Method for Bounding Destructive Single-Event Effect Rates with Limited Statistics

Ray Ladbury
Radiation Effects and Analysis Group
NASA Goddard Space Flight Center

To be presented by Ray Ladbury at the Single-Event Effects Symposium and Military and Aerospace Programmable Logic Devices (SEE-MAPLD), La Jolla, CA, April 9-12, 2013, and published on http://nepp.nasa.gov/.

Destructive Single-Event Effects (SEE) Challenges

- Destructive nature of single-event latchup (SEL), single-event burnout (SEB), single-event gate rupture (SEGR), *etc*. complicates testing and radiation hardness assurance (RHA)
  - Consequences for mission can be severe
  - In testing, every data point may represent a failed device $\rightarrow$ limited statistics
  - Both factors necessitate conservatism in rate estimation, but how conservative?
- May have to combine data for several devices to improve statistics
  - Testing may be done at different facilities—different linear energy transfers (LETs)
  - If parts are thinned, variations may also result in different LETs for each part
  - Part-to-part variation combines with Poisson fluctuation
  - Effective LET may not apply
- 2007 method estimated SEE rates for a given confidence limit (CL) for poor statistics assuming Weibull σ vs. LET and Poisson fluctuations
  - For truly destructive SEE, # of events per run always equal to 1
  - Fluence to failure exponentially distributed about mean
  - Can we adapt the 2007 method?

Statistics of Destructive Failure

- Destructive SEE are Poisson processes
- # events=1, so σ=1/(Expected Fluence)
- Introduce model for σ vs. LET

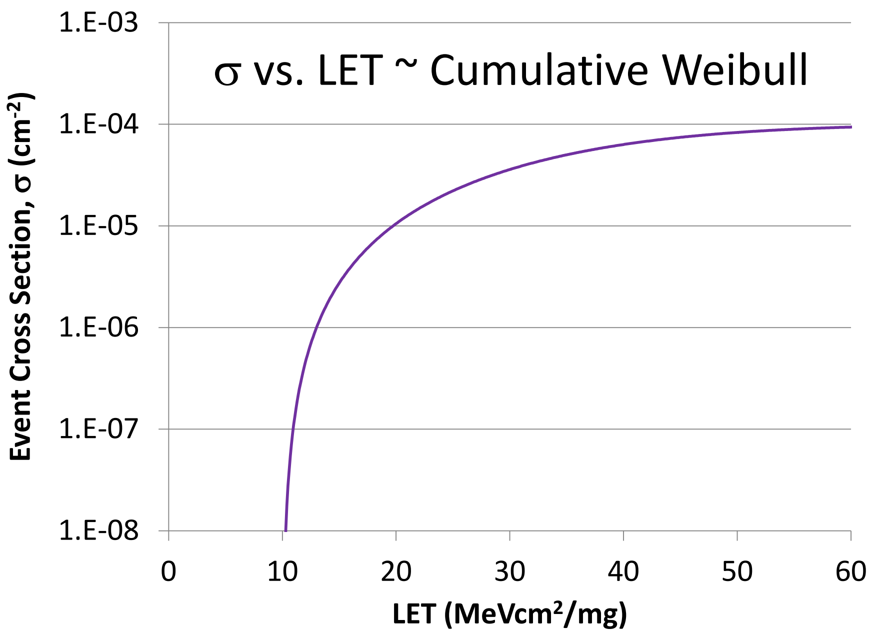
$$\sigma(LET) = \sigma_0 \times \mathrm{Weibull}(LET - LET_0, w, s)$$

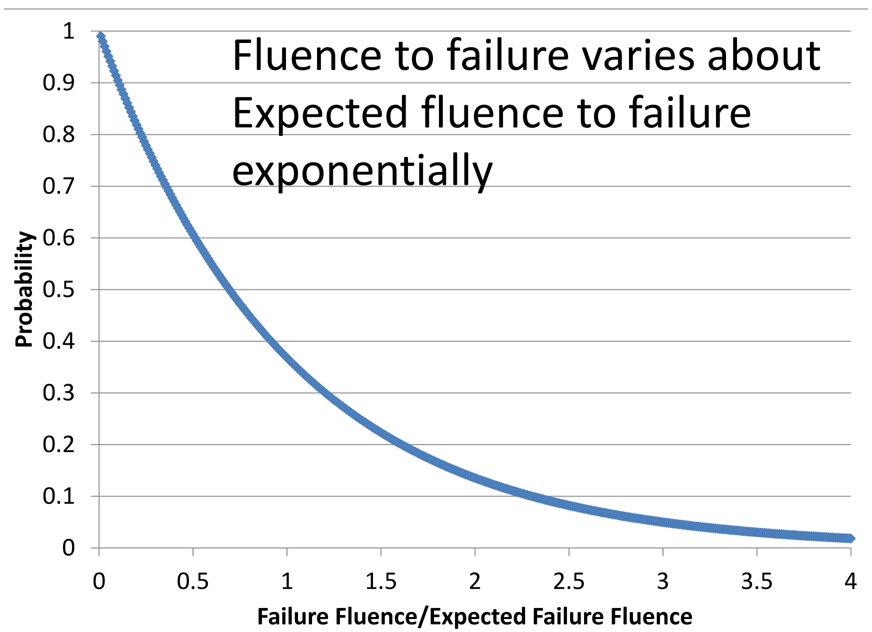
  - σ_0=Saturated cross section, LET_0= onset LET; w, s = Weibull width, shape

- Fluence to failure varies about expected value (mean) according to an exponential distribution

$$P(F, \sigma(LET)) = \sigma(LET) \times \exp(-\sigma(LET) \times F)$$

  - Ignores part-to-part variation, but we could also introduce this factor





Solve Using Generalized Linear Model

- Likelihood over n data points, $L = \prod_{i=1}^{n} P_i(data_i : model)$
- Likelihood of fluences to failure for all runs, i=1 to n

$$L(\{F_i, LET_i\}, \sigma_o, LET_0, w, s) = \prod_{i=1}^{n} \sigma(LET_i) \times \exp[-\sigma(LET_i) \times F_i]$$

  – σ_0, LET_0, w and s that maximize L give best fit to data $\{\sigma_{0BF}, LET_{0BF}, w_{\mathrm{BF}}, s_{\mathrm{BF}}\}$
  – Confidence contour for confidence level CL given in terms of INVχ^2 distribution with degrees of freedom = # parameters in fit

$$L_{CL}/L_{BF} = \exp(-\mathrm{INV}\chi^2(1-CL, \#\mathrm{parameters} = 4))$$

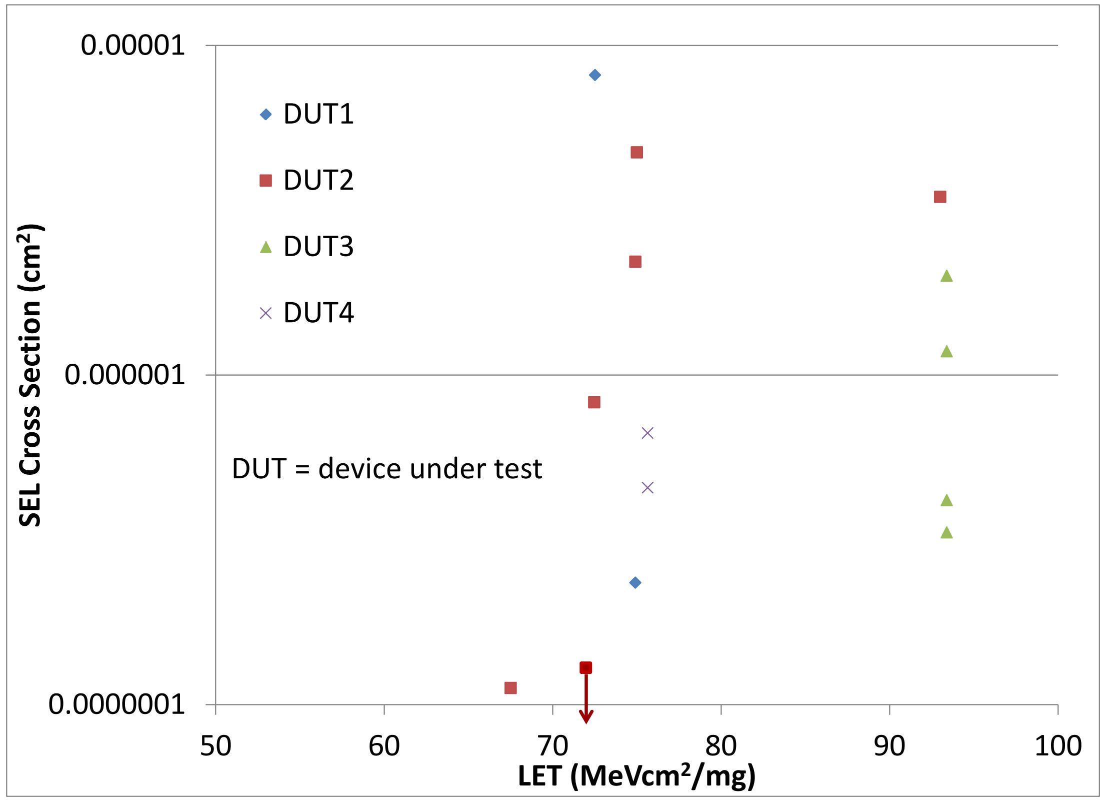
- WC fit for confidence level CL is parametric combination yielding highest rate within parametric contour CL
- Can use Figure of Merit to find promising parametric combinations
  – $FOM = C * \sigma_{sat} / LET_{0.25}^2$,
  – C depends on environment (~400 in geostationary orbit (GEO))

To be presented by Ray Ladbury at the Single-Event Effects Symposium and Military and Aerospace Programmable Logic Devices (SEE-MAPLD), La Jolla, CA, April 9-12, 2013, and published on http://nepp.nasa.gov/.

Fitting Poor Quality Data

SELs for TI SN54LVTH16244

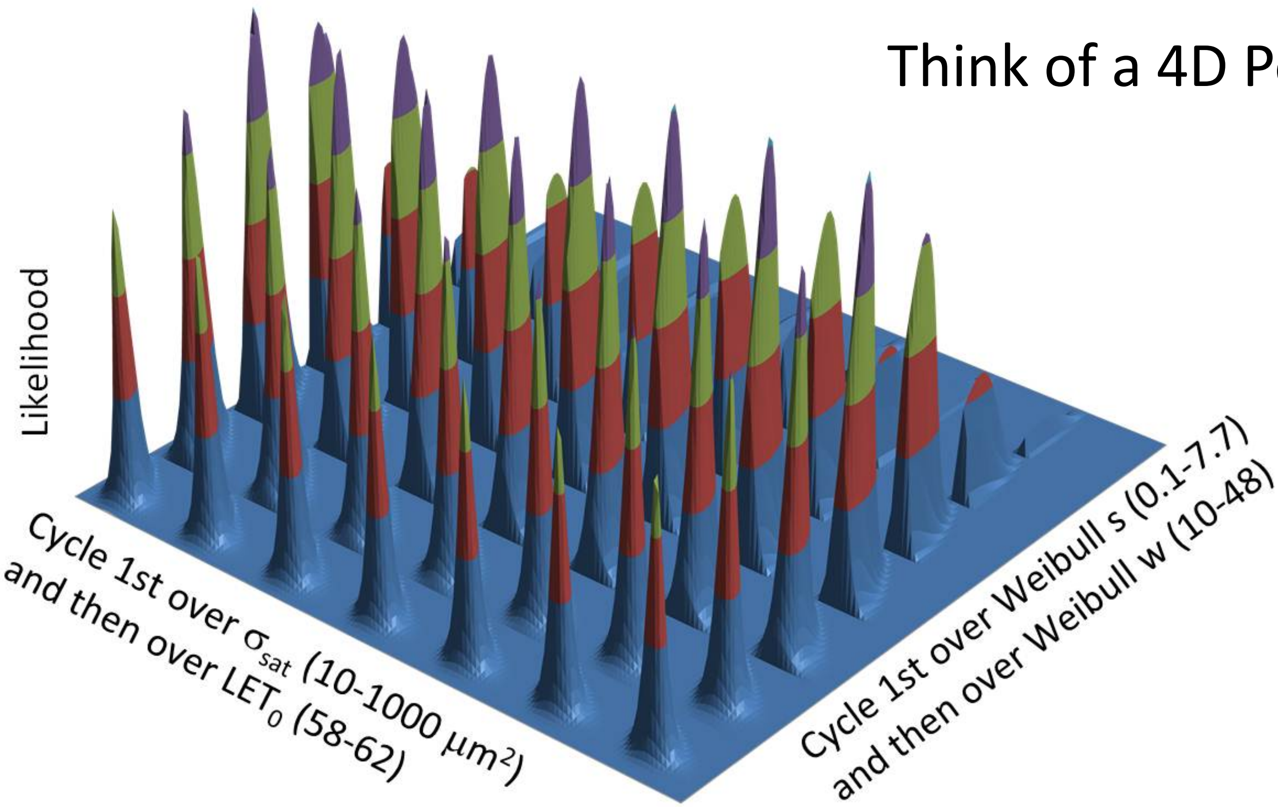
DUT #	Eff. LET (MeVcm^2/mg)	Cross-section (cm^2)
2	67.5	1.12E-07
2	72.5	8.26E-07
1	72.5	8.13E-06
1	74.9	2.34E-07
2	74.9	2.21E-06
2	75.0	4.74E-06
4	75.6	6.67E-07
4	75.6	4.55E-07
2	93.0	3.47E-06
3	93.4	3.33E-07
3	93.4	1.18E-06
3	93.4	2.00E-06
3	93.4	4.17E-07
2	72.5	Null



Only fourteen events with which to estimate a rate!

Probability in 4 dimensions?

Likelihood of TI LVTH16244 SEL data for parametric combinations $\{\sigma_{sat}, LET_0, w, s\}$



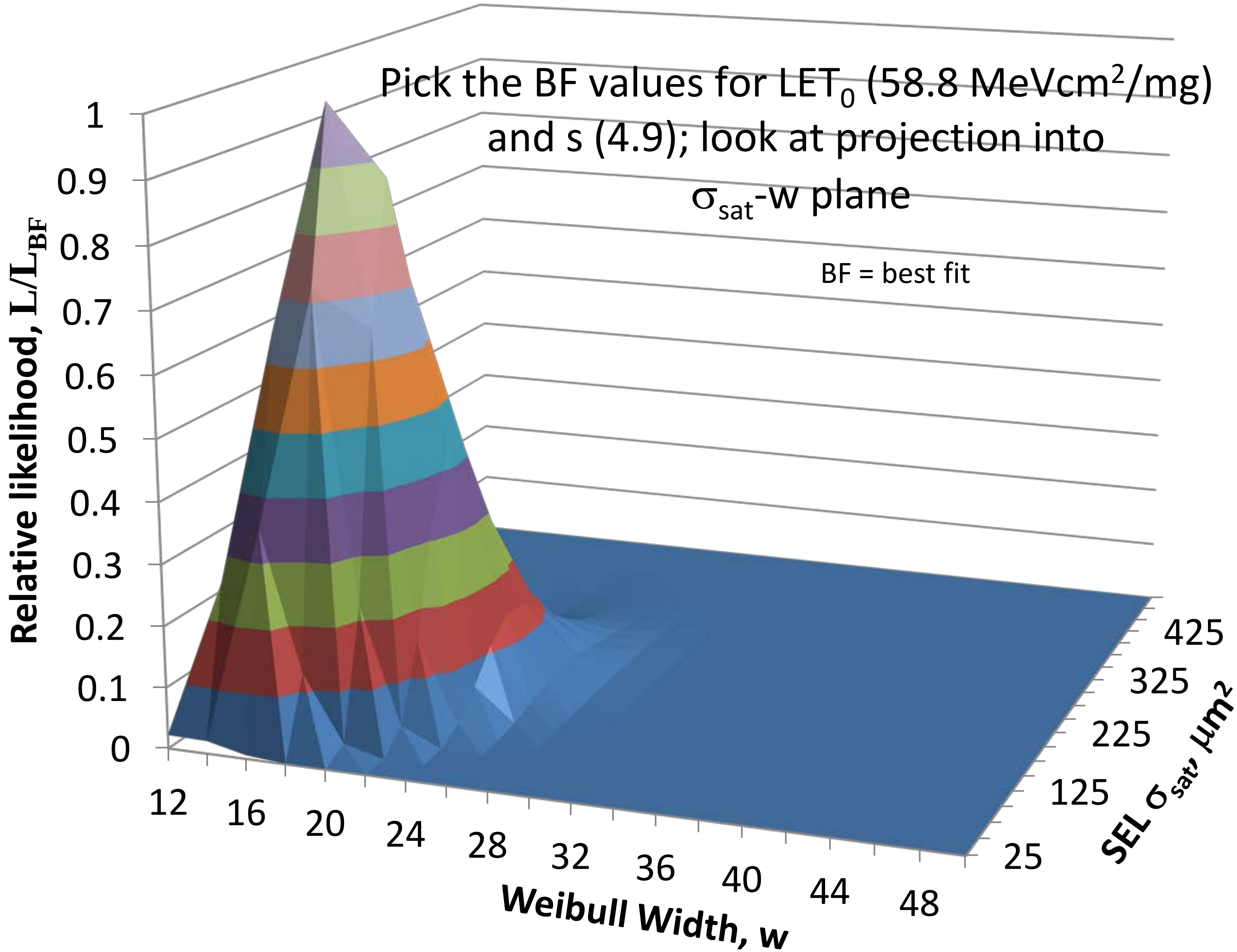
Think of a 4D Porcupine

TI = Texas Instruments

Projection into 2 dimensions?

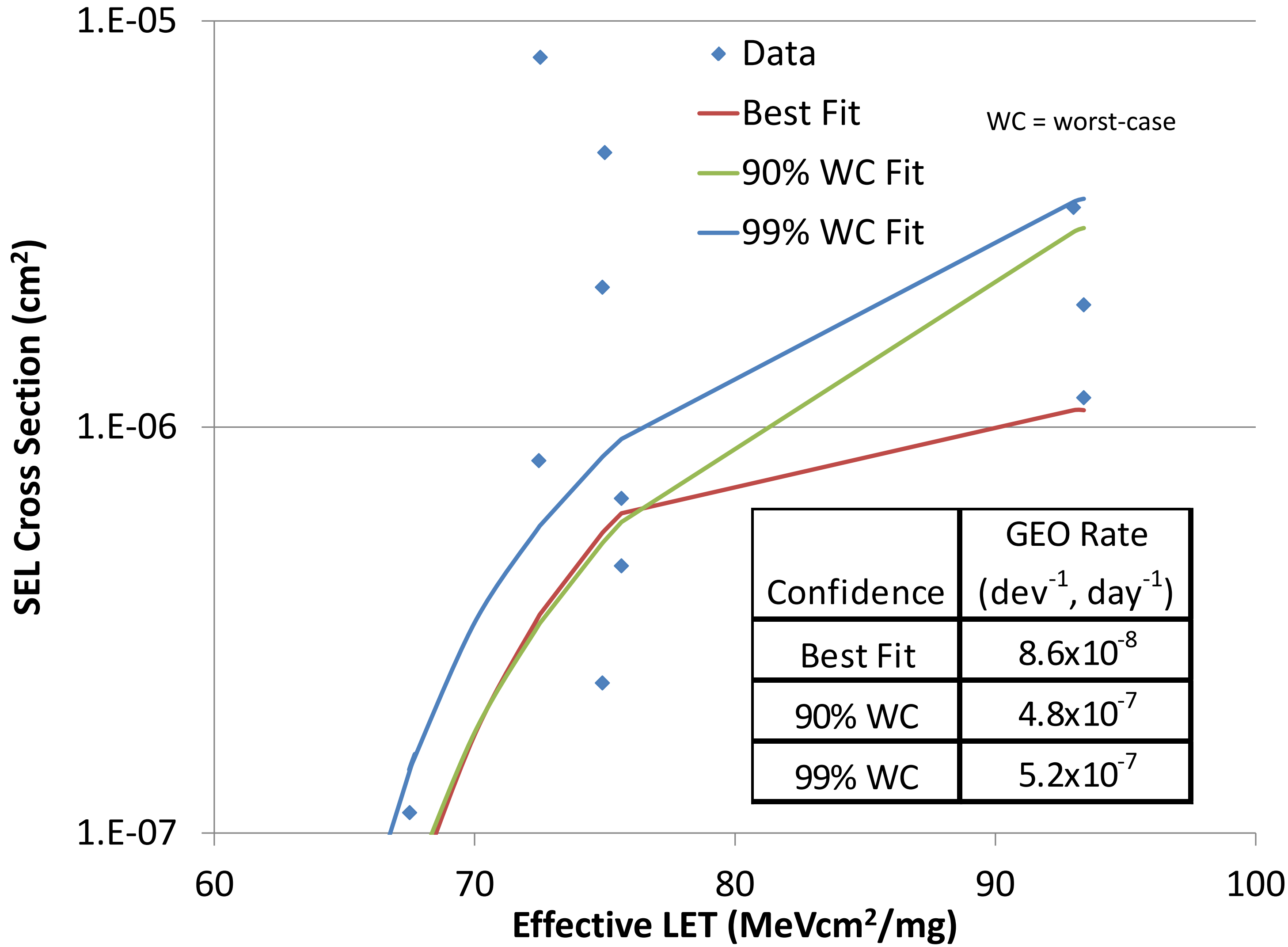
Pick the BF values for LET_0 (58.8 $MeVcm^2/mg$) and s (4.9); look at projection into σ_{sat}-w plane

BF = best fit



To be presented by Ray Ladbury at the Single-Event Effects Symposium and Military and Aerospace Programmable Logic Devices (SEE-MAPLD), La Jolla, CA, April 9-12, 2013, and published on http://nepp.nasa.gov/.

How bad can it be?



Confidence	GEO Rate (dev^{-1}, day^{-1})
Best Fit	$8.6x10^{-8}$
90% WC	$4.8x10^{-7}$
99% WC	$5.2x10^{-7}$

Other Applications—Test Planning

- Experiment can be simulated prior to run to determine
  - Test conditions that best constrain/bound rate estimation
  - How to allocate scarce parts to best constrain/bound rate estimate.
    - How many parts near threshold?
    - How many to determine saturation?
    - How many in between?
    - Vary LET or accumulate statistics at the same LET?
- Can optimize allocation of parts and beam time in response to new data
  - Go to higher or lower LET to constrain fit?
  - Accumulate statistics or sample other LETs/test conditions?
  - Check for systematic errors, part-to-part variation by detecting failure fluences that deviation significantly from Poisson fluctuations (exponential about mean)
  - Are the data following effective LET?
  - And so on

Other Applications: Data Analysis

- Detection of outliers
  - Fluence to failure should follow exponential distribution about mean
  - Can data for different DUTs be combined, or do variations exceed Poisson errors?
  - Is lot-to-lot variation significant for a part type?
- Model comparison
  - Weibull form of σ vs. LET curve is only one candidate
  - Model can have angular, ion or any other dependence if sufficient data available to calibrate it—can be adapted to SEGR and SEB
  - Model can be output of a Monte Carlo or analytical
- Radiation Hardness Assurance
  - Comparison of SEE rates from different SEE analysts
    - Can determine level of conservatism by comparing estimates to worst-case results for different confidence levels
  - Allows comparison of SEE failure rates and electrical/mechanical failures estimated for similar confidence levels

Conclusions

- Destructive SEE represent serious challenges to hardness assurance
  - Consequences are severe, but statistics for bounding rates or always poor.
  - As a result, rates must be estimated conservatively,
    - but how conservatively?
- Generalized linear models offer flexible method to allow confidence level of rate to be determined
  - σ vs. LET can follow any model
    - Could be output of a physics-based Monte Carlo
  - Errors can be Poisson or more general (e.g. including part-to-part variation)
- Method can facilitate test planning
  - Allocation of parts, test LETs, etc.
- Also useful for data analysis
  - Detection of outliers, comparison of models, etc.
- Enables comparison of failure rates from other analysts or other causes

To be presented by Ray Ladbury at the Single-Event Effects Symposium and Military and Aerospace Programmable Logic Devices (SEE-MAPLD), La Jolla, CA, April 9-12, 2013, and published on http://nepp.nasa.gov/.