# Practicality of Evaluating Soft Errors in Commercial sub-90 nm CMOS for Space Applications

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*Abstract*—**Inclusion of commercial technologies in civil spaceflight applications is reality. These technologies enable higher performance, reduce power consumption, and ultimately yield better science. However, the benefits do not come without cost, and radiation-induced soft errors in advanced, sub-90 nm CMOS technologies present new challenges. These challenges include sensitivity to proton direct ionization, memory technology evaluation, as well as testing and evaluation complexity.**

*Keywords-space environment, soft errors, CMOS, proton, heavy ion, memory*

## I. INTRODUCTION

The National Aeronautics and Space Administration (NASA) faces many radiation hardness assurance challenges as microelectronic components used in spacecraft scale below the 90 nm process node. This is particularly true for commercial off the shelf (COTS) complementary metal oxide semiconductor (CMOS) parts. While these parts enable improved scientific investigations, evaluating the semiconductor technologies required for the missions creates unique testing challenges like the examination of low-energy proton-induced soft errors [1-4].

Another key area of ongoing investigation in scaled commercial spacecraft electronics concerns volatile and non-volatile memory applications. These applications include processor program storage, temporary data buffers, mass data storage in solid-state recorders, and configuration storage for static random access memory (SRAM)-based field programmable gate arrays (FPGAs) [5, 6]. Each of these memory applications carries with it different levels of soft error criticality risk – some soft errors may result in scientific or housekeeping data loss, while others may require ground-based intervention for spacecraft safe-hold conditions. Engineers can determine this risk a number of different ways, one of which is a radiation- specific form of failure mode, effects, and criticality analysis called single-event effects criticality analysis (SEECA) [7], another is a Bayesian analysis approach [8].

Testing and evaluation challenges include matching the space environment using ground-based accelerator and pulsed laser facilities, experimental coverage of operational modes, budgetary concerns over non-recurring engineering, the limited lifetime of commercial product generation manufacturing relative to typical spacecraft mission development lifetime, and confronting things like controlled collapse chip connection, or flip-chip, device packaging styles. The use of advanced COTS CMOS in space-based applications has given rise to new soft error experimental and modeling evaluation techniques [5, 9-14] to overcome these challenges.

## II. LOW-ENERGY PROTON SOFT ERRORS

Traditional proton soft errors are caused by inelastic nuclear reactions, much the same as high-energy neutron soft errors. Since the inception of space-based radiation effects [15] until very recently, indirect ionization soft errors were the only proton-based concern aside from ionizing dose and displacement damage. For scaled, sensitive COTS parts, protons are able to generate enough charge through electronic stopping, called direct ionization, to cause soft errors. K. P. Rodbell *et al*. [1] and D. F. Heidel *et al*. [2] published the first demonstration of low-energy proton direct ionization soft errors in 2007 and 2008 for a commercial 65 nm silicon-on-insulator (SOI) CMOS process; the results from D. F. Heidel *et al*. [3] are shown in Fig. 1. Scientists and engineers within the radiation effects community predicted the onset of low-energy proton direct ionization soft errors when heavy ion linear energy transfer (LET) thresholds dropped below 1 (MeV·cm$^2$)/mg while maintaining a sufficient sensitive volume structure; *cf*. [16]. LET is often referred to as mass stopping power. It is the electronic stopping power, d$E$/d$x$, normalized by the density of the target material, which is either given as g/cm$^3$ or mg/cm$^3$. LET is, by definition, a measure of direct ionization.

Proton direct ionization soft errors represent a significant threat to spacecraft electronics. They cannot be effectively shielded due to the fact that proton energies in space exceed several hundred megaelectron volts for solar, trapped, and galactic cosmic ray environments [17-19]. The external high-energy protons will lose energy and become low-energy protons as they transit the mass between outer space and the electronics boxes within the spacecraft. The spacecraft shielding distribution will determine which portion of the external proton energy spectrum becomes the low-energy spectrum that impacts sensitive microelectronic devices [2]. Low-energy protons have thus far been defined as protons with a kinetic energy less than 10 MeV, though energies that result in soft errors are typically below 2 MeV for the 65 and 45 nm process technologies documented thus far [1-4].
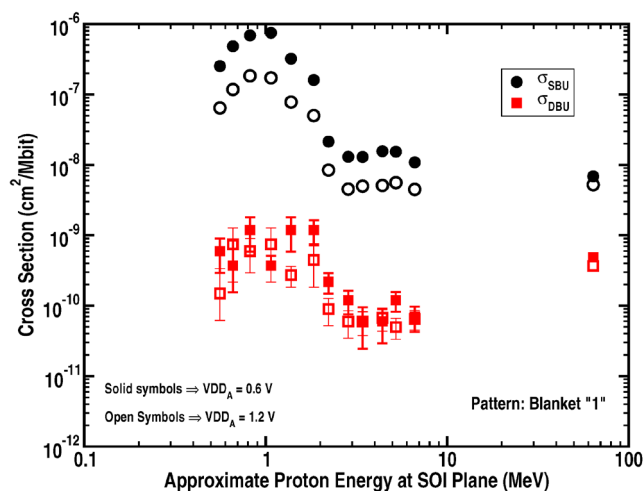
**Fig. 1:** Single- and double-bit proton upsets (SBU and DBU) in an IBM 45 nm SOI CMOS SRAM, after [3]. The cross sections for proton energies below 2 MeV are the points dominated by direct ionization, resulting in a 100x increase for SBU and a 10x increase for DBU. These irradiations were carried out at the UC Davis Crocker Nuclear Laboratory, which is pictured in Fig. 2.
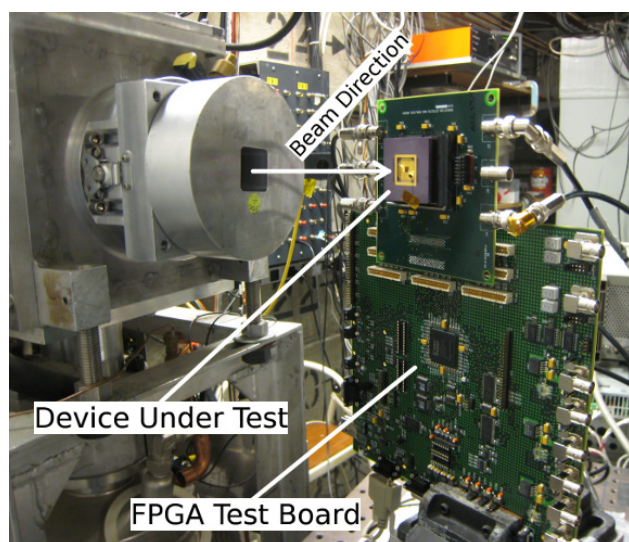


**Fig. 2:** Test setup for experimental low-energy proton testing at the University of California at Davis Crocker Nuclear Laboratory. The cyclotron at the Crocker Lab can provide low-energy proton tunes of a few megaelectron volts that can be degraded further by using micrometer-thick aluminum and Mylar foils in air, downstream of the beam collimator. The daughter card is attached to the NASA/GSFC Xilinx Spartan-II-based low cost digital tester [20].

Recent results published by B. D. Sierawski *et al.* [4] show that for space environments with large proton populations – low Earth orbit, highly-elliptical orbit, and solar particle events – direct ionization soft errors from low-energy protons either dominate the overall soft error rate or constitute a significant fraction of it. The problem facing radiation engineers then becomes one of hardness assurance. However, guaranteeing component performance in the space environment by conducting ground-based low-energy proton tests, like the one shown in Fig. 2 using the NASA Goddard
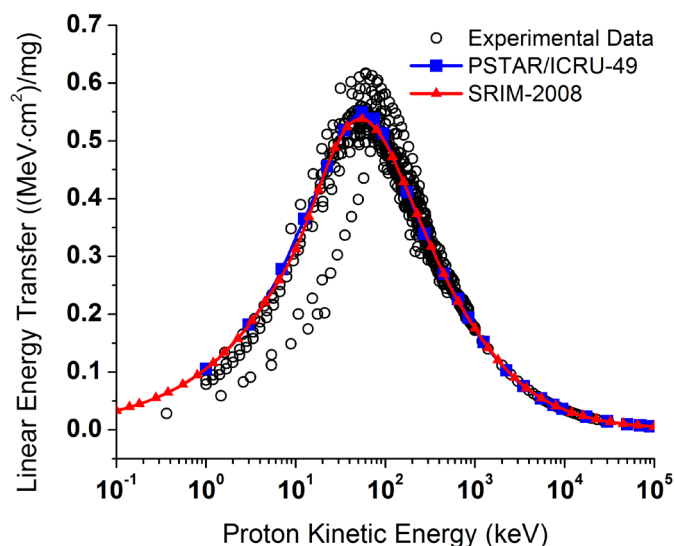


**Fig. 3:** Experimental and simulated proton linear energy transfer (mass stopping power) as a function of energy in silicon. The experimental values, shown as open circles, are from Helmut Paul's database [22, 23]. The simulated linear energy transfer curves were calculated using SRIM-2008 [24, 25] and NIST PSTAR [26, 27]. The points on the simulation curves are sparse to aid viewing. Note that the PSTAR calculations do not go below 1 keV.

Space Flight Center's low-cost digital tester [20], is fraught with physics-imposed difficulties.

The issues with accelerated low-energy proton testing can be summarized as limited range, energy straggling, and uncertainty in electronic stopping power. A 2 MeV proton has a range of approximately 50 $\mu$m in silicon and 74 mm in air, which means that testing either has to be carried out in a vacuum or tested in air using foil degraders. The inconvenience of testing in vacuum aside, the difficulty is exacerbated by the fact that at 2 MeV the LET of the proton is too low to generate enough charge to cause a soft error. Facilities can lower the proton energy below the beam tune energy using a combination of aluminum and Mylar degraders from hundreds of nanometers to several micrometers thick along with air columns and the semiconductor die itself. Particle range limitations become severe with flip-chip ball grid arrays where irradiation has to be done through the substrate. In-situ device thinning is often necessary, which is problematic because the ball grid array is under stress and will crack the die without sufficient mechanical support [21].

Fig. 3 shows experimental measurements of proton LET in silicon, compiled from Helmut Paul's database [22, 23], as well as two theoretical calculations of proton LET in silicon using SRIM-2010 [24, 25] and the National Institute of Standards and Technology's PSTAR tool [26]; the latter is based on ICRU Report 49 [27]. As the figure shows, at high energy there is good agreement between experiment and theory. However, below 1 MeV, moving up towards the Bragg peak, the spread in experimental data becomes large. These low-energy transmission measurements require thin foils, making the presence of pin holes and other material variations critical. The critical angle for ion channeling also increases at low energy along with the importance of multiple scattering [27]. These experimental facts translate to uncertainty in
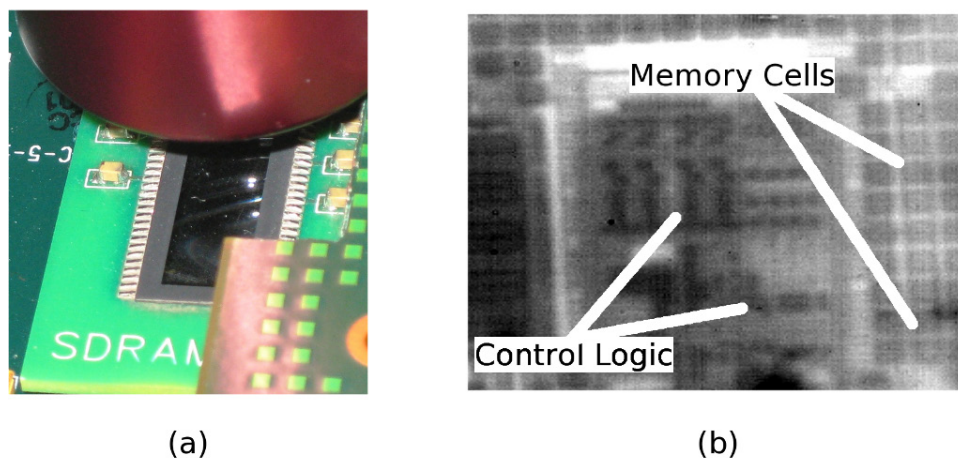
**Fig. 4:** (a) A close-up of the setup for two-photon absorption pulsed laser carrier generation on an Elpida 512 Mbit SDRAM, after [5]. The surface has to be polished to a near-specular finish, evident from the reflection of the objective lens, in order to keep optical losses to a minimum. (b) Infrared image of the SDRAM control logic and memory cells as viewed through the microscope optics.

empirical stopping power formulations that rely on these data, such as SRIM, PSTAR, and GEANT4 [14]. The same difficulties present in measuring the stopping power are also present in soft error testing.

There are generally two options for accelerating proton beams: Van de Graaff accelerators and cyclotrons. Van de Graaff accelerators have much tighter energy spectrums than cyclotrons – a few kiloelectron volts wide versus several hundred kiloelectron volts. However, cyclotrons offer the benefits of in-air irradiation and higher energies. The spread in beam tune energy matters since the protons at the Bragg peak, around 50 keV in silicon, generate the most charge and are therefore the most likely to cause soft errors. Since protons at the Bragg peak have a range of approximately $0.5\ \mu$m in silicon, the soft error cross section effect is sharp and dramatic. A beam that has a large energy spread will smear out the dramatic increase in soft errors at low proton energies for susceptible technologies. This makes interpreting results and mechanisms difficult if not impossible. As a general rule, more mass between the tuned beam and the device under test will result in poor energy resolution and less conclusive data. The best scenario is to tune the beam to the exact energy desired and to avoid external degraders. B. D. Sierawski *et al*. [4] has a nice example of this effect shown in their Fig. 13.

The radiation effects community is moving in several directions with regard to low-energy proton testing and soft error rate evaluation. B. D. Sierawski *et al* [4] advocate characterizing the device under test with high-energy, low-LET, light ions like helium and nitrogen that have LETs close to low-energy protons. Using these ions provides a well-defined electronic stopping power as the ion traverses the device and makes model calibration easier; *cf*. [12, 28, 29]. Other groups, like D. F. Heidel *et al*. [2, 3], are continuing to pursue improved low-energy proton irradiation techniques that reduce systematic errors and unlock underlying soft error mechanisms.

## III. EVALUATING SPACECRAFT MEMORY TECHNOLOGIES

Spacecraft memory has gone through several evolutions, from magnetic core, also known as Forrester core, memory in the 1960s and 1970s, to magnetic tape memory in the 1970s and 1980s, and finally to silicon solid-state recorders and other applications in the 1990s and beyond. Current technologies include both volatile and non-volatile random access memory (RAM). For space use, volatile memories consist of dynamic random access memory (DRAM) and SRAM. Non-volatile memory currently in use is limited to NAND flash, but there are many varieties of non-volatile memory currently under investigation for space applications.

From a radiation effects perspective, the only current radiation-hardened memory solutions are SRAMs. Of these, the largest amount of memory per die is 16 Mbit. Radiation-hardened computer offerings still use this type of memory extensively; however some designs have transitioned to DRAM. Due to memory size and power limitations, flight projects transitioned their solid-state recorders from SRAM to DRAM in the mid-1990s. Synchronous DRAMs (SDRAMs) are currently in-flight, with many designs using double data rate (DDR) and DDR2 interfaces. SDRAM is dense and low-power, making it ideal for mass storage applications that need to accommodate fast access times.

However, soft error evaluations of SDRAM indicate that they suffer from cross-contamination from multiple error modes, testability issues related to packaging, a large number of functional modes, soft error latency, and test data repeatability [5, 21, 30-36]. Despite all these drawbacks, commercial SDRAMs are indispensable for mass data storage in solid-state recorders. Though, due to soft error-induced data loss, they are not usually used to store mission-critical information.

Soft error data loss in SDRAMs can occur through single- and multiple-bit upset, control logic errors, block errors, and single-event functional interrupts (SEFIs). The classification categories are not standardized and vary among test groups [5, 32-34]. Block errors and SEFIs can circumvent error detection and correction schemes without periodic scrubbing, and in
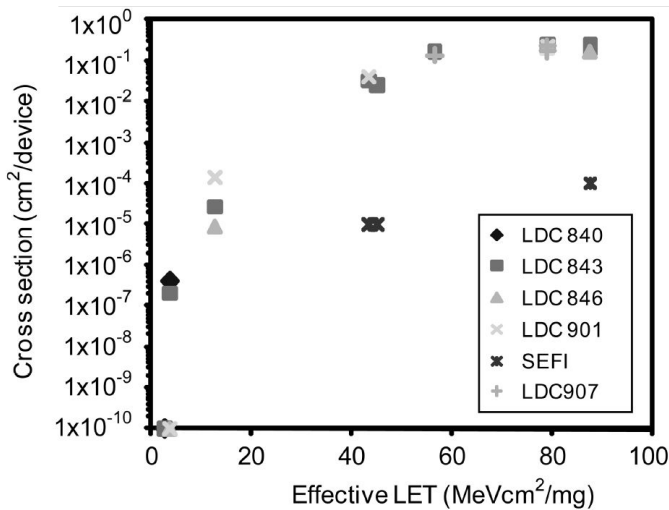
**Fig. 5:** Static bit-error and SEFI cross sections for five Samsung K9F4G08U0A 4 Gbit single-level cell NAND flash lots, after [6]. T. R. Oldham *et al.* [6] conducted these irradiations at the Texas A&M Cyclotron Facility.

some cases require power cycling causing complete data loss. Since mass memory is assembled into 3-dimensional stacks, having to recycle one die in the stack means losing the data in the entire stack, which can affect other data words if they are split across multiple stacks.

The complex nature of the possible errors in SDRAMs necessitates careful soft error evaluation. The standard technique employs ground-based broadbeam heavy ion testing, but because of latency and the time it takes to read out an entire memory, it could be many seconds before the errors get registered. Broadbeam testing lacks spatial correlation, so there is no definitive connection between the ion strike location and the observed error signature. This limitation has led to testing of SDRAMs with pulsed laser sources [5, 35, 36], similar to the test shown in Fig. 4.

Two-photon absorption [37, 38] is ideally suited for testing SDRAMs since it injects photons through the backside of the die and most SDRAMs are flip-chip mounted – shown in Fig. 4(a). For two-photon absorption, the laser spot size is approximately 2 $\mu$m in diameter. While this is large compared to the size of a single memory cell, it is easy to differentiate between stimulating control logic and memory cells, as shown in Fig. 4(b). This type of testing provides a relative measure of soft error sensitivity for different portions of the device by changing the laser pulse energy.

The approaching challenge for SDRAMs in space systems is two-fold. The cost and time required to qualify a SDRAM technology means that by the time a vendor's product is approved for flight use it is nearly obsolete in the marketplace with limited availability. Furthermore, SDRAM scaling beyond the 40 nm process node faces many challenges related to the present ArF lithography process, capacitor dielectric equivalent dielectric thickness, and equivalent electric field of the capacitor dielectric [39]. The International Technology Roadmap for Semiconductors predicts these challenges on its current roadmap as soon as 2012 with no known manufacturing solutions. This raises concerns about the

current qualification efforts focused on DDR3 SDRAMs and what might replace SDRAM.

Along with SDRAMs, NAND flash is the other major component in spacecraft memory applications [6, 40-42]. Like other space memory technologies, non-volatile memories have evolved from early one-time programmable PROMs, to EPROMs, to EEPROMs, to the current generation of single- and multi-level cell NAND flash technologies. The high density of NAND flash makes it attractive for mass storage in solid-state recorders. There are obvious power consumption benefits as well.

However, these benefits come at the cost of access time and requirements for high voltage to complete the read/erase/write cycle. The high voltage, generated with a charge pump, increases the threat of hard errors. The presence of mode registers, as with SDRAMs, means that flash devices are susceptible to SEFIs. However, flash storage density per die is much larger than SDRAM. Static (no read/write modes) heavy ion soft error cross sections for a Samsung 4 Gbit NAND flash are shown in Fig. 5. The onset LET for SEFIs is a critical parameter that will affect how the memory has to be protected on orbit.

Other types of non-volatile memory under investigation for space applications include phase-change RAM, ferroelectric RAM, resistive RAM, spin-torque transfer RAM – a type of magnetoresistive memory, and carbon nanotube RAM. A clear leader has not yet emerged from this group, but access time and thermal stability are key issues for a technology if it does replace SDRAMs in the coming years.

IV.    DISCUSSION AND SUMMARY

For commercial technology soft errors, low-energy protons represent one of the greatest mitigation threats due to sheer abundance in the space environment. The radiation effects community must devise a clear and uniform path forward to test, evaluate, and predict the consequences of low-energy proton direct ionization soft errors. Ground testing with low-energy protons will be an inextricable part of the process, but modeling and simulation will also play an important role. The MRED [14] and NOVICE [43-46] codes are two examples that might hold a solution given proper experimental data constraints. The debate at this point revolves around how to calibrate the simulation models – with high-energy light heavy ions or directly with low-energy protons. The answer may depend on differences in interaction mechanisms and track structure between protons and alpha particles.

Along the same path, we need a soft error simulation solution that's not dependent on technology intellectual property or destructive physical analysis. Most of the detailed soft error calculations that have been done to date – *i.e.*, [10, 28, 47-49] – rely on detailed technology information. This is often not available or affordable to obtain for standard commercial products. The radiation effects community needs to work towards a general-purpose modeling technique that can be applied to a variety of problems while maintaining predictive power based on limited data.

Constraining soft error analysis parameter spaces leads to the inevitable problem of incomplete state space coverage

when doing ground-based heavy ion or proton testing. With the possible exception of SRAMs, most modern commercial memory technologies like SDRAMs and NAND flash have too many operational modes to have full test coverage when ion species, tilt and roll angles, biasing, data patterns, and temperature are incorporated. K. A. LaBel *et al.* [50] calculated the costs of a scaled-down 1 Gbit SDRAM heavy ion test at the Texas A&M University Cyclotron facility and arrived at approximately $80,000 for 16 hours of beam time. Full state space coverage would require several years of continuous testing. This means that any testing has to be application specific without omitting important variables that could affect on-orbit operation. Effective modeling and simulation approaches could alleviate some of this burden by prescribing the data needed to optimally constrain subsequent simulations used to extrapolate coverage to more of the operational state space.

In lieu of heavy ion testing, pulsed laser irradiation has grown as an evaluation technique, largely due to the work of several groups [37, 38, 51-53]. While there have been several direct comparisons of pulsed laser data to heavy ion data, *cf.* [54-56], the pulsed laser technique's speed, spatial correlation, and ease of energy adjustment are the most valuable features. However, as technologies scale, the once relatively small laser spot size of 1-2 $\mu$m is now large compared to single transistors meaning that it is impossible to probe single devices in 65 and 45 nm process technologies with current pulsed laser techniques. There is movement in the radiation effects community to overcome this difficulty, perhaps with the use of solid immersion lenses [57], though a practical solution has not yet been demonstrated.

The challenge of evaluating soft errors in commercial technologies for space applications has been and will continue to be centered on memory technologies. Aside from FPGAs and microprocessors, memory technology represents one of the fastest moving semiconductor development sectors and an ideal point for space systems to leverage commercial non-recurring engineering and technological advances. However, this rapid development cycle puts the space electronics community at a disadvantage due to the inherent dichotomy in development cycle time constants. Spacecraft memory choices in the next several years will likely continue their transition to more non-volatile technologies as the search for one or more SDRAM successors continues.

REFERENCES

[1] K. P. Rodbell, D. F. Heidel, H. H. K. Tang, M. S. Gordon, P. Oldiges, and C. E. Murray, "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.

[2] D. F. Heidel, P. W. Marshall, K. A. LaBel, J. R. Schwank, K. P. Rodbell, M. C. Hakey, M. D. Berg, P. E. Dodd, M. R. Friendlich, A. D. Phan, C. M. Seidleck, M. R. Shaneyfelt, and M. A. Xapsos, "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.

[3] D. F. Heidel, P. W. Marshall, J. A. Pellish, K. P. Rodbell, K. A. LaBel, J. R. Schwank, S. E. Rauch, M. C. Hakey, M. D. Berg, C. M. Castaneda, P. E. Dodd, M. R. Friendlich, A. D. Phan, C. M. Seidleck, M. R. Shaneyfelt, and M. A. Xapsos, "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.

[4] B. D. Sierawski, J. A. Pellish, R. A. Reed, R. D. Schrimpf, K. M. Warren, R. A. Weller, M. H. Mendenhall, J. D. Black, A. D. Tipton, M. A. Xapsos, R. C. Baumann, D. Xiaowei, M. J. Campola, M. R. Friendlich, H. S. Kim, A. M. Phan, and C. M. Seidleck, "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.

[5] R. L. Ladbury, J. Benedetto, D. McMorrow, S. P. Buchner, K. A. LaBel, M. D. Berg, H. S. Kim, A. B. Sanders, M. R. Friendlich, and A. Phan, "TPA laser and heavy-ion SEE testing: complementary techniques for SDRAM single-event evaluation," *IEEE Trans. Nucl. Sci.,* vol. 56, no. 6, pp. 3334-3340, Dec. 2009.

[6] T. R. Oldham, M. R. Friendlich, A. B. Sanders, C. M. Seidleck, H. S. Kim, M. D. Berg, and K. A. LaBel, "TID and SEE response of advanced Samsung and Micron 4G NAND flash memories for the NASA MMS mission," in *IEEE Radiation Effects Data Workshop*, Quebec City, Quebec Canada, 2009, pp. 114-122.

[7] M. Gates. *Single Event Effect Criticality Analysis.* Available: http://radhome.gsfc.nasa.gov/radhome/papers/seecai.htm

[8] R. Ladbury, J. L. Gorelick, M. A. Xapsos, T. O'Connor, and S. Demosthenes, "A Bayesian treatment of risk for radiation hardness assurance," in *8th European Conference on Radiation and Its Effects on Components and Systems*, Cap d'Agde, France, 2005, pp. PB1-1-PB1-8.

[9] H. H. K. Tang and E. H. Cannon, "SEMM-2: a modeling system for single event upset analysis," *IEEE Trans. Nucl. Sci.,* vol. 51, no. 6, pp. 3342-3348, Dec. 2004.

[10] R. A. Reed, R. A. Weller, M. H. Mendenhall, J.-M. Lauenstein, K. M. Warren, J. A. Pellish, R. D. Schrimpf, B. D. Sierawski, L. W. Massengill, P. E. Dodd, N. F. Haddad, R. K. Lawrence, J. H. Bowman, and R. Conde, "Impact of ion energy and species on single event effects analysis," *IEEE Trans. Nucl. Sci.,* vol. 54, no. 6, Dec. 2007.

[11] V. Ferlet-Cavrois, D. McMorrow, D. Kobayashi, N. Fel, J. S. Melinger, J. R. Schwank, M. Gaillardin, V. Pouget, F. Essely, J. Baggio, S. Girard, O. Flament, P. Paillet, R. S. Flores, P. E. Dodd, M. R. Shaneyfelt, K. Hirose, and H. Saito, "A new technique for SET pulse width measurement in chains of inverters using pulsed laser irradiation," *IEEE Trans. Nucl. Sci.,* vol. 56, no. 4, pp. 2014-2020, Aug. 2009.

[12] G. Hubert, S. Duzellier, C. Inguimbert, C. Boatella-Polo, F. Bezerra, and R. Ecoffet, "Operational SER calculations on the SAC-C orbit using the multi-scales single event phenomena predictive platform (MUSCA SEP$^3$)," *IEEE Trans. Nucl. Sci.,* vol. 56, no. 6, pp. 3032-3042, Dec. 2009.

[13] H. Park, D. J. Cummings, R. Arora, J. A. Pellish, R. A. Reed, R. D. Schrimpf, D. McMorrow, S. E. Armstrong, U. Roh, T. Nishida, M. E. Law, and S. E. Thompson, "Laser-induced current transients in strained-Si diodes," *IEEE Trans. Nucl. Sci.,* vol. 56, no. 6, pp. 3203-3209, Dec. 2009.

[14] R. A. Weller, R. A. Reed, K. M. Warren, M. H. Mendenhall, B. D. Sierawski, R. D. Schrimpf, and L. W. Massengill, "General framework for single event effects rate prediction in microelectronics," *IEEE Trans. Nucl. Sci.,* vol. 56, no. 6, pp. 3098-3108, Dec. 2009.

[15] D. Binder, E. C. Smith, and A. B. Holman, "Satellite anomalies from galactic cosmic rays," *IEEE Trans. Nucl. Sci.,* vol. 22, no. 6, pp. 2675-2680, Dec. 1975.

[16] R. A. Reed, P. W. Marshall, H. S. Kim, P. J. McNulty, B. Fodness, T. M. Jordan, R. Reedy, C. Tabbert, M. S. T. Liu, W. Heikkila, S. Buchner, R. Ladbury, and K. A. LaBel, "Evidence for angular effects in proton-induced single-event upsets," *IEEE Trans. Nucl. Sci.,* vol. 49, no. 6, pp. 3038-3044, Dec. 2002.

[17] R. A. Nymmik, M. I. Panasyuk, T. I. Pervaja, and A. A. Suslov, "A model of galactic cosmic ray fluxes," *Nucl. Tracks Radiat. Meas.,* vol. 20, no. 3, pp. 427-429, 1992.

[18] M. A. Xapsos, G. P. Summers, J. L. Barth, E. G. Stassinopoulos, and E. A. Burke, "Probability model for cumulative solar proton event fluences," *IEEE Trans. Nucl. Sci.,* vol. 47, no. 3, pp. 486-490, Jun. 2000.

[19] M. A. Xapsos, C. Stauffer, G. B. Gee, J. L. Barth, E. G. Stassinopoulos, and R. E. McGuire, "Model for solar proton risk assessment," *IEEE Trans. Nucl. Sci.,* vol. 51, no. 6, pp. 3394-3398, Dec. 2004.

[20] J. W. Howard, H. Kim, M. Berg, K. A. LaBel, S. Stansberry, M. Friendlich, and T. Irwin, "Development of a low-cost and high-speed single event effects testers based on reconfigurable field programmable gate arrays (FPGA)," presented at the SEE Symposium, Long Beach, CA, 2006. Available: http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/2006 0028135_2006228899.pdf

[21] R. Ladbury, M. D. Berg, K. A. LaBel, M. Friendlich, A. Phan, and H. Kim, "Radiation performance of 1 Gbit DDR2 SDRAMs fabricated with 80-90 nm CMOS," in *IEEE Radiation Effects Data Workshop*, Tucson, AZ, 2008, pp. 42-46.

[22] H. Paul and A. Schinner, "Judging the reliability of stopping power tables and programs for protons and alpha particles using statistical methods," *Nucl. Instr. and Meth. B,* vol. 227, no. 4, pp. 461-470, 2005.

[23] H. Paul. (2010). *Stopping Power for Light Ions: Graphs, Data, Comments and Programs.* Available: http://www.exphys.jku.at/stopping/

[24] J. F. Zeigler, "SRIM-2003," *Nucl. Instr. and Meth. B,* vol. 219-220, pp. 1027-1036, Jun. 2004.

[25] J. F. Zeigler and J. P. Biersack. (2010). *Stopping and Range of Ions in Matter*. Available: http://www.srim.org/

[26] M. J. Berger, J. S. Coursey, M. A. Zucker, and J. Chang. (2005). *ESTAR, PSTAR, and ASTAR: computer programs for calculating stopping-power and range tables for electrons, protons, and helium Ions (version 1.2.3)*. Available: http://physics.nist.gov/Star

[27] "Stopping Powers and Ranges for Protons and Alpha Particles," International Commission on Radiation Units and Measurements Report 49, May 1993.

[28] K. M. Warren, A. L. Sternberg, R. A. Weller, M. P. Baze, L. W. Massengill, R. A. Reed, M. H. Mendenhall, and R. D. Schrimpf, "Integrating Circuit Level Simulation and Monte-Carlo Radiation Transport Code for Single Event Upset Analysis in SEU Hardened Circuitry," *IEEE Trans. Nucl. Sci.,* vol. 55, no. 6, pp. 2886-2894, Dec. 2008.

[29] K. M. Warren, R. A. Weller, B. D. Sierawski, R. A. Reed, M. H. Mendenhall, R. D. Schrimpf, L. W. Massengill, M. Porter, J. Wilkinson, K. A. LaBel, and J. H. Adams Jr, "Application of RADSAFE to Model Single Event Upset Response of 0.25 $\mu$m CMOS SRAM," *IEEE Trans. Nucl. Sci.,* vol. 54, no. 4, pp. 898-903, Aug. 2007.

[30] K. A. LaBel, P. W. Marshall, J. L. Barth, R. B. Katz, R. A. Reed, H. W. Leidecker, H. S. Kim, and C. J. Marshall, "Anatomy of an in-flight anomaly: investigation of proton-induced SEE test results for stacked IBM DRAMs," *IEEE Trans. Nucl. Sci.,* vol. 45, no. 6, pp. 2898-2903, Dec. 1998.

[31] T. Langley, R. Koga, and T. Morris, "Single-event effects test results of 512MB SDRAMs," in *IEEE Radiation Effects Data Workshop*, Monterey, CA, 2003, pp. 98-101.

[32] J. Benedetto, "Examination of single event functional interrupts (SEFIs) in COTS SDRAMs," presented at the Single-Event Effects Symp., Long Beach, CA, 2006.

[33] R. K. Lawrence, "Radiation characterization of 512 Mb SDRAMs," in *IEEE Radiation Effects Data Workshop*, Honolulu, HI, 2007, pp. 204-207.

[34] J. Benedetto, J. D. Black, and G. Ott, "Soft error case study: Single event functional interrupts (SEFIs) in COTS SDRAMs," presented at the IEEE Nuclear and Space Radiation Effects Conf. Short Course, Tucson, AZ, 2008.

[35] A. Bougerol, F. Miller, and N. Buard, "SDRAM architecture & single event effects revealed with laser," in *IEEE Int. On-Line Testing Symp.*, Rhodes, Greece, 2008, pp. 283-288.

[36] A. Bougerol, F. Miller, N. Guibbaud, R. Gaillard, F. Moliere, and N. Buard, "Use of laser to explain heavy ion induced SEFIs in SDRAMs," *IEEE Trans. Nucl. Sci.,* vol. 57, no. 1, pp. 272-278, Jan. 2010.

[37] D. Lewis, V. Pouget, F. Beaudoin, P. Perdu, H. Lapuyade, P. Fouillat, and A. Touboul, "Backside laser testing of ICs for SET sensitivity evaluation," *IEEE Trans. Nucl. Sci.,* vol. 48, no. 6, pp. 2193-2201, Dec. 2001.

[38] D. McMorrow, W. T. Lotshaw, J. S. Melinger, S. Buchner, and R. L. Pease, "Subbandgap laser-induced single event effects: carrier generation via two-photon absorption," *IEEE Trans. Nucl. Sci.,* vol. 49, no. 6, pp. 3002-3008, Dec. 2002.

[39] *International Technology Roadmap for Semiconductors*. Available: http://www.itrs.net/Links/2009ITRS/Home2009.htm

[40] F. Irom and D. N. Nguyen, "Single event effect characterization of high density commercial NAND and NOR nonvolatile flash memories," *IEEE Trans. Nucl. Sci.,* vol. 54, no. 6, pp. 2547-2553, Dec. 2007.

[41] T. R. Oldham, R. L. Ladbury, M. Friendlich, H. S. Kim, M. D. Berg, T. L. Irwin, C. Seidleck, and K. A. LaBel, "SEE and TID characterization of an advanced commercial 2 Gbit NAND flash nonvolatile memory," *IEEE Trans. Nucl. Sci.,* vol. 53, no. 6, pp. 3217-3222, Dec. 2006.

[42] H. R. Schwartz, D. K. Nichols, and A. H. Johnston, "Single-event upset in flash memories," *IEEE Trans. Nucl. Sci.,* vol. 44, no. 6, pp. 2315-2324, Dec. 1997.

[43] T. M. Jordan, "An adjoint charged particle transport method," *IEEE Trans. Nucl. Sci.,* vol. 23, no. 6, pp. 1857-1861, Dec. 1976.

[44] T. M. Jordan, "The accuracy of NOVICE electron shielding calculations," in *1st European Conf. on Radiation and Its Effects on Components and Systems*, La Grande-Motte, France, 1991, pp. 320-324.

[45] T. M. Jordan, "Space system analysis using the NOVICE code system," in *Radiation and its Effects on Devices and Systems, 1991. RADECS 91., First European Conference on*, 1991, pp. 312-316.

[46] P. Calvel, C. Barillot, A. Porte, G. Auriel, C. Chatry, P. F. Peyrard, G. Santin, R. Ecoffet, and T. M. Jordan, "Review of Deposited Dose Calculation Methods Using Ray Tracing Approximations," *IEEE Trans. Nucl. Sci.,* vol. 55, no. 6, pp. 3106-3113, Dec. 2008.

[47] K. M. Warren, R. A. Weller, M. H. Mendenhall, R. A. Reed, D. R. Ball, C. L. Howe, B. D. Olson, M. L. Alles, L. W. Massengill, R. D. Schrimpf, N. F. Haddad, S. E. Doyle, D. McMorrow, J. S. Melinger, and W. T. Lotshaw, "The contribution of nuclear reactions to heavy ion single event cross-section measurements in a high-density SEU hardened SRAM," *IEEE Trans. Nucl. Sci.,* vol. 52, no. 6, pp. 2125-2131, Dec. 2005.

[48] K. M. Warren, B. D. Sierawski, R. A. Reed, R. A. Weller, C. Carmichael, A. Lesea, M. H. Mendenhall, P. E. Dodd, R. D. Schrimpf, L. W. Massengill, H. Tan, W. Hsing, J. L. De Jong, R. Padovani, and J. J. Fabula, "Monte-Carlo based on-orbit single event upset rate prediction for a radiation hardened by design latch," *IEEE Trans. Nucl. Sci.,* vol. 54, no. 6, pp. 2419-2425, Dec. 2007.

[49] A. D. Tipton, J. A. Pellish, J. M. Hutson, R. Baumann, X. Deng, A. Marshall, M. A. Xapsos, H. S. Kim, M. R. Friendlich, M. J. Campola, C. M. Seidleck, K. A. LaBel, M. H. Mendenhall, R. A. Reed, R. D. Schrimpf, R. A. Weller, and J. D. Black, "Device-Orientation Effects on Multiple-Bit Upset in 65 nm SRAMs," vol. 55, no. 6, pp. 2880-2885, Dec. 2008.

[50] K. A. LaBel, R. L. Ladbury, L. M. Cohn, and T. R. Oldham, "Radiation test challenges for scaled commercial memories," *IEEE Trans. Nucl. Sci.,* vol. 55, no. 4, pp. 2174-2180, Aug. 2008.

[51] S. P. Buchner, D. Wilson, K. Kang, D. Gill, J. A. Mazer, W. D. Raburn, A. B. Campbell, and A. R. Knudson, "Laser simulation of

single event upsets," *IEEE Trans. Nucl. Sci.,* vol. 34, no. 6, pp. 1227-1233, Dec. 1987.

[52]  J. S. Melinger, S. Buchner, D. McMorrow, W. J. Stapor, T. R. Weatherford, A. B. Campbell, and H. Eisen, "Critical evaluation of pulsed laser method for single-event effects testing and fundamental studies," *IEEE Trans. Nucl. Sci.,* vol. 41, no. 6, pp. 2574-2584, Dec. 1994.

[53]  A. Douin, V. Pouget, F. Darracq, D. Lewis, P. Fouillat, and P. Perdu, "Influence of Laser Pulse Duration in Single Event Upset Testing," in *8th European Conference on Radiation and Its Effects on Components and Systems*, Cap d'Agde, France, 2005, pp. C13-1-C13-7.

[54]  S. Buchner, K. Kang, W. J. Stapor, A. B. Campbell, A. R. Knudson, P. McDonald, and S. Rivet, "Pulsed laser-induced SEU in integrated circuits: a practical method for hardness assurance testing," *IEEE Trans. Nucl. Sci.,* vol. 37, no. 6, pp. 1825-1831, Dec. 1990.

[55]  D. McMorrow, J. S. Melinger, S. Buchner, T. Scott, R. D. Brown, and N. F. Haddad, "Application of a pulsed laser for evaluation and optimization of SEU-hard designs," *IEEE Trans. Nucl. Sci.,* vol. 47, no. 3, pp. 559-565, Jun. 2000.

[56]  S. Buchner, D. McMorrow, C. Poivey, J. Howard, Y. Boulghassoul, L. W. Massengill, R. Pease, and M. Savage, "Comparison of single-event transients induced in an operational amplifier (LM124) by pulsed laser light and a broad beam of heavy ions," *IEEE Trans. Nucl. Sci.,* vol. 51, no. 5, pp. 2776-2781, Oct. 2004.

[57]  K. A. Serrels, E. Ramsay, and D. T. Reid, "70 nm resolution in subsurface optical imaging of silicon integrated-circuits using pupil-function engineering," *Appl. Phys. Lett.,* vol. 94, no. 7, p. 073113, Feb. 2009.
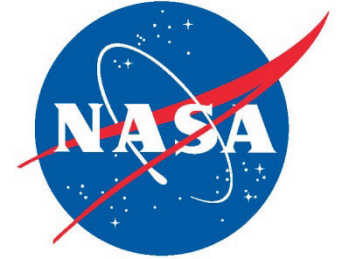
# Practicality of Evaluating Soft Errors in Commercial sub-90 nm CMOS for Space Applications

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### Greenbelt, MD 20771 USA

# Purpose

- **Highlight space memory evaluation evolution – this is the discussion driver**

- **Review recent developments regarding low-energy proton direct ionization soft errors**

- **Assess current space memory evaluation challenges, including increase of non-volatile technology choices**

- **Discuss related testing and evaluation complexities**

# Presentation Outline

- **Introduction**
- **Low-energy protons**
  - **First data sets**
  - **Evaluation methods and testing challenges**
- **SDRAMs and NAND flash**
  - **Evaluation methods and testing challenges**
- **Remaining questions and future challenges**
- **Conclusions**

# Introduction

| THEN | NOW |
|---|---|
| Magnetic core memory | NAND flash, RRAM, MRAM, and PCM |
| Small-capacity SRAM | DDR(1, 2, 3) SDRAM |
| Radiation hardened | RHA what? |
| Single-bit upset | Multiple-bit upset, block errors, and single-event functional interrupts |
| Heavy ions and high-energy protons | Heavy ions, high- and low-energy protons, maybe even delta rays |

**Increase in capability introduces additional evaluation challenges**

# Low-Energy Proton Soft Error Data

## IBM 65 nm SOI SRAM – top-side irradiation
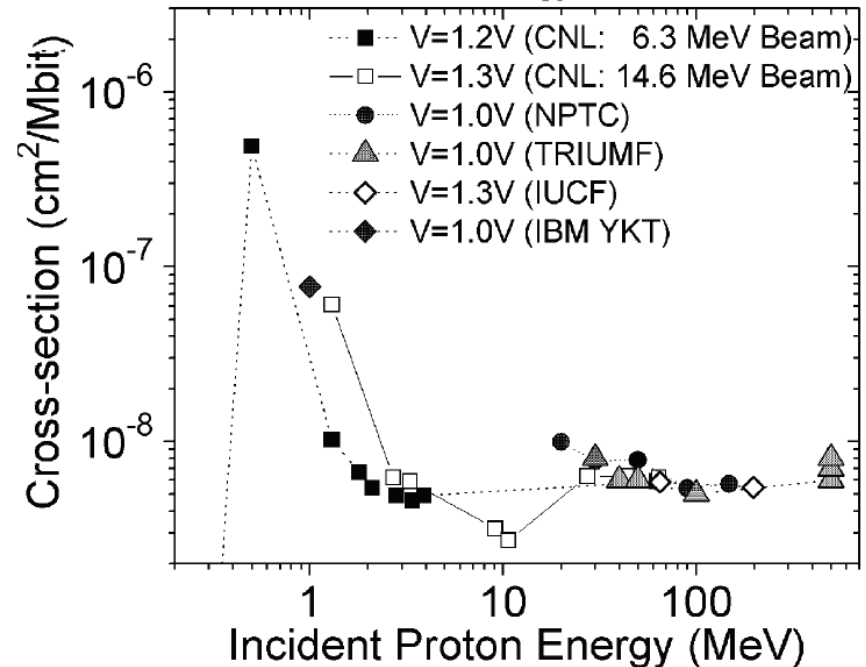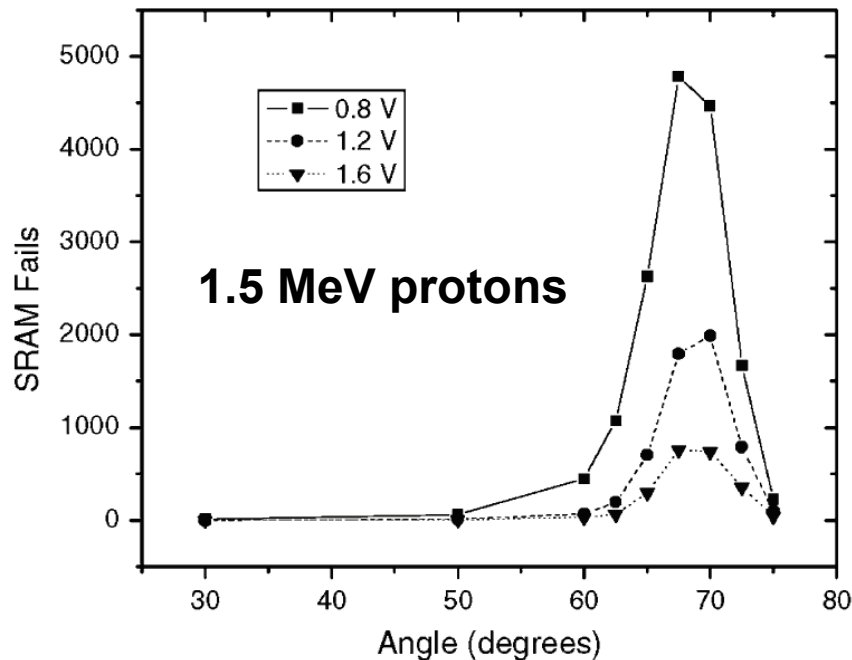


K. P. Rodbell, *et al.*, *IEEE TNS*, Dec. 2007.          D. F. Heidel, *et al.*, *IEEE TNS*, Dec. 2008.

- **First published low-energy proton soft errors**
- **Energy below Coulomb barrier – interactions are constrained to electromagnetic and nuclear elastic reactions**

**Rapid cross section increase at grazing angles and below 2 MeV**
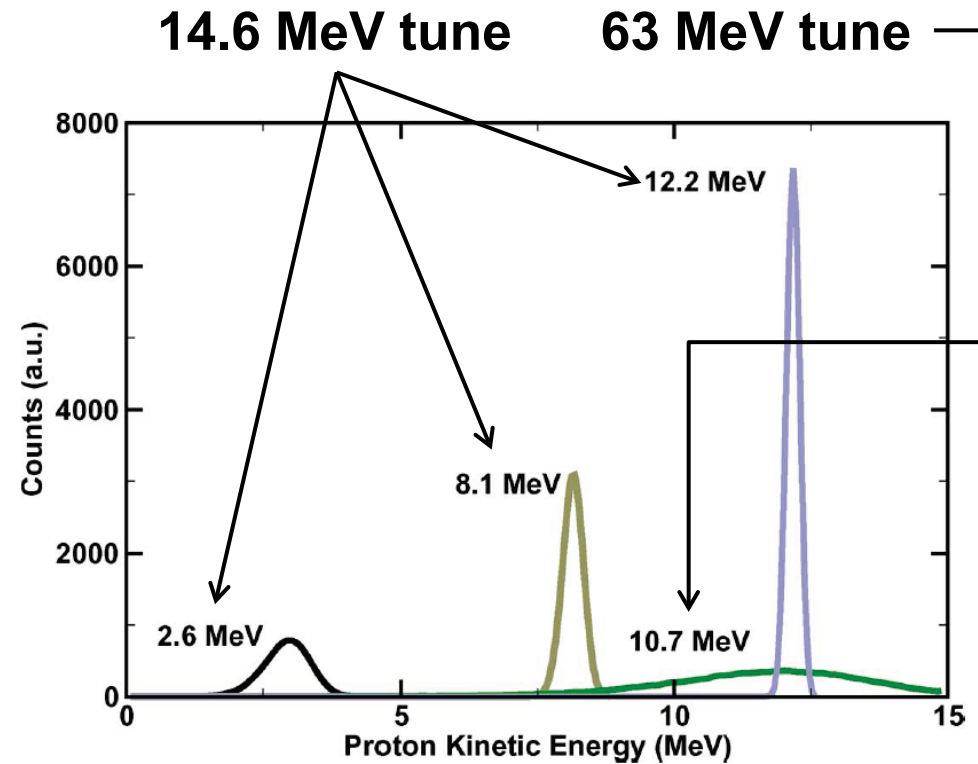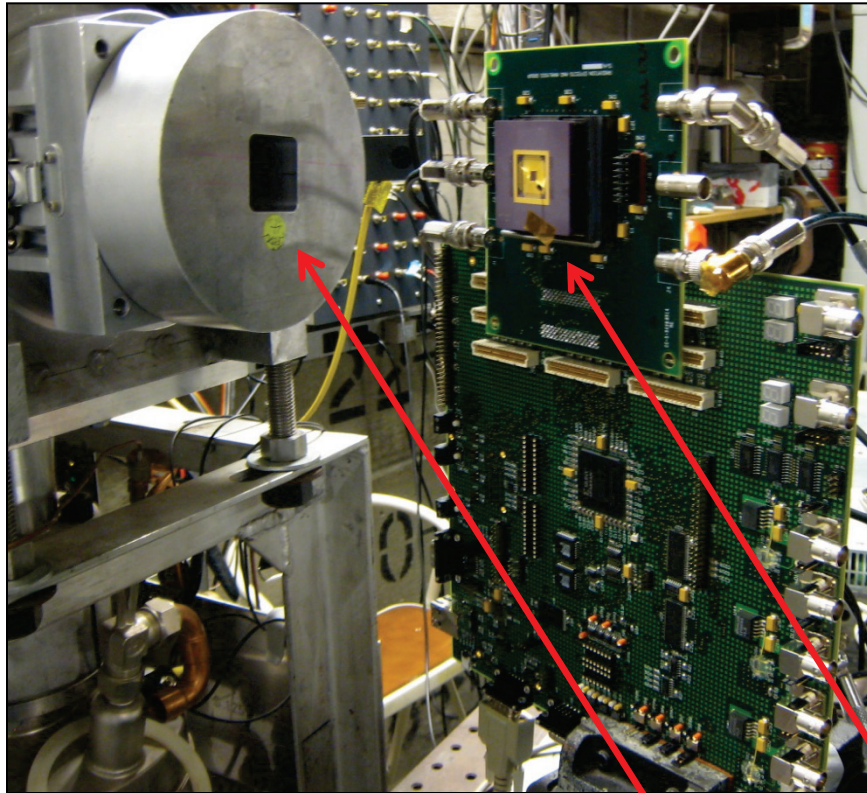
# Proton Energy Spectrum in Space



**Differential**

**Integral**
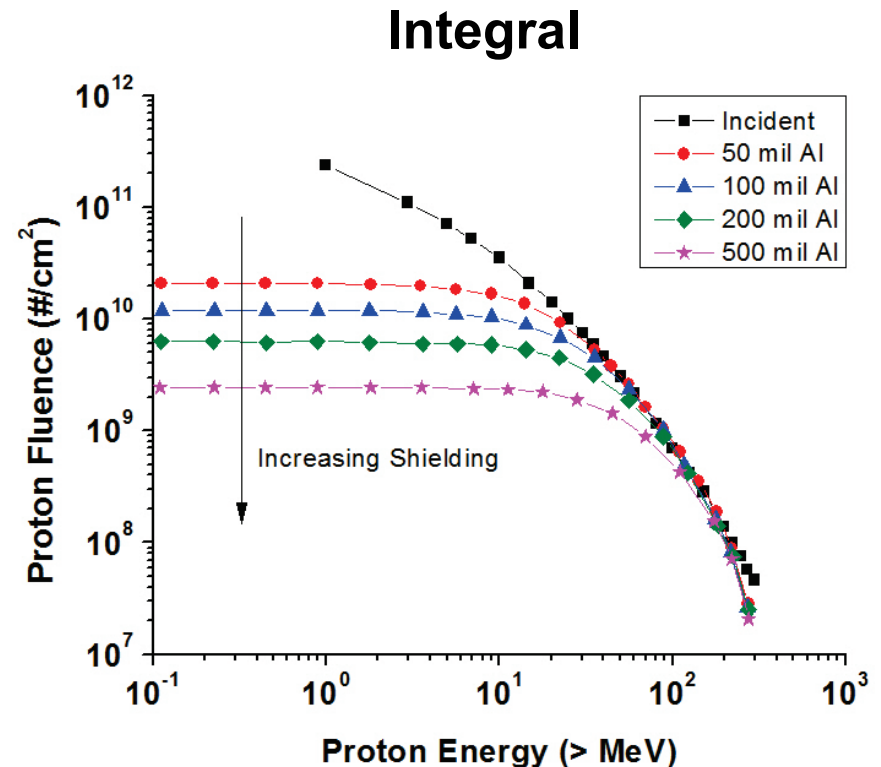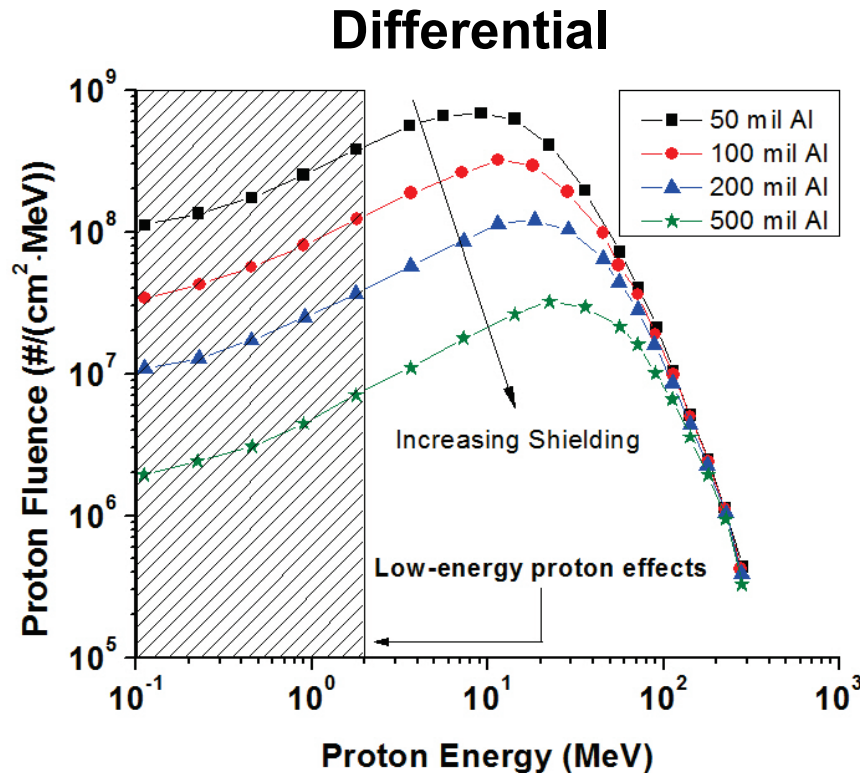
Both charts adapted from D. F. Heidel, *et al.*, *IEEE TNS*, Dec. 2008.

- **Both charts employ 4π sr solid spherical shielding**

**Cannot shield low-energy protons – shielding hardens spectra**
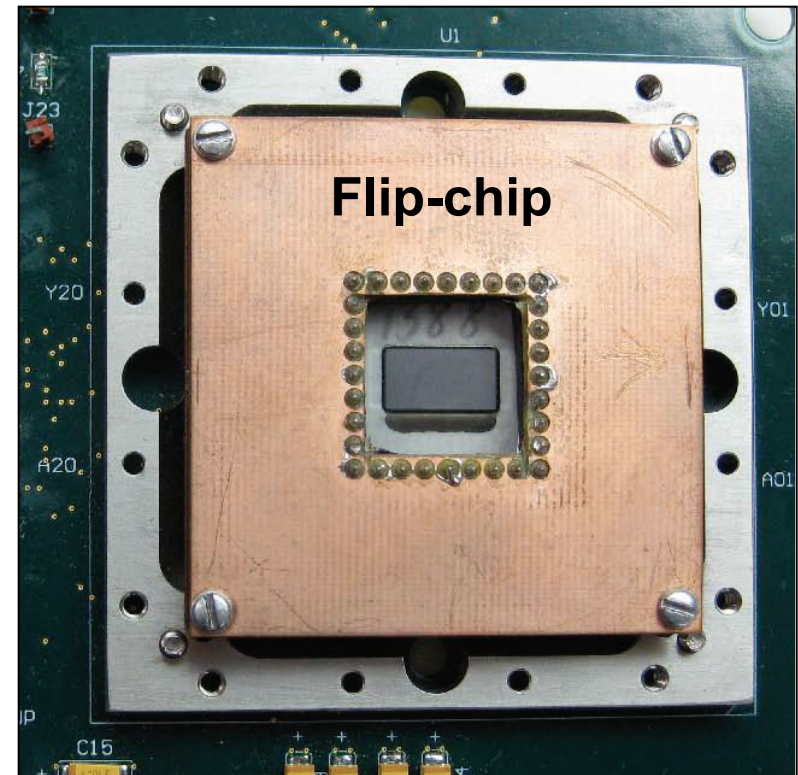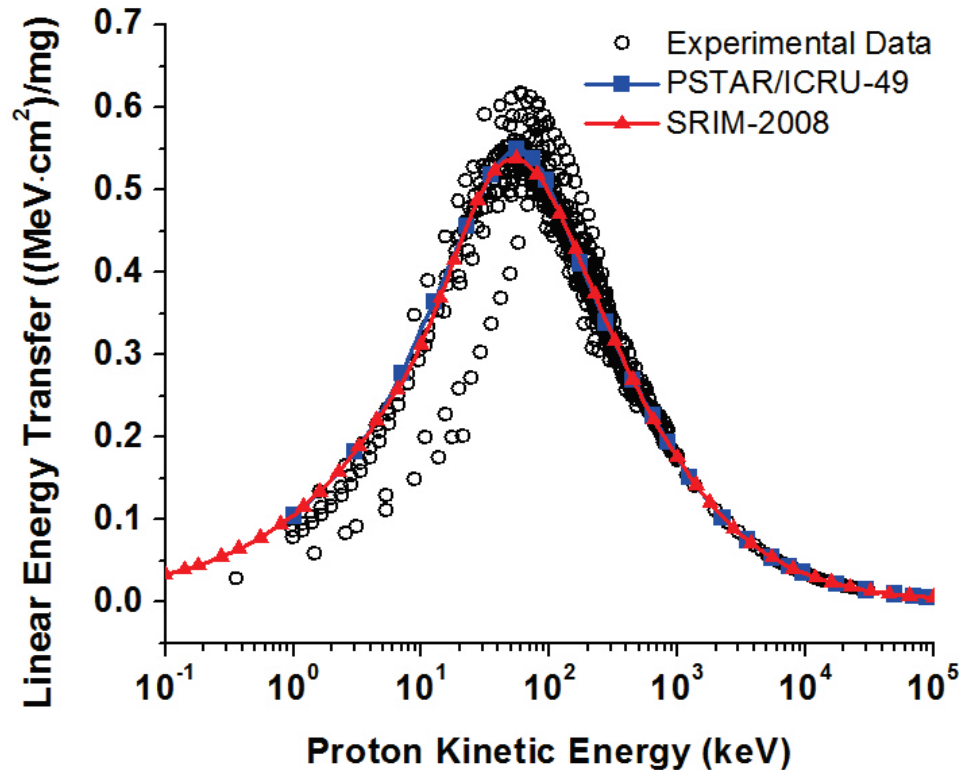
# Low-Energy Proton Testing Challenges



14.6 MeV tune    63 MeV tune

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

**External degrader stack here; experiments usually at normal incidence**

**Degrading beam broadens spectrum and produces left skew**

# Low-Energy Proton Testing Challenges



Data from H. Paul, http://www.exphys.jku.at/stopping/

- Increased (dE/dx)/$\rho$ variability at the Bragg peak – systematic error

- Problems increase with flip-chip irradiation

**Energy/range straggling close the Bragg peak makes (dE/dx)/$\rho$ a stochastic process**

# Commercial Space Memory: SDRAM or Flash (excludes EEPROM)

- **Speed and endurance versus capacity and power**

- **Higher soft error cross section and block errors versus functional interrupts and latchup**

- **Both suffer cross-contamination, testability, error latency, and repeatability issues**
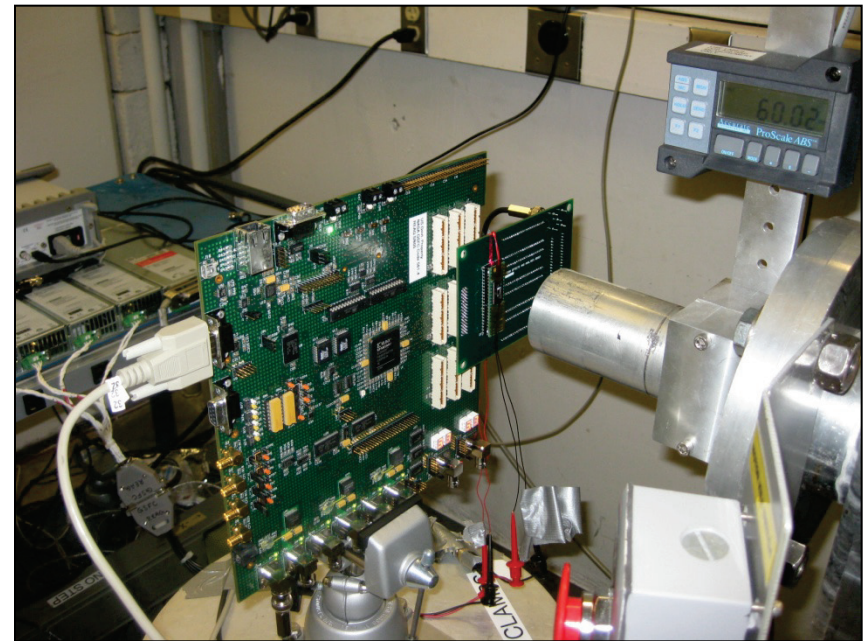


**Both technologies have strengths and can be used together to improve spacecraft performance**

# SDRAM Evaluation: Heavy Ions

- **Testing done with Texas A&M cyclotron**

- **SEU and small logic cross sections are similar – block error cross section lower**

- **SEFI cross section is low and likely state-/time-dependent**

**Elpida 512 Mbit SDRAM**
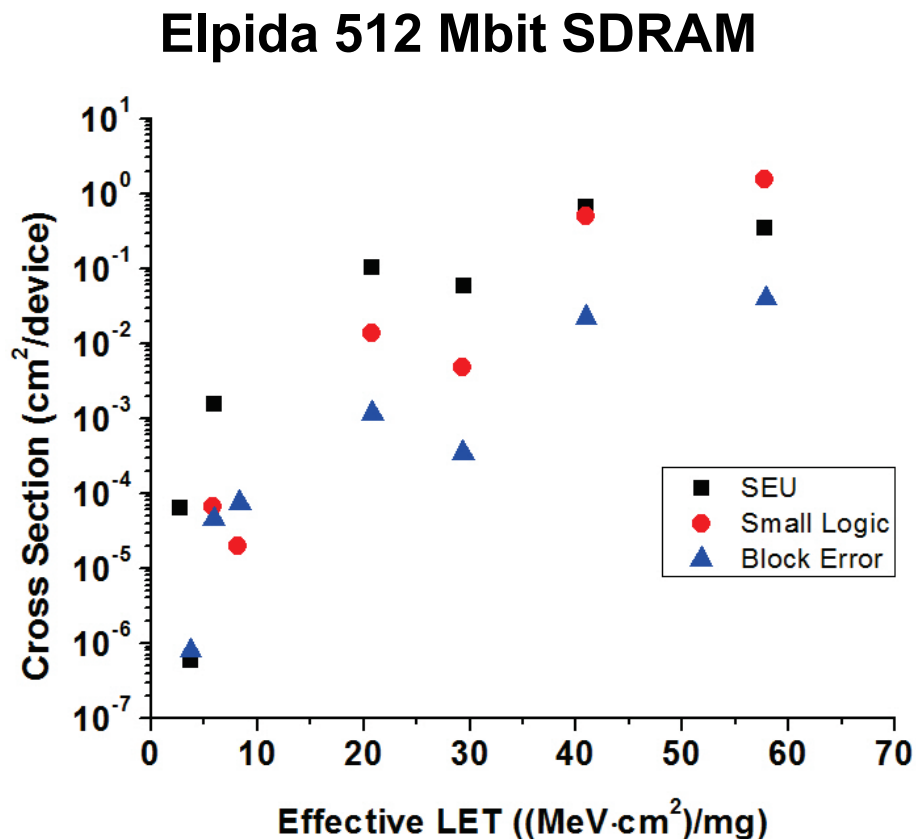


Data adapted from R. L. Ladbury, *et al.*, *IEEE TNS*, Dec. 2009.

**Broadbeam heavy ions provide fidelity to the space environment and proper track structure, but lack spatio-temporal information**
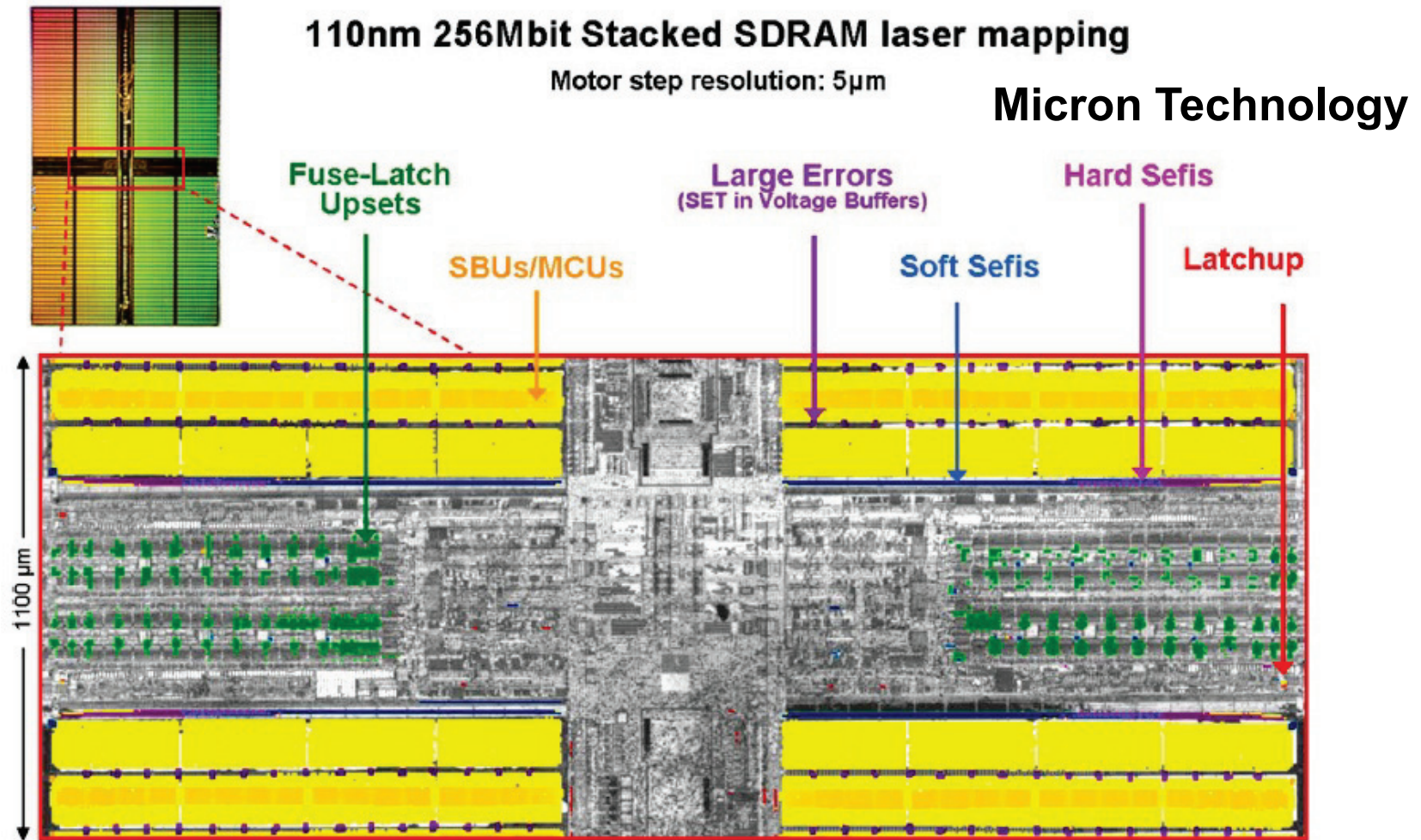
# SDRAM Evaluation: Pulsed Laser



110nm 256Mbit Stacked SDRAM laser mapping
Motor step resolution: 5μm

Micron Technology

Fuse-Latch Upsets

Large Errors (SET in Voltage Buffers)

Hard Sefis

SBUs/MCUs

Soft Sefis

Latchup

1100 μm

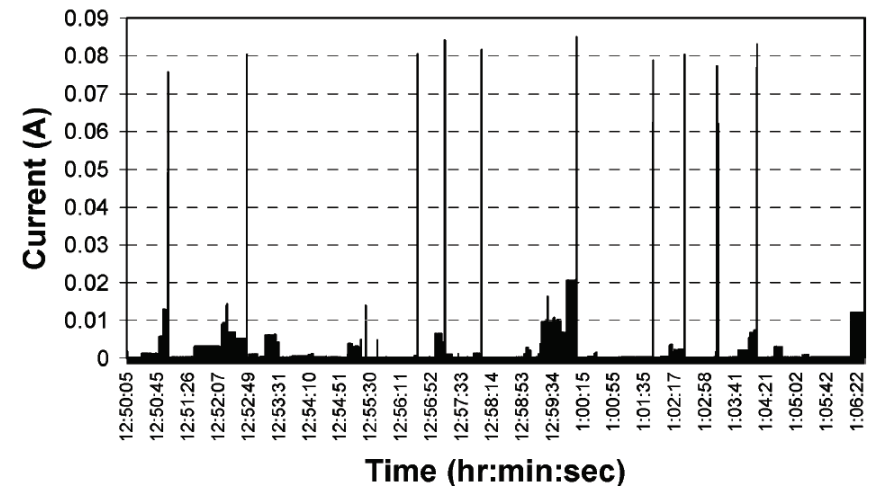Figure from A. Bougerol, *et al.*, *IEEE TNS*, Jan. 2010.

**Pulsed laser provides spatio-temporal information, repeatability, and lower cost versus heavy ion testing**

# NAND Flash Evaluation

**Samsung 4 Gbit flash**
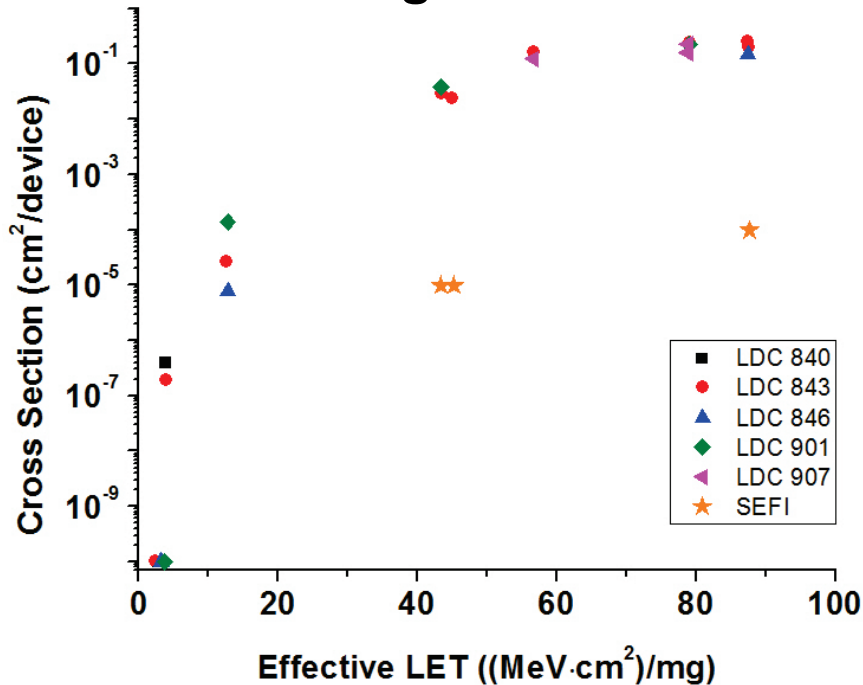


**Micron 4 Gbit flash**



F. Irom, *et al.*, *IEEE TNS*, Dec. 2007.

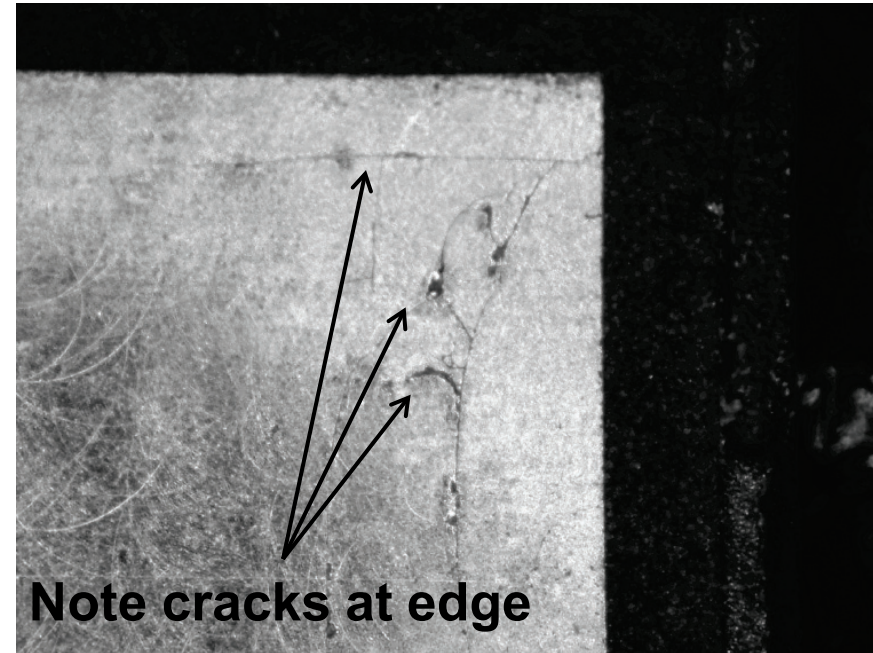T. R. Oldham, *et al.*, *IEEE Radiation Effects
Data Workshop*, 2009.

- **Flash bit cross section is lower than volatile memory**
- **Due to the charge pump, destructive failures have been a concern**

**NAND flash has a lower SEU cross section than SDRAM, but can suffer destructive effects due to high voltages required for access processes**

# Commercial Memory Testing Challenges

- **Difficult to stay ahead of memory commercialization curve**
  - DDR3 predicted to exceed 50% of all SDRAM shipments in 2010
- **Thinning and polishing for backside irradiation is not trivial**
- **As with any commercial technology, destructive effects are always a concern – statistics?!?**
- **Soft error repeatability from lot to lot**

**1 Gbit DDR2 SDRAM Die**



**Note cracks at edge**

R. L. Ladbury, *et al.*, *IEEE Radiation Effects Data Workshop*, 2008.

# Questions to Consider

- **Are high-energy, light heavy ions with equivalent LETs the same as low-energy protons?**

- **What are we doing to improve low-energy proton testing?**

- **How do engineers calculate low-energy proton soft error rates?**

- **What is the most cost effective solution for qualifying SDRAMs?**

- **Which non-volatile technology will displace SDRAMs for aerospace applications?**

# Conclusions

- **Commercial components in civil space systems will be driven by advancing science requirements**

- **Piece part qualification of commercial memory technologies is driven in part by soft errors**

- **Current evaluation and qualification challenges are focused on low-energy protons, testability, and speed of commoditization**