National Aeronautics and Space Administration

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

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To be presented by J. Pellish at the 2012 Microelectronics Reliability & Qualification Workshop (MRQW), 11-12/Dec/2012 in Los Angeles, CA and published on https://nepp.nasa.gov/

This work was supported in part by the NASA Electronic Parts and Packaging (NEPP) program and the Defense Threat Reduction Agency (DTRA).

Thanks to Dr. Carlos Castaneda and the staff at the University of California/Davis Crocker Nuclear Laboratory for enabling many NASA low-energy proton experiments.

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

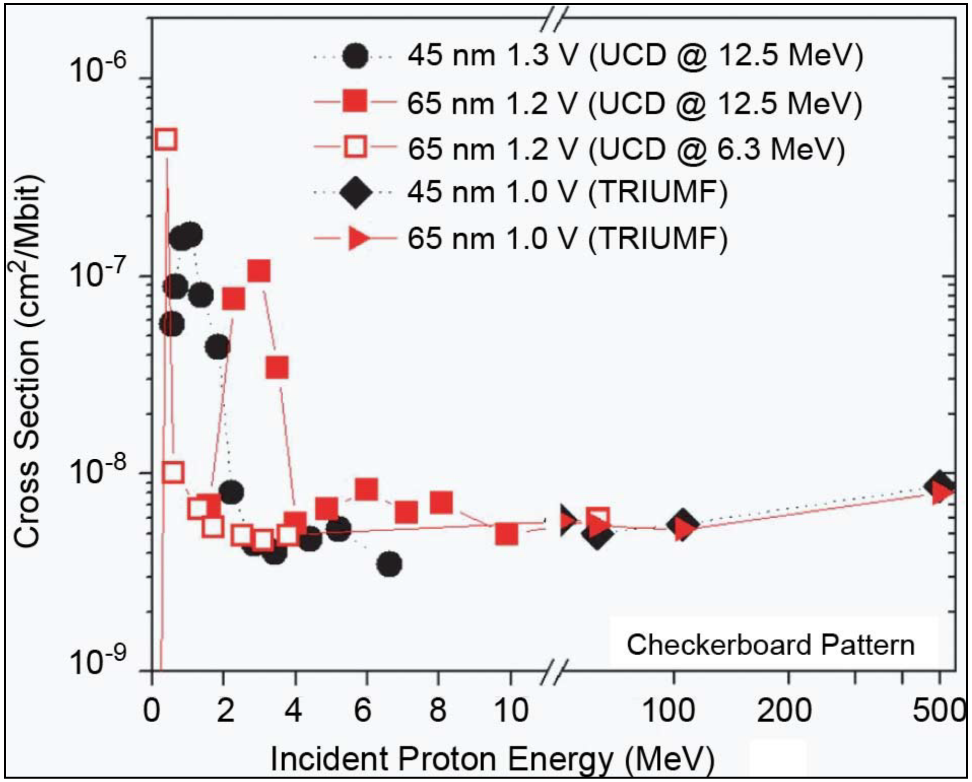
Elemental abbreviations used – *e.g.*, N = nitrogen, O = oxygen, *etc.*

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

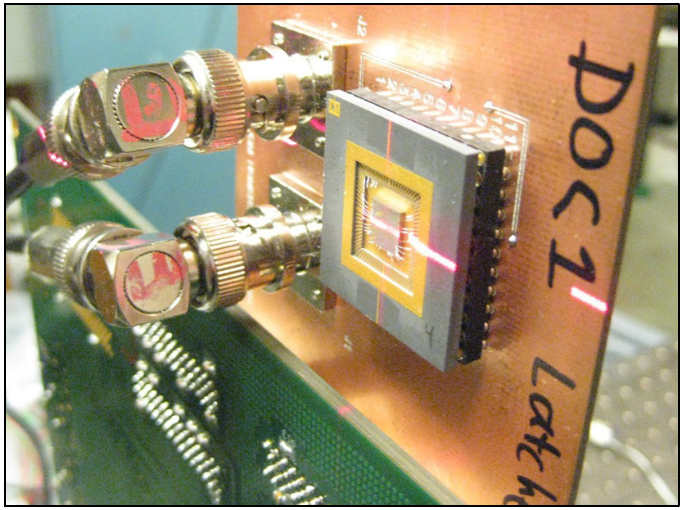


J. R. Schwank *et al.*, *IEEE TNS*, 2012.

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

Two Goals for Low-Energy Proton Test Guideline Development

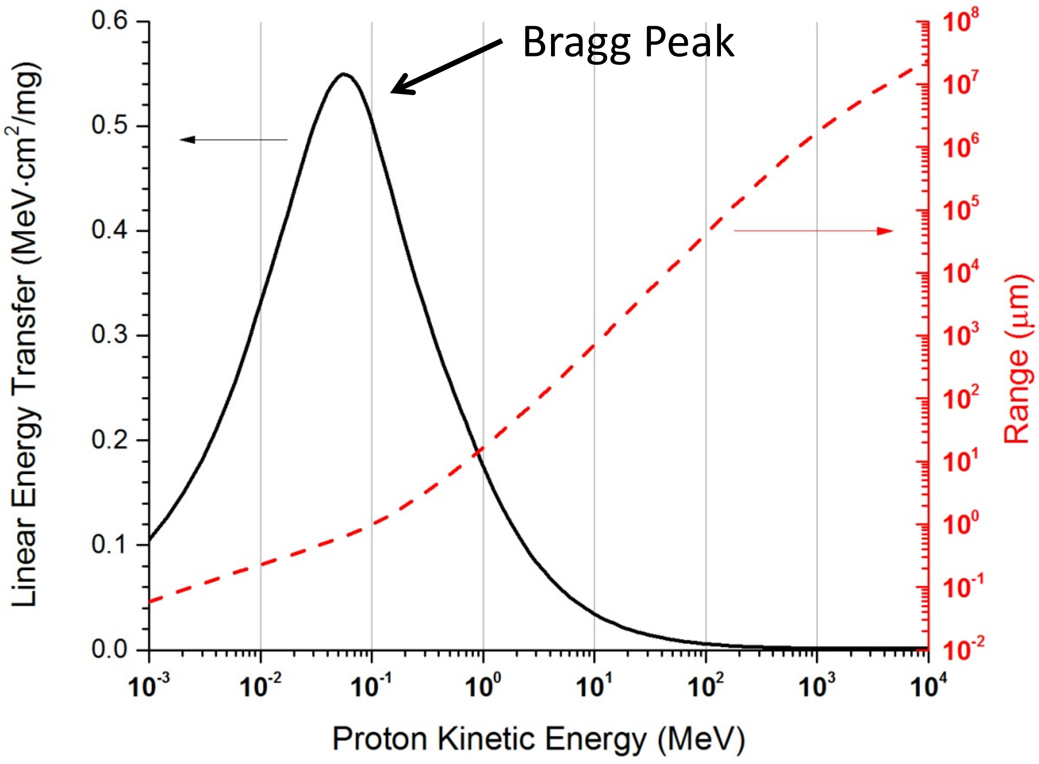
- Evaluate new technologies for low-energy proton sensitivity
  - Will it upset or not?
  - What accelerator source do I use?
- Determine effective error rate contribution from space environment
  - What's the incident environment?
  - How can you calculate an upset rate?



Device under test at UCD CNL.

Evaluation of Low-Energy Proton Sensitivity

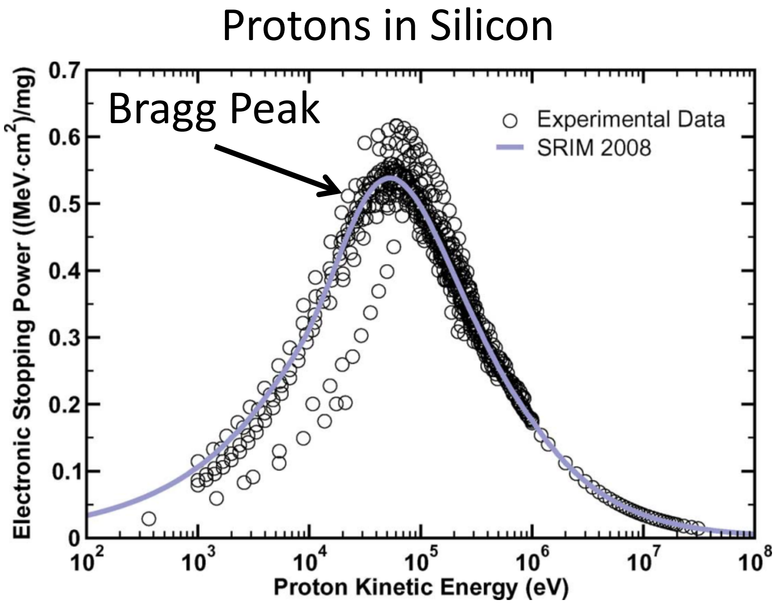
Protons in Silicon



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



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

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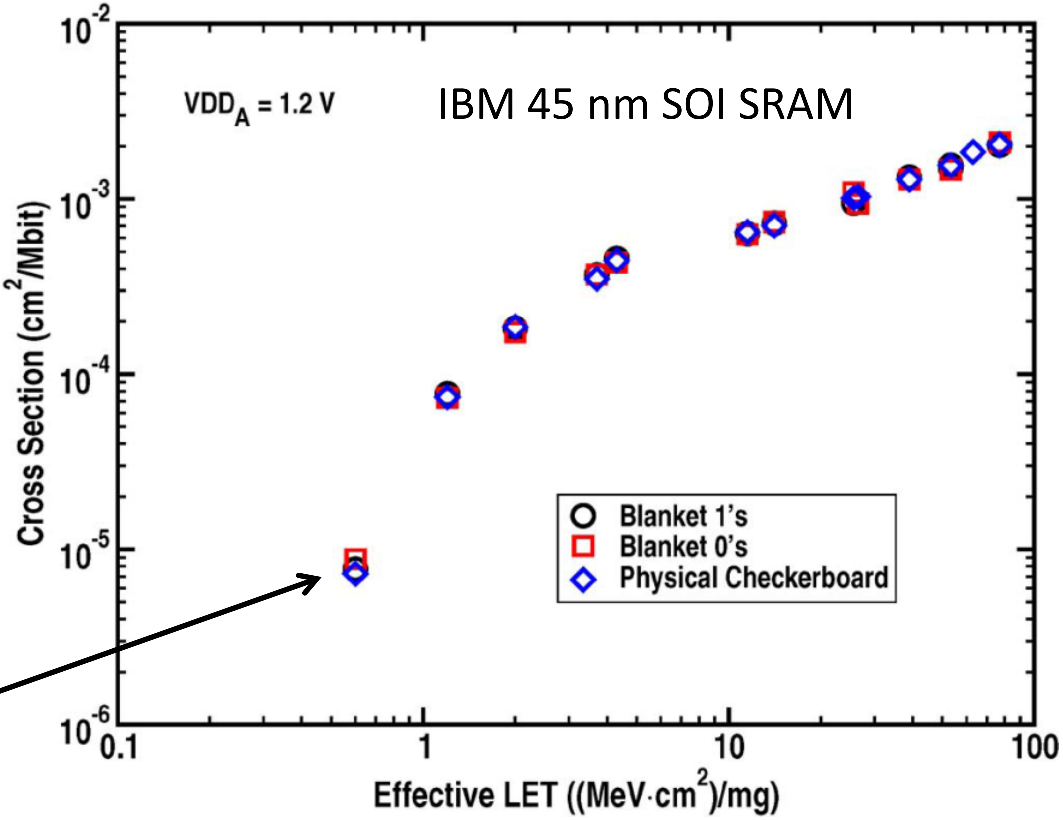
Evaluation of Low-Energy Proton Sensitivity

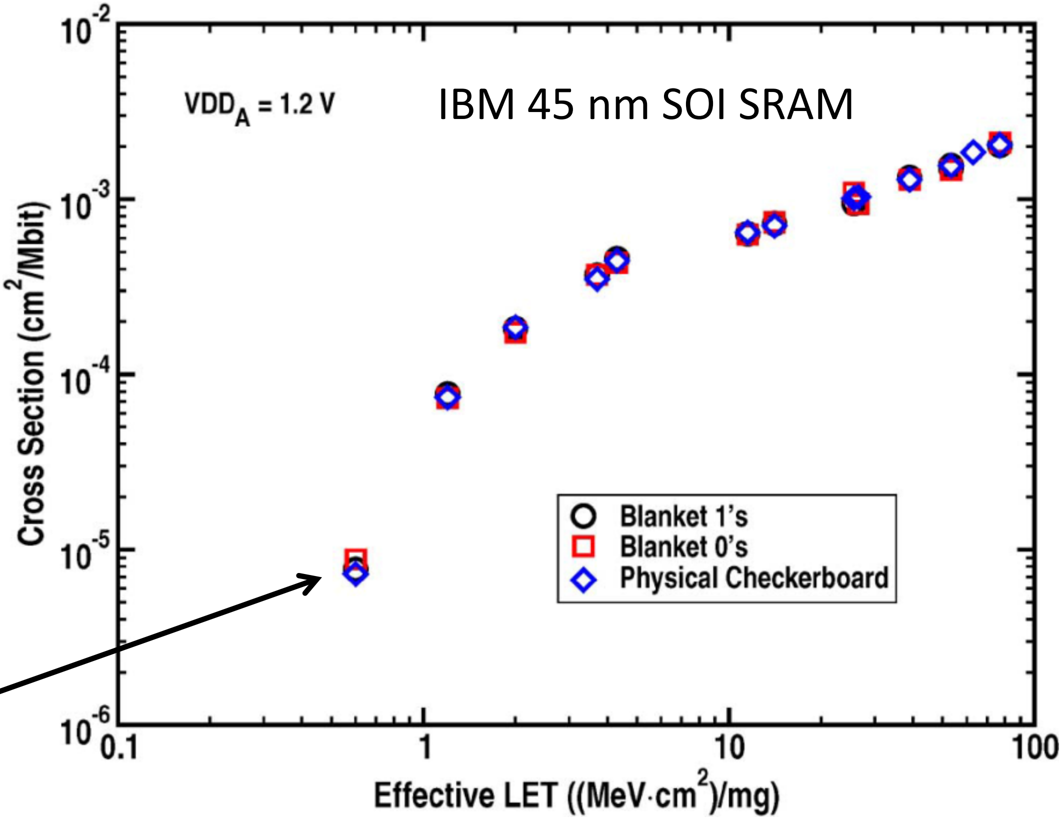


40 MeV/amu nitrogen @ TAMU

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

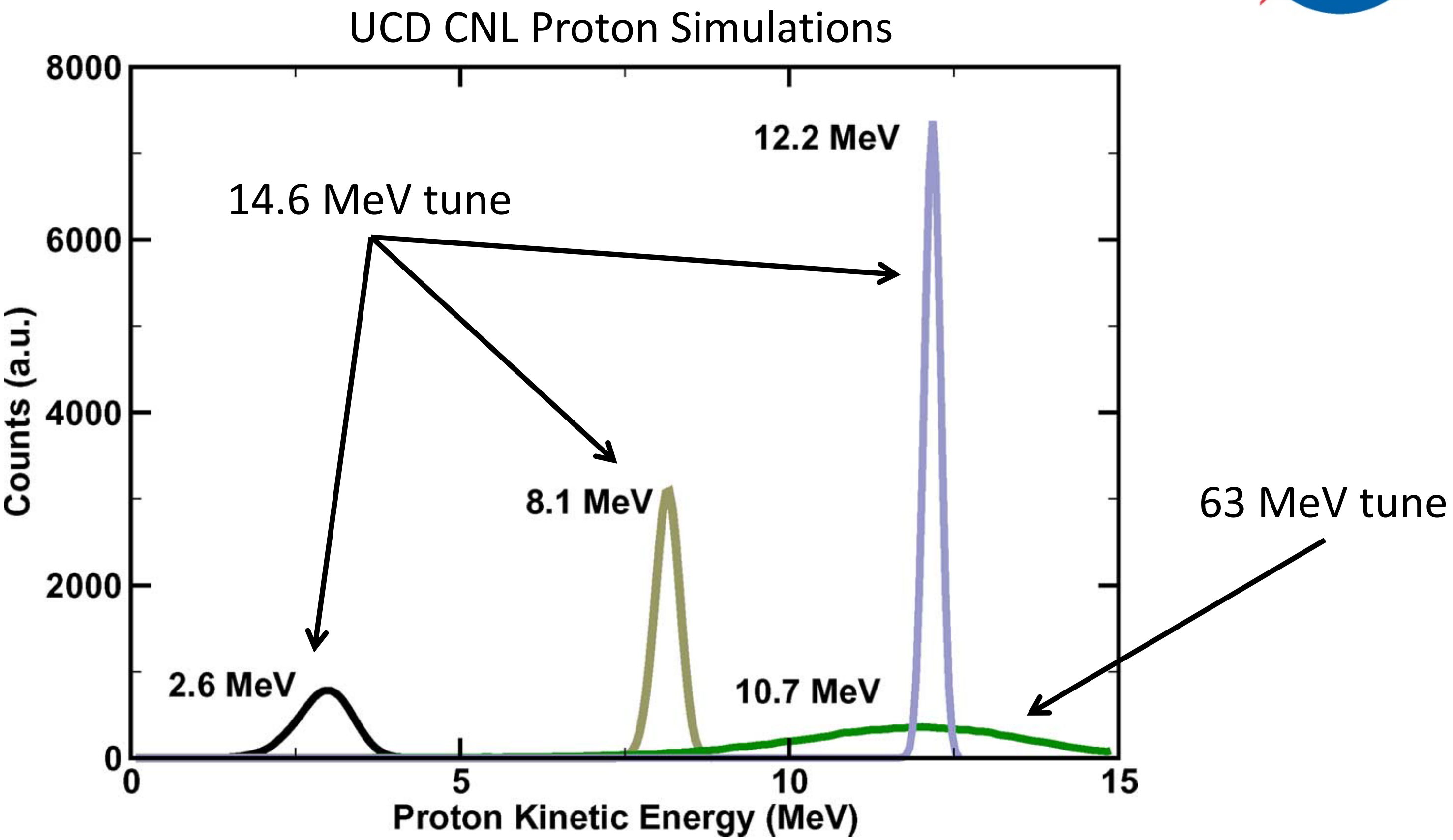
Van de Graaff

- 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

14.6 MeV tune

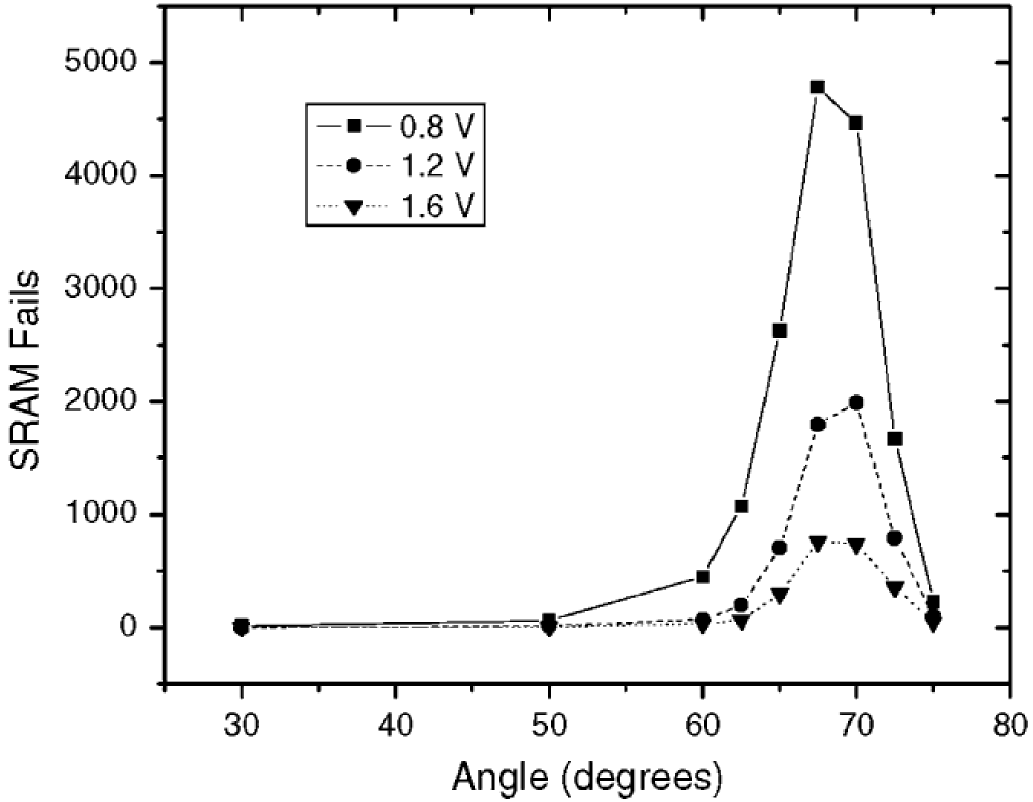
63 MeV tune

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

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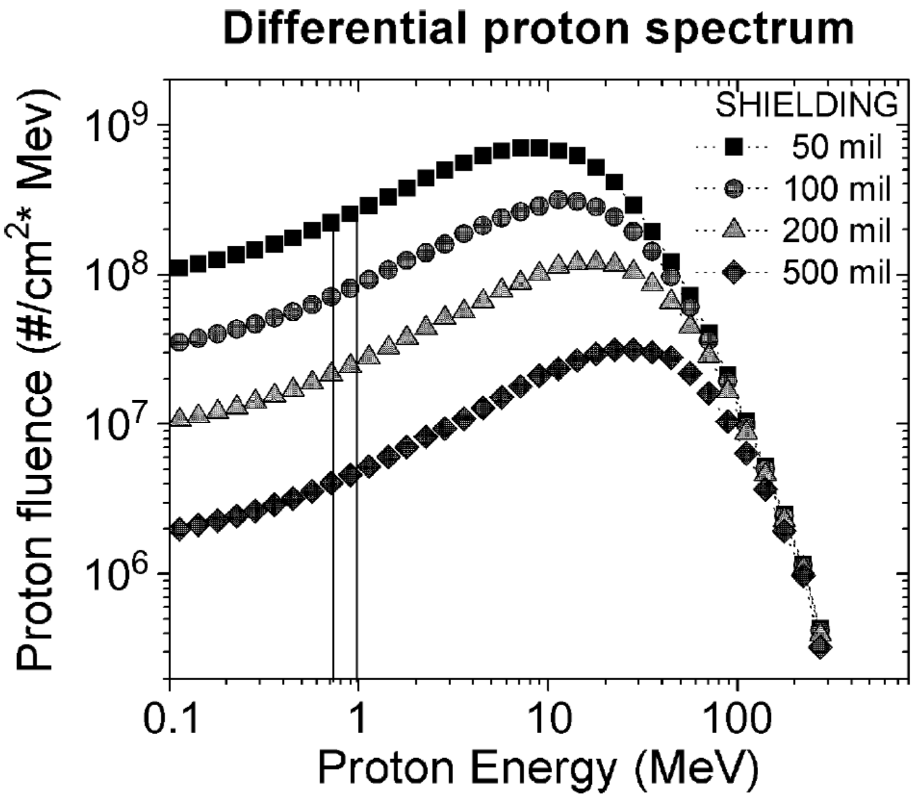
Space Environment



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

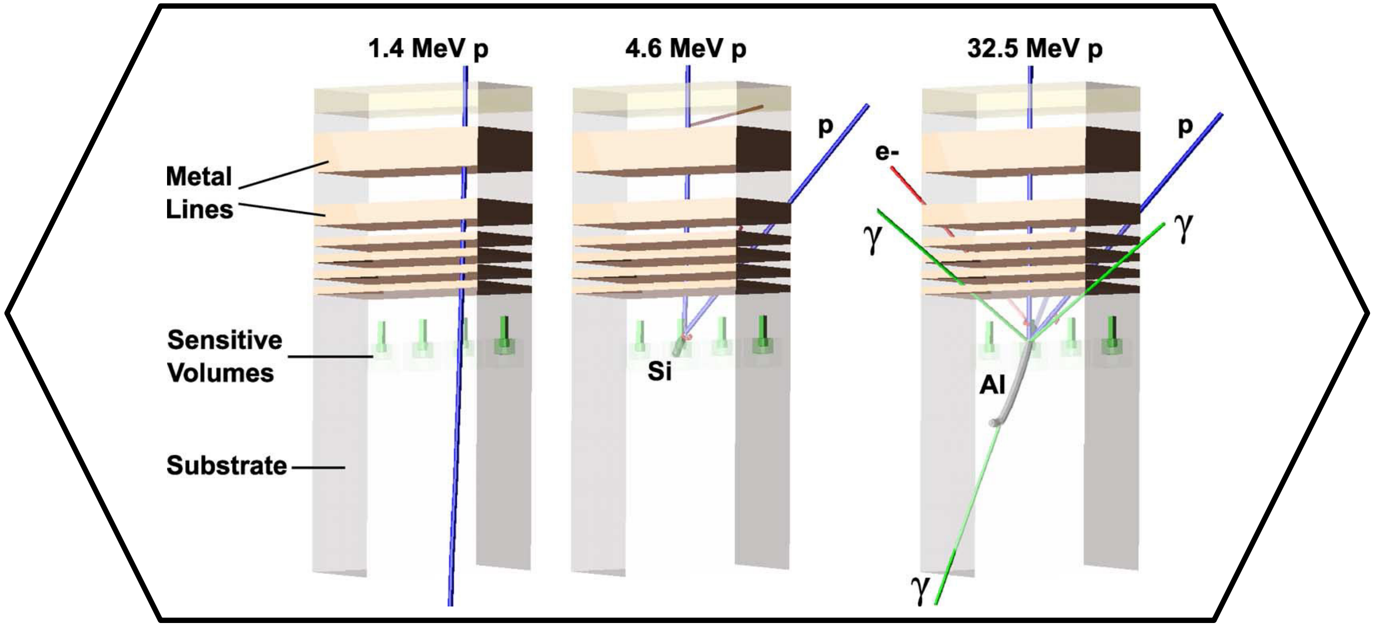
Incident environment defined in interplanetary space by ESP model (example here)

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

Caveat Emptor!

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!

- 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 potential 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 *<u>relevant data collection</u>* and *<u>calibrated models</u>*

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.
- N. F. Haddad *et al.*, “Incremental Enhancement of SEU Hardened 90 nm CMOS Memory Cell,” *IEEE Trans. Nucl. Sci.,* vol. 58, no. 3, pp. 975-980, Jun. 2011.
- J. R. Schwank *et al.*, “Hardness Assurance Testing for Proton Direct Ionization Effects,” *IEEE Trans. Nucl. Sci.,* vol. 59, no. 4, pp. 1197-1202, Aug. 2012.