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Hardness assurance for proton direct ionization-induced SEEs using a high-energy proton beam

N. A. Dodds, J. R. Schwank, M. R. Shaneyfelt, P. E. Dodd,
B. L. Doyle, M. C. Trinczek, E. W. Blackmore, K. P. Rodbell,
R. A. Reed, J. A. Pellish, K. A. LaBel, P. W. Marshall,
S. E. Swanson, G. Vizkelethy, S. Van Deusen

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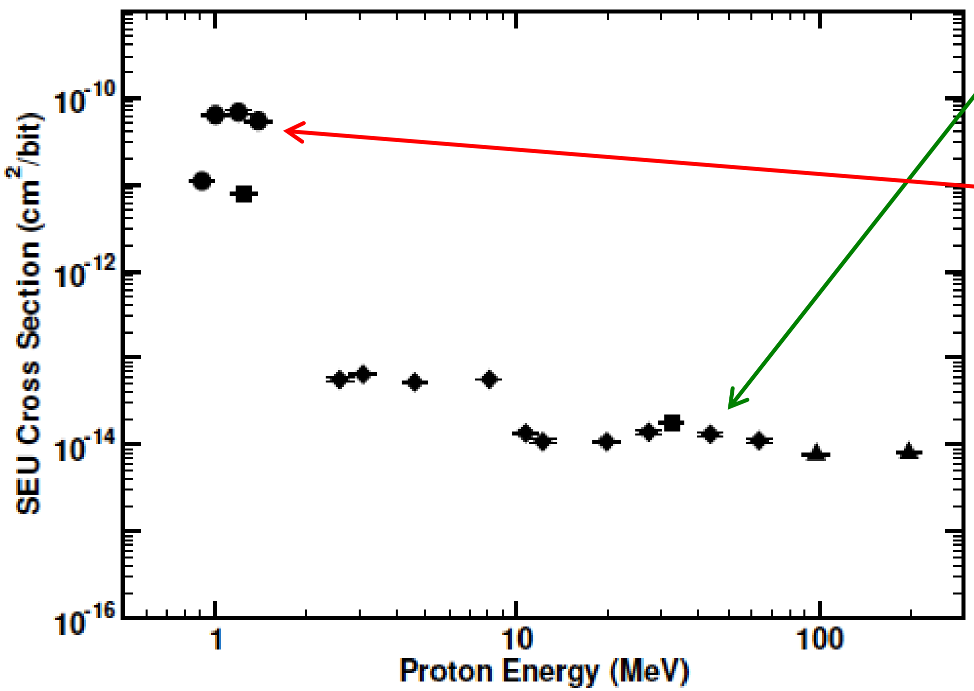
Outline

- Background on proton direct ionization (PDI)
- Use of a high-energy proton beam to
  - identify PDI susceptibility
  - predict PDI error rate
- PDI angular effects
- Summary

Background

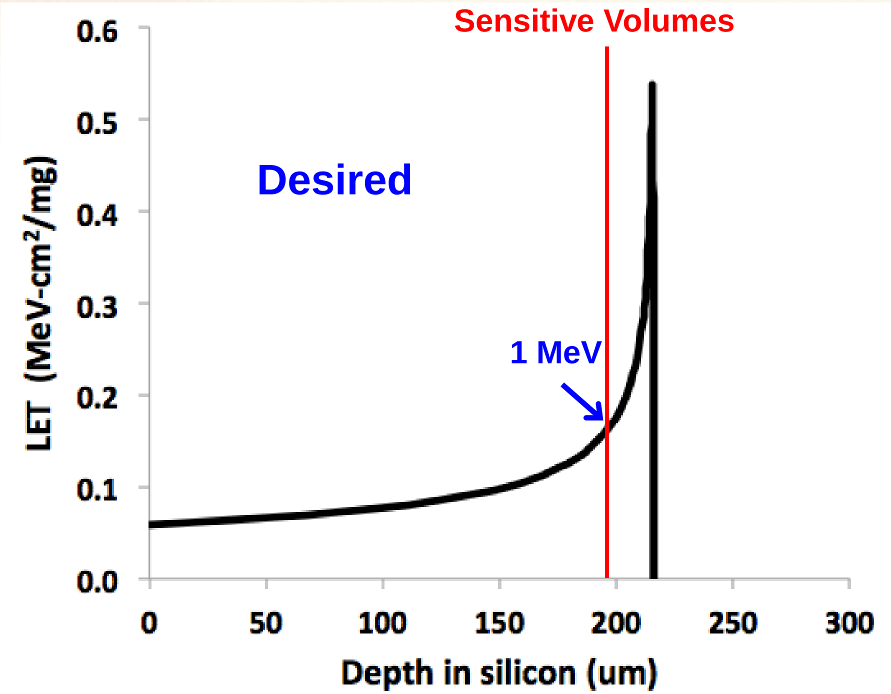
65 nm SRAM

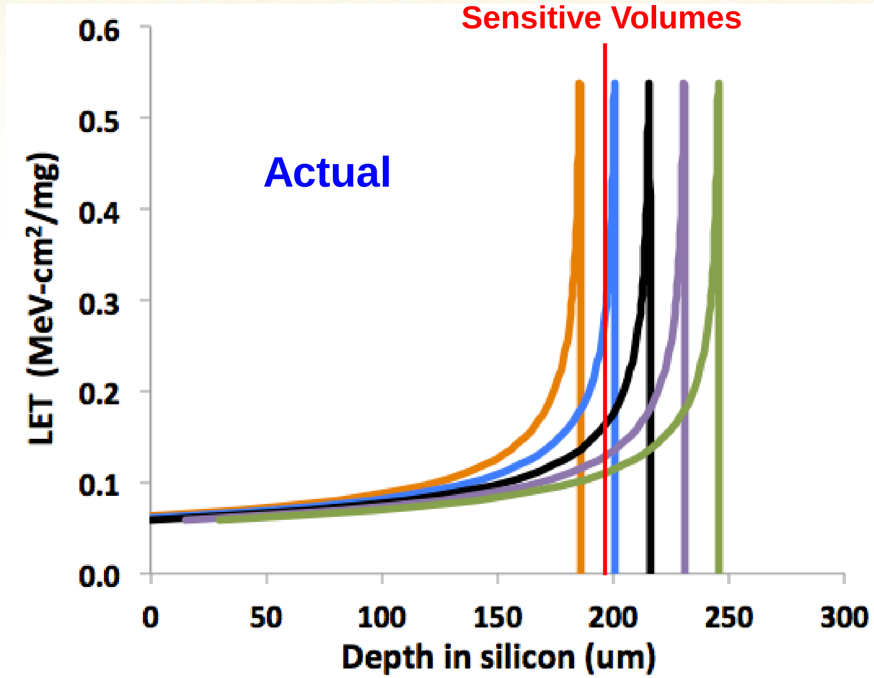


[Sierawski *et al.*, TNS 2009]

- Historically, protons only caused SEEs through nuclear reactions
- PDI also causes SEEs in modern ICs

Proton Energy Straggle





Ways to minimize energy straggle:

- **Test with low initial beam energies, in vacuum, without degraders**
- **Decapsulate DUT. Thin the substrate if DUT is flip chip**
- **Test at 0° angle**

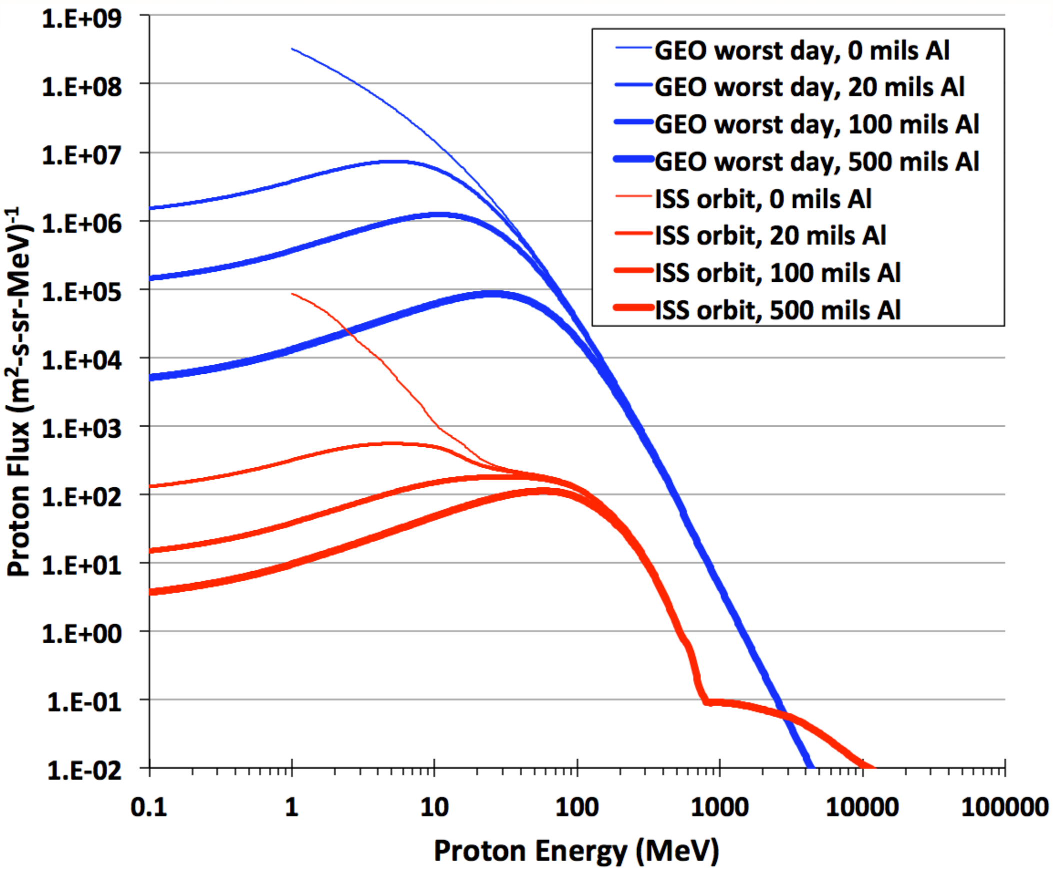
Proton energy straggle forced previous studies to either

1. **Only use data qualitatively**
2. **Build a calibrated model [Sierawski TNS 2009]**

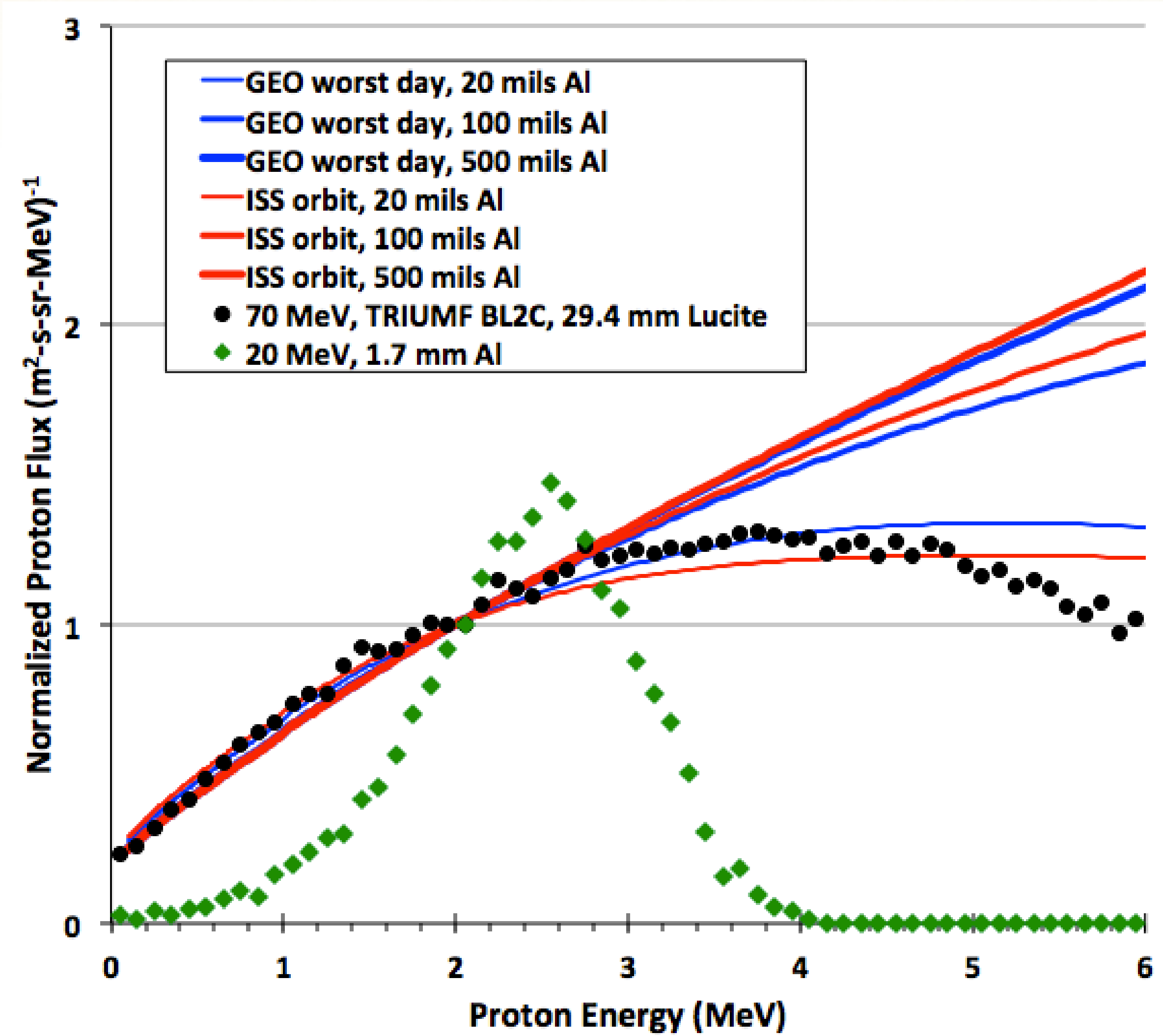
Space Proton Environments

- All shielded space environments have qualitatively similar low-energy proton spectra, regardless of
  - Orbit
  - Solar conditions
  - Shielding thickness
  - Shielding material

- Assumption: Only protons that reach SVs with < 3 MeV can cause errors through PDI



A space-like energy spectrum, in the lab!



- 70 MeV proton beam can be degraded to reproduce space's sub 3 MeV energy spectrum
- Degraded 20 MeV beam has insufficient energy straggle to reproduce space's sub 3 MeV energy spectrum
  - Energy straggle <u>helps</u> us reproduce environment of interest

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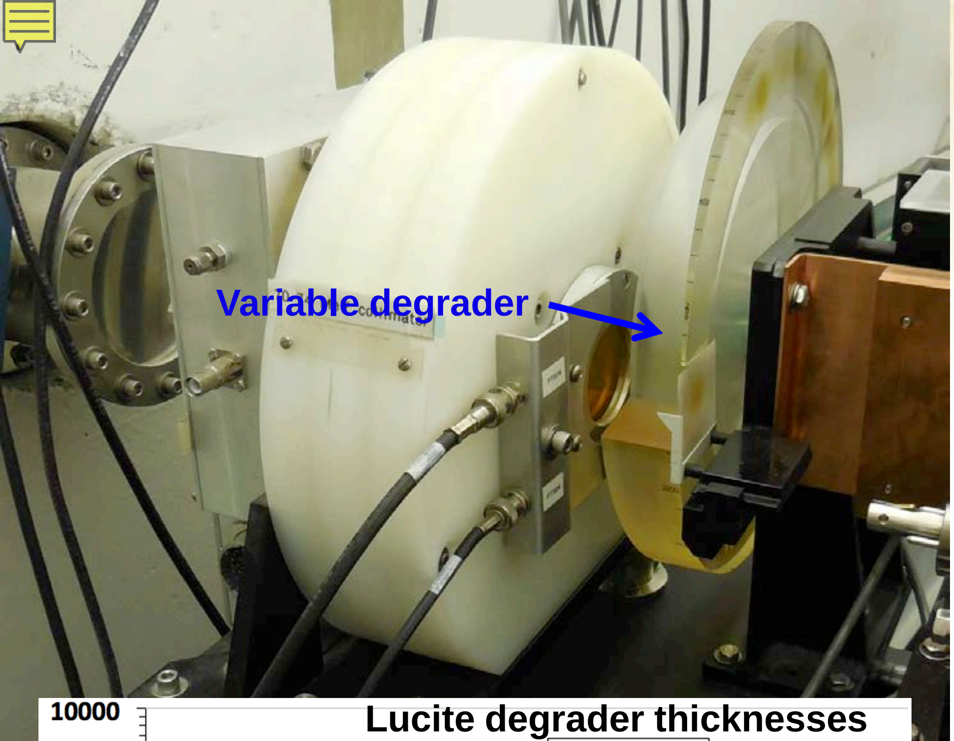
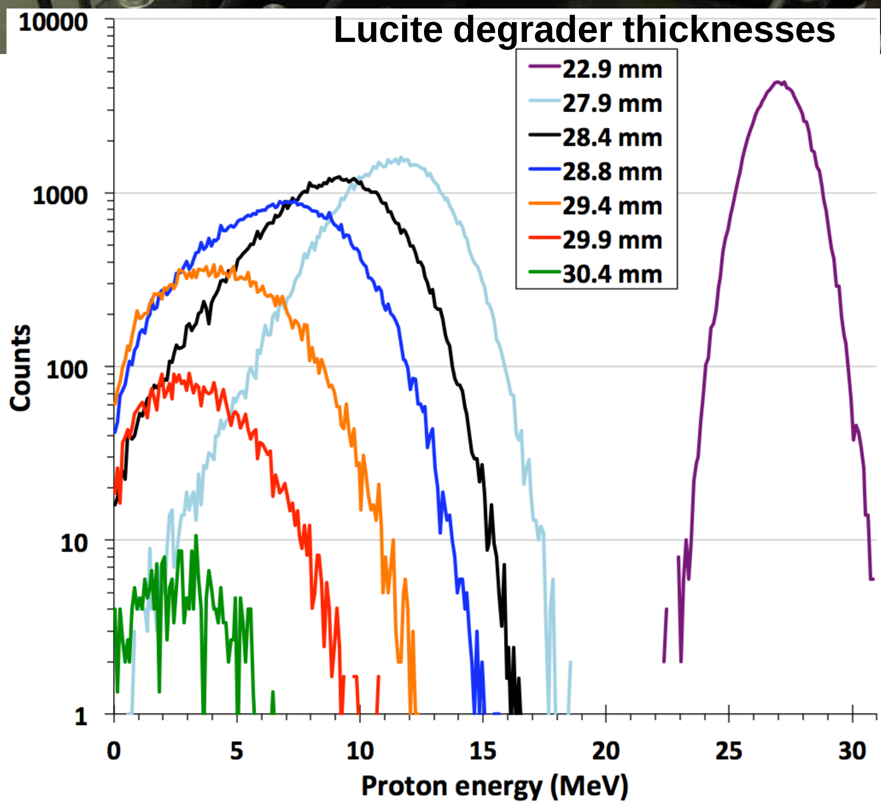
TRIUMF's proton beamline





- Increasing degrader thickness decreases the average proton energy
- Certain range of degrader thicknesses maximizes flux of sub 3 MeV protons
- 1-Mbit IBM 65 nm SOI SRAMs were irradiated at 0.8 V, room temperature

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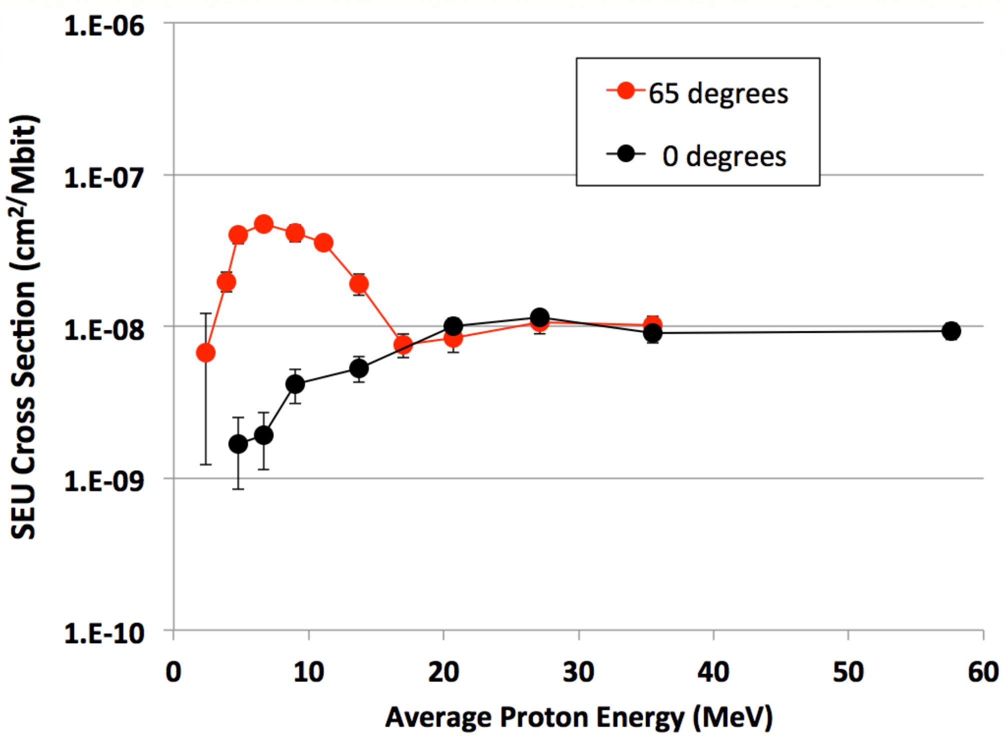
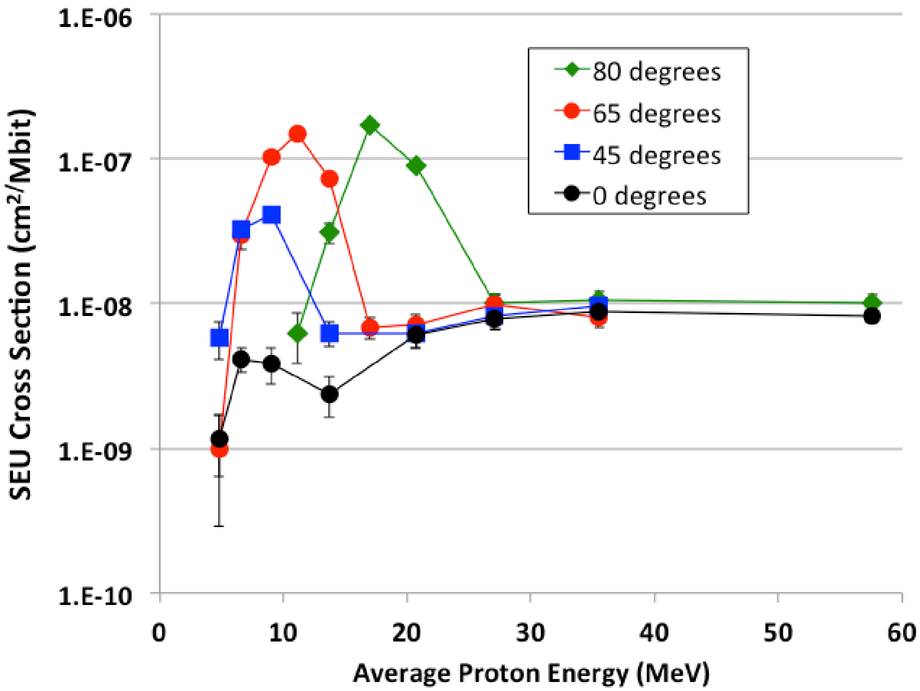
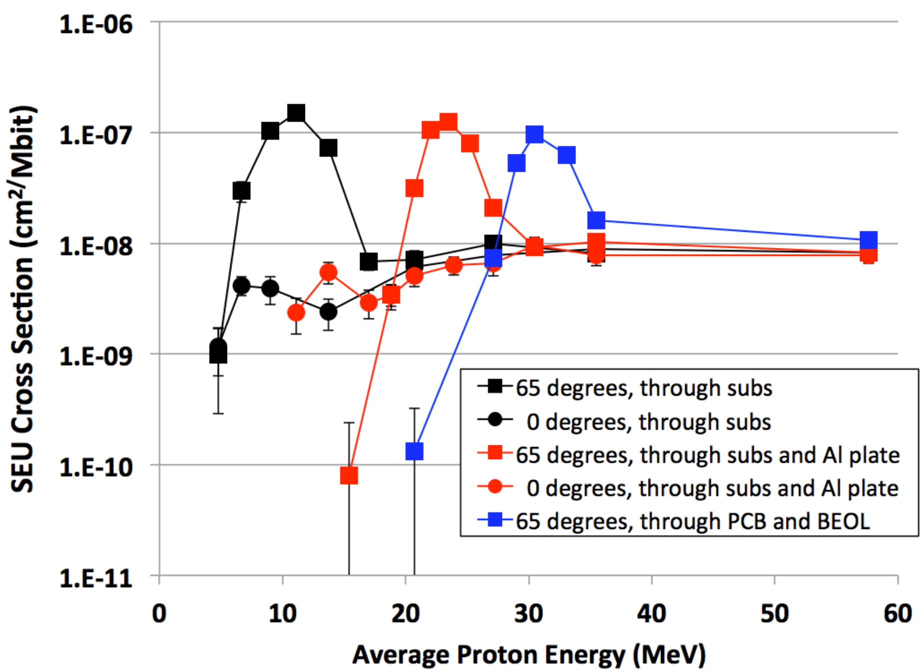
SRAM with no substrate



- Substrate removed down to BOX using XeF_2 etch [Shaneyfelt *et al*., TNS 2012]
- Backside irradiation through only 150 nm BOX ➔ same energy spectrum reached SVs at 0° and 65° angles
- 65° cross sections higher due to higher effective LET
  - PDI rate predictions must account for angular response. Angled tests not usually done due to increased energy straggle





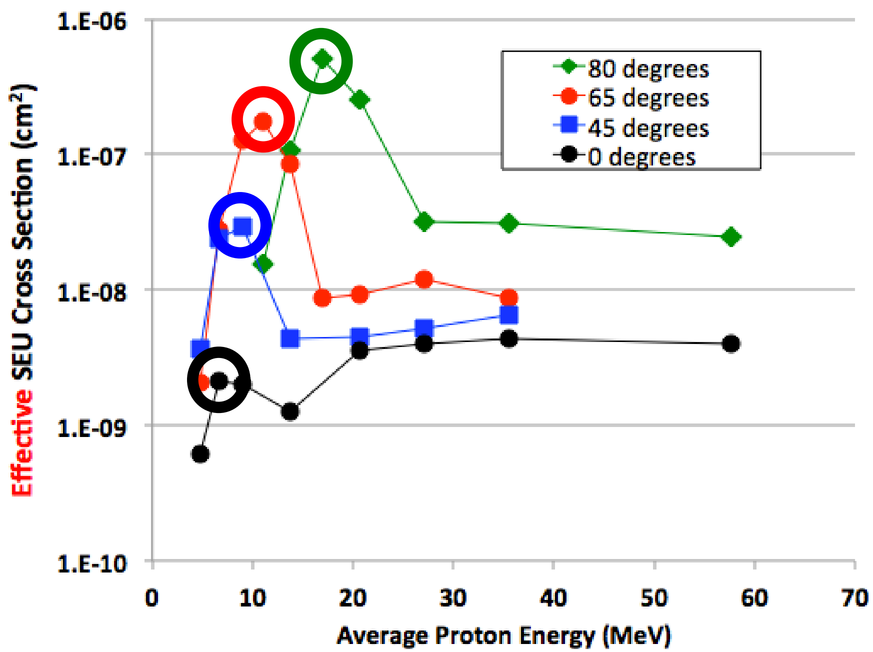
Angular response

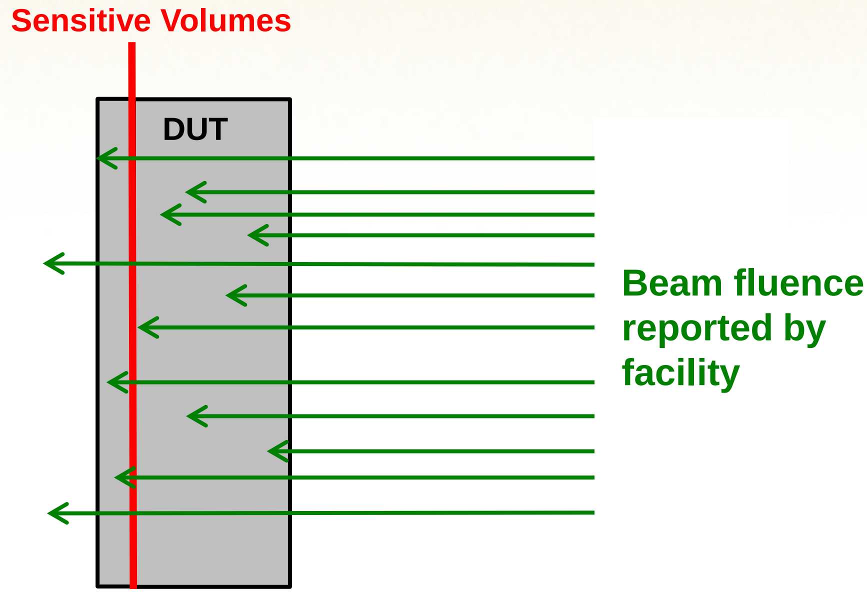
- **Irradiated from backside through BOX and 350 um substrate**

- **Increasing angle**
  ➔ increases effective LET
  ➔ increases peak cross section
  ➔ improves PDI susceptibility detection beyond that of 0° method from [Schwank *et al.*, TNS 2012]

- **Tests also work well on encapsulated parts**

PDI Error Rate Calculation

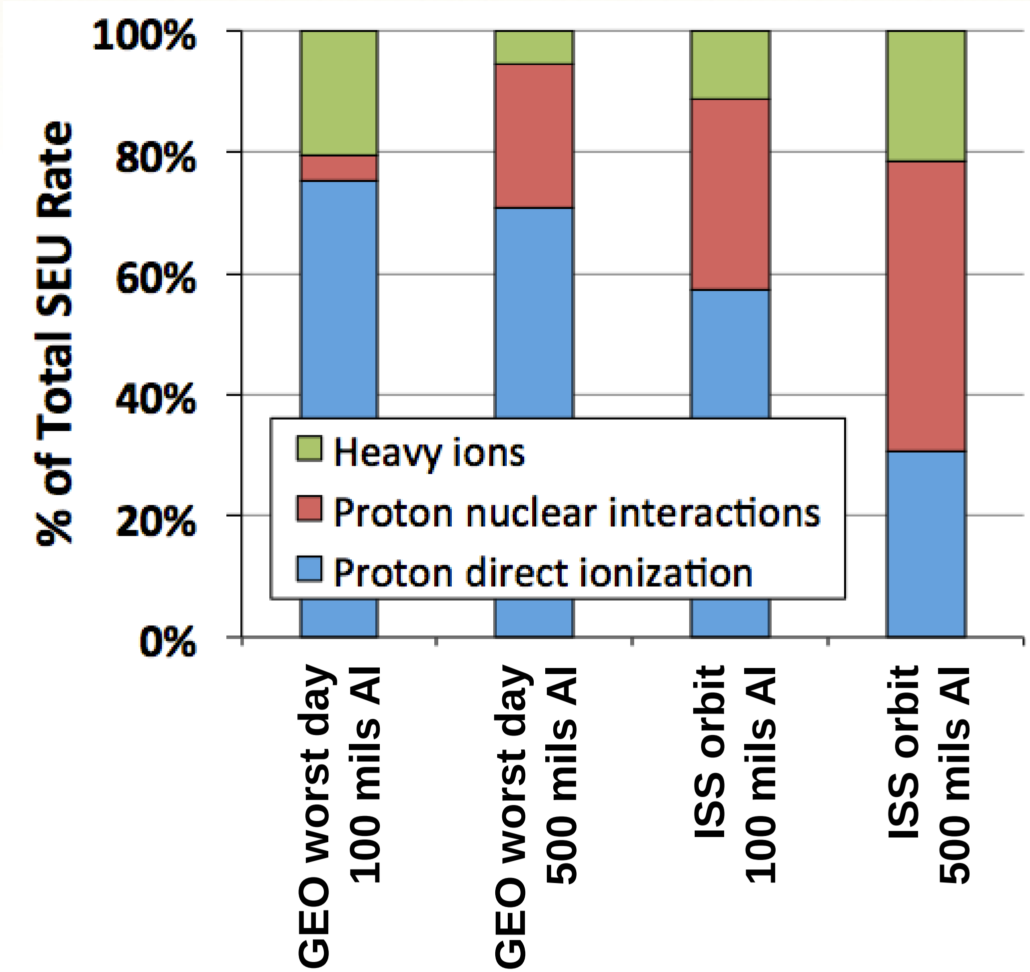




Angle	Effective Peak SEU Cross Section (cm²/Mbit)	Fraction of fluence that reaches sensitive volume plane with < 3 MeV	SEU Cross Section for < 3 MeV space protons (cm²/Mbit)	Probability proton strikes at this angle	SEU Cross Section for isotropic < 3 MeV space protons (cm²/Mbit)
0°	4.2E-09	0.143	2.9E-08	0.18 (0°-35°)	3.0E-06
45°	5.8E-08	0.128	4.5E-07	0.25 (35°-55°)	
65°	3.5E-07	0.127	2.8E-06	0.31 (55°-75°)	
80°	9.8E-07	0.125	7.8E-06	0.26 (75°-90°)	

Predicted contributions to SEU rate

- **Heavy ion rate prediction used data from [Heidel *et al.*, TNS 2009]**



Summary

- A high-energy proton beam can be degraded to produce a low-energy spectrum that matches that of all shielded space environments
  - This observation could dramatically simplify PDI rate prediction, allowing tests at high-energy facilities, on encapsulated parts, without knowledge of circuit design

- Increasing beam angle increases proton effective LET and measured cross sections

- Susceptibility to PDI effects is best identified at large angles of incidence when using a degraded high-energy proton beam