally, we carried out a device inspection based on SEM (Scanning Electron Microscopy) of most of the parts involved in order to validate some of the model parameters.

The main characteristics of the parts tested in the scope of the SEL study are shown in Table 6.1. Moreover, a summary of the device’s available test data and information used in the SEL analysis is shown in Table 6.2.

**Table 6.1.** Main characteristics of the components tested and their identification name used in the present work. A dash is used in the cases the information is not available.

<table>
<thead>
<tr>
<th>ID</th>
<th>Part Numbers</th>
<th>Manufacturer</th>
<th>Size</th>
<th>Tech. (nm)</th>
<th>Date Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRAM A</td>
<td>IS61LV5128AL-10TLI [108]</td>
<td>ISSI</td>
<td>512K x 8</td>
<td>180</td>
<td>1247</td>
</tr>
<tr>
<td>SRAM B</td>
<td>CY7C1069AV33-10ZXC [109]</td>
<td>Cypress</td>
<td>2M x 8</td>
<td>180</td>
<td>1237</td>
</tr>
<tr>
<td>SRAM C</td>
<td>AS7C34098A-10TCN [110]</td>
<td>Alliance</td>
<td>256K x 16</td>
<td>200</td>
<td>1205, 1210</td>
</tr>
<tr>
<td>SRAM D</td>
<td>K6R4016V1D-TC10 [111]</td>
<td>Samsung</td>
<td>256K x 16</td>
<td>180</td>
<td>922</td>
</tr>
<tr>
<td>SRAM E</td>
<td>IS62WV20488BL-25TLI [112]</td>
<td>ISSI</td>
<td>2M x 8</td>
<td>130</td>
<td>1228</td>
</tr>
<tr>
<td>SRAM F</td>
<td>BS62LV1600EIP55 [113]</td>
<td>Brilliance</td>
<td>1M x 8</td>
<td>180</td>
<td>-</td>
</tr>
<tr>
<td>SRAM G</td>
<td>LY62W20488ML-55LL [114]</td>
<td>Lyontek</td>
<td>2M x 8</td>
<td>-</td>
<td>1251</td>
</tr>
<tr>
<td>SRAM H</td>
<td>IS61WVS128EBLL-10TLI [115]</td>
<td>ISSI</td>
<td>512K x 8</td>
<td>65</td>
<td>1214</td>
</tr>
<tr>
<td>ADC</td>
<td>ADS1271B [116]</td>
<td>TI</td>
<td></td>
<td>300</td>
<td>-</td>
</tr>
</tbody>
</table>

**Table 6.2.** SEL test and analysis information for the different parts considered in the study. Proton measurements were performed at PSI for all components and at TRIUMF for all except SRAMs E, G and H. Neutron measurements were carried out in the VESUVIO atmospheric-like spectrum. Mixed-field results are from H4IRRAD.

<table>
<thead>
<tr>
<th>Device</th>
<th>Test Data</th>
<th>Part Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HI</td>
<td>Proton</td>
</tr>
<tr>
<td>SRAM A</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>SRAM B</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>SRAM C</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>SRAM D</td>
<td>✓</td>
<td>x</td>
</tr>
<tr>
<td>SRAM E</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>SRAM F</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>SRAM G</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>SRAM H</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>ADC</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

### 6.2 SRAM and ADC Test Results

As was the case for the ESA SEU Monitor, evaluating the part-to-part sensitivity spread of the tested components is essential in order to provide an accurate estimation of the measure-
6.2. SRAM and ADC Test Results

We can however perform a quantitative analysis of the spread for those components and energies for which a relatively large number of individual measurements (i.e. different parts) each with a sufficiently large number of counts per measurement are available. This was the case for SRAM D at 230 MeV (4 measurements) and 480 MeV (3 measurements) and SRAM C at 230 MeV (3 measurements). In all cases, the spread of the data ($\sigma_{\text{data}}$) was compatible with that expected from the count statistics of the individual measurements ($\sigma_{\text{count}}$). Therefore, the sensitivity spread is expected to be small when compared to the count statistics contribution. For this reason, we decided to neglect this uncertainty source for all parts and energies, thus only considering the count statistical error. However it is to be born in mind that this conclusion (i) is based on calculated spreads extracted from a small number of measurements and therefore themselves subject to large uncertainties; (ii) is only applied to a restricted set of components and energies. A more detailed evaluation of the part-to-part spread for each component would involve a broader measurement set for each device and test condition (for example, determining the standard deviation with a relative $2\sigma$ uncertainty better that 20% requires 50 measurements [94, 118]).

6.2.1 | DUTs and test description

The components we tested in the scope of the SEL study were introduced in Table 6.1. SRAMs A to G were selected on the grounds of available HI test data indicating that they were expected to be sensitive to protons as well, or were provided by the distributors as an alternative to the initially requested parts. Moreover, SRAM H was selected in order to extend the study to more integrated technologies (65 nm) however this part was found to be SEL-free both for protons and HI. Finally, the ADC was included in the energy dependency analysis provided it is a candidate component for different LHC systems and therefore represents a direct application case of the results we will present.

In the case of the SRAMs, the SEL detection and power cycle were performed through a power supply driven by a LabVIEW interface, with an alarm current of 50 mA (a power cycle was triggered after three consecutive readings above this value) and a current limit of 70 mA$^1$. Different settings with larger current alarm and limit values were selected, confirming they had no measurable impact on the retrieved SEL cross section value. The standby current

---

$^1$An exception to this was SRAM G, for which the current during the SEL state was $\sim$35 mA and would therefore not trigger the power cycle. The alarm and current limit were accordingly reduced to 10 and 25 mA respectively.
consumption for the components ranged from under 1 mA for SRAMs F and G to 35 mA for SRAM A. A simplified schematic layout of the test setup is shown in Fig. 6.1. The total time for the SEL detection plus power cycle ranged from 6s to 10s depending on the specific settings. For SRAM D, several runs were performed without a current limitation, and the value reached during the SEL state was \sim 550 mA. After one power cycle in these conditions, the part tended to latch constantly and was therefore considered as damaged and not further used in the measurements. In all cases, the average time between failures did not change in an appreciable manner during the tests, therefore indicating that the SEL cross section did not depend on the TID or total number of accumulated SELs. This is illustrated in Fig. 6.2, showing 50 SEL events accumulated at PSI and TRIUMF for three different SRAMs, and correlating linearly with the fluence. The slope of the curves corresponds to the ratio between counts and fluences and is therefore equal to the SEL cross section.

Fig. 6.1. Schematic representation of the SRAM SEL detection setup. Elements in red boxes were placed in the test beam and those in the blue boxes were in the irradiation zones (but several meters away from the beam). The rest were located in the control room. Two versions of the setup were used, with and without the FPGA connected to the DUTs.

Otherwise, the functionality of the parts was verified during and after the test for the cases in which the memory was connected to an FPGA and could therefore be accessed. For some components, the current consumption between the two settings was different\(^2\), whereas the SEL cross section was the same within the statistical uncertainty.\(^3\)

\(^2\)The standby current consumption of SRAM A was 33 mA when only powered and 12 mA when connected to the FPGA. For SRAM E, the values were 2.5 mA when not connected and 0.15 mA when accessible from the FPGA. For the rest of the cases, no difference in the current consumption was measured.

\(^3\)An exception to this was SRAM E, which was measured to have a much lower cross section at TRIUMF (480 MeV), where it was connected to the FPGA, than at PSI (230 MeV), where it was only powered. As the latter data set was compatible with the previous proton results from ESA, it is the one we use in the present work. This point is however to be further investigated by using the same component with both test configurations at the same facility.
Fig. 6.2. SEL count dependency with fluence for different SRAM memories tested in the TRIUMF 480 MeV (SRAMs C and D) and PSI 30 MeV (SRAM F) proton beams. The flux and dose rate are considered to be constant with time. The average flux and TID for SRAMs C, D and F were, respectively, $5.1 \times 10^7$, $2.1 \times 10^7$ and $7.5 \times 10^6 \text{cm}^{-2}\text{s}^{-1}$; 41, 22 and 29 Gy. For runs requiring larger doses in order to achieve 50 events (e.g. at 100 MeV) the SEL count dependency with time was similar.

Regarding the SRAM test procedure, the general approach was to limit the flux to a value that would result in an average time between events of 10 times the dead-time of the SEL detection and power cycle (e.g. 1min interval for the 6s cycle case), which therefore limits the overall dead-time to < 10%. In this situation, accumulating 50 events takes approximately 50 min. In all cases, the SEL efficient fluence was computed by subtracting the fluence accumulated during the detection and power cycle periods from the total value and used to derive the respective cross sections. In the case of SRAM F (very sensitive to SEL) the requirement of separating events in this way was not achievable for certain voltage biases and energies even when using the lowest possible proton flux, therefore measurements could not be performed under these conditions.

Concerning the ADC, it is a 24-bit, wide-bandwidth component from Texas Instruments (part number ADS1271B, here referred to as ADC). In this case, the SEL detection and power cycle were performed through a dedicated analog circuit and therefore had a much quicker response than the SRAM system. A simplified schematic view of the test setup is shown in Fig. 6.3. Owing to its very low SEL cross section, it was designed with the purpose of maximizing the number of components tested simultaneously. Four boards containing four DUTs each were stacked together, enabling the simultaneous evaluation of 16 components. Fig. 6.4 shows...
a picture of the four test boards. FLUKA simulations were performed confirming that the worst-case impact of the material upstream the DUTs (4 ADC packages plus 3 PCBs) on the proton beam was a negligible intensity loss and a reduction of the 100 MeV beam to an average of 92 MeV, with 1 MeV of Full Width at Half Maximum (FWHM), still considered as representative for 100 MeV.

![Diagram of the ADC SEL detection setup.](image)

**Fig. 6.3.** Schematic representation of the ADC SEL detection setup. Elements in red boxes were placed in the test beam and those in the blue boxes were in a very low radiation zone of the irradiation area. The rest were located in the control room. The red connection is an RS485 cable, blue is an Ethernet cable and gray is a GPIB connection.

### 6.2.2 Heavy Ion test data

The HI cross section is a crucial input to the SEL model we will introduce in Section 6.3. In fact, the impact of many of the complex design and operation parameters on the SEL sensitivity (well contact density, lateral well dimensions, voltage bias, well and substrate resistivity, etc.) are considered to be represented by the HI response. The strong reliance of our model on the experimental HI cross section is the reason why we refer to it as *semi-empirical*. Furthermore, a qualitative correlation between the SEL HI sensitivity and the SEL proton cross section based on the experimental data will be introduced in this section.

Heavy ion measurements were performed on several of the components considered in the study at RADEF by ESA (SRAMs A through E, results published in [6]) and UCL by an R2E team (SRAM B, SRAM H and ADC). The test data and corresponding Weibull fits for SRAM B and the ADC are shown in Fig. 6.5. SRAM H was found to be latchup free until an LET value of 40.4 $MeV cm^2/mg$ and a fluence of $10^7 cm^{-2}$.
6.2. SRAM and ADC Test Results

As a means of comparing their relative LET sensitivities, the normalized SEL cross section curves for all parts (except SRAM G, for which no HI data was available) are shown in Fig. 6.6. In order to quantify the HI sensitivity, an SEL onset parameter ($L_{1\%}$) is introduced as the LET value at which the SEL cross section corresponds to 1% of the saturated value. This value is shown in Table 6.3 together with the HI response Weibull fit parameters for the different components considered. As can be seen, its value ranges from 3.7 to 18 MeV cm$^2$/mg. As to what regards the cross section saturation values, they are in the 0.1-0.7 cm$^2$ range, thus equivalent to a significant proportion of the die surface and therefore compatible with SELs occurring in the memory array. Regarding the ADC, the saturated cross section was $\sim 10^{-4}$ cm$^2$, therefore representing a much smaller sensitive surface.

6.2.3 | PSI and TRIUMF: 30-480 MeV protons

In the context of the SEL study presented in this thesis, we performed proton measurements at PSI and/or TRIUMF (see subsections 3.2.1 and 3.2.2 for the respective facility descriptions) on the eight different SRAMs and ADC presented in Table 6.1. The cross section results are reported in Tables 6.4 and 6.5 for the different energies and SRAM$^4$ and ADC components respectively. Measurements at PSI were performed up to 230 MeV whereas tests at

---

$^4$SRAM H was SEL free for 230 MeV protons up to a fluence of $2.5\cdot10^{12}/cm^2$, consistent with the SEL free HI measurement (see subsection 6.2.2).
Chapter 6. SEL Measurements and Simulations

Fig. 6.5. HI test data and respective Weibull fits (see Table 6.3 for the parameter values) for SRAM B and the ADC. The values for the latter are scaled by a factor $10^2$.

Table 6.3. Weibull fit parameters for the components considered in the study together with the onset LET ($L_{1\%}$) selected as a Figure-of-Merit for the HI SEL sensitivity. The saturation cross section ($\sigma_{sat}$) was considered as the experimental point corresponding to the largest LET value and the remaining three parameters were determined through a least-squares fit. SRAM H was also tested and found to be SEL free up to an LET of $40.4\text{ MeV cm}^2/\text{mg}$.

<table>
<thead>
<tr>
<th>Device</th>
<th>$\sigma_{sat}$ ($\text{cm}^2$)</th>
<th>$L_o$ ($\text{MeV cm}^2/\text{mg}$)</th>
<th>$L_{1%}$ ($\text{MeV cm}^2/\text{mg}$)</th>
<th>$W$</th>
<th>$s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRAM A</td>
<td>0.24</td>
<td>2.1</td>
<td>5.9</td>
<td>16.8</td>
<td>3.4</td>
</tr>
<tr>
<td>SRAM B</td>
<td>0.65</td>
<td>2.9</td>
<td>6.5</td>
<td>31.9</td>
<td>1.9</td>
</tr>
<tr>
<td>SRAM C</td>
<td>0.13</td>
<td>0</td>
<td>15</td>
<td>27.6</td>
<td>7.4</td>
</tr>
<tr>
<td>SRAM D</td>
<td>0.10</td>
<td>0</td>
<td>18</td>
<td>34.5</td>
<td>7.0</td>
</tr>
<tr>
<td>SRAM E</td>
<td>0.24</td>
<td>4.0</td>
<td>12</td>
<td>22.8</td>
<td>4.3</td>
</tr>
<tr>
<td>SRAM F</td>
<td>0.60</td>
<td>2.4</td>
<td>3.7</td>
<td>13.7</td>
<td>1.8</td>
</tr>
<tr>
<td>ADC</td>
<td>$3.0 \cdot 10^{-4}$</td>
<td>7.0</td>
<td>12</td>
<td>51.0</td>
<td>1.9</td>
</tr>
</tbody>
</table>

TRIUMF were carried out in the 230-480 MeV interval. The proton SEL cross section results are plotted in Fig. 6.7 for the three SRAMs with a low LET onset ($L_{1\%} < 8\text{ MeV cm}^2/\text{mg}$) as well as SRAM G, which has a proton cross section in the same range but for which no HI data is available. Likewise, results are shown in Fig. 6.8 for components with a high LET onset ($L_{1\%} \geq 12\text{ MeV cm}^2/\text{mg}$).
6.2. SRAM and ADC Test Results

Fig. 6.6. Normalized Weibull fits to the HI SEL cross section data obtained by ESA for SRAMs A, C, D and E [6], and an R2E team for SRAM B and the ADC (see Fig. 6.5 for the experimental values of the two latter). The fit parameters are shown in Table 6.3.

In the case of SRAM F, the cross section could not be measured above 30 MeV due to its very high SEL sensitivity and a relatively slow detection and power cycle procedure which resulted in the dominance of the dead-time for the component. However, the test data was provided by ESA for the same component\footnote{In fact, the part tested by ESA both for HI and protons was the 8Mbit version (BS62LV8001) of the memory, as opposed to the 16Mbit version included in our analysis.}, corresponding to measurements of the SEL proton cross section at PSI with a faster SEL detection and correction method in June 2009. The corresponding results are shown in Table 6.6\footnote{The SEU cross section for this same memory was measured to be $2.56 \cdot 10^{-14} \text{cm}^2/\text{bit}$, which if we consider a memory size of 16 Mbit results in a total SEU cross section of $4.3 \cdot 10^{-7} \text{cm}^2/\text{device}$, comparable to its SEL cross section for the same energy, thus manifesting its very strong SEL sensitivity.}. For 30 MeV, the cross section value is a factor 2.4 larger than what we measured for the same energy and voltage bias, and the results are not compatible when considering their uncertainty intervals. This could be due to differences in the memories tested in each case, however when comparing HI and proton data for SRAM F, we will in both cases consider the ESA measurements, which were performed using the same experimental setup and components.

Several important conclusions can be extracted from the data we present here. First of all, the seven SRAMs considered show a very broad proton sensitivity, spanning over almost 3 orders of magnitude for 230 MeV (from $3.4 \cdot 10^{-10} \text{cm}^2$ for SRAM C to $2.6 \cdot 10^{-7} \text{cm}^2$ for SRAM F) despite being of similar technology nodes and supplied with the same voltage. In addition,
Table 6.4. Proton SEL cross sections in units of $cm^2$ for the different SRAM components. All results shown apply to components tested at room temperature, normal incident angle and a voltage bias of 3.3V except SRAM G, which was tested at 5.0V. For components which were tested at 230 MeV at TRIUMF in addition to PSI, the cross section result for the former is shown in italic. The relative uncertainties are omitted due to space limitations, however cross section values obtained with less than 50 events (relative $2\sigma$ count error of 28%) are highlighted in bold.

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>$1.1 \cdot 10^{-9}$</td>
<td>$2.8 \cdot 10^{-10}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>$8.7 \cdot 10^{-9}$</td>
<td>$2.4 \cdot 10^{-8}$</td>
</tr>
<tr>
<td>60</td>
<td>$6.0 \cdot 10^{-9}$</td>
<td>$2.0 \cdot 10^{-9}$</td>
<td>$2.5 \cdot 10^{-11}$</td>
<td>$1.8 \cdot 10^{-11}$</td>
<td>-</td>
<td>-</td>
<td>$2.1 \cdot 10^{-8}$</td>
</tr>
<tr>
<td>100</td>
<td>$1.1 \cdot 10^{-8}$</td>
<td>$7.3 \cdot 10^{-9}$</td>
<td>$4.3 \cdot 10^{-11}$</td>
<td>$1.0 \cdot 10^{-10}$</td>
<td>$1.6 \cdot 10^{-9}$</td>
<td>-</td>
<td>$3.0 \cdot 10^{-8}$</td>
</tr>
<tr>
<td>150</td>
<td>$2.1 \cdot 10^{-8}$</td>
<td>-</td>
<td>$1.8 \cdot 10^{-10}$</td>
<td>$2.2 \cdot 10^{-10}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>230</td>
<td>$2.3 \cdot 10^{-8}$</td>
<td>$2.5 \cdot 10^{-8}$</td>
<td>$3.4 \cdot 10^{-10}$</td>
<td>$4.4 \cdot 10^{-10}$</td>
<td>$3.5 \cdot 10^{-10}$</td>
<td>$5.1 \cdot 10^{-9}$</td>
<td>-</td>
</tr>
<tr>
<td>355</td>
<td>$3.3 \cdot 10^{-8}$</td>
<td>$3.5 \cdot 10^{-8}$</td>
<td>$6.4 \cdot 10^{-10}$</td>
<td>$7.3 \cdot 10^{-10}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>480</td>
<td>$2.9 \cdot 10^{-8}$</td>
<td>$3.3 \cdot 10^{-8}$</td>
<td>$7.4 \cdot 10^{-10}$</td>
<td>$1.2 \cdot 10^{-9}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 6.5. SEL test results for the ADC.

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>$\sigma_{SEL} (cm^2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>$1.9 \cdot 10^{-13} \pm 30% \pm 10%$</td>
</tr>
<tr>
<td>230</td>
<td>$4.1 \cdot 10^{-13} \pm 23% \pm 10%$</td>
</tr>
<tr>
<td>480</td>
<td>$7.3 \cdot 10^{-13} \pm 28% \pm 10%$</td>
</tr>
</tbody>
</table>

Table 6.6. Proton SEL cross section for SRAM F as measured by ESA at PSI. The supply voltage was 3.3V and the temperature 41°C.

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>$\sigma_{SEL} (cm^2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>$2.1 \cdot 10^{-8} \pm 21% \pm 10%$</td>
</tr>
<tr>
<td>50</td>
<td>$7.1 \cdot 10^{-8} \pm 18% \pm 10%$</td>
</tr>
<tr>
<td>75</td>
<td>$1.2 \cdot 10^{-7} \pm 21% \pm 10%$</td>
</tr>
<tr>
<td>150</td>
<td>$1.8 \cdot 10^{-7} \pm 12% \pm 10%$</td>
</tr>
<tr>
<td>230</td>
<td>$2.6 \cdot 10^{-7} \pm 23% \pm 10%$</td>
</tr>
</tbody>
</table>

as expected, the proton cross section shows a correlation with the HI response: components with lower LET onsets have larger proton cross section values.

Moreover, when analyzing the energy dependency of the test results, it is clear that the saturation value is reached at a much larger energy than in the case of SEU, if reached at all before the largest value tested for. In addition, components with a larger LET onset tend to have a stronger energy dependency. In order to quantify this behavior, we calculate the ratios between the 230 MeV and 100 MeV and 480 MeV and 230 MeV cross sections and compare them for the different components. Results for these cross section ratios are shown in Table 6.7 together with the respective onset LETs and 230 MeV proton cross section values. The
latter are plotted as a function of the former in Fig. 6.9 together with the 480 to 230 MeV ratios. The plot clearly shows a correlation between larger LET onset values and (i) lower absolute proton cross sections and (ii) a stronger dependence with energy. In fact, while the low onset components (A and B) are compatible with saturation in the 230-480 MeV at a 2σ level, high onset components (SRAM C and D) have cross sections that are clearly not saturated. This fact is in principle incompatible with a silicon dominated cross section, as the fragment production in the 50-500 MeV range was shown to be relatively stable (see [28] and Section 4.2). In fact, as was first suggested in [36], the SEL cross section increase in this energy range is attributed to the high-Z material fission fragments, which have a production cross section that strongly depends on the energy in this interval.

A detailed analysis of the SEL cross section energy dependence is provided in Section 6.3 through a modeling approach. Likewise, the implications of the cross section increase above the standard experimental energies on the test procedures and failure rate estimations for highly energetic environments are treated in Chapter 7.

![Proton SEL cross section for the low LET onset devices and SRAM G, lacking HI data while showing a similar proton SEL sensitivity.](image)

**Fig. 6.7.** Proton SEL cross section for the low LET onset devices and SRAM G, lacking HI data while showing a similar proton SEL sensitivity.

In addition to these results, two further test parameters were varied in order to analyze their impact on the SEL cross section. The angle of incidence for SRAM D was set to 90° (grazing incidence) both in the direction parallel to the wells and that perpendicular to them. A strong SEL cross section dependency on both the pitch and the roll angle was reported in [119] for HI and a 65 nm technology, showing that the direction parallel to the wells was clearly more...
sensitive. Results for the grazing incidence measurements are shown in Table 6.8. As can be seen, there is a weak dependency with the angle, the largest value still significantly below the 480 MeV cross section measurement. Therefore in this case using 230 MeV protons at grazing angle (worst-case) would not have been representative of the 480 MeV environment, contrary to the case reported in [120] for a 140 nm SRAM. In [120] the cross section difference between normal and grazing incidence at around 200 MeV was shown to be approximately a factor 5. This difference could be related to the fact that, as will be shown in Section 6.3, the SEL cross section for SRAM D has a strong contribution from high-Z material fission fragments, which are isotropic in the laboratory reference frame and will therefore have an effect independent of the angle of incidence.

Table 6.7. 230 MeV SEL cross section and different ratios for the components tested.

<table>
<thead>
<tr>
<th>Device</th>
<th>$L_{1%}$ (MeV cm²/mg)</th>
<th>$\sigma_{230\text{ MeV}}$ (cm²)</th>
<th>$\sigma_{230\text{ MeV}} / \sigma_{100\text{ MeV}}$</th>
<th>$\sigma_{480\text{ MeV}} / \sigma_{230\text{ MeV}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRAM F</td>
<td>3.7</td>
<td>$2.6 \cdot 10^{-7}$</td>
<td>1.8 ± 0.3</td>
<td>-</td>
</tr>
<tr>
<td>SRAM G</td>
<td>-</td>
<td>$4.6 \cdot 10^{-8}$</td>
<td>1.5 ± 0.6</td>
<td>-</td>
</tr>
<tr>
<td>SRAM A</td>
<td>5.9</td>
<td>$2.3 \cdot 10^{-8}$</td>
<td>2.1 ± 0.7</td>
<td>1.3 ± 0.4</td>
</tr>
<tr>
<td>SRAM B</td>
<td>6.5</td>
<td>$2.3 \cdot 10^{-8}$</td>
<td>3.2 ± 1.2</td>
<td>1.4 ± 0.5</td>
</tr>
<tr>
<td>SRAM E</td>
<td>12</td>
<td>$1.6 \cdot 10^{-9}$</td>
<td>3.2 ± 1.4</td>
<td>-</td>
</tr>
<tr>
<td>SRAM C</td>
<td>15</td>
<td>$3.4 \cdot 10^{-10}$</td>
<td>7.9 ± 6.2</td>
<td>2.2 ± 0.6</td>
</tr>
<tr>
<td>SRAM D</td>
<td>18</td>
<td>$4.3 \cdot 10^{-10}$</td>
<td>4.3 ± 2.4</td>
<td>2.7 ± 0.6</td>
</tr>
<tr>
<td>ADC</td>
<td>12</td>
<td>$4.3 \cdot 10^{-13}$</td>
<td>2.2 ± 1.3</td>
<td>1.7 ± 0.7</td>
</tr>
</tbody>
</table>
6.2. SRAM and ADC Test Results

**Fig. 6.9.** Correlation between the LET onset for the different components and the proton cross section value at 230 MeV as well as the energy dependency above this value, quantified through the cross section ratio between 480 and 230 MeV.

**Table 6.8.** SEL cross section for SRAM D using the 230 MeV proton beam at PSI and different incidence angles, parallel or perpendicular to the doping wells.

<table>
<thead>
<tr>
<th>Incidence Angle</th>
<th>Cross Section (cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>4.1 · 10⁻¹⁰ ± 28% ± 10%</td>
</tr>
<tr>
<td>90°, perpendicular</td>
<td>5.4 · 10⁻¹⁰ ± 28% ± 10%</td>
</tr>
<tr>
<td>90°, parallel</td>
<td>6.0 · 10⁻¹⁰ ± 26% ± 10%</td>
</tr>
</tbody>
</table>

Moreover, the cross section for SRAM F was measured at different supply voltages. Results are shown in Table 6.9 manifesting a very strong dependency on this parameter. A description of the SEL mechanism and its dependency with the supply voltage was introduced in Chapter 1 and references therein.

**Table 6.9.** SEL cross section for SRAM F and different supply voltages.

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>2.5V</th>
<th>3.3V</th>
<th>5.5V</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>5.0 · 10⁻⁹ ± 28 ± 10%</td>
<td>8.7 · 10⁻⁹ ± 28 ± 10%</td>
<td>9.1 · 10⁻⁸ ± 20 ± 10%</td>
</tr>
<tr>
<td>60</td>
<td>6.1 · 10⁻⁸ ± 28 ± 10%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>100</td>
<td>1.5 · 10⁻⁷ ± 19 ± 10%</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Finally, two measurements were performed using a 100 $\mu$m tungsten slab placed on top of an open device for SRAM C and D in order to evaluate its impact on the SEL cross section. Results are presented in Table 6.10 suggesting a moderate increase in the 480 MeV cross section for SRAM C in the case of the tungsten layer. However, this result is subject to the large statistical error in the ratio value and therefore needs to be further explored in order to extract stronger conclusions.

Table 6.10. SEL cross section for the SRAMs tested with a 100 $\mu$m tungsten slab on top of the open die compared with the standard package value. Only the statistical error is considered as the compared measurements were performed in the same facility.

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Device</th>
<th>$\sigma_{SEL}$ (cm$^2$)</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>tungsten</td>
<td>normal</td>
</tr>
<tr>
<td>230</td>
<td>SRAM D</td>
<td>$4.7 \cdot 10^{-10} \pm 20%$</td>
<td>$4.0 \cdot 10^{-7} \pm 17%$</td>
</tr>
<tr>
<td>480</td>
<td>SRAM C</td>
<td>$1.1 \cdot 10^{-9} \pm 28%$</td>
<td>$7.4 \cdot 10^{-10} \pm 16%$</td>
</tr>
</tbody>
</table>

6.2.4 | VESUVIO: Atmospheric-like neutron spectrum

As can be seen in Table 6.2, we tested three of the studied components (SRAMs A, F and G) in the VESUVIO neutron spectrum (see subsection 3.3.1 for details on the facility and beam). These were selected on the grounds of having a large proton SEL cross section, as the available neutron flux was considered to be too low to retrieve significant count statistics for the less sensitive components. In order to increase the number of SELs, four memories of each type were tested at once with the current consumption measured in two channels: the first for the pair upstream and the second for the pair downstream. In all cases, the SEL count difference between the two channels was compatible with a Poisson distribution (i.e. consistent with the statistical spread, characterized by a standard deviation of $\sqrt{N}$, where $N$ is the total count number). In addition, SRAM E was tested at different bias conditions, one of them outside the device specification (7.0V, whereas the specified operation range is 2.5-5.5V). For this very sensitive component, a run was performed using a cadmium slab to reduce the thermal neutron flux (see Fig. 3.10 for the respective neutron spectra) confirming that it was not sensitive to thermal neutrons within our measurement resolution.

The test results are shown in Table 6.11 for the different components and test configurations, expressed as mixed-field HEH cross sections ($\sigma_{HEH}$, i.e. using the HEH fluence) and failure rates (in units of FITs for the Geneva neutron environment, and related to the cross section through Eq. 5.8 using the HEH values instead of the equivalent HEH ones). The use of the HEH fluences (and respective cross sections) as opposed to the equivalent ones is justified by the fact that, provided SELs typically require larger energy deposition events than SEU,

---

In the case of SRAM D, the measurements with and without tungsten were performed on the same chip, therefore the results for the standard package apply to the same component in order to reduce potential contributions from the sensitivity spread.
the contribution of the intermediate energy neutrons is expected to be negligible even in an environment such as that of VESUVIO, with a significant proportion of its spectrum in this energy range. This point will be further supported by simulations in Section 6.3.

One of the main observations that can be extracted from the results shown in Table 6.11 is the extremely large SEL sensitivity for SRAM F in an atmospheric-like environment. If we consider the measured cross section (or SEL rate) and the Geneva environment, the average failure rate for the maximum specified supply voltage (5.5V) would be one per year and \( \sim 30 \) components, which can of course pose serious reliability issues depending on the criticality of its application.

Table 6.11. SEL results for the SRAMs tested at VESUVIO. Each device type was tested using four different components placed simultaneously in the beam. The relative uncertainties include the statistical and systematic contributions and are only shown for the cross sections (same values apply to the failure rates).

<table>
<thead>
<tr>
<th>Device</th>
<th>Bias (V)</th>
<th>Spectrum</th>
<th>( \sigma_{HEH}^* ) (cm²)</th>
<th>SEL rate (FITs in Geneva)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRAM A</td>
<td>3.3</td>
<td>Full</td>
<td>( 5.7 \cdot 10^{-9} \pm 26% \pm 10% )</td>
<td>1.0 \cdot 10^2</td>
</tr>
<tr>
<td>SRAM F</td>
<td>2.5</td>
<td>Full</td>
<td>( 4.6 \cdot 10^{-8} \pm 16% \pm 10% )</td>
<td>8.4 \cdot 10^2</td>
</tr>
<tr>
<td></td>
<td>5.5</td>
<td>Full</td>
<td>( 2.3 \cdot 10^{-7} \pm 19% \pm 10% )</td>
<td>4.2 \cdot 10^3</td>
</tr>
<tr>
<td></td>
<td>5.5</td>
<td>Cadmium</td>
<td>( 2.2 \cdot 10^{-7} \pm 20% \pm 10% )</td>
<td>4.0 \cdot 10^3</td>
</tr>
<tr>
<td></td>
<td>7.0</td>
<td>Full</td>
<td>( 5.7 \cdot 10^{-7} \pm 19% \pm 10% )</td>
<td>1.0 \cdot 10^4</td>
</tr>
<tr>
<td>SRAM G</td>
<td>5.5</td>
<td>Full</td>
<td>( 9.8 \cdot 10^{-9} \pm 39% \pm 31% \pm 10% )</td>
<td>1.8 \cdot 10^2</td>
</tr>
</tbody>
</table>

Provided all three SRAMs we tested for neutrons had also been characterized with protons at PSI, we make use of the fits of their respective proton cross sections to Weibull functions in order to calculate their HEH cross section in the VESUVIO neutron field by folding the former with the neutron energy spectrum and compare them with the measured results. The proton data and fits\(^8\) are shown in Fig. 6.10 and correspond to the parameters reported in Table 6.12.

Table 6.12. Weibull fit parameters for the thee SRAM memories tested in VESUVIO. The threshold energy was fixed at 20 MeV and the remaining three parameters were determined through a least-squares fit.

<table>
<thead>
<tr>
<th>Device</th>
<th>( \sigma_{sat} ) (cm²)</th>
<th>( E_o ) (MeV)</th>
<th>( W ) (MeV)</th>
<th>s</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRAM A</td>
<td>3.5 \cdot 10^{-8}</td>
<td>20</td>
<td>183</td>
<td>1.14</td>
</tr>
<tr>
<td>SRAM F</td>
<td>2.0 \cdot 10^{-7}</td>
<td>20</td>
<td>68</td>
<td>1.92</td>
</tr>
<tr>
<td>SRAM G</td>
<td>5.0 \cdot 10^{-8}</td>
<td>20</td>
<td>87</td>
<td>1.29</td>
</tr>
</tbody>
</table>

\(^8\)Due to measurement limitations, SRAM F was not characterized at 230 MeV. However, provided that the increase between 150 and 230 MeV in the measurements performed by ESA on similar components was 44 %, we have assumed an analogous increase between the 100 MeV value and saturation. In any case, provided the soft nature of the VESUVIO spectrum, the dependency above 100 MeV hardly affects the SEL rate.
Fig. 6.10. Proton SEL cross section as a function of energy for the components tested in the VESUVIO neutron beam together with the fit of the data to a Weibull function. All points correspond to at least 50 events. SRAM F was biased at 2.5V, A at 3.3V and G at 5.0V.

Results for the calculated mixed-field cross sections ($\sigma_{HEH}^{calc}$) are shown in Table 6.13 both in absolute terms and normalized to the measured values reported in Table 6.11. As can be seen, the calculations extracted from the proton data are compatible with what was measured in the mixed neutron beam, while pointing towards a potential systematic overestimation. Moreover, it is also worth comparing the 230 MeV proton cross section values with the measured results, as the former are typically used to evaluate the SEE rate in a mixed field environment when using the HEH approach. These results show that, if the 230 MeV cross sections are used to calculate the SEL rate in an accelerator context with an energy dependency similar to the VESUVIO test beam (e.g. the UJ alcoves) the latter would be overestimated by a factor 4 to 6 depending on the components. This is due to the fact that, in the case of SEL, the approximation that the cross section is constant between 20 and 230 MeV does not hold, and its significant increase in this range yields a higher failure rate when applying the HEH approach to soft spectra such as that in VESUVIO.

Alternatively, we can use the fits to the proton cross section in order to evaluate the HEH cross section for different operation environments relative to the VESUVIO measurements. Results for SRAM A (providing a good agreement between the calculation and measurements as seen in Table 6.13) and different radiation fields introduced in Chapter 2 are shown in Table 6.14. As can be seen, scaling the VESUVIO failure rate by the HEH flux for different environments would result in underestimations of the operational SEL rate up to a factor 3.4,
6.2. SRAM and ADC Test Results

Table 6.13. Calculated HEH cross section for the VESUVIO environment and comparison with the measured values. The ratio between the 230 MeV and HEH mixed-field cross sections is also included\(^9\), as the later is used to derive the failure rate in the standard HEH approach.

<table>
<thead>
<tr>
<th>Device</th>
<th>Bias (V)</th>
<th>(\sigma_{HEH}^{calc}) ((cm^2))</th>
<th>(\sigma_{HEH}^{calc}/\sigma_{HEH})</th>
<th>(\sigma_{230,MeV}/\sigma_{HEH})</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRAM A</td>
<td>3.3</td>
<td>7.2 \cdot 10^{-9}</td>
<td>1.26 ± 0.33</td>
<td>0.28 ± 0.09</td>
</tr>
<tr>
<td>SRAM F</td>
<td>2.5</td>
<td>6.4 \cdot 10^{-8}</td>
<td>1.39 ± 0.22</td>
<td>0.18 ± 0.06</td>
</tr>
<tr>
<td>SRAM G</td>
<td>5.5</td>
<td>1.5 \cdot 10^{-8}</td>
<td>1.53 ± 0.06 (\pm 0.47)</td>
<td>0.21 ± 0.10 (\pm 0.09)</td>
</tr>
</tbody>
</table>

owing to the more energetic character of the particle spectra. As will be detailed in Chapter 7, this factor can be significantly larger when considering components with a stronger SEL cross section energy dependency such as SRAMs C or D.

Table 6.14. Calculated HEH cross sections for different operational environments detailed in Chapter 2 relative to the calculated value at VESUVIO for SRAM A. As the ratio corresponds to two calculations, no uncertainty is considered.

<table>
<thead>
<tr>
<th>Environment</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC UJ</td>
<td>1.7</td>
</tr>
<tr>
<td>LHC RR</td>
<td>2.5</td>
</tr>
<tr>
<td>LHC tunnel</td>
<td>3.3</td>
</tr>
<tr>
<td>Ground Level</td>
<td>2.3</td>
</tr>
<tr>
<td>Stratospheric (20 km)</td>
<td>3.4</td>
</tr>
</tbody>
</table>

6.2.5 | H4IRRAD: Accelerator-like mixed-field

The ADC included in the SEL study was also tested at H4IRRAD during the November 2012 test slot. A detailed description of the facility and particle energy spectra can be found in subsection 3.3.2. In this case, and provided it was known from a previous test slot that the device’s SEL sensitivity was low, we placed two ADC components downstream the target in order to maximize (i) the particle fluence and (ii) the hardness of the particle energy spectra. The location was 100 cm downstream the target in the beam direction and 8 cm away radially.

The total intensity of the run was \(5.15 \cdot 10^{13}\) protons on target, which according to the respective FLUKA simulation for this test slot corresponds to a HEH fluence of \(1.96 \cdot 10^{11}/cm^2\) at the ADC test location. As to what regards the hardness energies, the values for \(H_{50\%}\) and \(H_{10\%}\) were 1.3 and 5.3 GeV respectively, thus showing a very hard character, similar to that of the ESA Monitor described in Table 3.5\(^{10}\). When compared to the operational environments, this experimental case is significantly harder than the LHC tunnel (see Table 2.4) and stratospheric

---

\(^9\)SRAM G was operated at 5.5V in VESUVIO whereas a 5.0V bias was used in the PSI proton tests.

\(^{10}\)The ESA Monitor was in fact placed in a very similar location relative to the target as can be seen in Table 3.4.
context (see Table 2.7) and is comparable in terms of its hardness to the LHC experiment case (see Table 2.6).

However, during the available H4IRRAD test slot, only two SEL events were recorded, one on each ADC. The first occurred after a HEH fluence of $1.94 \cdot 10^{10} / cm^2$ ($\sim 10\%$ of the total fluence) and the second at $8.09 \cdot 10^{10} / cm^2$ ($\sim 40\%$ of the total). The corresponding cross section extracted from the two events on two devices and the total fluence of the run is therefore $5.1 \cdot 10^{-12} cm^2$, however provided the very low count statistics, this value is obviously subject to a very large uncertainty. In fact, this cross section value is over a factor 10 larger than the one measured at 230 MeV for the same device, however the lower limit at a 95\% confidence level of 2 events is 0.2, which would therefore correspond to a HEH cross section very similar to that measured at 230 MeV. Therefore, whereas these results suggest an important increase in the SEL cross section owing to the harder spectrum, a much more moderate raise cannot be ruled out due to the weak significance of the measurement. The ADC cross section in the 100-480 MeV range is plotted in Fig. 6.11 together with the normalized reverse integral ($NR_{HEH}$) of the HEH flux during the H4IRRAD test. As can be seen, $\sim 70\%$ of the HEH flux lies above the maximum energy that the ADC was tested for, and the data points in the 100-480 MeV range suggest a strong dependency with energy which could therefore lead to a larger failure rate as that extracted from the HEH approach. This point will be further developed in Section 6.3 and Chapter 7 for the SRAM components.

![Fig. 6.11. ADC SEL cross section together with the normalized reverse HEH spectrum for its test location at H4IRRAD.](image-url)
Moreover, further measurements of this type will be performed at the new CHARM facility (see subsection 3.3.3), with an increased intensity and beam availability which will contribute to enhance the count statistics.

6.3 Semi-Empirical Monte Carlo SEL Model for SRAMs

The test results shown in Section 6.2 together with the weak dependency of the proton-silicon reaction product distributions with energy in the 200-500 MeV range suggest that the SEL cross section increase in this interval is due to high-Z material fission fragments. However, in order to relate this to the actual tungsten volume in the components considered and to predict the dependency for larger energies and different hadrons, a model in the scope of a MC transport code is required. Whereas the code will account for the nuclear physics involved in the energy deposition events, the model will relate these to the actual SEL induction. For this second step, the approach here presented strongly relies on (i) the HI experimental data and (ii) assumptions on the SEL SV geometry.

6.3.1 Tungsten fission in FLUKA

As initially introduced in [36], the observed SEL cross section increase in the 200-500 MeV range for two commercial SRAMs of unknown feature size was attributed to high-Z material fission fragments generated near the device’s SV. Therefore, the importance of reproducing this nuclear process in any attempt of modeling the effect through MC simulations is crucial. This is even more evident if we consider that, as shown in [121], the experimental data for the (p,f) cross section in tungsten is scarce, especially at very high energies (E > 1 GeV). For neutron induced fission, no measurements are available above 400 MeV. For other materials potentially relevant for microelectronic components such as hafnium [122], no fission cross section data is available at all. Moreover, as was shown in [123], the nuclear reaction code used in the MC simulation tool can have a very strong impact on the calculated fission cross section.

Because we will include tungsten in our SEL model, it is first of all meaningful to study the hadron induced fission cross section in FLUKA as well as the properties of the fission fragments generated. We performed this using the internal FLUKA production tool introduced in Chapter 4, which uses inelastic interactions as a source and enables the study of subsets of this process, such as for example fission. We then compare this output to the experimental data available in the EXFOR nuclear database [124]. Fig. 6.12 shows the resulting values for tungsten, revealing first of all a very good agreement of the simulated results with the experimental data, and secondly, a very strong dependency with energy, with the cross section increasing 4 orders of magnitude between 50 MeV and the saturation reached at ~3 GeV. With the purpose of rendering the comparison more general, Figs. 6.13(a) to 6.13(c) show the experimental and simulated fission cross sections for high-Z elements with a richer experimental data set, further
confirming the very good agreement. In Fig. 6.13(d), the simulated fission cross section for hafnium is shown compared to that of tungsten.

Moreover, it is to be noted that, as presented in [105], the fission cross section for protons and neutrons in tungsten in the 40-200 MeV range differs significantly. For this reason, we included the full set of hadrons relevant to the high-energy accelerator environment in the analysis. The resulting fission cross sections in tungsten are shown in Fig. 6.14, indicating that the calculations confirm the significant differences up to an energy of $\sim 1$ GeV, for which the different cross sections converge. The implications of such differences in the context of a mixed-field environment are discussed further in Chapter 7.

The same FLUKA production tool can also be used to extract information about the fission fragments produced in the different materials. This was performed for different proton energies on tungsten, generating a number of inelastic interactions such that the total number of fission events per energy was in the $5 \times 10^3$ interval. A summary of the total inelastic and fission cross sections for the energies considered as well as the number of inelastic events generated is shown in Table 6.15. The average particle generation multiplicity of the fission events is also shown, manifesting a pronounced increase of the nucleus fragmentation with increasing incident proton energy.

After generating histograms of the different high LET ($>14\ MeV\ cm^2/mg$) fragment properties scored we first of all analyze the $Z$ distributions of the products generated in the fission
Fig. 6.13. (p,f) cross section in different materials as extracted from the EXFOR database and simulated in FLUKA.

events, which are plotted in Fig. 6.15(a) for the different energies. As can be seen, the distributions clearly peak at $Z_W/2$ for energies up to 1 GeV and flatten out for larger energies. In addition, the energy distribution of the fragments is shown in 6.15(b), manifesting that for larger incident proton energies, the energy available from the fission process is distributed among a larger amount of fragments, thus resulting in lower kinetic energies for the heavy fragments.

Furthermore, two highly relevant fragment properties when considering SEE induction are the range and LET in silicon. The corresponding distributions for the energies considered are shown in Figs. 6.16(a) and (b) respectively. As can be seen, the average ranges for the energies up to 1 GeV is 11-12 $\mu$m, with an increasing spread for larger incident proton energies. Above 3 GeV, the distributions shift towards lower ranges, consistent with the kinetic energy distributions of the fragments. In the case of LET, again a similar behavior can be identified,
Fig. 6.14. Fission cross section in $^{nat}W$ as simulated in FLUKA for different hadrons relevant to the high-energy accelerator radiation field.

### Table 6.15. General information about the FLUKA production runs of proton induced inelastic events in tungsten. $N_{inel}$ and $N_{fiss}$ are the number of inelastic and fission events simulated. $M$ corresponds to the average particle multiplicity (i.e. number of fragments per fission event).

<table>
<thead>
<tr>
<th>Energy</th>
<th>$\sigma_{inel} (mb)$</th>
<th>$\sigma_{fiss} (mb)$</th>
<th>$N_{inel}$</th>
<th>$N_{fiss}$</th>
<th>$M (A &gt; 1)$</th>
<th>$M (Z &gt; 14)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>60 MeV</td>
<td>1834</td>
<td>$5.48 \cdot 10^{-2}$</td>
<td>$2.5 \cdot 10^4$</td>
<td>$5.1 \cdot 10^3$</td>
<td>2.00</td>
<td>2.00</td>
</tr>
<tr>
<td>230 MeV</td>
<td>1507</td>
<td>3.50</td>
<td>$4 \cdot 10^6$</td>
<td>$9.3 \cdot 10^3$</td>
<td>2.24</td>
<td>2.00</td>
</tr>
<tr>
<td>480 MeV</td>
<td>1618</td>
<td>9.98</td>
<td>$1.6 \cdot 10^6$</td>
<td>$9.8 \cdot 10^3$</td>
<td>2.76</td>
<td>1.98</td>
</tr>
<tr>
<td>1 GeV</td>
<td>1703</td>
<td>30.3</td>
<td>$4.7 \cdot 10^5$</td>
<td>$8.4 \cdot 10^3$</td>
<td>4.21</td>
<td>1.90</td>
</tr>
<tr>
<td>3 GeV</td>
<td>1743</td>
<td>130</td>
<td>$1 \cdot 10^5$</td>
<td>$7.5 \cdot 10^3$</td>
<td>8.36</td>
<td>1.60</td>
</tr>
<tr>
<td>24 GeV</td>
<td>1716</td>
<td>158</td>
<td>$1 \cdot 10^5$</td>
<td>$9.2 \cdot 10^3$</td>
<td>12.6</td>
<td>1.29</td>
</tr>
<tr>
<td>400 GeV</td>
<td>1725</td>
<td>135</td>
<td>$1 \cdot 10^5$</td>
<td>$7.8 \cdot 10^3$</td>
<td>13.1</td>
<td>1.24</td>
</tr>
</tbody>
</table>

with average values shifting from $\sim 31\text{ MeV}\text{cm}^2/\text{mg}$ at 230 MeV to $\sim 24\text{ MeV}\text{cm}^2/\text{mg}$ and a very large spread above 3 GeV. In addition, it is to be noted that the maximum generated LET is $\sim 37\text{ MeV}\text{cm}^2/\text{mg}$ for all cases, therefore significantly larger than the respective value in silicon ($\sim 14\text{ MeV}\text{cm}^2/\text{mg}$ as shown in Chapter 4). Therefore, another very important conclusion that can be extracted from these distributions is that the maximum LET and range of the fission fragments do not depend on the incident proton energy.

In addition to the tungsten fission fragments, other inelastic products with similar properties as the former need to be considered in the analysis. This was performed by scoring
all secondary particles that were not fission fragments but had LET values larger than 14 $\text{MeV cm}^2/\text{mg}$, which we will hereafter refer to as high LET non-fission fragments in order to distinguish them from the fission fragments. The number of high LET non-fission fragments are shown in Table 6.16 normalized to the number of fission events. Likewise, the number of fission fragments with an LET above 14 $\text{MeV cm}^2/\text{mg}$ are also displayed per fission event. Finally, the ratio between the number of high LET non-fission and high LET fission fragments is also shown. As can be seen, the number of high-LET fission fragments per fission event decreases with increasing energy as a consequence of the larger fragmentation of the nucleus. However, if we consider the total production yield of fission and non-fission high LET fragments together,
it slightly increases with energy.

Provided the high LET fragment production in the case of 24 and 400 GeV proton energies is dominated by the non-fission fragments rather than the fission products, we compare their respective range and LET distributions, which are plotted in Figs. 6.17(a) and 6.17(b), showing that while more numerous, the non-fission fragments have a lower average LET and range. In contrast, the maximum values are similar.

Table 6.16. Calculated number of high LET (above 14 MeV cm\(^2\)/mg) fission and non-fission fragments per fission event for the different energies considered. The ratio between the non-fission and fission fragments is shown in brackets.

<table>
<thead>
<tr>
<th>Energy</th>
<th>Fission</th>
<th>Non-fission</th>
</tr>
</thead>
<tbody>
<tr>
<td>60 MeV</td>
<td>2.00</td>
<td>-</td>
</tr>
<tr>
<td>230 MeV</td>
<td>2.00</td>
<td>3.36 \times 10^{-2} (1.7 \times 10^{-2})</td>
</tr>
<tr>
<td>480 MeV</td>
<td>1.95</td>
<td>0.319 (0.16)</td>
</tr>
<tr>
<td>1 GeV</td>
<td>1.88</td>
<td>0.922 (0.49)</td>
</tr>
<tr>
<td>3 GeV</td>
<td>1.46</td>
<td>1.35 (0.93)</td>
</tr>
<tr>
<td>24 GeV</td>
<td>1.14</td>
<td>2.16 (1.9)</td>
</tr>
<tr>
<td>400 GeV</td>
<td>1.11</td>
<td>2.46 (2.2)</td>
</tr>
</tbody>
</table>

Fig. 6.17. LET and range distribution for high LET fission and non-fission products of 24 GeV protons in tungsten. The counts are normalized to the total number of fission events in both cases.

In addition, the LET distribution for the high LET non-fission fragments is shown in Fig. 6.18 for different energies for which the production yield of the former is similar or larger than that of fission fragments. As can be seen, although the relative yield of non-fission fragments increases with energy, the maximum LET produced is constant and near 37 MeV cm\(^2\)/mg.
6.3. Semi-Empirical Monte Carlo SEL Model for SRAMs

**Fig. 6.18.** LET distribution of the high LET non-fission fragments generated in proton interaction with tungsten. The counts are normalized to the total number of fission events per energy.

Finally, the fragment emission angle distributions are shown in Fig. 6.19, confirming that, as was presented in [37] for incident proton energies up to 500 MeV, the fission fragments are isotropic in the laboratory reference frame also at larger projectile energies. In addition, the non-fission fragment angular distribution is included as well, displaying a quasi-isotropic production, while slightly peaking towards normal emission ($90^\circ$).

To summarize, the main SEE-related implications of the tungsten fragment analysis performed in this section are listed below:

- **FLUKA** is successful in reproducing the experimental fission cross section data for tungsten as well as other high-Z materials for which a broader experimental data set is available.

- The proton fission cross section in tungsten has a very strong dependency with energy until reaching saturation at around 3 GeV, with an increase of a factor 37 between 230 MeV and saturation.

- The four hadrons dominating the high-energy accelerator mixed-field ($p$, $n$, $\pi^\pm$) have significantly different fission cross section below $\sim 500$ MeV, especially at lower energies.

- The maximum LET produced in ($p$,f) reactions in tungsten is $\sim 37$ MeV cm$^2$/mg, regardless of the proton energy. As the proton energy increases, the LET distributions tend to
flattening out and shifting to lower average LET values due to the increased fragmentation of the nucleus.

- Non-fission fragments generated in interactions between protons and tungsten are also produced with LETs above those generated in silicon (14 MeV cm²/mg), with maximum LET values similar to those produced in fission reactions. The relative production of such high LET non-fission fragments with respect to the fission counterparts increases with energy and becomes dominant at around 3 GeV.

### 6.3.2 | SEL model: definition and calibration

After having introduced the fission cross section and fragment properties, we now present the methodology used to define and calibrate an IRPP-based model\(^\text{11}\) to the proton SRAM SEL data in the 100-230 MeV range (typically available for standard proton testing for CERN groups). The calibrated model can then be used to estimate the SEL response for larger energies still relevant in the accelerator and avionics contexts by means of the FLUKA Monte Carlo tool.

---

\(^\text{11}\)IRPP stands for Integral-RPP and in this context refers to the fact that, as will be explained later, the energy deposition distribution is integrated with the HI response in order to obtain the proton cross section, as was introduced in section 4.4.
As will be shown, the absolute value of the output of the predictive model has an important dependency on the input and fitted parameters, however the relative cross section increase is stable as it mainly depends on the physical proton induced fission cross section in tungsten. Therefore, the core result extracted from it can be regarded as applicable in general.

The approach is similar to other methods presented in the past. It is based on Eq. 6.1, where $\sigma_{HI}(E_d)$ is the heavy ion cross section as a function of deposited energy, $p(E_p, E_d)$ is the probability that a proton of energy $E_p$ deposits an energy $E_d$ in the sensitive volume, and $\sigma_p(E_p)$ is the proton SEE cross section. $\sigma_{HI}(E_d)$ is an experimental input, whereas $p(E_p, E_d)$ is extracted through Monte Carlo simulations and $p(E_p, E_d)$ is the output of the calculation.

\[
\sigma_p(E_p) = \int \sigma_{HI}(E_d)p(E_p, E_d)dE_d
\] (6.1)

SIMPA [125, 126] was to our best knowledge the first available model to consider Eq. 6.1 with the deposited energy as the integration variable as opposed to LET for SEUs. The approach we propose here, while using the same formalism as SIMPA and other similar methods [127], has several very important differences with respect to them:

- In SIMPA, the function $p(E_p, E_d)$ is extracted experimentally from measurements using a 6 $\mu$m diode, whereas in the model we present, the FLUKA Monte Carlo (MC) tool is used to obtain it.
- Provided a diode is used in the SIMPA calibration, very large lateral dimensions are considered, whereas in the present context, a finite sensitive SEL surface compatible with laser inspections of similar devices is assumed.
- Only silicon is considered in SIMPA, whereas other materials (notably tungsten) are included in the approach presented here.

While the SIMPA model (and analogous approaches) have proven to successfully predict proton SEU data from HI measurements for relatively old technologies (SV thickness in the 6 – 12 $\mu$m range) they have also shown to systematically overestimate the proton cross section when applied to SEL [128–130]. This point will be analyzed in more detail when comparing the results obtained here with those extracted using SIMPA in subsection 6.3.4.

Furthermore, the three main considerations for the model we introduce are:

(i) The assumption of the geometry of the SEL sensitive volume is based on different laser studies [117, 131, 132]. It consists of a group of neighboring cells, extending over two cells in the direction perpendicular to the p and n wells, and a number of cells (e.g. 16 or 32) in the direction parallel to the wells, corresponding to the region between two well contacts. For the SRAM components included in our analysis (130-200 nm technology) a cell size of 2 x 2 $\mu m^2$ is considered [133]. The SEL sensitivity increases with increasing
distance to the well contacts as the voltage drop for a given energy deposition is larger owing to the increased path resistance [134]. As will be shown in subsection 6.3.5, the output of the model is relatively independent of the considered SV dimensions in a fairly large parameter range, as the sensitivity is mainly driven by the HI cross section.

(ii) The SEL HI cross section shape as a function of LET is a result of point (i): for a given LET, the cross section is proportional to the sensitive surface. As the LET increases, the surface of this sensitive region grows accordingly until eventually reaching a saturation value. Therefore, with a realistic knowledge of the sensitive volume dimensions and materials surrounding it, it is possible to estimate the proton cross section by convoluting the simulated indirect proton energy deposition distribution with the HI response.

(iii) For components with an LET onset below $\sim 20 \text{ MeV cm}^2/\text{mg}$ and tungsten volumes compatible with those typically present in SRAM cells, the 100 MeV cross section will be dominated by silicon fragments owing to the relatively small tungsten volumes and low fission cross section at this energy. As we will show, the calculated tungsten 100 MeV contribution for the device with the largest LET onset is in fact $\sim 30\%$.

Following point (i), and for the SRAM technologies considered here (130-200 nm), an LET sensitive surface of $4 \times 20 \mu m^2$ is assumed compatible with $2 \times 10$ cells of $2 \times 2 \mu m^2$ surface. These assumptions are then compared to the construction analysis of the parts in subsection 6.3.6 showing a good agreement. Moreover, and taking into account point (iii), 5 $\mu m$ of silicon BEOL are considered. Including layers of aluminum and/or silicon dioxide instead of silicon does not affect the outcome of the model.

According to points (i)-(iii) above, the model for 100 MeV is entirely defined except for the SV thickness. Therefore, it is possible to fit this single parameter to the corresponding experimental value through MC simulations. This was done by obtaining the event-by-event energy deposition distribution and convoluting it with the experimental HI cross section as a function of deposited energy (Eq. 6.1) as detailed in Chapter 4. The latter is extracted from the LET-dependent curve by multiplying this variable times the material thickness and density. In this way, the weighting of the energy deposition is performed assuming the distribution extracted from the HI cross section, which is 2D in the sense that it maps the surface of the component (perpendicular to the beam). No weighting is considered in the direction perpendicular to the device’s surface (i.e. the thickness of the SV).

As an example of how the proton cross section is extracted as a function of energy, we consider the HI response from SRAM D and two thickness values: 1.4 and 2.6 $\mu m$. Both the energy deposition distribution and the HI cross section as a function of deposited energy depend on the thickness. Indeed, more energy is deposited in the thicker SV as a consequence of the larger volume, however the HI cross section as a function of deposited energy will also have a higher onset for the thicker case, as the deposited energy is the LET times the thickness. Following the mathematical expression in Eq. 6.1, the resulting proton cross
section is proportional to the product of the heavy ion cross section and the energy deposition distribution, which for the example represented in Fig. 6.20 is larger in the case of the thinner geometry.

![Graph showing energy deposition and cross section](image)

**Fig. 6.20.** FLUKA simulated energy deposition distributions and SRAM D HI cross section curve as a function of deposited energy for two different considered thicknesses. The respective cross sections are proportional to the product of both functions and the bin width as described in Eq. 6.1.

The dependency of the simulated SEL cross section for SRAM D as a function of the SV thickness is plotted in Fig. 6.21 together with the PSI experimental values. The best fit value for this parameter for the simulated thickness resolution was found to be 1.8 µm, which according to a laser inspection for a component of a similar technology is realistic [117]. The scaled SIMPA output is also plotted as a function of the SV thickness, using the respective HI fits as inputs. While reproducing the thickness dependency extracted using the method presented here, the absolute SIMPA value overestimates the experimental data by a factor ~25. Regarding SRAM A, the best 100 MeV fit for the thickness was 3.4 µm and the SIMPA output again reproduced the thickness dependency trend with an absolute value overestimation of a factor ~2. A possible explanation to the SIMPA overestimation is proposed in subsection 6.3.4.

Concerning SRAM C, a statistically meaningful proton cross section value at 100 MeV is not experimentally available. However, provided the trend at 150 and 230 MeV is very similar to that of SRAM D, and considering their similar technology, we assume that at 100 MeV the ratio between both cross sections is similar (σC/σD ≈ 0.8), in which case the corresponding 100 MeV cross section is estimated to be ~8.0 · 10⁻¹¹ cm². Using this value, the best fit of the thickness
Chapter 6. SEL Measurements and Simulations

Fig. 6.21. FLUKA simulated 100 MeV proton SEL cross section for SRAM D and different SV thickness values. The fitted value for this parameter was determined to be 1.8 μm. The scaled SIMPA output is also included showing a very similar dependence with energy, however a factor 25 overestimation.

for SRAM C was calculated to be 3.2 μm.

For SRAM B, the SEL sensitive thickness was measured to be 3.0 ± 0.5 μm through a laser inspection [117]. Using this thickness together with the HI response and extracting the proton cross section at 100 MeV through the method presented here yields a cross section value of $3.2 \times 10^{-8}$ cm$^2$, a factor ~4 larger than the experimental measurement. Even for larger thicknesses, the overestimation is still significant. A possible explanation for this is that, as can be seen in Fig. 6.5, the LET threshold (strongly affecting the proton cross section output) is dominated by the low LET points. As has been shown in the past, SELs can be induced in the sub-LET threshold region through nuclear interactions [135–137]. It could therefore be the case that the point which determines the LET threshold is actually due to indirect energy deposition as opposed to direct energy deposition. Under this circumstance, the LET threshold to be considered in the model applied here would be larger. In order to retrieve the experimental value, an LET threshold of 5.8 MeV cm$^2$/mg needs to be set (as opposed to the best fit value of the test data of 2.8 MeV cm$^2$/mg as can be seen in Table 6.3), potentially compatible with the HI cross section data if the low-LET point is dominated by nuclear events.

Table 6.17 shows a summary of the different SV thicknesses extracted using the calibration model presented here. In the case of SRAM B, this value is taken from the laser measurement (in fact, 3.2 μm is considered in order to use the same simulated energy deposition distribution
as SRAM C) and, as explained above, a larger LET threshold value than that extracted from the fit to the HI data is assumed.

Table 6.17. SV thickness considered for the different SRAM components as extracted by the fit to the 100 MeV proton cross section value for SRAMs A, C and D; and as measured using a laser inspection for SRAM B.

<table>
<thead>
<tr>
<th>SRAM</th>
<th>Thickness (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRAM A</td>
<td>3.4</td>
</tr>
<tr>
<td>SRAM B</td>
<td>3.2</td>
</tr>
<tr>
<td>SRAM C</td>
<td>3.2</td>
</tr>
<tr>
<td>SRAM D</td>
<td>1.8</td>
</tr>
</tbody>
</table>

In a next step, by means of further MC simulations, it is possible to fit the second model parameter, the amount of tungsten per cell in the SRAM memories, to the 230 MeV proton data point. Tungsten is typically used in vias and connectors accessing the active part or first metal layers (M1, M2) of the cell, and is therefore present near the SEL sensitive region. Tungsten can even be employed in the full M1 layer. Therefore, this material is introduced in the geometry as a thin RPP plane 0.2 µm above the SV. The x-y dimensions are taken as 2.2 x 11 µm², and thicknesses up to 1 µm are considered. The corresponding maximum tungsten volume per cell, considering a cell size of 2 x 2 µm² and an SV surface of 4 x 20 µm² (i.e. 20 cells) is therefore 1.2 µm³/cell. In reality, the tungsten present near the SV will not be in the shape of a continuous RPP, but rather separated in small vias and contacts. However, since the secondary reaction fragments are isotropic and with relatively long ranges when compared with the distance to the SV (see Figs. 6.16(a) and 6.19), the specific material distribution does not significantly affect the simulation output as long as the contacts are near the SV region (relative to the fission fragment ranges).

The 230 MeV proton cross section output for the SRAM D model and the different tungsten volumes per cell considered is shown in Fig. 6.22. The main conclusion extracted from this analysis is that a geometry with no tungsten is not compatible with the experimental value at 230 MeV. In the pure silicon case, there is in fact an expected increase with respect to the 100 MeV value (factor 2.7), however not as large as the experimental one (factor 4.5). This is an important result, as for smaller, SEU-like sensitive RPP geometries, this is not the case. The reason behind the expected SEL cross section increase in the 100-230 MeV range even for pure silicon geometries is that, provided a larger SV, the increased fragment energy and range result in a larger energy deposition. For smaller SVs, the increased secondary range will hardly have an impact on the deposited energy owing to the shorter path-lengths.

Moreover, as shown in Fig. 6.22, the best fit of the tungsten cell volume parameter for SRAM D was found to be 0.48 µm³. For SRAM C, the simulated cross section dependency with the tungsten volume is similar and the respective best fit value is also 0.48 µm³. This value is

---

12 This selection was based on the estimated average distance of the active layer vias to the SEL sensitive region.
compatible with that obtained from the construction analysis of the parts, as we will also show in subsection 6.3.6.

![FLUKA simulated 230 MeV proton SEL cross section for SRAM D and different tungsten volumes per cell values. The fitted value for this parameter was 0.48 µm³.](image)

For SRAM A, the tungsten volume has no statistically meaningful effect on the simulated cross section up to the maximum value considered (1.2 µm³), showing that for low-LET onset components, silicon fragments fully dominate the energy deposition distribution. For this reason, instead of using the thickness value extracted from the fit to the 100 MeV cross section measurement (3.2 µm) we use that obtained from the overall fit in the 30-230 MeV range, which is 2.5 µm.

Regarding SRAM B, the simulated cross section at 230 MeV for a pure silicon geometry is \((8.7 \pm 0.4) \cdot 10^{-9} \text{ cm}^2\), whereas for the maximum tungsten volume per cell considered (1.2 µm³) it is \((9.7 \pm 0.8) \cdot 10^{-9} \text{ cm}^2\). Therefore also in this case it is not possible to find a best fit to this parameter due to its weak dependency. For this reason, a default tungsten volume of 0.48 µm³ is considered in order to use the same event-by-event energy deposition distribution simulation output as SRAM C (with the same SV thickness).

Once the model input and fitted parameters are defined for the different SRAMs considered, the simulated SEL cross section can be plotted as a function of energy together with the experimental data for each case. Results are shown in Figs. 6.23(a) to 6.23(d) for SRAMs A to D respectively. It is important to note that the two fitted parameters (SV thickness and
6.3. Semi-Empirical Monte Carlo SEL Model for SRAMs

The tungsten volume) are calibrated using the data in the 100-230 MeV range, therefore simulated results above this interval do not rely on the corresponding experimental data (i.e. the TRIUMF measurements in the 230-480 MeV range). Thus, it is worth underlining that:

(i) the model is very successful in reproducing the SEL cross section in the 230-480 MeV range, which is beyond its calibration interval.

(ii) the TRIUMF measurements for SRAM C and D strongly support the conclusion that the cross section increase is not compatible with a purely silicon geometry.

It is also worth noting that, as can be seen in Fig. 6.23(b), the thickness that best fits the data in the 30-100 MeV interval is significantly different to the optimal value for the 230-480 MeV range. This discrepancy is attributed to the uncertainty in the model inputs (SV and surroundings geometry, experimental heavy ion cross section). In any case, the model output is within a factor 3 of the test data for both thickness values.

6.3.3 | Using the model as a predictive tool

The model is defined in such a way that the proton cross section data in the 100-230 MeV range is used to extract the SEL SV thickness as well as the tungsten volume in the case the former has an impact on the cross section energy dependency. However, it is possible to revert the approach and obtain the proton cross section from the HI data assuming a certain thickness and tungsten volume values or value intervals. This was performed for SRAMs E and F, for which the HI cross section was available from ESA measurements (see Fig. 6.6 for the fits and Table 6.3 for the parameters).

Using these HI cross sections as an input and the FLUKA MC code as a simulation tool, we calculated the proton cross sections for SRAMs E and F using the SEL model for two realistic SEL thickness limit values: 1.8 and 3.0 µm. As to what regards the tungsten volume, provided it did not have a significant impact on the model output, pure silicon geometries were thus considered. The outputs of the model are plotted in Figs. 6.24(a) and (b) together with the experimental data, which in both cases is contained in the thickness interval considered. In the case of SRAM E, the thinner SV is more successful in reproducing the data, whereas for SRAM F, it is the thicker one that better resembles the measurements. We regard these as very satisfactory results provided the calculated proton cross section is fully independent of the proton measurements and only relies on the HI cross section and an SV geometry assumptions as an input.

6.3.4 | Comparison with previous approaches

In analogy to what was achieved in the SEU case [127], [126] early efforts to develop models capable of predicting proton and neutron SEL cross sections from HI test data and the sensitive
Fig. 6.23. SEL model output for the different SRAMs and input parameters together with the PSI proton SEL data to which it was calibrated (100-230 MeV range) and TRIUMF SEL data in a larger energy interval (230-480 MeV). The respective SV thickness ($t$), tungsten volume per cell ($W_{vol}$) and LET onset ($LET_{1\%}$) are included in the individual captions.

Volume thickness and/or dimensions have been previously published [128–130]. They are based on Eq. 6.1 expressed in different forms, and though proving moderately successful for SEUs, tended to largely overestimate the nucleon SEL cross sections. Corrections to the initially proposed model were introduced that lead to a reduction of the predicted SEL probability: in [130] the reduced LET concept was employed, accounting for charge carrier recombination (more important for highly charged, large-LET, low ranged fragments), whereas in [129] a lower limit to the recoil range was included as an SEL-induction criterion. Both corrections had similar effects on the estimated cross sections and were successful in reproducing the particular data sets, but have to our knowledge not been applied in a more general scope.
6.3. Semi-Empirical Monte Carlo SEL Model for SRAMs

Fig. 6.24. Proton SEL data and predicted values using the model we present here for two different thicknesses. A pure silicon geometry is considered. The LET onset ($LET_{1\%}$) for the two models is included in the individual legends.

We focus our comparison on the SIMPA model introduced in subsection 6.3.2 as it is available through the OMERE online tool [138] which we used to extract the proton cross sections for the different SRAMs. The HI cross section and SV thickness need to be provided as an input. The resulting 230 MeV values are shown in Table 6.18 for the different SRAMs and thicknesses considered, relative to the experimental values shown in Table 6.4. As can be seen, this approach works relatively well for components with low LET onsets (F, A and B), while it overestimates the 230 MeV cross section by over a factor 10 for components with high LET onsets (C and D). This overestimation is even larger if lower energies such as 100 MeV are considered, as can be seen in Fig. 6.25 for SRAM D, for which both the SIMPA and FLUKA model output are plotted together in the 30-480 MeV range.

Table 6.18. SIMPA output for the 230 MeV cross sections relative to the measured value.

<table>
<thead>
<tr>
<th>SRAM</th>
<th>$LET_{1%}$ ($MeV cm^2/mg$)</th>
<th>SV thickness ($\mu m$)</th>
<th>$\sigma_{SIMPA}$/$\sigma_{exp}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>3.7</td>
<td>3.0</td>
<td>0.77 ± 0.18</td>
</tr>
<tr>
<td>A</td>
<td>5.9</td>
<td>2.5</td>
<td>2.2 ± 0.3</td>
</tr>
<tr>
<td>B</td>
<td>6.5</td>
<td>3.2</td>
<td>2.2 ± 0.4</td>
</tr>
<tr>
<td>E</td>
<td>12</td>
<td>1.8</td>
<td>5.6 ± 1.6</td>
</tr>
<tr>
<td>C</td>
<td>15</td>
<td>3.2</td>
<td>10 ± 2</td>
</tr>
<tr>
<td>D</td>
<td>18</td>
<td>1.8</td>
<td>14 ± 2</td>
</tr>
</tbody>
</table>

According to the definition of the SIMPA model [125, 126], this overestimation can be attributed to the following two reasons:

- The $p(E_p, E_d)$ term is experimentally extracted (and benchmarked against the HETC Radiation Fields at High-Energy Accelerators and their impact on Single Event Effects
Fig. 6.25. Simulated SEL cross section for SRAM D using SIMPA (output only available until 260 MeV) and the FLUKA model we present here. The PSI and TRIUMF test data are also included.

code [139]) for a diode sensitive volume, therefore having very large lateral dimensions when compared to the fragment ranges (i.e. effectively infinite in terms of energy deposition for most fragments).

• The $p(E_p, E_d)$ term is empirically defined for a thickness of 6 $\mu$m and is assumed to have a linear dependency with the thickness. This is clearly not the case for large energy deposition events, as was shown for example in [125]. This treatment changes in a subsequent version of the code [126] in which the dependency with the thickness is explicitly considered through the HETC code, however this is not included in the OMERE package version.

In order to validate these hypotheses, the two points above can be considered in FLUKA by defining a large SV surface with respect to the fragment ranges (e.g. 40 x 40 $\mu$m$^2$) and scaling the 6 $\mu$m energy deposition distribution with the considered thickness. This was performed for 2 $\mu$m and a proton energy of 100 MeV, and the resulting cross section values as a function of the LET threshold (considering a step function for the HI response) are plotted in Fig. 6.26 together with the respective SIMPA output. The obtained cross section dependency with the thickness value is similar to that extracted from SIMPA, while being significantly larger than the one obtained considering more realistic SV dimensions. Fig. 6.26 also explains why the underestimation is more significant for larger LET threshold values.
As a brief summary of this subsection, it is worth underlining that the semi-empirical SEL model we present here:

- Yielded best fits of the SEL volume thicknesses in the 1.8-3.2 \( \mu m \) interval, compatible with what has previously been published for similar SRAM technologies.

- Yielded best fits of the tungsten volume per cell consistent with the construction analysis inspection (detailed in subsection 6.3.6) for the two SRAMs for which this parameter was relevant (SRAMs C and D).

- Was successful in reproducing the SEL cross section energy dependence in the 30-230 MeV range.

- Was successful in predicting the proton SEL cross section based on the HI data considering a realistic SEL sensitive volume thickness for SRAMs E and F.

- Was successful in predicting the SEL cross section value at 480 MeV, even in the cases in which the energy dependency was still strong in this range (SRAMs C and D).

- Significantly improves the accuracy of other previous approaches owing to the more realistic description of the SV dimensions and the inclusion of tungsten near it.
6.3.5 | Application of the model to GeV energies

Once the two model parameters (SV thickness and tungsten volume) are fitted to the experimental data in the 100-230 MeV range, it is possible to use the calibrated model to estimate the cross section for larger energy values still relevant for the high-energy accelerator and avionics radiation environments. The calculated cross section values for energies in the GeV interval are shown in Table 6.19 for the different cases together with the 100 and 230 MeV values, successfully reproducing the experimental data as shown in Figs. 6.23 and 6.24. In order to quantify and compare the expected cross section energy dependence of the different SRAMs, we consider the ratio between the simulated values at 3 GeV and 230 MeV as a Figure-Of-Merit and refer to it in the following as the **Hardness Risk Factor** (HRF). This value is also shown in Table 6.19 for the different components. As can be seen, it has a very strong dependency with the LET threshold (increasing from left to right of the table) and reaches values that suggest a critical underestimation of the SEL failure rate if using the 230 MeV cross section value for highly energetic environments. This very important conclusion will be further quantified and its implications discussed in Chapter 7.

Table 6.19. Simulated proton SEL cross section in units of \( \text{cm}^2 \) for the different SRAM models considering a purely silicon geometry. In brackets, results including 0.48 \( \mu \text{m}^3 \) of tungsten are shown. SRAMs A, B, C and F use a thickness of 3.2 \( \mu \text{m} \), whereas for SRAMs D and E, a value of 1.8 \( \mu \text{m} \) is considered. The relative \( \pm 2\sigma \) statistical uncertainties for the simulations were below 10% in all cases. The Hardness Risk Factor (HRF, defined in the text) is also included and is shown in bold for the components for which tungsten was expected near the SV through the SEL model.

<table>
<thead>
<tr>
<th>Energy ((\times 10^{-7}))</th>
<th>F</th>
<th>A (\times 10^{-8})</th>
<th>B (\times 10^{-8})</th>
<th>E (\times 10^{-9})</th>
<th>C (\times 10^{-10})</th>
<th>D (\times 10^{-10})</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 MeV</td>
<td>2.7 (2.5)</td>
<td>1.2 (1.1)</td>
<td>0.72 (0.66)</td>
<td>2.5 (2.5)</td>
<td>0.83 (1.0)</td>
<td>1.5 (1.2)</td>
</tr>
<tr>
<td>230 MeV</td>
<td>2.9 (2.9)</td>
<td>1.4 (1.4)</td>
<td>0.87 (0.90)</td>
<td>4.4 (4.9)</td>
<td>1.4 (3.3)</td>
<td>2.6 (4.3)</td>
</tr>
<tr>
<td>480 MeV</td>
<td>3.4 (3.5)</td>
<td>1.6 (1.9)</td>
<td>1.0 (1.3)</td>
<td>5.9 (7.6)</td>
<td>1.8 (7.8)</td>
<td>4.0 (9.3)</td>
</tr>
<tr>
<td>1 GeV</td>
<td>3.9 (4.2)</td>
<td>1.9 (2.5)</td>
<td>1.2 (1.9)</td>
<td>6.9 (13)</td>
<td>2.6 (19)</td>
<td>5.0 (20)</td>
</tr>
<tr>
<td>3 GeV</td>
<td>3.6 (4.9)</td>
<td>1.8 (3.9)</td>
<td>1.2 (3.5)</td>
<td>6.5 (29)</td>
<td>2.6 (59)</td>
<td>4.9 (63)</td>
</tr>
<tr>
<td>30 GeV</td>
<td>3.0 (4.6)</td>
<td>1.4 (4.6)</td>
<td>0.84 (4.1)</td>
<td>5.2 (36)</td>
<td>1.9 (73)</td>
<td>3.9 (76)</td>
</tr>
<tr>
<td>HRF</td>
<td>1.7</td>
<td>2.8</td>
<td>3.9</td>
<td>5.9</td>
<td><strong>18</strong></td>
<td><strong>15</strong></td>
</tr>
</tbody>
</table>

In order to further analyze the cross section increase with energy and its dependency on the LET response and the presence of tungsten near the SV, Figs. 6.27(a) and (b) are introduced showing the SEL cross section as a function of the volume-equivalent LET for different proton energies. In the case of (a), only silicon is considered in the geometry. If we look at the low LET end of the curves \( (LET < 5 \text{MeV cm}^2/\text{mg}) \), the cross section does not increase between 60 and 230 MeV, while it increases by \( \sim 50\% \) for the GeV cases. This situation is similar to the typical SEU case, in which the cross section is saturated in the \( \sim 50-200 \text{ MeV} \) interval and slightly increases above it due to the light fragments produced in p+Si interactions. For larger LETs, the cross section does in fact increase between 60 and 230 MeV and even 230 MeV and 1 GeV. This is related to the larger SV for SEL, which results in an increasing energy deposition with...
increasing fragment energy and range. When tungsten is included in the model (Fig. 6.27(b)), even in a relatively small proportion when compared to silicon (0.48 μm³), the high-LET fission fragments result in a significant cross section increase for components with large onset LETs.

![Figure 6.27](image)

(a) Si

(b) Si + W

**Fig. 6.27.** SEL model cross section as a function of the volume-equivalent LET threshold considering an SV thickness of 1.8 μm. In (a), only silicon is considered, whereas for (b) a tungsten volume of 0.48 μm³ per cell is included.

An important observation to be made of Fig. 6.27(b) is that, though not observed due to statistical limitations, for a large enough fluence, the maximum deposited energy by the different incident energy protons will be roughly the same, as derived from the fact that the maximum fragment production LET is similar in all cases as was shown in Fig. 6.16(b). An implication of this is that, even for components with large LET onset values, the fission induced SEL can be triggered at relatively low energies provided a large enough fluence is achieved. However, in this case one would need to consider a compensation factor accounting for the strong fission cross section energy dependence if the SEL cross section measurement was to be applied to an environment with larger hadron energies. As will be discussed in detail in Chapter 7, this is often unpractical and sometimes unfeasible due to test time constrains and TID effects.

As a summary of these results, the main conclusion extracted from the empirically-calibrated SEL model presented here is that, for components with a high-LET threshold and tungsten near the SV in a significant proportion, the cross section increase with energy can extend up to several GeVs and saturate at a value 15-20 times larger than that at 230 MeV.

Therefore, it is important to assess the impact of the model parameters on this crucial result. In order to do so, we consider individual variations of the parameters and compute the HRF for the different cases, comparing it with those extracted from the model parameters used as inputs and best fits in the calibration step. Table 6.20 shows the lower and upper limits
defined for each of the input and fitted parameters. Their impact is considered individually through the HRF and is shown in Table 6.21 for SRAM D. As can be seen, despite the large parameter variations considered, the HRF is stable between \( \sim 10 \) and \( \sim 20 \) while the model here considered predicts 15, showing that the core conclusion of GeV-range calculation does not significantly depend on the model parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Lower Limit</th>
<th>Upper Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>HI cross section</td>
<td>+10% W, s</td>
<td>−10% W, s</td>
</tr>
<tr>
<td></td>
<td>−10% ( \sigma_{sat}, L_o )</td>
<td>+10% ( \sigma_{sat}, L_o )</td>
</tr>
<tr>
<td>SV surface</td>
<td>−50%</td>
<td>+50%</td>
</tr>
<tr>
<td>SV thickness</td>
<td>+50%</td>
<td>−50%</td>
</tr>
<tr>
<td>Tungsten volume</td>
<td>−50%</td>
<td>+50%</td>
</tr>
</tbody>
</table>

Table 6.21. HRF for the different parameter limits considered compared to the model used for SRAM D. In the case of the SV surface, provided the tungsten volume per cell is kept constant, no statistically significant parameter dependence is observed.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Lower Limit</th>
<th>Model</th>
<th>Upper Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>HI cross section</td>
<td>10</td>
<td>15</td>
<td>18</td>
</tr>
<tr>
<td>SV thickness</td>
<td>9.2</td>
<td>15</td>
<td>17</td>
</tr>
<tr>
<td>Tungsten volume</td>
<td>12</td>
<td></td>
<td>17</td>
</tr>
</tbody>
</table>

Finally, a worst-case cross section increase can be considered by assuming an energy dependence fully dominated by tungsten fragments. Components with larger tungsten volumes and/or higher LET onsets than those here studied are expected to tend to this behavior. Following the model of SRAM D, such a situation can be considered by calculating the HRF for the tungsten fragments only (i.e. subtracting the silicon contribution to both the 3 GeV and 230 MeV cases). The resulting value is 37.5, fully consistent with the respective proton fission cross section ratio extracted using FLUKA. The value at 230 MeV is \( 3.55 \pm 0.15 \text{ mb} \) and at 3 GeV is \( 128.8 \pm 1.6 \text{ mb} \), and \( 128.8/3.55 \) yields a factor 37.5.

### 6.3.6 | Construction analysis and implications on the model

In order to examine the accuracy of the input and fitted parameters of the SEL models introduced before, we performed a construction analysis of a subset of the parts involved in this study based on the SEM (Scanning Electron Microscopy) technique. The information extracted from the study includes the BEOL materials and thickness, the cell size, the process...
6.3. Semi-Empirical Monte Carlo SEL Model for SRAMs

node and the number of cells between two well contacts in the well direction. In addition, the study also focused on identifying the tungsten elements near the active part of the component as well as their volume. On the other hand, this inspection does not provide any information about the SEL SV depth, which needs to be determined through other means such as laser testing.

Table 6.22 shows a summary of the main characteristics extracted from the analysis for the different SRAM components. Several interesting remarks relevant to the SEL cross sections and modeling approach can be extracted from this information:

(i) The saturation SEL cross section for the SEL sensitive memories (see Table 6.3) corresponds to a significant proportion (between 40 and 75%) of the respective total die surfaces, therefore evidencing that SELs occur in the memory array.

(ii) The BEOL thicknesses are compatible with the 5 \( \mu m \) considered in the model. The number of layers increases from 3-4 to 7 for the more complex 65 nm structure.

(iii) The main BEOL metal is aluminum for the 180 nm and larger technologies, and copper for the more integrated ones. Moreover, tungsten is used in M1 for SRAM D.

Table 6.22. Main characteristics extracted from the construction analysis of the SRAMs.

<table>
<thead>
<tr>
<th>SRAM</th>
<th>Tech. node (nm)</th>
<th>Die Surface ((cm^2))</th>
<th>Cell dim. ((\mu m^2))</th>
<th>BEOL thick. ((\mu m))</th>
<th>Metal Layers</th>
<th>Metal Layer Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>180</td>
<td>0.39</td>
<td>2.5 x 1.7</td>
<td>5.1</td>
<td>3</td>
<td>Al</td>
</tr>
<tr>
<td>B</td>
<td>180</td>
<td>0.89</td>
<td>1.8 x 1.6</td>
<td>4.4</td>
<td>4</td>
<td>Al, Ti (M1)</td>
</tr>
<tr>
<td>C</td>
<td>200</td>
<td>0.30</td>
<td>2.5 x 1.7</td>
<td>6.4</td>
<td>4</td>
<td>Al</td>
</tr>
<tr>
<td>D</td>
<td>180</td>
<td>0.24</td>
<td>2.1 x 1.6</td>
<td>4.1</td>
<td>3</td>
<td>Al, W (M1)</td>
</tr>
<tr>
<td>E</td>
<td>130</td>
<td>0.56</td>
<td>1.8 x 1.2</td>
<td>4.9</td>
<td>4</td>
<td>Cu</td>
</tr>
<tr>
<td>H</td>
<td>65</td>
<td>0.11</td>
<td>-</td>
<td>6.7</td>
<td>7</td>
<td>Al (M7), Cu</td>
</tr>
</tbody>
</table>

Provided the vias were found to be the dominating contributor to the total tungsten volume per cell, they deserve a more detailed analysis in the scope of this work. The corresponding information is shown in Table 6.23 for the different parts inspected.

Concerning the number of cells between two well contacts in the well direction, it was found to be 16 for SRAM A and 32 for SRAMs C and D. Therefore, the 10 cells we consider in the model are enough to represent the large SEL SV dimension in this direction. As was shown in subsection 6.3.5, a larger number of cells does not have an impact on simulated cross section as long as the tungsten volume per cell is kept constant.

In order to illustrate the vias structure, Fig. 6.28 shows a vertical cut of the SRAM cell and BEOL for SRAM C. As can be seen, the V0, V1 and V2 vias are made out of tungsten. Moreover,
Table 6.23. Information about the vias in the different SRAMs. V0 are on the actives, V1 are on M1 and V2 are on M2. Vias above this level are not included in the analysis as (i) they are typically not made out of tungsten (ii) their contribution to the SEL rate is expected to be negligible due to the decreasing total volume and increasing distance to the SV. W is often actually TiW with a majority of W. For SRAM D, the information about M1 is also considered, provided it is made out of tungsten. This layer was found to cover ∼30% of the cell surface.

<table>
<thead>
<tr>
<th>SRAM</th>
<th>Vias</th>
<th>Material</th>
<th>Diameter (nm)</th>
<th>Thickness (µm)</th>
<th>Distance to SV (µm)</th>
<th>Average number per cell</th>
<th>Total W Volume (µm³/cell)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>V1</td>
<td>W</td>
<td>270</td>
<td>810</td>
<td>1.1</td>
<td>2.5</td>
<td>0.49</td>
</tr>
<tr>
<td></td>
<td>V0</td>
<td></td>
<td>270</td>
<td>765</td>
<td>0</td>
<td>8.5</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>V1</td>
<td>W</td>
<td>195</td>
<td>285</td>
<td>0.9</td>
<td>2.25</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td>V0</td>
<td></td>
<td>210</td>
<td>690</td>
<td>0</td>
<td>8.5</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>V2</td>
<td>W</td>
<td>280</td>
<td>775</td>
<td>2.4</td>
<td>1</td>
<td>0.66</td>
</tr>
<tr>
<td></td>
<td>V1</td>
<td></td>
<td>300</td>
<td>810</td>
<td>1.2</td>
<td>4.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>V0</td>
<td></td>
<td>280</td>
<td>690</td>
<td>0</td>
<td>8.5</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>V1</td>
<td>W</td>
<td>230</td>
<td>490</td>
<td>1.1</td>
<td>2.25</td>
<td>0.52</td>
</tr>
<tr>
<td></td>
<td>M1</td>
<td></td>
<td>-</td>
<td>310</td>
<td>0.7</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>V0</td>
<td></td>
<td>210</td>
<td>650</td>
<td>0</td>
<td>8.5</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>V1</td>
<td>Cu</td>
<td>255</td>
<td>355</td>
<td>0.8</td>
<td>-</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td>V0</td>
<td>W</td>
<td>160</td>
<td>480</td>
<td>0</td>
<td>8.5</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>V1</td>
<td>Cu</td>
<td>110</td>
<td>155</td>
<td>0.6</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>V0</td>
<td>W</td>
<td>130</td>
<td>430</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Fig. 6.29 shows a horizontal cut of the same cell at the polysilicon level. There are six contacts completely contained in the cell, three per inverter forming the flip-flop. Moreover, four contacts are shared between two neighbor cells: two for $V_{SS}$, one for the bit line and one for the bit line bar. Finally, two $V_{DD}$ contacts are shared between four cells each, yielding a total number of V0 vias of 8.5 per cell. This layout is a relatively standard SRAM design as can be seen in [140].

From Table 6.23 it can be concluded that, at least for the commercial SRAM memories we included in our study, the use of tungsten vias is generalized. Even more modern components with copper metal layers use tungsten for the V0 vias. Moreover, the total volume per cell for SRAMs C and D is in very good agreement with the value extracted from the SEL model with a best fit to the 230 MeV data (0.48 µm³). Finally, the position of the bulk of the tungsten volume in the cell is either directly on top (V0) or just ∼1 µm (V1, M1) away from the SEL sensitive part of the components, therefore justifying the use of a tungsten RPP directly above the SV in our model.

Lastly, the ADC was also inspected using the same technique and was also found to have tungsten vias in V0 and V1. In addition, tungsten was used in the silicide (SiW) directly above the gate oxide. In the case of the ADC, and provided the lack of knowledge on the shape of the SEL SV, the FLUKA SRAM model was not applied to it, however provided the relatively large tungsten volume near the CMOS structure in the digital part of the memory and the strong energy dependence of the SEL cross section (see Fig. 6.11) it seems plausible that the
6.3. Semi-Empirical Monte Carlo SEL Model for SRAMs

Fig. 6.28. Vertical section of SRAM C across the access NMOS. The lighter color (V2, V1 and V0 vias) is tungsten.

Fig. 6.29. Horizontal section of SRAM C at polysilicon level showing the V0 vias in white (i.e. tungsten) N1+P3 and N2+P4 form the cross-coupled inverters of the cell.
dependency is also due to the fission fragments generated in tungsten.

### 6.4 High-Z Impact on Hardened SEU Cross Section

Though initially identified experimentally in the case of SEL [36], a strong hadron energy dependence of the SEU cross section for hardened SRAM components was predicted through simulations in [38]. In this reference, the simulated tungsten overlayers for a 65 nm device were found to have no effect for typical unhardened critical charges (1-2 fC) whereas a pronounced increase in the SEU cross section was expected for critical charge values above 27 fC, therefore compatible with hardened components of this same technology. Owing to its analogy with the SEL case introduced in the subsections above, we have included the SEU analysis of a radiation hardened SRAM in this chapter.

At CERN, a Renesas 16Mbit TFT PMOS SRAM with DRAM capacitors was found to have a very strong SEU dependence with proton energy in the tested range. The part was selected as the central memory for the storage of critical system data in the FGClite system due to its immunity to SEL and an SEU sensitivity several orders of magnitude lower than standard SRAMs [141].

The Renesas memory (reference R1LV161RBG-7SI [142], date codes 1328 and 1343) was tested by an R2E team at PSI and TRIUMF. Results are published in [143] and also showed a very strong increase in the 60-480 MeV range. Whereas standard SEU cross sections are typically saturated at 60 MeV (similar to the ESA SEU Monitor response shown in Fig. 5.1), the Renesas memory was measured to have an increase of a factor 10 between 100 and 480 MeV. The part was also included in the construction analysis reported in subsection 6.3.6, showing it had different tungsten elements near the SEU sensitive part of the memory cell. First of all, tungsten silicide is used to cover part of the polysilicon level of the cell, increasing its conductivity. Secondly, tungsten vias are used to connect the cell with M1, and finally, the M1 lines themselves are also made out of tungsten.

Owing to this interesting behavior and the analogy with the SEL case, we developed an RPP model to further investigate the energy dependence and use it to predict the behavior at larger energies by means of a simulation approach. In this case, the x and y dimensions of the RPP were selected to be 0.35 and 0.45 µm, corresponding to twice the transistor drain dimensions. The depth was fixed at 0.4 µm knowing that, as was reported by Renesas in an internal communication with CERN, the architecture used a special shallow well geometry to reduce the charge collection. These dimensions are in good agreement with the values reported in [58] for similar technologies, while being slightly shallower in the z direction due to the special well technique. As can be seen in subsection 5.3.1, the RPP dimensions for the ESA Monitor model were 0.63 x 0.63 x 0.63 µm³, consistent with the fact that it is built on a larger technology node (250 nm). Furthermore, a beam size and surrounding silicon region of 5 x 5...
μm and a silicon BEOL of 5 μm were considered in the simulation.

Initially, tungsten was included in the FLUKA model considering the 2D inspection of the component (based on a vertical cut). In this case, a thickness of 180 nm was assumed, accounting for M1 and the tungsten silicide. Both were placed together as a single layer covering the full geometry and at a distance of 700 nm from the sensitive volume, corresponding to the location of M1. Because the cell dimensions were measured to be 1.0 x 1.2 μm², this tungsten configuration corresponds to 0.22 μm³ per cell.

After this, the more detailed 3D inspection of the component was used, including horizontal cuts at different levels. This enabled a more detailed construction of the geometry in the model, considering the actual volumes and locations for the tungsten elements at polysilicon level, in the V0 vias plane and in M1. The corresponding construction analysis horizontal cuts and respective FLUKA geometries are shown in Figs. 6.30 to 6.32. In this case, the total tungsten volume per cell is 0.083 μm³ placed at different locations with respect to the sensitive volume.

![Construction analysis](image1.png)  ![FLUKA model](image2.png)

(a) Construction analysis  (b) FLUKA model

Fig. 6.30. Horizontal cut of the SRAM cell construction analysis and FLUKA model at the polysilicon level of the component. Tungsten is shown in light gray and gray respectively. The layer is placed directly above the SV and the tungsten thickness is 90 nm. The tungsten volume per cell of this element is 0.030 μm³.

We performed simulations using three different geometries: a purely silicon case, the simple single layer approximation, and the more detailed model including the individual positions and volumes of the tungsten elements. The simulation of the cross section as a function of the critical charge was then performed for 100 MeV protons and a best fit of this parameter to the respective data point was found at 66 fC for all three cases. This is consistent with the fact that, at this energy, tungsten fragments play an insignificant role in the SEU
**Fig. 6.31.** Horizontal cut of the SRAM cell construction analysis and FLUKA model at the V0 vias level of the component. Tungsten is shown in light gray and gray respectively. The layer is placed 490 nm above the SV and the tungsten thickness is 210 nm. The tungsten volume per cell of this element is $0.018 \, \mu m^3$.

**Fig. 6.32.** Horizontal cut of the SRAM cell construction analysis and FLUKA model at the M1 level of the component. Tungsten is shown in light gray and gray respectively. The layer is placed 700 nm above the SV (directly above the vias) and the tungsten thickness is 100 nm. The tungsten volume per cell of this element is $0.035 \, \mu m^3$. 

---

Radiation Fields at High-Energy Accelerators and their impact on Single Event Effects
induction process. Moreover, as can be seen in [143] this value was considered compatible with the technology and radiation hardening elements in the SRAM architecture (higher capacitance through multiple polysilicon levels and DRAM capacitors). For non-hardened components of the 150 nm technology, critical charges of ∼3 fC have been used in previous RPP models [58, 101].

The 66 fC critical charge value was then used to obtain the simulated SEU cross section value at the different energies tested for. Results for the three simulated cases are plotted in Fig. 6.33 together with the experimental data.

First of all, it is worth noting that if critical charges compatible with standard SRAMs of the same 150 nm technology are considered, the retrieved simulated cross section is equal to ∼1·10^{-14} cm^2/bit, an order of magnitude that is often obtained experimentally throughout different technologies (for example, of the SRAMs used or referenced in this work, SRAM F of 180 nm, the ESA SEU Monitor of 250 nm, or the Toshiba of 400 nm). Therefore, the experimental 230 MeV cross section for the Renesas memory is three orders of magnitude smaller than its standard technology counterparts. Moreover, it is important to note that, according to the results shown in Fig. 6.33, a pure silicon case is not compatible with the strong energy dependence in the 230-480 MeV range. On the other hand, both the simple layer and detailed tungsten model reproduce the trend, with a simulated 480 MeV value 20% and 40% lower than the experimental one respectively. This disagreement is attributed to the RPP dimensions and critical charge value considered in the model as well as to other model limitations such as the fact that in the case of the detailed geometry we only include the tungsten elements in one single cell and not those in the neighbor cells, which according to their distance and tungsten fission fragment ranges could still contribute to the SEU rate.

It is also worth noting that, similarly to what was published in [38], the presence of tungsten in a realistic proportion in the Monte Carlo geometry was shown to have no impact on the cross section in the case of a standard critical charge (∼5 fC) and SEU cross section (∼10^{-14}−10^{-13} cm^2/bit) as silicon secondary products clearly dominate the energy deposition distribution.

As was done in the SEL case, it is possible to use the FLUKA model to calculate the SEU cross section for larger energies (e.g. 3 GeV, where saturation is expected to be reached). In this case, the calculated HRF values (ratio between 3 GeV and 230 MeV cross sections) were 21 for the detailed W model and 32 for the single layer one. From a modeling perspective, the reason why both these values are larger than those obtained in the case of SEL for SRAMs C (18) and D (15) even with a smaller tungsten volume per cell (0.08 and 0.20 as opposed to 0.48 µm^3) is related to the fact that in the SEL case, path-lengths are available in the SV which are significantly larger than its thickness, therefore yielding larger volume-equivalent LET values for the silicon fragments, thus increasing the contribution of this material to the proton SEL cross section.
6.5 Summary

We carried out an experimental characterization of the SEL cross section of different commercial CMOS components, finding that for three of them (two SRAMs and an ADC), the cross section between 230 and 480 MeV increased by a factor $\sim 2$ and was therefore not compatible with a saturated behavior. Similar results were first presented for older SRAM technologies in [36], and fission fragments from high-Z materials were pointed out as the source of the strong energy dependence. We therefore developed a semi-empirical IRPP model including tungsten near the SEL sensitive regions. The model was found to be successful in reproducing the experimental data for realistic tungsten volumes as was supported by a detailed construction analysis of the parts. This same model was used to estimate the cross sections for larger energies, finding that the predicted saturation is reached at around 3 GeV and a value 15-20 times larger than that at 230 MeV for the cases with the strongest energy dependency. In addition, a similar energy dependency was measured and modeled for the SEU cross section in a hardened component, showing that the FLUKA based calculations are
in good agreement with the experimental data and showing that the study is also relevant for hardened devices.

Moreover, it was also determined through FLUKA simulations that the maximum LET produced in the interaction between protons and tungsten is independent of the energy above 60 MeV and equal to $\sim 37 \text{ MeV cm}^2/\text{mg}$. This implies that the worst-case energy deposition can already be achieved at this energy, however the production rate will be orders of magnitude lower than that at larger energies or high-energy mixed fields. This point will be further quantified in Chapter 7.
In the present chapter we quantify the impact of the significant cross section energy dependences introduced in Chapter 6 and discuss the implication on the high-energy accelerator test and failure rate estimation approaches. Other radiation environments relevant to electronic component operation are also included in the analysis.

7.1 Introduction

As introduced in Chapter 2, the standard approach to calculated SEE rates in a mixed-field radiation environment is through the product of the thermal and equivalent HEH fluxes and their respective cross sections. It is worth recalling at this stage that this method assumes that:

- All relevant hadrons in the mixed-field are equally efficient in inducing SEEs.
- Their HEH cross section can be approximated to a step-function above 20 MeV, with a value equal to that measured at 230 MeV.

While these hypotheses generally hold for the SEU case, in Section 6.2 we showed several SEL cross section examples for which significant deviations from this saturated behavior were observed. Likewise, in Section 6.4 we introduced an SEU case for a hardened component for which a saturation below 230 MeV clearly did not apply. In addition, SEU calculations in Chapter 5 and the simulated fission cross sections in Chapter 6 suggest that important differences in the SEE cross sections for the different hadron species might apply. In these cases, using information extracted from the Monte Carlo models can be very useful in order to
obtain a more realistic SEE rate estimation or to establish safety margins to be applied. This chapter describes the application of the models to the operational SEE rate calculations as well as their implications on the more general failure rate estimation and test approaches.

### 7.2 Mixed-Field Environment Description

The operational and experimental environments considered in this thesis were introduced in Chapters 2 and 3 respectively. The relative contributions of the predominant HEH species (neutrons, protons and charged pions) were presented and their energies were described and quantified through the reverse HEH integrals and hardness energies. In this section, we will complete this characterization by including an individual analysis of the energy distribution of each hadron species, which will be relevant in order to consider their separate contribution to the SEE rate and to evaluate the need of performing hadron-specific analyses on a regular basis.

In terms of the accelerator-like mixed-fields, we consider three different cases: the RR and tunnel environment examples introduced in Section 2.3, and the downstream H4IRRAD test location for the ESA SEU Monitor, described in subsection 3.3.2. It is to be recalled that for the two former operational contexts, test configurations at CHARM will be available that will closely reproduce the environments at an accelerated rate (see subsection 3.3.3). Moreover, as shown in Chapter 2 it is to be recalled that the LHC tunnel spectrum is similar to the high altitude environment in terms of its energy hardness, therefore conclusions for the former related to its energy spectrum apply to the latter as well.

The differential particle energy spectra above 20 MeV are shown in Fig. 7.1(a) to 7.1(c) for the three different radiation environments considered using the same scale in the energy axis. As can be seen, charged pions are generally the most energetic particle, followed by protons and finally neutrons, which tend to have a larger flux than the charged hadrons below several hundred MeVs.

In addition, we also consider the GCR interplanetary environment, rich in high energy particles and therefore potentially having an impact on the SEE rate with respect to considering only direct ionization effects from HI. The spectra are calculated using the CREME96 online tool [56, 144] considering the CREME96 GCR model, Solar minimum (Cosmic Ray maximum) conditions, and a near-Earth interplanetary/geosynchronous orbit. The flux is transported through 100 mils (2.5 mm) of aluminum using the Creme96 TRANS/UPROP transport code. The resulting differential energy spectra are plotted in Fig. 7.1(d) for protons, helium and iron nuclei. As can be seen, fluxes peak at an energy near 500 MeV per nucleon and fall off as a power law of index ~-2, extending to very large energies still with a significant flux.
7.3. Model-based SEE Failure Rate Calculations

In this thesis, we have presented two different types of semi-empirical SEE models: the RPP-based SEU cases (Sections 5.3 and 6.4) calibrated to the proton data in the 30-230 MeV range and an IRPP-based SEL model (Section 6.3) calibrated to both the 100-230 MeV proton data and the HI experimental cross section. Once an SEE model is defined and calibrated, it can be used to extract the SEE rate for a given mixed-field environment in two ways:

(i) Simulating the SEE cross section for each relevant hadron at different energies and folding it with the respective particle energy spectra.

(ii) Directly using the environment particle energy spectra as a source beam in FLUKA.

Fig. 7.1. Simulated differential particle energy spectra. (a) to (c) were extracted through FLUKA and (d) was obtained using the CREME online tool.

7.3 Model-based SEE Failure Rate Calculations

Radiation Fields at High-Energy Accelerators and their impact on Single Event Effects
Whereas both procedures are conceptually equivalent, they can in practice lead to slightly different results as these will depend on the resolution of the particle energy spectra and (notably) the simulated cross sections, as well as the goodness of the analytic fit or interpolation in the case of method (i). Generally speaking, method (ii) will provide more accurate results as it does not depend on the energy resolution of the simulated cross section points and its interpolation or fit to a function in order to fold it with the environmental spectra. Moreover, the approaches can also be more or less efficient from a CPU time and precision point of view depending on their specific application. While method (i) will require running calculations for the different hadrons in a certain energy interval covering the operational conditions, method (ii) only involves a single run with the considered environment as an input. On the contrary, provided they are available in a large enough energy range, results from (i) can be applied to any mixed-field and are therefore more general, whereas the output from (ii) only applies to the specific mixed-field used as an input.

In Section 5.3, method (i) was employed to extract the proton, neutron and pion SEU cross section for the ESA Monitor and convolute it with different environments, yielding the results shown in Fig. 5.10. We now apply method (ii) to the same model and radiation field in order to verify the equivalence of both approaches. Their respective results are shown in Table 7.1, including the individual mixed-field HEH cross sections as well as the value including the full environment. Results confirm that both approaches are within a ±7% difference for all hadrons considered. It is worth noting at this stage that, though not shown explicitly in the tables, the 2σ relative statistical uncertainty for the different calculations presented in this chapter was kept below 5%.

<table>
<thead>
<tr>
<th>Spectrum</th>
<th>%</th>
<th>Method (i)</th>
<th>Method (ii)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$</td>
<td>11</td>
<td>$4.21 \cdot 10^{-14}$ (1.60)</td>
<td>$4.50 \cdot 10^{-14}$ (1.71) [+6.9%]</td>
</tr>
<tr>
<td>$n$</td>
<td>28</td>
<td>$3.34 \cdot 10^{-14}$ (1.27)</td>
<td>$3.49 \cdot 10^{-14}$ (1.33) [+4.5%]</td>
</tr>
<tr>
<td>$\pi^{\pm}$</td>
<td>54</td>
<td>$4.50 \cdot 10^{-14}$ (1.71)</td>
<td>$4.75 \cdot 10^{-14}$ (1.81) [+5.5%]</td>
</tr>
<tr>
<td>$K^{\pm}$</td>
<td>7</td>
<td>-</td>
<td>$3.83 \cdot 10^{-14}$ (-)</td>
</tr>
<tr>
<td>total</td>
<td></td>
<td>$4.10 \cdot 10^{-14}$ (1.56)</td>
<td>$4.29 \cdot 10^{-14}$ (1.63) [+4.5%]</td>
</tr>
</tbody>
</table>

In absolute terms, the overall effect of either method is to increase the predicted SEU rate by ~50% with respect to the HEH approximation. As can be seen when analyzing the cross section energy dependence (Fig. 5.10), two main effects can potentially contribute to this: (a) the hadron SEU cross section increase with energy in the 200 MeV - 3 GeV range and (b) the pion resonance at ~150 MeV. The relative impact of each of these effects will be quantified later on in this section.
7.3. Model-based SEE Failure Rate Calculations

This thesis also describes components with a strong SEE cross section energy dependence in the 100-500 MeV range, and therefore not compatible with silicon-dominated energy deposition processes. This was the case of the ADC and SRAMs C and D for SEL (see Section 6.2) and the Renesas memory for SEU (see Section 6.4). Fission fragments from high-Z materials are regarded as the cause of such an energy dependence [36], and the SEU and SEL models used in this thesis were successful in reproducing the dependency when including realistic amounts of tungsten near the SVs. However, as was shown in Fig. 6.14, the fission cross section in tungsten is different for the hadrons considered, especially below \( \sim 1 \) GeV and, to a lesser extend, at saturation (i.e. above \( \sim 3 \) GeV).

Therefore, in order to provide general guidelines to apply monoenergetic (or mixed-field) test results to mixed-field operational SEE rate estimations (potentially in a different radiation field) it is essential to study the dependency of the SEE cross section with the hadron species (as will be done in subsection 7.3.1) and the energy spectrum (as will be done in subsection 7.3.2).

7.3.1 | Impact of hadron species

One of the two assumptions on which the HEH approach for SEE rate estimation is based is the equivalence above 20 MeV of the different hadrons present in the mixed-field. From a physical interaction point of view, several differences between neutrons and charged pions with respect to protons (typically employed in monoenergetic tests) can however be noted:

- Elastic and inelastic interactions in silicon:
  
  (i) Neutrons have a larger interaction probability below \( \sim 50 \) MeV, therefore resulting in a larger SEE probability.

  (ii) Pions have an inelastic interaction resonance around 150 MeV, also resulting in an increased SEE probability. In addition, negative pions can still be generated in inelastic reactions in silicon even at very low (\( \sim \) keV) energies.

  (iii) The saturated inelastic interaction probability is slightly larger for nucleons than for charged pions.

- Fission reactions in tungsten:

  (i) The fission probability below \( \sim 1 \) GeV depends on the hadron type, and this dependency is larger for lower energies, as can be seen in Fig. 6.14. Positive pions are the hadron with a larger cross section, followed by negative pions, protons and finally neutrons.

  (ii) The saturated fission cross section is slightly larger for nucleons than for charged pions (as also seen in Fig. 6.14).
In order to evaluate the impact of the hadron type on the simulated cross section, we consider different environments and SEE models and compare the obtained results simulating the individual hadrons with those extracted considering them all as protons (typically used in monoenergetic SEE tests). In the second case, it is worth bearing in mind that, whereas protons are selected as the input particle in the FLUKA simulations, the individual hadron energy spectra are still considered.

First of all, we consider a silicon-dominated case: the ESA SEU Monitor model. The two environments examined are the H4IRRAD mixed-field (see Fig. 7.1(c)) and the LHC RR example (see Fig. 7.1(a)). The mixed-field HEH cross section results derived from using the respective particle energy spectra as an input in FLUKA and considering (a) the individual hadrons or (b) all hadrons as protons are shown in Tables 7.2 and 7.3. The total value corresponds to the overall mixed-field HEH cross section, which is the average of the individual hadron values weighted by their HEH proportion.

Table 7.2. Impact of the spectra and hadron types on the simulated mixed-field HEH cross section (in units of $cm^2/bit$) for the ESA Monitor model in the H4IRRAD environment. The differences between considering all hadrons as protons and the individual hadron are shown in brackets.

<table>
<thead>
<tr>
<th>Spectrum</th>
<th>%</th>
<th>Hadron type</th>
<th>Individual $\times 10^{-14}$</th>
<th>Proton $\times 10^{-14}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$</td>
<td>11</td>
<td>4.50</td>
<td>4.50 · $10^{-14}$</td>
<td></td>
</tr>
<tr>
<td>$n$</td>
<td>28</td>
<td>3.49 · $10^{-14}$</td>
<td>3.51 · $10^{-14}$ (+0.6%)</td>
<td></td>
</tr>
<tr>
<td>$\pi^+$</td>
<td>27</td>
<td>4.72 · $10^{-14}$</td>
<td>4.78 · $10^{-14}$ (+9.1%)</td>
<td></td>
</tr>
<tr>
<td>$\pi^-$</td>
<td>27</td>
<td>3.83 · $10^{-14}$</td>
<td>5.34 · $10^{-14}$ (+39%)</td>
<td></td>
</tr>
<tr>
<td>$K^\pm$</td>
<td>7</td>
<td>4.29 · $10^{-14}$</td>
<td>4.65 · $10^{-14}$ (+8.4%)</td>
<td></td>
</tr>
<tr>
<td>total</td>
<td></td>
<td>4.29 · $10^{-14}$</td>
<td>4.65 · $10^{-14}$ (+8.4%)</td>
<td></td>
</tr>
</tbody>
</table>

Table 7.3. Impact of the spectra and hadron types on the simulated mixed-field HEH cross section (in units of $cm^2/bit$) for the ESA Monitor model in the LHC RR environment. The differences between considering all hadrons as protons and the individual hadron are shown in brackets.

<table>
<thead>
<tr>
<th>Spectrum</th>
<th>%</th>
<th>Hadron type</th>
<th>Individual $\times 10^{-14}$</th>
<th>Proton $\times 10^{-14}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$</td>
<td>13</td>
<td>2.84 · $10^{-14}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$n$</td>
<td>71</td>
<td>2.88 · $10^{-14}$</td>
<td>2.86 · $10^{-14}$ (−0.7%)</td>
<td></td>
</tr>
<tr>
<td>$\pi^+$</td>
<td>8</td>
<td>4.63 · $10^{-14}$</td>
<td>4.53 · $10^{-14}$ (+13%)</td>
<td></td>
</tr>
<tr>
<td>$\pi^-$</td>
<td>8</td>
<td>3.44 · $10^{-14}$</td>
<td>3.44 · $10^{-14}$ (+13%)</td>
<td></td>
</tr>
<tr>
<td>total</td>
<td></td>
<td>3.15 · $10^{-14}$</td>
<td>2.95 · $10^{-14}$ (−9.3%)</td>
<td></td>
</tr>
</tbody>
</table>

When comparing the individual results with those extracted using the proton response, it can be noted that individual differences are below 15% (except for the case of kaons in the H4IRRAD environment, however this particle typically has a very low contribution to the total HEH flux). For a very hard environment such as that in the H4IRRAD location considered,
assuming the proton response for all hadrons results in a \(~10\%\) overestimation of the SEU cross section, whereas in the case of the softer RR environment, the result is a 10\% underestimation. This is due to the fact that, for a very energetic environment, the larger proton saturation cross section with respect to pions dominates the total difference, whereas for a more intermediate context in terms of energy hardness, the pion resonance plays a stronger overall role. In any case, differences due to the hadron species can be regarded as small when compared with other sources of uncertainly in the SEE rate calculations.

Moreover, it is to be noted that, when considering the individual calculations for the different hadrons, in the RR case, pions have a larger cross section than nucleons (by 60\%), whereas in the H4IRRAD case, it is neutrons that have a slightly lower cross section than the remaining three hadrons (by 25\%). These differences are larger than those extracted from comparing the hadron-specific and the proton results, therefore it can be concluded that they are dominated by the individual energy spectra (with harder spectra resulting in larger cross sections) as opposed to differences in the specific particle type SEU cross sections. This is illustrated in Fig. 7.2, showing the simulated differential contribution of each hadron as a function of energy for the ESA SEE Monitor model in the H4IRRAD environment. As can be seen, the pion resonance around 150 MeV hardly plays a role, and the charged particles have a stronger contribution than neutrons owing to their harder energy spectra.

![Simulated contribution to the total SEU rate per HEH type as a function of energy, both for the HEH approach and the model output. One spill corresponds to $10^9$ protons on target.](image-url)
In addition, the ESA Monitor mixed-field HEH SEU cross section was calculated using method (ii) introduced in the beginning of Section 7.3 for the VESUVIO test environment. In this case, the simulated value was $2.97 \cdot 10^{-14}$ $cm^2/bit$, whereas in subsection 5.2.4 the calculations performed to estimate the error count in the VESUVIO beam used a HEH cross section of $2.6 \cdot 10^{-14}$ $cm^2/bit$. The fact that the simulated mixed-field cross section is larger than the value measured at 230 MeV is consistent with the simulated ESA Monitor neutron SEU cross section bump below 100 MeV and extending down to 20 MeV (minimum energy simulated) as can be seen in Fig. 5.10. If protons are simulated instead of neutrons for the same spectrum, the resulting mixed-field HEH cross section value is $2.58 \cdot 10^{-14}$ $cm^2/bit$, therefore ∼15% smaller than the neutron value.

As to what regards tungsten-dominated cross sections, we use the SRAM D model as an example and consider the LHC RR and tunnel environments. The results of the simulated mixed-field HEH cross sections are shown in Tables 7.4 and 7.5. In this case, the overall impact of considering protons instead of the specific hadrons is less than ±5%. However, the differences between the individual hadron mixed-field cross section is larger than for the ESA SEU Monitor model, owing to their different energy spectra and notably very strong cross section energy dependence. For example, the mixed-field pion cross sections are a factor ∼5 larger than the neutron ones in the tunnel environment, and a factor ∼7 in the RR case. Therefore, it is important to simulate the individual hadron spectra when performing the radiation field characterization in FLUKA, or to score the HEH generalized particle spectra, which will include the contribution of all the different hadrons.

<table>
<thead>
<tr>
<th>Spectrum</th>
<th>%</th>
<th>Hadron type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Individual</td>
</tr>
<tr>
<td>$p$</td>
<td>19</td>
<td>8.7 $\cdot 10^{-10}$</td>
</tr>
<tr>
<td>$n$</td>
<td>45</td>
<td>4.0 $\cdot 10^{-10}$</td>
</tr>
<tr>
<td>$\pi^+$</td>
<td>18</td>
<td>2.3 $\cdot 10^{-9}$</td>
</tr>
<tr>
<td>$\pi^-$</td>
<td>18</td>
<td>2.0 $\cdot 10^{-9}$</td>
</tr>
<tr>
<td>total</td>
<td></td>
<td>1.13 $\cdot 10^{-9}$</td>
</tr>
</tbody>
</table>

7.3.2 | Impact of energy dependence

The impact of the simulated ESA Monitor SEU cross section increase with energy on the mixed-field SEU rate calculation was evaluated in Section 5.3.2, resulting in a ∼50% increase with respect to the HEH approach result. As we just showed in subsection 7.3.1, this is mainly due to the energy dependence of the hadrons as opposed to the differences in the hadron-specific response.
7.3. Model-based SEE Failure Rate Calculations

Table 7.5. Impact of the spectra and hadron types on the simulated mixed-field HEH cross section (in units of cm$^2$) for the SRAM D model in the LHC RR environment. The difference between considering protons and the individual hadron are shown in brackets.

<table>
<thead>
<tr>
<th>Spectrum</th>
<th>%</th>
<th>Hadron type</th>
<th>Individual</th>
<th>Proton</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>13</td>
<td>6.8 · 10$^{-10}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>n</td>
<td>71</td>
<td>2.5 · 10$^{-10}$</td>
<td>3.0 · 10$^{-10}$ (+22%)</td>
<td></td>
</tr>
<tr>
<td>$\pi^+$</td>
<td>8</td>
<td>1.8 · 10$^{-9}$</td>
<td>1.6 · 10$^{-9}$ (-6%)</td>
<td></td>
</tr>
<tr>
<td>$\pi^-$</td>
<td>8</td>
<td>1.6 · 10$^{-9}$</td>
<td>1.6 · 10$^{-9}$ (-6%)</td>
<td></td>
</tr>
<tr>
<td>total</td>
<td></td>
<td>5.4 · 10$^{-9}$</td>
<td>5.6 · 10$^{-9}$ (+4%)</td>
<td></td>
</tr>
</tbody>
</table>

In order to evaluate the effect of the mixed field environment on the SEL failure rate, the respective cross sections are calculated considering a low LET onset, pure silicon case (SRAM A model) and a high LET onset with $\sim$0.5 μm$^3$ of tungsten per cell (SRAM D model).

Different particle energy spectra are then used to extract the SEL cross section for the respective environments $^1$. Moreover, a worst-case energy dependence is considered as well by using a model with 10 times more tungsten per cell than that of SRAM D and assuming a step-function HI response with a threshold at 20 MeV cm$^2$/mg. In this case, the fit to the simulated proton cross section points is used as a method to obtain the SEL rate. The calculated proton SEL cross section values for the SRAM D and worst-case models and their respective fits are plotted in Fig. 7.3 together with the (p,f) cross section in tungsten. The Weibull fit parameters can be found in Table 7.6. As expected by construction, the worst-case SEL cross section closely follows the tungsten fission probability $^2$.

Table 7.6. Weibull fit parameters for the simulated SEL cross section for the SRAM D and worst-case models.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SRAM D</th>
<th>Worst-case</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{sat}$ (cm$^2$/bit)</td>
<td>6.6 · 10$^{-9}$</td>
<td>3.5 · 10$^{-8}$</td>
</tr>
<tr>
<td>$E_0$ (MeV)</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>$W$ (MeV)</td>
<td>2.2 · 10$^3$</td>
<td>2.7 · 10$^3$</td>
</tr>
<tr>
<td>s</td>
<td>1.3</td>
<td>1.5</td>
</tr>
</tbody>
</table>

The corresponding simulated cross sections are shown in Table 7.7 for different environments both as absolute values and normalized to the 230 MeV case. The latter can be interpreted as safety margins to be applied to the 230 MeV cross section when used to derive

$^1$Results are very similar to those we published in [145] using the fit to the simulated proton cross section to extract the mixed-field HEH cross section.

$^2$In fact, as was shown in subsection 6.3.1, fission events become less efficient in generating high LET particles for larger proton energies due to the increased fragmentation of the nucleus, however this fact is compensated by the generation of high LET non-fission fragments, recovering the direct relation between the tungsten dominated SEL cross section and the tungsten fission cross section.

Radiation Fields at High-Energy Accelerators and their impact on Single Event Effects
failure rates in mixed-field operational environments. The main conclusion that can be extracted from these results is that, while for SRAM A the calculated cross sections are within a +50% margin of the 230 MeV value, the failure rate for SRAM D has a very strong dependency with the environment. For hard spectra such as the LHC tunnel or the stratospheric cases, the SEL rate for SRAM D can be up to a factor 3 larger than what would be extracted from considering the 230 MeV cross section value. This underestimation can be more severe if a lower energy is used in order to retrieve the experimental cross section or if a mixed-field with a softer spectrum (such as VESUVIO) is employed. Likewise, having considered the 230 MeV cross section for a component with a response of the worst-case type for an LHC tunnel or atmospheric 20 km altitude environment would have led to a factor 6-7 underestimation of the failure rate, which depending on the application can lead to crucial limitations.

Furthermore, using a lower test energy such as 60 MeV (as was the initial test scenario for the CPLD characterized at UCL for LHC operation [107]) for the worst-case response would lead to a failure rate underestimation factor as large as ~60 for an LHC tunnel environment and ~85 for a 20 km altitude radiation field. For the more realistic SRAM D model, the corresponding underestimation factor is ~20 for both cases. Therefore, it is important to note that the representativeness and corresponding safety margins to be applied for each case need to be carefully considered.

Fig. 7.3. Simulated SEL cross section for the SRAM D and worst-case energy dependency models together with their corresponding fits to Weibull functions. The proton fission cross section in tungsten is also shown in a different axis of the same logarithmic size.
7.3. Model-based SEE Failure Rate Calculations

Table 7.7. Simulated mixed-field HEH cross sections (in units of $cm^2$) for the models of SRAM A and D as well as the worst-case scenario introduced in the text. The ratios with the 230 MeV value are shown in brackets.

<table>
<thead>
<tr>
<th>Spectrum</th>
<th>$H_{10%}$ (MeV)</th>
<th>SRAM A</th>
<th>SRAM D</th>
<th>Worst-case</th>
</tr>
</thead>
<tbody>
<tr>
<td>60 MeV</td>
<td>-</td>
<td>$9.2 \cdot 10^{-9}$ (0.44)</td>
<td>$6.6 \cdot 10^{-11}$ (0.16)</td>
<td>$7.1 \cdot 10^{-11}$ (0.08)</td>
</tr>
<tr>
<td>VESUVIO</td>
<td>150</td>
<td>$8.1 \cdot 10^{-9}$ (0.39)</td>
<td>$8.4 \cdot 10^{-11}$ (0.20)</td>
<td>$1.7 \cdot 10^{-10}$ (0.19)</td>
</tr>
<tr>
<td>LHC UJ</td>
<td>180</td>
<td>$1.2 \cdot 10^{-8}$ (0.57)</td>
<td>$1.2 \cdot 10^{-10}$ (0.28)</td>
<td>$2.6 \cdot 10^{-10}$ (0.29)</td>
</tr>
<tr>
<td>Polar Orbit</td>
<td>280</td>
<td>$1.3 \cdot 10^{-8}$ (0.62)</td>
<td>$2.7 \cdot 10^{-10}$ (0.64)</td>
<td>$6.5 \cdot 10^{-10}$ (0.73)</td>
</tr>
<tr>
<td>Atm, 375m</td>
<td>380</td>
<td>$1.5 \cdot 10^{-8}$ (0.71)</td>
<td>$2.9 \cdot 10^{-10}$ (0.68)</td>
<td>$8.9 \cdot 10^{-9}$ (1.0)</td>
</tr>
<tr>
<td>230 MeV</td>
<td>-</td>
<td>$2.1 \cdot 10^{-8}$ (1.0)</td>
<td>$4.3 \cdot 10^{-10}$ (1.0)</td>
<td>$8.9 \cdot 10^{-10}$ (1.0)</td>
</tr>
<tr>
<td>LHC RR</td>
<td>690</td>
<td>$1.7 \cdot 10^{-8}$ (0.81)</td>
<td>$5.2 \cdot 10^{-10}$ (1.2)</td>
<td>$1.7 \cdot 10^{-9}$ (1.9)</td>
</tr>
<tr>
<td>LHC tunnel</td>
<td>1.8 GeV</td>
<td>$2.0 \cdot 10^{-8}$ (1.0)</td>
<td>$1.1 \cdot 10^{-9}$ (2.7)</td>
<td>$4.3 \cdot 10^{-9}$ (4.8)</td>
</tr>
<tr>
<td>Atm, 20km</td>
<td>3.2 GeV</td>
<td>$2.0 \cdot 10^{-8}$ (1.0)</td>
<td>$1.5 \cdot 10^{-9}$ (3.5)</td>
<td>$6.1 \cdot 10^{-9}$ (6.9)</td>
</tr>
<tr>
<td>ATLAS</td>
<td>3.8 GeV</td>
<td>$2.9 \cdot 10^{-8}$ (1.4)</td>
<td>$2.4 \cdot 10^{-9}$ (5.6)</td>
<td>$1.0 \cdot 10^{-8}$ (12)</td>
</tr>
<tr>
<td>Interplanetary</td>
<td>5.5 GeV</td>
<td>$2.5 \cdot 10^{-8}$ (1.2)</td>
<td>$6.3 \cdot 10^{-9}$ (15)</td>
<td>$2.7 \cdot 10^{-8}$ (30)</td>
</tr>
</tbody>
</table>

Moreover, from the simulated SEL cross section values shown in Table 7.7, the VESUVIO environment has an available measurement for SRAM A as was shown in subsection 6.2.4. As can be seen in Table 6.11, the measured mixed-field HEH cross section was $5.7 \cdot 10^{-9} \pm 28\%$, therefore the simulated value ($8.1 \cdot 10^{-9}$ $cm^2$) overestimates the measurement by 42%. Furthermore, it also overestimates the calculation using the fit to the proton data (shown in Table 6.13) by 13%. The fact that the simulated response for the neutron spectrum is larger than that extracted from a fit to the proton data is consistent, provided the latter have a larger SEL cross section in the 20-50 MeV range, in which the VESUVIO spectrum is prominent. It is also worth noting that, as shown in Table 6.13, using the HEH approach (i.e. considering a step function for the response with an onset at 20 MeV and a saturated value equal to that measured at 230 MeV) in order to retrieve the VESUVIO failure rate would have led to an overestimation of a factor 3.6.

In order to represent the dependency of the simulated SEL cross section with the environment, different cases for SRAM D are shown as a function of the volume-equivalent LET (introduced in Section 2.4) in Fig. 7.4. As was shown in Fig. 6.27(b) for the monoenergetic case, the cross section difference between the environments is small for low volume-equivalent LET thresholds (as is the case for SRAM A) while increasing significantly for less sensitive devices with tungsten present near the SV. It is also worth remembering that the maximum deposited energy per event does not depend on the specific environment, as the maximum production LET of tungsten fragments is already reached at a relatively low hadron energy (at least 60 MeV for protons, as shown in Fig. 6.15(b)). This is a key point when applying the safety margin approach to the estimation of the operational SEL failure rate, as otherwise, if the maximum deposited energy increased with increasing proton energy, this effect could not be compensated by a larger fluence at lower energies.
7.3.3 | Impact of interplanetary protons

As shown in Table 7.7, the effect of a strong energy dependence on the proton SEE cross section becomes more important as the hardness of the environment increases. For the interplanetary proton spectrum, an increase of a factor 15 with respect to the HEH approach result for a dependency similar to that for SRAM D is expected, and a factor 30 for a worst-case response. However, high energy interplanetary protons will be present together with heavier ions that have large enough LET values to induce SEEs through direct ionization and which will in general dominate the total SEE rate. Therefore, traditional in-orbit SEE rate estimation methods for geostationary and interplanetary missions are based on the direct ionization of heavy ions and do not consider the indirect energy deposition contribution. However, as has been shown in [137, 146], heavy ion nuclear reactions can play a dominant role in the error rate for hardened devices with tungsten near the SV.

In order to evaluate the impact of the tungsten fragments in the interplanetary space environment, we will consider the Renesas memory model introduced in Section 6.4 and the particle energy spectra shown in Fig. 7.1(d). As to what regards the tungsten volume, we consider a 1 \( \mu m \) thick layer above the SV as a worst-case condition, corresponding to a total tungsten volume per cell 10 times larger than the actual value. First of all, we will focus on the interplanetary proton contribution and analyze the effect of the indirect energy deposition, both from silicon and tungsten. Secondly, we will compare this quantity to the direct energy deposition from the overall heavy ion spectrum.
For a given space environment and component geometry, the daily SEE rate as a function of critical energy is provided as an output in the CREME MC tool [56]. By disabling the nuclear processes in the input options, only direct ionization is considered. Moreover, one can use the same primary proton spectrum as an input for the FLUKA simulations. In this case, an isotropic flux was selected in order to consider the same situation as that in CREME MC. The resulting event-by-event energy deposition distribution can then be integrated and normalized in order to obtain the SEU rate. The normalization factor is extracted from the fluence in FLUKA, which is equal to \( \frac{1}{\pi R^2} \) (where \( R \) is the radius of the sphere inside which the isotropic flux is present), and when integrating the CREME96 interplanetary proton spectrum (transported through 100 mils of aluminum) above 20 MeV results in \( 3.86 \cdot 10^5 \, \text{HEH/cm}^2/\text{day} \).

This was performed for two different Renesas model geometries: both with a 1 \( \mu \)m layer above the SV, in one case of silicon, and in the other of tungsten. The resulting SEU rate outputs are plotted in Fig. 7.5 as a function of critical charge and volume-equivalent LET. As can be seen, at low LET values (<2 \( \cdot \) \( 10^{-2} \) MeV cm\(^2\)/mg) the direct ionization and the indirect silicon and tungsten curves coincide. In this range, proton direct ionization therefore clearly dominates the error rate. Between 0.02 and 1 MeV/cm\(^2\)/mg, the direct ionization curve is much larger than the direct plus indirect ones. This is due to the fact that the FLUKA simulations, aimed at extracting the indirect energy deposition, only consider protons above 20 MeV, which have an LET below 2 \( \cdot \) \( 10^{-2} \) MeV cm\(^2\)/mg, whereas the CREME MC simulation includes the spectrum above 100 keV, therefore also considering protons near their Bragg peak (with an LET of 0.54 MeV cm\(^2\)/mg at 55 keV).

As to what regards the indirect energy deposition curves for silicon and tungsten, they reach a maximum volume-equivalent LET value of \( \sim 15 \) and \( \sim 50 \) MeV cm\(^2\)/mg respectively, therefore below but near the product of the maximum possible LET generation (\( \sim 14 \) and \( \sim 37 \) MeV cm\(^2\)/mg) and the ratio between the longest possible path-length in the SV and its thickness (1.75 for the dimensions considered).

Furthermore, though not included in this analysis, the indirect energy deposition from HI also needs to be incorporated in order to complete the in-orbit SEU rate estimation. As was shown in [146], the indirect HI contribution is expected to strongly dominate the total SEU rate for components with a large critical charge and a significant amount of tungsten near the SV.

Once the proton indirect contribution to the interplanetary SEU rate is calculated, its relative contribution to the total SEU rate can be determined by comparing it with the total direct ionization rate from HI, including all relevant heavy ions (i.e. up to \( Z = 92 \)). The outcome of this estimation is shown in Fig. 7.6. As can be seen, the total direct HI contribution clearly dominates throughout the full critical charge range, except for a window between 75 and 120 pC (volume-equivalent LET of 30-50 MeV cm\(^2\)/mg, therefore representing the region above the iron knee) for which both contributions are comparable. Hence, given we are considering a worst-case tungsten cell volume (corresponding to a factor \( \sim 10 \) larger than the actual Renesas value), provided that the critical charge window is relatively narrow, and considering that...
Fig. 7.5. Simulated interplanetary SEU rate for the proton spectrum after 100 mils of aluminum extracted using the CREME MC online tool for the Renesas RPP model. The direct ionization contribution of protons above 100 keV (direct) was calculated using CREME MC, whereas the indirect silicon (Si) and tungsten (W) cases for protons above 20 MeV were simulated using FLUKA.

The sensitivity to tungsten fragments is typically correlated with a low absolute SEE rate, the interplanetary proton contribution can therefore in general be neglected when compared to the total HI direct ionization. It is to be noted however that the contribution from heavy ion nuclear reactions is not considered in this analysis.

In addition, the fact that, as shown in Fig. 7.6, the tungsten fragments have an LET distribution similar to that of the iron knee in the interplanetary environment could be potentially useful from a testing and hardness assurance point of view. If an electronic component can be opened in such a way that the sensitive region is accessible through a thickness of several µm (e.g. the BEOL), overlaying a thin high-Z material slab on top of it would yield an LET spectrum similar to the interplanetary one in the SV. In addition, if we consider that the proton flux used to extract Fig. 7.6 was the interplanetary one (4.5 HEH/cm²/s) it is also reasonable to assume that very large acceleration factors could be achieved with respect to the operational case. The main drawback of this option however is that, first of all, it might not be possible to access the sensitive region from a distance near or smaller than the average fission fragment ranges in silicon (11-12 µm for tungsten), and secondly, if reachable, the absolute value of the LET spectrum in the SV will strongly depend on the distance and materials between it and the tungsten converter, which is often difficult to determine.
7.4 Implications on Testing and Failure Rate Calculation Approaches

The estimation of the tungsten-dominated SEL cross section performed in the present work was based on detailed knowledge of the device’s HI and proton cross section. In addition, provided the SEL SV volume shape and dimension for similar SRAM components have been studied in the past and are therefore well known, a realistic geometry could be implemented in the FLUKA MC simulation. Finally, a detailed construction analysis of the volume and location of the tungsten elements near the SV region was also available and used as a benchmark for the values retrieved as outputs from the model.

More generally, effects and components may be more complex. In addition, information such as the tungsten volume or heavy ion cross section is typically not available for components to be operated in hadron environments. Therefore, in the light of the study presented in this thesis, we recommend applying the following procedure when performing SEL failure rate estimations for hard environments based on proton data in the 60-230 MeV range (corresponding to typically available energies in cyclotron radiation facilities):

(i) Carefully study the energy dependence in the 60-230 MeV range and determine whether

---

Radiation Fields at High-Energy Accelerators and their impact on Single Event Effects
it is saturated, or if it is still increasing at an appreciable rate (~linearly or above).

(ii) If saturated, consider the 230 MeV cross section as representative for the environment.

(iii) If still increasing, consider a cross section with the same power index until 3 GeV (tungsten-like dependency) or otherwise assume a worst-case, fully tungsten-driven response.

(iv) If the dependency cannot be extracted from the data (e.g. only one energy value available) assume a worst-case, tungsten dominated response.

(v) Fold the extrapolated response with the differential hadron energy flux of the application environment in order to obtain the respective expected SEL rate for the specific mixed-field, or use the worst-case factors in Table 7.7 if this assumption was considered and the environment of interest is available.

As a consequence of this approach, when characterizing components to be operated in hard spectra with (for example) 230 MeV proton beams, factors in Table 7.7 should be applied to the targeted total fluence in order to obtain a statistically meaningful failure prediction result for a given operational lifetime fluence. Moreover, whereas in the high-energy accelerator context SEL immunity is not necessarily a requirement for the selection of a part (thus rendering an accurate SEL failure rate estimation very important to evaluate its use) these margins also have an important impact on the test approach for components only to be accepted if SEL-free. While HI testing is probably the most efficient approach to validate a part as SEL immune, monoenergetic proton tests can also be carried out for this purpose if the part is to operate in a hadron environment. In this case, being SEL-free is experimentally defined as not having an SEL up to a certain fluence, which will itself need to have the respective safety margin applied to, relating the monoenergetic test condition to the operational environment. Depending on the value of the safety margin, the test method might not be appropriate in terms of beam time or TID effects. Moreover, not applying this safety margin involves the risk of considering a component as SEL-free up to a certain fluence according to the monoenergetic test results and encountering failures in high energy operational environments for significantly lower fluences than those specified by the tests.

A real-life example of such considerations in the high-energy accelerator context is the ADC presented here which is a candidate to be used in the LHC power converter control unit. Despite its low SEL cross section (~4 \times 10^{-13} \text{ cm}^2 at 230 MeV), because the component would be used in over 1000 systems (the main part of which will operate in the LHC tunnel) the risk of underestimating the failure rate when using a monoenergetic cross section value is significant, and could have a negative impact on the LHC operation. For an LHC tunnel area and a response of the type of SRAM D, a factor 3-4 increase in the failure rate is expected with respect to the value extracted from a 230 MeV measurement. This factor could be as large as 10 if the failure rate estimation was based on a 100 MeV cross section measurement.
Finally, many of the considerations and drawbacks related to monoenergetic proton testing for high-energy accelerator environments can be overcome if a facility is available where representative particle energy spectra can be produced. This is one of the main motivations driving the construction of the CERN high-energy Accelerator Radiation Mixed-facility (CHARM, described in subsection 3.3.3) providing a broad range of particle energy spectra with different hardnnesses as shown in Fig. 3.18. Even in this case, the characterization and comparison of the operational and test environments is essential in order to select the appropriate measurement conditions and apply the corresponding safety margins if required.

7.5 Summary

This chapter analyzes the application of the SEU and SEL models introduced in Chapters 5 and 6 to operational SEE rate estimations. The main conclusions extracted from the study are that:

- The different hadron responses have a limited impact on the mixed-field HEH cross section for the environments considered. Therefore, proton data can be applied directly.

- For devices with strong energy dependencies in the several hundred MeV range, the mixed-field HEH cross sections will strongly depend on the environment. Thus, the application of monoenergetic or soft mixed-field test results to hard mixed-field operational environments can lead to a significant underestimation of the operational SEE rate.

- Therefore, margins have been calculated and should be applied to monoenergetic or soft mixed-field test results for components showing a strong (or unknown) energy dependency.
EIGHTH CHAPTER

CONCLUSIONS AND OUTLOOK

8.1 Thesis Summary

This thesis is devoted to the analysis of the SEE rate calculation for a high-energy accelerator operational environment based on information extracted from measurements and simulations. More specifically, it is aimed at quantifying the risk related to the presence of particle species and energies in the operational environment that are not fully covered in the experimental context.

The work here presented shows that, when compared to other operational environments such as the trapped proton belts or the ground level, the high-energy accelerator mixed-field is characterized by more energetic particle spectra (extending to the GeV range) and a broader set of particles species (notably including charged pions at locations near the interaction points). From an experimental perspective, the main implication of the high-energy accelerator environment character is that a significant amount of particles in it will have energies larger than those tested for at standard cyclotron facilities (e.g. typically around 200 MeV, with very limited availability of test centers offering energies up to 1 GeV). Similar conclusions apply to the avionics case. Therefore, the question that naturally arises is whether the larger operational energies can potentially result in an increased failure risk.

The way this question is approached in the scope of this thesis is twofold: from an experimental point of view, a broad data set is presented in the 30-480 MeV range. Whereas some components and effects have a saturated SEE cross section before the upper energy limit, others still show a very strong dependency with energy. In addition, Monte Carlo simulations of the energy deposition events leading to the effects strongly support the interpretation that
the failure probability increase with energy is due to the increase in the high energy hadron induced fission probability in high-Z materials (notably tungsten) near the sensitive volume. When comparing the model output of the tungsten volume near the SV compatible with the cross section increase with the value retrieved through an inspection of the components, both quantities were in very good agreement.

Experimental and simulation results are used in combination with the LHC environment parametrization in order to quantify the risk of testing at a standard cyclotron facility and using the derived SEE cross section to estimate the error or failure rate in the operational context. The outcome is that, for a worst-case situation (fully dominated by tungsten fragments) the safety margin to be applied to a 230 MeV cross section measurement (typically used by CERN groups) for an LHC tunnel spectrum is a factor 5. If a 100 MeV test energy is used instead, the factor increases to 17. Similar (slightly larger) factors apply to a 20 km altitude stratospheric spectrum. Moreover, this thesis provides the guidelines to extract more accurate safety margins for specific cases depending on the available knowledge (i.e. heavy ion cross section, proton cross section in a certain energy range, device architecture, etc.).

In addition to this main conclusion, the thesis also provides other results and approaches of practical interest. The calibration of the ESA SEU Monitor in a broad range of test facilities enables its use as a complement of the RadMon detector for dosimetry purposes in different experimental contexts, including the future CHARM mixed-field facility at CERN. In addition, as a by-product of the analysis of the high-Z material impact on the SEL energy dependence, a general methodology to estimate the hadron cross section from the HI response is introduced. The accuracy and versatility of the method is improved with respect to previous tools mainly owing to the consideration of a more realistic description of the SEL sensitive volume dimensions and the presence of tungsten in its surroundings. Moreover, the models and approaches introduced for the devices treated in this thesis are also applicable to a broader set of components, environments and effects.

8.2 Future Work

The semiconductor microelectronic industry covers a very broad range of applications and is very dynamic in terms of research and development. Thus, the appearance of new components in the market (as well as the obsolescence of old ones) takes place at a very quick rate, with the consequent arrival of new effects and dependencies with the operational parameters and environments. Therefore, there is a strong need of continuously adapting test approaches and SEE rate estimation methods. Likewise, the availability of new test facilities enables the possibility of accumulating further knowledge on the response of the devices to a broader range of radiation fields. For these reasons, it is highly important to pursue research on SEEs in the high-energy accelerator environment in a sustained manner. Several subjects of potential research interest related to the study presented in this thesis are listed in the following
paragraphs.

First of all, the availability of the CHARM facility at CERN will enable the measurement of SEE cross sections in a very broad range of particle energy spectra. Notably, the hardness of the spectra will cover an interval including the vast majority of the operational environments of interest. Such an opportunity will yield experimental data to be contrasted with the results presented in this thesis. Moreover, depending on the test availability, performing monoenergetic measurements beyond 500 MeV (e.g. 1 GeV available in several facilities) would also be of interest in order to obtain an experimental benchmark of the calculated cross section dependence with energy. Likewise, 24 GeV proton measurements will be possible at CHARM as well. Furthermore, monoenergetic tests with pions are also an imaginable means of benchmarking the SEE models here presented and therefore more accurately determining their potential impact on the SEE rate. Indeed, extending the study to a more general range of components and effects would also be of practical and scientific interest.

In particular, whereas this thesis concentrates on SEU and SEL effects in digital components, other destructive failures in power electronics such as SEB and SEGR are likewise highly relevant for the LHC system radiation hardness assurance. Therefore, extending this study to such effects, notably through measurements and potentially also in combination with simulations, would be pertinent. Although the charge collection and SEE induction mechanisms significantly differ between the different cases, the underlying radiation-matter interaction physics is common, therefore similar qualitative results in terms of the increase of the cross section probability with energy can be expected.

Moreover, whereas the technological node range for the CMOS technologies studied in this thesis is 150 to 250 nm, state-of-the-art devices are built on nodes as small as 22 nm. In this case, effects such as the ionization track structure, the sensitivity to direct ionization from singly charged particles or the potential contribution from elastic recoils need to be addressed both from an experimental and modeling point of view. In particular, evaluating whether deep sub-micron SRAMs are sensitive to singly charged particles and would experiment a significant increase in the error rate with respect to their technological predecessors in mixed-field accelerator environment is highly relevant.

Likewise, the use of new materials in microelectronic devices and its potential impact on the radiation hardness assurance is also a potentially relevant subject of further study based on the work here presented. In particular, hafnium is a promising candidate to be used as a high-κ gate oxide instead of silicon dioxide, increasing the gate capacitance without the need of reducing its thickness and therefore also reducing power losses. However, hafnium will undergo fission in the presence of high energy hadrons, with a cross section similar to that of tungsten, and therefore producing highly energetic and ionizing particles near the sensitive region of the transistors. Consequently, evaluating its effect in terms of possible SEE induction is another potentially meaningful research line.
Furthermore, also related to the high energy hadron induced fission study presented in this work, the use of high-Z material slabs placed directly above the sensitive volume of a component (e.g. the BEOL in an SRAM) could be exploited to generate high LET particles with ranges long enough to reach the former, thus generating a radiation field similar to that encountered in deep space missions. This is in principle feasible as high-Z fission products can have ranges up to several tens of \( \mu \text{m} \) in silicon, therefore long enough to travel through standard component BEOLs (similarly to what is performed when \( ^{252}\text{Cf} \) is used as a radioactive source of spontaneous fission). However, the application of this possible test approach in practical terms would need to be evaluated through dedicated simulations of the generated LET spectra in the sensitive volumes as well as experimental benchmarks.

From an SEE modeling point of view through Monte Carlo simulations, the limitations of the RPP approach, mainly related to the assumption that the sensitive volume is a cubic region where all the generated charge is collected, are expected to gain importance with microelectronic component scaling. Therefore, the use of more sophisticated models reproducing the dynamics of the charge collection and circuit response in a more realistic manner is desirable in order to accurately reproduce the SEE cross sections of interest. One first step towards this is that of considering nested regions with different charge collection efficiencies (either analytically or empirically determined) in order to simulate the diffusion processes contributing to the charge collection. Likewise, a realistic SEE model for hadrons should also be capable of accurately reproducing heavy ion cross section data, both above and below the LET threshold.

### 8.3 List of Publications

The work performed during the doctoral thesis here presented has led to the publication of several IEEE TNS main author papers, some of which have been presented in international conferences. The published work is listed below.


Abstract: We use a Single Event Latchup (SEL) model calibrated to Heavy Ion (HI) and proton data below 230 MeV to extrapolate the proton cross section to larger energies and evaluate the impact of the potential cross section increase with energy on the SEL rate in different environments. We show that in the case of devices with a large LET onset for HI data and a certain amount of tungsten near the Sensitive Volume (SV), the calculated failure rates for energetic environments based on monoenergetic test data can significantly underestimate the real value. In addition, we show through measurements using a 480 MeV beam and an
inspection of the device's architecture that the model was successful in estimating the SEL cross section and tungsten volume per cell.


Abstract: The energy dependence of proton-induced Single Event Latchup (SEL) failures is investigated for different Static Random Access Memories (SRAMs) and an Analog-to-Digital Converter (ADC) through experimental measurements in the 30-230 MeV range. It is observed that for several of them, the measurements are not compatible with a saturation below the maximum energy tested. A Monte Carlo based model is proposed that explains the observed cross section increase through the presence of tungsten near the sensitive region and is used to extrapolate the SEL cross section to larger energies. The significant cross section increases expected by the model up to 3 GeV are quantified and discussed, potentially having a strong impact on the failure rate for energetic environments such as high-energy accelerators or the avionics contexts.


Abstract: Single Event Upset (SEU) measurements were performed on the ESA SEU Monitor using mono-energetic GeV-energy hadron beams available in the North Experimental Area at CERN. A 400 GeV proton beam in the H4IRRAD test area and a 120 GeV mixed pion and proton beam at the CERN-EU high Energy Reference Field facility (CERF) were used for this purpose. The resulting cross section values are presented and discussed as well as compared to the several hundred MeV case (typical for standard test facilities) from a physical interaction perspective with the intention of providing a more general understanding of the behavior. Moreover, the implications of the cross section dependence with energy above the several hundred MeV range are analyzed for different environments. In addition, analogous measurements are proposed for Single Event Latchup (SEL), motivated by discussed simulation results. Finally, a brief introduction of the future CHARM (CERN High-energy Accelerator Mixed facility) test installation is included.

Abstract: Single Event Upset (SEU) measurements were performed using the European Space Agency's (ESA) Standard SEU Monitor in the H4 Irradiation mixed-field test area at CERN. The results, tightly correlated with the radiation environment, are compared with those obtained with the CERN Radiation Monitors (RadMons) as well as with the Monte Carlo simulation of the experimental setup using the FLUKA Monte Carlo transport code. In addition, the SEU cross section of the device for particles and energies not available in standard testing (such as charged pions or GeV-energy hadrons) are simulated and discussed, showing an increase of over a factor 2 for nucleons in the 200 MeV-3 GeV range. A monoenergetic SEU cross section measurement at 120 GeV is included in the analysis.
Of all the highly enriching aspects related to the development of this thesis, the most valuable has certainly been the chance of meeting and interacting with people who have in many different ways contributed to broaden my knowledge and understanding.

I first of all want to thank my supervisors for their guidance and support. Markus Brugger has provided me with a constant and extremely valuable direction including both sharp scientific perception and enthusiasm towards learning. I can only warmly thank him for his support and the unique opportunity provided. Likewise, the iteration with Frédéric Saigné and Frédéric Wrobel throughout the thesis has been extremely fruitful and enriching.

I would also like to thank Eamonn Daly for introducing me to the radiation effects research community, as well as Hugh Evans for providing me with the first insights of Monte Carlo particle transport simulations and showing me the importance of normalization. Likewise, I thank Ketil Røed for welcoming me to the high-energy accelerator applications domain, providing both valuable research guidelines and useful technical support regarding FLUKA simulations. To this regard, the contributions from Francesco Cerutti and Alfredo Ferrari in terms of helping me understand the code and its applications has been truly decisive. Moreover, counting with the advice from an expert in the radiation field such as Rémi Gaillard has been remarkably beneficial.

Furthermore, I can only express gratitude towards Salvatore Danzeca and Slawosz Uznan- ski, who with their engineering skills and flair provided crucial support to the work presented in this thesis in terms of experimental setups, measurement campaign support and interpretation of the results. Likewise, the help provided by Julien Mekki in relation to the component construction analysis and CHARM facility is also very much appreciated. In addition, the aid from Véronique Ferlet-Cavrois and Christian Poivey from ESA in terms of identifying commercial components of potential interest for our study and sharing their knowledge and experience (as well as data!) was highly valuable.

Finally, the measurements presented in this thesis would have not been possible without the cooperation from the test facility experts. To this regard, I would especially like to thank Michael Trinzcek and Ewart Blackmore from TRIUMF, Wojtek Hajdas from PSI and Christopher Frost from ISIS.
BIBLIOGRAPHY


Bibliography


Radiation Fields at High-Energy Accelerators and their impact on Single Event Effects


[56] “CREME site by the Vanderbilt University School of Engineering,” https://creme.isde.vanderbilt.edu/.


Radiation Fields at High-Energy Accelerators and their impact on Single Event Effects


[81] ISIS centre for research in the physical and life sciences at the STFC Rutherford Appleton Laboratory. [Online]. Available: http://www.isis.stfc.ac.uk/


Radiation Fields at High-Energy Accelerators and their impact on Single Event Effects


Radiation Fields at High-Energy Accelerators and their impact on Single Event Effects


Radiation Fields at High-Energy Accelerators and their impact on Single Event Effects

Reference:


