Status and Plans for Vanderbilt's SEU Tools and Research

NEPP
2nd Annual Electronics Technology Workshop

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Outline

- Brief Introduction to Vanderbilt's Monte-Carlo Radiative Energy Deposition (MRED) tool
  - "Vanderbilt's SEU Tools"
- Validation/Verification
  - Physics models validation/comparisons
- Applications
  - Wide range of applications for SEU and beyond
  - Vanderbilt Radiation Effects Research (RER) group
- CRÈME MC Update
- MRED Spinoff - VRT

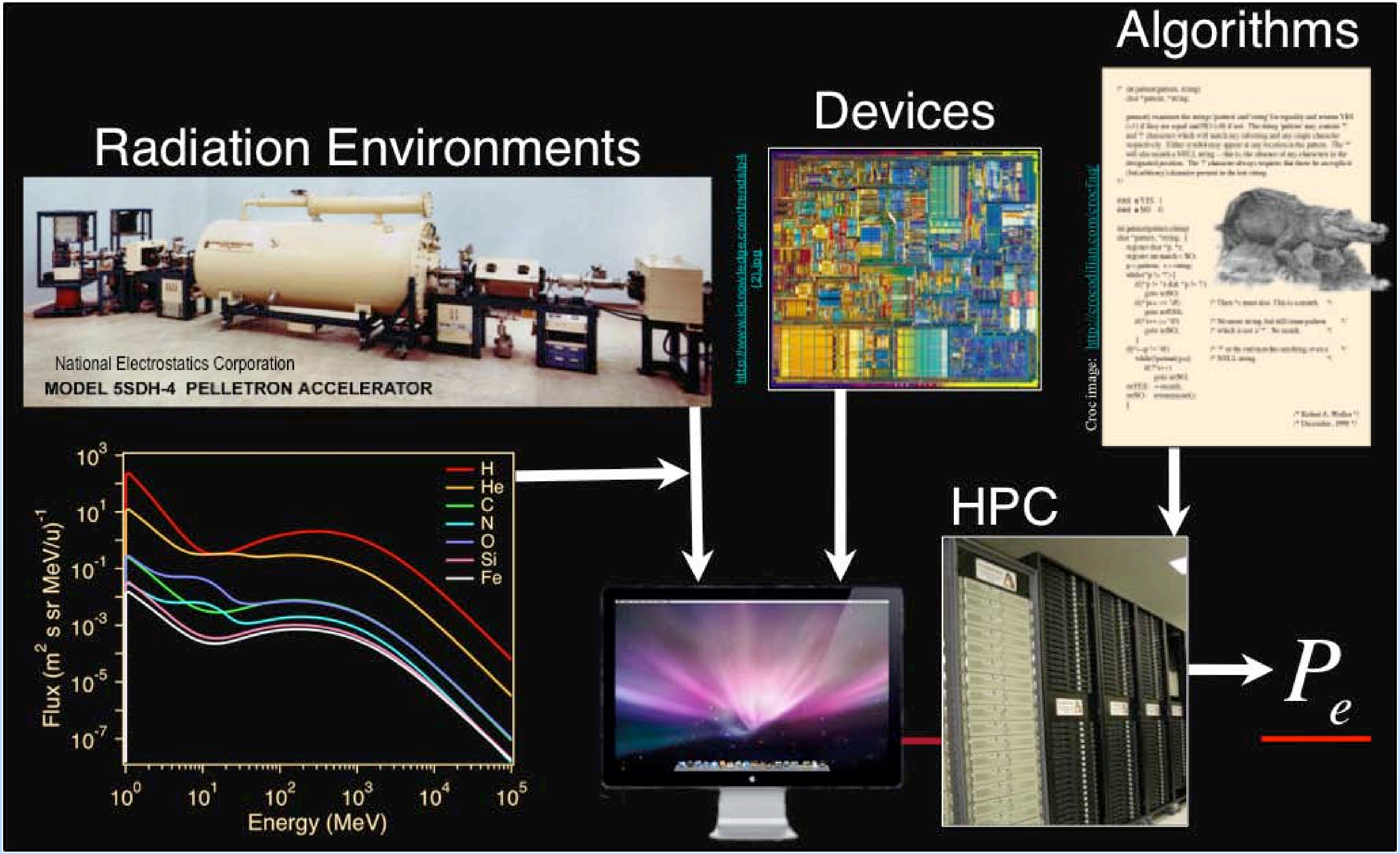
Motivation

- Existing methods for predicting the rate of single event upsets in semiconductor devices have begun to fail because their of their basic assumptions.
- New computational methods developed at Vanderbilt have exposed gaps in basic science that limit our ability to make accurate predictions of single event effects.
- Two important areas needing basic work are:
  - The generation of final states of ionizing particles following nuclear reactions.
  - The microstructure of energy deposition and charge generation by ions, including the spatial and energy distributions of carriers.
- Experiments cannot be understood without good modeling.

MRED Basics

- Monte-Carlo based radiation transport tool
  - Built around the Geant4 libraries (C++ classes)
  - Python wrapped for rapid development, analysis, and integration
- Capabilities
  - Rich suite of physics models for transporting radiation through user defined materials
  - Ability to import user-defined radiation spectra of one or many particle types
  - User can define simple layered structures (e.g., semiconductor process) or complex CAD structures
  - Monitor energy deposition in any number of geometric regions or the entire track structure of any and all events
- Interface to external tools is largely unlimited

MRED Concept



Physical Processes

- **Photons**
  - Rayleigh scattering
  - Photoelectric effect
  - Compton scattering
  - Gamma conversion
  - Photo-nuclear reaction
- **Electrons and positrons**
  - Ionization
  - Multiple scattering
  - Bremsstrahlung
  - Electro-nuclear reactions
  - e+ annihilation at rest
- **Muons**
  - Ionization
  - Multiple scattering
  - μ+ annihilation at rest
  - μ-nuclear reactions
- **Pions and Kaons**
  - Ionization
  - Multiple scattering
  - Hadronic interactions
- **Protons and neutrons**
  - Ionization
  - Bremsstrahlung
  - Pair production
  - Screened scattering
  - Hadronic interactions
- **Ions**
  - Ionization
  - Screened scattering
  - Hadronic interactions
- **Elementary particles**
  - Ionization
  - Multiple scattering
  - Decay/annihilation

Example MRED Successes

- Identified nuclear reactions from heavy ions as the rate dominating effect on the Quantum 4MBIT SRAM aboard the MESSENGER spacecraft
  - Chord length distribution models not adequate in all cases
- Able to model multi-node SEU phenomena in DICE latches & FF – accurately reproduce experimental data and provide SEU rate prediction
  - Not possible with single volume model
- Demonstrated that single response models are portable across environment types (one model, multiple environments)

Technical Updates

- Status of physics model validation – comparison of nuclear breakup model prediction to published data
  - Mohammad Sabra (post doc)
- MBU multiplicity as a function of incident n/p energy and experimental validation of enhanced energy deposition due to the presence of tungsten
  - Michael Clemens (Ph.D. candidate
- Sensitive volume models for single event latchup SEU rate prediction
  - Nathaniel Dodds (Ph.D. candidate)
- Modeling displacement damage effects using MRED
  - Elizabeth Auden (Ph.D. student)
- Examining dose enhancement in hi-Z capacitors using MRED
  - Aritra Dasgupta (Ph.D. candidate)
- MRED and Modelsim integration
  - Dolores Black (Ph.D. candidate)
- CRÈME MC status

Status of Physics Model Validation – Comparison of Nuclear Breakup Model Prediction to Published Data

DTRA 6.1 & NEPP Support

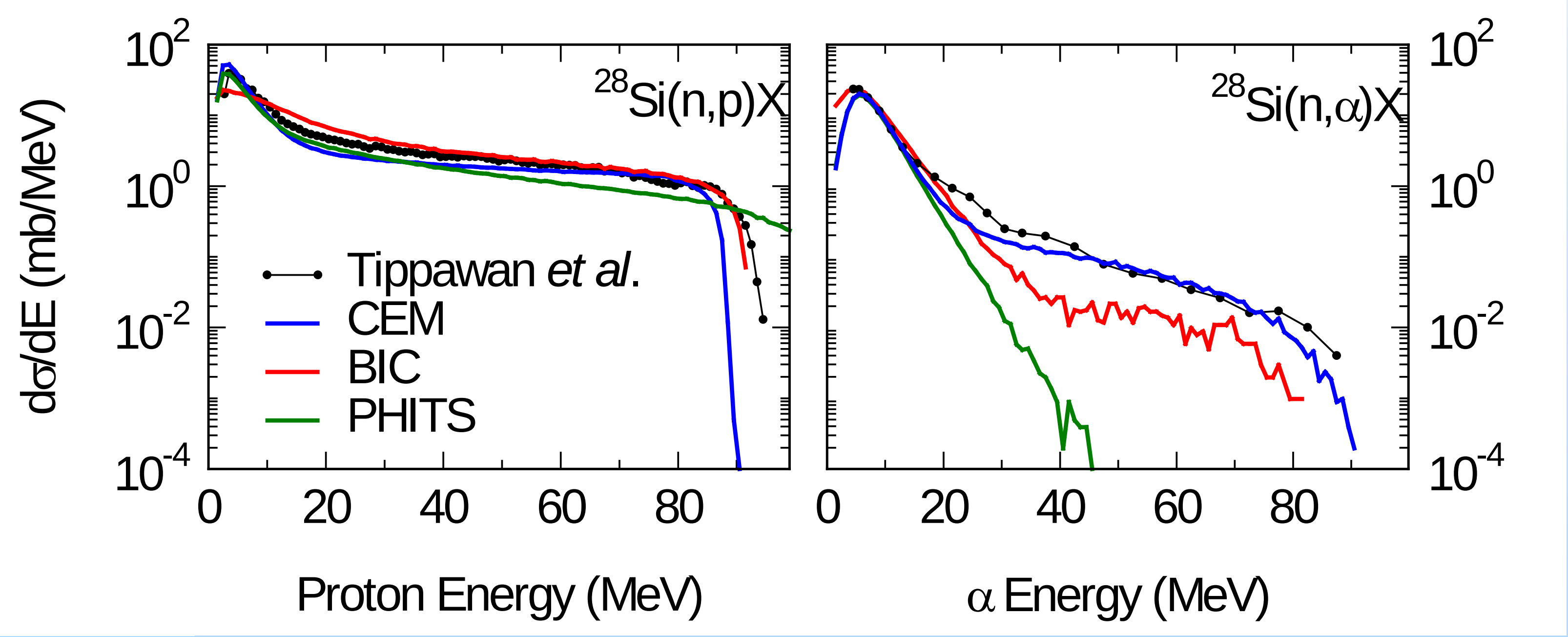
Mohammad Sabra

Nuclear Physics Models: Simulations and Analysis

- **Simulation codes based on nuclear physics models are essential tools in design and study of radiation effects in microelectronic devices.**
- **The accuracy of these codes is evaluated by their ability to reproduce the measured cross sections of target fragments, including energy spectra, and angular distributions.**
- **It is critical to test and improve the codes of interest like Cascade Exciton Model (CEM), Binary Cascade Model (BIC), Bertini-INC, PHITS, and Liège intra-nuclear Cascade coupled with Ablation Model (INCL-ABLA).**
- **Tested Simulation codes are implemented within MRED.**

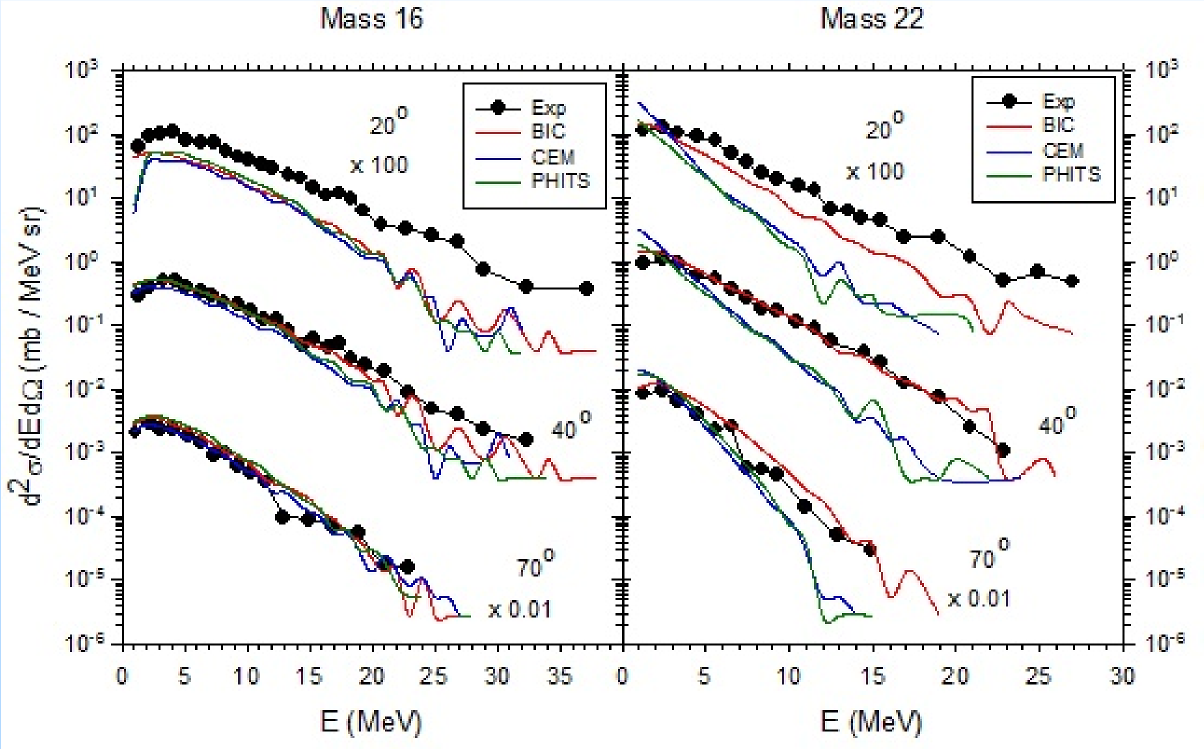
96MeV neutron + ^{28}Si reaction

- Figure shows experimental angle-integrated energy spectra of protos(left) and alpha particles (right) produced from 96 MeV n + 28Si, compared with the calculations of CEM, BIC and PHITS codes.
- For proton spectra, both CEM and BIC are in good agreement with the data, but PHITS overestimates protons with higher energies.
- For alpha spectra, CEM fits the data well, but BIC and PHITS underestimate the data for E > 20MeV.



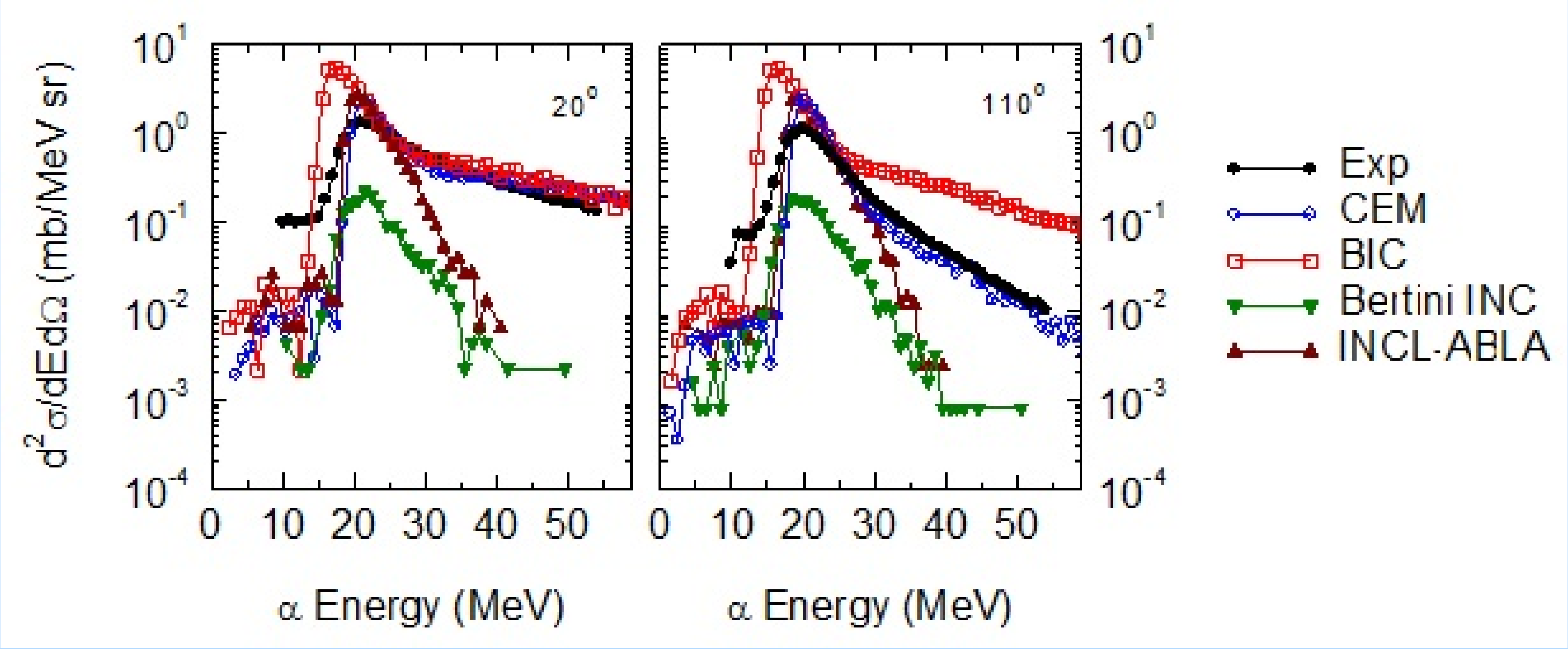
180MeV proton + ^{27}Al reaction

- **Figure shows the energy spectra of masses 16 (left) and 22 (right) produced from 180MeV p + ^{27}Al at 20º, 40º, and 70º, compared with the calculations of CEM, BIC and PHITS codes.**
- **For mass 16, the models are relatively in good agreement with the data, especially for angles greater than 20º.**
- **For mass 22, BIC fits the data relatively well, but CEM and PHITS underestimate them especially for 20º and 40º.**



200MeV proton + ^{197}Au reaction

- **Figure shows the energy spectra of masses alpha particles at 20º (left) and 110º (right) produced from 200MeV p + ^{197}Au, compared with the calculations of CEM, BIC, Bertini INC, and INCL-ABLA.**
- **At both angles, CEM shows a very good agreement with the data especially for E > 20MeV, but BIC overestimates them at backward angles.**
- **Both Bertini INC and INCL-ABLA fail to predict the data.**
- **Discrepancies found are attributed to nuclear physics theory behind each model.**



MBU Multiplicity as a Function of Incident n/p Energy
Experimental Validation of Enhanced Energy Deposition Due to the Presence of Tungsten

DTRA 6.1 & NEPP

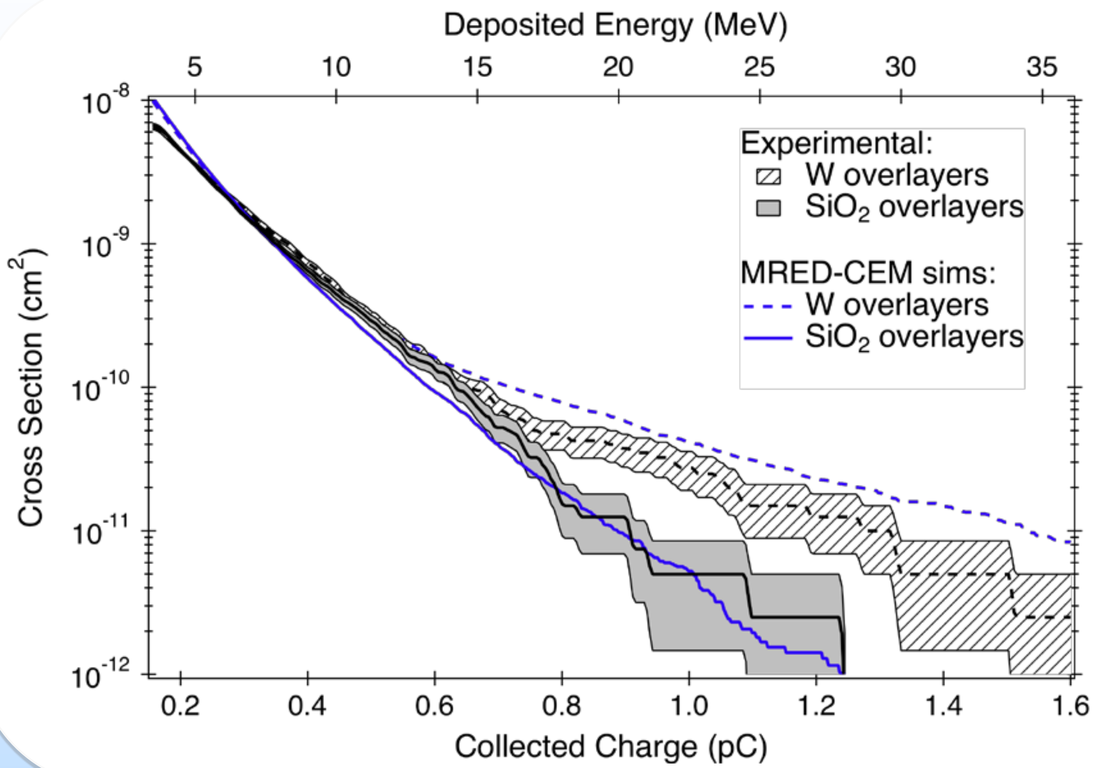
Michael Clemens

Energy and Material Dependence on Multi-bit Upset Probability

- Scope of research is two-fold:
  1) Understand the role that high-Z materials commonly found in modern integrated circuits (ICs) can play in the Multiple-Bit Upset (MBU) response.
  2) Understand how incident proton/neutron energy effects the MBU response of a device.

- Approach is both simulation (MRED) and experimental based.
  – MRED's nuclear physics models are validated with experimental charge collection data.
  – Nested sensitive volume model is used to simulate a 65 nm SRAM to investigate MBU effects using MRED.

Validation of Physics Models in MRED

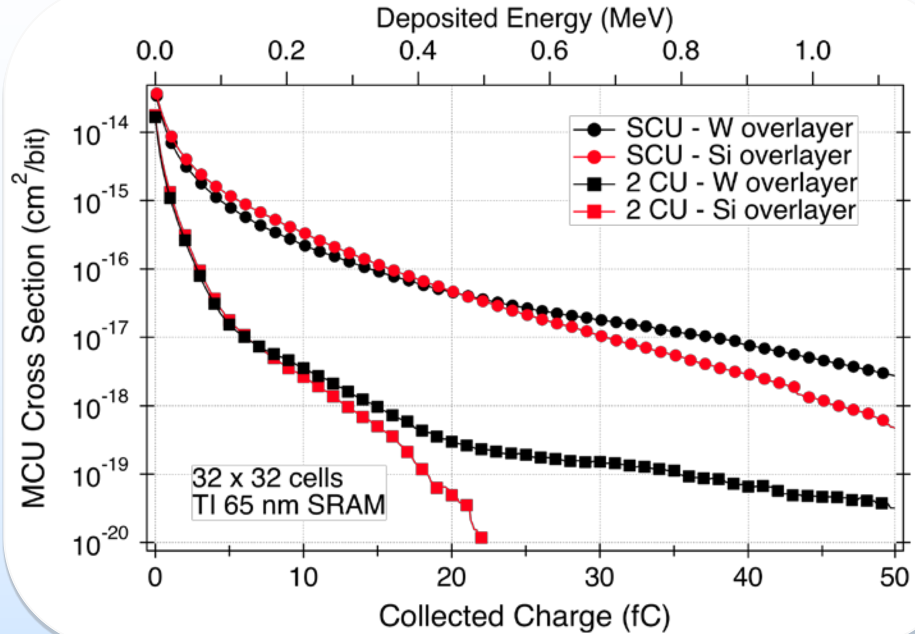


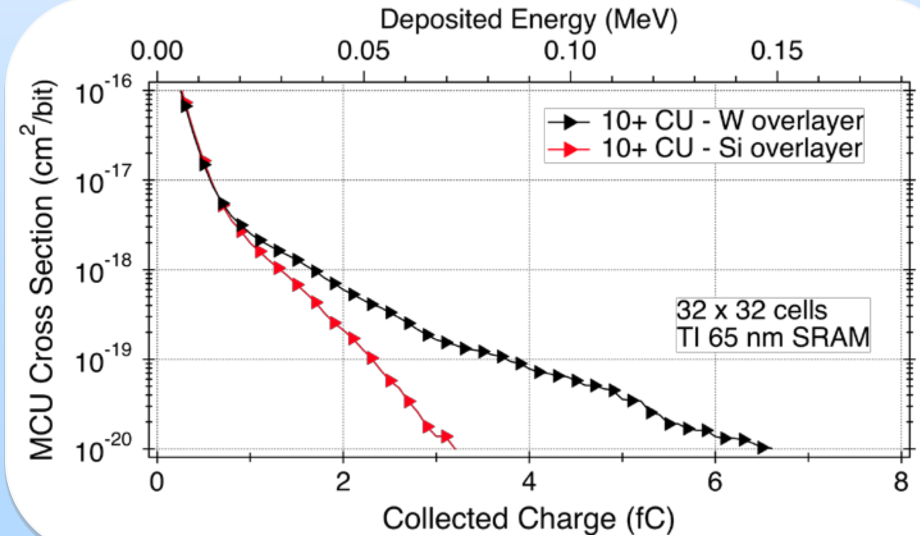
- A comparison between MRED simulations and experimental charge collection data on devices which have tungsten (W) overlayers and SiO_2 overlayers shows good agreement, validating the physics models.
- The over-prediction by MRED for devices with W is due partially to experimental uncertainties.

Effect of Tungsten on MBU/MCU

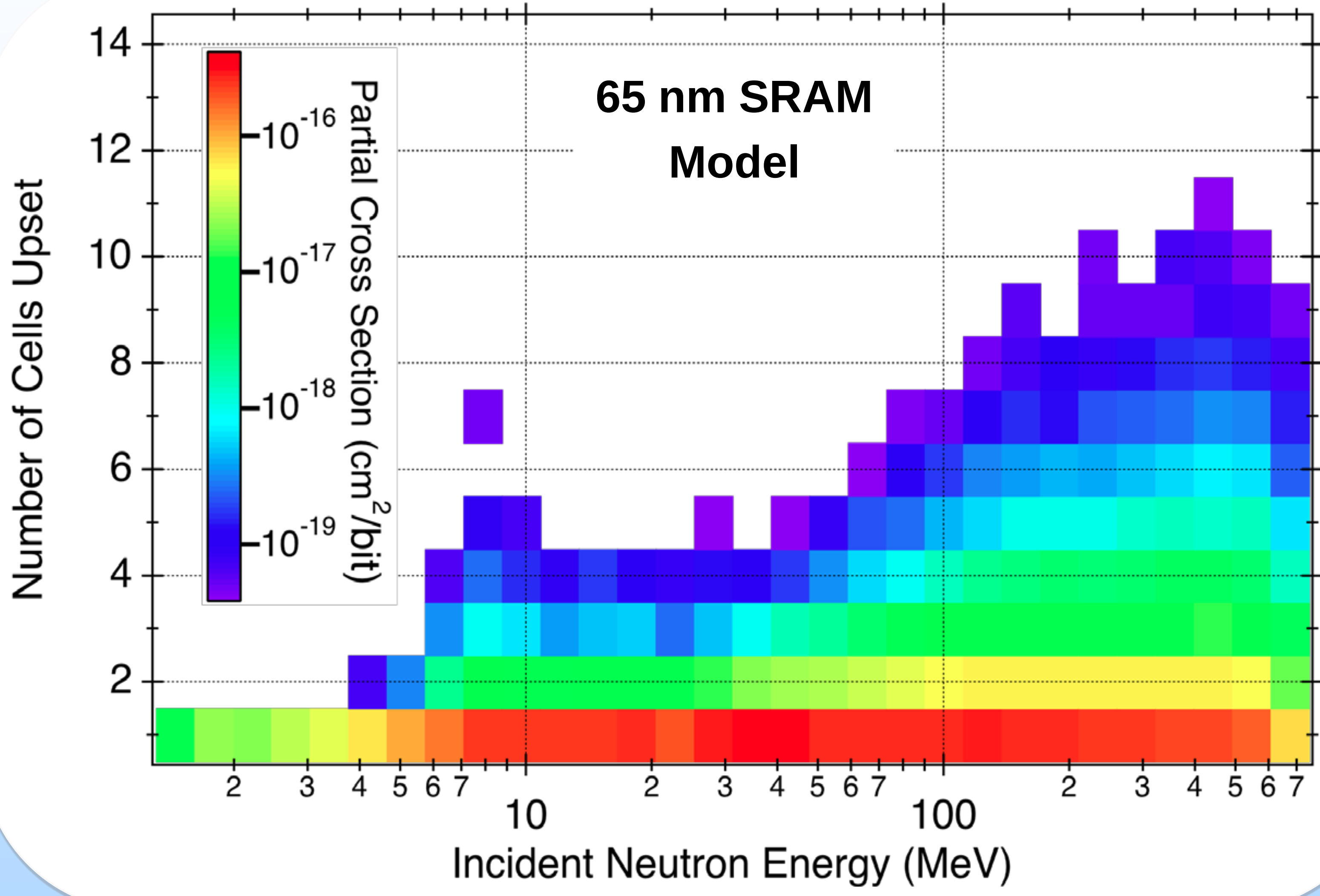
- The effect that the presence of tungsten (W) has on MBU probability is investigated for proton and neutron environments with a wide range of particle energies.

- The presence of W can cause the Single Cell Upset (SCU) probability to increase slightly for high-Q_{crit} devices, and can have a very significant effect on the Multiple Cell Upset (MCU) probability, even for lower Q_{crit} devices.





Effect of Particle Energy on MCU



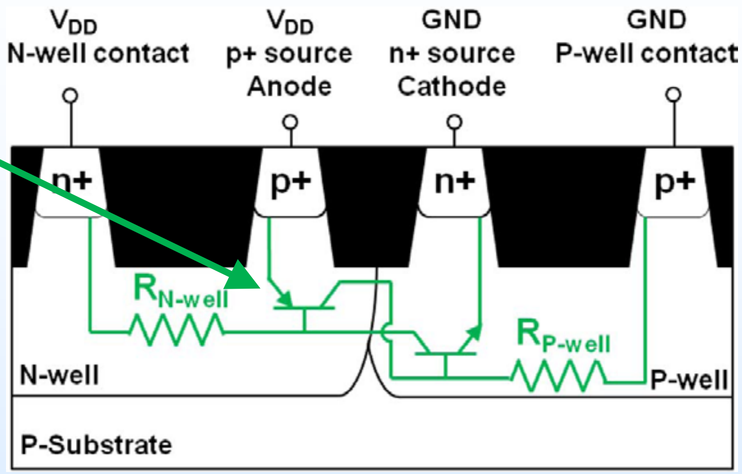
Sensitive Volume Models for Single Event Latchup (SEL) Rate Prediction

NEPP

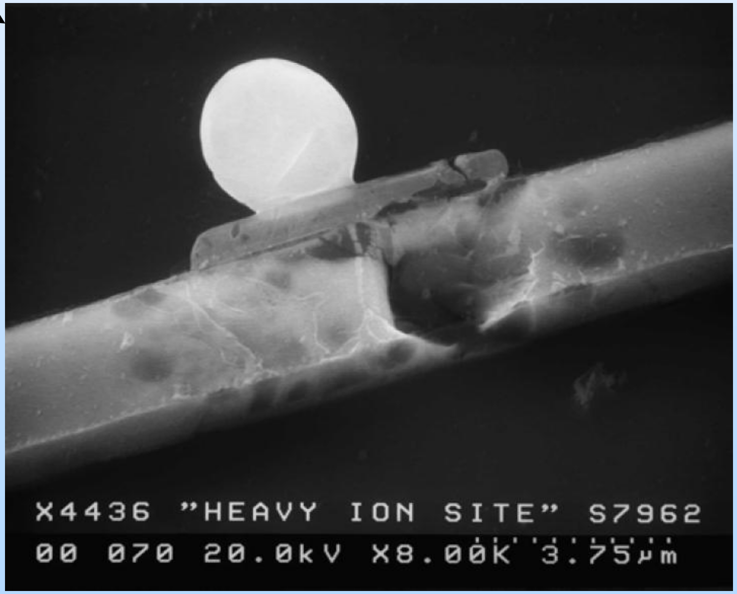
Nathaniel Dodds

SEL rate prediction

- Charged particles can activate parasitic thyristors in CMOS circuits. Known as single event latchup (SEL).



- SEL causes large currents to flow that can damage metal interconnects.

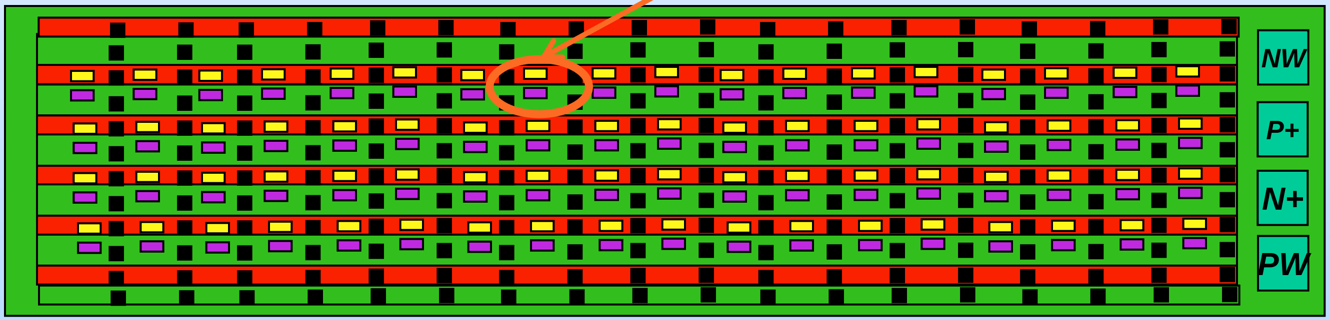


Miyahira et al., TNS 2001

- Methods exist to accurately predict on-orbit SEU rates but not SEL rates.
- Goal: Advance the state of SEL rate prediction by accurately predicting SEL cross sections for simple test structures with known geometries. Model will be valid over a large range of LETs and angles at a single temperature.
  - Nathaniel Dodds, EE PhD student

Experimental approach

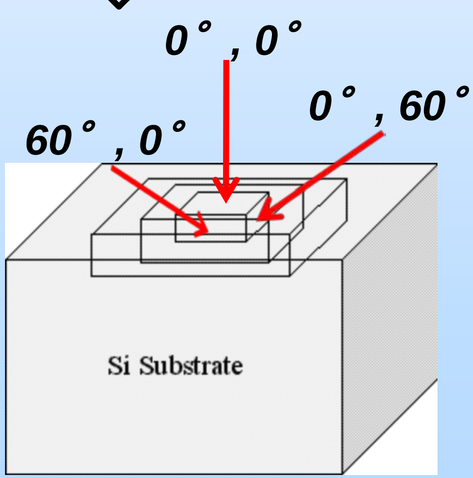
- **Previous studies had little success when applying RPP rate prediction methods to SEL, in part because they used complex circuits with many dissimilar latchup paths and had little knowledge of the layout**
  - **[P. McNulty *et al.*, TNS Dec 1993] , [J. Levinson *et al.*, *Appl. Phys. Lett.,* 1993], [E. Normand *et al.*, NSREC REDW 1995]**
- **Test structures for this study**
  - **Are being fabbed in the Jazz 180 nm bulk 1.8V/3.3V CMOS technology and will be received in Sept 2011**
  - **Are 1 mm^2 arrays composed of thousands of identical thyristors having the same SEL susceptibility. Four arrays were designed with different layout properties.**

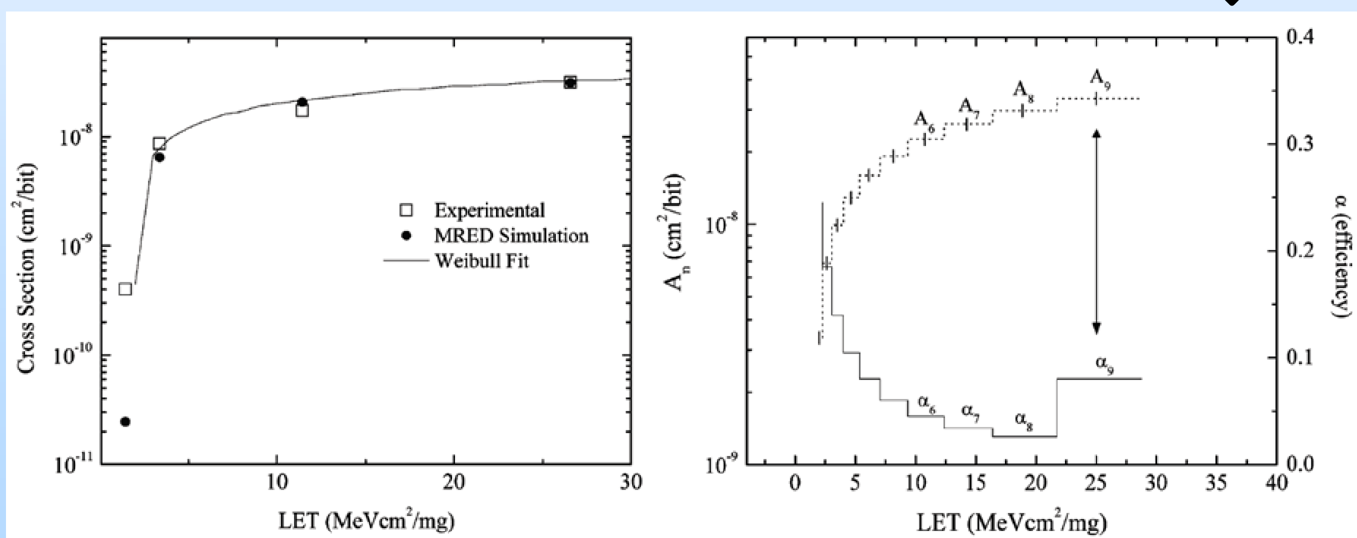


- **Heavy ion tests planned for Dec 2011 at LBNL. SEL cross section vs. LET will be characterized for various rolls and tilts at a single temperature.**

Modeling approach

- MRED will be used to develop an empirical nested sensitive volume model to fit SEL data. Model constrained to be physically accurate by
  - Using known layout and process geometries to make initial guesses at sensitive volume geometries
  - Matching data for irradiations of various ion trajectories. These data allow determination of the areas of the 3 faces of the sensitive volumes.
  - Matching data as a function of LET using nested sensitive volumes of varying charge collection efficiencies as was done in [Warren *et al.*, TNS Dec 2007]





Impact

- **Successful completion of this study will**
  - **Improve SEL rate prediction methods. The ability to predict on-orbit SEL rates may allow the use of COTS parts that are currently rejected by overly conservative parts selection requirements.**
  - **Give insight into the nature of SEL sensitive volumes, which has implications for current hardness assurance and parts selection methods.**

Modeling Displacement Damage Effects Using MRED

DTRA 6.1 & NEPP

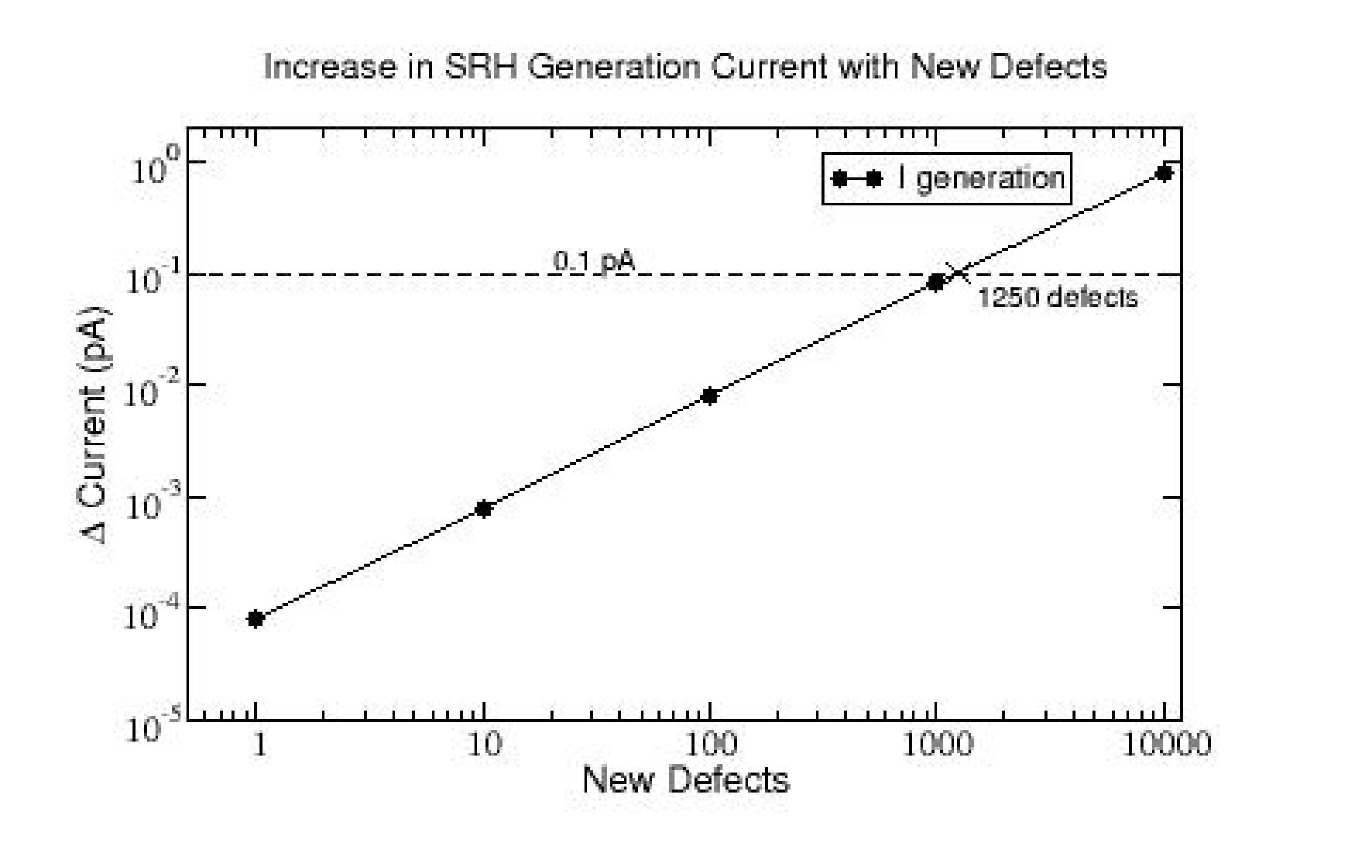
Elizabeth Auden

Single Event Displacement Damage

- **SEDD: one radiation particle displaces enough atoms to degrade or destroy a semiconductor device.**
- **SEDD creates dark current variation in CCD pixels. As device sizes shrink, SEDD will affect diode and transistor operation on satellite instruments.**
  - **Diodes: increased leakage current**
  - **DRAMS: loss of charge**
  - **Transistors: disrupted channel mobility**
- **Elizabeth Auden, 3rd year PhD student. Research: investigation of SEDD in diodes and transistors.**

Leakage Current Increase with Defects

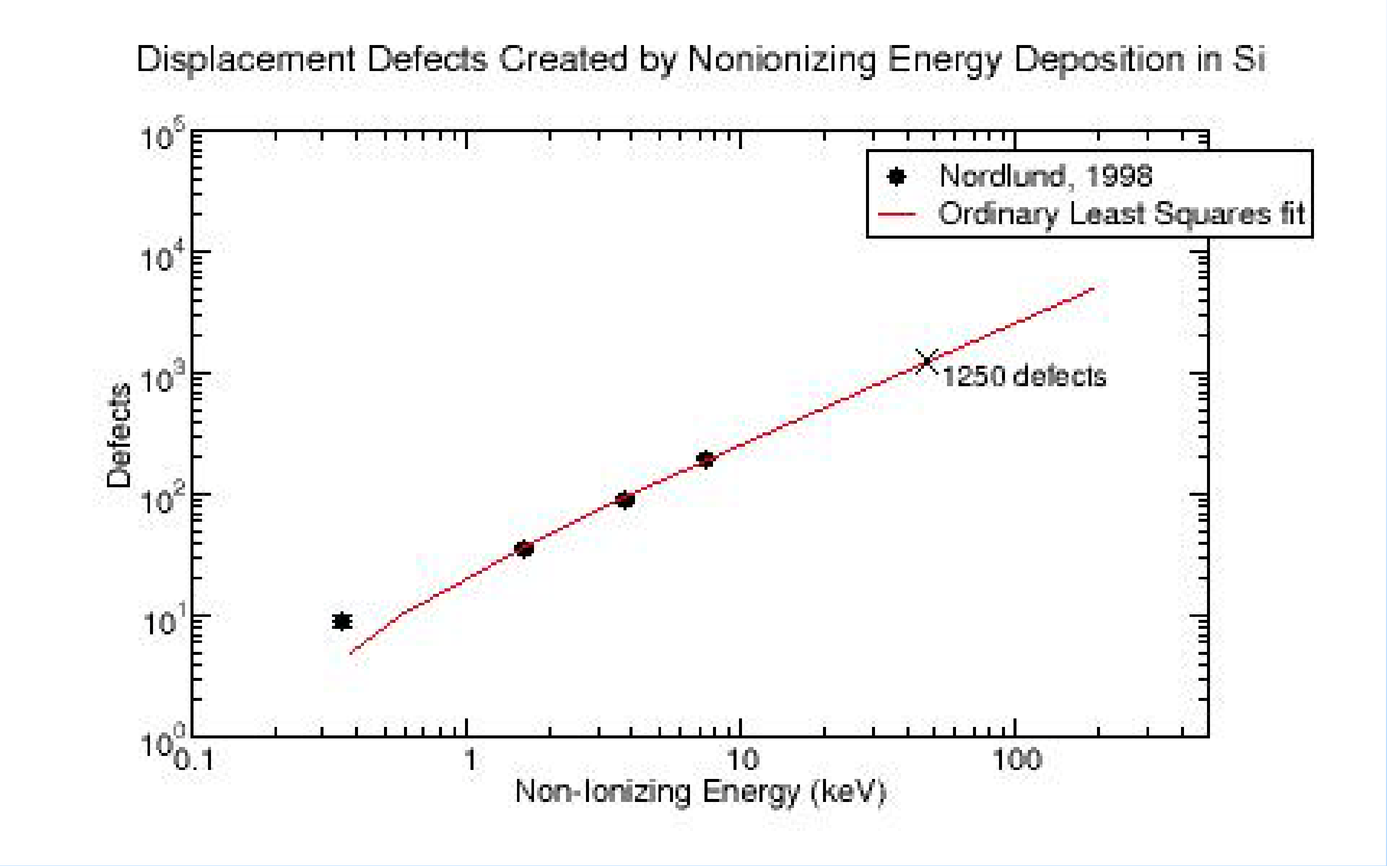
Displacement defects increase SRH generation current inside a pn-junction's depletion region [1]. 1250 defects increase leakage current by 0.1 pA.



[1] Muller, Kamins & Chan, *Device Electronics for Integrated Circuits*, 3rd Ed,, 2003

Defects and Nonionizing Energy

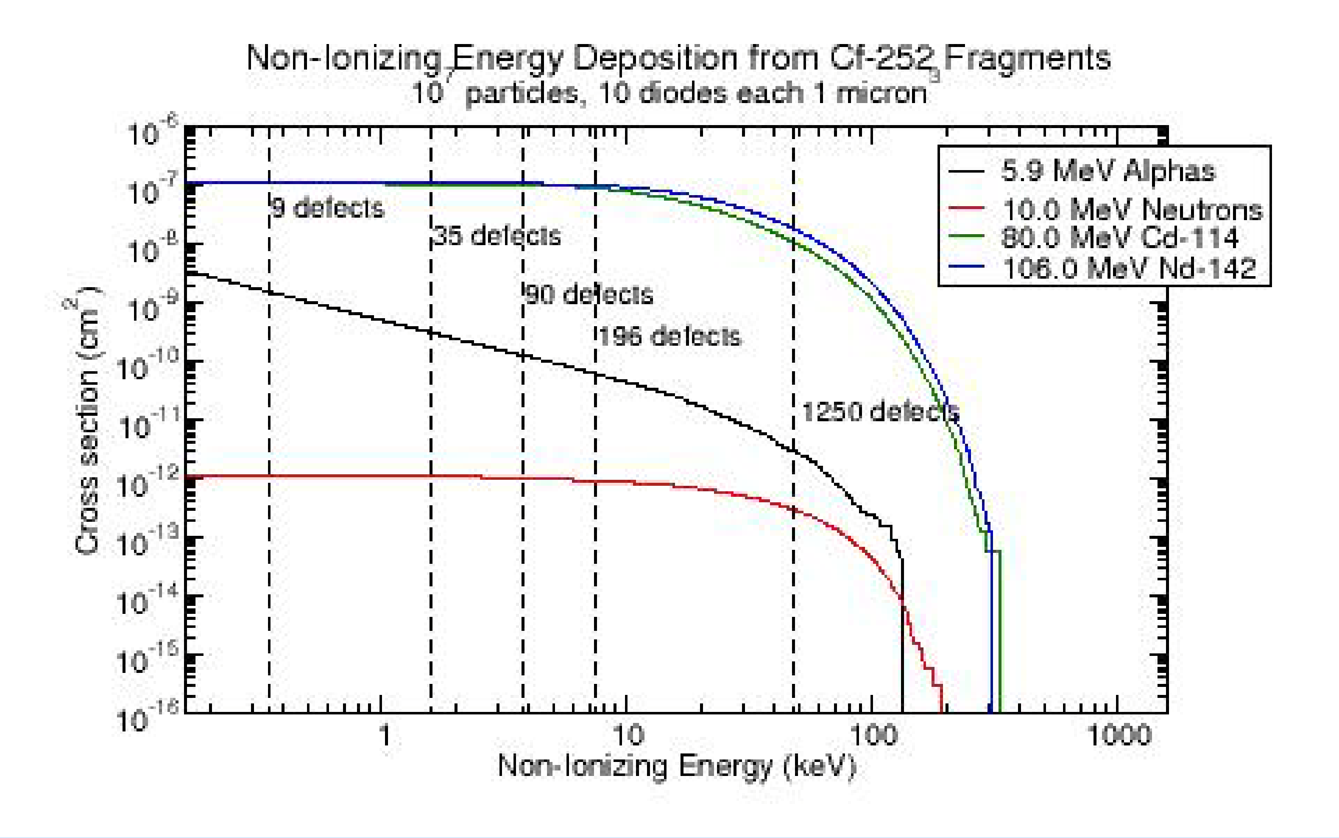
Nordlund et al. use molecular dynamics simulations to determine the number of stable defects resulting from non-ionizing energy deposition in Si [2].

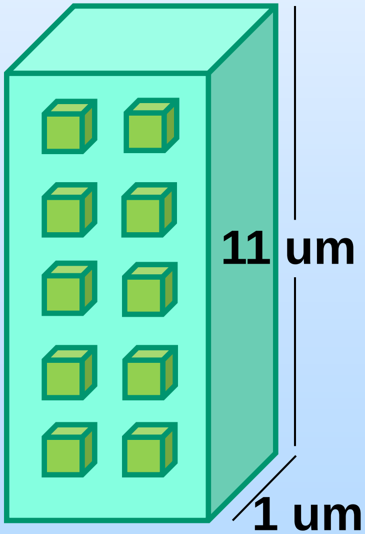


[2] Nordlund et al., *Phys. Rev. B* 57, 1998

MRED & Nonionizing Energy Deposition

MRED can be used to predict how much nonionizing energy individual particles can deposit for a given device and radiation source (in this case, Cf-252) [3].

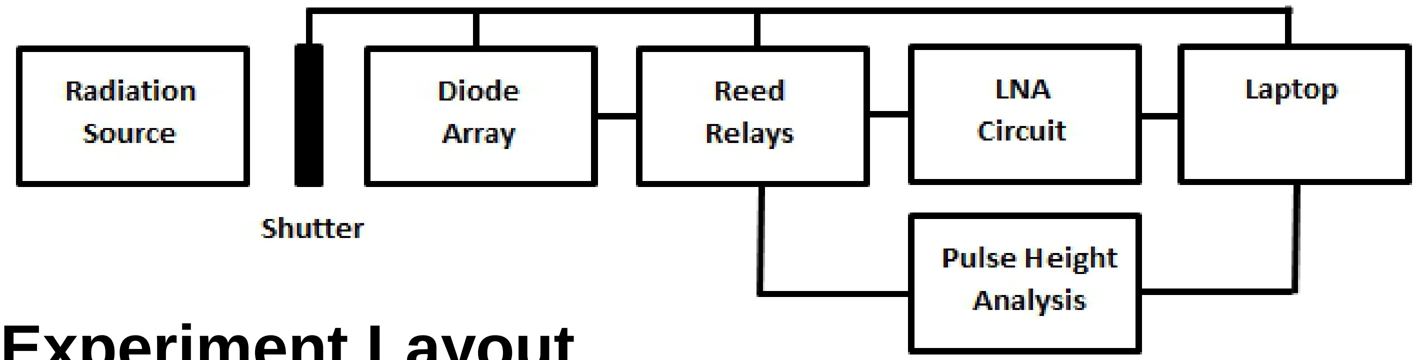




Simulated Si Structure

[3] Weller, Mendenhall & Fleetwood, *TNS* 51, 2004

Measuring SEDD in Diodes



Experiment Layout

– Irradiate an array of reverse-biased diodes with Cf-252.
– Stop irradiation when pulse height analysis detects particle strike.
– Identify any diode whose leakage current has increased by at least 0.1 pA compared to its previous value as well as its nearest neighbors' leakage current values.
– Use MRED to predict the number of particles capable of depositing enough nonionizing energy to increase leakage current by 0.1 pA, the LNA circuit's resolution.

Dose Enhancement and Reduction in SiO_2 and high-κ MOS Insulators

DTRA 6.1 & NEPP

Aritra Dasgupta

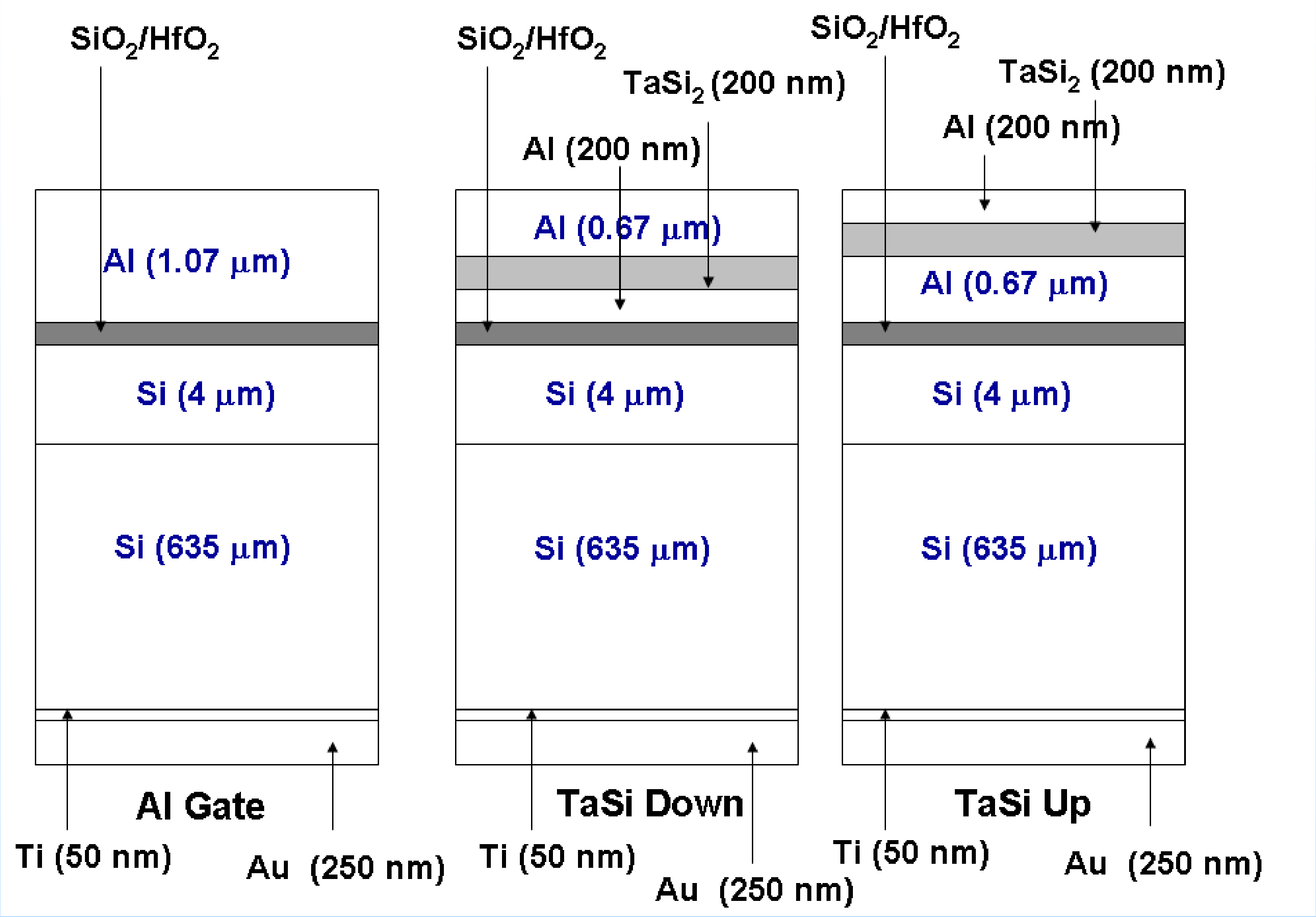
Motivation

- In semiconductor devices, high atomic number (high-Z) materials can occur in
- A) the chip metallization (W vias etc.)
- B) the device package (Gold)

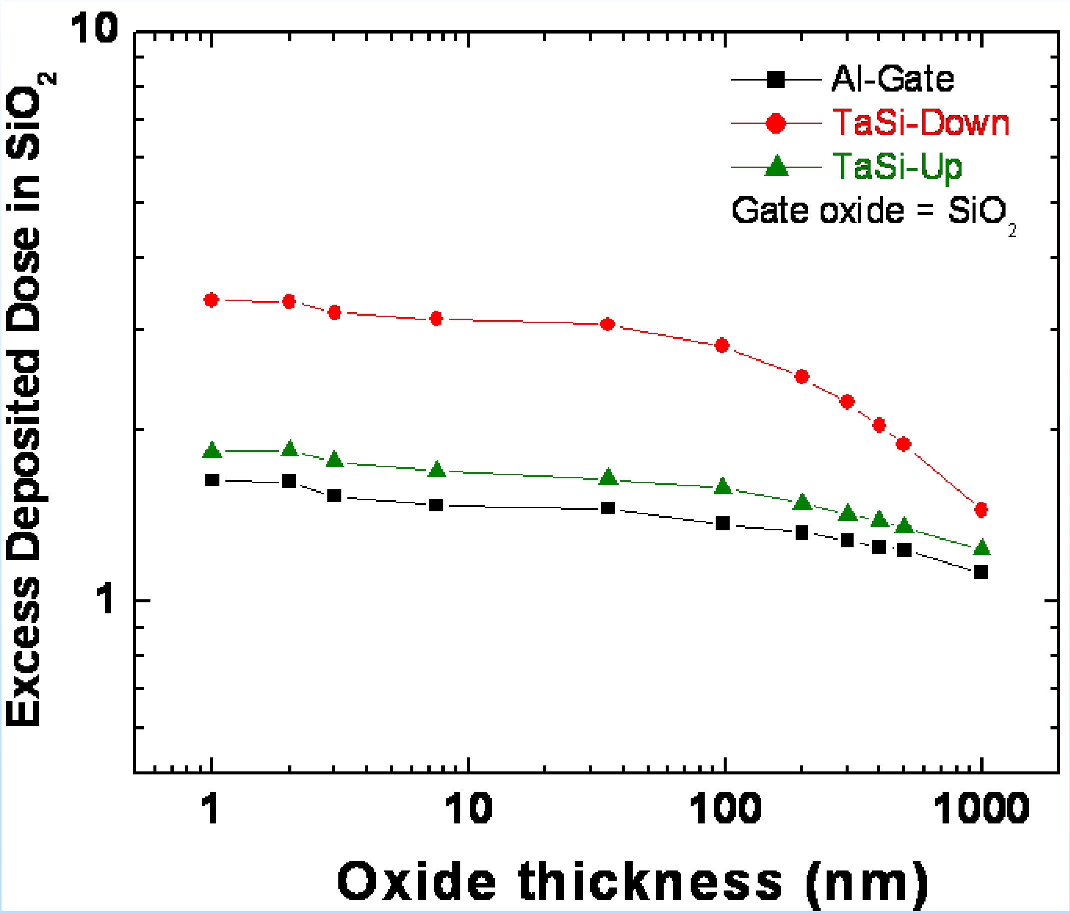
- Significant dose enhancement can occur in space employed devices & parts at the critical device regions (e.g. gate oxides) due to interaction of high-Z materials with ionizing radiation.

- We benchmarked our MRED simulations to experimental work on high-Z gate metallization in SiO2 based devices.

Simulated MOS devices



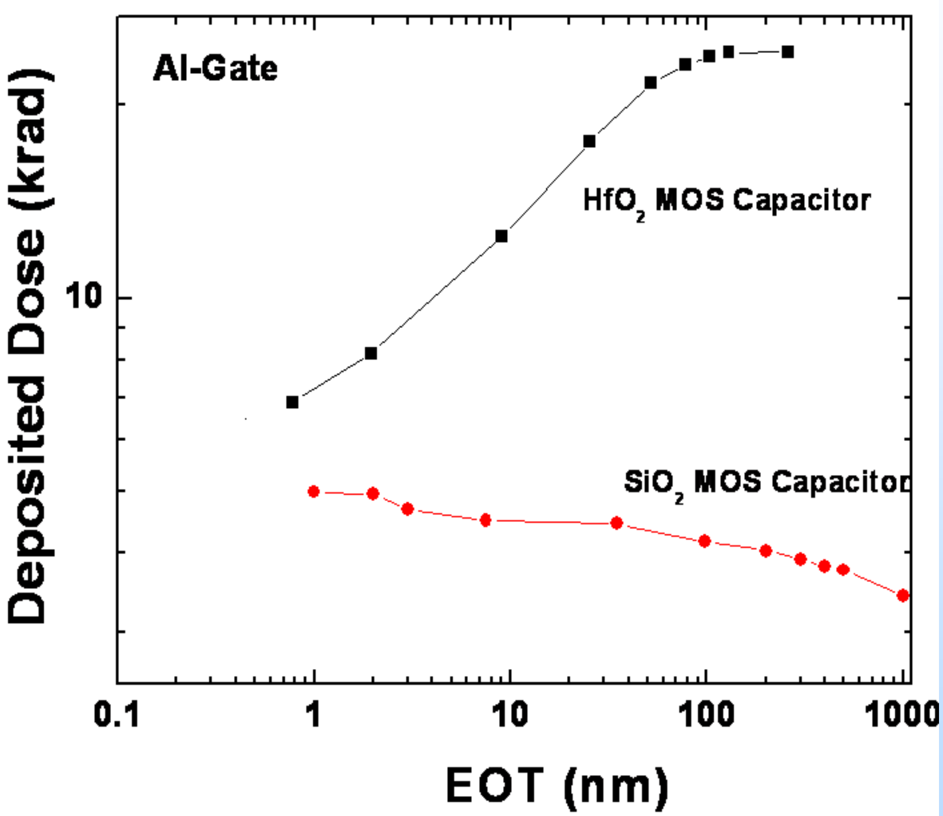
Effect of TaSi2 gate on SiO2 capacitors



- Excess dose is calculated relative to block of pure SiO_2 of same thickness to capacitor structure

- The enhanced dose depends strongly dependent on the position of $TaSi_2$ layer with respect to gate oxide.

Deposited Dose vs. EOT



- We further studied high-k MOS devices (Hf-based) used in modern deep-submicron technologies.
- Deposited dose decreases as gate oxide physical thickness t_{phys} is scaled down. This is opposite of dose enhancement in SiO_2 based devices.
- At EOT ~ 1-2 nm, deposited dose is higher in HfO_2 than in SiO_2.

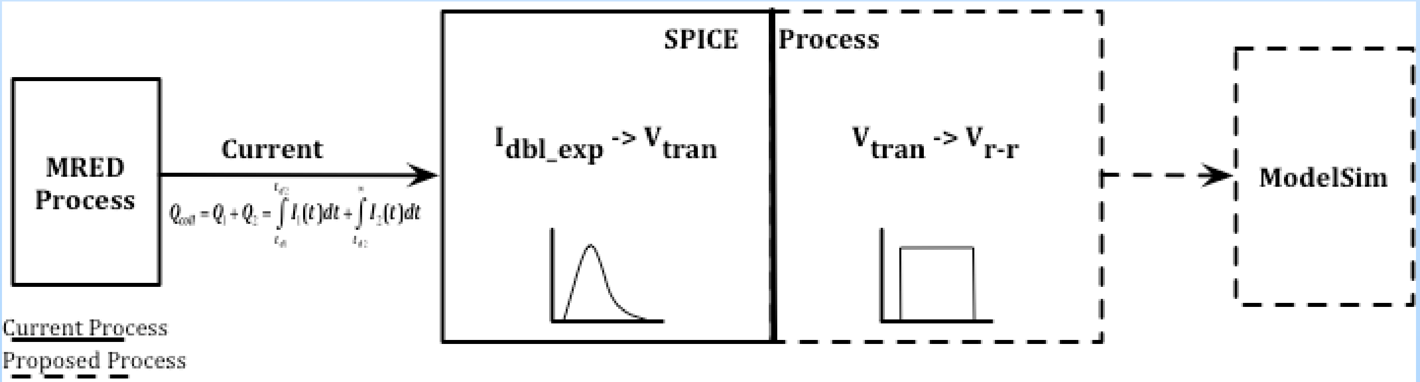
MRED and Modelsim Integration

NEPP

Dolores Black

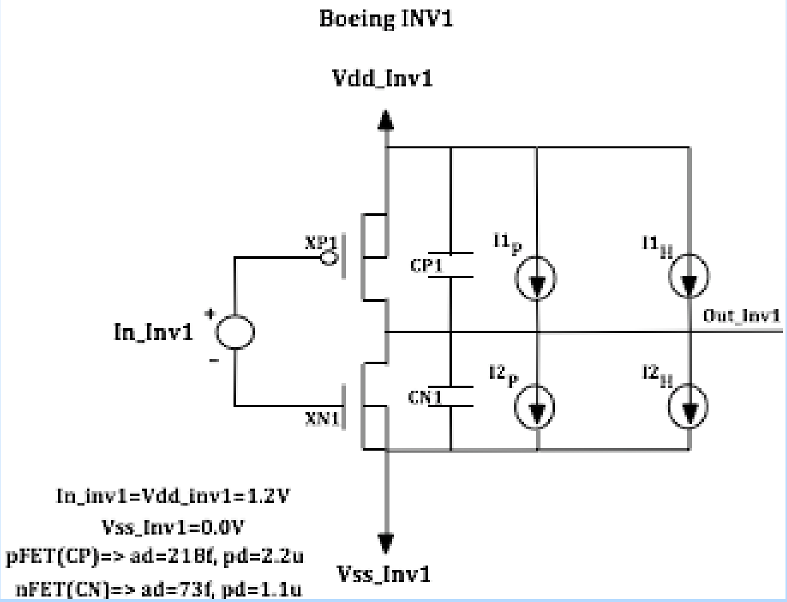
Direct Ionization-Induced Transient Faults in Complex Digital ICs

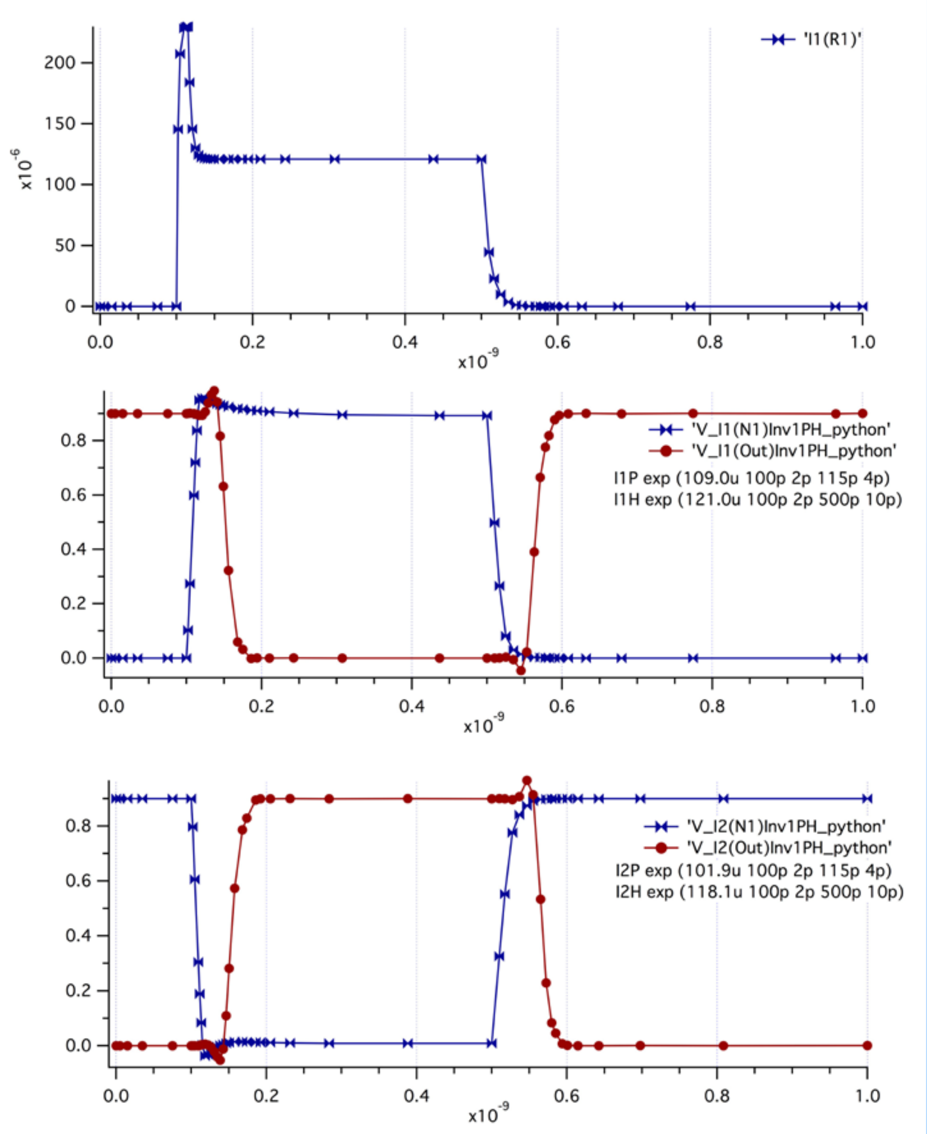
- **The proposed work will lead to an understanding of appropriate techniques to model Single Event Transient (SET) generations, propagation and capture from energy deposition to IC response for the direct ionization caused by particles that have a linear energy transfer less than 2 MeV-cm2/mg.**
  - **Expand the MRED-Based Rate Prediction to Include Errors Observed at an Integrated Circuit (IC)**
    - **MRED has been coupled to SPICE for SEUs**
    - **MRED-based rate prediction of sequential cells/memory**
    - **MRED2SPICE for SET development is complete**



SET Generation at the Cell Level

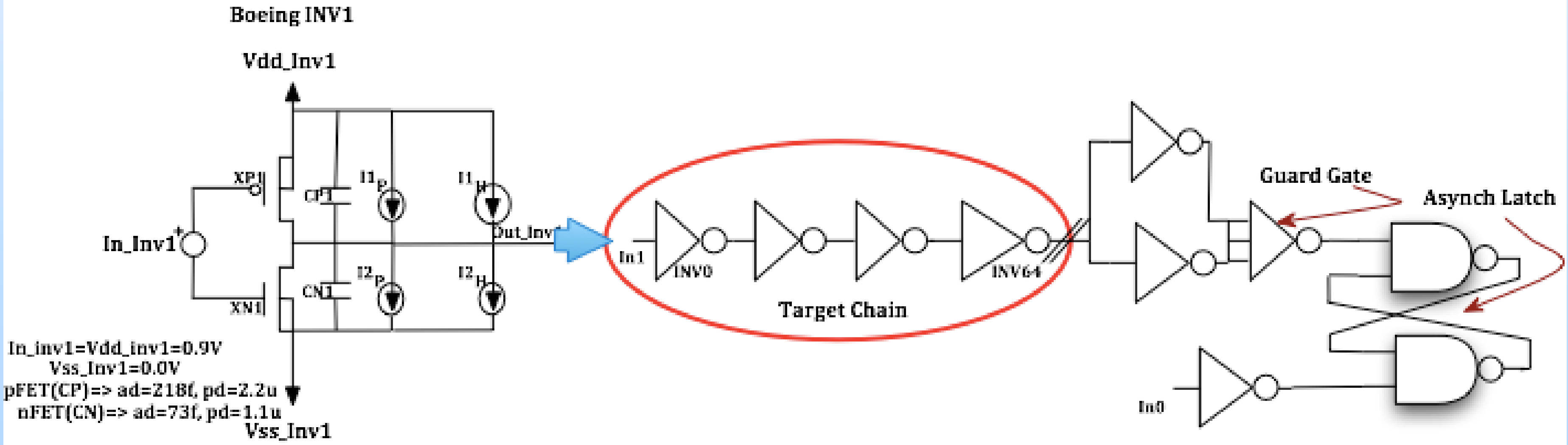
- Model using 2 current sources (Ex: $I_1 = I_{1P} + I_{1H}$)
  - One for "prompt" => enough to get to "rail"
  - one for "hold" => enough to keep node at "rail"





SET Tool Flow Development

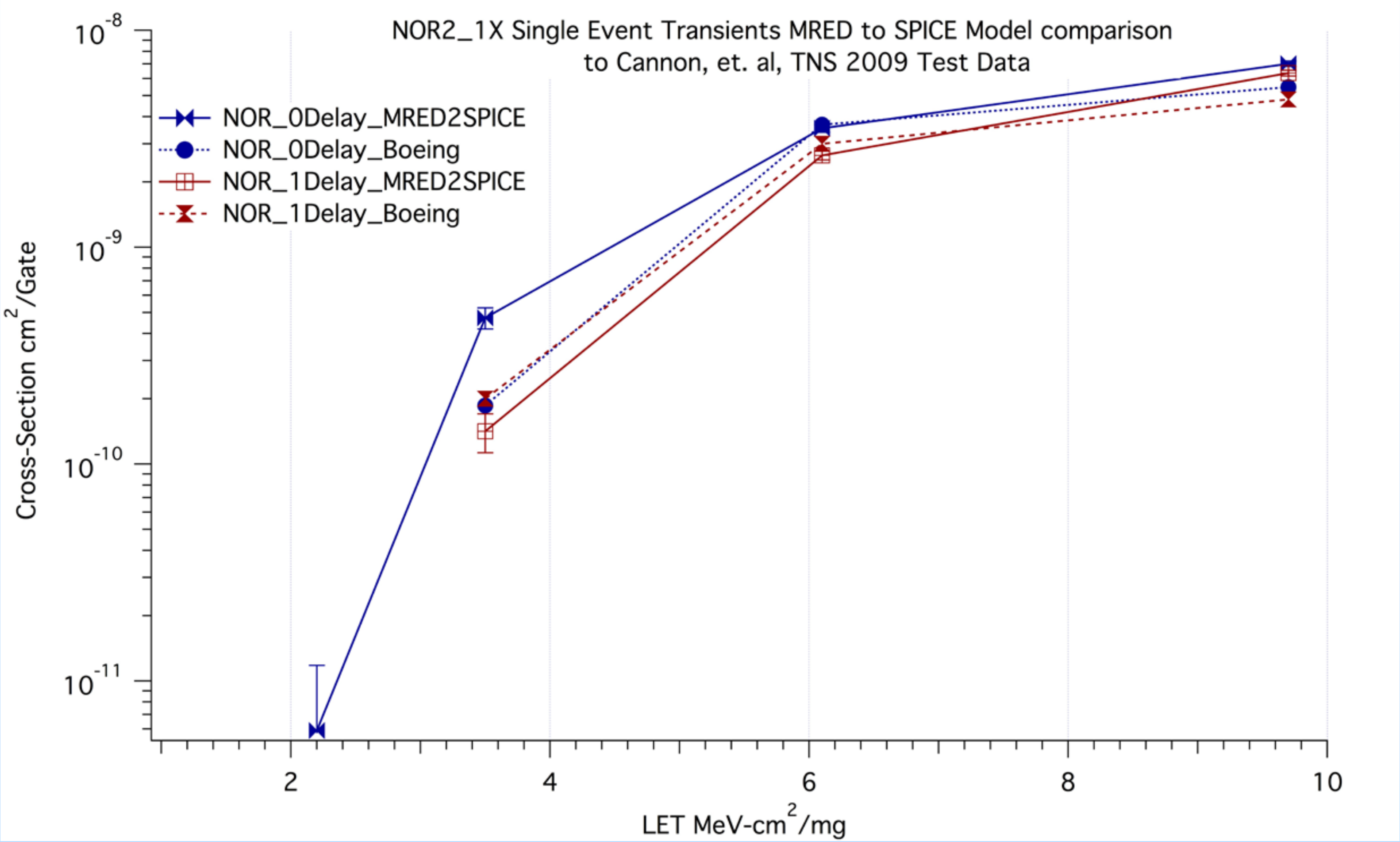
- **Test design for development of tool implementation**
  - **Target chain of 65 INV1s/NAND2s/NOR2s**
  - **Followed by a Guard Gate and Asynchronous Latch**
    - **Mimics Cannon, et al., TNS 2009**
- **Model circuit in Spice and compare to data**



SET Tool Flow Development

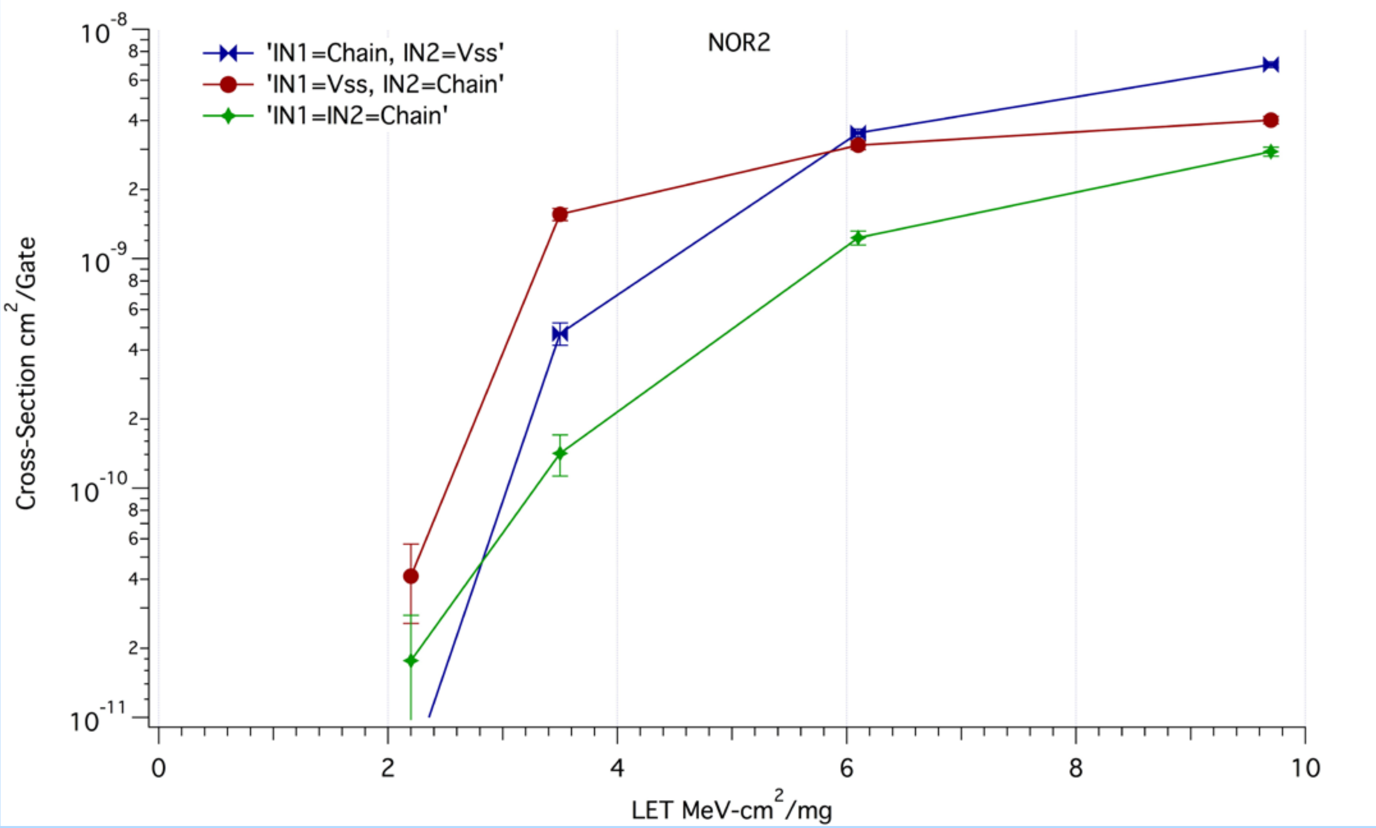
- Thorough simulation of SEEs requires techniques that describe the physical processes at different levels of abstraction. For example, soft error simulation should include such items as:
  - (1) energy deposition in semiconductor process materials
  - (2) the conversion of energy into charge
  - (3) the transistor-level response resulting from incident radiation
  - (4) the circuit response that includes radiation-induced transients.
- The MRED to SPICE Model (MRED2SPICE) takes into account these items and was compared to data taken by Cannon, et al., TNS 2009

SET Tool Flow Development – Results



SET Tool Flow Development – Results

- **The model's design also allows one to predict the SET response for a logic cell and its different input configurations.**
  - **IN1=Chain, IN2=Vss (v1)**
  - **IN1=Vss, IN2=Chain (v2)**
  - **IN1=IN2=Chain (v3)**



CRÈME MC Update

NASA AAPS

Brian Sierawski

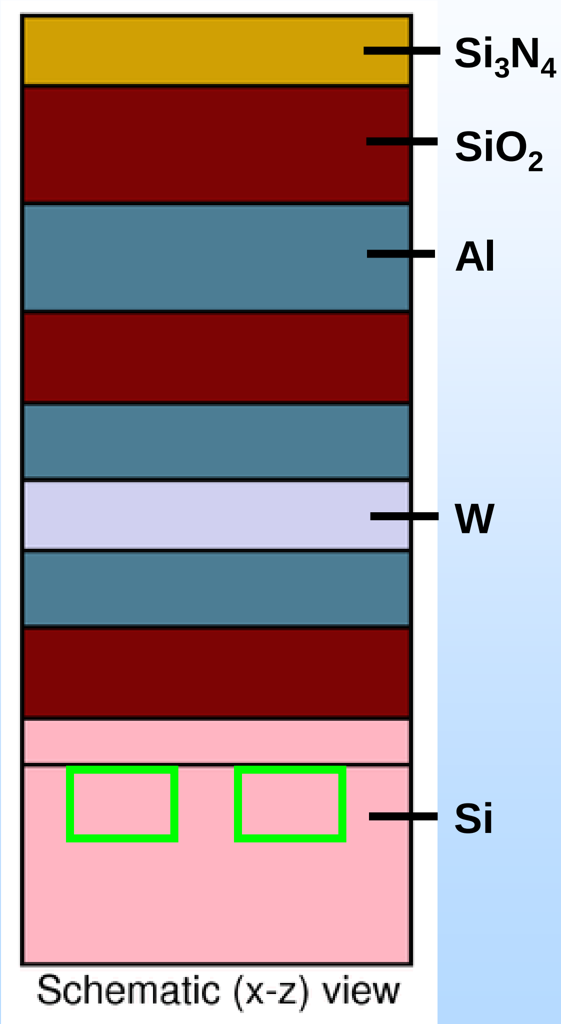
CRÈME

- Cosmic Ray Effects on MicroElectronics codes have been used since early 1980's to predict the effects of ionizing radiation on 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 has become the host for the CRÈME tools [https://creme.isde.vanderbilt.edu]
  - Supporting over 650 user accounts spanning aerospace, government, university entities worldwide
- Extension to include Vanderbilt's Monte Carlo codes began in 2006
- Public release scheduled for the end of June 2011

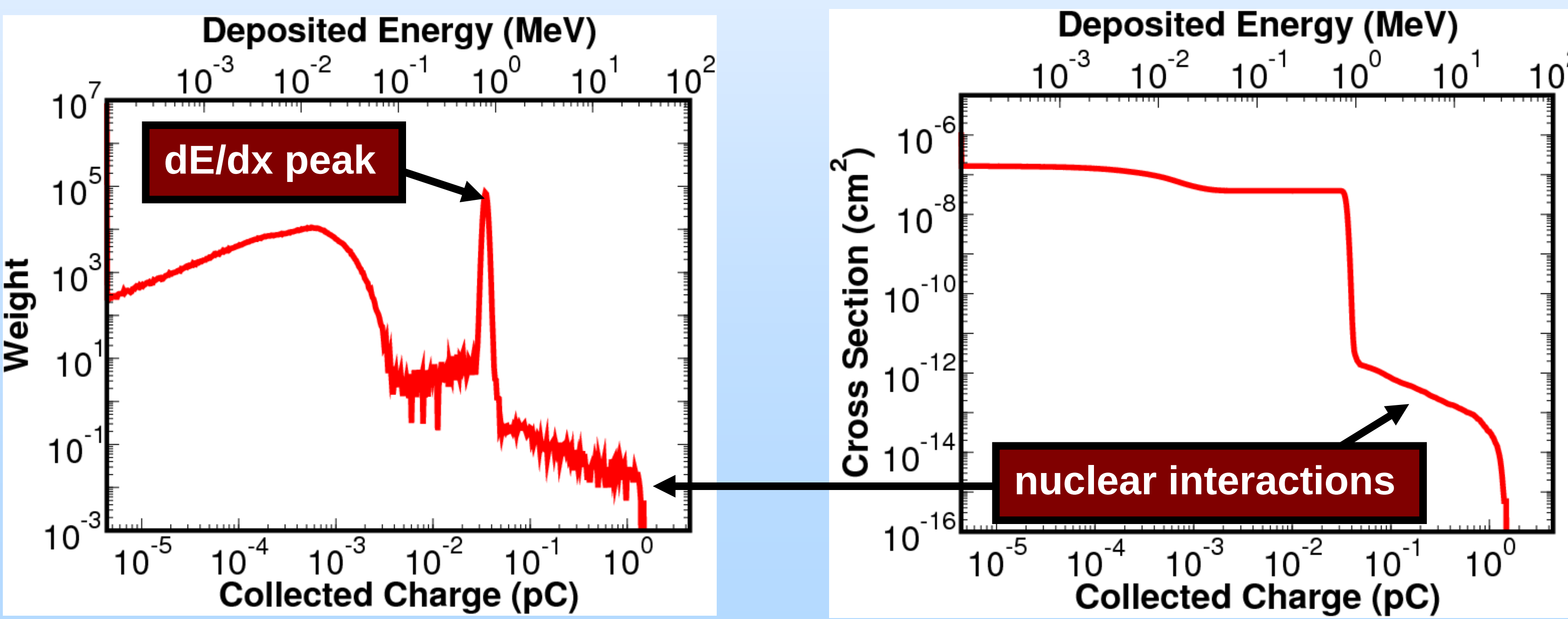
Multilayer Planar Stacks

- Hi-Z materials can influence energy deposition altering SEU rate or total ionizing dose
- Constructor builds three-dimensional multilayer structure
  - Common electronic materials available
- Weighted sensitive volumes relate spatial ionizing energy deposition with charge collected at a circuit node
- Multiple volumes represent class of failures requiring multiple circuit nodes to collect charge
  - Multiple cell upsets, DICE latches, etc
- Volumes may be rectangular parallelepipeds or ellipsoids



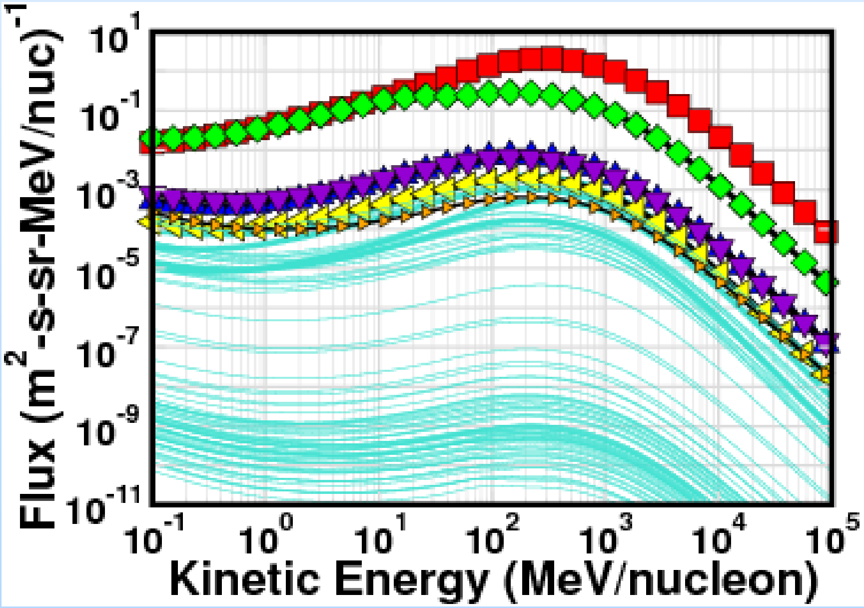
Broadbeam Simulations

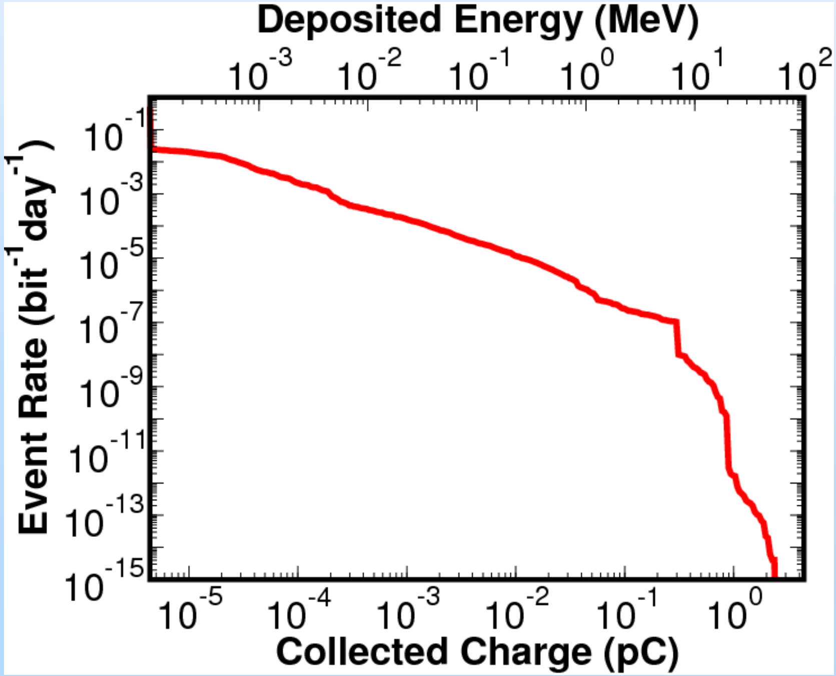
- **Provides Monte Carlo Radiation transport through complex material stacks**
- **Incorporates high-fidelity nuclear physics codes**
- **Allows users to**
  - **calibrate models to experimental data**
  - **evaluate high-angle effects**



Environment Results

- Evaluates direct ionization and nuclear reactions including ions on heavy metals
- Incorporates advanced sigma biasing for improved statistics
- Allows users to compute multiple device error rates





VRT

- Vanderbilt has been approached to develop a distributable version of MRED
  - Sponsored by industry
  - Eliminate or reduce concerns related to IP
- Distributable version is called the Vanderbilt Radiation Transport (VRT) tool
  - Proprietary physics modules removed
  - Otherwise retains full MRED functionality
- Challenges
  - Documentation
  - Example code
  - Educating the customer
  - Maintenance

VRT Status

- VRT v 1.0 has been created
- Creating example problems related to industry interests
  - Multi-node SEU rate prediction
  - Multiple sensitive volume model calibration
  - Integration with external EDA tools
- Expect deliverable version to customer within a calendar year

Conclusions

- MRED validation and verification an on-going process
  - Identifying best physics models for solving problems in the community
- MRED application space extended beyond basic SEU rate prediction
  - Displacement damage
  - Single event latchup
  - Dose enhancement
- CRÈME MC web site running
  - Retains CREME96 models
  - Enhanced with MRED-like features for Monte Carlo simulation
- Distributable version of MRED, VRT near release