National Aeronautics and Space Administration

Low-Energy Proton Test Method Development

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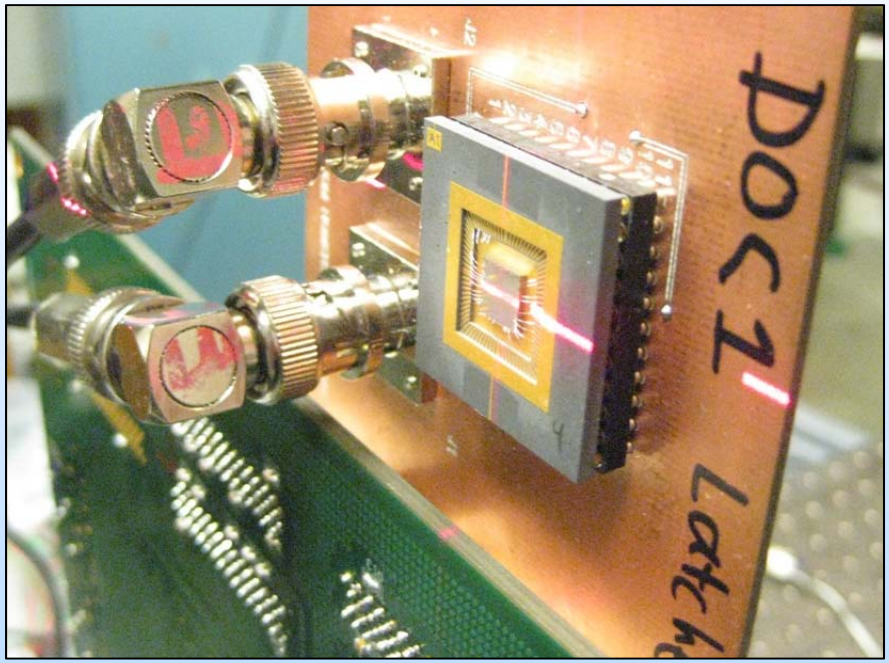
  - Vanderbilt University

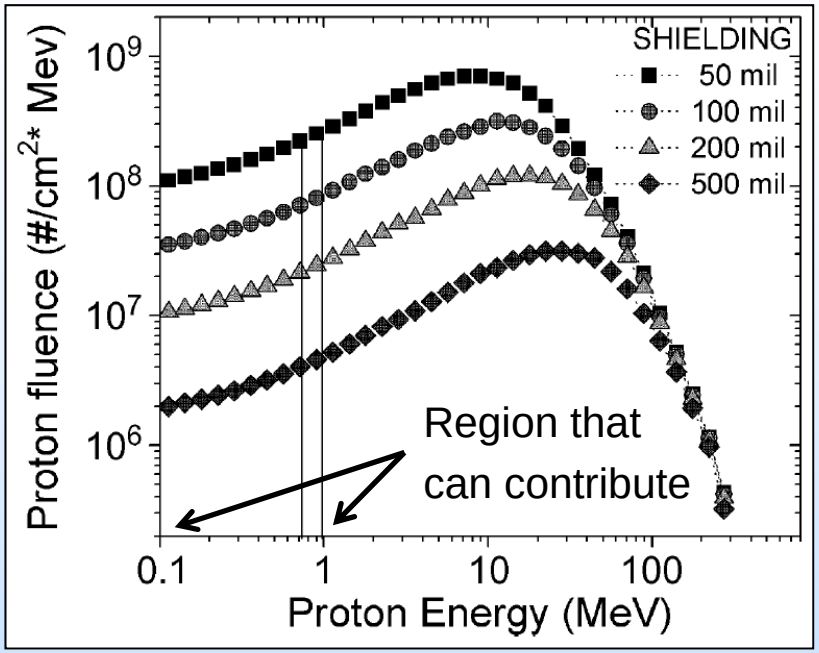
Outline

- **Why do/should we care?**
- **Proton facility and data collection**
  - **Low-energy proton test results**
  - **Experimental setups**
  - **Beam line monitoring**
  - **Systematic considerations**
- **Analysis**
  - **Proton transport simulations**
  - **Error rate calculations**
- **Current recommendations**
- **Future work**



There are lots of protons in space and you cannot shield them

Shielding hardens spectrum

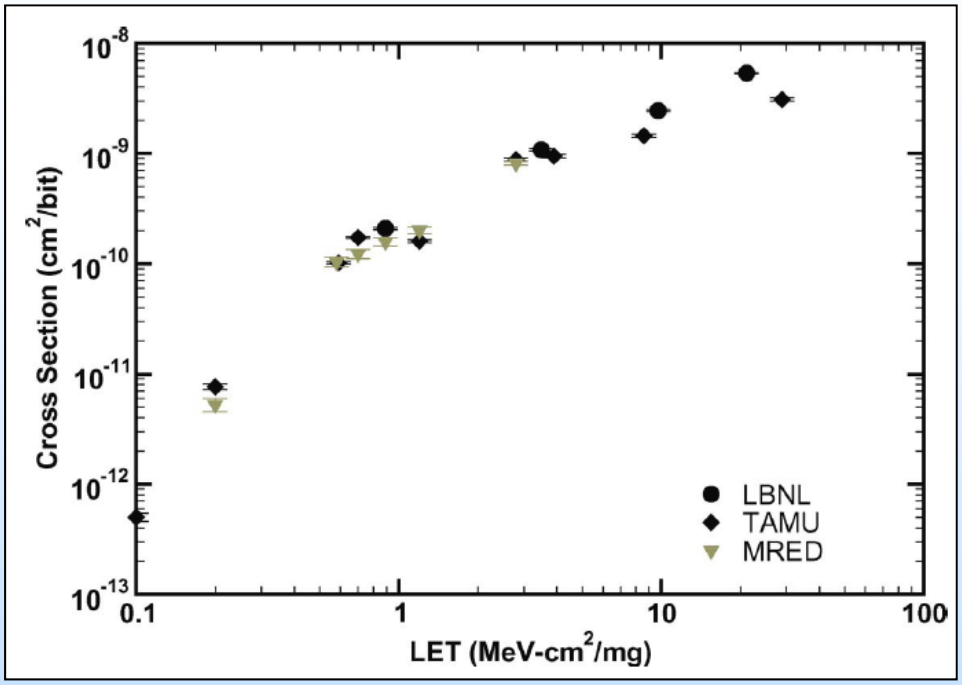


Low-energy protons don‘t go away

Differential Proton Spectrum
for the near-Earth Interplanetary Environment
D. F. Heidel, et al., *IEEE TNS*, vol. 6, 2008.

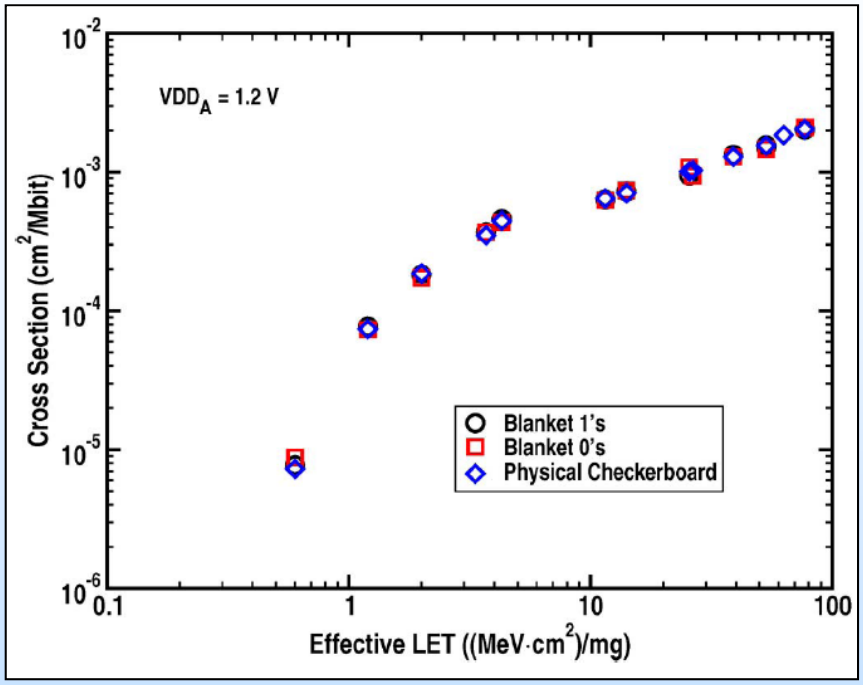
Low-Earth, highly-elliptical, and geostationary/interplanetary orbits can all have substantial proton environments with which to contend

How do you know if low-energy protons are a soft error issue for your technology?



Texas Instruments 65 nm bulk CMOS SRAM

B. D. Sierawski, et al., *IEEE TNS*, vol. 6, 2009.



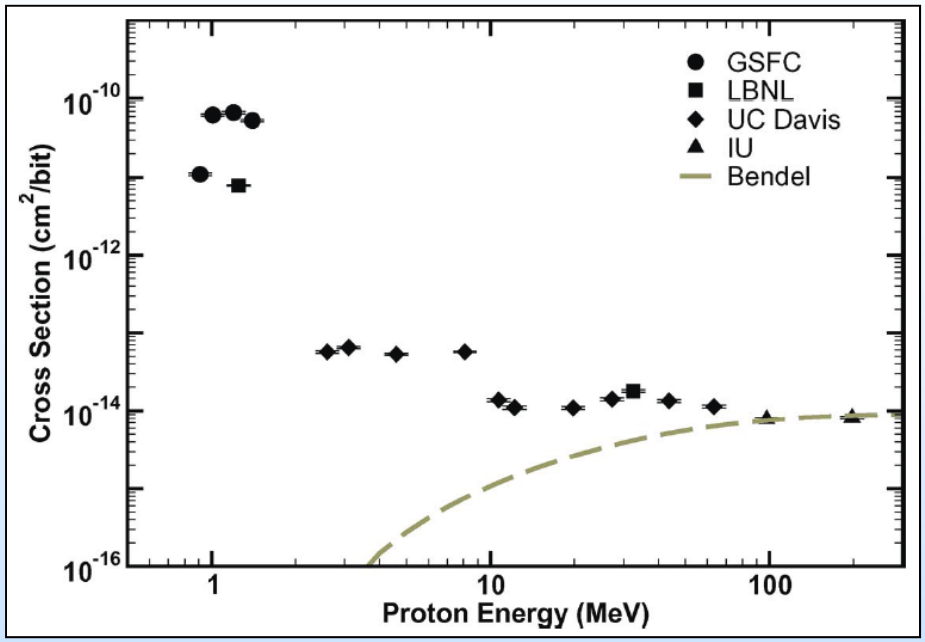
IBM 45 nm SOI CMOS SRAM

D. F. Heidel, et al., *IEEE TNS*, vol. 6, 2009.

Helium, nitrogen, LET, CMOS and SOI…

Are low-LET heavy ions equivalent to low-energy protons?

Texas Instruments and IBM Low-Energy Proton Results



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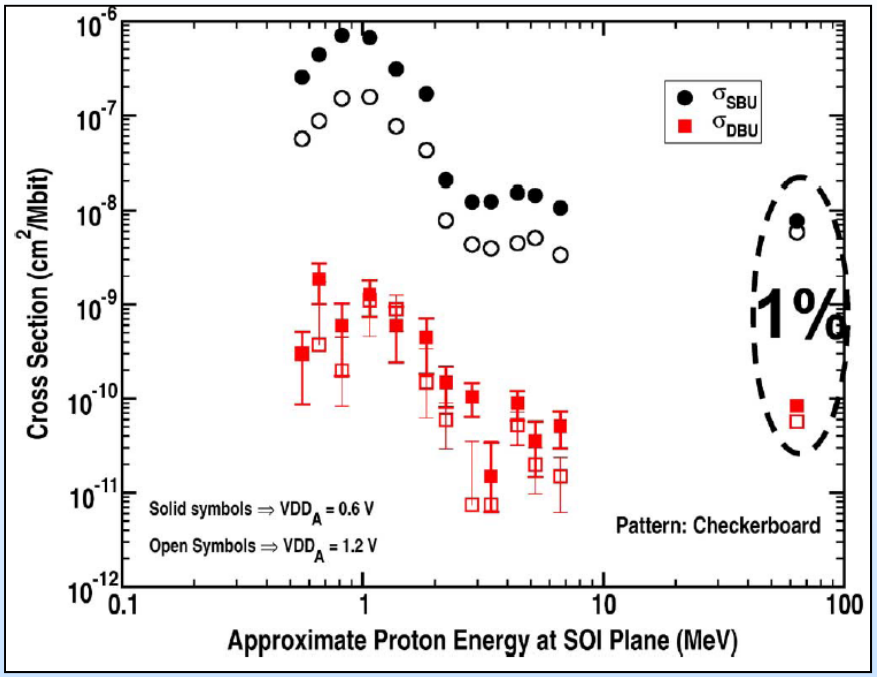

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Top-side versus flip-chip irradiation

Starting energy of the proton beam affects peak width

Typical UC Davis Experimental Setup

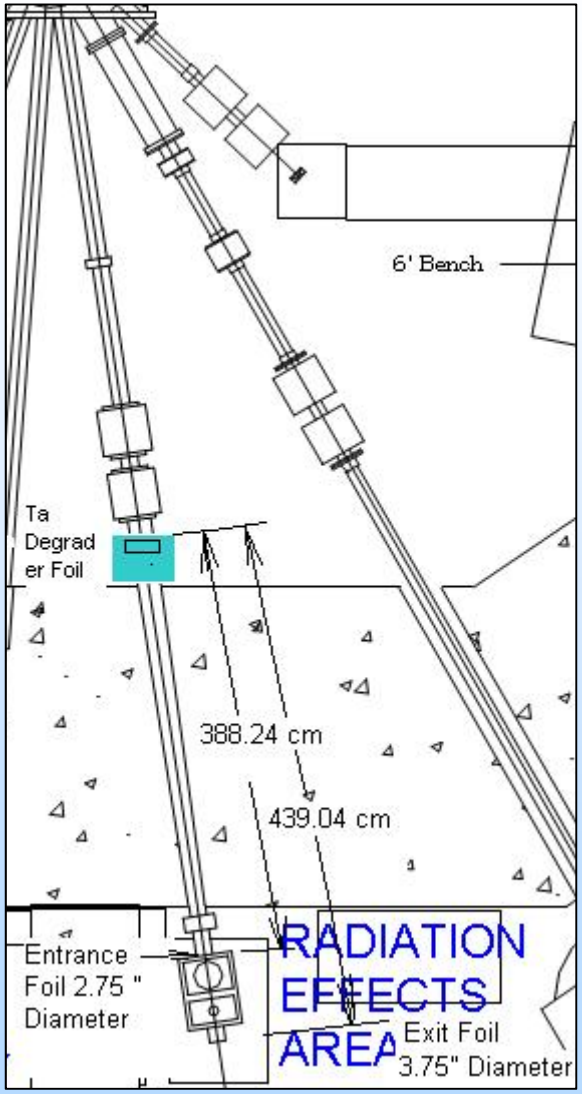
Assuming Setup In-Air (can do vacuum)

In Vault

- **Beam diameter on 0.25 mil Ta foil is 0.79 cm (Quadrupole focused)**
  - **Some questions about angular dispersion**
- **Defining collimator diameter is 5.97 cm**

In Users' Cave

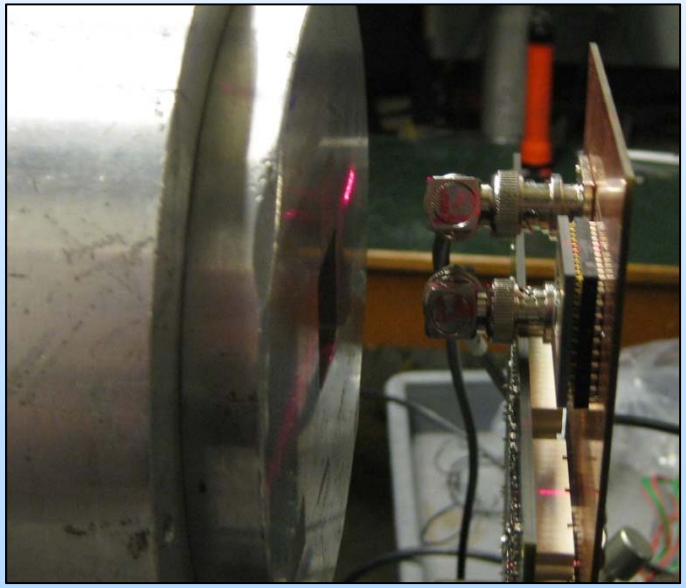
- **Secondary electron emission monitor (SEEM) uses three 0.25 mil Al foils**
- **User-selected degraders are inserted here (Al or Mylar)**
- **Kapton exit window**
- **Air gap is user-selected within experimental parameters**
  - **Could eliminate w/ vacuum chamber**

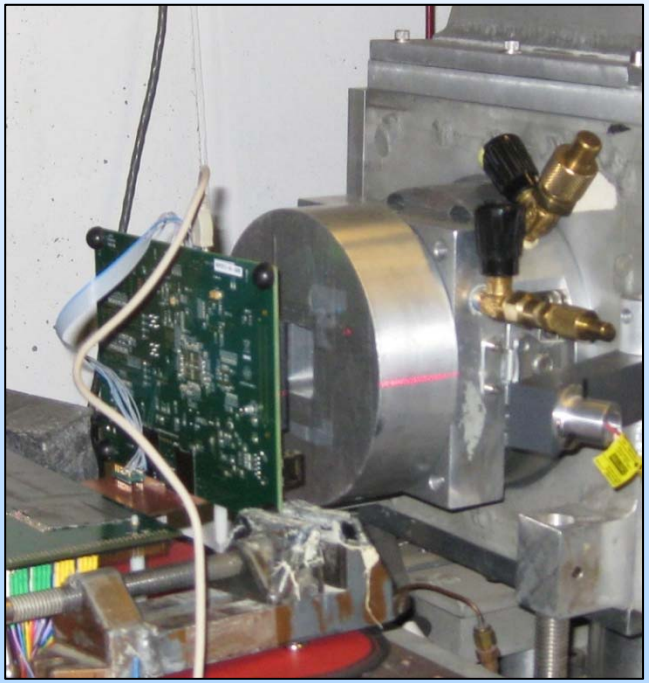


Courtesy of T. Essert and M. Van de Water (UCD/CNL)

Typical UC Davis Experimental Setup

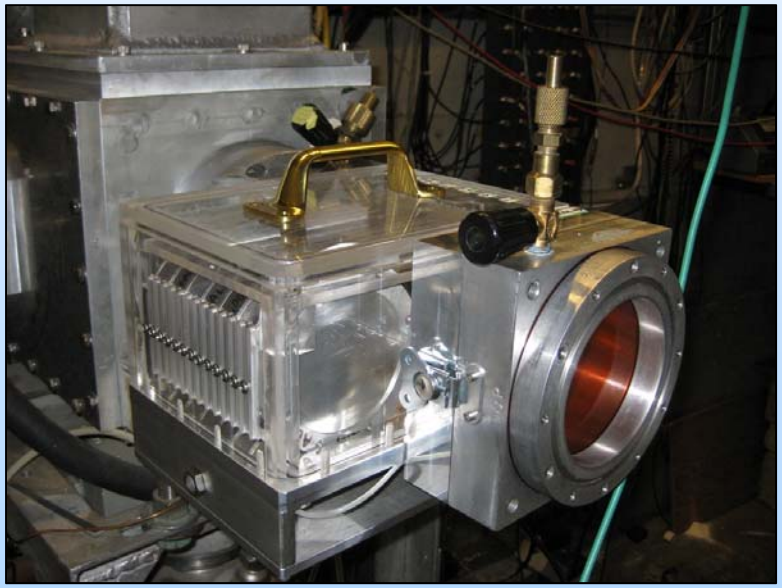
- **Try to keep air gap as small as possible or work in vacuum**
- **Most irradiations to-date have been at normal incidence, though angles do produce interesting results**





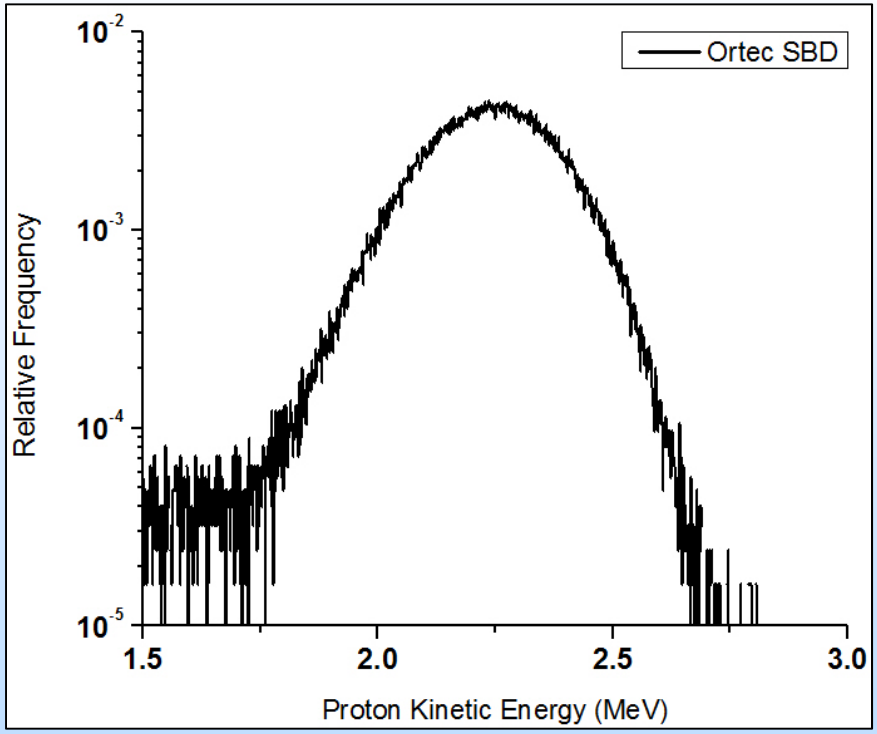
Typical UC Davis Experimental Setup

- **Old degraders were foils taped to the front of the external collimator**
- **New degraders are user-controlled from the South Cave**



Beam Line Monitoring

- **Use Ortec fully-depleted silicon surface barrier detectors**
  - **Calibrated with ^{241}Am source**
  - **Degraded to different energies for multiple cal points**
- **Provides in-situ information regarding mean and distribution**
  - **Not a particle counter**

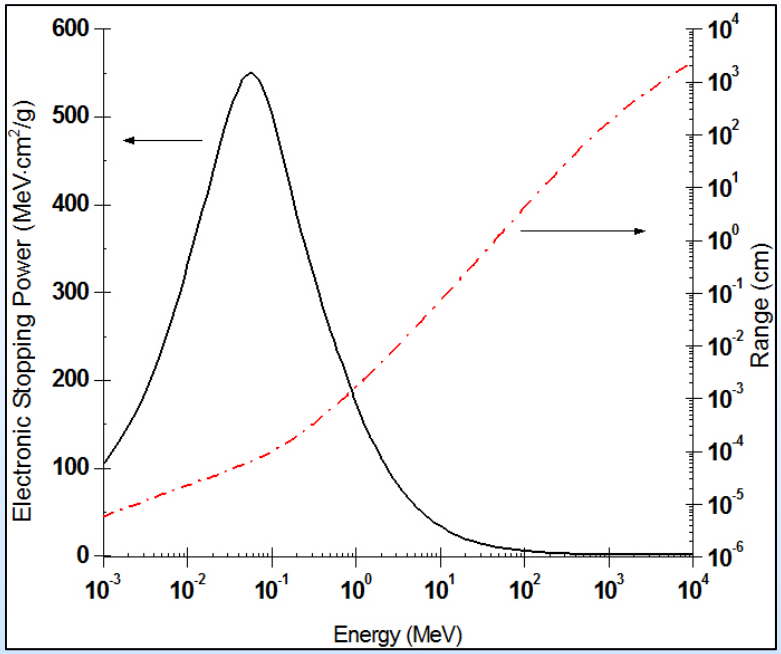


Example SSBD Proton Energy Spectrum

Periodic energy profile monitoring has become essential

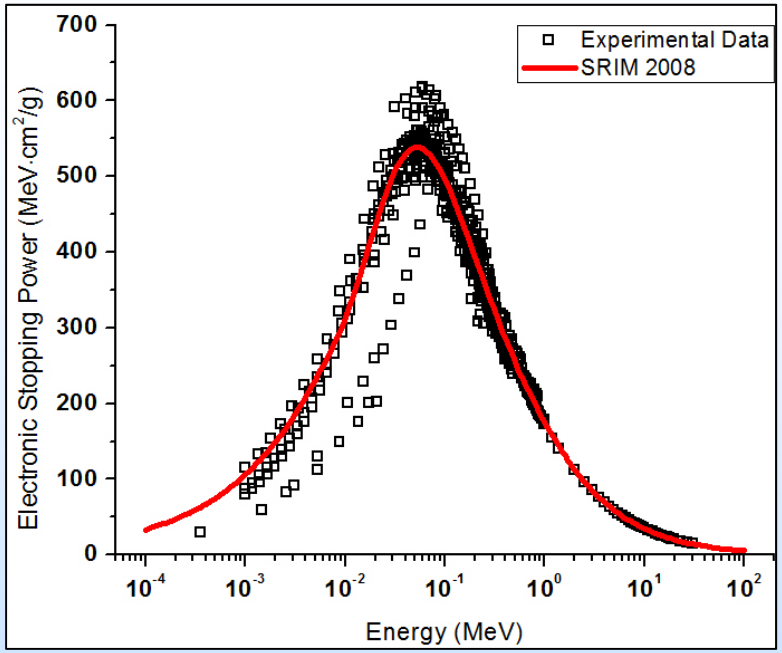
Repeatable single-turn beam extraction not always possible

Proton d*E*/d*x* and Range—Systematics



NIST PSTAR tool (ICRU Report 49, 1993)

Stopping Power & Range in Silicon



Protons on silicon—Helmut Paul's Database

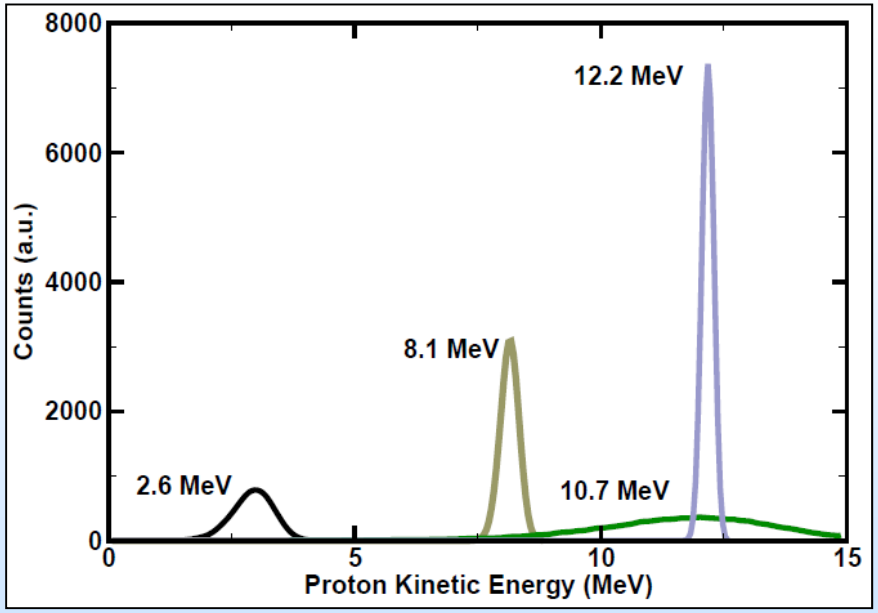
Experimental and Simulated Stopping Power

Greatest effect in the shortest distance

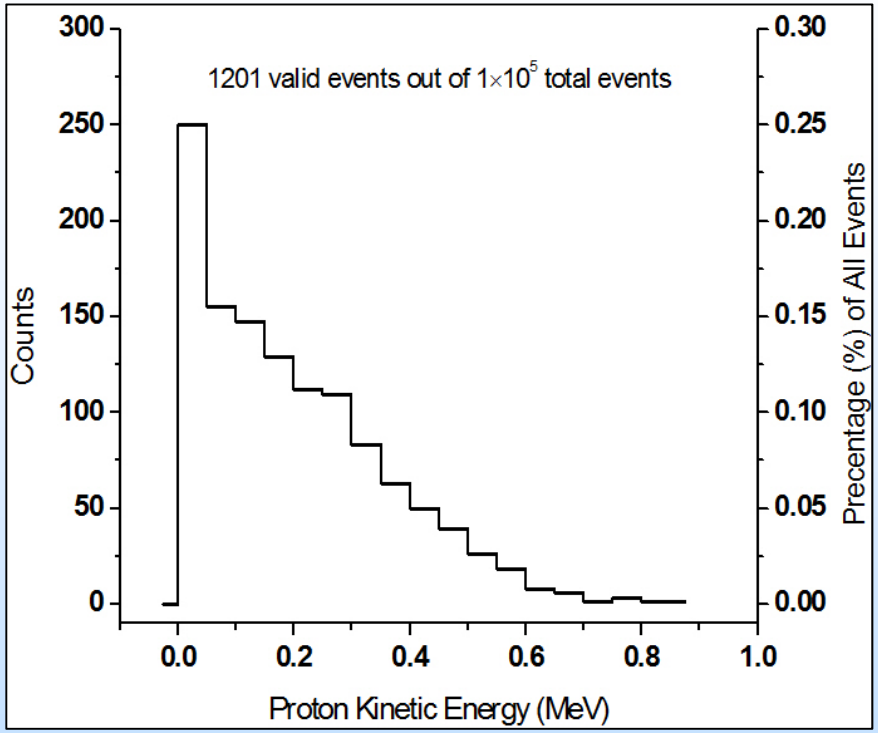
Uncertainty in experimental data at low energy

H. Paul data located at:
http://www.exphys.jku.at/stopping/

Proton Energy Straggling—Systematics



B. D. Sierawski, et al., *IEEE TNS*, vol. 6, 2009.



SRIM-2008

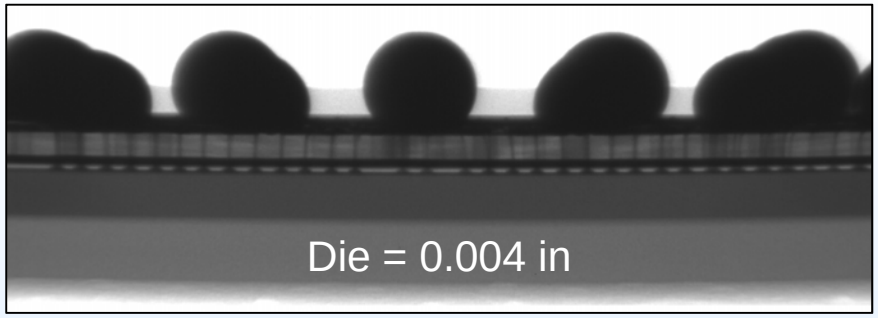
Tuned beam energy should be low—keep degraders to a minimum

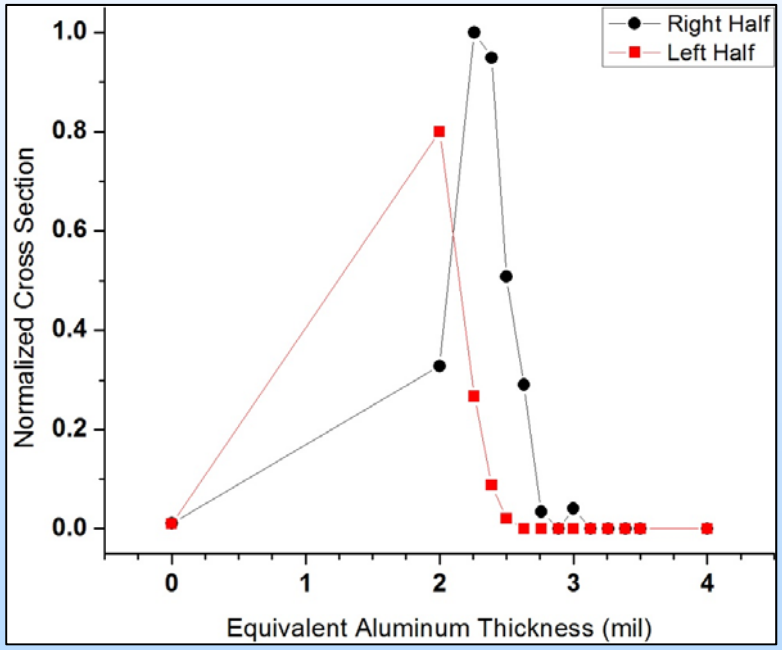
Short range at stopping implies beam loss in addition to straggling

Sample Preparation—Systematics

- **Flip-chip (C4) assembly thinned to ~100 um and irradiated in-air using 6.5 MeV H^+**
- **Thickness difference of < 15 μm from one side of die to other**
  - **Same scenario possible for thick back end of line**
  - **X-ray not accurate enough**

Sample preparation can distort device cross section



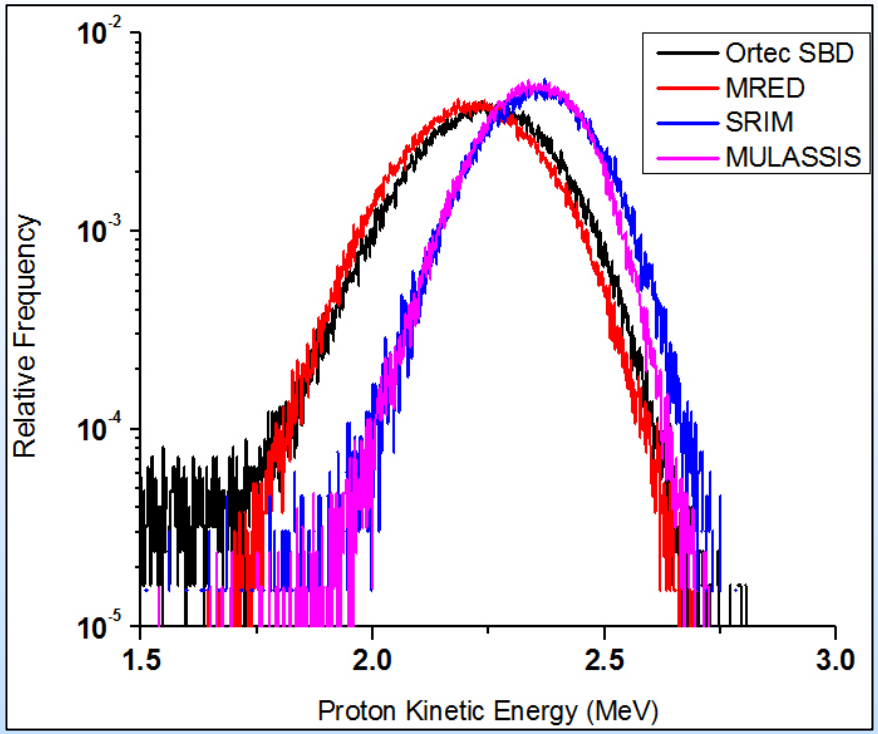


36 Mbit, 45 nm SOI SRAM
Irradiated with 6.5 MeV protons at UC Davis/CNL
Original data from D. F. Heidel, *et al.*, TNS, vol. 6, 2009.

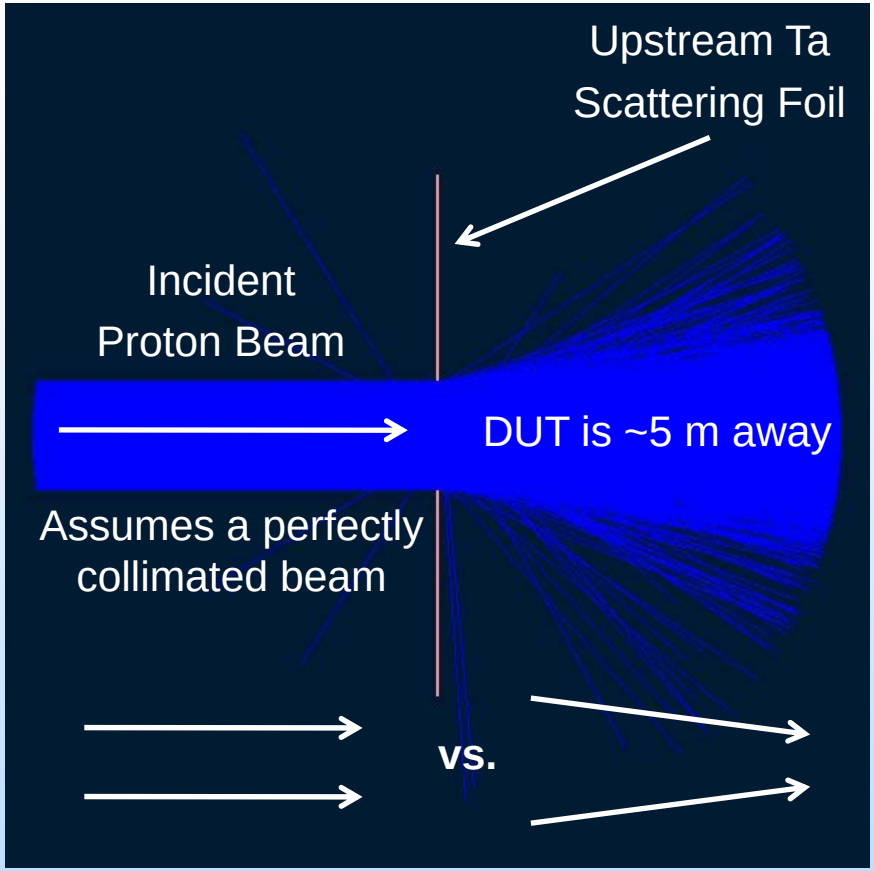
Proton Transport Simulations

Degraders

2 mil aluminum & 0.125 mil Mylar



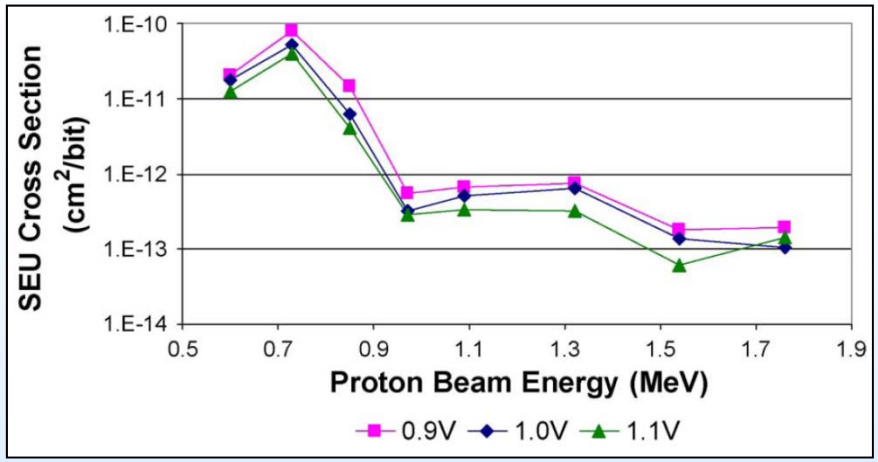
2.21 MeV MRED | 2.25 MeV SBD | 2.34 MeV MULASSIS | 2.35 MeV SRIM



MRED calculation for 6.5 MeV protons

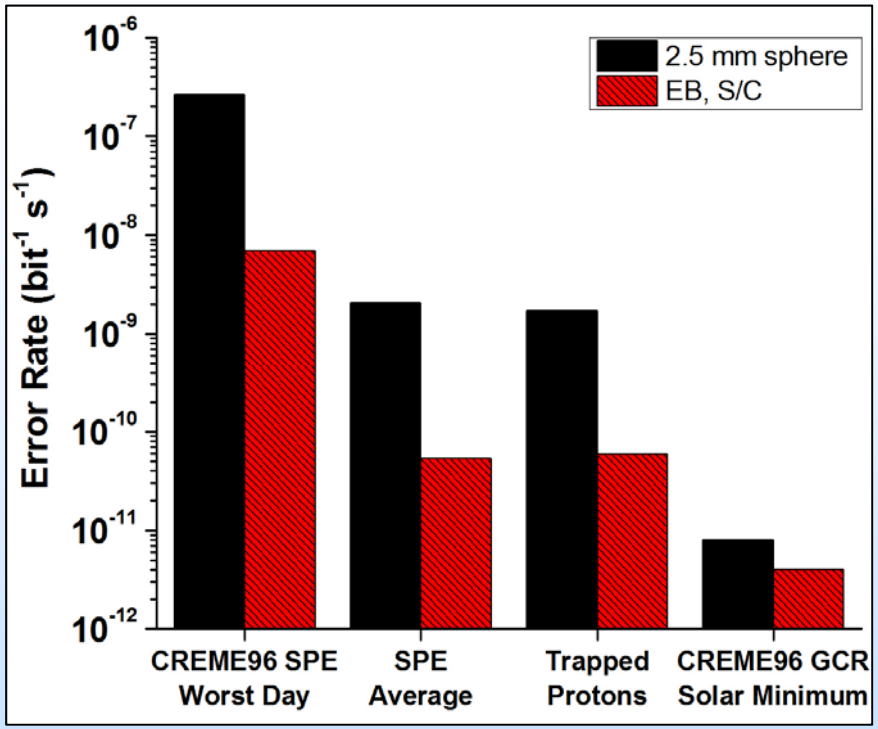
Current simulations capture energy distribution, but not the spatial distribution

Error Rate Calculation Methods



$$\text{SEU rate} = \sigma_{\text{peak}} \cdot \frac{d\phi}{dE} \cdot \Delta E \cdot 4\pi$$

E. H. Cannon, et al., *IEEE TNS*, vol. 6, 2010.



J. A. Pellish, et al., *IEEE TNS*, vol. 6, 2010.

Current models cover both analytic and Monte Carlo methods

Both approaches suffer different weaknesses

Can be traced back to source data set or physical basis

Current Recommendations Assuming Risk is Established

- **Tune beam energy as low as reasonably achievable (cyclotron/Van de Graaff ALARA)**
- **Measure beam energy profile at the DUT position (measure as we test)**
  - **Account for beam emittance if possible**
- **Record <u>all</u> materials in the beam line from the source to the DUT**
  - **Degrader material (if cyclotron) should be of high quality and the beam should be degraded in vacuum**
- **Employ physical analysis to reduce sample preparation uncertainties**
- **Reproduce cross section results to check for consistency**
- **Calculate soft error rates using as much physical reality as possible**

Future Work

- **Measure/calculate angular dispersion of UC Davis beam on tantalum foil**
  - **Confirm Monte Carlo simulations can reproduce**
- **Develop position on angular irradiations**
  - **Like heavy ions, protons can be more "effective" at larger incident angles**
- **Flesh out standard procedures/options for aforementioned recommendations**
  - **Beam energy measurements**
  - **Material properties/dimensions recording keeping**
  - **Physical analysis procedures**
  - **Error rate calculation levels of rigor**
- **Complete first version of low-energy proton test method by end of current fiscal year**