Single Event Effect Analysis

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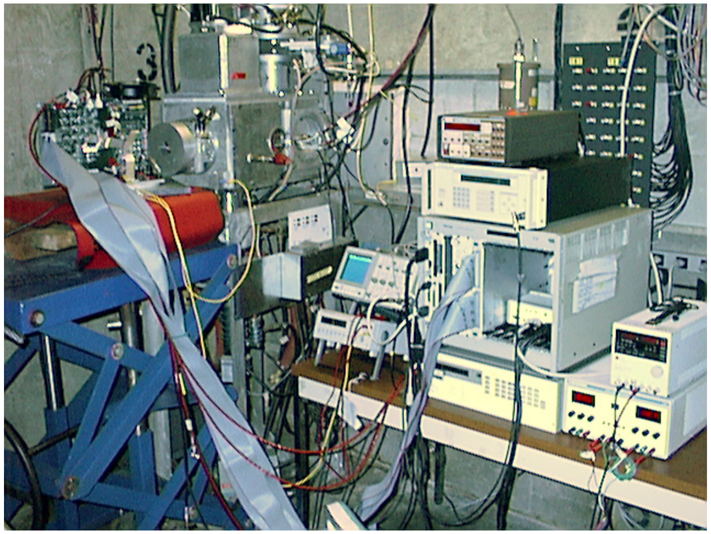
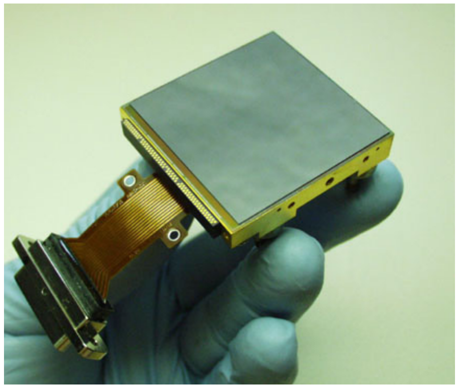
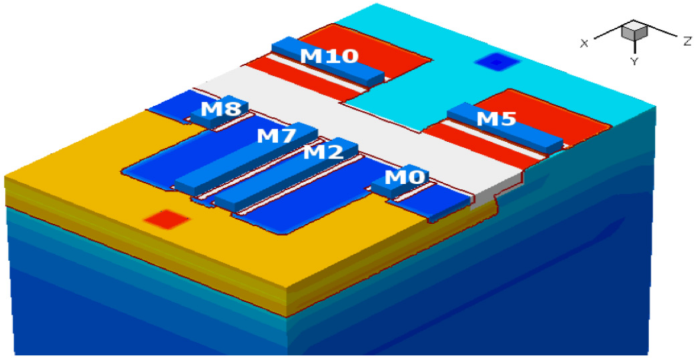
Sponsoring Agencies: NASA, DTRA, AFOSR, and AEDC

OUTLINE

- Challenges for SEE analysis of modern technology
- Description of RADSAFE for SEEs







Historical View of Single Event Effect Analysis

- **Modeling effects have taken two directions**
  1. **Mitigating radiation effects by design**
     - **Detailed device physics models**
     - **Detail circuit response modeling**
     - **Well developed understanding of basic mechanisms**
     - **Techniques have matured with technology**

  2. **On-orbit prediction of response**
     - **Space environment consists of multiple species that have a large range of energies and are omnidirectional**
     - **Complex environment forces simplifying assumptions for device and circuit response**
     - **Current, widely available models are based on technologies manufacture circa 1980**

Historical View of Single Event Effect Modeling

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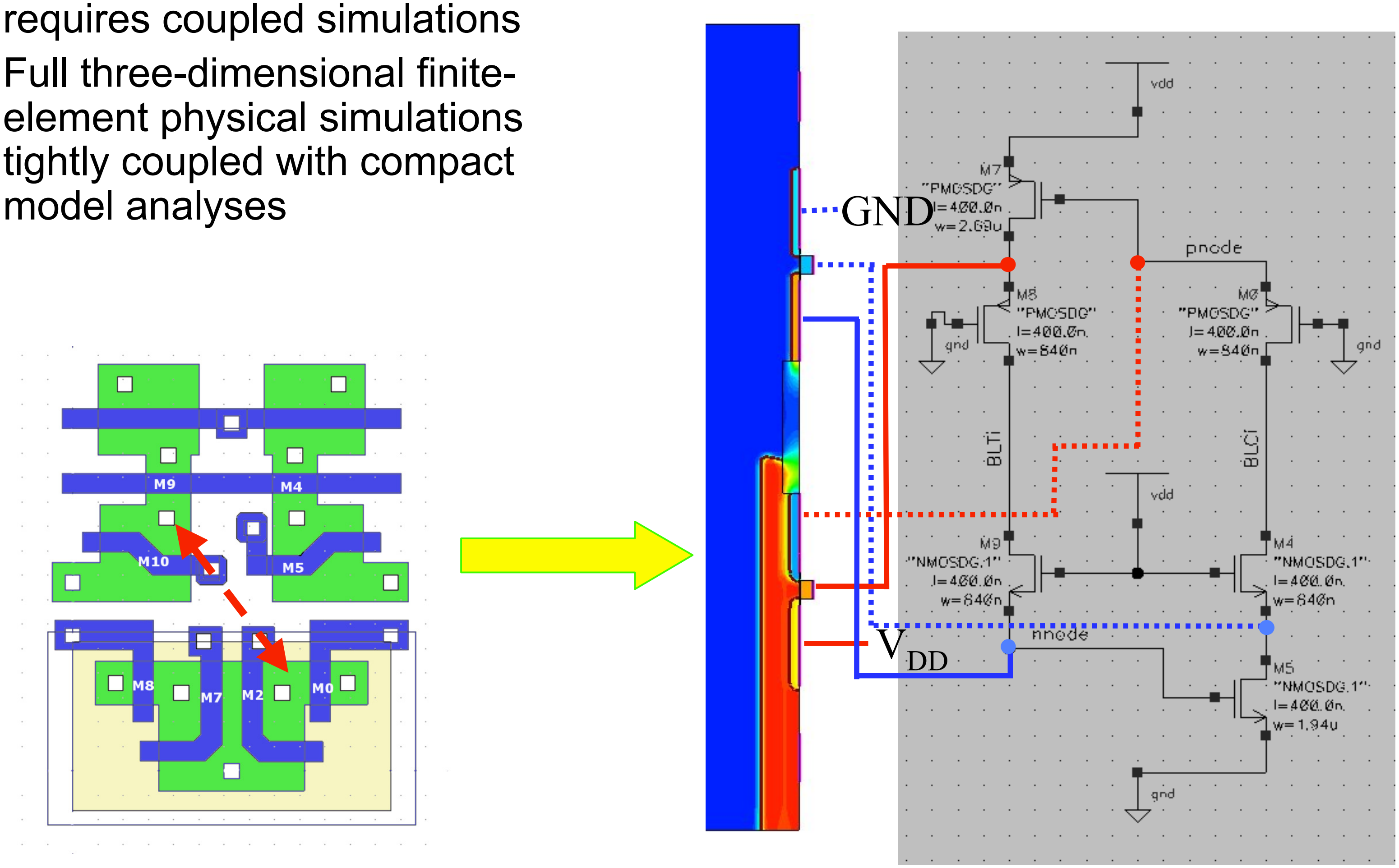
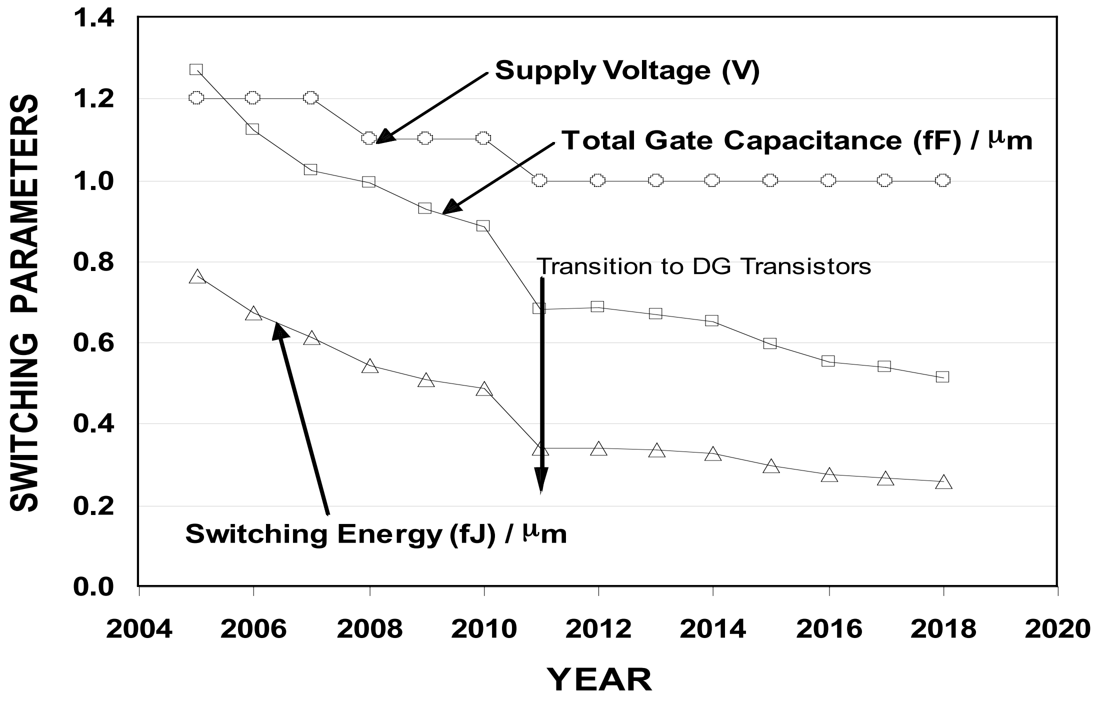
Modeling Response:
3-d Mixed Mode Analysis

- High Fidelity Modeling of circuit requires coupled simulations
- Full three-dimensional finite-element physical simulations tightly coupled with compact model analyses

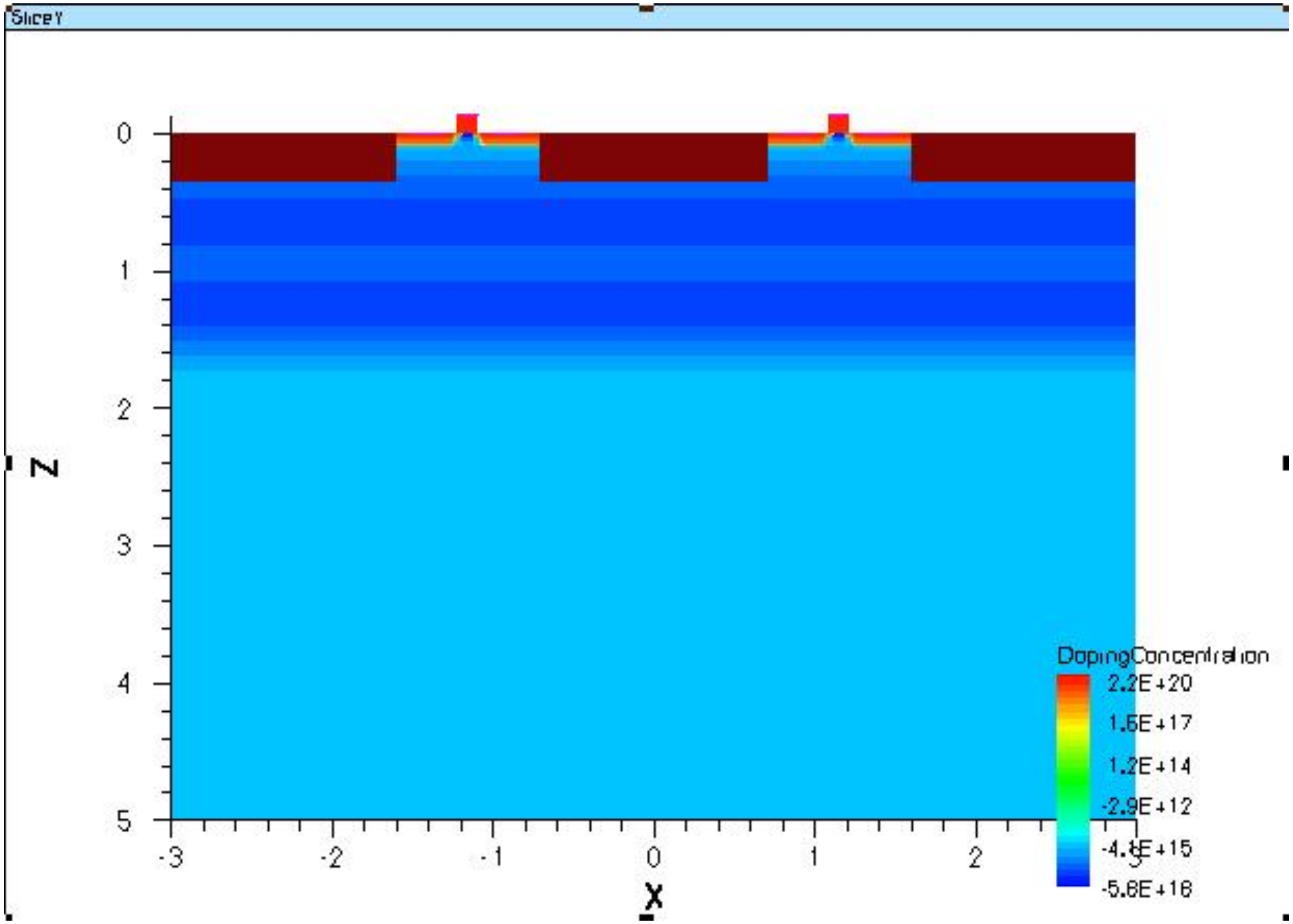


Challenge: Reduced Switching Energy

- **Nanoscale fabrication has introduced switching energies below one fJ**
- **Expanded spectrum of important radiation events to be modeled**
- **Circuits sensitive to a larger family of ions and energies**
- **Circuits are responsive to the statistical variability of the radiation interaction**



NMOS Charge Sharing



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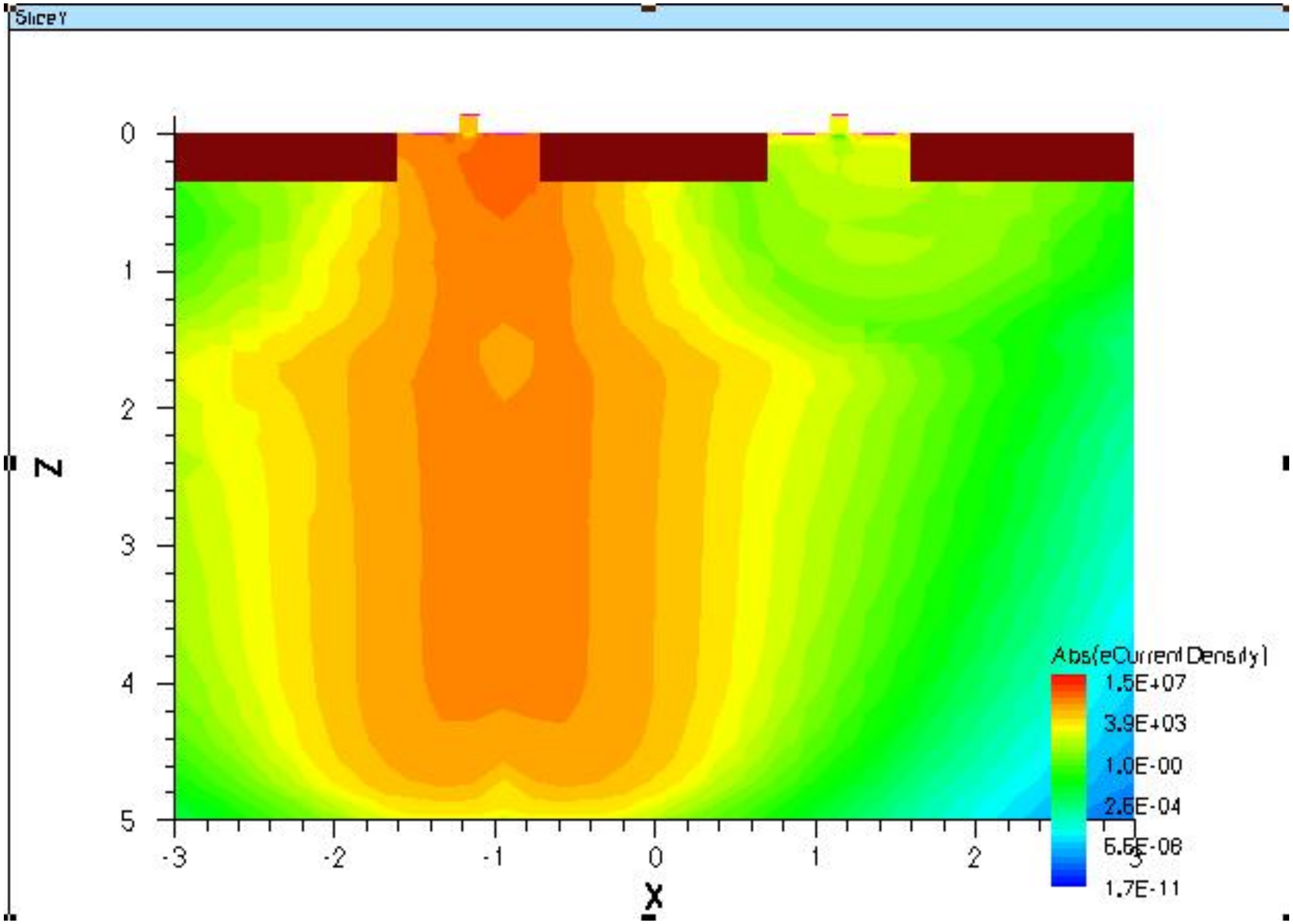

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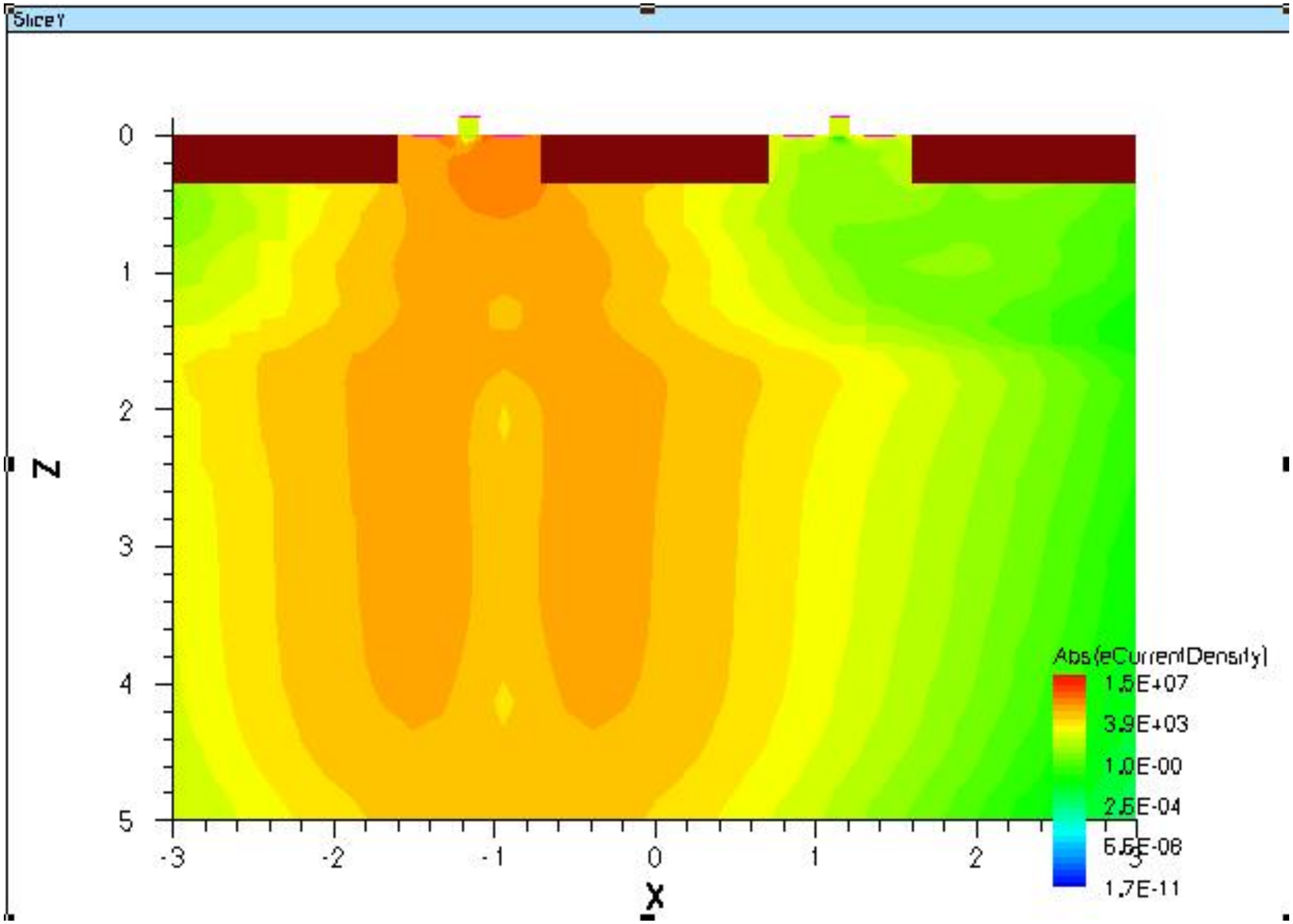

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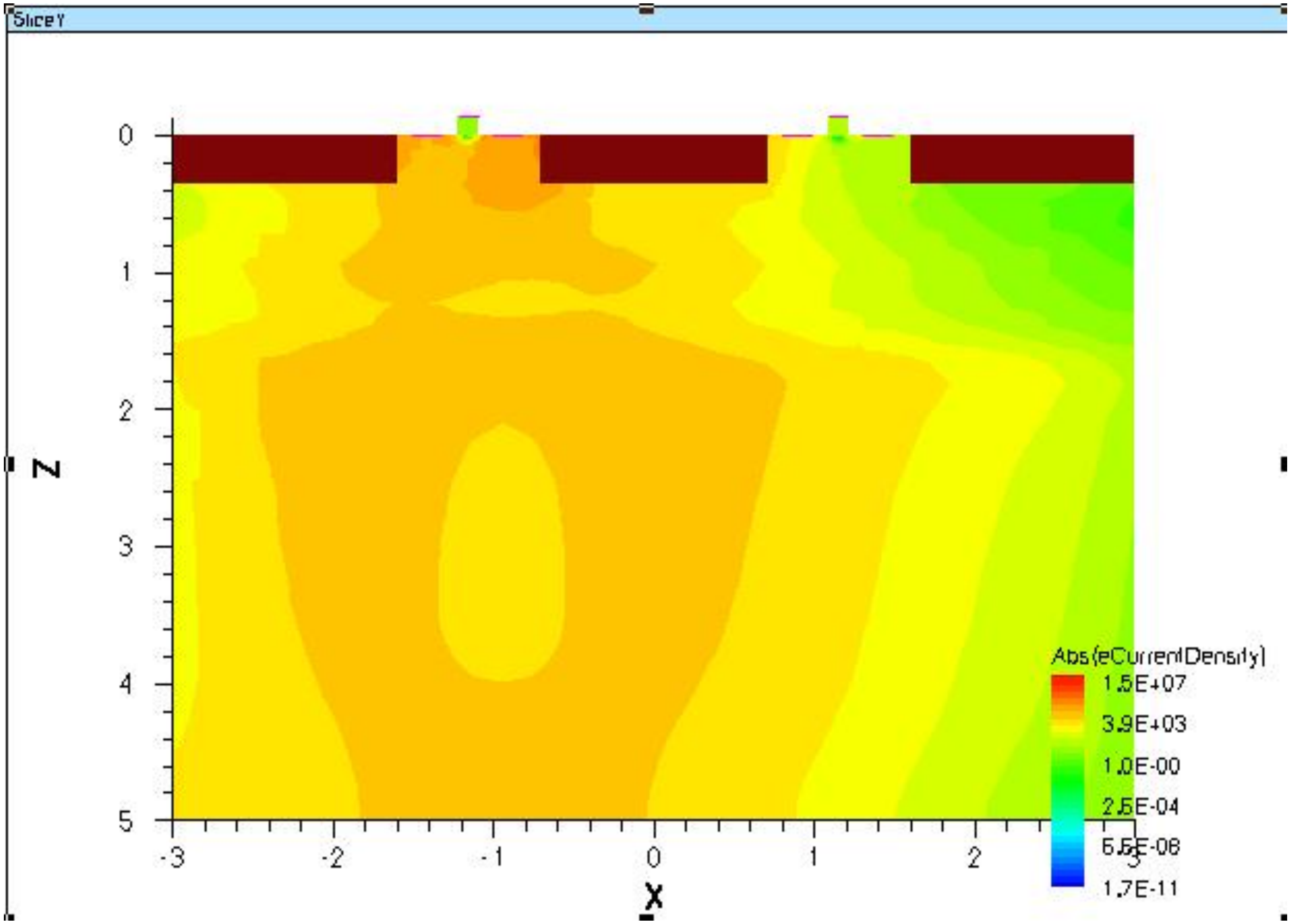

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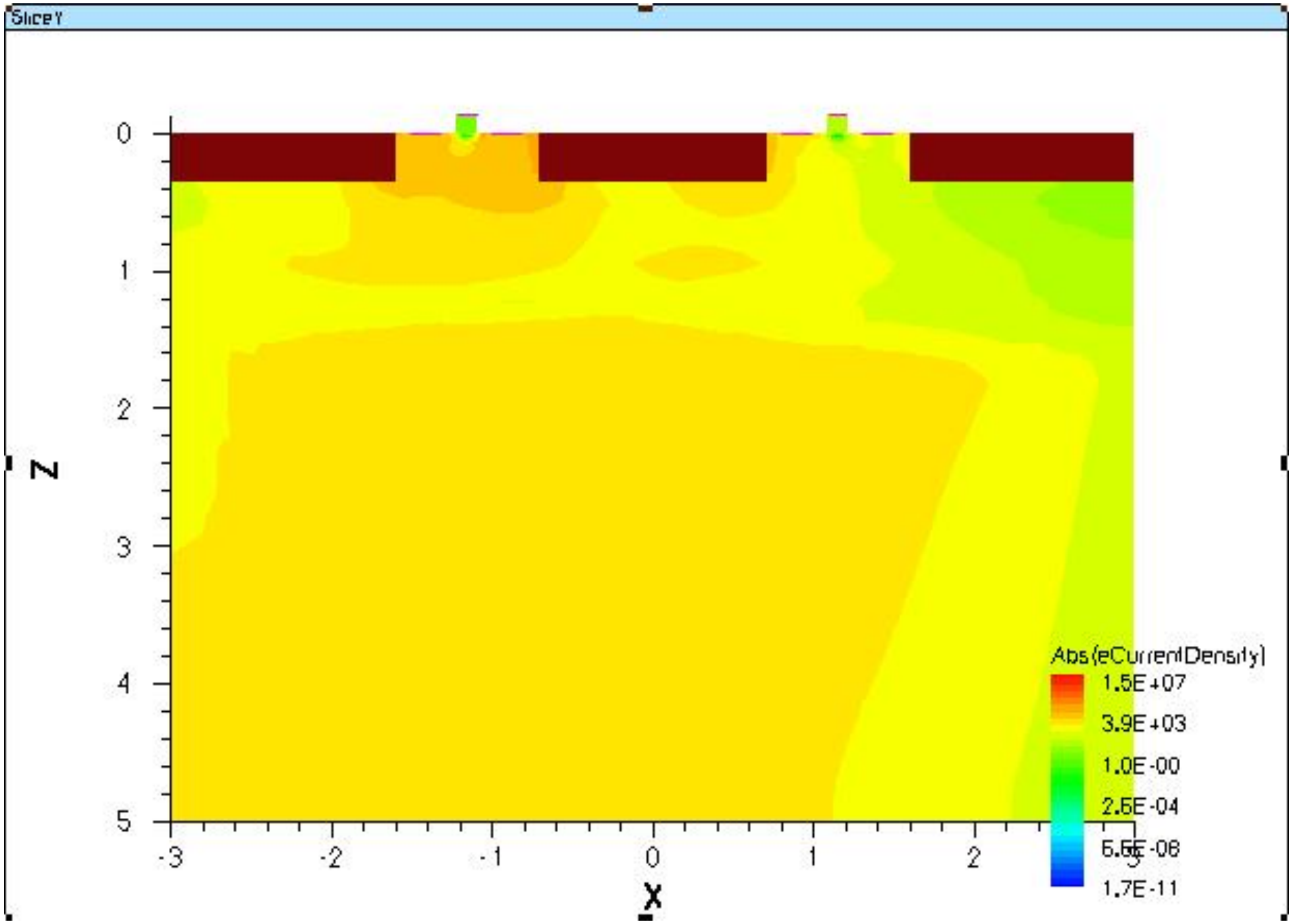

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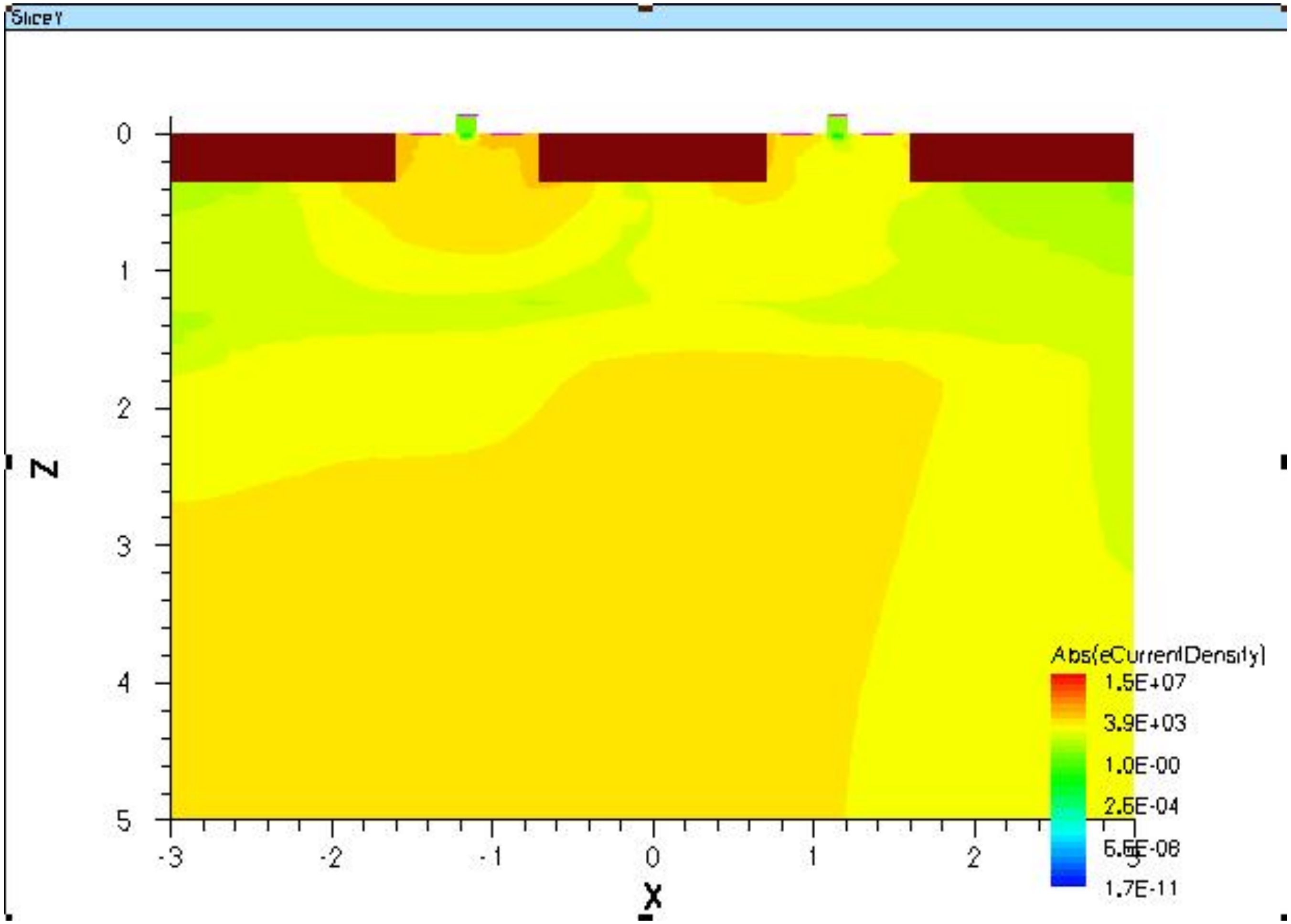

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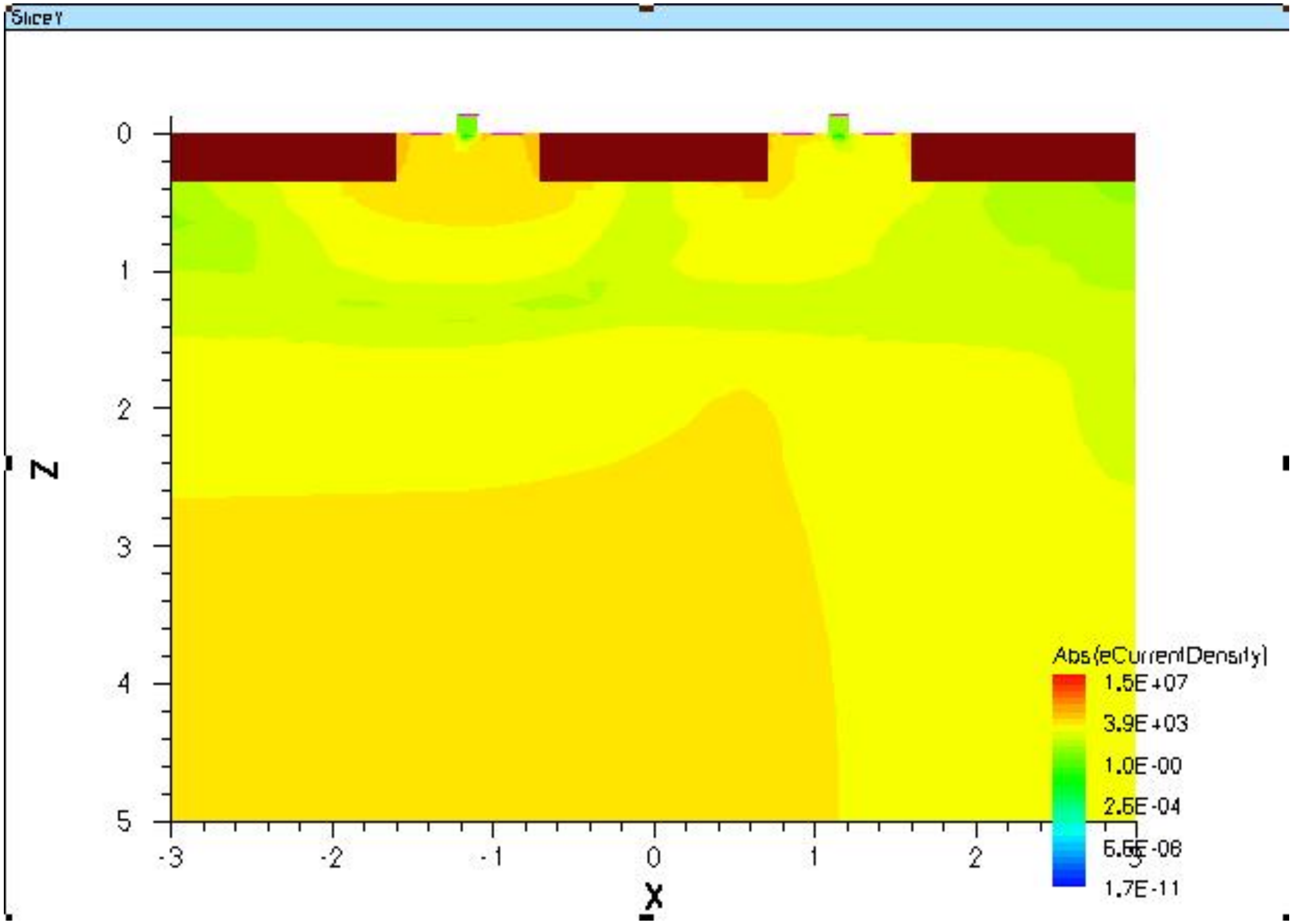

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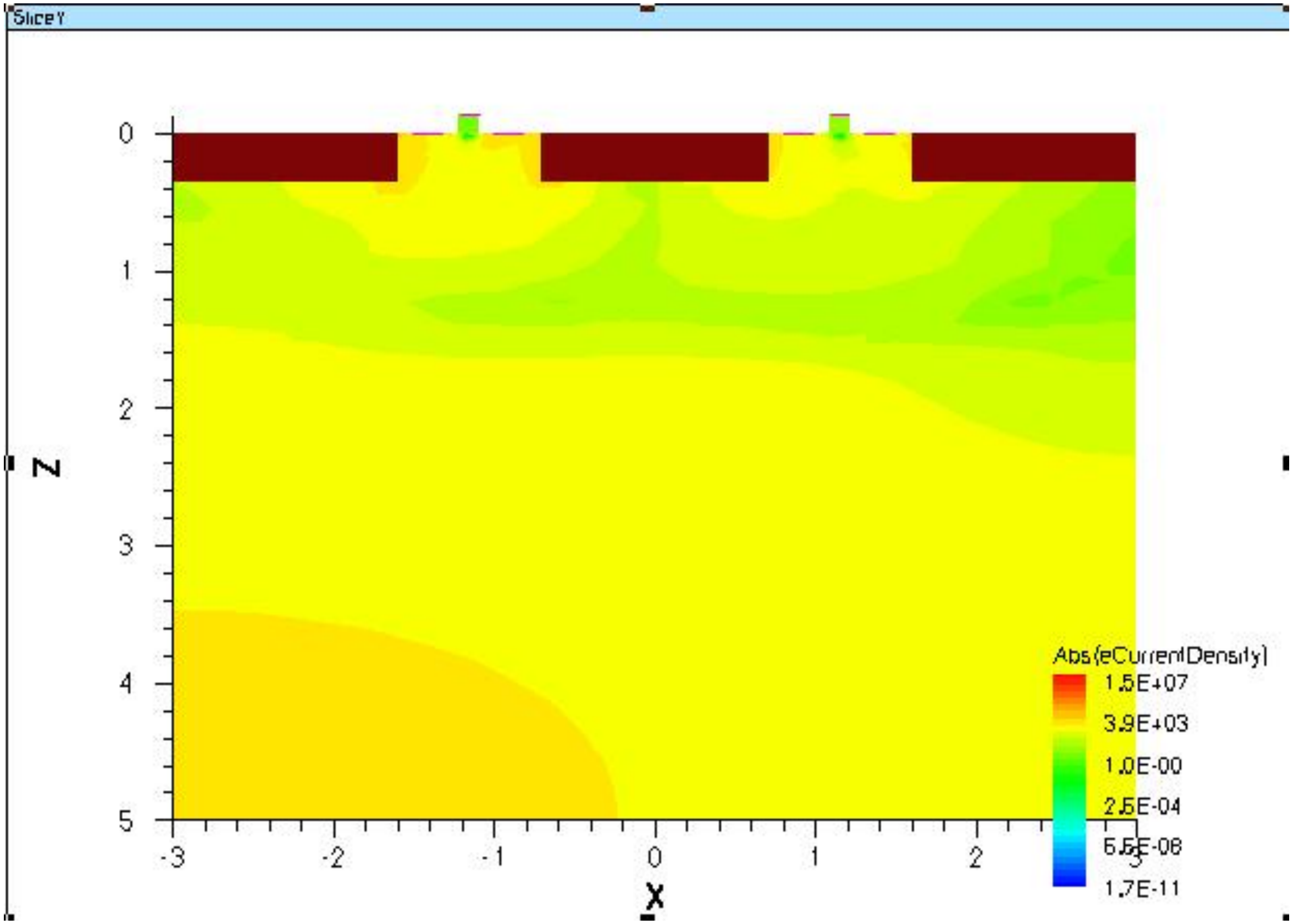
NMOS Charge Sharing

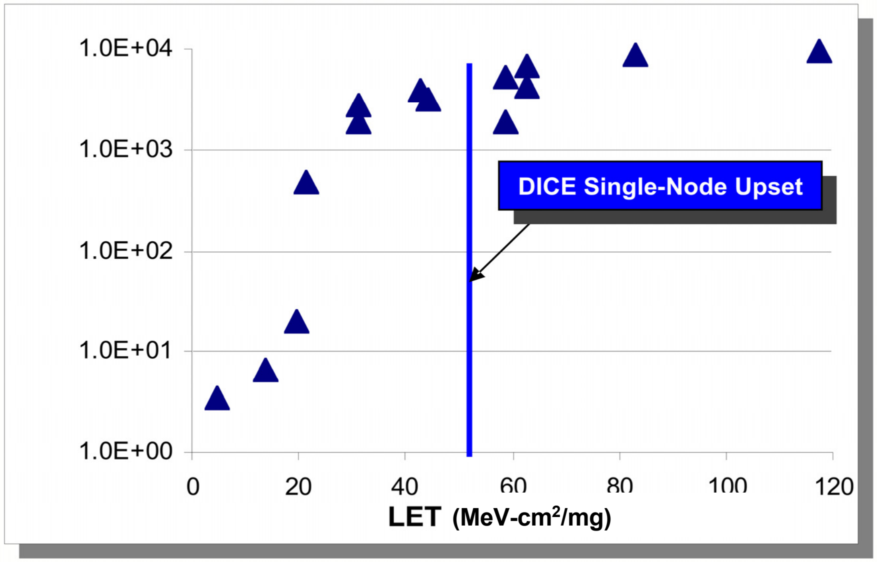


t=2ns

Scaled Geometries
Charge Sharing

Nanometer scale technologies can fool conventional wisdom.

- ❑ **DICE latches virtually immune to single node SE hits**
- ❑ **VU single-node SEE analyses on RHBD DICE latch designs show LET_{th}=50 MeV-cm^2/mg**
- ❑ **RHBD test chip DICE array show LET_{th}~20, with upsets observed down to LET=5 MeV-cm^2/mg**
- ❑ **DICE upsets requires a multiple node hit [1]**
- ❑ **Similar effect seen in a BAE hardened SRAM cells [2]**



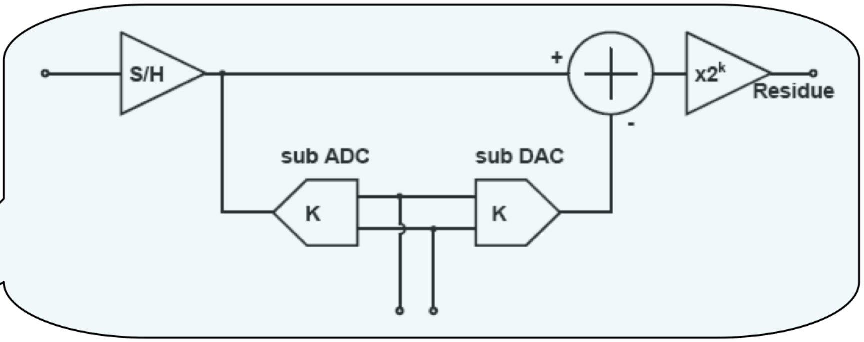
Detail simulation show that upset below ~40 MeV-cm^2/mg are due to charge sharing

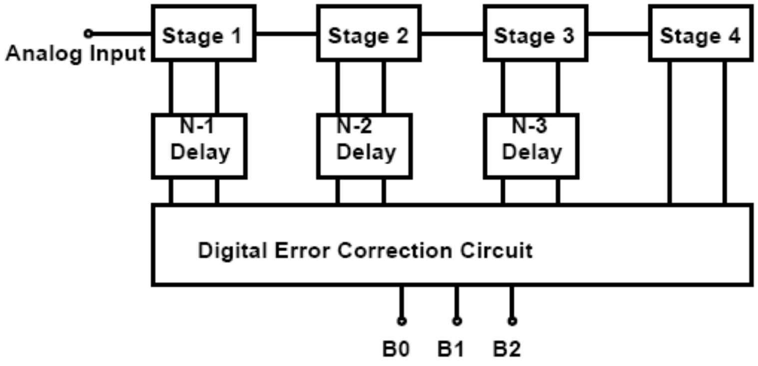
1. T. Calin. et al., IEEE Trans Nuclear Science, Dec, 1996.
2. K. Warren et al., IEEE Trans. Nuclear Science, Dec. 2005.

Challenge: Mixed Signal / System on a Chip

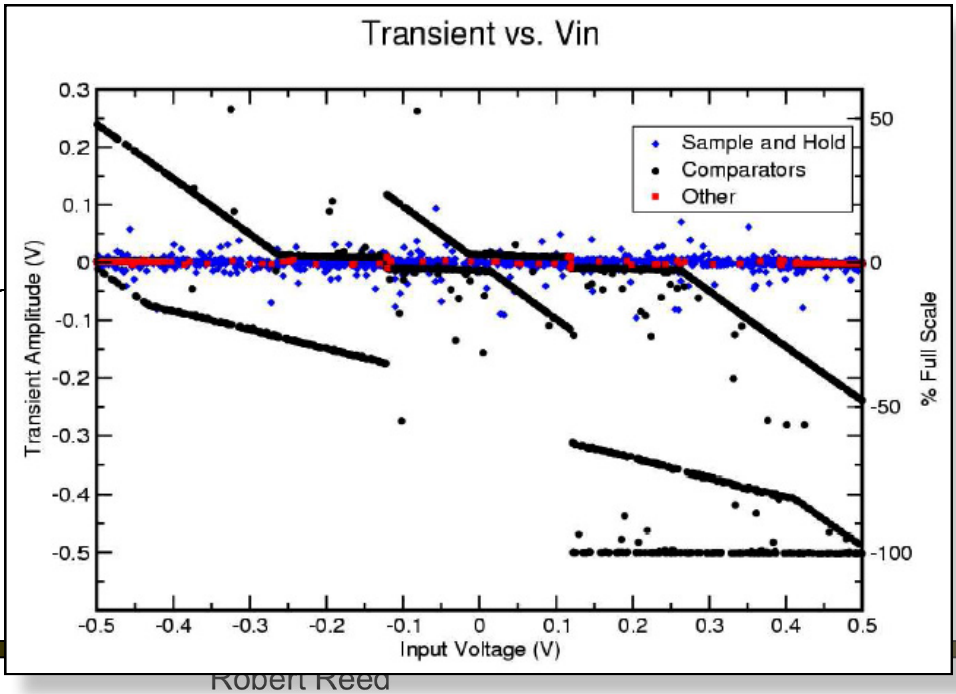
Mixed signal or high-speed SOC characterization requires functional simulations over many degrees of freedom

Models must be hierarchical





200,000 full ADC circuit simulations over input bias, spatial location, temporal position



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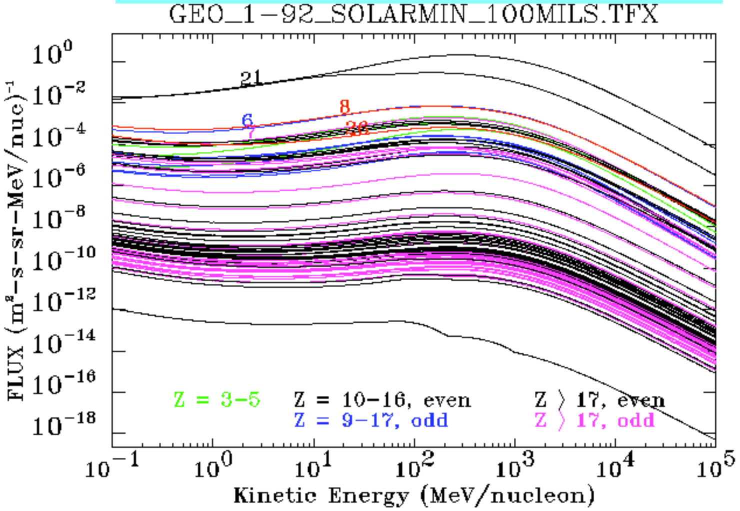
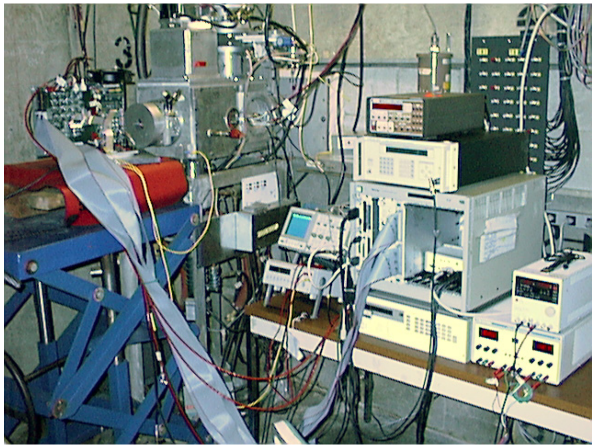
Classical On-Orbit SEE Performance Predictions

Space Environment



Ground Testing

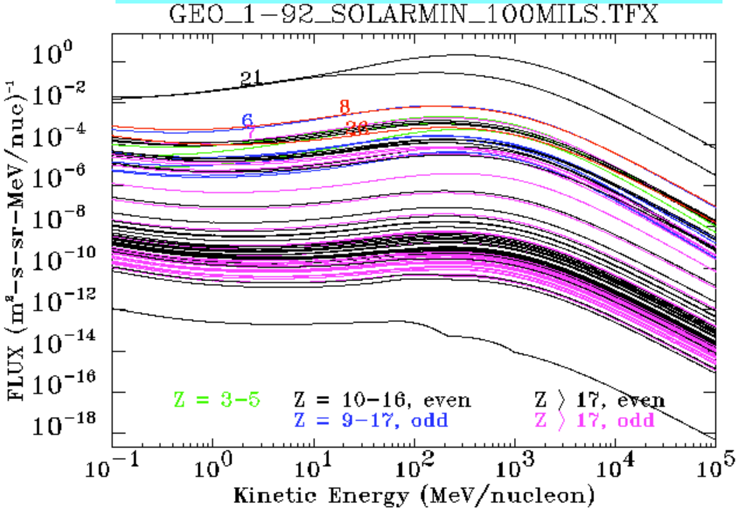


Direct Ionization: Rectangular Parallelepiped (RPP) model
Nuclear Reactions (proton only): Bendel Model
(both are circa 1980)
https://creme96.nrl.navy.mil/

On-Orbit SEE Rate

Classical On-Orbit SEE Performance Predictions

Space Environment



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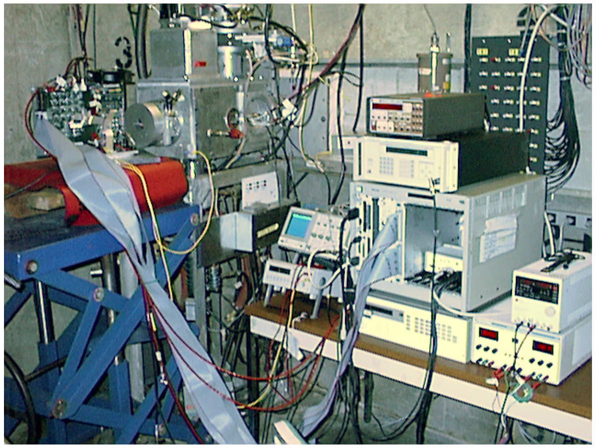
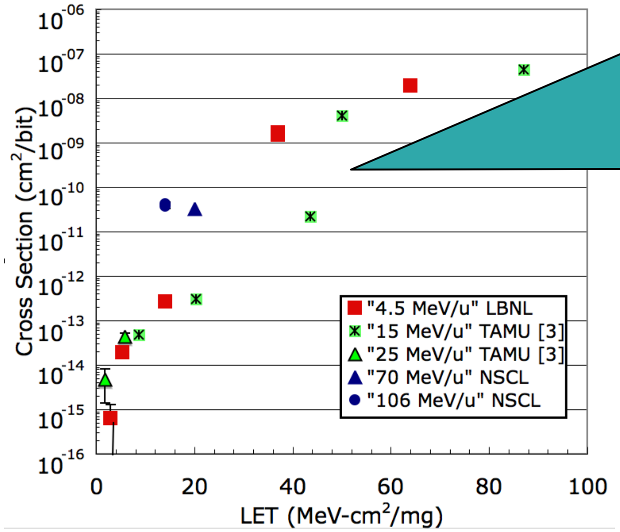


These models no longer capture the physical processes that drive the response of modern technology to ionizing radiation

On-Orbit SEE Rate ?

Examples of Breakdown of Existing SEE Models



Large discontinuities in heavy ion data for RADHARD SRAM

1) R.A. Reed, submitted to 2007 NSREC
2) K.M. Warren, et. al IEEE Trans. Nuc. Sci., vol. 48, no. 6, Dec. 2005, pp. 2125 – 2131.

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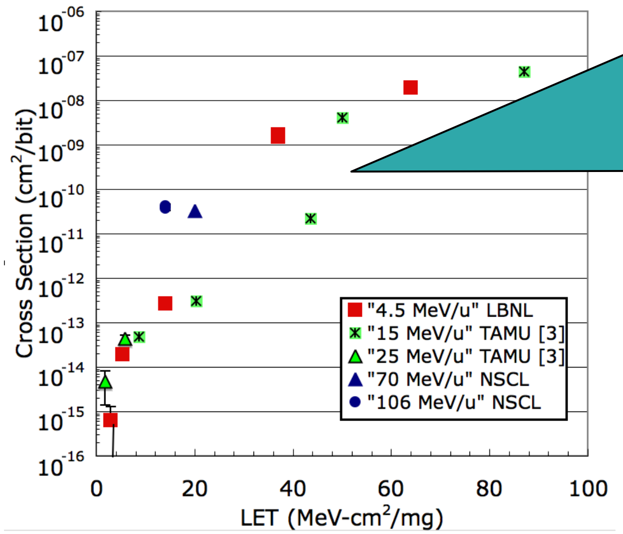

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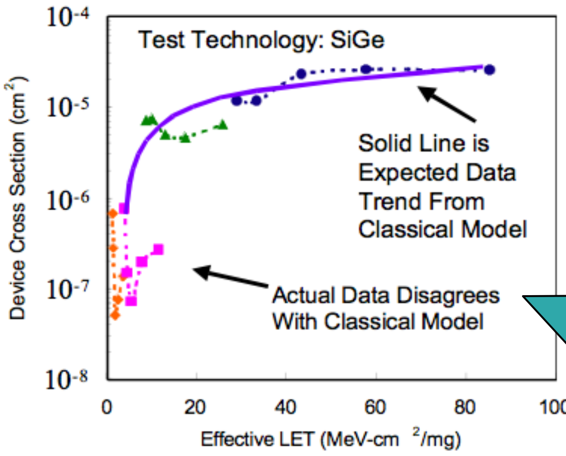

Inconsistent Effect from ion Angle for SiGe HBT circuits

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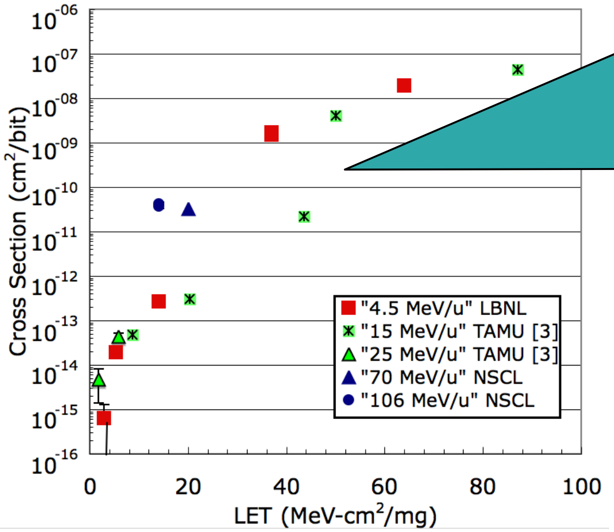

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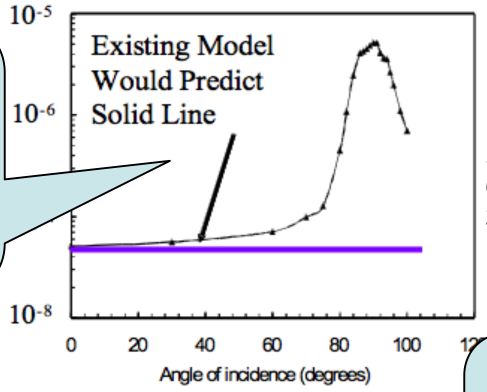
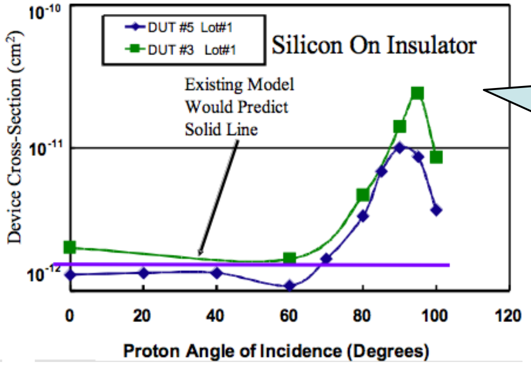
Protons Effects in Optical Links

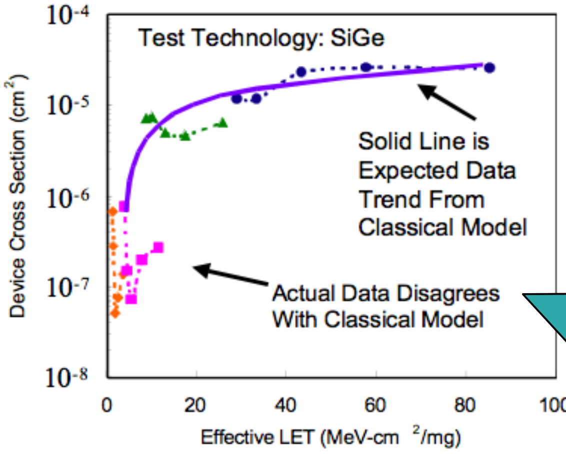


R.A. Reed, et. al IEEE Trans. Nuc. Sci., vol. 48, no. 6, Dec. 2001, pp. 2202 – 2209.



Proton effects in SOI based memories

R.A. Reed, et. al, IEEE Trans. Nuc. Sci., vol. 49, no. 6, Dec. 2002, pp. 3038 – 3044



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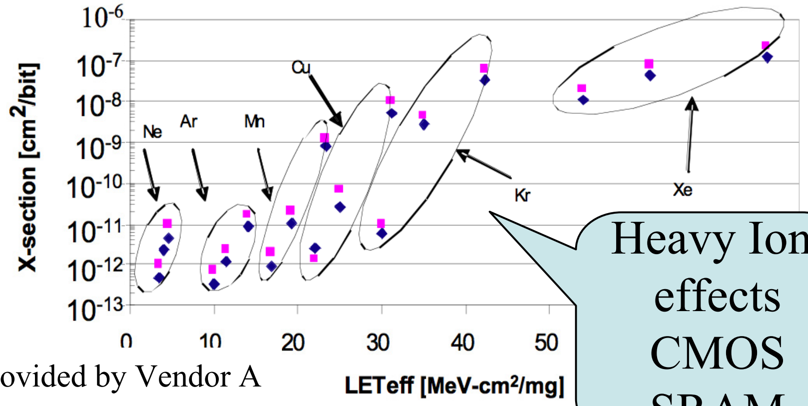

Provided by Vendor A

Heavy Ion effects CMOS SRAM

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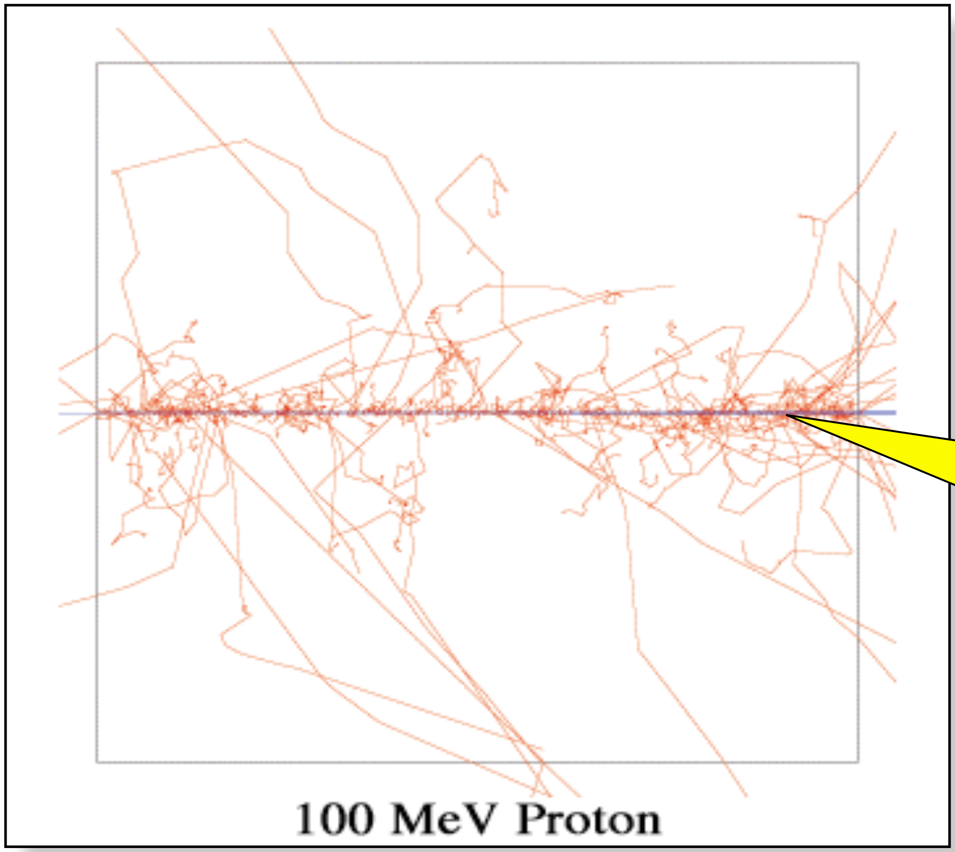
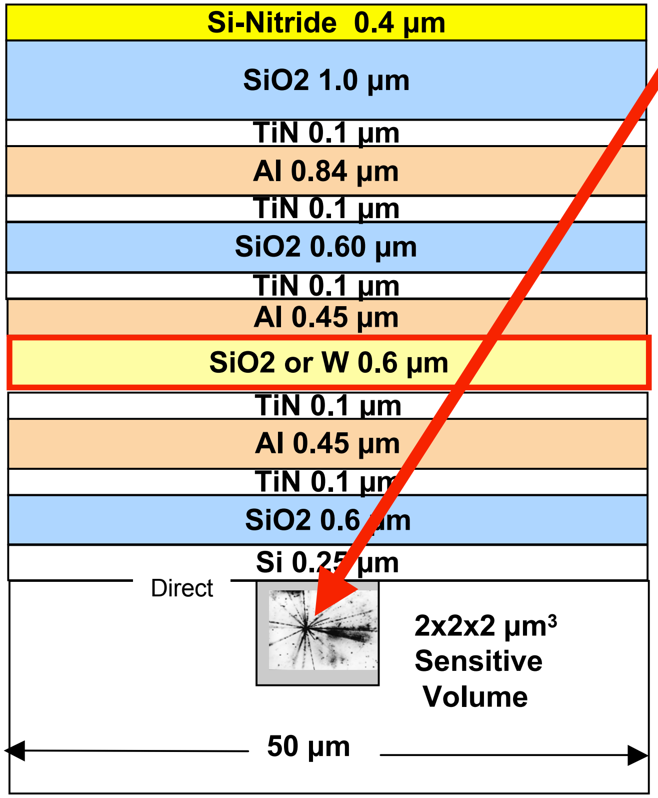
New Mechanisms to be Considered

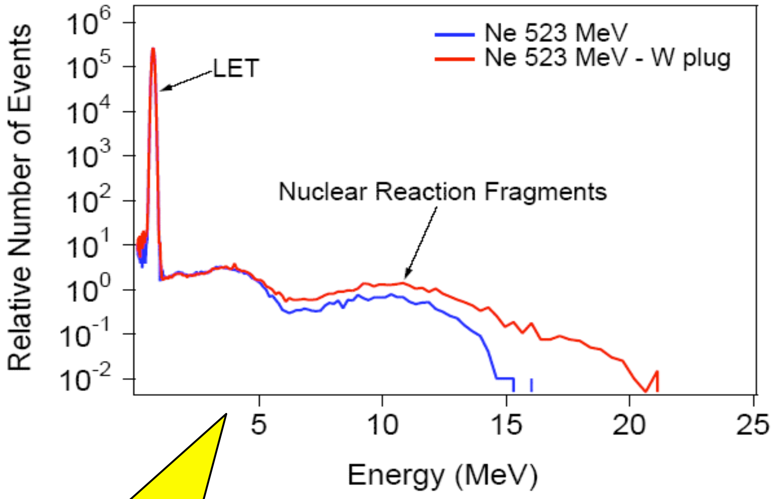
- **Nanoscale devices can be sensitive to the discrete energy deposition of the radiation**
- **Models based on average energy (e.g. LET) are suspect**



Ionization structure produced by 1000 individual incident particles on a 6um cube of Silicon

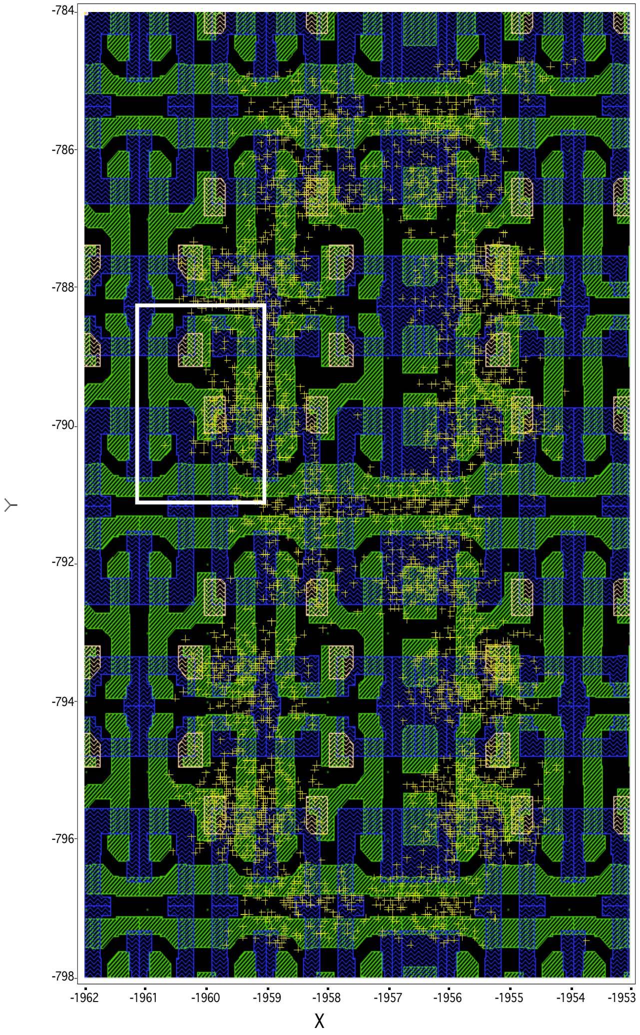
Contribution From Secondary Products in Overylaying Materials

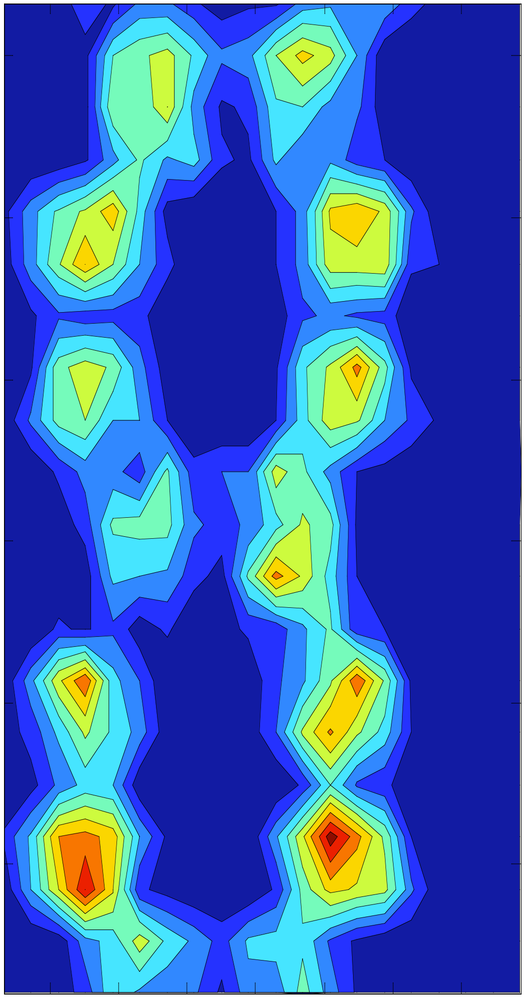




High energy secondary particles created by ionizing radiation interaction with W in the IC back end processing (overlayer)

FOCUSED ION MICROPROBE





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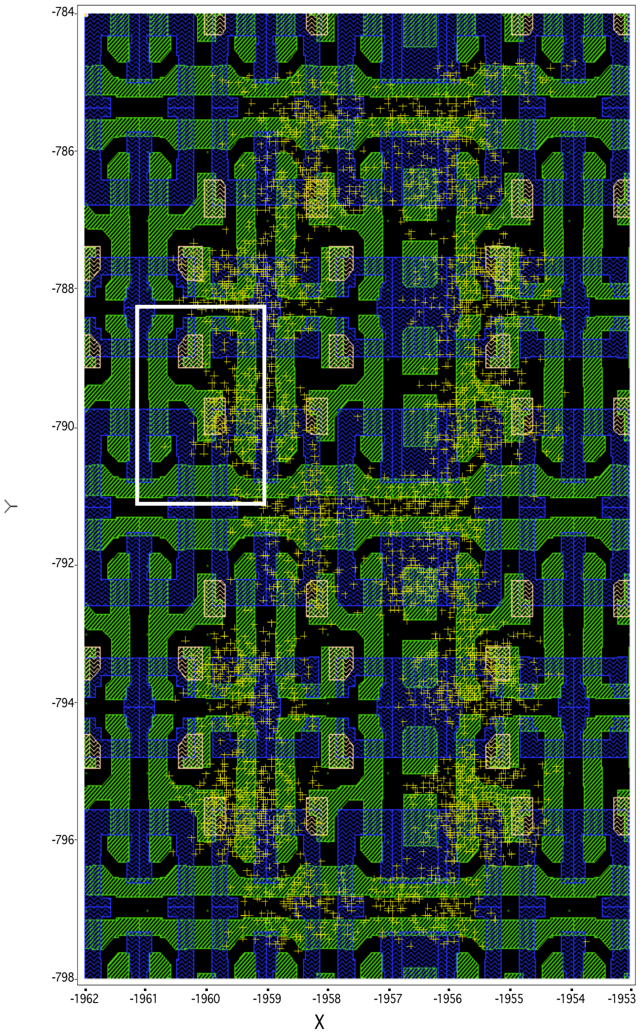
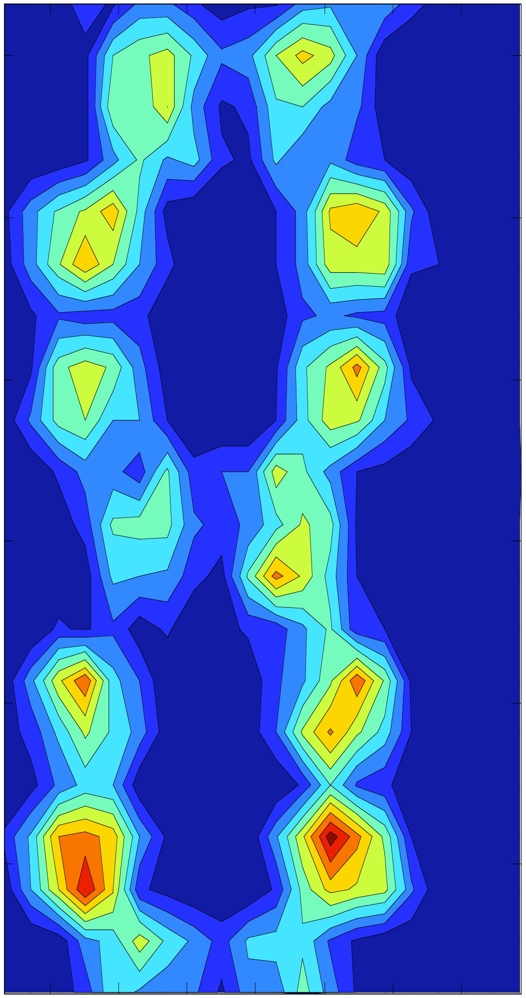
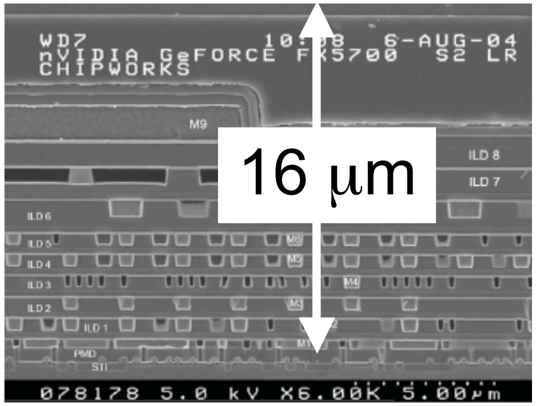




Existing facilities have limited ion range and spatial resolution



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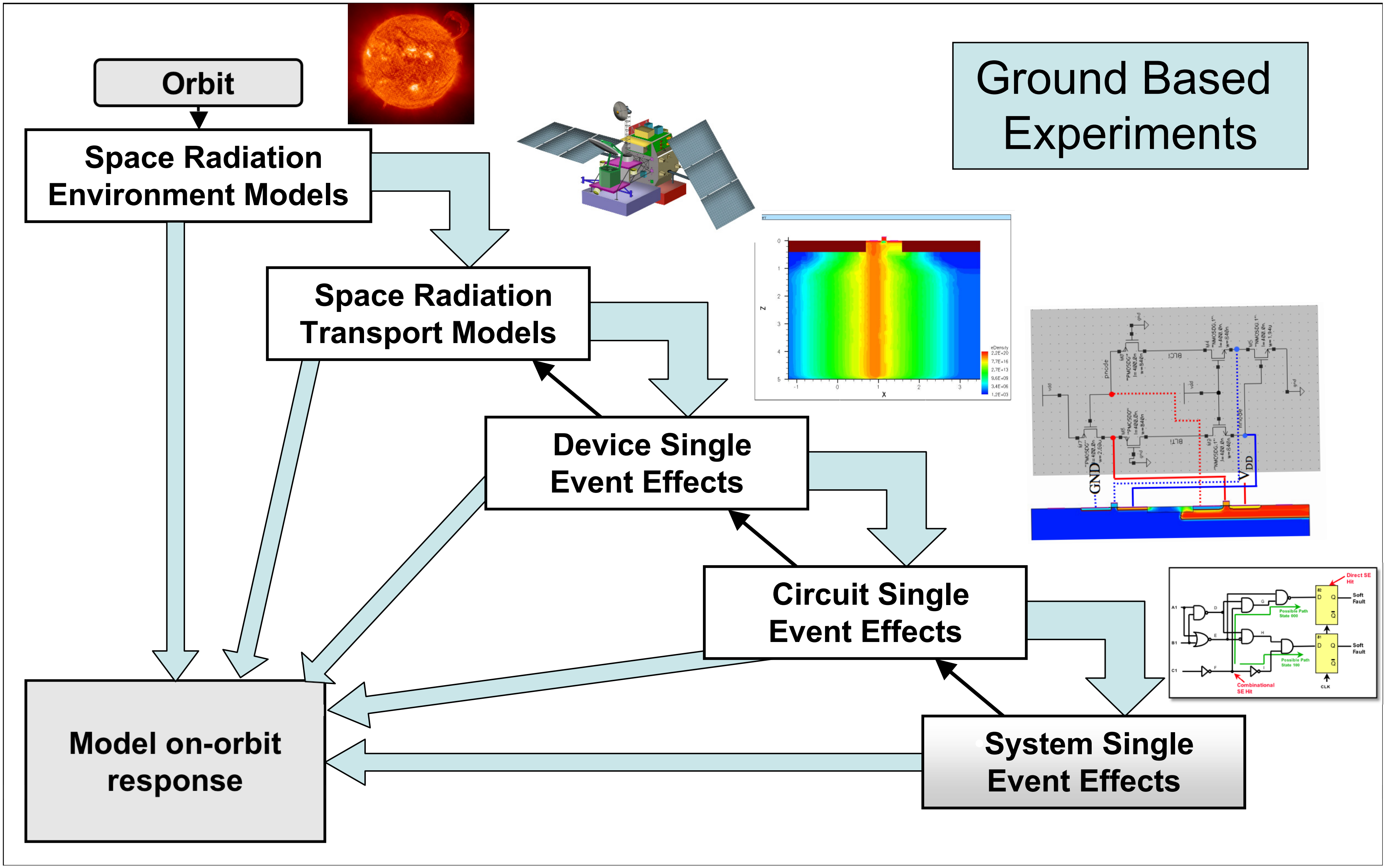
Advanced Radiation Effects Analysis



Orbit

Space Radiation Environment Models

Space Radiation Transport Models

Device Single Event Effects

Circuit Single Event Effects

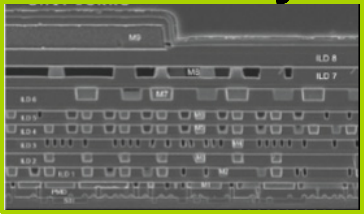
System Single Event Effects

Model on-orbit response

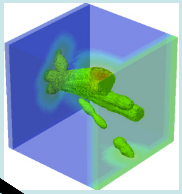
Ground Based Experiments

Components of the RADSAFE Concept for SEE Analysis

Geometry

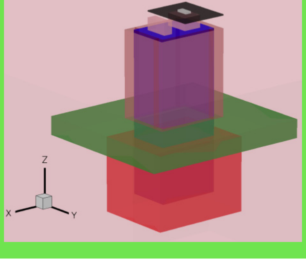


Charge Generation

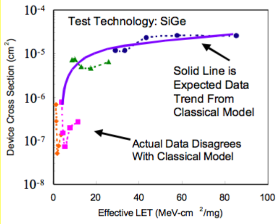


Energy Deposition

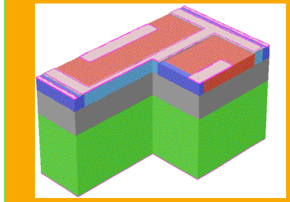
Approximate Response

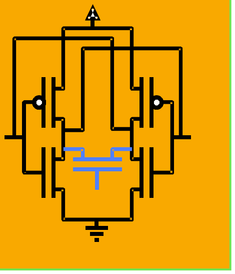


Experiment

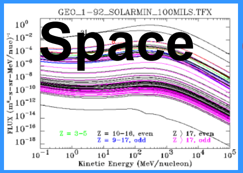


TCAD and/or Spice





Radiation Environment

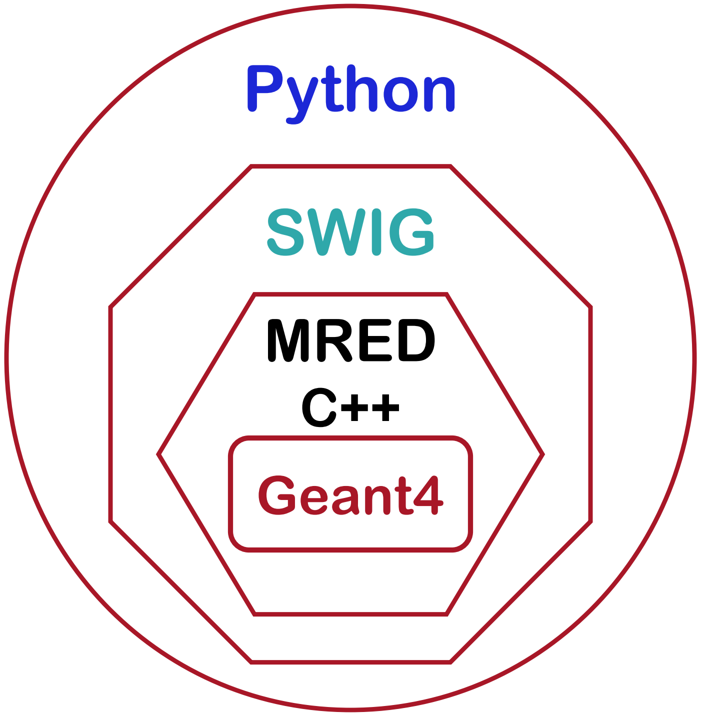


Space or **Ground**

Device and Circuit Response (Cross Section, Rate,…)

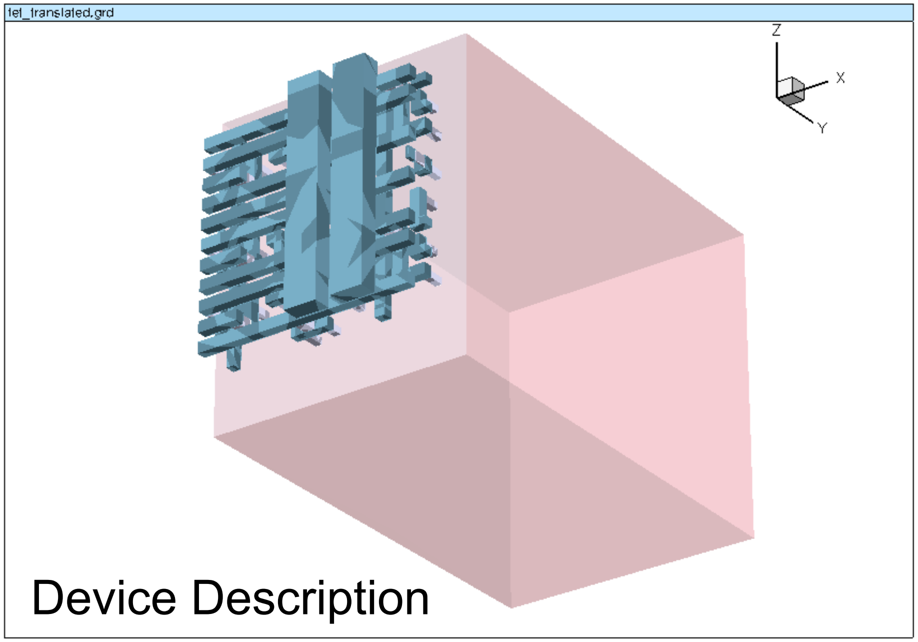
Key Technology: MRED

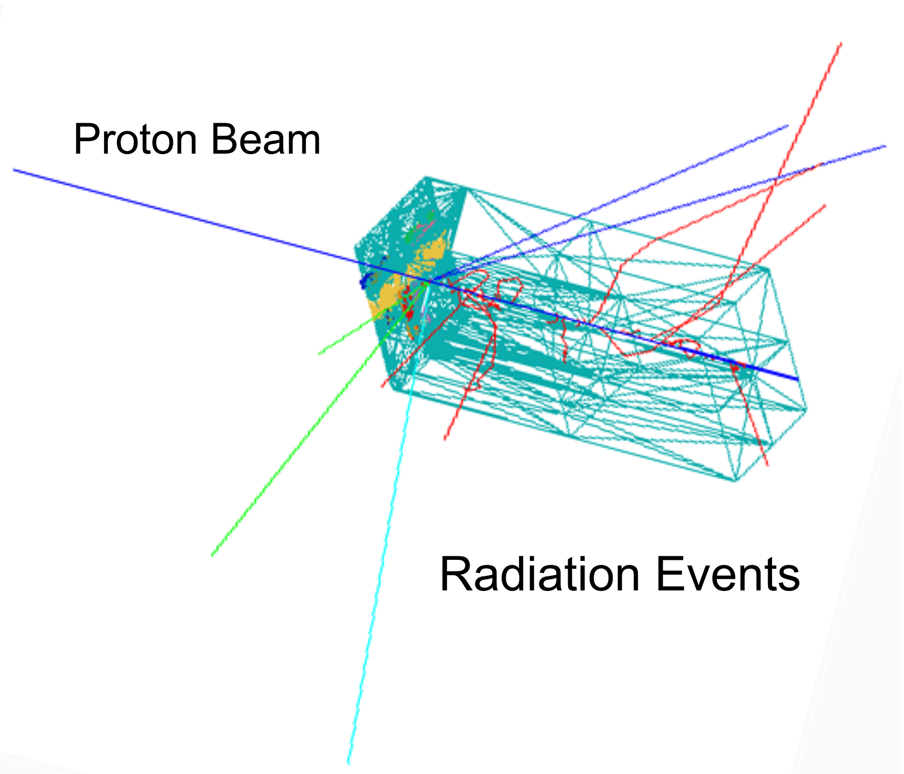
- MRED8 is the first generation Python/Geant4 application
  - Contains the best available physics
- Computes energy deposition from all types of interactions:
  - Primary ion LET
  - Coulombic scatters
  - Nuclear reactions



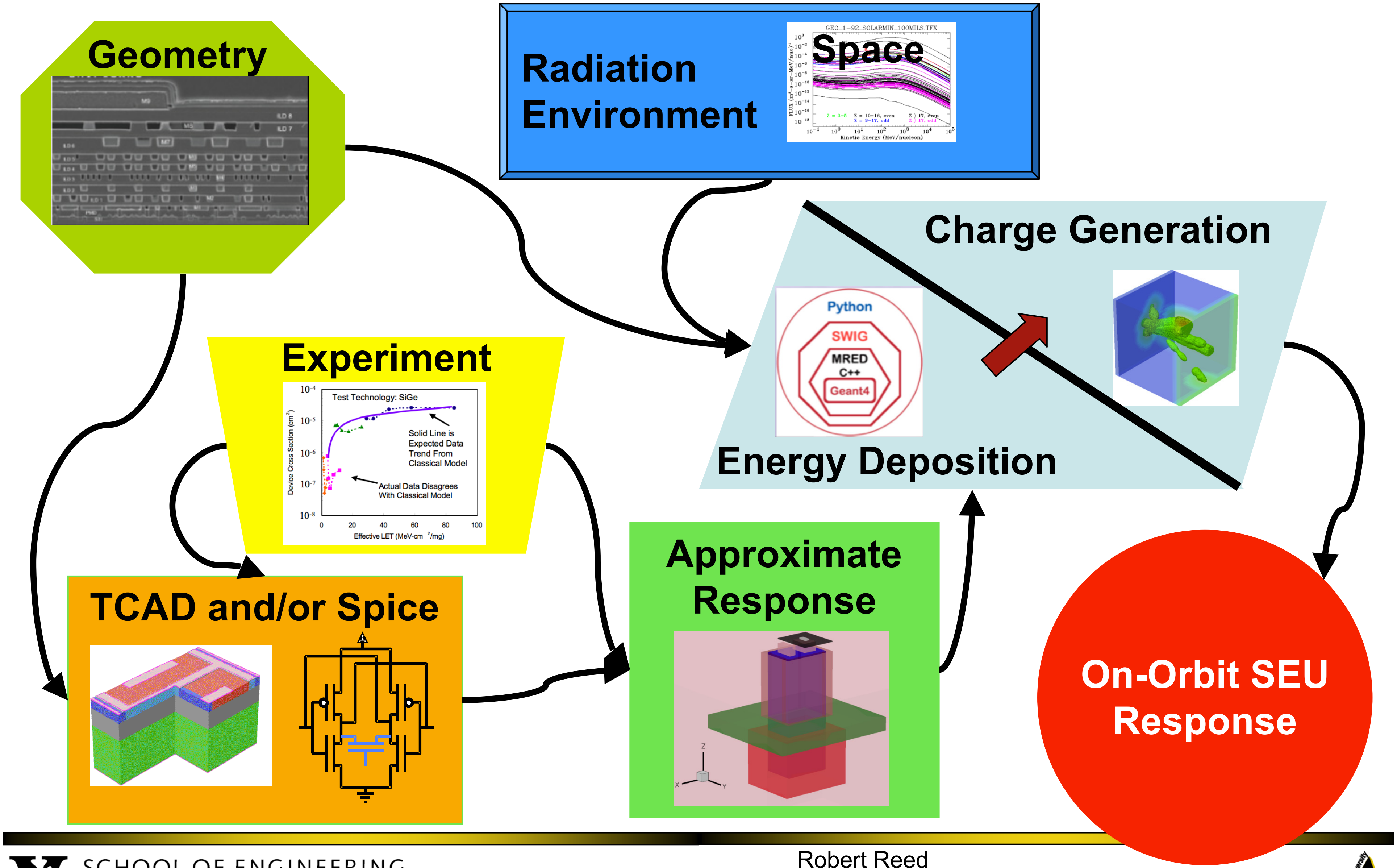
MRED8-TCAD Interface

- Protons incident on an advanced CMOS integrated circuit
- Reactions in the metal layers increase energy deposition





RADSAFE:Complex Approximation Models (II)



Geometry

Radiation Environment

Space

Charge Generation

Energy Deposition

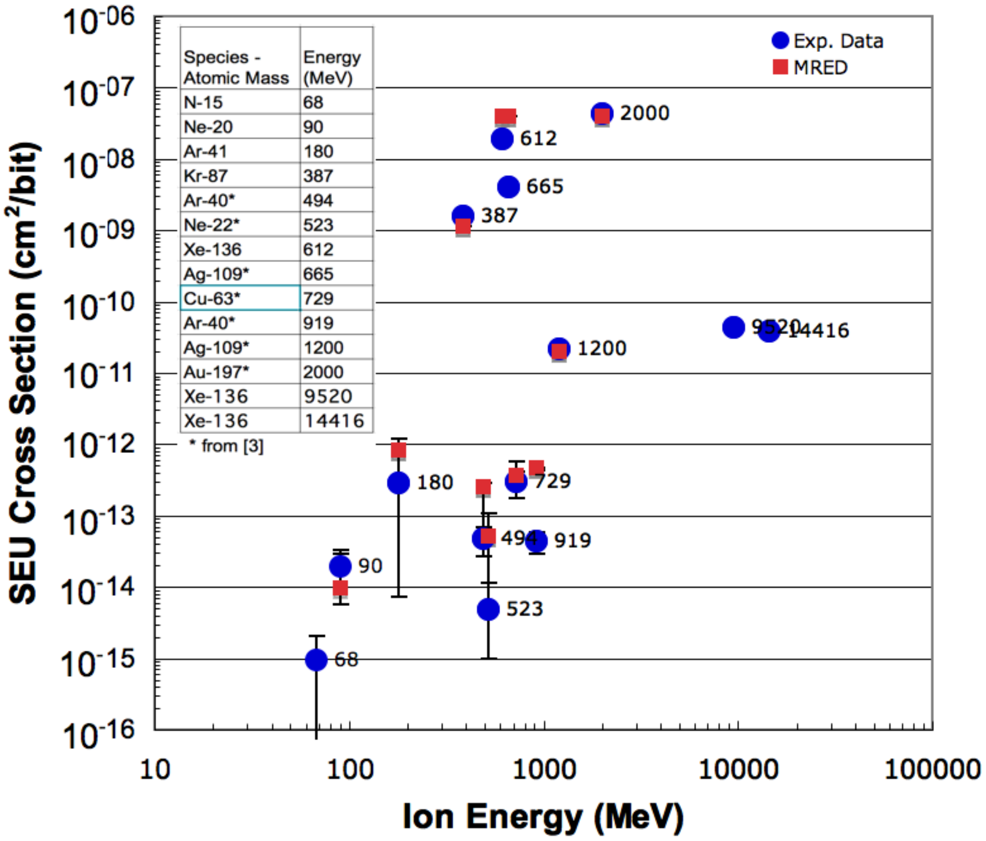
Experiment

TCAD and/or Spice

Approximate Response

On-Orbit SEU Response

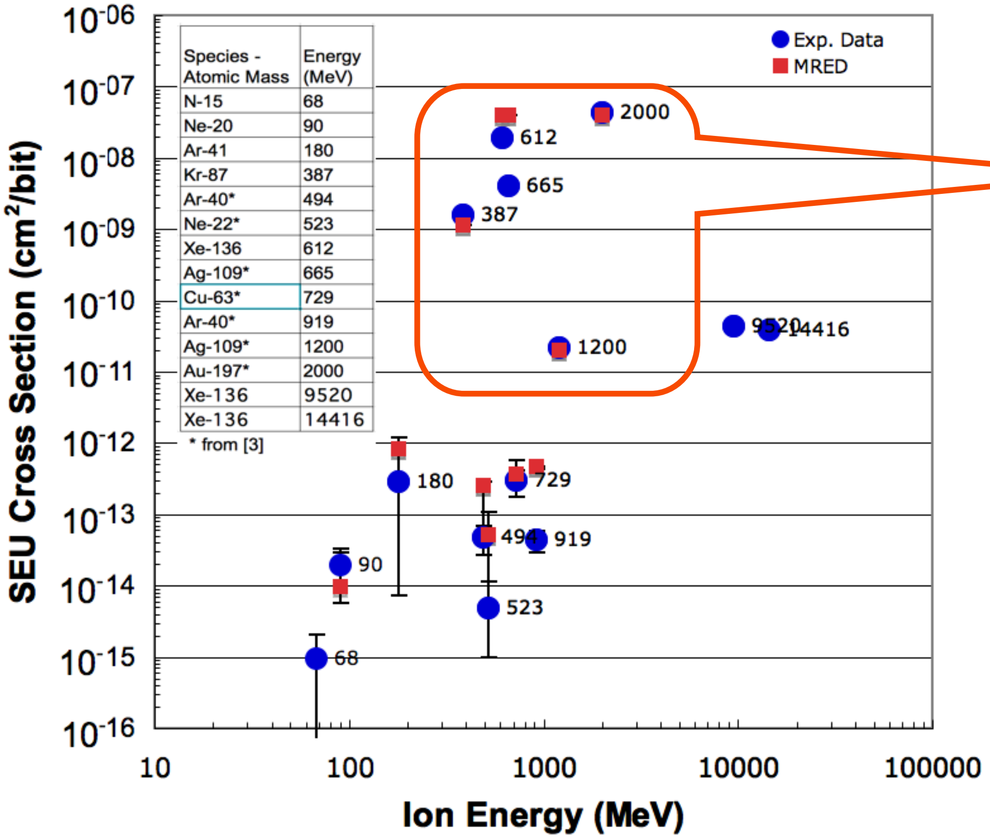
Using Ground Data to Calibrate Model



Species - Atomic Mass	Energy (MeV)
N-15	68
Ne-20	90
Ar-41	180
Kr-87	387
Ar-40*	494
Ne-22*	523
Xe-136	612
Ag-109*	665
Cu-63*	729
Ar-40*	919
Ag-109*	1200
Au-197*	2000
Xe-136	9520
Xe-136	14416

* from [3]

Using Ground Data to Calibrate Model



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* from [3]

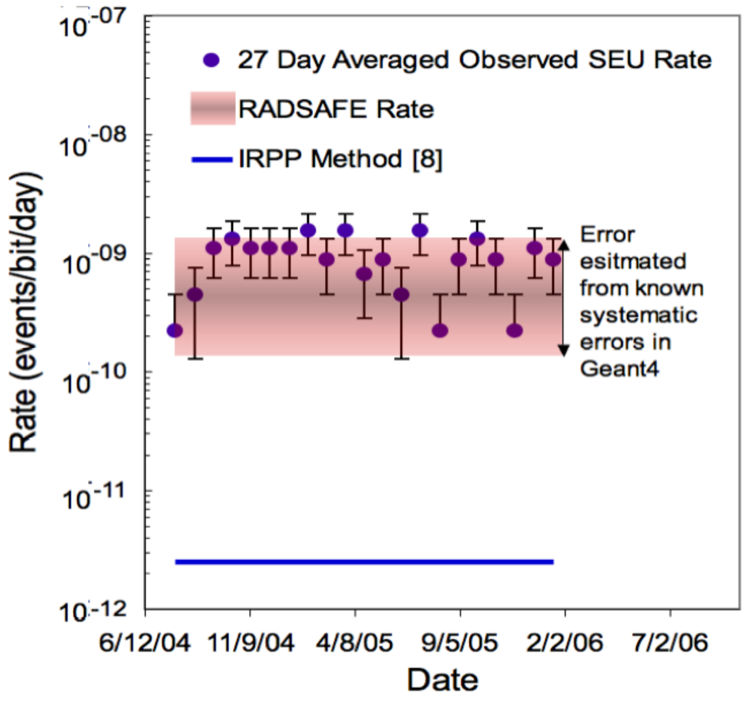
Model predicts that these events are dominated by direct ionization from primary

All others are dominated by nuclear reactions.

Classical heavy ion models to not allow for nuclear reaction contribution.

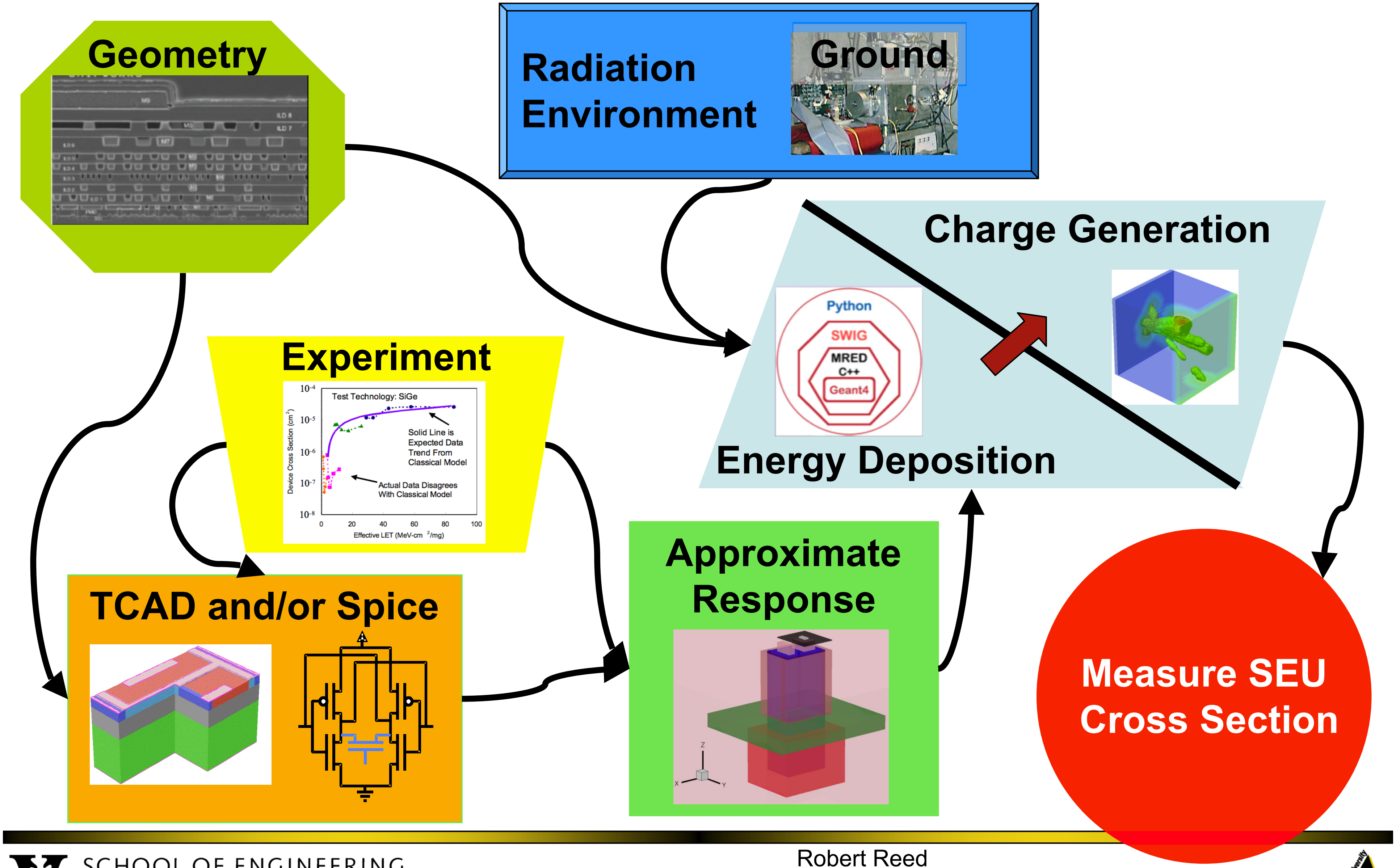
Observed and Predicted SEU Rate for a Modern SRAM

- SRAM used on NASA spacecraft
- Observed Average SEU Rate:
  - **1×10^{-9} Events/Bit/Day**
- Predict rate by classical methods (CREME96)
  - 2×10^{-12} Events/Bit/Day
  - Classical Method nearly a factor 500 lower than observed rate
- RADSAFE rate that includes reaction products:
  - **Between 1.3×10^{-10} and 1.3×10^{-9} Errors/Bit/Day**



RADSAFE rate agrees with observed rate

RADSAFE:Complex Approximation Models



Geometry

Radiation Environment

Ground

Charge Generation

Energy Deposition

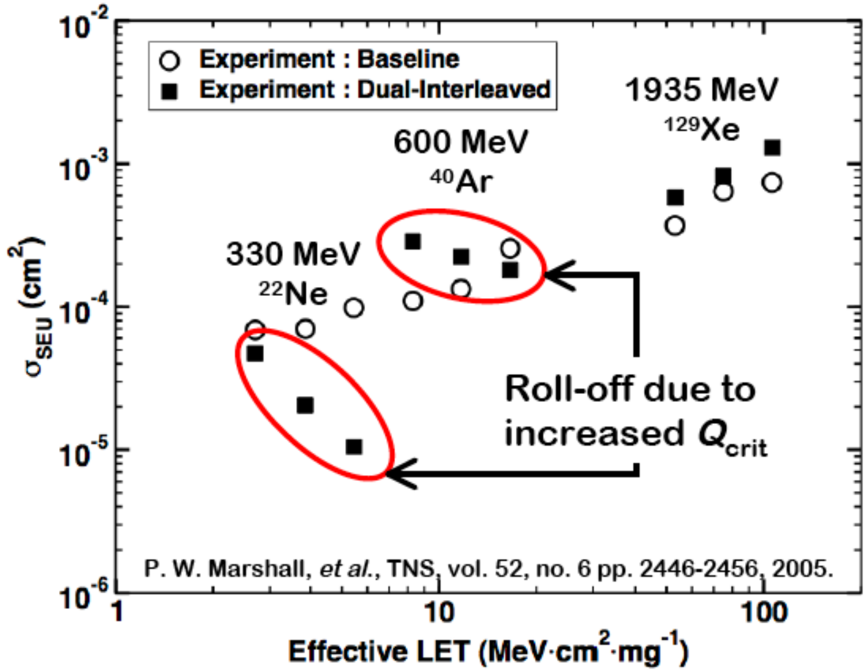
Experiment

TCAD and/or Spice

Approximate Response

Measure SEU Cross Section

Measured SEU Response for Shift Registers Design using SiGe HBTs

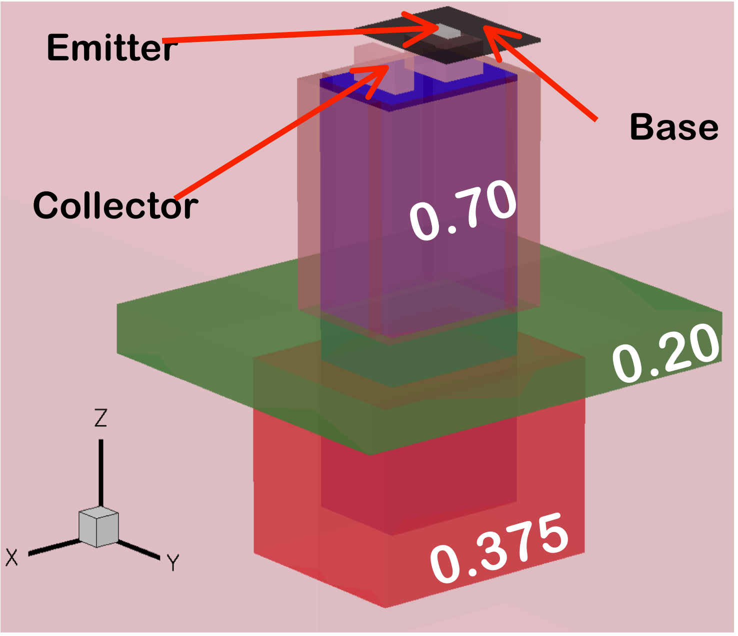


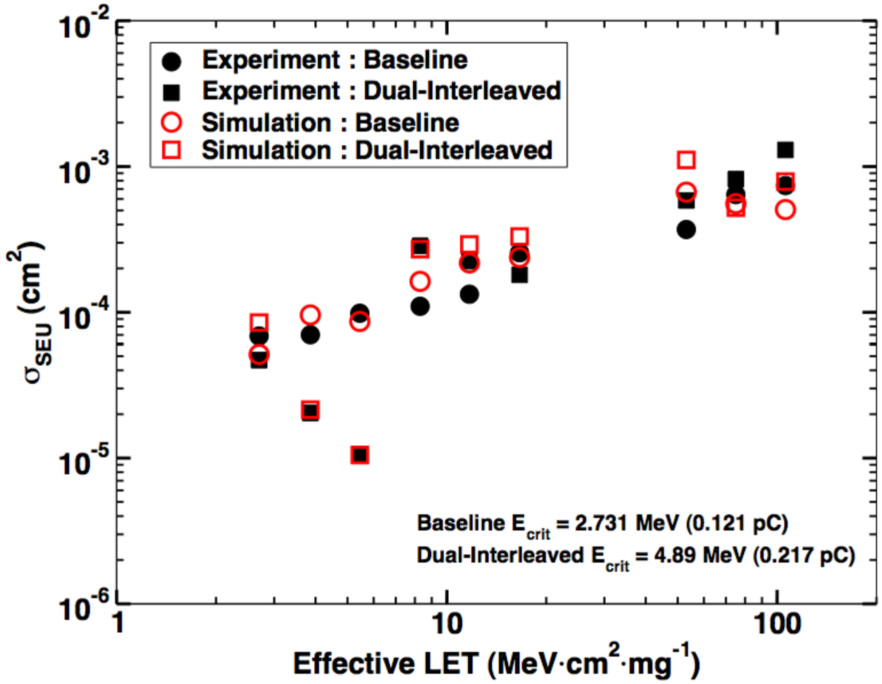
P. W. Marshall, *et al.*, TNS, vol. 52, no. 6 pp. 2446-2456, 2005.

- **Each cross section triplet represents irradiations at: 0°, 45° and 60°.**

- **Dual-interleaved topology is RHBD (↑ Q_{crit})**

IBM 5AM SiGe HBT Weighted mRPP Model





- **Create calibrated sensitive volume structure**
  - **Derived from TCAD simulations, broadbeam data, and microbeam data**
  - **Weighted sensitive volumes to capture charge induction efficiency**

Enabling Technology – Cost-Effective Hardware
Efficient Cluster Computing

Vanderbilt Multi-Processor Integrated Research Engine (VAMPIRE)

- Beowulf cluster consisting of >1400 processors
- Myrinet fiber network for minimal latency
- $8.3M investment from Vanderbilt VC fund
- Plan for ongoing upgrades and growth

Scope of RADSAFE Applications

- Full RADSAFE (MRED+TCAD) on-orbit predictions of SEU rate
  - 0.25 µm CMOS SRAM
  - IBM 5HP SiGe HBT Flip Flop
  - Xilinx FPGA-based SIRF SRAM
- Single-event, multiple-bit upsets in <130 nm CMOS SRAM
- SEE in 130 nm, 90 nm, and 65 nm CMOS devices
- Neutron-induced SEU in CMOS SRAM
- SEU in SiGe HBTs
- SEGR in MOS devices
- Transient effects in HgCdTe IR-FPAs
- Displacement damage in Si, III-V, HgCdTe, and other semiconductors
- TID dose enhancement effects

Technology Trends Affecting Radiation Analysis

As a result of relentless progress toward nanoscale fabrication…
Radiation modeling must deal with:

Novel Threats:

- **Discrete energy deposition**
- **Reaction products from overlayers**
- **Direct ionization from protons**

Scaled Geometries:

- **Device sizes on the order of single event**
- **Complex charge collection mechanisms**

Increased Speed:

- **Circuit response as fast as the radiation event**

Mixed-signal and SOC:

- **Upsets vs Errors vs ASETs vs DSETs**

SEE Test Facilities

- **High ion energy is not available at existing microbeam facilities**