Proton Particle Test Fluence: What's the Right Number?

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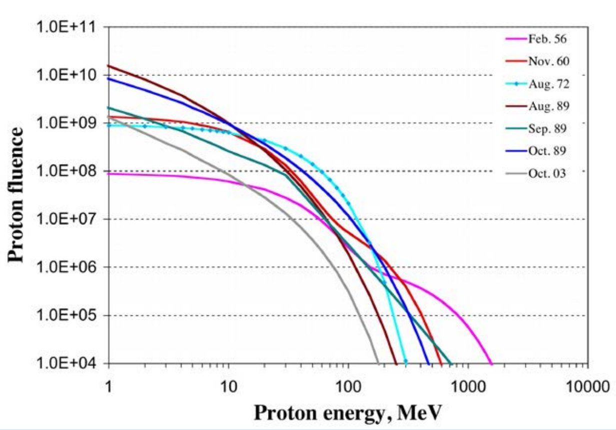
Acronyms

Acronym	Definition
Au	Gold
DRAMs	Dynamic Random Access Memory
DUT	Device Under Test
EDAC	Error Detection and Correction
F	Fluence
Gbit	Gigabit
HST	Hubble Space Telescope
IEEE	Institute of Electrical and Electronics Engineers
ISC	Irvine Sensor
LET	linear energy transfer (MeV•cm^2/mg)
MeV	Million electronvolts
MHz	Megahertz
NEPP	NASA Electronic Parts and Packaging
nsec	Nanosecond

Acronym	Definition
Nucl	Nuclear
Pb	Lead
POF	Physics of Failure
Pt	Platinum
RHA	Radiation Hardness Assurance
Sci	Science
SEE	Single Event Effect
SEFI	Single Event Functional Interrupt
SEL	Single-Event Latchup
SEU	Single Event Upset
SOC	Systems on a Chip
SSR	Solid State Recorder
Trans	Transactions

Outline

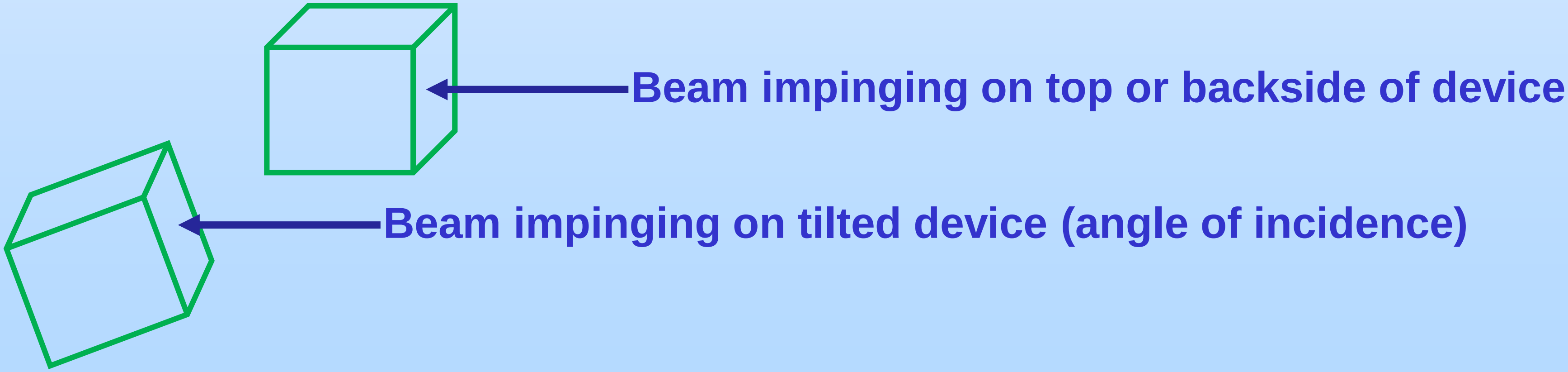
- What’s fluence?
  - Brief history lesson
- The factors that influence fluence levels:
  - Number of transistors/nodes,
  - Number of dynamic operating states,
  - Number of samples being used in flight, and
  - Mission environment and particle kinematics.
- Considerations and implications
- Summary



http://journalofcosmology.com/images/StraumeFigure3a.jpg

Definition of Fluence

- **Fluence is:**
  - **The number of particles impinging on the surface of a device during a single ion beam test run normalized to a square centimeter. Denoted F.**
- **It is NOT:**
  - ***Cumulative fluence*: the sum of all individual fluence levels for all beam runs (usually only for a given test condition such as proton energy).**
  - ***Effective fluence*: beam run fluence normalized by cos(θ), where θ is the angle of incidence.**



Beam impinging on top or backside of device

Beam impinging on tilted device (angle of incidence)

Motivation

- **Each transistor and operating-state (in a dynamic system) has the same random probability of getting hit.**
  - **That's the challenge: single event effects (*SEE) are random* processes*.**
  - **In other words, the error signature will be a function of where a particle hits and when a particle hits in a dynamic operating system.**
- **Testing is an attempt to quantify this random process and provide:**
  - ***Reasonable* coverage of the possible error signatures by getting sufficient particle fluences to provide confidence in coverage of the transistor/state space.**
- **For a billion-transistor, complex, system on a chip (SOC) device, how do we ensure this?**
  - **This is the crux of this presentation: doing enough testing to have a reasonable level of confidence.**

****Okay, it's really a Markov process –***
where the occurrence of an SEU in the future and past are independent.

Tradition: When Do We Stop a Test at the Particle Beam?

- Existing test standards provide guidance on setting a “beam stop” at either a given fluence or specific number of events.
- Fluence is (number of particles)/cm^2 for a given test run
- JESD57* (the long time guidance for heavy ion SEE) gives recommendations of:
  - A fluence of 1×10^7 particles/cm^2, or
  - 100 events, or
  - Significant event (such as SEFI or SEL).
- Proton testing is often stopped at a fluence of 1×10^{10} protons/cm^2 (or 100 errors or a significant event).
- Are these numbers taking into account:
  - Physics of failure (POF),
  - Circuit operation, and
  - Sufficient statistics?

** JEDEC JESD57: Test Procedures for the Measurement of Single-Event Effects in Semiconductor Devices from Heavy Ion Irradiation, Revised 1996 – this is currently being revised*

The Challenges

- **There are four basic considerations for determining fluence levels:**
  - **Geometry:**
    - **The number of potentially sensitive nodes or transistors in the device (statistical node coverage).**
  - **Operation (and propagation):**
    - **The dynamic operation of the device under test (statistical state and error propagation coverage).**
  - **Sample size:**
    - **The number of samples of the device being used for test (statistical system and variability coverage).**
  - **POF and (more) statistics:**
    - **The environment exposure and particle kinematics (i.e., what happens when a particle strikes the semiconductor).**
- ***For dynamic operations, we are looking not only at measuring a cross-section for rate determination, but capturing as many possible error signatures as reasonable to provide to design teams.***
  - ***A simple example is the range of transients induced in an amplifier.***

Geometric Node Coverage

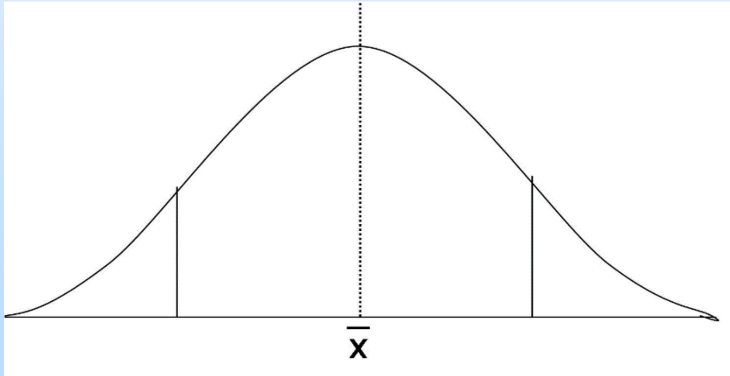
- **This is the simplest of the challenges to discuss. So consider,**
  - **A memory device under test (DUT) has a Million memory cells (Mbit), -**
    - ***How many protons on the die surface are required to cover a sufficient number of potentially sensitive bits in order to obtain good statistics on variability?***
    - **I.e., what's the right number of "events" to detect versus array size?**
      - **1%?, 10%?, 50%?, 100%?**
  - **What is the objective?**
    - **Mean distribution? Corner cases? Other?**
  - **1% equates to 1000 events in this example, but what does that say about variability across the die?**
    - **Consider 10% at a minimum**

Dynamic Operation Constraints

- **Assume that a particle strikes a specific location (sensitive node). What can happen?**
  - **An error can occur immediately,**
  - **An error can occur at a undetermined time (and/or location) later (temporal or circuit propagation), or**
  - **Nothing.**
- **Why? Let's look at a Gbit memory.**
  - **Assume it takes a minute to cycle through the address space.**
    - **Errors may occur before I reach an address (I see the error), while I'm at an address (may or may not see the error), or after I'm at an address (don't see it now, but may or may not see it later).**
- **Now look at a logic circuit such as a 32-bit counter.**
  - **There are 2^{32} states.**
  - **Operational frequency of 50 MHz (20 nsec per state) – over 300 billion seconds to cover all states.** ***Beam runs are too short to cover this statistically.***
    - **Key is understanding the error signature space and propagation effect.**
      - **Tests should be prognostic on capturing error signatures that designers may need to properly design fault tolerance.**
  - **Remember, each state has the same random chance of taking a hit.**
    - **Consider a truly complex device like a system on a chip.**
- ***Operating state coverage (statistics), and error signatures*****.**

(Sample) Size Matters

- **Besides the usual discussion of statistical relevance of samples from a single wafer lot, consider what the test results will be applied to.**
  - **How many samples in the flight application are being used?**
    - **There's a big difference between flying two samples of a device and one thousand!**
    - **Outlier results are important when device is being used extensively. [1]**
- **It's also important to grasp the idea of limiting cross-section (i.e., no events observed).**



How important is knowing outliers in SEE testing?

[1] K.A. LaBel, A.H. Johnston, J.L. Barth, R.A. Reed, C.E. Barnes, "Emerging Radiation Hardness Assurance (RHA) Issues: A NASA Approach for Space Flight Programs," IEEE Trans. Nucl. Sci., Vol. 45, No.6, pp. 2727-2736, Dec. 1998.

Example: Hubble Space Telescope (HST) Solid State Recorder (SSR) – 1 of 2

- Contained
  - IBM Luna ES Rev. C 5.0V 16Mbit DRAMs (4Mx4)
  - 12 Gbits total (1440 die)
    - Die are packaged in Irvine Sensor (ISC) 320 Mbit memory stacks
- System utilized error detection and correction (EDAC)
  - Reed-Solomon (224,234)
- 2 “events” observed in first 9 months each with ~100 correctable EDAC errors
  - Errors occurred in differing logical block ranges
  - Isolated to specific memory die row
  - Errors remained even when new data was written to these erroneous memory locations

Example: Hubble Space Telescope (HST) Solid State Recorder (SSR) – 2 of 2

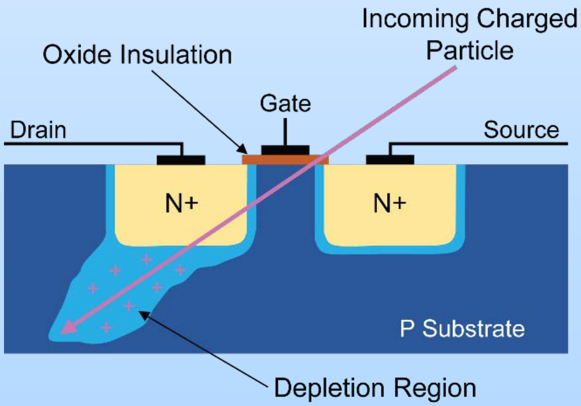
- IBM Luna ES 5.0 V Rev C die – test data prior to flight
  - Heavy ions
    - Events similar to in-flight anomaly observed with a LET_0 of 5 MeV*cm^2/mg
    - Event cleared by power cycle or device reset, but not by a rewrite of new data
    - Denote this event as a ***block SEFI*** (Single Event Functional Interrupt)
  - 3 die were proton single event effect (SEE) tested to proton fluences of 1e10 or 1e11 protons/cm^2
    - No block SEFIs observed: test report notes that they were expected due to heavy ion results
- Re-test of 100 die after anomaly observed at 1e11+ protons/cm^2 correlated with flight observations
  - Thankfully Reed-Solomon worked fine, so no true impact to mission
- Proton testing pre-flight did not provide enough error signature coverage

Application Environment

- ***Rule #1: Ground irradiation is a confidence test and not a precise risk definition process.***
  - **The test is being performed to “bound” a problem. In other words,**
    - **Test fluence levels are not meant to be the same as what a device will be exposed to, but to provide confidence that the risk will be less than X of occurring.**
    - **Remember, X can be based on a limiting cross-section when no events have been observed**
      - **Though not likely true, assume that the next particle that hits the DUT causes an event, so that the limit of the cross-section is ~1/F.**
  - **It is important to remember that a test fluence of two to ten times a mission predicted fluence only goes so far in reducing risk.**
    - **Higher levels should be considered (keeping in mind total dose concerns at the DUT level) for better risk reduction.**
    - **If a mission proton fluence (of energies of interest) is 10^9, what does a test to 10^{10} buy?**

More on POF

- Not all particles are created equal:
  - Some deposit energy “on a track” as per image below (traditional heavy ion).
  - Some interact with materials and cause secondary particles to deposit the energy.
    - This is the traditional proton SEU concern (though direct ionization with low energy protons is a consideration for advanced technology nodes).
    - This is a lesser concern for heavy ions though it shouldn’t be ignored.
- So what’s this have to do with fluence levels?



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Proton Physics

- Total nuclear production cross section
  - # ions out/#protons in

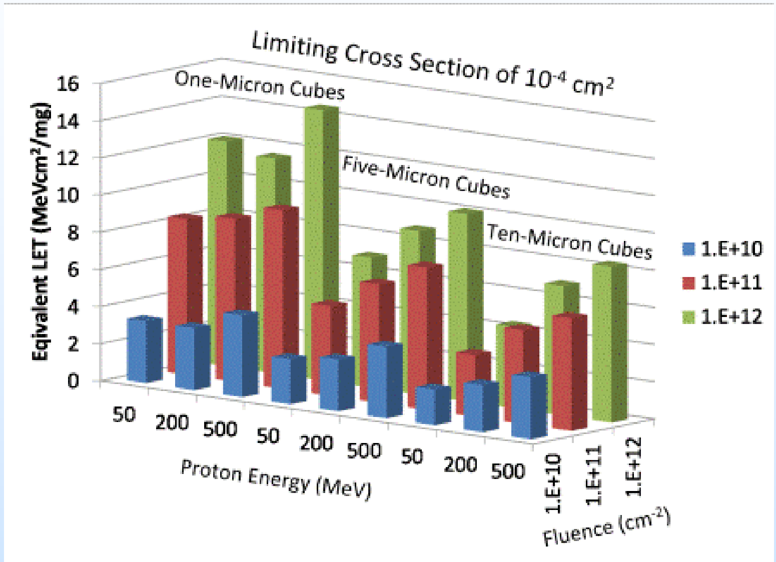
Energy(MeV)	Sigma (cm^-2)
50	4.76E-06
100	3.89E-06
200	3.46E-06
500	5.37E-06

- These secondary particles have a distribution of linear energy transfer (LET) as well as usually being of short range.
  - These are particle kinematic effects to consider when establishing a proton fluence:
    - Number of interactions that occur that have secondary ion spallations,
    - Distribution of the secondary ions, and
    - Risk coverage versus mission environment, sample size, geometry, etc…
  - Is 10^{12} protons/cm^2 a realistic choice? Approximates the 10^7 ions/cm^2 in JESD57

Be wary of total dose or displacement damage at higher fluence levels: consider more samples of the DUT at lower fluence levels.

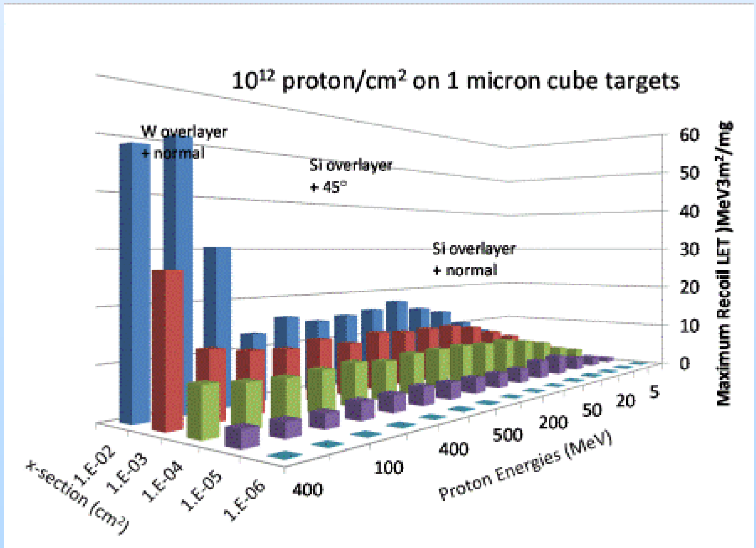
Visual Protons

(courtesy R. L. Ladbury and J.-M. Lauenstein, NASA/GSFC)



How good are protons at simulating heavy ions?

Silicon's not the only culprit In creating problems



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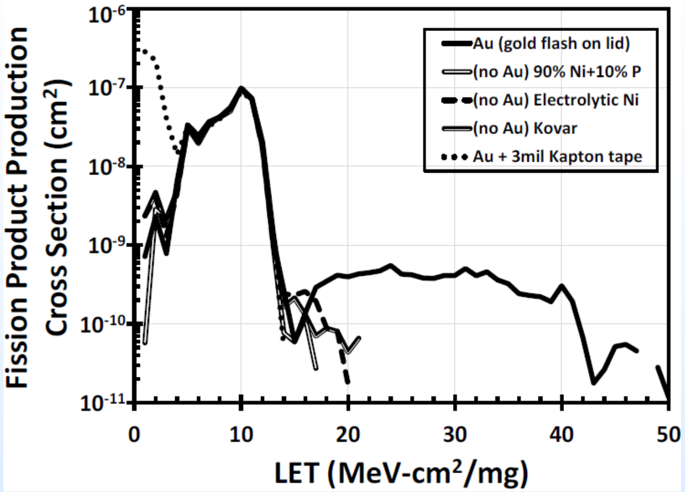
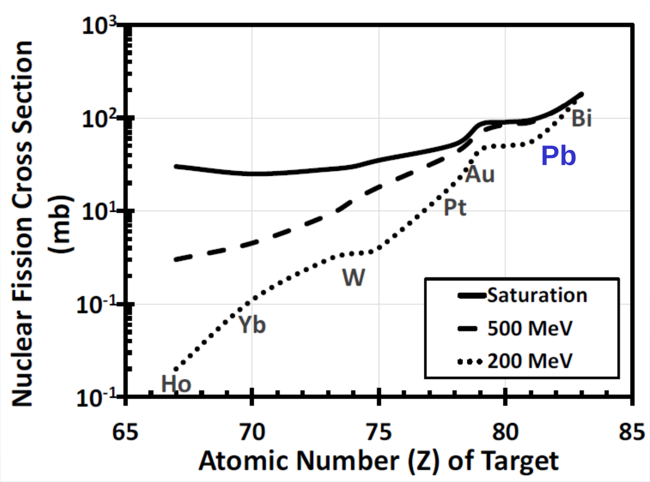
And Another Thing:
Heavy-ions Come from Many Places



Figures from T. Turflinger et al., submitted to IEEE Trans. on Nucl. Sci., 2015



- Destructive ***proton-induced*** **SEE seen on OP470**
  - **Similar failure seen with heavy ions but at LETs above those attainable from usual proton recoils**
  - **Problem resolved and attributed to Au fission fragments from Au ions knocked off of Au plating on part lid**
- **If failure not previously observed w/ heavy ions**
  - **Failure mechanism would probably remain mysterious**
  - **Proton rate dominate in proton dominant environment**

- **Au is not the only high-Z material in packaging**
  - **Pb solder is ubiquitous**
  - **Pt also used in some parts**
- **Effect likely to be important if part experiences severe SEE with onset at LET>20 MeVcm²/mg**
- **Effect likely not seen w/ only 10^{10} 200-Mev protons/cm²**

And You Just Wanted a Number…

- Sorry folks, there’s no easy answer when you consider that:
  - F is a function of (geometry, operations, sample size, and POF).
- Suggestions:
  - Remember, it’s a bounded problem and reducing risk is the desired outcome.
    - Risk can’t fully be eliminated, but weeding out a reasonable coverage of error signatures and sensitivity levels is the goal.
  - Understand the dynamics of an accelerated beam test versus what you’ll be exposed to in space:
    - Drives data collection and how to apply it.
- Final thought:
  - Even for sensitive devices 10^{10} protons/cm^2 isn’t enough.

Acknowledgements

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