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

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NNSA National Nuclear Security Administration

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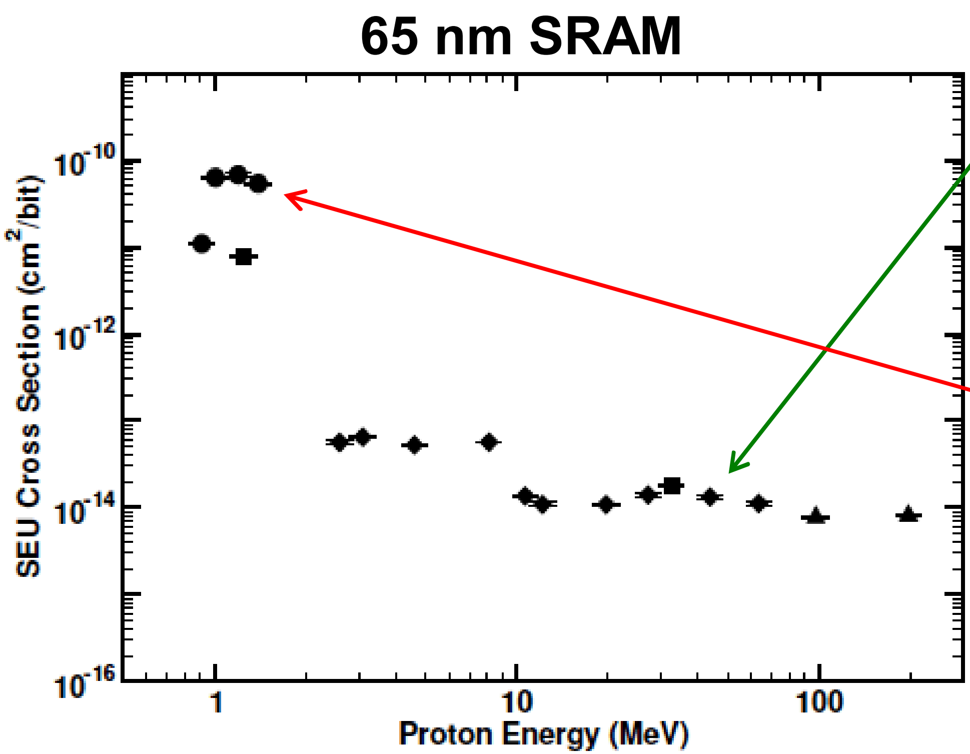
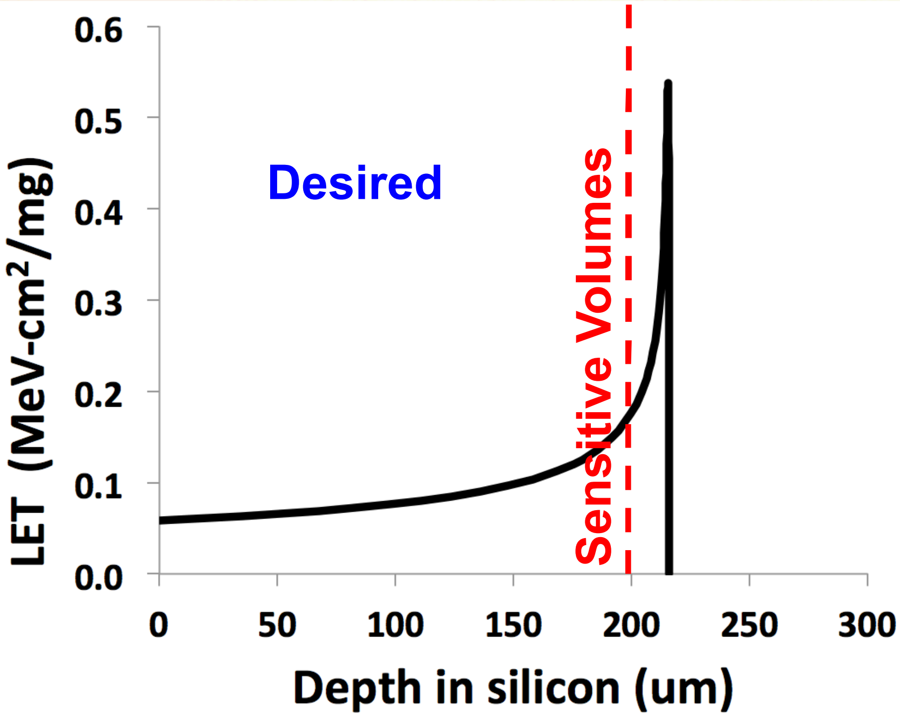
Background

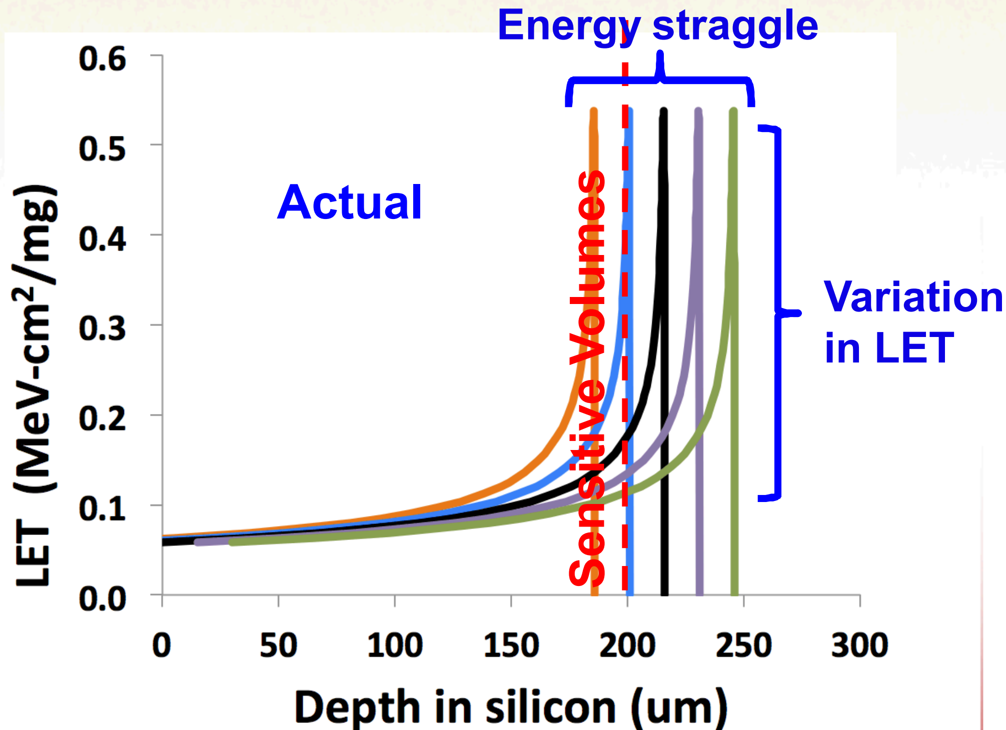


[Sierawski *et al.*, TNS 2009]

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

Proton direct ionization has been a hard problem because of energy straggle





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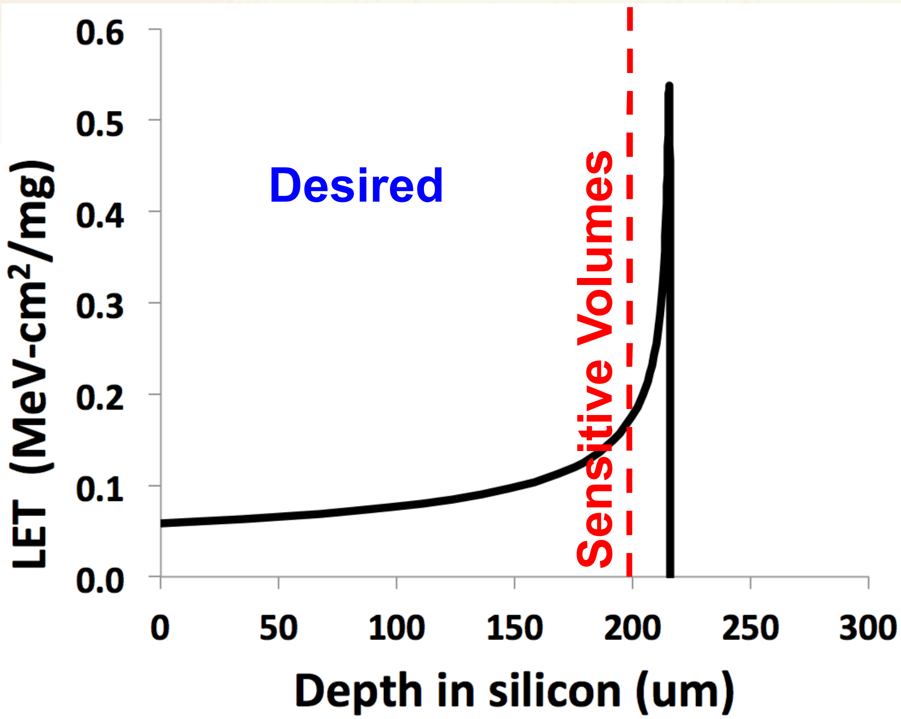
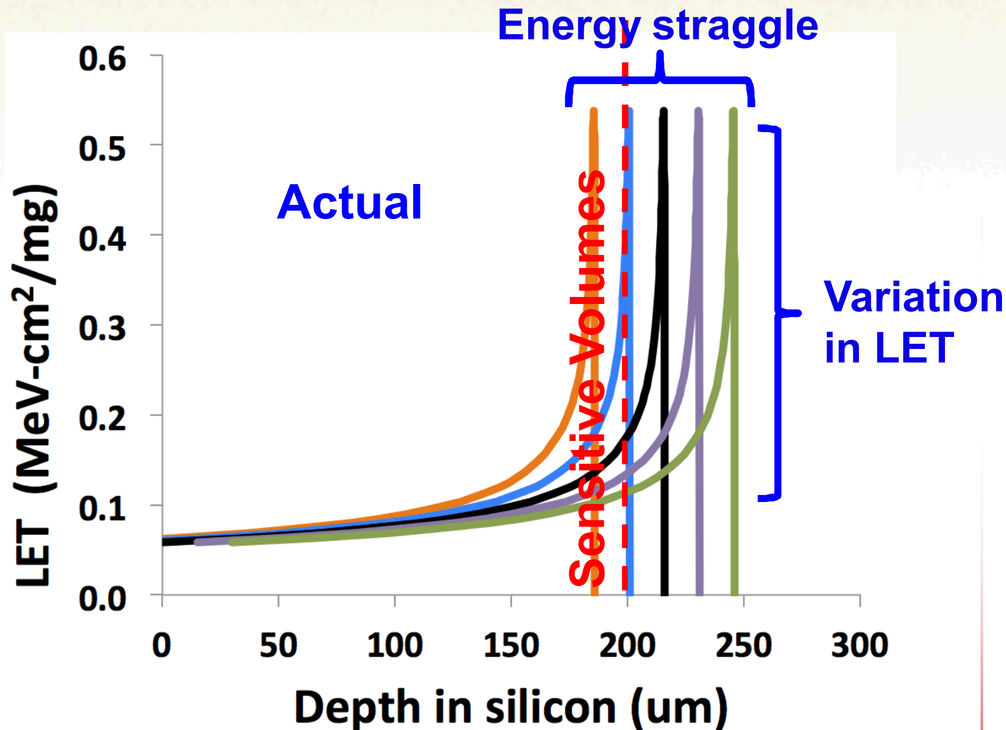




- **Proton energy straggle can be <u>reduced</u> by testing at low energy facilities, in vacuum, without degraders, on decapsulated DUTs**
  - **Very costly and time consuming, and doesn't <u>eliminate</u> straggle**

- **Energy straggle forced previous studies to either**
  1. **Only use data qualitatively**
  2. **Build a calibrated model**

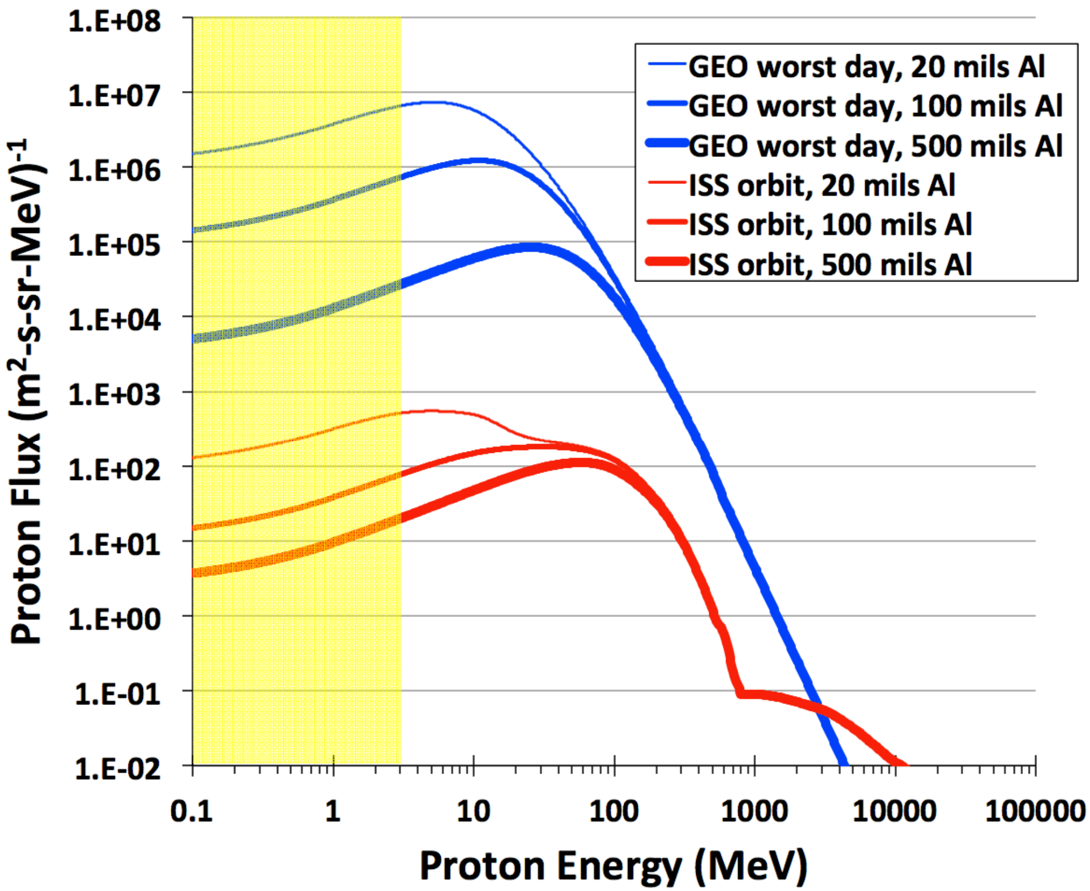
What's new in this work

- Use of a degraded high-energy proton beam to predict PDI error rate
- PDI angular effects

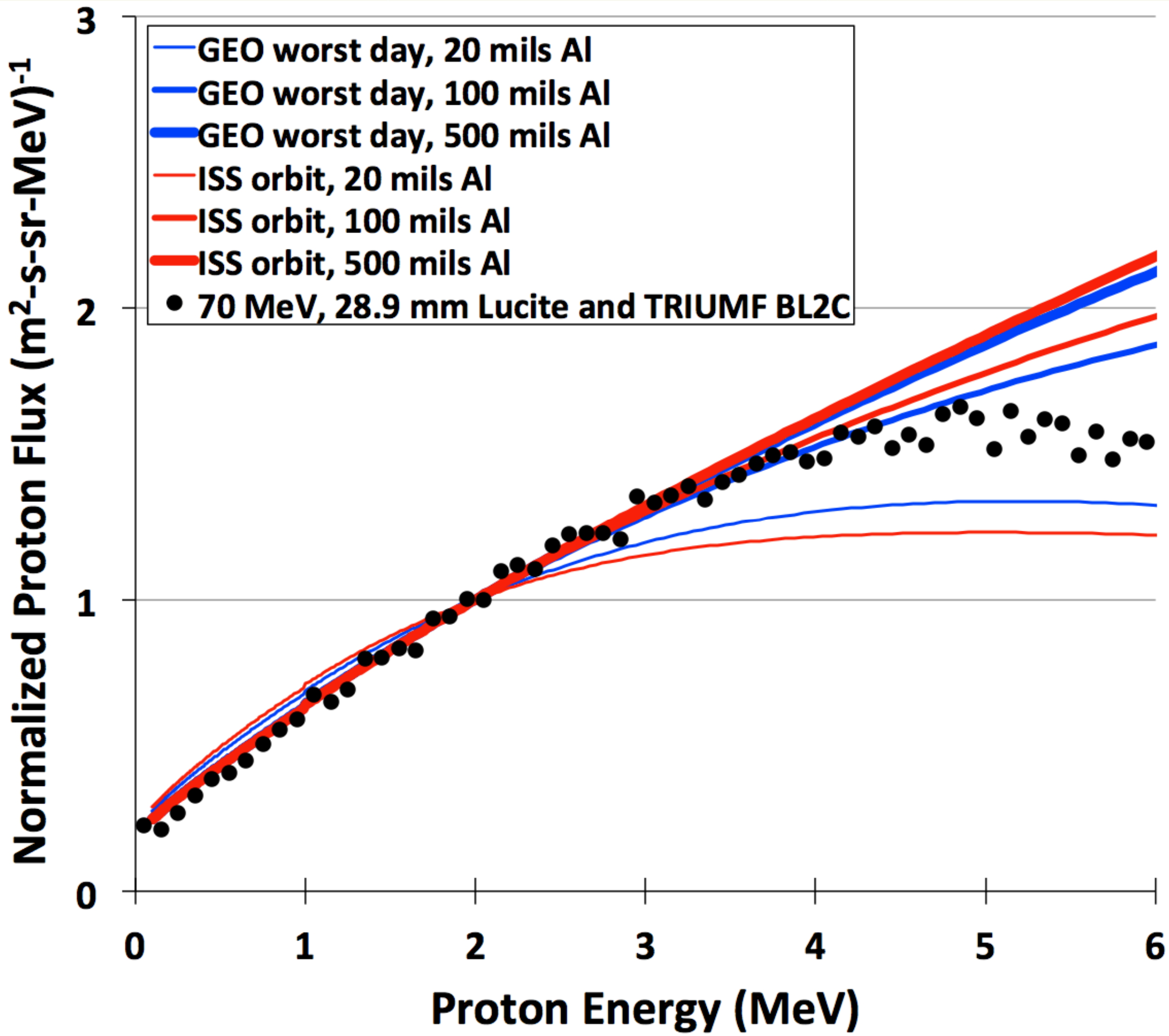
Space Proton Environments

- **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**

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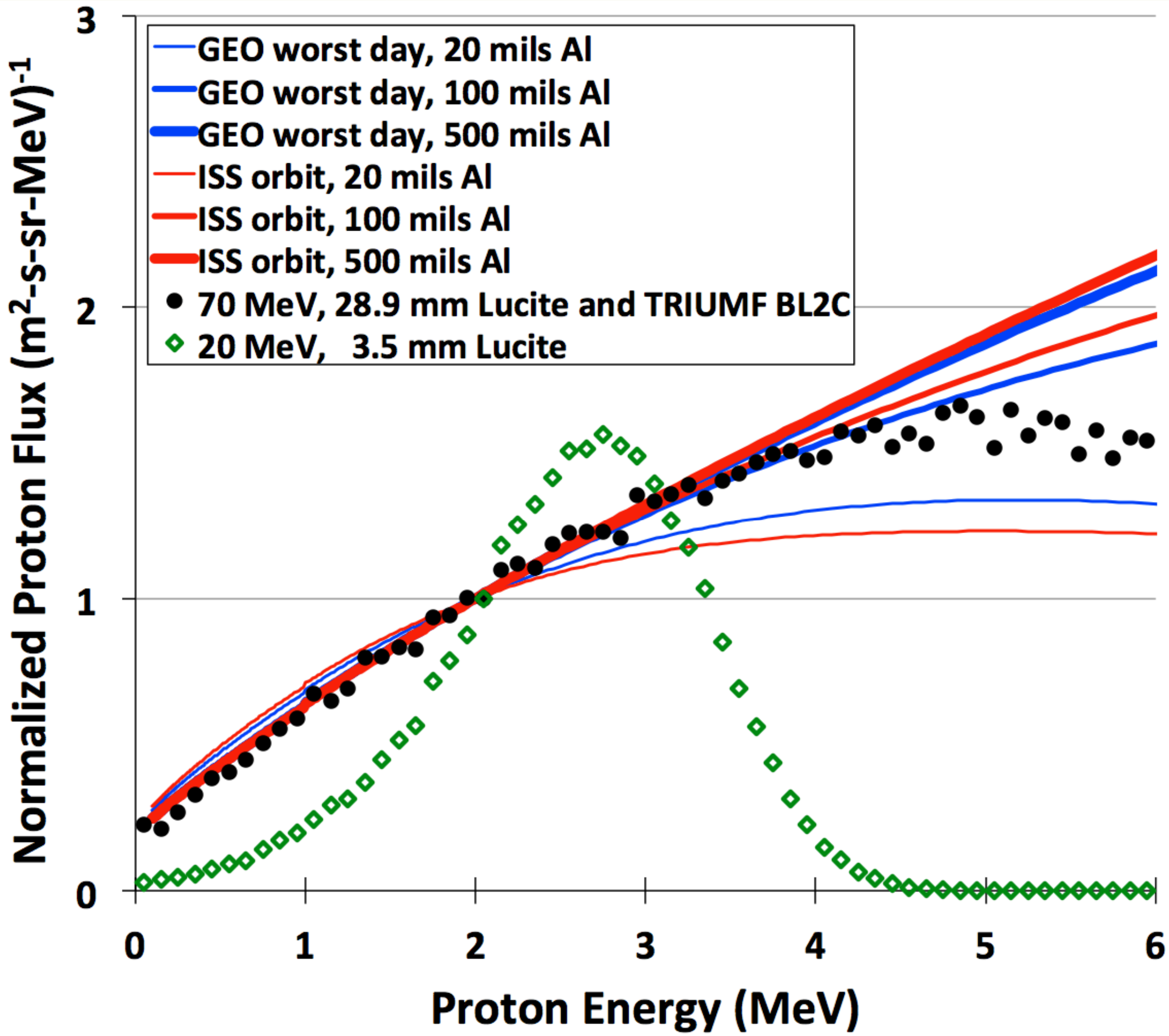
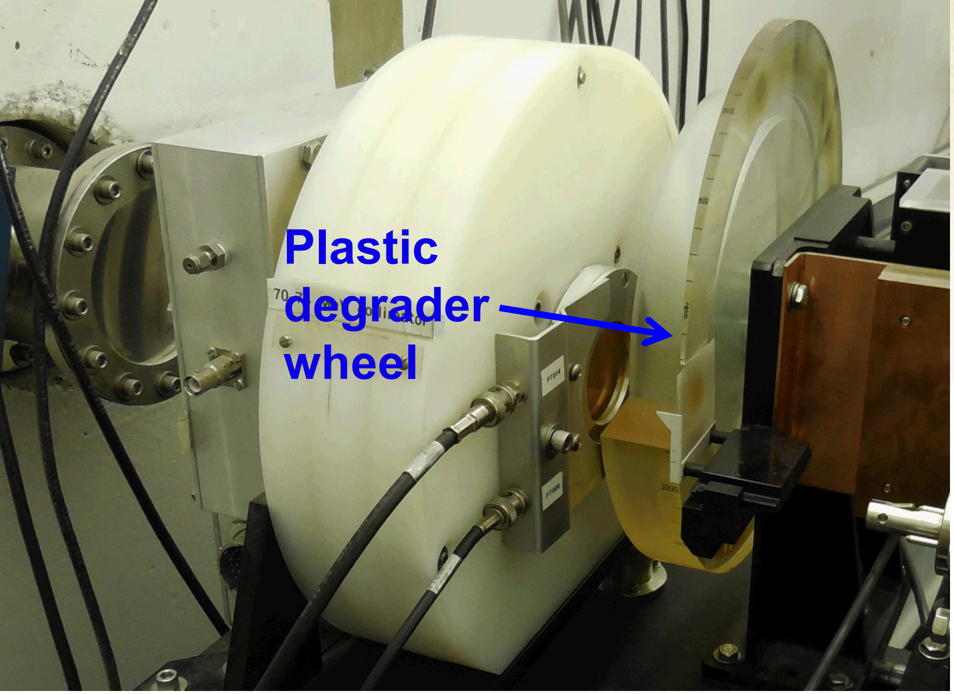
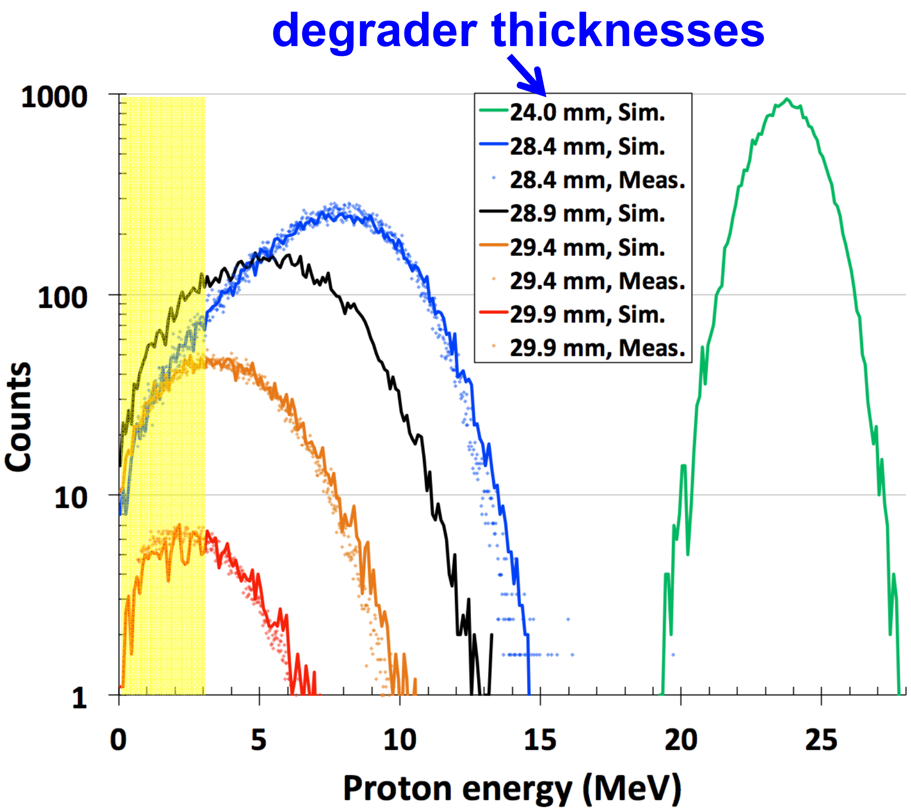
A space-like energy spectrum, in the lab!



- 70 MeV proton beam can be degraded to reproduce space's sub 3 MeV energy spectrum
- Significant energy straggle is necessary to reproduce environment of interest

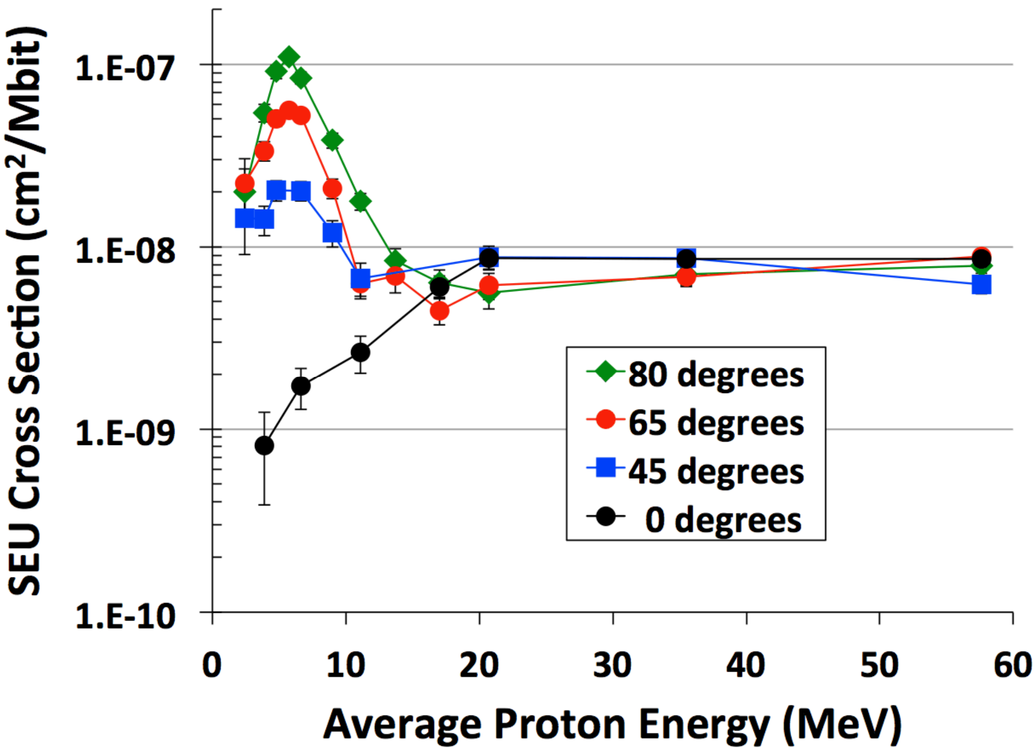
TRIUMF's proton beamline





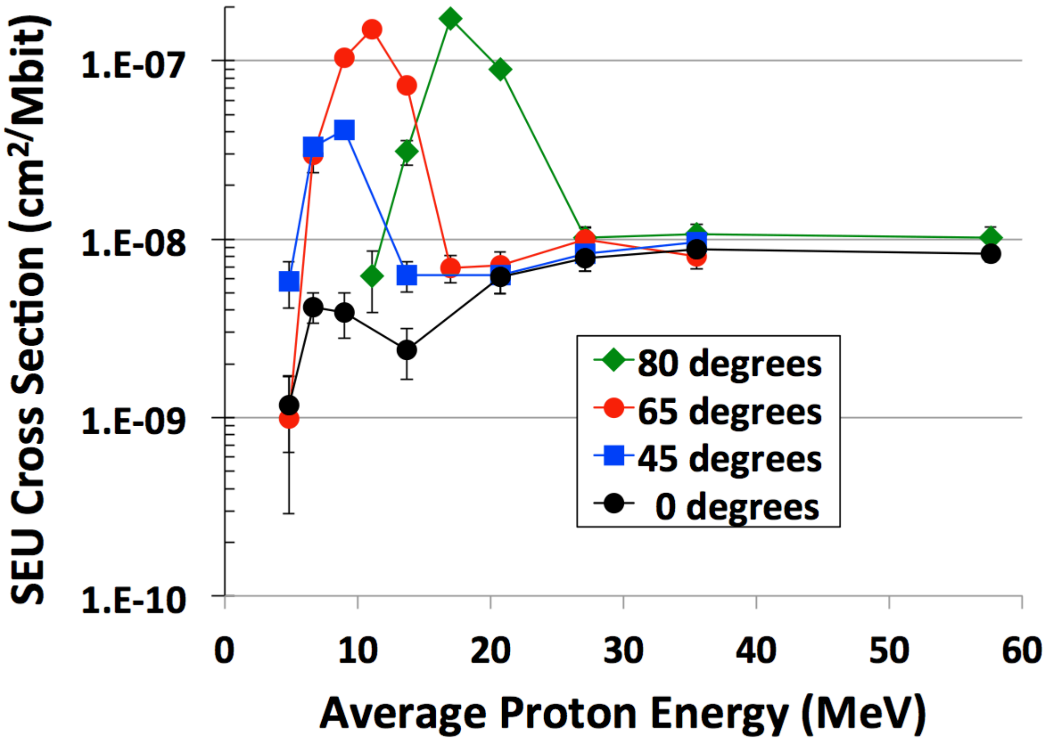
- **Increasing degrader thickness decreases the average proton energy**
- **Certain degrader thickness maximizes flux of sub 3 MeV protons**
- **IBM 65, 45, and 32 nm SOI SRAMs were irradiated at room temp.**
    - **65 nm data presented here**
    - **45 and 32 nm data in the paper**

Increasing angle increases PDI cross sections



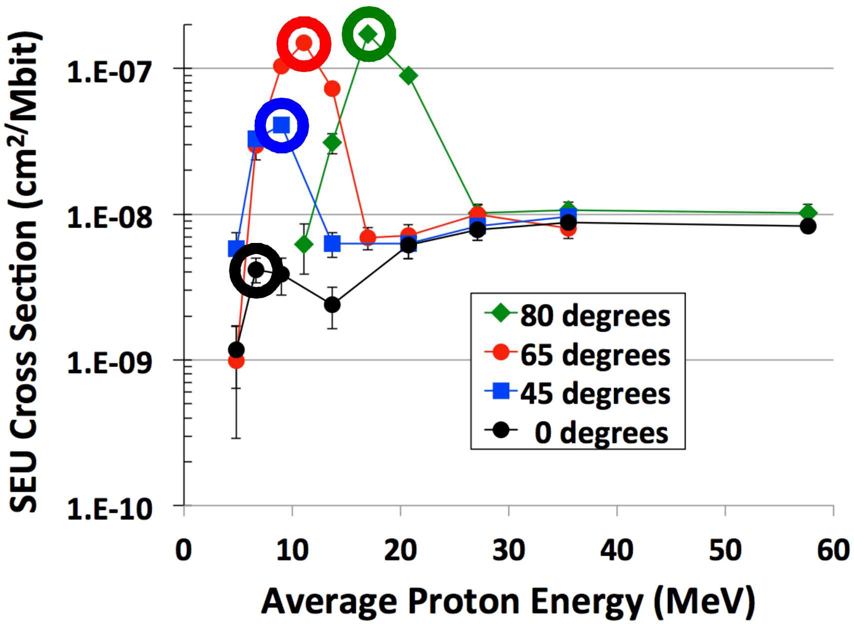
- Substrate removed down to BOX using XeF_2 etch [Shaneyfelt *et al.*, TNS 2012]
- Backside irradiation through only 150 nm BOX ➔ same energy spectrum reaches SVs at all angles
- Cross sections increase with angle due to increase in effective LET
  - PDI rate predictions must account for angular response. Angled tests not usually done due to increased energy straggle

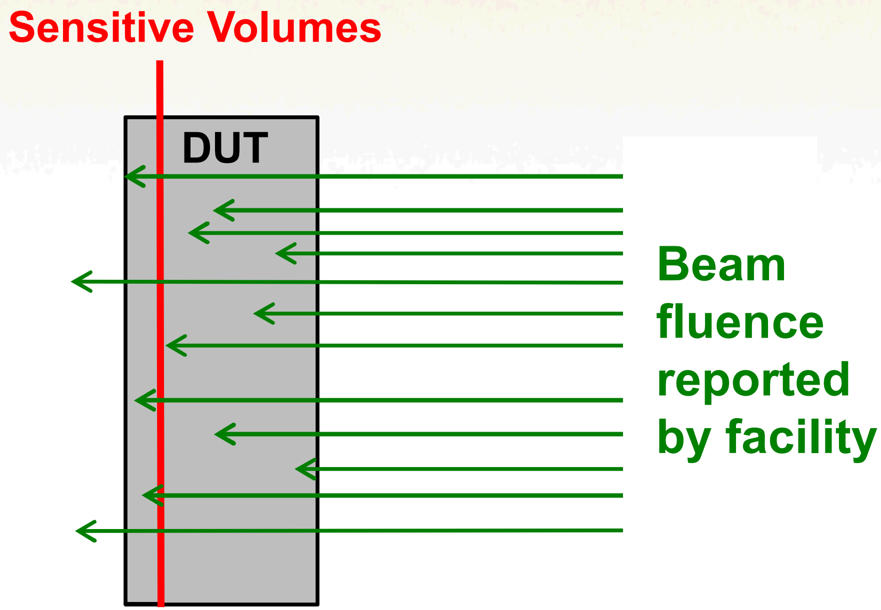
PDI susceptibility best detected at large angles



- Irradiated from backside through BOX and 350 um substrate
- As angle ↑, effective LET ↑, and peak cross sections ↑

PDI Error Rate Calculation





Angle	SEU Cross Section of Peak (cm^2/Mbit)	Fraction of fluence that reaches sensitive volume plane with < 3 MeV	SEU Cross Section for < 3 MeV space protons (cm^2/Mbit)	Probability proton strikes at this angle	SEU Cross Section for isotropic < 3 MeV space protons (cm^2/Mbit)
0°	4.2E-09	0.13	3.2E-08	0.18 (0°-35°)	**7.9E-07**
45°	4.1E-08		3.2E-07	0.25 (35°-55°)	
65°	1.5E-07		1.2E-06	0.31 (55°-75°)	
80°	1.7E-07		1.3E-06	0.26 (75°-90°)	

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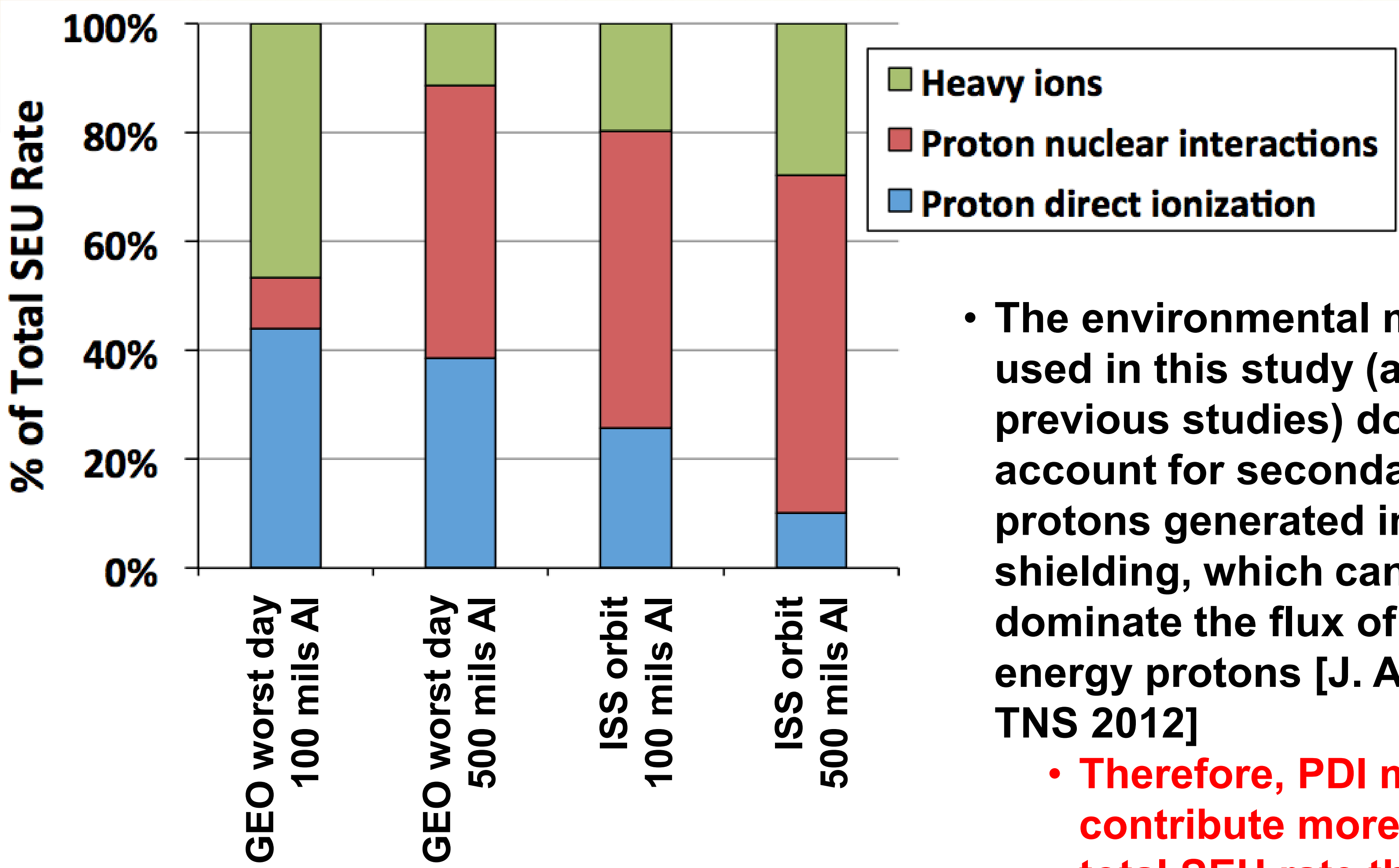
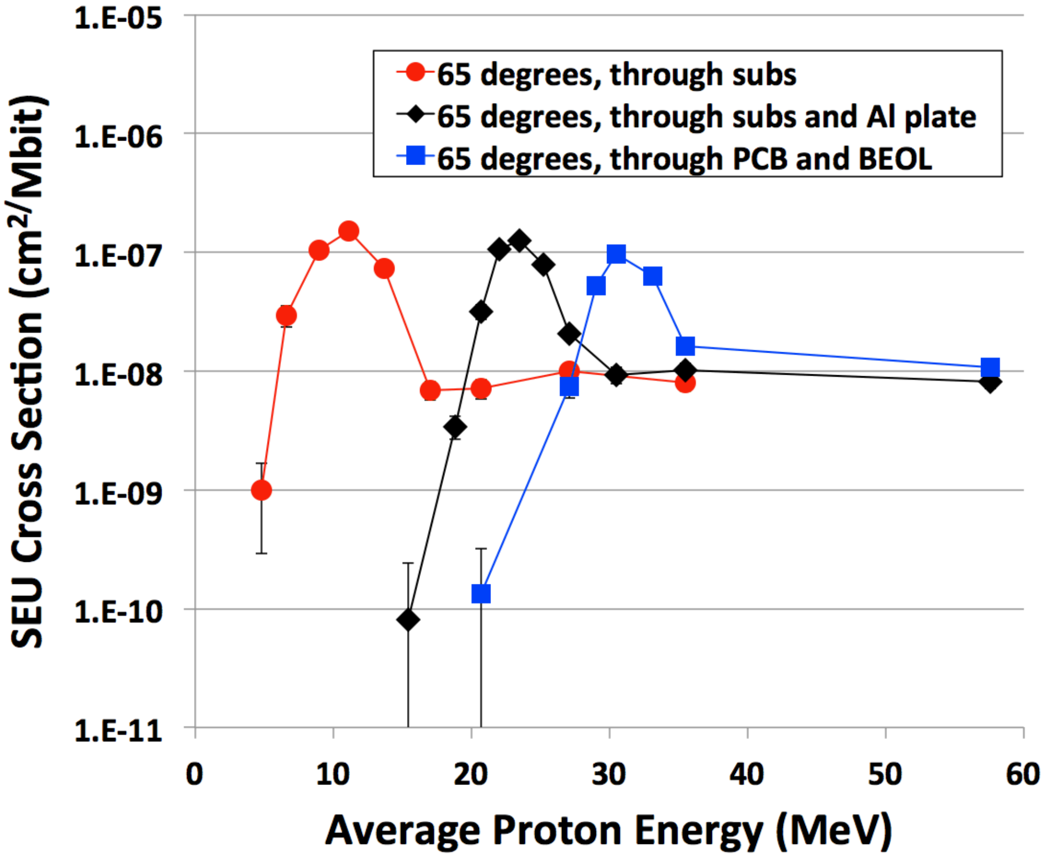
PDI significantly contributes to total SEU rate



- The environmental models used in this study (and previous studies) do not account for secondary protons generated in shielding, which can dominate the flux of low energy protons [J. Adams, TNS 2012]
  - Therefore, PDI may contribute more to the total SEU rate than shown in this and previous studies

Method also works on encapsulated parts



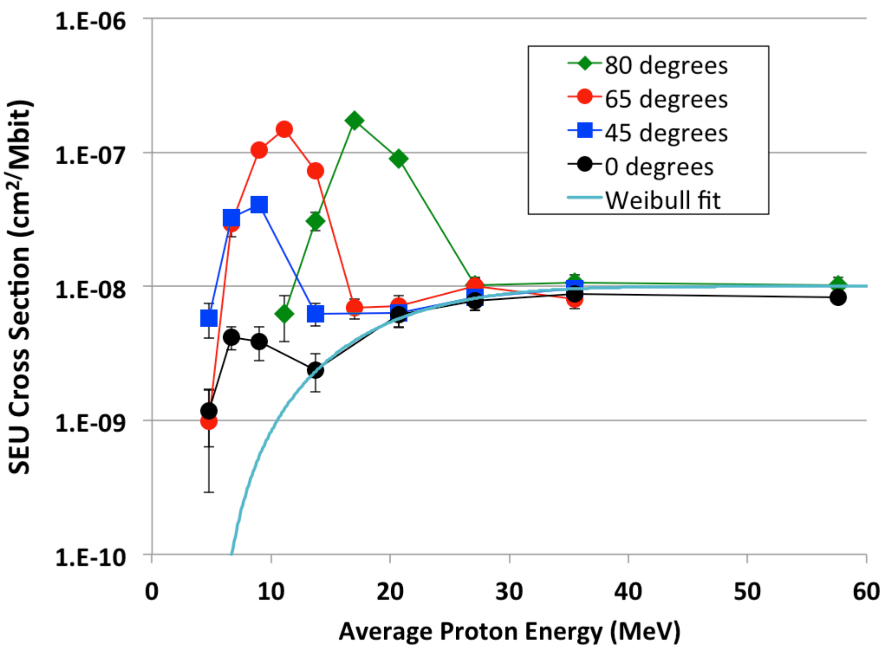
- **Thicker package materials shift curves to higher energies, but peak cross section is nearly identical**

Summary

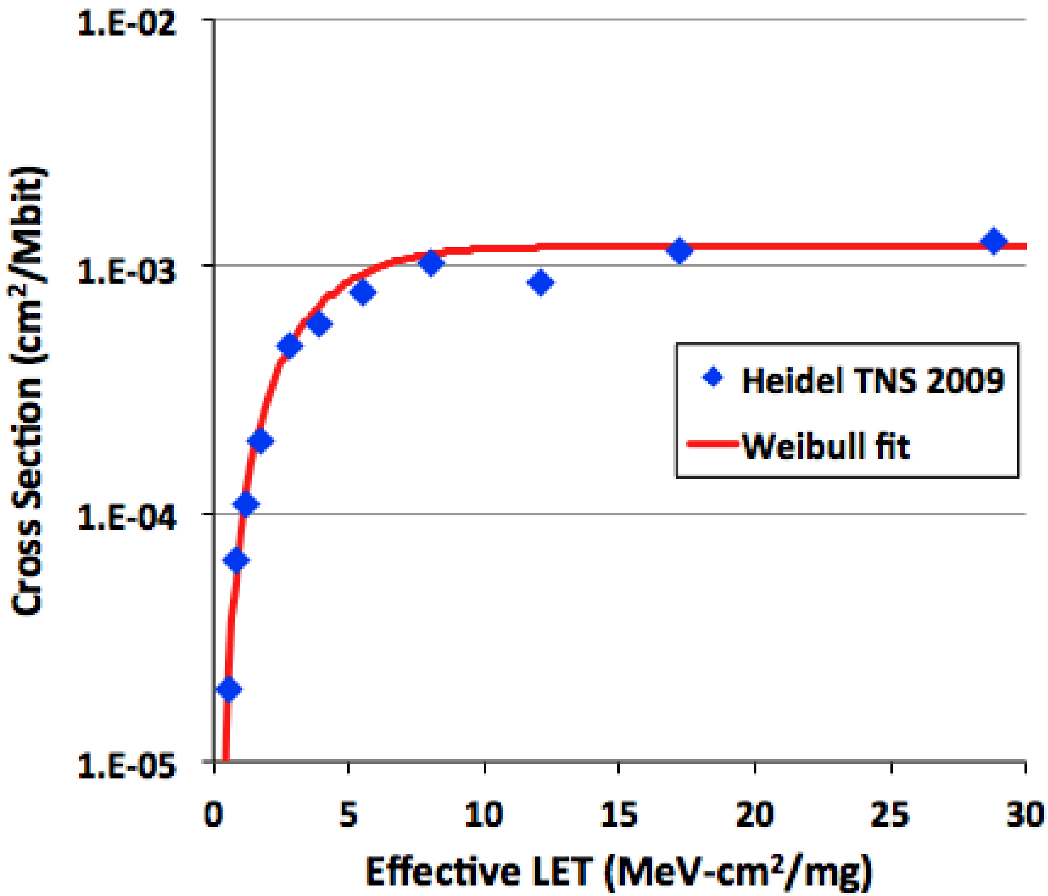
- **A high-energy proton beam can be degraded to produce a low-energy spectrum that matches that of all shielded space environments**
  - **This observation dramatically simplifies PDI rate prediction, allowing tests at high-energy facilities, on encapsulated parts, without knowledge of circuit design**
    - Practical guidelines for applying this rate prediction method are given in the paper

- **Increasing beam angle increases proton effective LET and increases PDI cross sections**

Backup slides



1.E-06
1.E-07
1.E-08
1.E-09
1.E-10
SEU Cross Section (cm²/Mbit)
0
10
20
30
40
50
60
Average Proton Energy (MeV)
80 degrees
65 degrees
45 degrees
0 degrees
Weibull fit



1.E-02
1.E-03
1.E-04
1.E-05
Cross Section (cm²/Mbit)
0
5
10
15
20
25
30
Effective LET (MeV-cm²/mg)
Heidel TNS 2009
Weibull fit