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The contribution of low-energy protons to the total on-orbit SEU rate

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Previous studies on the contribution of LEPs to total error rate

Study	Max. Error Rate from LEPs / Error Rate from *All Particles*	*All Particles* includes	Circuit
Heidel *et al.*, TNS Dec 2008	0.91	LEPs + HEPs	65 nm SOI SRAM
Hubert *et al.*, Proc. RADECS 2009	0.90	LEPs + HEPs + HIs	45 nm SRAM
Dodds *et al.*, TNS Dec 2014	0.45	LEPs + HEPs + HIs	65 nm SOI SRAM
Sierawski *et al.*, TNS Dec 2009	0.41	LEPs + HEPs + HIs	65 nm bulk SRAM
Haddad *et al.*, TNS June 2011	0.23	LEPs + HEPs + HIs	90 nm bulk SRAM
Cannon *et al.*, TNS Dec 2010	0.17	LEPs + HEPs + HIs	90 nm bulk SRAM
Sukhaseum *et al.*, NSREC 2014	0.005	LEPs + HEPs	45 nm bulk SRAM
Seifert *et al.*, TNS Dec 2011	0.003	LEPs + HEPs	32 nm bulk latches

- **Each study**
  - **Used different methods**
  - **Focused on different space environments**
  - **Used a small # of different circuits**
- **Results are not expected to be the same, but these differences and the small # of circuits investigated in each study have made it difficult to evaluate the general importance of LEP effects**
- **This study evaluates the general importance of LEPs by applying the same method to many circuits and tech nodes**

Circuits tested with protons at TRIUMF

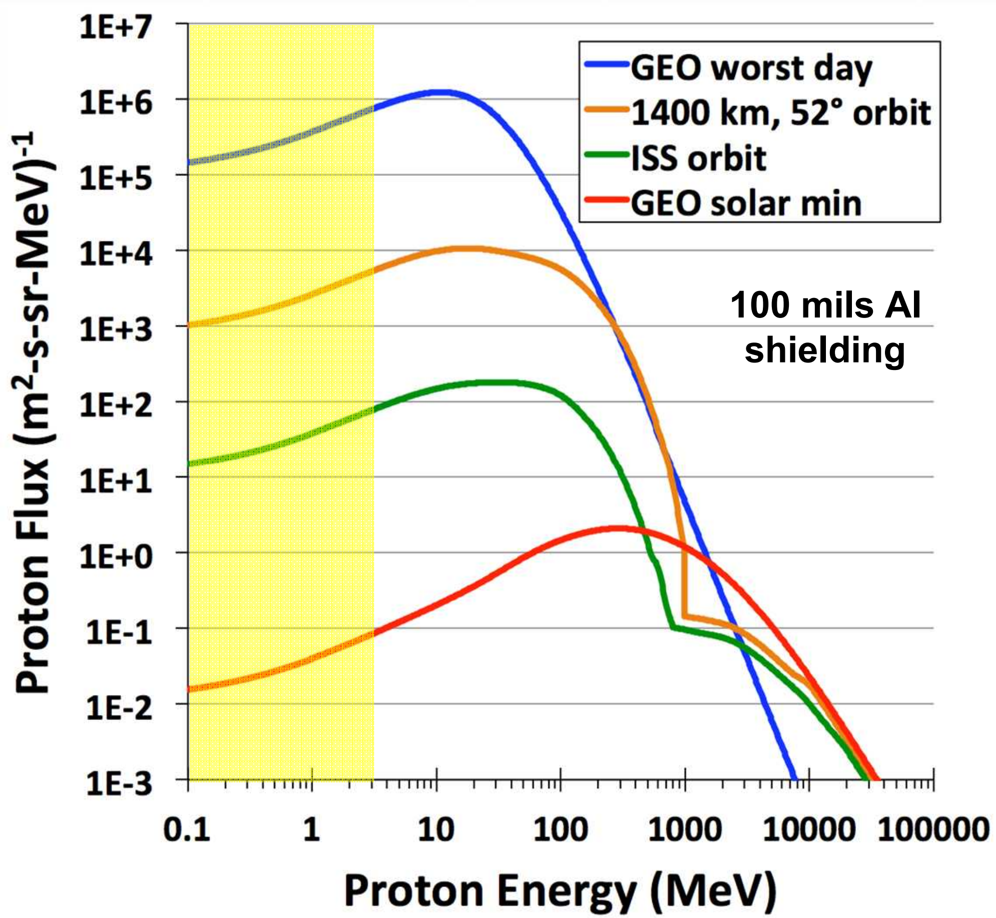
ID #	Circuit type	Technology	Designed by	Model No.	V_{DD}	Proton data from	Heavy ion data avail?
1a	SRAMs	20 nm bulk	Xilinx	Kintex UltraScale XCKU040	nominal	This work	Yes
1b					25% undervoltage		No
2	FFs	20 nm bulk	Vanderbilt	Test Structure	10% overvoltage	This work	Yes
3a	SRAM	28 nm bulk	*"Vendor A"*	Test Structure	nominal	This work	Yes
3b					45% undervoltage		
4	SRAM	40 nm bulk	TSMC	Test Structure	10% overvoltage	Prev. work	No
5	SRAM	45 nm SOI	IBM	Test Structure	10% undervoltage	Prev. work	Yes
6	SRAM	55 nm bulk	*"Vendor B"*	*Proprietary*	nominal	This work	No
7	SRAM	55 nm bulk	TSMC	Test Structure	nominal	Prev. work	No
8	SRAM	65 nm SOI	IBM	Test Structure	30% undervoltage	Prev. work	Yes
9	SRAM	65 nm bulk	Xilinx	Virtex-5QV XQR5VFX130	nominal	This work	Yes
10	SRAM	65 nm bulk	Cypress	CY7C1512KV18	nominal	This work	Yes
11	SRAM	90 nm bulk	Cypress	CY62137FV30LL	nominal	This work	No

- **Large collaboration worked to gather comprehensive data set**
- **Worst-case LEP error rates predicted for all the circuits above using the same method, from [Dodds *et al*., TNS 2014]**

Space Proton Environments

- **Physics of proton energy loss cause all shielded space environments to have qualitatively similar low-energy proton spectra, regardless of**
  - **Orbit**
  - **Solar conditions**
  - **Shielding thickness**
  - **Shielding material**

- **Energy spectroscopy measurements and simulations in [Dodds *et al.*, TNS 2014] showed that this space-like LEP spectrum is easily reproduced by degrading a high-energy proton beam**
  - **Allows us to deliver the environment of interest to the sensitive volumes with a known fluence**
  - **Dramatically simplifies LEP error rate prediction. Allows work to be done on encapsulated parts, without knowledge of IC design, and with no simulations required.**



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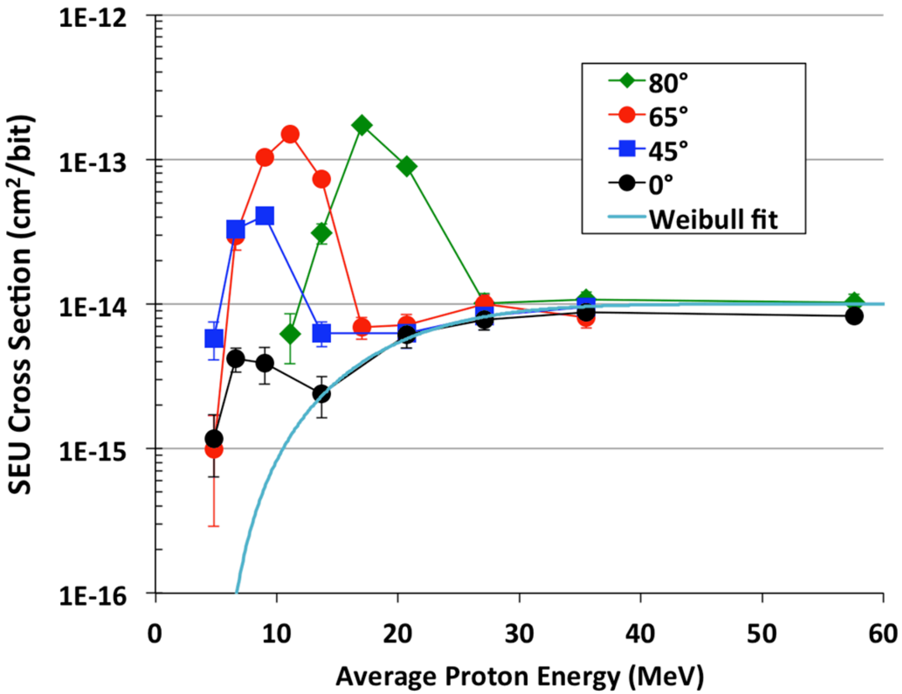
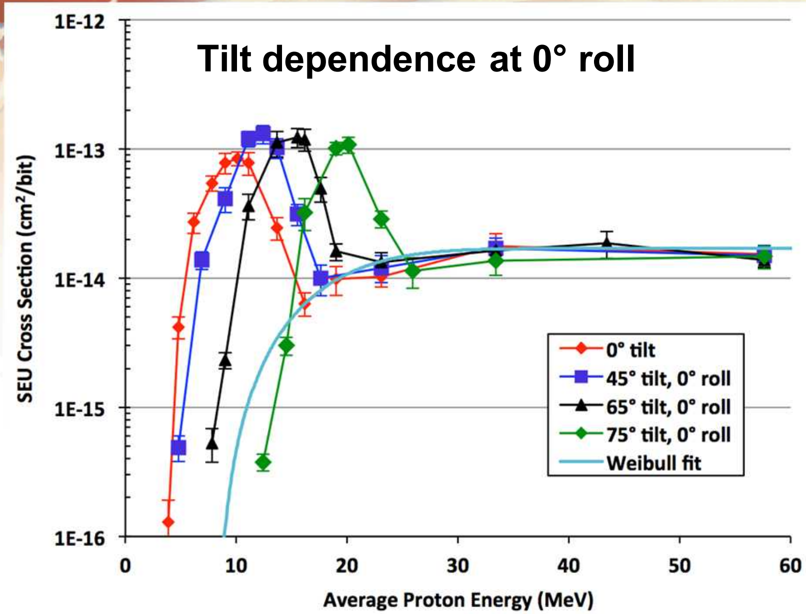
LEP error rate prediction method

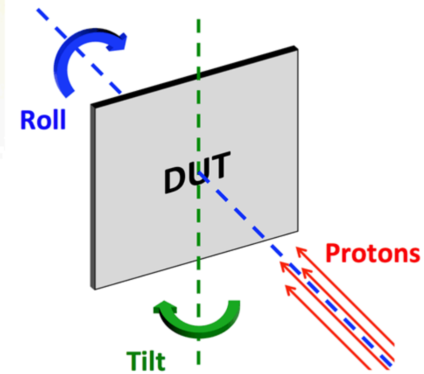
from [Dodds et al., TNS 2014]

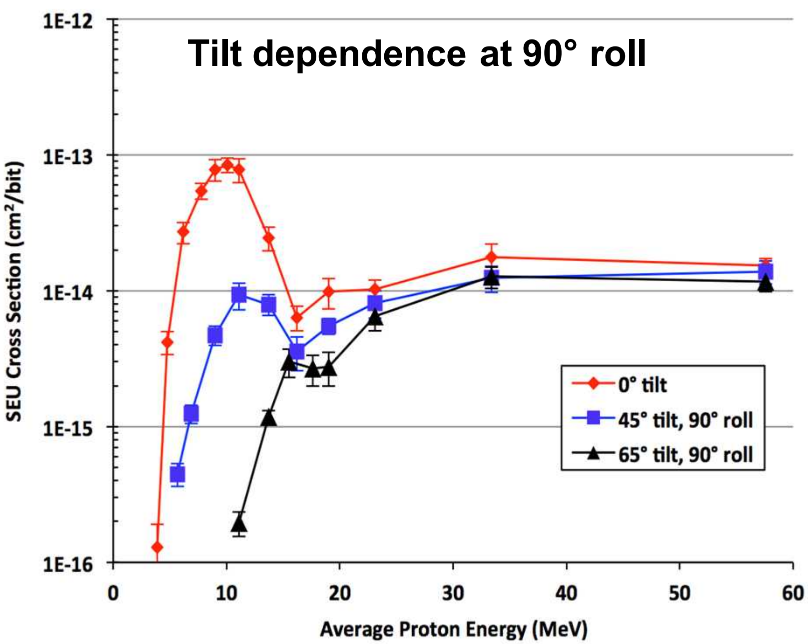


- IBM 65 nm SOI SRAM
- Irradiated through 350 µm Si Substrate
- Reduced proton energy from 70 MeV using plastic degraders
- Peaks at low average energies occur due to LEPs
- As beam angle ↑,
  - The peak cross sections ↑. This strong angular response has now been seen in 3 different SOI SRAMs, showing that grazing angles are the worst case for LEPs in SOI.
  - Peaks shift to higher average energies due to thicker intervening materials.
- At peaks, the LEP energy distribution found in all shielded space environments is delivered to the sensitive volumes with a known fluence, allowing a LEP error rate calculation
- Error rates for this same part were calculated using monoenergetic proton data in [Dodds, NSREC 2015 paper F-4], and were only 50% higher that those that used only the TRIUMF data, showing that this method is accurate
- Weibull fits to the high-energy proton data and heavy ion data used to calculate error rates, allowing us to calculate the % contribution of LEPs to the total error rate

LEP angular response of a 55 nm bulk SRAM

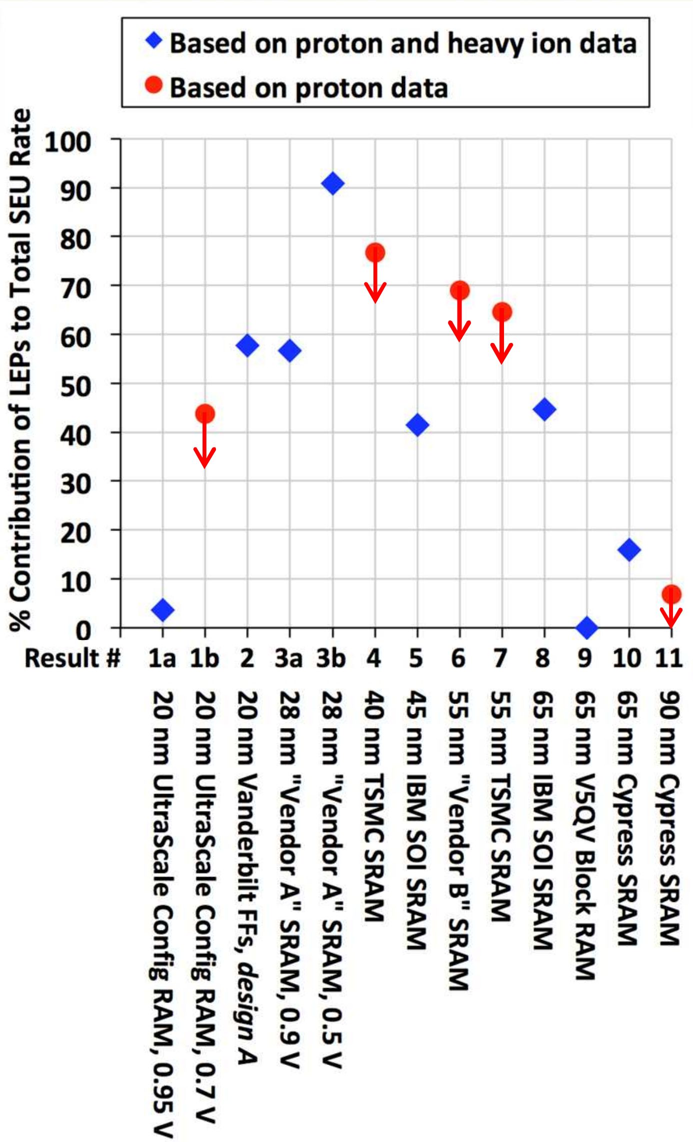






- This bulk SRAM has a very different angular response than the 4 SOI SRAMs
- A similar LEP angular dependence was found for 2 other bulk SRAMs
- Conclusion: For bulk SRAMs, normal incidence is at or near the worst-case angle for LEPs
  - All the LEP rate predictions in this paper used the worst-case angle
  - This same roll angle dependence probably also exists for heavy ions near the threshold LET in highly-scaled circuits. Therefore, if using tilted heavy ion beams, the worst case roll angle (0° or 90°) must first be found

Contribution of LEPs for GEO Worst Day, 100 mils Al



- **Across all circuits, when within 10% of nominal V_{DD}, the contribution of LEPs to the total SEU rate was < 77%**

- **No clear trend with scaling**

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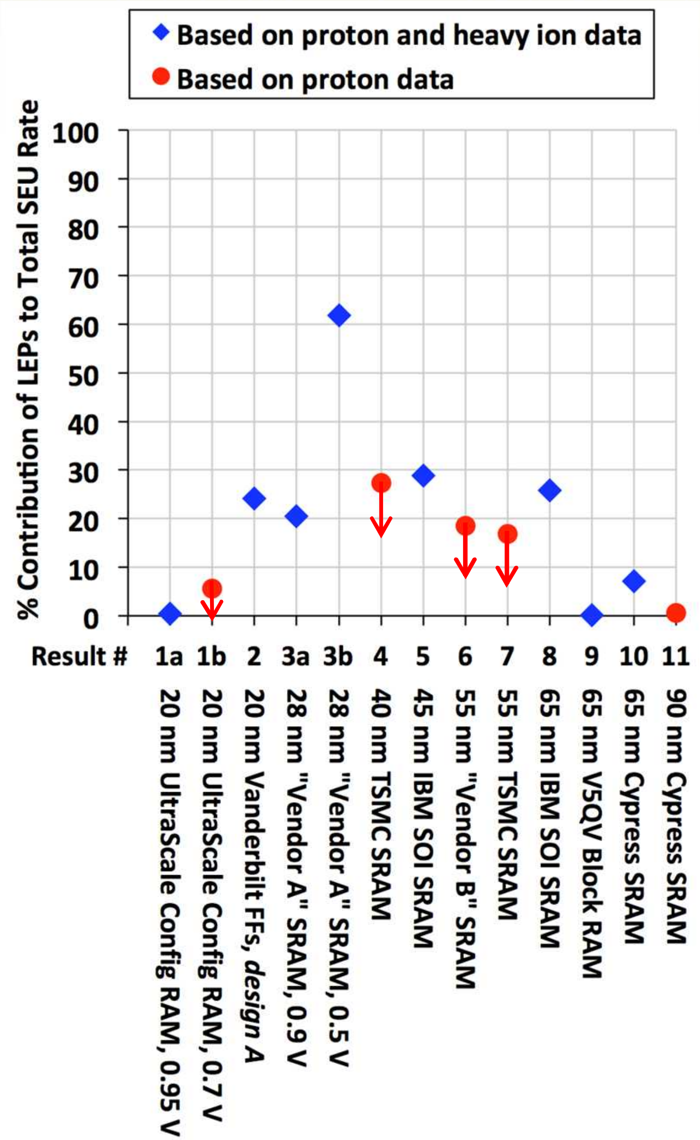
Contribution of LEPs for ISS orbit, 100 mils Al



- **Across all circuits, when within 10% of nominal V_{DD}, the contribution of LEPs to the total SEU rate was < 29%**

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Maximum contribution of LEPs

Orbit	Shielding	Max. % contribution of LEPs to Total SEU rate across all 11 circuits when within 10% of nominal V_{DD}
GEO worst day	100 mils Al	77 %
	500 mils Al	40 %
1400 km, 52°	100 mils Al	42 %
	500 mils Al	16 %
ISS	100 mils Al	29 %
	500 mils Al	12 %
GEO solar min	100 mils Al	4 %
	500 mils Al	8 %

Largest. LEPs ↑ total SEU rate by up to 3.3×

2nd largest. LEPs ↑ total SEU rate by up to 0.7×

Summary

- The worst-case angle for low-energy protons is
  - grazing angles, for SOI circuits
  - at or near normal incidence, for bulk circuits

  Difference is attributable to differences in sensitive volume thickness

- Across many circuits from the 20-90 nm nodes and when operating within 10% of nominal V_{DD}, LEPs increase the total SEU rate by up to
  - 3.3× for worst case environment (GEO Worst day, 100 mils Al)
  - 0.7× across the other seven environments considered

- Although contributions of up to 3.3× are significant, these contributions are smaller than some have feared (e.g., 100×)

- These results suggest that the best approach is to calculate the total error rate from high energy protons and heavy ions, then multiply it by some safety margin. If you can tolerate that error rate, then it may be justified to waive LEP tests.