Single Event Upset Rate Prediction Methods for Circuit-level Hardened Devices

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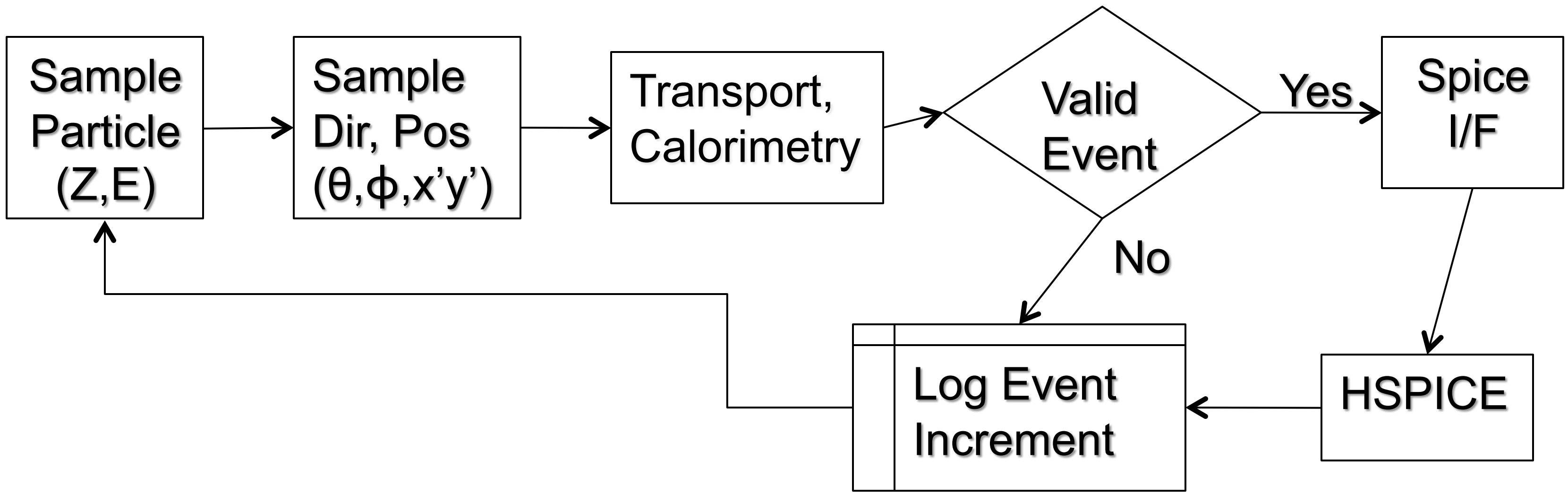
Outline

- Describe the process of using Monte-Carlo Radiative Energy Deposition (MRED) tools to determine single event upset (SEU) rates and mechanisms.
  - Simulation flow
  - Calorimetry
  - Spice Interface
  - Calibration
  - Analyses
  - Conclusions
- Example component – Master-Slave latch
  - Dual Interlocked Cell (DICE) design; 90nm process
  - No static *single-node* SEU mechanisms
  - Cannot use rectangular parallelpiped (RPP) model

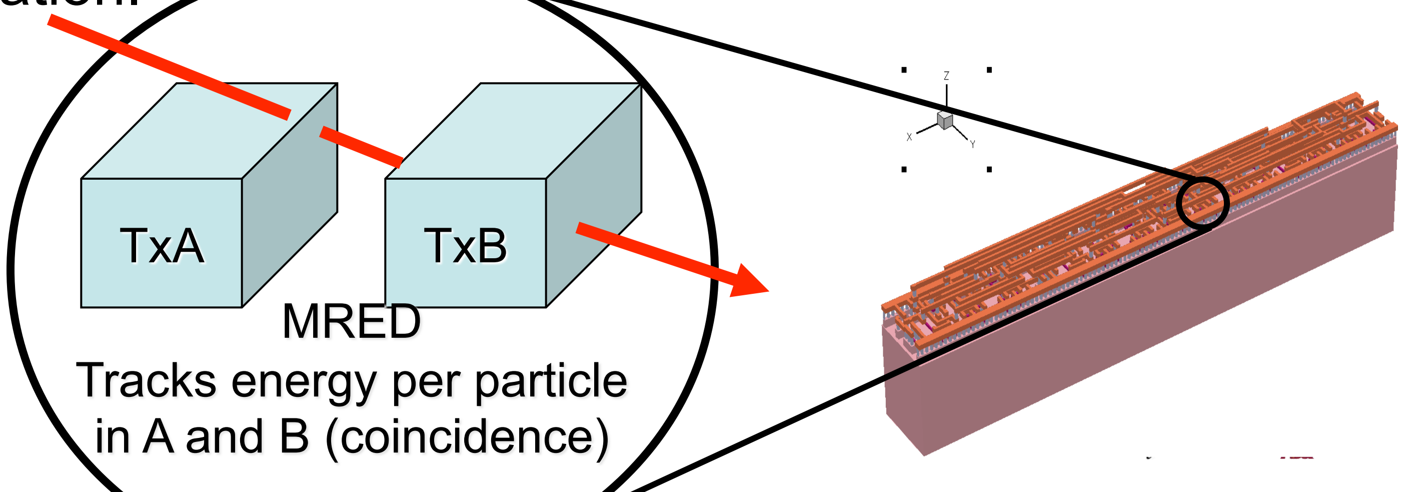
MRED Simulation Flow



- Simplified flow of a particle event in the space environment
  - Particle: Random selection from spectrum (Z,E)
  - Direction: Random plane and position
  - Transport: Move particle through CAD object, track energy deposition
  - If transistors are hit, send to HSPICE
  - Record SEU/no SEU, perform logging, repeat

Transport, Calorimetry, Event Selection

- Track energy deposition in complex solid models using physics models from Geant4, collaborators, and those internally developed.
- Correlate energetic events in regions/sensitive volumes (SV) of the device – Required for simulating multiple-node mechanisms.
- Select only those events that deposit energy in the SV for spice simulation.



Solid model of the
latch structure used in MRED

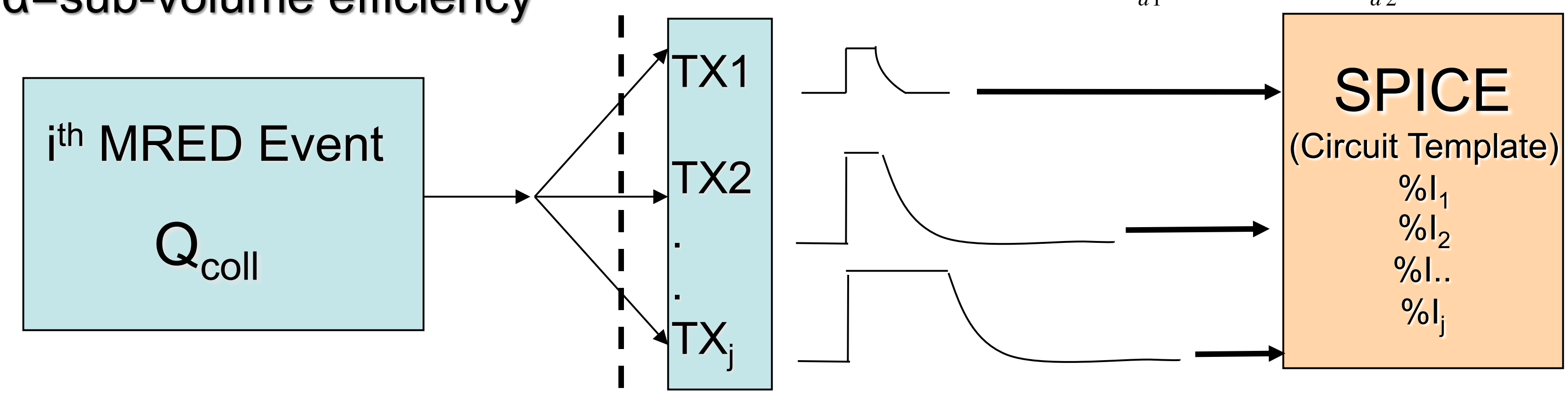
Spice Interface

- After an event, each transistor's Q_{coll} is converted to a double exponential current pulse and directed to the appropriate node.

$$Q_{collected;i,j} = \frac{pC}{22.5\,MeV} \sum_{k=1}^{N_j} \alpha_{k,j} E_{dep;i,j,k}$$

i=event number
j=transistor index
k=sub-volume index
N_j=total volumes for Tx_j
α=sub-volume efficiency

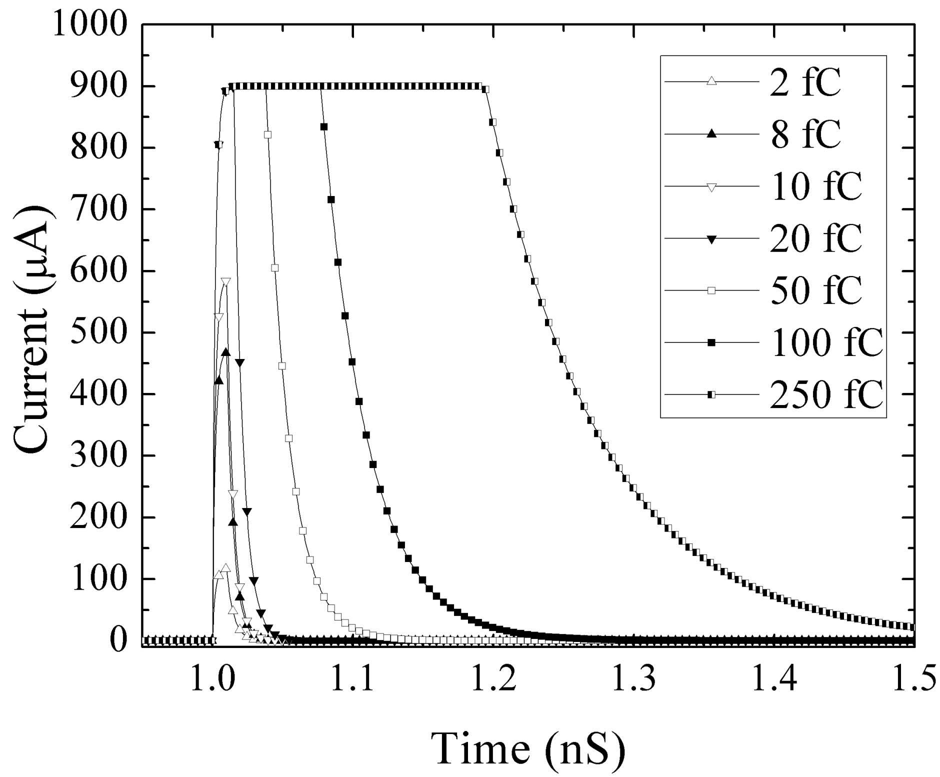
$$Q_{collected;i,j} = Q_1 + Q_2 = \int_{t_{d1}}^{t_{d2}} I_1(t)\,dt + \int_{t_{d2}}^{\infty} I_2(t)\,dt$$



Spice simulation of the i^{th} particle event

Spice Interface: Q_{coll} to Node Current

- Sensitive Volume parameters define relationship between deposited energy and collected charge, Q_{coll}.
- "Small" Q_{coll} (~ < 15 fC)
  - Use fixed time constants and vary peak current, I_m
- "Large" Q_{coll} (~ > 15 fC):
  - Saturate I_m and vary hold time and decay time.
- Integral of I(t) == Q_{coll}

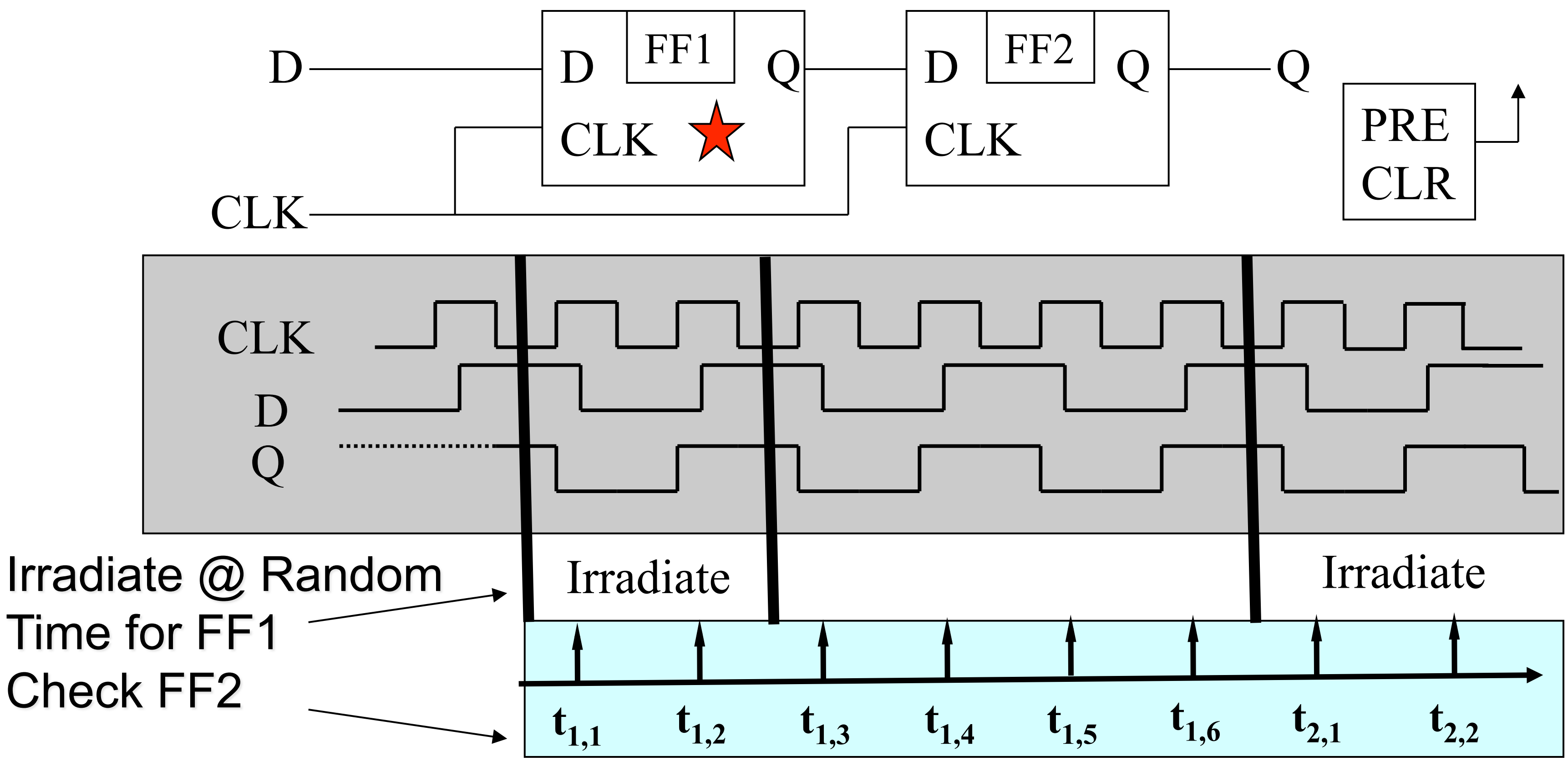


$$I_1(t) = I_m \left[1 - e^{-\frac{(t - t_{d1})}{\tau_1}} \right] \quad \{ t_{d1} \le t < t_{d2} \}$$

$$I_2(t) = I_m e^{-\frac{(t - t_{d2})}{\tau_2}} \quad \{ t \ge t_{d2} \}$$

Spice Timing and Flow, Dynamic

- MRED queues a set of events for SPICE evaluation – determines if SEU occurs (not from Q_{crit})

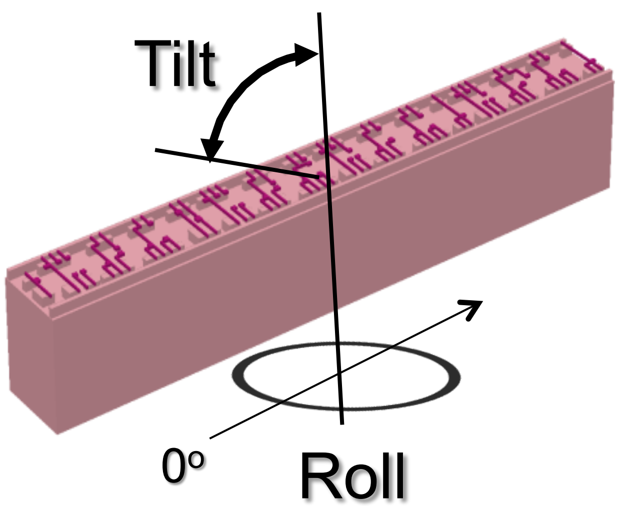


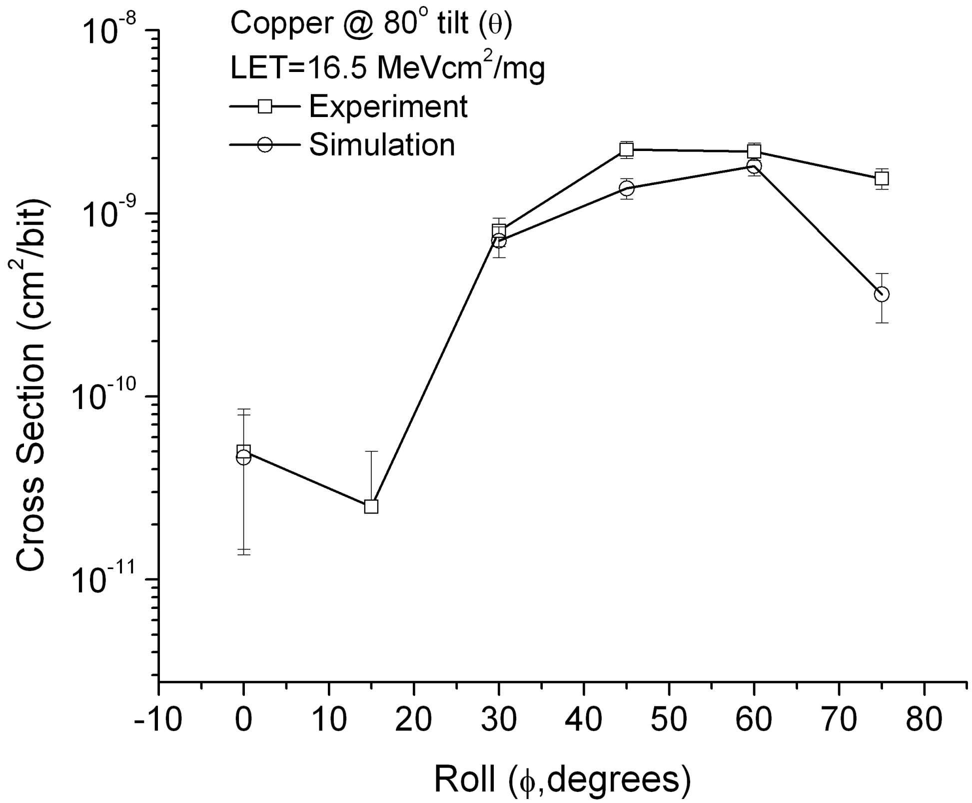
Model Calibration

- Current approach is iterative
  - Simulate and compare to experimental data, adjust parameters and re-simulate as required.
- Guidelines
  - Physical structures bound depth and lateral dimensions
    - Isolation (STI), n/p-well depth, etc.
    - Layout and process information, including TCAD radiation simulations establish foundation for 'first-pass' at sensitive volume parameterization.
    - Refine sensitive volume parameters to produce best agreement possible between simulation and experiment
- Post-simulation analyses used to verify that SEU mechanisms are physically justifiable.
- Charge sharing and coincident node SEU mechanisms are challenging to model (as in the DICE latch).

Example Calibration

- Initial results (qualitative) provide user with good sense of SEU mechanisms.
- Refinement of SV parameters improves quantitative agreement.

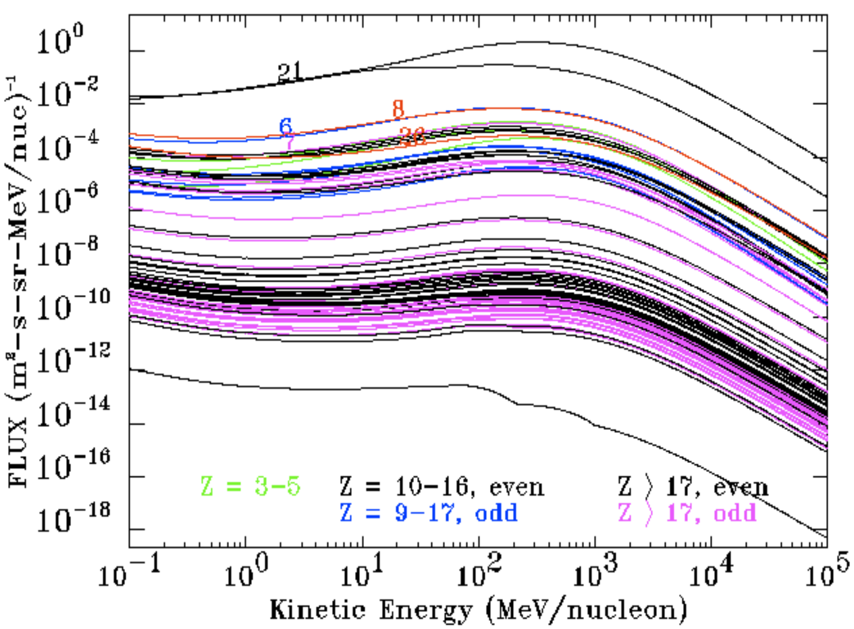




Determining SEU Rate

- The calibrated model serves as the basis for SEU rate predictions. Only change the ‘gun’ parameters and post-processing routines.
- User must select an environment

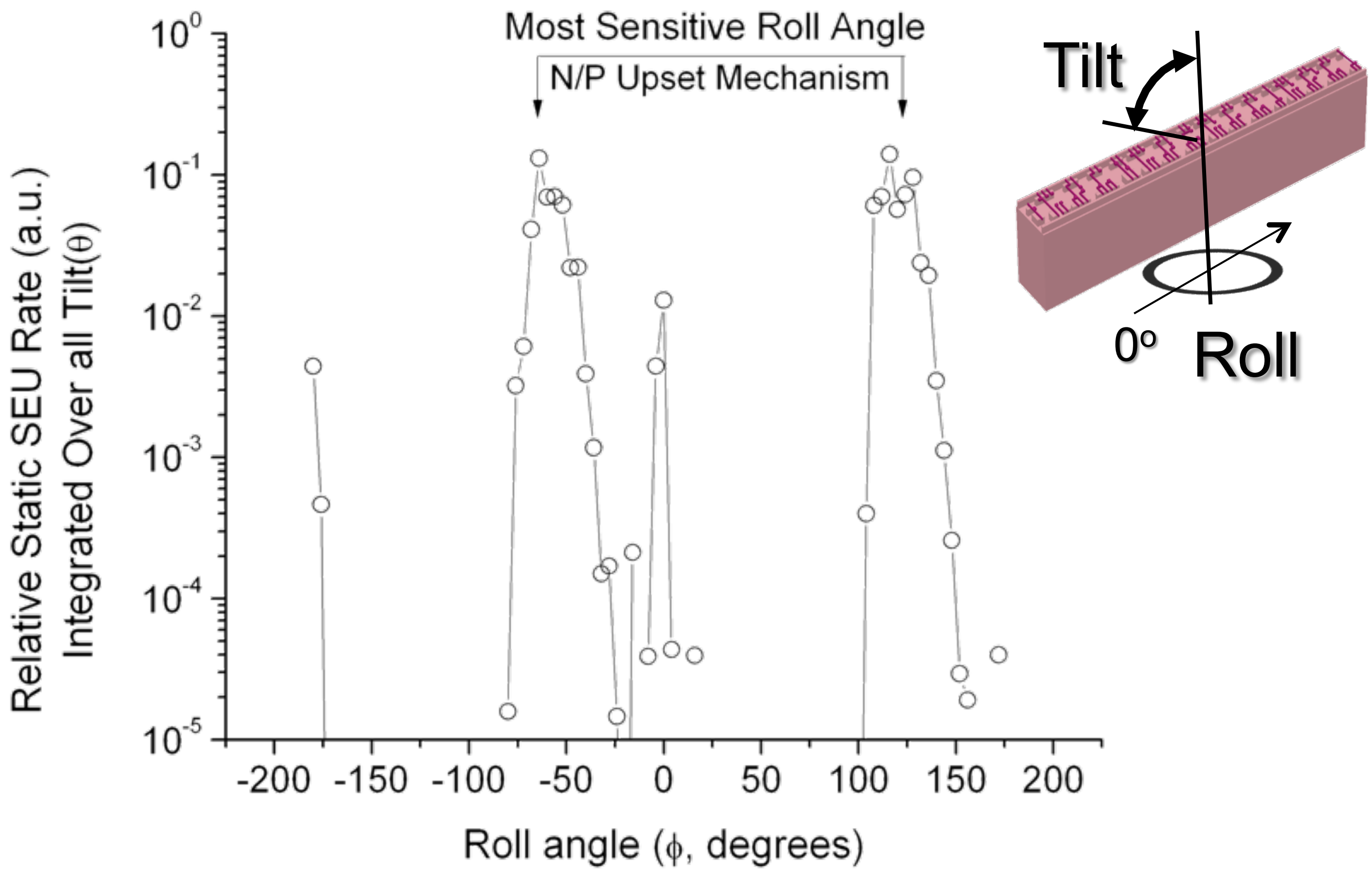
Adams 90%



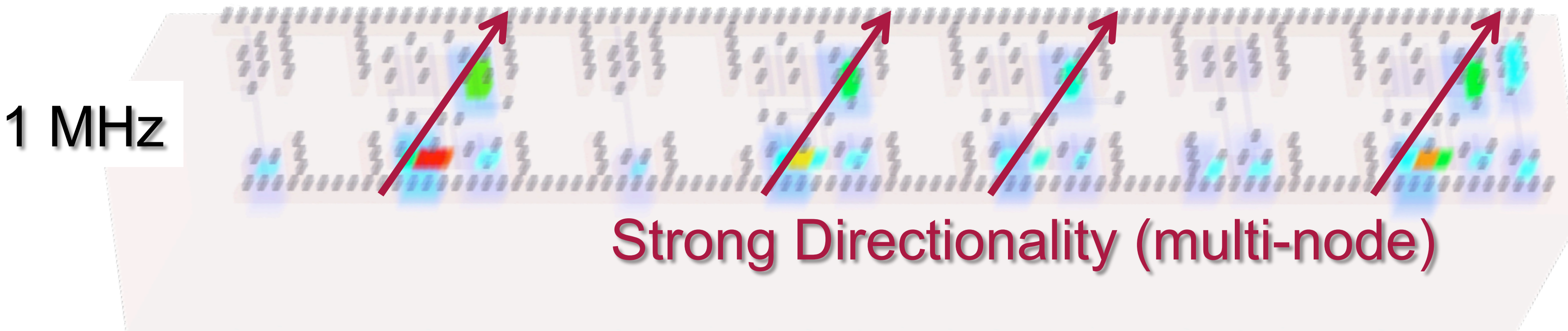
- Simulator output can be as simple as a single line, the SEU rate.
- $2x10^6$ events per CPU
- 200 CPUs per batched simulation
- 2000 CPU-hrs total
- <u>Adams 90% ~$1.5x10^{-8}$ /bit-day</u>
  - Frequency dependent

Detailed Analyses: Directional Sensitivity

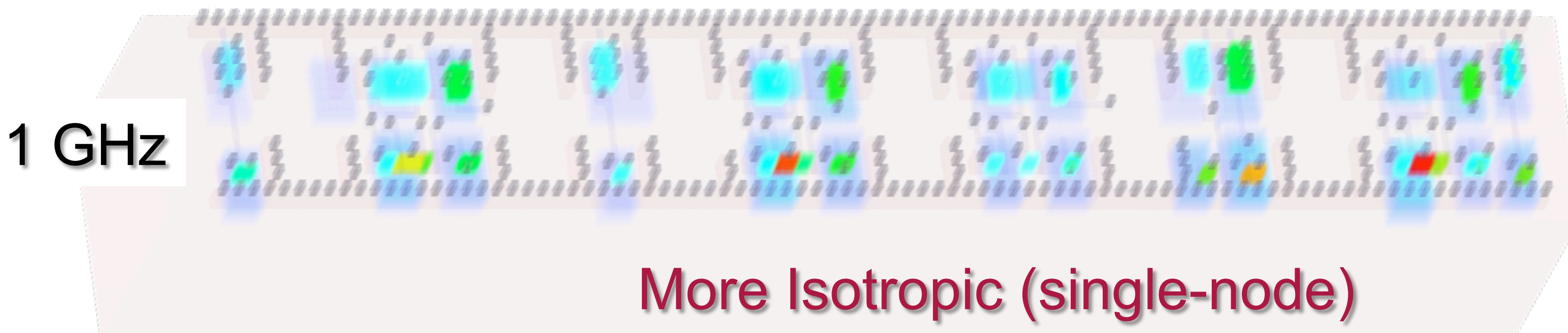
- Most SEU in the environment occur at very specific angles
- Points to specific mechanisms – Two-node process



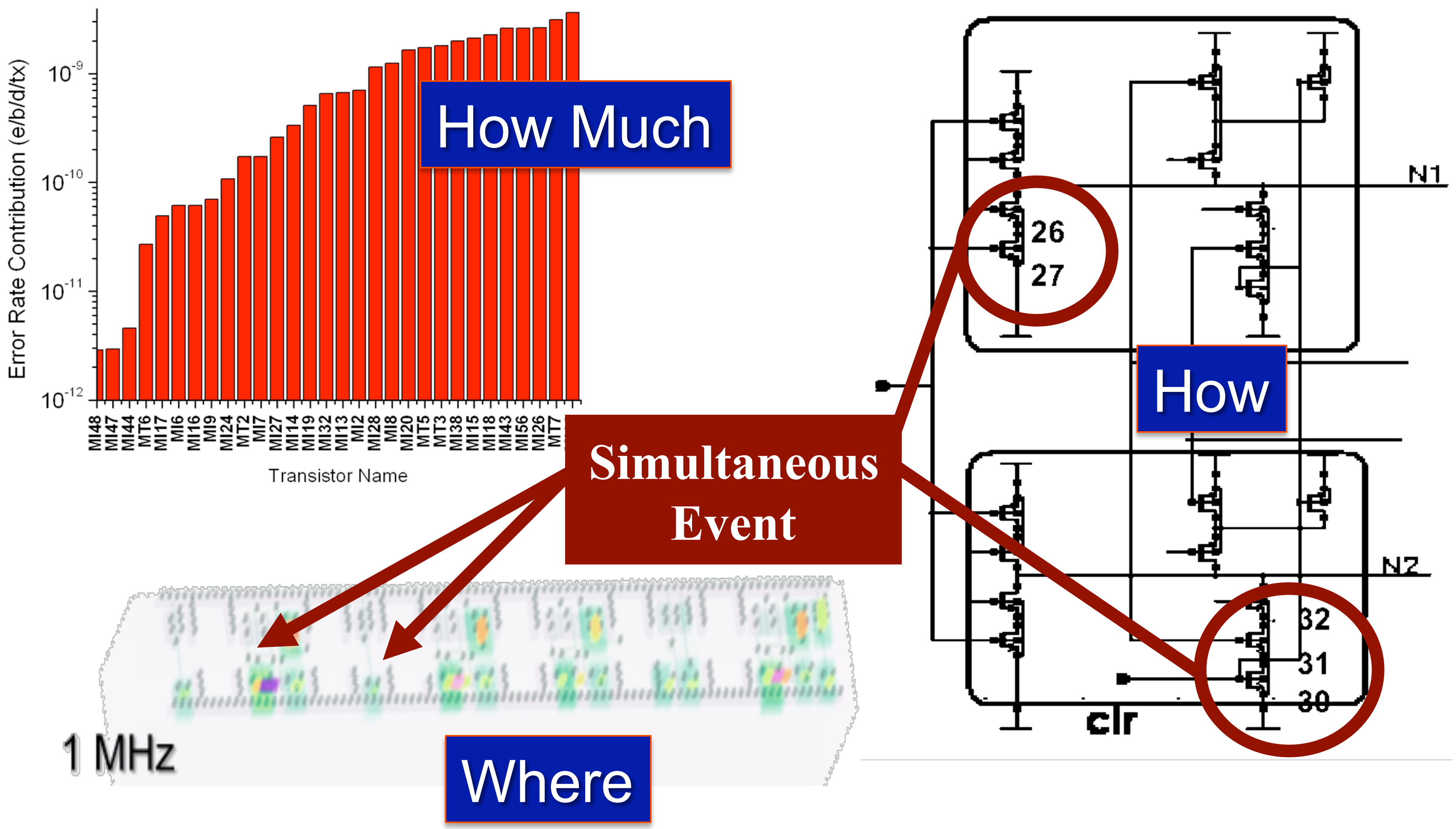
MRED Visualization



- OpenDX interface to MRED provides powerful visualization capabilities
- Layout to schematic to SEU rate – identify sensitive areas

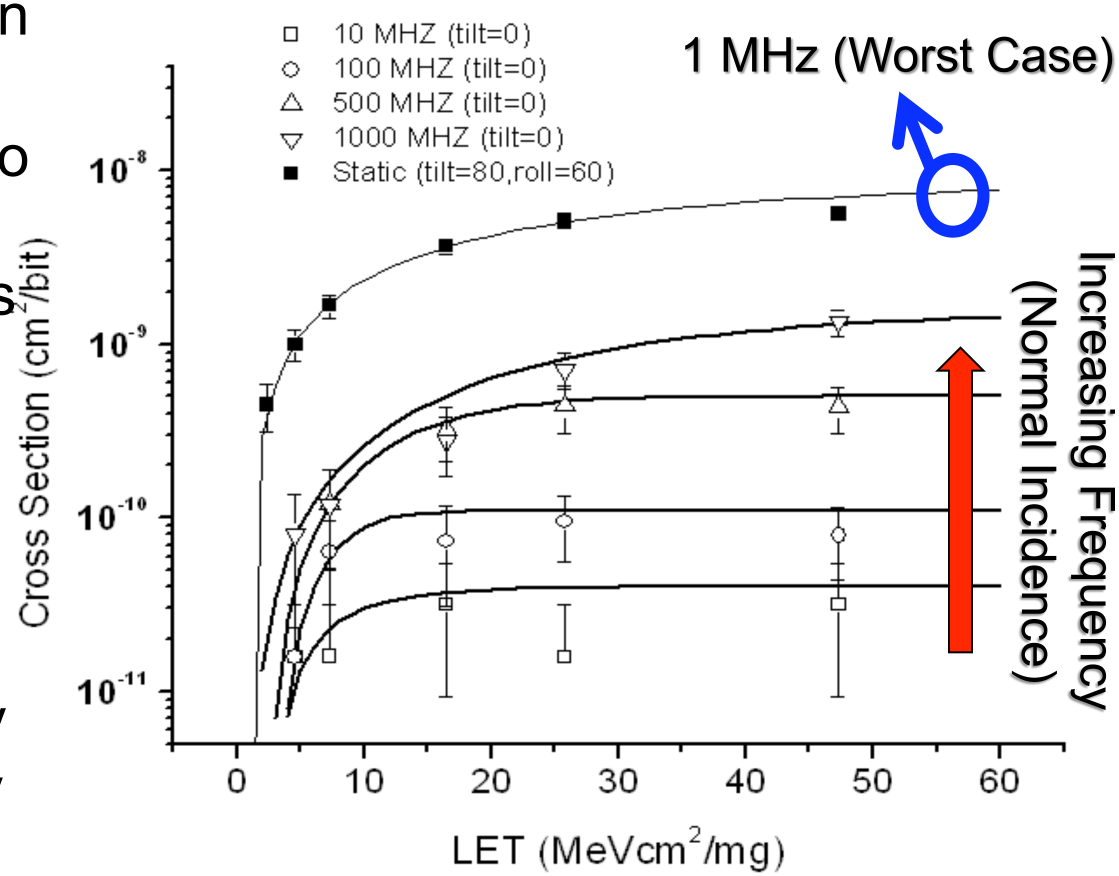


Quantify and Correlate Design to SEU Rate



Analysis: Frequency Dependence

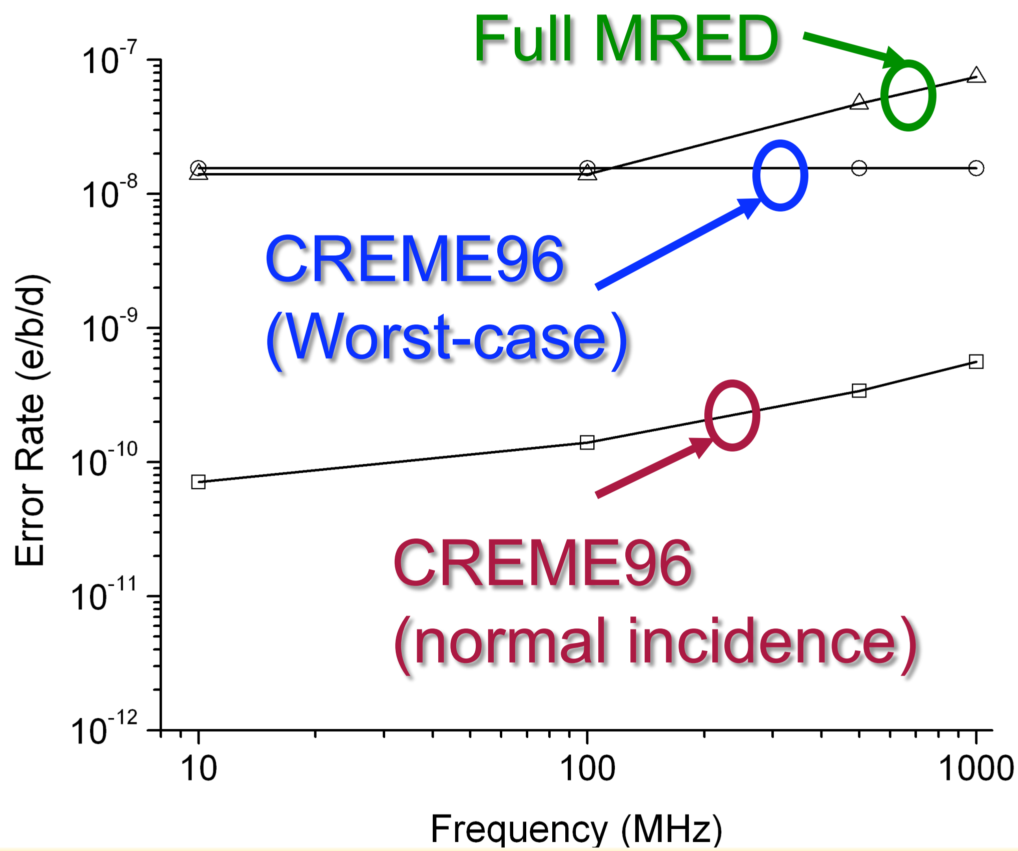
- Investigate SEU properties as a function of frequency
- What is the right way to predict the SEU rate?
- Are our measurements sufficient?
- At certain beam angles, cross-sections are insensitive to frequency.
- Weibull fits to normally incident data only may under-predict on-orbit rate.

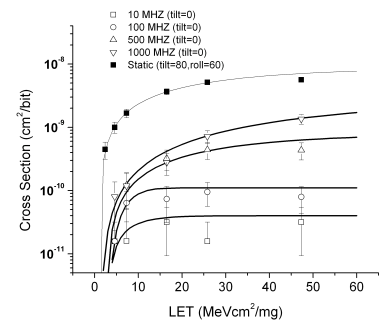


SEU Cross-section as a function of LET and frequency

Analysis: Frequency Dependence

- CREME96 @ normal incidence under-predict rate for all frequencies
- Static cross section establishes baseline SEU rate





Conclusions

- MRED:
  - Provides a means for determining the SEU rate of circuit hardened devices.
  - Identifies sensitive node combinations and their relative probability, in units of cross-section or rate in a given environment.
  - Suitable when multiple node SEU mechanisms cannot be fit to the RPP model
- Frequency analyses indicate one cannot determine the correct SEU rate without first quantifying the cross-sections that determine the quasi-static SEU rate.
- While circuit-hardened technologies represent an improvement over their non-hardened counterparts, they do not provide complete SEU immunity and require extensive testing to properly determine their on-orbit single event upset error rates.