Radiation Effects: Overview for Space Environment Specialists

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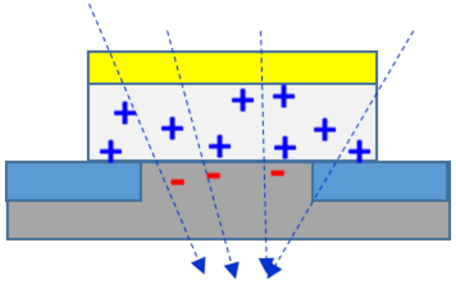
Key to Abbreviations and Symbols

DSEE	Destructive single-event effect
GCR	Galactic cosmic ray
GPU	Graphics processing unit
IC	Integrated circuit
I/O	Input/output
LET	Linear energy transfer
p^+	Proton
SEB	Single-event burnout
SEE	Single-event effect
SEGR	Single-event gate rupture
SEL	Single-event latchup
SV	Sensitive volume
VDS	Drain-source voltage
WC	Worst case
xstr	Transistor
Z	Ion atomic number

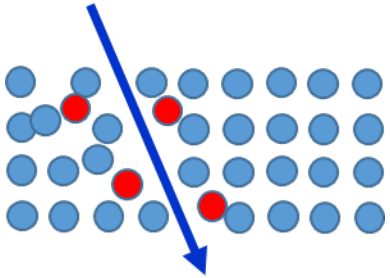
Radiation Effects and the Space Environment

- Motivation: Mike Xapsos 2016 NSREC paper proposed replacing conventional margin-based RHA approach w/ choice of environment confidence +success probability for part
  - Issue: Margin covers a lot of sins in addition to uncertainty on the environment
  - What are implications for TID and SEE testing and analysis of an idea that makes sense?
- Types of Radiation Effects and Environments Important for Them
  - Cumulative—Total Ionizing Dose (TID) and Displacement Damage Dose (DDD)
  - Single-Event Effects (SEE)
    - Destructive SEE
    - Nondestructive SEE
- Sources of Error
  - Cumulative Effects
  - SEE
- Hardness Assurance Methodologies
  - TID and DDD
  - SEE

One Slide: Cumulative Effects of Radiation Environments



- Charge trapped in oxides alters electrical properties of transistors and other devices.

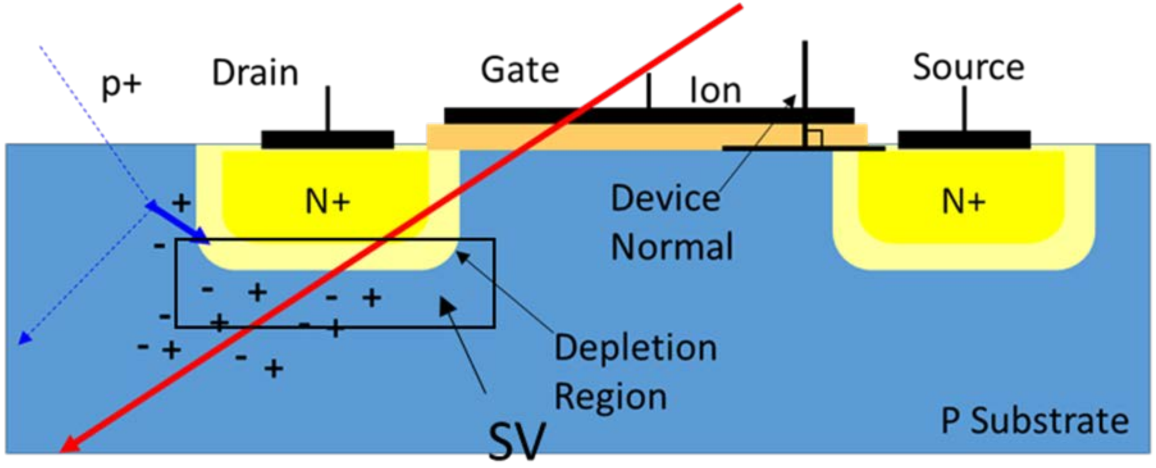


- Displaced atoms in semiconductor crystal lattice form vacancies and interstitials that alter semiconductor electrical properties

- Main particles of concern are protons and electrons
  - Trapped proton, Cumulative Solar Protons
  - Trapped electrons (Earth, Jovian…)
  - GCR, solar heavy ion fluxes too low to worry about
  - Transported environment important
- Cumulative effect, so short-term fluctuations not a concern except for short missions (<2 years)
- Greater concern on longer missions
- Hardness Assurance Approach
  - Test sample representative of flight lot w/ x/γ rays
  - Looks like wear-out (failure rate increases w/ dose)
    - Overtest and RDM effective mitigations by ensuring failure rate remains low
  - Redundancy ineffective as a mitigation

- Affects mainly minority-carrier devices
- Main concern: protons + electrons for some devices
  - Trapped proton, Cumulative Solar Protons
  - Trapped electrons (Earth, Jovian…)
  - GCR, solar heavy ion fluxes too low to worry about
- Cumulative effect, so short-term fluctuations not a concern except for short missions (<2 years)
- Greater concern on longer missions
- Hardness Assurance approach similar to TID
  - Less dependence on bias, dose rate, etc
  - Less part-to-part variation…usually

One Slide: Single-Event Effects (SEE)



- SEE caused by ionizing particle traversing device SV
  - Direct ionization—particle from mission environment
    - GCR heavy-ion, solar heavy-ion environments
    - Charge depends on linear energy transfer (LET) and path length
  - Indirect ionization—secondary particle produced by particle (usually proton) from mission environment
    - Solar and Trapped proton environments
  - Low-energy proton (direct ionization)
    - Transported environment for deep-submicron CMOS
    - Multiple scattering important for mechanism
- Poisson process, so constant probability (per ion)

- Consequences of SEE
  - Momentary disturbance of device output (SET)
  - Corruption of one or more bits of data (SEU)
  - Corruption of large amounts of data (block error)
  - Permanent corruption of data bit (stuck bit)
  - Recoverable loss of device functionality (SEFI)
  - Catastrophic failure
- RHA approach: Any SEE can happen any time—Need to test to expose susceptibilities, not to the environment
    - 10^7 ions/cm^2 ~913 years at ISS (LET>1 MeVcm^2/mg)
    - ~347 years at GEO (LET>1 MeVcm^2/mg)
- Constant failure rate→redundancy is effective mitigation
  - Need worst case (e.g. WC SPE) SEE rates as well as mean rates
    - CRÈME-96 has used October '89 SPE
    - Ability to get Solar Event LET spectra vs. confidence to feed into CRÈME-96would be interesting
  - Redundancy implemented at all levels—cell to spacecraft
    - Must pay in currency of the realm—bits for bits, functional parts to maintain availability, cold spares to improve survivability

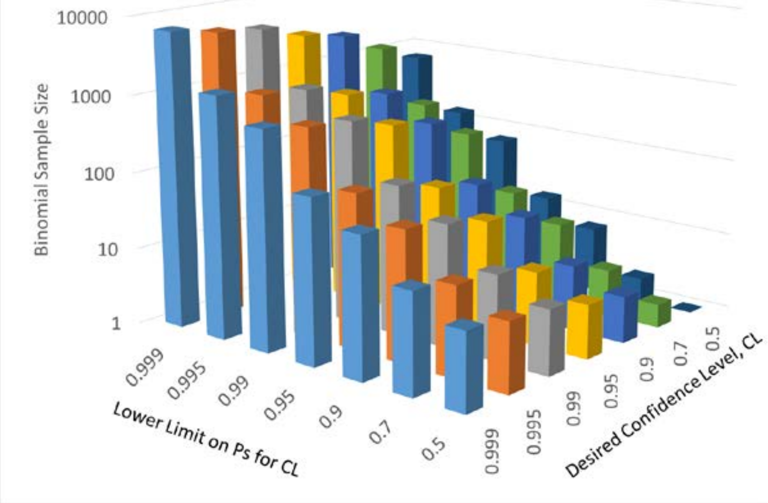
RHA is About Error Sources and Control

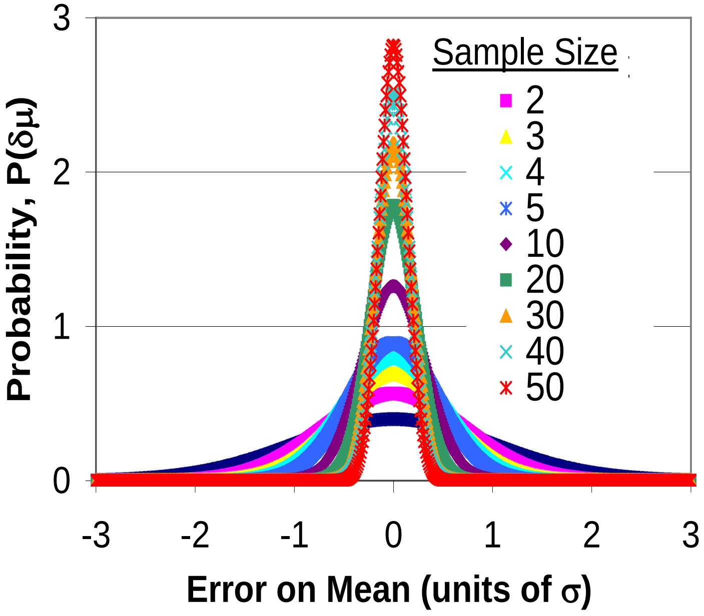
- Space Environment
  - Models only good if data underlying them is representative of current conditions
  - Environment is constantly fluctuating—not reflected in all models
  - Goodness of models depends on mission duration, shielding, etc.
- Sample Variation (part-to-part, lot-to-lot, part-type-to-part-type)
  - Basic question: Is test sample sufficiently representative of flight parts?
  - Quandary: Sample size must be large enough to define distribution…but…size required to define distribution depends on what the distribution is
  - Pathological distribution (e.g. multiple modes) require binomial sampling
- Other Statistical Errors
  - Poisson errors on event counts determining SEE cross sections
  - Sampling errors on time-dependent, intermittent or rare errors/failures
- Systematic errors
  - "Mistakes" in measurement, test procedure, etc.
  - Incorrect assumptions in analysis (e.g. assuming incorrect distribution form).

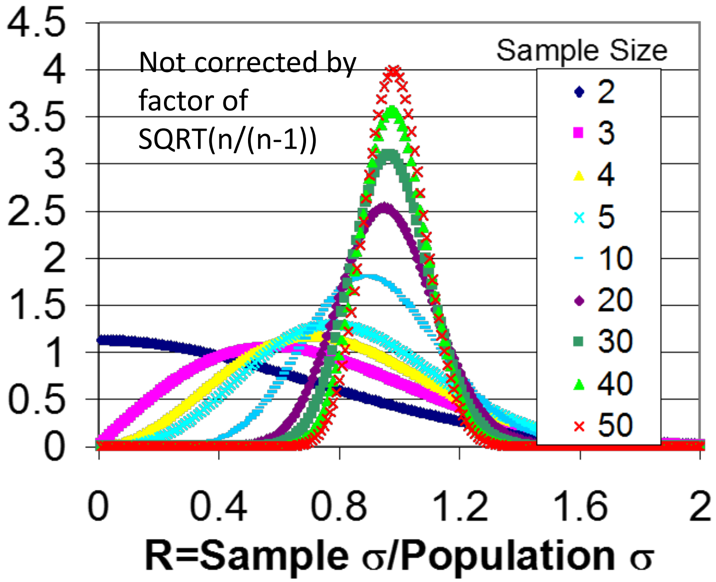
TID RHA Errors

Binomial Sampling

Assumes 0 failures observed



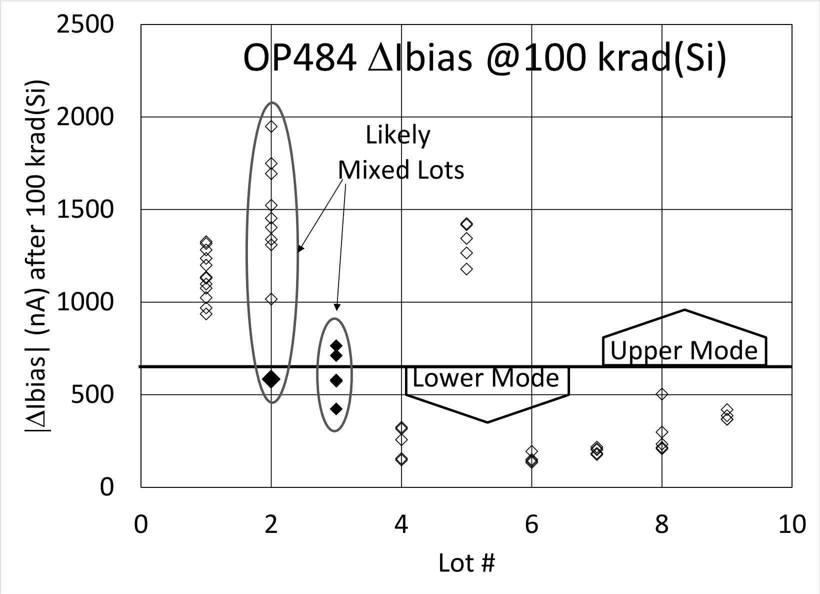


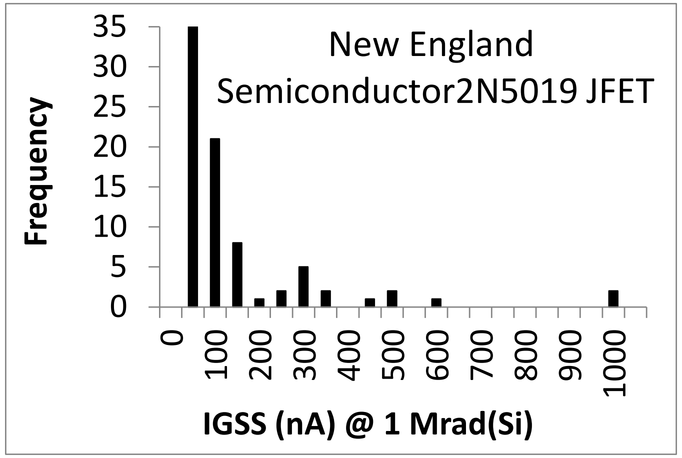


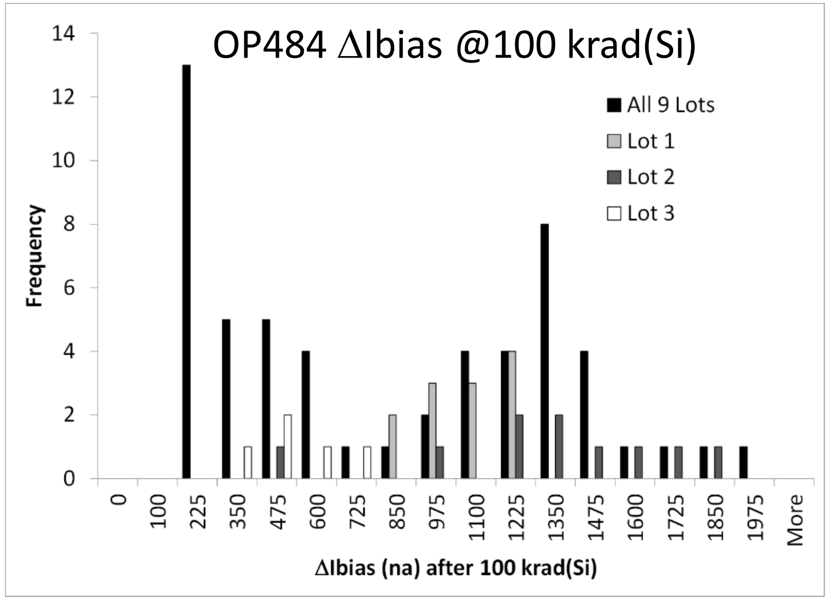
- Environment is only one source of error
  - Mainly issue for short missions
- Binomial sampling errors may dominate
  - 5 parts→41% CL that Ps≥0.9, 83% CL Ps>0.7
  - Valid even for multimodal distributions
  - Margin does not help—only looks at proportions above and below test level—not how much

- Most TID RHA assumes failure distributions well behaved
  - Parameter estimates converge rapidly w/ sample size
  - Much higher confidence and Ps possible w/ smaller samples
  - Overtest, design margin effective strategies to avoid failure
- But…trade confidence + >Ps for possibility of systematic error
  - How common are pathological failure distributions?
  - How likely is a small sample-size test to detect pathology?
  - What should we look for? (technology? data characteristics?)

TID RHA: Pathological Distributions Do Occur

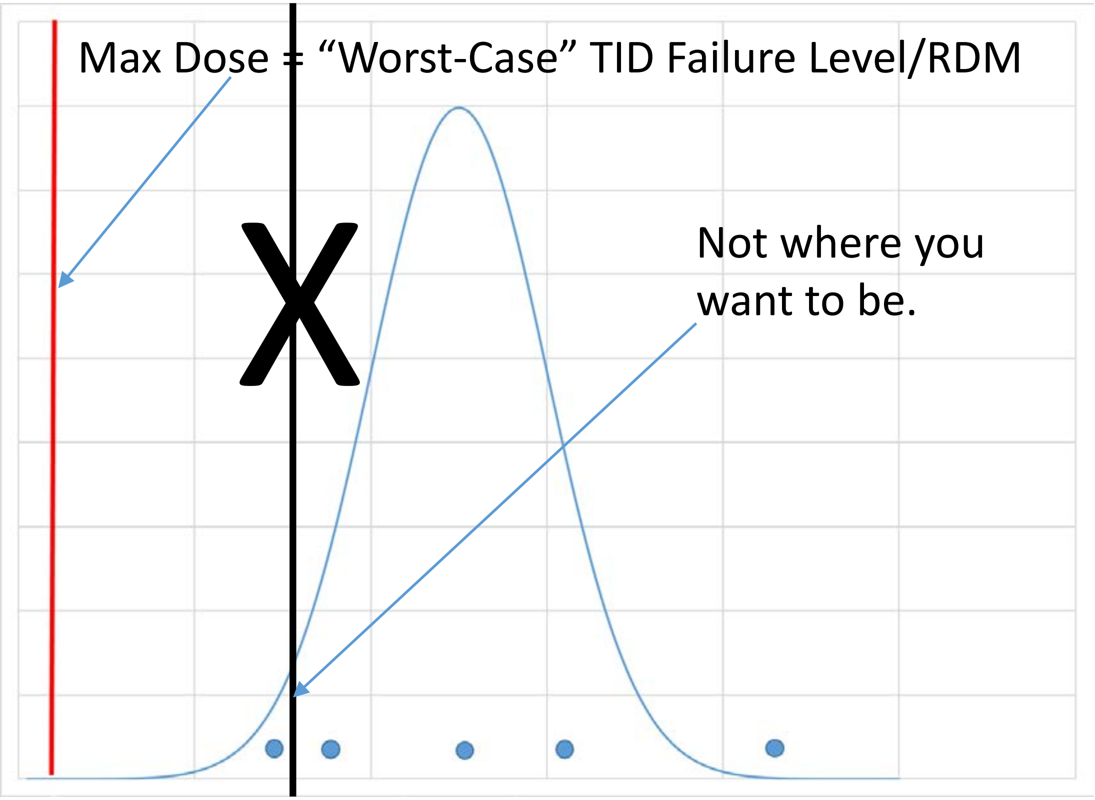






- Many parts known to exhibit pathological TID response (ADI OP484, OP400, AD590, National LM111, many discretes, commercial parts such as SDRAMs)
- Bimodal distributions (e.g.OP484), thick tailed distributions (2N5019 JFET)
- What to do?
  - Similarity is not a reliable indicator—several ADI bipolar devices show anomalies; most do not
  - Test larger samples
  - Look for “outliers”
  - Combine lots to see if “outliers” resolve into thick tails or multiple modes

Conventional RHA Approach Uses Radiation Design Margin (RDM)



- Conventional approach to TID RHA defines part TID capability or failure level for a part type (WCFL)
- Radiation Design Margin (RDM) defined by project requirements
- Maximum allowed dose for part type =WCFL/RDM

What is WCFL?

- Mean, Median and Mode of failure distribution are not appropriate--failure probability too high

1) Worst performing part in TID lot test
   - Advantage—has an empirical basis--does not assume a statistical model
   - Disadvantage—Odd statistical properties—testing more parts improves knowledge of failure distribution, but WCFL gets worse with sample size
2) Ps=X%, CL=Y% one-sided tolerance limit (KTL)
   - $\mu \pm KTL(n,Ps,CL)*\sigma$ (Example 99/90 limit)
   - Advantage—good statistical properties
   - Disadvantage—assumes normal or lognormal distribution
3) Worst performing part for all lots of part tested
   - Advantage—Empirical and more conservative than 1); well suited to high-volume qualification program
   - Disadvantage—still has same odd statistical properties as 1)—more lots tested gives more conservative value

- 2) best in most cases; or 3) in high-production operations or if normality in doubt

Radiation Design Margin vs. Confidence and Success Probability

- Xapsos proposed replacing RDM with requirement at success probability exceed X% in Y% CL environment
  - Offers improved flexibility and ability to combine radiation and reliability +it is really what we want to know
  - Need to understand why current system works (mostly) to assess impact of change.
- So, why does a fixed 2x-4x RDM work as well as it does?
  - For short missions:
    - Environmental uncertainty is higher—less margin available for uncertainty in TID failure distribution
    - But, TID is lower, so fewer parts to worry about failing
  - For longer mission:
    - Higher TID means more parts prone to failure
    - Lower environmental uncertainty—more margin available for uncertainty in TID failure distribution
- Any approach must reflect uncertainties in failure distribution as well as radiation environment
- Part-to-part, lot-to-lot and part-type-to-part-type variation also require statistical treatment
  - Confidence level applies to inference of WCFL from data
  - What does 90% CL on failure distribution in a 90% WC environment mean?
  - Note: Same question also applied when dealing with RDM—it was just more hidden
- And as with any method assuming a distribution, how do we deal with the risk of systematic errors?

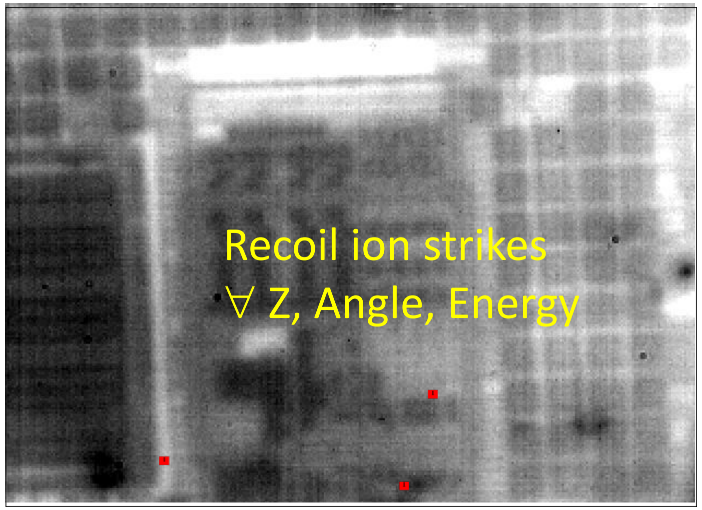
SEE Hardness Assurance

- Goals of SEE Hardness Assurance
  1) Identify all SEE modes to which part is susceptible
     a) Spatial coverage—ions/cm^2 or ions per device (transistor, gate, etc.)
     b) Temporal and Logic masking also affect coverage
  2) Map out dependence of SEE modes vs. collected charge/LET/(Z, energy, angle)
  3) Estimate SEE rate using above information (if possible)
     a) Use CRÈME-96 and σ vs. LET curve if
        i. Sensitive Volume (SV) is rectangular parallelepiped
        ii. Susceptibility depends only on LET (or effective LET)—no nuclear/secondary processes
        iii. LET in SV~constant
     b) Otherwise, use Monte Carlo SEE rate estimation (CRÈME-MC, MRED) and σ vs. Ion energy, species, angle…, or
     c) Bound using lethal-ion type calculation (SEGR and SEB)
     d) Assess implications for mitigation strategies
- What environments are interesting?
  - Background Environment to answer: "Will the device be able to perform its function in the environment?"
    - GCR + Average Solar and trapped protons
  - "Peak" Environment to answer: Will redundancy mitigation be compromised by peak environment?
    - SPE Heavy-ion + proton environments (but which SPE?)

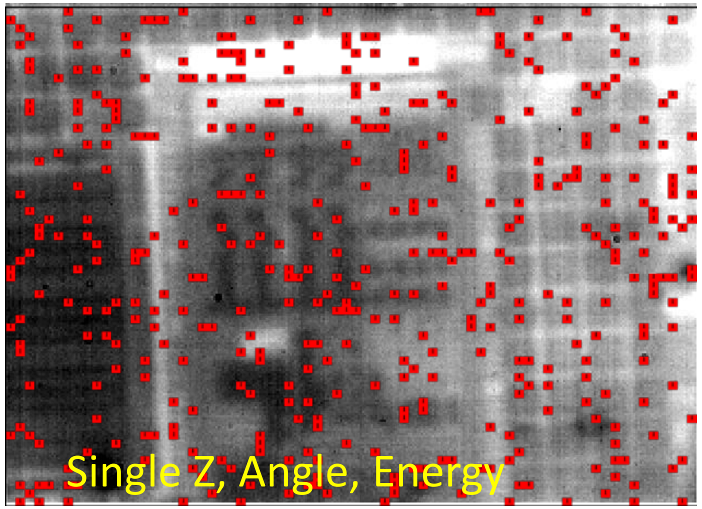
Spatial Coverage: How Much is Enough?

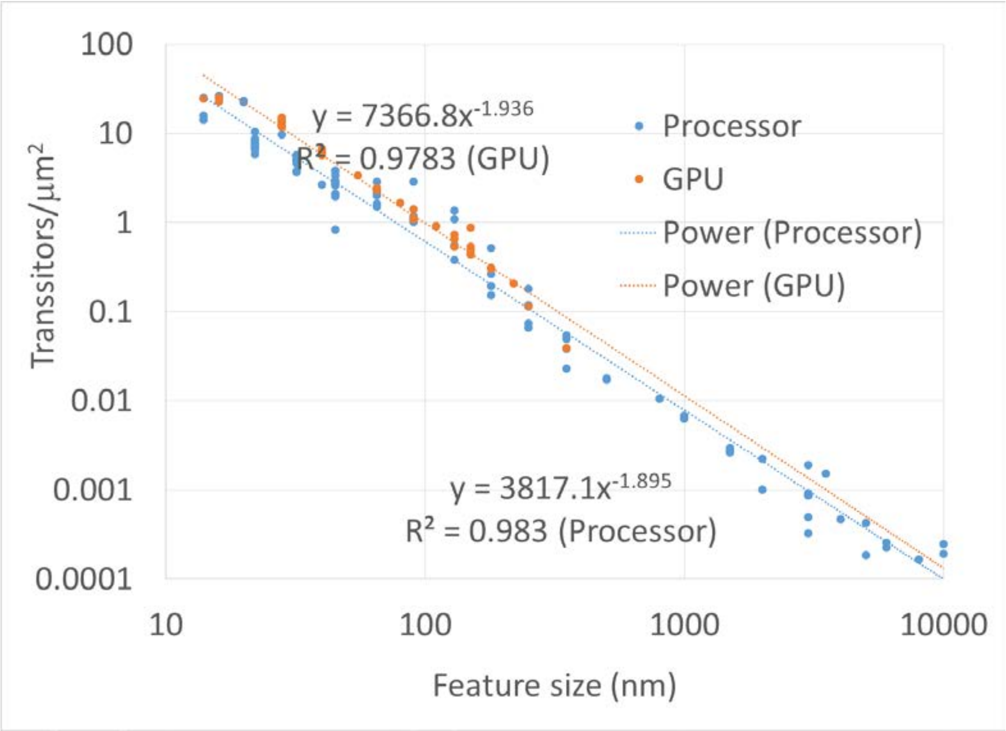
Simulated Ion Strikes in 60x70 μm² portion of 512 Mbit SDRAM

1E10 200 MeV protons/cm²



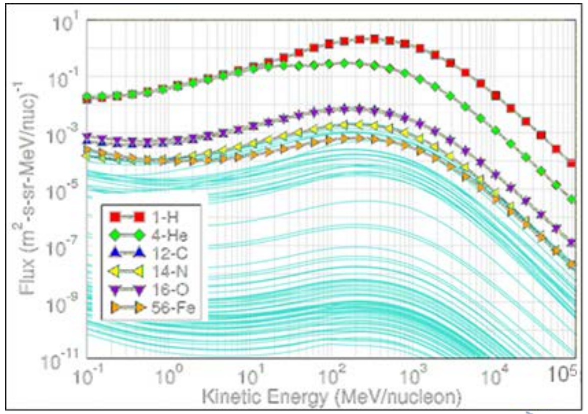
1E7 heavy ions/cm²

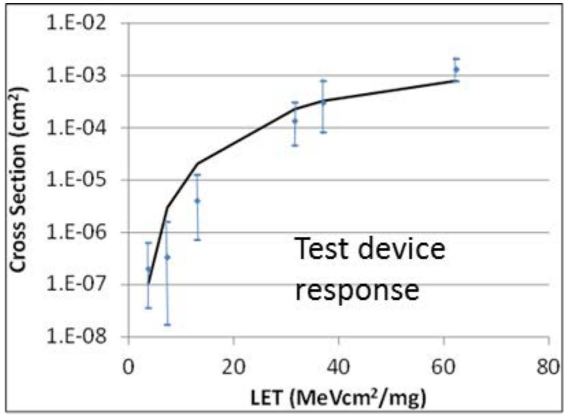




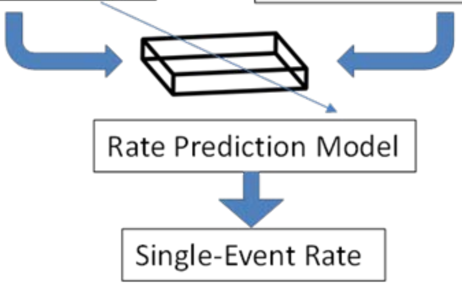
- If fluence too low, SEE modes go undiscovered—mode could be seen on orbit even if not seen in test
- "Good enough" depends on device feature sizes, device complexity, application, but also on track size and how often susceptible features repeated within device
  - Measure of device complexity may be total # of transistors, or transistors/μm², although function (e.g. processor, memory, FPGA…)also an indicator
  - More on track size later.

What Makes a Good SEE Test?





Each curve represents flux vs. energy for a different ion in the radiation environment.



- IRPP rate estimation separates device response and environment portions of integral
- Fit to device response (σ vs. LET) usually “worst case”—same independent of environment
- At least 4 parameters, onset LET (LET_0), limiting cross section (σ_{lim}), Weibull width and shape parameters

- A Good SEE Test
  - # of LET values ≥ 6; 12 values reduces errors ~60%
  - # events per cross section enough to make error bars negligible
  - Both # events and # LET values improve fit
- Errors on rate scale ~square of errors on LET_0 or width
  - Worse for very small limiting cross sections
- Errors on rate scale ~linearly w/ error on σ_{lim}
  - Again, worse for very small σ_{lim}
- Typical test
  - ≥2 parts
  - >>6-12 runs at different LET values
  - ≥ 1 low-LET run w/ fluence >10^7 ions/cm^2 to find LET_0
  - ≥ 1 high-LET run w/ fluence >10^7 ions/cm^2 to preclude presence of undetected destructive/disruptive SEE modes
- Total coverage of typical SEE test usually ≥10^8 ions/cm^2 for all ions of all Z, energy, angle

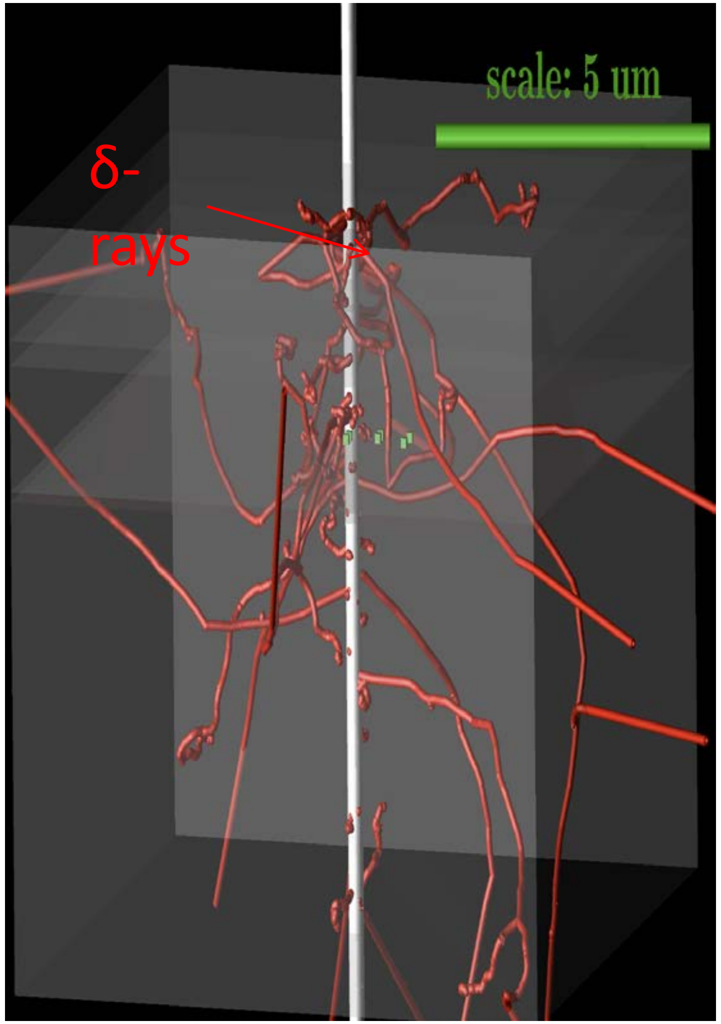
How Good Are SEE Rates?

- Statistical errors for SEE can be controlled, so accurate SEE rate estimation should be possible
- Ed Petersen found on-orbit rates agreed with predicted rates within ~2x (CRÈME-96 and AP8)
- SDRAMs (Ladbury-2009 and Miller-2009) agree w/in ~3-5x if knowledge of shielding, statistics adequate
  - Rates for disruptive errors (SEFI, block errors, etc) due to poor statistics
  - Rates for parts in Van Allen Belts sensitive to shielding
  - Fabricated in CMOS processes w/ feature sizes down to ~130 nm, so CRÈME-96 can be adequate to this level
- For smaller feature sizes, situation is more muddled
  - Expect departures from RPP, but rate estimation also more sensitive to errors on fit
- Above indicates errors due to environment over long term <~2x
- So, we're good, right?

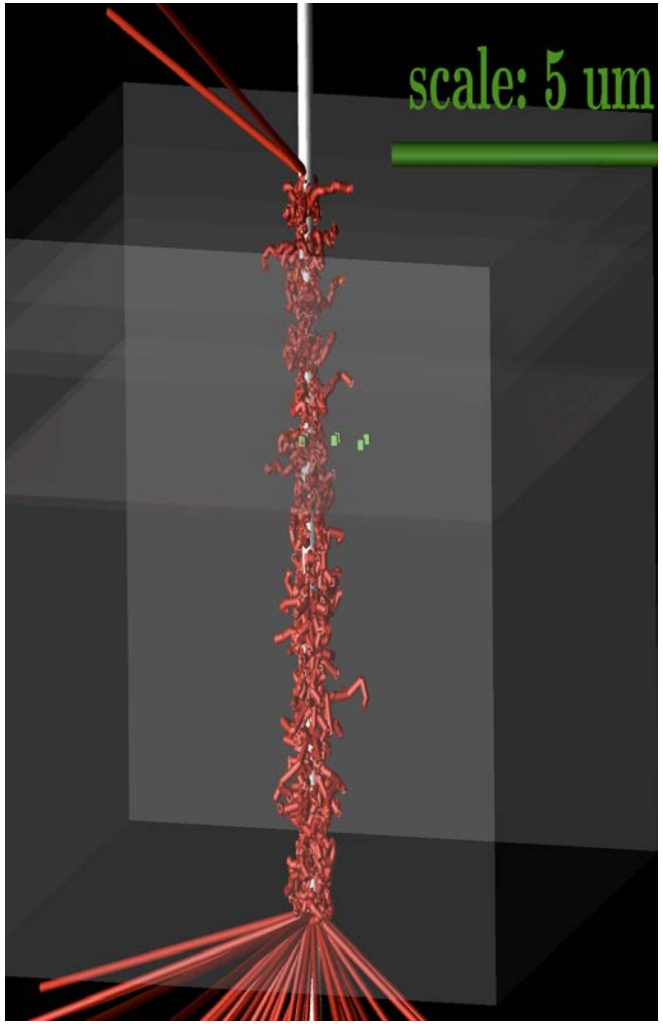
- Multiple Sources of Systematic Error
  - Nuclear Effects
    - Scattering of high-Z nuclei by light nuclei
    - p + Au fission events
- Departures from LET
  - High-energy ion tracks have more energetic delta rays
    - More MBUs
    - Ultra-high energy events
    - Multi-node upsets in hardened logic
- Proton upset via direct ionization
  - Low-energy proton environment variable and uncertain
  - Detailed shielding model essential to determine low-energy proton flux in the device SV
  - Multiple scattering plays critical role in mechanism
- CRÈME-96 won't work for these mechanisms
- Monte Carlo methods can work, but we're still figuring out how to use them.

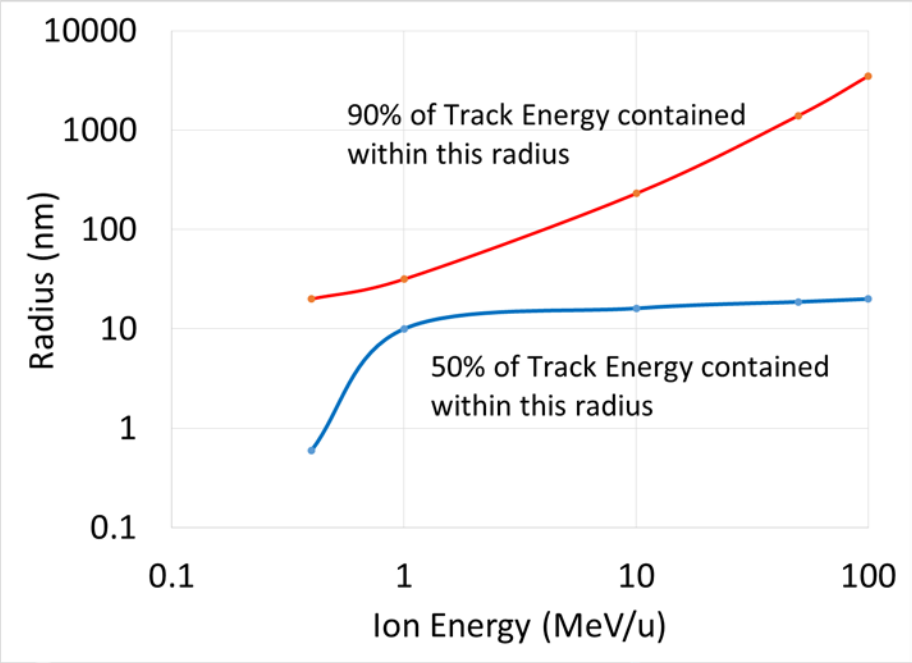
Track Structure: Wild Card of the Future (and always will be?)

28 GeV Fe ion (500 MeV/u)



280 MeV Fe ion (5 MeV/u)





- Track structure has always been a wild card
  - Up to now a wild card with few consequences
- Transistors now have dimensions ~100 µm
  - Energy deposition not uniform @ high energy
  - δ ray can traverse dozens of transistors
  - δ ray multiple scattering important
  - Implications for MBU and SEE hardening

Courtesy of Robert Reed, Vanderbilt University

Conclusions: TID and DDD

- Different environments important for different missions
  - TID: All ionizing particles contribute—solar and trapped protons and electrons dominate
    - Long missions—average environment dominates
    - Short missions—one large solar particle event can dominate TID for missions <1-2 years
  - DDD: Massive, energetic particles—protons (trapped and solar) usually the main contributors, also electrons
    - Situation similar to TID—long missions dominated by average; short missions can be dominated by SPE
    - Jupiter—electrons energetic and plentiful…can contribute to DDD
- Environmental uncertainty is only one source of error; usually not dominant
  - TID: Part-to-part variation usually the dominant source of error
    - Very large sample sizes required to have high confidence of high success probability
      - Binomial sampling has to work for even pathological distributions
      - Increased Radiation Design margin does not help
    - Assuming well behaved distribution allows reduced sample size for higher Ps at higher confidence
      - Replaces sampling error with systematic error if distribution is pathological—which can occur
      - Important to look for signs of pathology
      - Going to environmental confidence + success probability may force more rigorous treatment of variability and pathologies
- Displacement damage somewhat more tractable
  - Pathological distributions less common; fewer application conditions

Conclusions: Single-Event Effects

- Important fact about SEE—can happen any time, regardless of probability
  - First goal of testing is to identify SEE susceptibilities, NOT to bound relevant environments
  - Second goal: Rate estimation combines device susceptibilities + Environment Models
- Environments important for Single-event effects: GCR+ solar heavy ions + protons + trapped protons
  - Average environment important for ensuring part meets its requirements
  - Peak environment (for given confidence) important because redundancy is the predominant mitigation for SEE
    - SEE rate for a redundant system scales as a power of particle flux, rather than linearly
  - Low-energy protons highly variable, uncertain, and role of multiple scattering makes mechanism "fuzzy"
  - Electrons starting to cause SEE as well—multiple scattering even more important (no Bragg peak)
- Many sources of error other than environment
  - Poisson errors on cross section can dominate for small event counts (especially for DSEE, SEFI, disruptive errors)
  - Deviations from CRÈME-96 model assumptions (constant LET in single RPP SV, no nuclear/secondary effects)
    - Monte Carlo with accurate physics needed if deviations significant.
- Track structure effects may assume greater importance as devices continue to shrink
  - Less containment of ionization within any given track radius
  - Process more random
  - Mostly important for multi-node effects (MBU and upset of cells hardened by redundant nodes)