Single Event Upset Error Rate Predictions using MRED

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Motivation

- **Single event upset test data does not always conform to the standard rectangular parallelepiped model (CREME96)**
  - Secondary particle generation from high energy heavy ions.
  - Single particle-multiple node effects.
- **MRED provides an alternative solution to CREME96 for performing error rate predictions**
  - Includes nuclear physics and tracks secondary particles.
  - TCAD interface for solid model creation, materials specification, and event capture.
  - Allows for the tracking of charge generation in multiple sensitive regions.
  - Flexible interface for real-time spice analysis of circuit response.
- **MRED has been used for heavy ion error rate predictions in**
  - Hardened SRAM
  - DICE latches
  - DICE Flip Flops

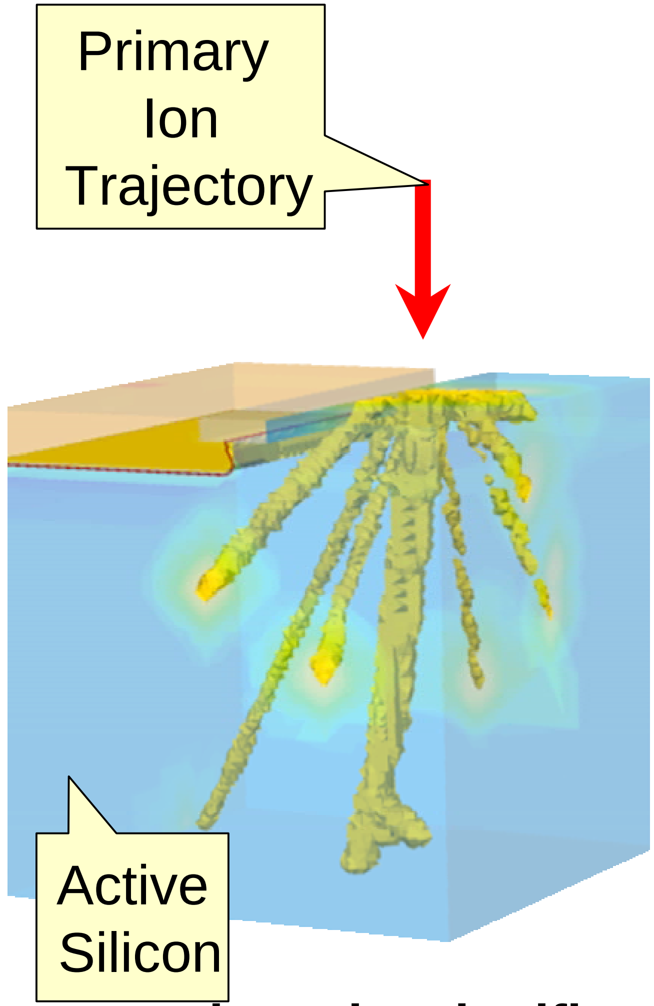
Nuclear Reactions and SEU Response

- **One of the original applications of MRED was understanding the SEU response of a 0.25 μm hardened SRAM.**
- **Identified nuclear reactions as a contributor to the measured SEU cross section curve.**
- **Inclusion of nuclear reactions was vital to determining the proper in-flight SER.**

- K.M. Warren, et al., "The Contribution of Nuclear Reactions to Heavy Ion Single Event Upset Cross-section Measurements in a High-density SEU Hardened SRAM," IEEE Trans. Nuc. Sci. Vol 52, Dec. 2005 pp 2125 – 2131.
- R.A. Reed, et al., "Implications of Nuclear Reactions for Single Event Effects Test Methods and Analysis", IEEE Trans. Nuc. Sci., Vol 53, Dec 2006. Pp 3356-3362.
- D.R. Ball, et al., "Simulating Nuclear Events in a TCAD Model of a High-Density SEU Hardened SRAM Technology," IEEE Trans. Nuc. Sci., Vol 53, Aug 2006. Pp 1794-1798.
- C.L. Howe, et al., "Role of heavy-ion nuclear reactions in determining on-orbit single event error rates," IEEE Trans. Nuc. Sci., Vol 52, Dec 2005, pp 2182-2188.
- R.A. Reed, et al., "Impact of Ion Energy and Species on Single Event Effects Analysis," IEEE Trans. Nuc. Sci., in print.

Nuclear Reactions

- Nuclear reactions between high energy ions and high Z materials used in semiconductor manufacturing produce secondary particles
- May produce high-mass fragments
- Fragments can have higher LET than primary.
- Probability of a nuclear reaction is small, but can still dominate error rate for hardened technologies.

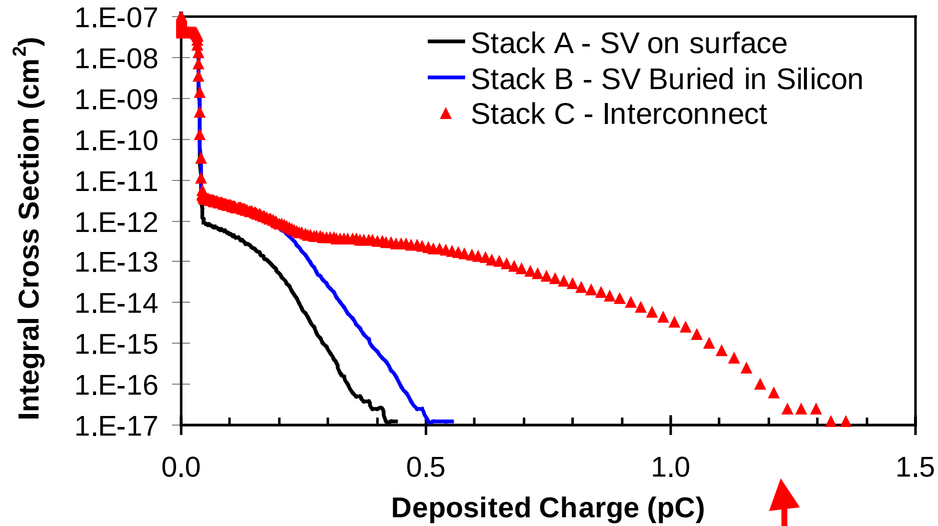


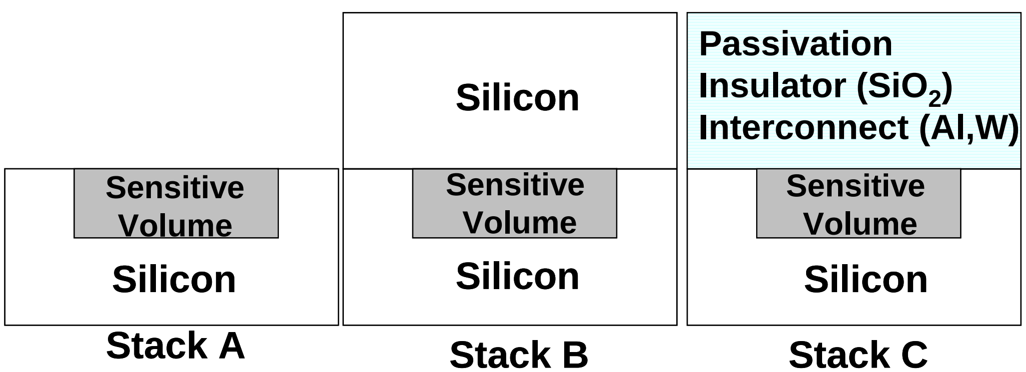
This event deposits significantly more energy than that by a single primary ion.

Nuclear Reactions

- **Quantitatively, what is the effect of high Z materials?**
- **The addition of tungsten pushes peak charge deposition over 30x primary LET**

523 MeV Neon

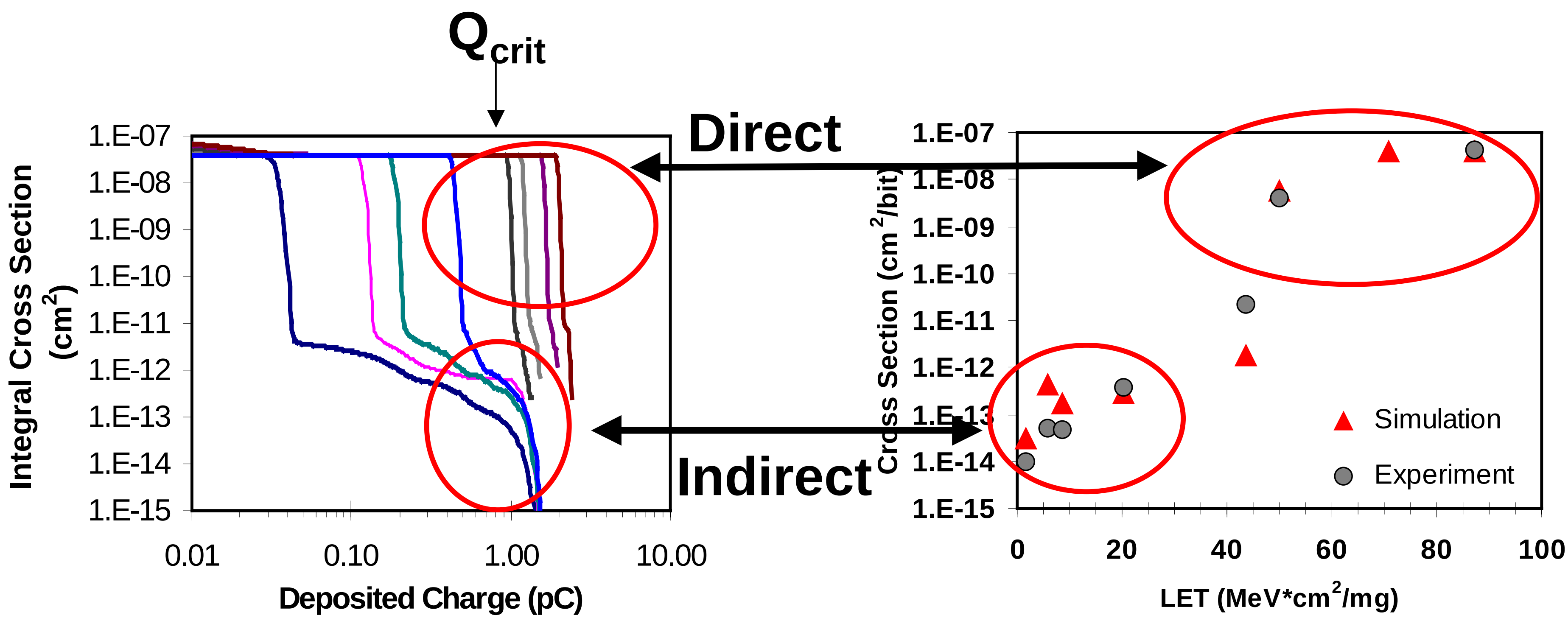




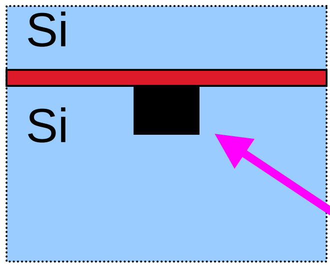
Tungsten layer exacerbates effect

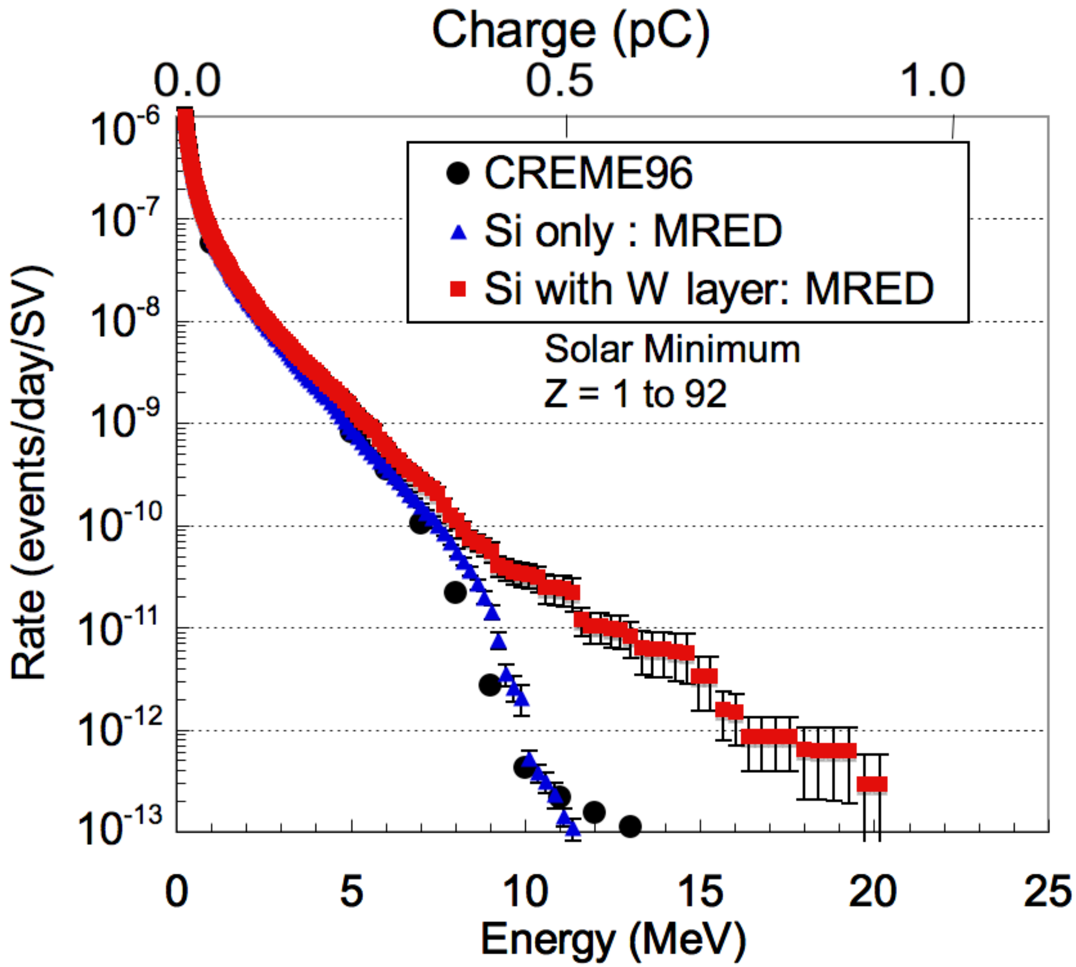
Nuclear Reactions

- Calorimetry on the sensitive volume (left figure) indicates two relevant regions
  - Direct Ionization – the generated charge is from ionization by the primary particle
  - Indirect Ionization – the generated charge is from the secondary product(s) of a nuclear reaction



Nuclear Reactions



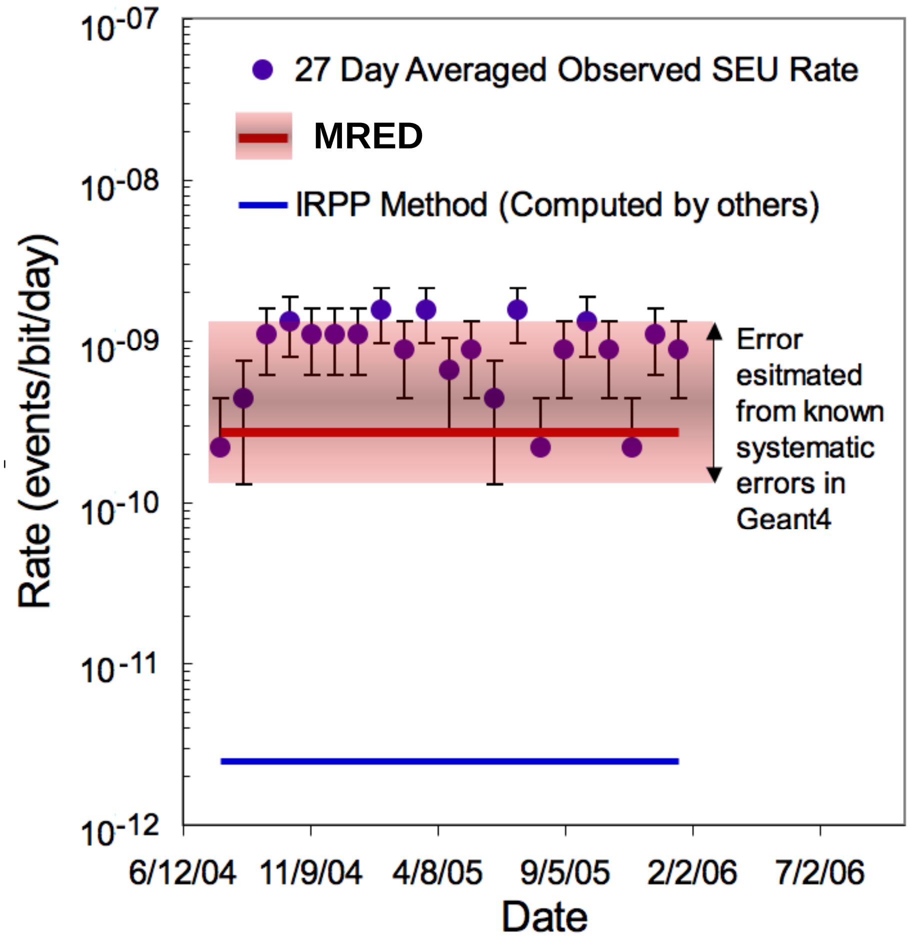


The red squares are the event rates when a thin tungsten layer is placed near the sensitive volume.

- **Conclusion: High Z materials in BEOL processing, such as tungsten, can increase the on-orbit SER**

Nuclear Reactions – on orbit SER

- Modeling nuclear reactions *can* be vital to predicting the correct on-orbit error rate.
- Flight data on a hardened 4 Mbit SRAM support hypothesis.
- Direct ionization and IRPP method under-predict in flight SER by over 3 orders of magnitude.
- The inclusion of nuclear reactions and BEOL materials in the MRED model dramatically improves the fidelity of the rate prediction.
- Test and analysis must be performed to correctly identify when the higher fidelity models are needed.



On-orbit flight data 4Mbit SRAM (BAE)

SEU Rate Prediction – 90 nm DICE Latch

- **Multiple node charge collection and/or charge generation processes dominate the SEU response of single node hardened circuitry**
- **Difficult or impossible to accurately model using RPP methods.**
- **Demonstrate the use of MRED for developing a SEU response model suitable for in-flight SEU rate predictions.**
- **K.M. Warren, et al., "Monte-Carlo Based On-Orbit Single Event Upset Rate Prediction in a Radiation Hardened by Design Latch," IEEE Trans. Nuc. Sci., in print.**

DICE Latch – Multi-node processes (90nm)

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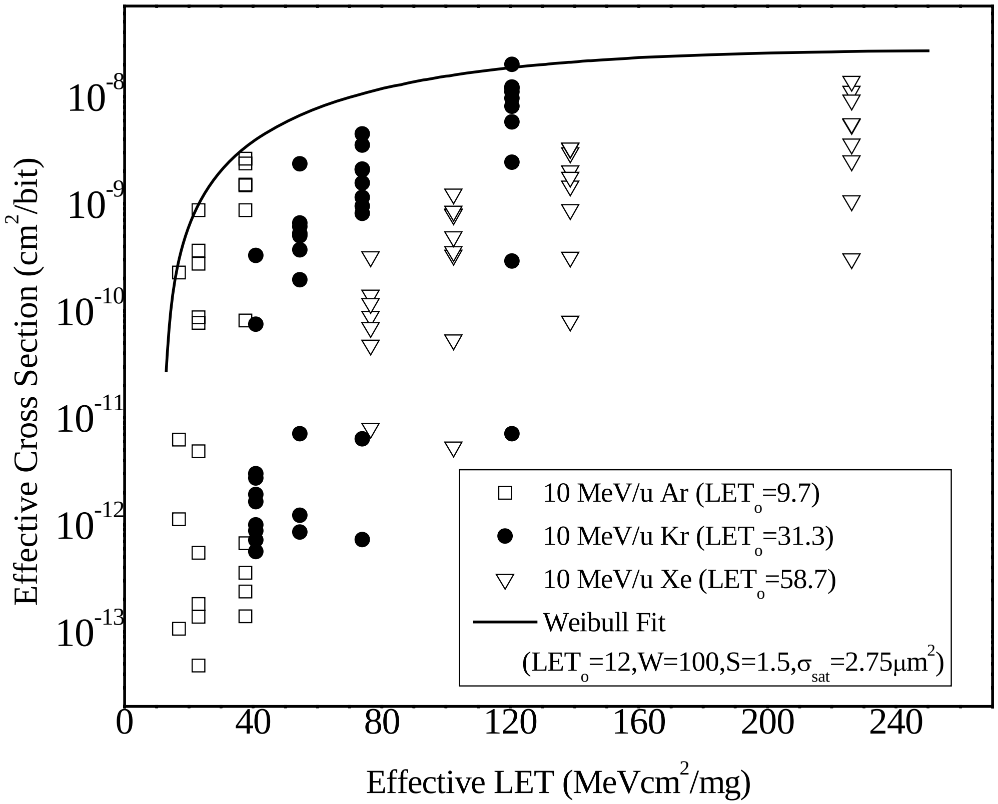
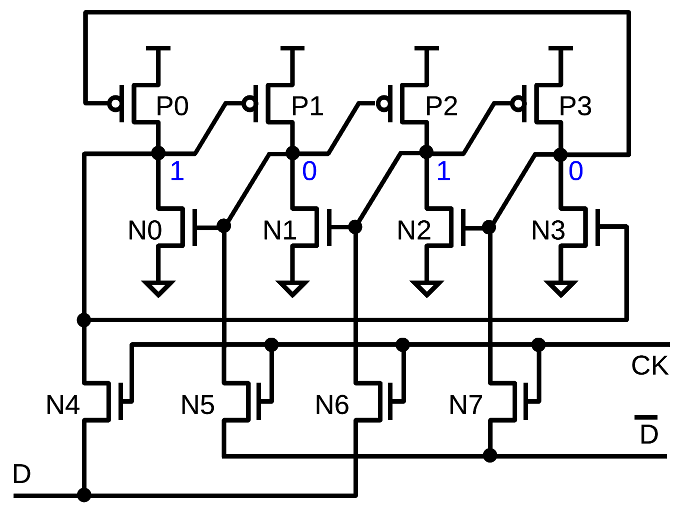


Heavy ion data and circuit for a 90nm DICE latch

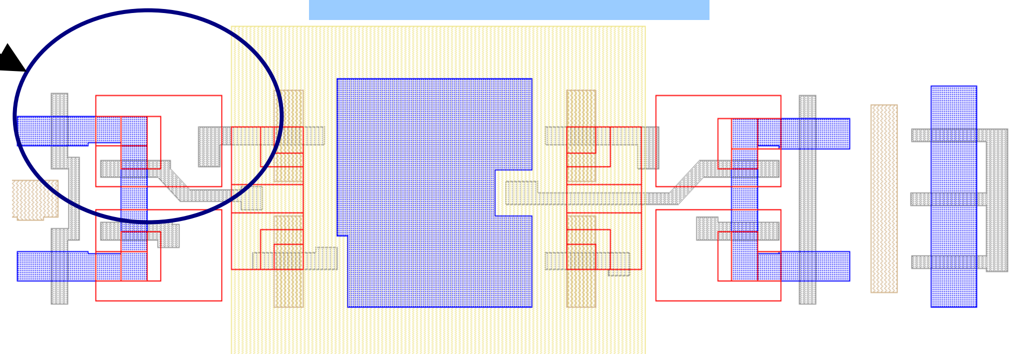


- In hardened circuits, heavy ion SEU test data may not fit the traditional RPP model used in CREME96 calculations.
- When two regions must be struck simultaneously, the the probability of an upset becomes one of coincidence between two regions.
- Identified by a cross section curve that is not well behaved in terms of effective cross section versus effective LET.
- The data above show an azimuthally dependent cross section and the cosine law is not applicable

DICE Latch (90nm) – MRED Implementation

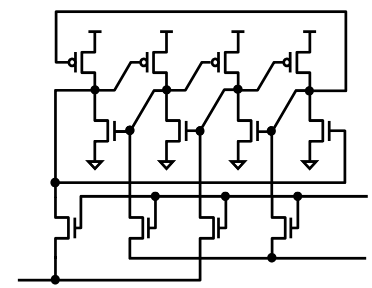
Red Square Denote Sensitive Volumes

MRED



Test for Valid Events

SPICE



Identify Sensitive Tx Pairs

- This latch had 10 combinations of two-node events that would lead to an SEU.
- Calibrated volume sizes and placements based on test data, TCAD results, and engineering judgment.

Dice Latch (90nm) - Results

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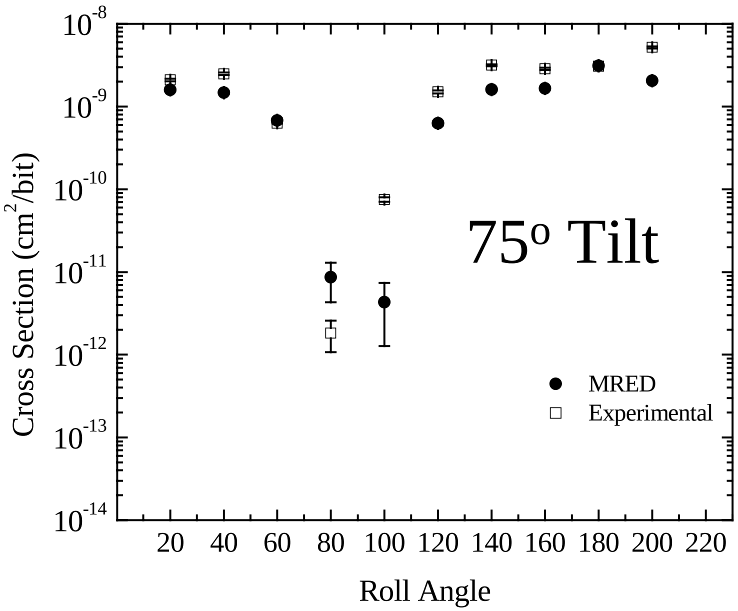
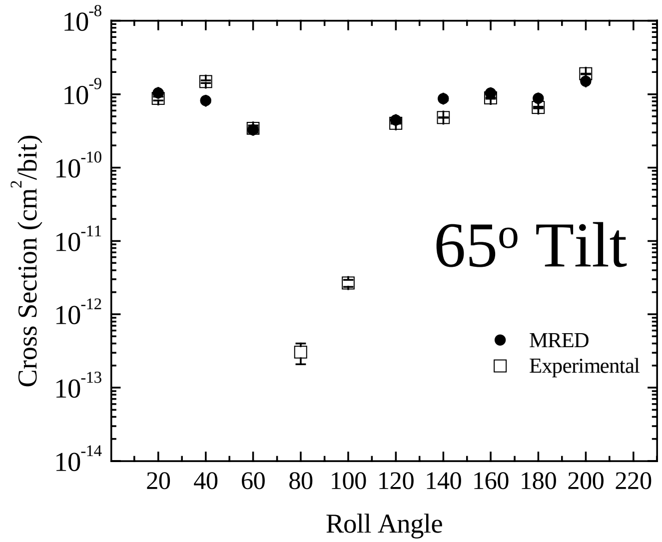
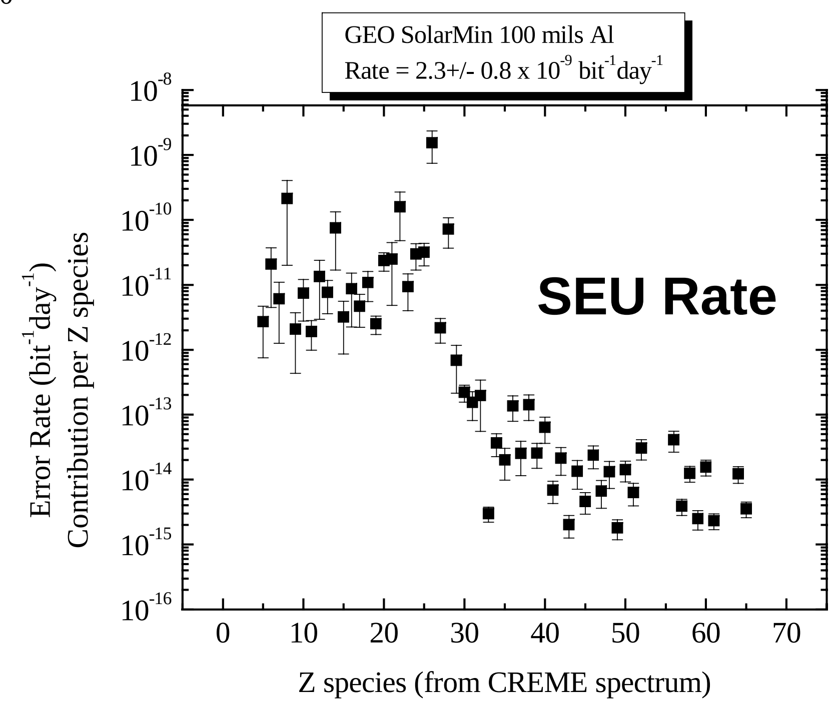




- **Using multiple volumes and coincidence testing with calibration resulted in a model that captured the SEU cross section as a function of LET, azimuth (roll), and tilt.**
- **Space environment fed into calibrated model for SEU rate calculation.**



Dice Latch (65nm)

- **A similar rate prediction was performed for the same DICE latch circuit in 65 nm.**
- **In this case, MRED was used to evaluate possible re-design ideas to improve SEU performance.**

Sensitive Pairs - Circuit in data high q=1

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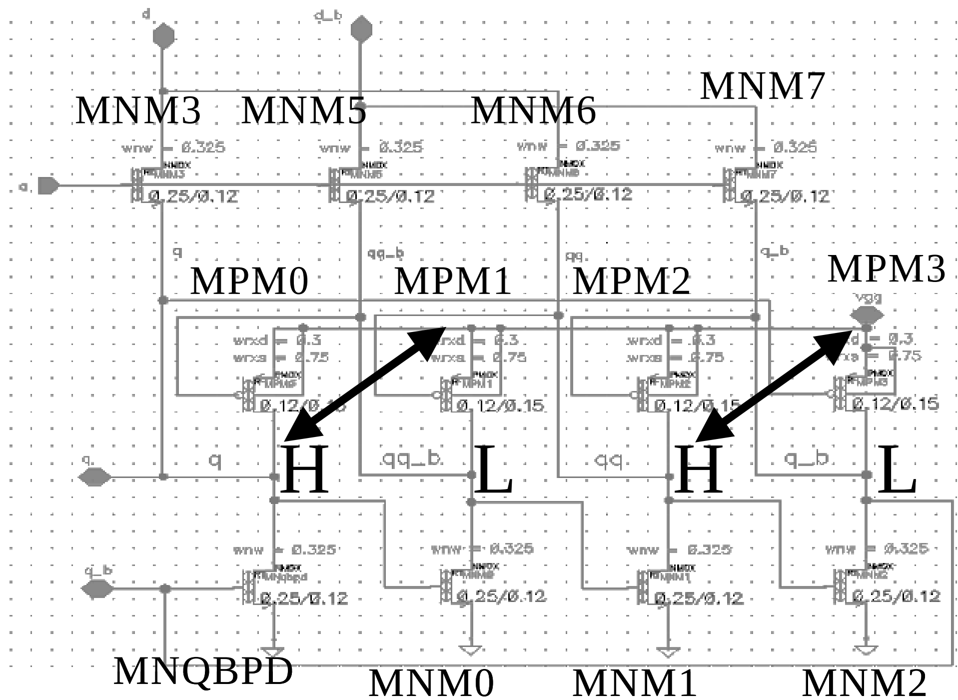
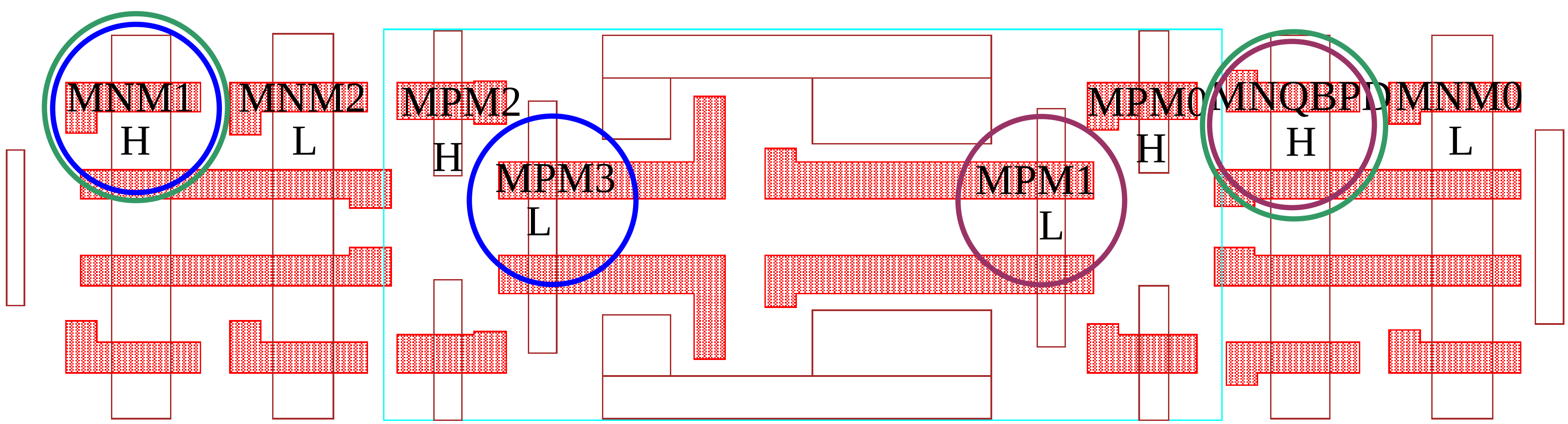
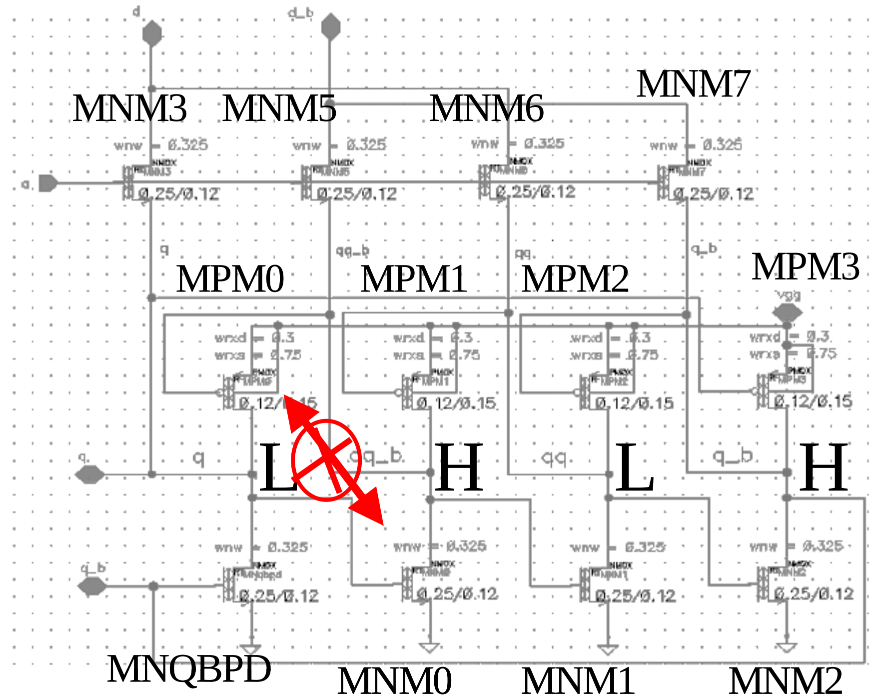
- **The current sensitive node pairs dominate the cross sections**
  - Shallow tilt angles
    - ◆ MNM1-MPM3
    - ◆ MNQBPD-MPM1
  - Steep tilt angles
    - ◆ MNM1-MNQBPD

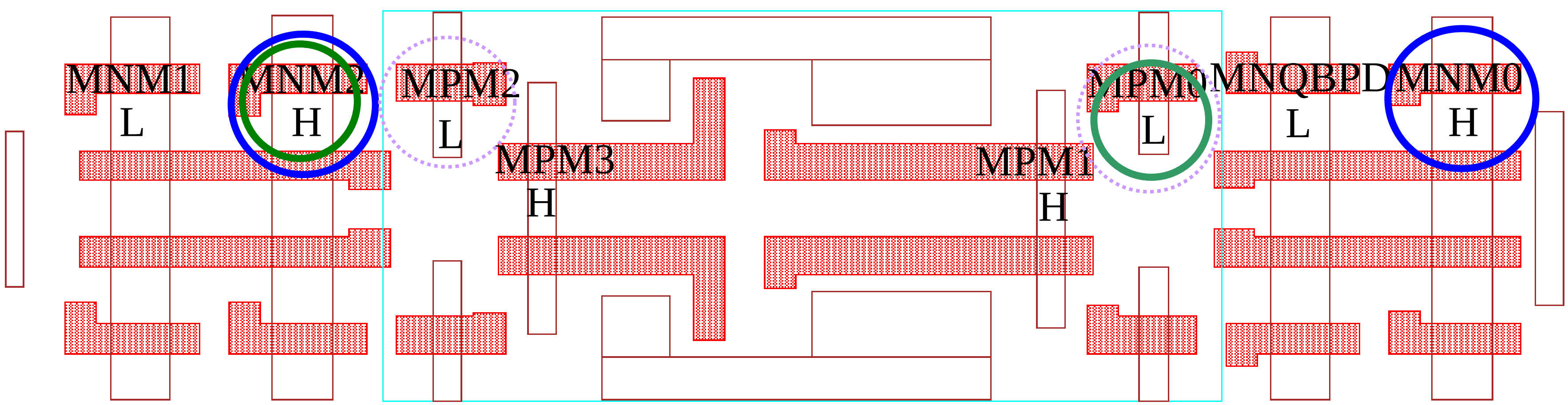




Sensitive Pairs - Circuit in data low q=0

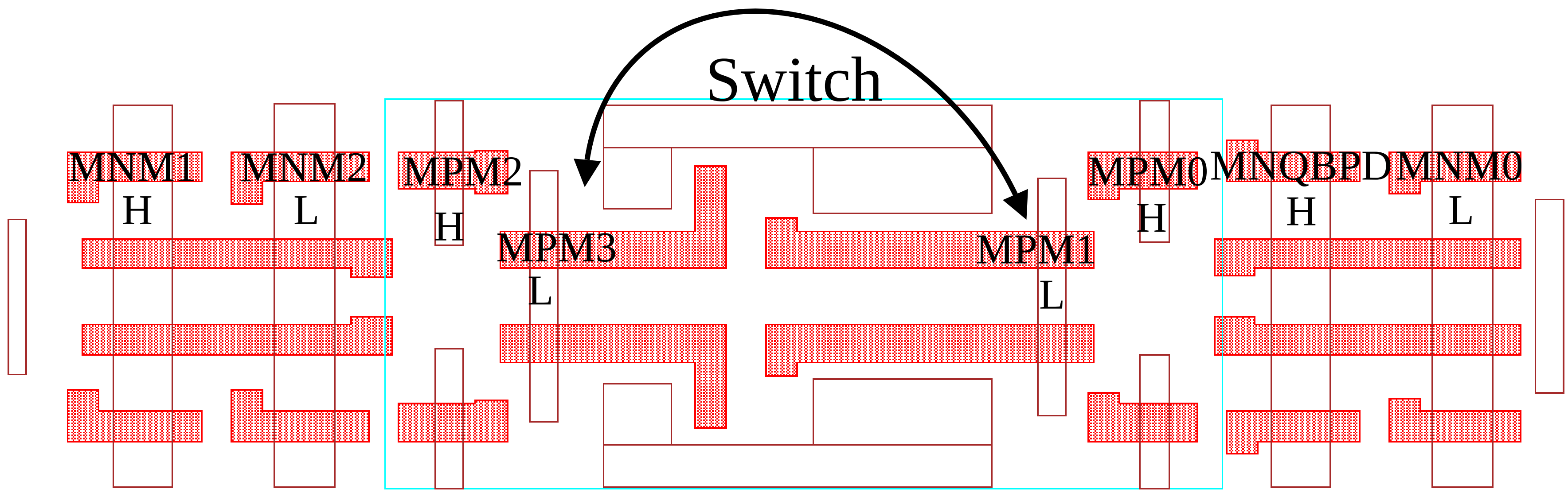
- MNM2/MPM0, MNM2, MNM0 pairs are main error contributors.
- <u>Much</u> smaller experimental cross section for q=0.
- Note that there is <u>not</u> a sensitive N-P combination on the left side of the layout.



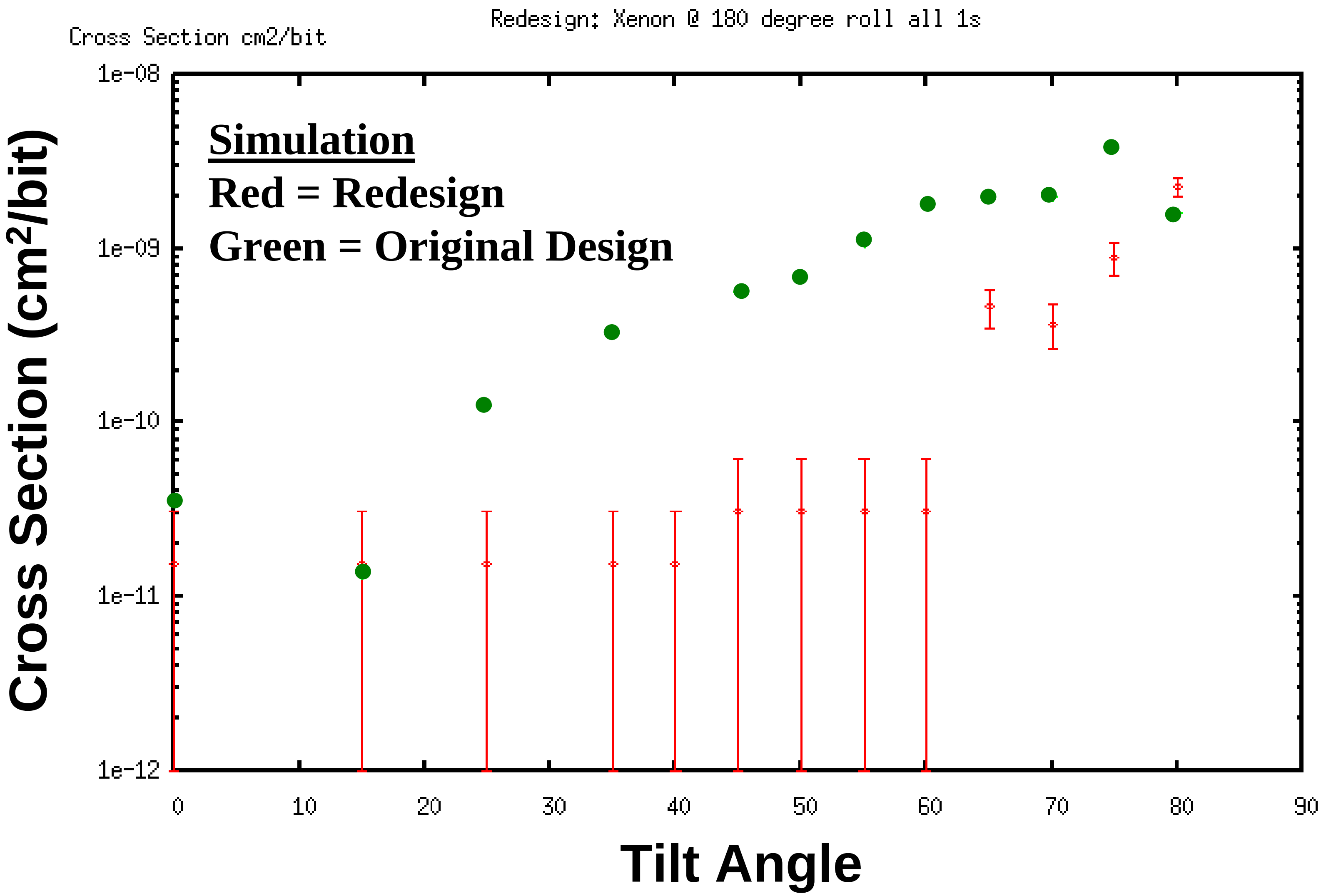


Re-design Idea!

- It appears that in q=0, there are no adjacent sensitive pairs – every sensitive node pair is well separated. This does not appear to be true in q=1. How can we use this?
- We know that it is possible that MPM3/MNM1 and MPM1/MNMQBPD coupling can upset the circuit (not sure how much at this point)
- Switching the location of MPM3 and MPM1 might solve the problem! This would not require a change in silicon, only a change in interconnect (theoretically)
- In this condition, no previously identified sensitive node combinations would exist together on either side of the layout.

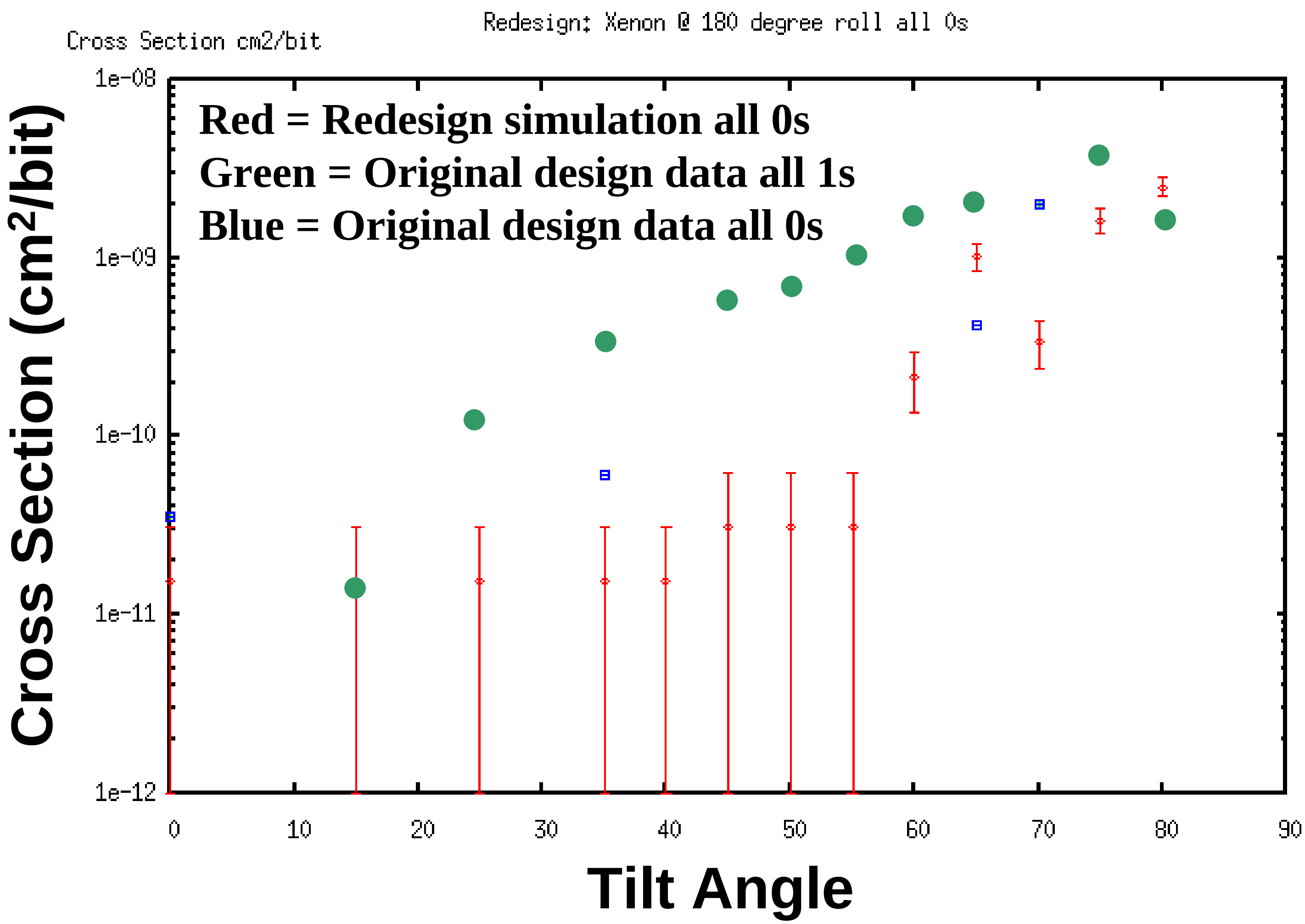


All 1's, Xenon over tilt



- **Moving sensitive pairs produces a reduction in SEU cross section.**

Xenon over tilt



- **Note that the all 1s and all 0s cases are now very similar. Fortunately, the prediction is that both 1s and 0s will have a low cross section.**

Copper over tilt

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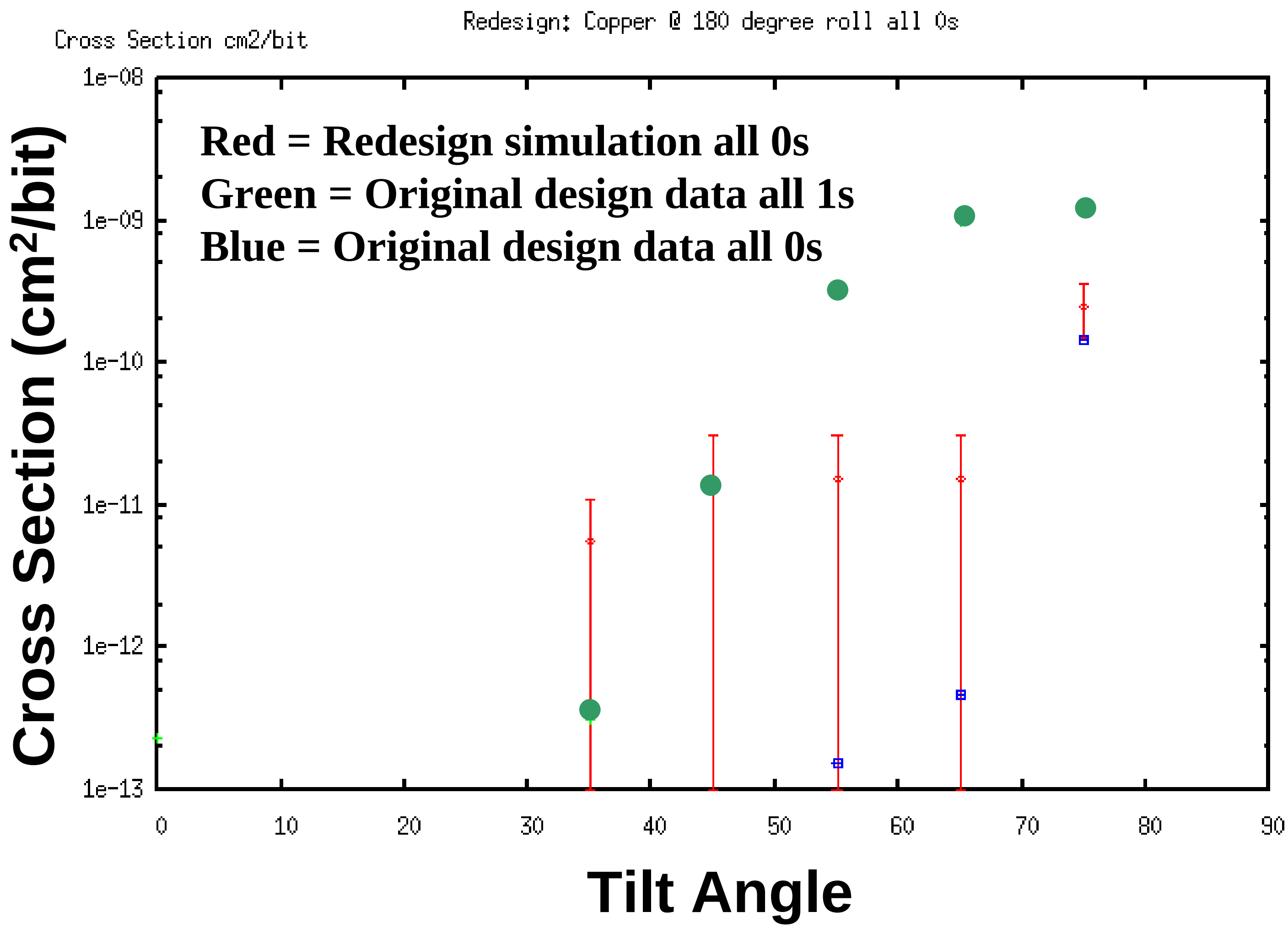


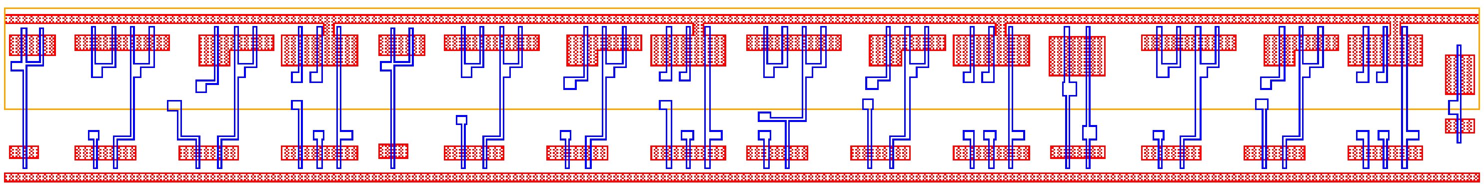
- **All 1's and all 0's data are now similar and have smaller cross sections.**

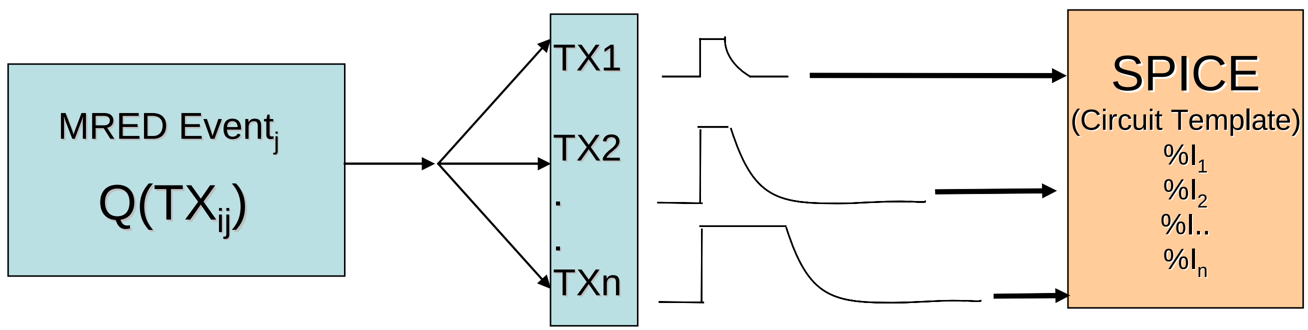
Hardened Master Slave Flip Flop

- **A rate prediction was performed for a master slave flip flop (90nm)**
- **Significant developments in MRED include the inclusion of Spice in the loop**
- **Avoid hand identification of sensitive nodes and sensitive node pairs**

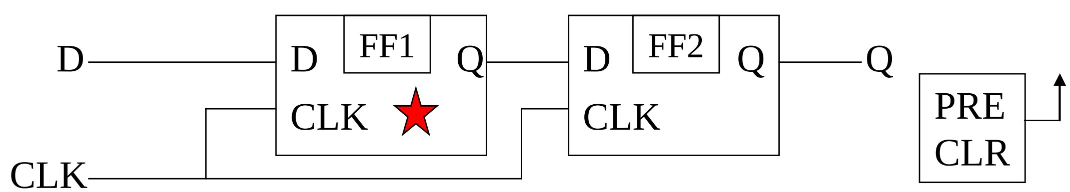
Hardened Master Slave Flip Flop

- **Spice and MRED have been coupled during run-time to evaluate valid SEU conditions on an event by event basis.**
- **Very useful for large circuits such as the 60+ transistor DICE master-slave flip flop shown below.**
- **Avoids manually identifying sensitive node combinations and critical charges.**

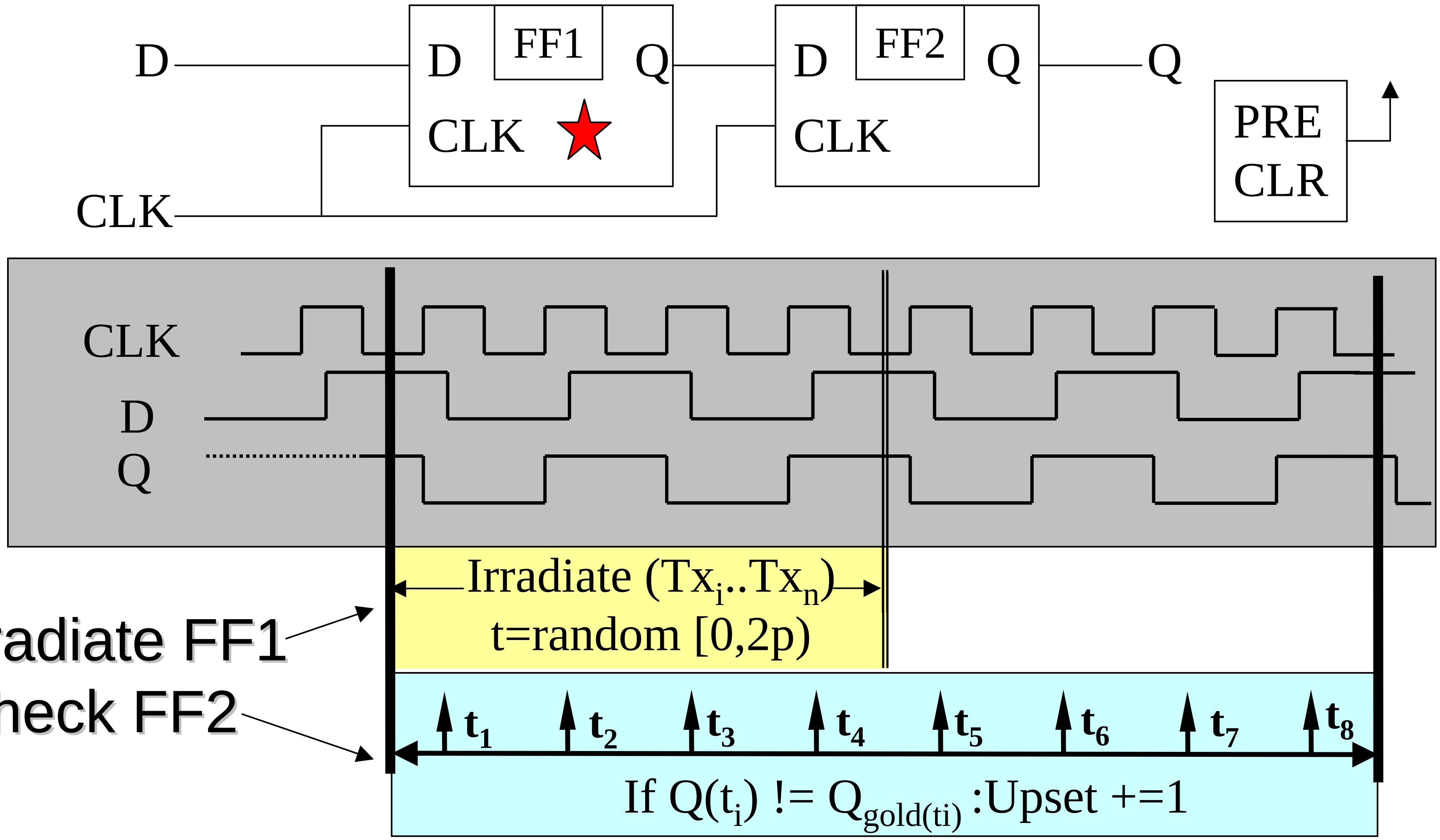




Irradiate FF1 at a random time and watch for an upset clocked out of FF2. This process was repeated over 100,000 times for the final simulation set.



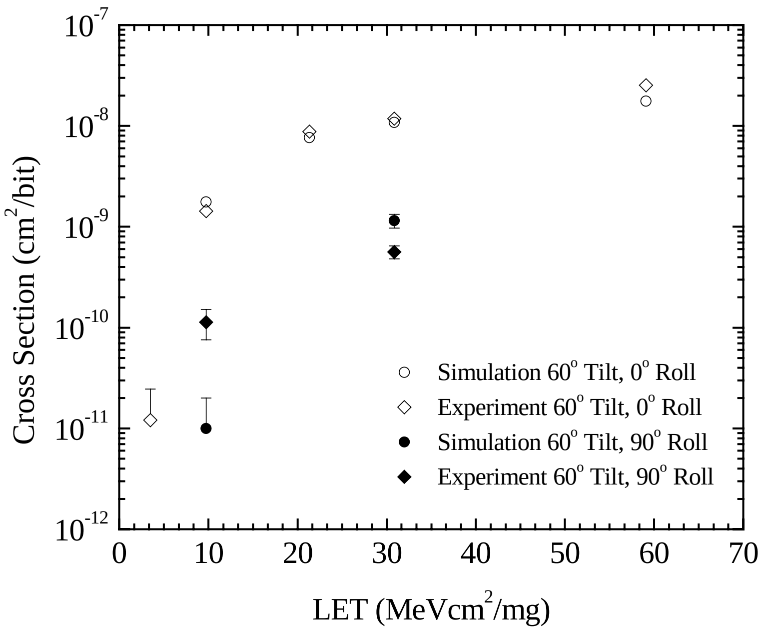
SPICE Timing and Flow

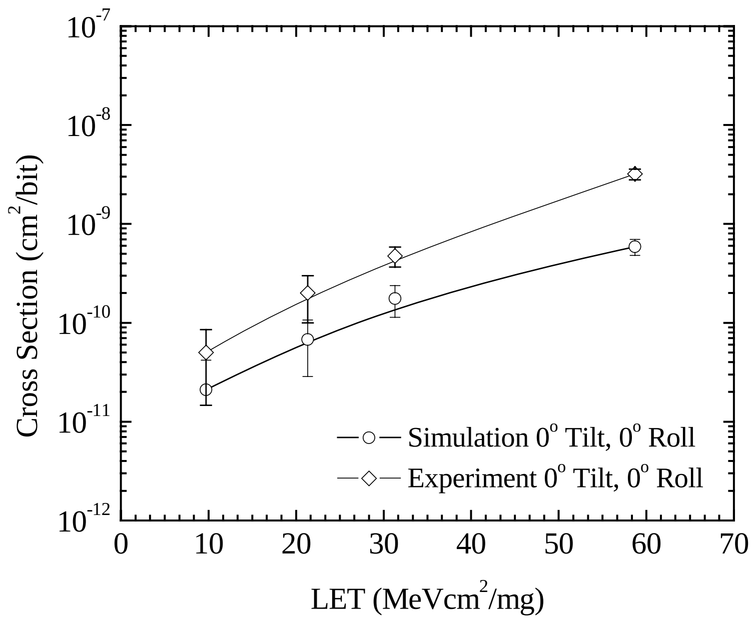


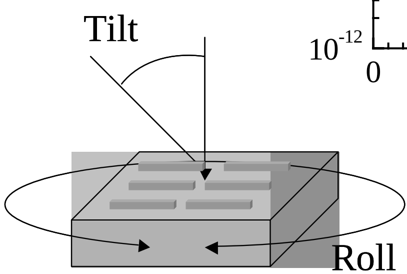
- Irradiate FF1
- Check FF2

Irradiate FF1 at a random time and watch for an upset clocked out of FF2. This process was repeated over 100,000 times for the final simulation set.

Hardened Master Slave Flip Flop





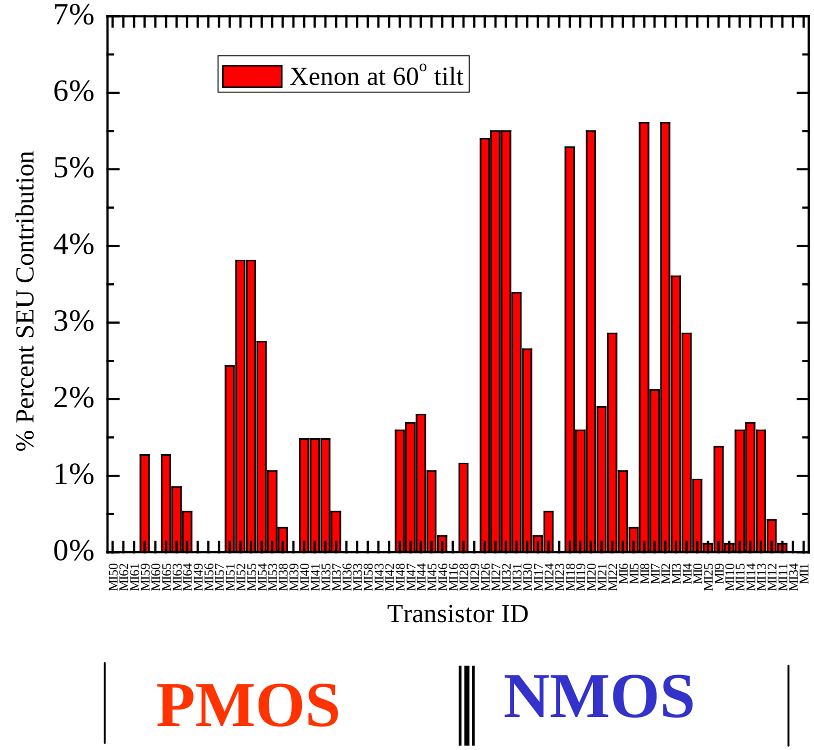


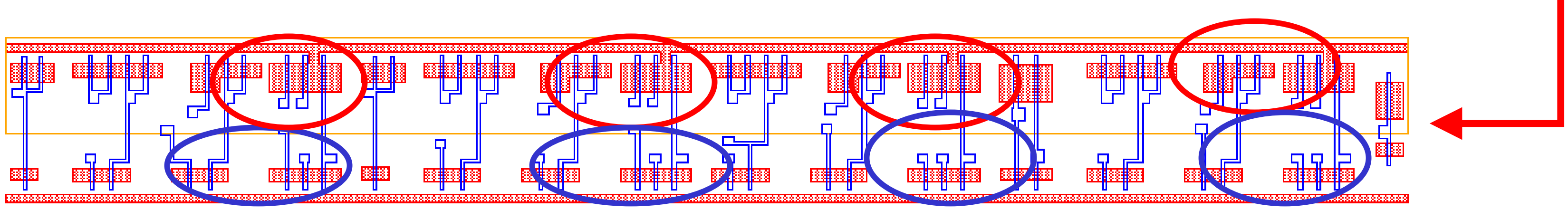
- **The modeled SEU response is completely self contained.**
- **The model must still be calibrated to heavy ion data – sensitive volume dimensions and placement.**
- **The results can be used to directly identify weakness in the layout.**

Hardened Master Slave Flip Flop

- All information related to each SEU event can be recorded.
- Identify sensitive regions in the layout.
- Perform qualitative assessment of new layouts (non-calibrated).

8 Distinct Clusters





Conclusions

- **MRED provide a unique solution to determining on-orbit SER**
  - Nuclear reaction physics – high critical charge circuits, process dependence on SEU response.
  - Multi-node mechanisms – unique ability to place and track energy deposition in multiple sensitive volumes.
  - Exploring hardening solutions.
  - Spice coupling – provides a more automated means for identifying sensitive nodes and relating SEU response to layout.
- **Current MRED development focus with respect to error rate prediction**
  - Guidelines for sensitive volume parameters as a function of process/technology.
  - Methodologies for generating current pulses from sensitive volume charge generation in MRED-Spice simulations.
  - Interfacing MRED to higher level simulators (e.g. VHDL, SEU Tool).
  - Developing guidelines for heavy ion testing for the purpose of identifying when nuclear reactions are important in rate predictions.