CRÈME-MC: A Physics-Based Single Event Effects Tool

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Introduction

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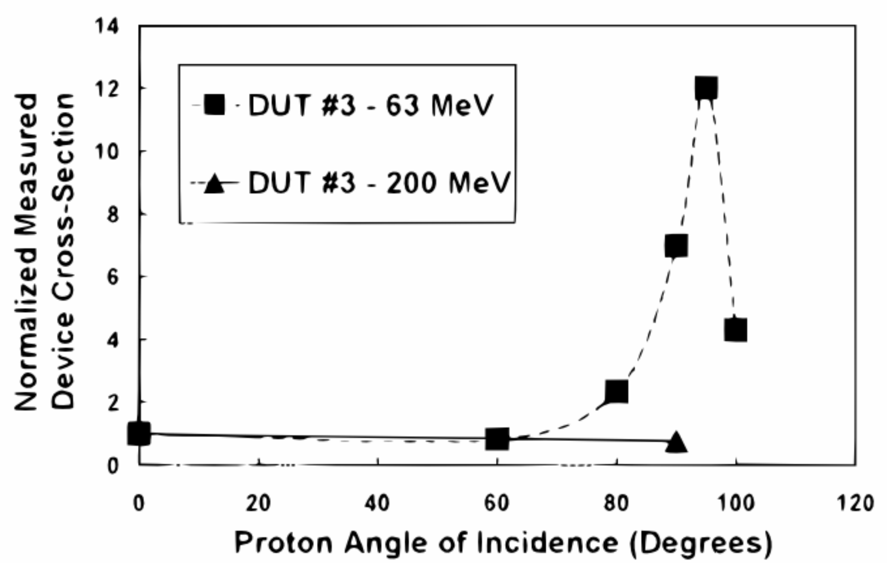
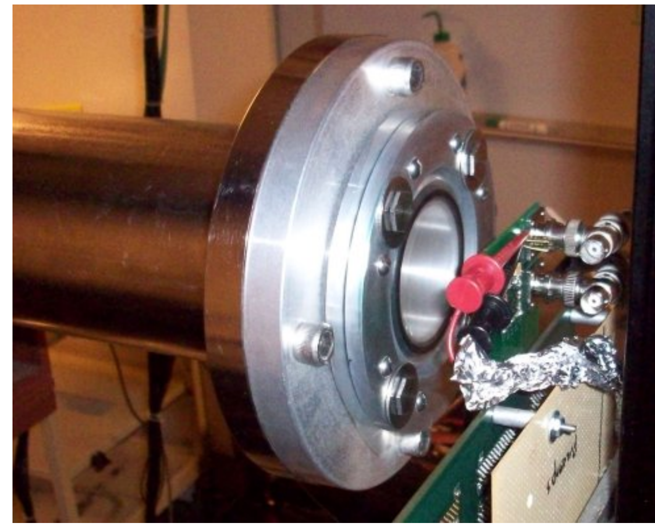
- Cosmic Ray Effects on MicroElectronics codes have been successfully used since early 1980's to predict the effects of ionizing radiation for on-orbit semiconductor devices
- Several works have shown where these analytical computations are not applicable in some cases due to nuclear interactions and multiple sensitive junctions
- Vanderbilt and NASA have led an effort to provide advanced physical modeling using Geant4 including
  - State-of-the-art radiation transport codes for sub-100nm feature sizes
  - Improved on-orbit radiation environment models

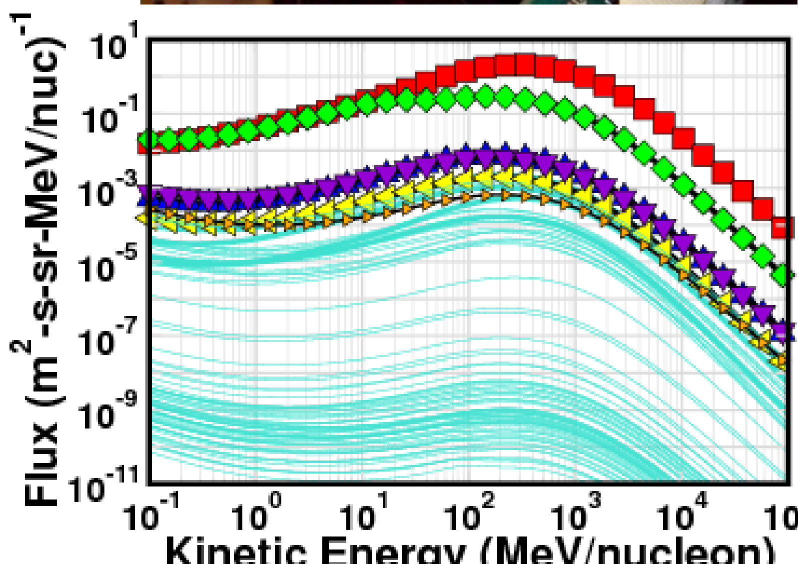


http://creme.isde.vanderbilt.edu

Single Event Effects

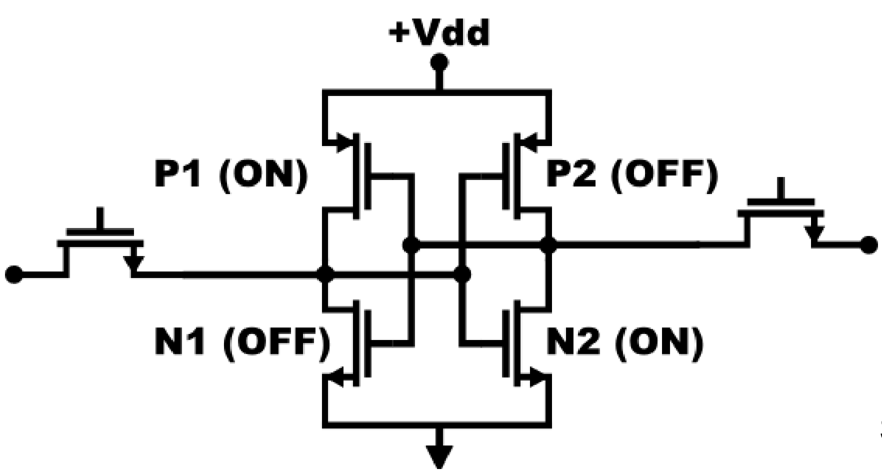
- **Effects in microelectronics caused by a single primary particle, or shower of secondary particles, passing through semiconductor materials**
  - Hard (destructive) errors:
    - Single event latchup (SEL)
    - Single event gate rupture (SEGR)
    - Single event burnout
    - Stuck bits, noise, etc
  - Soft (non-destructive) errors:
    - Single event upset (SEU) in memories
    - Single event transient (SET) in logic
- **Accelerated testing must be performed and on-orbit event rates must be predicted**



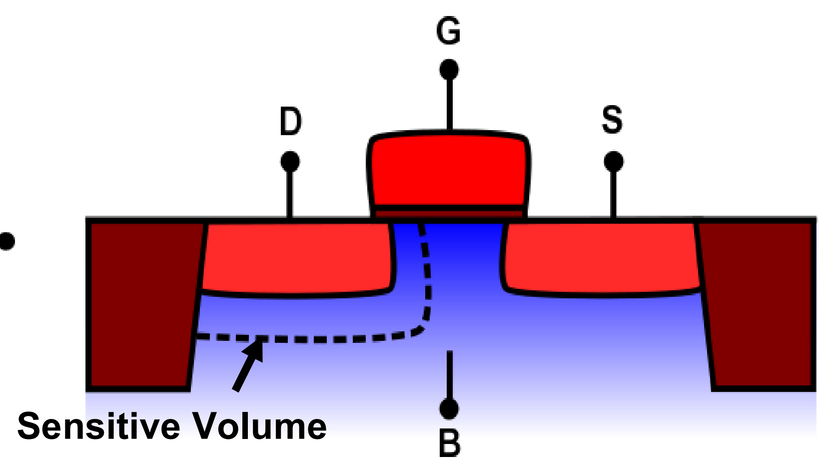


SEU Mechanisms

- **Charge storage devices utilize capacitors to hold logic state**
- **CMOS logic utilizes electrostatic potentials in bistable circuits to denote logic state**
- **SEEs, particularly soft errors, are encountered as the result of localized energy deposition and charge generation**
  - Spatial position is termed **sensitive volume**
  - Temporary short circuit of N1 drain to body causes voltage drop
  - The quantity of charge required to produce an error for a given circuit is termed the **critical charge**



6T SRAM circuit schematic



Transistor N1 physical view

Indicators for Physics-Based Analysis

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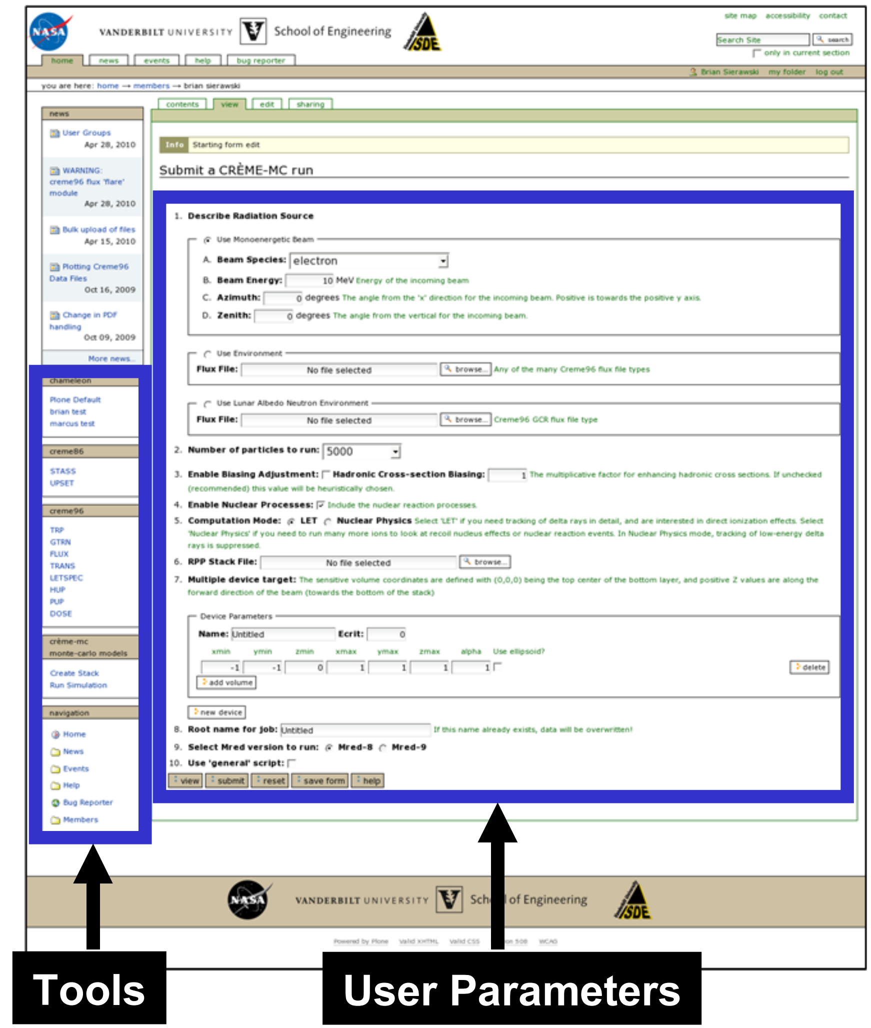
Weller, *et al.*, 2009

- **Known technology or system application characteristics:**
  - Basic assumptions of the RPP or IRPP model are known to be inappropriate to the technology under investigation
  - Upsets are known to require near simultaneous, **multiple-transistor, multiple-node** perturbations
- **Experimental observations:**
  - **Unexpected upsets** are observed in what is assumed to be a hardened technology
  - **Different ions with the same LET** produce upset cross-sections that differ statistically
  - Cross sections for multiple ions cannot be correlated with a single sensitive volume
  - Strong **azimuthal angle dependence** (rotation around the die surface normal) is observed with heavy ions
  - Strong **angular dependence** is evident in test data using protons

Event Modeling

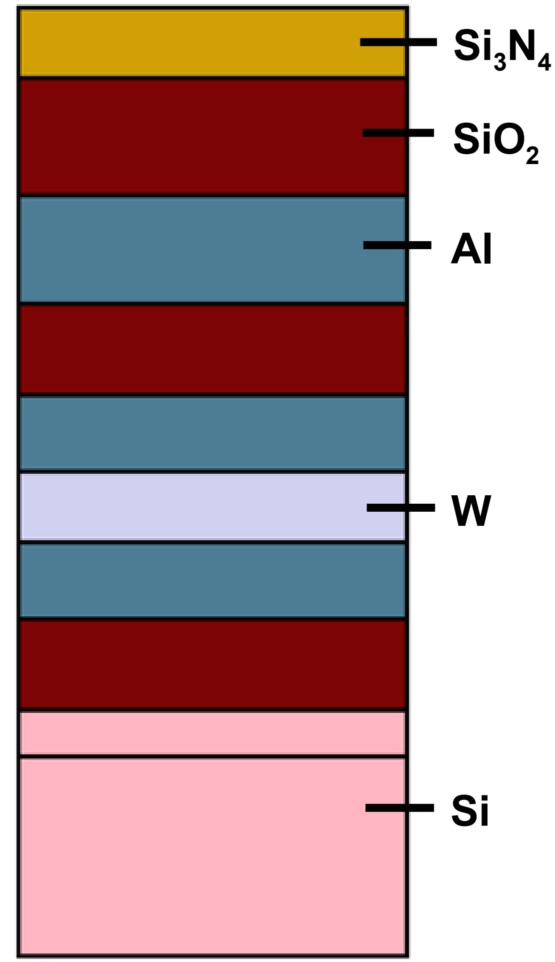
- **CRÈME-MC provides access to MRED scripts and Geant4 radiation transport libraries**
  - Electronic stopping
  - Coulombic scattering
  - Nuclear elastic and inelastic scattering
- **Monte Carlo sampling provides energy deposition events including**
  - Energy straggling
  - Energy loss variation
  - Delta electron production
- **CRÈME site runs a Plone server on a dual quad-processor XServe**



Multilayer Planar Stacks

- **Hi-Z materials can influence energy deposition altering SEU rate or total ionizing dose**
- **Constructor builds three-dimensional multilayer structure**
  - Common electronic materials available
- **Lateral dimensions affect**
  - Primary particle loss due to scattering-out
  - Secondary particle loss due to scattering-in
  - Particle fluence

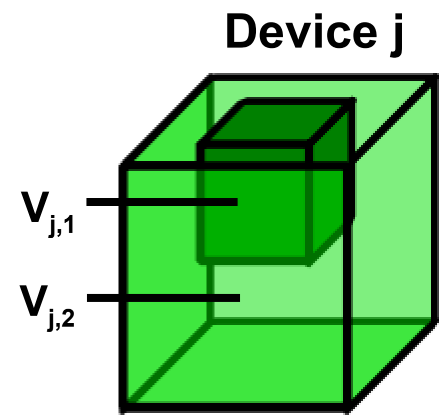
	Material	X (µm)	Y (µm)	thickness (µm)
	Si3N4	5	5	0.40
	SiO2	5	5	1.00
	aluminum	5	5	0.84
	SiO2	5	5	0.60
	aluminum	5	5	0.45
	tungsten	5	5	0.40



Schematic (x-z) view

Sensitive Volumes

- **Weighted sensitive volumes relate spatial ionizing energy deposition with charge collected at a circuit node**
- **Volumes may be rectangular parallelepipeds or ellipsoids**
  - Each have a location within the multilayer stack, size, and efficiency
  - Volumes may overlap or be disjoint
- **Sensitive volume sizes determined through heavy-ion broadbeam testing**



$$Q_{coll,j} = \sum_{i=1}^{N_j} \alpha_{j,i} \times I(Z) \times E_{dep,j,i}$$

Device Parameters

Name: NMOS **Eth:** 0

xmin	ymin	zmin	xmax	ymax	zmax	alpha	
-0.5	-0.5	0	0.5	0.5	0.5	0.75	delete
-1	-1	0	1	1	1	0.25	delete

add volume

Broadbeam Simulations

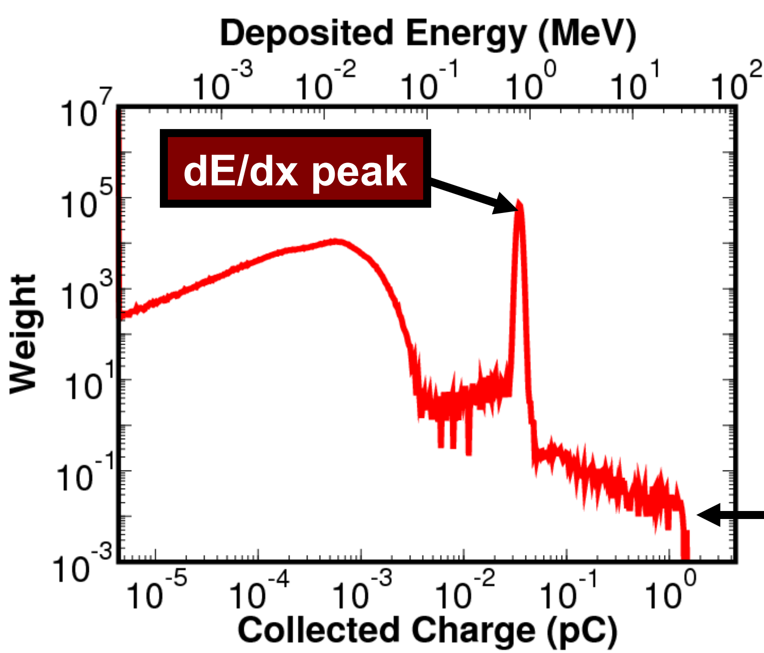
Use Monoenergetic Beam

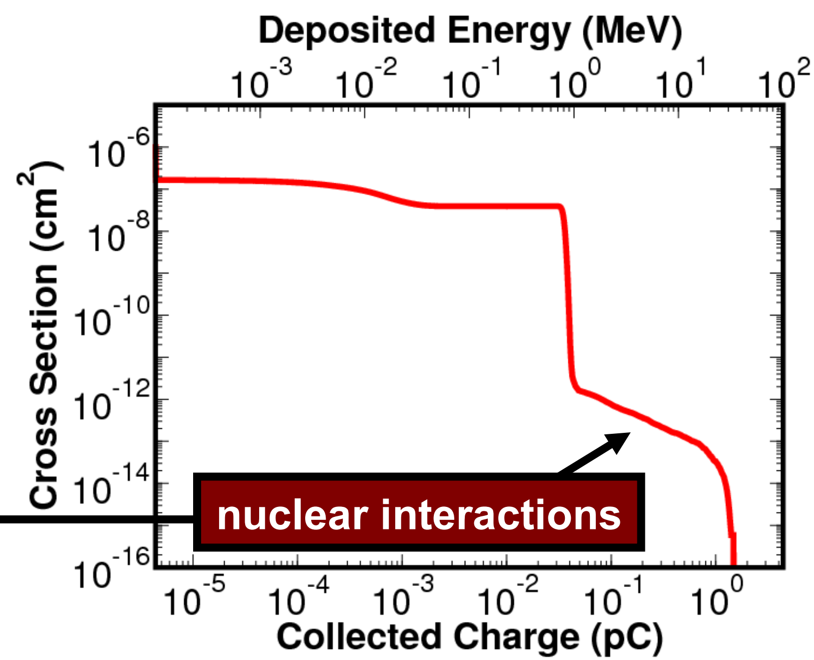
A. **Beam Species:** Oxygen (16-O)

B. **Beam Energy:** 250 MeV Energy of the incoming beam

C. **Azimuth:** 0 degrees The angle from the 'x' direction for the incoming beam. Positive is towards the positive y axis.

D. **Zenith:** 0 degrees The angle from the vertical for the incoming beam.





Multiple Device Models

- **Represent class of failures requiring multiple circuit nodes to collect charge**
  - Multiple cell upsets, DICE latches, etc
- **Sensitive volume models are specified for each device and given upset threshold**
- **Cross sections and SEU rates are provided based on frequency of events meeting coincidence requirement**

Name: Device1 **Eth:** 0.0225

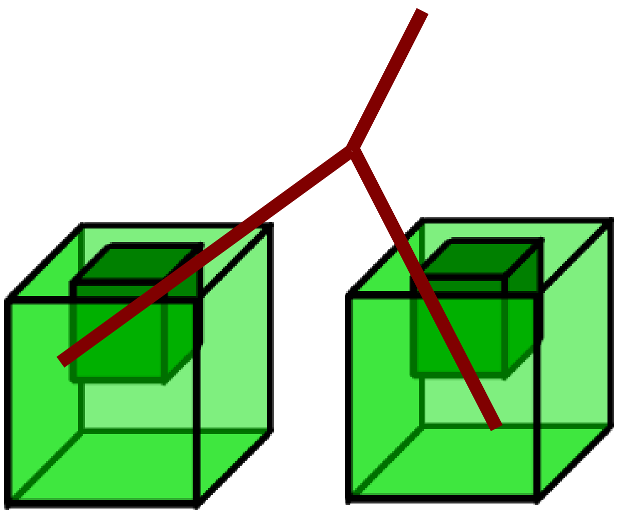
xmin	ymin	zmin	xmax	ymax	zmax	alpha	
-3	-1	0	-1	1	1	1	delete

add volume

Name: Device2 **Eth:** 0.0225

xmin	ymin	zmin	xmax	ymax	zmax	alpha	
1	-1	0	3	1	1	1	delete

add volume



Device 1 **Device 2**

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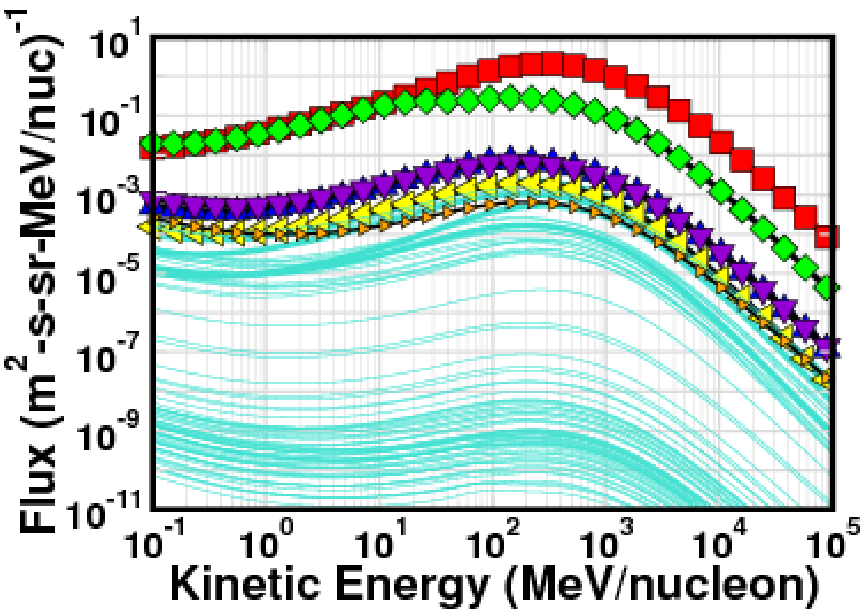
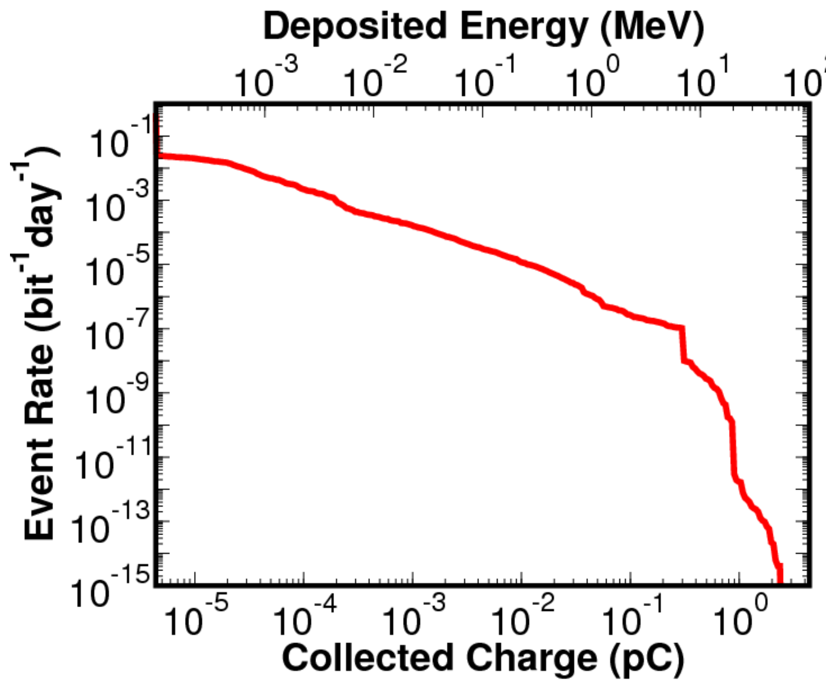
Environment Results





- **Specifying a CREME96 environment produces an event rate**
  - Imposing critical charge determines SEU rate
- **Computation differs from RPP methods**
  - Contributions from both direct and indirect ionization from Z = 1 to 92
  - Energy deposition from delta production
  - Intracell variation in charge collection rather than intercell

Status

Feature	Status
CREME96 Modules	Public
Updated GCR Model	Public
Multiplanar Stack	Beta
MC Sensitive Volumes	Beta
HZETRN Radiation Transport	Beta
CREME86	Alpha
Lunar Neutron Albedo Model	Alpha
Probabilistic Solar Proton Models	Development
Radiation Transport Through Spacecraft	Development
Revised Geomagnetic Cutoff Model	Development

- **Users may register with CRÈME https://creme.isde.vanderbilt.edu**

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Summary

- **Existing SEE prediction tools do not include effects found in modern devices**
  - Complex dependencies between geometry, multiple sensitive volumes, and nuclear interactions
- **CRÈME-MC provides users the capabilities to**
  - Evaluate the effects of overlayer materials, ion species, and beam angle
  - Extend the single sensitive volume model to capture diffusion and multiple node charge collection