NEPP Electronics Technology Workshop

June 13 - 16, 2022

This work was funded in part by the NASA Electronic Parts and Packaging (NEPP) Program and the Trusted & Assured Microelectronics Program Under Interagency Agreement A2005-097-080-003983

National Aeronautics
and Space Administration

The Value of “Test-As-You-Fly”: Modernizing Experimentation And Data Analysis for NASA Missions

Melanie Berg(1)

Melanie.D.Berg@NASA.gov;
Melanie.Berg@SSAIHQ.com

Michael Campola(2), Hak Kim(1), Scott Linton (1), Anthony Phan(1)

1. SSAI Inc. in support of the NEPP Program and NASA/GSFC

2. NASA Goddard Space Flight Center

Acronyms

ASIC	Application Specific Integrated Circuit	[redacted]	NP	Number of Points
BRAM	Embedded Block Random Access Memory	[redacted]	R_h	Error rate (variable
DUT	Device under test	[redacted]	RHBD	Radiation Hardened by Design
DFF	D-flip-flop (clocked sequential cell)	[redacted]	RTD	Representative Tactical Design
EDAC	Error Detection and Correction	[redacted]	SEE	Single Event Effect
$f(L)$	Differential flux across linear energy transform	[redacted]	SEF	Single Event Failure
FPGA	Filed Programmable Gate Array	[redacted]	SEFI	Single Event Functional Interrupt
L	Linear Energy Transfer (variable)	[redacted]	SET	Single Event Transient
LBNL	Lawrence Berkeley National Laboratory	[redacted]	SEU	Single Event Upset
LET	Linear Energy Transfer	[redacted]	SRAM	Static Random Access Memory
LET_{TH}	Linear Energy Transfer Threshold	[redacted]	TMR	Triple Modular Redundancy
$LET_{0.25}$	Linear Energy Transfer where cross-section is 0.25 of saturation cross-section	[redacted]	σ	Cross section
LTMR	Localized Triple Modular Redundancy	[redacted]		
NASA	National Aeronautics and Space Administration	[redacted]		

Overview

- Present new methods for characterizing FPGA performance in radiation environments.
- Walk-through NASA Mission use case example:
  - Device under test: Microsemi ProASIC3 FPGA.
  - Mission requires “work-through” harsh radiation environments with minimal ground intervention.
- Show: Old methods are insufficient while new methods provide better characterization and assistance towards suitable design strategies.

Mission Use Case

- Evaluation of the ProASIC3 FPGA per mission requirements.
- Evaluation steps:
  - Get data: Gather existing SEE data… or perform accelerated SEE testing.
  - Perform conservative (upper-bound) error rate calculations; and determine if error rates satisfy mission requirements.
    - Conservative calculations should be derived from established bounding mechanisms for the target FPGA.
    - Warning: said bounding mechanisms vary per FPGA type. Be aware of the appropriate bounding scheme.
  - If conservative estimates do not meet mission requirements, or if existing SEU data are deficient across LET, then:
    - Will inserting mitigation solve the problem?
    - Is more SEE testing required?

Although several FPGA designs are being evaluated for this mission, this presentation focuses on only one. Details are spared to protect intellectual property.

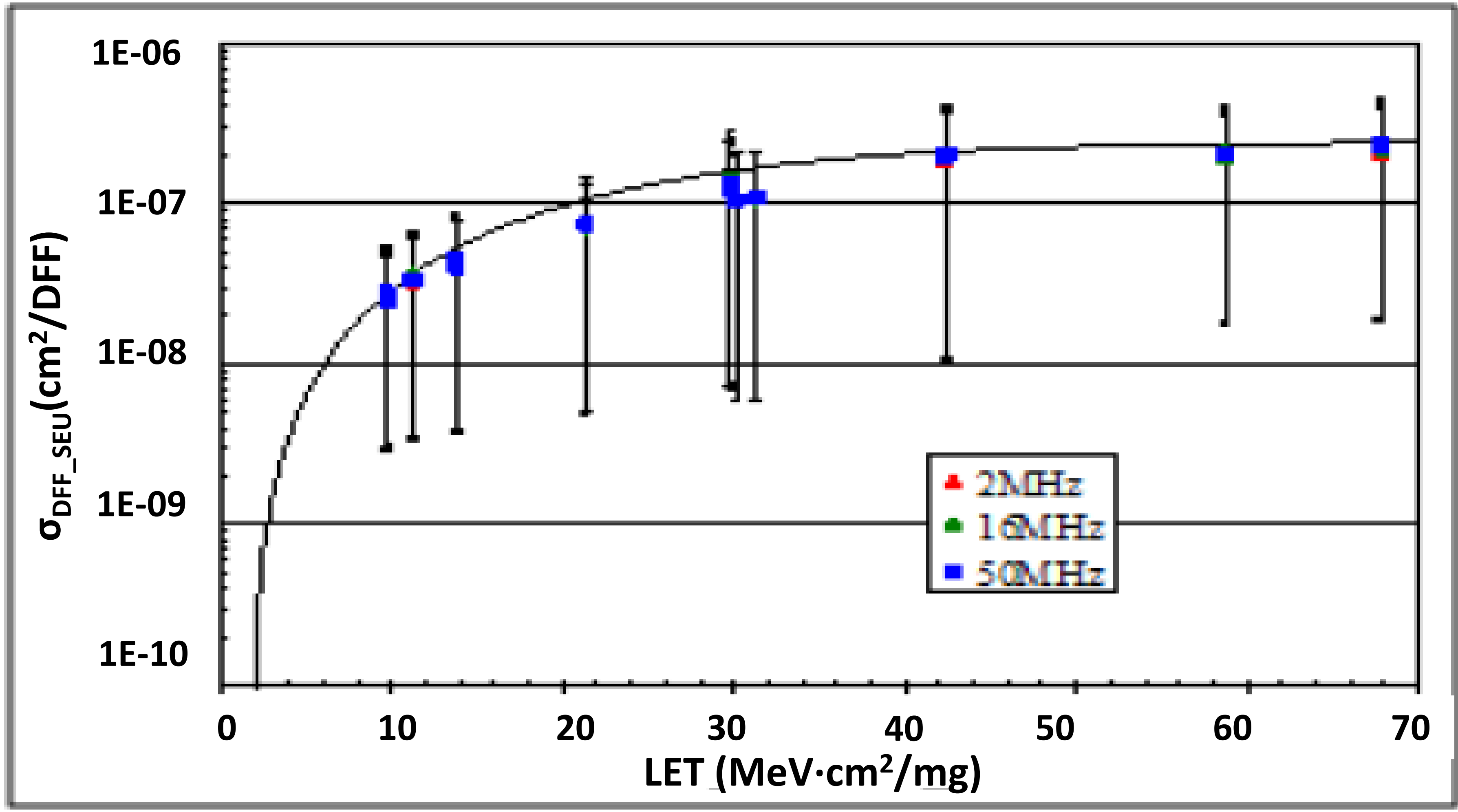
It’s a ProASIC3… What Could Possibly be New?

- ProASIC3 has flown in many missions…Why not rely on heritage flight information?
- For this mission, requirements are more stringent:
  - Role of ProASIC3 (for this mission) is now critical… availability is paramount.
  - Must operate through solar storm conditions (worst week).
  - Requirement: Ground intervention not greater than 1 per day.
- SEE data exist but, available data are deficient across LET. Consequently, rate predictions for mission assurance can be compromised.
- Rough estimates show critical operations will not satisfy requirements – mitigation is required.
- Existing analysis methods cannot uncover specific susceptibilities that require mitigation and if the selected mitigation will be effective.
  - Moving from transistor level (simple circuit) analysis to complex system analysis.

Manufacturer data

https://www.microsemi.com/document-portal/doc_view/131374-radiation-tolerant-proasic3-fpgas-radiation-effects-report

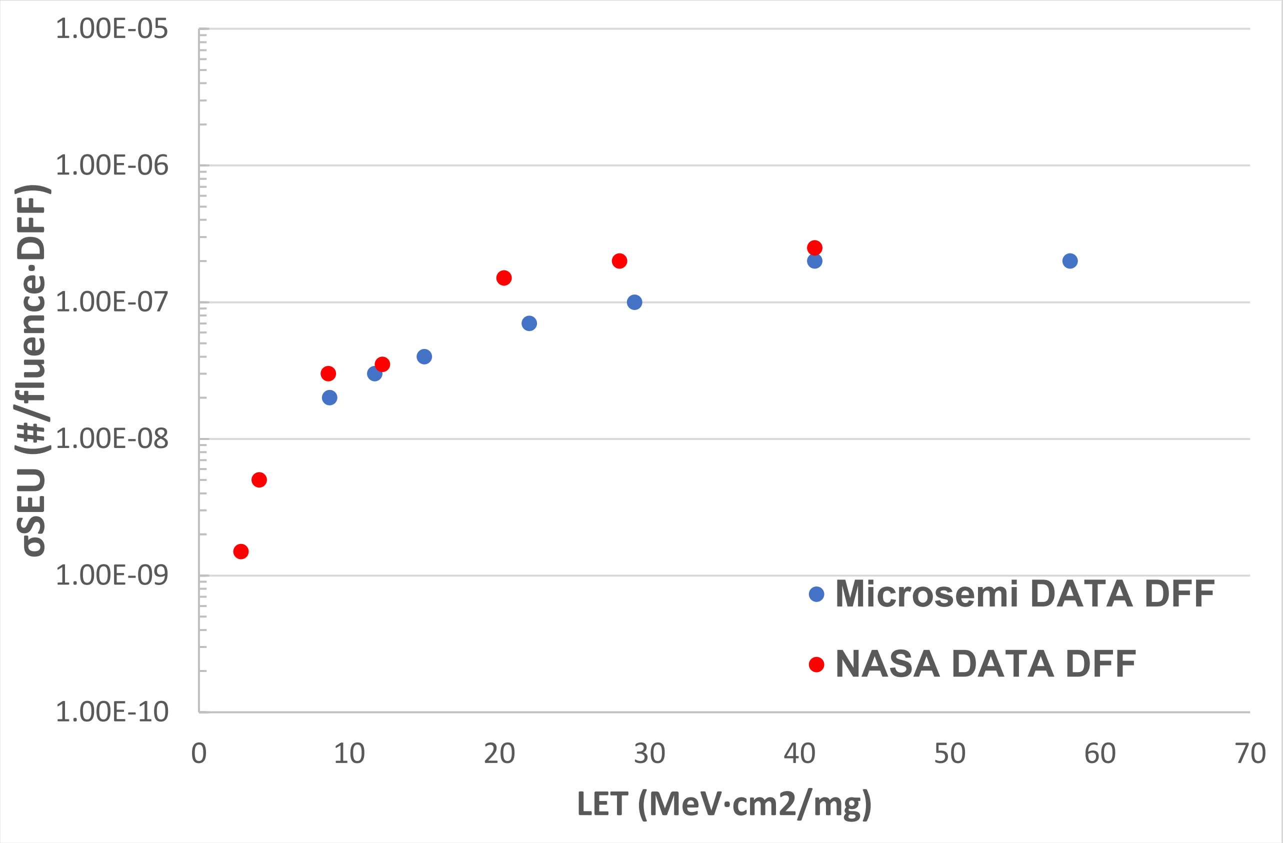
- Low LET test points are missing.
- Curve-fit extrapolation assumes LET_{TH} near 2.0 $MeVcm^2/mg$.



NASA Data Contain Lower LET Test Points

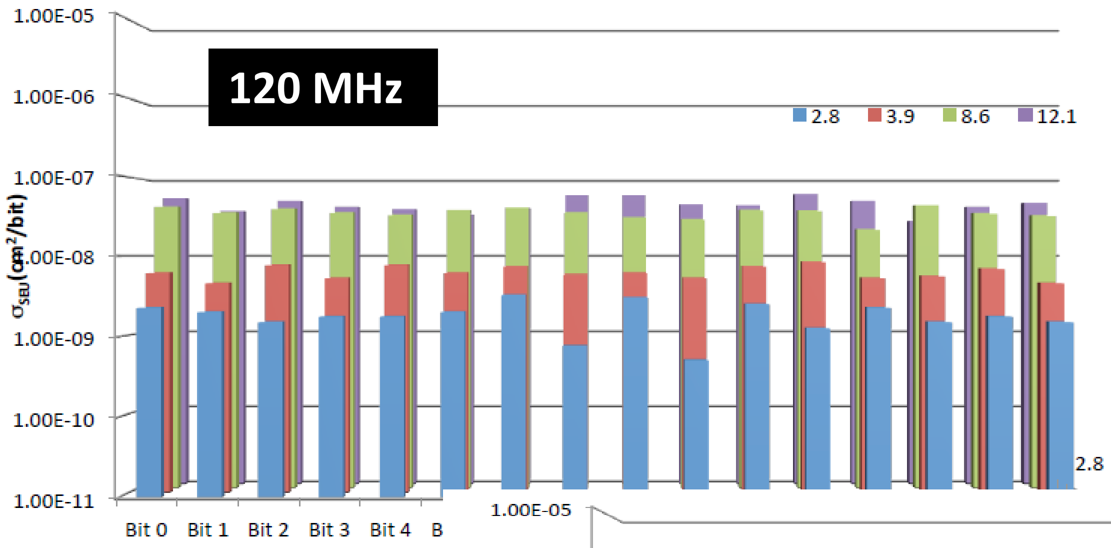
[Actel ProASIC A3PE3000L-PQ208 Field Programmable Gate Array Single Event Effects (SEE) High-Speed Test Plan- Phase II (nasa.gov)]

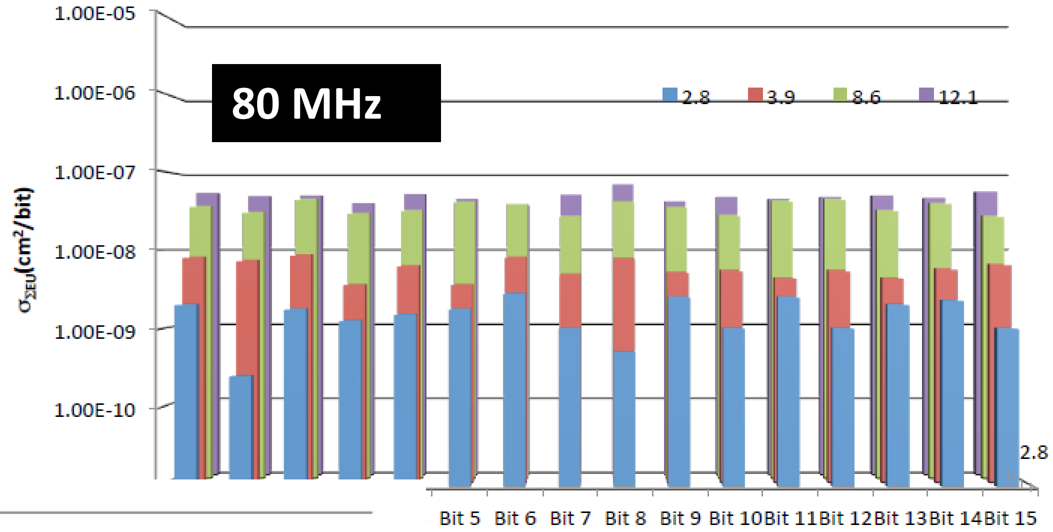
- NASA and Microsemi data agree.
  - NASA Lowest test point: 2.8 MeVcm^2/mg.
  - Microsemi Lowest test point: 8.7 MeVcm^2/mg.
  - There are no embedded RAM data. Assumptions must be made.
- ProASIC3 DFFs SEUs are the dominant mechanisms for failure:
  - No frequency dependency.
  - No data path dependency
  - No significant hidden logic
- Data should be easily extrapolatable.

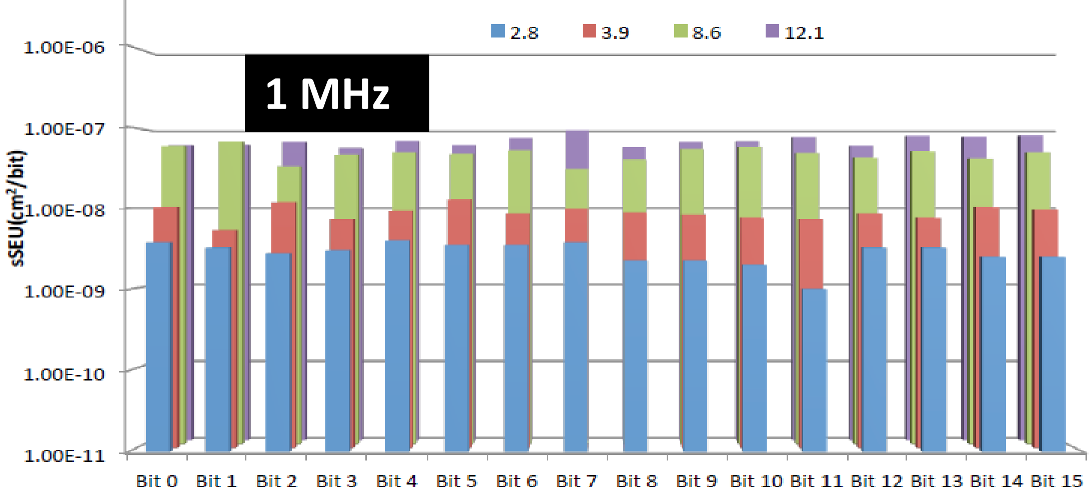


16-bit Counters at Various Frequencies

Actel ProASIC A3PE3000L-PQ208 Field Programmable Gate Array Single Event Effects (SEE) High-Speed Test Plan- Phase II (nasa.gov)







No Datapath or frequency dependency across bits.

Counter bit SEU Data match DFF data.

SEU bit cross sections (for non-mitigated designs) appear to not be design dependent (for the ProASIC3).

Preparation for Error Rate Upper Bound Calculations

- As previously mentioned, upper bound error rate calculations should be performed. If they comply with mission requirements, then not much more analysis is necessary.
- Process for ProASIC3 upper bound error rate calculations:
  - Analyze Data (see previous slides). Prepare to extrapolate SEU bit data.
  - Data suggest multiplying DFFs by DFF error rate should provide a bounding-conservative estimate for design error rates.
    - Obtain the number of non-mitigated DFFs (multiply by DFF rate)
    - Obtain the number of mitigated DFFs (multiply by LTMR DFF rate)
  - There are no BRAM data available. BRAM-bit error rates will be calculated using DFF error rates.
    - If EDAC is used, BRAM upset rate contribution can be considered negligible.
- **This methodology (for calculating bounding error rates) will work for the ProASIC3 because it is an older device with limited embedded hidden logic.**

Conservative (Bounding) Error Rate Calculations

Do conservative calculations comply with mission requirements?

	100 Mils	**350 Mils**
Error Rate No TMR (#/(bit·day))	1.30E-04	1.20E-05
Error Rate LTMR (#/(bit·day))	6.60E-06	2.60E-07

LET_{TH} = 2.0 MeV·cm²/mg

	100 Mils	**350 Mils**
Error Rate No Mitigation (#/(day))	26	2.4

Error rates are calculated using these design factors

- Design under evaluation contains:
  - ≈ 2×10^4 non-TMR DFFs
  - ≈ 2×10^5 embedded BRAM (no error detection and correction (EDAC))
- Conservative estimate (multiply #bits by bit upset rate) > 1 upset per day.
- Mitigation might be required with 350 mils shielding… estimate is conservative
- Using EDAC with the BRAM can significantly reduce the upset rate.

Non-mitigated BRAM dominate… overly conservative calculation

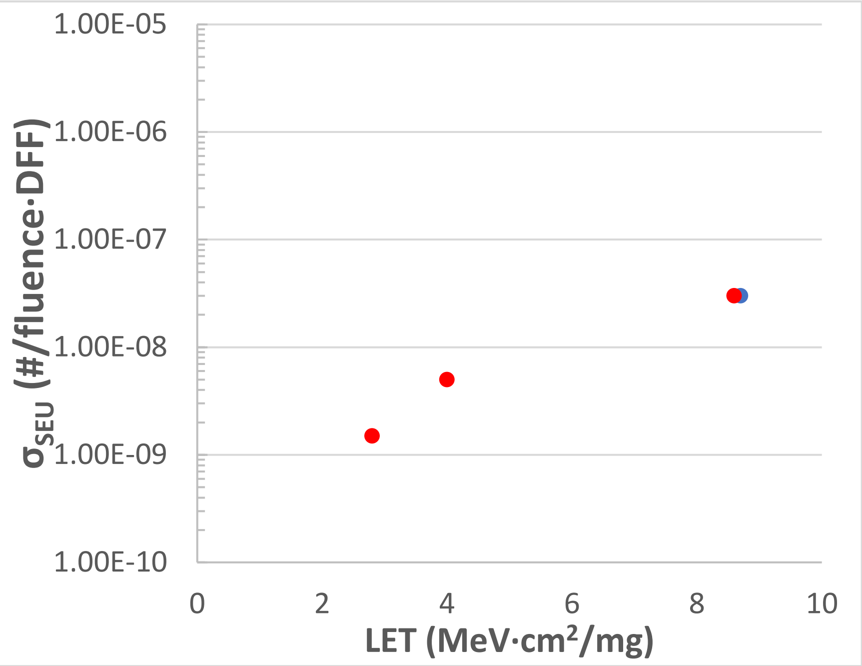
In this case, conservative calculations do not comply with mission requirements.

Challenges/Considerations: LET_{TH}

	100 Mils	350 Mils
Error Rate No TMR (#/(bit·day))	1.30E-04	1.20E-05
Error Rate LTMR (#/(bit·day))	6.60E-06	2.60E-07

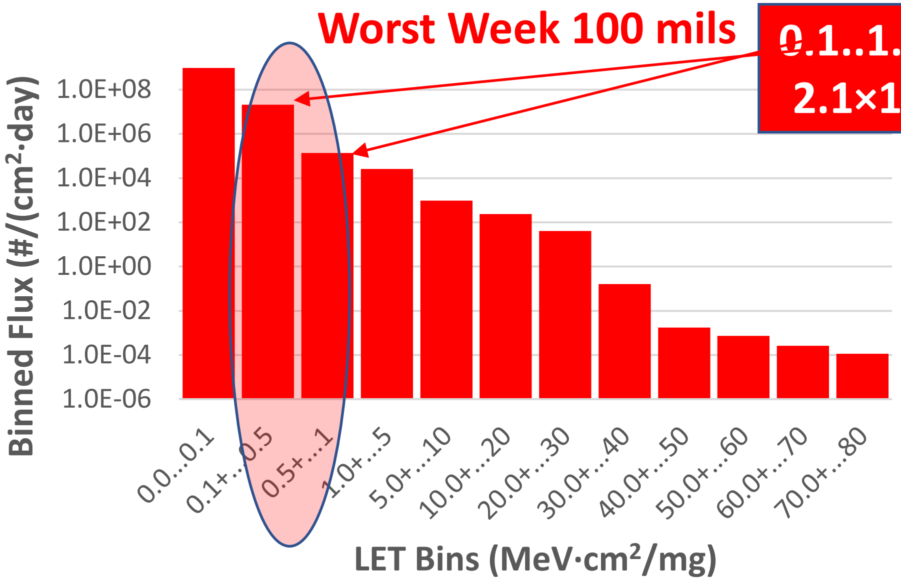
Assumption:
LET_{TH} = 2.0 MeV·cm²/mg

- **Consideration: There are no data points below LET = 2.8 MeV·cm²/mg.**
  - Assumption is LET_{TH} = 2.0 MeV·cm²/mg.
  - Solar storm conditions contain magnitudes greater flux than solar-max and solar-min conditions.
  - LET_{TH} < 1.0 MeV·cm²/mg can cause the error rate to increase by magnitudes.
  - **Because of the harsh radiation environment, the conservative calculations (using LET_{TH} = 2.0 MeV·cm²/mg are) not reliable. Error rates might be significantly higher.**

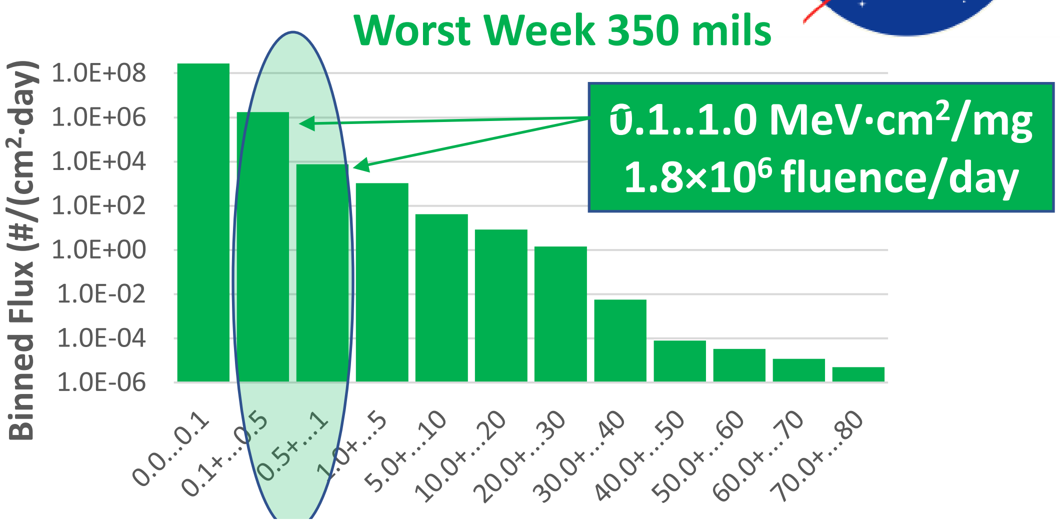


Why Are Low LET Data Important?

Comparing Particle Flux Across Conditions



0.1..1.0 MeV·cm²/mg
2.1×10^{7} fluence/day

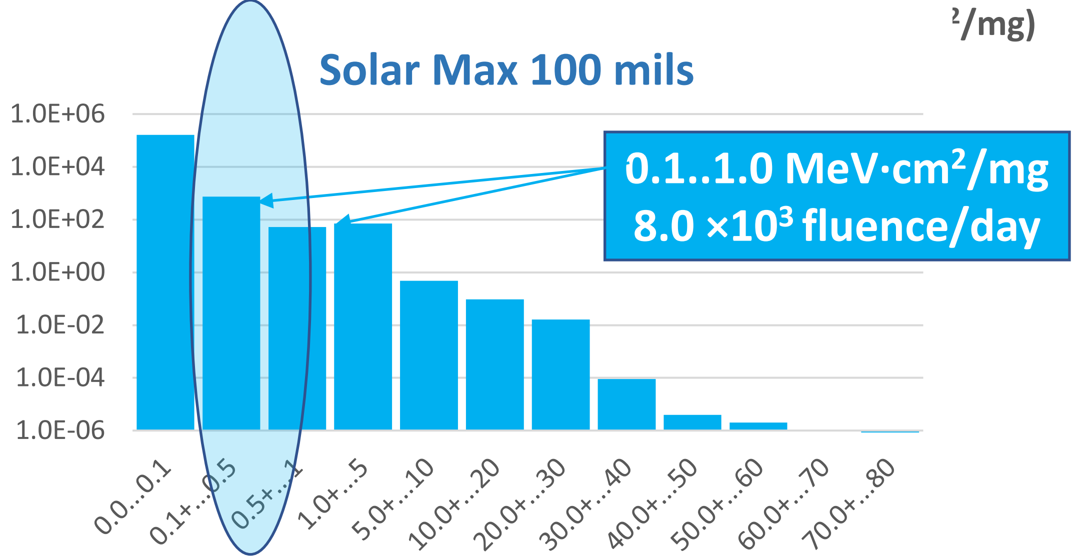


0.1..1.0 MeV·cm²/mg
1.8×10^{6} fluence/day

Usually, upsets→0 with LET< 0.1 MeV·cm²/mg. Flux lower than 0.1 MeV·cm²/mg does not contribute to error rate calculations

As LET_{TH} is increased, error rate will decrease.

Observe low flux at high LET values.



0.1..1.0 MeV·cm²/mg
8.0×10^{3} fluence/day

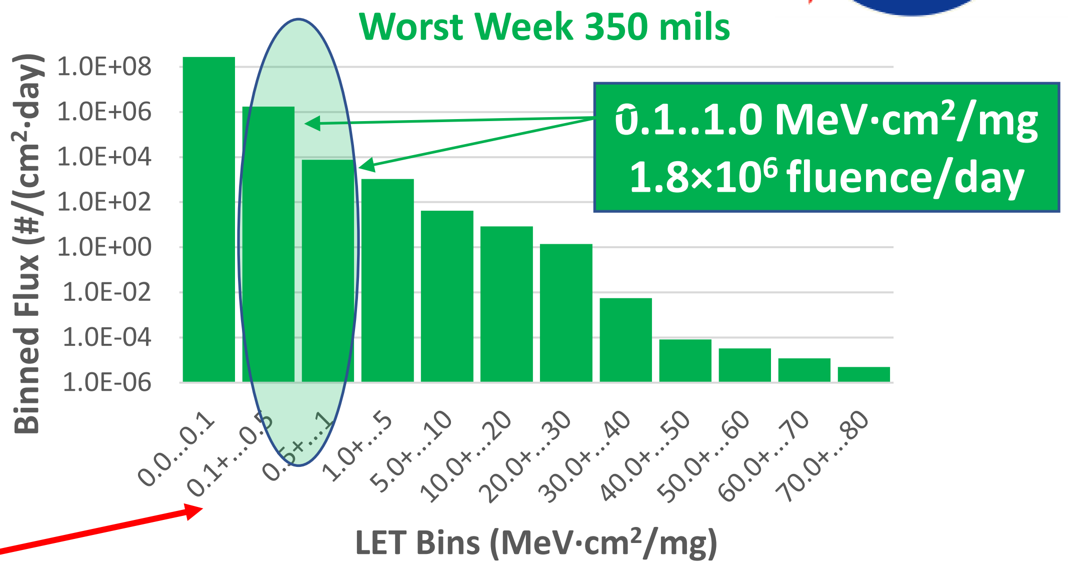
Transformation from Cross Sections (Fluence Domain) to Error Rates (Time Domain)

$$R_h = \int_0^\infty f(L)\sigma(L)dL$$

Transformation to numerical integration

$$R_h = \lim_{\Delta L \to 0} \sum_{L=0}^{NP} f(L) * \sigma(L)\Delta L$$

For L<1, if $\sigma(L)$ >10^{-7}, the error rate can significantly increase.



Output of CREME96 contains bins with small *ΔL* *(i.e., ΔL →0)*

Above LET Bins are sized to demonstrate the flux of particles with LET <1.0 MeV·cm^2/mg

R_h = *Error rate*

L = LET

σ(*L*) = *Single Event Failure Cross Section*

f(L) = differential flux

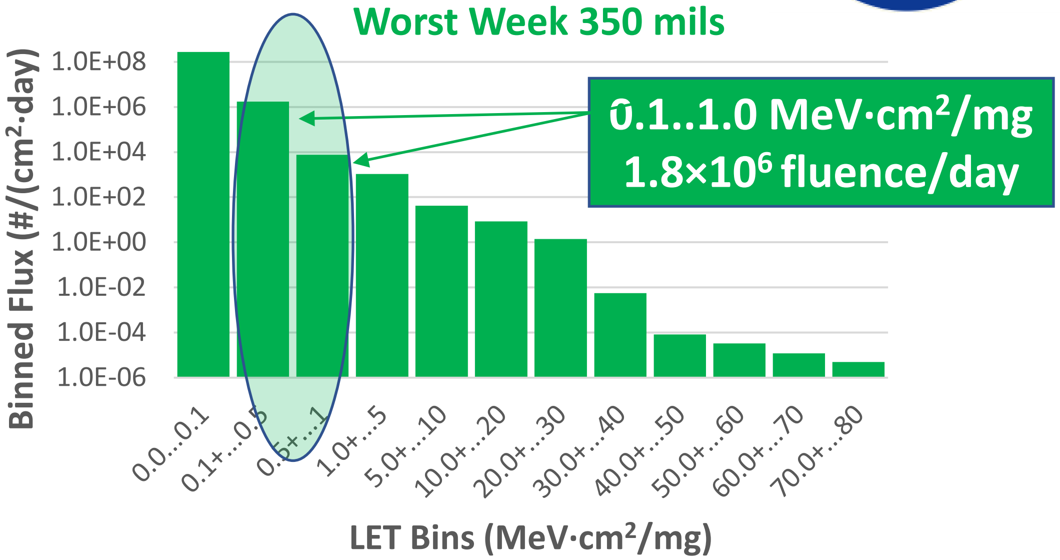
BinnedFlux = *f(L)*ΔL*

BinnedFlux* $\sigma(L) = \frac{fluence}{discrete\ time} \times \frac{\#errors}{fluence}$

Warning: Estimating LET_{TH} at Too High of A Value Can Drastically Underestimate Error Rates

$$R_h = \lim_{\Delta L \to 0} \sum_{L=0}^{NP} f(L) * \sigma(L)\Delta L$$

- **LET_{TH} dictates point at which flux starts to contribute to the error rate.**
- **LET_{TH} that is too high will not include a significant amount of flux.**
- **Low LET data points are essential for applications with stringent requirements and significant SEU susceptibilities.**



	100 Mils	350 Mils
Error Rate No Mitigation (#/(day))	30	2.5

Worse than we thought. Error rate calculated with LET_{TH} = 2.0 MeV·cm²/mg. Actual error rate can be decades higher.

Challenges/Considerations: Mitigation

	100 Mils	350 Mils
Error Rate No TMR (#/(bit·day))	1.30E-04	1.20E-05
Error Rate LTMR (#/(bit·day))	6.60E-06	2.60E-07

LET_{TH} = 2.0 MeV·cm^2/mg

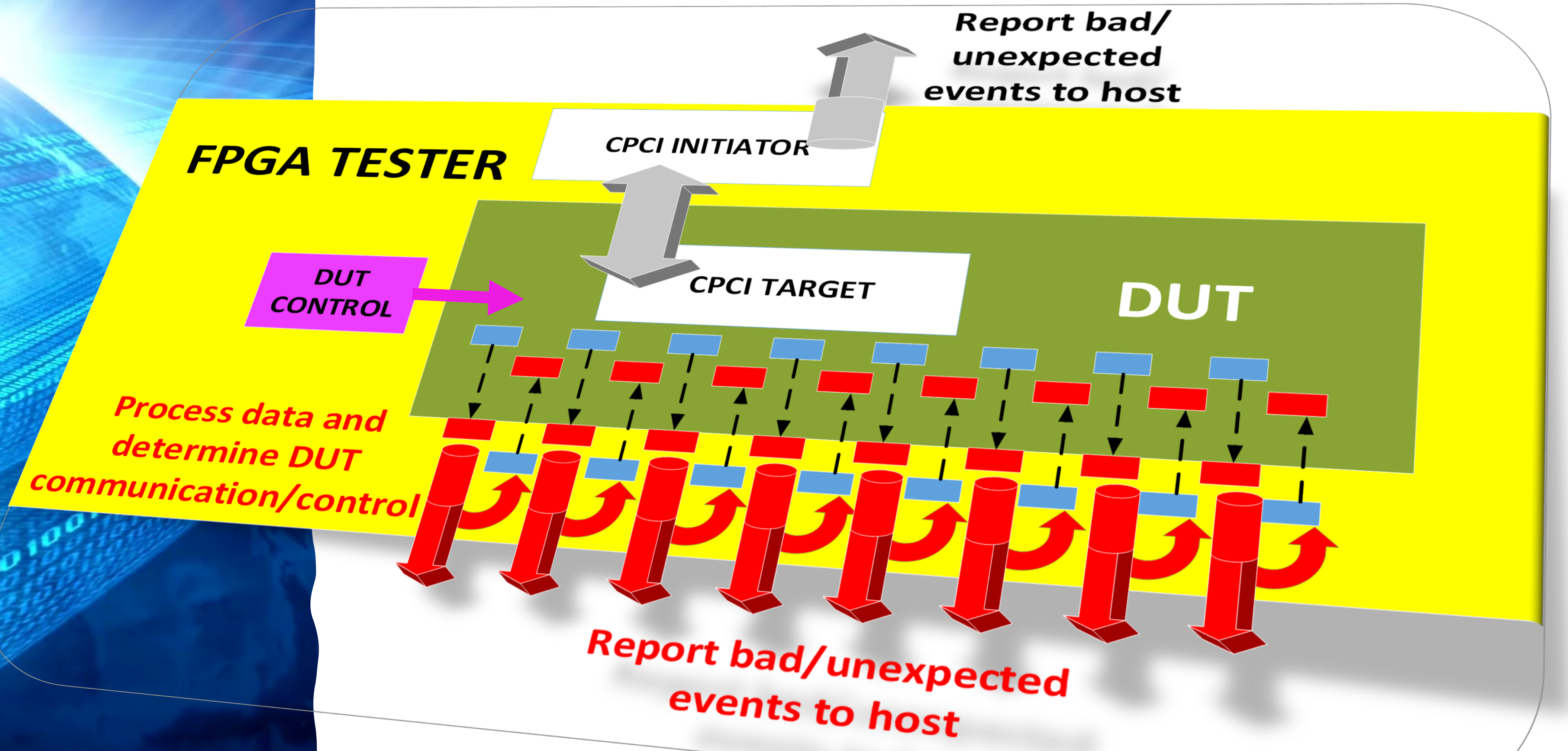
- As shown, LTMR can significantly reduce the error rate in ProASIC3 FPGA designs.
- **Problem: For this design under investigation, we are unable to mitigate the entire design (not enough resources inside the FPGA).**
- Mitigation must be carefully selected:
  - What should/can be TMR'd? This can reduce the rate for up to 2×10^4 bits.
  - Can EDAC be added? This can reduce the rate for 2×10^5 bits.
- Testing of mitigated design is required… a case for "test as you fly."

Accelerated radiation testing is expected to measure the efficacy of user-inserted mitigation and to fine-tune conservative predictions.

Mission Has Decided on Additional SEE Testing

- Test-as-you fly and Fluence-to-failure methodology:
  - Single event failure (SEF) are used as cross sections and compared to upper bound calculations.
  - Tests are performed monitoring events that affect system behavior.
    - This goes beyond SEU or SET detection.
    - Mission specific behavior must be controlled and monitored.
- Search for LET_{TH}
- Determine what functionality would benefit from TMR.
  - The device has limited resources – hence must choose how to mitigate wisely.

Example Test as You Fly System



Differentiating Modern SEE Test Systems From Conventional

- Full complex systems
- From the DUT’s point of view, it operates as if it were in flight.
- DUT is controlled by the tester:
  - Controls are at-speed
  - Controls can respond as they would in the tactical system.
  - Controls emulate actual peripherals to the DUT
- DUT responses are analyzed by the tester.
- Mission protocols are adhered to between the DUT and Tester.
- Tester emulates DUT peripherals (per peripheral datasheets) and responds to DUT outputs.
- No test vectors, no side-by-side comparisons to expected data. Alternatively, DUT activity is monitored in situ system operation.

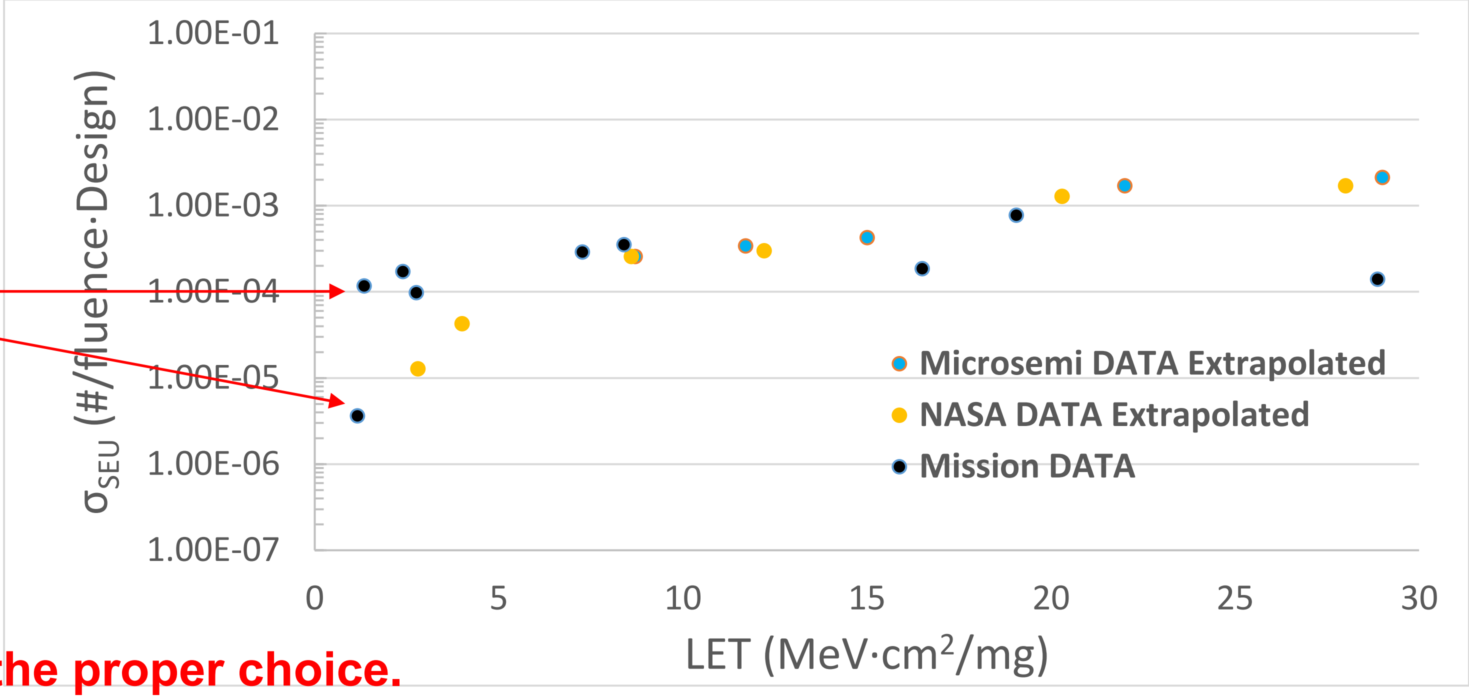
Test as You Fly Challenges (Only a few are listed)

- System creation is complex:
  - Requires expertise of a designer.
  - Requires expertise of a test engineer.
  - Requires expertise of a radiation effects engineer.
- System development must be done in a relatively short period of time.
  - Complexity is underestimated and design cycle is generally not realistic.
- Ability to obtain the actual design under investigation.
- Ability to traverse a significant amount of state space while testing. Tricks of the trade… increase visibility points.

Test Campaign I: Use of Representative Tactical Design

RTD: Representative Tactical Design

- The first campaign was considered a “first look”.
- Testing was performed at Lawrence Berkeley National Laboratory (LBNL) 88-inch Cyclotron.
- An RTD was developed; and only a portion of the design was tested.
- The total number of DFFs was 8500; and a small percentage of the embedded memory was tested.
- Findings:
    - LET = 1.0 MeV·cm^2/mg was the lowest available LET at LBNL.
    - **σ is significant at LET = 1.0 MeV·cm^2/mg for Solar Storm conditions; and cannot be considered LET$_{TH}$.**
    - Depending on the LET$_{TH}$ error rates can vary by decades.



LET$_{TH}$ = 2.0 MeV·cm^2/mg was not the proper choice.

Next Test Campaign

- The full design will be tested.
- Additional TMR and EDAC have been added to the design.
  - Efficacy of the mitigation will be monitored and reported.
- LET values as low as 0.1 MeV·cm^2/mg will be tested at Texas A&M University Cyclotron Facility.
  - Facility can go as low as 0.1 MeV·cm^2/mg.
  - Next ion from 0.1 MeV·cm^2/mg is 1.0 MeV·cm^2/mg.
  - Degraders and angle will be used to fine-tune SEU cross sections between 0.1 MeV·cm^2/mg is 1.0 MeV·cm^2/mg. This will provide for more accurate error rate calculations.
- The campaign will be conducted the week of June 23rd 2022.

Summary

- A mission use case for the ProASIC3 FPGA has been presented.
- A specific design was selected because of its critical role within the mission and because its bounding error rate calculations do not meet mission requirements.
- Concerns that were identified:
  - Mitigation must be added but is extremely limited to partial mitigation.
  - Optimal mitigation schemes must be determined and measured.
  - Error rate calculations must be refined and LET_{TH} must be found.
- It has been shown how essential finding LET_{TH} is regarding error rate calculations.
  - Flux versus LET have been presented showing high flux at low LET values.
  - Depending on the target environment, low LET_{TH} with significant cross-sections can change error rates by decades.
- Test as you fly with fluence-to-fluence methodology has been (and still is being implemented); and is proving to be essential for complex system analysis.