Estimation of proton induced single event rate in very deep submicron technologies

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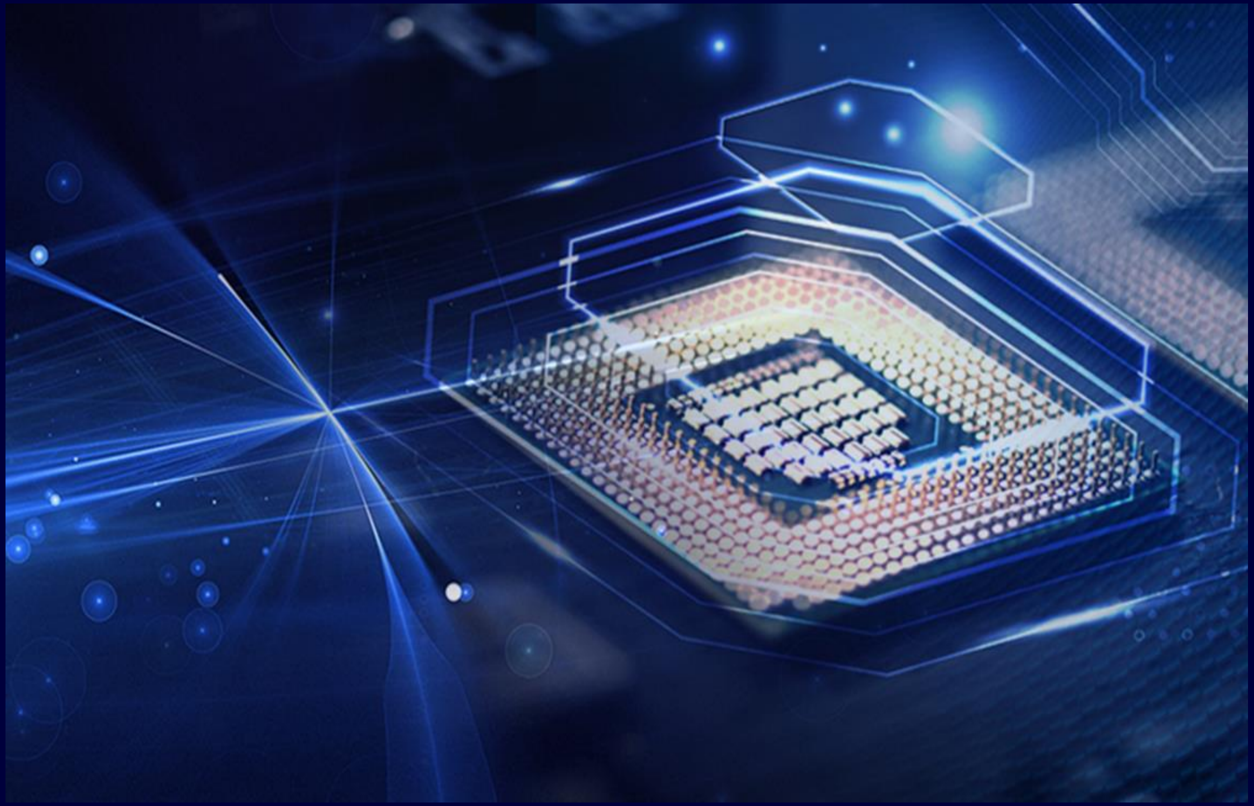
Background

- Deep submicron technologies (< 65 nm feature size) are more and more used in space applications
- FPGA, Flash memories, DDR3, ...
- Low Energy Protons (LEP) can induce **SEUs through direct ionization** in these highly scaled technologies as demonstrated in [1-3] among others
- => Of great importance to consider the **contribution of LEPs** (Ep+ < 3 MeV) to the on-orbit soft error rate (**SER**)
- To date, there is no accepted standard method to characterize proton SEE sensitivity by direct ionization, and then estimate the SEE rate on-orbit



[1] N. A. Dodds *et al.*, "Hardness assurance for proton direct ionization induced SEEs using a high-energy proton beam," *IEEE Trans. Nucl. Sci.*, vol. 61, no. 6, pp. 2904–2914, Dec. 2014.
[2] N. A. Dodds *et al.*, "The contribution of low-energy protons to the total on-orbit SEU rate," *IEEE Trans. Nucl. Sci.*, vol. 62, no. 6, pp. 2440–2451, Dec. 2015.
[3] J. A. Pellish *et al.*, "Criticality of low-energy protons in single-event effects testing of highly-scaled technologies," *IEEE Trans. Nucl. Sci.*, vol. 61, no. 6, pp. 2896–2903, Dec. 2014.

Objectives

- Bound accurately the on-orbit SEE rate of deep submicron technology electronic components, 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

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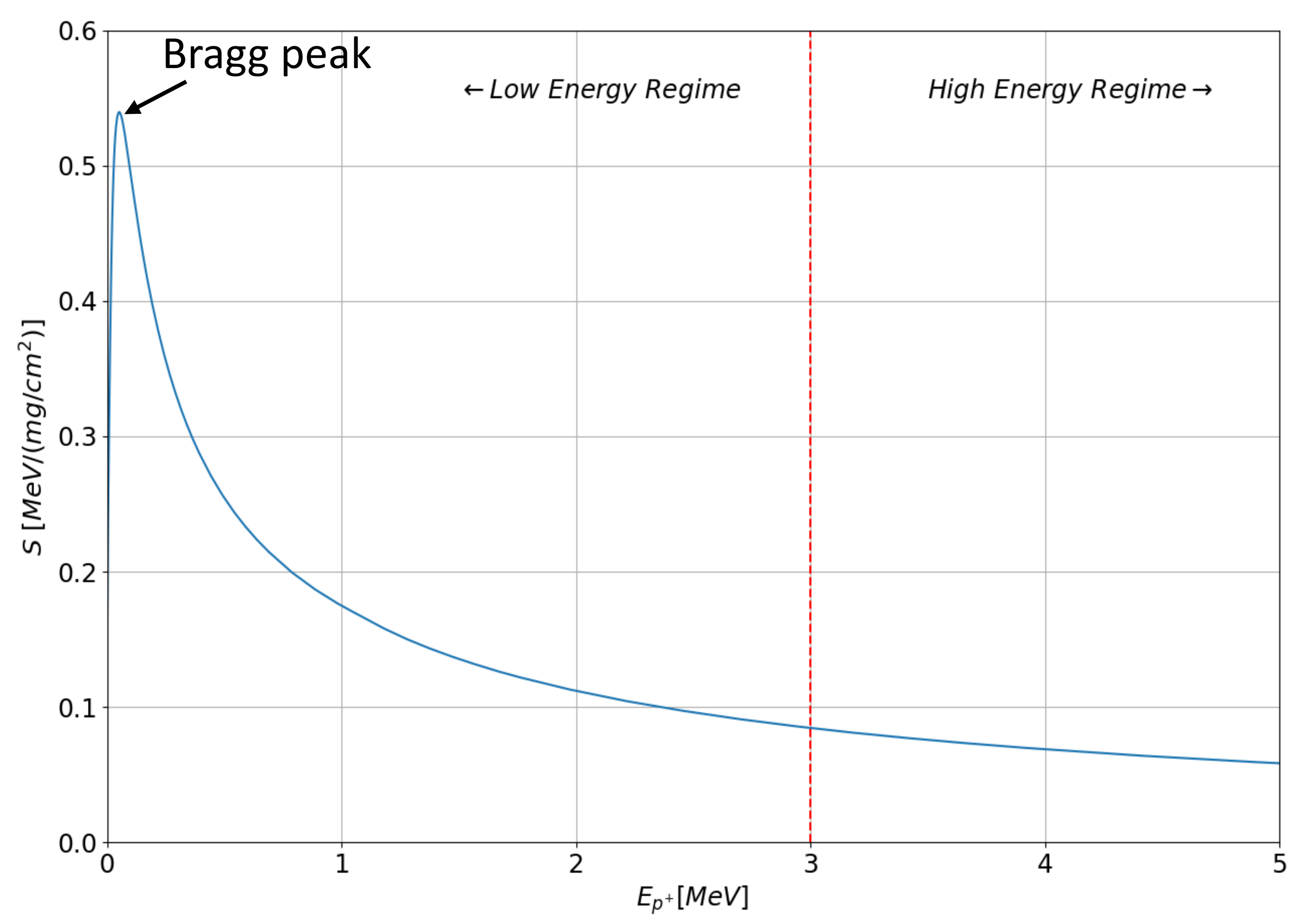
What is done in this work?

- Three submicron devices have been tested. Bulk and SOI technologies
- A sensitive volume method (SVM) based on RPP approach is proposed
- The SVM method is applied on collected data to extract the SV information (RPP geometry + critical charge)
- SER estimates using the SVM method

Low Energy Protons

- **LEPs** : Ep+ < 3 MeV
- Bragg peak: Ep+ = 55 keV, LET = 0.538 $MeV.cm^2.mg^{-1}$
- PDI induced SEEs usually occur when the LET of the proton is close to the Bragg-peak and the critical charge of the DUT is relatively low, e.g. in highly scaled electronics



Experiment : Tested devices

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

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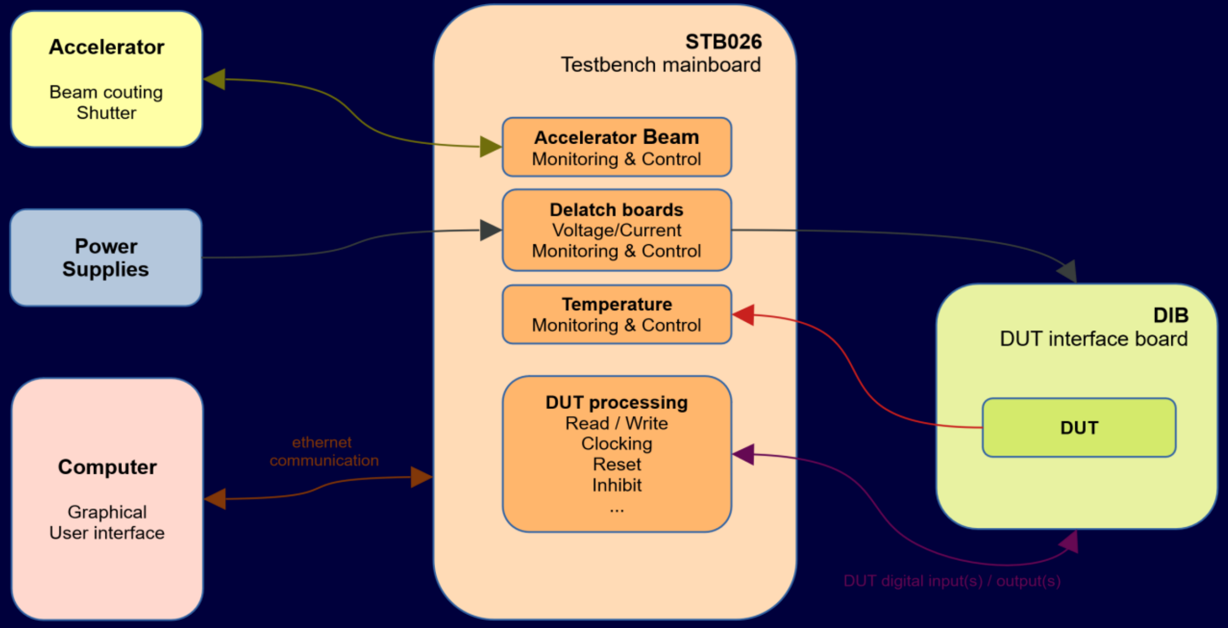
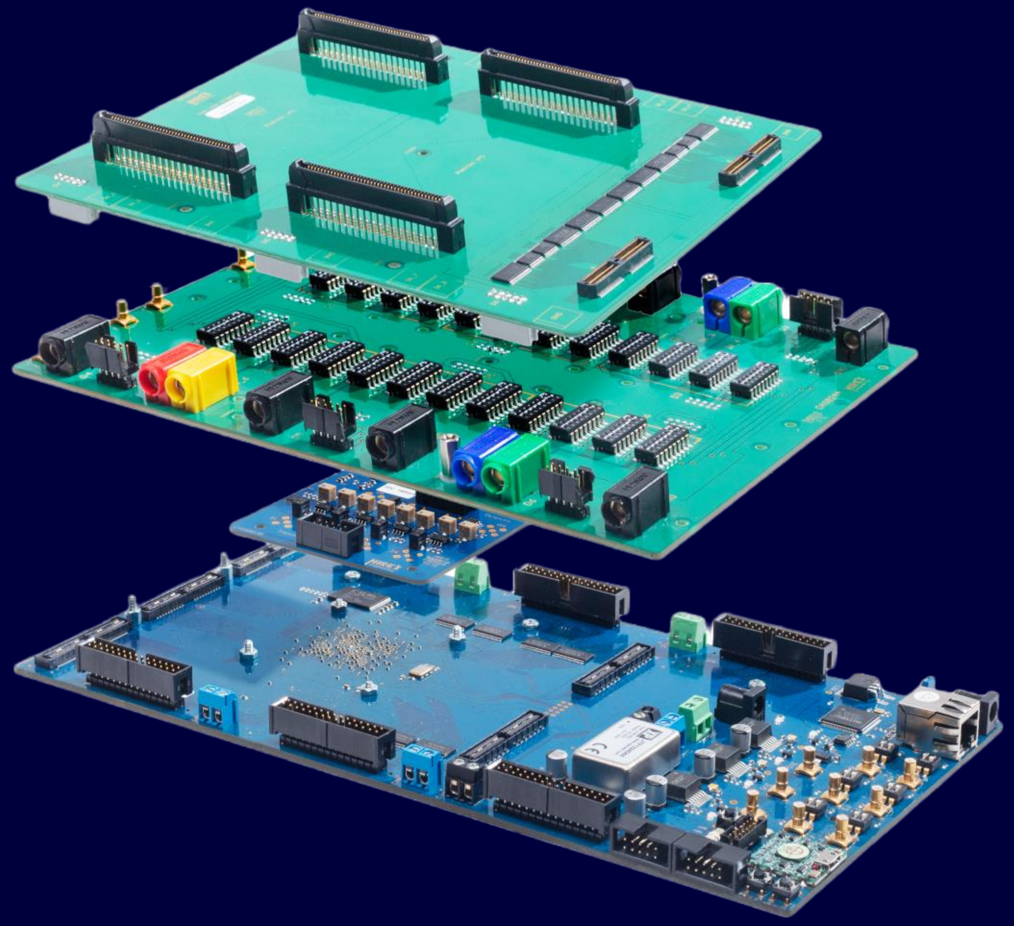
Experimental Setup





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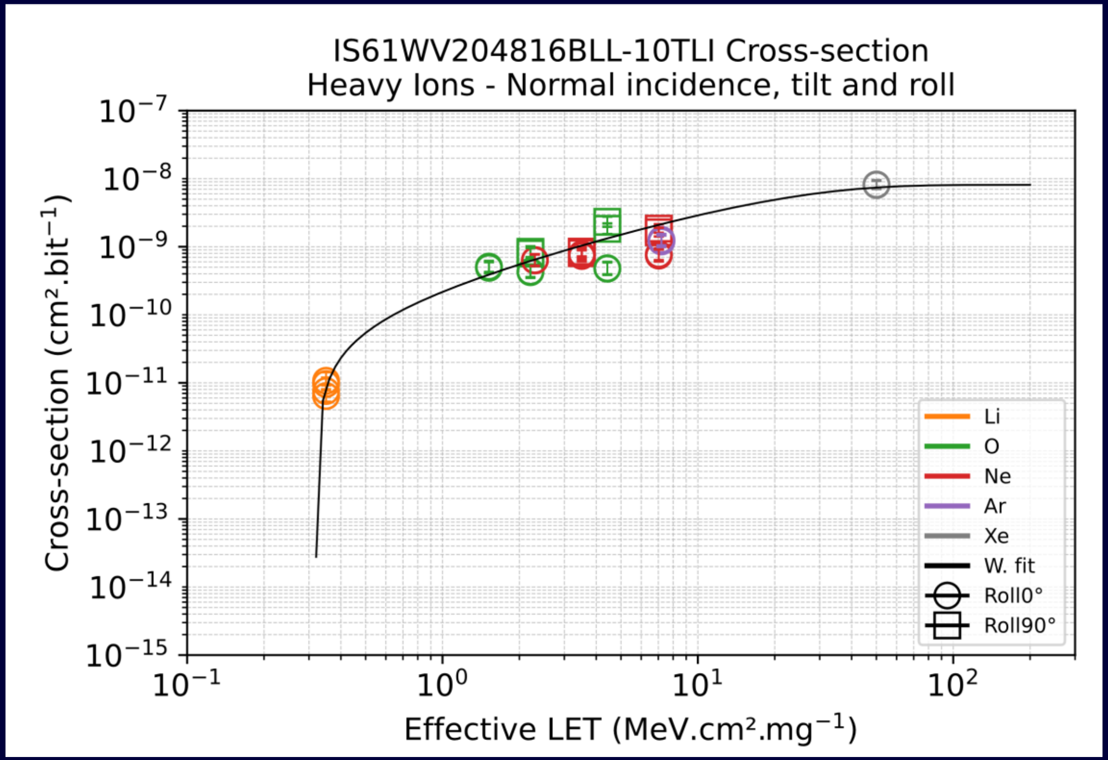
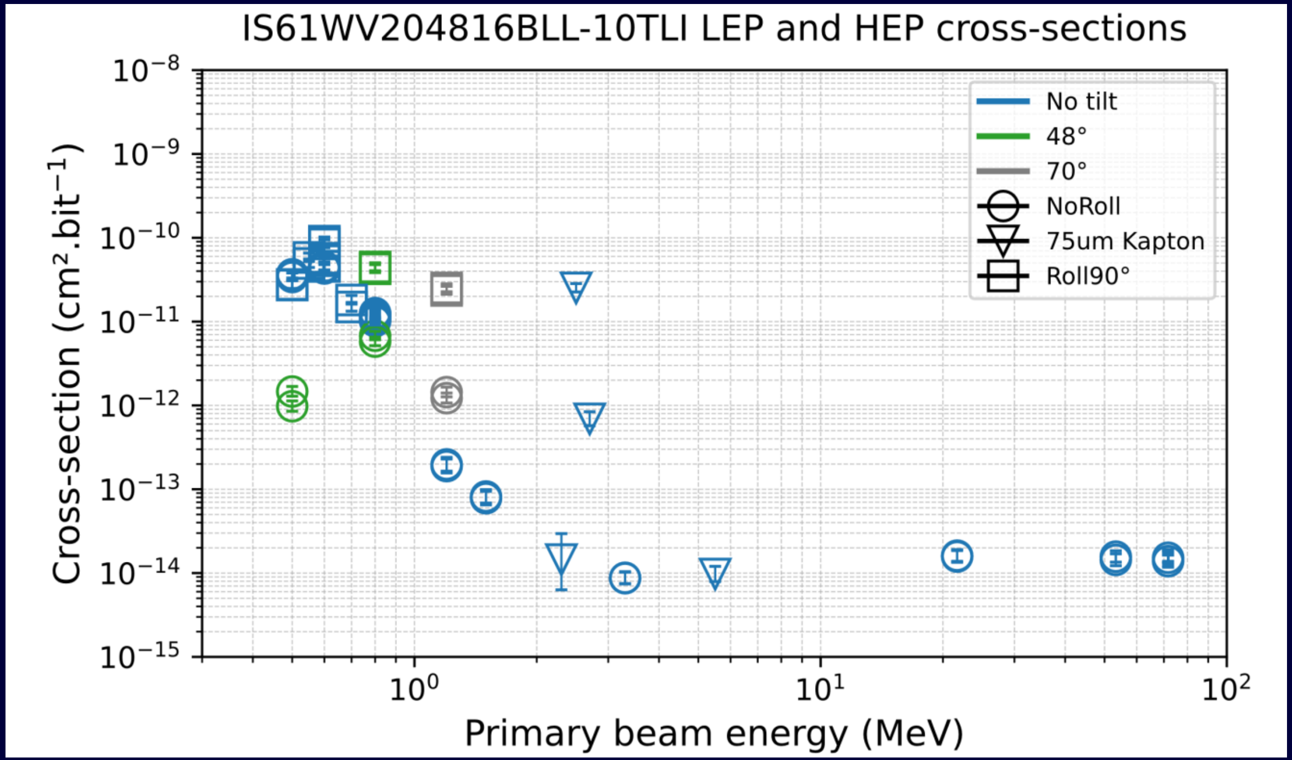
Glimpse of Test Results

B. Tanios et al., "Heavy ion and Proton induced SEU in very deep sub-micron technologies", *2022 21th European Conference on Radiation and Its Effects on Components and Systems (RADECS).*, Venice, Italia, 2022.

- Devices sensitive to very low LETs (< 0.35 MeV.cm².mg^{-1})
- Lattice and ISSI exhibit PDI peak, but not Xilinx

- HEP sat. cross-section σHEP reached at Ep+ ≥ 3 MeV
- Tilt and Roll effects depending on technology (Bulk vs SOI)





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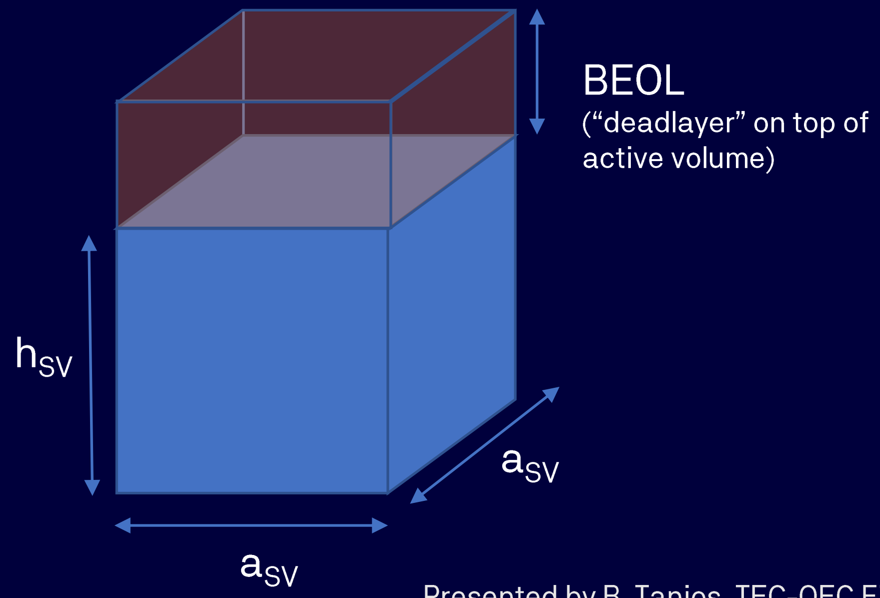
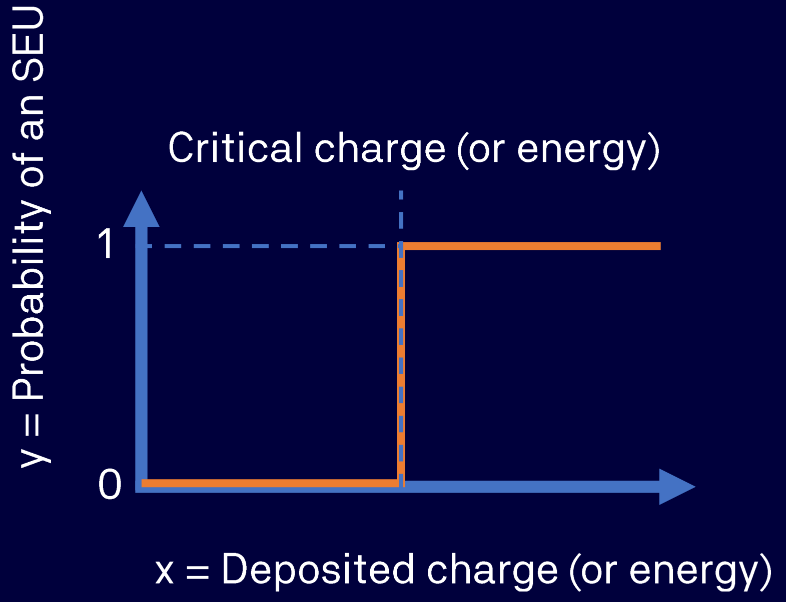
"Anatomy" of an SEU

- One of the main methods to investigate SER is RPP method
- Sensitive Volume (SV) : Simple Rectangular Parallelepiped (RPP) "box" is used as a surrogate of DUT
- This work uses only a *single SV*
- The SV **emulates** the device' SEU response in radiation transport simulations



Charge (or energy deposition) vs. SEU probability

- If deposited charge exceeds the critical value → SEU
- Critical charge is SV (i.e. device) dependent



Energy deposition in the SV

- Energy deposition is (always) a ***stochastic process***
- ***Energy deposition is more accurately described by a distribution rather than a single number***
- LET gives (only) the ***mean*** (for this *electronic stopping force* values)
- ***Standard deviation*** is determined by ***straggling***
- Stochastic nature becomes ***more prevalent for smaller targets*** (and also with increasing projectile velocities)

- **During this work, (simple) semi-empirical models for electronic stopping force and straggling have been established**
- Primarily demonstrated for ***protons in silicon***, but models are applicable also for other (*elemental*) projectile-target combinations (with some limitations)

- For more details on these models: S. Lüdeke *et al.*, "*Proton Direct Ionization in Sub-Micron Technologies: Numerical Method for RPP Parameter Extraction*", IEEE TNS, vol. 69, (2022), available at: https://ieeexplore.ieee.org/document/9696332

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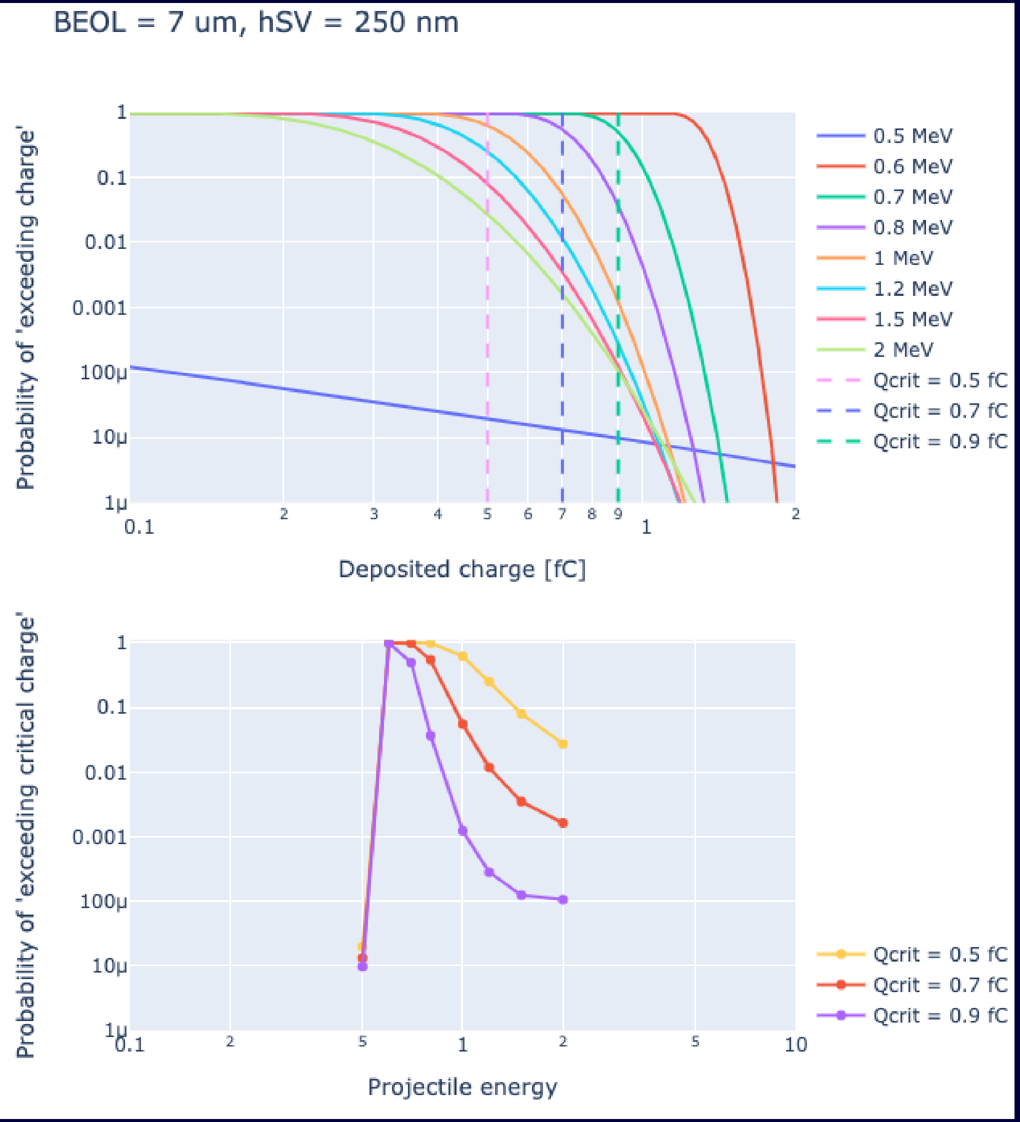
From stopping/straggling models to SEU cross-sections

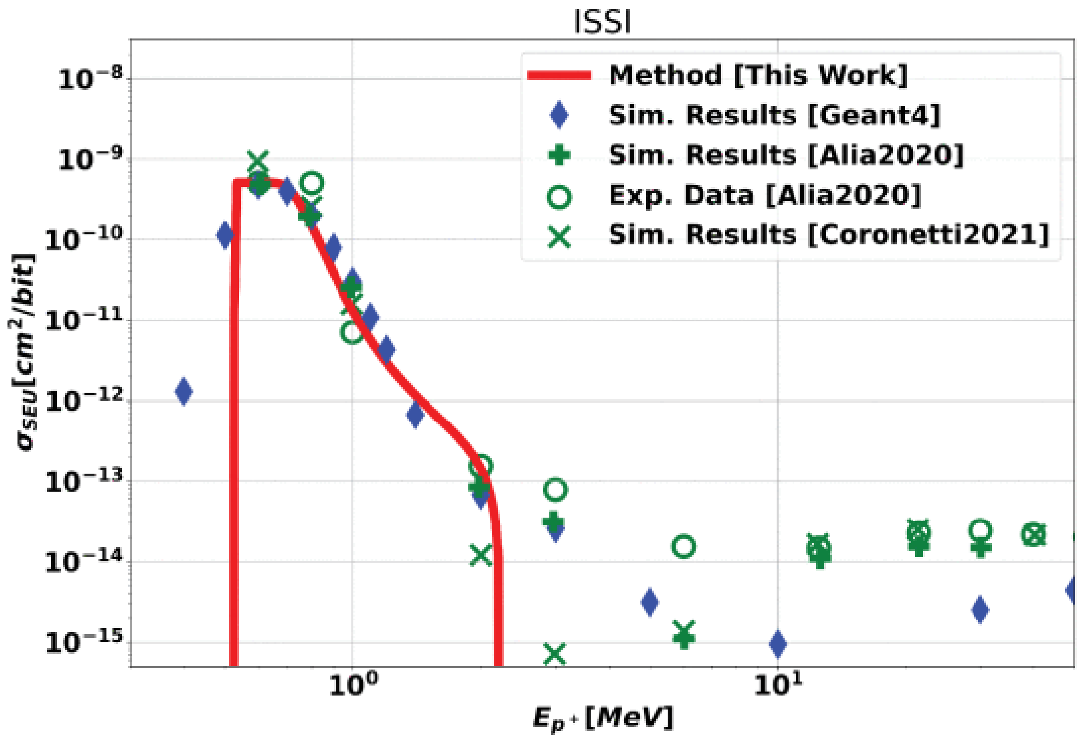
- For a given thickness and projectile energy, there is the energy deposition distribution, which can be presented as a ”***tail distribution***”. This gives the probability for events higher than certain value of x.
- By ”*probing*” the distributions with fixed values of critical charge (or energy), one can find the “PDI peak”. *(c.f. the step function presented before)*
  - *This will give the probability for charge (or energy) deposition events above critical charge (or energy)*
  - *By normalizing this with the cross-sectional area of the SV (a_{SV}^2), one can get the energy dependent SEU xsection curve for LEP*
- *Note! BEOL will shift the peak horizontally. If BEOL = 0, the PDI peak is always around 50 keV (i.e. the Bragg peak energy for protons*



RPP parameters and critical charge from (quasi)monoenergetic (*QME**) proton data

** Quasimonoenergetic because the experimental beams always have finite width*

- BEOL thickness, SV-geometry (*thickness*, h_{SV}, *and cross-sectional area*, a_{SV}^2) and the critical charge (Q_{crit}) can be extracted from QME LEP SEU data by fitting
- **The fitting process is relatively fast (*from 10's sec to a few min, depending on the CPU*)**
  - Still some room for code optimization to speed up the procedure
- Good agreement with (more computationally demanding) Geant4-simulation approaches
- Requires sufficient data around the "*PDI peak*"
- Do not handle high energy part in the SEU data
  - The model only is based only on physics related to primary ionization
  - Proton SEUs at higher energies (>10MeV) are related to nuclear reactions



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Parameter extraction from DHEP data

- Degraded High Energy Proton (DHEP) beams can be used for LEP studies
- Moreover, the abovementioned model(s) can be used to extract the RPP geometry and Qcrit information from the SEU data
- This is not as straightforward and easy as for monoenergetic LEP data
- *Calibration of the beam at DUT level for each degrader setting is very crucial, i.e. the measurement conditions need to be very well-known*
- *More data points the better accuracy (as usual for fitting)*

- This approach and its limitation has been reported in detail by S. Lüdeke *et al.*, "*Proton Direct Ionization in Sub-Micron Technologies: Test Methodologies and Modeling*", IEEE TNS, vol. 70, (2023), available at https://ieeexplore.ieee.org/document/10064328

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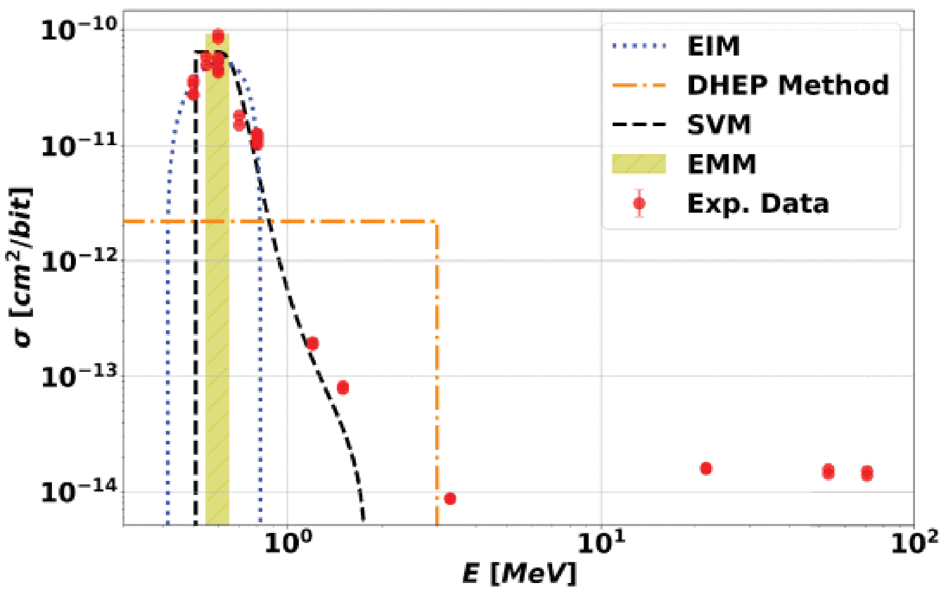
SER estimates from QME LEP data

- The aforementioned *Sensitive Volume Model* (SVM) provide a "*quasiphysical*" proxy for the SV (RPP size and critical charge) that can be used for more elaborate SER analyses (raytracing or Monte Carlo sim.) with omnidirectional particle spectra
- In the simplest case the fitted curve in the SEU xsection vs. proton energy can be used for SER estimates
  - *Note! This assumes isotropic SEU response*
- SVM provides comparable SER estimates with "conventional" approaches (i.e. Energy Integration (EIM) and Energy Multiplication (EMM) Models)
- EIM and EMM approaches are very simple but they are merely an "*ad hoc*" curve fitting, whereas the SVM has more physical basis

ISSI Device



Shielding [mm]	τ_{EMM}	τ_{EIM} [Errors/day/Mbit]	τ_{SVM}
		LEO	
12.70	$1.94 \cdot 10^{0}$	$3.09 \cdot 10^{0}$	$2.88 \cdot 10^{0}$
6.35	$6.94 \cdot 10^{0}$	$1.11 \cdot 10^{1}$	$1.03 \cdot 10^{1}$
2.54	$5.01 \cdot 10^{1}$	$8.00 \cdot 10^{1}$	$7.45 \cdot 10^{1}$
		GEO	
12.70	$1.49 \cdot 10^{-6}$	$2.38 \cdot 10^{-6}$	$2.22 \cdot 10^{-6}$
6.35	$1.20 \cdot 10^{-6}$	$1.91 \cdot 10^{-6}$	$1.78 \cdot 10^{-6}$
2.54	$1.04 \cdot 10^{-6}$	$1.65 \cdot 10^{-6}$	$1.54 \cdot 10^{-6}$
Ratio	0.67	1.07	1.00

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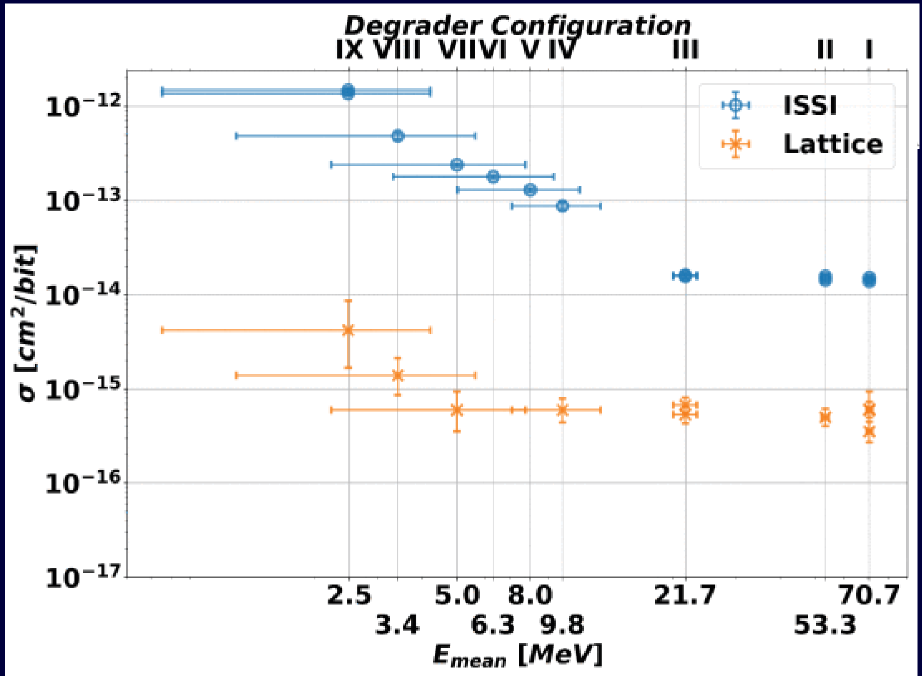
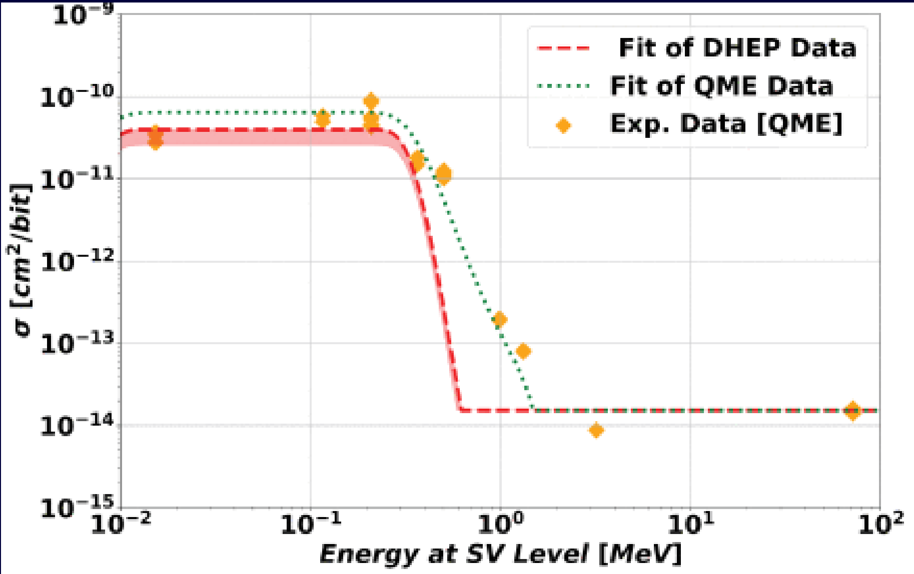
SER estimates from DHEP data

- As mentioned, the SV information (size and Qcrit) can be extracted from sufficient amount of (**well-calibrated**) DHEP SEU data

- As in case of QME data, the extracted information provides the proxy for the DUT's SV, which can be used for more elaborate SER analyses

- For a simple approach one can use the "*DHEP method*" proposed by Dodds et al. [1]
  - This requires less calibration for the beam (*spectrum needed only for the degraded setup with maximum observed xsection*)
  - This approach does NOT provide any further information on the SV





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Conclusion

1. Test using a QME LEP beam
   - Option 1:
     - Extraction of SV information (RPP size and critical charge) using the *Sensitive Volume Model* (SVM) proposed in this work.
     - The SV characteristics can then be used for more elaborate SER analyses (raytracing or Monte Carlo sim.)
   - Option 2 : SER estimates using EIM and EMM conventional approaches but they are merely an "*ad hoc*" curve fitting
2. Test using a DHEP beam
   - Option 1: Use the SVM method to extract the SV information (size and Qcrit) and therefore SER estimates. However, a sufficient amount of well-calibrated DHEP SEU data is needed
   - Option 2: Use the simpler approach "DHEP method" proposed by Dodds et al.. This requires less calibration for the beam, BUT does NOT provide any further information on the SV

Publications

- S. Lüdeke *et al.*, "*Proton Direct Ionization in Sub-Micron Technologies: Numerical Method for RPP Parameter Extraction*", IEEE TNS, vol. 69, (2022), available at: https://ieeexplore.ieee.org/document/9696332
- S. Lüdeke *et al.*, "*Proton Direct Ionization in Sub-Micron Technologies: Test Methodologies and Modeling*", IEEE TNS, vol. 70, (2023), available at https://ieeexplore.ieee.org/document/10064328
- B. Tanios et al., " *Heavy ion and Proton induced SEU in very deep sub-micron technologies*", RADECS2022, Venice, Italia, 2022 (*Won the Best DataWorkshop Award)*

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The Team

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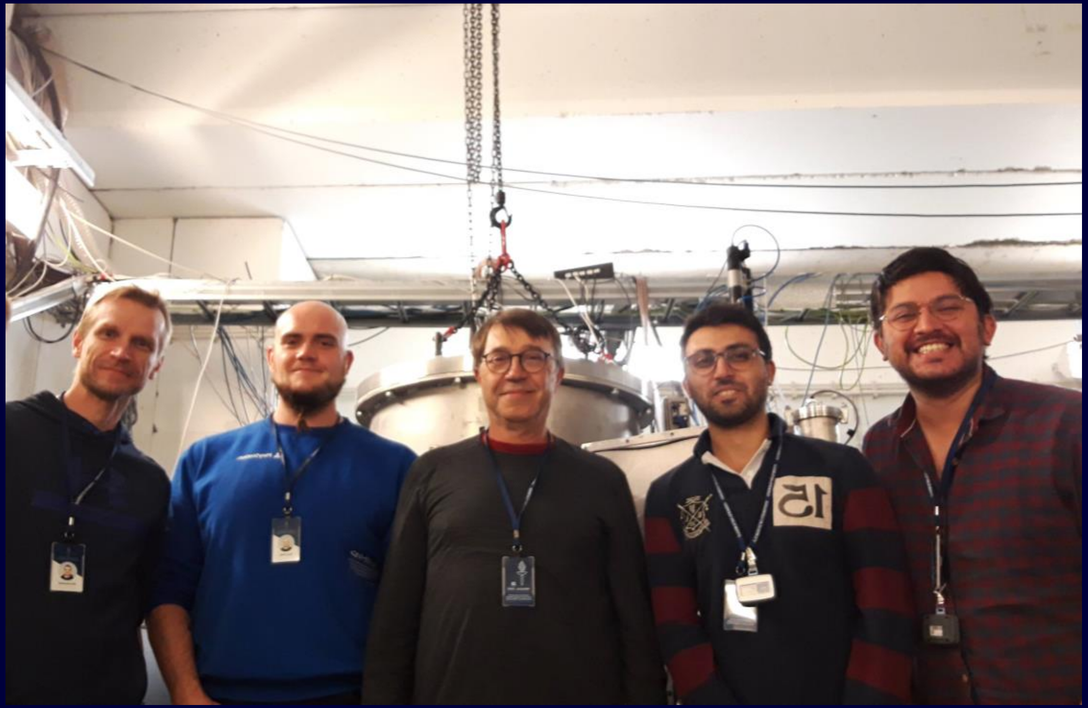

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Lattice device