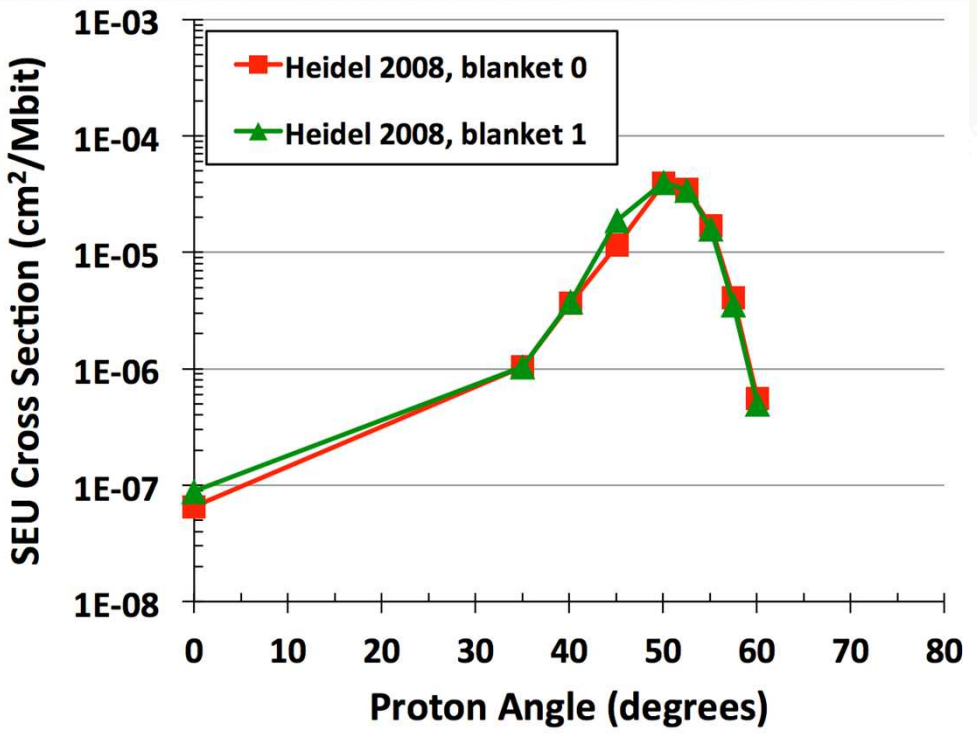
SAND2015-7241C

New insights gained on mechanisms of low-energy proton-induced SEUs by minimizing energy straggle

N. A. Dodds, P. E. Dodd, M. R. Shaneyfelt, F. W. Sexton, M. J. Martinez, J. D. Black, P. W. Marshall, R. A. Reed, M. W. McCurdy, R. A. Weller, J. A. Pellish, K. P. Rodbell, and M. S. Gordon

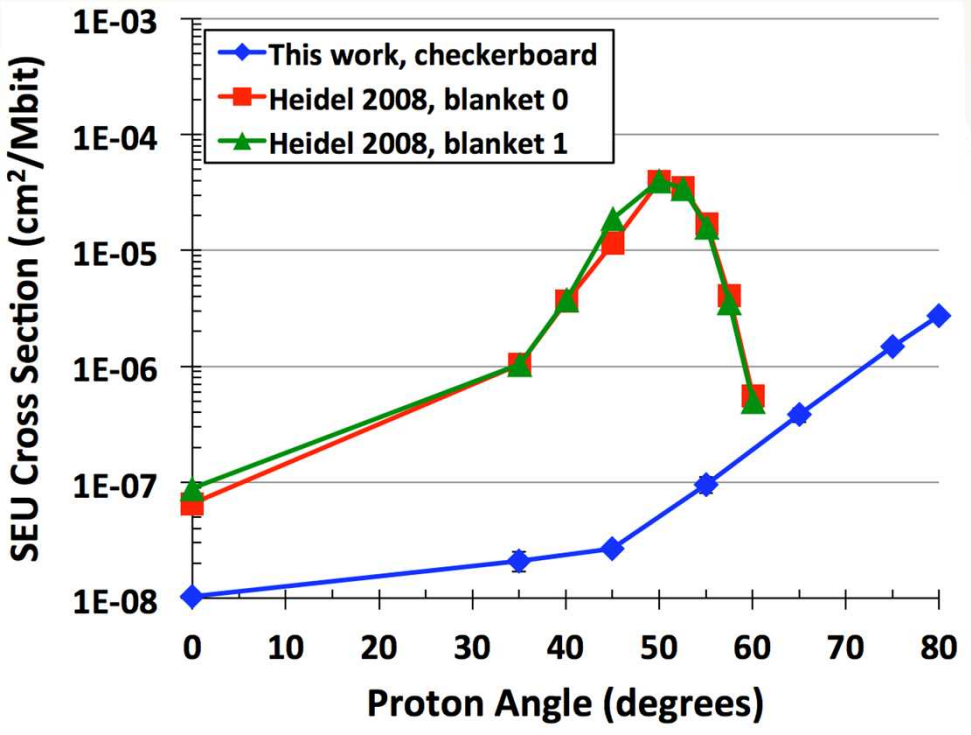
Supported by Lab Directed Research and Development program at Sandia National Laboratories, a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the **United States Department of Energy**, under contract DE-AC04-94AL85000.

Conventional LEP measurements



- **Heidel's 2008 work used**
  - **IBM 65 nm SOI SRAM biased to 1.0 V**
  - **1 MeV protons, in a vacuum**
  - **Irradiated though 11 µm of BEOL overlayers**
    - Significant energy loss
    - Significant energy straggle
    - Significant flux attrition
    - Significant angular scattering

LEP measurements of this work

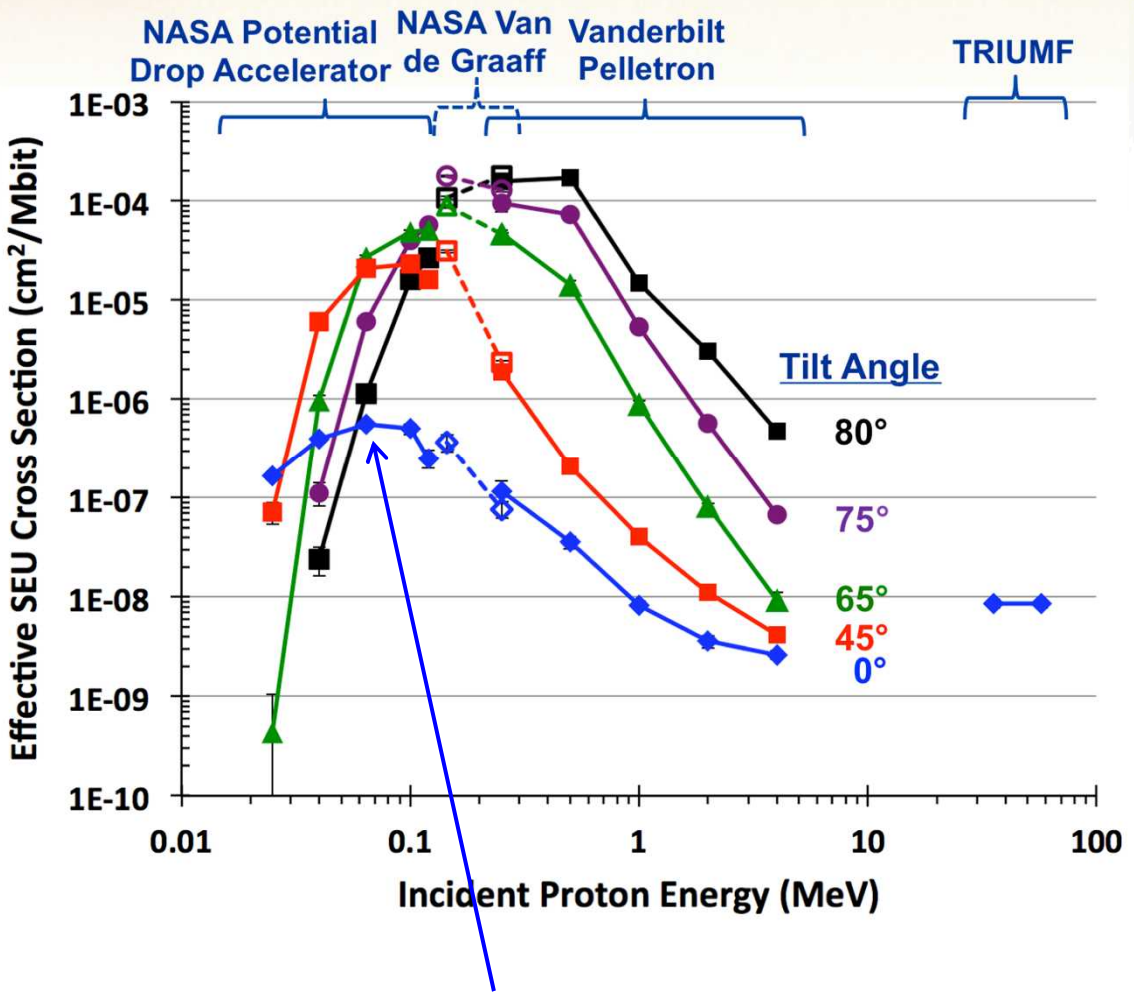


- **Heidel's 2008 work**
  - **IBM 65 nm SOI SRAM biased to 1.0 V**
  - **1 MeV protons, in a vacuum**
  - **Irradiated though 11 µm of BEOL materials**
    - Significant energy loss
    - Significant energy straggle
    - Significant flux attrition
    - Significant angular scattering
- **This work**
  - **IBM 65 nm SOI SRAM biased to 1.0 V**
  - **1 MeV protons, in a vacuum**
  - **Irradiated though 0.15 µm of SiO_2**
    - Far less energy loss
    - Far less energy straggle
    - Far less flux attrition
    - Far less angular scattering

Experimental Details

- **Si Substrate of IBM 65 nm SOI SRAM was completely removed via a XeF_2 etch,** as done in [Kanyogoro et al., TNS 2010], [Shaneyfelt et al., TNS 2012]
  - **Sensitive volumes only covered by 150-nm thick buried oxide**
- **Used 3 low-energy accelerators: Vanderbilt Pelletron, Goddard Van de Graaff, Goddard Potential Drop Accelerator**
  - **Tuned proton beams to energies of 25 keV to 4 MeV**
  - **Maintained monoenergetic beams by testing in vacuum and not using degraders**
  - **Tested at angles of 0° to 80°**
- **Checkerboard patterns**
- **SRAM not exercised during irradiations**
- **Room temperature**

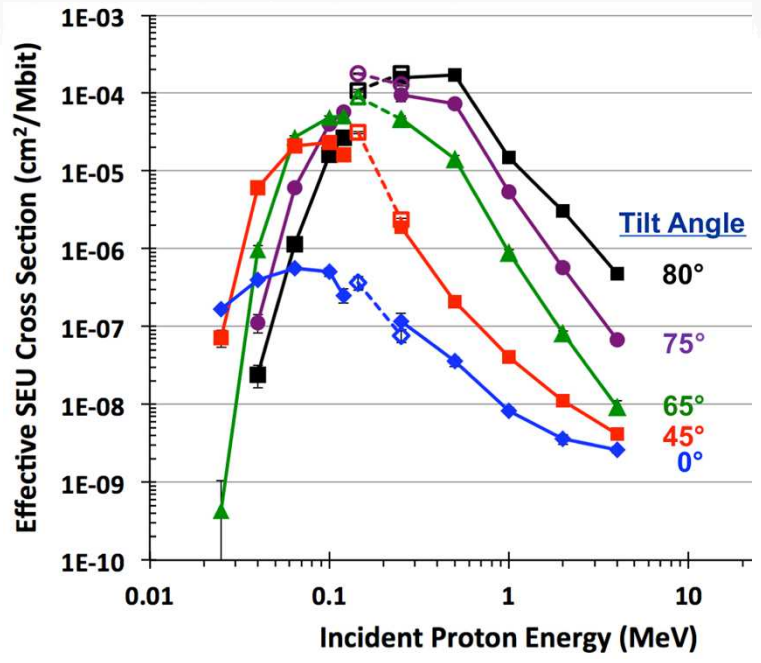
LEP Energy and Angular Dependence

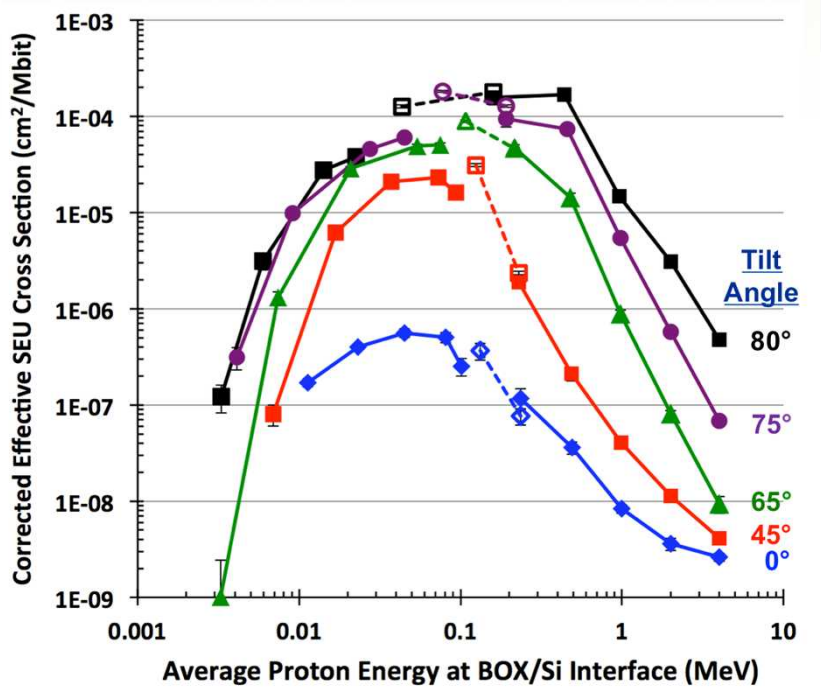


- Error bars represent 95% confidence interval
- At similar energies, cross sections fairly consistent across facilities
- Very strong energy and angular dependences seen
- Even 25 keV proton beams caused SEUs
  - Lowest energy particles ever observed to cause SEUs

- Max cross section occurred near Bragg peak energy of ~50 keV
  - Expected for years, and finally shown!
  - Shows that proton direct ionization is dominant mechanism

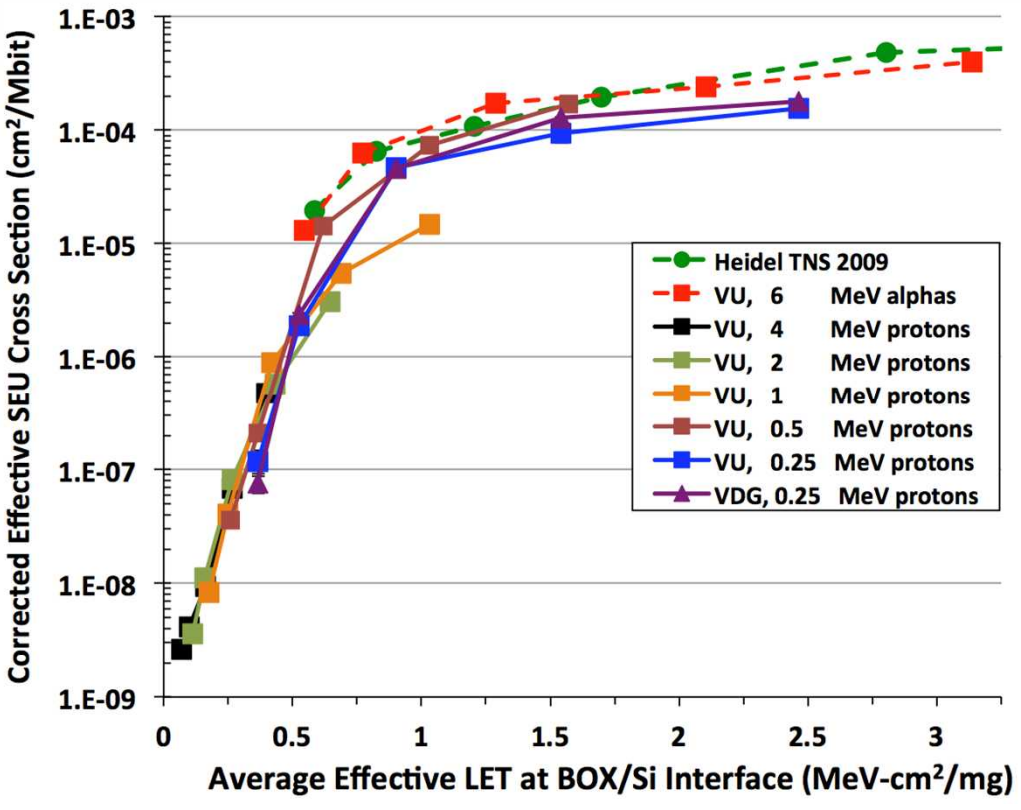
Correcting results to account for energy loss and flux attrition in BOX using SRIM





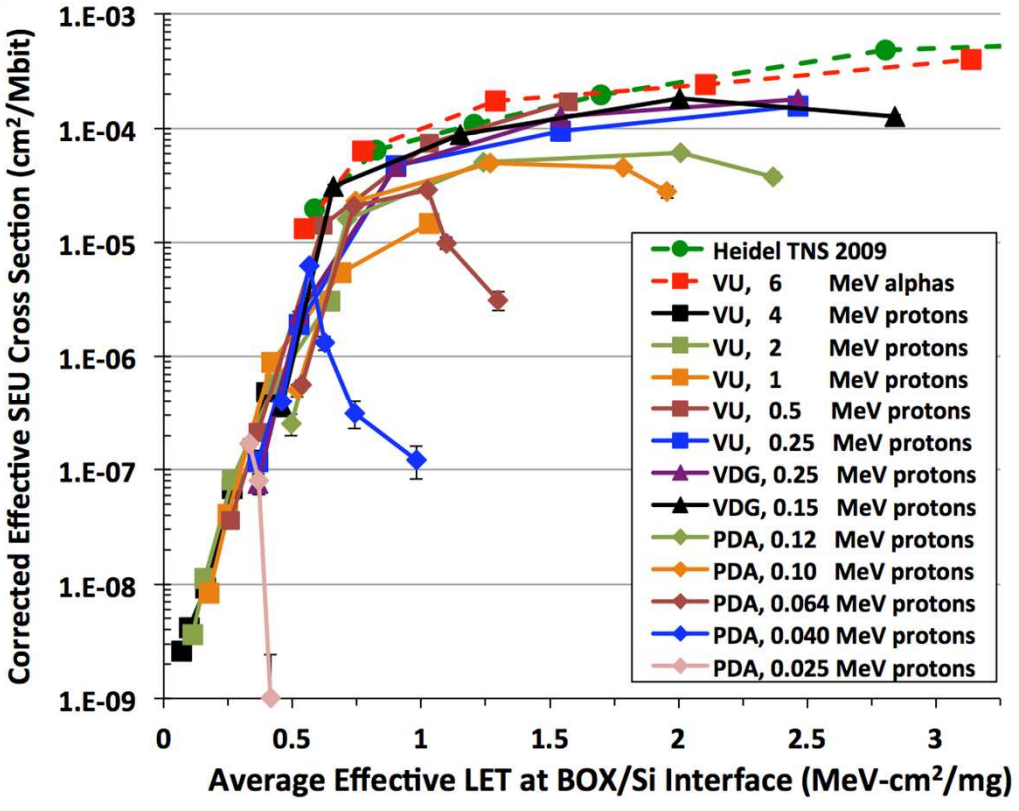
- Corrections reveal that larger angles caused higher SEU cross sections across all energies
- Grazing angles are the worst-case for LEP effects in SOI circuits, per these results and those of [Dodds, NSREC 2015 paper B-1]
- However, for bulk circuits, normal incidence is the worst-case for LEP effects, per [Dodds, NSREC 2015 paper B-1]

Results, replotted vs. Effective LET using SRIM



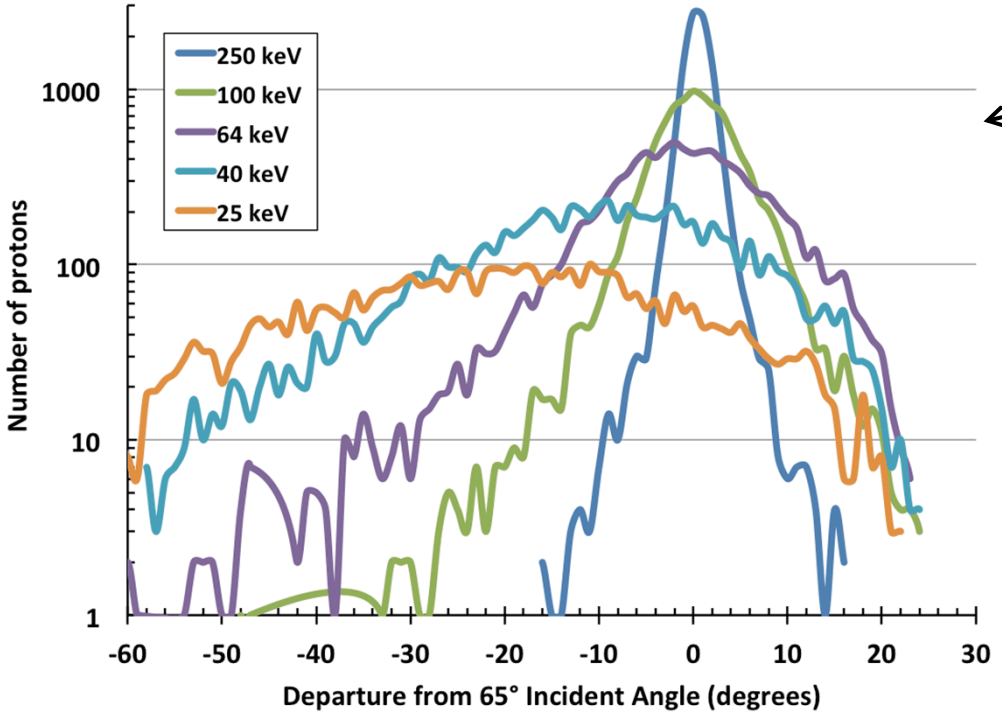
- **Excellent agreement of data across a broad range of particle species, angles, and energies**
- **Proves that direct ionization is the dominant mechanism for LEP-induced SEUs, at least in this circuit**

Results, replotted vs. Effective LET using SRIM



- Data taken with with lowest energy proton beams diverge from main curve at highest angles
- Other SRIM simulations show the cause:
  - Proton energies are too low to maintain their effective LETs all the way through the 60-nm thick sensitive volume

Angular scattering affects LEP measurements



- SRIM simulations of 10k protons at different initial energies through 150-nm buried oxide at 65° angle
  - Angular histograms generated
- As initial energy reduced, protons are more likely to scatter at large angles
- Negative angles on X-axis correspond to shorter path lengths through BOX
- At lowest initial energy, most protons were transmitted through BOX because scattering caused them to have shorter path lengths through BOX
- Therefore, scattering even affected these measurements though 150 nm SiO_2. Likely has stronger affect on conventional measurements through 10+ μm of material

Summary

- Conventional LEP SEU data are significantly affected by energy loss, energy straggle, flux attrition, and angular scattering in intervening materials
- This study dramatically reduced these sources of error by testing through only 150-nm thick SiO_2 layer, deepening insight into mechanisms
- Results show that grazing angles are the worst-case for LEPs, at least in these SOI circuits
- Results prove that direct ionization is the dominant mechanism for LEP-induced SEUs, at least in these circuits