Modernizing Single Event Effect Test and Analysis Methods for Complex FPGA Applications

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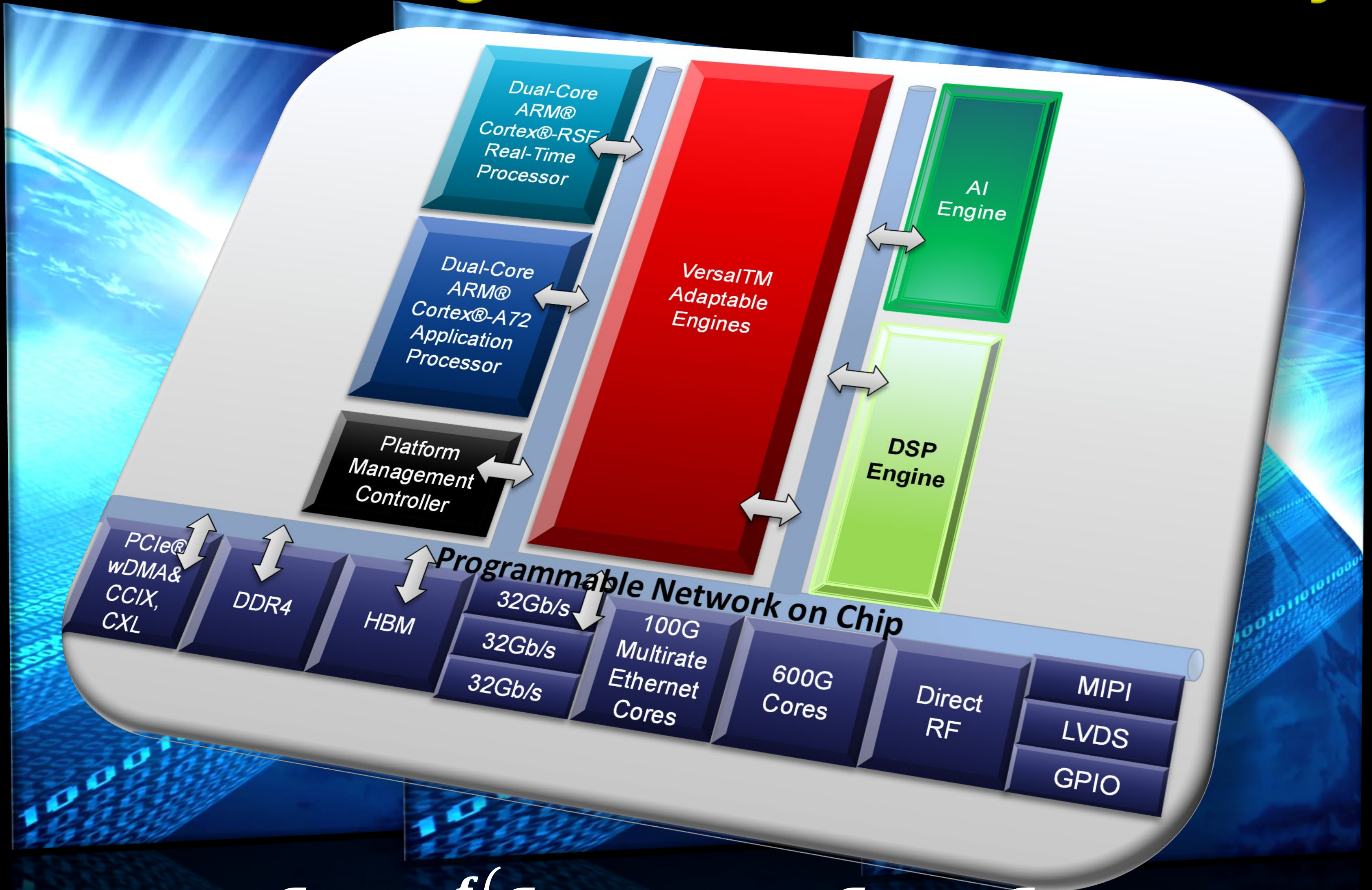
Acronyms

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

New Generation FPGA Is A System on Chip (SoC)… New Challenges for SEE Test and Analysis



- Cannot test every basic mechanism.
- Not all basic mechanisms are linearly extrapolatable (topology matters).
- For most blocks, bit counting does not apply.
- SoCs contain significant amount of embedded circuitry (hidden logic).
- Hidden circuits are extremely complex and require complex test methods.
- Increased focus on $\sigma_{HiddenLogic}$

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

Challenges Using Conventional SEE Cross-Section Data for System Characterization

$$\sigma_{SEU} = \frac{\#events}{\#ions/_{cm^2}} = \frac{\#events}{Fluence} \qquad \sigma_{SEF} = \frac{1}{Fluence}$$

FTF: fluence-to-failure

- 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 concept has been extrapolated to systems:
    - Low-level component cross-sections (bit-level/basic mechanisms) are obtained and are usually extrapolated to characterize system SEE behavior.
- **Challenges**:
  - Low-level metrics do not consider circuit topology. In this case, systems are poorly characterized under the conventional cross-section metric definition.
  - Modern devices contain a significant amount of hidden logic… bit level evaluation is impossible.
- **Approach to Solution:** Supplement classical system-level failure methodologies with (FTF) methodologies (top-down) and test-as-you-fly techniques.

FTF FAQ Responses and Challenges

Modern FPGA and SoCs have complex states that cannot be characterized by countable basic mechanism SEUs: e.g., IP cores, complex logic blocks, blocks with hidden logic, or systems with functional state space.

FTF: measure fluence to inoperable states.

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

- **FTF is used when events are not countable per experiment.**
  - However, FTF events are countable across experiments
  - The question changes from how many events per ion (countable) to how many ions until event (FTF).
- **FTF and Test-as-you-fly are not synonymous**:
  - FTF is a metric; Test-as-you-fly is an experimental approach.
- **FTF is not a replacement to traditional testing**. It is applied when necessary.
- **FTF and Statistics:**
  - FTF requires more experiments than conventional tests (countable basic mechanisms).
  - For a good test system, 5 -10 tests (per energy or LET) will suffice.
  - Any ionizing particle can cause an SEF. However, the majority of FTFs will occur near the mean (most likely events).
  - Dominant mechanisms of failure will override.
- **FTF may require complex test systems:**
  - FTF usually requires a robust real-time test system.
  - Design experience is required.
- **FTF Event Recovery**
  - The test developer defines failures/upsets/events that will be monitored/characterized.
  - The system should be brought back to its original working state (this might include autonomous diagnostics to signify system health) after an event has been detected; to prepare monitor/capture systems for the next event.
- **Not easy – consider the following prior to test development.**

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

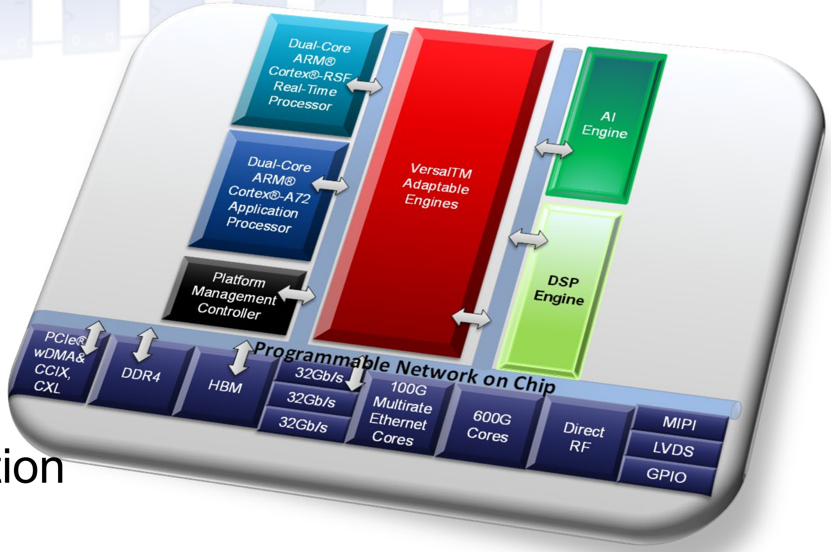
$$\sigma_{SEF} = P_{gen} \times P_{Effect} \times P_{observe}$$

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:**
  - 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:**
  - 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

Fluence-to-Failure Experiments and The Exponential Model

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

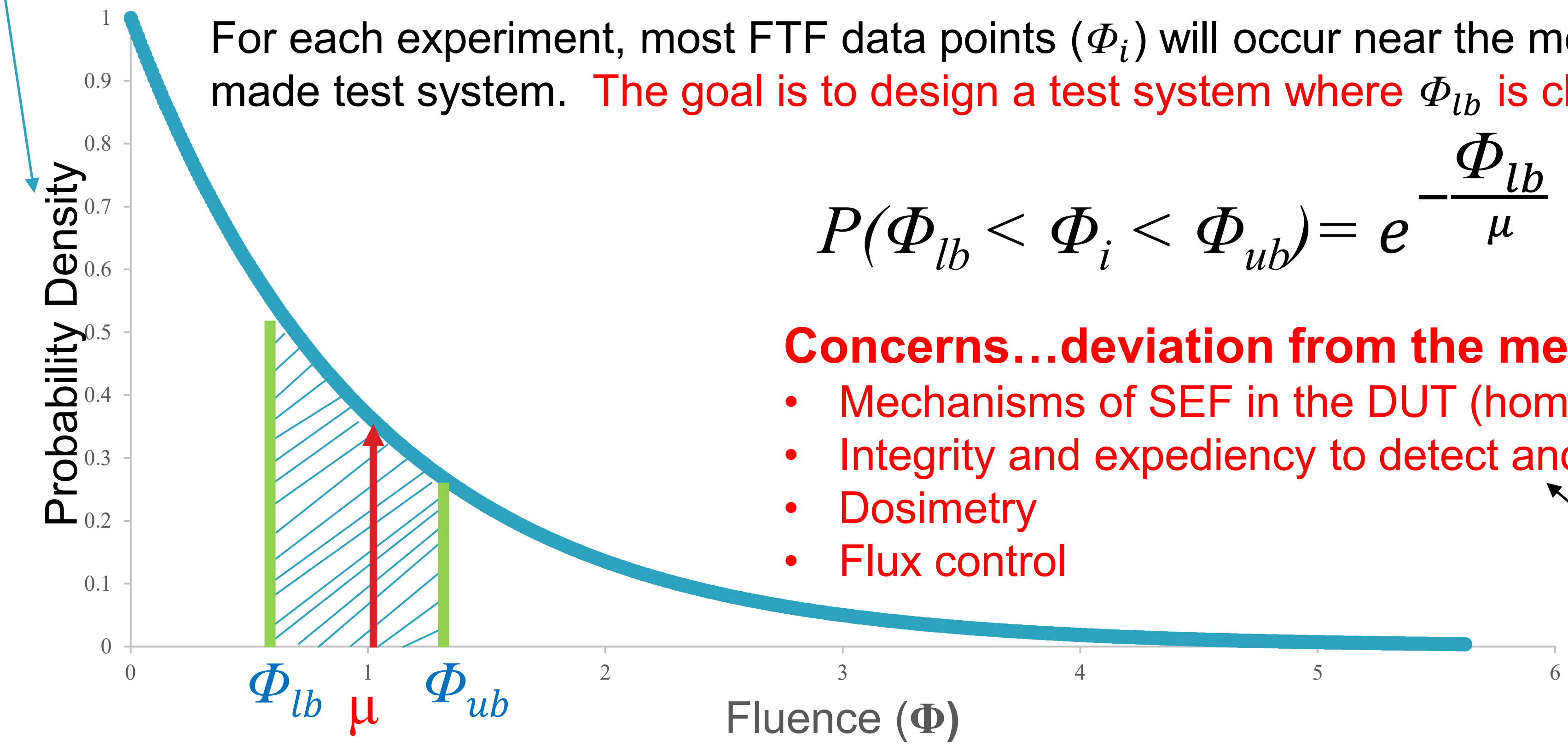
	Exponential Distribution Variables	
Fluence-to-failure (FTF)	Φ_i	Random Variable: per experiment-*i* for a selected LET
SEF Cross-section (rate w.r.t. fluence)	$\sigma_{SEF_i} = \frac{1}{\Phi_i}$	
Sample mean (MFTF)	$\mu = \frac{1}{n}\sum_{i=i}^{T}\Phi_i$	Average of fluence-to-failure test results. ***n* = 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?

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

ub: upper bound
lb: lower bound

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



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}

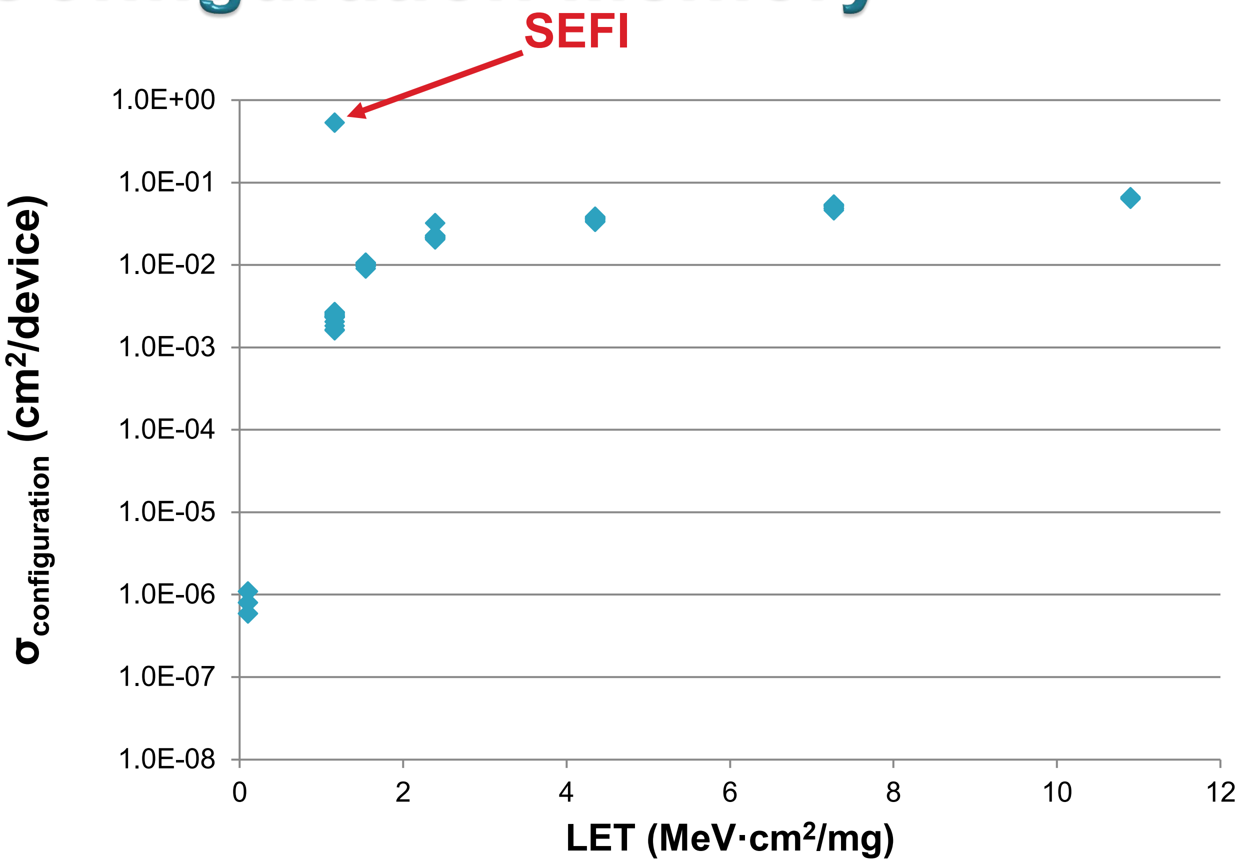
$$P(\Phi_{lb} < \Phi_i < \Phi_{ub}) = e^{-\frac{\Phi_{lb}}{\mu}} - e^{-\frac{\Phi_{ub}}{\mu}}$$

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.

Homogenous Cross Sections: FPGA Configuration Memory

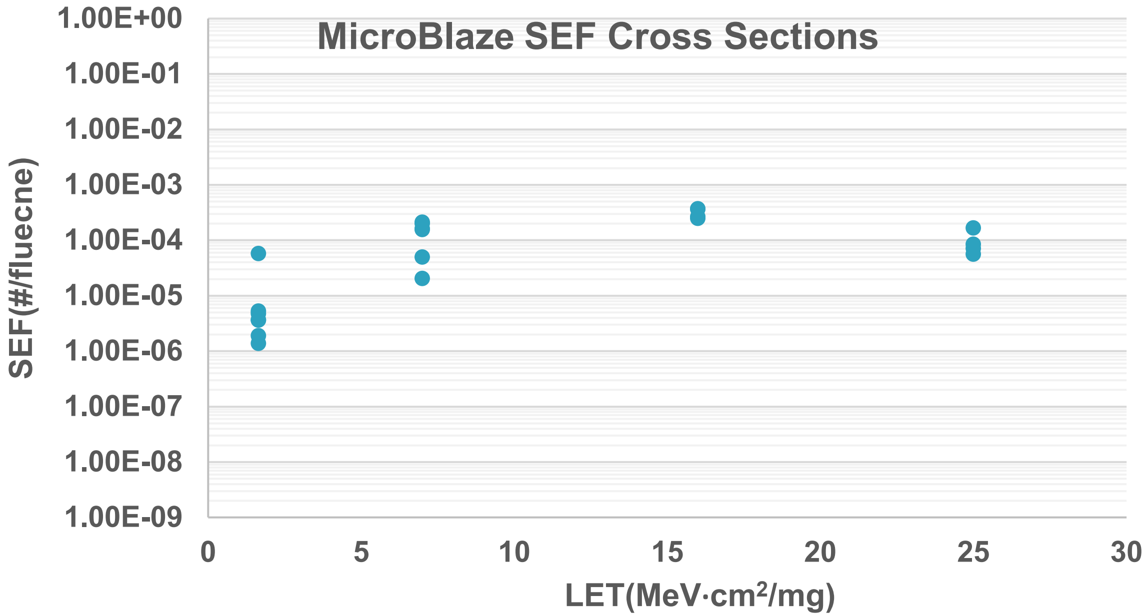


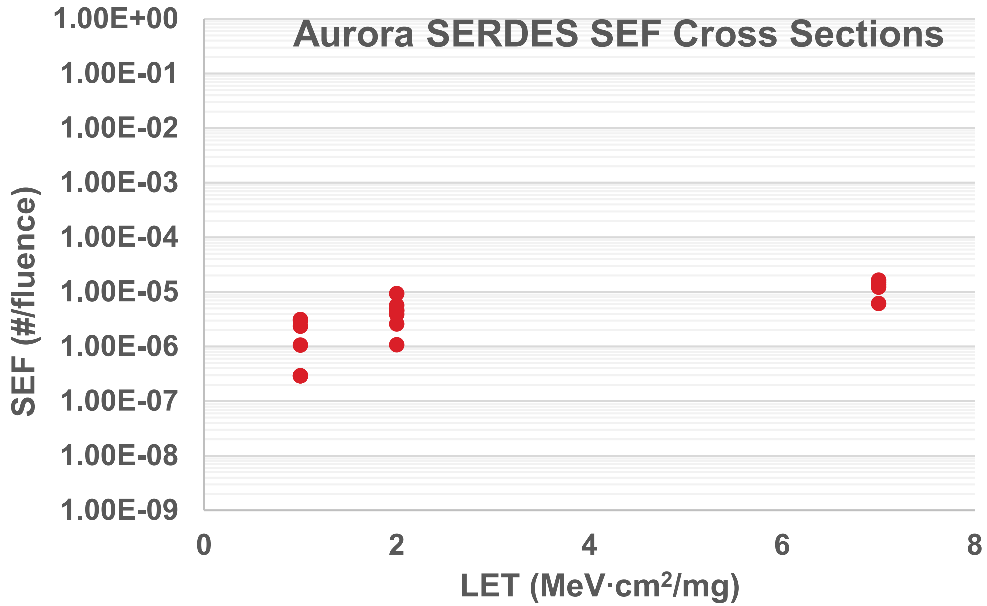
LET	Number of Experiments (82 total tests)
0.1	3
1.16	21
1.54	16
2.39	15
4.35	12
7.27	12
10.9	3

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

- 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

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 majority of tests, increase fluence (and check your tests 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.

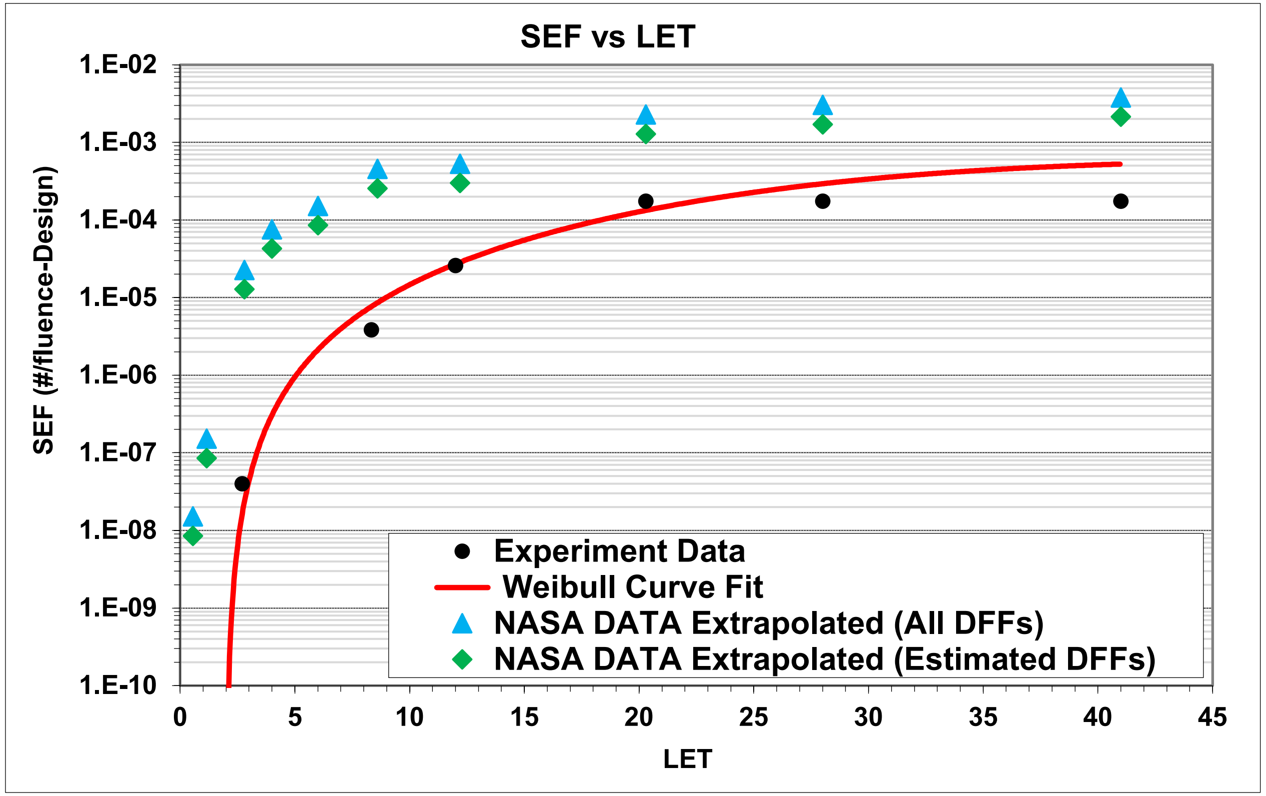
Microchip RTProASIC FTF Data versus Bounding Extrapolation Data

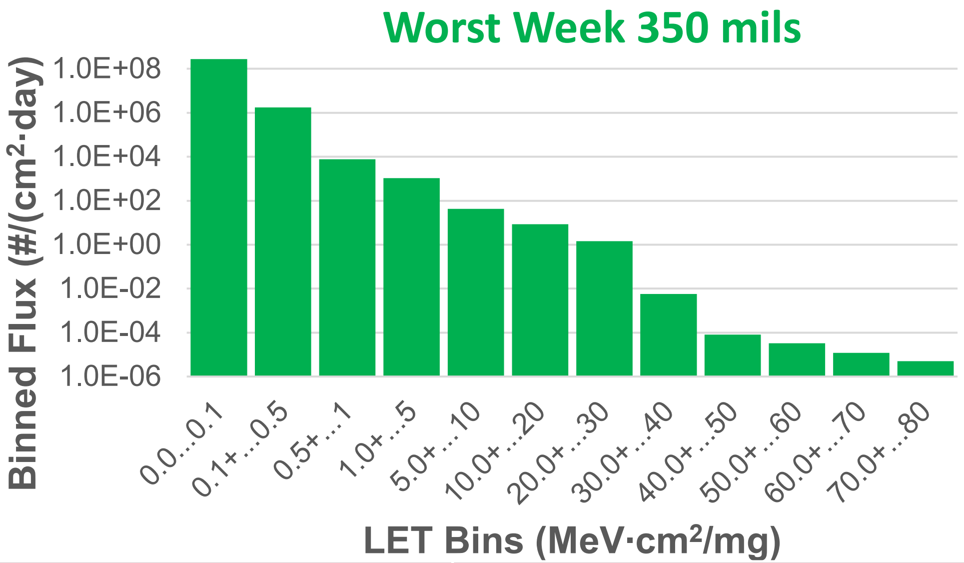
RTD: representative tactical design

- 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.

SEF: single event failure

LET: Linear energy transfer





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.

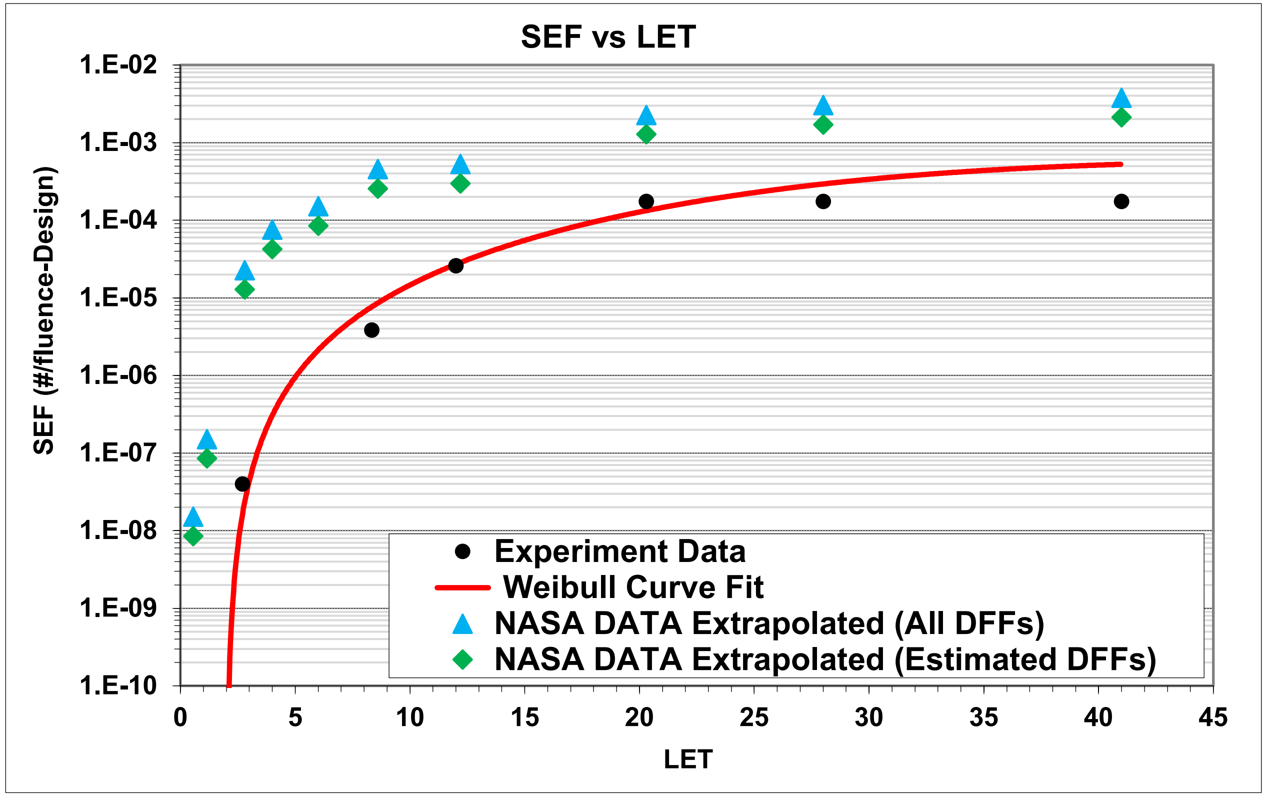
Test-As-You-Fly FTF Refined Data Meet Requirements

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

- Modern FPGA and SoCs have complex states that cannot be characterized by countable basic mechanism SEUs:
  - IP cores, complex blocks, blocks with hidden logic, systems with functional state space, etc.
- FTF is not a replacement for traditional testing. It is supplementary and is applied when necessary.
- FTF and Statistics:
  - FTF requires more experiments than conventional tests.
  - For a good test system, 5 -10 tests (per energy or LET) will suffice.
  - Any ionizing particle can cause an SEF. However, the majority of FTFs will occur by the mean (most likely events).
  - Dominant mechanisms of failure will override.
- FTF may require complex test systems:
  - FTF usually requires a robust real-time test system.
  - Design experience is required.
- FTF has been successfully applied to NASA test systems since 2010.