Radiation Effects on Electronics

Why does this matter for accelerators?

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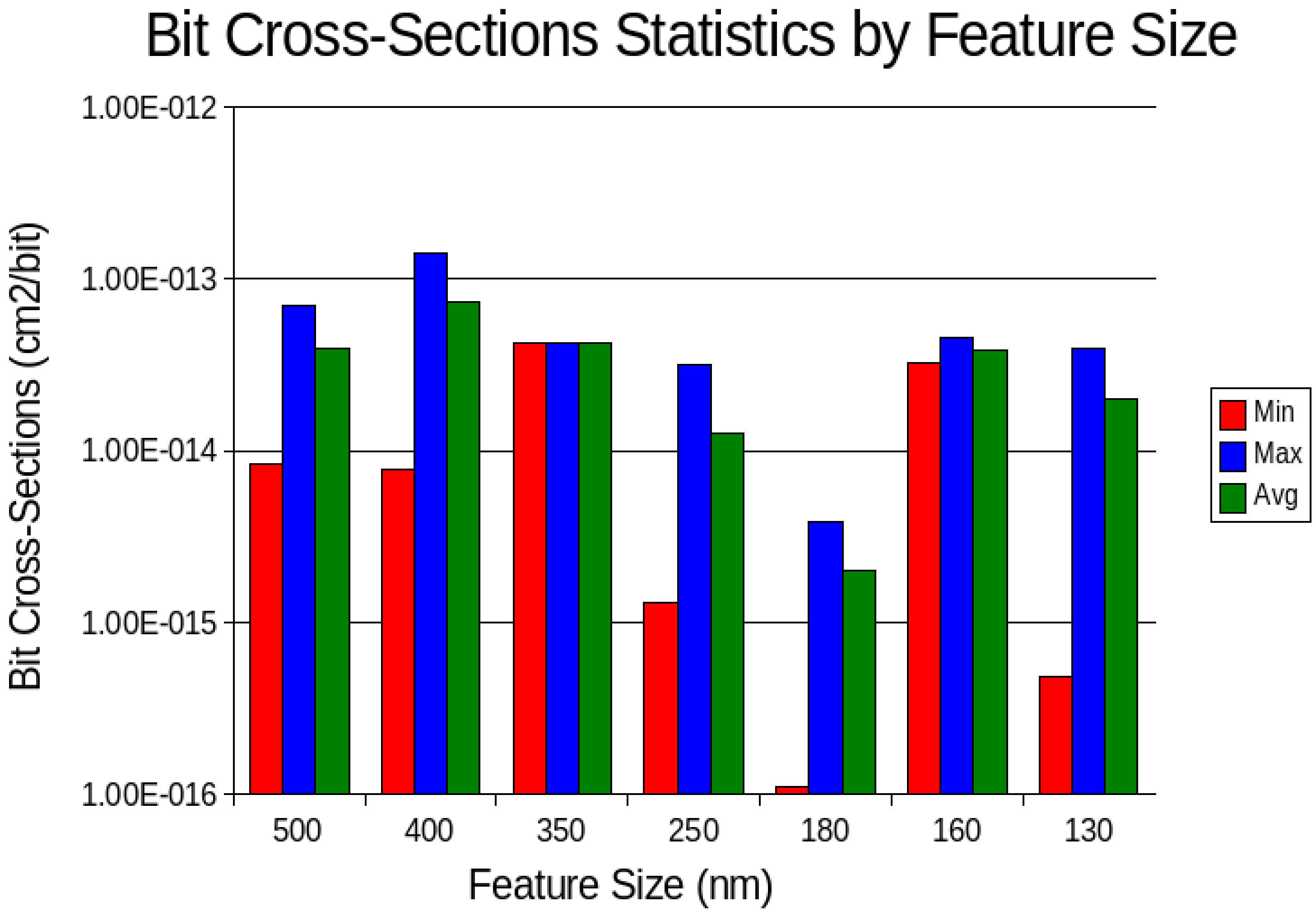
Accelerators and Electronics

- Many accelerators have aging infrastructures, including their electronics
- While this might be a problem on many other fronts, the older electronics are better suited to high radiation environments than modern electronics
- As many accelerators are modernizing their electronics or are significantly changing their infrastructures, facilities are finding that newer electronics cannot tolerate as much radiation as the older electronics
- Why is this so?

The History of Radiation Effects in Electronics

- **The original failures were seen in boats around nuclear weapons testing done post-WWII**
- **During this same time period, the first satellites were launched**
  - We were also doing exo-atmospheric testing of nuclear weapons
  - Several satellites were accidentally damaged during these nuclear tests
  - The issue was still nuclear weapon effects
- **Eventually, we started seeing issues from the accumulation of both ionizing and non-ionizing radiation in satellites that was not tied to nuclear tests**
- **In the 1970s, we started seeing the first single-event effects from single charged particles in satellites**
  - Over time this started dominating effects in satellites, supercomputers, and accelerators
  - If Moore’s law states that transistor density doubles every 18 months, that all means there is 2x more SEE issues every 18 months, assuming all things are equal

In fact, it is a bit more complicated



Factors in radiation effects

- **The feature size is only one factor. There is also:**
  - The voltage used to switch a device (transistor, finFET, bipolar, etc)
  - The amount of charge needed to switch a device (Q_crit)
  - The dimensions of the device
    - Especially the z-axis in power transistors
  - The temperature of the system
  - The energy, species, etc of the particle
  - The angle of the arrival

The Designers and Manufacturers Have a Role, Too

- **Designers**
  - In 130nm feature size parts, the radiation effects were noticeable in terrestrial systems
  - The designers figured out that they needed to make the devices more robust, but still make the dimensions decrease in size
  - Most of the designers “game” the transistors so the feature size is smaller, but the Q_crit is not smaller

- **Manufacturers**
  - Most of the design houses are now “fabless” and do not manufacture/fabricate their own parts
  - (Trust me, the fabrication process is an environmental disaster, and other countries can use it as a part of the “t-shirt economy” process.)
  - The fabs have their own secret sauce that adds to the problem. Usually in the form of B10 and W.

Devices Keep Changing

- **There were some standard trends that we saw over the years:**
  - Issues with accumulated radiation effects kept getting better
  - Issues with single particles effects kept getting worse
    - Worse enough that “radiation-hardened” has become a useless term

- **The newest digital devices, finFETs, have flipped:**
  - The single particle effects is much better, except some destructive effects
  - The accumulated radiation effects is getting worse

- **So how are we supposed to figure out what is going on?**

Test, Test, Baby

- **Or literature study this week**

- **Each untested electronic component has unknown radiation sensitivities**
  - You are going to have to test the parts in some sort of radiation source to determine whether it will work

- **Here is the worst news I have to give you:**
  - There are approximately 500 radiation effects researchers in the world
  - The US has the corner on the market with about 200-250 people with the French coming in second with about 50-75 people. We expect more from India, China and Russia, but their progress has been slow, which is weird for engineering.
  - In July 2018 there were 30 open jobs in the US for US nationals.
  - We currently graduate 3 persons/year who knows how to do radiation testing, which means that 30 existing researchers changed jobs and 30 new jobs opened up
  - You are going to have to do your own testing

Some Potentially Even Worse News

- In between a few high profile problems, most of the community is focused on solving a few very specific problems
- Most of the accelerators were already maxed out on radiation testing, and then these problems hit
  - SpaceX is also hoovering up time everywhere
- There is literally not enough time at particle accelerators to meet the needs for radiation effects testing
- If there is anything you learn this week, it is that you can start to think about the radiation testing needs for your own facilities and to figure out ways to help the radiation test community

What is radiation effects in electronics

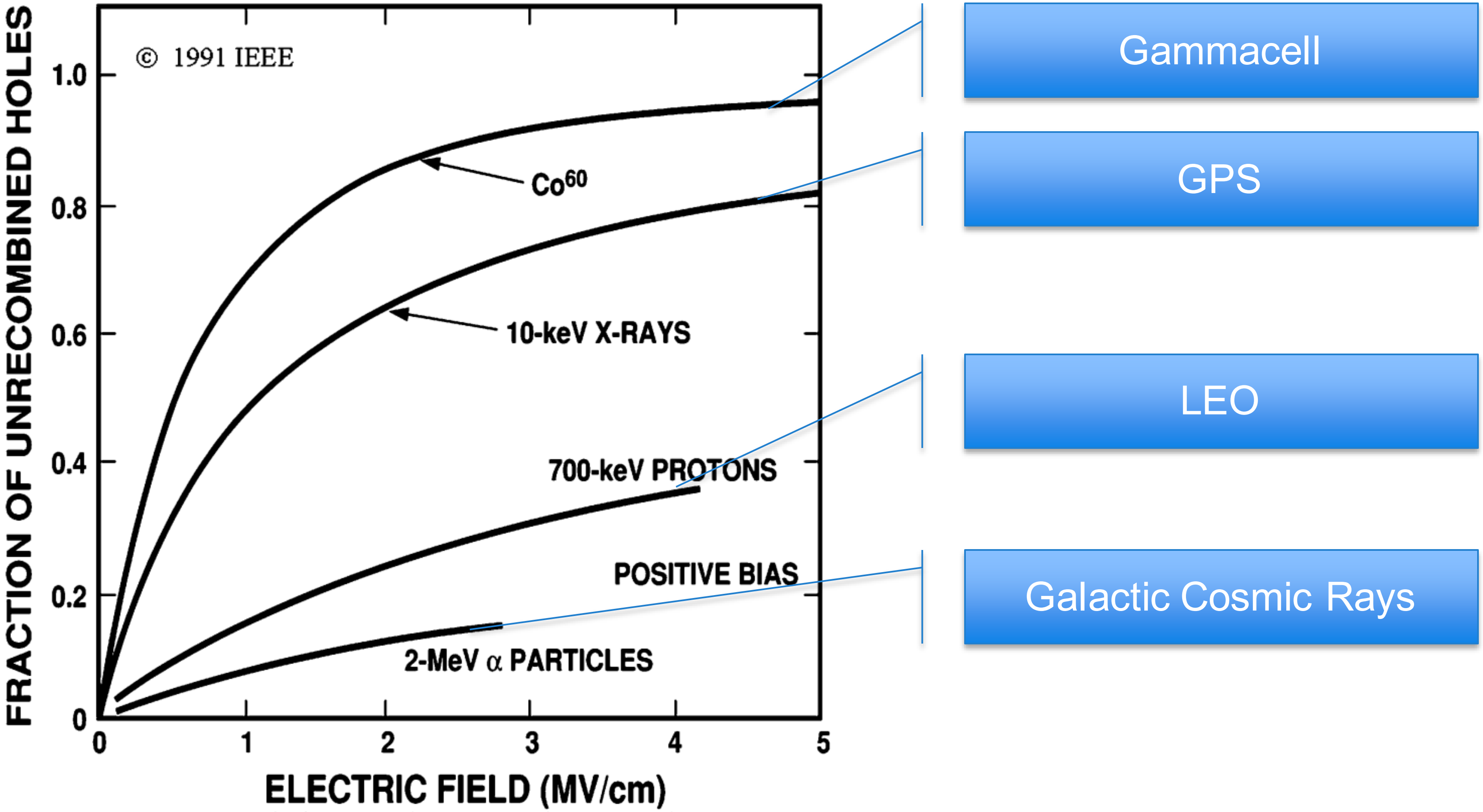
Three Types of Radiation Effects in Electronics

- Total ionizing dose (TID)
- Displacement damage (DD)
- Single-event effects (SEE)

Total Ionizing Dose (TID)

- **Historically, the dominant problem for satellites**
  - Caused by most forms of charged particles, but not neutrals
- **Prolonged exposure to ionizing radiation can cause “MOSFET threshold voltage shift, increased leakage current, and degraded timing parameters” [L. D. Edmonds, C. E. Barnes, and L. Z. Scheick, “An introduction to space radiation effects on microelectronics,” Tech. Rep., 2000, Available at http://parts.jpl.nasa.gov/docs/JPL00-62.pdf]**
- **These parametric changes cause essentially an accelerated aging effect that leads to often permanent failure of the electronic component**
  - In some cases it is possible to anneal the effect, but generally annealing deployed electronics is not possible

Types of Radiation and TID Efficiency

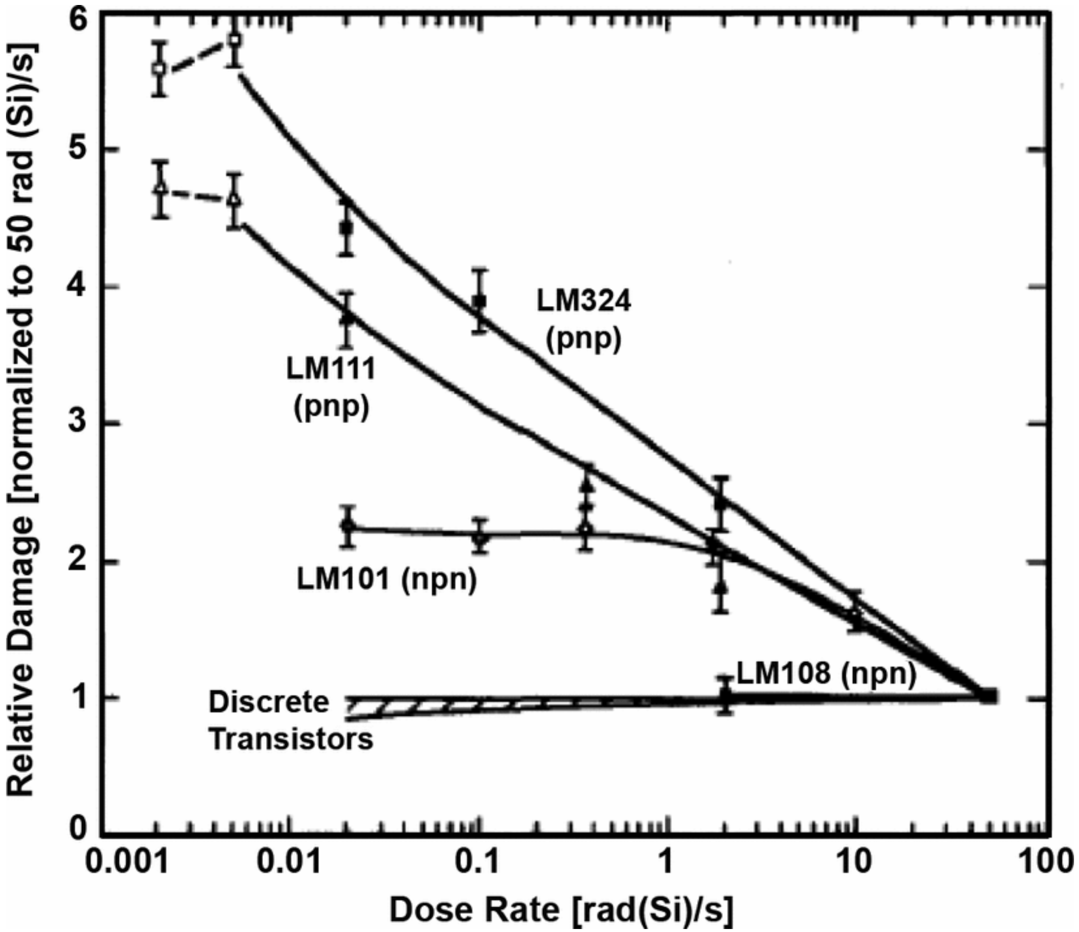


Fractional yield of holes generated in SiO_2 as a function of electric field in the material. [H. J. Barnaby, "Total-Ionizing-Dose Effects in Modern CMOS Technologies," in *IEEE Transactions on Nuclear Science*, vol. 53, no. 6, pp. 3103-3121, Dec. 2006.]

Testing Dose Rates vs. Space Dose Rates

- **Dose rate is the rate in which the electronics accumulate TID**
- **In space, the dose rate is very low**
  - We cannot practically test at that dose rate
  - The dose rate for testing is >> the dose rate in space
  - This discrepancy is fine as long is there is not an issue with the dose rate
- **In 1998 it was discovered that bipolar electronics (analog, linears) are susceptible to Enhanced Low Dose Rate Sensitivity (ELDRS) [D. M. Fleetwood, "Total Ionizing Dose Effects in MOS and Low-Dose-Rate-Sensitive Linear-Bipolar Devices," in *IEEE Transactions on Nuclear Science*, vol. 60, no. 3, pp. 1706-1730, June 2013.]**
  - Several linear components had on-orbit failures after being thoroughly tested in a Co60 source
  - It was later determined that the components were more sensitivity to TID when the dose rate was at a space dose rate level than the test dose rate level

Measured ELDRS Effects in Linears



Normalized degradation, relative to responses at 50rad (SiO2), as a function of dose rate for a variety of linear bipolar transistors and integrated circuits. [D. M. Fleetwood, "Total Ionizing Dose Effects in MOS and Low-Dose-Rate-Sensitive Linear-Bipolar Devices," in *IEEE Transactions on Nuclear Science*, vol. 60, no. 3, pp. 1706-1730, June 2013.]

Examples of TID in Current Components

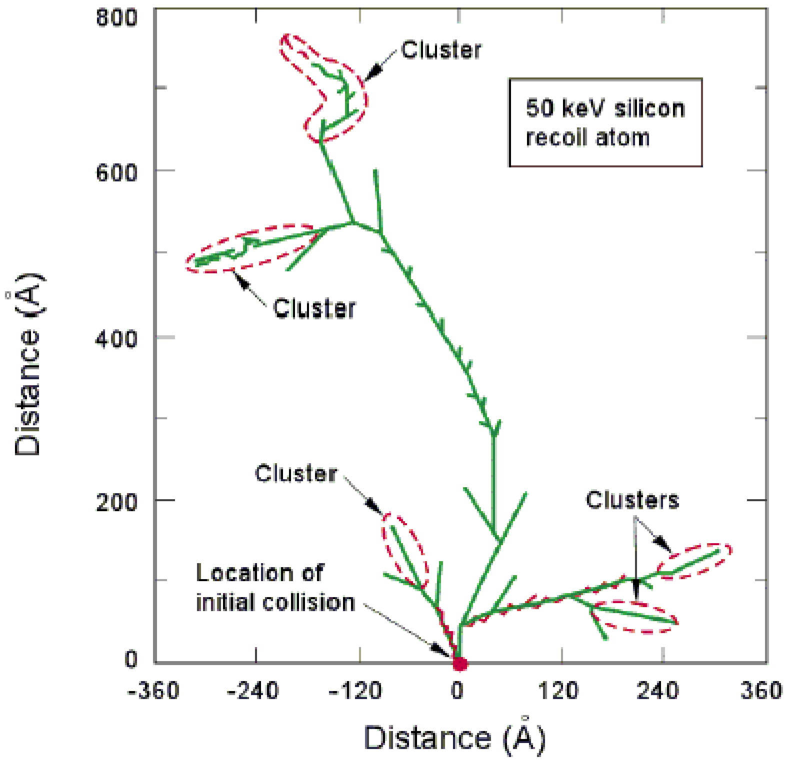
- **Analog devices:**
  - Commercial components can be as low as 5 krad(Si)
  - Radiation-hardened components can be higher
- **Memory devices**
  - Traditionally problems with non-volatile memory have been the focus
  - Flash memory handle about 20-30 krad(Si)
  - Radiation-hardened memory components that can handle 1 Mrad(Si)
- **Commercial digital processing elements (field-programmable gate arrays, microprocessors, complex digital components):**
  - Are often 100-300 krad(Si) components, but often need testing

TID in Components

- **All electronics have a sensitivity to TID: it is a matter of threshold and testing**
- **Rad-hard or “space-grade” parts have likely been tested for TID tolerances**
  - Rad-hard does not mean ITAR, so check the data sheet to guarantee what it can tolerate
- **Many commercial parts have a reasonable TID tolerances, but the parts have to be tested to determine the sensitivity**
  - We have seen many commercial parts with very high tolerances to TID
  - We are seeing in the literature that the new finFET transistors might be more sensitive to TID than the older bulk transistors

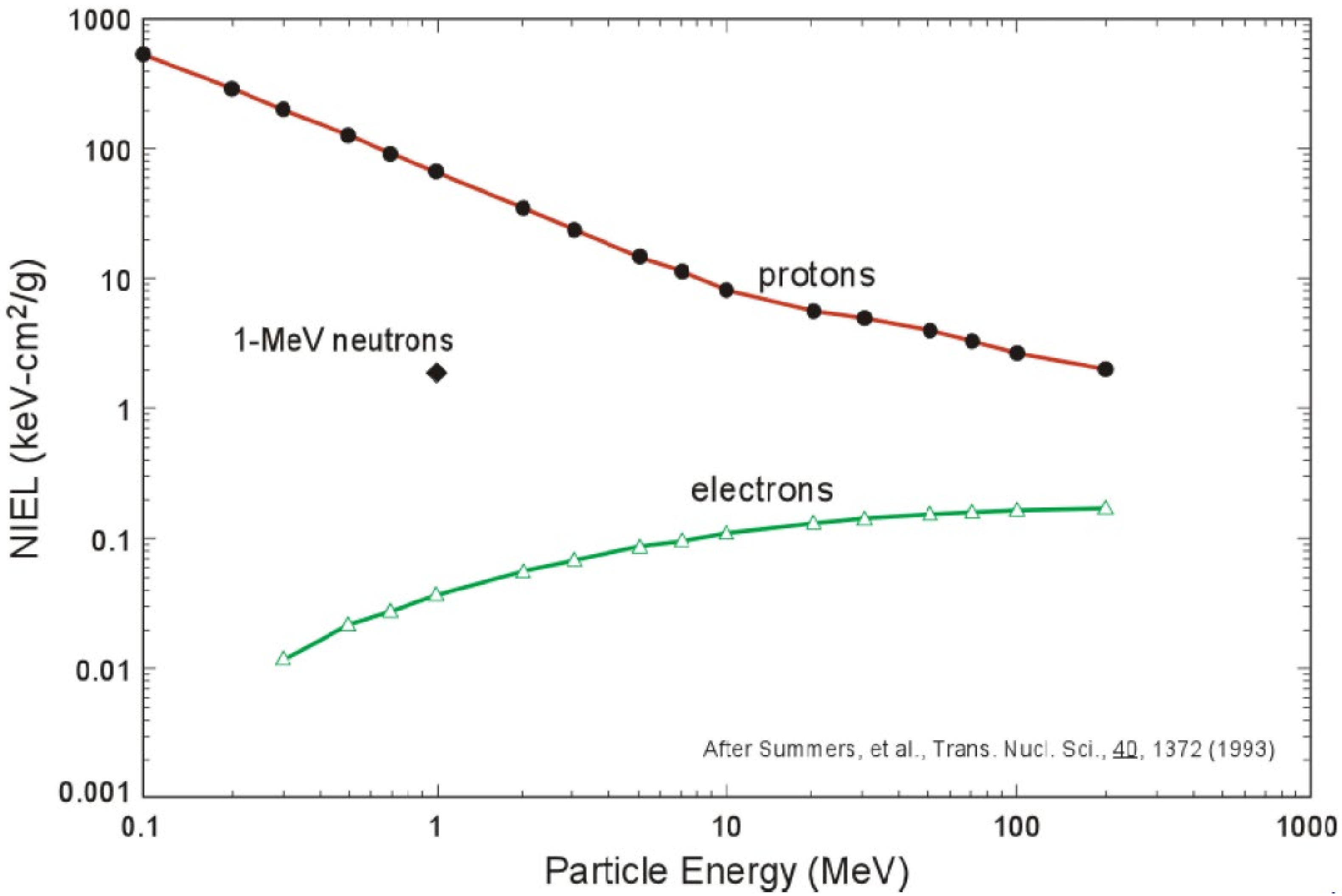
DD Mechanism

- **Heavier particles interacting with the electronics can cause damage to the rigid Silicon lattice**
- **Classical physics types of interactions:**
  - A heavy particle knocks-on a Silicon atom or a dopant and removes it from the lattice
  - In some cases, the interaction can cause a cascade of displacements
  - Over time the lattice structure is gradually turned into an amorphous crystalline structure
- **The energy involved in this interaction is the nuclear energy loss**
  - Low energy interactions most common – particle is at the end of its range and has lost most of its energy from electrical energy loss



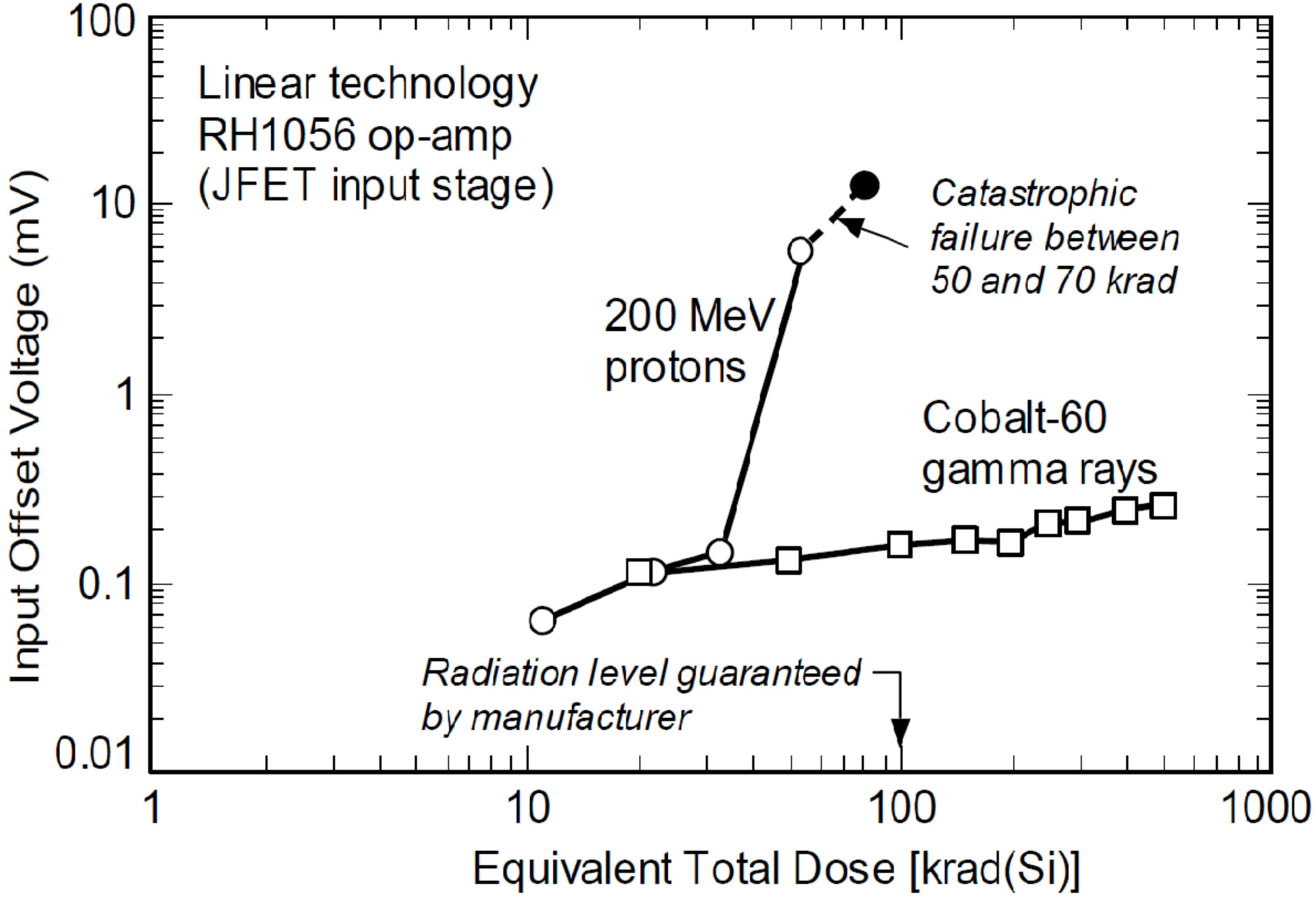
Displacement Cascade Damage in Silicon ["Space Radiation Effects on Microelectronics," NASA Jet Propulsion Laboratory]

Energy Dependence for DD



[https://parts.jpl.nasa.gov/docs/Radcrs_Final.pdf]

DD vs. TID



[https://parts.jpl.nasa.gov/docs/Radcrs_Final.pdf]

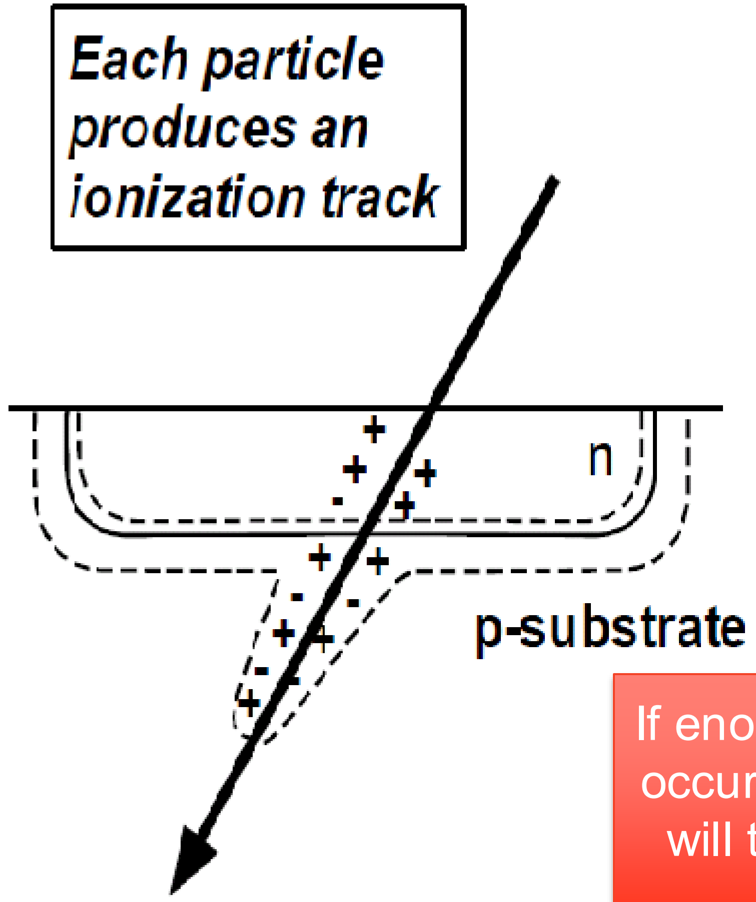
DD in Components

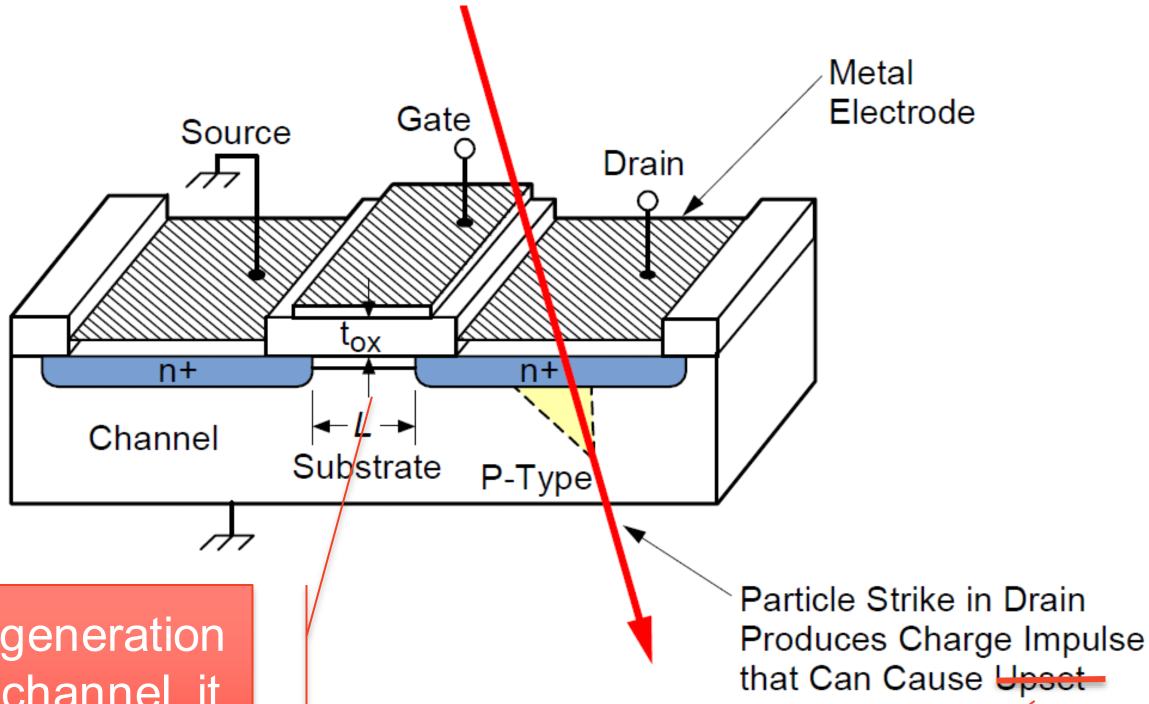
- **Generally takes more than 3E10 particles/cm^2 to cause a noticeable change to the components**
  - Low-earth orbit in the trapped proton belt
  - Prompt dose effect from manmade nuclear environments
- **Analog components appear to have more problems than digital components**
- **We've had DD problems at LANSCE after a few days of testing**
  - The parts are not completely non-functional, but are no longer stable

Single-Event Effects (SEEs)

- **Currently, neck and neck with TID for top problem for satellites**
  - Caused by many forms of charged particles and neutrals
- **SEEs is an umbrella term that covers about 10 different types of effects**
- **The root mechanism comes from EHPS causing charge generation in the transistor**
  - Transistor on: a little overcurrent, but no problem
  - Transistor off: transistor turns on

SEE Mechanism



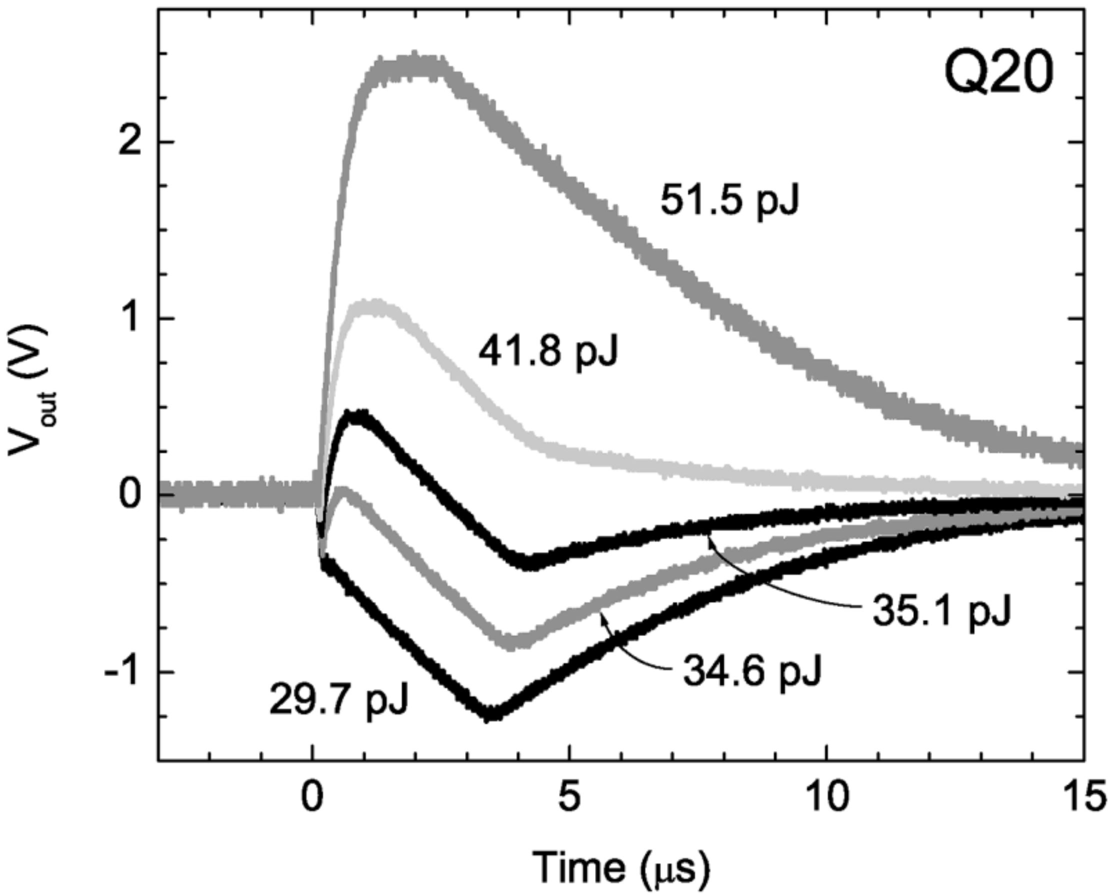


If enough charge generation occurs under the channel, it will turn an "off" transistor "on" temporarily

A Transient

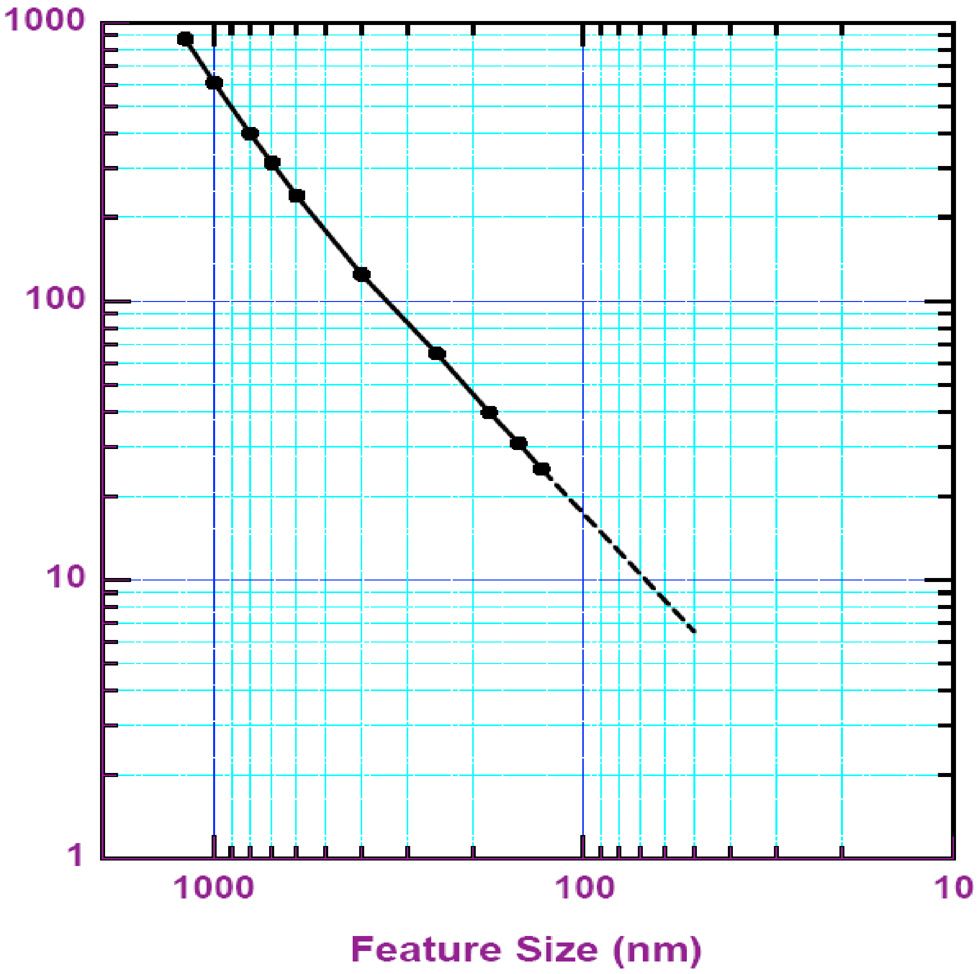
[https://parts.jpl.nasa.gov/docs/Radcrs_Final.pdf]

SEEs Create Transients in Transistors



Q20 SET waveform for different laser energies for 815-nm laser, [R. L. Pease *et al.*, "Comparison of SETs in bipolar linear circuits generated with an ion microbeam, laser light, and circuit simulation," in *IEEE Transactions on Nuclear Science*, vol. 49, no. 6, pp. 3163-3170, Dec 2002.]

Critical Pulse Width for Unattenuated Propagation



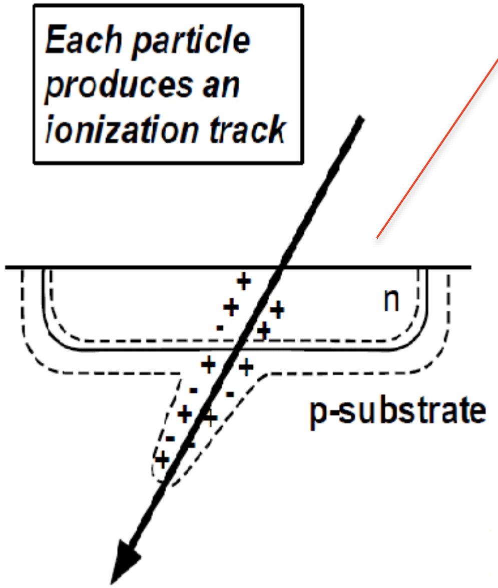
Mavis, "Single-Event Transient Phenomena: Challenges and Solutions." MRQW, 2002.

Does This Transient Matter?

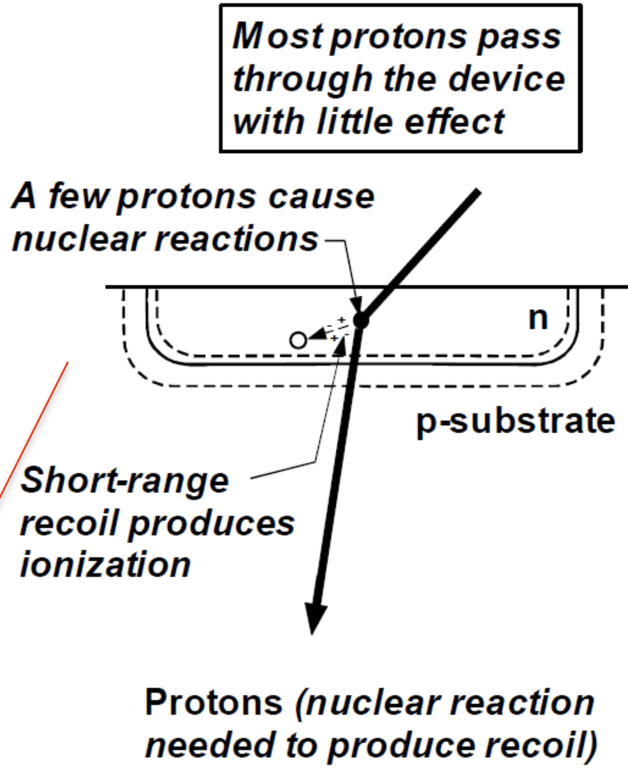
- **Depends on the circuit and the transient location**
  - More logic: the transient might dampen or might not
  - A latch: the transient might “latch” and become state
  - The transient is inside of a memory cell: the transient only needs to last long enough to change the inverter value to lead to persistent memory value change
  - The transient is in one of the extra transistors we were talking about: the transient might cause permanent damage to the component
- **What we are talking about is a single-event transient (SET) and it is the ur mechanism for all single-event effects (SEE)**
  - SET in memory causes single-event upsets (SEUs), which are memory bitflips
  - SET in the extra vertical transistor under the source or drain causes single-event latchup (SEL)
  - SET in the extra transistor in the mesa structure of a power MOSFET causes single-event burnout (SEB) or single-event gate rupture (SEGR)

Types of Radiation and SEE Efficiency

- To a certain degree, it is part specific
- In the original image showing charge generation, the EHPS are being generated through <u>direct ionization</u>: the charged particle is causing the EHP production
- In the new image, the EHPS are being generated through <u>indirection ionization</u>: the neutron or proton cause a nuclear recoil with the Si atoms and it is the recoil atom that causes the EHP production
- As transistors have decreased in size, the onset threshold to SEE has decreased
- For awhile the sensitivities were also increasing, but manufacturers started seeing more problems with neutrons so altered their designs to be naturally less sensitive to neutrons



Heavy ions: > 0.1 LET
Protons: ~0.1 MeV
Muons: ? MeV
Electrons: > 20 MeV



Neutrons: > 0.1 MeV
Protons: >3 MeV

SEE in Components

- **Most digital and analog components have some form of SEE**
  - Traditionally we fly rad-hard parts to avoid these issues, but even rad-hard parts have SEUs, SETs, and SEFIs these days
  - Many of the parts we fly are upscreened commercial parts, and will have at least SEUs, SETs, SEFIs
- **Some families of parts have issues with particular SEE types**
  - High-voltage power MOSFETS and diodes have SEB and SEGR sensitivities
  - Analog components tend to be sensitive to SEL and SETs
  - Memory components have SEUs and SEFIs
  - DRAM components have SEU, SEDD and SEFIs
  - Processing elements have SEL, SEU, SETs, and SEFIs
- **As we can no longer easily avoid these issues, we need to build our systems to be more resilient to SEE faults and/or quickly recover from SEE faults**

Particle Accelerators as Laboratory Analogs

The Use of Particle Accelerators by the Radiation Test Community

- **To us, the particle accelerator is a “laboratory analog”**
  - That means we are using the radiation as a surrogate for the radiation from the expected environment
- **The environment is crucial.**
  - Avionics is neutron dominated
  - Low Earth orbit is proton dominated,
  - Mid-Earth orbits are electron dominated,
  - Outside of the magnetosphere is cosmic ray dominated
  - And the planets and moons can be really weird, especially Jupiter
  - And reactors are different
  - And particle accelerators are different
  - And very few environments are only one type of radiation
- **We need some sort of radiation source for all of these different environments**
- **Here is what is working and not working**

Terrestrial Neutron Analogs

- **Best options: LANSCE and TRIUMF**

- **Right now, these are good analogs to the terrestrial neutron environment**
  - The spectra match a good portion of the terrestrial spectra
  - Neither facility has the high energy portion of the terrestrial environment, but right now most results saturate
    - Let's revisit that issue later this week

- **We are tracking issues with 1-10 MeV neutrons**
  - The test standard explicitly states to start counting fluence at 10 MeV
  - But we know that we are getting events from 1-10 MeV neutrons
  - We just don't have enough mono-energetic test results in that energy range to figure out whether to change the test standard: cue a lot of testing at Duke's tandem

Proton Analogs

- **Many proton options, especially at the new medical facilities**
- **Might need some more low-energy options, but right now TRIUMF has absorbed all of that work**

- **The proton facilities we have are good analogs**
  - Using a number of facilities, we can piece together most of the spectrum using mono-energetic sources
  - Like neutrons, the reaction saturates as energy increases
    - Let’s discuss this more later

- **There has been on-going issues with facility availability, but the new Knoxville accelerator will solve that issue**

Galactic Cosmic Ray (GCR) Analogs

- **There are no good analogs, although Brookhaven is closer GCR**
- **The kinetic energy of terrestrial made heavy ions is much lower than space by many orders of magnitude**
  - In space, heavy ions can go through an entire satellite and your part
  - In terrestrial analogs, heavy ions cannot even get through the package
- **We have adapted by deprocessing parts so that the terrestrial heavy ions can get into the parts**
- **There are ongoing issues with the amount of beam availability for heavy ion testing: TAMU and LBL are saturated; Brookhaven is expensive and pulsed**

Electron Analogs

- **It is likely an open question if the electron facilities are reasonable analogs**
  - For the usual electron problems, the facilities are fine, albeit old and sparse
  - But with the new Europa missions, do we need higher energy electron test facilities? Possibly. But that environment is uniquely bad.

- **There are also holes in the radiation effects research – there has only been a sparse amount of research on modern electronics in electron environments**
  - Part of this is driven by the fact that most of that research only affects the Europa missions

Gamma Analogs

- We will talk in more detail over the course of the week, but the gammacells that we use for accumulated ionizing radiation testing are reasonable analogs, except for one particular type of device (bipolars)

- We have a solution for bipolar devices, but it makes for a deliberately long test

All of the Other Environments

- **The nice thing about the other issues we are seeing around reactors and accelerators could be tested in situ, which is the best analog**

- **It might still be a bad idea – the test might take too long or the location too difficult to work on**
  - If that is the case, then particle accelerators are also possible

Neutron Generators

- **Over time we stopped using NGs, because most of the neutron problems were in the terrestrial environment**
  - NGs are not a great analog of the terrestrial environment – the white beams give us a better average of what the environment actually is, and the NG is too low energy to even give a saturated response
  - NGs are a great analog to other environments, though, so they are used for that
- **That said, there is not enough time at LANSCE or TRIUMF, so we are exploring the use of NGs again**
  - Maybe useful for “fault injection” experiments
  - Use LANSCE and TRIUMF only for validation

Sealed Sources

- **A good source for Alphas, if designed right**
  – Given the short mean free path, you need to be able to put the deprocessed part right on top of the source

- **Sealed alpha sources are used for a lot of terrestrial testing, where alpha emitters in the package are problematic.**

- **Also good as a “fault injection” source**

Summary

This week…

- **We will cover the basics of radiation effects in electronics, the basics of testing, and the basics of prediction**

- **We are hoping that over the course of the week we also do some mind meld on:**
  - What the radiation effects community needs from the accelerator community
    - We have many good analogs, but we need more!
    - We always need more time at accelerators!
    - We could likely use some nuclear physics help with using our less useful analogs better, such as NGs!
  - What the accelerator community will need to do to prepare their accelerators for next-generation electronics