

Dealing with Ion LET Uncertainties: An Application of Generalized Linear Models

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Abstract— Although most SEE rate estimation methods presume a fit to SEE cross section vs. LET, fitting SEE data is challenging because the data are not compatible with the assumptions of many common fitting techniques (e.g. linear regression). The difficulty of fitting such data is compounded when the LET of the ion responsible for an SEE is uncertain. We modify a Generalized Linear Model SEE data fitting methodology to accommodate uncertain LET and apply the method to the problem of backside heavy-ion SEE testing to demonstrate the utility of the method, explore the dependence of systematic errors that arise from improper treatment of LET uncertainty and develop guidelines for minimizing such systematic errors when proper treatment is not possible. Additional applications are suggested and assessed for suitability of treatment by the model.

Index Terms— Single-event effects, reliability estimation, quality assurance, statistical techniques

I. INTRODUCTION

The most common version of the Rectangular Parallelepiped (RPP) approach to Single-Event Effects (SEE) rate estimation presumes a fit of the SEE cross section σ as a function of Linear Energy Transfer (LET) to a cumulative Weibull form. The fit is combined with radiation environment models assuming a simplified sensitive volume (SV=RPP) to estimate charge deposited. However, for many environments, LET of the ion that causes a given SEE is uncertain, including:

1. Secondary ions from nuclear collisions in the semiconductor [1,2] or surrounding material [3].
2. Space [4] and accelerator [5] environments.
3. Ion beams degraded by traversing nonuniform material thicknesses—e.g., parts thinned for back-side irradiation [6] or packaged parts with variable overburden
4. Situations where SV dimensions and ion energies render the concept of a single, well-defined LET problematic [7]

Even for the ideal case, fitting SEE cross sections spanning orders of magnitude and having variable errors can be difficult. Uncertain LET values further complicate the process, adding systematic errors to the random errors in event counts.

To date, attempts to deal with the effects of uncertain LET have been limited, either limiting the role of LET in the analysis [1,2,7] or assigning “representative” LET values for different cross sections [6].

In this work, we develop an approach for treating LET uncertainties by modifying a Generalized Linear Model (GLM), [8] developed previously for fitting SEE cross section vs. LET data to a desired form. Below we first discuss GLM as they relate to SEE data, then introduce the changes required to account for LET uncertainty and finally apply the model in detail to a realistic problem occurring in SEE testing. We end by discussing possible additional applications.

II. GENERALIZED LINEAR MODELS AND SEE DATA

GLM [9] are a generalization of linear regression (LR) techniques that preserves the advantages of LR for data that does not conform to LR assumptions—particularly data for which errors are not normally distributed or have limited range (e.g. SEE counts). In particular, GLM lend themselves to solution by Maximum Likelihood (ML) estimation, [9] and the near-normal behavior of the likelihood near its maximum also allows estimation of confidence contours in the parameter space for the model under consideration. We illustrate these properties by describing the GLM for fitting SEE data.

GLM, rather than requiring normally distributed errors, instead allow errors to be distributed according to any member of the exponential family of distributions—e. g. Normal, exponential, Poisson.... We chose the Poisson distribution, since the predominant errors in most SEE tests are the Poisson errors on event counts. The mean for the Poisson distribution at the i^{th} LET value, LET_i , is the number of counts predicted $N_P(LET_i)$ by the Weibull fit to σ vs. LET, given the fluence for that LET $F(LET_i)$:

$$N_P(LET_i) = F(LET_i) \times \sigma_s \times \text{Weibull}(LET_i - LET_0, s, w) \quad (1)$$

where the fit is the usual 4-parameter Weibull

σ_s =saturated cross section

LET_0 =Onset LET

w =Weibull width

s = Weibull shape

The best-fit values for the parameters are those that maximize the likelihood Λ for the data—the set of observed counts for each of the n LET values, $\{N_O(LET_i)\}$:

$$\Lambda = \prod_{i=0}^n \text{Poisson}(N_O(LET_i), N_P(LET_i)) \quad (2)$$

As mentioned above, in addition to these best fit values, we can also determine the confidence contours in the parameter

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space based on the roughly normal behavior of likelihood near its maximum, Λ_{MAX} . This means the likelihood contours for confidence level CL will have a χ^2 dependence:

$$\frac{\Lambda(CL)}{\Lambda_{MAX}} = \exp(-0.5 * INV\chi^2(1 - CL, DOF)) \quad (3)$$

where $DOF = \#$ parameters in fit=4. If we select the parametric combination satisfying (3) that yields the maximum SEE rate, then that rate will bound the SEE rate with at least confidence level CL. We designate this rate as $R_{WC}(CL)$. This provides a way of bounding the σ vs. LET fit—and therefore the SEE rate—for any desired confidence as long as Poisson errors on event counts dominate errors on the rate estimation process. We next consider how the model must be modified to accommodate uncertainties in ion LET.

III. GLM FOR UNCERTAIN ION LET

When the LET of the ion causing a SEE is uncertain, the situation for likelihood analysis is analogous to interval data for reliability or TID testing. We only know that an ion within the range of LETs for that run caused the event. As such, rather than evaluating the probability for a particular time/dose/LET, one integrates the probability density function over the interval in which the failure is observed. For the SEE GLM, the only quantities that depend directly on LET are the predicted count values, $\{N_i^p\}$. For the i^{th} SEE test run, the fluence for a given LET is replaced by a fluence distribution over a range of LET:

$$F_i(LET) = F_i \times \Phi_i(LET) \quad (3)$$

where the F_i are the total ion fluence for the run and the Φ_i are distributions integrating to 1 over the LET range (from lower to upper limit, l_i to u_i) for the i^{th} cross section. Then the predicted counts for the i^{th} run will be

$$N_i^p = F_i \times \int_{l_i}^{u_i} \Phi_i(LET) \times \sigma(LET) dLET \quad (4)$$

The integral in (4) is just the average cross section over the LET distribution for the run, so N_i^p is the total ion fluence multiplied by average cross section. We refer to this version of the SEE data fitting GLM as the Interval GLM and that dealing with known LET as the Point GLM.

To illustrate this method, we consider the backside irradiation of a microcircuit thinned to ensure ions reach the sensitive volume of the device. While thinning can be done by a several methods (e.g., mechanical grinding, chemical etching or laser/plasma ablation), the process usually results in the die having nonuniform thickness. We take as an example, a test of thinned DDR2 SDRAMs.[6] Taking the scanned thickness profile for the an Infineon HYB1825128AF-3.7 512 Mbit DDR2 (SN25) from Fig. 2 of [6], we estimated the proportion of the die falling into each of the seven 10-micron thickness bins (see first 2 rows of Table I). We then estimated LET for several representative ions and angles for the 25 MeV and 15 MeV energy tunes at the Texas A&M University (TAMU) cyclotron facility (remaining rows in Table I) after traversing a 5 cm air gap and then the thicknesses for each bin. LET was determined at various depths into the Si by means of a lookup table constructed using output from the Stopping Range of Ions in Matter (SRIM) [10] for the ions in the table.

Using the proportions/distribution in row 2 of Table I and the corresponding LETs for each ion, we can use Eq. (4) to construct the likelihood for a set of observed counts for any subset of the ions in the table. We can also look at how results differ if we instead assume a single LET for each ion rather than a distribution. To investigate the effect, we generated Monte Carlo (MC) events with counts exhibiting Poisson fluctuations about a mean. The mean was generated assuming a Weibull dependence with a given value for σ_{sat} , LET_0 , W and s . For each MC event, we determined the approximate best and 90% WC fits and compared them to the parameters for the event generator. For convenience, we use the Figure of Merit (FOM) rate approximation, since the characteristics that give rise to high rates for FOM (high cross section, low onset and rapid cross section rise with LET) will give high rates for RPP or even Monte Carlo rate estimations.

Section IV presents results for several assumed σ vs. LET generating functions and assuming a range of expected event totals for each of the ions, allowing discussion of the effects of LET uncertainty in conjunction with those of Poisson variation.

TABLE I:
LET DISTRIBUTIONS FOR SELECTED TAMU IONS FOR DDR2 EXAMPLE

Thick- ness (μm)	0	30- 40	40- 50	50- 60	60- 70	70- 80	80- 90	95- 100
% of Die		0.11	0.33	0.19	0.18	0.1	0.08	0.02
LET After Overburden (MeVcm ² /mg), TAMU 25 MeV Tune								
N@0°	0.86	0.86	0.88	0.88	0.88	0.89	0.89	0.90
N@45°	1.22	1.22	1.25	1.25	1.26	1.27	1.28	1.29
N @60°	1.72	1.72	1.78	1.80	1.82	1.84	1.86	1.88
Ne@0°	1.73	1.73	1.77	1.79	1.80	1.81	1.82	1.84
Ne@45°	2.45	2.45	2.53	2.55	2.58	2.61	2.64	2.68
Ne @60°	3.47	3.47	3.63	3.69	3.75	3.81	3.88	3.94
Ar@0°	5.60	5.60	5.78	5.85	5.92	5.98	6.05	6.12
Ar@45°	7.92	7.92	8.31	8.45	8.59	8.72	8.86	9.04
Ar@60°	11.2	11.2	12.0	12.3	12.6	13.0	13.3	13.7
Xe@0°	13.3	44.6	45.5	46.5	47.5	48.7	49.9	51.2
Xe@45°	20.0	65.0	67.0	69.3	71.8	74.5	77.6	81.0
Xe @60°	32.7	96.2	101	107	113	121	129	138
Cu@0°	41.8	14.0	14.2	14.5	14.7	14.9	15.2	15.5
Kr@0°	59.1	21.2	21.6	22.0	22.5	23.0	23.5	24.0
Ag@0°	83.5	34.9	35.6	36.4	37.3	38.2	39.2	40.3
LET After Overburden (MeVcm ² /mg), TAMU 15 MeV Tune								
N@0°	1.32	0.88	0.88	0.88	0.89	0.89	0.90	0.90
N@45°	1.87	1.25	1.25	1.26	1.27	1.28	1.29	1.30
N @60°	2.64	1.78	1.80	1.82	1.84	1.86	1.88	1.90
Ne@0°	2.59	1.77	1.79	1.80	1.81	1.82	1.84	1.85
Ne@45°	3.66	2.53	2.55	2.58	2.61	2.64	2.68	2.71
Ne @60°	5.18	3.63	3.69	3.75	3.81	3.88	3.94	4.01
Ar@0°	7.90	5.78	5.85	5.92	5.98	6.05	6.12	6.19
Ar@45°	11.2	8.31	8.45	8.59	8.72	8.86	9.04	9.22
Ar@60°	15.8	12.0	12.3	12.6	13.0	13.3	13.7	14.1
Cu@0°	18.0	20.0	20.7	21.5	22.5	23.6	24.9	26.4
Kr@0°	26.7	29.7	30.7	31.8	33.1	34.4	35.8	37.3
Ag@0°	42.3	47.9	49.9	52.1	54.5	56.9	58.9	59.0
Xe@0°	53.1	59.2	61.3	63.5	65.7	67.8	69.2	68.7
Ho@0°	69.9	75.5	77.3	79.1	80.7	81.9	82.1	80.0
Au@0°	80.9	86.5	88.3	90.2	92.0	93.5	94.3	93.3

IV. RESULTS FOR THINNED SDRAM EXAMPLE

In the example of the thinned DRAM considered here, uncertainty in ion LET affects the fit to cross section data in two, somewhat competing ways. First, because the ions in Table I are on the high-energy side of the Bragg peak, traversing more overburden raises their LET (except for the last bin for 15 MeV Au). This effect is most pronounced for heavier, higher LET ions and ions incident at large angles to the normal. Second, higher LET tends to raise the SEE cross section, and this effect is most pronounced at lower LET, near onset. This gives the effect of LET uncertainty a complicated dependence not just on the onset LET for the SEE but also on how rapidly cross section increases with LET (as reflected by the Weibull parameters w and s) as well as on the ion energy—particularly its proximity to the Bragg peak.

To assess the efficacy of the Interval GLM (using (4) to predict event counts) and to evaluate the errors introduced by instead using point-estimates of LET—we generated Monte Carlo (MC) runs for 3 different Weibull distributions—all with $\sigma_{sat}=5\times 10^{-4}$ cm², $LET_0=1$ MeVcm²/mg, and Weibull shape $s=2$, but having Weibull widths $w=5, 20$ and 80 , to represent rapidly rising, moderately rising and slowly rising σ vs. LET curves. We selected ions from those in Table I with the goal of best measuring the cross-section form for each Weibull width. This means ensuring that the 7 ions for each MC run must sample near or below onset, saturation and the rapidly rising portion of the curve. Table II shows the ions used for the MC runs discussed here as a function of the Weibull width w and the beam energy tune. (Unless otherwise specified, the ions were incident normally.) In all cases, the lowest LET ion is normally incident N. For the 25 MeV tune, all the LETs for this ion are below the onset, so 0 events are generated regardless of fluence. N for the 15-MeV tune has $LET > LET_0$, so fluence was chosen to generate an expected event count of 1 (which has comparable efficacy for constraining LET_0 to the 0 events for the 25-MeV tune). The fluence for the ion with the lowest LET exceeding LET_0 was chosen so the expected event count was 1. The remaining ions and angles were chosen to best define σ_{sat} and w , and fluences were chosen so that the expected counts for each ion was 2, 4, 8 or 16.

Fig.1 illustrates the convergence of the best fit rate, normalized to the rate for the generating distribution and averaged over 1000 MC runs. For event count >2 , they are within the error range expected for a 1000-event MC run, except for those with $w=80$. For these, the cross section rises so slowly they do not saturate even at the highest LET, so Poisson errors for low event counts can affect the fit.

TABLE II:
IONS USED FOR MONTE CARLO RUNS VS. w AND BEAM TUNE

Ions Used Un MC Runs, 25 MeV Tune							
Ion#	1	2	3	4	5	6	7
$w=5$	N	Ne	Ne@45°	Ar	Ar@45°	Cu	Xe
$w=20$	N	Ne	Ar	Cu	Kr	Ag	Xe
$w=80$	N	Ne	Ar	Kr	Xe	Xe@45°	Xe@60°
Ions Used Un MC Runs, 15 MeV Tune							
$w=5$	N	N@45°	Ne	Ne@60°	Ar	Ar@60°	Xe
$w=20$	N	Ne	Ar	Cu	Kr	Ag	Xe
$w=80$	N	Ne	Ar	Kr	Xe	Ho	Au

Fig. 2 shows that if instead of using the Interval GLM, one instead uses the Point GLM, one can introduce a systematic error, which will not improve as one adds statistics. The magnitude of the systematic error depends on the LET distributions for the ions used in the run and the rapidity with which the cross section rises with LET. The range for the LET distribution is larger the closer the surface LET is to the ion's Bragg peak (as reflected by the larger errors for 15-MeV than 25-MeV tune). The latter effect is illustrated for the increase in systematic errors with increasing w . Evaluating the cross section at the mean LET for the distribution reduces but does not eliminate the systematic error, since the cross section at the mean LET will not in general be the mean cross section.

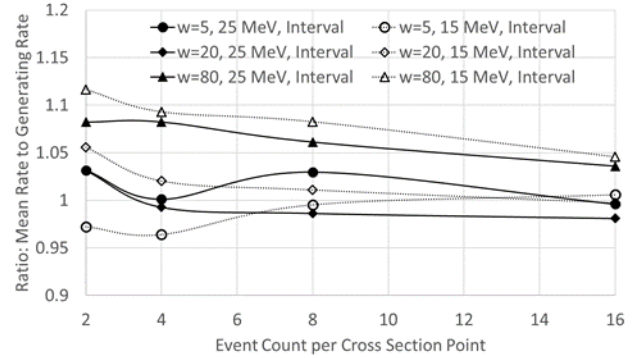


Fig. 1. When the fitting routine correctly treats ion LET uncertainty, the average fit rate for the 1000 MC events is close to the value used to generate the events, even for modest event counts ($2 \leq n \leq 16$) and regardless of whether the cross section rises rapidly ($w=5$), moderately ($w=20$) or slowly ($w=80$) with LET.

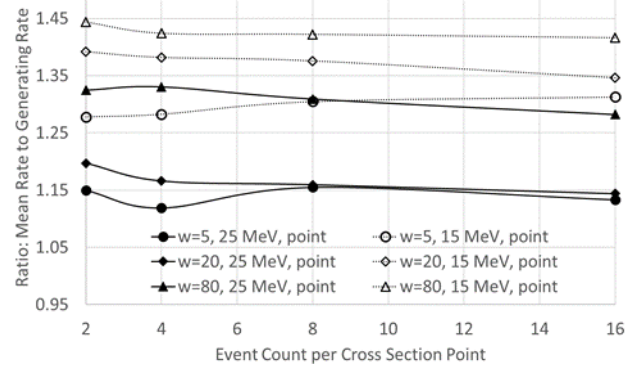


Fig.2 Fitting data assuming point LET values rather than LET distributions introduces systematic uncertainties, with magnitude depending on the uncertainty (and distribution) in LET over the die and how slowly the cross section rises with LET

Figs.1 and 2 show that the best fit selected by the Interval GLM converges on average to the true value, while the Point GLM results in a systematic error. Fig. 3 illustrates the rate of convergence in terms of the coefficient of variation (COV)—the ratio of the standard deviation to the mean for the best-fit rate. Here we present curves only for $w=5$ (other values behave similarly), but for both beam tune energies and Point and Interval GLMs. As expected, COV decreases roughly as a power law of the event count per cross section (raised to the power ~ 0.4). Moreover, the convergence is largely independent of the beam tune, the Weibull width or even whether the fit is done by the Interval or Point GLM. This is also consistent with

the systematic nature of errors introduced by failing to consider LET uncertainties properly. The behavior of the COV suggests that even for expected event counts as low as 2 per cross section, the GLM rate is likely to be within a factor of 3 of the correct value. However, one of the most valuable aspects of GLM for SEE rate estimation is the ability to select $R_{wc}(CL)$ using (2) to ensure the rate is bounded.

$R_{wc}(CL)$ generally bounds the actual rate more than $CL\%$ of the time. In part, this is because for low event counts, there are often correlations between parameters of the Weibull fit, so the true number of degrees of freedom in (3) is less than 4. To evaluate this effect and assess the efficacy of the model in bounding SEE rates, we ranked the $R_{wc}(90\%)$ for each of the MC runs and selected the 100th smallest out of the 1000 entries (the 90% confidence lower limit). We defined the excess margin (EM) by subtracting and then dividing the difference by the generating SEE rate R_{Gen} for that MC run:

$$EM(90\%) = ((90\% \text{ smallest } R_{wc}(90\%)) - R_{Gen}) / R_{Gen} \quad (5)$$

If $EM(90\%) > 0$ for the 100th smallest $R_{wc}(90\%)$ for our MC run, then $R_{wc}(90\%)$ represents a conservative bound with $>90\%$ confidence. Fig. 4 shows $EM_{90\%}$ vs. expected event count for $w=5$ (other values of w behave similarly). ($EM_{90\%}$ decreases approximately as expected event count raised to the -0.7 power. Also, the Interval GLM maintains slightly tighter (but still positive) margins compared to the point GLM—likely due the positive systematic errors introduced by the point GLM.

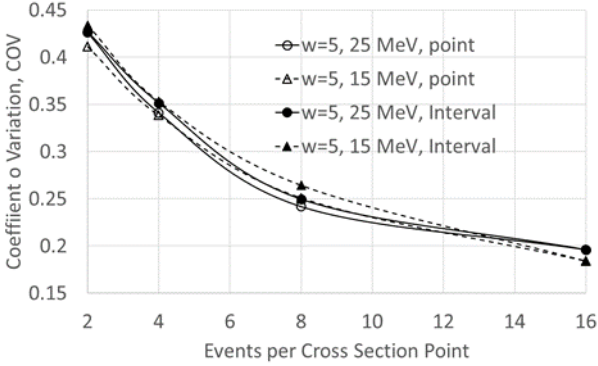


Fig. 3 The coefficient of variation decreases roughly as a power law of expected event count, independent of the treatment of LET uncertainties.

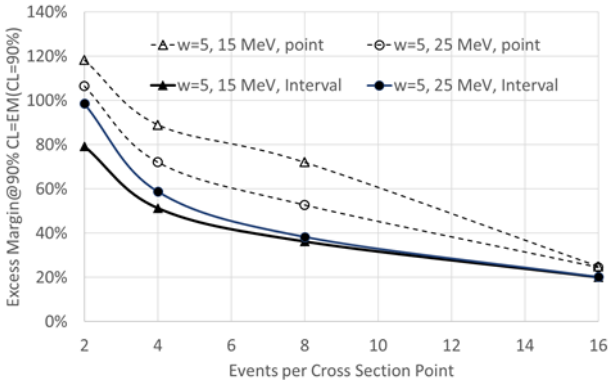


Fig. 4. The WC rate consistent with the 90% CL of the GLM fit, $R_{wc}(90\%)$ typically bounds the actual rate more than 90% of the time. This is reflected by the positive excess margin of $R_{wc}(90\%)$ which decreases but does not vanish with increasing expected event count.

Among the most important questions when discussing a potential systematic error are its sign and how large it can become. In the case of the example discussed here, because the ions remain on the high-energy side of the Bragg Peak for all thicknesses traversed (except 15 MeV Au traversing $>90 \mu\text{m}$ of Si), the systematic error resulting from incorrect treatment of LET uncertainty tends to result in higher estimated cross sections and rates than the correct values. On the other hand, if some of the depths resulted in ion energies lower than the Bragg peak, the systematic errors could result in an underestimate of the cross section and rate.

The question of how large the systematic errors could be is more complicated. As mentioned above, the magnitude of the systematic error on SEE rates depends on the magnitude of the LET uncertainties for the ions used, but also on how σ vs. LET behaves over the ranges of those uncertainties. Changes in σ_s mainly change the scale, but not the form of σ vs. LET or the relative contributions of the ions used to systematic error. In general, higher LET_0 will increase the systematic error as a proportion of the SEE rate, since energies of higher LET ions degrade more than low LET ions. The effects of Weibull w and s are more complicated. As s increases above 1, the rise of σ vs. LET near threshold becomes slower, while the rise near $LET = w + LET_0$ becomes more rapid. Fig. 5 explores some of these effects, in this case holding w constant and varying s and LET_0 . In general, the larger the onset LET and value for s , and the more ion LET uncertainty overlaps the range around $w + LET_0$, the greater will be the systematic error of incorrect treatment of that uncertainty as a proportion of the SEE rate. We discuss these results and develop hardness assurance guidelines in the next section.

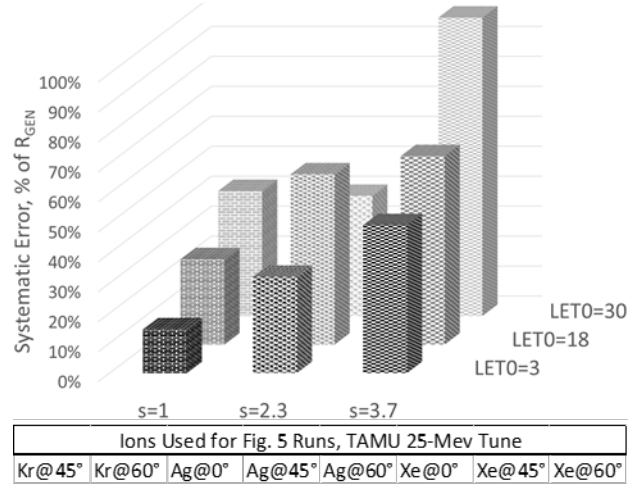


Fig. 5 If instead of s and σ_s , we hold w and σ_s constant, increasing LET_0 generally increases systematic error (as a proportion of SEE rate). The effect of increasing s depends on whether the LET uncertainty range for one of the test ions overlaps the rapidly rising portion of σ vs. LET.

V. DISCUSSION AND HARDNESS ASSURANCE IMPLICATIONS

In general, the larger the LET_0 and value for s , and the more ion LET uncertainty overlaps the range around $w + LET_0$, the greater will be the contribution for that ion to the systematic error of incorrect treatment of that uncertainty as a proportion

of the SEE rate. The contribution also depends on the relative flux of ions over the LET uncertainty range for each ion. Fig. 6 illustrates the reasons why graphically. This analysis illustrates that while variable overburden contributes to systematic error for all ions, the most significant contributions will be for ions where the LET uncertainty is a significant fraction of w , where σ vs. LET increases significantly over that LET range (that is, the range is centered near $w + LET_0$), and the ion flux in the mission environment over the LET uncertainty range contributes significantly to the SEE rate. These characteristics have important implications not just for understanding SEE rates and the errors on them, but also for test planning and execution so that those errors can be minimized.

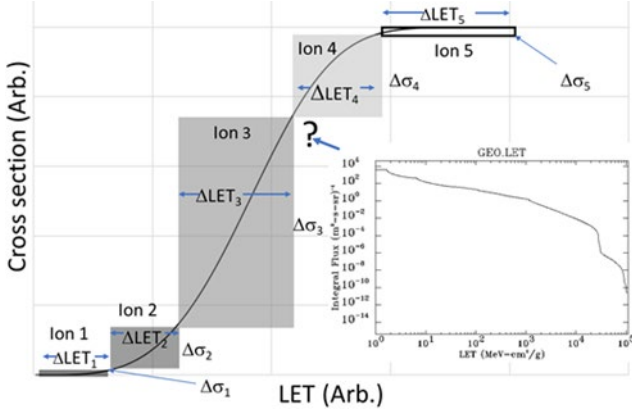


Fig. 6 The contribution an ion makes to systematic error depends on the magnitude of the LET uncertainty, but also on the behaviors of σ vs. LET and ion flux $\geq$ LET for the environment. In this plot Ions 1 and 2 have low LET, so the LET uncertainties (Δ LETs) are small as are the increase in σ . Ion 3 has a greater Δ LET and increase in σ , so its contribution to the error may dominate if the ion flux in the uncertainty range is high enough. Ion 4's contribution would likely be flux limited, and Ion 5 would be limited by both ion flux and the small increase in σ near saturation.

While we have considered only one example of irradiation of a part with variable overburden, this is adequate to formulate some guidelines for obtaining best results with the Interval GLM or for minimizing systematic errors if one does not:

- 1) If ion paths traverse variable overburden, it is important to ensure energies remain on the high-energy side of the Bragg peak, so systematic errors do not result in underestimation of SEE rates.
- 2) Although higher-energy ions usually have lower LET uncertainty, if one must irradiate at angle to get sufficient effective LET to reveal σ_s , the longer ion paths can result in higher LET uncertainty for the high-energy beam.
- 3) Because the ions that contribute most to systematic errors are those with large LET uncertainties and which overlap rapidly rising regions where σ vs. LET, it is important to minimize LET uncertainty for this part of the σ vs. LET curve.
- 4) If critical features of σ vs. LET—e.g. onset, saturation and steep rise with LET—are not well defined in the data, the resulting uncertainty in fit parameters can augment the systematic errors due to LET uncertainty.

Even when using the Interval GLM to fit data, it can be important to follow the above guidelines, especially if the fit parameters for σ vs. LET are important. This is because the fit

is constrained only by the known data, that is, the average behavior of the cross section over the LET uncertainty. While most fits with comparable behavior over this range will yield similar rates, the precise values for the fit may not be well determined if LET uncertainties are large, especially over the range where σ vs. LET rises rapidly. Conversely, if the ion flux in the environment is negligible in an LET range, or if cross section vs. LET changes negligibly over that range, use of the Interval GLM may be less important. This can be important as we consider other applications.

VI. OTHER APPLICATIONS

SEE measurements in which LET is uncertain are not uncommon. Similar challenges arise when packaged parts are tested in high-energy heavy-ion beams. Many parts require packaging with high-density features—e.g. metal lead frames and heat sinks—that obscure portions of the die—resulting in ions having a range of LETs. This can mean that the ion responsible for any given SEE is uncertain. Sensitive volumes inside complicated packages may be covered by heat sinks, metal lead frames, various fillers and even other die in Systems In Packages (SIP).

More challenges are emerging as three-dimensional ICs assume greater importance in increasing performance of and miniaturizing in microelectronics. The magnitude of these challenges is evident from the evolution of 3D NAND Flash memory. Not only do current state-of-the-art devices have 176 layers,[11] but the devices also include control logic at the bottom of this stack [12]. They may also be getting less homogeneous, which would tend to increase LET uncertainties. Test methods that try to maximize LET in device SV [13,14] may further worsen LET uncertainty. LET changes most rapidly near—and the derivative changes sign at—the Bragg Peak. In a complex part or package or when testing an electronics board with multiple packaged parts, placing the Bragg Peak in a sensitive volume for one SEE mode may lead to the LET being uncertain for other modes.

The number of potential applications of the Interval GLM is increased if we consider the dependence of cross section on volume equivalent LET as well as LET [15,16]. In a material of density ρ , volume equivalent LET is defined in terms of the energy deposited in the sensitive volume, E_{dep} and the SV thickness z as:

$$LET_{Eq} = E_{dep} / (\rho \times z) \quad (6)$$

Using (6), as long as an E_{dep} distribution can be determined and a charge collection depth estimated, (4) can be used to determine not just a best fit to the SEE data, but also worst-case fits for a given confidence. As an example, we consider the distribution of E_{dep} for primary ions and the secondary particles produced when those particles are incident on layers for Back-End-Of-Line (BEOL) typical of many packaged parts. In Fig. 7, all the ions have comparable LET, but have different cross sections for production of highly ionizing secondary particles in BEOL materials, which deposit large amounts of charge in the nominal $2 \times 2 \times 2.25 \mu\text{m}$ sensitive volume.[17]

In this plot, although the cross sections for nuclear events are orders of magnitude below those for ionization, the large charge

deposited by nuclear events can significantly increase SEE rates for some parts. This is especially true for ions where LET is at or below onset LET. The long tail on E_{dep} due to nuclear events also makes it difficult to fit σ vs. LET, because a precise value for LET is difficult to define. If SEE are observed due to nuclear events for an ion with LET below the onset, the fit will be forced to choose values for LET_0 that are below the actual threshold. If instead one uses the Interval GLM, the average cross section for the LET distribution of an ion can be nonzero even if the ion's $LET < LET_0$, allowing a more realistic fit for σ vs. LET as a whole. Indeed, if the nuclear events are sufficiently rare, it may be possible to use the Interval approach only for the lowest LET ions.

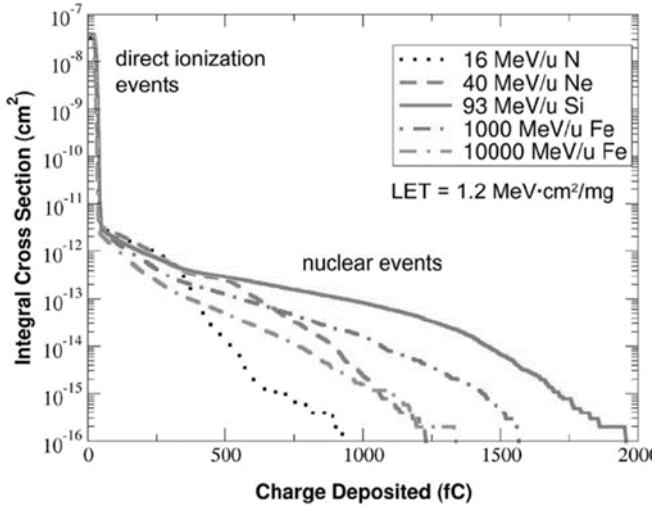


Fig. 7 This figure (adapted from [17]) illustrates that while primary ions may have more or less the same LET due to direct ionization, their potential for generating rare events in which secondary ions from BEOL materials deposit significant amounts of charge in the SV (here a $2 \times 2 \times 2.25$ micron slab). This can result in dramatically different event counts, especially then the primary ion's LET is near or below threshold.

Similar E_{dep} distributions arise when rare events involving high-energy ions generate multiple delta rays that deposit large amounts of energy in small sensitive.[18] Here as well, the events with high-energy deposition are rare compared to the events in the peak of the distribution (defined by ion LET), so the importance will be greatest near threshold. Again, the Interval treatment is most important for ions with LET at or below threshold.

Unfortunately, unless tests can be carried out under test conditions sufficiently varied to produce LET_{Eq} distributions that define the onset, rapidly rising, knee and saturation portions of the cross section, the results will not be useful for constraining SEE rates. An example of such a situation can be seen in Fig. 8, which compares the recoil ion flux vs. LET_{Eq} distributions for protons with energies from 20-500 MeV (assuming 1-micron cube SV). Although proton recoils can in principle have LET values up to ~ 15 MeVcm²/mg, the vast majority of ions have low energies, short ranges and $Z < 14$. As a result, the median, mean and upper 75% quantiles for proton recoil LET_{Eq} change little over $20 \leq E_p \leq 500$ MeV, and even the 90% upper bound changes $< 37\%$. Given the predominant overlap of the LET_{Eq} distributions for the recoil ions produced by E_p and the fact that what little difference exists is found only

in the upper tails of the distribution, testing with high-energy protons is unlikely to constrain possible fits for σ vs. LET sufficiently to constrain SEE rates.

Many other situations occur where the ion LET responsible for an SEE is uncertain. These include daughter products of nuclear reactions [3], which could prove amenable to treatment using LET_{Eq} , and even anomalies in the space environment itself, where event rates in various environments (e. g. solar particle events, the South Atlantic Anomaly, etc.) can yield insight into which device is most likely responsible.[4] If a program is using large numbers of devices with different sensitivities, changes in the relative rates for such devices could provide insight into the particle content in different environments. The approach may also be useful for accelerator environments, [5,14] where high-energy hadron fluxes give rise to a complicated mix of primary and secondary particles and where SEE performance may limit reliability.

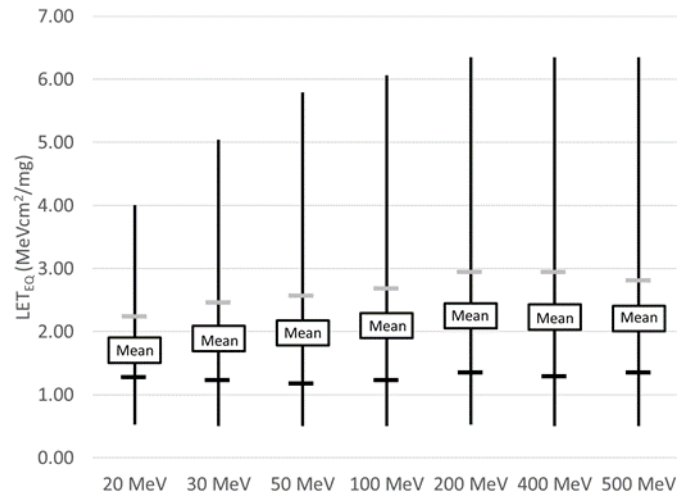


Fig. 8 Proton-recoil LET_{Eq} spectrum varies little for usual proton test energies ($20 \text{ MeV} \leq E_p \leq 500 \text{ MeV}$). Vertical lines encompass 90% of the flux, and black and grey horizontal bars the 50% (median) and 75% quantiles, respectively.

VII. CONCLUSION

Although conventional SEE hardness assurance methods use fits to SEE σ vs. LET curves for rate estimation, in many situations, the LET of the ion that causes an SEE may be uncertain. Failure to properly treat this uncertainty may result in systematic errors for the SEE rate—especially when the test ions have energies near their Bragg peaks and/or the SEE cross section changes rapidly over the LET uncertainty ranges for those ions. A proper treatment must use only the information that is known—the range of possible LETs and if known, the distribution of ion flux within that range.

We have developed an Interval Generalized Linear Model for fitting SEE data to a Weibull (or other) form that meets these requirements and avoids such systematic errors. As with its point-LET predecessor, the tool yields not only best-fit, but also worst-case rates for any desired confidence level. This makes the tool useful not only for data analysis, but also for test planning and for on-the-fly test decisions for a variety of situations—e.g. backside irradiation of thinned parts, irradiation of packaged parts, testing of 3DICs or circuit boards using high-energy and ultra-high energy ion beams and so on.

As an application of the tool, we chose the backside heavy-ion irradiation of a thinned DDR2 SDRAM die. This example demonstrates the utility of the Interval GLM and explores how systematic errors depend on ion LET uncertainties and the characteristics of the σ vs. LET curve. This study reveals that the systematic errors are greatest when LET uncertainty ranges overlap the rising portion of the curve and regions of high ion flux vs. LET for the environment. The example also suggests guidelines for minimizing systematic errors when ion LETs are uncertain.

When applied along with equivalent LET (LET_{Eq}), the Interval GLM also proves useful when irradiating in mixed radiation environments, including those where rare secondary particles (recoil ions, fission daughter products, neutrons, delta rays, etc.) can significantly augment charge deposited by the primary ion. Such secondaries can be especially important when LET of the primary ion is near or below onset LET. Although such a σ vs. LET curve would be difficult to fit using conventional techniques (being forced to artificially low onset), the Interval GLM averages σ over the LET_{Eq} uncertainty distribution, preserving the possibility of observing events below the LET threshold.

However, constraining σ vs. LET requires that it be sampled over all portions of the curve—near onset, rapidly rising, knee and saturation—if rates and fit parameters are to be determined reliably. We have illustrated this by discussing the limitations of proton testing as a means of constraining SEE rates, even if irradiation is done over a range of test energies. Regardless of the data analysis method, it is essential for alternative SEE characterization methodologies to overcome this limitation.

Finally, while ref. [8] illustrated the utility of GLM for SEE test planning and data analysis and for understanding confidence levels for SEE rate estimation/bounding, the current analysis illustrates the flexibility and power of the method. The fit to σ vs. LET occurs only in the expression for the predicted counts (eqs. (2) or (4))—and these expressions can be revised to accommodate virtually any model. Meanwhile, the predominant random errors are treated via the member of the exponential family of probability distributions used in the GLM, and this could also be generalized for situations where Poisson fluctuations are not the dominant errors in the process. GLM could be an important set of tools for dealing with future challenges in SEE data analysis and hardness assurance.

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