Modernization of FPGA Risk Analysis for Critical Space Applications

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Acronyms

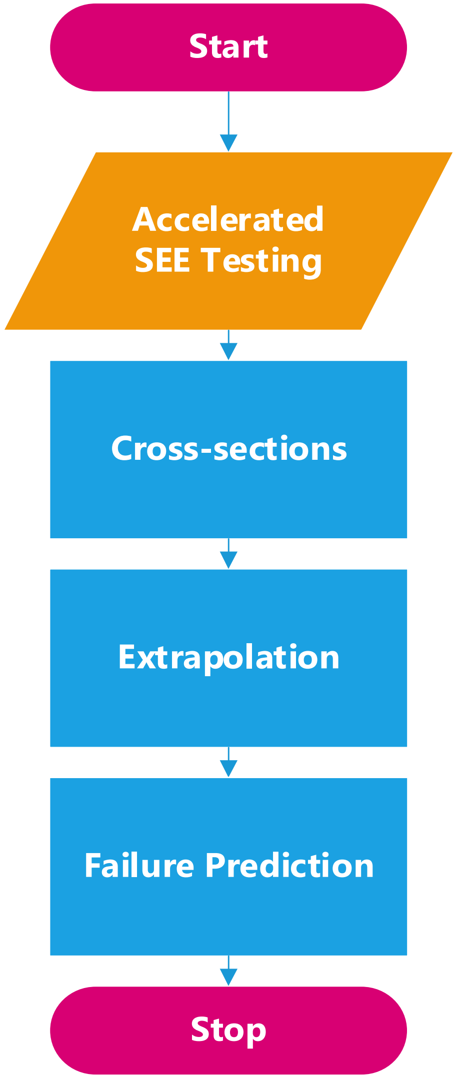
Acronym	Description	Acronym	Description	Acronym	Description
AI	Artificial Intelligence	IP	Intellectual property	RPP	Rectangular parallel pipe
BRAM	embedded static random-access memory	lb	lower bound	SEE	single event effect
CCIX	Interconnect consortium	LBNL	Lawrence Berkeley National Laboratory	SEF	single event failure
CLB	configurable logic block	LET	linear event transfer	SEFI	single event functional interrupt
CMOS	Complementary MOSFET	LUT	Look Up Table	SERDES	serializer -deserializer
CXL	Compute express link	LVDS	low Voltage Differential Signaling	SET	single event transient
DDR4	Double Data Rate 4 Synchronous Dynamic Random-Access Memory	MFTF	mean fluence to failure	SEU	single even upset
DFF	Flip-flop	MIPI	mobile industry processor interface	SoC	system on chip
DSP	Digital signal processor	n	number of events	SRAM	static random access memory
DUT	device under test	NoC	network on chip	T	number of experiments
FPGA	Field programmable gate array	P	probability	ub	upper bound
FTF	fluence to failure	PCIe	Peripheral Component Interconnect Express	wDMA	Direct memory access
G	Giga	P_{effect}	Probability an event can exist through system topology	μ	mean
Gb/s	Gigabits/second	P_{gen}	Probability an event can occur from ionization	σ	cross section
GPIO	general purpose input/output	$P_{observe}$	Probability an event can can be observed	Φ	fluence
GR	global route	RF	radio frequency	Qcoll	Collection charge
HBM	High Bandwidth Memory	RHA	Radiation Hardness Assurance	Qcrit	Critical charge
I/O	input/output	RTD	representative tactical design	twidth	Transient width

The Space Environment and Mission Operation

- The space environment consists of a variety of ionizing particles (radiation) that can disrupt mission operations.
- Risk analysis or failure analysis is performed to determine component-level susceptibilities and how they can potentially affect system operation in radiation environments.
- Goal: investigate susceptibilities and predict (calculate) the probability of an upset:
  - Requires space environment particle flux data.
  - Requires component susceptibility data

Radiation Hardness Assurance (RHA)

- Radiation Hardness Assurance (RHA) is the process of:
  - Identifying possible susceptibilities, vulnerabilities and failure modes
  - Obtaining single event effects (SEE) data… performing radiation testing on components at a beam facility (accelerated testing).
  - Analyzing SEE data (calculating cross-sections).
  - Extrapolating SEE data (using target environment particle flux) to a tactical system:
    - Transform accelerated (beam) SEE data to target space environment.
    - Transform test structure susceptibilities to target system topology.
  - Calculating failure rates based on extrapolation information.
  - Based on mission requirements, mitigation (fault tolerance) insertion



Device Penetration of Heavy Ions and Linear Energy Transfer (LET)

How Do Heavy Ions Affect Electronics?

- LET characterizes the deposition of charged particles passing through a device.
- Based on Average energy loss (dE) per unit path length (dx) (stopping power)
- Density is used to normalize LET to the target material (ρ).

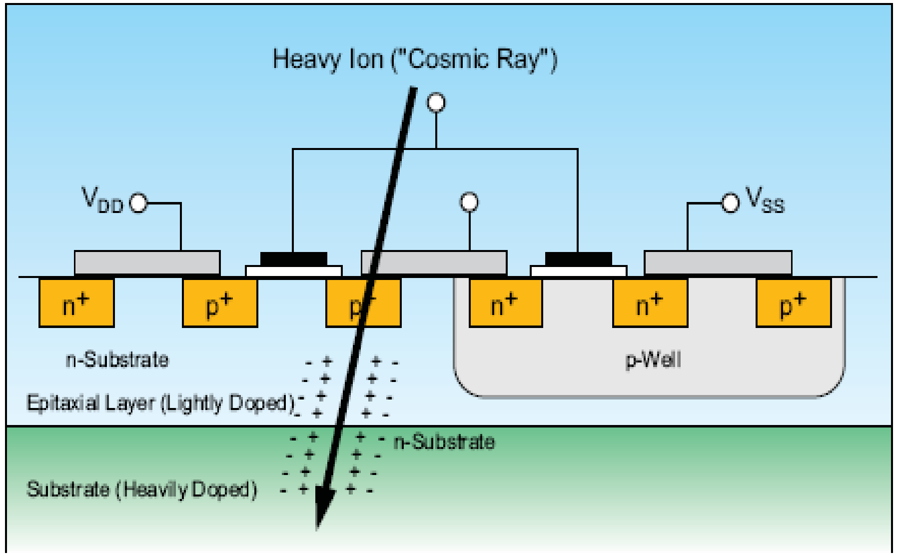
$$LET = \frac{1}{\rho}\frac{dE}{dx} \qquad MeV\frac{cm^2}{mg}$$

Energy

Linear path length

Units

Density of target material



Average energy deposited per unit path length

Sensitive region: Rectangular Parallelpiped

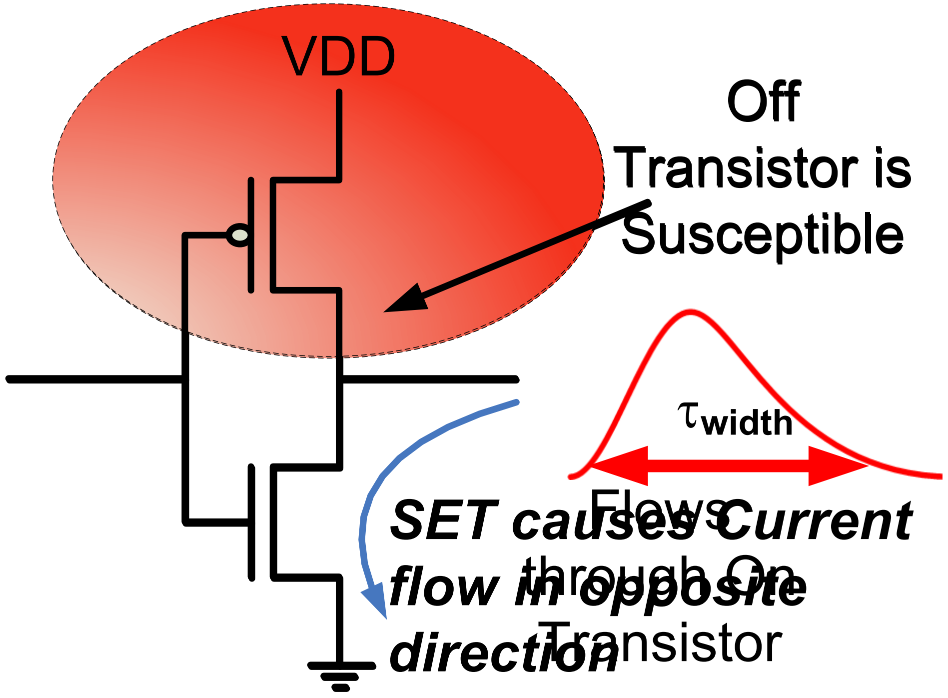
Energy Collection and SET Generation

Collected Charge *Critical Charge*

$$Q_{coll} > Q_{crit}$$

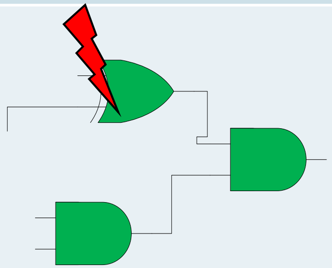
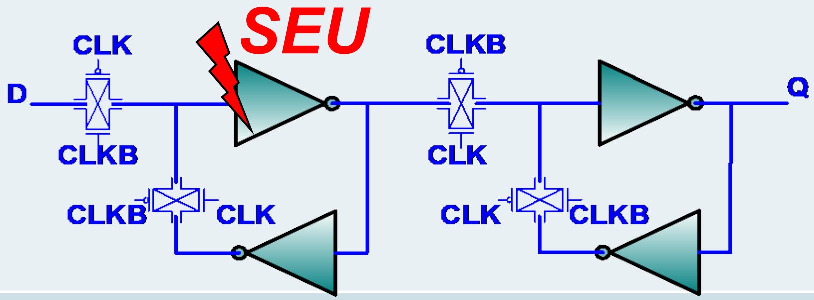
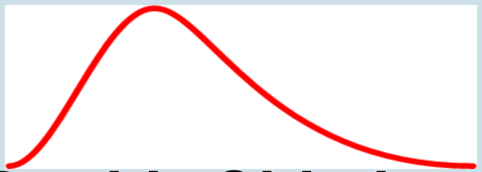
- For CMOS, SET generation occurs due to an “off” gate turning “on”.
- For a CMOS SET: there is a push-pull between the on gate and the off gate Q_{coll}
- SETs can have significant metastable states

VDD: Voltage



- SET has an amplitude and width (τ_{width}) based on:
  - Amount of Q_{coll} (i.e. small LET →small SET)
  - The capacitance of the gate’s load
  - The strength (current) of its complimentary “ON” gate
  - The dissipation strength of the process.
- Captured SET is a SEU

SEUs and SETs in Combinatorial Logic and Edge Triggered Flip Flops (DFF)

Combinatorial (CL)	Sequential (DFF)
Logic function generation (computation)	Captures and holds state of data input at rising edge of clock
SET 	
Glitch in the CL:  *Double Sided*	SET Capture in DFF loop  *Single Sided*

Edge triggered DFF SEEs are significantly different than a latch due to master-slave capture topology.

Investigating Failure Modes: Radiation Testing and SEE Cross Sections

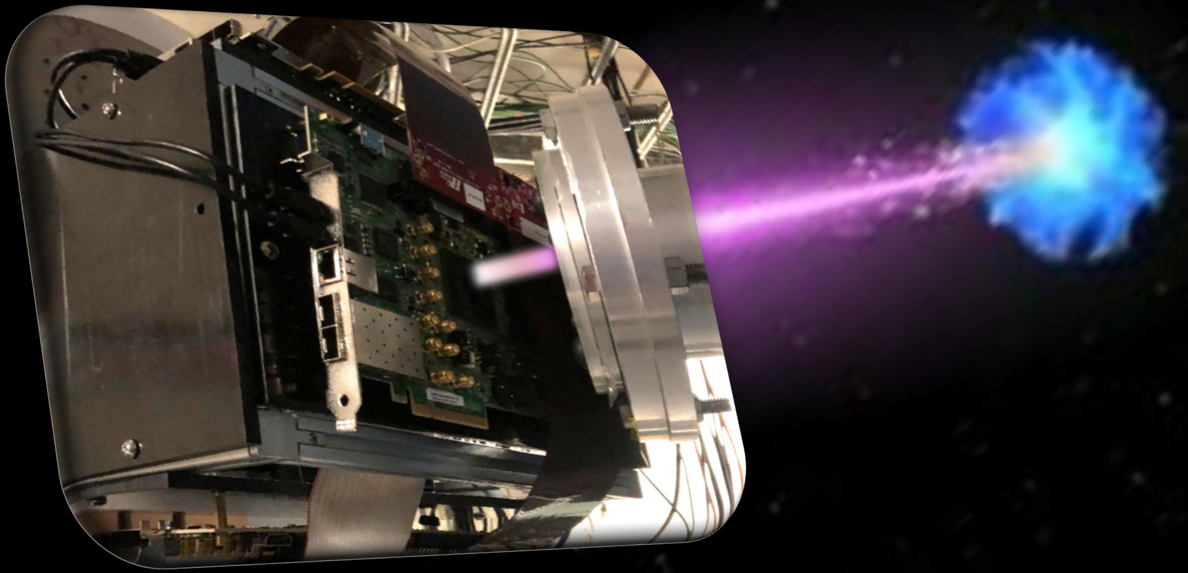
System failures due to SEEs are second order:

- Probability that a transistor will change state, and
- Probability the SEU or SET will cause system malfunction.

Cross sections are metrics derived from beam testing

$$\sigma_{SEU}(LET) = \frac{\#events}{\#ions/_{cm^2}} = \frac{\#events}{Fluence}$$

σ_{seu}s are empirical data that are calculated per selected LET values (particle spectrum).



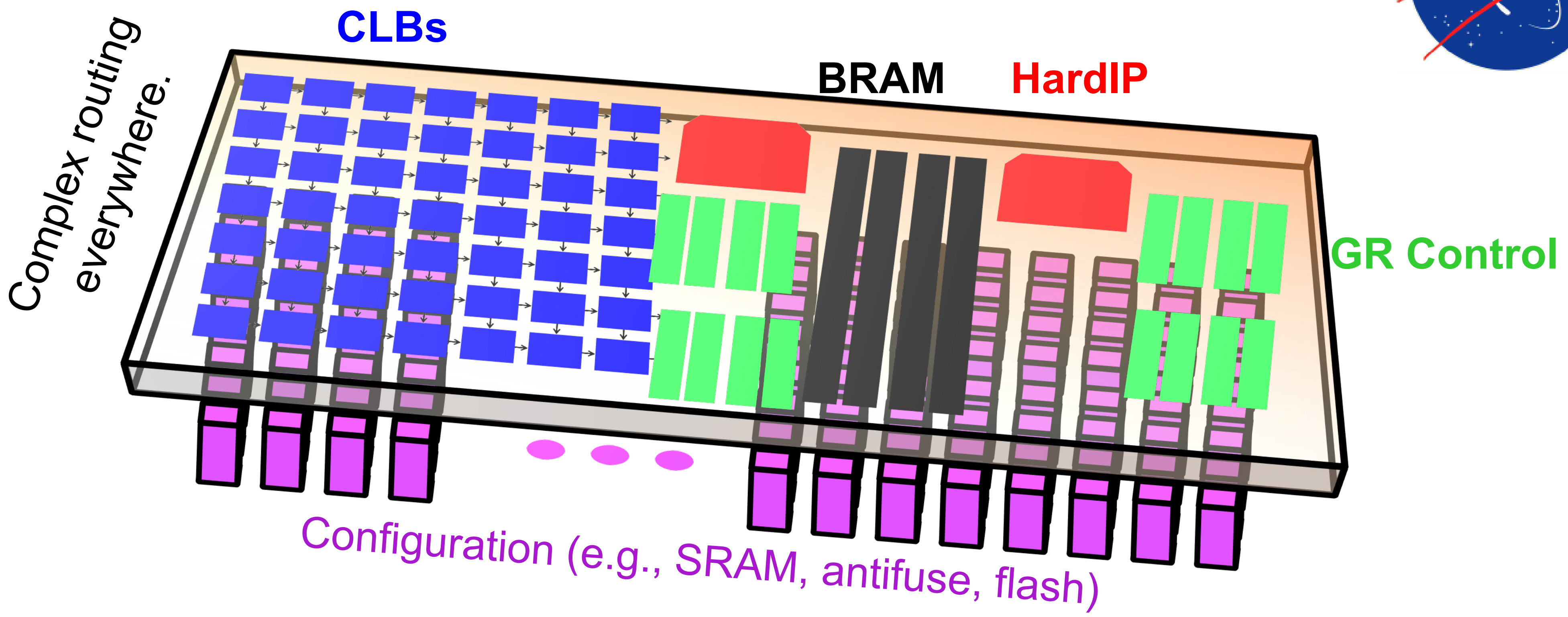
SEE testing at LBNL 88in Cyclotron

LBNL: Lawrence Berkeley National Laboratory

Terminology:

- Flux: Particles/(sec-cm^2)
- Fluence: Particles/cm^2
- Linear energy transfer (LET MeV·cm^2/mg)

FPGA SEU Cross Section Model



SEU Cross sections for a mapped design (σ_{SEF}) are based on the FPGA's internal elements and the mapped design's topology.

$$\sigma_{SEF} = f\left(\sigma_{configuration}, \sigma_{BRAM}, \sigma_{functionalLogic}, \sigma_{HiddenLogic}\right)$$

There are established testing techniques to study various FPGA elements

Melanie Berg et. al, "FPGA SEU Radiation Test Guidelines:" https://nepp.nasa.gov/files/23779/fpga_radiation_test_guidelines_2012.pdf

Challenges Using Conventional SEE Cross-Section Data for System Characterization

$$\sigma_{SEU} = \frac{\#events}{\#ions/_{cm^2}} = \frac{\#events}{Fluence}$$

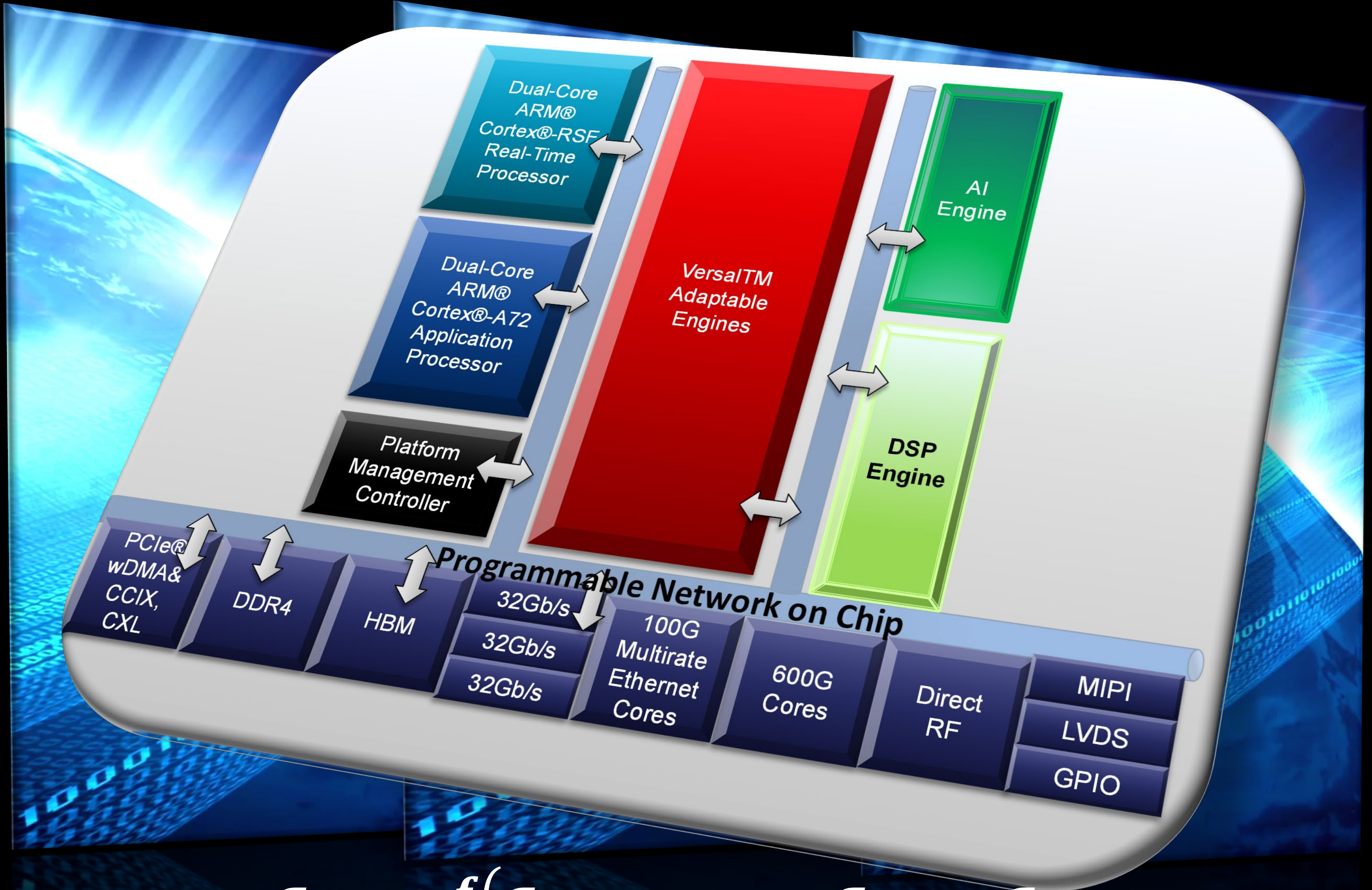
RPP

- Methods for calculating Single Event error rates rely on cross-sections.
  - Conventionally, $\sigma_{SEU}s$ are metrics that describe a sensitive area (SEE susceptibility) of a device.
  - The concept of sensitive area/volume works well for transistor or bit-level component metrics.
  - This (old-school, conventional) concept is used to extrapolate SEE data to systems:
    - Fine-grain component cross-sections (bit-level/basic mechanisms) are obtained and are usually multiplied to characterize system SEE behavior.

$$Error\ Rate = \#\left(fine_{grain_{elements}}\right) \times error\_rate\left(fine_{grain_{element}}\right)$$

Linear Bounding (presumed)… this is not extrapolation…topology is ignored

Challenges for SEE Test and Analysis of New Generation SoC/FPGA



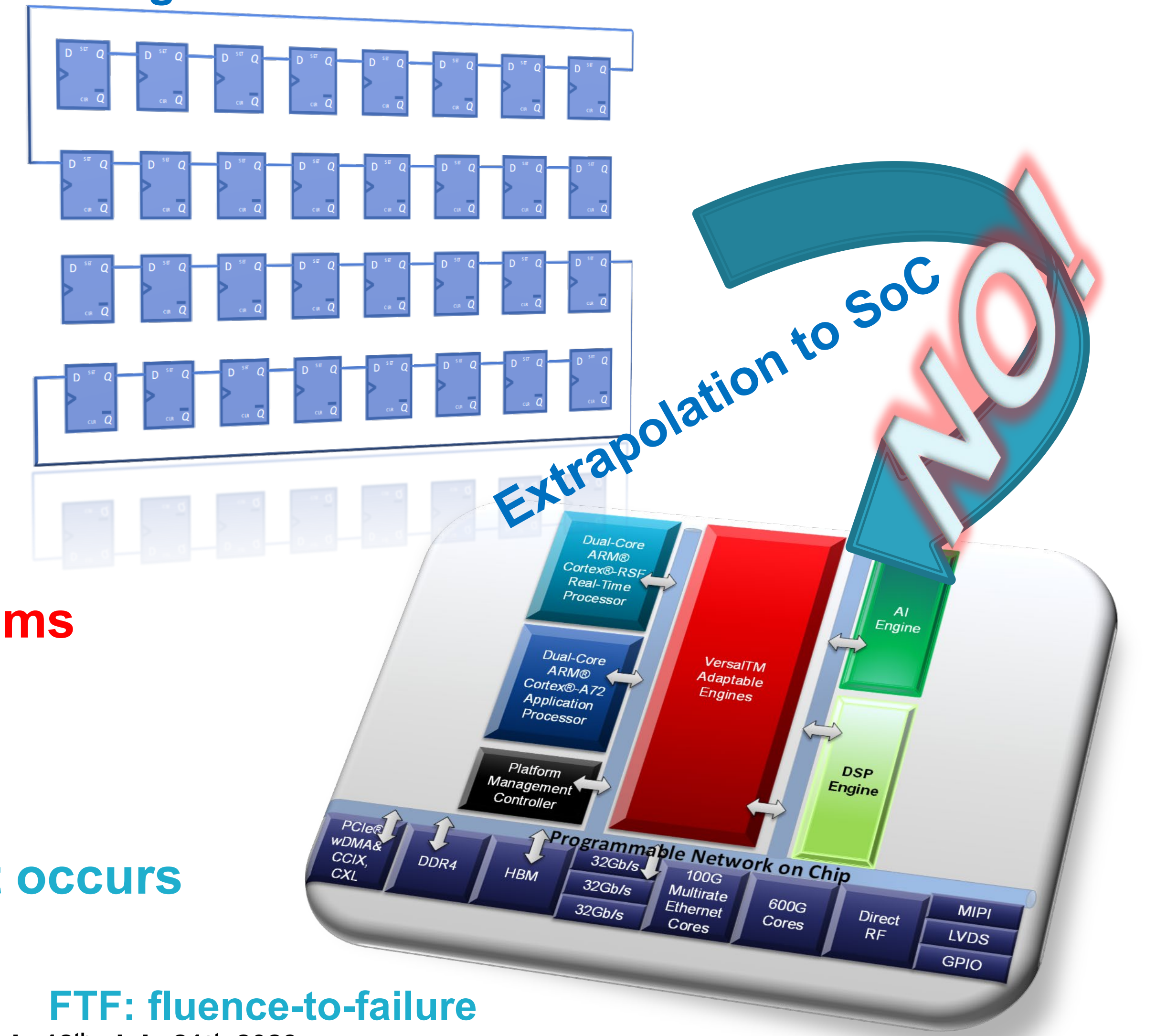
- Cannot test every fine grain (basic mechanism).
- Not all basic mechanisms are linearly extrapolatable (topology matters).
- SoCs contain significant amount of embedded circuitry (hidden logic).
- Hidden circuits are extremely complex and require complex test methods.
- Increased focus on $\sigma_{HiddenLogic}$

$$\sigma_{SEF} = f(\sigma_{configuration}, \sigma_{BRAM}, \sigma_{functionalLogic}, \sigma_{HiddenLogic})$$

Fine-Grain Test Structures Should Not Be Used for SoC Extrapolation

- Conventional test structure: shift register.
- Shift register data (the conventional golden metric) is insignificant towards the characterization of an SoC.
- Instead, test using coarse-grain structures:
  - Test operation in similar modes to flight.
  - Flight-like high-speed I/O protocols
  - Flight-like state-based controls and functions

Fine-grain test structure



Move from counting events of basic mechanisms

$$\sigma_{SEU} = \frac{\#events}{\#ions/_{cm^2}} = \frac{\#events}{Fluence}$$

To obtaining the fluence until an event occurs

$$\sigma_{SEF} = \frac{1}{Fluence}$$

FTF: fluence-to-failure

Reimagine Cross Sections as Probabilities

$$Single\ Event\ Failure = \sigma_{SEF} = \frac{\#events}{Fluence}$$

Failure Rate in the fluence domain

For system analyses: Step away from the conventional methods of cross-sections representing sensitive areas and the RPP method.

Redefine the cross-section metric to be a probability.

The probability an event will occur when the target is subjected to a given number of particles (per area).

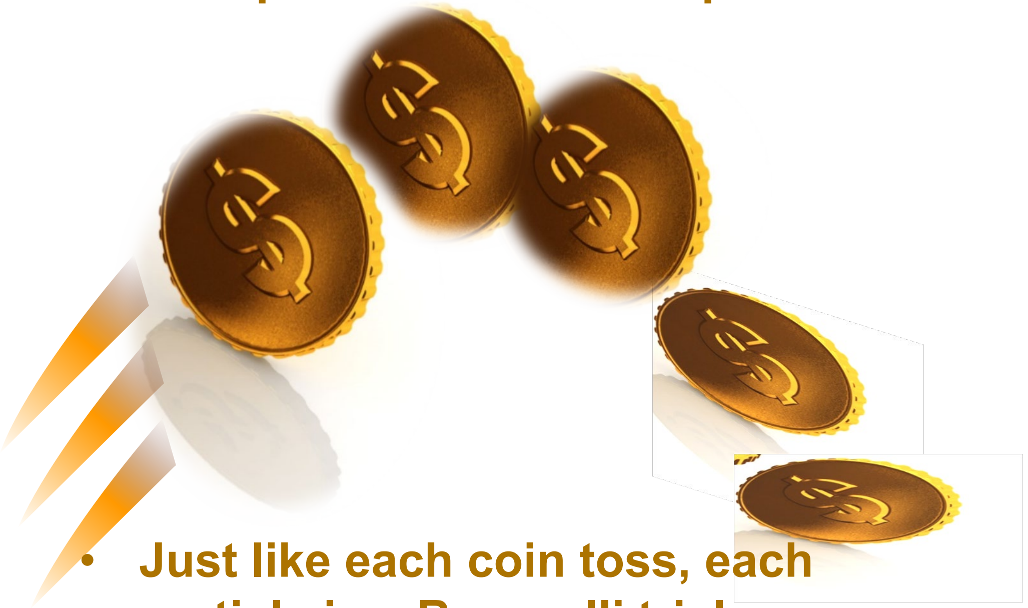
σ_{SEF} is now a rate. However, the rate is in the fluence domain not the time domain.

Single Event Effects And The Binomial Distribution

Trial → Event→ Effect (Response)

- Each ion can either cause an event or not:
  - Binomial distribution… over multiple Bernoulli trials … each ion is an independent random trial with two (2) possible outcomes
  - Trial outcomes:
    - event (1) or
    - no event (0)
- For this definition, cross-sections can never be greater than 1.
- Law of large numbers states that these binomial experiments can be characterized by Poisson distributions.
- For systems, there will be times when the exponential distribution is a better model. The exponential distribution is a special case of the Poisson… P(X=0)

Flipping a coin is the most common example of a binomial experiment



- **Just like each coin toss, each particle is a Bernoulli trial**
- **An Event is an upset/failure**

$$\sigma_{SEF} = \frac{\#events}{\#ions/cm^2} < 1$$

Makes sense if we are redefining a cross section as a probability

Modeling System-Level Susceptibilities as They Pertain to Empirical Cross-Sections

Raw Probability
(failure rate)

Probability a transistor is affected (lowest level of upset… sensitive area)

Measured Probability
(failure rate)

Probability the system malfunctions AND your test can observe/report the failure

Be careful… your test system can greatly impact the quality of your cross-section data.

Cross-Section (σ_{SEF}) As A Set of Transfer Functions of P_{gen}

Probability ionization + design topology will cause an effect

P_{gen} → DUT SYSTEM H(s) → P_{Effect} → TEST SYSTEM T(s) → $P_{observe}$, σ_{SEF}

Probability ionization will cause an event

Probability test system can report event

Poor test systems, $P_{observe} \rightarrow 0$:

- *Test system adds noise to data (bad system design, dosimetry, flux control)*
- *Inability to reliably observe and report failures:*
  - *Missed events/upsets*
  - *Latency from event to observation*
  - *False events*
  - *Flux/fluence control*

Empirical cross sections are not pure

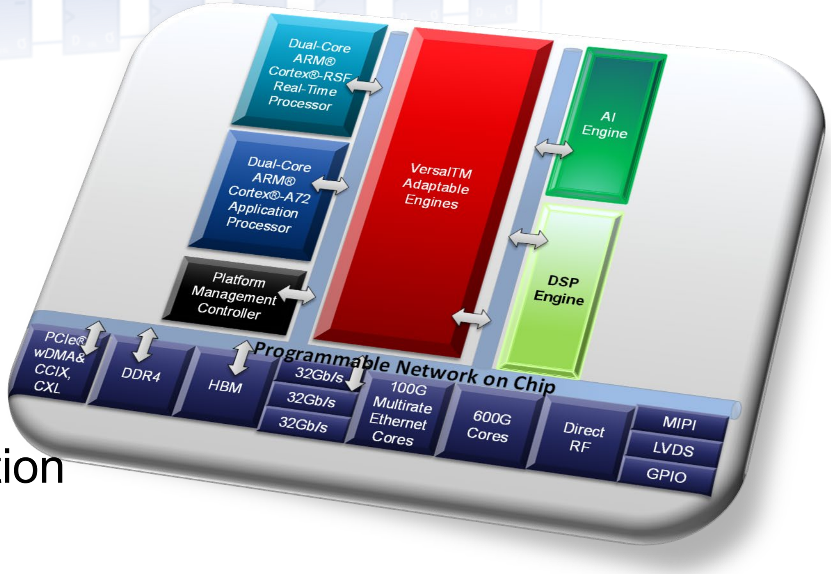
$$\sigma_{SEF} = P_{gen} \times P_{Effect} \times P_{observe}$$

Many assume, $P_{observe} = 1$; and
Many assume they are measuring critical charge(P_{gen})

For a system, these assumptions are not true

Testing Homogenous Cells versus Complex Systems

- **Homogenous Cells ($P_{effect} \rightarrow 1$):**
  - Copies of a simple structure (inverters, buffers, memory cells)
  - Each test has many targets (that are the same components) and hence increases statistics.
  - In most cases, FTF is not the best approach. Instead, use a countable metric.
- **Complex systems ($0 < P_{effect} < 1$):**
  - Many variables, moving parts, and state space exploration paths
  - Difficult to test and requires strategic planning.
  - Planning includes taking advantage of dominant mechanisms of failure.
  - Alternatively, the tests are evaluating probabilities of failure with respect to fluence exposure.

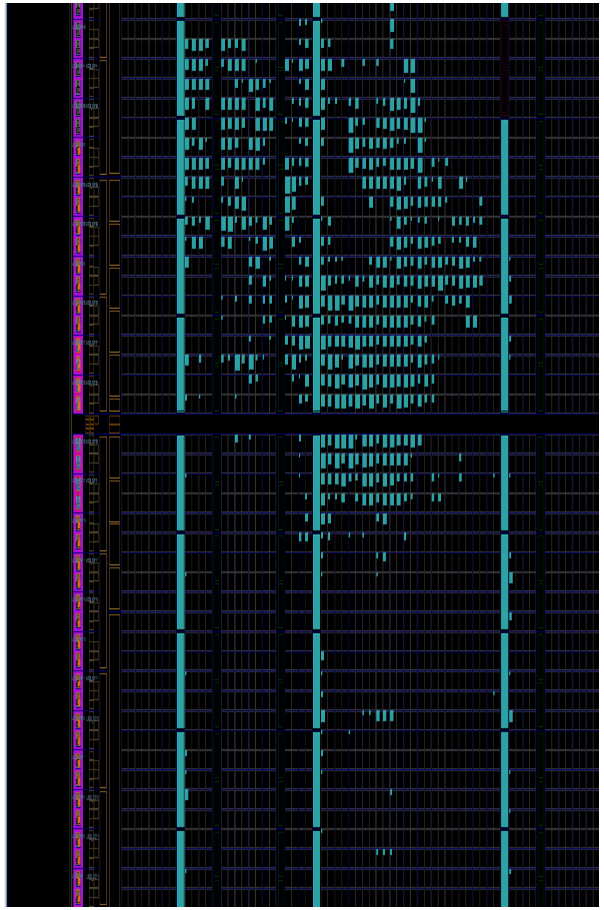


Countable systems (how many events per ion) ➡ Poisson distribution

FTF (how many ions until event) ➡ Exponential distribution

An Example of When to Use Homogenous Testing and Linear Bounding

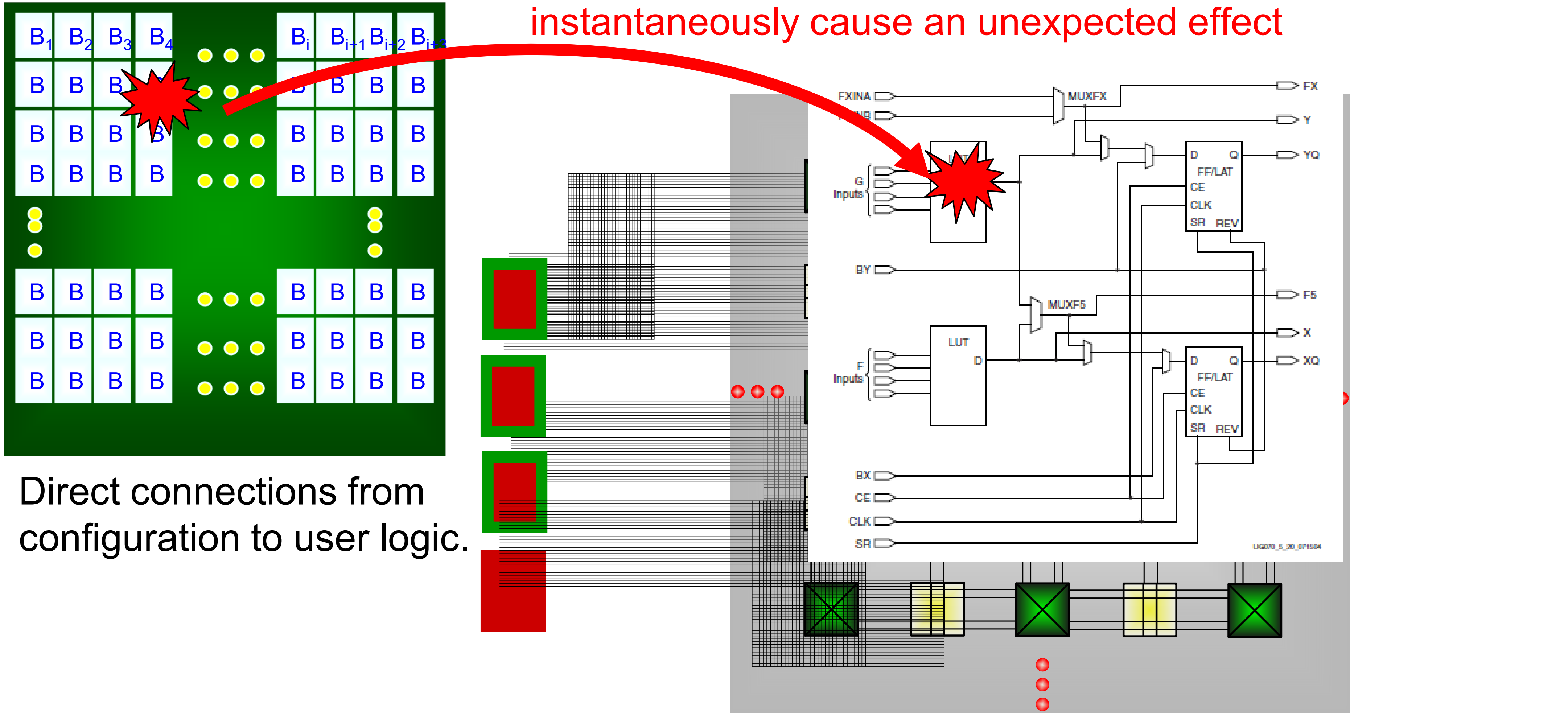
$$\sigma_{SEF} = f(\sigma_{configuration}, \sigma_{BRAM}, \sigma_{functionalLogic}, \sigma_{HiddenLogic})$$



For SRAM-Based FPGA Devices, The Configuration Cells Are The Dominant Sources of Upsets

Configuration SEU and Functional Upsets

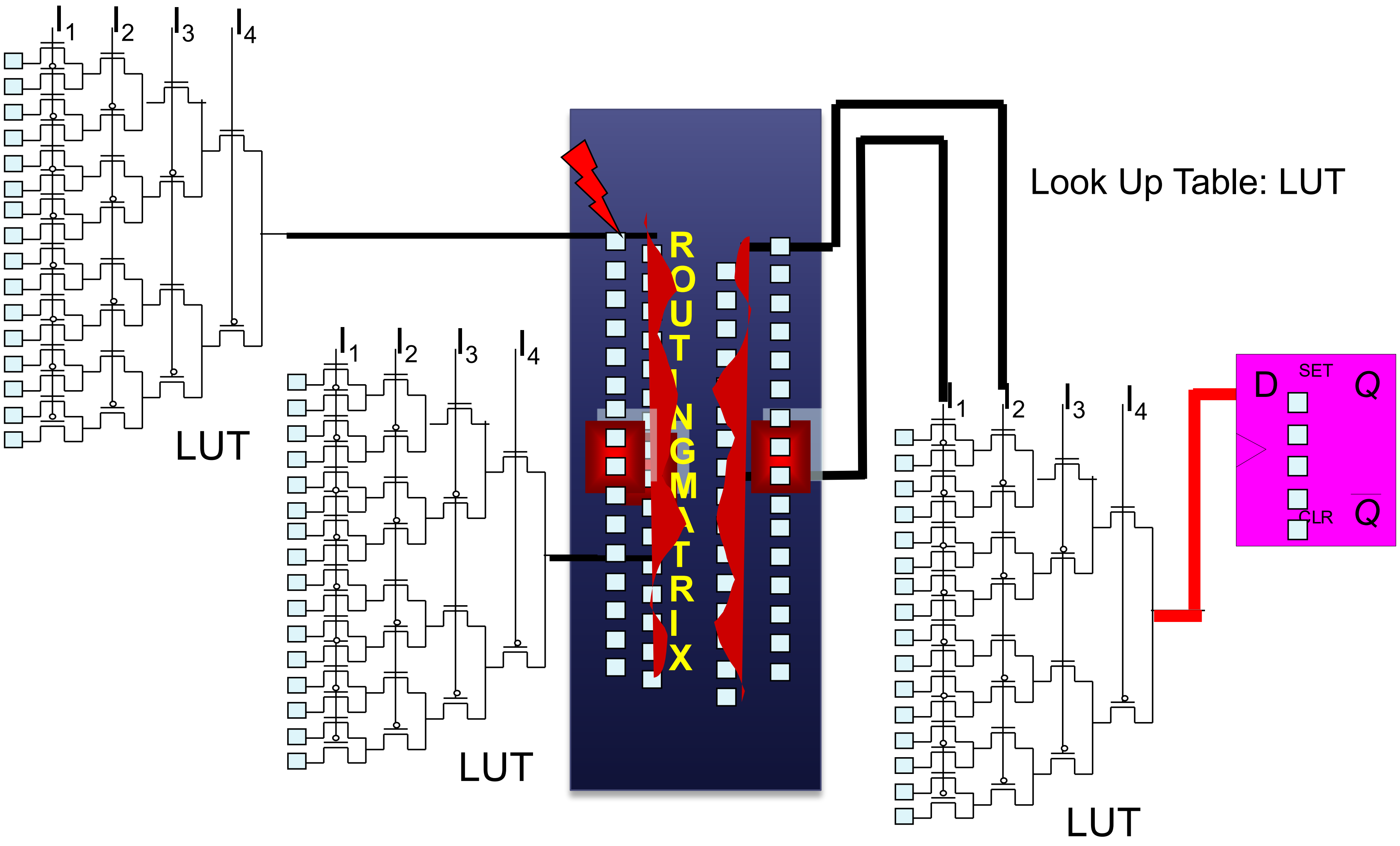
An affected active/used bit has the ability to instantaneously cause an unexpected effect



- Direct connections from configuration to user logic.

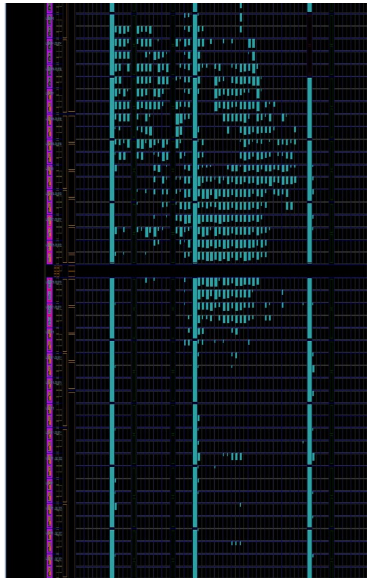
No Read-Write cycle required!

Example: Routing Configuration Upsets in a Xilinx Virtex FPGA



SRAM-Base FPGAs and SEU Cross-Sections

For SRAM-Based FPGAs, Configuration bits are the dominant mechanisms of failure.



We first obtain configuration-bit cross-sections

We perform a linear transformation:
(#essential_bits × configuration cross-section)

We use the linear transformation as a bounding cross-section (error rate)

$$\sigma(LET)_{configuration\_Device} = \frac{\#events}{\#Particles/cm^2}$$

$$\sigma(LET)_{configuration\_bit} = \frac{\#events}{\left(\#\frac{Particles}{cm^2}\right) * (\#unmaskedconfigurationBits)}$$

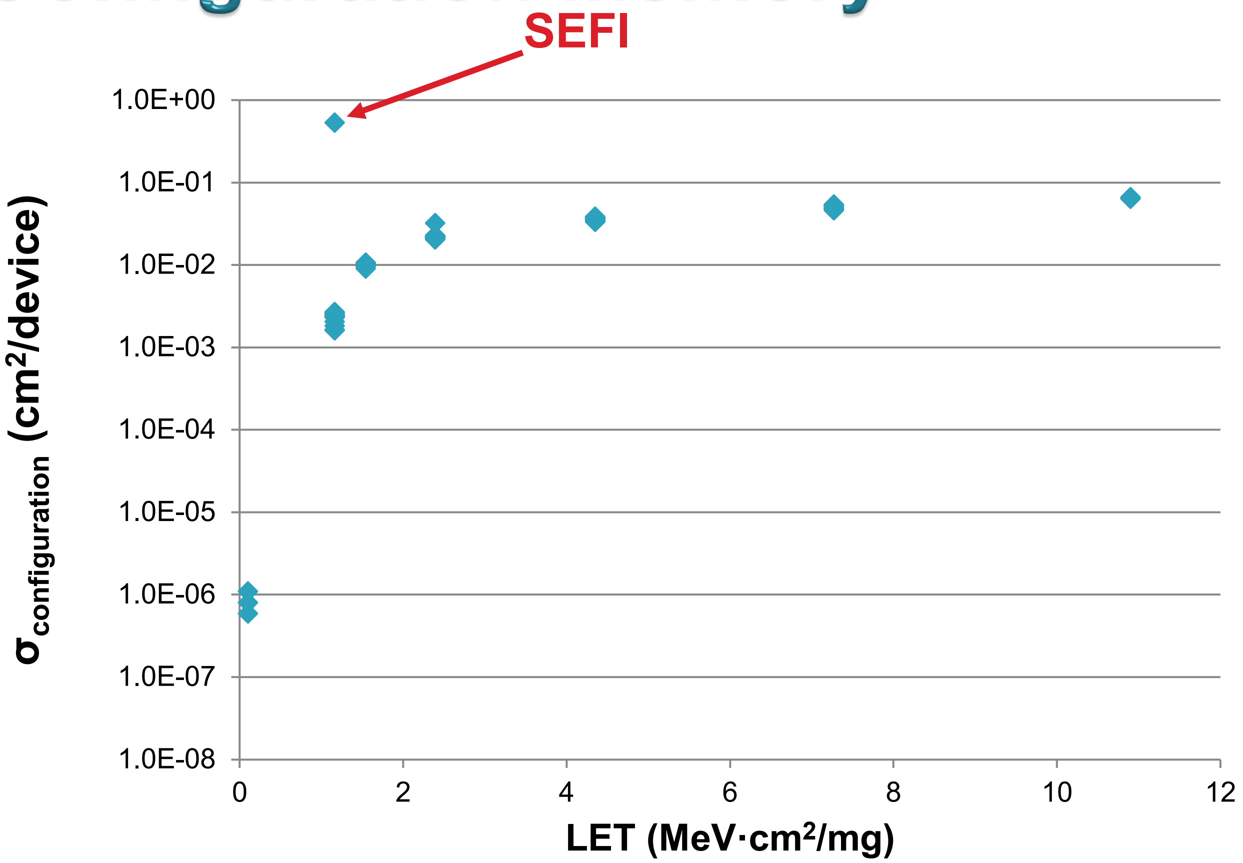
$$\sigma(LET)_{\mathrm{Essential}\_bit} = Essential\_bits \times \sigma(LET)_{configuration\_bit}$$ **Bound**

$$\sigma(LET)_{SEF} = \mathbf{1}/\mathrm{FTF} = \mathbf{1}/((FailureTime - BeamStartTime) * \mathrm{AverageFlux})$$

System Extrapolation

Which cross-sections do we use for failure analysis? … Must consider mission requirements.

Homogenous Cross Sections: FPGA Configuration Memory



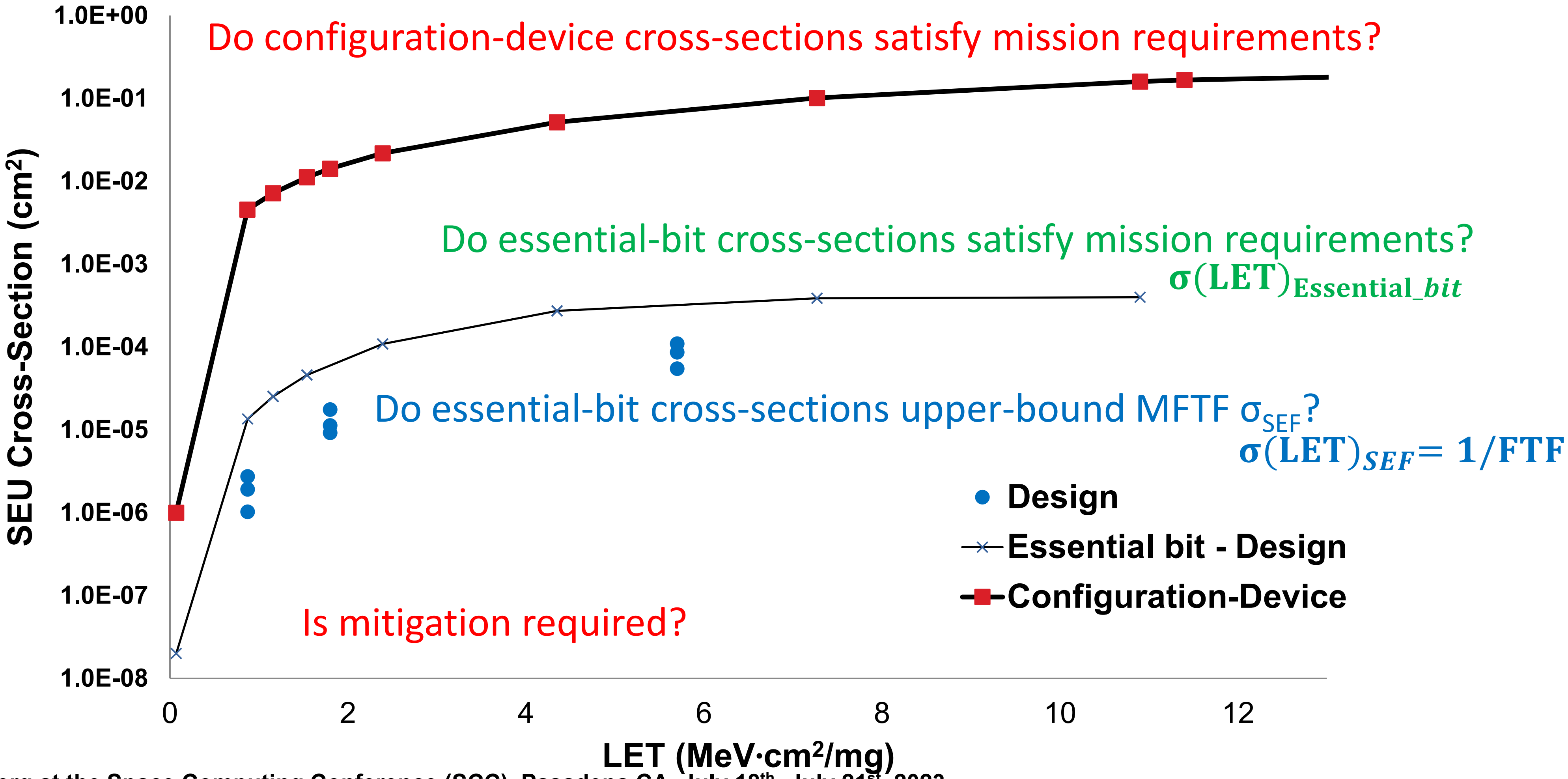
LET	Number of Experiments (82 total tests)
0.1	3
1.16	21
1.54	16
2.39	15
4.35	12
7.27	12
10.9	3

All 82 tests are represented in the graph. The results are so close that it is difficult to decipher between each experiment per LET.

- Single event functional interrupt (SEFIs) can occur, however, they have a low event probability during testing (depending on fluence).
- If the experiments go to a high enough fluence, it is highly likely that a SEFI will occur… yet its σ_{SEFI} will be low.

SRAM-Based FPGAs and Using Configuration Memory as An Upper-Bound

If Upper-bounds Satisfy Mission Reliability/Survivability Requirements, Then No FTF (Data Refinement) Necessary



Error Bounding is Easy… Why Not Always Use It?

- Error bounding provides extreme upper bounds without knowledge of design topology.
  - Error rates calculated using error bounds might not meet requirements. Will need to refine SEE data by performing FTF type SEE testing.
  - Can't be used to study the efficacy of mitigation.
- When using error bounding… prove it before you use it.
  - $\sigma(LET)_{\text{Essential\_}bit}$ should only be used if it is known/proven to be an upper-bound (or close enough depending on criticality).
  - The proof of bounding has been the missing factor; and is now necessary.
  - Why now? Device complexity includes a significant amount of hidden logic.
    - Hidden logic have components that are not included in the essential bit count.
    - It has shown (in flight) to impact susceptibility (e.g., internal scrubbers).

Fluence-to-Failure Experiments and The Exponential Model

Classical Reliability : transformation from the time domain to the fluence domain.

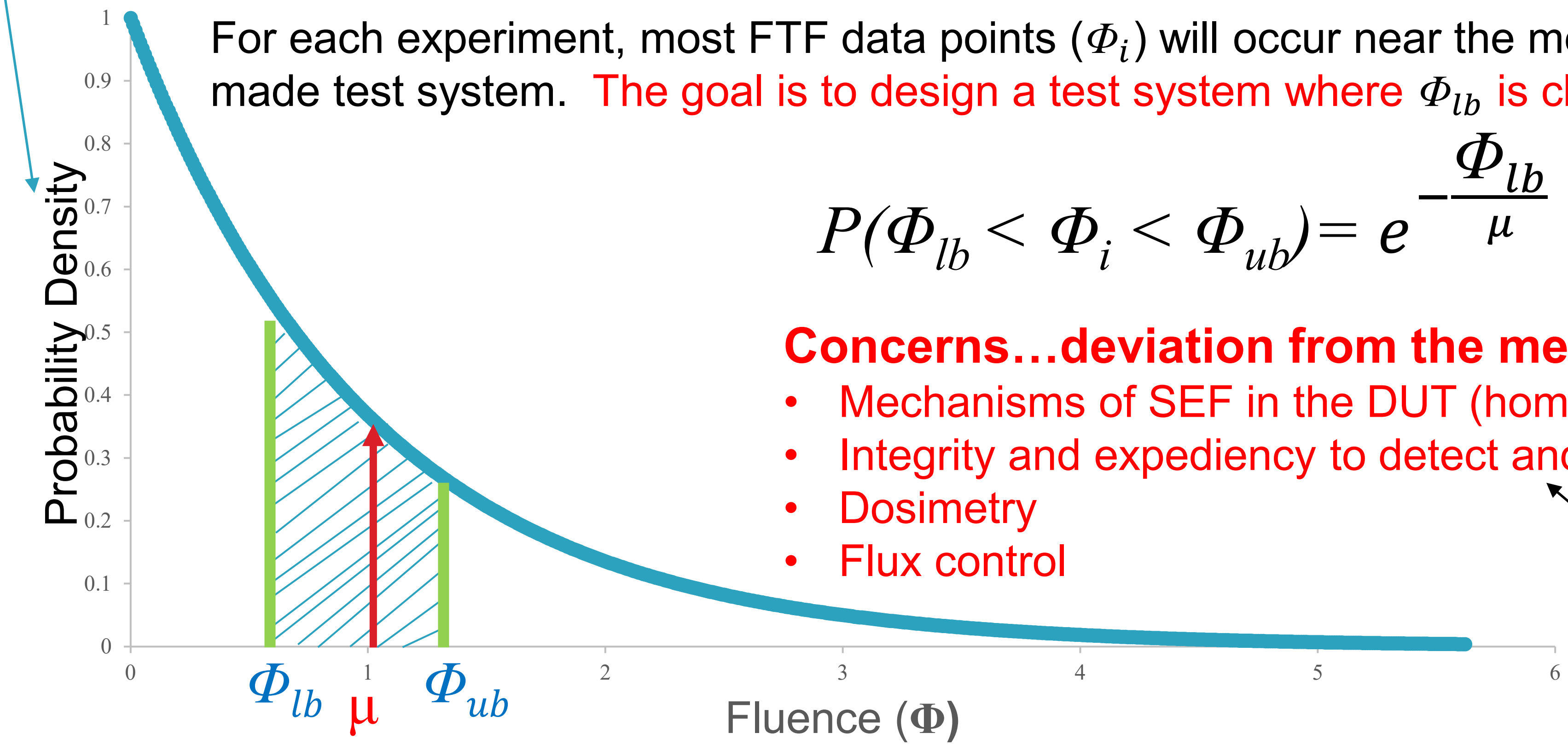
	Exponential Distribution Variables	
Fluence-to-failure (FTF)	Φ_i	Random Variable: per experiment-*i* for a selected LET
SEF Cross-section (rate w.r.t. fluence)	$\sigma_{SEF_i} = \frac{1}{\Phi_i}$	
Sample mean (MFTF)	$\mu = \frac{1}{n}\sum_{i=i}^{T}\Phi_i$	Average of fluence-to-failure test results. ***n* = number of events** ***T* = number of experiments**
Mean SEF	$\sigma_{SEF\mu} = \frac{1}{\mu}$	Classical Reliability: Constant per LET
Standard deviation	$\mu = MFTF$	Use of exponential population standard deviation definition
Standard error of the mean (SEM)	$\frac{\mu}{\sqrt{n}}$	Generally used for error bars
Exponential PDF Probability distribution function	$\sigma_{SEF_\mu} e^{-\sigma_{SEF_\mu}\Phi}$ or $\frac{1}{\mu} e^{-\frac{1}{\mu}\Phi}$	

FTF PDF Expected Empirical Data: How Can 5-10 Tests Be Sufficient?

$$\textit{Experiment fluence to failure} = \Phi_i = \frac{1}{\sigma_{SEF_i}} \qquad MFTF = \mu$$

$$f(\Phi) = \sigma_{SEF_\mu} e^{-\sigma_{SEF_\mu}\Phi}$$

ub: upper bound
lb: lower bound



For each experiment, most FTF data points (Φ_i) will occur near the mean, for a well-made test system. The goal is to design a test system where Φ_{lb} is close to Φ_{ub}

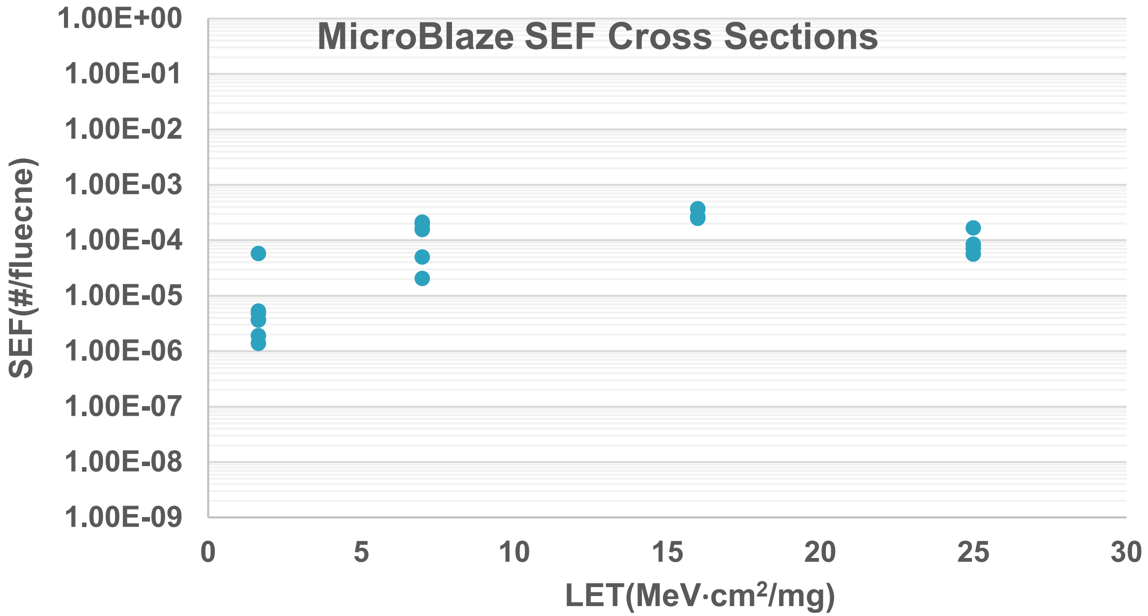
$$P(\Phi_{lb} < \Phi_i < \Phi_{ub}) = e^{-\frac{\Phi_{lb}}{\mu}} - e^{-\frac{\Phi_{ub}}{\mu}}$$

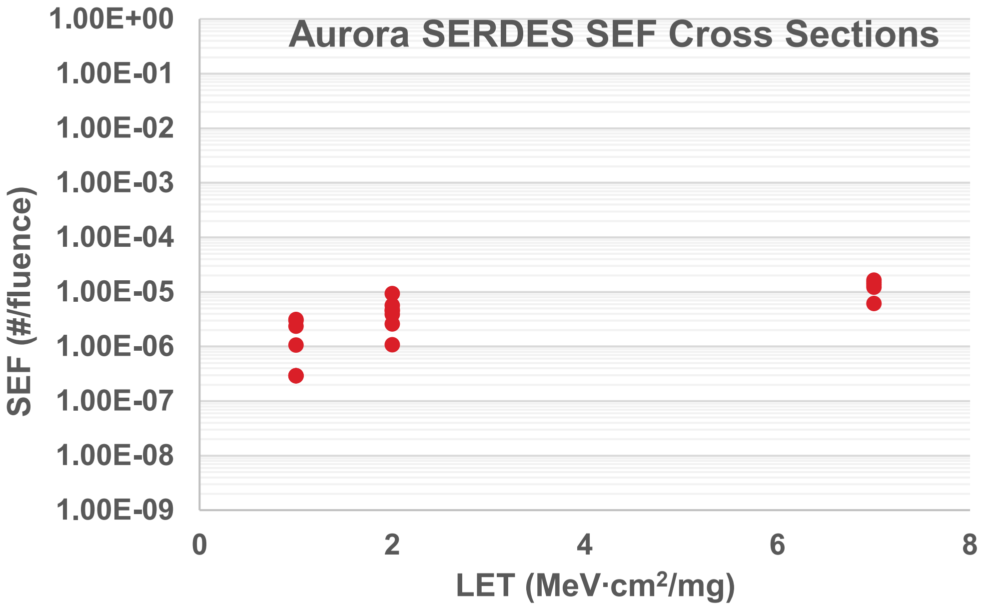
Concerns…deviation from the mean depends on:

- Mechanisms of SEF in the DUT (homogenous, multi-modal)
- Integrity and expediency to detect and report SEF
- Dosimetry
- Flux control

The reality is: increasing the number of tests will not bring your empirical mean closer to the actual mean if concerns are not controlled.

Xilinx/AMD Kintex-Ultrascale…FTF Data for Complex Operations





- FTF cross section data are within a decade and are sufficient for calculating SEF cross-section means
- Calculate mean per LET analyzing each experiment i :
  - No event for experiment i: n=0 and Φ_i = fluence for experiment i
  - Event for experiment i: n=1 and Φ_i = recorded fluence for event occurrence
- If n=0 for a majSority of tests, increase fluence (and check your test system).

$$\mu = \frac{1}{n}\sum_{i=i}^{T} \Phi_i$$

$$\sigma_{SEF\mu} = \frac{1}{\mu}$$

NASA Mission Requiring Test-As-You-Fly (FTF) Radiation Data

$$\sigma_{SEF} = f(\sigma_{configuration}, \sigma_{BRAM}, \sigma_{functionalLogic}, \sigma_{HiddenLogic})$$

- DUT: Microchip RTProASIC3 mission critical.
- Mission Requirement: work through worst-week with ground intervention restricted to 0.01/day.
- DUT area constraints limit mitigation.
- **Extrapolated (upper-bound) Error rates do not** meet requirements (use of shift register data).
- **Test-as-you-fly** heavy-ion testing required (**FTF data refinement**).

Texas A&M Cyclotron Facility

A robust complex system was developed:

Multi-use Test Platform enabled testing the DUT with the NASA flight image. DUT was controlled and operated (at speed) as it would be in flight. FTF data were successfully obtained.

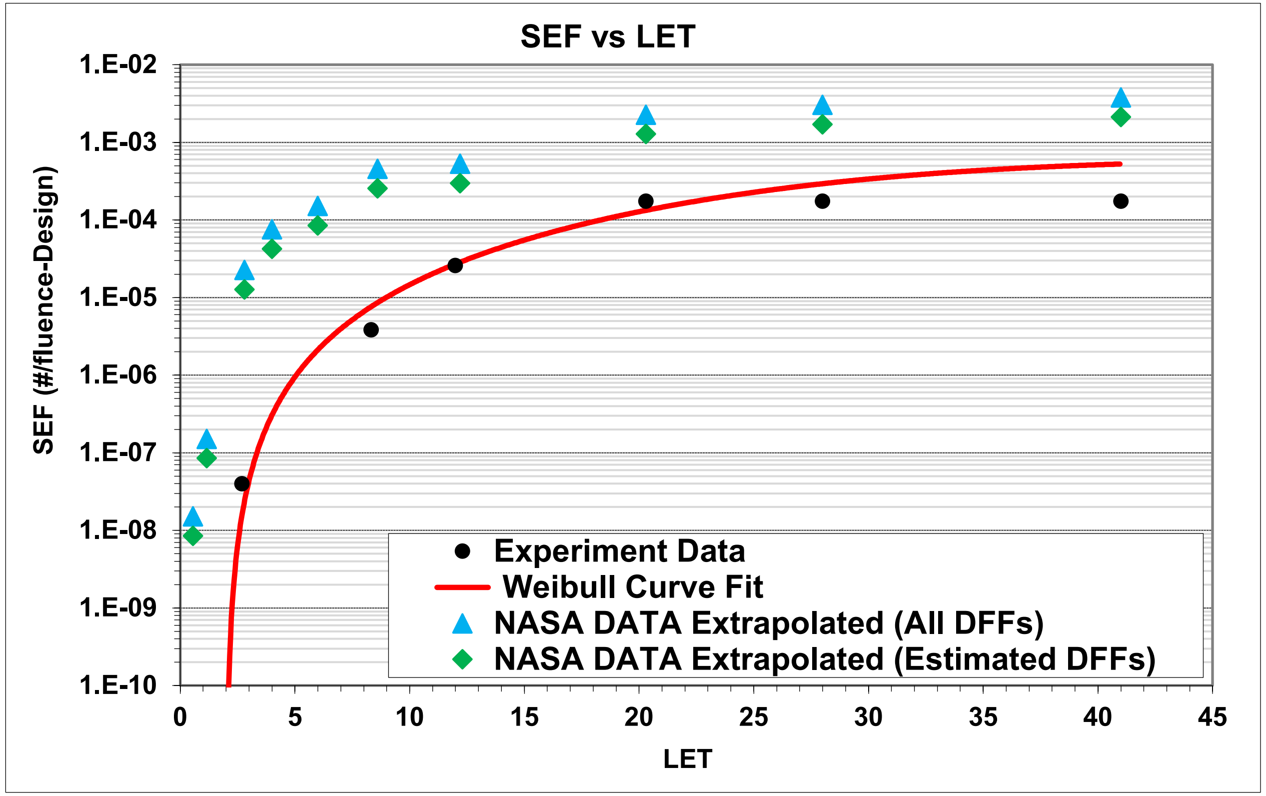
Microchip RTProASIC FTF Data versus Bounding Extrapolation Data

- FTF experiments were RTD-Test-as-you-fly.
- SEF data for a specified function within the NASA flight design is illustrated. Extrapolated data cannot be refined to specific function.

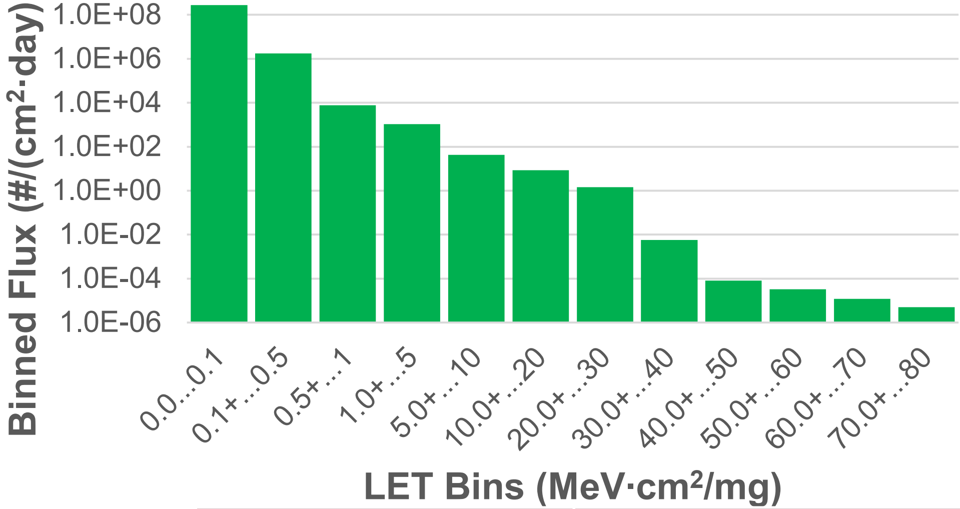
RTD: representative tactical design

SEF: single event failure

LET: Linear energy transfer



Worst Week 350 mils



LET Range	Fluence/Day
0.1 …0.5	**1.8×10^{6}**
0.5 …1.0	**7.6×10^{3}**
1.0…5.0	**1.0×10^{3}**
5.0…10.0	**4.2×10^{1}**
10.0…20.0	**8.4×10^{0}**

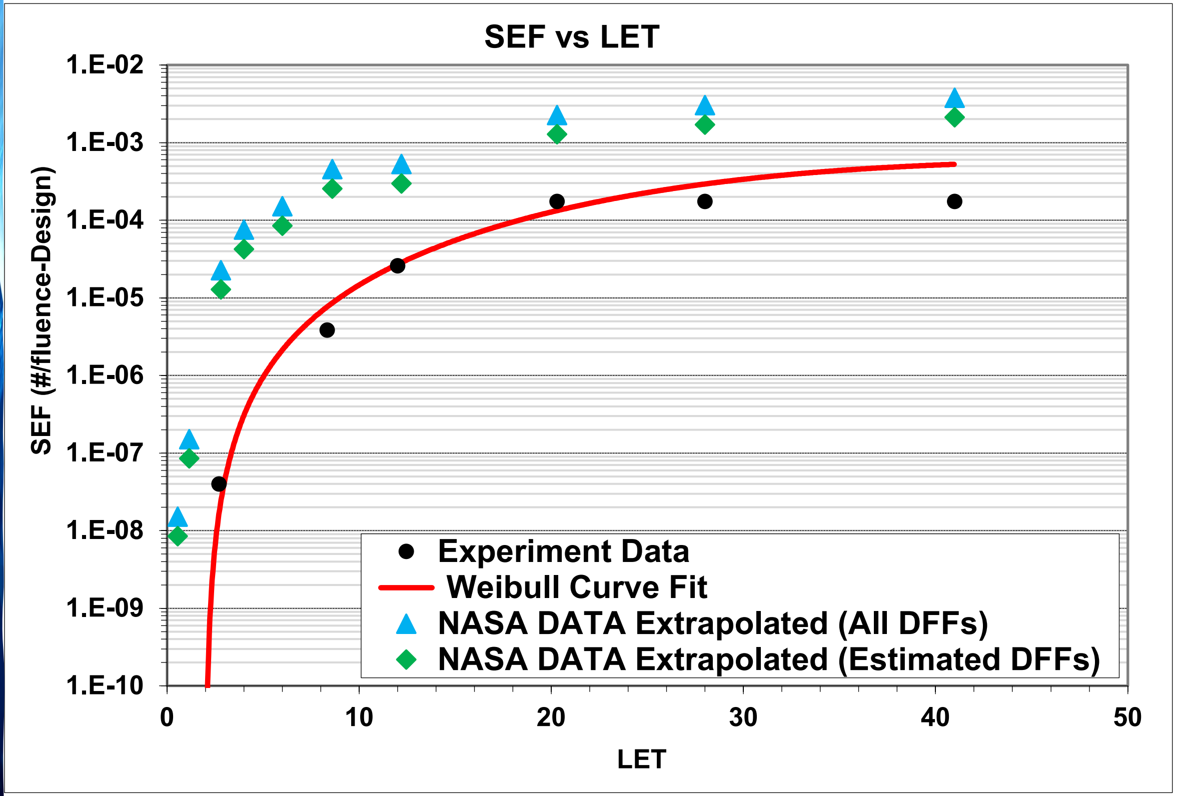
Large number of low LET Particles per day during worst week.

Test-As-You-Fly FTF Refined Data Meet Requirements

Extrapolated data do not meet requirements while Test-as-you-fly data do.

SEF: single event failure

LET: Linear energy transfer



Weibull Parameter	Description
LET_{onset}	Onset LET
σ_{SAT}	Saturation cross-section
W	width
S	shape

Parameter	Extrapolated	Test-As-You-Fly
LET_{onset}	0.5 MeV·cm^2/mg	2.0 MeV·cm^2/mg
σ_{SAT}	60 µm^2	6000 µm^2
W	42.58 MeV·cm^2/mg	30 MeV·cm^2/mg
S	2.0	2.8
Multiplier	15200	1
Error rate	2.1×10^{-1} errors/day	2.3×10^{-3} errors/day

Does not meet requirements

Does meet requirements

Summary

- Modernization of FPGA SEE Risk Analysis:
  - Test:
    - Application of course grained experiments (test smart logic).
    - Test systems and DUT test structures become complex… in turn data better characterize missions.
  - Analysis: Top-Down approach:
    - For cross-section analysis, use classical reliability models transformed to the fluence domain.
    - Cross-sections become probabilities (instead of areas).
  - Extrapolation:
    - Course-grain SEE data in the form of probabilities become easier to extrapolate to complex space applications.