# SEU Threshold model and its experimental verification

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***Abstract*—This work presents a simplified procedure to obtain that ionization profile from SRIM2010 and the Katz radial dose model applied to oxygen ions with kinetic energy from 11 to 18 MeV. Device simulation of Single Event Upsets needs LET(z) and w(z) (linear energy transfer and lateral radius) as inputs. TCAD Simulations with the calculated ionization profile of a digital test chip predicts a SEU threshold. That threshold is experimentally confirmed using the ion microprobe of the Tandem Van de Graaf at the CNA facility (Spain), validating the ionization model.**

***NOTA: revisar la composición de las figuras para la versin definitiva de proceedings (deadline, 5 Septiembre 2011). Poner otra figura del artículo PNST protones e iones para comparar con la figura 3 actual (máximo radio lateral), colocando los comentarios de comparativa al final de la sección II y aumentar mucho la parte de exposición del experimento, tengo página y media para expandirme). La figura 4 no se ve tal y como está ahora.***

***Index Terms*—Low energy accelerators, SEU, Spice, TCAD.**

## I. Introduction

TCAD device simulators are well known tools now used to simulate Single Event Effects in electronics. A TCAD simulator, Sentaurus in this work, [1], needs the ionization profile as input in order to calculate how evolves in response the potential and the electron and hole currents in the device. An ionization profile is determined by the triplet $\{z, LET(z), w(z)\}$, where $z$ is the charged particle range depth, $LET(z)$ is the linear energy transfer distribution and $w(z)$ is the profile lateral radius.

A simple ionization model, validated with the experiments, is a powerful tool for realistic TCAD simulations of single event effects in electronic devices because establishes a clear relation between the ionization profile and the particle physics. The objective here is to validate our simple ionization profile model by means of an experiment. With the calculated ionization profile as input we simulate with TCAD Sentaurus a SEU on a flip-flop cell in order to determine the SEU Threshold in terms of particle energy. A threshold experiment is simple enough to be made using a digital test chip and the ion microprobe from the Tandem accelerator at the CNA [1] facility in Sevilla, Spain.

There is no need of precise determination of the ionization profile if big particle accelerators are used for testing. In this case the particle range depth exceeds the device active depth and $LET(z)$ can be considered a constant, also with constant lateral radius conforming a cylindrical ionization profile. For low LET particles, typical at low energy accelerators, those approximations are no longer valid. Low energy accelerators are very common at Universities along the world, used for materials science.

Nowadays a conventional approach for ion SEU simulation, [2], is to calculate the radial dose, $D(r)$, using an application built with the GEANT4 toolkit, [3]. From the radial dose it is possible to determine the ionization profile lateral radius imposing a minimum dose threshold (conventionally less than 1 eV/$\mu m^3$, [2]). The radial dose is also related to the (dominant) electronic LET(z), [4], through the formula (1).

$$LET(z)_{\text{electronic}} = 2\pi \int_0^R r \mathrm{d}r D(r,z) \ , \qquad (1)$$

That approach was followed by several of us, [5], [6]. The GEANT4 application defined a cylindrical detector comprised of a stack of concentric rings, following a "bull's" eye structure in order to track the main particle and the delta electrons. That approach is precise but the effort was considered excessive.

The LET(z) function can also be calculated using SRIM2010, [7]. As a reference with our GEANT4 application, it is depicted in figure 1 the comparative between the SRIM2010 direct calculation of LET and the calculation of LET from the radial dose given by our GEANT4 application, both of them for an oxygen ion with 18 MeV impinging on a 4 $\mu$m thick $SiO_2$ layer on top a 12 $\mu$m thick Si layer. The results are very similar but SRIM2010 needs a lot less computational and programming effort.

The radial dose $D(r)$ and its lateral profile can also be obtained from the classical Katz-Waligorski-Fageeha (KWF), [8], [9] formulas using a spreadsheet. The KWF model has been used before for $w(z)$ calculation, [2], [10], with good results for ions. In this case we are considering low energy ions so it is compulsory to calculate $D(r)$ in iterative way because the remnant ion kinetic energy changes with depth. The remnant energy dependence with depth is solved by means of the Stapor rule, [11].

The model is weakly related to the VLSI integration scale of the target chip. For the LET calculation is needed only the

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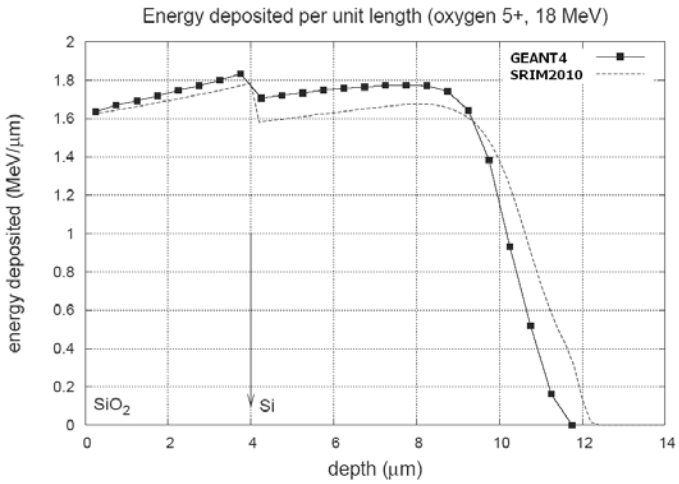


Fig. 1. SRIM2010 vs GEANT4 comparative, from [5]. It is shown the linear energy deposition of 18 MeV oxygen ions at a 4 $\mu$m thick $SiO_2$ layer over a 12 $\mu$m thick Si layer (bulk).

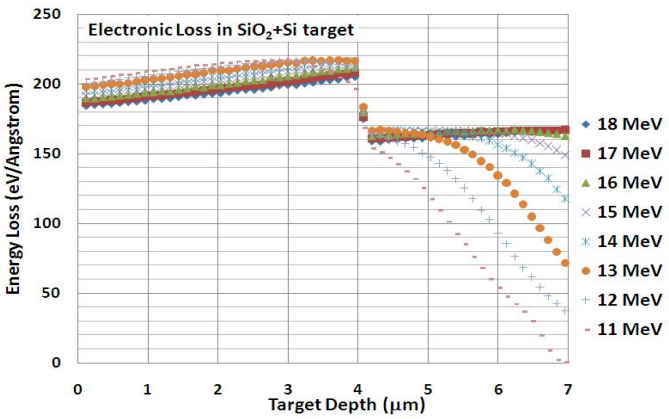


Fig. 2. SRIM simulation for linear energy loss in case of 4 $\mu$m $SiO_2$+ Si layer model. Oxygen ions from 18 to 15 MeV have similar linear energy transfer in the 2-3 $\mu$m of the silicon active layer (transistor drains+funneling depth).

TABLE I
LET MEAN VALUES (FROM SRIM SIMULATIONS) ALONG 2 AND 3 $\mu$M DEPTH IN CASE OF 4 $\mu$M $SiO_2$+ SI LAYERS.

| Energy (MeV) | LET 2$\mu$m (MeV-cm$^2$/mg) | LET 3$\mu$m (MeV-cm$^2$/mg) |
|---|---|---|
| 18 | 6.97 | 7.02 |
| 17 | 7.06 | 7.09 |
| 16 | 7.13 | 7.11 |
| 15 | 7.16 | 7.01 |
| 14 | 7.11 | 6.66 |
| 13 | 6.81 | 5.89 |
| 12 | 6.06 | 4.80 |
| 11 | 4.85 | 3.48 |

thickness data of the passivation and metallization layers and the active depth in the silicon bulk. The radial dose formula is applied to bulk silicon in order to obtain the lateral ionization profile. For that reasons we choose a well known test chip made on 0.6 $\mu$m scale, described in our previous papers, [12], [13] and [14]. The critical LET is known in advance because it has been determined before for the 0.6 $\mu$m scale, [15], [16] and in one of our papers, [12].

Taking the ionization profile as input, the TCAD simulations of a test flip-flop predicted a SEU threshold at 15 MeV for oxygen ions, with no SEU at 14 MeV. The experiment confirmed that prediction, validating the simplified ionization profile model. The model can calculate the ionization profile for any ion and energy with targets up to 8 layers due to limitations of SRIM2010.

## II. PHYSICAL MODELING

As discussed in the introduction, the TCAD Sentaurus heavy ion model needs the triplet $\{z, LET(z), w(z)\}$. $LET(z)$ is calculated from a SRIM2010 simulation. Our test chip is made with the OnSemiconductorC5 process, available from the MOSIS university program. That process has a gate length of 0.6 $\mu$m, 2 metals and n-well. More details in [12]. It is well known, [17], that the nmos drains are very vulnerable to single event effects. From the layout and the foundry data sheets, the most exposed drains in the test chip have a 4 $\mu$m of $SiO_2$ passivation layer over the active silicon.

The critical LET for the 0.6 $\mu$m technology is $\sim$ 7 MeV-cm$^2$/mg, [15], [16]. Considering the available ion species for the CNA microprobe, the LET range around 7 MeV-cm$^2$/mg is provided by oxygen ions with kinetic energy from 11 to 18 MeV. At those energies the LET cannot be considered constant in the silicon active depth.

Figure 2 shows the SRIM2010 calculations for linear energy loss (in eV/Angstrom) considering the layer model and oxygen ions from 11 to 18 MeV. Table I shows the mean LET values, calculated by averaging the SRIM LET values between the silicon starting depth to the maximum active depth. The C5 process has an n-well depth of 2.5 $\mu$m so it is reasonable to estimate the average LET for 2 and 3 $\mu$m.

The lateral radius, $w(z)$, comes from a modification of the Katz-Waligorski-Fageeha (KWF) radial dose ($D(r)$) model, [8], [9]. In this case we are considering low energy ions so it is compulsory to calculate $D(r)$ in iterative way because the remnant ion kinetic energy changes with depth. The remnant energy dependence with depth is solved by means of the Stapor rule, [11]. The KWF equation set is:

$$D(r) = \left[\frac{Ne^4}{m_e c^2}\right]\left[\frac{Z^{*2}}{\alpha\beta^2}\right]\left[\frac{\left(1-\frac{r+\theta}{R+\theta}\right)^{\frac{1}{\alpha}}}{r(r+\theta)}\right] \quad (2)$$

where $N$ is the electron density in the target material, $e$ is the electron charge (in statcoulombs), $m_e c^2$ is the electron rest energy, $\beta = v/c$ with v the ion speed and $c$ the speed of light and $r$ is the radial distance from the ion track. The ion speed is calculated from its kinetic energy using the relativistic formula:

$$\beta_{ion} = \frac{v_{ion}}{c} = \sqrt{1-\left(\frac{1}{1+\frac{T_{ion}}{m_{ion}c^2}}\right)^2} \quad (3)$$

where $T_{ion}$, $m_{ion}$, are the kinetic energy and the rest mass of the projectile ion. The ion losses electrons during the initial

collisions, so we get an effective ion charge, $Z^*$:

$$Z^* = Z\left(1 - e^{-125\beta Z^{-\frac{2}{3}}}\right) \quad (4)$$

where $Z$ is the atomic number for the projectile ion. The electron density in the target material comes from:

$$N = A_v \frac{\rho Z}{A} \quad (5)$$

with $A_v$ the Avogadro number and $\rho$, Z, A the density, atomic number and atomic mass of the target material, respectively. The minimum energy delta electron (10 eV) has a range from:

$$\theta = k(0.010\ keV)^{1.079} \quad (6)$$

where $k$=6×10$^{-6}$g cm$^{-2}$ keV$^{-1.079}$. The maximum delta electron radial range, $R$ is:

$$R = kW^{\alpha} \quad (7)$$

where $\alpha$ in (7) and in (2) is such that for $\beta < 0.03$, $\alpha = 1.079$ and for $\beta > 0.03$, $\alpha = 1.667$. $W$ is, due to relativistic reasons, the maximum collisional energy transfer by Coulomb scattering to a delta electron coming from rest:

$$W = \frac{2m_e c^2 \beta^2}{1 - \beta^2} \quad (8)$$

From a projectile initial kinetic energy $T$, the remnant kinetic energy at depth z is calculated with the Stapor rule, [11] and inserted in (3):

$$T_j = T_{j-1} - LET_{j-1}\,\Delta z \quad (9)$$

where $\Delta z$ is the unit depth length ($\Delta z = 0.12$ $\mu$m for SRIM2010) and $LET_{j-1}$ is the LET value given by SRIM2010 at the actual depth. Every time the ion goes down 120 nm the radial dose $D(r)$ and the maximum lateral radius, $R$ is reevaluated. For oxygen ions in the range 11 to 18 MeV the radial dose shows a very abrupt cutoff so the lateral radius of the ionization profile can be approximated by the maximum lateral radius, equation (7). The TCAD simulations show no difference taking the maximum radius or the radius for $D(r) < 1eV/\mu m^3$.

The final result, shown in figure 3, is the (revolution) ionization profile for the particle track until stops in the silicon substrate. The radial profile for TCAD simulations start in silicon at 4 $\mu$m depth, under the $SiO_2$ passivation layer.

## III. SEU VULNERABILITY ANALYSIS

For experimental validation of the ionization profile model we designed a SEU threshold analysis. The target in the test chip is a shift register comprised of 32 master-slave flip-flops. An electrical vulnerability analysis of the flip-flop using Cadence gives the most vulnerable nodes. With that information we implement the TCAD simulations without excessive computational resources. In the SEU threshold experiment is expected that the most vulnerable nodes will be also those detected with the electrical analysis so the TCAD SEU threshold prediction could be confirmed.

Referring to the flip-flop schematics, figure 4, the SEU vulnerable transistors are C3, C4 (master flip-flop, inverter n.2), C5, C6 (master flip-flop, inverter n.1), C9, C8 (slave flip-flop, inverter n.6) and C13, C14 (slave flip-flop, inverter n.3) because they are feedback coupled pairs, [18].

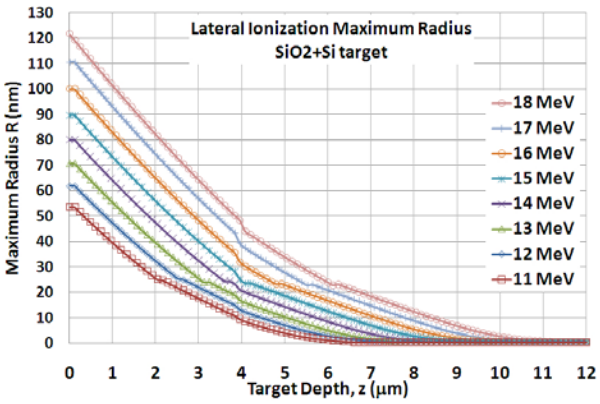


Fig. 3. Maximum lateral radius for oxygen ions striking through 4 $\mu$m of $SiO_2$ on top of bulk silicon.

TABLE II
$Q_c$ VALUES FROM ELECTRICAL SIMULATION, $\tau_r$=1 PS, $\tau_d$=160 PS

| *MOS* | $Q_{crit}$ (fC) |
|---|---|
| C3 | 550 |
| C4 | 284 |
| C6 | 356 |
| C9 | 458 |
| C10 | 278 |
| C14 | 307 |

The first vulnerability analysis is made by electrical simulation, using the double exponential current pulse, [19]:

$$I_{rad} = \frac{Q_c}{\tau_d - \tau_r}(e^{-t/\tau_d} - e^{-t/\tau_r}) \quad (10)$$

The value of $\tau_r$ =1 ps is conventional, [20]. It is related to the short time scale of the particle plasma track. The $\tau_d$=160 ps comes from literature, [21], and it is consistent with the $\tau_d$ range associated to LET $<$ 10 MeV. $\tau_d$ depends linearly on LET and it is relatively independent of technology, [22], [23], [24].

The parametric variable for simulation is $Q_c$. When a bitflip is observed, a $Q_{crit}$ is declared. The precise $Q_{crit}$ found is not important from this analysis because precision comes only from device simulation. The point is the trend: from table II one concludes that the nmos C4 and C10 are the transistors most vulnerable to SEU.

The second analysis is made by layout inspection and SRIM2010 simulation of LET. From layout, C4 has its drain exposed but C10 has its drain covered with metallization. For low energy ions, as those available at CNA, the metallization layers are a problem. From the analysis it is concluded that the most vulnerable transistor is the nmos C4, belonging to the master flip-flop.

## IV. TCAD SEU SIMULATIONS

The vulnerability analysis has shown that the C4 nmos in the master flip-flop is the most vulnerable. For that reason the

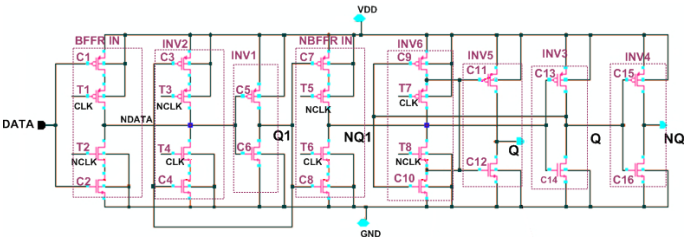


Fig. 4. C3-C4 is the CMOS pair in the input inverter for the master flip-flop. C5-C6 is the CMOS pair in the master flip-flop output inverter. C9-C10 and C13-C14 are the respective ones in the slave flip-flop

TCAD simulation is a mixed-mode one, with a 3D model of the C4 nmos transistor and an electrical model of the remainder flip-flop. The TCAD simulation transistor model, including the doping profiles for the 3D nmos is described in [13]. The circuit is depicted in figure 5 and it corresponds to the master flip-flop in the figure 4. The ionization profile comes from the method described in section II. The model let to state that an ionization profile corresponds to a specific ion and kinetic energy. Considering the expected threshold LET around 7 MeV-cm$^2$/mg we calculate ionization profiles for oxygen ions from 11 to 18 MeV.

The simulation results show a SEU (a bitflip) from 18 to 15 MeV and no bitflip from 14 to 11 MeV. Figure 6 shows the transient response to an oxygen ion with 15 MeV impinging on the C4 nmos drain with 0° of incidence. V(A) is the voltage at node A (see figure 5), V(B) is the voltage at node B and $I_{drain}$ is the C4 drain current. Node A is the input inverter gate node and node B is the output inverter gate node. With the key transistors T4 and T3 conducting, the flip-flop is identical to a SRAM cell, so for a bitflip a state change in the output inverter induces through feedback a state change in the input inverter. This is the behavior shown by V(B) and V(A) in figure 6.

Figure 7 shows the transient response to an oxygen ion with 14 MeV, also with 0° of incidence. In this case there is no bitflip because V(A) and V(B) return to their original state after the transient.

The simulation results are shown in table III. The charge $Q_c$ is obtained from the simulation $I_{drain}$ output by integration, equation (11). The conclusion from the TCAD analysis is a prediction of the SEU threshold between 14 and 15 MeV for oxygen ions incident at 0° to the most vulnerable node of the master-slave flip-flop.

$$Q_c = \int I_{drain} dt \tag{11}$$

## V. Experimental Results

The previous analytical SEU threshold prediction needs experimental validation. For that purpose, an experiment was made with the target chip using the microbeam probe from the Tandem CNA accelerator.

The microprobe is an Oxford Microbeam Endstation OM2000 associated to a tandem Van de Graaf pelletron, model NEC 9DSH2 with 3 MV of maximum acceleration voltage. The ions come from a SNICS II ion source. The experiments

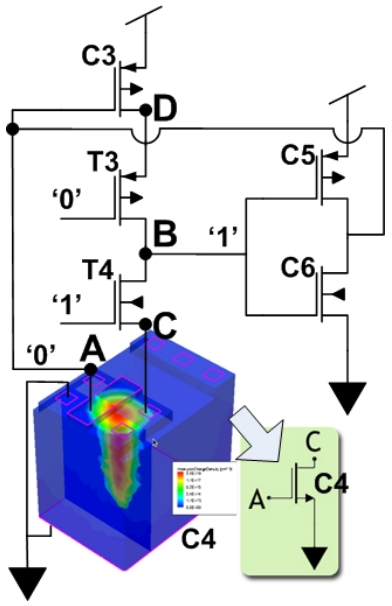


Fig. 5. Sentaurus mixed-mode simulated model: it corresponds to the master flip-flop, with nMOS C4 as the most vulnerable transistor. Voltage at node A corresponds to the gate voltage of the input inverter gate voltage and voltage at node B to the output inverter gate voltage.

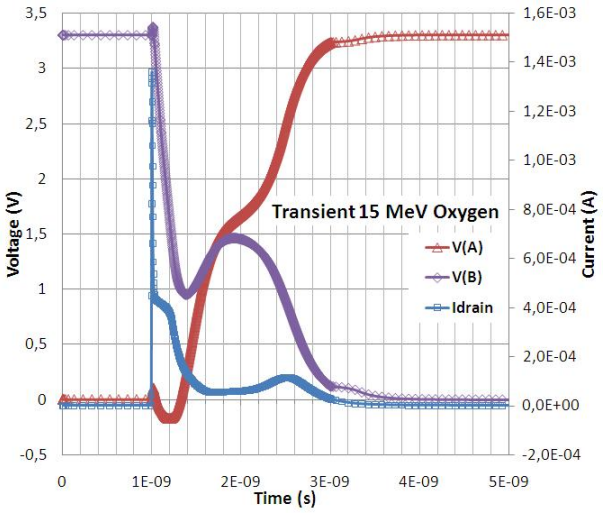


Fig. 6. Transient TCAD simulation corresponding to a impact with an oxygen ion with 15 MeV of kinetic energy. There is a bitflip because the input inverter gate voltage, V(A), changes its state in response through the feedback to the change in the output inverter gate voltage, V(B).

range from 11 to 18 MeV, with a 1 MeV step. In the expected threshold energies the oxygen beam was configured at 14.1 and 15.1 MeV in order to obtain the maximum beam stability. More details about the experimental setup in [12].

The beam impacted the target orthogonally to chip surface. It was focused on the shift register of the test chip. The flux was adjusted to 200±15 cps, for a 5 min of irradiation time so the fluence was ∼1.4 ions/$\mu$m$^2$. A flip-flop has an area of 20×50 $\mu$m$^2$ and the shift register has an area of 220×200 $\mu$m$^2$.

The low fluence ensures at least one ion hit in every sen-

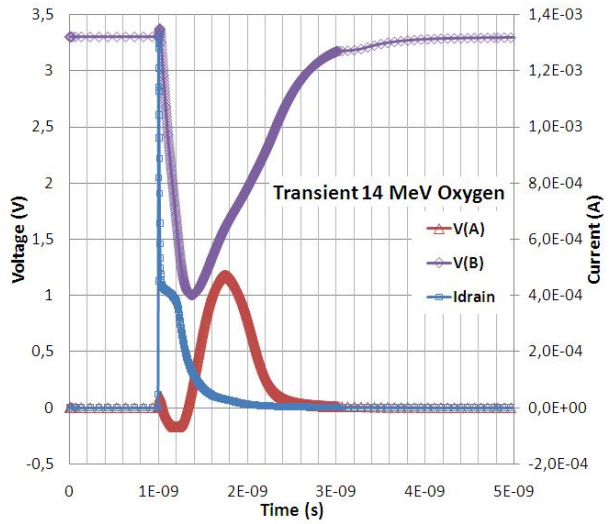


Fig. 7. Transient TCAD simulation for oxygen at 14 MeV. There is no bitflip because the input inverter gate voltage, V(A) returns to its original state. The output inverter gate voltage, V(B) also recovers its original state.

TABLE III
SENTAURUS SIMULATION RESULTS. $Q_c = \int I_{drain} dt$

| Energy | Bitflip? | $Q_c$ (fC) |
|---|---|---|
| 18 | Yes | 251.7 |
| 17 | Yes | 251.0 |
| 16 | Yes | 252.6 |
| 15 | Yes | 268.8 |
| 14 | No | 172.4 |
| 13 | No | 121.7 |
| 12 | No | 90.5 |
| 11 | No | 62.8 |

sitive volume of the shift register without excessive radiation damage. The test chip is monitored by a coincidence detector, thoroughly described in [14]. The FPGA in the coincidence detector maintains a synchronized replica of the irradiated circuit. Any change in the irradiated circuit outputs generates a discrepancy with the synchronized replica output.

The shift register is loaded, for the test, with logical '0's. A scrubbing is performed every minute comparing the output with a replica and resetting the shift register. For practical purposes the shift register can be considered as a static array of memory cells, so any change in their content is due to SEUs.

The experimental results confirm the simulations: several SEU's (a maximum of 6) are observed from 18 to 15.1 MeV. From 14.1 down to 11 MeV there are no observed SEUs. A precision of 1 MeV in the prediction is enough in order to design SEE experiments for the 9DSH2 accelerator. Those kinds of accelerators are relatively common in different universities across Europe so the model could be a useful tool for SEE studies.

## VI. CONCLUSIONS

The use of low energy accelerators for SEE experiments compels the use of simulation models able to predict the necessary collection of ionic species and kinetic energies. Those models must discover the vulnerable circuits in the target chip and its SEU thresholds without unsurmountable computational complexity. This work presents a combination of models for vulnerability assessment by means of current pulses and chip layer analysis and a model for physical modeling able to predict the SEU energy thresholds.

The models have been validated experimentally using a low energy accelerator, model NEC 9DSH2. Those models are now used to ensure the proper ionization physics as input to TCAD device simulators. They are precise and simple enough to allow the electronic designer to concentrate in the electronics without to have an expertise in particle physics software toolkits as GEANT4.

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