Proton Single Event Effects (SEE) Guideline

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Disclaimer: 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.

Single Event Effects (SEE) – Acronyms

SEE = Single Event Effect
SEU = Single Event Upset
SET = Single Event Transient[1]
SEFI = Single Event Functional Interrupt
SES = Single Event Snapback
MBU = Multiple Bit Upset (MBU)
MCU = Multiple Cell Upset

[1] We note that Analog SET (ASET) and Digital SET (DSET) are significant concerns for modern devices. For this document, we have grouped and SETs under SEU concerns.

When is proton SEE testing required

Determining when proton SEE[2] testing is required is a function of several factors:

- 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.

In general, proton SEE testing is NOT required if:

- A device has an heavy ion LET_{th} > 37 MeV*cm^2/mg where LET_{th} is where no events occur at a test fluence of $1x10^7$ particles/cm^2 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 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[3] 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.

Proton SEE testing is required when:

- A device has an heavy ion LET_{th} < 37 MeV*cm^2/mg 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 Table 1). And,
- Device is being used in a critical application or has operate-through 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.

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 LET_{th} < 37 MeV*cm^2/mg, proton SEE testing would be highly recommended, but 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 table below is only a representative guide and even **green** orbits have some risk associated.

Table 1: Proton SEE Risk by Orbit Type

[2] SEE includes all manner of both transient effects (SEU, SET,…) and destructive (SEL, SES,…)

[3] All subsets of SEU categories such as SET, SEFI, MBU, etc…are included in "SEU".

	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	Moderate-High	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.
Medium Earth Orbit (MEO) or sometimes called high LEO	Yes	Yes	Very High	High	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 yellow concern.
Highly Elliptical Orbit (HEO)	Yes	Yes	High	Very High	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.

When to test based on Heavy Ion data

First and foremost, for SEL testing, we highly recommend performing heavy ion SEL/SEE testing as a go/no-go.

- If SEE is not observed with heavy ions at LET_{th} => 37 MeV*cm^2/mg, 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 LET_{th} <= 20 MeV*cm^2/mg, then proton SEL with 100 MeV< E < 200 MeV is required. Additional margin on predicted proton SEL rate should be included. A factor of 10X is sufficient.
- For those devices whose 20 MeV*cm^2/mg < LET_{th} < 37 MeV*cm^2/mg, 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 facilties capable of this high energy regime.
    - Alternately, a heavy ion rate prediction for LET_{th} < 37 MeV*cm^2/mg is performed
      - A factor of 200-400X may be added to SEL 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.

Proton SEE Testing by Technology Issues and Conditions

The tables that follow define when different proton energies and angles are required for testing for various technology types assuming the above criteria are already in place. It is noted that worst-case biasing and temperature should be included in all tests and that SEU test approaches should be either worst-case or application-specific and fully documented as such. More details are found in the Appendix.

It is also noted that:

- Low energy proton testing (< 10 MeV) is an evolving research effort that is applicable only to technologies that have a very low critical charge ($Q_{crit)}$ for SEE (LET_{th} ~ 1 or less). This has only been demonstrated on CMOS technologies < 90 nm at this point, but is conjectured to possibly apply to other low-Q_{crit} devices.
    - When mapping out low energy sensitive, beam straggle (i.e., actual energies as prime energy is degraded through materials including device packaging and construction) should be considered. It expected that guidelines for low energy proton testing will be available in FY10.
    - If low energy testing is not feasible a 10X margin on predicted SEU rates based on higher energy data should be considered.
- While a full cross-section versus energy curve is highly desired, it is suggested that three energies be used as a minimum to develop a proton sensitivity curve. Energies of 60, 120, and 190 MeV +/- 10 MeV should be considered. If a very low sensitivity is noted at any of the three energies for SEU, additional energy test requirements may be waived. For SEL, additional high-energy tests or margin is described separately.
- Technologies that are not suspected to be sensitive to direct ionization from protons (ex., CMOS >90 nm) are not required to be tested over a variety of beam incidence angles. New devices that are sensitive to the directionality of spallation recoils or direct ionization require angular tests nominally looking at 45° and a grazing angle at a minimum, but good engineering judgment should be used for determining if additional angles (say 30° or 60°), angular mapping around grazing, or varying roll (if asymmetry is a possible issue) is required.
- Total ionizing dose (TID) and displacement damage (DD) are imparted during proton SEE testing and devices will degrade or fail based on accumulated levels. It is recommended that TID and DD tolerance of a device be known prior to proton SEE testing and that accumulated levels during proton SEE do not exceed 80% of tolerance levels (i.e., 100 krads(Si) device tested to no more than 80krads (Si) equivalent exposure). If no TID or DD data is known, a sample should be exposed to determine rough degradation/failure levels with sufficient parametric and functional testing to determine operation. A maximum of 80% of this measured level is recommended for TID accumulation during SEE testing.

Table 2: Digital CMOS Technologies

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.
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
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

For bipolar technologies, SEL is rarely a concern, but lack of destructive events needs to be verified. Heavy ion testing is recommended to provide this data.

Table 2: Bipolar Technologies

SEE Condition	Proton test constraint	Linear	Digital	Mixed Signal	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	Y	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	Y	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	Y	
SEL	**Grazing angle**	N	N	N	Must be taken in concert with normal incidence. Should consider roll angle variation as well as tilt.
SEU	**E<10MeV**	Possibly	N	Possibly	For devices that have an ultra-low Qcrit, this can be considered. Devices such as an low noise amplifier (LNA) might have SET sensitivity in this regime, for example, but no known data exists on bipolars and this energy regime. 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**	Y	N	Y	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	N	Possibly	Only a concern for directionality of secondary recoils (elastic reactions) or potential for direct ionization
SEU	**Grazing Angles**	N	N	Possibly	Only a concern for directionality of secondary recoils (elastic reactions) or potential for direct ionization
SEU	**Roll Angular**	N	N	Possibly	Only performed if tilt angular tests are performed and there is a concern about asymmetry of device layout

For other high speed digital technologies technologies, destructive single events have not been observed. Heavy ion testing is recommended to provide this data if required.

Table 3: Other high speed digital technologies (e.g., SiGe, GaAs, InP, antemonides, etc,)

SEE Condition	Proton test constraint	High Speed	Notes
SEU	**E<10MeV**	Yes	For devices that have an ultra-low Qcrit, this can be considered. Given the known sensitivity of GaAs based on heavy ion data, expectations that direct ionization with protons is possible for GaAs. 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**	Y	Insufficient energy range without other energy ranges
SEU	**30MeV<E<100MeV**	Y	Sufficient for some projects, but risks are further reduced with higher energy data.
SEU	**100MeV<E<200MeV**	Y	Better data point for risk reduction
SEU	**E>200MeV**	Y	Only performed if mission environment and LET_{th} warrants
SEU	**Tilt Angular**	Possibly	Only a concern for directionality of secondary recoils (elastic reactions) or potential for direct ionization
SEU	**Grazing Angles**	Possibly	Only a concern for directionality of secondary recoils (elastic reactions) or potential for direct ionization
SEU	**Roll Angular**	Possibly	Only performed if tilt angular tests are performed and there is a concern about asymmetry of device layout

For optoelectronic components (e.g., optocouplers, imagers, APDs, fiber link detectors), considerations are broken down by the electronic technologies used in conversion and control (CMOS, GaAs, etc…) and the optical diodes, LASERS, or other devices used to detect or provide light. The former should be treated as per above for CMOS, GaAs, etc…, while the latter is considered below. Any destructive concerns from a single particle are focused on the electrical portion of the device(s) and not the optical. Optical components are known to have possible direct ionization issues. We recommend use of previous guidance in this matter – (http://radhome.gsfc.nasa.gov/radhome/papers/2002_opto.pdf and http://radhome.gsfc.nasa.gov/radhome/papers/OptoToolAssmt_032802.pdf).

Table 4: Optoelectronic Technologies (Optical Portion Only)

SEE Condition	Proton test constraint	Optical	Notes
SEU	**E<10MeV**	Possibly	We would expect that if direct ionization
SEU	**10MeV<E <30MeV**	Possibly	Insufficient energy by itself and possible packaging limitations
SEU	**30MeV<E<100MeV**	Y	Sufficient for some projects, but risks are further reduced with higher energy data.
SEU	**100MeV<E<200MeV**	Y	Better data points for risk reduction
SEU	**E>200MeV**	**Y**	Only performed if mission environment warrants and previous energy data has flat response cross-section.
SEU	**Tilt Angular**	Y	Only a concern for directionality of secondary recoils (elastic reactions) or potential for direct ionization
SEU	**Grazing Angles**	Y	Only a concern for directionality of secondary recoils (elastic reactions) or potential for direct ionization
SEU	**Roll Angular**	N	Not needed since diodes are symmetric. If an asymmetric diode is used, then this should be performed.

Appendix

- Proton kinematics where the energy regime of the incident proton beam changes how the energy is deposited in sensitive device-under-test (DUT) regions.
    - 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 $(MeV \cdot cm^2)/mg$ 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.
- Highlight 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.
- Maintain awareness that worst-case bias conditions for proton SEU and SEL tend to be opposite. Include this in the test plan.
- Angle of incidence, though clearly an issue for heavy ions, has not been universally verified to be a testing concern for protons. Probably ought to require spot checks at a couple of angles – bare minimum.
    - 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.
- If possible, use a tool like SPENVIS (http://www.spenvis.oma.be/) 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.