Estimation of Proton induced Single-Event rate in very-deep submicron Technologies

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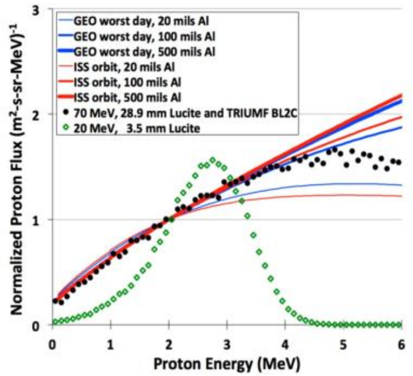
Project Overview

- Main objectives:
  - Definition of a SEE test procedure for Low Energy Protons
    - Meaningful
    - Reproductible
  - Definition of a method to estimate in-flight SEE-rate induced by LEP
    - Accurate
    - Reliable
- Constraints:
  - 2 years project
  - 4 major tasks:

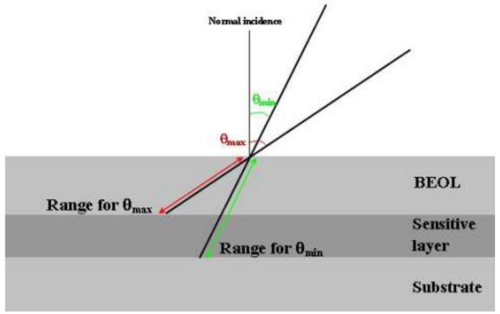
Literature Survey and Simulation → Definition of LEP Test and Error Rate Estimation Method → Experimental Work → Data Analysis and Reporting

State of the Art Review

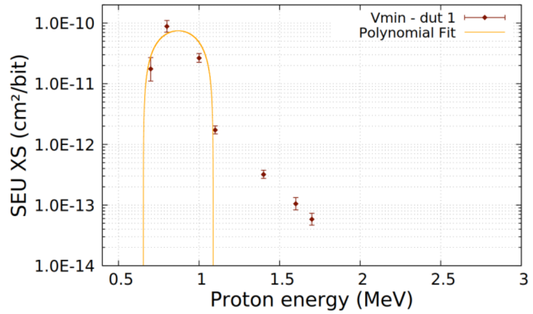
- [Dodds] Proposed to use degraded proton beam to reproduce orbital low energy proton spectrum, behind a shielding
  - Mainly focused on SOI devices
- [Guillermin] Proposed to sweep low-energy proton angle of incidence in order to define a sensitive layer to PDI
  - Some arbitrary hypothesis
- [IROC] Proposed to fit LEP test result to 2nd order polynomial and perform convolutional product with orbital flux
  - Angle of incidence is not considered



Dodds



Guillermin



IROC

[Dodds] N. A. Dodds "The Contribution of Low-Energy Protons to the Total On-Orbit SEU Rate," *IEEE TNS* 2015.
[Guillermin] J. Guillermin, "Worst-Case Proton Contribution to the Direct Ionization SEU Rate," in *2017 RADECS*
[IROC] Error Rate Estimation in JUICE Mission Environment", ESA Study Report, IROC, 2018

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Proposed Approach

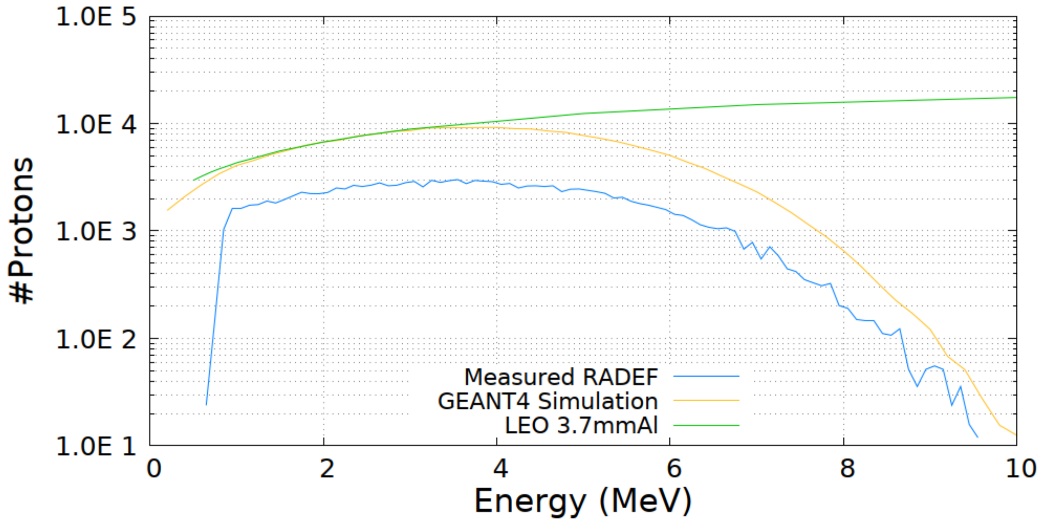
- [Dodds] and [IROC] method provided similar results on CYPRESS 65nm SRAMs

Environment	Shielding	[Dodds] #SEUs/bit-day	[IROC] #SEUs/bit-day	[Dodds]/ [IROC] Ratio
GEO, CREME96 Worst day	100 mil Al	7.6e-5	1.05e-4	0.72
	500 mil Al	2.8e-6	4.66e-6	0.6

- Proposed Approach:
  - Implements [Dodds] and [IROC] methodologies
  - Proposes some improvements for each of them
  - Compares their results on a set of representative components

Degraded Beam Methodology

- RADEF 55 MeV proton beam was degraded
  - 12 mm of POM plastic
  - Aluminum sheet of different thickness
- Orbital LEP spectra behind a shielding is reproduced

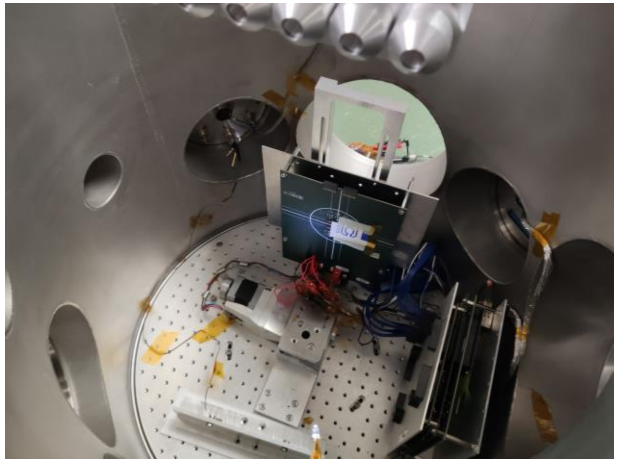


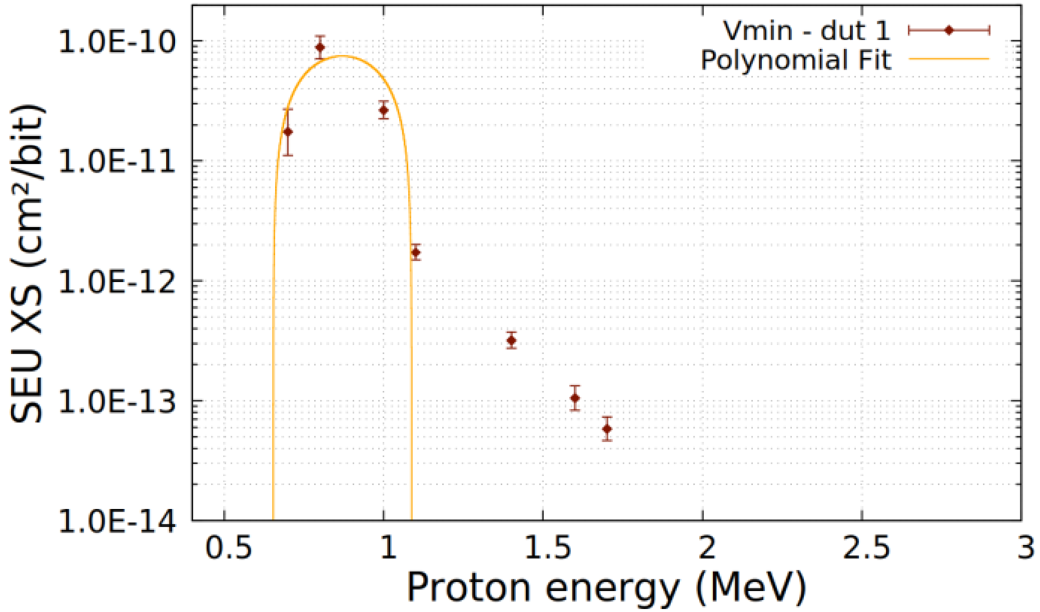
- Simple Acceleration factor can be considered

Mono-Energetic Beam Methodology

- Device sensitivity to LEP characterized versus proton energy with mono-energetic beam
  - All DUT tested at ONERA MIRAGE
  - ISSI cross-tested at RADEF
- Cross-Section Peak fitted to 2nd Order Polynomial
- Orbital error rate obtained with convolutional product with the flux

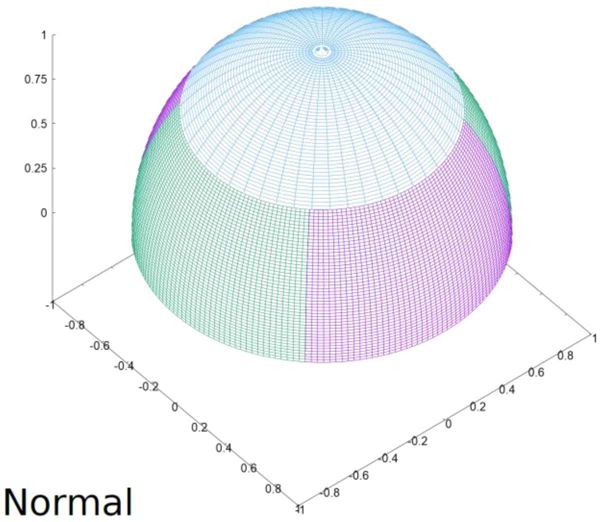
$$SEUrate_{PDI} = \int_E XS_{PDI}(E) \times \Phi(E) dE$$

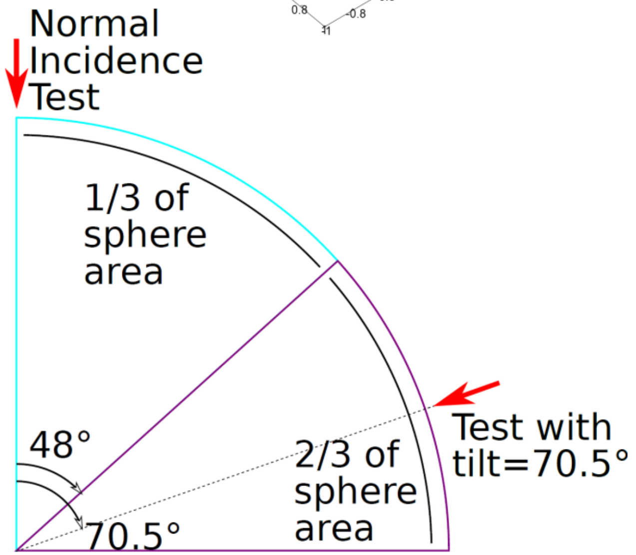




Impact of the Angle of Incidence

- For both methodologies, the impact of proton angle of incidence is considered
- Semi-sphere is slitted in 3 region of equivalent solid angles
  - Possible because SRAM array layout is symmetrical in X and Y directions
- If different angles are used, dedicated weighting coefficients can be calculated





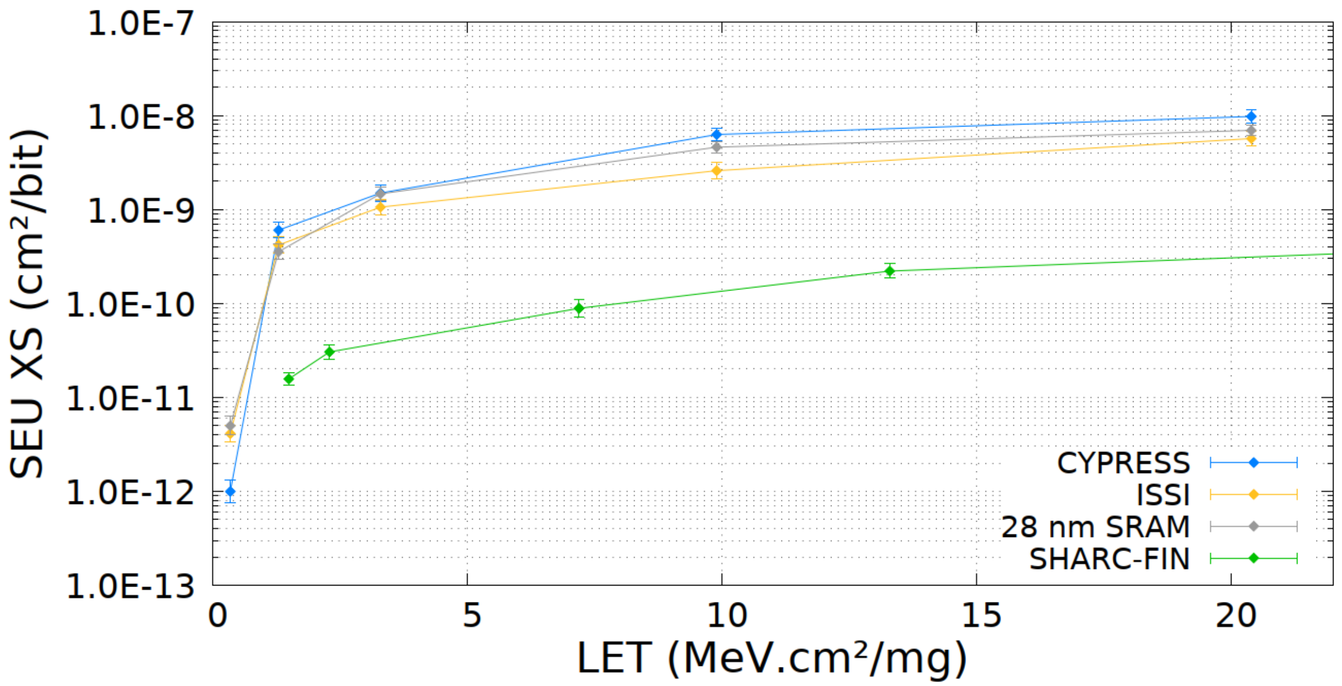
Selection of Representative Components

- Set of 4 bulk SRAM devices from 65 nm down to 16 nm FinFET

Manufacturer	Reference	Capacity	Node	HI data available	HEP data available	Comment
CYPRESS	CY7C2562XV18	72 Mb	65nm	✓	✓	
ISSI	IS61WV204816BLL	32 Mb	40nm			
IROC partner	28 nm SRAM	64 Mb	28nm	✓	✓	Confidential manufacturer
ESA/IROC	SHARC-FIN	96 kb	16nm FinFET	✓	✓	Test chip of ESA-IROC AO9828 activity

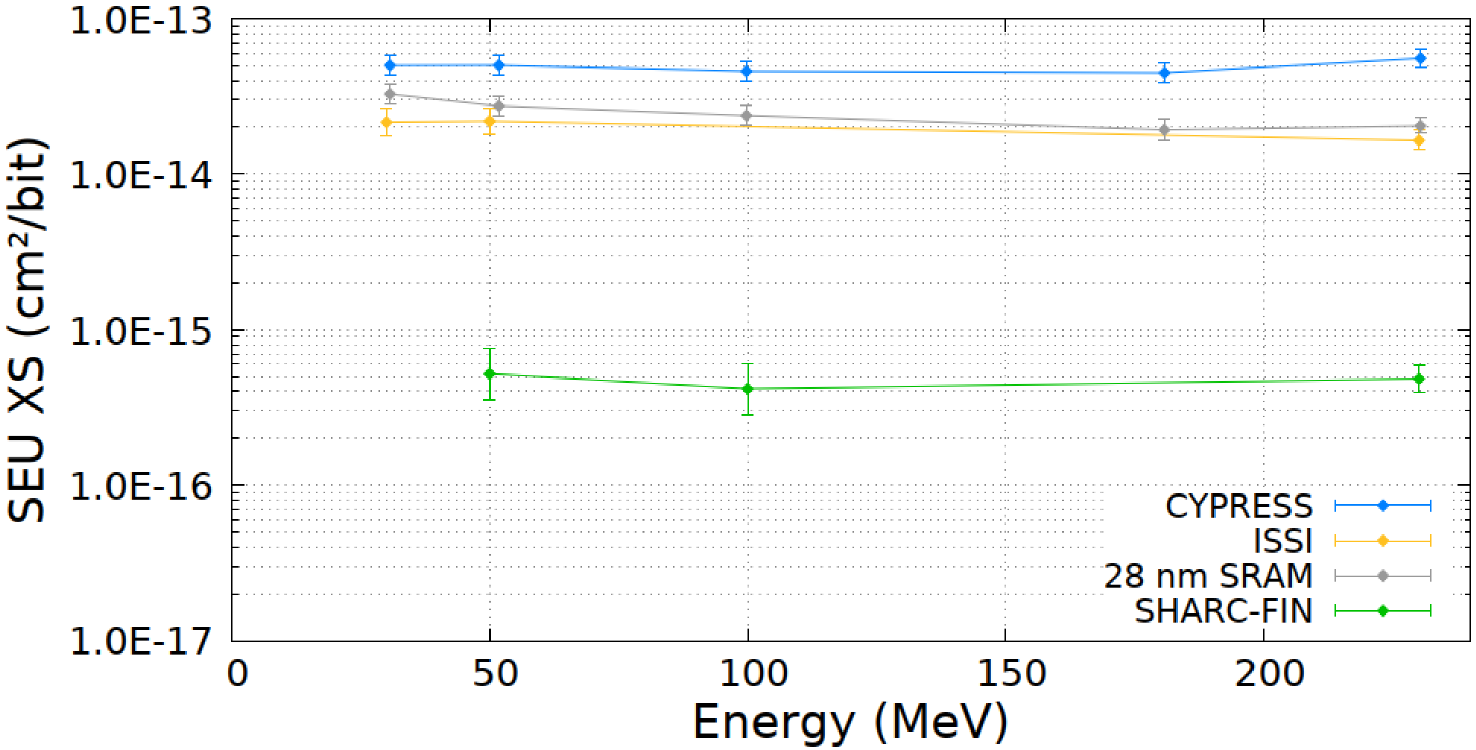
Heavy-Ion Test Results

- CYPRESS, ISSI and 28nm SRAM tested at UCL
  - Takes advantage of Li ion for LET threshold characterization
- SHARC-FIN tested at RADEF
  - Takes advantage of higher available flux



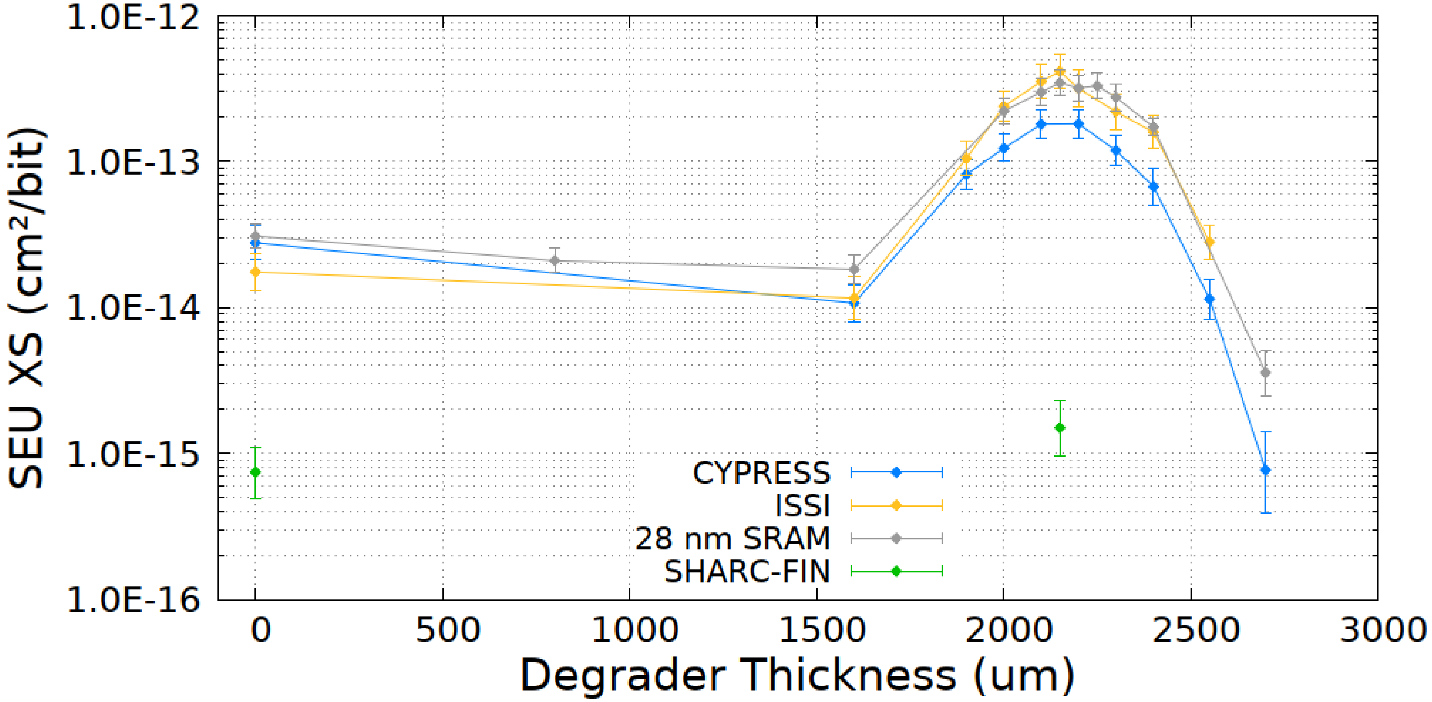
High-Energy Proton Test Results

- HEP Test performed at PSI PIF
  - CYPRESS and 28nm SRAM characterized in the context of JUICE activity
  - ISSI and SHARC-FIN tested in April 2022



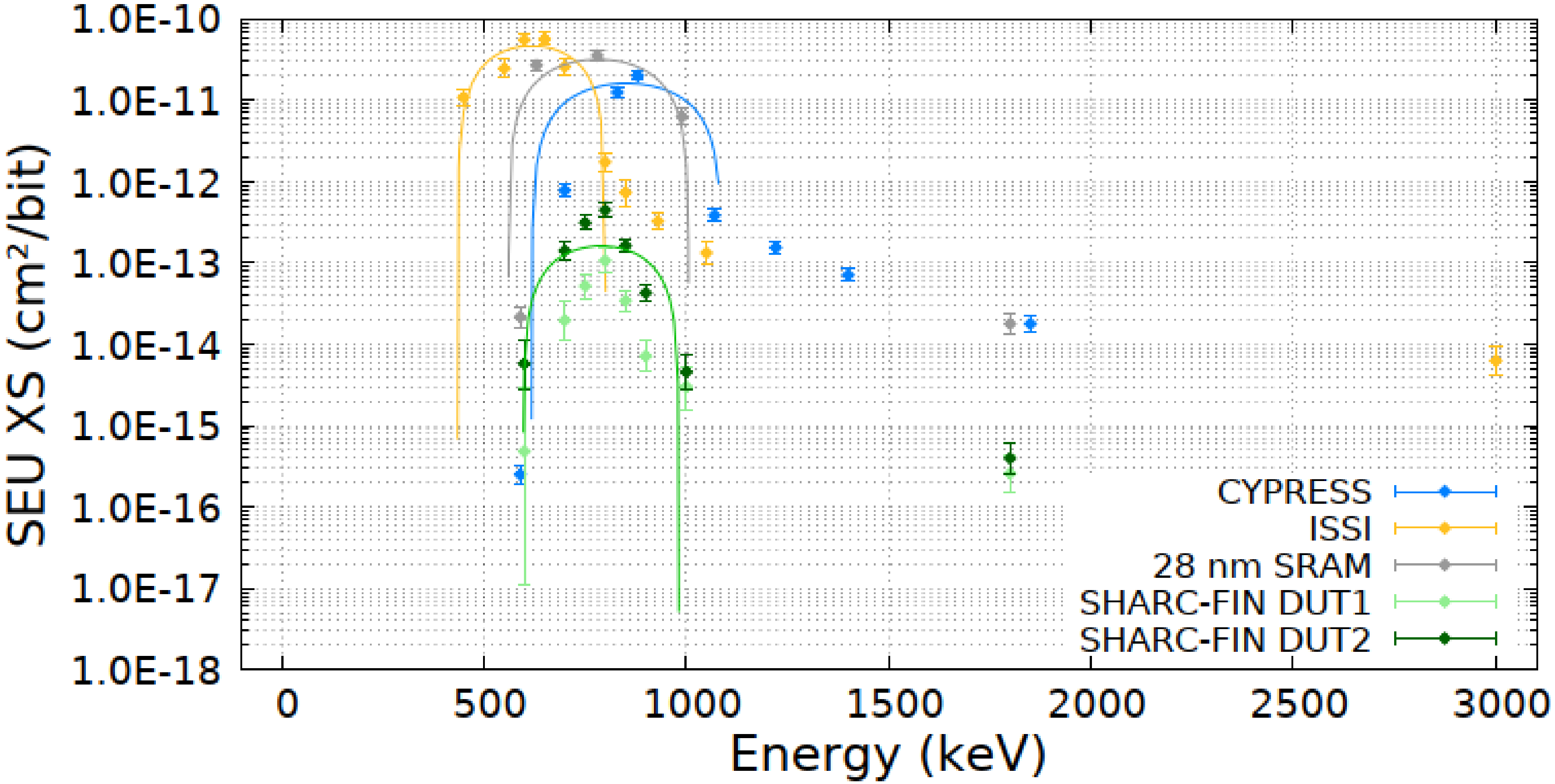
Degraded Beam Test Results

- Degraded Low Energy Proton (DLEP) performed at RADEF
- Normal incidence test result vs Aluminum degrader thickness
  - 0 degrader thickness correspond to 55 MeV (without POM neither Al degrader)



Mono-Energetic Beam Test Results

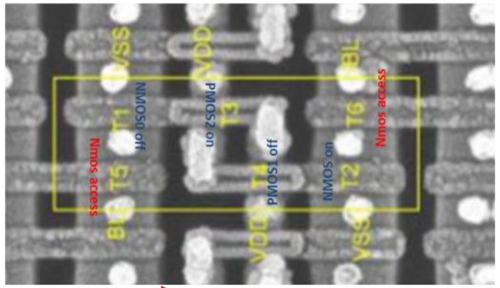
- Mono-energetic, low-energy proton (MLEP) performed at ONERA and RADEF



Impact of Angle of Incidence on LEP

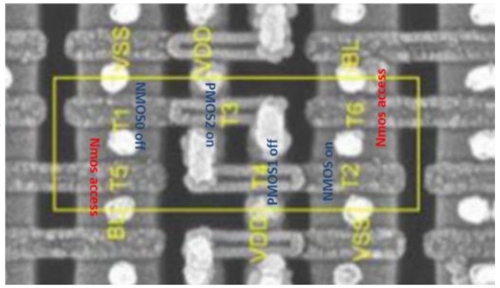
- Experimental evidence of tilt and Roll impact on the SEE cross section on a 28nm SRAM

60° Tilt in y orientation



Proton beam

60° Tilt in x orientation



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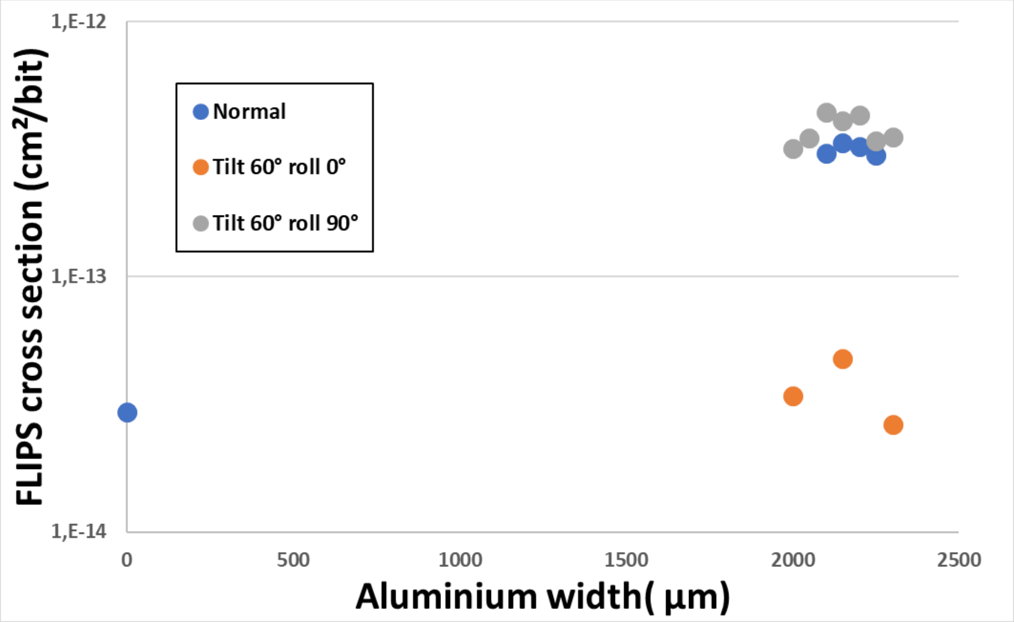


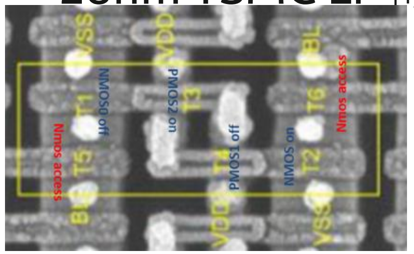
→ One roll direction shows similar SEU sensitivity as the normal incidence

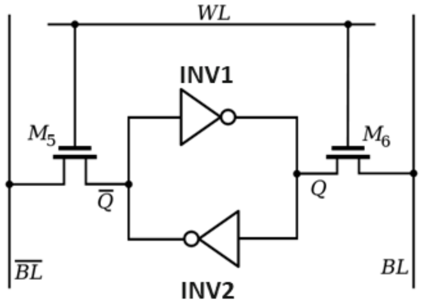
→ The other roll direction induces a low SEU sensitivity

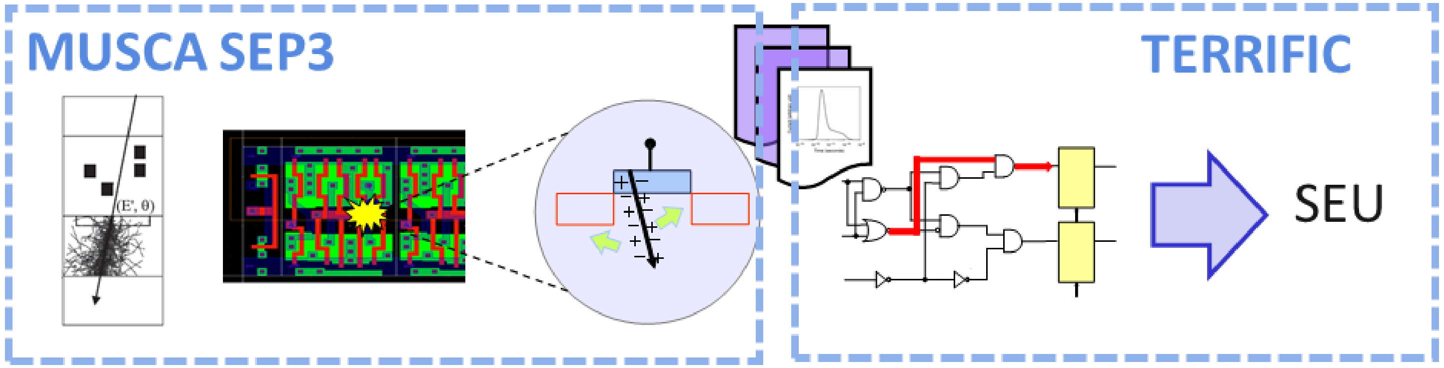
Impact of Angle of Incidence on LEP

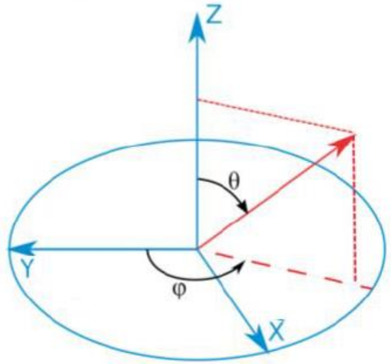
- Simulations of roll impact on the SEE responses
  - ➢ Simulations with ONERA tools (MUSCA SEP3 / TERRIFIC) of a SRAM in 28nm technology as a function of the tilt of the proton beam

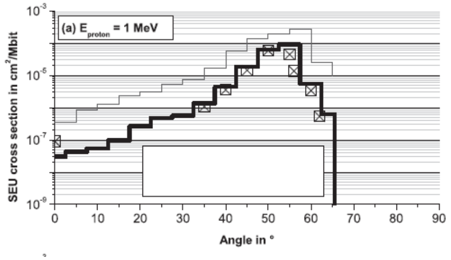
Technology hypotheses:
- 6µm of BEOL
- 28nm TSMC LP [1]











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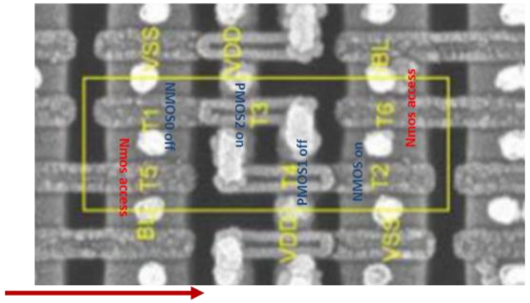
IROC technologies

Impact of Angle of Incidence on LEP

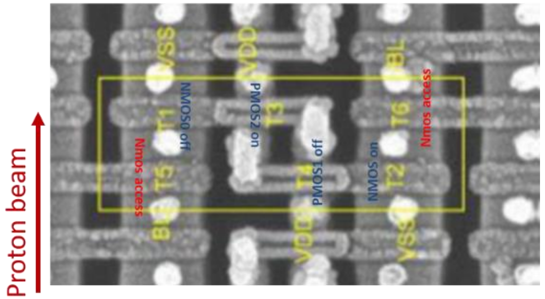
- Roll impact on the SEE cross section on a 28nm SRAM
  - ➢ Simulations with ONERA tools (MUSCA SEP3 / TERRIFIC) of a SRAM in 28nm technology as a function of the tilt of the proton beam

60° Tilt in y orientation

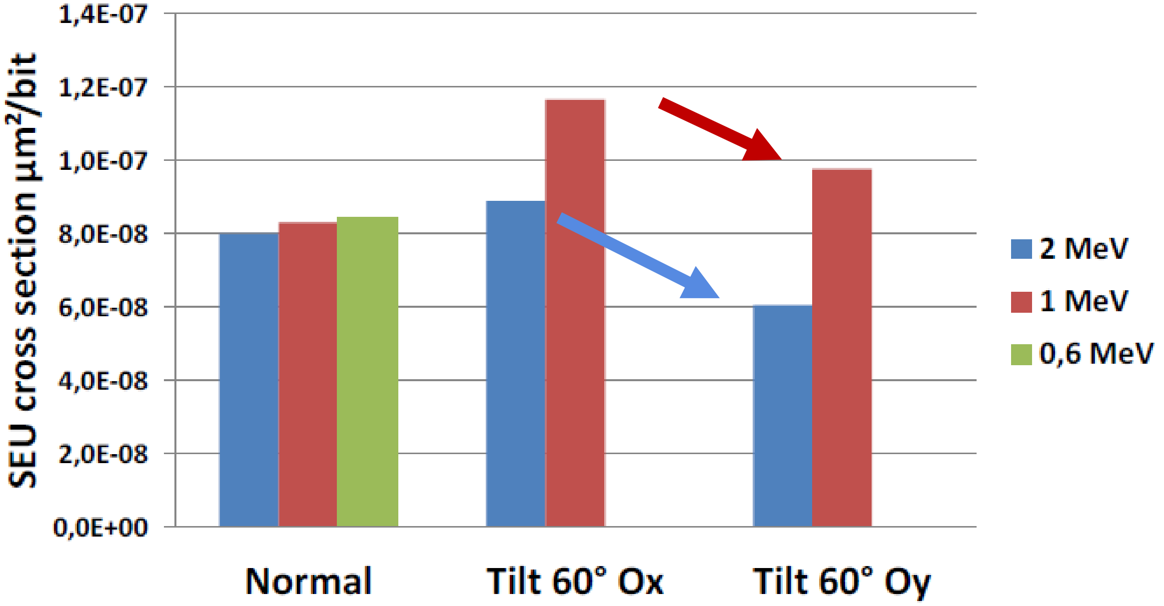


Proton beam

60° Tilt in x orientation



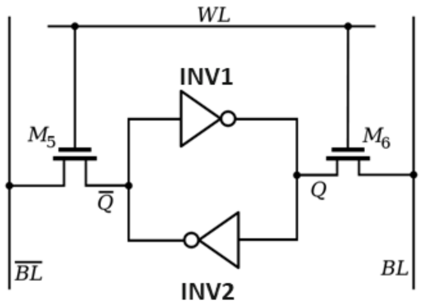
Proton beam



→ Roll impacts the SEU cross sections differently as a function of energy
→ Lower sensitivity when tilted LEPs cross the N-well and P-well

→ Analyze at electrical level

Impact of Angle of Incidence on LEP



- Roll impact on the SET induced in a 28nm SRAM
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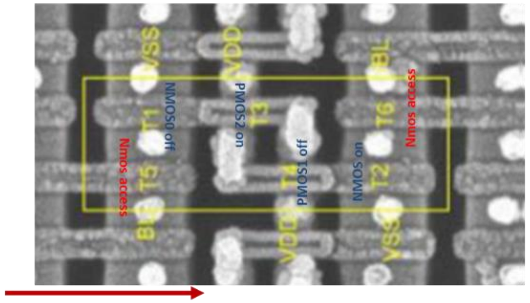

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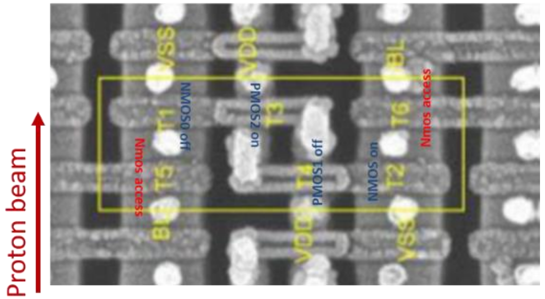
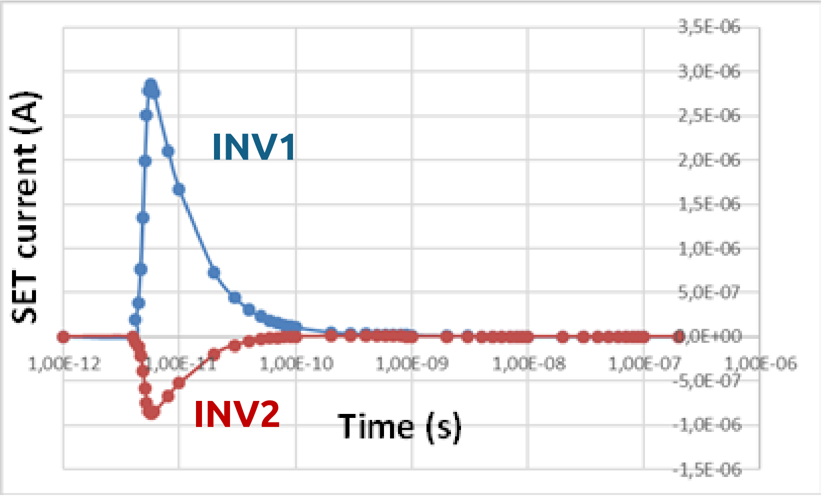
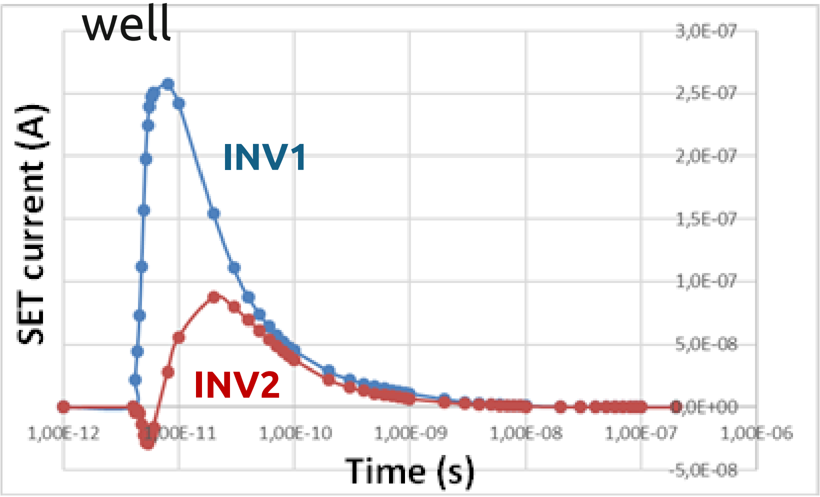


Along the gate access



Across the N-well and P-well



→ Electrical feedback loop operated by the INV2 maintains the stored state of the SRAM bit

→ **Roll of LEP impacts the charge sharing between both inverters**

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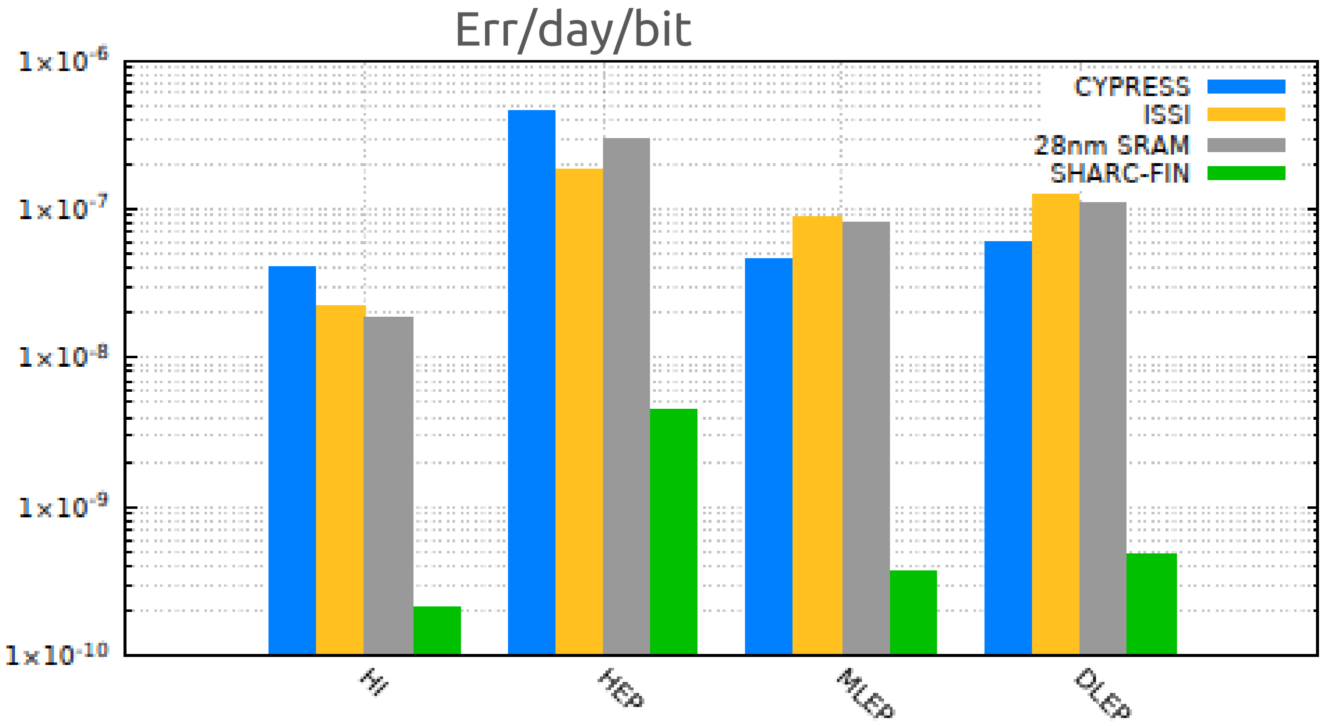
LEO Event Rate Estimations

- LEO orbit (800km – 98° inclination – 3.7 mm Al Shielding):
  - Heavy-ions: ISO15390 model – IRRP calculation with 2 µm sensitive volume
  - Protons: AP8 model
- Observations
  - HEP Dominates
  - DLEP/MELP are closed
  - LEP significant for ISSI and 28nm SRAM
  - FinFET more robust and LEP contribution is 10x lower than HEP



Conclusions

- Two methodologies proposed to estimate LEP error rate in orbit
- Both approaches provided comparable results on 4 SRAM devices, from 65nm down-to 16nm FinFET
- Angle of incidence as strong impact on LEP test results
- Each approach has specific advantages / limitations

<table>
<tr><th></th><th>DLEP</th><th>MLEP</th></tr>
<tr><td rowspan="2">Advantages</td><td>No need to de-lid DUT</td><td>Easier to characterize less sensitive/ lower capacity devices</td></tr>
<tr><td>Energy sweep is fast</td><td>More accurate characterization of the mechanism</td></tr>
<tr><td>Limitations</td><td>Degrader activation</td><td>Longer beam time need</td></tr>
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