National Aeronautics and Space Administration

Test Guideline for Evaluating Low-Energy Proton-Induced Single-Event Effects in Space Systems

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Finally, thanks to Ken Rodbell, Dave Heidel (IBM ret.), and their colleagues at IBM Yorktown Heights, Burlington, and East Fishkill for providing test devices and technical expertise.

Acronym Definitions

- BNL = Brookhaven National Laboratory
- CAD = Computer-Aided Design
- CMOS = Complementary Metal Oxide Semiconductor
- CNL = Crocker Nuclear Laboratory
- ESP = Emission of Solar Protons
  - M. A. Xapsos *et al.*, *IEEE Trans. Nucl. Sci.,* vol. 46, no. 6, pp. 1481-1485, 1999.
- ICRU = International Commission on Radiation Units & Measurements
- IUCF = Indiana University Cyclotron Facility
- IEEE = Institute of Electrical and Electronics Engineers
- LBNL = Lawrence Berkeley National Laboratory
- LET = Linear Energy Transfer
- NASA/GSFC = NASA Goddard Space Flight Center
- NIST PSTAR (National Institute of Standards and Technology)
  - http://physics.nist.gov/PhysRefData/Star/Text/PSTAR.html
- SEU = Single-Event Upset
- SNL = Sandia National Laboratories
- SOI = Silicon-On-Insulator
- SRAM = Static Random Access Memory
- SRIM = Stopping and Range of Ions in Matter
  - http://www.srim.org
- TAMU = Texas A&M University
- TNS = Transactions on Nuclear Science
- TRIUMF = Tri-University Meson Facility
  - Definition no longer used – dropped after University of Alberta joined the TRIUMF consortium (http://www.triumf.ca/)
- UCD = University of California/Davis

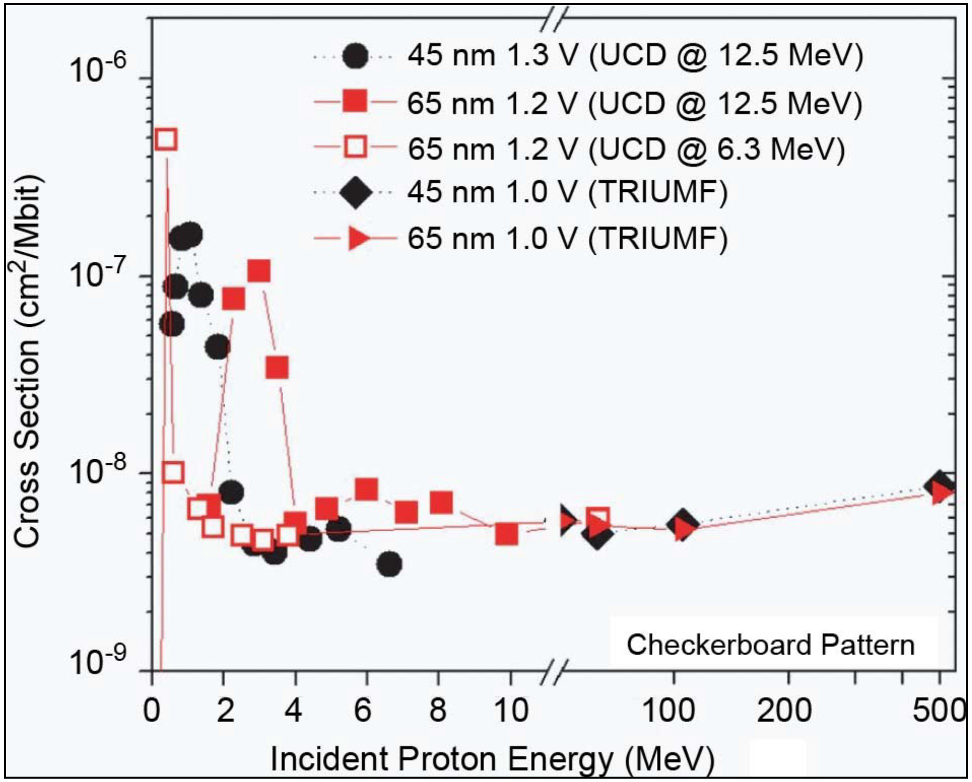
Elemental abbreviations used – *e.g.*, N = nitrogen, O = oxygen, *etc.*

Literature Background

- Observed first low-energy proton, direct ionization SEUs in 2007 through IBM internal effort
  - IBM 65 nm SOI CMOS latches and SRAM
  - K. P. Rodbell *et al.*, *IEEE Trans. Nucl. Sci.*, vol. 54, no. 6, pp. 2474-2479, Dec. 2007.
- Confirmed the following year by a NASA/GSFC, IBM, and Sandia National Labs collaboration
  - IBM 65 nm SOI CMOS SRAM
  - D. F. Heidel *et al.*, *IEEE Trans. Nucl. Sci.*, vol. 55, no. 6, pp. 3394-3400, Dec. 2008.
- Expanded research efforts reported in subsequent publications

Low-Energy Proton SEUs

IBM 45 and 65 nm SOI SRAMs

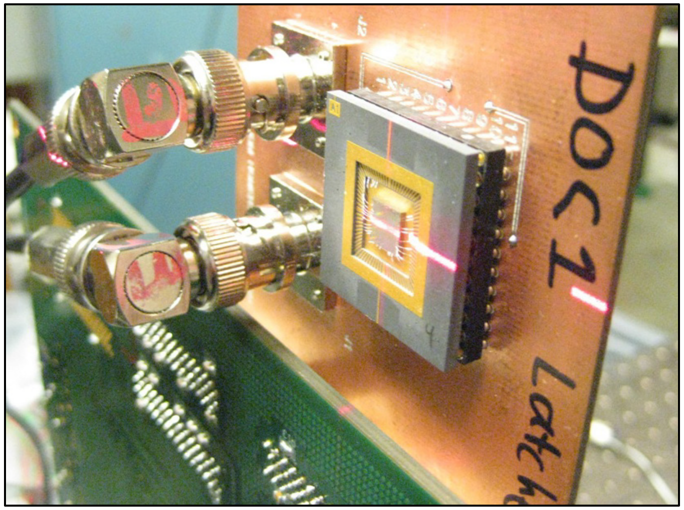


J. R. Schwank *et al.*, *IEEE TNS*, 2012.

Cross sections increase by one or more orders of magnitude below 2 MeV

Two Goals for Low-Energy Proton Test Guideline Development

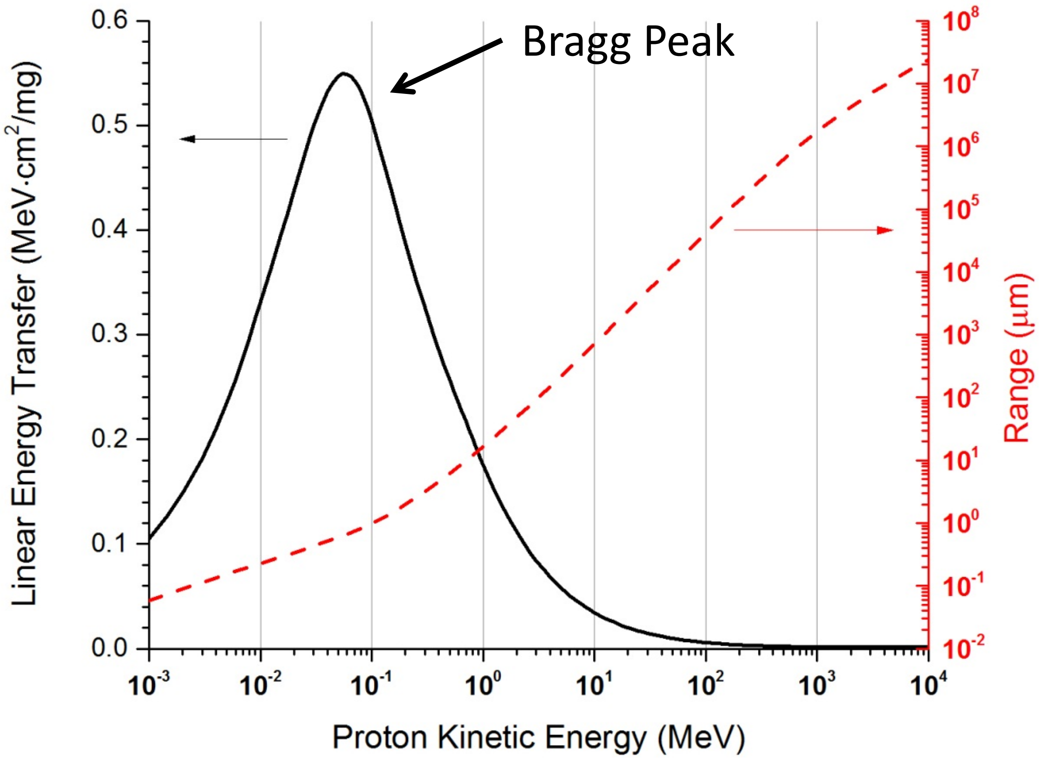
- Evaluate new technologies for low-energy proton sensitivity
  - Will it upset or not?
  - What accelerator source do I use?
- Determine effective error rate contribution from space environment
  - What's the incident environment?
  - How can you calculate an upset rate?



Device under test at UCD CNL.

Evaluation of Low-Energy Proton Sensitivity

Protons in Silicon

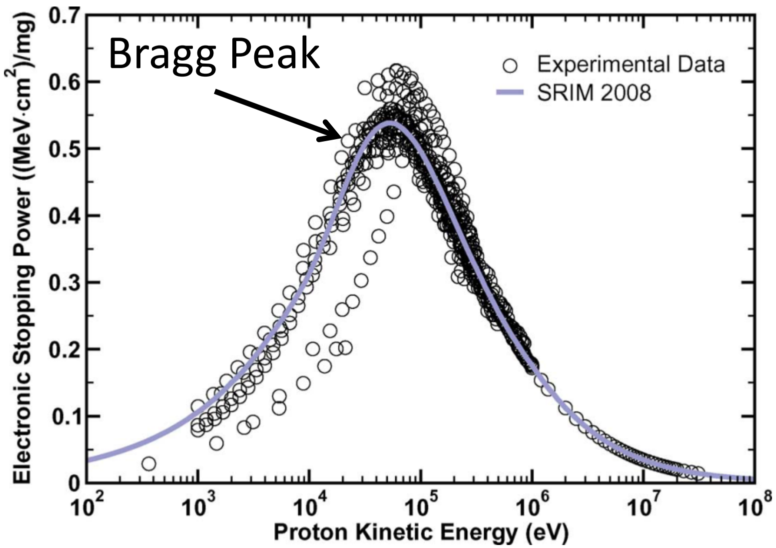


NIST PSTAR tool (ICRU Report 49, 1993)

- Only protons near the Bragg Peak can cause SEUs
  - Protons (and other ions) near end-of-range behave erratically

Evaluation of Low-Energy Proton Sensitivity

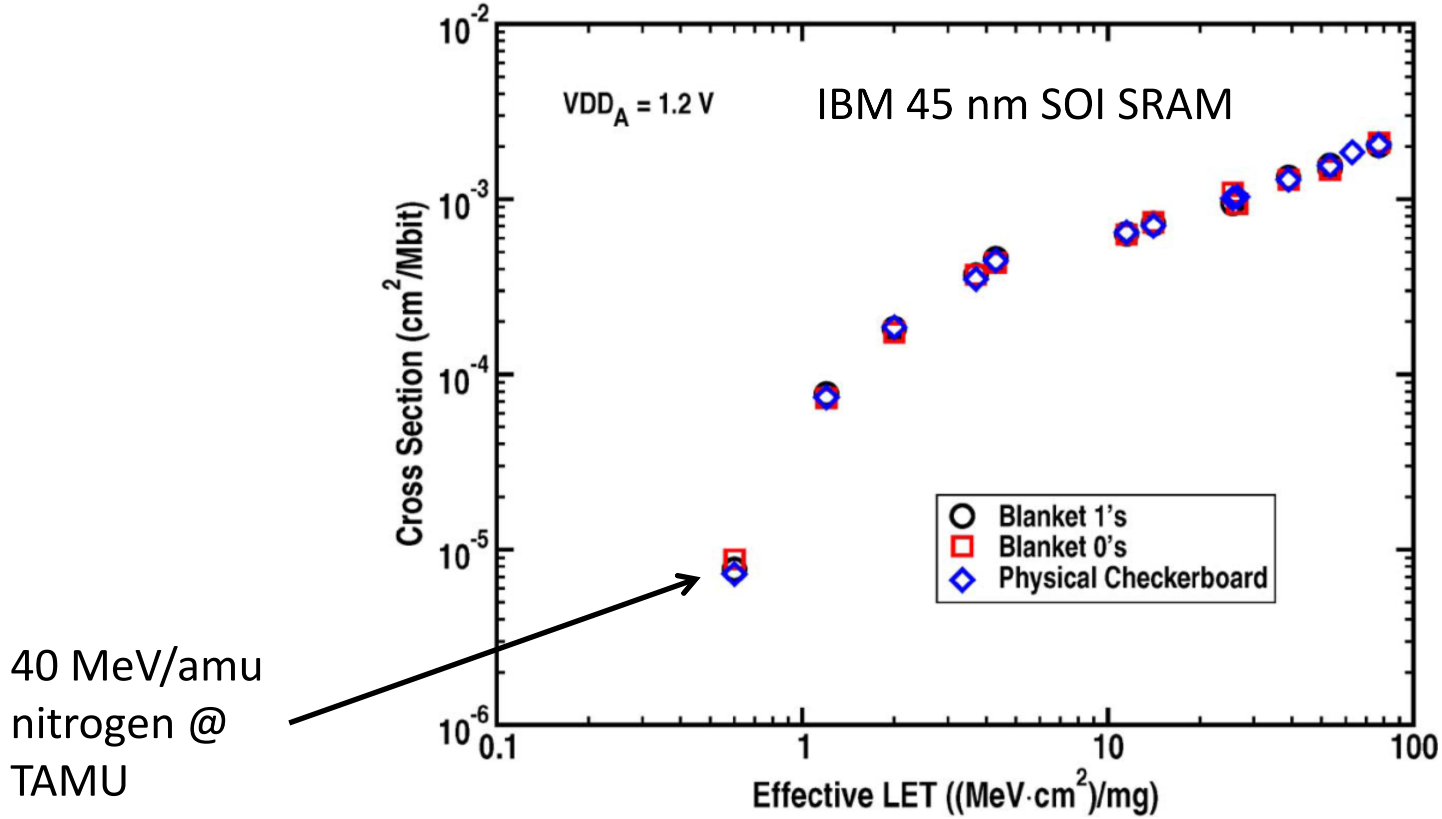
Protons in Silicon



B. D. Sierawski *et al.*, *IEEE TNS*, 2009.

- As proton energy decreases, the uncertainty in the experimental mass stopping power (LET) increases.
- Origin of the suggestion to use high-energy, light heavy ions as a surrogate
  - Sierawski *et al., IEEE TNS*, 2009.
  - He, C, N, and O
  - Greater than 16 MeV/amu
  - Higher energy beams could utilize heavier ions

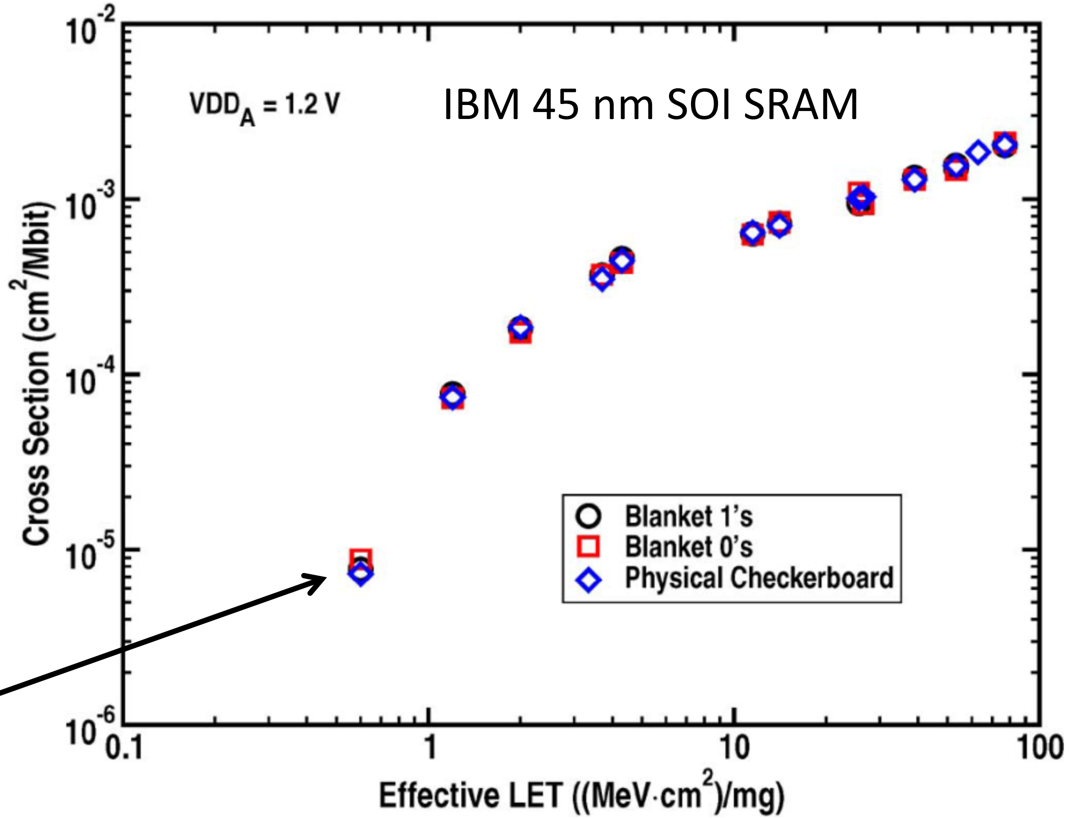
Evaluation of Low-Energy Proton Sensitivity



D. F. Heidel *et al.*, *IEEE TNS*, 2009.

Components with measurable cross sections below a LET of 1 MeV-cm^2/mg are likely sensitive to low-energy protons.

Evaluation of Low-Energy Proton Sensitivity



40 MeV/amu nitrogen @ TAMU

D. F. Heidel *et al.*, *IEEE TNS*, 2009.

Lingering questions as to whether or not low-energy proton and high-energy, light heavy ion upset mechanisms are identical.

Choosing an Accelerator Source

Van de Graaff

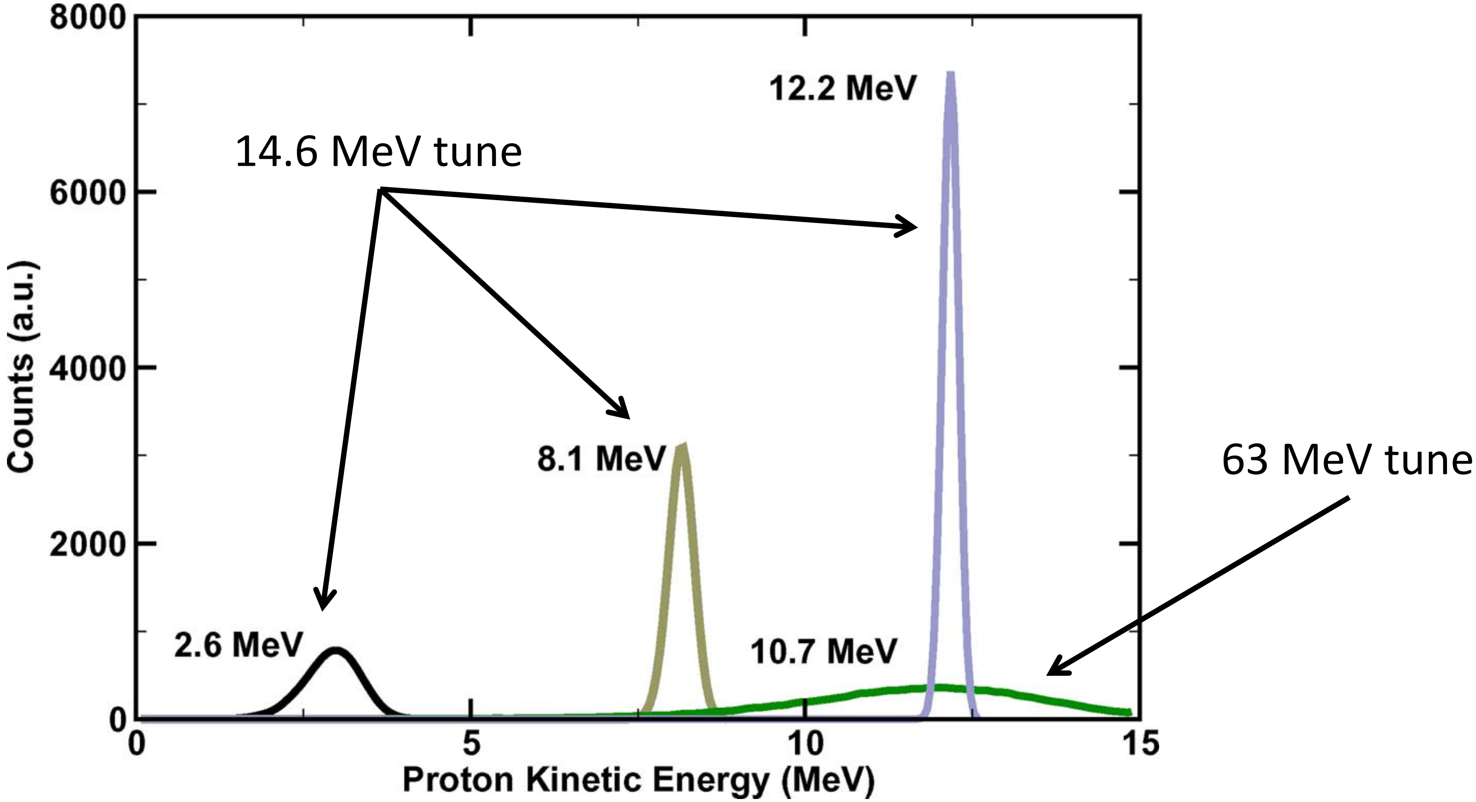
- Small, low-cost
- Energy range for modest machines tends to be less than 10 MeV – most less than 5 MeV
  - BNL and SNL Van de Graaffs are exceptions
- Energy width of tuned beam is excellent (~1 keV)
- Particle range is limited
  - Constrains angled irradiations

Cyclotron (Excludes synchrotrons)

- Large, high-cost
- Energy range up to 500 MeV
  - UCD = 6.5 MeV < x < 63 MeV
    - Excluding degraders
  - IUCF = 30 MeV < x < 200 MeV
  - TRIUMF = 70 MeV < x < 500 MeV
    - Excluding degraders
- Energy width is larger (typically of order 100 keV)
- Particle range is large
  - Less constraints, but more systematic uncertainty

Uncertainty of Degraded Beams

UCD CNL Proton Simulations

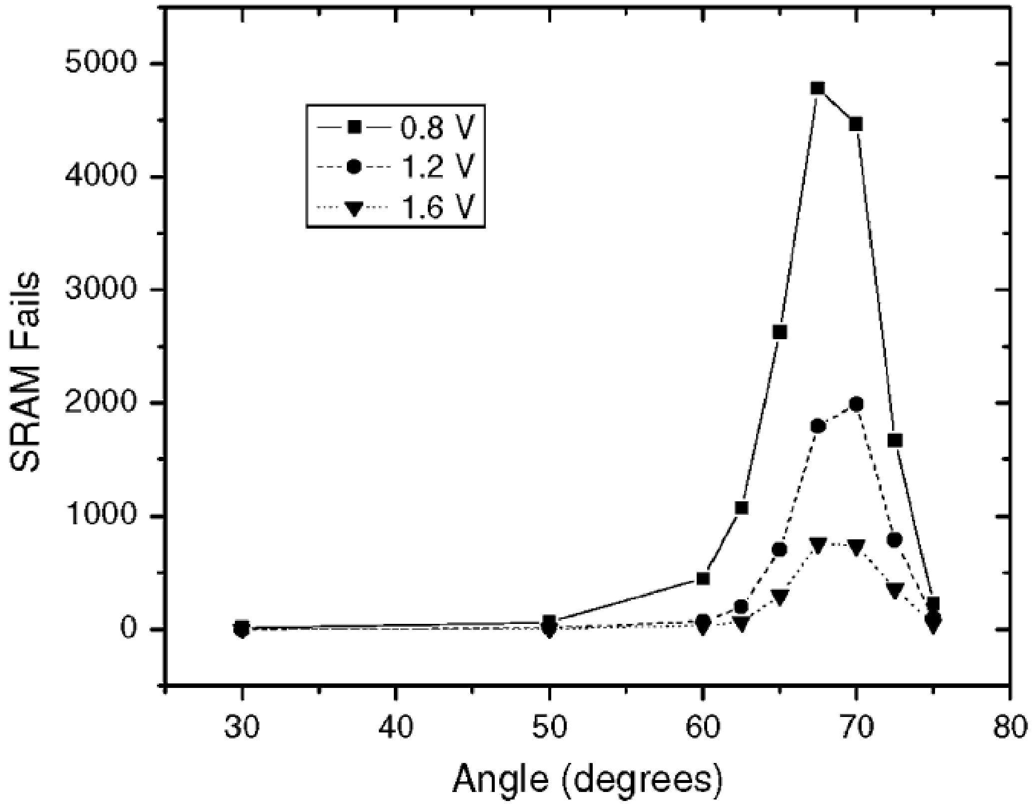


B. D. Sierawski *et al.*, *IEEE TNS*, 2009.

Degrading high-energy beams increases energy and range dispersion
Removes quasi-monoenergtic characteristics

Angular Effects with Protons

65 nm SOI SRAM Fails with 1.5 MeV Protons



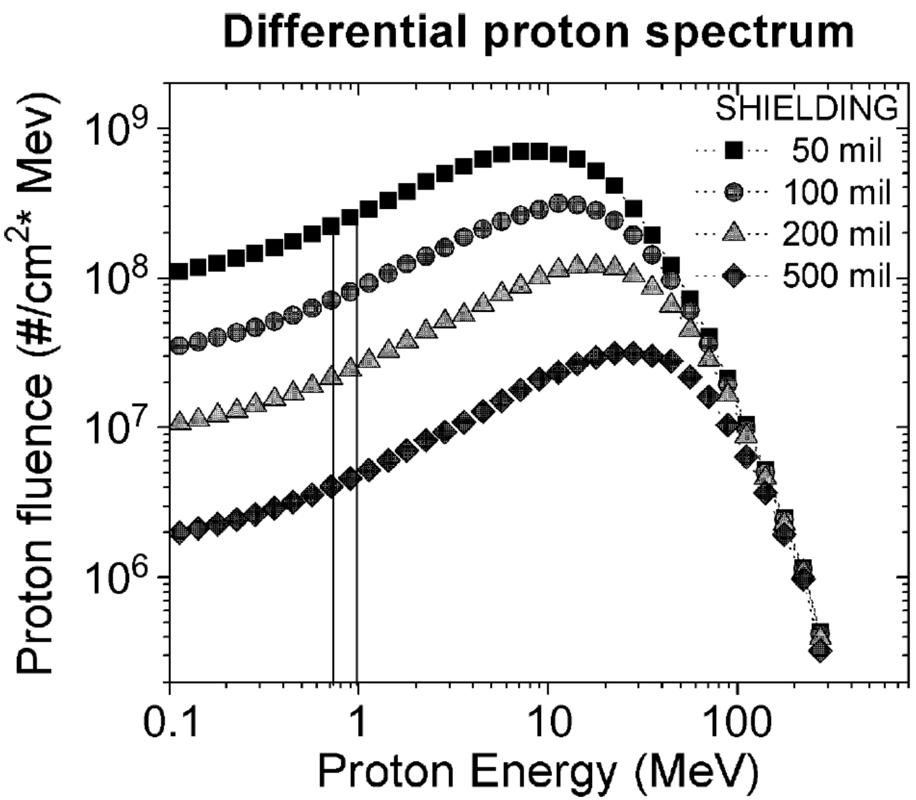
K. P. Rodbell *et al.*, *IEEE TNS*, 2007.

Path length (*i.e.*, angle of incidence) and LET affect efficacy of low-energy protons
Cannot capture this important effect with high-energy, light heavy ions

Considerations for Low-Energy Proton Measurements

- Measure and record materials in the beam line upstream from the device-under-test
- Experimentally determine the mean beam energy and beam energy-width at the device-under-test location
  - Angular dispersion knowledge a plus if attainable
- Complete transport calculations using accurate and properly ordered material stacks
  - Analytic methods acceptable, though Monte Carlo often required
- Different levels of systematic error in the form of energy loss straggling can be introduced depending on the type of device-under-test package, silicon thickness, degraders, *etc*.
- If the die is thinned, variations in proton stopping power can occur in different regions of the device producing non-uniform SEE response

Space Environment



D. F. Heidel *et al.*, *IEEE TNS*, 2008.

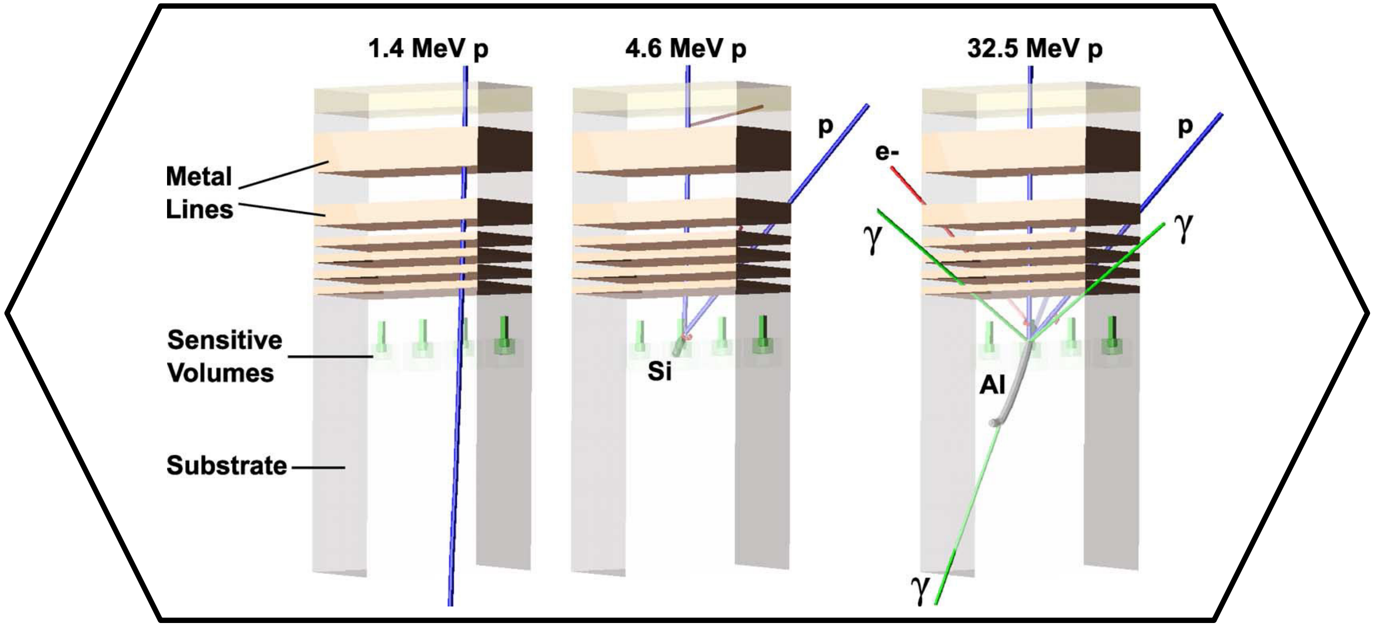
Incident environment defined in interplanetary space by ESP model (example here)

Some “slice” of the environment will impact sensitive components

Shielding does not eliminate low-energy protons
Accurate determination of local radiation environment requires 3-D CAD analysis

Low-Energy Proton Modeling

Inside box on a spacecraft



B. D. Sierawski *et al.*, *IEEE TNS*, 2009.

- Modeling, informed by accelerated ground data, is essential for on-orbit event rate prediction for low-energy proton effects
- Simulations must be 3-D and have adequate radiation transport physics to handle necessary electromagnetic interactions

Possible Modeling Techniques

Name	Type
Cannon 2010	Analytic
CREME96	Analytic
CRÈME-MC	Monte Carlo
Edmonds 2008	Analytic
MRED	Monte Carlo
MUSCA SEP^3	Monte Carlo
NOVICE	Monte Carlo
TIARA	Monte Carlo

Modeling name acronyms are defined in references below.

Caveat Emptor!

Caveat Emptor!

- Cannon 2010: E. H. Cannon *et al.*, *IEEE Trans. Nucl. Sci.,* vol. 57, no. 6, pp. 3493-3499, Dec. 2010.
- CREME96: https://creme.isde.vanderbilt.edu/ (other references available at URL)
- CRÈME-MC: https://creme.isde.vanderbilt.edu/ (other references available at URL)
- MRED: R. A. Weller *et al.*, *IEEE Trans. Nucl. Sci.,* vol. 57, no. 4, pp. 1726-1746, Aug. 2010.
- Edmonds 2008: L. D. Edmonds *et al.*, *IEEE Trans. Nucl. Sci.,* vol. 55, no. 5, pp. 2666-2678, Oct. 2008.
- MUSCA SEP^3: G. Hubert *et al.*, *IEEE Trans. Nucl. Sci.,* vol. 56, no. 6, pp. 3032-3042, Dec. 2009.
- NOVICE: T. M. Jordan, *IEEE Trans. Nucl. Sci.,* vol. 23, no. 6, pp. 1857-1861, Dec. 1976.
- TIARA: S. Uznanski *et al.*, *IEEE Trans. Nucl. Sci.,* vol. 57, no. 4, pp. 1876-1883, Aug. 2010.

Hardness Assurance Strategy

- Measure the upset cross section with long-range, low-LET, light ions (He, C, N, and O) to detect <u>potential</u> low-energy proton sensitivity
  - Determines potential sensitivity to low-energy protons
  - Should have energy greater than 16 MeV/amu, though 16 MeV/amu N and O at LBNL could be considered
  - Could be optional if already planning to test with low-energy protons
  - ***Assumes that upset mechanisms are the same/similar***
- Create an event model using low-LET data and technology information
  - Applicable if using Monte Carlo techniques
  - Some intentional ambiguity regarding "technology information"
- Validate the model by comparing it with the measured low-energy proton response
  - Some methods would skip directly to this step
- Use the [*calibrated*] model to predict the on-orbit error rate

Conclusions

- CMOS nodes at and below 90 nm have been identified as sensitive to low-energy proton direct ionization
- Energy/range variation inherent to particles near end-of-range increase low-energy proton testing systematic errors
- Hardness assurance practices for including low-energy proton sensitivity must address the issue with a combination of *relevant data collection* and *calibrated models*

Main References and Additional Reading

- S. Gerardin *et al.*, "Exploiting a low-energy accelerator to test commercial electronics with low-LET proton beams," presented at the European Conf. on Radiation Effects on Components and Systems, *IEEE*: Athens, Greece, 2006.
- K. P. Rodbell *et al.*, "Low-Energy Proton-Induced Single-Event-Upsets in 65 nm node, Silicon-on-Insulator, Latches and Memory Cells," vol. 54, no. 6, pp. 2474-2479, Dec. 2007.
- D. F. Heidel *et al.*, "Low energy proton single-event upset test results on 65 nm SOI SRAM," *IEEE Trans. Nucl. Sci.,* vol. 55, no. 6, pp. 3394-3400, Dec. 2008.
- D. F. Heidel *et al.*, "Single-event upsets and multiple-bit upsets on a 45 nm SOI SRAM," *IEEE Trans. Nucl. Sci.,* vol. 56, no. 6, pp. 3499-3504, Dec. 2009.
- B. D. Sierawski *et al.*, "Impact of low-energy proton induced upsets on test methods and rate predictions," *IEEE Trans. Nucl. Sci.,* vol. 56, no. 6, pp. 3085-3092, Dec. 2009.
- N. Haddad *et al.*, "Heavy ion, high energy and low energy proton SEE sensitivity of 90-nm RHBD SRAMs," presented at the European Conf. on Radiation Effects on Components and Systems, Langenfeld, Austria, 2010.
- J. A. Pellish *et al.*, "Impact of Spacecraft Shielding on Direct Ionization Soft Error Rates for Sub-130 nm Technologies," *IEEE Trans. Nucl. Sci.,* vol. 57, no. 6, pp. 3183-3189, Dec. 2010.
- E. H. Cannon *et al.*, "Heavy Ion, High-Energy, and Low-Energy Proton SEE Sensitivity of 90-nm RHBD SRAMs," *IEEE Trans. Nucl. Sci.,* vol. 57, no. 6, pp. 3493-3499, Dec. 2010.
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