National Aeronautics and
Space Administration

Radiation 101: Effects on Hardware and Robotic Systems

Jonathan A. Pellish

NASA Goddard Space Flight Center
Greenbelt, MD USA

September 2015

This work was sponsored in part by the NASA Electronic Parts and Packaging (NEPP) program.

To be published on the web at https://nepp.nasa.gov/.

Objectives

- Increase knowledge of radiation effects amongst
  - Space weather professionals,
  - Space operations community, and
  - Other science and engineering stakeholders.
- Provide overview of
  - Total ionizing dose (TID),
  - Displacement damage (DD) / non-ionizing energy loss (NIEL), and
  - Single-event effects (SEE).

Stop me any time to ask questions

A little history…

- Much of our community's history is captured in the evolution of the Nuclear and Space Radiation Effects Conference (NSREC), now an Institute of Electrical and Electronics Engineers (IEEE) meeting run by the Nuclear and Plasma Sciences Society.
  - First meetings were 1962/63, but still part of AIEE and IRE/AIEE. 1964 was first official IEEE NSREC.
  - In the beginning, lots of involvement from the nuclear weapons effects community in addition to the civil and military space communities.
  - Just celebrated our 50th anniversary.

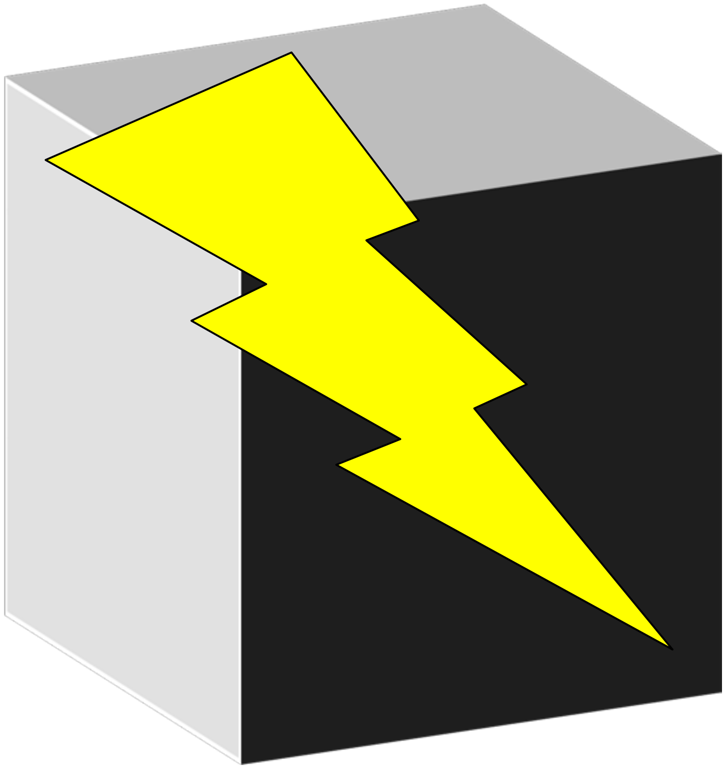
E. E. Conrad, "Reflections on 47+ Years of NSREC," presented at the IEEE Nuclear and Space Radiation Effects Conf., Denver, CO, Jul. 2010.

A little more history…

- Radiation community started during the Cold War
- Sputnik, 4 Oct 1957
- Van Allen Belts, Jan & Mar 1958 (Explorer I and III)
  - Army Ballistic Missile Agency in Huntsville, AL
- Space Race started; Space Act signed into law by President Eisenhower on 29 Jul 1958
- President Kennedy was in office
  - “Going to the Moon Speech,” 25 May 1961 / 12 Sep 1962
- STARFISH PRIME (Ops. Fishbowl / Dominic), 9 Jul 1962
- Limited Test Ban Treaty, 5 Aug 1963

E. E. Conrad, "Reflections on 47+ Years of NSREC," presented at the IEEE Nuclear and Space Radiation Effects Conf., Denver, CO, Jul. 2010.

What are radiation effects?



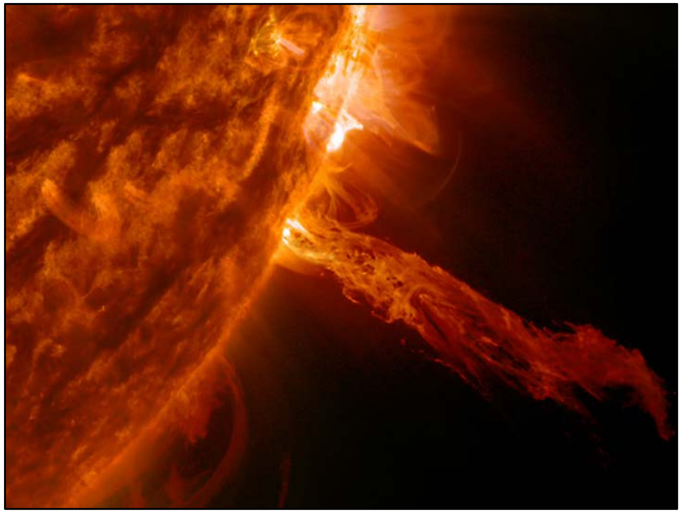
- Energy deposition rate in a “box”
- Source of energy and how it’s absorbed control the observed effects

What makes radiation effects so challenging?

- Field is still evolving because of the technologies we want to use in space systems
- A problem of dynamic range
  - Length: 10^{16} m → 10^{-15} m (1 light year, 1 fm)
    - » 10^{31}
  - Energy: 10^{19} eV → 1 eV (extreme energy cosmic rays, silicon band gap)
    - » 10^{19}
  - That's just two dimensions; there are others.
    - » Radiation sources, electronic technologies, etc.
- Variability and knowledge of the environment

Radiation sources

- Primary
  - o Galactic cosmic rays (GCRs),
  - o Solar protons and heavy ions, and
  - o Trapped particles in planetary magnetospheres.



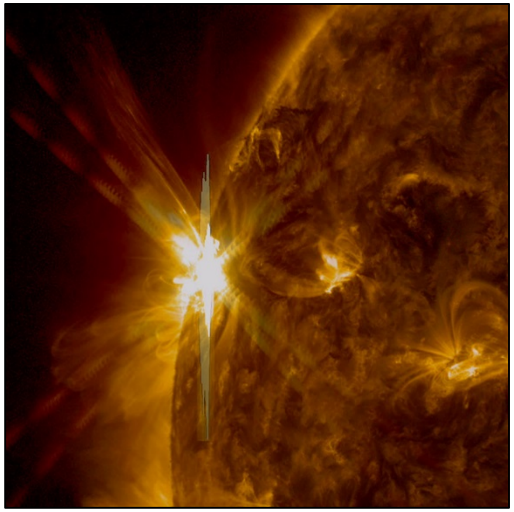


Image credit: Solar Dynamics Observatory/NASA
http://sdo.gsfc.nasa.gov/gallery/main/item/520; http://sdo.gsfc.nasa.gov/gallery/main/item/622

What is a rad?

- 1 rad = 100 erg/g = 0.01 J/kg; 100 rad = 1 Gy
  - Always specified for a particular material
  - 1 rad(SiO_2), 10 krad(Si), 100 Gy(H_2O)
- This is absorbed dose, not exposure (R), or dose equivalent (Sv)
- Missions have a wide range of absorbed dose requirements, driven in large part by persistent environment components
  - Trapped particles, solar protons, etc.

What is total ionizing dose?

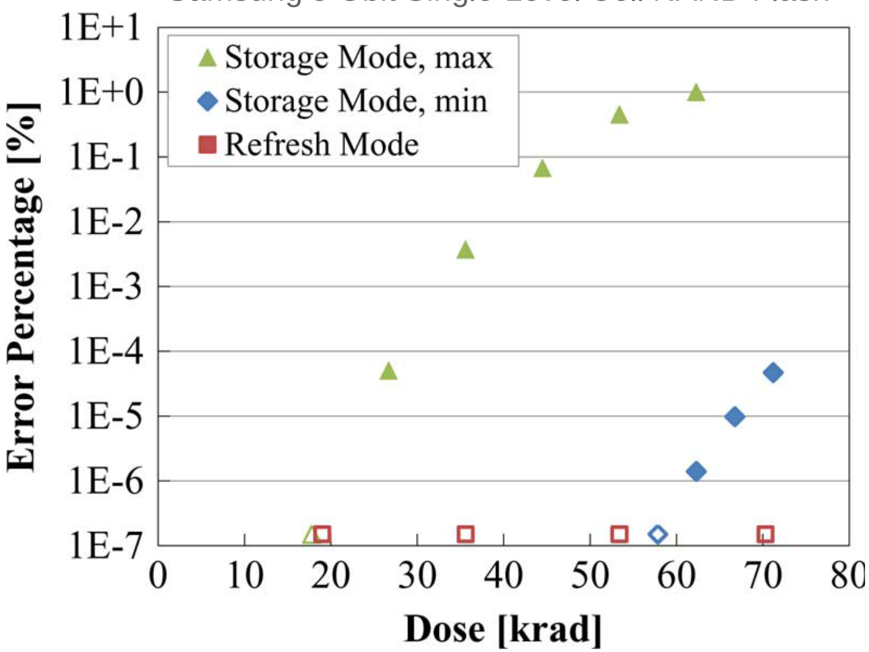
- Total ionizing dose (TID) is the absorbed dose in a given material resulting from the energy deposition of ionizing radiation.
- Total ionizing dose results in cumulative parametric degradation that can lead to functional failure. This is analogous to wear out.
- In space, caused mainly by protons and electrons.

Examples

Metal Oxide Semiconductors Devices	Bipolar Devices
Threshold voltage shifts	Excess base current
Increased off-state leakage	Changes to recombination behavior

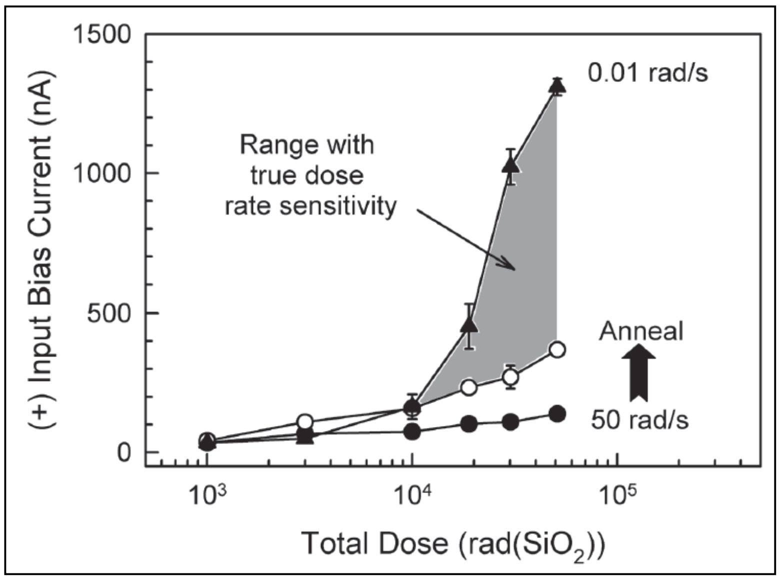
Total ionizing dose

Samsung 8 Gbit Single-Level Cell NAND Flash



H. Schmidt, et al., *IEEE Trans. Nucl. Sci.*, 2009.

I_{B+} *vs.* Total Dose for LM111 Voltage Comparators



M. R. Shaneyfelt, et al., *IEEE Trans. Nucl. Sci.*, 2000.

- Caused by the energy deposition of protons, electrons, energetic heavy ions, and photon-material interactions – *focused on insulators*
- Holes build up in deep traps and interface traps, which are manifest as electrical changes in device performance

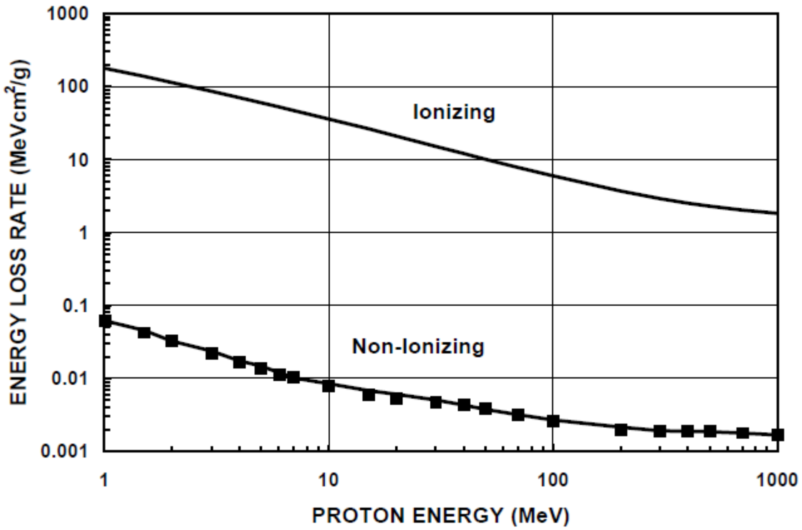
To be published on the web at https://nepp.nasa.gov/.

What is NIEL?

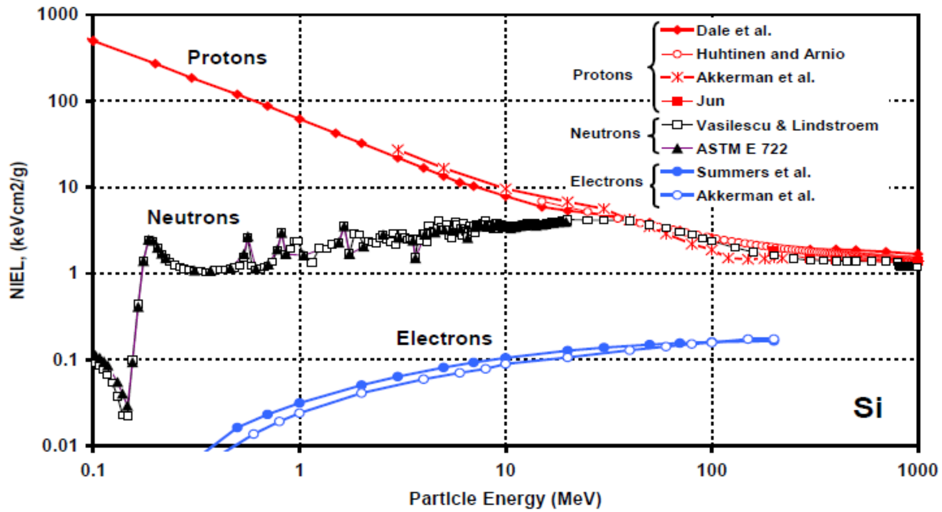
- Most always applies to protons and electrons.
- Vast majority of incident kinetic energy lost to ionization, creating TID and single-event effects.
- A small portion of energy lost in non-ionizing processes causes atoms to be removed from their lattice sites and form permanent electrically active defects (i.e., displacement damage) in semiconductor materials.
- NIEL (non-ionizing energy loss) is that part of the energy introduced via both Coulomb (elastic), nuclear elastic, and nuclear inelastic interactions, which produces the initial vacancy-interstitial pairs and phonons (e.g., vibrational energy).

What is NIEL?

Silicon Material System



C. J. Marshall, *IEEE NSREC Short Course*, 2009.



C. Poivey & G. Hopkinson, “Displacement Damage Mechanism and Effects,” Space Radiation and its Effect on EEE Components, EPFL Training Course, 2009.

- Non-ionizing energy causes cumulative damage, much like TID

NSREC: Nuclear and Space Radiation Effects Conference

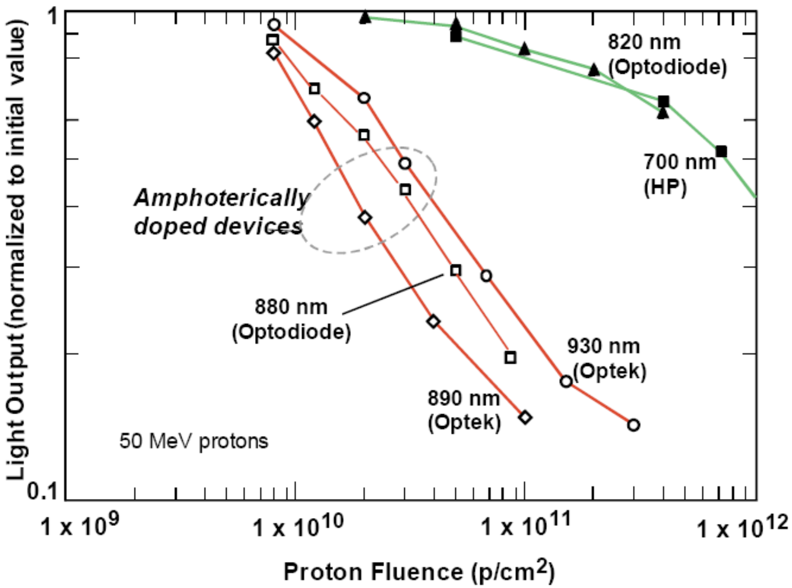
What is displacement damage?

- Displacement damage dose (DDD) is the non-ionizing energy loss (NIEL) in a given material resulting from a portion of energy deposition by impinging radiation.
- DDD is cumulative parametric degradation that can lead to functional failure. This is analogous to wear out.
- In space, caused mainly by protons and electrons.

DDD Effects
Degraded minority carrier lifetime (e.g., gain reductions, effects in LEDs and optical sensors, etc.)
Changes to mobility and carrier concentrations

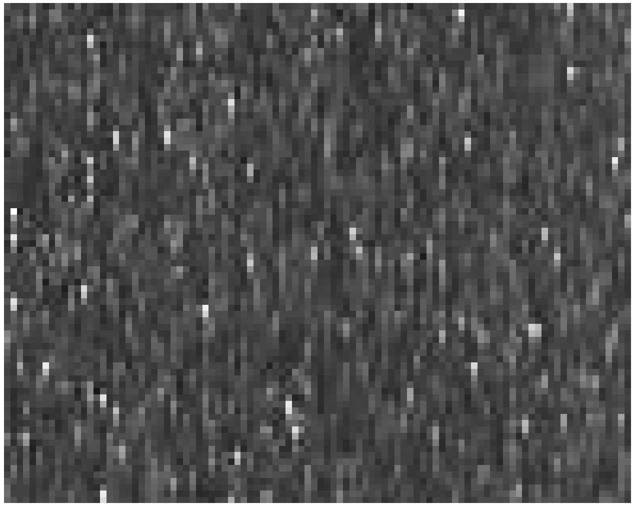
Displacement damage, visually

Device-Level Effects



A. Johnston, *IEEE NSREC Short Course, 2000.*

Dark Spikes and CTI damage - 1.8×10^{10} 10 MeV protons/cm^2

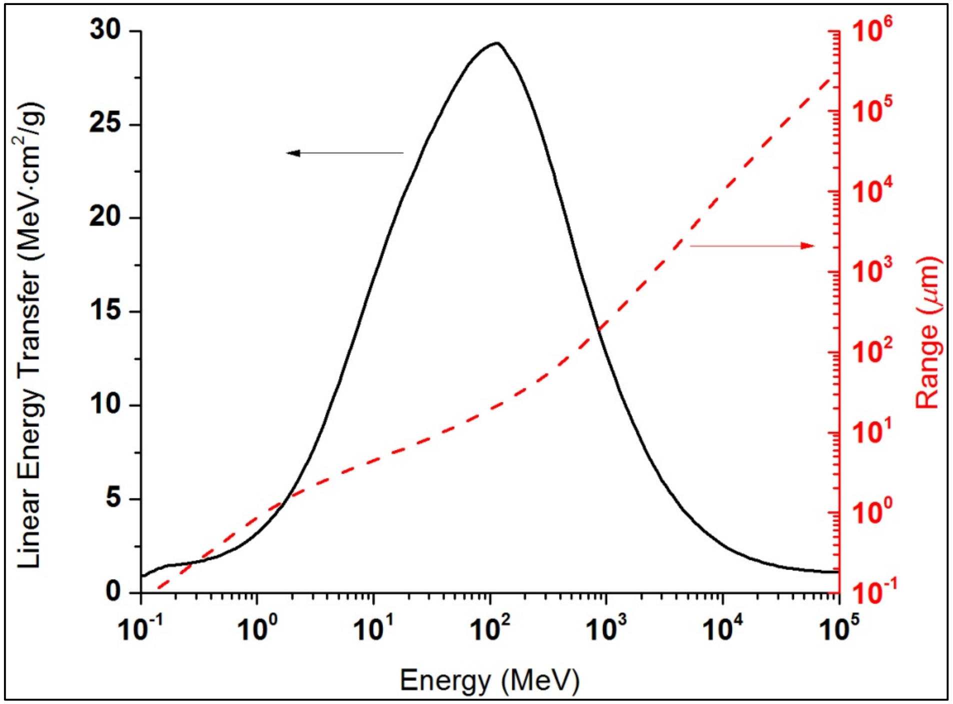


C. Poivey & G. Hopkinson, “Displacement Damage Mechanism and Effects,” Space Radiation and its Effect on EEE Components, EPFL Training Course, 2009.

- Pictorial relating the initial defect configuration to the primary knock-on atom (PKA) energy in Si material.
- For recoil energies above a couple of keV, the overall damage structure is relatively unchanged due to the formation of cascades and sub-cascades.
- Which defects are electrically active? Synergy with TID & SEE…

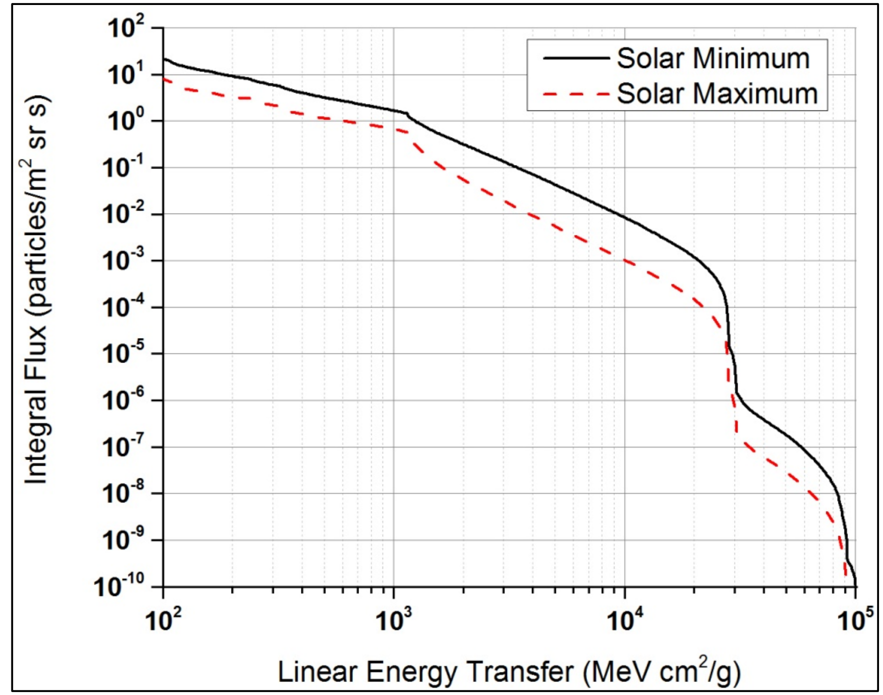
What is linear energy transfer (LET)?

Iron in Silicon



Generated with SRIM-2008

GEO LET Spectrum behind 2.5 mm of Aluminum



Generated with CREME96

$$S = -\frac{dE}{dx} \Rightarrow \text{LET} = -\frac{1}{\rho}\frac{dE}{dx}$$

Stopping power (S), depends on target material; LET does not

What are single-event effects?

- A single-event effect (SEE) is a disturbance to the normal operation of a circuit caused by the passage of a single ion (proton or heavy ion) through or near a sensitive node in a circuit.
- SEEs can be either destructive or non-destructive.

Examples

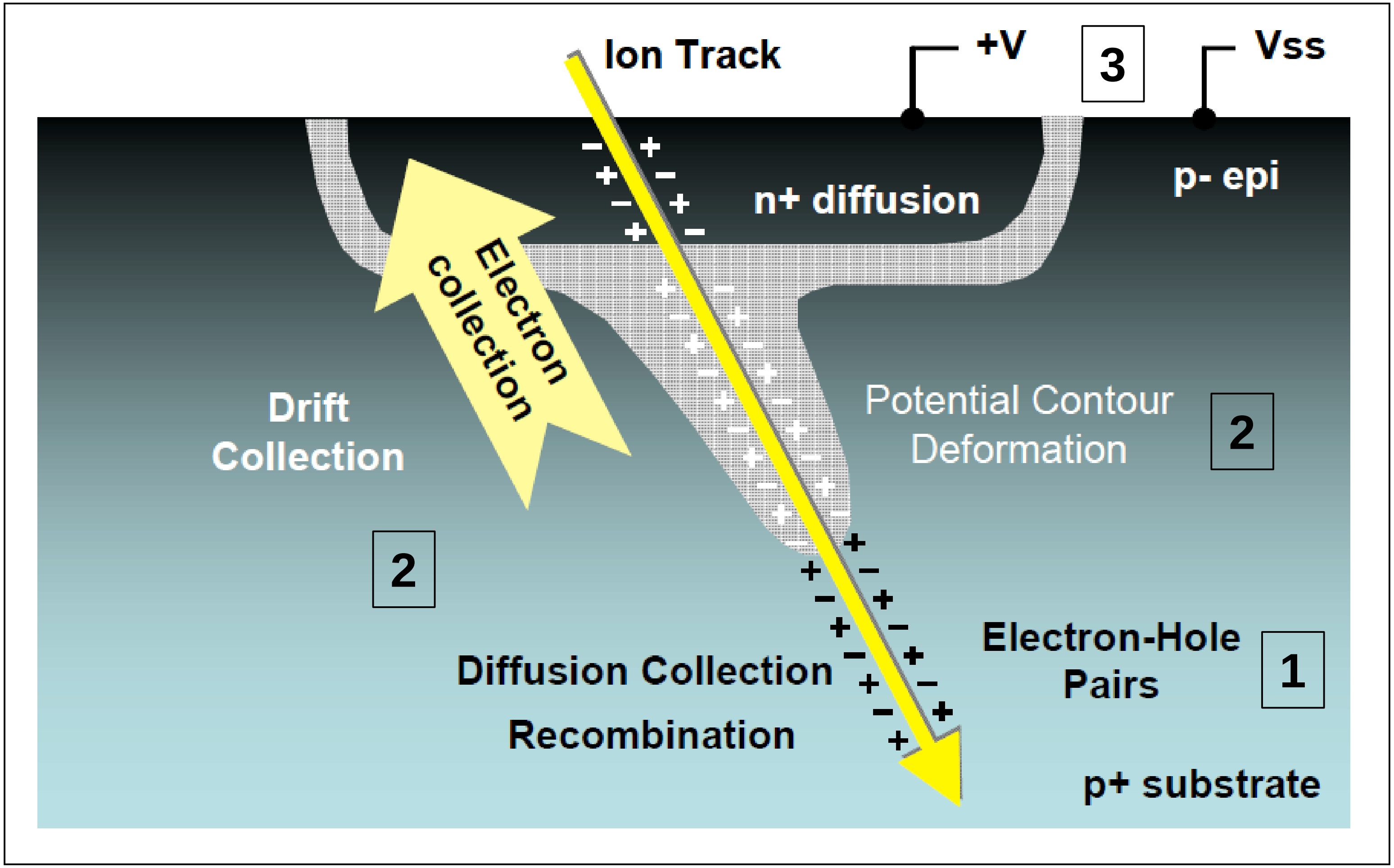
Non-Destructive	Destructive
Single-Event Upset (SEU)	Single-Event Latchup (SEL)
Multiple-Bit Upset (MBU)	Single-Event Burnout (SEB)
Single-Event Transient (SET)	Single-Event Gate Rupture (SEGR)
Single-Event Functional Interrupt (SEFI)	

After S. Buchner, *SERESSA 2011 Course*, Toulouse, France.

Proton SEE notes

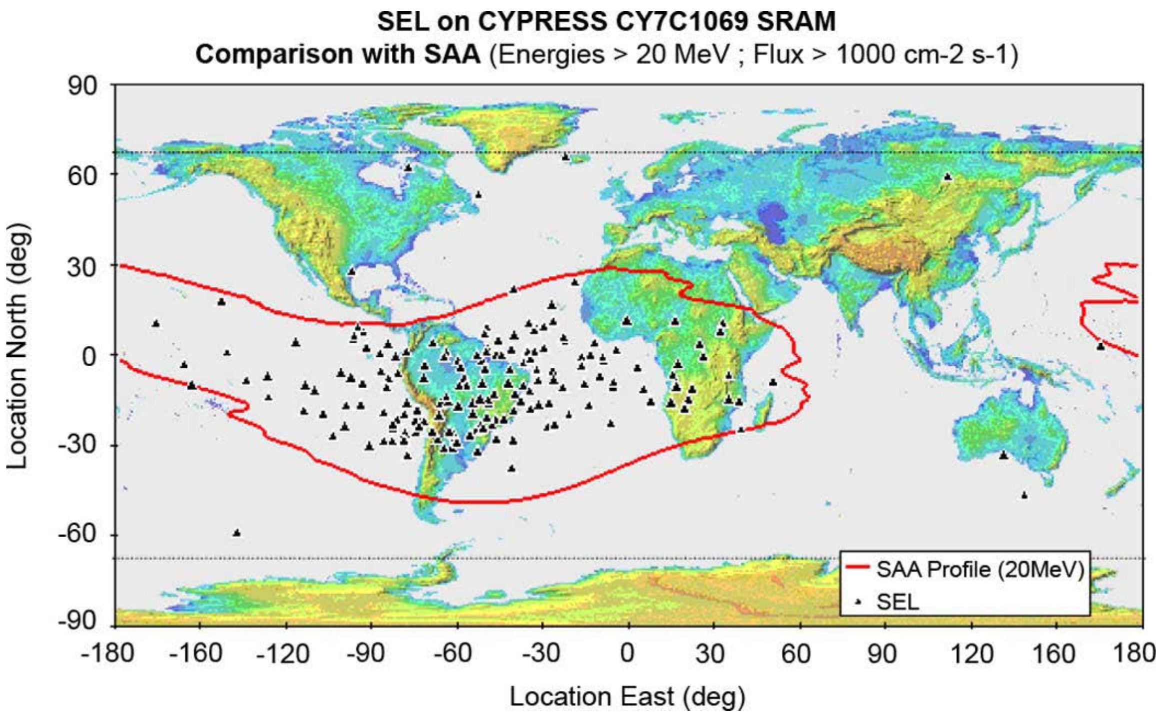
- Proton LET is very low (<< 1 MeV-cm^2/mg)
  - Upsets are usually dominated by indirect ionization – nuclear reactions
  - Reaction products have appreciable LETs, usually less than 15 MeV-cm^2/mg, but short ranges compared to GCRs
  - Since 2007, low-energy proton SEE have become relevant
- Importance of proton SEE
  - In proton-dominated environments, can be a large portion of the overall SEE rate – LEO, for instance

Single-event effects processes



R. Baumann, *IEEE NSREC Short Course*, 2005.

Single-event effects - latchup



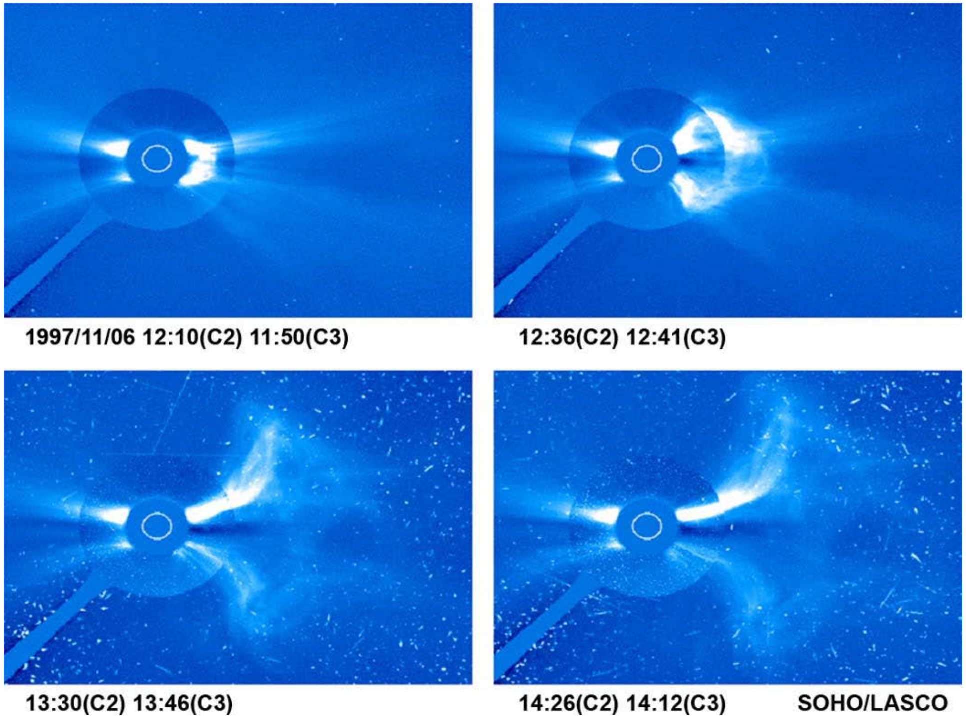
Location of CY7C1069 SRAM latch-ups recorded by the CARMEN-2 experiment on JASON-2

R. Ecoffet, *IEEE NSREC Short Course*, 2011.

- Events are likely due to proton indirect ionization and/or cosmic rays

Single-event effects – sensor corruption

Solar Particle Event Tracks on SOHO LASCO Instrument



R. Ecoffet, *IEEE Trans. Nucl. Sci.*, 2013.

- Transient imager corruption due to solar particle event ions striking the device

The SOHO/LASCO data used here are produced by a consortium of the Naval Research Laboratory (USA), Max-Planck-Institut fuer Aeronomie (Germany), Laboratoire d'Astronomie (France), and the University of Birmingham (UK). SOHO is a project of international cooperation between ESA and NASA.

Short history of single-event effects

- The possibility of single event upsets was first postulated in 1962 by Wallmark and Marcus. *J.T. Wallmark, S.M. Marcus, "Minimum size and maximum packaging density of non-redundant semiconductor devices," Proc. IRE, vol. 50, pp. 286-298, March 1962.*
- The first actual satellite anomalies were reported in 1975. SEUs in flip-flops. *D. Binder, E.C. Smith, A.B. Holman, "Satellite anomalies from galactic cosmic rays," IEEE Trans. on Nuclear Science, vol. 22, no. 6, pp. 2675-2680, Dec. 1975.*
- First observation of SEUs on earth was in 1978. Observed in RAM caused by the alpha particles released by U and Th contaminants within the chip packaging material and solder. Vendors took specific actions to reduce it. *T. C. May and M. H. Woods, "A New Physical Mechanism for Soft Errors in Dynamic Memories", Proceedings 16 Int'l Reliability Physics Symposium, p. 33, April, 1978.*
- First report of SEUs due to cosmic rays on earth in 1979. *J. F. Ziegler and W. A. Lanford, "Effect of Cosmic Rays on Computer Memories", Science, 206, 776 (1979).*
- First report of destructive SEE (proton induced latch-up) in a memory operating in space in 1992 *L. Adams et al.*, *"A Verified Proton Induced Latch-up in Space," IEEE TNS vol. 39, No. 6, pp. 1804 – 1808, Dec. 1992.*

After S. Buchner, *SERESSA 2011 Course*, Toulouse, France.

Summary

- Radiation affects electronic, optical, optoelectronic, and material systems deployed into the space environment
- Performance impacts can be manifest as cumulative degradation (e.g., TID and DD) or transient effects (e.g., SEE)
- Mitigation is possible and requires a multifaceted, systematic approach
- Trading between cost, schedule, and technology will define the level of risk for the mission

Always remember your ***MEAL***

Mission, **E**nvironment, **A**pplication, and **L**ifetime

Acronyms

Acronym	Definition
AIEE	American Institute of Electrical Engineers
DD	Displacement Damage
ELDRS	Enhanced Low Dose Rate Sensitivity
GCR	Galactic Cosmic Ray
GEO	Geostationary Orbit
IRE	Institute of Radio Engineers
LASCO	Large Angle and Spectrometric Coronagraph Experiment
LEO	Low Earth Orbit
LET	Linear Energy Transfer
MBU	Multiple Bit Upset
MEAL	Mission, Environment, Application, and Lifetime
NEPP	NASA Electronic Parts and Packaging program
NESC	NASA Engineering & Safety Center
NIEL	Non-Ionizing Energy Loss
NSREC	Nuclear and Space Radiation Effects Conference
PKA	Primary Knock-on Atom
RAM	Random Access Memory
SAA	South Atlantic Anomaly
SEB	Single-Event Burnout
SEE	Single-Event Effects
SEFI	Single-Event Functional Interrupt
SEGR	Single-Event Gate Rupture
SEL	Single-Event Latchup
SET	Single-Event Transient
SEU	Single-Event Upset
SOHO	Solar & Heliospheric Observatory
SRAM	Static Random Access Memory
TID	Total Ionizing Dose

To be published on the web at https://nepp.nasa.gov/.