Considerations for a Proton Single Event Effects (SEE) Guideline

Kenneth A. LaBel
Co- Manager,
NASA Electronic Parts and Packaging (NEPP) Program
NASA/GSFC
ken.label@nasa.gov
301-286-9936
http://nepp.nasa.gov
Unclassified
Sponsored by the NASA Electronic Parts and Packaging (NEPP) Program and The Defense Threat Reduction Agency (DTRA) under IACRO 09-4057I

Abstract

- **The intent of this document is to provide guidance on when and what type of SEE tests should be performed on a device under test (DUT) based on orbit, technology, existing data, and application.**
- **It is NOT intended to provide a detailed guideline for how to perform proton SEE radiation tests on electronics.**

Outline of Presentation

- Why now?
- Deciding to perform proton SEE testing
- Mission orbit parameters
- Existing heavy ion data
- Criticality of device usage
- Technology specific trade space

Disclaimer:

This is not a comprehensive how-to talk, but about considerations for test

Why Now?

- Protons are the dominant particle for low earth orbits and major component (offshoot) from solar particle events
  - This is not new
- What is new
  - Technology has scaled and interactions with semiconductor materials is more complex
  - Examples
    - Proton direct ionization realized
    - High aspect ratio device sensitivity
    - Roles of secondaries more complicated

Deciding to perform SEE testing

- Four factors are traded
  - Mission orbit, timeframe, and duration,
  - Impact or criticality of the device usage,
  - Device technology and circuit design, and,
  - Existence of adequate heavy ion test data.
- Each of these will be dealt with in turn, but first some general rules of thumb...

Note:
All linear energy transfers (LETs) discussed are in units of MeV*cm²/mg

When NOT to perform SEE testing

- In general, proton SEE testing is NOT required if:
  - A device has an heavy ion LET_{th} > 37 where LET_{th} is where no events occur at a test fluence of $1x10^7$ particles/cm² as per JEDEC JESD57 Guideline.
    - We note that Geosynchronous orbits (GEO) would normally require heavy ion LET_{th} consistent with above. Or
  - Mission proton exposure is minimal (green orbits/durations in upcoming Table 1) and risk acceptance is viable. Or,
  - Device is being used in a non-critical functional (i.e. acceptable down time, no operate-through requirement, or data loss) as long as risk can be accepted by the flight project.
    - This may be a judgment call by the systems engineering. Or,
  - Sufficient SEU heavy ion data exists demonstrating the differing signatures of SEU that can occur coupled with mitigation (external circuit, internal design, software, etc.) that has been demonstrated via test and/or modeling to be effective.

When to perform SEE testing

- Proton SEE testing is required when:
  - A device has an heavy ion LET_{th} < 37 where LET_{th} is the where no events occur at a test fluence of $1x10^7$ particles/cm^2, and,
  - Mission proton exposure is significant (red orbits/durations in upcoming Table 1). And,
  - Device is being used in a critical application or has operate-through (proton environment) requirements.
    - This may be a judgment call by the systems engineering. Or,
  - Insufficient SEU heavy ion data exists demonstrating the differing signatures of SEU that can occur coupled with mitigation (external circuit, internal design, software, etc.) that has been fully demonstrated via test and/or modeling to be effective.

Recommended time to test

- For all other combinations of orbit exposure, criticality, existing data, and mitigation approaches, proton SEE testing is recommended, but may be waived based on risk assumption.
  - This is a systems engineering judgment call.
- For example, in the case where we have a yellow orbit coupled with a device that has a heavy ion LETth < 37
  - Proton SEE testing would be highly recommended
  - However, if application criticality (such as operate-through) requirements are minimal, testing may be waived.
- Note that it is required that environment analyses be performed for all missions in order to determine proton risk probabilities based on orbit, timeframe, mission duration, and solar particle exposure.
  - The orbit table that follows only a representative guide and even green orbits have some risk associated.

Table 1: Proton SEE Risk by Orbit Type

	Trapped Protons	Solar Particles	Proton SEE Risk – Solar Min	Proton SEE Risk – Solar Max	Notes
GEO	No	Yes	Low	Moderate	Though solar events are a short duration exposure, operate through constraints need to be factored in.
Low Earth Orbit (LEO) (low-incl)	Yes	No	Moderate	Low-Moderate	Trapped protons higher at Solar Min
LEO Polar	Yes	Yes	Moderate	[illegible]	Risk of solar events higher during Solar Max
Shuttle	Yes	No	Very Low-Moderate	Very Low-Moderate	Short duration (weeks) exposures reduce risk
International Space Station - ISS	Yes	Yes - partial	Moderate	Moderate	Trapped protons are higher during Solar Min, but solar events may provide additional particles for a short time frame
Interplanetary	During phasing orbits; Planetary radiation belts possible	Yes – reduces farther away from the sun	Low-High	Low-High	Cruise phase is solar particle only and is lessened the farther the distance from the sun; Planetary proton exposures vary by planet and needs to be evaluated on a case-by-case basis.

Table 1: Proton SEE Risk by Orbit Type

	Trapped Protons	Solar Particles	Proton SEE Risk – Solar Min	Proton SEE Risk – Solar Max	Notes
Medium Earth Orbit (MEO) or sometimes called high LEO	Yes	Yes	[illegible]	[illegible]	The highest near-earth proton exposure. We note that the slot region between radiation belts is sometimes referred to as MEO and would be a concern.
Highly Elliptical Orbit (HEO)	Yes	Yes	[illegible]	[illegible]	Nearly as bad as MEO, but moves through the belts much quicker lessening daily proton exposure
Lagrangian Points (or Libration Points)	No	Yes	Low	Moderate	Though solar events are a short duration exposure, operate through constraints need to be factored in.

Utilizing heavy ion data to determine testing

- **First and foremost, for SEL testing, we highly recommend performing heavy ion SEE testing as a go/no-go.**
- **If SEE is not observed with heavy ions at LET_{th} => 37, then proton SEE testing is NOT required.**
  - An LET of 34 is approximately the highest LET secondary possible from a reaction with a 500 MeV proton and modern semiconductor materials.
- **If SEE is observed with a LETth <= 20, then proton SEE testing with 100≤MeV< E < 200 MeV is required.**
  - Additional margin on predicted proton SEE rate should be included.
  - A factor of 10X is sufficient.

To be presented by Kenneth A. LaBel at the Hardened Electronics and Radiation Technology (HEART) Conference, Tucson, AZ, April 19-23, 2010. 11

Utilizing heavy ion data to determine testing

- **For those devices whose 20 < SEE LET_{th} < 37, a risk-trade should be undertaken that compares**
  - Proton environment exposure above 200 MeV and below 200 MeV
    - There is a finite probability of higher energy secondaries being formed at energies in the 200-500 MeV regime that are in the particular LET range of interest.
    - If there are sufficiently few particles in the higher energy regime, testing for higher energies may be waived based on risk probabilities.
  - If the risk is deemed sufficiently high by environment exposure or criticality of application,
    - Testing at a high energy proton facility with energies > 400 MeV is considered.
      - Note that there are currently no CONUS proton facilities capable of this high energy regime.
    - Alternately, a heavy ion rate prediction for LETth < 37 is performed
      - A factor of 200-400X may be added to SEE rate prediction based on Petersen's Approximation and environment exposure.
      - This is worst-case.
- **Testing with100<MeV< E < 200 MeV is required for a sanity check with a 10X margin added for rate prediction based on this data**

To be presented by Kenneth A. LaBel at the Hardened Electronics and Radiation Technology (HEART) Conference, Tucson, AZ, April 19-23, 2010. 12

Technology considerations for test

- **Assumptions:**
  - **Orbit, criticality, and heavy ion criteria in place**
  - **Worst-case/application-specific test conditions are used and fully documented**
- **Considerations:**
  - **Low proton energy direct ionization (90nm and below, for example)**
  - **Angular effects**
  - **Total dose rule of thumb: 80% of rated level for device during SEE testing**
  - **Three energies used to map a curve (minimum) for indirect ionization effects**
    - **Nominally, 60, 120, 190 MeV**

To be presented by Kenneth A. LaBel at the Hardened Electronics and Radiation Technology (HEART) Conference, Tucson, AZ, April 19-23, 2010. 13

Types of tests: Digital CMOS - SEL

SEE Condition	Proton test constraint	>90 nm	<=90nm	SOI	Notes
SEL	E <30MeV	N	N	N	
SEL	30MeV<E<100MeV	N	N	N	Data in this regime is useful for developing SEL sensitivity curve versus proton energy for rate prediction.
SEL	100MeV<E<200MeV	Y	Y	N	Testing at this energy range is sufficient for many programs, but we recommend heavy ion SEL testing first as a go/no-go
SEL	E>200MeV	Y	Y	N	Higher energy up to 500MeV recommended if warranted by risk, but heavy ion data should be taken first as go/no-go.
SEL	Normal Incidence	Y	Y	N	
SEL	Grazing angle	Y	Y	N	Must be taken in concert with normal incidence. Should consider roll angle variation as well as tilt.

To be presented by Kenneth A. LaBel at the Hardened Electronics and Radiation Technology (HEART) Conference, Tucson, AZ, April 19-23, 2010. 14

Types of tests: Digital CMOS – SEU 1

SEE Condition	Proton test constraint	>90 nm	<=90nm	SOI	Notes
SEU	E<10MeV	N	Y	Y, when <90nm	Low energy testing with E at the die sensitive volume over a range of energies from 10 MeV down to 100s of keV. Low LET heavy ion beams may also be considered as an alternate when sufficient internal technology and circuit designs are known and modeling exists.
SEU	10MeV<E <30MeV	N	Y	Y, when <=90nm	Insufficient energy range without other energy ranges
SEU	30MeV<E<100MeV	Y	Y	Y	Sufficient for some projects, but risks are further reduced with higher energy data.
SEU	100MeV<E<200MeV	Y	Y	Y	Better data point for risk reduction
SEU	E>200MeV	Y	Y	Y	Only performed if mission environment and LET_{th} warrants
SEU	Tilt Angular	N	Y	Y	Only a concern for directionality of secondary recoils (elastic reactions) or potential for direct ionization

Types of tests: Digital CMOS – SEU 2

SEE Condition	Proton test constraint	>90 nm	<=90nm	SOI	Notes
SEU	Grazing Angles	N	Y	Y	Only a concern for directionality of secondary recoils (elastic reactions) or potential for direct ionization
SEU	Roll Angular	N	Y	Y	Only performed if tilt angular tests are performed and there is a concern about asymmetry of device layout

- **Tables also created for:**
  - **Bipolar technologies**
  - **Other high speed digital technologies**
    - **e.g., SiGe, GaAs, InP, antemonides, etc,**
  - **Optoelectronics (optical portion)**

Additional Thoughts and References

- Proton kinematics where the energy regime of the incident proton beam changes how the energy is deposited in sensitive device-under-test (DUT) regions. Angle of incidence has not been universally verified to be a testing concern for protons. Spot checks suggested depending on technology– bare minimum.
  - R. A. Reed *et al.*, "Evidence for angular effects in proton-induced single-event upsets," *IEEE Trans. Nucl. Sci.*, vol. 49, no. 6, pp. 3038-3044, Dec. 2002.
  - J. R. Schwank *et al.*, "Effects of particle energy on proton-induced single-event latchup," *IEEE Trans. Nucl. Sci.*, vol. 52, no. 6, pp. 2622-2629, Dec. 2005.
  - J. R. Schwank *et al.*, "Effects of angle of incidence on proton and neutron-induced single-event latchup," *IEEE Trans. Nucl. Sci.*, vol. 53, no. 6, pp. 3122-3131, Dec. 2006.
    - Spallation products with LETs less than 10 (MeV·cm²)/mg are more isotropically distributed for the highest energy proton beams (200 MeV), while at lower energies (63 MeV) these recoils tend to be forward-directed along with the other high-energy, high-LET products.
    - Differing proton kinematics are known to cause SEE cross section differences in SOI technologies.
  - J. R. Schwank *et al.*, "Effects of angle of incidence on proton and neutron-induced single-event latchup," *IEEE Trans. Nucl. Sci.*, vol. 53, no. 6, pp. 3122-3131, Dec. 2006
- Differences between direct and indirect ionization.
  - D. F. Heidel *et al.*, "Low energy proton single-event-upset test results on 65 nm SOI SRAM," *IEEE Trans. Nucl. Sci.*, vol. 55, no. 6, pp. 3394-3400, Dec. 2008.
    - Traditionally, protons only cause SEE via indirect ionization; this is still the case for SEL. However, modern sub-100 nm process technologies are sensitive to low-energy proton direct ionization and elastic scattering, which increases the single-event upset (SEU) cross section as much as several orders of magnitude.

To be presented by Kenneth A. LaBel at the Hardened Electronics and Radiation Technology (HEART) Conference, Tucson, AZ, April 19-23, 2010. 17

Suggestions

- Maintain awareness that worst-case bias conditions for proton SEU and SEL tend to be opposite. Include this in the test plan.
- If possible, use a tool like SPENVIS ( ) to verify obit lifetime fluences for a more accurate test. Due to environment uncertainties, a minimum of 2X margin should be included.
- Microlatchup, while not resulting the operational failure of the DUT, can cause parametric shifts (read/write cycle times), bad/stuck bits, etc. Keep track of parametrics and bad bit counts during irradiation cycles.
- Check holding voltage and current as a function of proton energy if possible.
- SEL testing is best conducted in a dynamic mode
  - Remove power from V_{DD} for a brief time to halt/quench the latch
  - Account for dead time to clear latchup and reduce fluence as a result – though total, uncorrected fluence should be used for TID and DD tally
  - Continue testing
- Need to specify a standard SEL current threshold – probably 10-20% above nominal.
- **Full document available at http://nepp.nasa.gov**
  - **Search for proton guideline**

To be presented by Kenneth A. LaBel at the Hardened Electronics and Radiation Technology (HEART) Conference, Tucson, AZ, April 19-23, 2010. 18