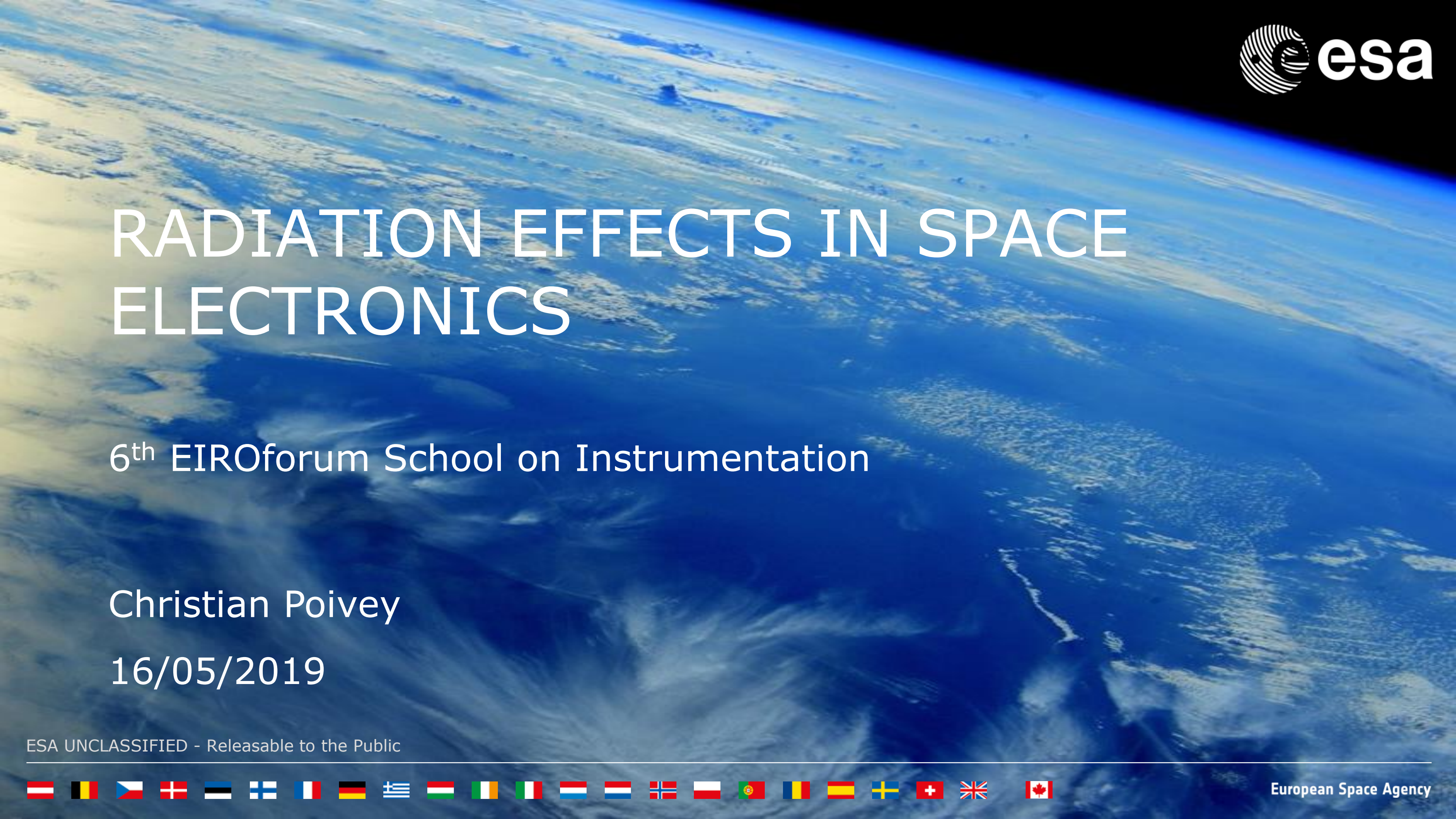


RADIATION EFFECTS IN SPACE ELECTRONICS

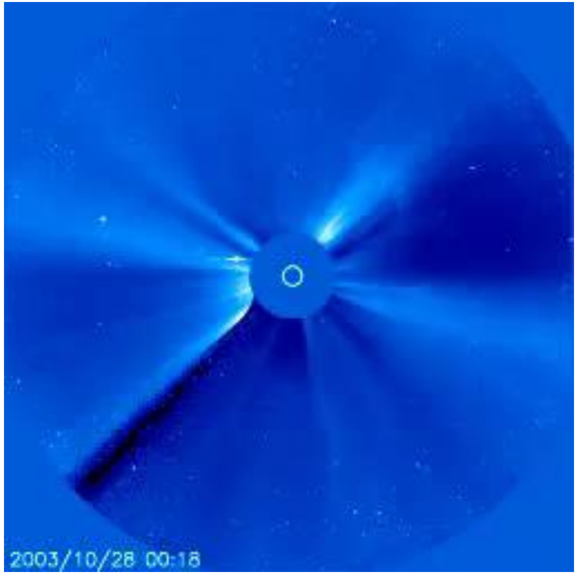
6th EIROforum School on Instrumentation

Christian Poivey

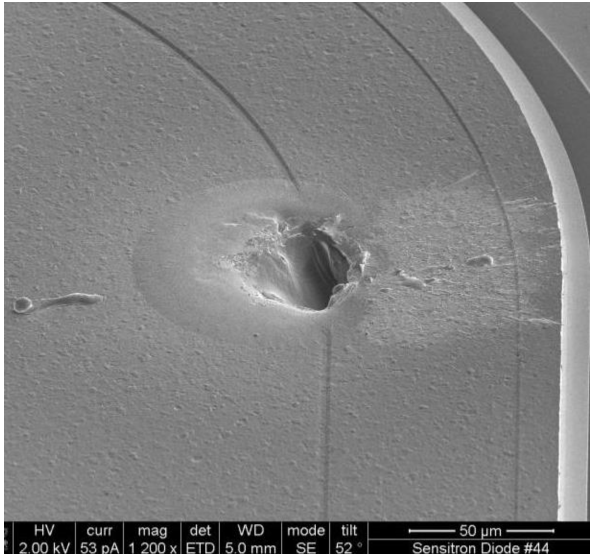
16/05/2019

Why Are We Concerned by Radiation in Space ?

- There is an abundance of high-energy particles in space
- Space radiation can be dangerous for humans in space.
- Space radiation environment may also be dangerous for materials and electronic components used in spacecraft



SOHO, the effect of solar Coronal Mass Ejection resulting in a strong high energy proton event. Proton impinging on the imaging sensor of the instrument are observed as bright pixels or streaks.



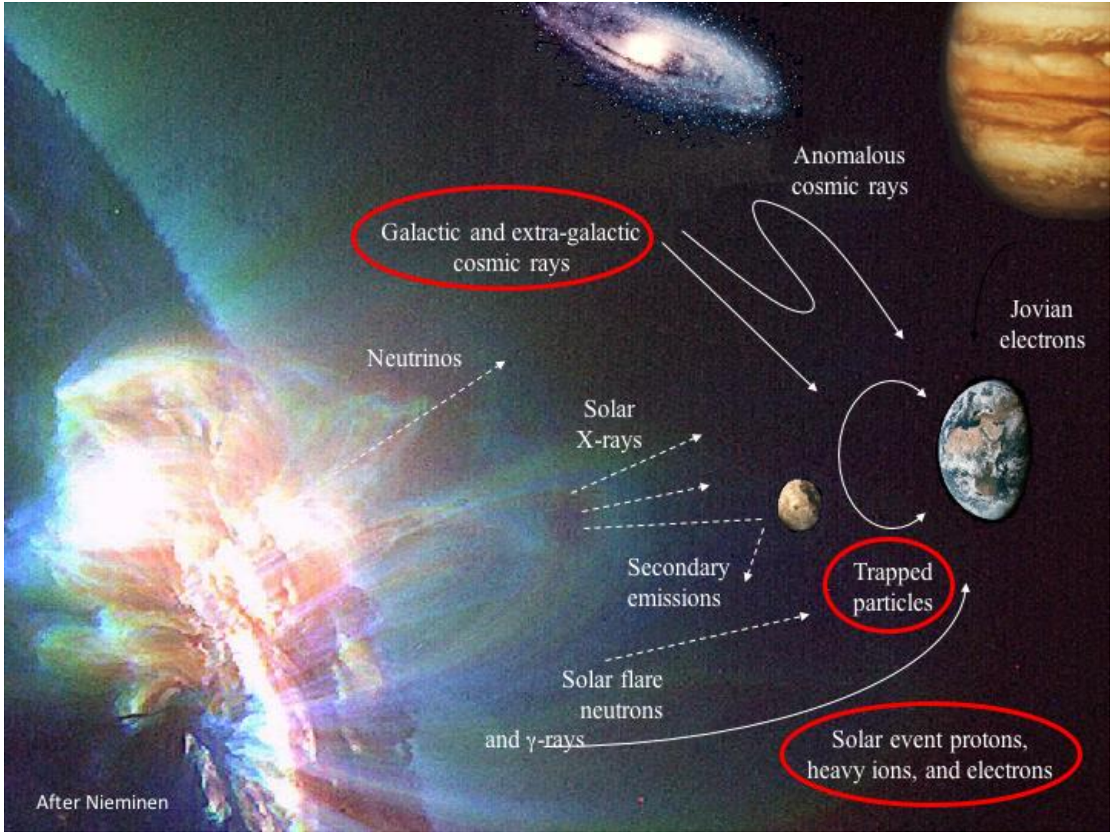
High-energy particle impact on Schottky diode.

(J. George NSREC Radiation Effects Data Workshop 2013)

OUTLINE

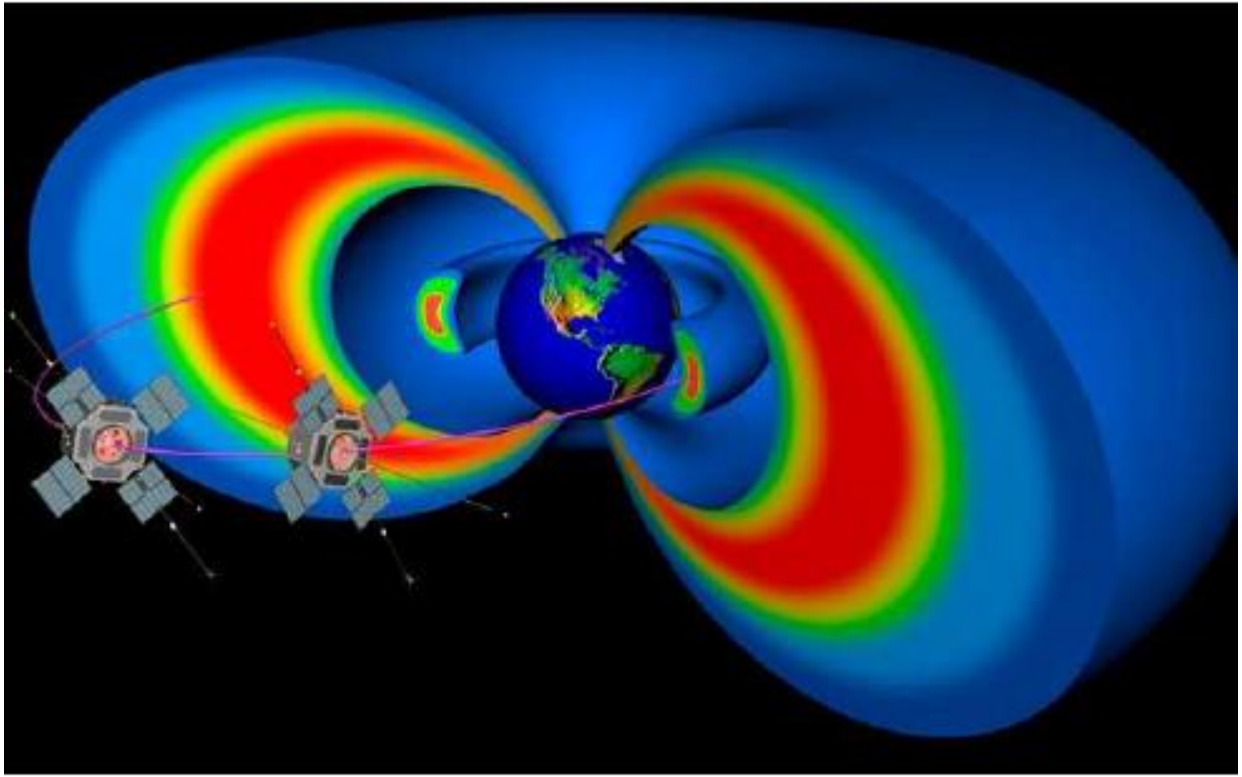
- Space radiation environment
- Radiation effects in space electronics
    - Total Ionizing Dose
    - Total Non Ionizing Dose (Displacement Damage)
    - Single Event Effects
- Conclusion

Sources of radiation environment in Space



1- Trapped Radiation Belts

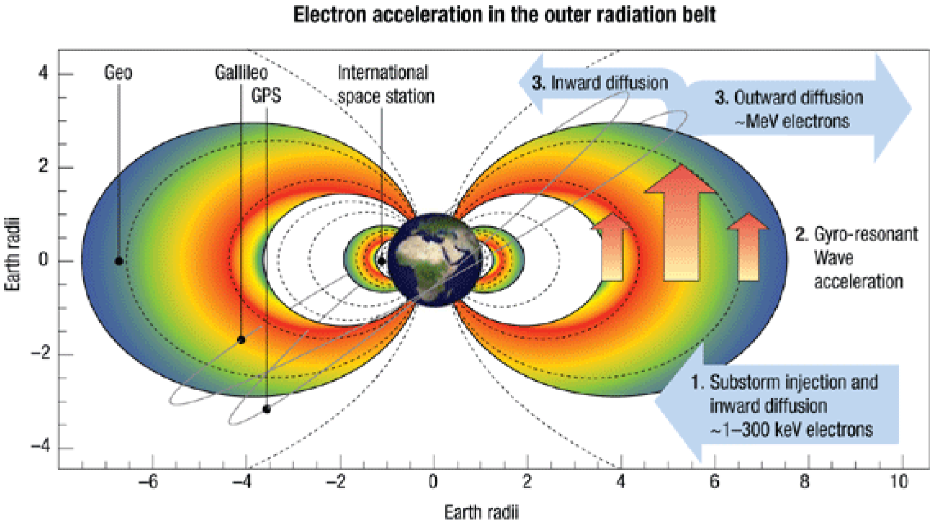
- Also known as Van-Allen belts
- They were discovered during the first space missions
- Electrons and protons trapped in Earth magnetic field (Lorentz force)



NASA, Radiation Belts Storm probe mission

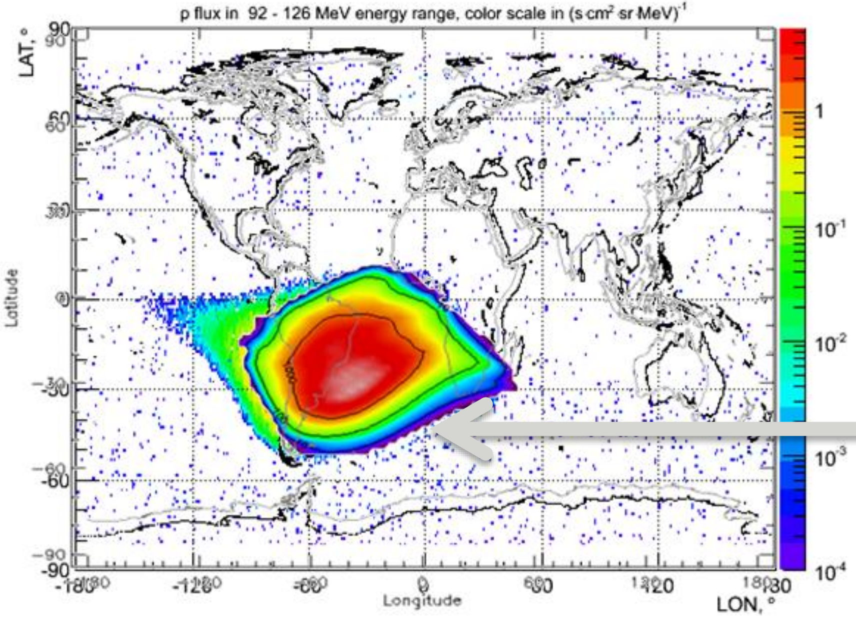
Trapped Radiation Belts, main characteristics

- Inner belt is dominated by a population of energetic **protons up to ~400 MeV energy range**
  - Inner edge is encountered as the South Atlantic Anomaly (SAA)
  - Dominates the Space Station and LEO spacecraft environments
- Outer Belt is dominated by a population of energetic **electrons up to 7 MeV energy range**
  - Frequent injections and dropouts associated with storms and solar material interacting with magnetosphere
  - Dominates the geostationary orbit environment (mostly telecom) and Navigation (Galileo, GPS) orbits, as well as certain Science missions in highly elliptic orbits (XMM-Newton, INTEGRAL)

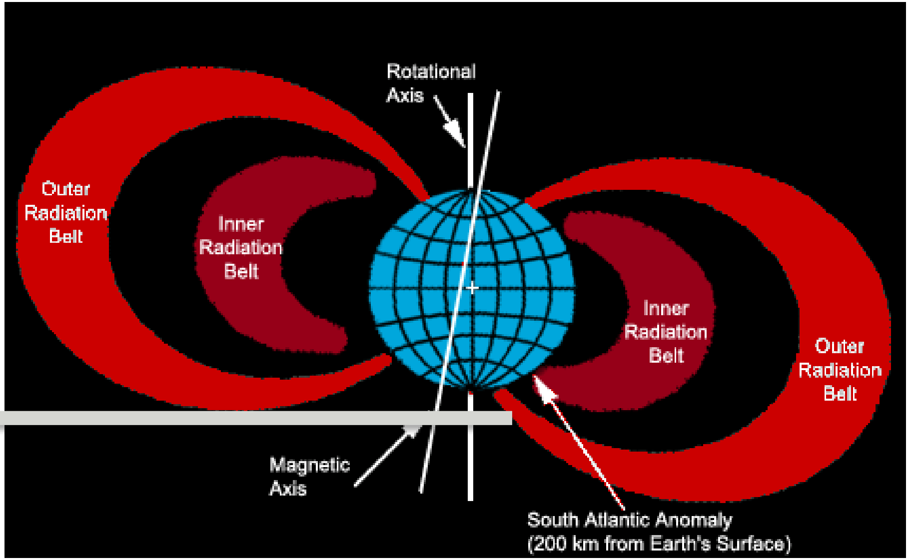


(Richard Bertram Horne Nature Physics 3, 2007)

The South Atlantic Anomaly



EPT flown on PROBA-V, 95 to 126 MeV proton channel

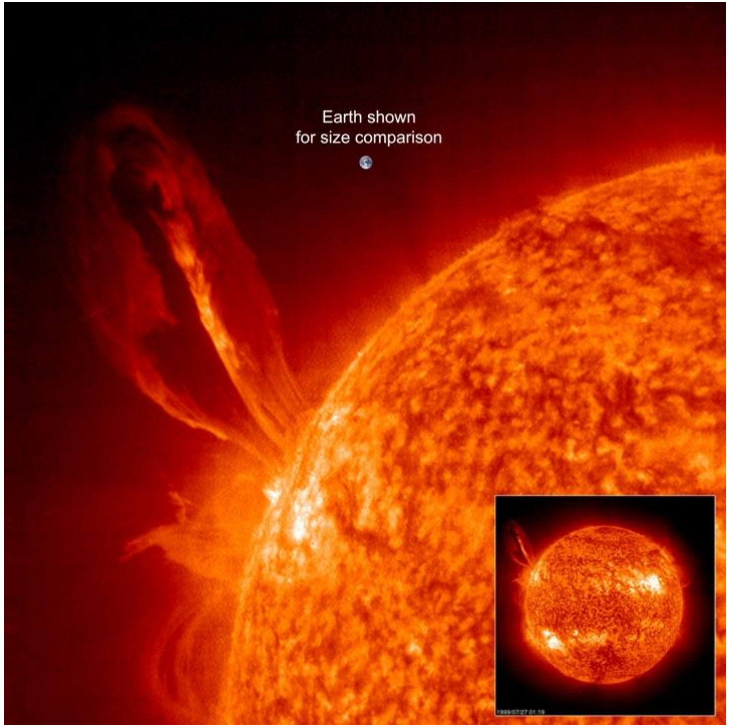


(Wikimedia Commons, the free media repository)

The South Atlantic Anomaly is observed as the magnetic axis is not aligned with the Earths rotational axis. The inner radiation belt thus is closer to earth above the South Atlantic as can be seen in the above images.

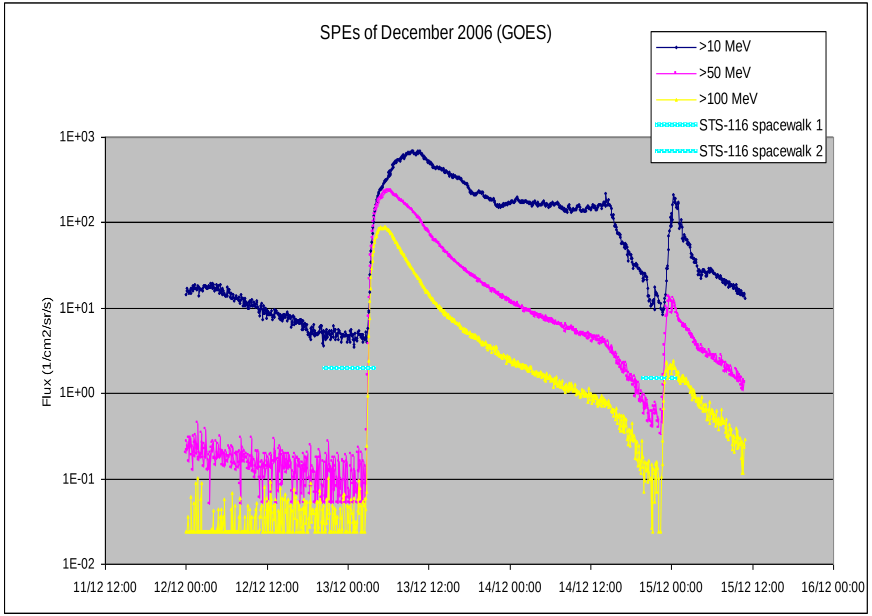
2 - Solar Event Particles

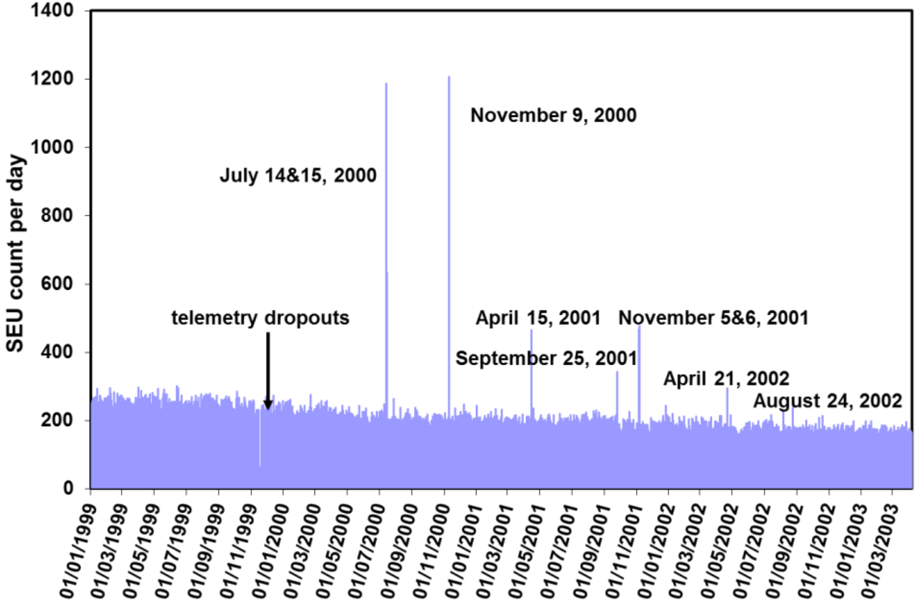
- SolarEvents (Solar Flares or Coronal Mass Ejection) represent emission of a broad spectrum of particles and very high energy release.
- The electrons, protons and heavier ions ejected reach Earth in a couple of days. Radiation fluxes can be high for several days during solar flares
- The energy spectra of ejected particles are highly variable
- Solar flare frequency depends on the Solar activity cycle approximately 11 years long
- Fluences high enough to cause damage => importance of proper shielding
- Essentially unpredictable, however efforts dedicated to address the problem in various Space Weather initiatives
- Solar particles are shielded by the Earth magnetic field, however, can reach lower orbits at the polar caps.



Large solar eruption captured by SOHO on the 27 July 1999. The eruption is larger that Earth.

Solar Particle Events – Examples





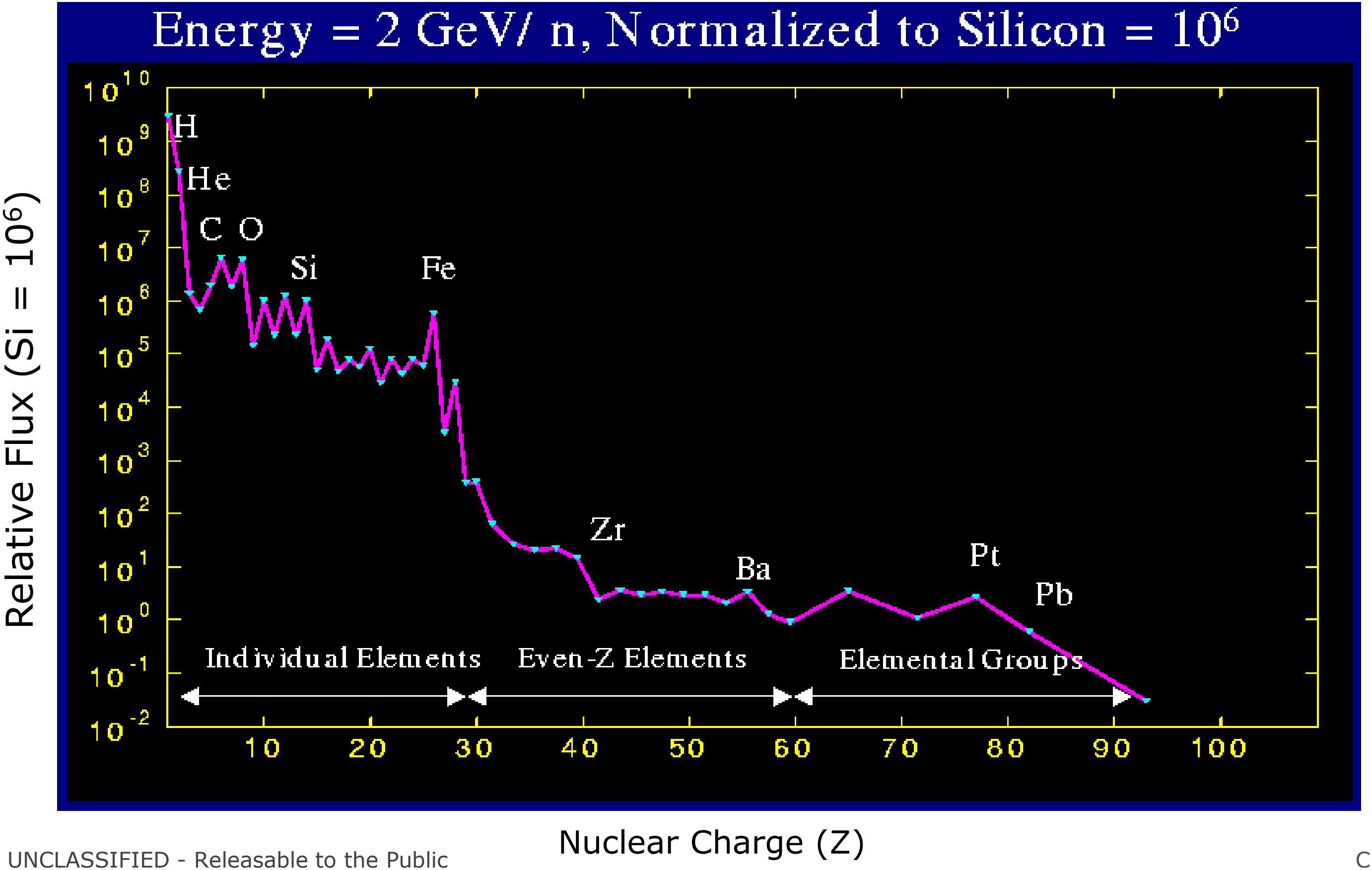
SEUs on SEASTAR SSR (Poivey 2003)

Single Event Effect rates increase significantly during a Solar event

3 – Galactic Cosmic Rays (GCRs)

- Discovered in 1912 by Austrian Victor Hess
- GCRs originate from outside our solar system, most probably from the Milky Way and are thought to be generated in supernovae (as suggested by Enrico Fermi in 1949).
- GCR are charged particles accelerated to near speed of light (can reach ~ **10^{20} eV** range (LHC ~ 10^{12} eV)
- Flux ~ **4 particles/cm^2/s** in space, anti-correlation with solar activity
- Geomagnetic field offers some shielding
- Atmosphere shields Earth’s surface from “primary” cosmic rays
- Collision in upper atmosphere produce “secondary” cosmic rays – some reach ground level (average person is crossed by ~ 100 relativistic muons per second)

3 – GCRs Composition



After J. Barth, 1997 NSREC short course

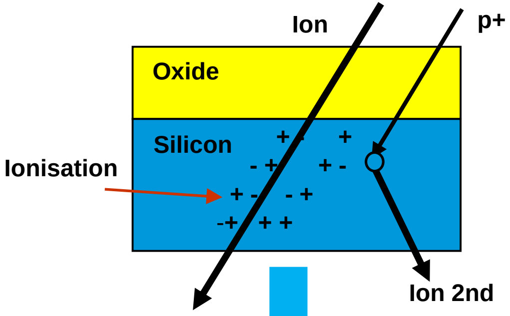
Interactions of Radiation with Electronic Devices

- The effects of radiation on electronic devices and materials depend on:
  - Type of radiation (photon, electron, proton,…)
  - Rate of interaction
  - Type of material (Silicon, GaAs)
  - Component characteristics (process, structure,…)

- Consequences
  - *Ionization*: **Total ionizing Dose (TID)** and **Single Event Effect (SEE)**
  - **Displacement Damage (DD or TNID)**

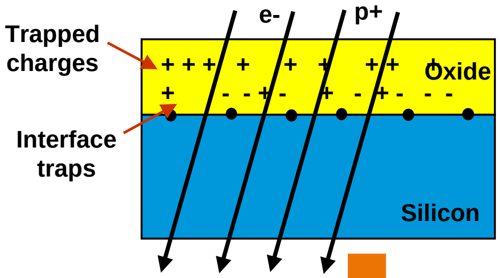
MAIN RADIATION EFFECTS

Single event effects

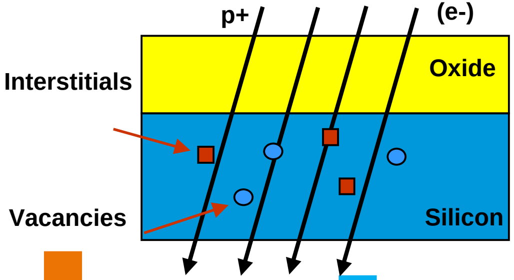


SET : transient
SEU : upset
SEL : latch-up
SEB : burn-out
SEGR : rupture

Ionising dose



Atomic displacement



Parametric drift
Function loss

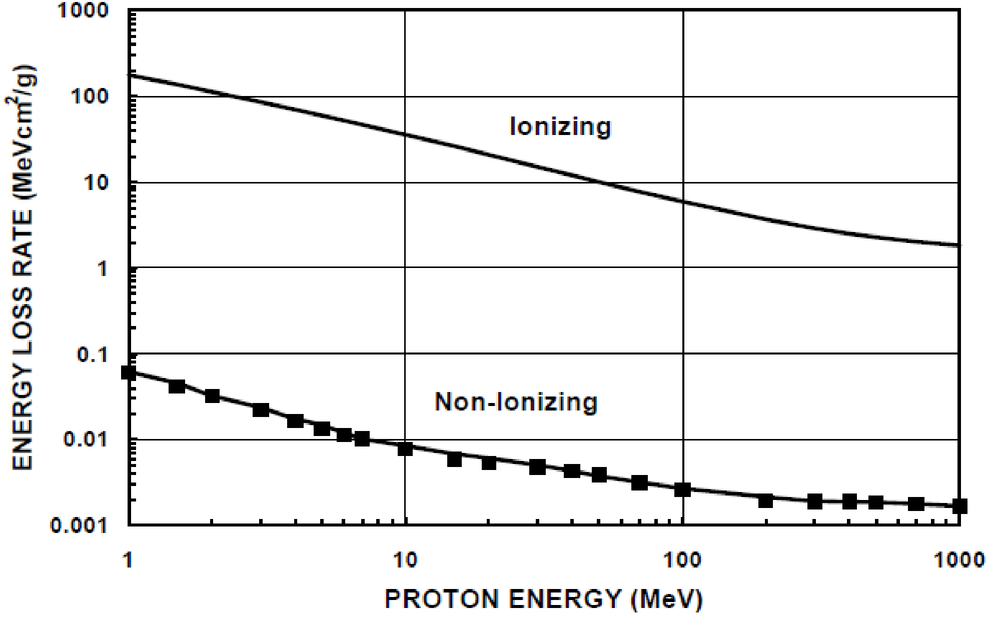
Lifetime

Hot pixels
RTS

Operating safety
Dependability/Availability
Performances

(S. Gerardin, RADECS2015 short course)

Ionizing and Non-Ionizing Energy Loss



LET: energy loss rate through ionization and excitation of the Si lattice

NIEL: energy loss rate through displacements, (about 0.1% of total energy)

(C. Marshall, Short-course notes, NSREC 1999)

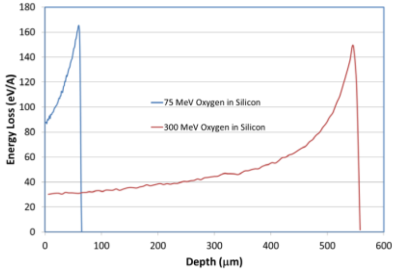
Ionizing Radiation Units

-Single Event Effects

- LET ($MeVcm^2/mg$) (direct ionization)

$$LET = \frac{1}{\rho}\frac{dE}{dx}\ MeV.cm^2/mg$$

(ρ=material density)



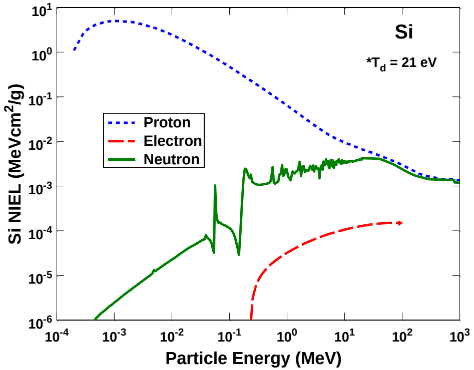
  - LET depends on particle type, energy and type of material
  - **LET is a mean parameter**
  - a LET of 92 $MeVcm^2/mg$ corresponds to a charge deposition of 1 pC/μm in Si
  - LET is not a single valued function, same ions with different energies can have the same LET, different ions with different energies can have same LET
- E (MeV) (indirect ionization)

-Total Ionizing Dose

- Radiation Absorbed Dose in Gray (Gy)
  - 1 Gy = absorbed energy in exposed material of 1J/Kg
  - the old unit rad is still commonly used in space community
    - 1 Gy = 100 rad

Non Ionizing (Displacement Damage) Radiation Units

- **NIEL** *(displacement kerma = **K**inetic **E**nergy **R**eleased to **MA**tter)*
  - In MeVcm²/mg or keVcm²/mg
  - Depends on target material, particle type and energy
  - **NIEL is a mean parameter**



- Non-Ionizing or Displacement Damage Dose **DDD**

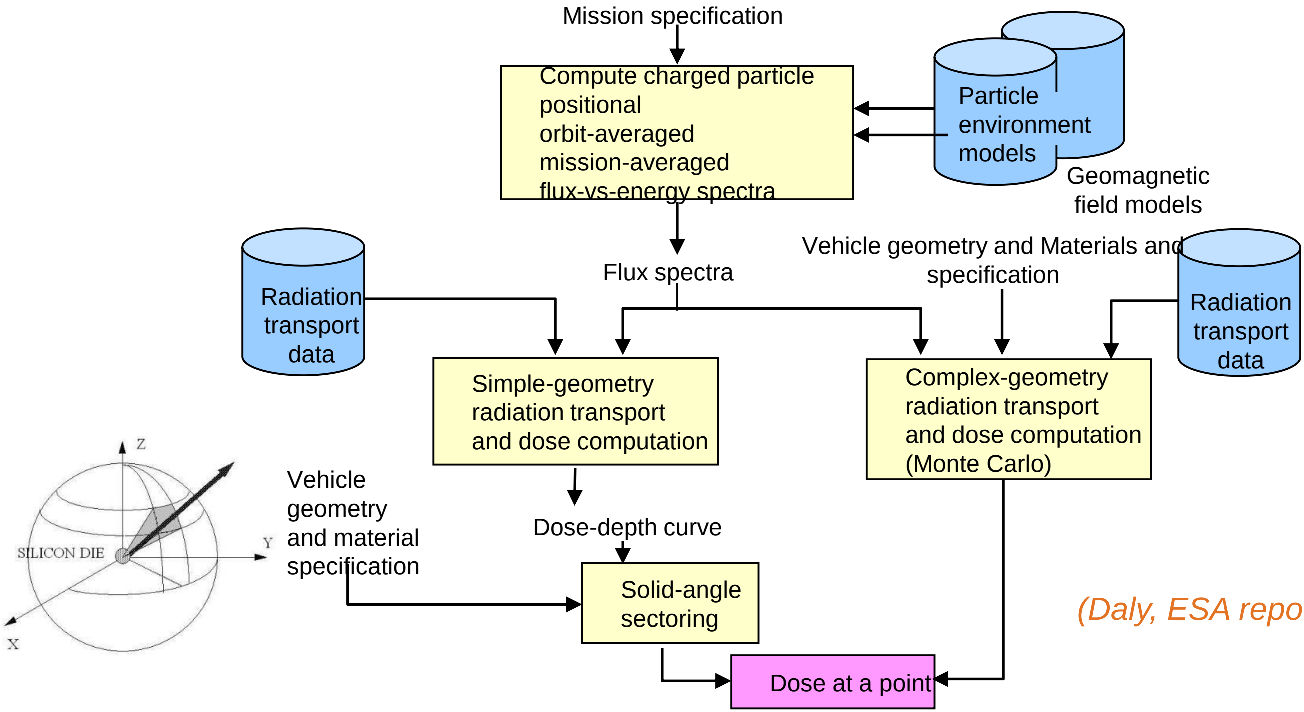
$$\mathrm{DDD} = \int_{E_{\min}}^{E_{\max}} \left(\frac{\partial \Phi}{\partial E}\right) \mathrm{NIEL}(\mathrm{E})\, dE \qquad (\text{keV/g or MeV/g})$$

- Displacement Damage Equivalent Fluence **DDEF** (mono-energetic beam)

$$F_{E0} = \int_{Emin}^{Emax} \left(\frac{\partial \phi}{\partial E}\right) \frac{NIEL(E)}{NIEL(E0)}\, dE$$

  - e.g. 10 MeV protons/cm² or 1 MeV neutrons/cm²

Computer Methods for Particle Transport



Mission specification

Compute charged particle positional orbit-averaged mission-averaged flux-vs-energy spectra

Particle environment models

Geomagnetic field models

Flux spectra

Vehicle geometry and Materials and specification

Radiation transport data

Simple-geometry radiation transport and dose computation

Radiation transport data

Complex-geometry radiation transport and dose computation (Monte Carlo)

Vehicle geometry and material specification

Dose-depth curve

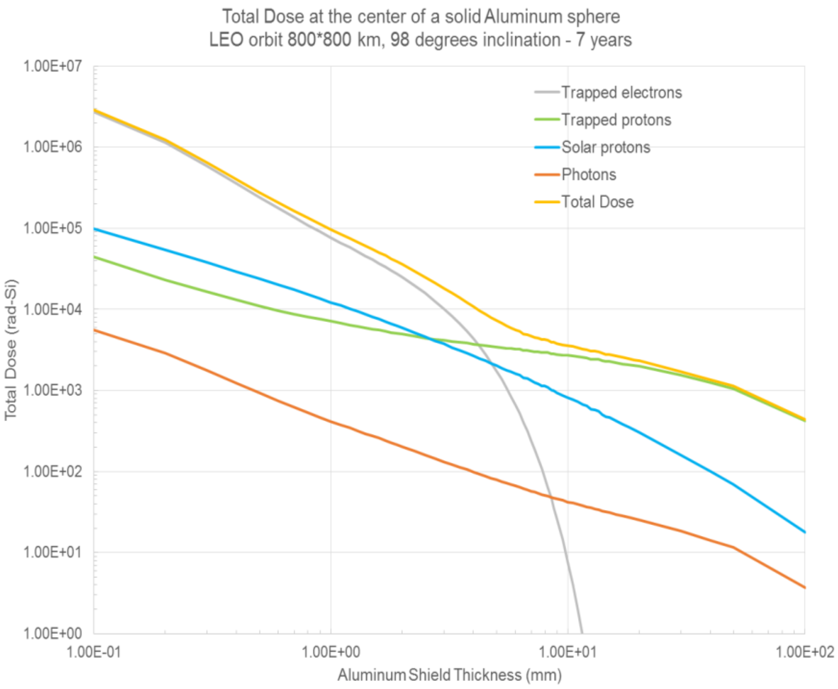
Solid-angle sectoring

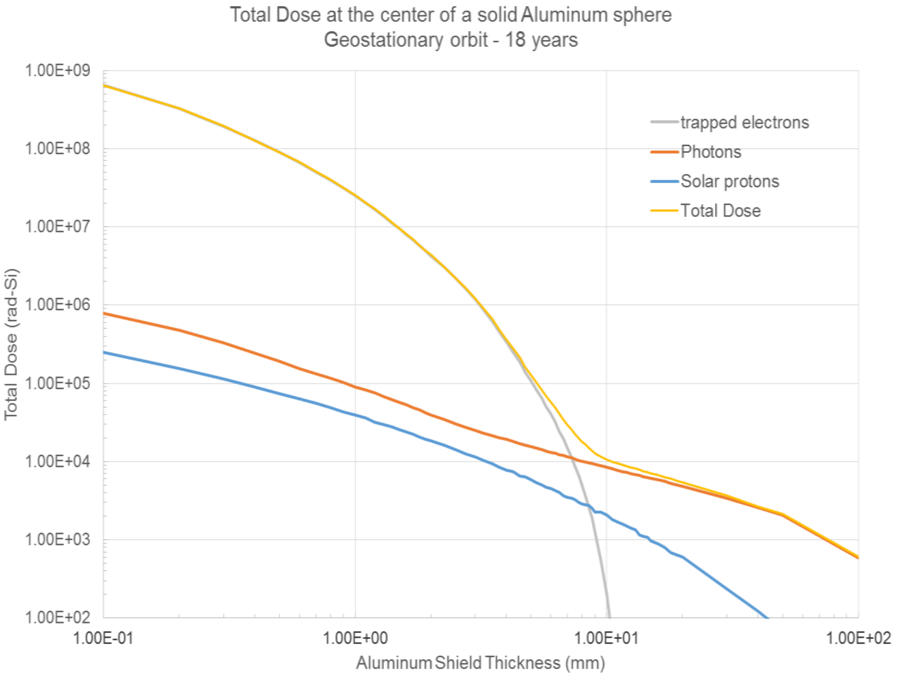
Dose at a point

Particle Environment models and simple geometry transport tools are available in **SPENVIS** (ESA supported webtool, *https://www.spenvis.oma.be*) or **OMERE** (CNES supported application, *http://www.trad.fr*)

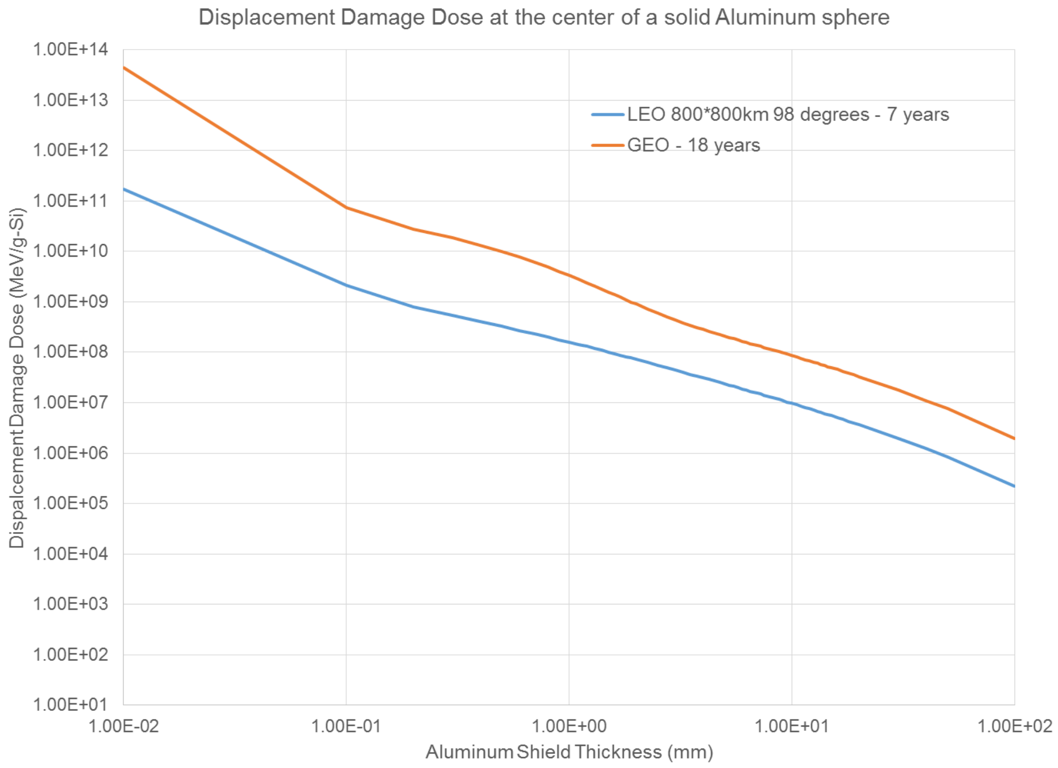
(Daly, ESA report 1989)

Dose versus depth curve - Examples

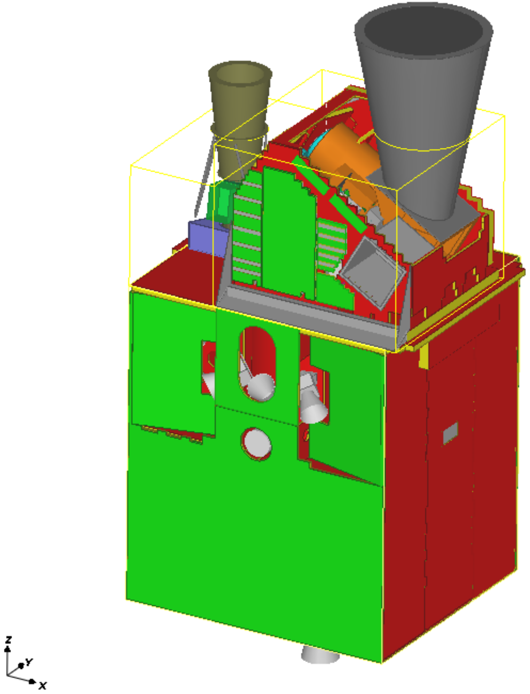

Total Dose at the center of a solid Aluminum sphere
LEO orbit 800*800 km, 98 degrees inclination - 7 years

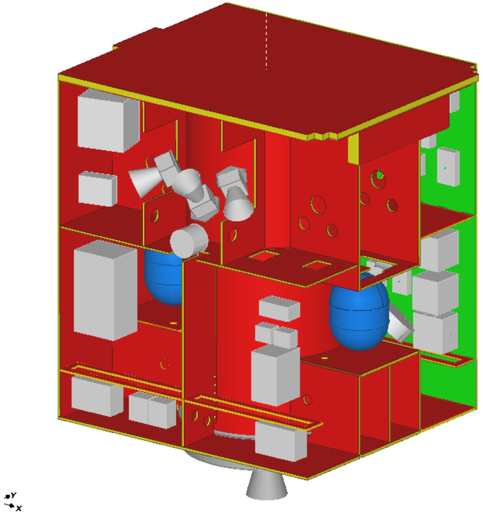

Total Dose at the center of a solid Aluminum sphere
Geostationary orbit - 18 years

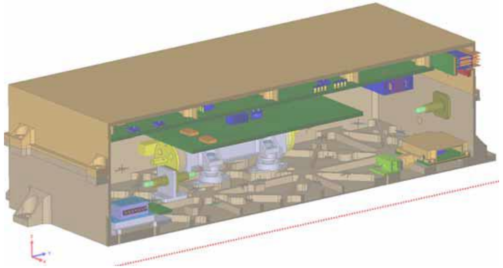
DD equivalent Fluence versus Depth Curve - Example

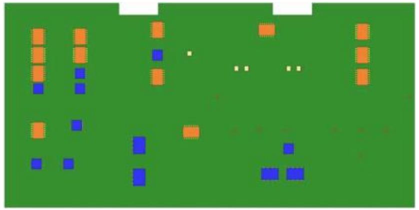


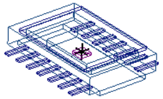
TID/TNID requirements at part Level



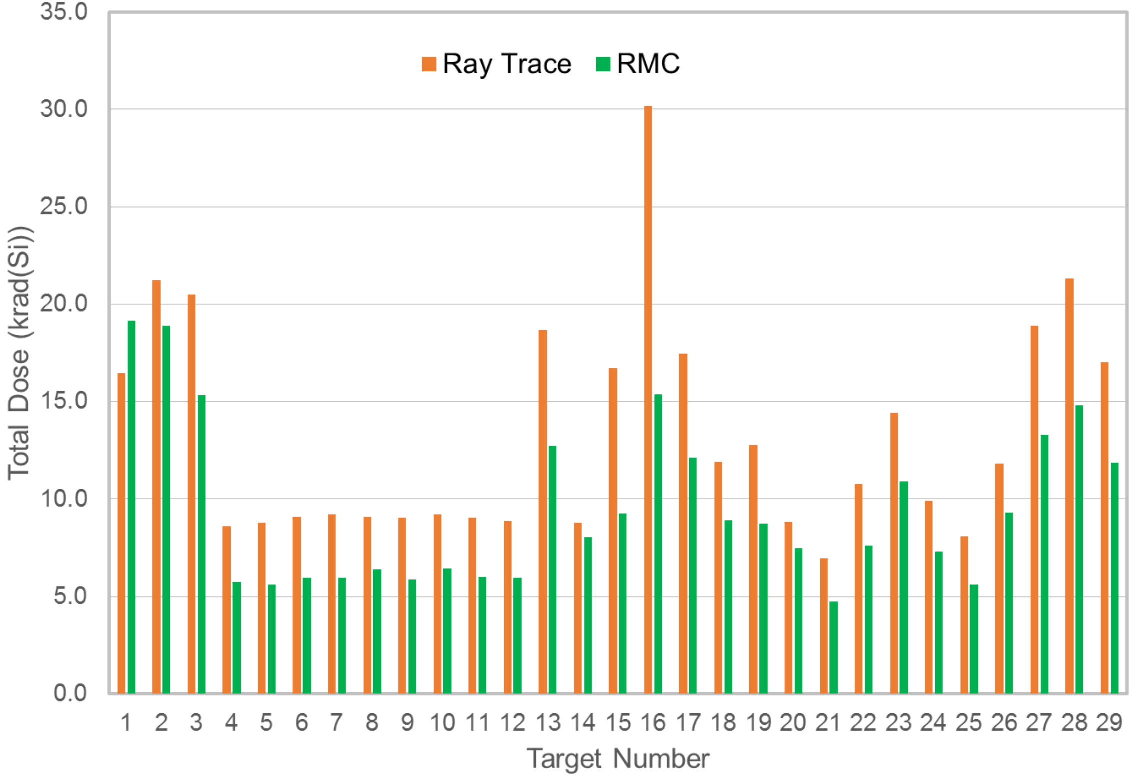








TID requirements at part level, Ray Trace versus Monte Carlo Analysis – GEO orbit 18 years

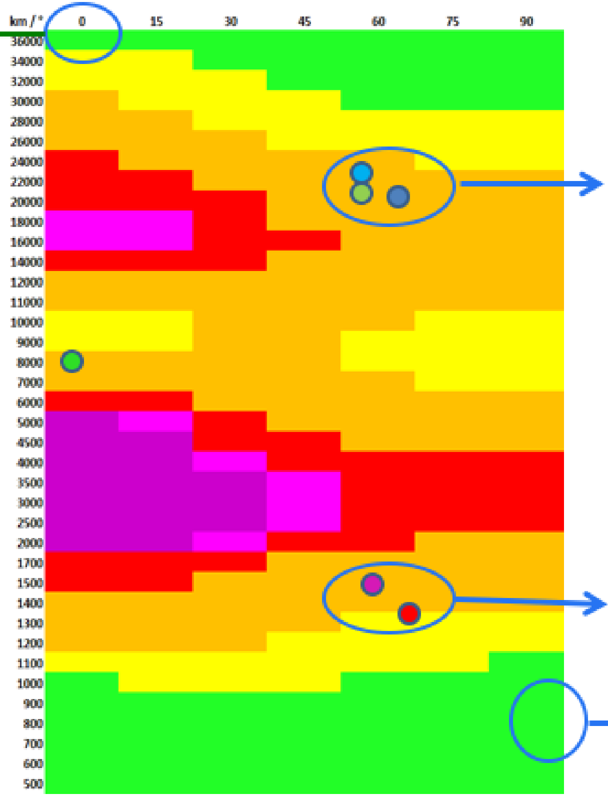


Ray Trace analysis overestimate dose levels for electron dominated orbit

(After A. Varotsou, GTTREF study)

Examples of Missions TID Levels

GEO



AE8 Max / AP8 Min - Circular Orbits

After Ecoffet & Gerardin, RADECS 2015

Outer electron belt

🟩 < 1 krad / year
🟨 1-3 krad / year
🟧 3-10 krad / year
🟥 10-20 krad / year
🟪 20-30 krad / year
🟪 > 30 krad / year

Proton belt and inner electron belt

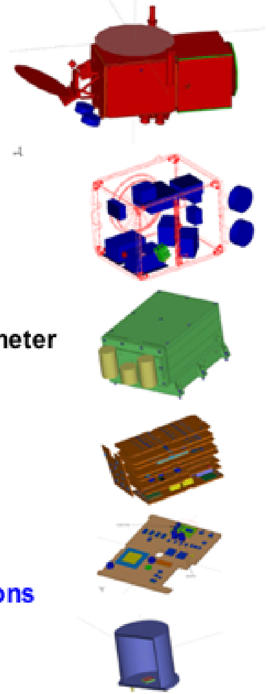
● GALILEO
● GPS
● GLONASS
● O3B
● GLOBALSTAR
● JASON

MEO Navigation

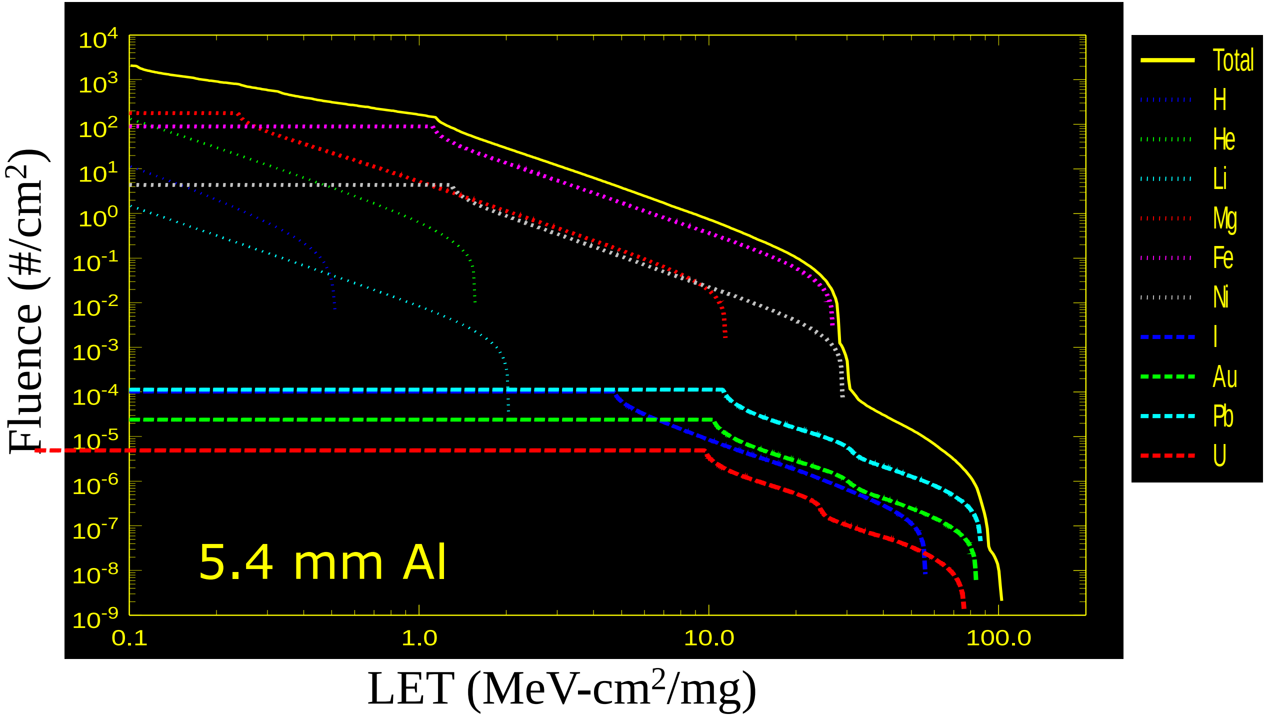
PMOS dosimeter CARMEN-2 JASON-2

LEO Constellations

LEO Observation Constellations

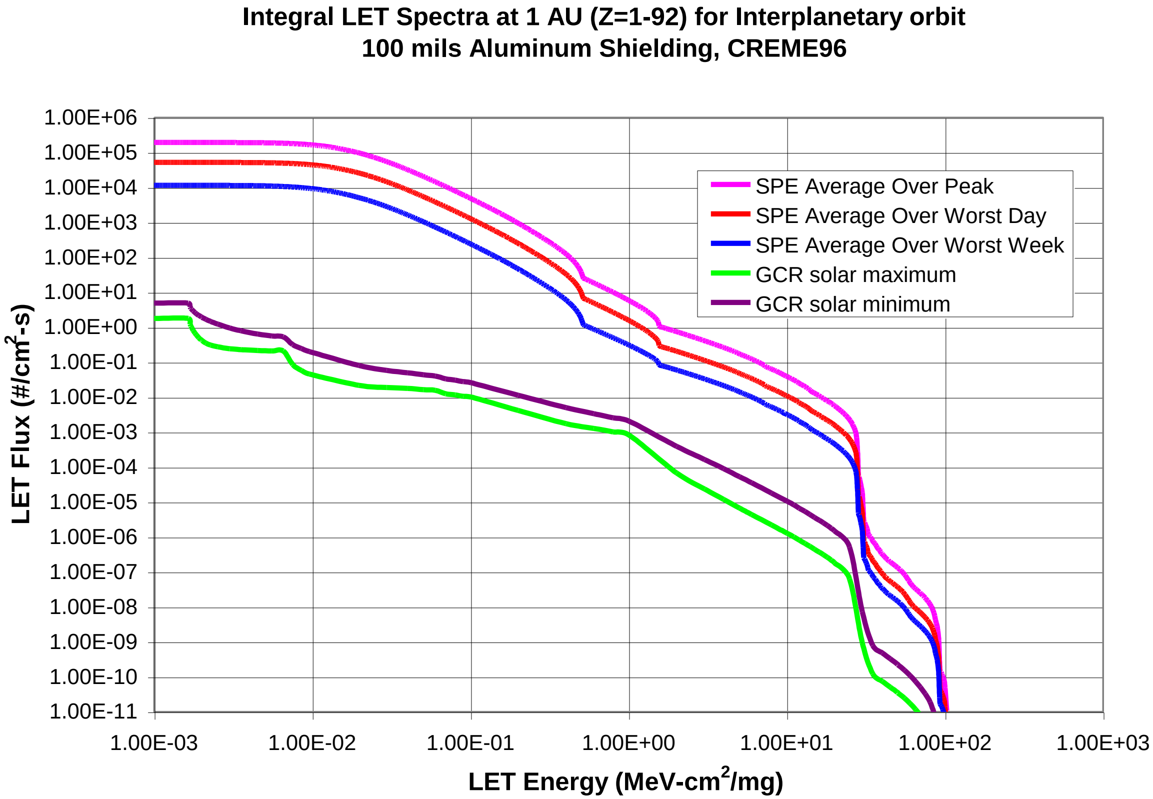


SEE – GCRs Space Environment vs. LET



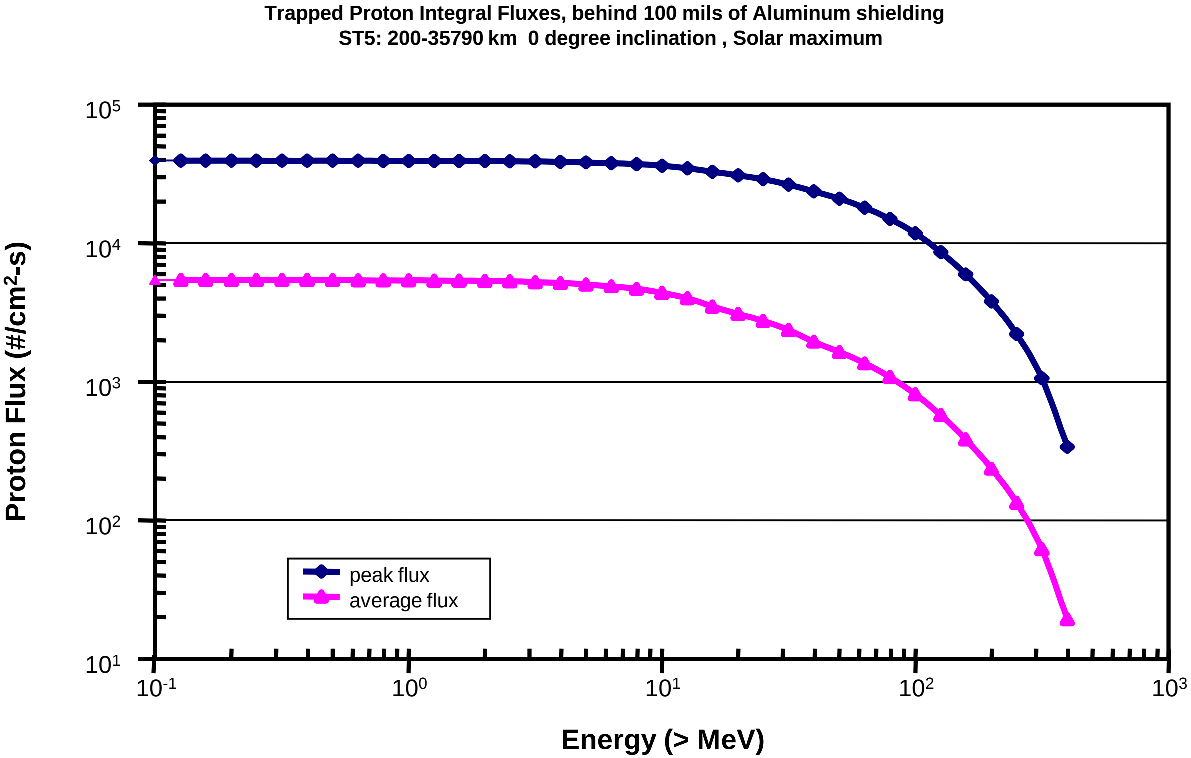
(J. Barth, 1997 NSREC Short course)

Ion SEE environment, GCRs and Solar Particles



- Ion SEE environment is generally calculated for a conservative value of shielding (ie. 1g/cm^{2}of Al)
- GCRs models and simple geometry transport codes are available in **SPENVIS** and **OMERE** as well as in **CREME** webtool (*https://creme.isde.vanderbilt.edu*)
- These tools also allow the calculation of SEE rate for a given mission

Proton SEE Environment – Trapped Protons and Solar Protons

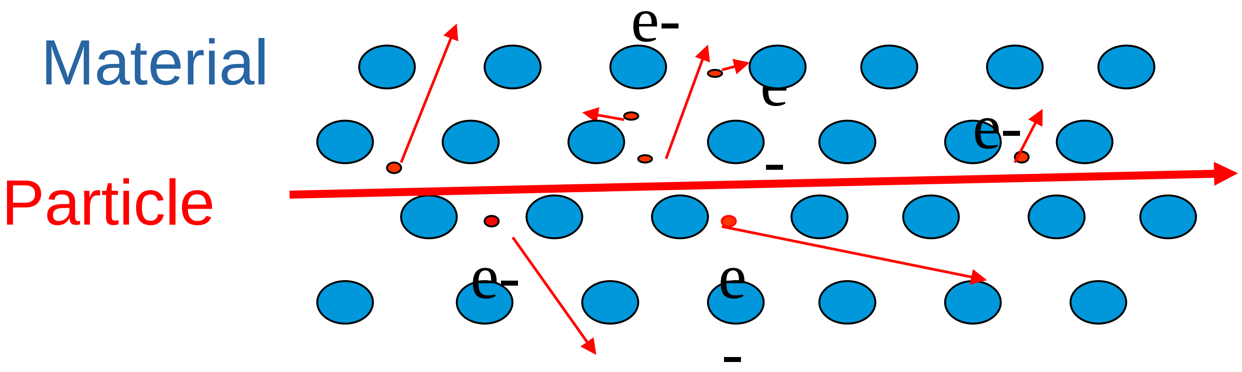


- Proton SEE environment is generally calculated for a conservative value of shielding (ie. 1g/cm^{2}of Al)
- For trapped protons, orbit average and maximum/peak fluxes are defined

OUTLINE

- Space radiation environment
- Radiation effects in space electronics
  - Total Ionizing Dose
  - Total Non Ionizing Dose (Displacement Damage)
  - Single Event Effects
- Conclusion

Ionization



Energy required to create one electron-hole pair:

- in Si: 3.6 eV
- in SiO_2: ~17 eV

- As a charged particle (electron, proton, ion) traverses a solid, its charge presents an electrostatic force to the orbital electrons of surrounding material. Excited electrons are freed from their bound state and create **electron-hole pairs** (Coulombic scattering).

- Some of the liberated electrons have sufficient energy (delta-rays)to generate themselves supplementary electron-hole pairs.

TID Effects

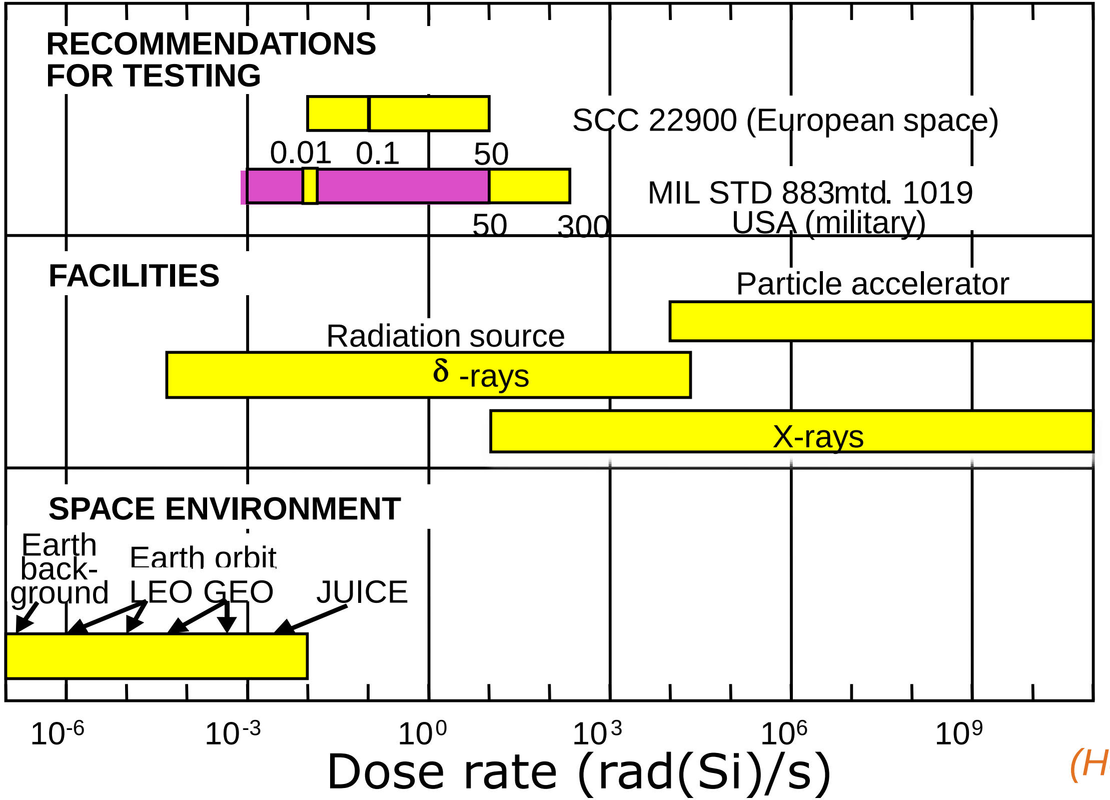
- Total Ionising Dose is mainly a semiconductor oxide effect (SiO_2, NO,HfO_2,..).
- Electron Hole pairs are mobile in the semiconductor oxide and may recombine (recombined electron hole pairs do not cause any damage).
  - Recombination rate depends on **electric field** applied to the oxide, and **type and energy of incident particle**
- In a device that is biased electron are swept out of the oxide and hole remain leading to trapped charges in the oxide or interface traps at the oxide-Silicon interface
- Component degradation is very much dependent on a device technology, process and bias conditions

Summary: Technologies susceptible to TID effects

Technology Category	Sub Category	Effects
MOS	NMOS PMOS CMOS CMOS/SOS/SOI	Threshold voltage shift Decreased in drive current Decrease in switching speed Increased leakage current
BJT		H_{fe} degradation
JFET		Enhanced source drain leakage current
Analog microelectronics		Change in offset voltage and offset current Change in bias current Gain degradation
Digital microelectronics		Enhanced leakage Logic failure
CCDs		Increased dark current Effects on MOS transistor elements
CIS		Same as CCD and change in pixel amplifier gain
Quartz resonant crystal		Frequency shifts

(ECSS-E-10-12)

TID, Bounding Part Response

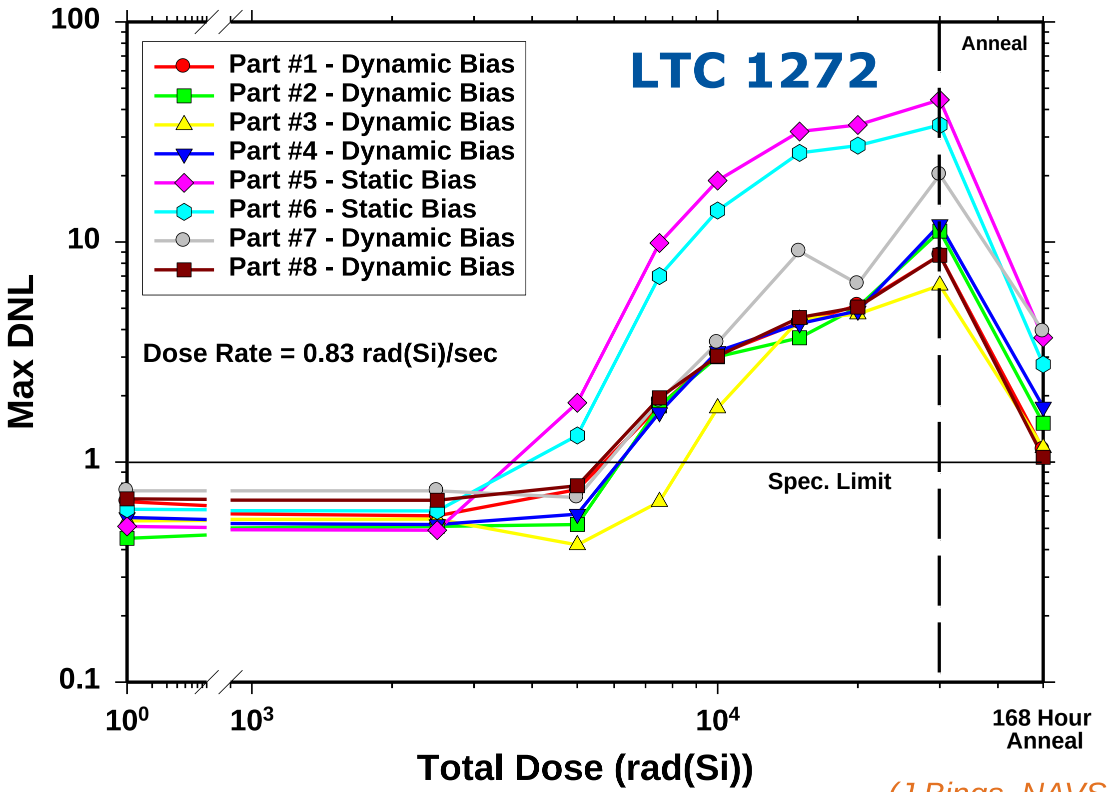


- Laboratory dose rates are significantly higher than the actual space dose rates.
  - ➢ Testing according to test standards gives conservative estimates of CMOS devices TID sensitivity
  - ➢ Testing bipolar ICs at a dose rate of 10 mrad/s, gives in most cases an acceptable bound of actual radiation test response in space

- Co-60 gives a conservative estimate of TID degradation compared to electrons or protons

(Holmes-Siedle & Adams)

TID Characterization - Example

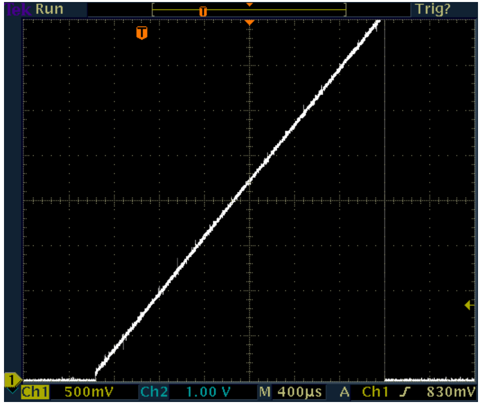


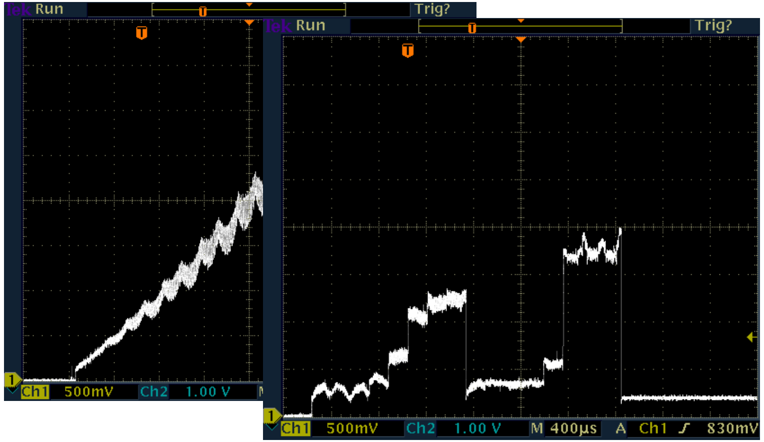
(J Bings, NAVSEA/CRANE test report, 2001)

- Worst case bias data is used for analysis of degradation
- annealing is not considered

TID Sensitive Part – Example DAC8800

- Total Unadjusted error (TUE): +/- ½ LSB
  - Out of spec limit after 2 krad-Si
  - TUE > 100 LSB after 5 krad-Si





OUTLINE

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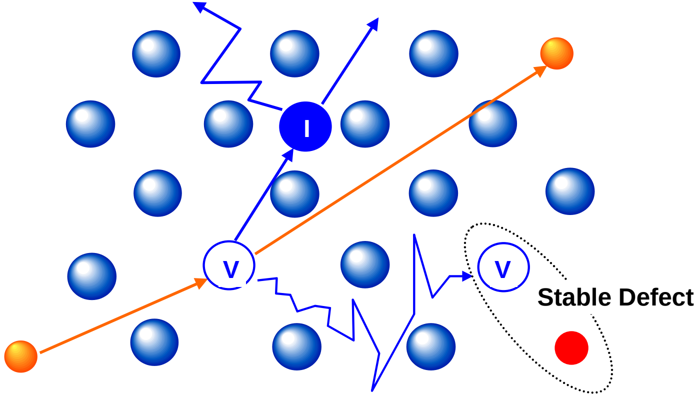
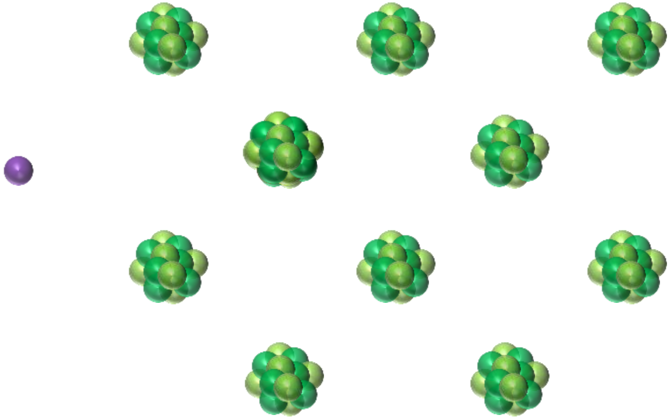
Displacement Damage - Mechanisms



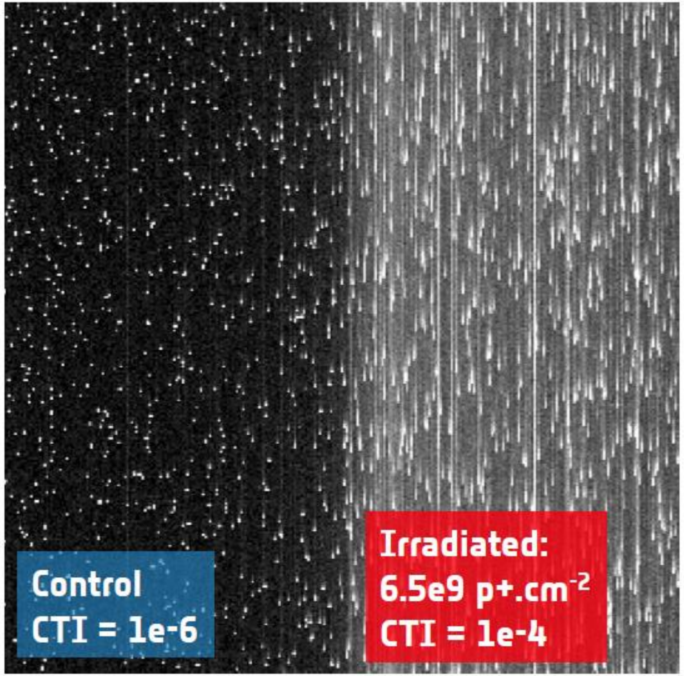


- If particle has sufficient energy it may displace a Si atom (21 eV is required to displace a Si atom from its lattice position), called Primary Knock on Atom (PKA).
- Vacancies and interstitials migrate, either recombine (~90%) or migrate and form stable defects (Frenkel pair).

Displacement Damage Device Effects Example – CCDs

- Dark image after irradiation with protons
  - Increase of dark current (overall)
  - Hot pixels
  - CTE degradation

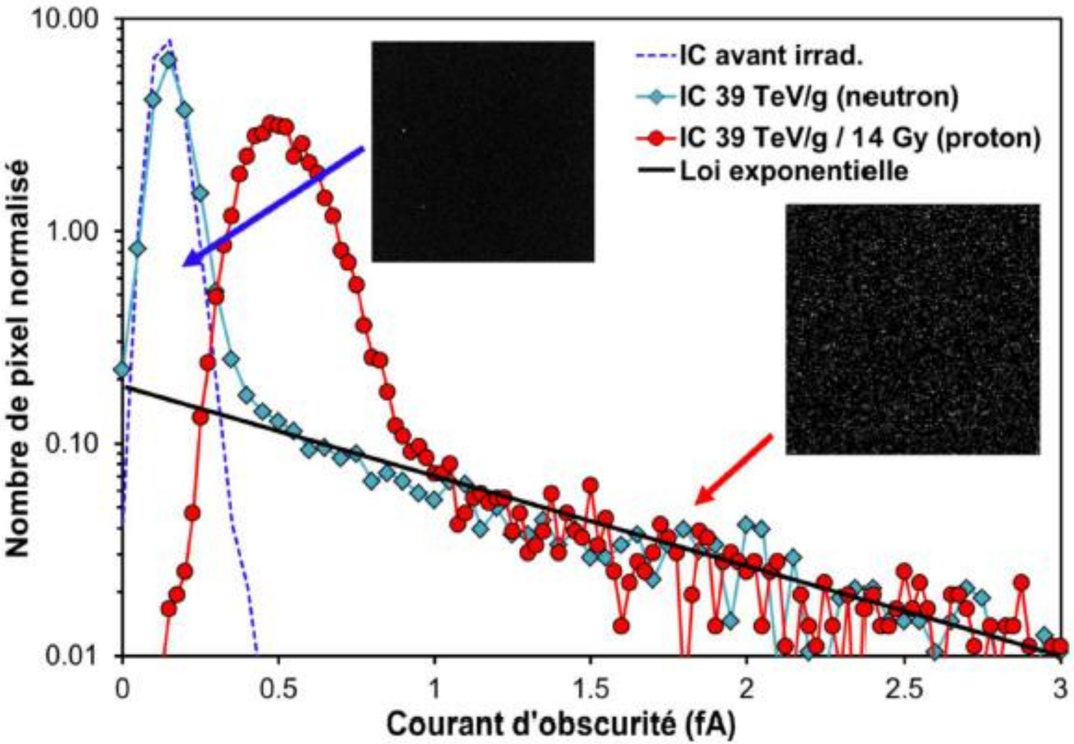
Sensor degradation is a significant constraint for payloads and star trackers



PLATO E2V CCD270, Image acquired while Illuminated by Fe55 X-ray source

(Prod'homme ESWW2016)

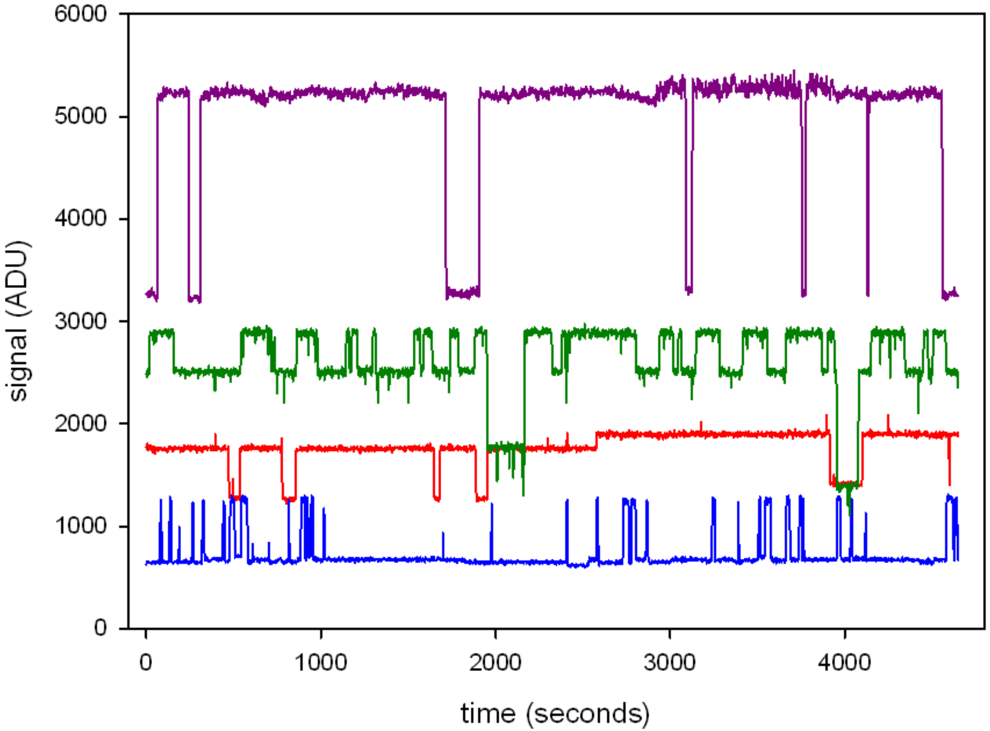
Displacement Damage Effect – Hot Pixels



- Number of hot pixels is reduced at low temperature
- Hot pixels can be eliminated by software treatment of images.

Dark Current histogram of a CIS irradiated with protons and neutrons (Virmontois 2012)

Device Effects – Random Telegraph Signal



Sample of 4 CCD pixels showingRandom Telegraph Signal (RTS) behaviour at 23°C

- Similar RTS behavior is seen in CMOS Image Sensors
- RTS disappears at low temperature

Displacement Damage Effect - Summary

Technology category	Sub-category	Effects
General bipolar	BJT	hFE degradation in BJTs, particularly for low-current conditions (PNP devices more sensitive to DD than NPN)
	Diodes	Increased leakage current increased forward voltage drop
Electro-optic sensors	CCDs	CTE degradation, Increased dark current, Increased hot spots, Increased bright columns Random telegraph signals
	CIS	Increased dark current, Increased hot spots, Random telegraph signals Reduced responsivity
	Photo diodes	Reduced photocurrents Increased dark currents
	Photo transistors	hFE degradation?? Reduced responsivity?? Increased dark currents??
Light-emitting diodes	LEDs (general)	Reduced light power output
	Laser diodes	Reduced light power output Increased threshold current
Opto-couplers		Reduced current transfer ratio
Solar cells	Silicon GaAs, InP etc	Reduced short-circuit current Reduced open-circuit voltage Reduced maximum power

Displacement Damage, Bounding Part Response

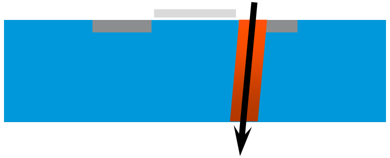
- **TNID test standards**
    - **ESCC 22500 (under review to be issued this year)**
- **Particle type**: protons generally one energy (most often in 40-60 MeV range)
- **Test fluence:** defined based on NIEL
- **Test flux**: generally in the range of 10^7 to 10^8 p/cm^2/s (4 to 7 orders of magnitude higher than space dose rate)
- **Bias conditions**: unbiased generally
- **Irradiation temperature**: generally room temperature
- In most case (especially for imagers) measurements are not possible in radiation facility and parts are measured several weeks after irradiation (activation issue)
- **Measurement temperature**: room temperature and application temperature for imagers

OUTLINE

- Space radiation environment
- Radiation effects in space electronics
  - Total Ionizing Dose
  - Total Non Ionizing Dose (Displacement Damage)
  - Single Event Effects
- Conclusion

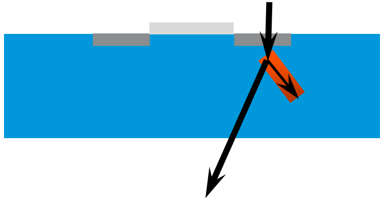
SEE Formation is a Three Steps process

- 1/ Charge generation
  - Direct ionization via Coulomb scattering (electron hole generation) to produce delta rays



Each ion produces an ionizing track

  - Indirect ionization via nuclear elastic or inelastic scattering



A few protons (~10^{-5}) cause nuclear reactions
Short range recoils produce ionization

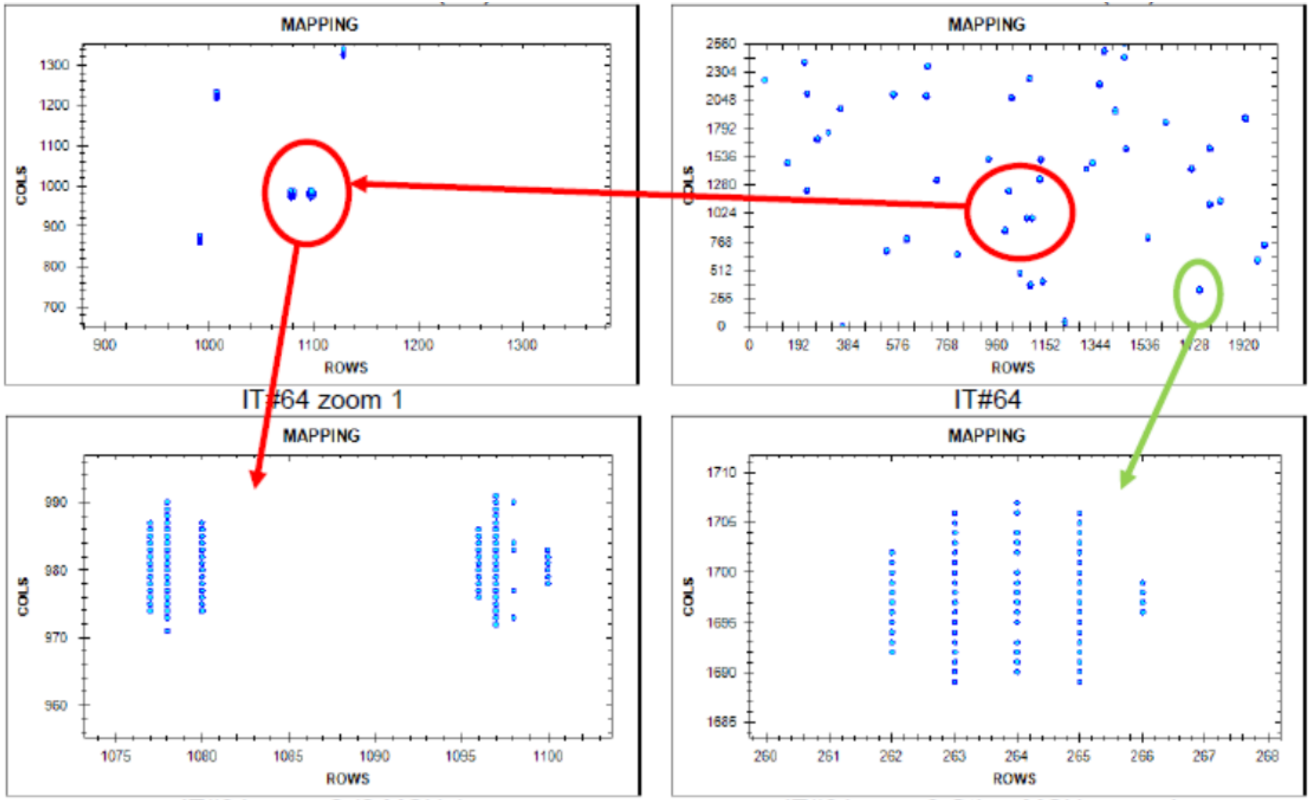
- 2/ Charge Collection and Recombination
- 3/ Circuit Response

Single Event Effects – Summary (non exhaustive)

Type of SEE	Effect	Type of devices sensitive
Single Event Transient (SET)*	Impulse response of a certain amplitude and duration	all
Single Event Upset (SEU)	Corruption of the information stored in a memory element	Memories, latches in logic devices
Multiple Cell Upset (MCU)	Several memory elements corrupted by a single ion or proton strike	Memories, latches in logic devices
Single Event functional Interrupt (SEFI)	Corruption of a data path leading to loss of normal operation	Complex devices with built-in state machine/control sections
Stuck bit / Intermittent Stuck bits (ISB)	Permanent or semi-permanent corruption of the information stored in a memory element	DRAM, SDRAM, DDR, DDR2, DDR3, DDR4
Single Event Latchup (SEL)	High current condition	CMOS, BiCMOS devices
Single Event Burnout (SEB)	Destructive burnout due to high current conditions	N channel power MOSFET, diodes
Single Event Gate/Dielectric Rupture (SEGR/SEDR)	Rupture of a (gate) dielectric due to high electrical field conditions	Power MOSFETs, Non volatile memories, linear devices,….

* Fundamental to all non-destructive SEEs

Multiple Cell Upsets (MCU)



IT#64 zoom 1

IT#64

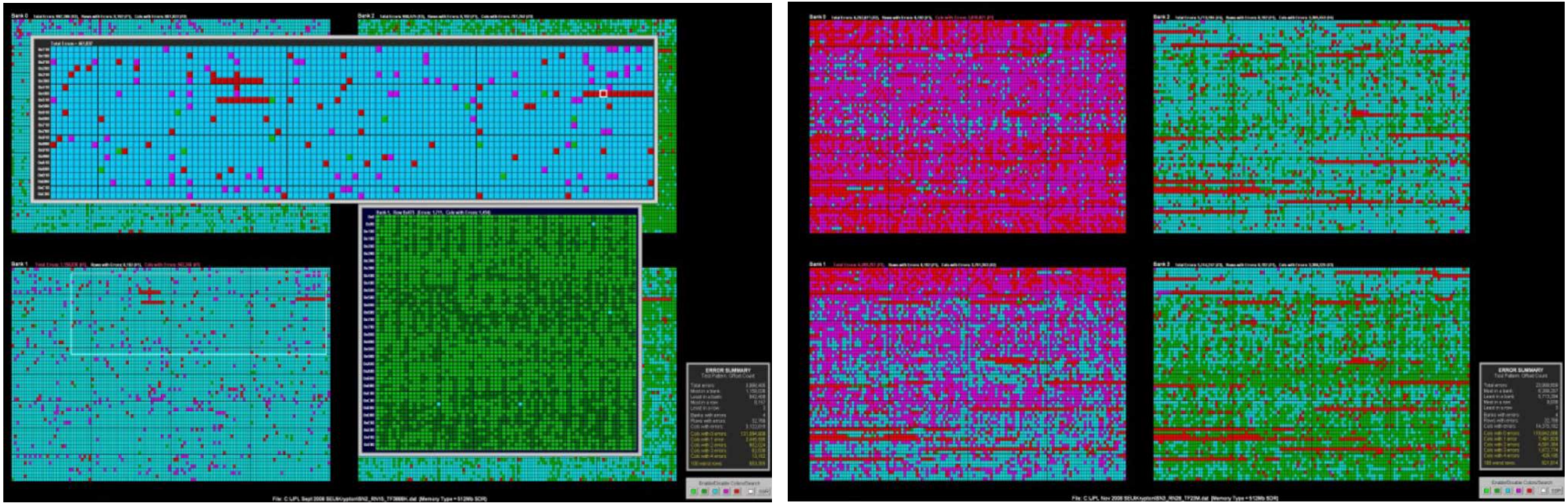
IT#64 zoom 2 (2 MCUs)

IT#64 zoom3 Other MCU example

- One ion strike can induce more than 100 cell SEUs

40 nm SRAM, (ESA study 18799/04/NL/AG)

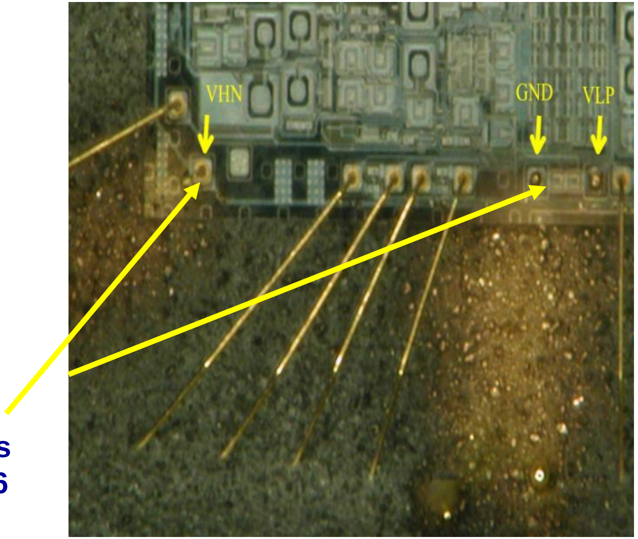
SEFI in SDRAM



Mapping of errors for different cases (typical on left, extreme on right), isolated green dots represent single errors, clusters consisting of 2 or more adjacent green dots are shown in red and indicate SEFI (Adell, 2011)

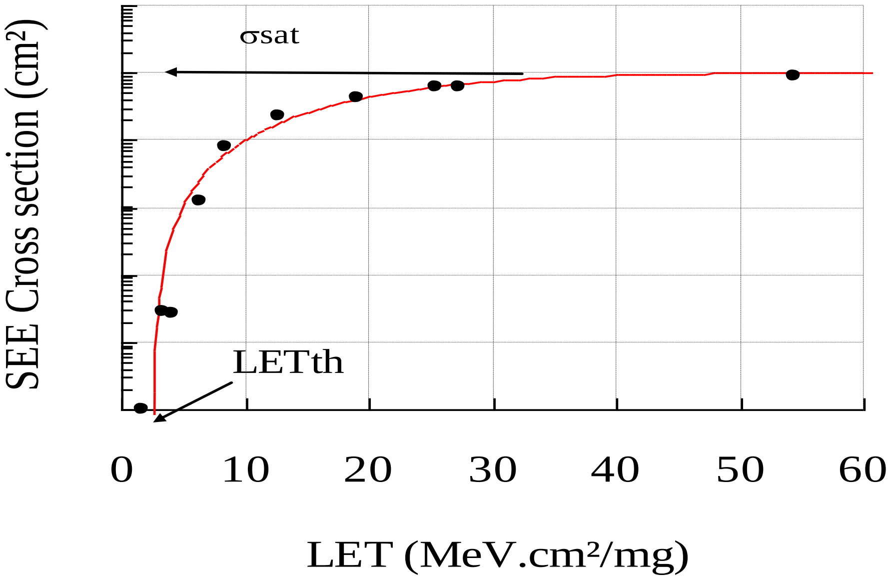
Destructive SEE Mitigation

- Recommendation 1: Do not use devices that exhibit destructive conditions in your environment and application
- Difficulties:
  - May require redundant components/systems
  - Conditions such as low current latchup (SEL) may be difficult to detect
- MANY DESTRUCTIVE CONDITIONS MAY NOT BE MITIGATED
- Mitigation methods
  - Current limiting
  - Current limiting w/autonomous reset
  - Periodic power cycles
  - Device functionality check
- Latent damage is also a grave issue
  - ➢ *"Non-destructive" events may be false!*



Vaporized wirebonds in an Agere LSP2916 MEMS Driver from an SEL

SEE, Bounding Part Response - SEE Cross Section vs. LET



$$[\mathrm{cm}^2] \longrightarrow \sigma = \frac{N_{events}}{Fluence} \longleftarrow [N_{particules}/\mathrm{cm}^2]$$

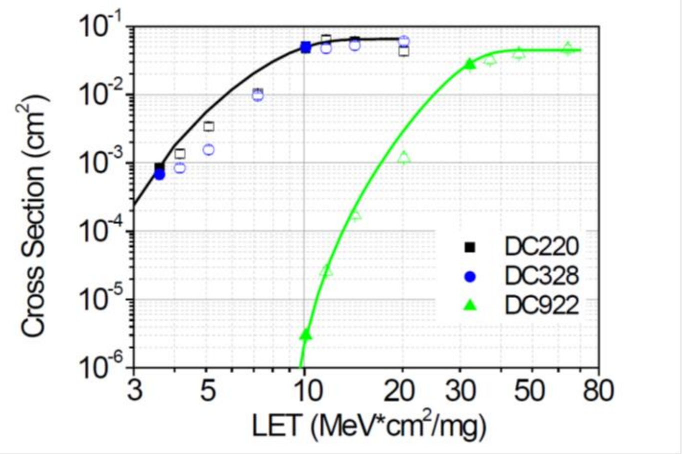
$$\sigma = \sigma_{sat}\left(1 - \exp\left(\frac{LET - LET_{th}}{W}\right)^{S}\right)$$

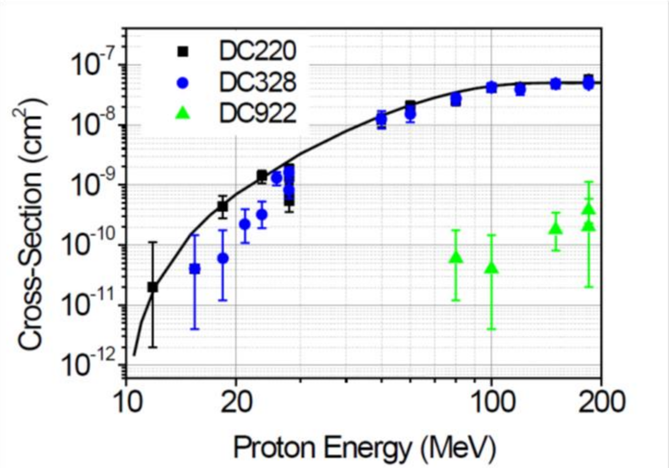
W and S are fitting parameters

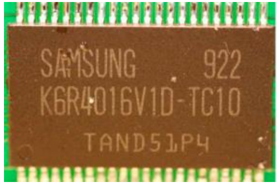
- SEE Test standards
  - ➢ESCC25100
  - ➢MIL-STD-883 method 1080 (SEB/SEGR)

SEE cross-section is a crucial input for in-orbit SEE rate estimation

COTS variability, Example
Samsung 4M SRAM K6R4016V1D



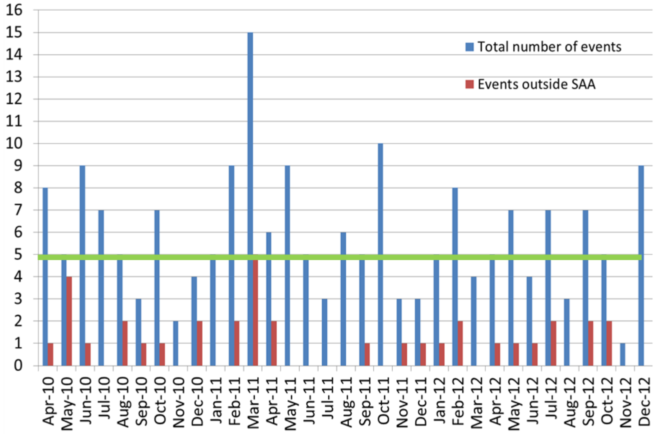


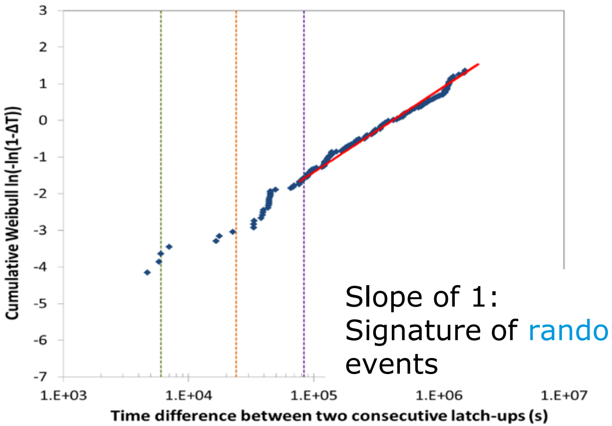


DC220 or DC328: ~ 1 SEL every 3 days on LEO polar orbit

SEEs are Random Events

- Rate of occurrence is not steady, it varies randomly





Slope of 1:
Signature of random events

PROBA-2 SEL experiment, ISSI IS615128 SRAM

(After d'Alessio, RADECS 2013)

A SEE with a low probability of occurrence can occur the first day of a mission

- MBU rate in AT65609 ATMEL SRAM: 1 event every 40 years on GEO, one MBU occurred after less than one month of flight
- SEB (destructive) on UCC1802 PWM: 1 event every 300 years for the mission. 1 failure occurred after ~1 year of flight

OUTLINE

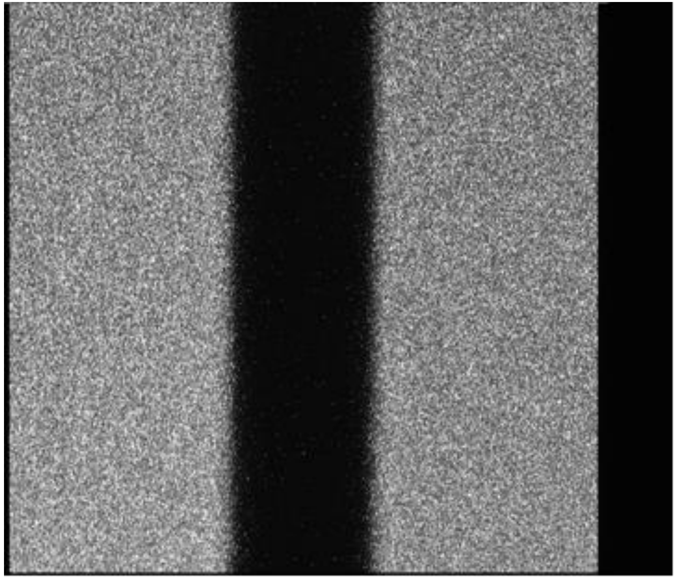
- Space radiation environment
- Radiation effects in space electronics
  - Total Ionizing Dose
  - Total Non Ionizing Dose (Displacement Damage)
  - Single Event Effects
- Conclusion

Conclusion

- Radiation effects on electronics in space have a direct impact on the reliability and availability of a system and, therefore, on the success of a mission.
- Radiation Hardness Assurance (RHA) process shall be implemented to ensure that the electronics and materials of a space system perform to their design specifications after exposure to the space environment.
- The RHA approach on space systems is based on risk management and not on risk avoidance. It requires radiation effect mitigation and tolerant designs.
- RHA and radiation engineering require a considerable effort throughout the development of a space system from the early phases of a program development.

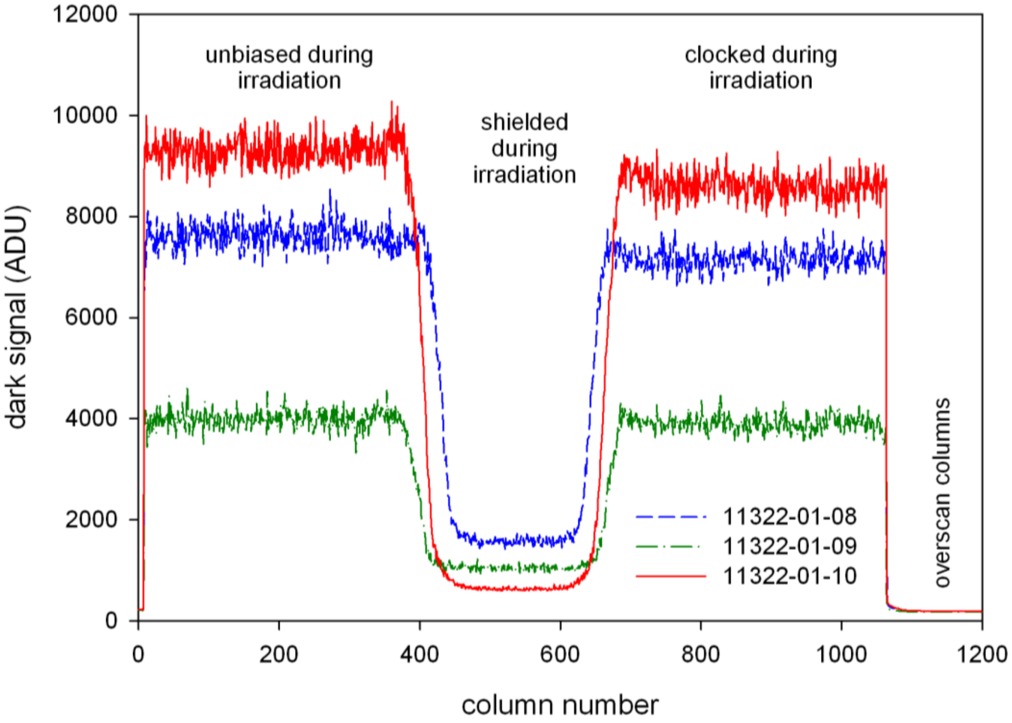
BACK-UP SLIDES

Displacement Damage, effect of bias during irradiation

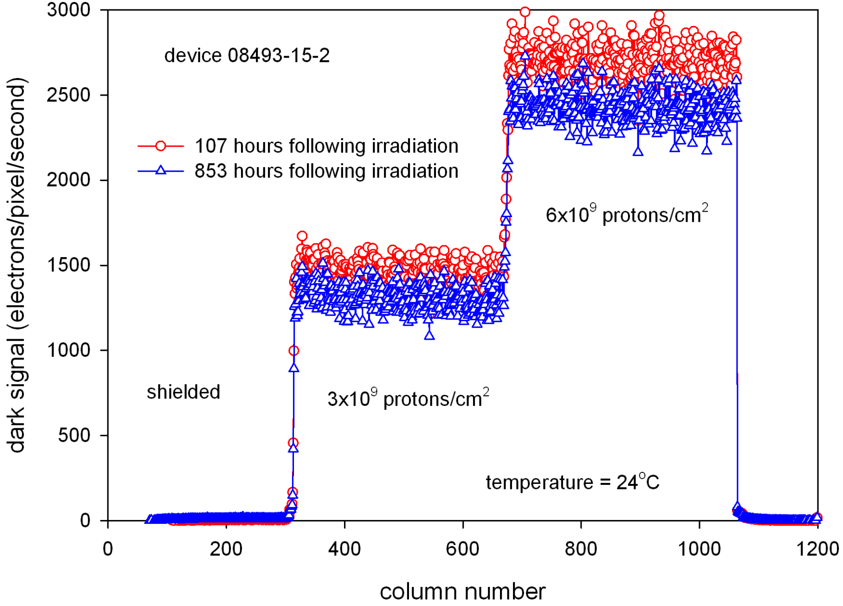


Test fluence: 6x10^9 10 MeV p/cm^2

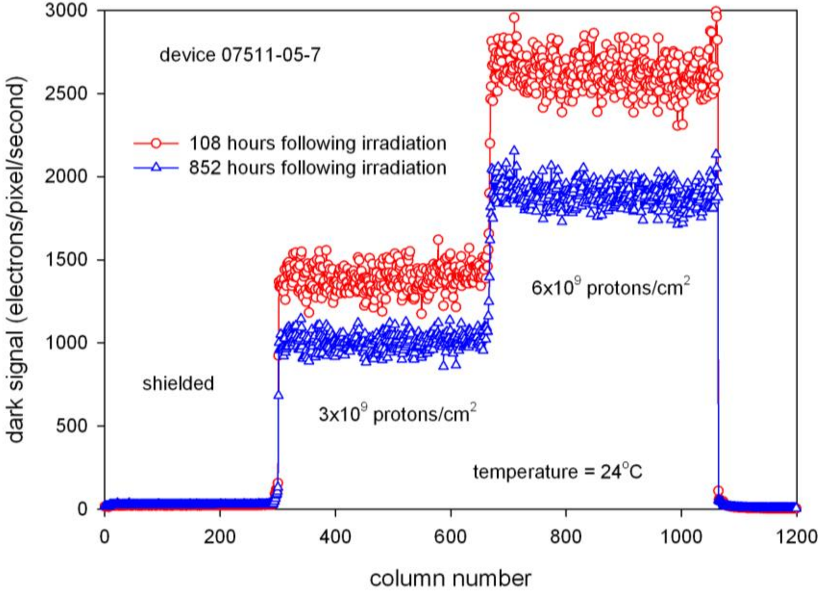
(Robbins, 2013)



Displacement Damage, effect of bias during annealing



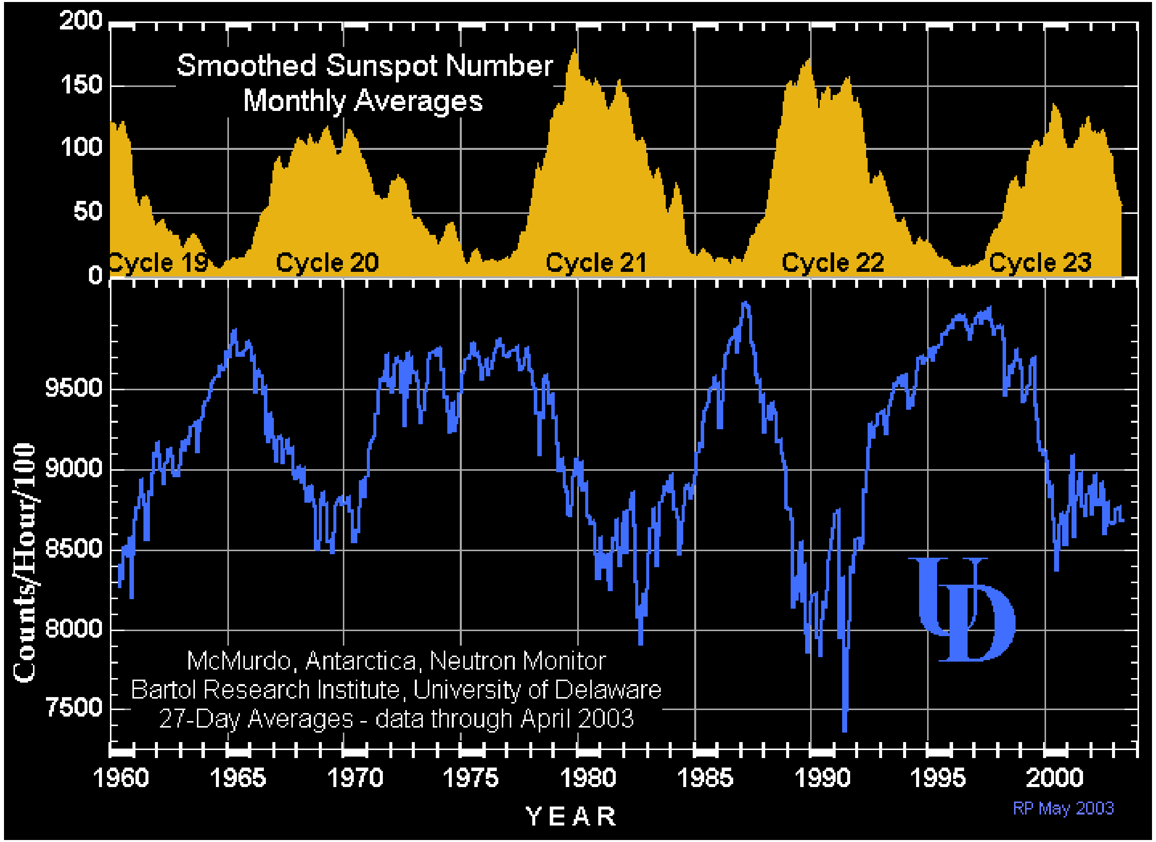
Dark signal annealing, unbiased



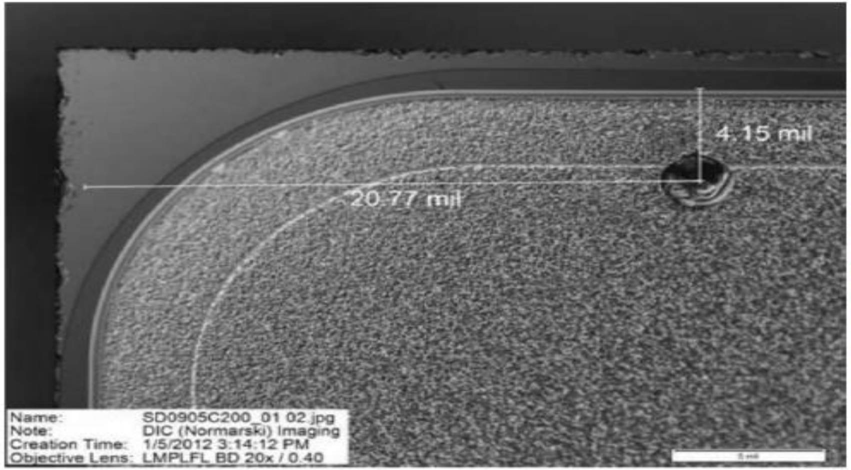
Dark signal annealing, clocked

(Robbins, 2013)

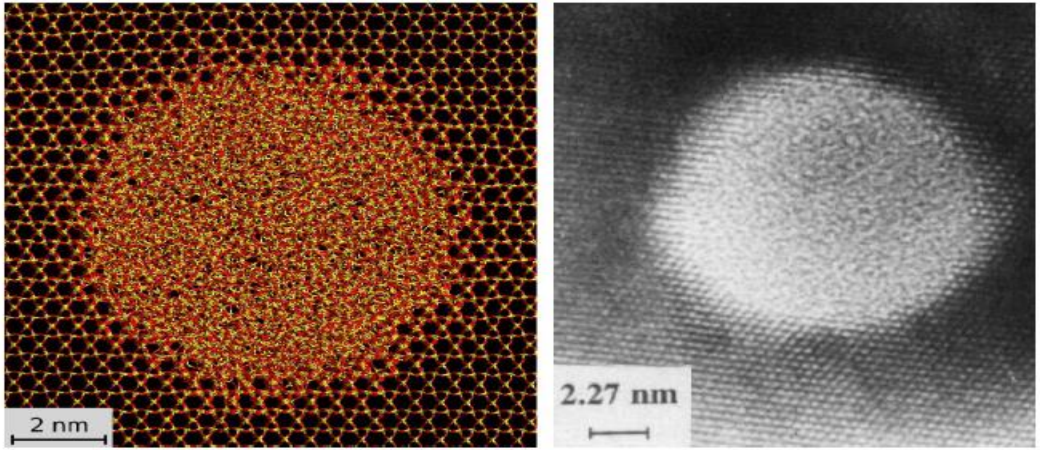
GCRs, Anti-Correlation with Solar Cycle



Destructive Events, SEB and SEGR

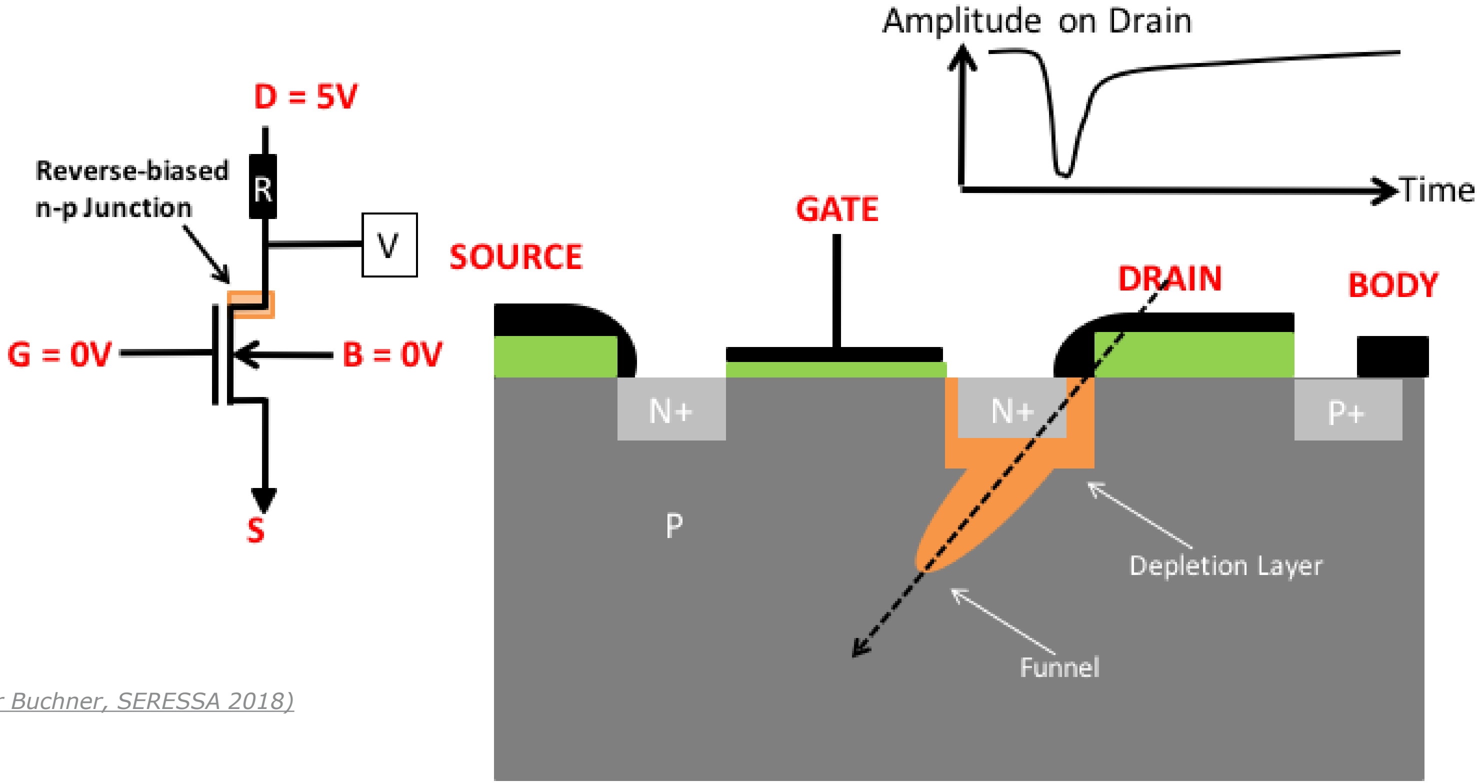


Single Event Burnout on a 200V Schottky diode (J.S. George, 2013)



Single Event Gate Rupture in a power MOSFET (Pakarinen 2009)

SET in an “off” N channel MOS transistor

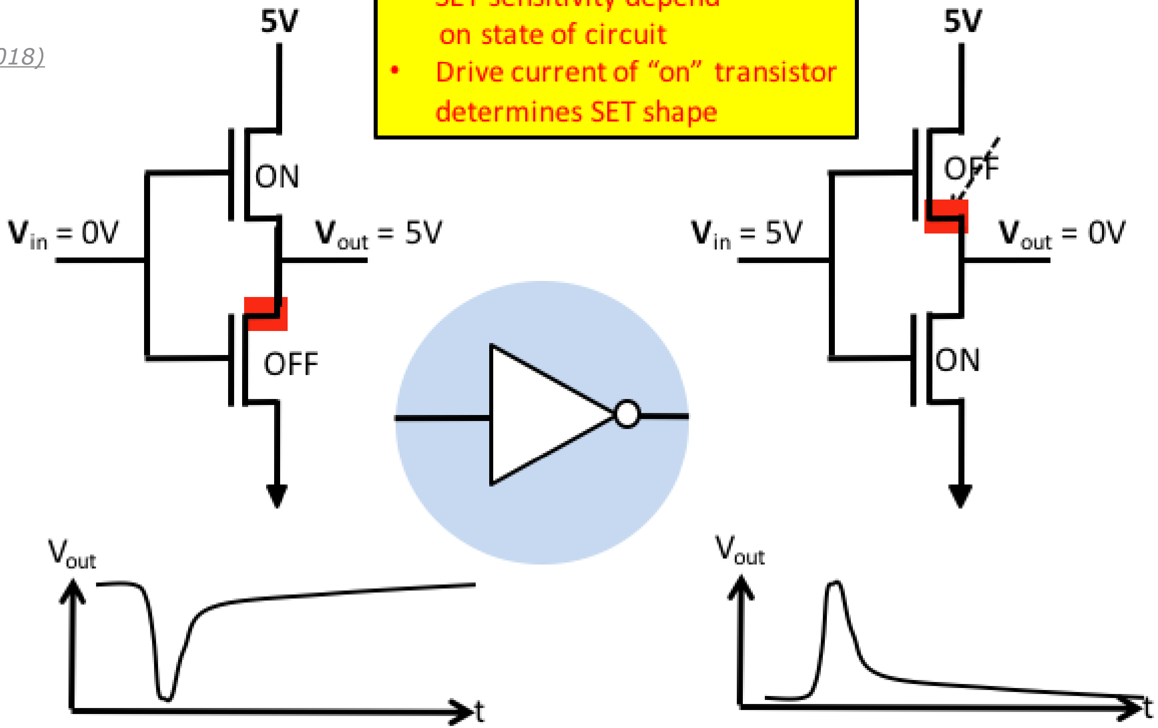


(After Buchner, SERESSA 2018)

SET in CMOS inverter

(After Buchner, SERESSA 2018)

- SET sensitivity depend on state of circuit
- Drive current of "on" transistor determines SET shape

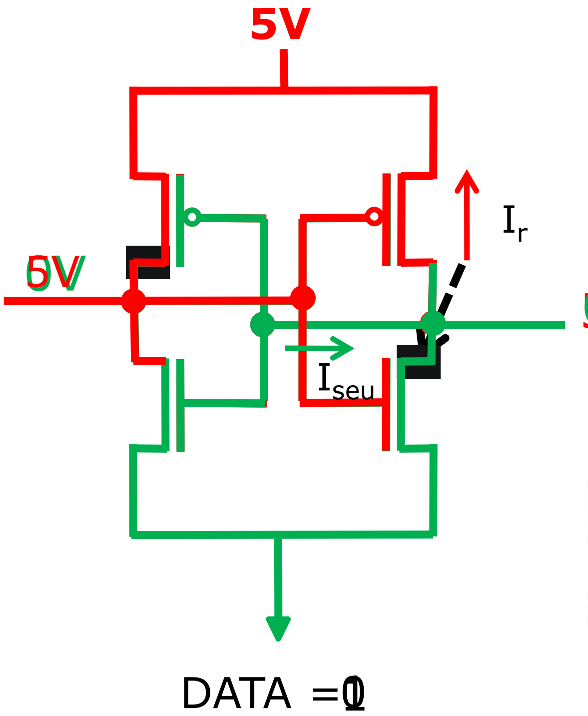


Upset in CMOS SRAM

- Two sensitive nodes for this SRAM cell – OFF n-channel and OFF p-channel transistors.
- Competition between upset (I_{seu}) and restoring (I_r) currents
- If charge deposited by ion over a time period comparable to the response time of the circuit exceeds Q_{crit} an SEU will occur
- $Q_{critical}$ depends on circuit parameters - parasitic resistance and capacitance
- Q_{coll} depends on amount of deposited charge and on device structure

(After Buchner, SERESSA 2018)

SEU if $Q_{coll} > Q_{critical}$



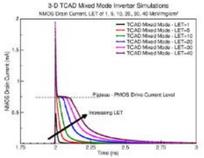
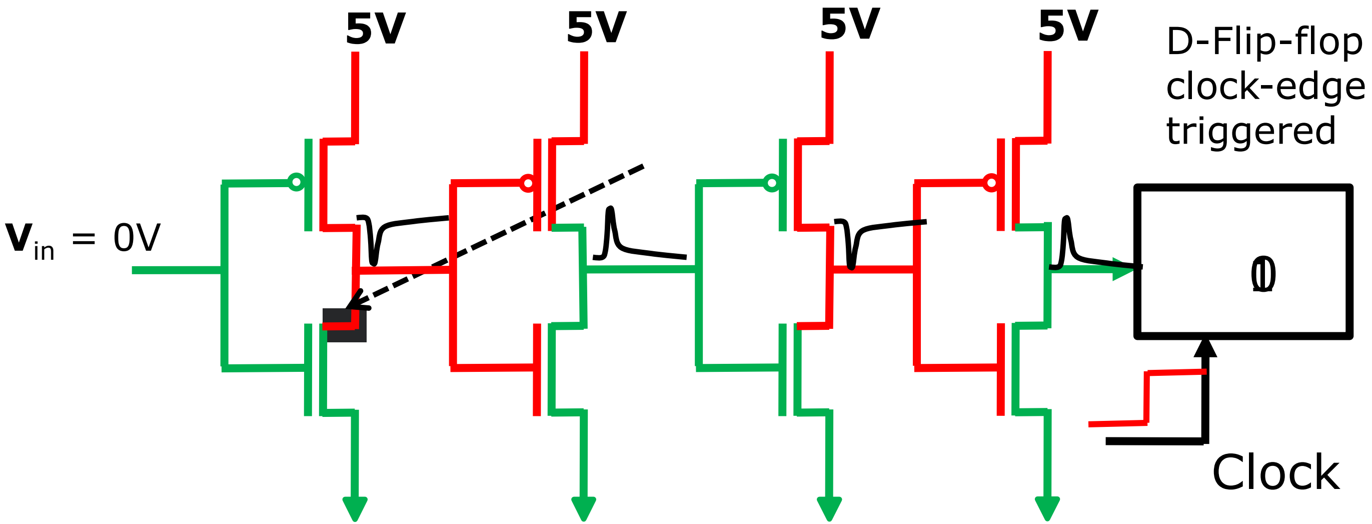
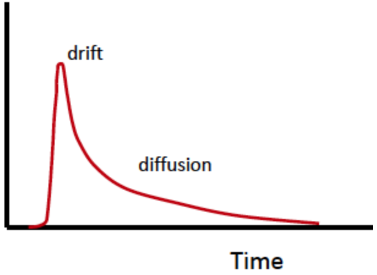


Fig. 4. 3-D TCAD mixed mode simulations results showing single-event induced nMOS drain current for various LET values. Low LET currents can be approximated by a double exponential waveform. As LET increases, the single-event induced drain current is clamped at a level equal to the pMOS drive current.

Transient Propagation in Logic Circuits



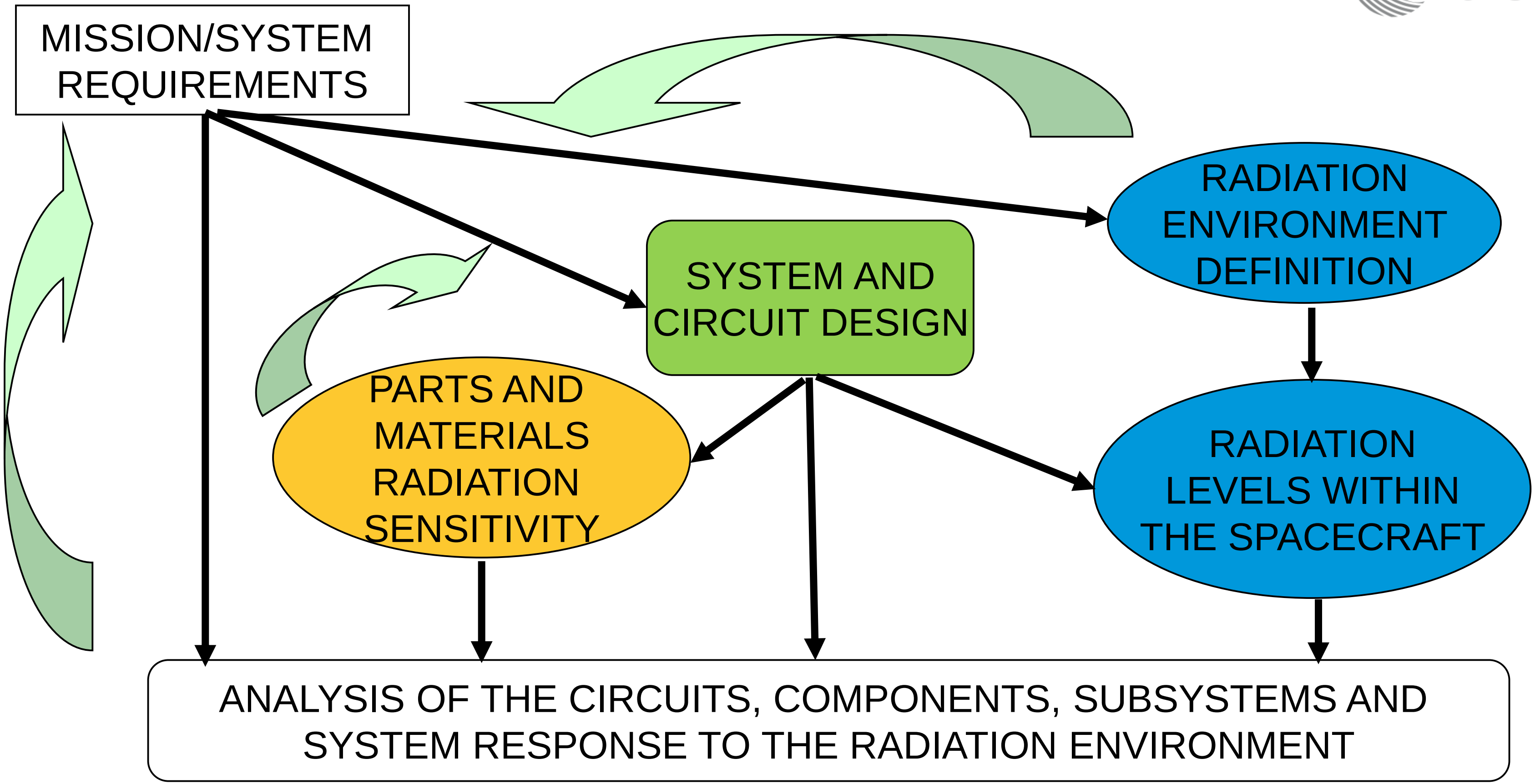
Charge collection



- Amplitude depends on LET of ion, magnitude of E, capacitance of node,…
- Width depends on diffusion component, capacitance of node, charge trapping

- Charge moving to a sensitive node is equivalent to current flow at that node. Will alter the voltage on that node
- Current transient has fast (drift) and slow (diffusion) components – faster than circuit response
- Total collected charge is integral over time of current = **Q_{coll}** (Q_{dep} > Q_{coll})
- Q_{crit} is a circuit parameter that depends on capacitance, voltage, etc.
- If Q_{col} > Q_{crit} an SEE will occur

RHA Overview – ECSS-Q-ST-60-15C



MISSION/SYSTEM REQUIREMENTS

RADIATION ENVIRONMENT DEFINITION

SYSTEM AND CIRCUIT DESIGN

PARTS AND MATERIALS RADIATION SENSITIVITY

RADIATION LEVELS WITHIN THE SPACECRAFT

ANALYSIS OF THE CIRCUITS, COMPONENTS, SUBSYSTEMS AND SYSTEM RESPONSE TO THE RADIATION ENVIRONMENT

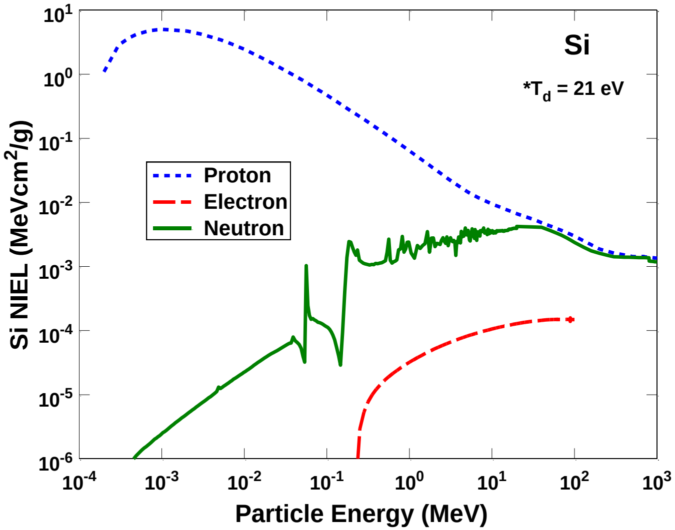
TNID, bounding part response - NIEL

- Rate at which energy is lost to displacement
- Analogous to LET or stopping power for ionizing irradiation
- Unit MeV.cm²/g
- Depends on the target material, the particle type and energy
- **NIEL is a mean parameter**

$$\mathrm{NIEL(E)} = \frac{\eta}{\rho}\int_{T_d}^{T_{\max}}\left(\frac{\partial\sigma}{\partial T}\right)\mathrm{T.L}\left(\mathrm{T}\right)dT$$

Lindhardt fraction

Differential cross section

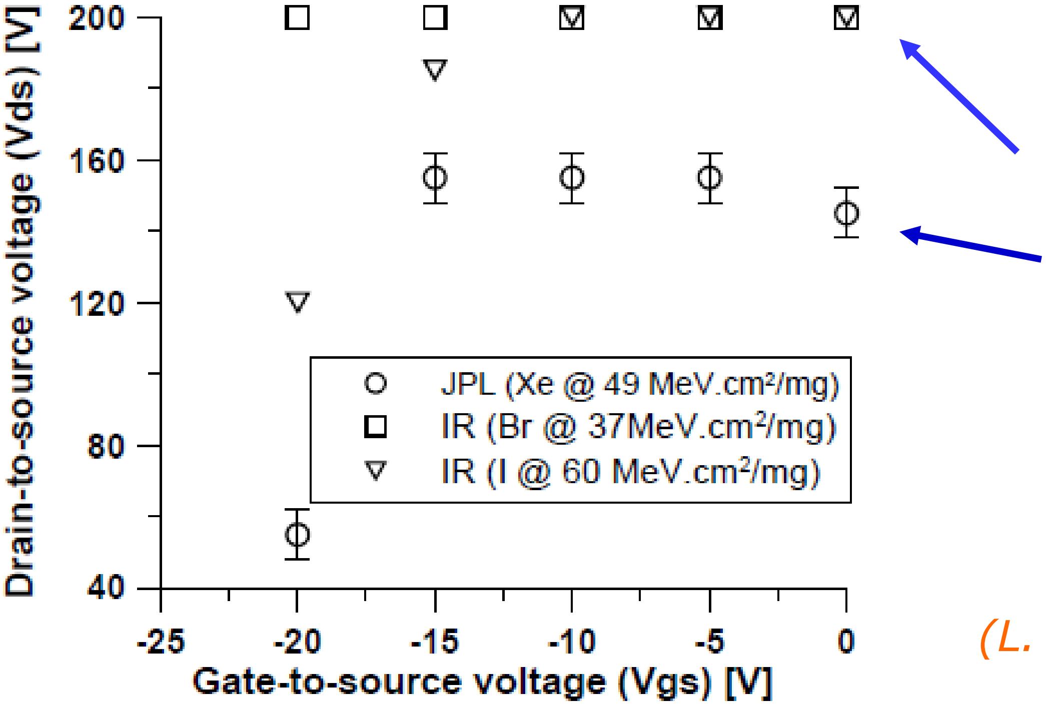


- The displacement damage dose (DDD) is the product of the NIEL and the fluence
  - For a spectrum of energy

$$\mathrm{DDD} = \int_{E_{\min}}^{E_{\max}}\left(\frac{\partial\Phi}{\partial E}\right)\mathrm{NIEL}\left(\mathrm{E}\right)dE$$

(in MeV/g)

Power MOSFETs, SEE Safe Operating Area, Example



IRHMB57260SE 200V NMOSFET

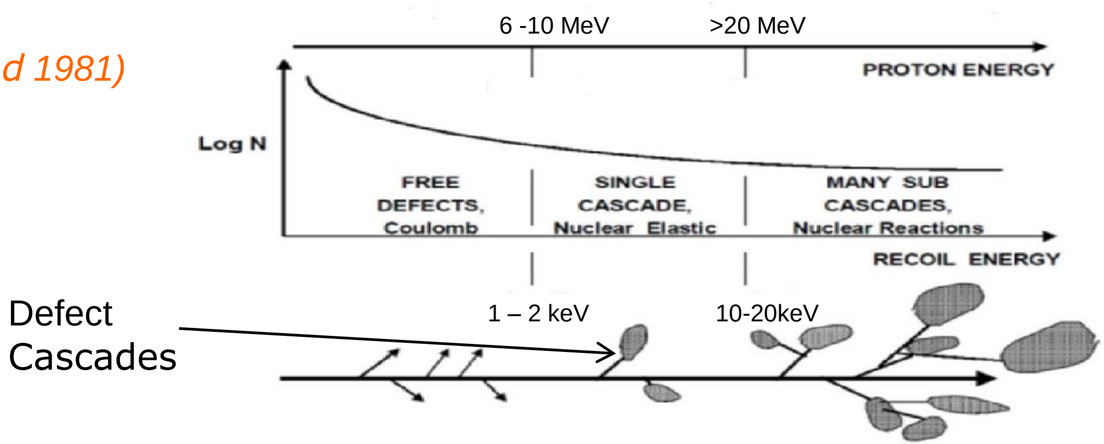
Manufacturer's data with short range ions

JPL data with long range ions

(L. Scheick, NSREC DW 2009)

Displacement damage - Mechanism

(Wood 1981)



Energy of recoil (PKA spectrum) is determined by collision kinematics

- For protons in Si at energies below 10 MeV, Si atoms are displaced from their lattice position via Coulomb interaction
- As the energy of the proton increases the energy transferred from the colliding proton with a Si atom occurs via nuclear elastic interaction.
- More energy is transferred to the recoil atom which again can go on and create additional recoil atoms and hence defect cascades.
- With even higher proton energies the probability of nuclear interaction increases. Many sub cascades may be generated.

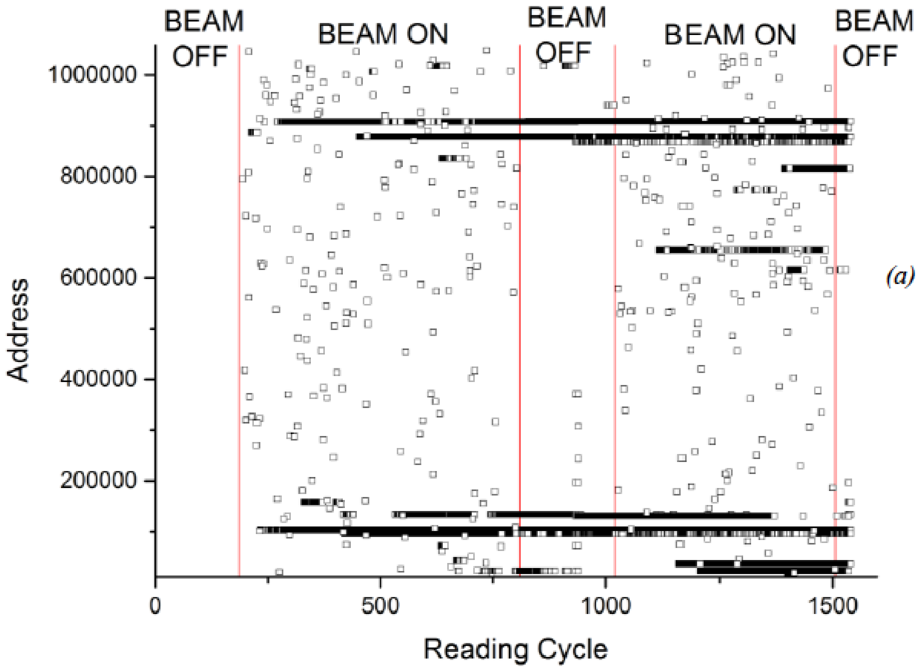
Displacement Damage Factor

- Final concentration of defects depends only on NIEL (*total energy that goes into displacements, about 0.1% of total energy loss*) and not on the type an initial energy of the particle
  - ➢ Number of displacements (I-V pairs) is proportional to PKA energy
    - Kinchin-Pease: $N=T/2T_D$; T: PKA energy; T_D: threshold energy to create a Frenkel pair)
  - ➢ In cascade regime the nature of the damage does not change with particle energy- just get more cascades
    - nature of damage independent of PKA energy
- It is assumed that ***underlying electrical effect proportional to defect concentration*** (Shockley Read Hall theory)
  - ➢ Damage constant depends on device and parameter measured

$$\boxed{\textbf{damage} = k_{damage} \times \textbf{Displacement Damage Dose}}$$

$$\int NIEL(E)\frac{d\phi(E)}{dE}dE$$

Stuck bits are very difficult to characterize



80 MeV protons, final fluence 8.36E10 /cm2, (Rodriguez, 2017)

- Only a small fraction of memory (<<1%) show ISB behavior (retention time degraded by several orders of magnitude)
- More ISB can appear after the end of the irradiation
- But some will anneal
- Temperature dependence
- Number of ISB is also dependent of refresh period
- Stuck bit were initially not considered because of their small number (compared to SEU and even SEFI) and it was (wrongly) assumed that they all anneal quickly