ESTIMATION OF PROTON INDUCED SINGLE EVENT EFFECT RATES IN VERY DEEP SUBMICRON TECHNOLOGIES

Executive Summary Report

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1 INTRODUCTION

1.1 Scope of the document

This document is the executive summary report for the activities of the project "Estimation of proton induced Single Event Effect rates in very deep submicron technologies" described in the Agency's Statement of Work, under ESA contract No. 4000130439/20/NL/KML. This work was done in collaboration with the University of Jyväskylä (JYU), Finland.

1.2 Background and Objectives

1.2.1 Background

More and more space applications and missions are considering the use of components processed with deep submicron technologies (< 65 nm feature size): ASIC, flash memories, DDR3 memories, FPGA, SoC. These technologies are scaled to the point that low energy protons (LEP) can cause Single Event Upset (SEU) through direct ionization. The large SEU cross section observed from LEPs raised concerns that this new mechanism might significantly increase on-orbit error rates. These concerns led to several studies that investigated how much LEPs contribute to the total error rate. Up to now, all studies show that LEP contribution to on-orbit rates, are much smaller than some have feared. However, the estimation varies from one study to the other because different methods are used to predict the LEP error rate [1], [2], [3]. To date, there is no accepted standard method to characterize proton SEE sensitivity by direct ionization, and then estimate the SEE rate in orbit.

1.2.2 Objectives

The main objective is to bound accurately the on-orbit SEE rate of deep submicron technology electronic components. In most missions, this rate will be dominated by proton induced SEE via direct ionization process. To this aim:

• a SEE test procedure with LEP shall be defined in order to obtain meaningful and reproducible test results.

• a standard method to estimate the in-flight SEE rate induced by proton via direct ionization shall be defined in order to get accurate and reliable predictions.

2 EXPERIMENTAL WORK

In order to compare different testing procedures in terms of preparation, proton beam type, data processing, and SER calculation, irradiation tests have been performed for the SRAM components of three sub-micron devices from different manufacturers [4]. The technology sizes are 40 and 28 nm respectively. A more detailed description of the devices under test (DUT) is given in Table I. All devices were prepared by delidding or thinning prior to testing and operated at nominal voltage. The tests include heavy ions (HI), low energy protons (LEP), high energy protons (HEP), and highly degraded high energy protons (DHEP).

HI tests were performed at RADEF and UCL facilities in vacuum under normal incidence as well as under tilt to cover a wider effective LET range. LEP tests were performed at RADEF facility in vacuum under normal incidence as well as under tilt. The HEP and DHEP tests were performed at the Paul Scherrer Institute (PSI), specifically at the proton irradiation facility (PIF). The energy of the primary proton beam was 71.1 MeV for the HEP and DHEP tests. The beam was degraded using a combination of Cu and Al slabs, with thicknesses up to 7.0 and 1.5 mm, respectively. The tests were performed in air.

2.1 Test Results

Although all three devices exhibit a LET threshold below 0.35 $MeV.cm^2.mg^{-1}$, i.e. below the PDI peak LET, the Xilinx 28 nm flip-chip device was less sensitive to LEPs than HEP and no particular PDI cross-section peak could be observed. Therefore, the hypothesis of PDI sensitivity assumption when the HI LET threshold is found lower than the peak LET of protons (~0.5 $MeV\ cm^2/mg$) was rejected.

The Lattice 28 nm SOI and the ISSI 40 nm bulk Si devices were sensitive to LEP and exhibit PDI peak cross-sections. The LEP SEU angular responses were different between the two devices. Tilted incidences were the worst case for the SOI device, unlike the bulk Si device for which the worst case was observed at normal incidence.

Table I: Tested devices main characteristics

Manuf.	Part Number	Device Function	Manufacturing Technology	Date code	Mounting technology	Overlayers thickness	Tested Function	Tested memory size (bits)
Xilinx	XC7K70T-2FBG484C	FPGA	CMOS – Si Bulk –28 nm	1917	Flip-chip	69 µm	SRAM	4 976 640
Lattice	LIFCL-17-7SG72C	FPGA	CMOS – SOI – 28 nm	2050	Wire-bounding	9.2 µm	SRAM	3 014 656
ISSI	IS61WV204816BLL-10TLI	SRAM	CMOS – Si Bulk – 40 nm	1640	Wire-bounding	5.9 µm	SRAM	33 554 432

3 LEP TEST GUIDELINES AND SOFT ERROR RATE CALCULATION METHODS

Two main test approaches for LEP SEE testing are provided with their respective soft error rate (SER) calculation methods. The advantages and disadvantages of the two test methods are compared, and the derived SER calculation using irradiation tests data with both of them.

3.1 Method 1: Quasi-Monoenergetic Low Energy Proton Beam

This LEP testing method uses a quasi-monoenergetic (QME) LEP beams. The method is referred to as QME-LEP. In this method, the DUT is irradiated with proton beam(s) with minimal energy straggling. This requires decapsulation of the device prior to testing to ensure well-defined beam energy at the sensitive layer of the device. The method provides detailed information about the LEP SEE response of the DUT, which can be used in a variety of SER calculations and so determine the rectangular parallelepiped (RPP) parameters for the DUT to be used in Monte Carlo (MC) simulations.

Due to the required low primary proton energies, device preparation is mandatory for QME-LEP method to ensure that particles are reaching the sensitive areas of the device without unnecessary straggling in the beam energy spectra. Device preparation can cost time and money. Furthermore, the low primary energy and high quality required of the proton beam restrict the choice of irradiation facilities. Not all proton facilities are able to provide the necessary combination of beam energies and quality.

On the contrary, this method provides versatile and easily interpretable information about the device's response to proton direct ionization (PDI) effects. With this information, an RPP geometry can be estimated, that provides a reliable surrogate for the device in MC simulations. This allows for further investigations without the immediate need for irradiation campaigns. Furthermore, the RPP geometry and the monoenergetic SEU cross-sections allow for a variety of SER calculations applicable to variety of radiation environments. Finally, while the addition of further tilt and roll measurements increases the amount of applicable SER calculation methods, they are not needed for worst-case scenario calculations if worst-case conditions are known for the DUT.

3.1.1 SER Calculation

Soft error rates (SER) can be calculated from the results of QME tests via a variety of methods. In this work, the following three SER approaches are used: energy multiplication method (EMM), energy integration method (EIM), and SV method (SVM).

The three approaches describe PDI peak mathematically with varying degrees of complexity and accuracy. In the following, the differential isotropic proton radiation in particles/(cm^2.s.MeV) for the radiation environment is referred to as Φ_{Env}. Moreover, the SEU sensitivity is assumed to be isotropic and represented by the SEU cross-sections obtained from normal incidence.

The following will give an overview of the three SER methods for the QME-LEP method:

- **Energy Multiplication Method (EMM)**: The peak cross-section value of the experimental data σ_{peak} in cm²/bit at proton energy E_{peak} and the full width at half maximum FWHM in MeV of the PDI cross-section peak are used to calculate the SER τ_{EMM} after

$$\tau_{EMM} = \sigma_{peak} \cdot \Phi_{Env}(E_{peak}) \cdot FWHM \tag{1}$$

This approach was adapted from [5].

- **Energy Integration Method (EIM)**: A second-order polynomial fit $\sigma_{LEP}(E)$ in cm²/bit is applied to the PDI cross-section peak and its zeros (E_{min}, E_{max}) in MeV determined [3]. The function is numerically fitted to the experimental data using the least-square method.

$$\sigma_{LEP}(E) = A \cdot (E_{max} - E) \cdot (E - E_{min}) \tag{2}$$

The SER τ_{EIM} for this method is calculated using

$$\tau_{EIM} = \int_{E_{min}}^{E_{max}} \sigma_{LEP}(E) \cdot \Phi_{Env}\, dE \tag{3}$$

- **SV Model Method (SVM)**: This method uses the numerical model [6] developed in this work. The model is used to extract a set of RPP geometry parameters for the PDI peak of the experimental cross-section data. In turn, these parameters can then be used in conjunction with the model to estimate a cross-section function $\sigma_{PDI,mod}$. This numerical function can then be used to calculate the SER τ_{SVM} in similar manner as the Weibull fit is used for HI:

$$\tau_{SVM} = \int_{0}^{\infty} \sigma_{PDI,mod} \cdot \Phi_{Env}(E)\, dE \tag{4}$$

Graphical representations for σ(E) of the three approaches (EMM, EIM and SVM) are given in Figure 1 for the LEP cross-section data obtained in this work for the ISSI device.

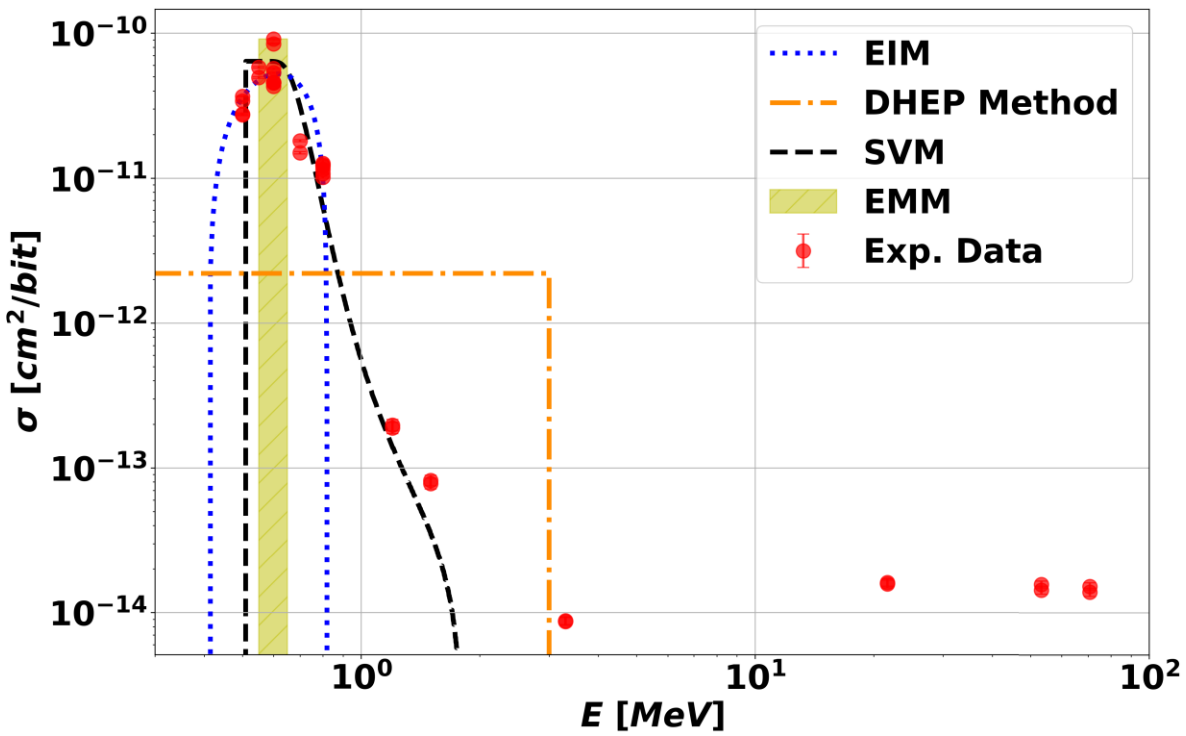

Figure 1: Measured proton SEU cross section σ data for the ISSI memory in cm²/bit is presented over the incoming proton energy E in MeV at device level (red circles). Graphical representations of the SER methods investigated in this work are displayed.

3.2 Method 2: Degraded High Energy Proton (DHEP) Beam

This second LEP testing method uses proton beams with broad energy spectra to irradiate the DUT. This method is referred to as DHEP test method. The broad energy spectrum is achieved by strong degradation of a high-energy proton beam. This assumes that the degraded beam and the most commonly shielded (space) radiation environments share qualitatively the same LEP energy spectrum. Due to the higher proton energies and the already strong degradation of the beam, no invasive device preparation is necessary. Furthermore, the unique approach to LEP testing makes the results more complicated to interpret and less applicable to other applications other than the SER calculation method devised for this testing approach.

This test method assumes that the LEP spectrum of a strongly degraded proton beams has similar characteristics as the LEP spectrum of the radiation environment investigated. This holds true for most shielded radiation environments [1]. Nonetheless, it should be considered whether this assumption holds true for the planned application of the DUT. Additionally, depending on the degrader material of the beamline, this assumption is to be confirmed prior to testing.

DHEP test method provides a way to estimate the LEP response and the PDI SER of a device using a single high energy proton beam. The utilization of the beam degradation eliminates the need for a low energy proton beam facility.

This approach deals with highly degraded proton beams that must be calibrated before (or after) the irradiation campaign. For all used degrader configurations, the fluence at device level must be determined to calculate the cross-sections accurately. Further, the minimum requirement is that the degraded proton spectrum for the configuration associated with the highest cross-section must be well defined if SER calculations are to be performed. The spectra for all degrader configurations must be measured if RPP parameters are to be determined from the test results using the numerical model developed in this work[6].

These measurements are performed during the booked irradiation time leading to a decrease of time measuring the DUT(s). Extra planning is necessary to ensure that appropriate dosimetry is present for the test. The measured spectra for the DHEP method are very wide, therefore it can be difficult to capture the entire spectrum experimentally. This would result in MC simulations of the degraded spectra to be necessary. These add further time requirements and sources of error into the post processing of the data.

Overall, the method can determine PDI sensitivity, but the degree of sensitivity is hard to assess from the DHEP data, because the broad spectrum of the beams reduces the PDI peaks greatly. Finally, the results obtained via this method do not lead directly to the RPP parameters. A method is available to extract RPP parameters from the DHEP data, but it requires the measured spectra for all degrader configurations and enough cross-section values [7].

3.2.1 SER Calculation

The SER can be calculated from the DHEP data when only one spectrum is known. The method is presented in the following.

- **Degraded High Energy Proton (DHEP) Method:**

For estimating SER from the DHEP test results, the maximum cross-section $\sigma_{\max}$ must be determined from the experimental data. The cross-section is then adjusted for the number of particles reaching the device with energies lower than 3 MeV for the tilt and roll and degrader configuration for which $\sigma_{\max}$ occurs. This is done because for this method only protons with less than 3 MeV are considered to contribute to the SER for PDI sensitive device. The adjusted cross-section is calculated after

$$\sigma_{adj} = \sigma_{max} \cdot \left(\frac{\int_0^{3MeV} \Phi_{DUT}\, dE}{\int_0^{\infty} \Phi_{DUT}\, dE} \right)^{-1} \tag{5}$$

where Φ_{DUT} describes the measured (or simulated) differential proton flux at the DUT level during the DHEP test. The SER rate τ_{DHEP} is then calculated after

$$\tau_{DHEP} = \sigma_{adj} \int_0^{3MeV} \Phi_{Env}(E)\, dE \tag{6}$$

where $\Phi_{\mathrm{Env}}(\mathrm{E})$ is the differential proton flux for the given radiation environment.

The results of the SER calculations are given and compared to the QME-LEP results in Section 3.3.2.1.

3.3 Comparison of the Test Methods

The two test methods are compared in several categories. Afterward, a recommendation for PDI test methodology is given.

3.3.1 Test Preparation and Execution

Regarding device preparations, the QME-LEP method requires device preparation. The packaging of the devices can be thick enough to introduce large energy straggle in the QME-LEP proton beam. This would increase the full width at half maximum FWHM of the beam's energy profile causing a change in the shape of the DUT's SEU response. This should be considered when interpreting the results of the tests. Further investigations must be performed to evaluate how data of beams with intermediate FWHM (between QME-LEP and DHEP methods) are to be interpreted. When the FWHM of the beam is kept as low as possible, the data evaluation is simpler and can follow the SERs described for the QME-LEP method here. Therefore, the devices should be prepared before irradiation. This can be very time intensive and/or expensive depending on personal expertise and device type. For the DHEP method, additional packaging of the device does not impact the test method to a great degree. The packaging or overlayers of the DUT can be considered in the simulations of the degraded spectra. For this to be viable, the thickness and composition of the packaging needs to be known. If this information is not available, minimizing the amount overlayers is recommended to reduce impact of the contribution from the "unknown" overlayers on the beam spectra. Additional preparation must be conducted in the DHEP method to estimate the degraded proton spectra expected during the tests with the chosen degrader material(s). This is necessary to assess irradiation time and whether the degraded spectra have the same shape as the investigated radiation environment for protons below 3 MeV.

During the tests, the flux, and spectra for the beam in the QME-LEP method are commonly well known or easy to measure by the facility. The setup of the facility is typically designed for the kind of beams used by the method and appropriate dosimetry should be in place. For the DHEP method, this does not always hold true. Because external degrader materials are introduced, and the beam is degraded more than the level commonly used by most HEP facilities, flux and beam spectra are not known or are not necessarily easy to measure. The measurement of the wide spectra used in the DHEP method can be complex and need appropriate equipment that must be either supplied by the user or the equipment at the facility might be used. In case the equipment cannot capture the entire spectrum, simulations can supplement the data. But this would introduce more uncertainties and steps needed to perform the evaluation of the DHEP tests.

Irradiations for the QME-LEP method must be performed in vacuum, because of the limited range of LEPs in air as well as to the potential straggle caused by the air. For the DHEP method, irradiations can be performed in air. The air thickness then needs to be considered as part of the degrader setup of the test. This gives the DHEP method more flexibility in the test planning as access to the device is not as time intensive as it would be for the QME-LEP method.

3.3.2 Results and Post-Processing

The QME-LEP method requires only the beam fluence and energy to be known for the calculation of the results and the post-processing. The cross-section data provided by this method gives a clear indication of the average device reaction to a proton at the given energy. No additional data is required to assess a variety of SER calculation methods and extraction of the RPP parameters.

To estimate the DHEP cross-sections, the fluence at device level must be known. As stated above, this requires additional calibration procedures, because the fluence at the device level can differ for the different degrader configurations. This method gives the cross-section data relative to the degrader configuration, as average energy is not a representative quantity for these wide spectra. Therefore, the results are not easily applicable to other contexts that do not provide similar spectra as the degrader configuration and initial beam combination. To calculate the SER from the results obtained by DHEP test method, the energy spectrum of the degrader configuration that produces the highest SEU cross-section must be known in sufficient detail. This can be achieved via measurements or simulations. This introduces a source of uncertainty for the SER calculations as neither measurements nor simulations are error free methods. If RPP parameters are to be derived from the DHEP data, the proton spectra for all degrader configurations must be well known.

A comparison summary is given in Table II below.

Table II: Overview over the comparison of the two LEP test methods presented here

Aspect	Method 1 Quasi-Monoenergetic Low Energy Proton Beam	Method 2 Degraded High Energy Proton Beam
Preparation	Device preparation necessary Overlayers/packaging impact the beam quality Preparation can be time intensive and/or expensive and might require external services	Simulation of the expected beam spectra for the given degrader materials Device preparation optional Overlayers can be considered in the simulations during the data evaluation Overlayers might have to be reduced as much as possible if no detailed information can be acquired to reduce the impact on simulations.
Dosimetry	Beam profiles and flux are given by the facility	Heavily degraded beams need dedicated spectral and flux measurements These might not be easily done by the facility equipment and might need additional dosimetry equipment Incomplete spectra can be supplemented with simulations
Irradiation Atmosphere	Vacuum is required due to the limited range of LEPs in air Testing time increases when device needs to be accessed during the test	Can be performed in air because the air can be treated as additional degrader material Allows for more flexible test setup DHEP beams can introduce high levels of activation in the test area depending on the used particle fluxes, which needs attention in terms of shielding the auxiliary test equipment, and area access times
Post-Processing	Hardly any post-processing needed Data gives direct access to several SER and RPP parameters extraction	Degraded beam spectra must be measured and evaluated carefully. These can be supplemented with simulations One spectrum for the SER method needed at minimum All spectra required for the extraction of RPP parameters

3.3.2.1 SER Results

For the SER calculation, radiation fluxes for the geosynchronous equatorial orbit (GEO) under worst day and solar maximum conditions were estimated via the CREME website (https://creme.isde.vanderbilt.edu/). The worst day condition describes the worst day of measured solar energetic particles measured on October 20th, 1989, over a duration of 18 hours. The solar maximum condition describes the ambient galactic cosmic proton background minimum observed in 1989-1991. Furthermore, a low earth orbit (LEO) during solar minimum under quiet magnetic weather conditions was estimated via the CREME website. This radiation environment describes the trapped proton fluxes during near solar minimum conditions using the AP8MIN model and quiet magnetic weather conditions. The radiation environments were estimated behind several different thicknesses of Al shielding. The resulting fluxes are displayed in Figure 2.

The calculated SER rates based on the radiation environments and the SER methods described in this work are presented in Table III and **Table IV** for the ISSI and Lattice device respectively. Additionally, the average ratio between the different SER methods and τ_{SVM} is given. Furthermore, the percentage of protons with energies below 3 MeV is given for each radiation environment.

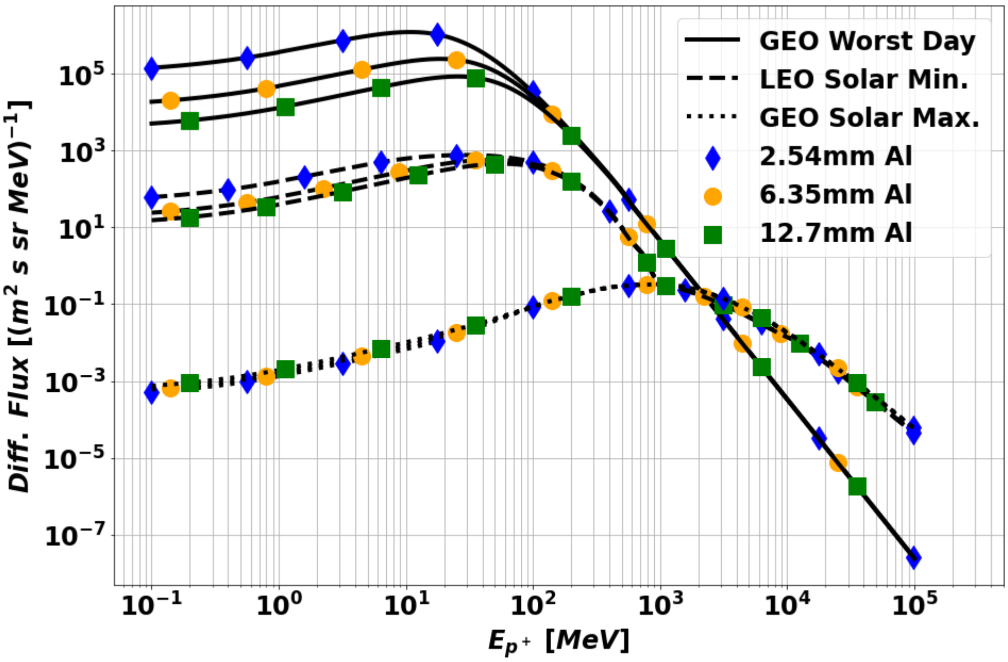

Figure 2: Differential fluxes of the different environmental proton fluxes used for the SER calculation.

Overall, the agreement for the SER estimates derived from the results obtained from QME-LEP tests is heavily based on the fits that are applied. For the ISSI device, both EIM and SVM agree quite well, while for the Lattice device those two methods show the greatest difference. The EMM method seems more consistent compared to SVM but is about 30% lower. Overall, it can be said that the accuracy of the SER estimates from QME-LEP test results is dependent on the fit accuracy. This discrepancy will increase when the PDI sensitivity is low (Lattice) and the extended right-hand shoulder of the peak has more impact on the overall SER, as out of these methods only the SVM method is able to appropriately model this part of the PDI peak.

The deviation of the DHEP from the other SER methods depends on the PDI sensitivity. For highly PDI sensitive devices, like in our case the ISSI, the method underestimates the SER and for the medium PDI sensitive device (Lattice) it overestimates the SER compared to the SVM method. The main source of uncertainty is that the spectrum used for the SER calculations contains protons up to 10 MeV. Therefore, the measured cross-section includes both the LEP and HEP parts of the cross-section. For the less sensitive devices, the HEP cross-section has a greater contribution on the overall degraded cross-section than for the strongly PDI sensitive devices. This results in the degraded cross-section of the DHEP method to overestimate the LEP response of the device even after the adjustment.

Table III: Results of the various SER methods presented here for the different radiation environments behind several thicknesses of shielding for the ISSI device

Shielding [mm]	τ_{EMM}	τ_{EIM} [Errors/day/Mbit]	τ_{SVM}	τ_{DHEP}	Protons < 3 MeV [%]
GEO Worst Day					
12.70	1.00e1	1.60e1	1.49e1	1.21e1	15.91
6.35	3.71e1	5.92e1	5.51e1	4.45e1	20.06
2.54	2.83e2	4.52e2	4.21e2	3.35e2	29.45
GEO Solar Maximum					
12.70	1.49e-6	2.38e-6	2.22e-6	1.81e-6	0.60
6.35	1.20e-6	1.91e-6	1.78e-6	1.46e-6	0.48
2.54	1.04e-6	1.65e-6	1.54e-6	1.25e-6	0.41
LEO Solar Minimum					
12.70	1.94e0	3.09e0	2.88e0	2.34e0	8.75
6.35	6.94e0	1.11e1	1.03e1	8.33e0	10.21
2.54	5.01e1	8.00e1	7.45e1	5.92e1	15.99
Ratio	0.67	1.07	1.00	0.79	

An important consideration to be made during the calculation of the SER from QME-LEP cross-section results is the impact of the device overlayers. The overlayers present during the irradiation impacts the location and shape of the measured cross-section values. None of the commonly used techniques for SER calculation consider this effect. Therefore, cross-section results and resulting SERs can differ between the same devices when the device preparation varies. This effect can be visualized in Figure 3. The figure shows the estimated response as a function of energy for three different overlayer thicknesses (h_{OL}). Additionally, a radiation environment behind three different overlayer thicknesses is plotted as a function of energy as well.

Therefore, it can be seen how the different responses have not only distinct shapes but also cover different parts of the radiation environment. This leads to a varying result in calculated SERs and could be accounted for by sufficient safety margins.

To avoid the use of extra safety margins and to increase the comparability of SERs and cross-section results, this work proposes to convert the proton energy at device level to proton energy at SV level. This provides a comparable metric for devices independently of the device preparation. The cross-section data as a function of proton energy at SV level should also be used for the SER calculations. Any potential shielding used for the calculation of the on-mission SERs should also be considered in the radiation environment used in the calculation.

4 CONCLUSION

In this work, firstly a numerical method to iteratively extract parameters of a RPP SV from experimental PDI SEU data is proposed. To benchmark the method, simulated cross section values based on RPP parameters derived with this method are compared with the literature data from SRAM devices. The RPP geometries determined by this method reproduced the experimental cross section values in the literature with good accuracy, therefore showing that this method can be used to reliably and quickly determine the RPP parameters for SVs in memories sensitive to PDI. The method is currently strictly

Table IV: Results of the various SER methods presented here for the different radiation environments behind several thicknesses of shielding for the Lattice device as well as the percentage of protons with energies below 3 MeV for the respective environment

Shielding [mm]	τ_{EMM}	τ_{EIM} [Errors/day/Mbit]	τ_{SVM}	τ_{DHEP}	Protons < 3 MeV [%]
GEO Worst Day					
12.70	1.10e-2	8.49e-3	1.53e-2	3.42e-2	15.91
6.35	4.05e-2	3.13e-2	5.62e-2	1.26e-1	20.06
2.54	3.08e-1	2.39e-1	4.27e-1	9.45e-1	29.45
GEO Solar Maximum					
12.70	1.63e-9	1.26e-9	2.27e-9	5.11e-9	0.60
6.35	1.31e-9	1.01e-9	1.83e-9	4.11e-9	0.48
2.54	1.13e-9	8.76e-10	1.58e-9	3.54e-9	0.41
LEO Solar Minimum					
12.70	2.12e-3	1.64e-3	2.94e-3	6.60e-3	8.75
6.35	7.57e-3	5.86e-3	1.05e-2	2.35e-2	10.21
2.54	5.45e-2	4.22e-2	7.55e-2	1.67e-1	15.99
Ratio	0.72	0.56	1.00	2.20	

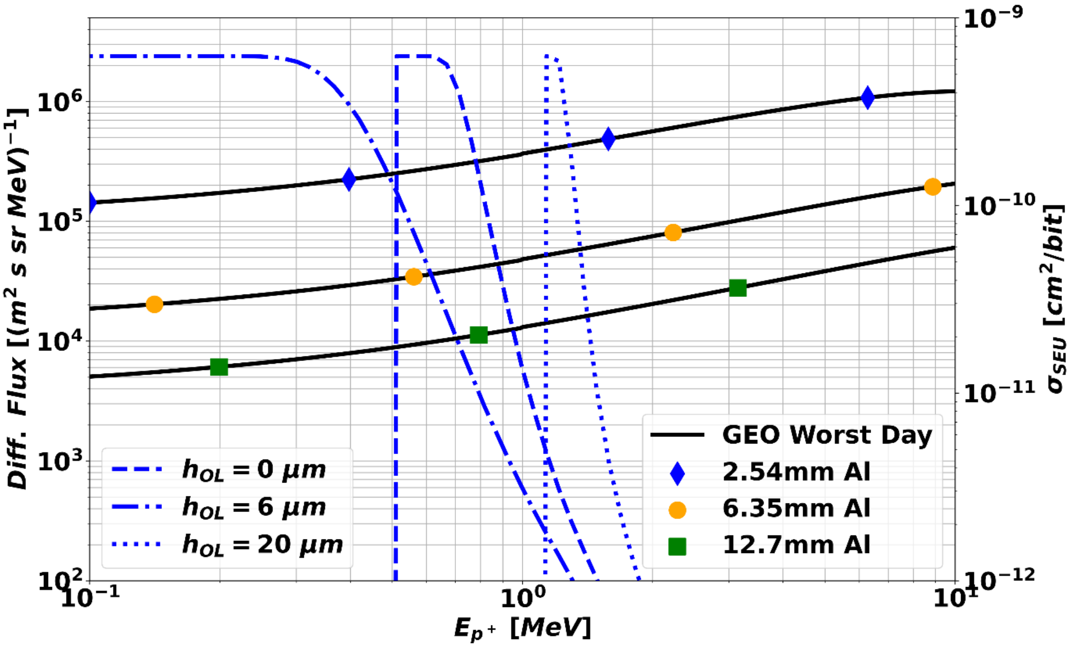

Figure 3: Estimated SEU response function for various overlayer thicknesses and a radiation environment behind various amounts of shielding.

limited to direct ionization effects, i.e., not taking into account any nuclear reaction mechanisms, and elemental materials due to the underlying models' definitions.

Secondly, three submicron devices of feature size below 40 nm have been tested with HI, HEP, and LEP, in order to collect data for SER calculations. Although all three devices exhibit a LET threshold under heavy ions below 0.35 MeV.cm².mg^{-1} i.e., below the PDI peak LET, the Xilinx 28 nm flip-chip device was less sensitive to LEPs than HEP and no particular PDI cross-section peak could be observed. Therefore, the hypothesis of a PDI sensitivity based on the Heavy Ions results (low LET threshold) can be rejected.

In the end, two test methods are presented to assess the LEP response of submicron technologies. The first method (QME-LEP) uses low energy proton beams with well-defined energy spectra, and high-quality device preparation to test the LEP response of the DUTs. Contrary to this, the second method (DHEP) utilizes strongly degraded high-energy proton beams to mimic the LEP spectra of shielded radiation environments to assess the LEP response of the DUT under these conditions.

The two methods lead to different results. The results from the QME-LEP method are easy to interpret due to the low energy straggling in the proton beams. The results can be directly used in a variety of SER calculations in addition to parameter extraction of the RPP geometry using the proposed numerical method (SVM). The results from the DHEP method are however more complex to interpret for any other purpose than the designated SER calculations. Furthermore, the concept of introducing excessive amounts of energy straggling in the beam requires an additional setup of degraders to be present. Intensive simulations and/or precise measurements are required to assess the beam spectra and the validity of the similarity of the beam profiles and the LEP spectra of the shielded radiation environments.

The additional calibration of the degraded beam spectra and the fluxes during the DHEP tests take additional time during the tests and introduce more uncertainty to the results and the post-processing of the data.

Due to the difference in required beam FWHM, a major difference between the methods is the amount of device preparation. For the QME-LEP method, it is important to reduce the amount of material in the beam's path to ensure a low FWHM of the beam due to minimum straggling, whereas the DHEP method does not necessarily require any device preparation. This can lead to additional time and money investment when using QME-LEP method.

Overall, the QME-LEP method provides more versatile and interpretable results that can be used in a variety of SER calculations and extracting detailed information on the SV geometry for further studies. Therefore, it is recommended to use QME-LEP method, if possible, despite the additional device preparation requirements.

If device preparation is not possible for the DUT or if the only accessible radiation source is a high-energy proton source, the DHEP method can be used. To do so, the assumption of the similarity of the low energy spectra of the degraded beam and the radiation environment under investigation is to be confirmed before SER estimates are made.

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