

MIXED-SIGNAL DESIGN METHODOLOGY USING A PRIORI SINGLE EVENT TRANSIENT RATE ESTIMATES

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- ▼ **Introduction**
- ▼ **Design Flow**
- ▼ **Qsim:**
 - **Determination of Critical Charge**
- ▼ **SETsim:**
 - **Rate vs Deposited Charge**
- ▼ **SET Error Rate Estimates**
 - **Intersection of Critical Charge with Rate vs. Deposited Charge**
- ▼ **SET Scorecard:**
 - **Compiled SET/SEU Error Rates for the Entire Mixed-Signal ASIC**
- ▼ **Some Results**
 - **Laser + Beamline vs SETsim + Qsim**
- ▼ **Summary**

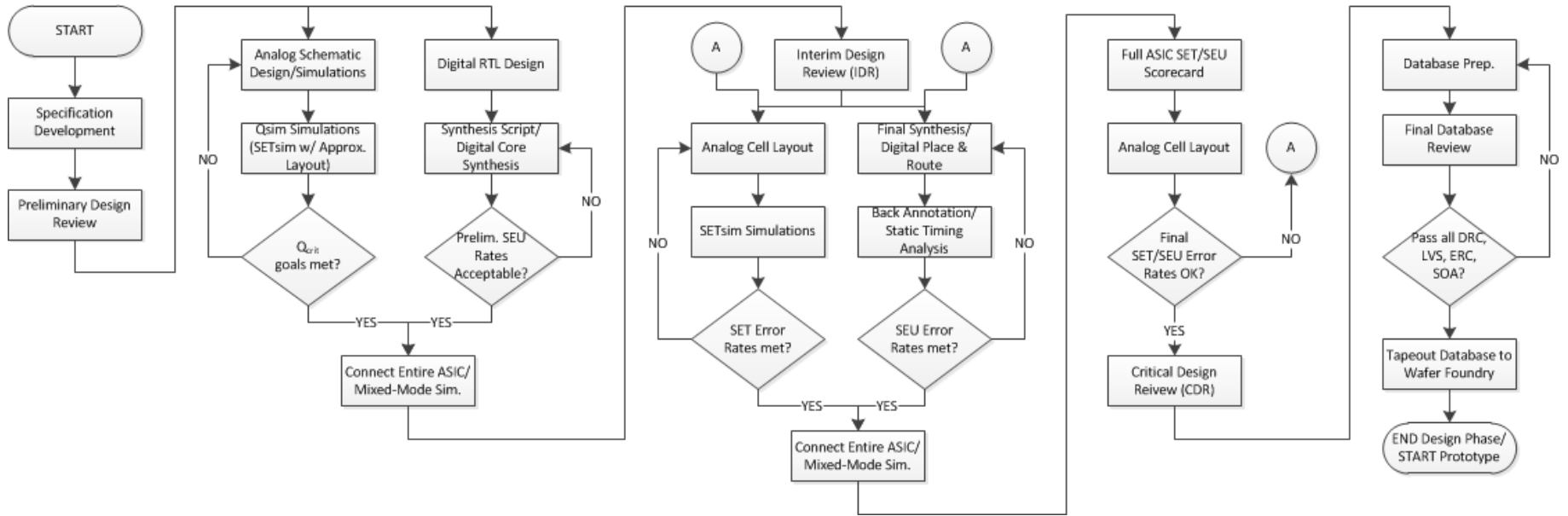
▼ Radiation Performance:

- Total Ionizing Dose (TID):
 - ▼ Must be characterized on test structures
- Single Event Latch-Up (SEL)
 - ▼ Must be characterized on test structures
- Single Event Upset (SEU)
 - ▼ Can be characterized using test chip containing digital cell library elements
- Single Event Transients (SET)
 - ▼ Are different for different analog circuits
 - ▼ Can lead to SEU

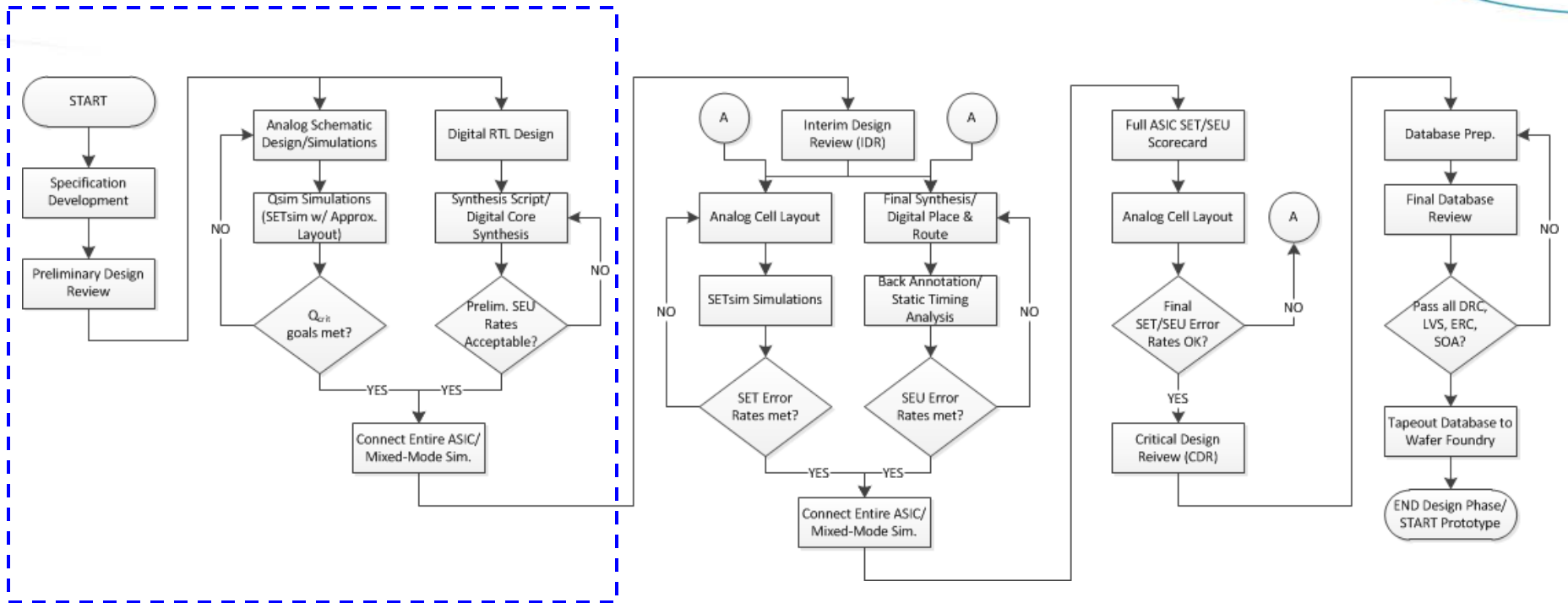
▼ How to deal with SET error rates?

- ▼ Characterize on unique test chip?
 - One test chip for every ASIC?
- ▼ **A Priori SET Rate Estimates**
 - Cost effective if the method is reliable

Design Flow

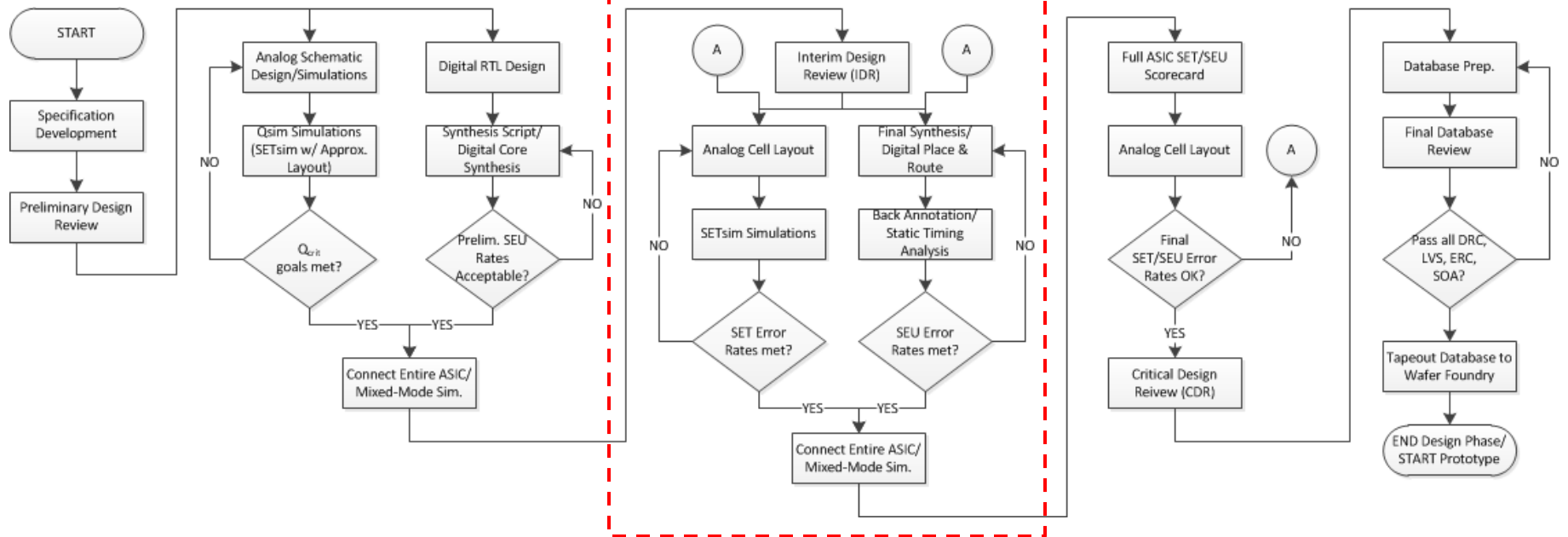


Design Flow



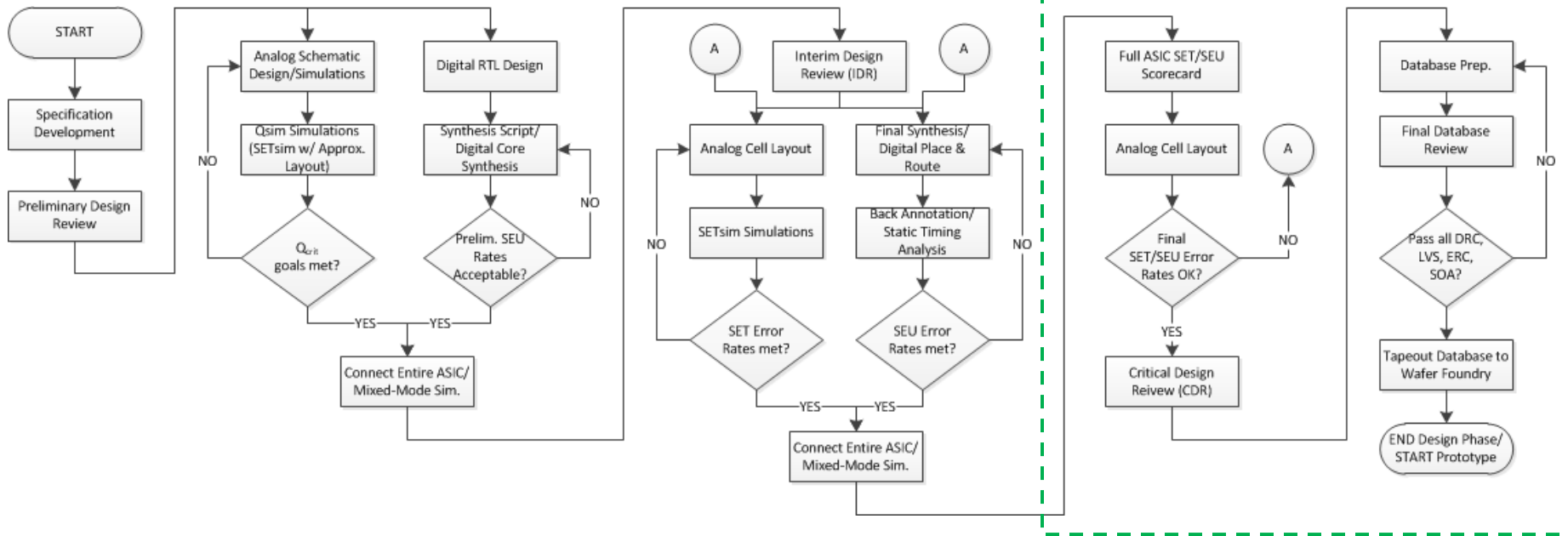
Part 1 Schematic Design

Design Flow



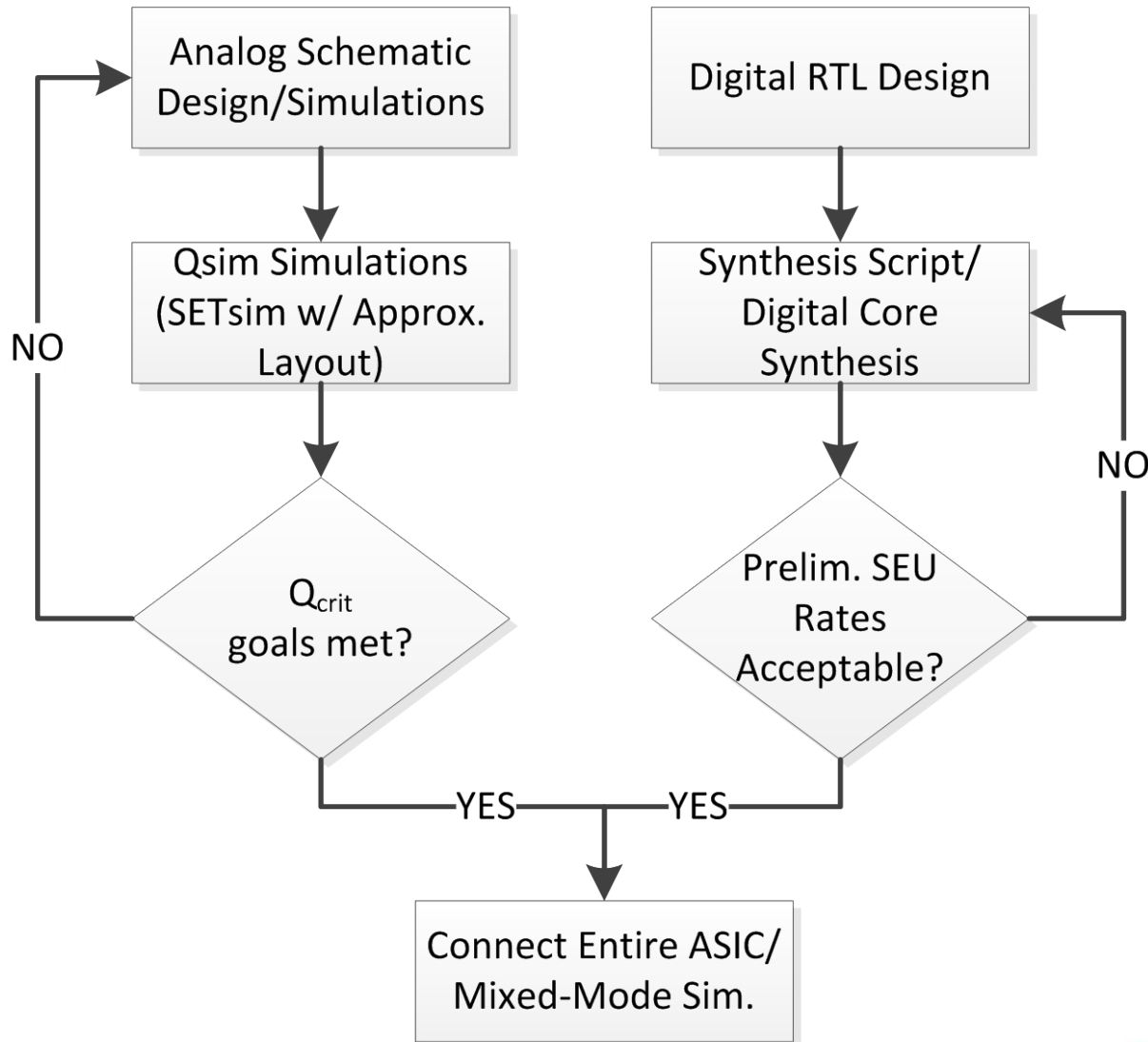
Part 2 Physical Design

Design Flow

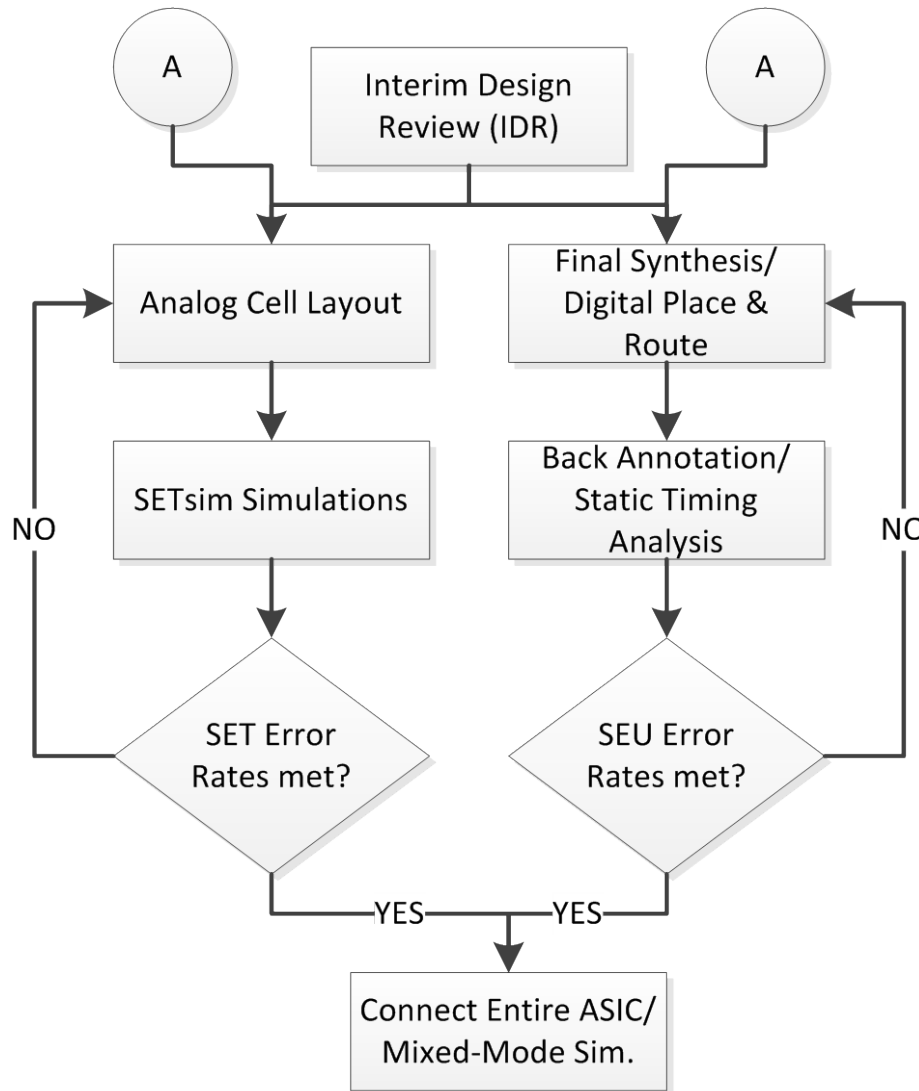


Part 3 Final Full-Chip Simulations + Database Prep.

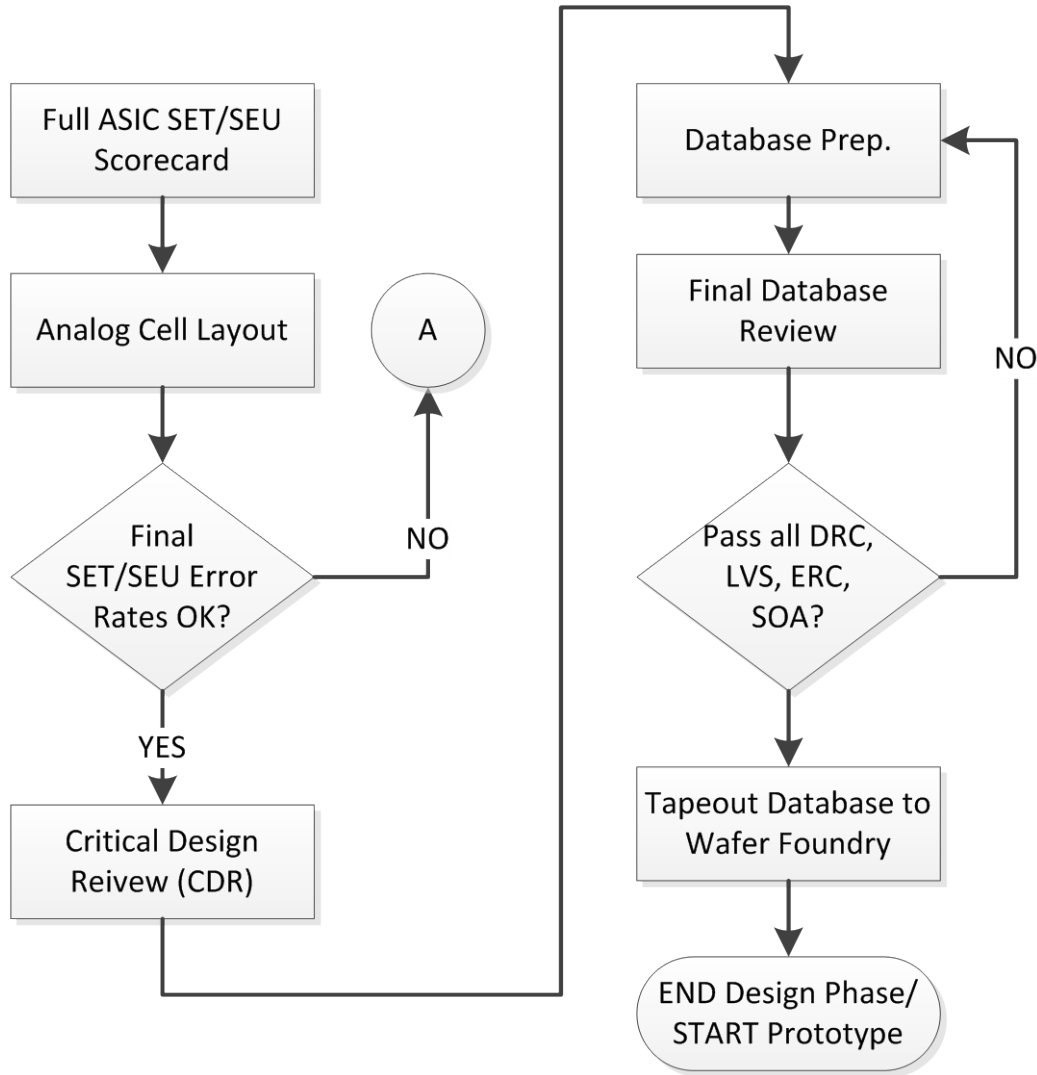
Design Flow: Part 1 Schematic Design



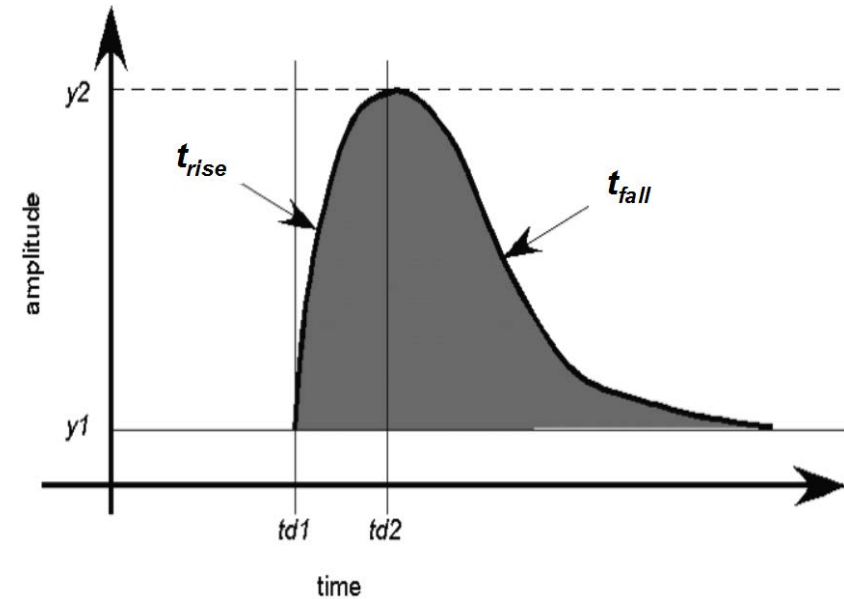
Design Flow: Part 2 Physical Design



Design Flow: Part 3



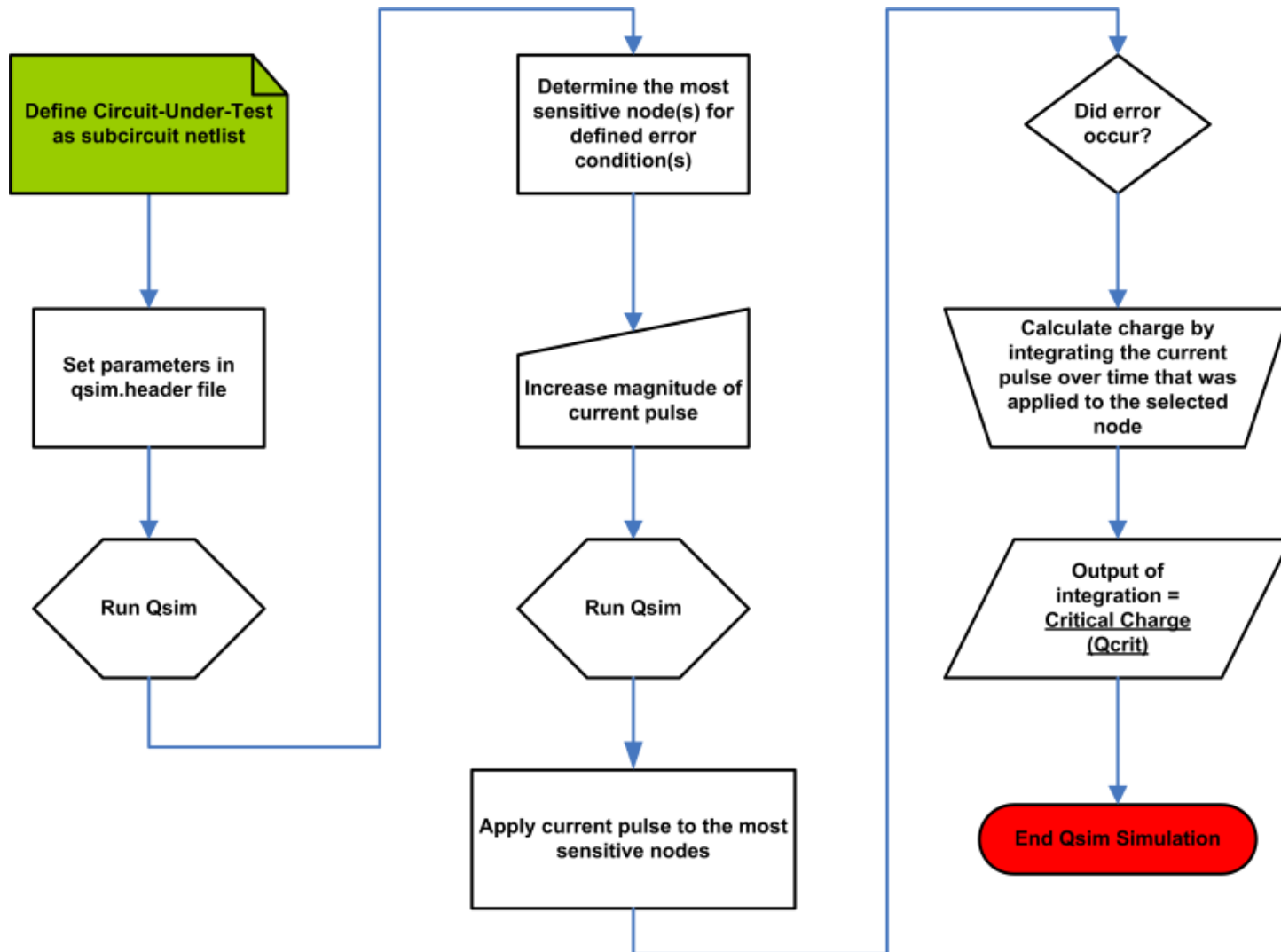
- ▼ Uses double-exponential model for funnel currents
- ▼ Total injected charge is the area under the double-exponential curve
- ▼ Current source:



$$I(t) = \begin{cases} y_1 & \text{for } 0 \leq t \leq t_{d1} \\ y_1 + (y_2 - y_1) \cdot \left(1 - \exp\left(\frac{t - t_{d1}}{\tau_1}\right)\right) & \text{for } t_{d1} \leq t \leq t_{d2} \\ y_1 + (y_2 - y_1) \cdot \left(1 - \exp\left(\frac{t - t_{d1}}{\tau_1}\right)\right) + (y_1 - y_2) \cdot \left(1 - \exp\left(\frac{t - t_{d2}}{\tau_2}\right)\right) & \text{for } t_{d2} \leq t \leq t_{\max} \end{cases}$$

- ▼ **SPICE™ based simulation engine**
- ▼ **Qsim parses SPICE netlist to find each unique electrical node**
 - If node is not reverse-biased, it is skipped
- ▼ **Qsim then creates new SPICE netlist containing double-exponential current sources**
 - User defines parameters of the current source:
 - ▼ τ_1, τ_2, y_2
 - ▼ y_1 based upon bias-point used for simulation
- ▼ **Qsim batches SPICE simulations**
- ▼ **User inspects output to determine whether SET caused an error**

Qsim: Determining Critical Charge, Q_{crit}



▼ Inputs:

- **3-Dimensional Sensitive Regions representing one or more electrical nodes**
 - ▼ **Multiple diffusions of same electrical node**
 - ▼ **Multiple diffusions of two or more different electrical nodes**
 - ▼ **6-sided prisms with 8 vertices (trapezoidal prisms)**
- **Particle Radiation Environment**
 - ▼ **No scattering: Flux Density vs. LET**
 - ▼ **Scattering: Flux Density vs E for each ion type in spectrum**

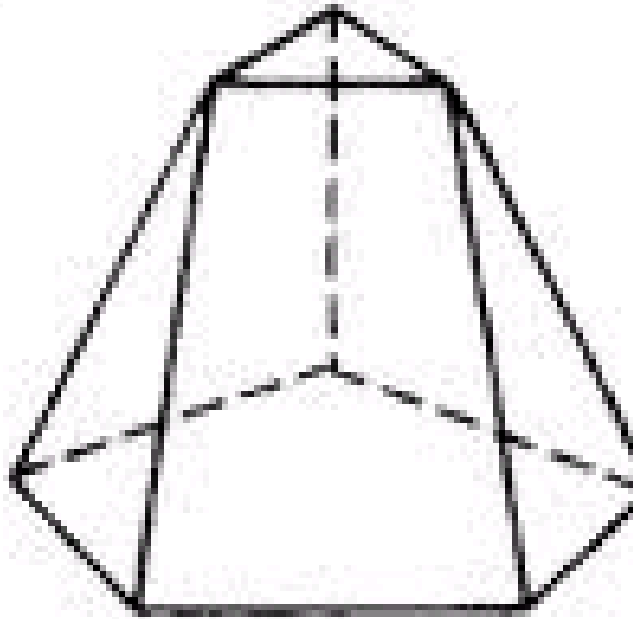
▼ Output:

- **Rate vs. Deposited Charge for the node in the analog cell being modeled, for the particular environment**

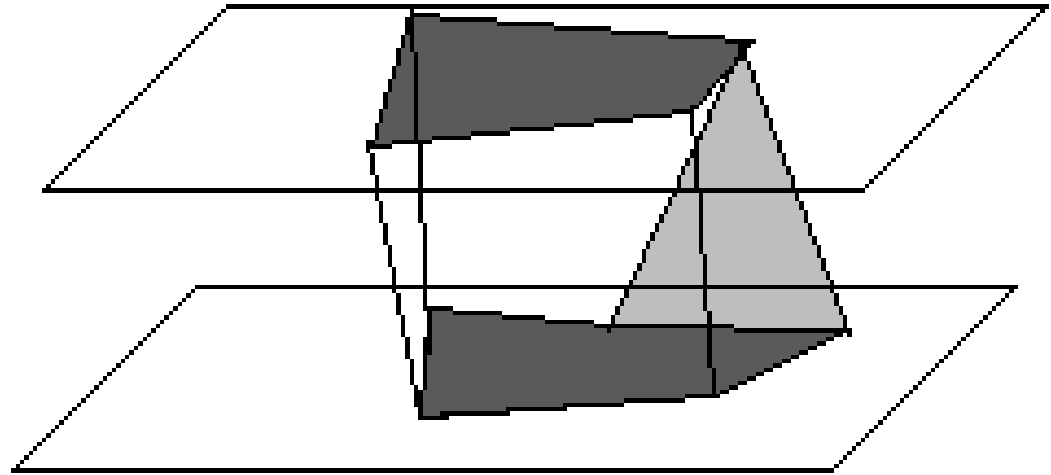
▼ 3-Dimensional Sensitive Regions: Prismatoids

- What is a Prismatoid?
 - ▼ Polyhedron with all vertices lying in one of two parallel planes
 - ▼ At least two parallel surfaces (surface of silicon and sensitive depth of silicon)
 - ▼ Other sides need not be perpendicular to the two parallel surfaces
 - ▼ Two parallel sides need not be the same size nor same number of vertices
- SETsim uses any number of 6-sided *prismatoids* with 8 vertices, 4 in each of the two parallel planes, i.e. *trapezoidal prismatoids*
 - ▼ Prismatoids may abut one another on any face to create arbitrarily complex geometries

Prismatoids



Unequal number of vertices in each of the parallel planes



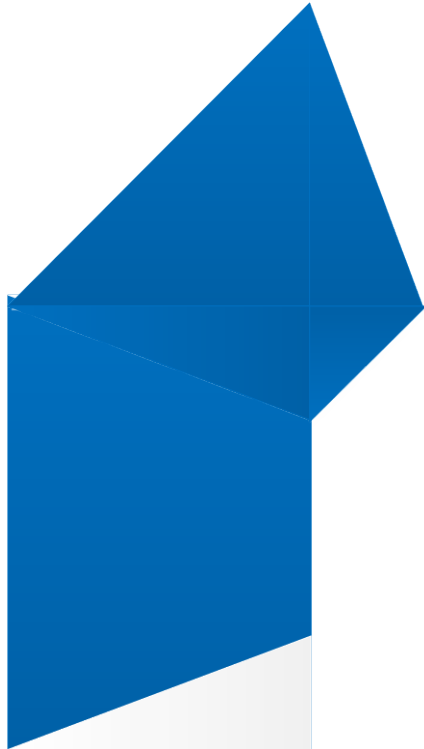
Equal number of vertices in each of the parallel planes.
(4 vertices in each plane = trapezoidal prismatoid)

Abutting Prismatoids: Plan View



Top surface plan view

Abutting Prismatoids: Plan View



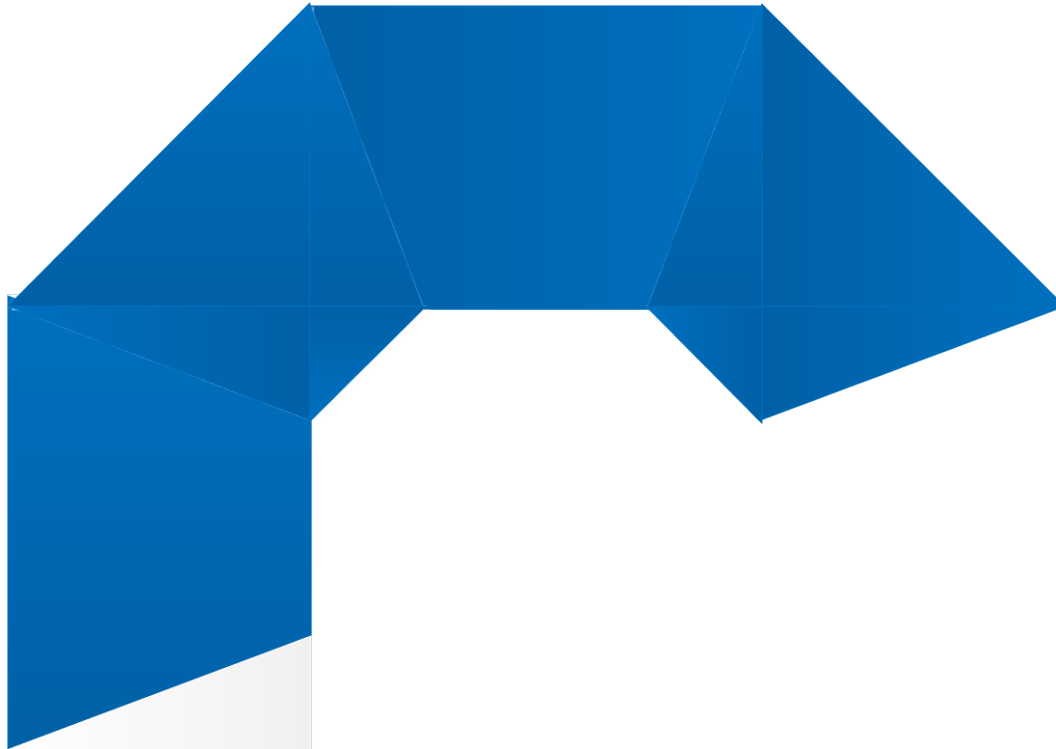
Add another trapezoidal prismatoid

Abutting Prisms: Plan View



and another....

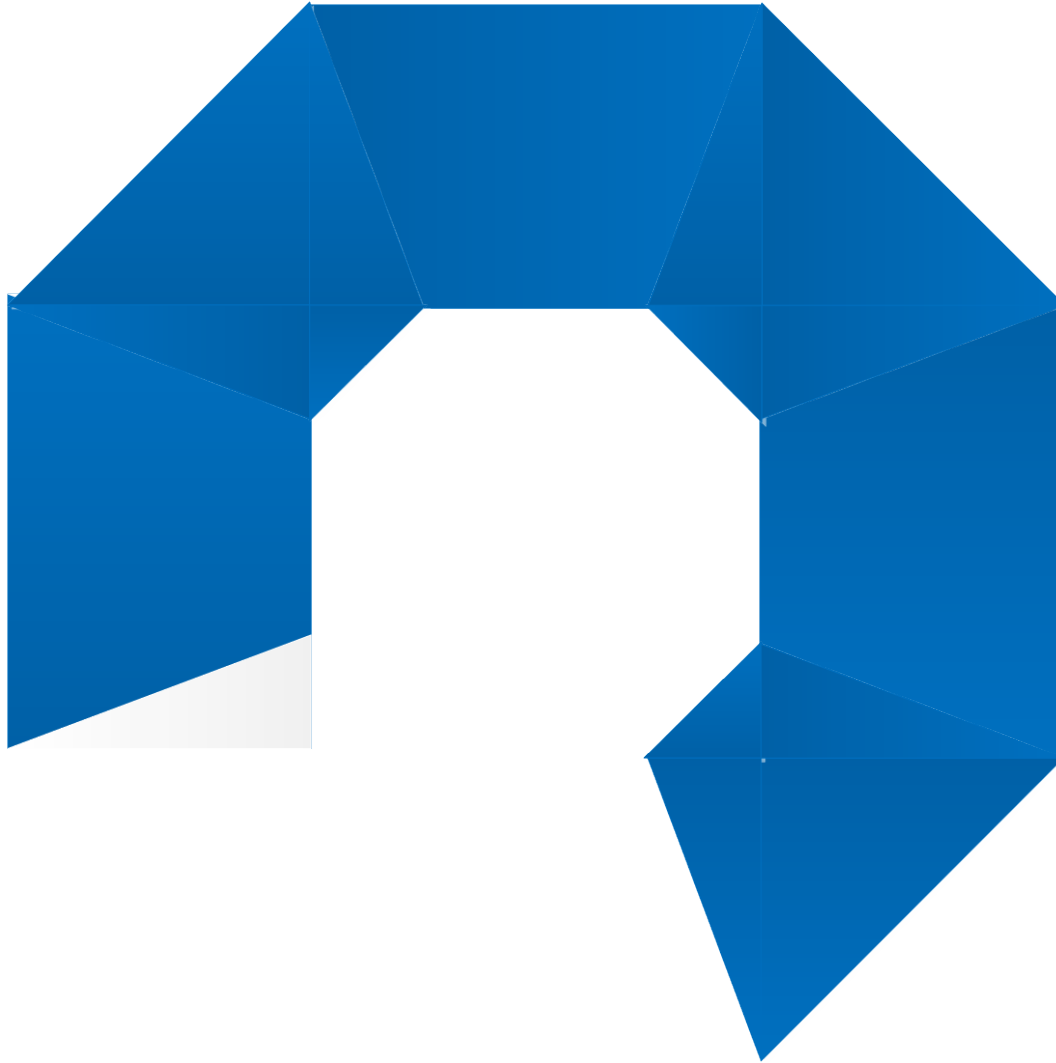
Abutting Prismatoids: Plan View



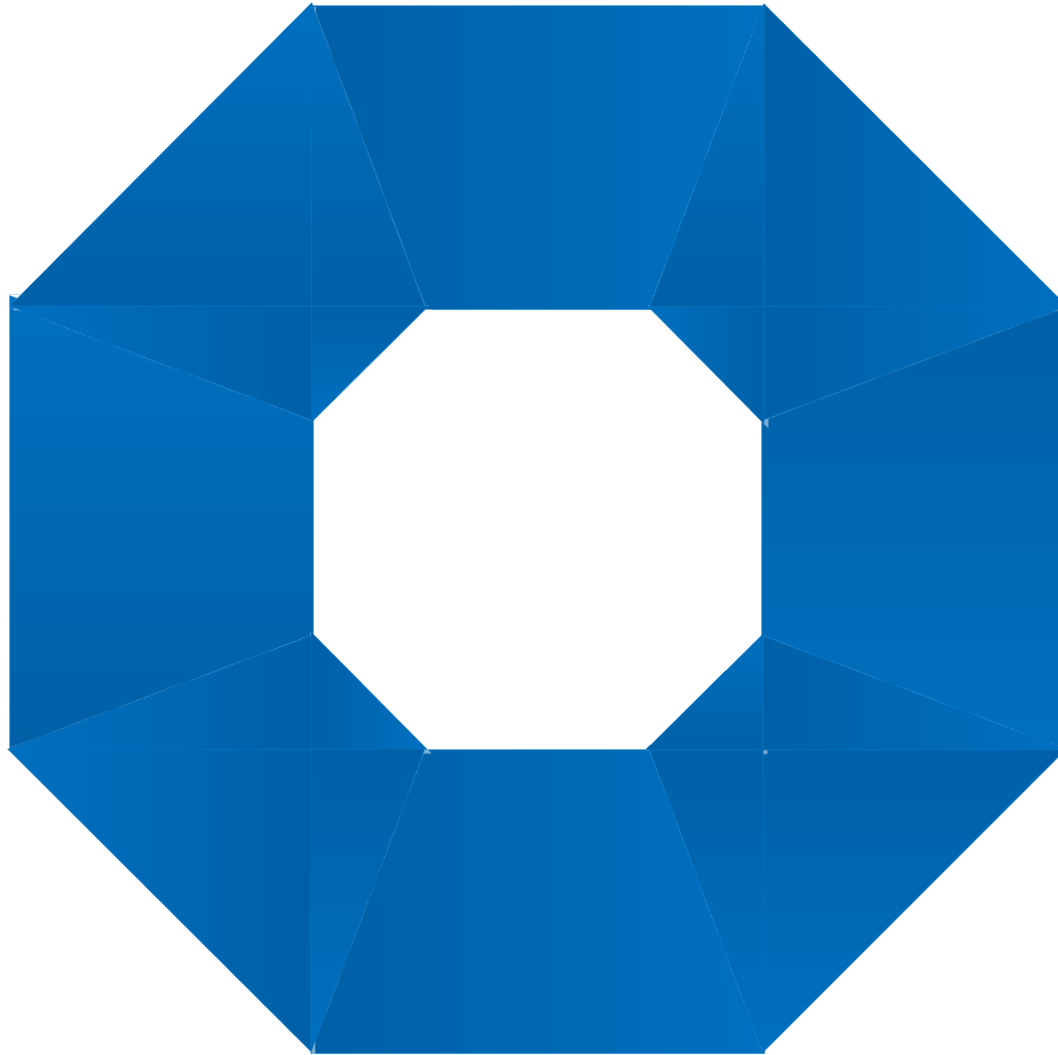
Abutting Prismatoids: Plan View



Abutting Prismatoids: Plan View



Abutting Prisms: Plan View



**Arbitrarily
Complex
Shapes
Can be Modeled**

Abutting Prismatoids: Cross-Section View



Effects of varying doping concentration with depth can be modeled.

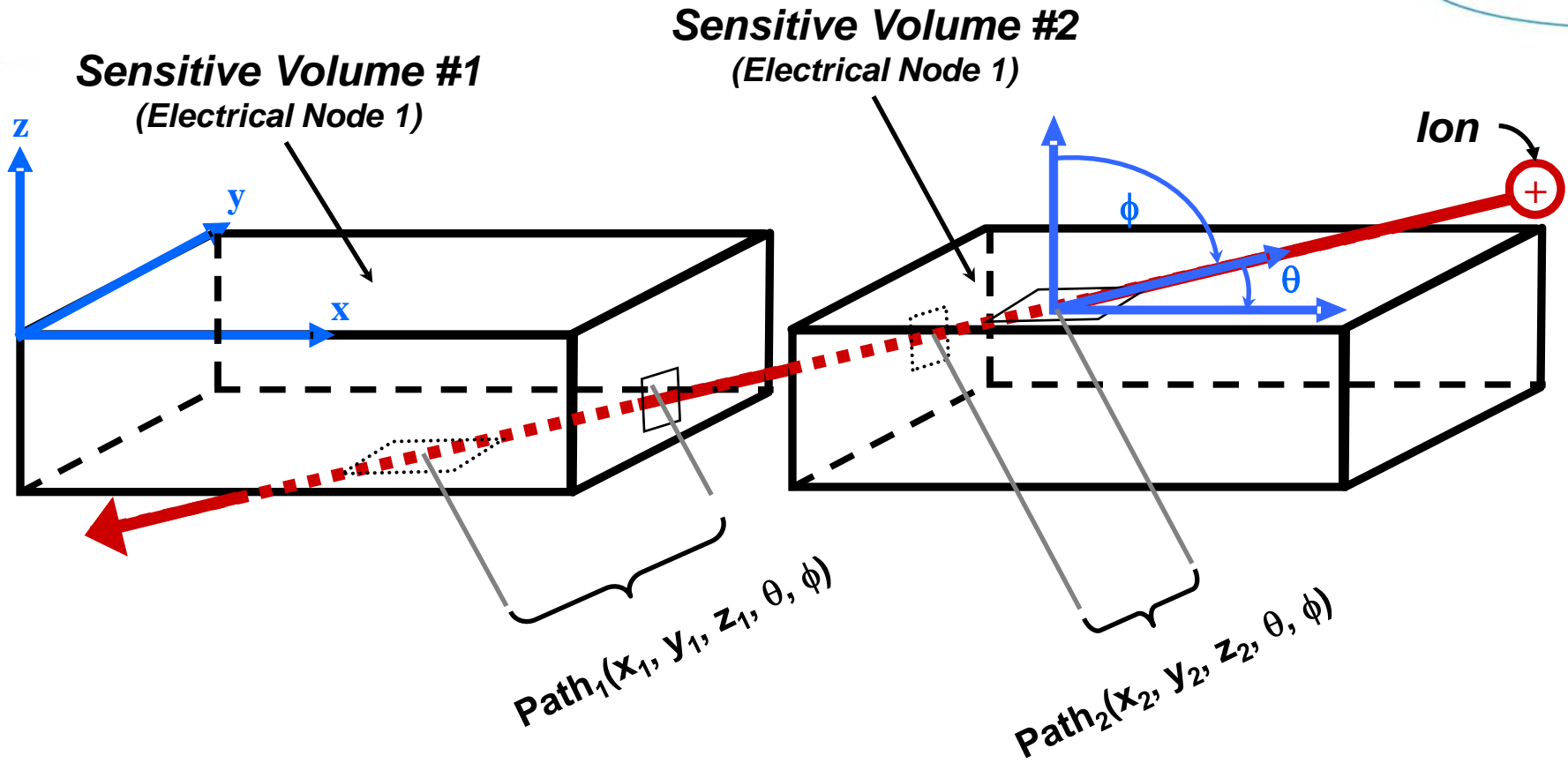
▼ Electrical Node:

- Index specifying which electrical node is being modeled
- May have multiple prismatoids defining the same electrical node
- May have multiple prismatoids defining different electrical nodes (as in multiple bit upset)

▼ Material Index:

- Index specifying material such as Si, SiO₂, Al, W, Cu
- For non-Si materials:
 - ▼ Ion Scattered; Ion Energy and LET modified
 - ▼ But no charge is collected
- For Si material index:
 - ▼ Ion Scattered; Ion Energy and LET modified
 - ▼ Charge is collected per electrical node

Multiple Sensitive Regions

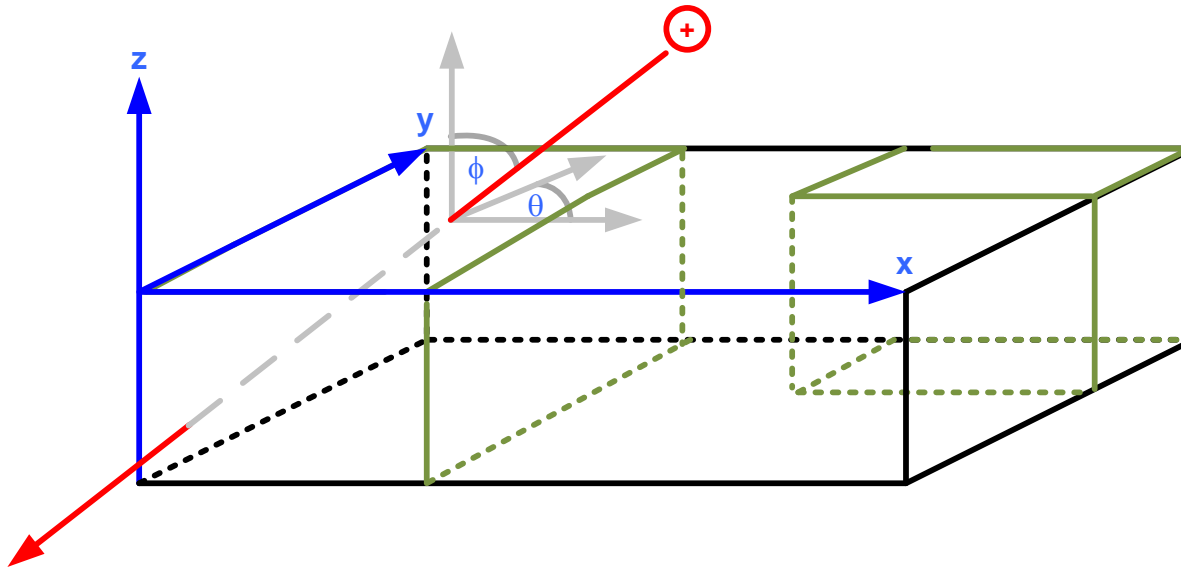


Total Path Length = $\Delta x = \text{Path}_1 + \text{Path}_2$

$$Q_{gen} = \frac{LET_{ion} \cdot \rho_{Si} \cdot \Delta x}{E_c}$$

SETsim Simulation Space

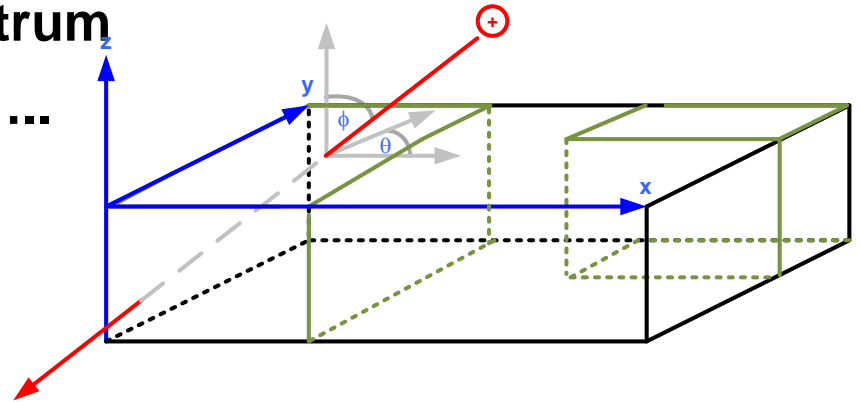
- ▼ RPP region enclosing ALL prisms constructed
 - This is the “simulation space”
 - Any region between prisms is considered Si, but not part of any electrical node



SETsim: Virtual Ion Generation is NOT Monte Carlo

▼ For each face of the RPP

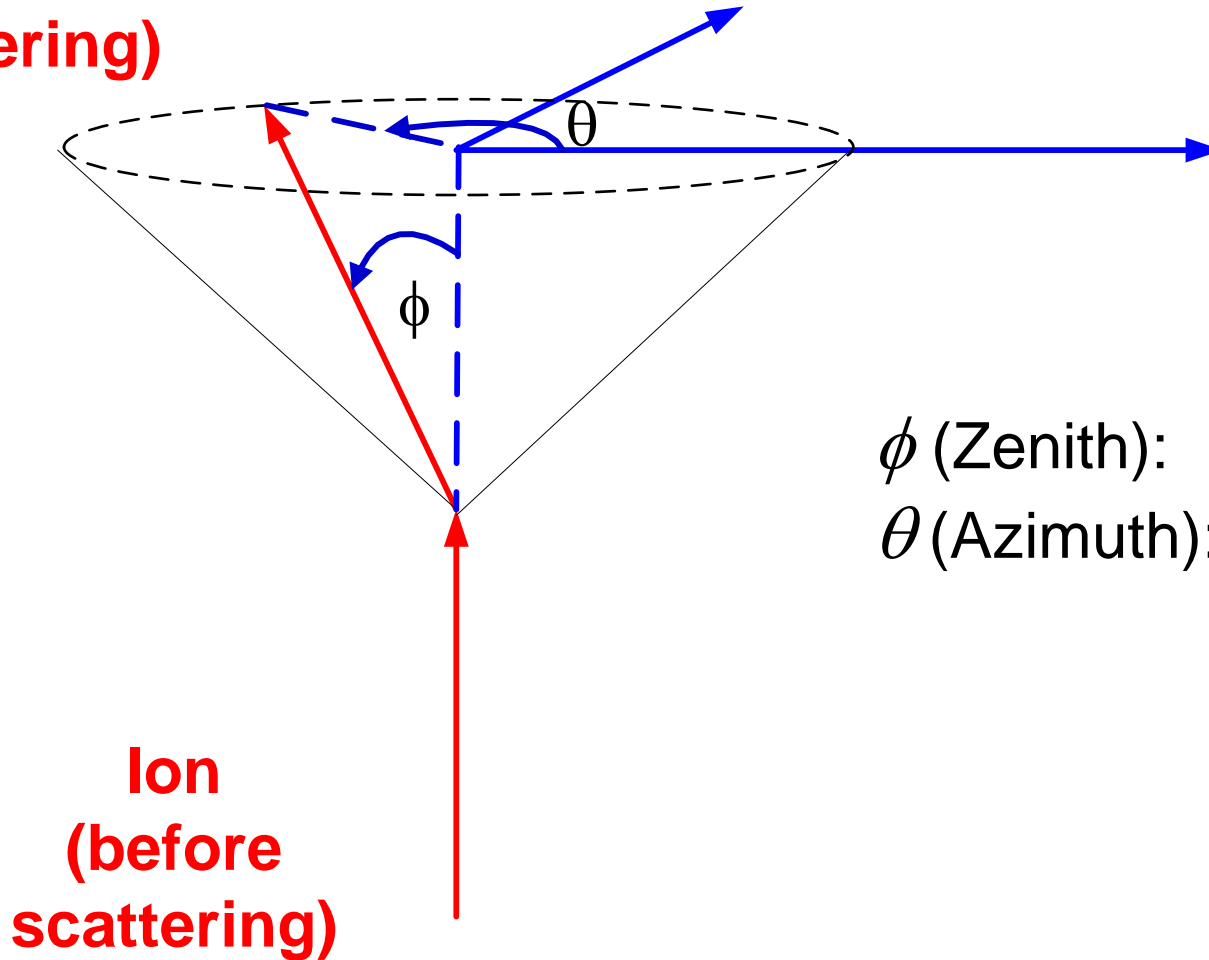
- For each ion type in the spectrum
- For each energy of such ion.....
- For $x = x_{min}$ to x_{max} step Δx
- For $y = y_{min}$ to y_{max} step Δy
- For $\theta = 0^\circ$ to 90° step $\Delta\theta$
- For $\phi = 0^\circ$ to 360° step $\Delta\phi$
- Create an Ion Object and “shoot” it into the simulation space
- Push Ion a fixed distance.
- Scatter Ion. Calculate new Ion Energy/LET
 - ▼ If ion inside prismatic of Si with nonzero electrical node index:
Collect Charge
- Repeat until Ion Energy < 0 or until ion has exited simulation space



▼ Next RPP face

Ion Scattering Problem

**Ion
(after
scattering)**



ϕ (Zenith): 0° to 180°

θ (Azimuth): 0° to 360°

- ▼ **Off-line simulations of ion scattering using TRIM**
- ▼ **For a fixed thickness of Si (or SiO₂, Al, etc.), and for a given ion energy, there is a distribution of ion positions at the back of the thin slice of material**
- ▼ **Reduce to Azimuth and Zenith angle distributions**
- ▼ **Azimuth is (not surprisingly) uniformly distributed between 0° and 360°**
- ▼ **Zenith distribution changes with energy and is highly peaked**
- ▼ **About 1k simulations per ion x 80 ions = 80k simulations per material.**

- ▼ **Fit the off-line simulation of zenith scattering angle to an appropriate statistical distribution**
 - Beta Distribution has upper and lower bound.
 - Scattered zenith angle has fixed upper and lower bound (0°, or no scattering, to 180°, completely back-scattered).
- ▼ **Beta Distribution: Two parameters, α and β**

$$P(x) = \frac{1}{B(\alpha, \beta)} x^{\alpha-1} (1-x)^{\beta-1}$$

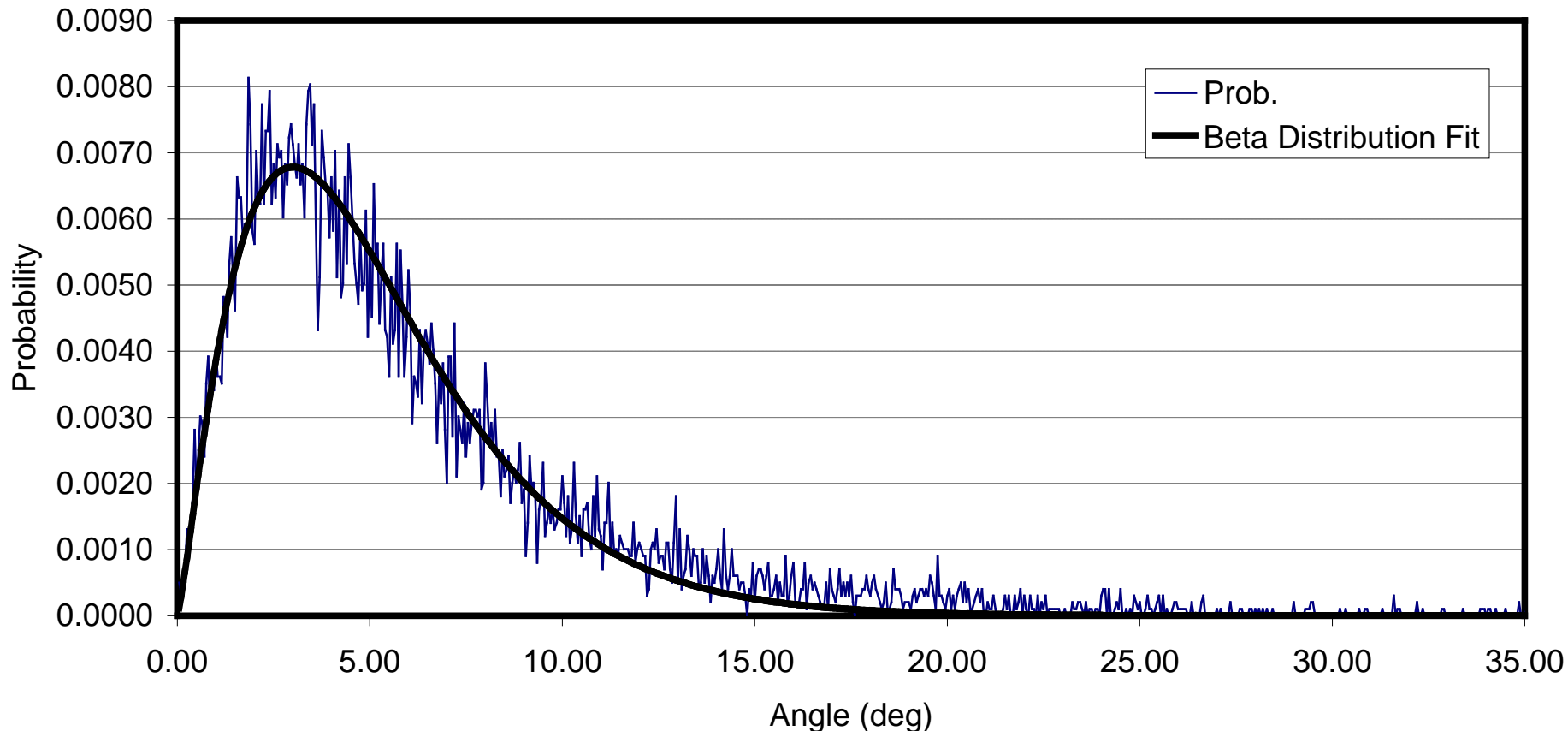
- Parameters α and β related to peak of distribution as follows:

$$x_{\max} = \frac{\alpha - 1}{\alpha + \beta - 2}$$

Fit to Beta Distribution: Fe in Si



Zenith Angle Probability Distribution for 500keV Fe ions traversing 0.1 microns Si

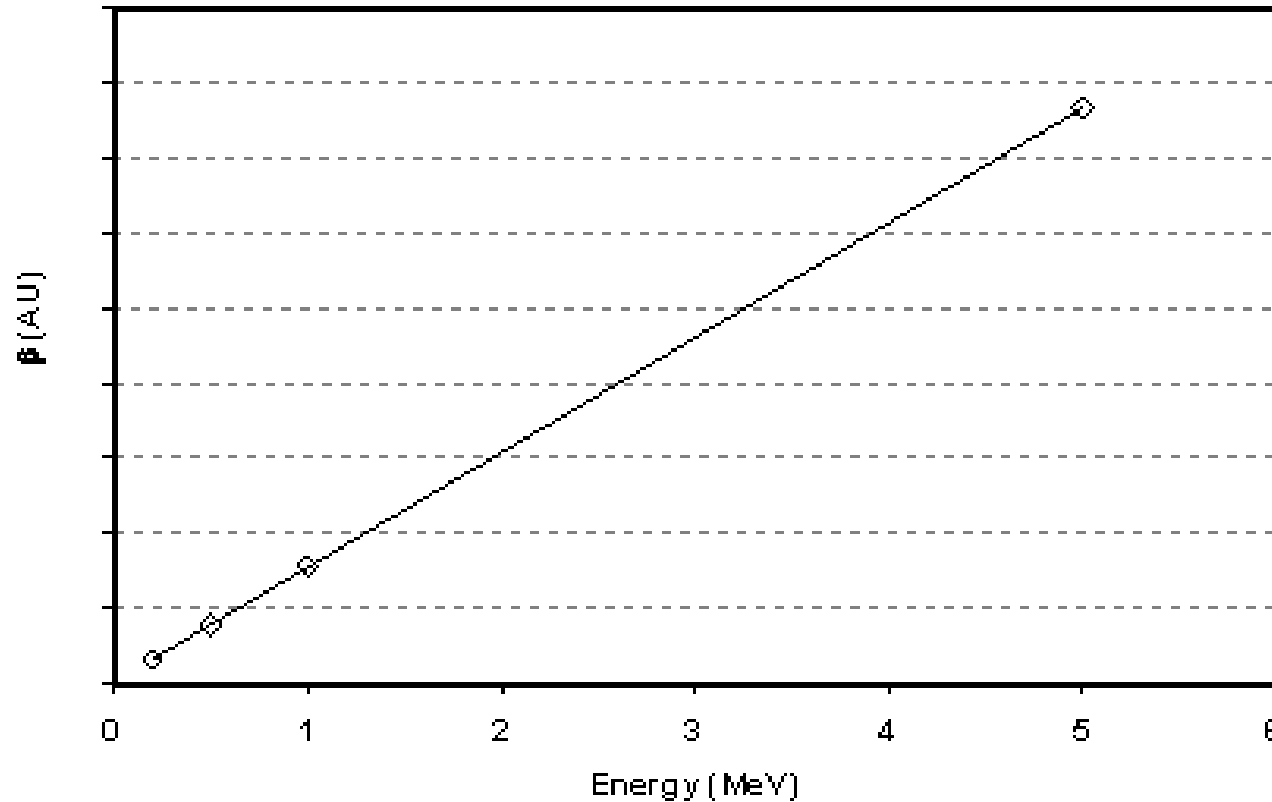


Blue: Simulation Data

Black: Beta Distribution Fit

Beta Distribution Parameters vs Ion Energy

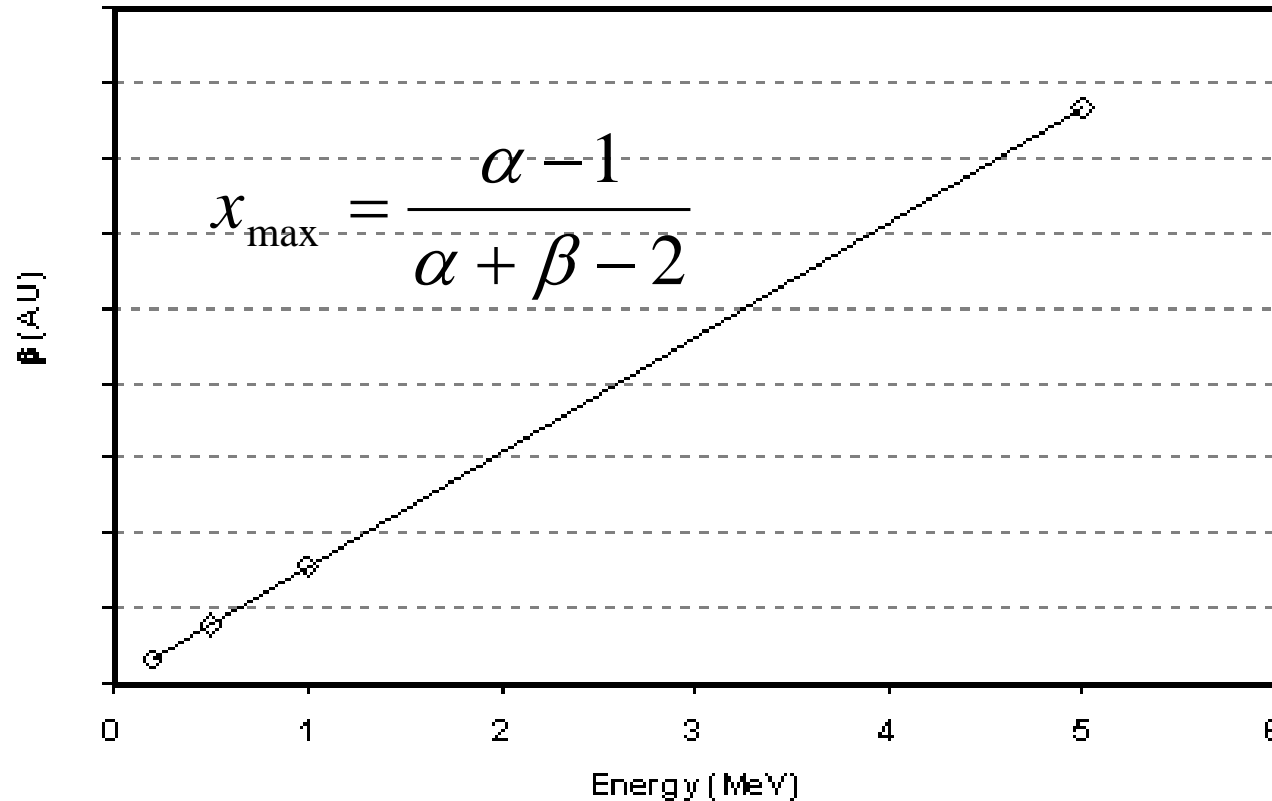
Fitting parameter β vs Energy
Fe into 0.1 micron Si



Linear (or Polynomial) Fit of the β parameter of Beta Distribution.

Beta Distribution Parameters vs Ion Energy

Fitting parameter β vs Energy
Fe into 0.1 micron Si



Linear (or Polynomial) Fit of the β parameter of Beta Distribution.

▼ Equations Pre-determined for:

- β vs E for each ion type
- ϕ_{max} vs E for each ion type
- α of scattering Beta Distribution can then be uniquely determined

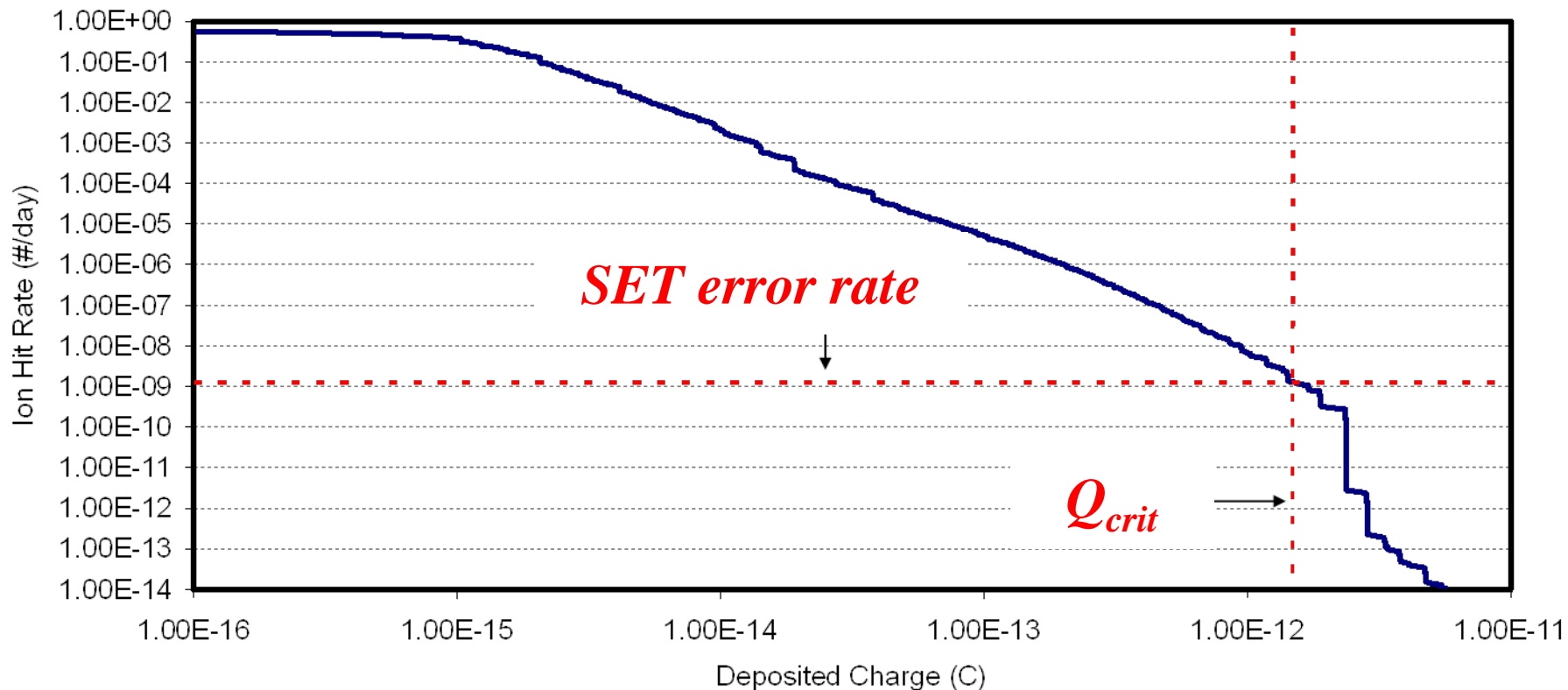
▼ Ion Scattering:

- Choose a random number between 0 and 1
 - ▼ Azimuth (θ): multiply random number by 360°
- Choose another random number between 0 and 1
 - ▼ Zenith (ϕ): use random number as probability in Inverse Beta Distribution to generate scattered zenith angle.
- This is the only part of simulation that is “Monte Carlo”.
 - ▼ If scattering not enabled, then simulation is completely deterministic.

SETsim Output: Rate vs Deposited Charge



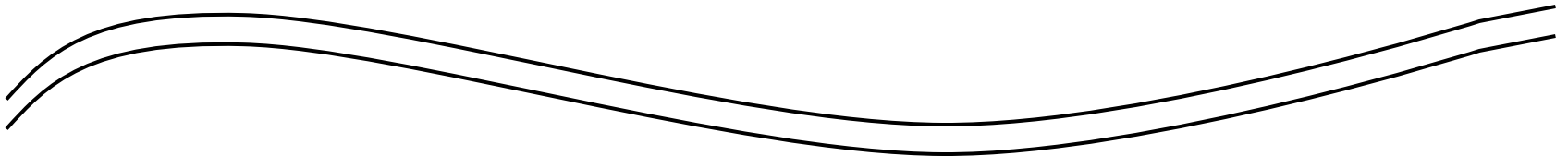
rhinv2, Ion Hit Rate vs. Deposited Charge



SET Scorecard Example (Worse Solar Day)



Cell Name	Cell Description	Critical Charge (Coulombs)	Worse Solar Day SET/SEU Rate per Cell (#/day)	Reset-Network			Clock-Network			Synchronous-Logic		
				Instances	Duty Cycle	SET Rate (#/day)	Instances	Duty Cycle	SET Rate (#/day)	Instances	Duty Cycle	SEU Rate (incl. SET) (#/day)
RHA02222	4-wide 2-2-2-2 inputs AND-OR	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	6.40E-08
RHA0I21	2-wide 2-1 inputs AND-NOR	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	6.40E-08
RHA0I22	2-wide 2-2 inputs AND-NOR	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	50	2.0%	3.20E-08
RHBUF1	1x Buffer	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	10	2.0%	6.40E-09
RHBUF2	2x Buffer	1.49E-12	6.95E-09		2.0%	0.00E+00	0	100.0%	0.00E+00	100	2.0%	1.39E-08
RHBUF4	4x Buffer	7.70E-13	3.20E-08		2.0%	0.00E+00	25	100.0%	8.01E-07	100	2.0%	6.40E-08
RHBUF4S	4x Buffer (4x-4x)	2.90E-12	2.30E-12	50	2.0%	2.30E-12	50	100.0%	1.15E-10	100	2.0%	4.60E-12
RHBUF8	8x Buffer	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	6.40E-08
RHBUF8S	8x Buffer (8x-8x)	5.80E-12	9.34E-14	50	100.0%	4.67E-12		100.0%	0.00E+00	100	2.0%	1.87E-13
RHENO	2-wide 2-2-2-inputs OR-NAND-NAND	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	6.40E-08
RHHAD1	Half Adder	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	6.40E-08
RHINV1	1x Inverter	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	6.40E-08
RHINV2	2x Inverter	1.49E-12	6.95E-09		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	1.39E-08



RHA0I211	3-wide, 2-1-1 input OR-NAND	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	6.40E-08
RHXNOR2	2-input exclusive-NOR	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	6.40E-08
RHXOR2	2-input exclusive-OR	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	6.40E-08
RHSDS2APCM - SEU	Scan D flip-flop, asynch preset/clear	1.50E-12	1.00E-12		100.0%	0.00E+00		100.0%	0.00E+00	1024	100.0%	1.02E-09
RHSDS2APCM - async SET	""	1.49E-12	1.00E-12		100.0%	0.00E+00		100.0%	0.00E+00		100.0%	0.00E+00
RHSDS2APCM - output SET	""	1.49E-12	1.00E-12		100.0%	0.00E+00		100.0%	0.00E+00		1.0%	0.00E+00
RHSDS2M - SEU	Scan D flip-flop, no preset/clear	1.50E-12	1.00E-12		100.0%	0.00E+00		100.0%	0.00E+00		100.0%	0.00E+00
RHSDS2M - output SET	""	1.49E-12	1.00E-12		100.0%	0.00E+00		100.0%	0.00E+00		1.0%	0.00E+00
				Subtotals:		1.39E-09			8.01E-07			2.31E-06

SET Scorecard Example (Worse Solar Day)



Cell Name	Cell Description	Critical Charge (Coulombs)	Worse Solar Day SET/SEU Rate per Cell (#/day)	Reset-Network			Clock-Network			Synchronous-Logic		
				Instances	Duty Cycle	SET Rate (#/day)	Instances	Duty Cycle	SET Rate (#/day)	Instances	Duty Cycle	SEU Rate (incl. SET) (#/day)
RHA02222	4-wide 2-2-2-2 inputs AND-OR	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	6.40E-08
RHA0I21	2-wide 2-1 inputs AND-NOR	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	6.40E-08
RHA0I22	2-wide 2-2 inputs AND-NOR	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	50	2.0%	3.20E-08
RHBUF1	1x Buffer	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	10	2.0%	6.40E-09
RHBUF2	2x Buffer	1.49E-12	6.95E-09		2.0%	0.00E+00	0	100.0%	0.00E+00	100	2.0%	1.39E-08
RHBUF4	4x Buffer	7.70E-13	3.20E-08		2.0%	0.00E+00	25	100.0%	8.01E-07	100	2.0%	6.40E-08
RHBUF4S	4x Buffer (4x-4x)	2.90E-12	1.16E-12	50	2.0%	2.30E-12	50	100.0%	1.15E-10	100	2.0%	4.60E-12
RHBUF8	8x Buffer	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	6.40E-08
RHBUF8S	8x Buffer (8x-8x)	5.80E-13	2.34E-14	50	100.0%	4.67E-12		100.0%	0.00E+00	100	2.0%	1.87E-13
RHENO	2-wide 2-2-2-inputs OR-NAND-NAND	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	6.40E-08
RHHAD1	Half Adder	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	6.40E-08
RHINV1	1x Inverter	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	6.40E-08
RHINV2	2x Inverter	1.49E-12	6.95E-09		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	1.39E-08

Cell Name	Cell Description	Critical Charge (Coulombs)	Worse Solar Day SET/SEU Rate per Cell (#/day)	Reset-Network			Instances	Duty Cycle	SET Rate (#/day)	Instances	Duty Cycle	SEU Rate (incl. SET) (#/day)
				Instances	Duty Cycle	SET Rate (#/day)						
RHA0I211		7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	6.40E-08
RHXNOR2		7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	6.40E-08
RHXOR2		7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	6.40E-08
RHSDS2AP		7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	1024	100.0%	1.02E-09
RHSDS2AP		7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00		100.0%	0.00E+00
RHSDS2AP								100.0%	0.00E+00		1.0%	0.00E+00
RHSDS2M - SEU	Scan D flip-flop, no preset/clear	1.50E-12	1.00E-12		100.0%	0.00E+00		100.0%	0.00E+00		100.0%	0.00E+00
RHSDS2M - output SET	""	1.49E-12	1.00E-12		100.0%	0.00E+00		100.0%	0.00E+00		1.0%	0.00E+00
Subtotals:						1.39E-09			8.01E-07			2.31E-06

SET Scorecard Example (Worse Solar Day)

Cell Name	Cell Description	Critical Charge (Coulombs)	Worse Solar Day SET/SEU Rate per Cell (#/day)	Reset-Network			Clock-Network			Synchronous-Logic		
				Instances	Duty Cycle	SET Rate (#/day)	Instances	Duty Cycle	SET Rate (#/day)	Instances	Duty Cycle	SEU Rate (incl. SET) (#/day)
RHAO2222	4-wide 2-2-2-2 inputs AND-OR	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	6.40E-08
RHAOI21	2-wide 2-1 inputs AND-NOR	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	6.40E-08
RHAOI22	2-wide 2-2 inputs AND-NOR	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	50	2.0%	3.20E-08
RHBUF1	1x Buffer	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	10	2.0%	6.40E-09
RHBUF2	2x Buffer	1.49E-12	6.95E-09		2.0%	0.00E+00	0	100.0%	0.00E+00	100	2.0%	1.39E-08
RHBUF4	4x Buffer	7.70E-13	3.20E-08		2.0%	0.00E+00	25	100.0%	8.01E-07	100	2.0%	6.40E-08
RHBUF4S	4x Buffer (4x-4x)	2.90E-12	2.30E-12	50	2.0%	2.30E-12	50	100.0%	1.15E-10	100	2.0%	4.60E-12
RHBUF8	8x Buffer	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	6.40E-08
RHBUF8S	8x Buffer (8x-8x)	5.80E-12	9.34E-14	50	100.0%	4.67E-12		100.0%	0.00E+00	100	2.0%	1.87E-13
RHENO	2-wide 2-2-2-inputs OR-NAND-NAND	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	6.40E-08
RHHAD1	Half Adder	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	6.40E-08
RHINV1	1x Inverter	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	6.40E-08
RHINV2	2x Inverter	1.49E-12	6.95E-09		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	1.39E-08



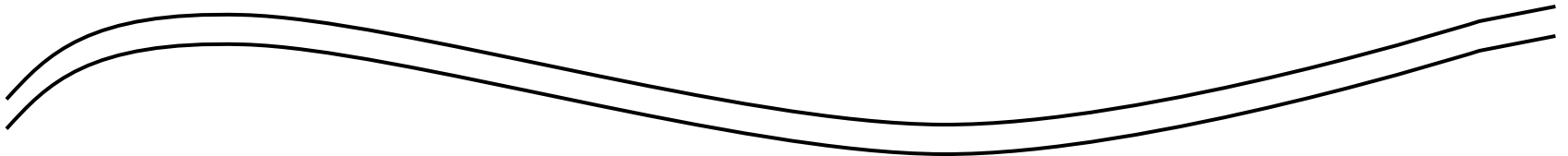
RHOAI211	3-wide, 2-1-1 input OR-NAND	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	6.40E-08
RHXNOR2	2-input exclusive-NOR	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	6.40E-08
RHXOR2	2-input exclusive-OR	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	6.40E-08
RHSDS2APCM - SEU	Scan D flip-flop, asynch preset/clear	1.50E-12	1.00E-12		100.0%	0.00E+00		100.0%	0.00E+00	1024	100.0%	1.02E-09
RHSDS2APCM - async SET	""	1.49E-12	1.00E-12		100.0%	0.00E+00		100.0%	0.00E+00		100.0%	0.00E+00
RHSDS2APCM - output SET	""	1.49E-12	1.00E-12		100.0%	0.00E+00		100.0%	0.00E+00		1.0%	0.00E+00
RHSDS2M - SEU	Scan D flip-flop, no preset/clear	1.50E-12	1.00E-12		100.0%	0.00E+00		100.0%	0.00E+00		100.0%	0.00E+00
RHSDS2M - output SET	""	1.49E-12	1.00E-12		100.0%	0.00E+00		100.0%	0.00E+00		1.0%	0.00E+00
Subtotals:						1.39E-09			8.01E-07			2.31E-06

Inadvertent RESET asserted.



SET Scorecard Example (Worse Solar Day)

Cell Name	Cell Description	Critical Charge (Coulombs)	Worse Solar Day SET/SEU Rate per Cell (#/day)	Reset-Network			Clock-Network			Synchronous-Logic		
				Instances	Duty Cycle	SET Rate (#/day)	Instances	Duty Cycle	SET Rate (#/day)	Instances	Duty Cycle	SEU Rate (incl. SET) (#/day)
RHAO2222	4-wide 2-2-2-2 inputs AND-OR	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	6.40E-08
RHAOI21	2-wide 2-1 inputs AND-NOR	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	6.40E-08
RHAOI22	2-wide 2-2 inputs AND-NOR	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	50	2.0%	3.20E-08
RHBUF1	1x Buffer	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	10	2.0%	6.40E-09
RHBUF2	2x Buffer	1.49E-12	6.95E-09		2.0%	0.00E+00	0	100.0%	0.00E+00	100	2.0%	1.39E-08
RHBUF4	4x Buffer	7.70E-13	3.20E-08		2.0%	0.00E+00	25	100.0%	8.01E-07	100	2.0%	6.40E-08
RHBUF4S	4x Buffer (4x-4x)	2.90E-12	2.30E-12	50	2.0%	2.30E-12	50	100.0%	1.15E-10	100	2.0%	4.60E-12
RHBUF8	8x Buffer	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	6.40E-08
RHBUF8S	8x Buffer (8x-8x)	5.80E-12	9.34E-14	50	100.0%	4.67E-12		100.0%	0.00E+00	100	2.0%	1.87E-13
RHENO	2-wide 2-2-2-inputs OR-NAND-NAND	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	6.40E-08
RHHAD1	Half Adder	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	6.40E-08
RHINV1	1x Inverter	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	6.40E-08
RHINV2	2x Inverter	1.49E-12	6.95E-09		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	1.39E-08



RHOAI211	3-wide, 2-1-1 input OR-NAND	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	6.40E-08
RHXNOR2	2-input exclusive-NOR	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	6.40E-08
RHXOR2	2-input exclusive-OR	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	6.40E-08
RHSDS2APCM - SEU	Scan D flip-flop, asynch preset/clear	1.50E-12	1.00E-12		100.0%	0.00E+00		100.0%	0.00E+00	1024	100.0%	1.02E-09
RHSDS2APCM - async SET	""	1.49E-12	1.00E-12		100.0%	0.00E+00		100.0%	0.00E+00		100.0%	0.00E+00
RHSDS2APCM - output SET	""	1.49E-12	1.00E-12		100.0%	0.00E+00		100.0%	0.00E+00		1.0%	0.00E+00
RHSDS2M - SEU	Scan D flip-flop, no preset/clear	1.50E-12	1.00E-12		100.0%	0.00E+00		100.0%	0.00E+00		100.0%	0.00E+00
RHSDS2M - output SET	""	1.49E-12	1.00E-12		100.0%	0.00E+00		100.0%	0.00E+00		1.0%	0.00E+00
Subtotals:						1.39E-09			8.01E-07			2.31E-06

SEFI



SET Scorecard Example (Worse Solar Day)

Cell Name	Cell Description	Critical Charge (Coulombs)	Worse Solar Day SET/SEU Rate per Cell (#/day)	Reset-Network			Clock-Network			Synchronous-Logic		
				Instances	Duty Cycle	SET Rate (#/day)	Instances	Duty Cycle	SET Rate (#/day)	Instances	Duty Cycle	SEU Rate (incl. SET) (#/day)
RHAO2222	4-wide 2-2-2-2 inputs AND-OR	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	6.40E-08
RHAOI21	2-wide 2-1 inputs AND-NOR	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	6.40E-08
RHAOI22	2-wide 2-2 inputs AND-NOR	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	50	2.0%	3.20E-08
RHBUF1	1x Buffer	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	10	2.0%	6.40E-09
RHBUF2	2x Buffer	1.49E-12	6.95E-09		2.0%	0.00E+00	0	100.0%	0.00E+00	100	2.0%	1.39E-08
RHBUF4	4x Buffer	7.70E-13	3.20E-08		2.0%	0.00E+00	25	100.0%	8.01E-07	100	2.0%	6.40E-08
RHBUF4S	4x Buffer (4x-4x)	2.90E-12	2.30E-12	50	2.0%	2.30E-12	50	100.0%	1.15E-10	100	2.0%	4.60E-12
RHBUF8	8x Buffer	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	6.40E-08
RHBUF8S	8x Buffer (8x-8x)	5.80E-12	9.34E-14	50	100.0%	4.67E-12		100.0%	0.00E+00	100	2.0%	1.87E-13
RHENO	2-wide 2-2-2-inputs OR-NAND-NAND	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	6.40E-08
RHHAD1	Half Adder	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	6.40E-08
RHINV1	1x Inverter	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	6.40E-08
RHINV2	2x Inverter	1.49E-12	6.95E-09		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	1.39E-08

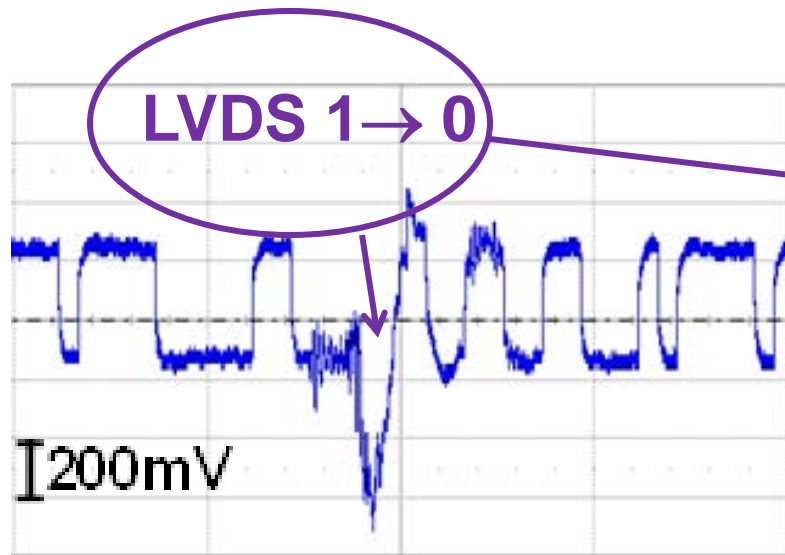


RHAOI211	3-wide, 2-1-1 input OR-NAND	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	6.40E-08
RHXNOR2	2-input exclusive-NOR	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	6.40E-08
RHXOR2	2-input exclusive-OR	7.70E-13	3.20E-08		2.0%	0.00E+00		100.0%	0.00E+00	100	2.0%	6.40E-08
RHSDS2APCM - SEU	Scan D flip-flop, asynch preset/clear	1.50E-12	1.00E-12		100.0%	0.00E+00		100.0%	0.00E+00	1024	100.0%	1.02E-09
RHSDS2APCM - async SET	""	1.49E-12	1.00E-12		100.0%	0.00E+00		100.0%	0.00E+00		100.0%	0.00E+00
RHSDS2APCM - output SET	""	1.49E-12	1.00E-12		100.0%	0.00E+00		100.0%	0.00E+00		1.0%	0.00E+00
RHSDS2M - SEU	Scan D flip-flop, no preset/clear	1.50E-12	1.00E-12		100.0%	0.00E+00		100.0%	0.00E+00		100.0%	0.00E+00
RHSDS2M - output SET	""	1.49E-12	1.00E-12		100.0%	0.00E+00		100.0%	0.00E+00		1.0%	0.00E+00
				Subtotals:		1.39E-09			8.01E-07			2.31E-06

SEU

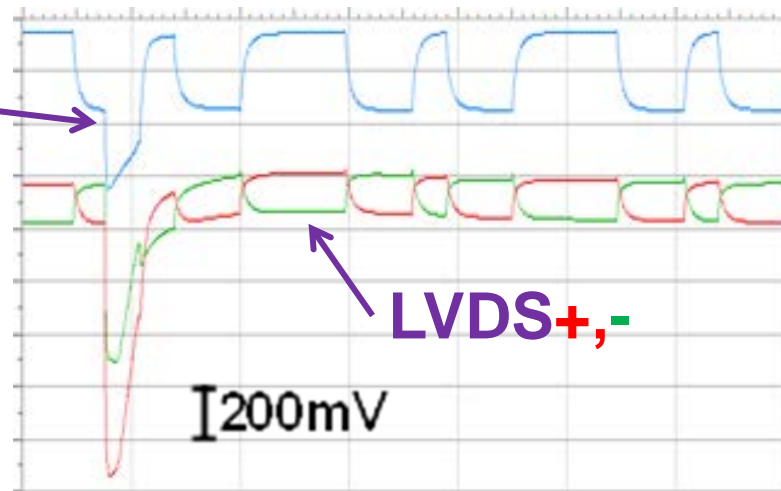


Some Results: Qsim vs Laser Irradiation



(a)

**Laser Irradiation of
LVDS Driver
(Laser Equivalent
LET = 330 MeV cm²/mg)**

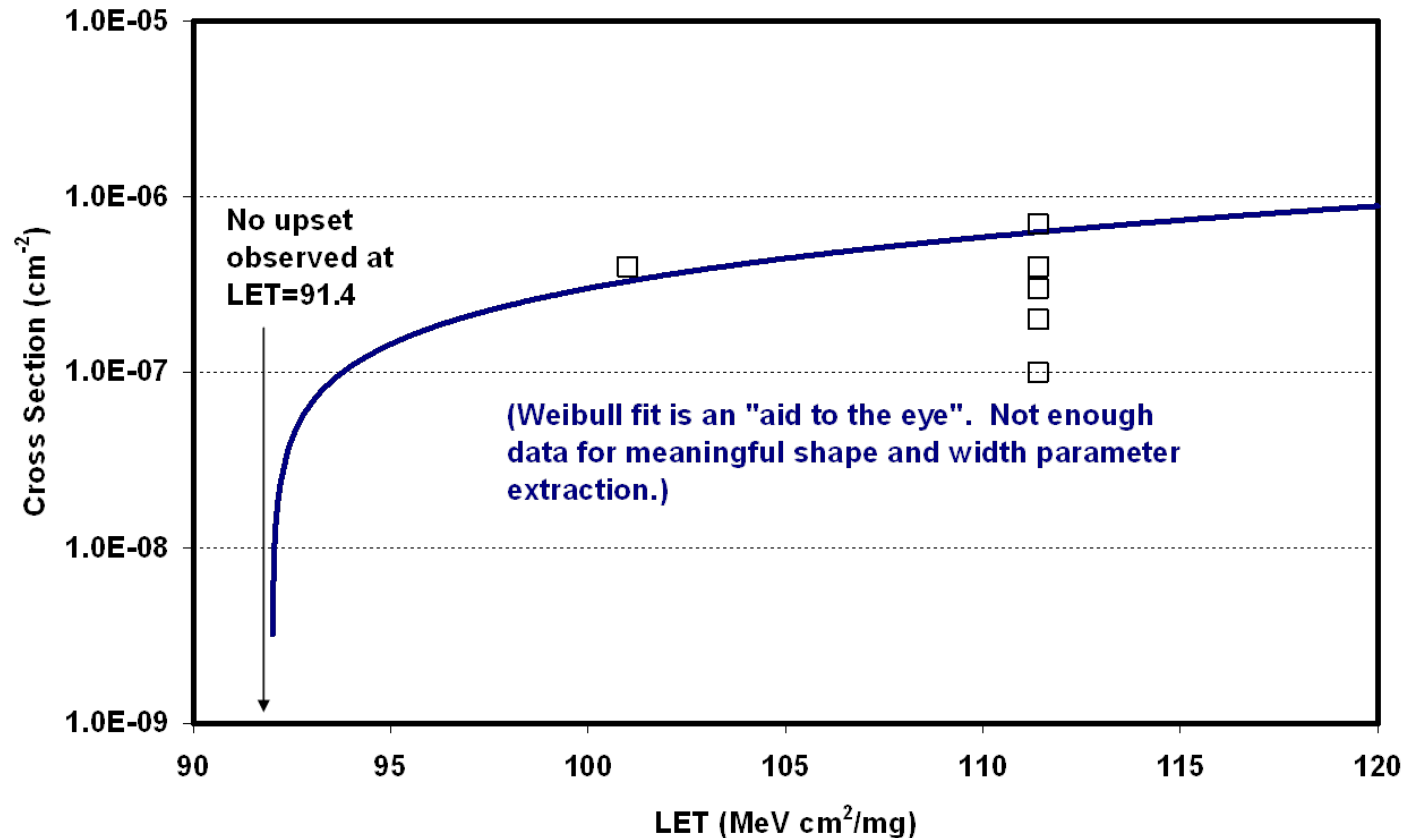


(b)

**Qsim Simulation of
same LVDS Driver
showing same error.
Magnitude of error
~same as oscilloscope
trace.**

SETsim Results:

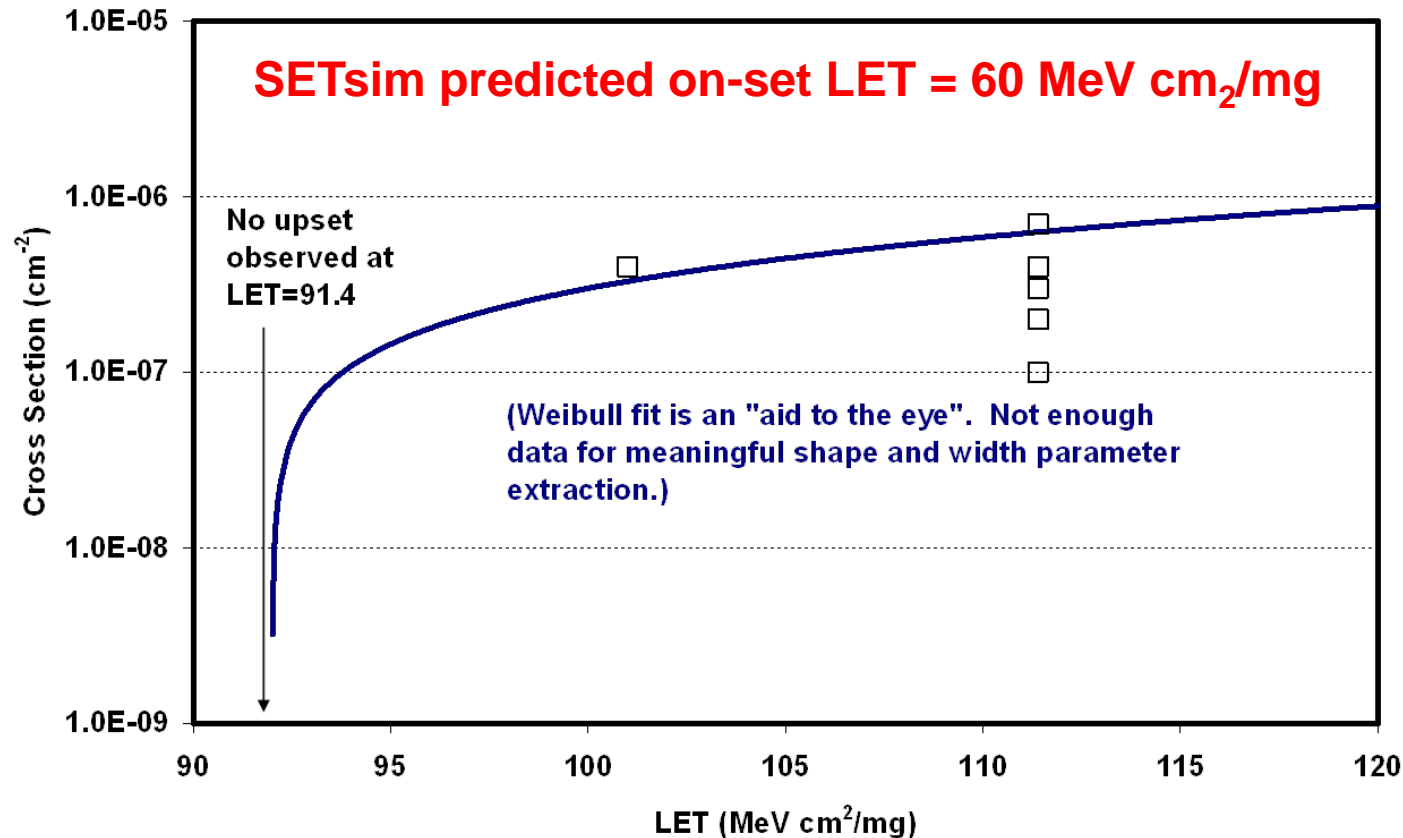
Digital SEU, YB03 ADC ASIC



Inverter chain feeding an SEU-hardened SDF

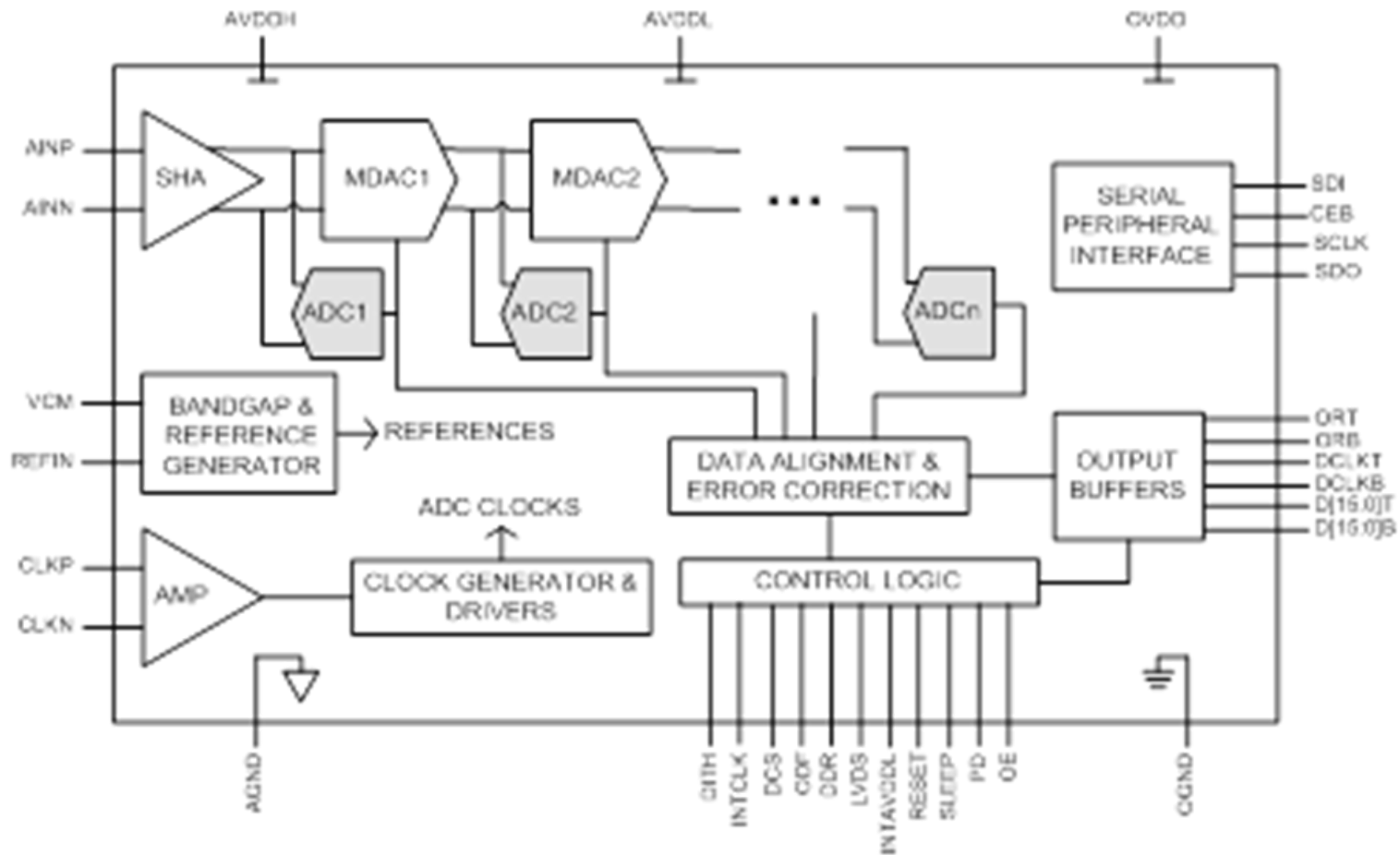
SETsim Results:

Digital SEU, YB03 ADC ASIC

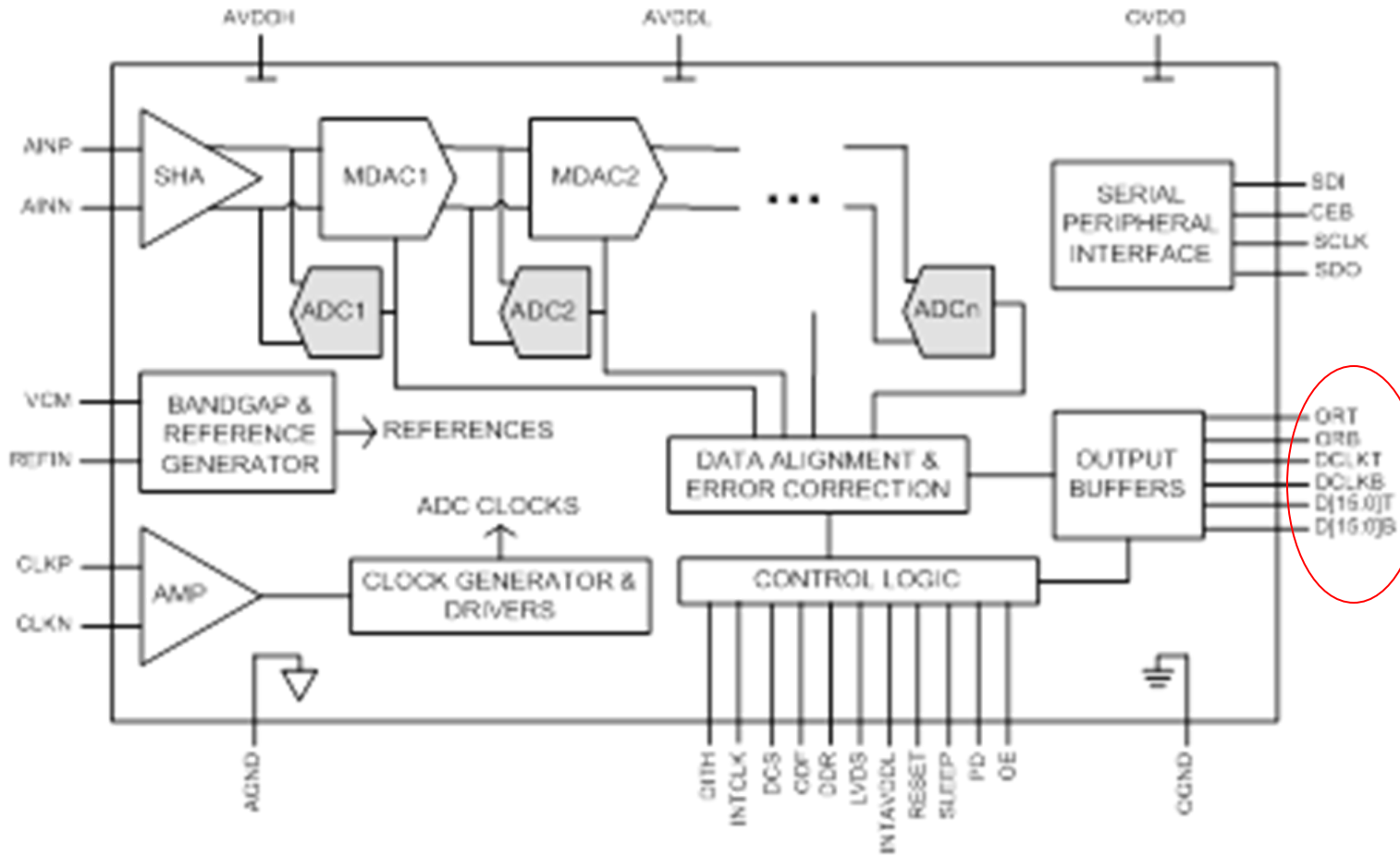


Inverter chain feeding an SEU-hardened SDF

16-bit 40MSps Pipeline ADC

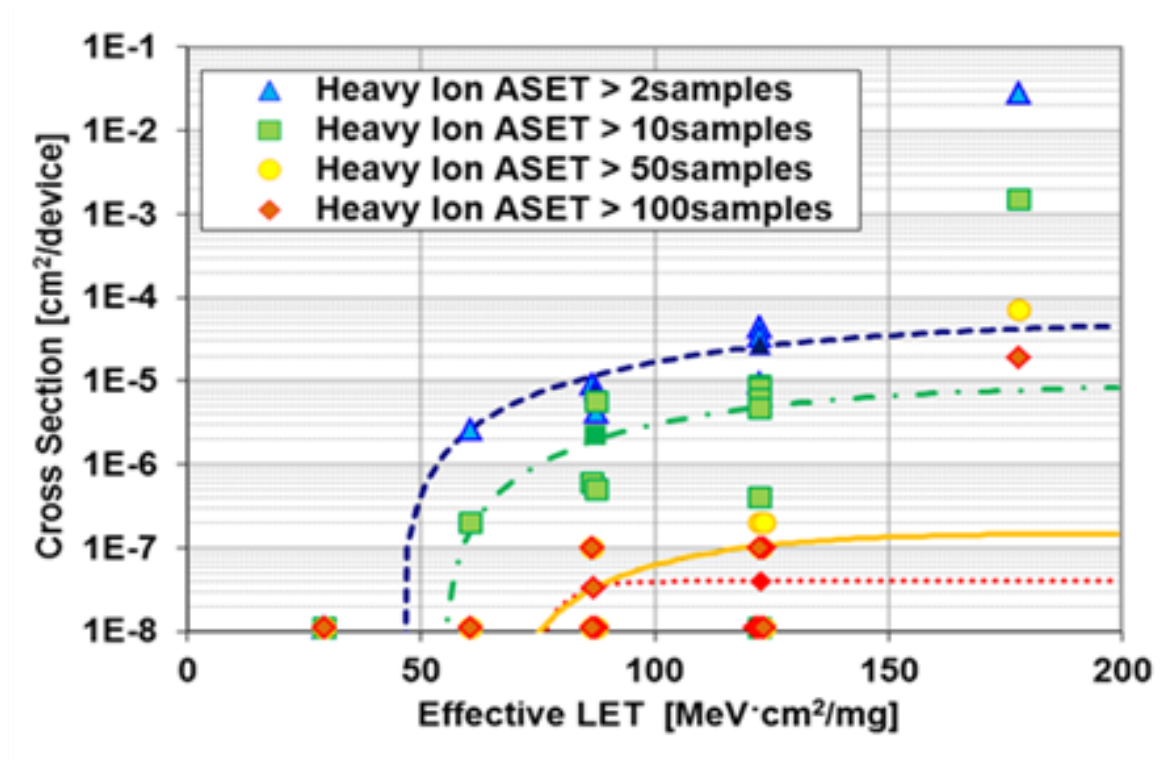


16-bit 40MSps Pipeline ADC



Converted Output deviation from normal noise level should last only 2 clock cycles

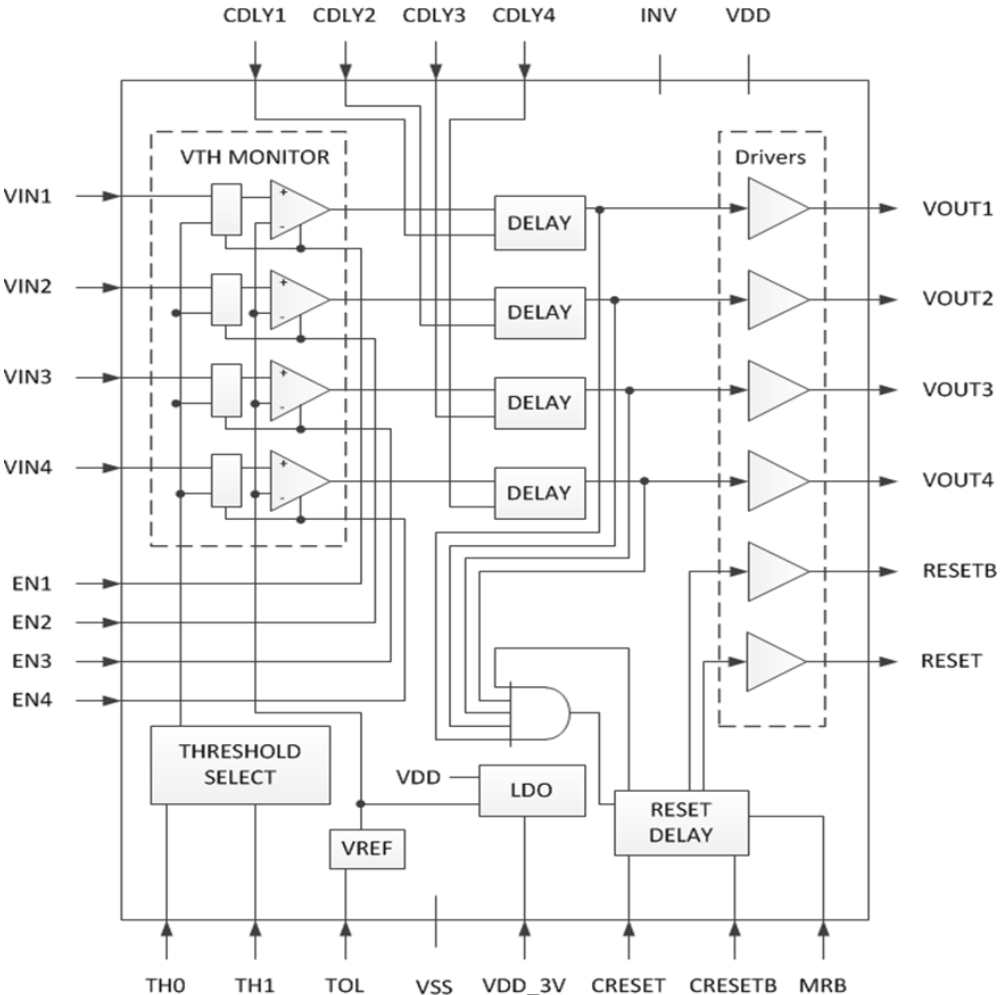
ASETs in 16-bit 40MSPS Pipeline ADC



Goal: No SETs lasting > 2 sample clocks for LET < 40 MeV cm²/mg

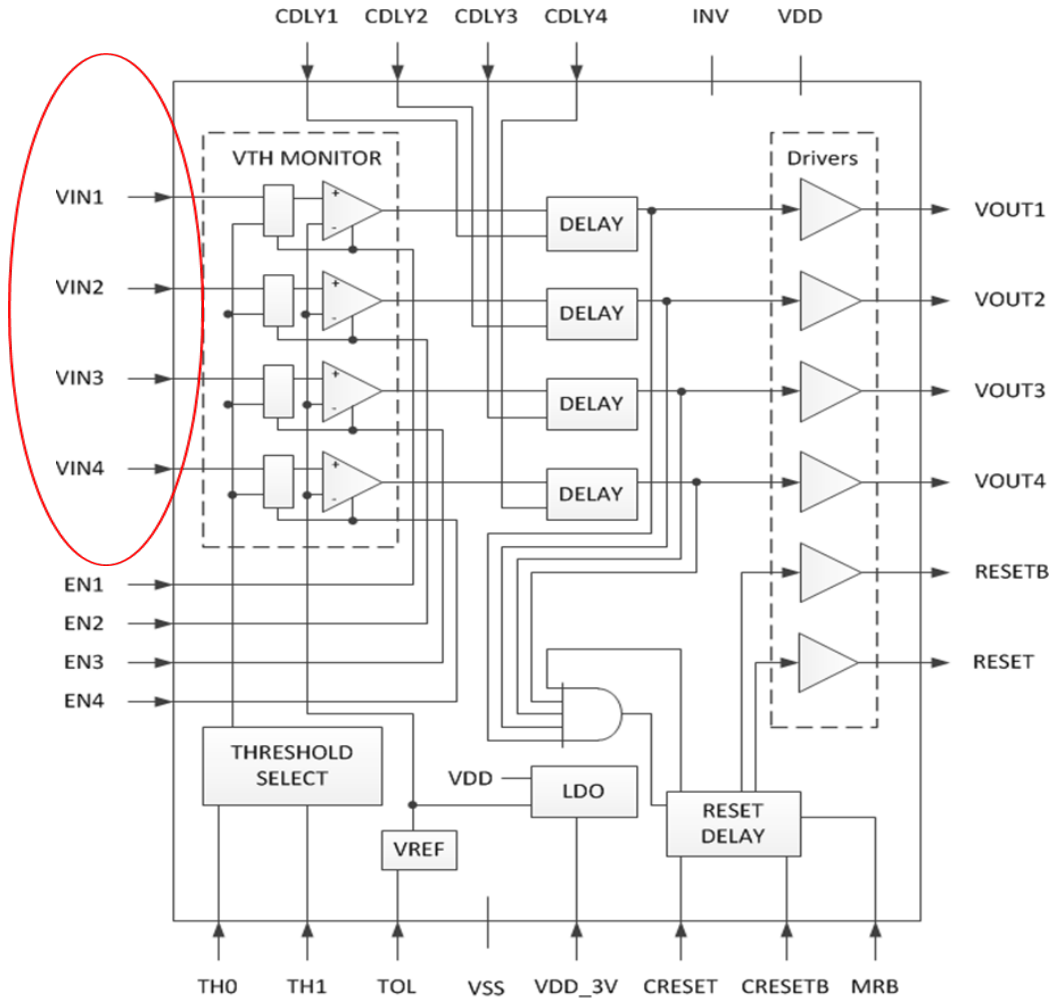
Result: ASET > 2 sample clocks on-set LET ~48 MeV cm²/mg

SETsim Results: 4-Channel Voltage Supervisor

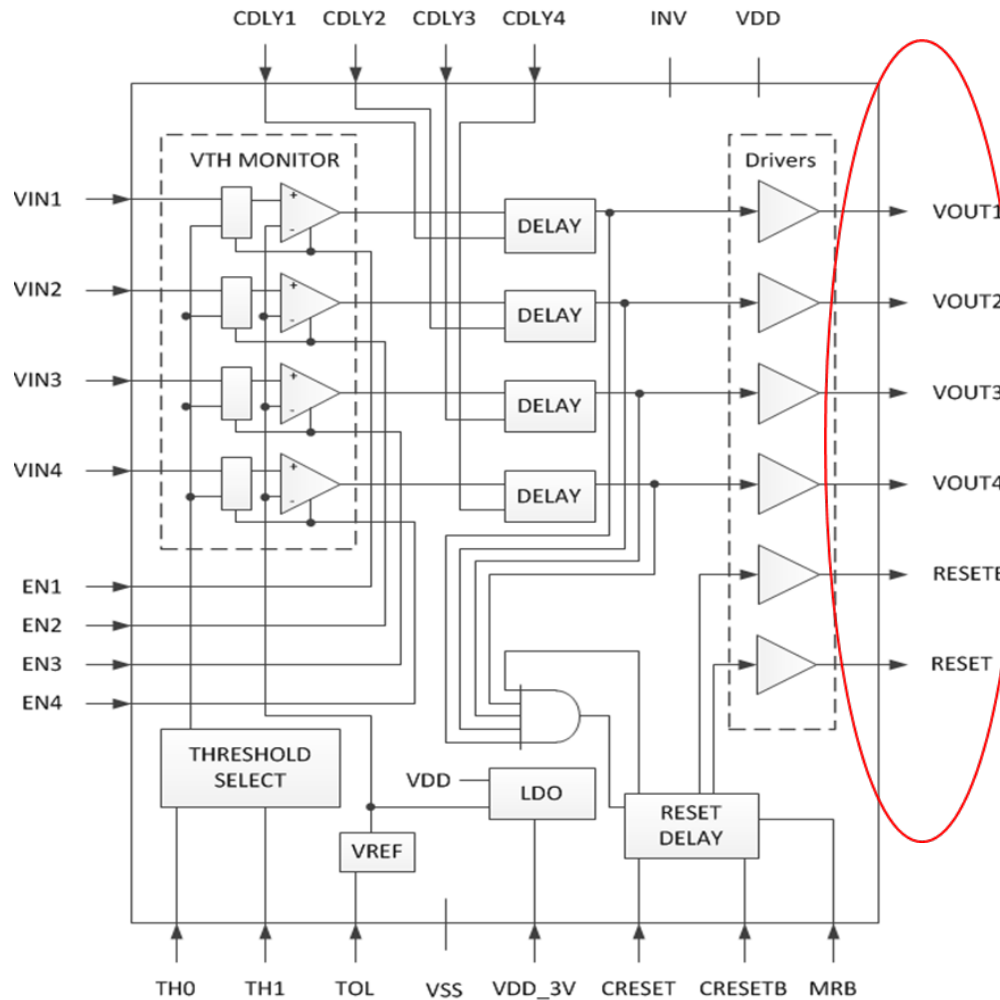


SETsim Results: 4-Channel Voltage Supervisor

Inputs set to 50mV above comparator trip point



SETsim Results: 4-Channel Voltage Supervisor



Outputs monitored for SET (either glitches or change in state)

4-Channel Voltage Supervisor Results

▼ Bias Conditions:

- 4 Inputs biased at 50mV above comparator trip point
- VDD=3.0V, 2.7V

▼ Beam:

- Xe, 60° angle of incidence (effective LET 112 MeV cm²/mg)
- 1E7 ions/cm²

▼ SETsim Prediction:

- SET on-set LET ~80 MeV cm²/mg

▼ Results:

- No SETs observed at 112 MeV cm²/mg at either VDD = 3.0V or VDD = 2.7V

SETsim vs CREME96

**Table I: Comparison of Predicted Error Rates: SETsim vs. CREME96
(Sensitive Volume = 1 x 5 x Depth μm)**

Depth(μm)	Environment	Error Rate from SETsim (errors/day)	Error Rate from CREME96 using HUP (errors/day)
1.0	Worse Solar Day	16.5E-8	7.4E-8
1.4	Worse Solar day	2.54E-7	1.5E-7
1.0	Solar Min/GCR Max	15.5E-11	6.84E-11
1.4	Solar Min/GCR Max	2.38E-10	1.48E-10

SETsim error rates ~60% to ~120% higher than CREME96:

SETsim integrates over 2π steradians over each of the six faces of simulation region.

This emphasizes longest path lengths.

Summary

- ▼ **A Priori SET Estimates made during Mixed-Signal ASIC design using Qsim and SETsim tools**
 - Qsim used to determine Critical Charge
 - SETsim used to determine rate vs Deposited Charge
- ▼ **Intersection of Q_{crit} (Qsim) with *Rate vs Charge* curve (SETsim) gives SET error rate for the cell**
- ▼ **SET Scorecard used to compile SET results for entire Mixed-Signal ASIC**
 - Error rates categorized: SEU, SET, SEFI, etc.
- ▼ **Results indicate beam-line and laser measured error rates are lower than those predicted by SETsim.**
 - Meeting error rate goals in ASIC design: high confidence that Mixed-Signal ASIC beam-line results will be within specification

Dank U!
Thank you!
Danke!
Merci!
Grazie!
Gracias!
Tack!
Ευχαριστούμε!
תודה!