SIMPA & METIS models
Proton cross section from heavy ion data

COMET-ENV
"Tools to predict Single Event Effects"

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SIMPA & METIS

- Prediction tools from heavy ions to protons
- No technological input parameters: end-user tool
- Fast calculations
- ECSS-Q-ST-60-15C: *For SEUs, proton cross-section curve can be obtained from heavy ion cross-section curve with simulation tools such as SIMPA or PROFIT;*
  The following RDM shall be applied on calculated error rate: 10, when proton error rate is based on simulation from heavy ion data;

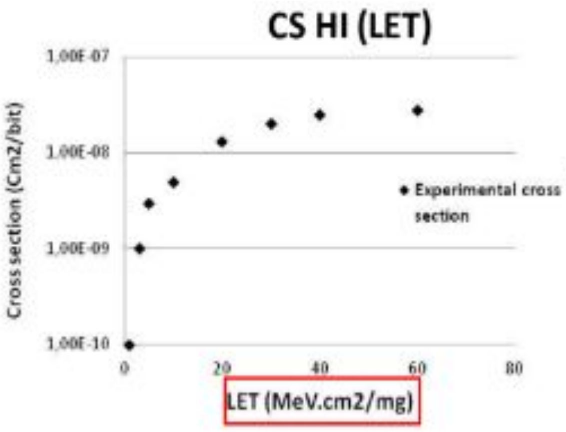
SIMPA overview

- **SIM**ulation of **P**roton **A**ccelerator
- Semi-empirical model developed by Matra Marconi Space in 1995
- Implemented in the OMERE tool suite
- SEU predictions for devices (DRAMs, µprocessors, SRAMs) with sensitive thicknesses > 2 µm (no SOI)
- Integration of the heavy-ion cross-section with the probability Φ_{Ep} to deposit given energy (E_d) from the secondary recoils of p-Si

$$\sigma(E_p) = \int_0^{E_p} \sigma_{IL}(E_d) \, . \, \Phi_{E_p}(E_d) \, . \, dE_d$$

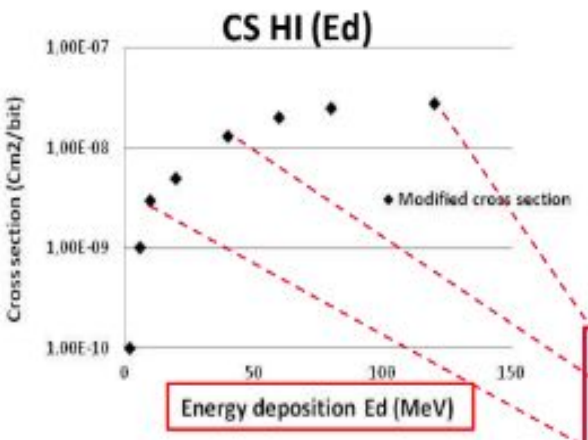
- Experimental data of the energy deposition in diodes and comparison with HETC nuclear code
  - The probability Φ_{Ep} of the deposited energy/µm is a function of the deposited energy and four parameters that depend on the incident proton energy and the thickness
  - For the implementation in OMERE, the variation with thickness is neglected and a sensitive thickness of 6 µm is considered.

SIMPA methodology

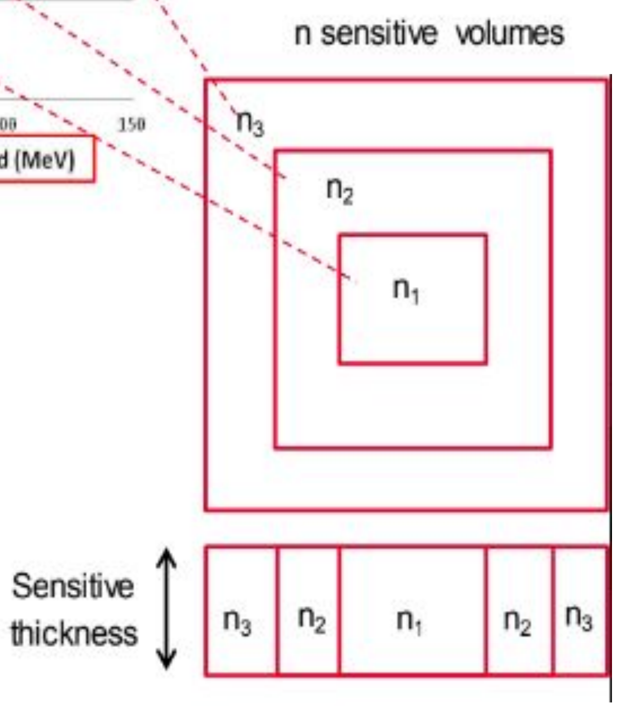


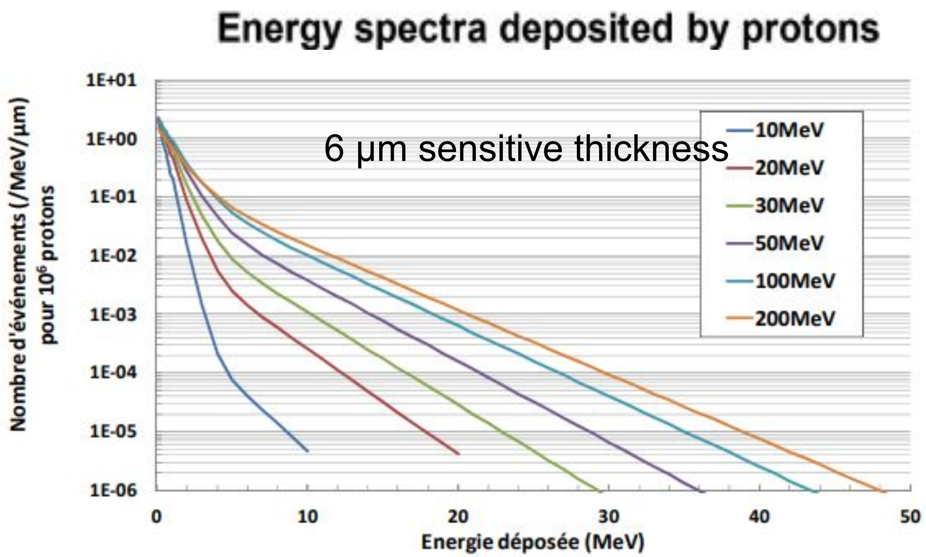
IRPP model:

Ed = LET x sensitive thickness



The heavy-ion cross-section (σ_{HI}) is expressed as a function of deposited energy by multiplying the LET by the charge collection depth.





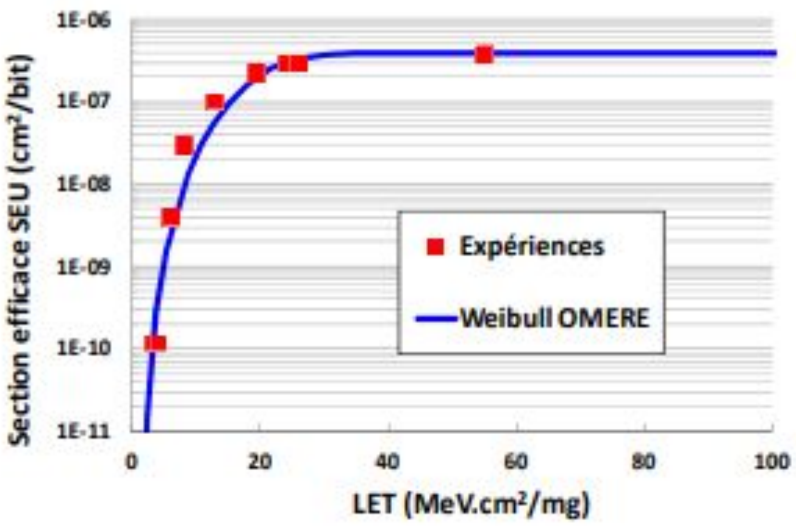
Proton cross section

Valid for protons > 30 MeV

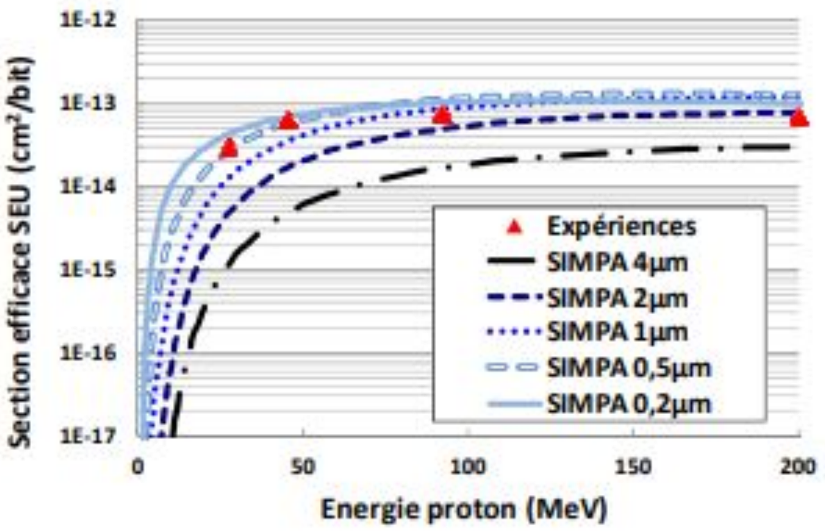
SIMPA parameters

- The only parameter which remains difficult to evaluate is the sensitive thickness.
- An overestimation of the thickness does not mean an overestimation of the predicted proton cross-section.

Exemple: HM62832 SRAM



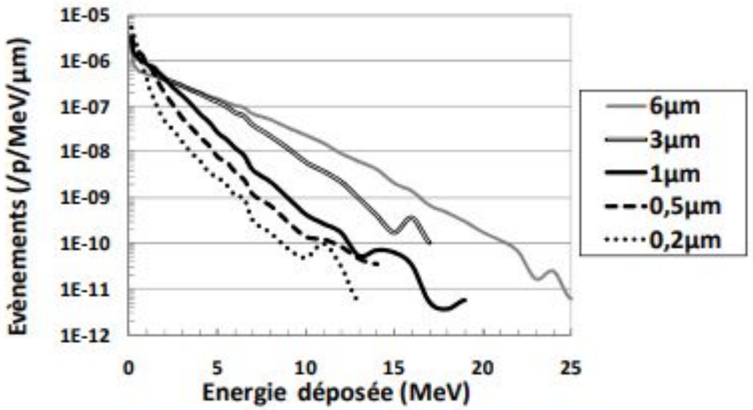
Heavy ion data



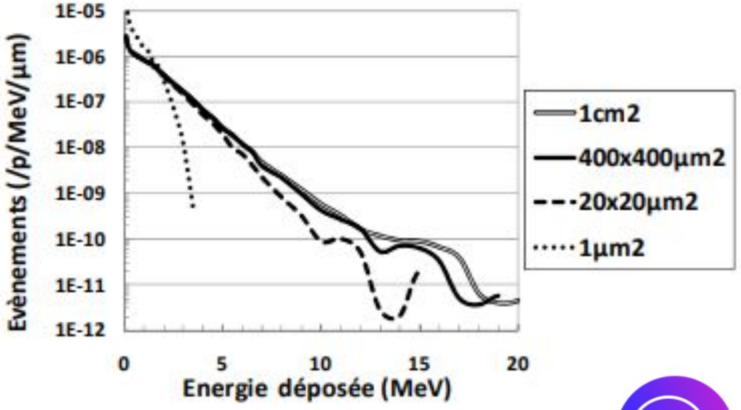
SIMPA predictions

SIMPA limitations

- 40% of SEU in 65nm SRAMs are induced by deposited energy < 3 MeV
- Not adapted for small sensitive volumes (nanoscale devices) due to 2 assumptions:
  - The deposited energy/µm does not depend on sensitive thickness
    - Experiments on diodes with ~6µm sensitive thickness
    - Simulation data with thickness from 2 to 20 µm
    - Sensitive thickness of 6 µm in OMERE
  - The deposited energy/µm does not depend on sensitive area



200 MeV protons in 400x400 µm^2 vs sensitive thickness



200 MeV protons for 1 µm sensitive thickness vs sensitive area

METIS overview

- **M**onte-Carlo **E**ngineering **T**ool for **I**on-induced **S**EE

- Proposed by Airbus in 2011

- SEU prediction in bulk SRAMs

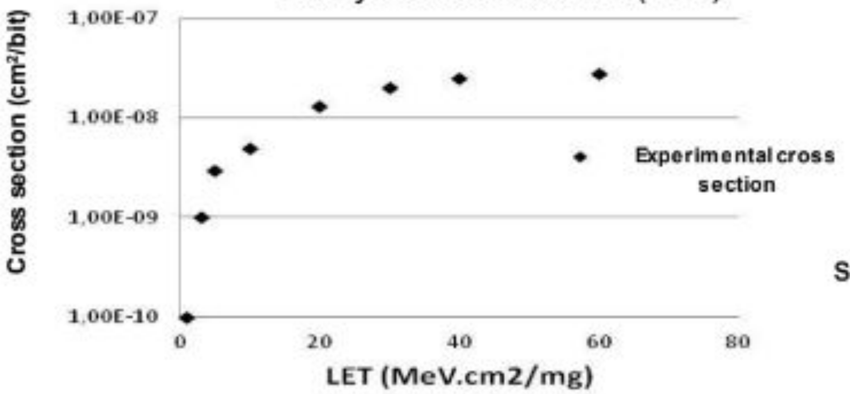
- Similar to SIMPA, critical energy and sensitive volumes are deduced from heavy ion data, sensitivity is completely characterized by a unity collection efficiency and composite RPP volumes with associated critical energies.

- But
  - Monte-Carlo selection of the nuclear reactions.
  - No free parameters: for each of the RPP sensitive volumes, the depth is half of the lateral length since the ambipolar diffusion mechanisms is predominant on deep-submicron technologies.

- Available in OMERE since 2018 (from version 5.2) (CNES funding): no more fully Monte-Carlo, same inputs will induce a single result.

METIS methodology

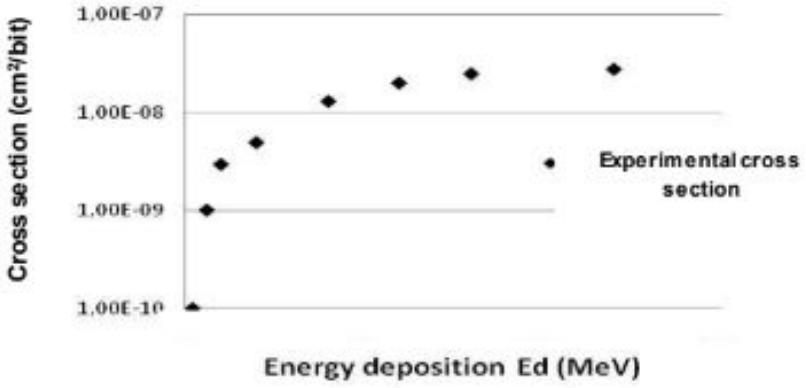
Heavy ion cross section (LET)



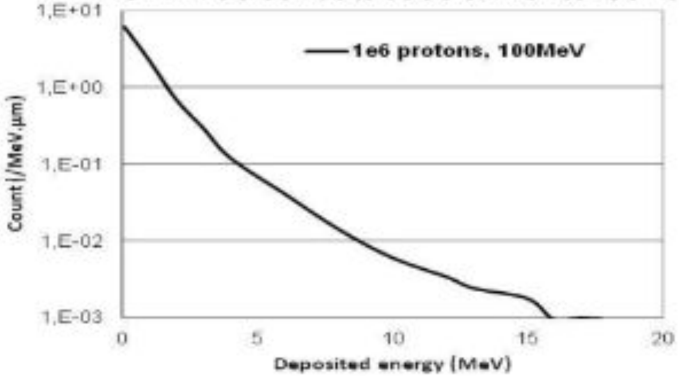
Ed = LET x <u>sensitive thickness</u>

sensitive thickness = half of the surface side (variable)

Heavy ion cross section (Ed)



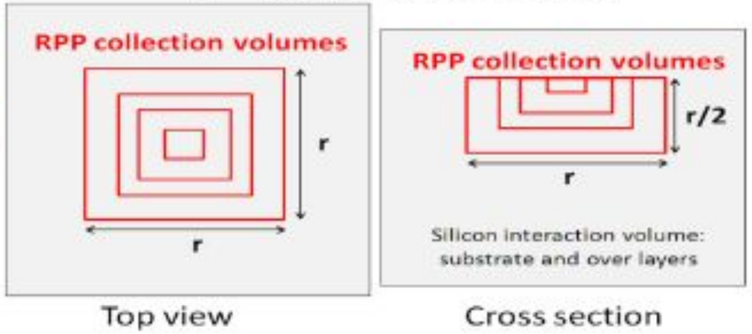
Energy spectra deposited by protons
SIMPA => experimental data & analytical formula
METIS => nuclear database & Monte-Carlo



<u>Proton cross section</u>

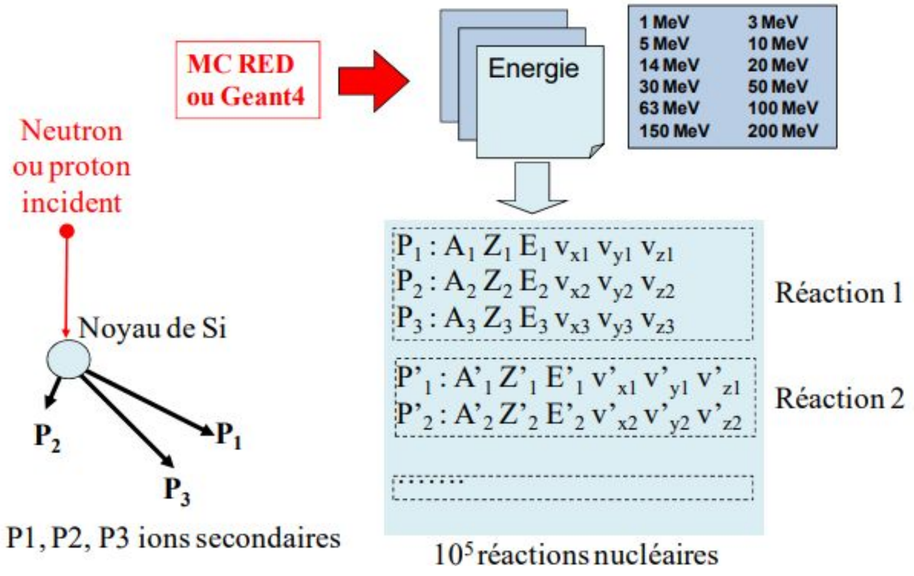
RPP model
(multiple sensitive volumes)

r^2 = heavy ion cross section



METIS nuclear database

- Monte-Carlo analysis of nuclear interactions induced by protons from precalculated nuclear databases
- Nuclear databases contain elastic scattering and non-elastic nuclear reactions
- Provide a detailed history of secondary ions from p/Si.
- MC-RED (IES) or GEANT4 nuclear physic codes
- Interaction volume 20 x 20 x 80 x µm^3 :
  trade-off between computing time and accuracy
- Easy to adapt other materials than Si
- Silicon simplification:
  - Little impact of SiO_2 on SEU prediction in bulk commercial technologies down to 90 nm (not valid for SOI technologies)
  - No impact of Tungsten on SEU prediction (low threshold LET)

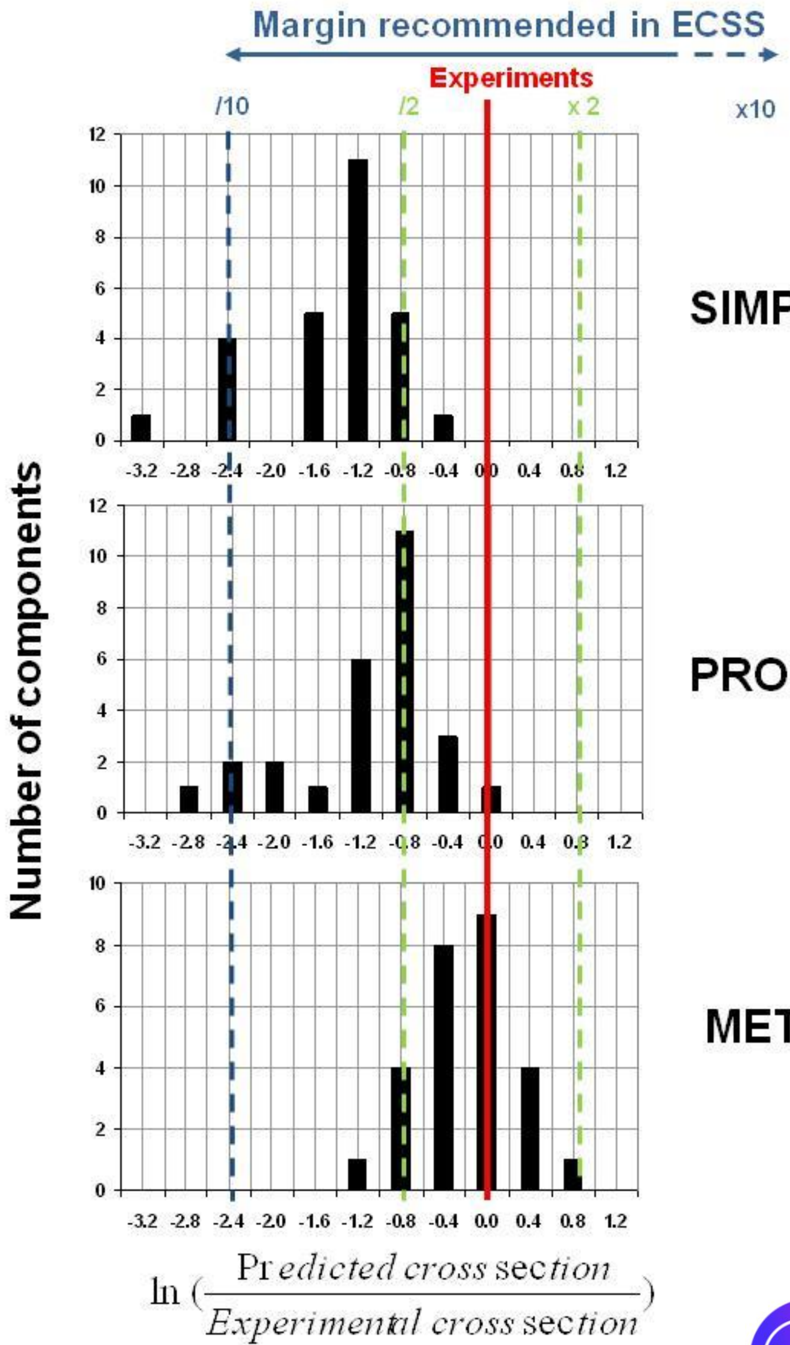


METIS methodology

- Initial validation on ~30 devices from 500 nm down to 45 nm CMOS (bulk & SOI) technologies
- From 2012 to 2017, validation on a large number of state of the art devices, down to 16 nm.
- Within a factor of 3 for the XS and SER (comparison with the one given by a Weibull function of the proton data)
- For SOI SRAMs METIS is less accurate, an RPP geometry with varying thickness is not appropriate for SOI-based devices (the diffusion mechanism will be not predominant) and nuclear reactions with Oxygen have to be considered.
- For FinFET SRAMs:
  - Different shape of the sensitive volume, the diffusion mechanism will not be predominant
  - Cell variability in the SEU response

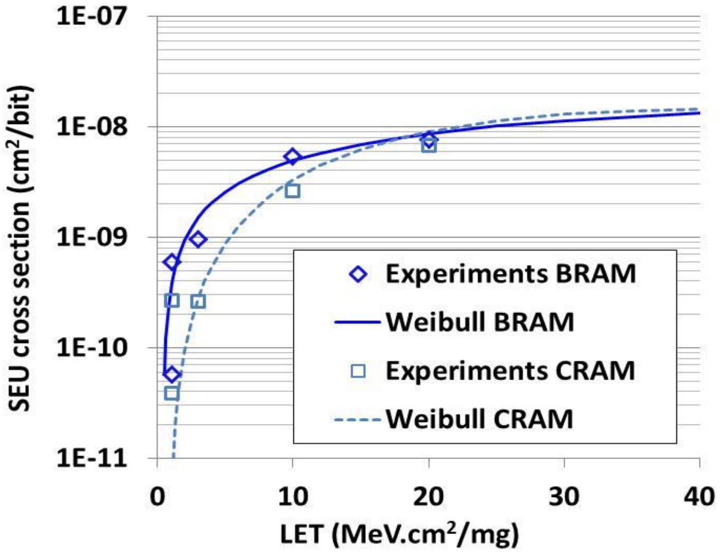
METIS validation

- Comparison with PROFIT & SIMPA
- ~ 30 devices : From 500 nm to 45 nm CMOS commercial (bulk & SOI) technologies
- 50 MeV proton XS
- Dispersion of the natural logarithm of the ratio of simulation to experiment
- METIS gives the most accurate predictions in 96% of tested cases



METIS validation

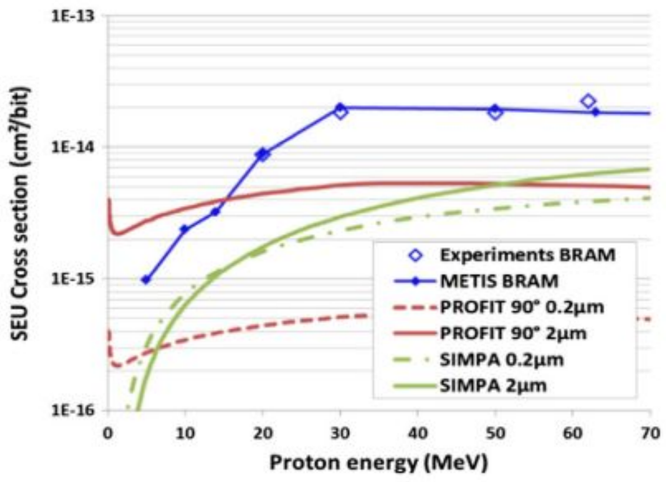
- 45 nm SRAM based FPGA (Spartan-6)



METIS

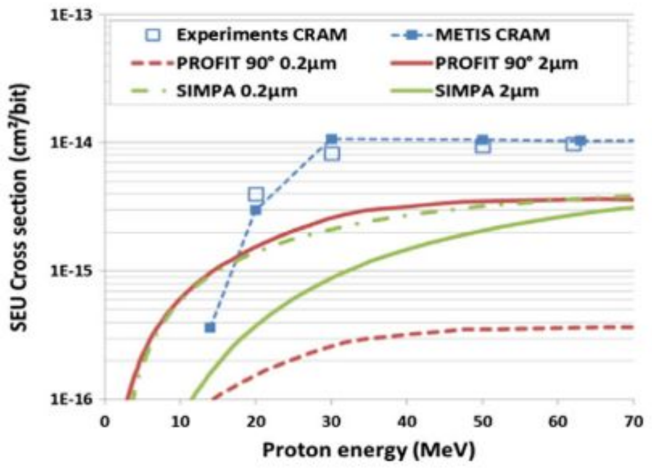
SIMPA

PROFIT



Block RAM

BRAM



Configuration memory

CRAM

METIS validation

- 20nm Xilinx UltraScale FPGA

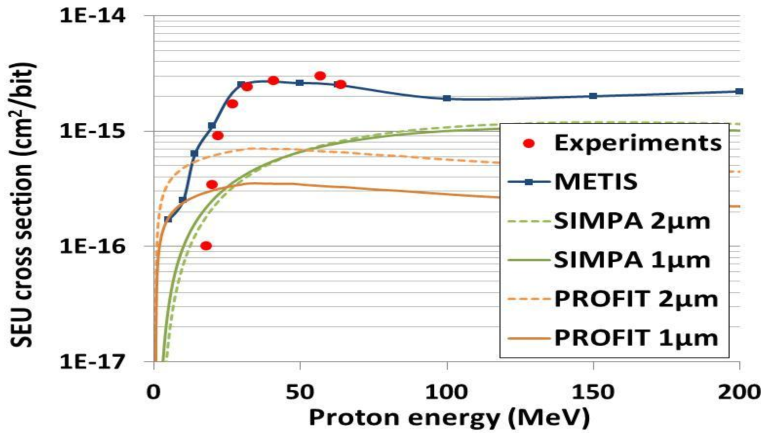
Heavy ion data - Weibull

Saturation cross section (cm^2/bit)	$2x10^{-9}$
Threshold LET (MeV-cm^2/mg)	0.8
Width (MeV-cm^2/mg)	12
S	1.5

METIS

SIMPA

PROFIT



Configuration memory

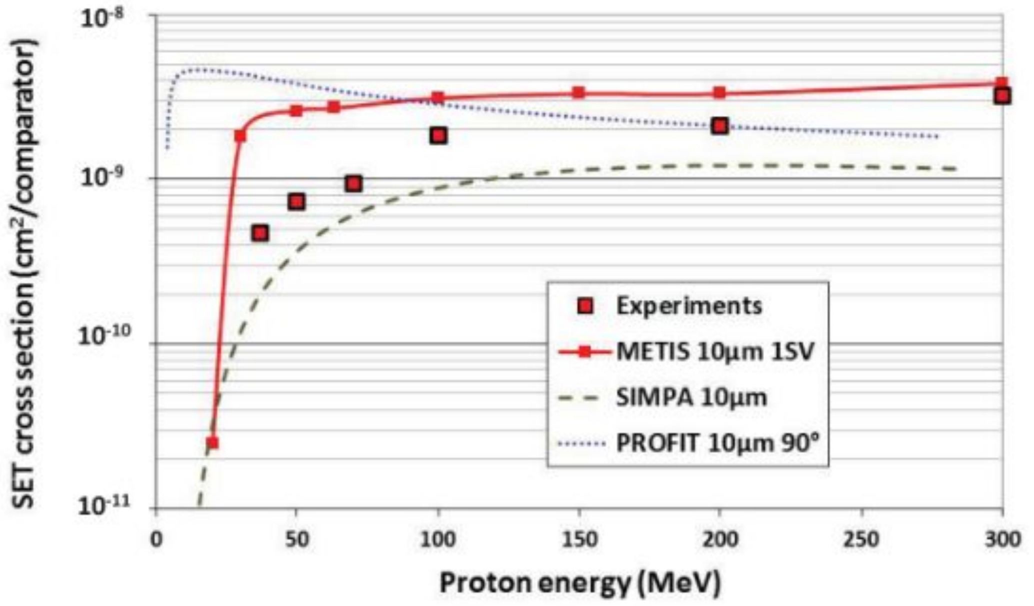
CRAM

"Single-Event Characterization of the 20 nm Xilinx Kintex UltraScale Field-Programmable Gate Array under Heavy Ion Irradiation," 2015.
"Neutron, 64 MeV proton, thermal neutron and alpha single-event upset characterization of Xilinx 20nm UltraScale Kintex FPGA," 2015.

Extended METIS

- METIS predictions using constant sensitive thickness (not possible in OMERE)
  in order to cover other SEEs such as SEL, SEU in DRAMS, analog SET in linear devices
  The diffusion mechanisms is no more predominant
  Large impact of the thickness

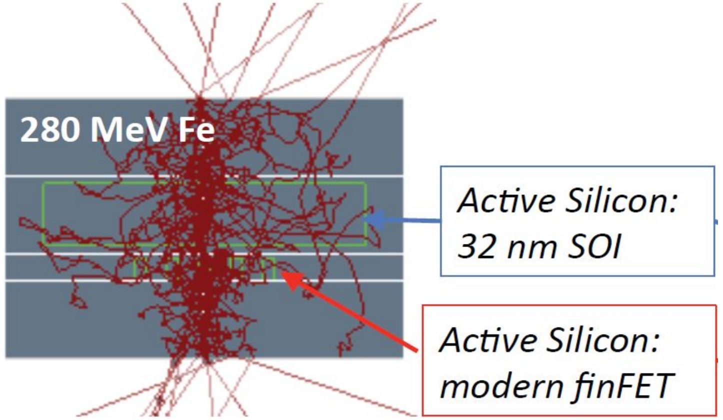
SET in LM139
Proton experiments compared with METIS, SIMPA and PROFIT results using a sensitive thickness of 10 µm.



- Multiple SEU (MCU) based on the definition of the cell size

METIS limitations and current status

- For feature size < 32nm bulk or 65nm SOI, particularly in FinFETs, variability in direct ionization (LET fluctuations, spatial energy deposition) is becoming a dominant process
- No further development / activities since 2018 when METIS was implemented the OMERE tool
- RADECS 2021 & IEEE TNS 2022, D. L. Hansen, "Proton cross-sections from heavy-ion data: a review of the models": *The METIS model had the best performance of the MC models.*



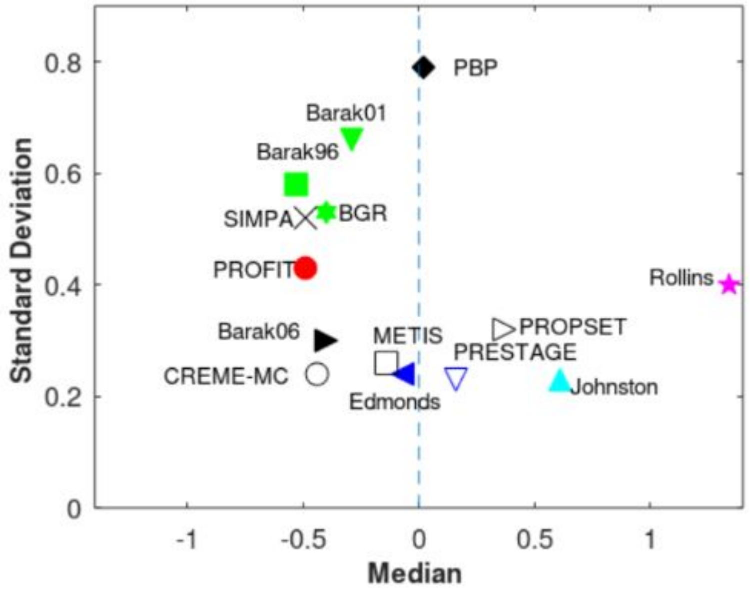


Fig. 4. Plot of median and standard deviation data from Table II. MC models are shown as hollow symbols. The origin represents perfect agreement.

Summary

	SIMPA	METIS in OMERE	METIS extended
	Semi-empirical	Monte-Carlo	
Year	1989-1995	2011	2014
Company	MATRA MARCONI SPACE	Airbus	
SEE	SEU with sensitive thicknesses > 2 µm	SEU in deep submicron non-hardened SRAM like memories	SET, SEL, SEU in SDRAMs
Inputs	σ_{HI}(LET) + sensitive thickness	σ_{HI}(LET) (sensitive thickness = 0.5 $\sigma_{HI}^{1/2}$)	σ_{HI}(LET) + sensitive thickness
Criteria	Critical energy		
Sensitive volumes	IRPP		
Nuclear data	Experimental energy deposition (diodes)	MC selection of nuclear reactions	
Time-efficiency	<1s	1 min	

Conclusion

- Underestimation of SIMPA predictions for SRAM < 1µm.
- METIS is a compromise between analytic approaches and Monte-Carlo based tools in order to get a fast and accurate engineering tool.
- Validated down to 20 nm bulk planar process (SEU in SRAMs).
- No validation below 20 nm and strong limitations
- Other models for proton cross section predictions based on heavy ion data
    - BGR (Burst Generation Rate)
    - PROFIT
    - Edmonds
    - Barak …

Publications

SIMPA

- T. Bion and J. Bourrieau, "*A model for proton-induced SEU*," IEEE Trans. Nucl. Sci., vol. 36, no. 6, pp. 2281–2286, Dec. 1989.
- B. Doucin, Y. Patin, J.P. Lochard, J. Beaucour, T. Carriere, D. Isabelle, J. Buisson, T. Corbiere, and T. Bion, "*Characterization of proton interactions in electronic components*," IEEE Trans. Nucl. Sci., vol. 41, no. 3, pp. 593–600, Jul. 1994.
- B. Doucin, T. Carriere, C. Poivey, P. Garnier, J. Beaucour, and Y. Patin, "*Model of single event upsets induced by space protons in electronic devices*," in Proc. 3rd Eur. Conf. Radiat. Effects Compon. Syst., 1995.

METIS

- C. Weulersse, F. Wrobel, F. Miller, T. Carrière, R. Gaillard, J-R Vaillé, and N. Buard, "*A Monte-Carlo engineer tool for the prediction of SEU proton cross section from heavy ion data*," in Proc. 12th Eur. Conf. Radiat. Effects Compon. Syst., Biarritz, France, Sep. 2011, pp. 376–383.
- C. Weulersse, F. Miller, T. Carrière, and R. Mangeret, "*Prediction of proton cross sections for SEU in SRAMs and SDRAMs using the METIS engineer tool*," in Microelectronics Reliability. 55. 10.1016/j.microrel.2015.06.117.
- C. Weulersse, S. Morand, F. Miller, T. Carrière, and R. Mangeret, "*Simulation of proton induced SET in linear devices and assessment of sensitive thicknesses*," 2015 15th European Conference on Radiation and Its Effects on Components and Systems (RADECS), Moscow, 2015, pp. 1-4. doi: 10.1109/RADECS.2015.7365668.
- C. Weulersse, S. Morand, F. Miller, T. Carrière, and R. Mangeret, "*Predictions of proton cross-section and sensitive thickness for analog Single-Event Transients*," IEEE Transactions on Nuclear Science. 63. 10.1109/TNS.2016.2541692.

Overview of models

- D. L. Hansen, D. Czajkowski, and B. Vermeire, "*Proton cross-sections from heavy-ion data: a review of the models,*" IEEE Trans. Nucl. Sci., vol. 69, 2022.