RADIATION EFFECTS IN SPACE ELECTRONICS

7th EIROforum School on Instrumentation

08/06/2021

Christian Poivey

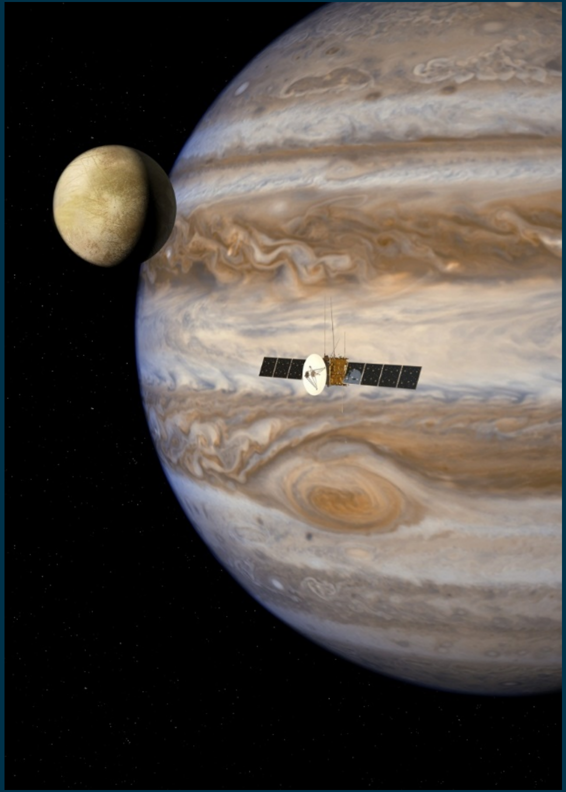
SPACE AND THE ENVIRONMENT: Copernicus Programme

- Copernicus is the European Union Earth Observation Programme, looking at our planet and its environment:
  - Atmosphere monitoring (air quality, ozone layer,..)
  - Land cover and land use mapping
  - Climate change (polar ice thickness, sea surface monitoring,…)
  - Mapping and early warning of natural disasters
    - Sentinel 1 to 6 spacecraft
- Future Copernicus:
  - **CHIME**: land cover mapping: spectrometer
  - **CIMR**: sea surface temperature and salinity: radiometer
  - **CO2M**: CO2 monitoring: spectrometer
  - **CRISTAL**: Polar ice and snow topography: altimeter and radiometer
  - **LSTM**: Land surface temperature: thermal IR sensor
  - **ROSE**: forest management, soil moisture monitoring: Synthetic Aperture Radar (SAR)

Artistic view of Sentinel 2 spacecraft

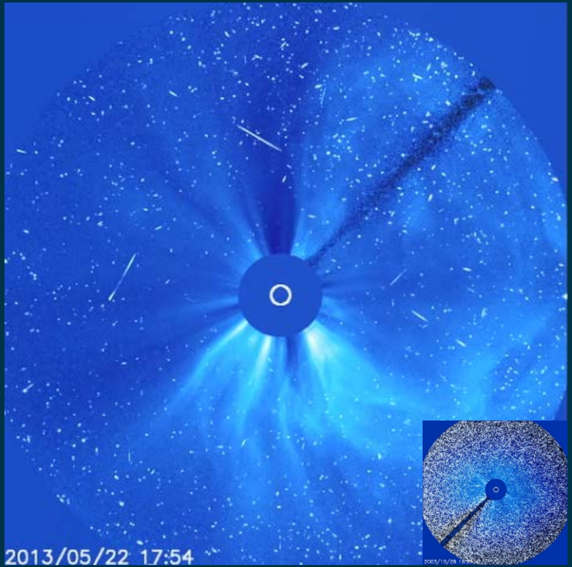
JUICE, The instrument suite

Name	Instrument	Scientific purpose
JANUS	Camera	Geology of icy moons, Jupiter atmosphere
MAJIS	Visible-IR spectrometer / spectro-imager	Moons surface composition, moons atmosphere, Jupiter atmosphere
UVS	UV spectrometer	Atmosphere of moons & aurora & Jupiter
SWI	Sub millimetre spectrometer	Jupiter atmosphere, icy moons atmosphere and surfaces, Io
GALA	Laser Altimeter	Moons shape & topography
RIME	Sub surface Radar	Moons sub-surface study
3GM	Radio science experiment	Gravity field and moon interiors
JMAG	Magnetometer	Characterisation of oceans and interior of moons, study of Jupiter magnetosphere
PEP	Plasma package (ions and electrons sensors,..)	Study of Jovian plasma system
RPWI	Radio plasma wave	Plasma and fileds measurements in the Jovian system

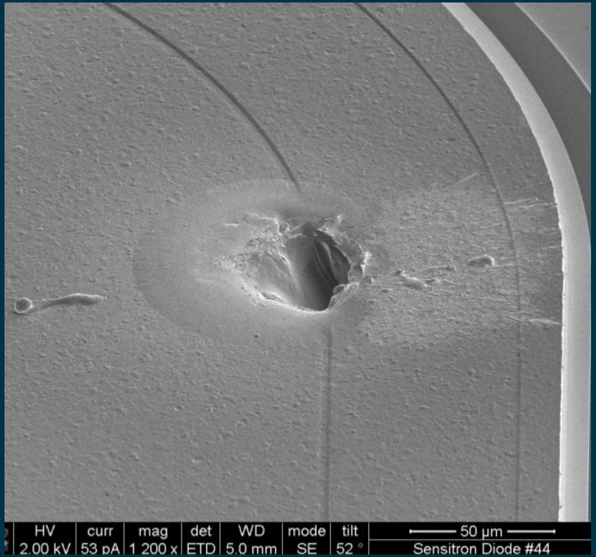


Why Are We Concerned by Radiation in Space ?

- 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.

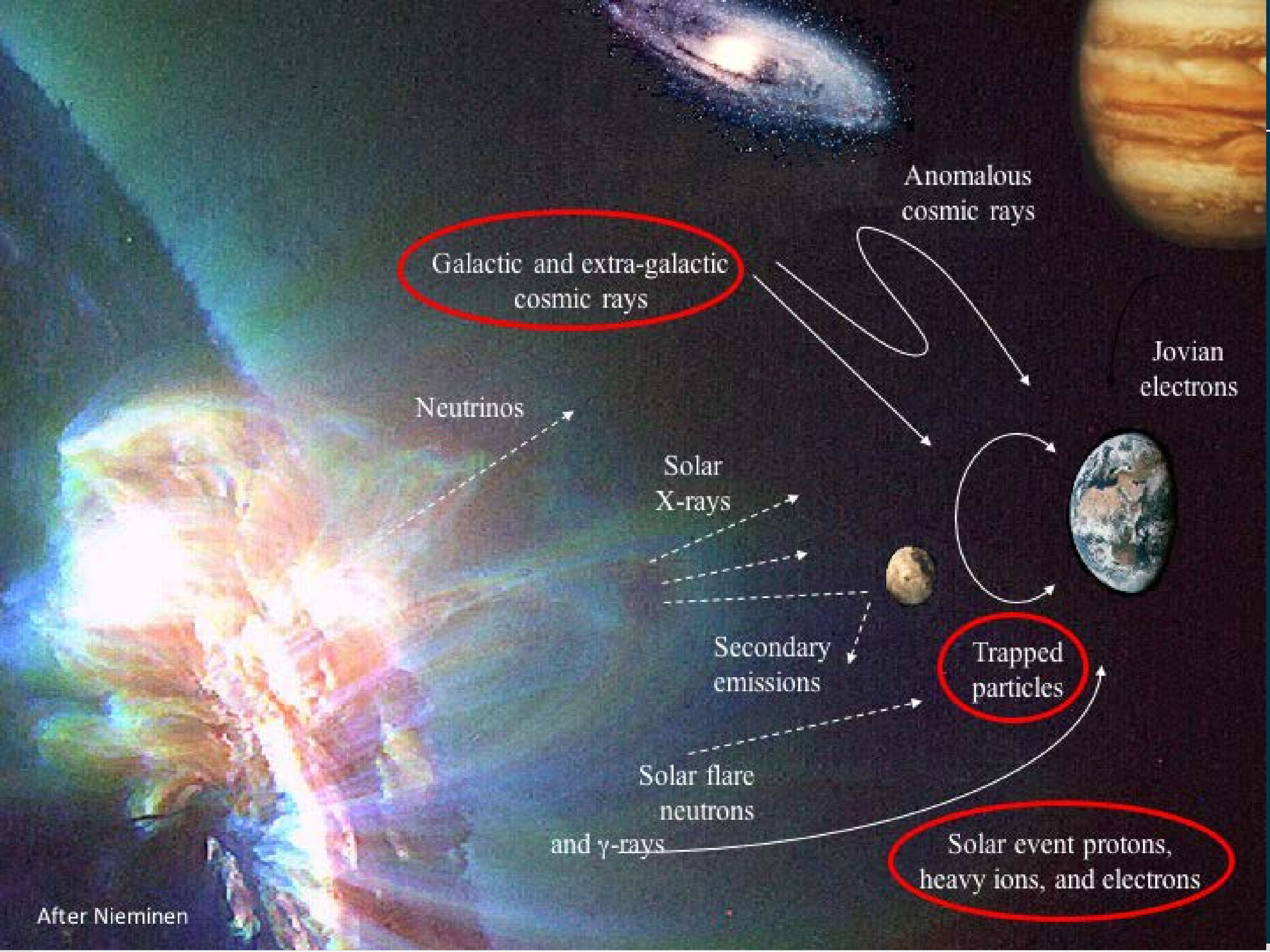


Single Event Burnout (SEB) in a power diode induced by an heavy ion

(J. George, NSREC REDW, 2013)

OUTLINE

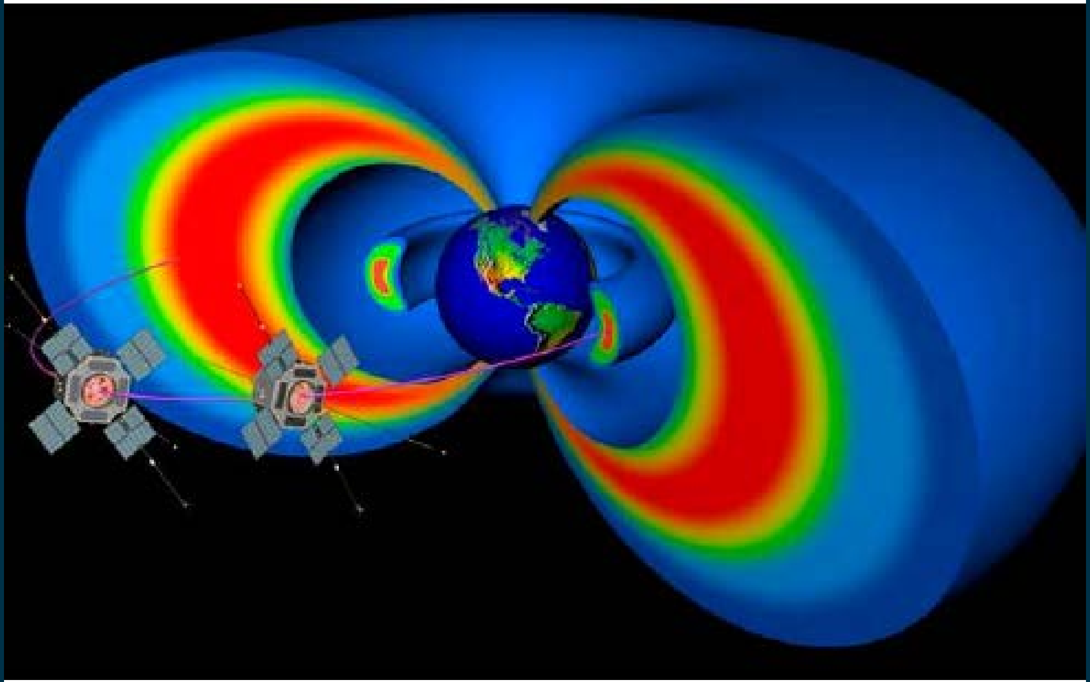
- Space radiation environment
  - External Environment
  - Inside a spacecraft
- Radiation effects in space electronics
  - Summary
  - Examples
- Conclusion



1) Trapped particles
2) Solar Events particles
3) Galactic Cosmic Rays

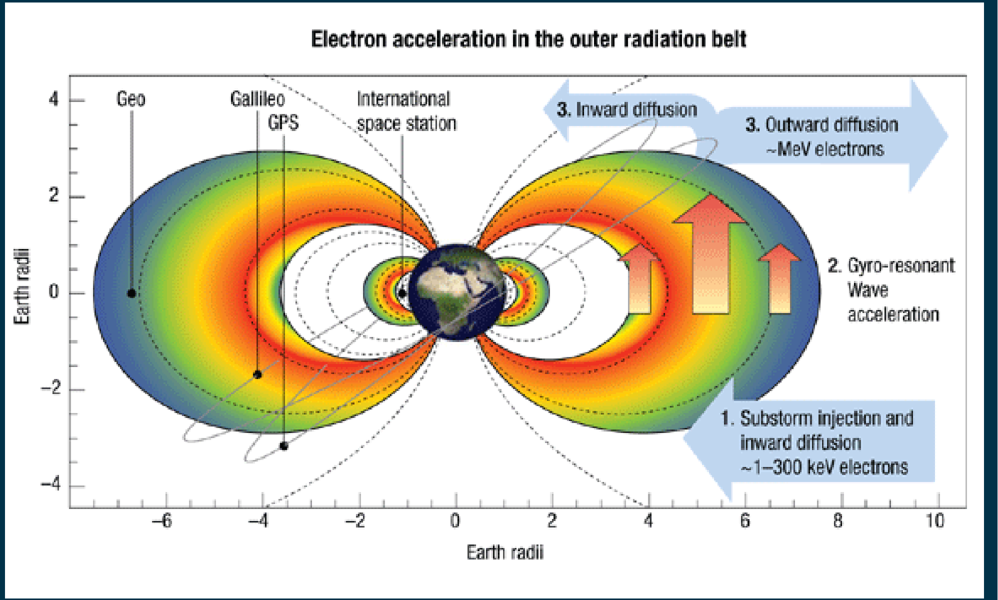
1- Trapped Radiation Belts

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



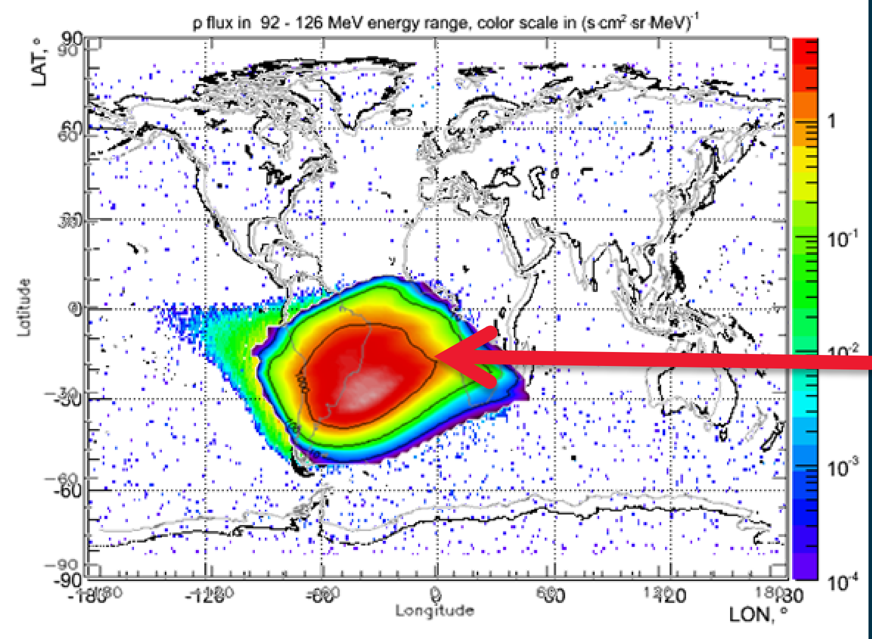
Trapped Radiation Belts, main characteristics

- Inner belt is dominated by a population of energetic **protons up to ~400 MeV energy range**
  - Inner edge is encountered at 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)

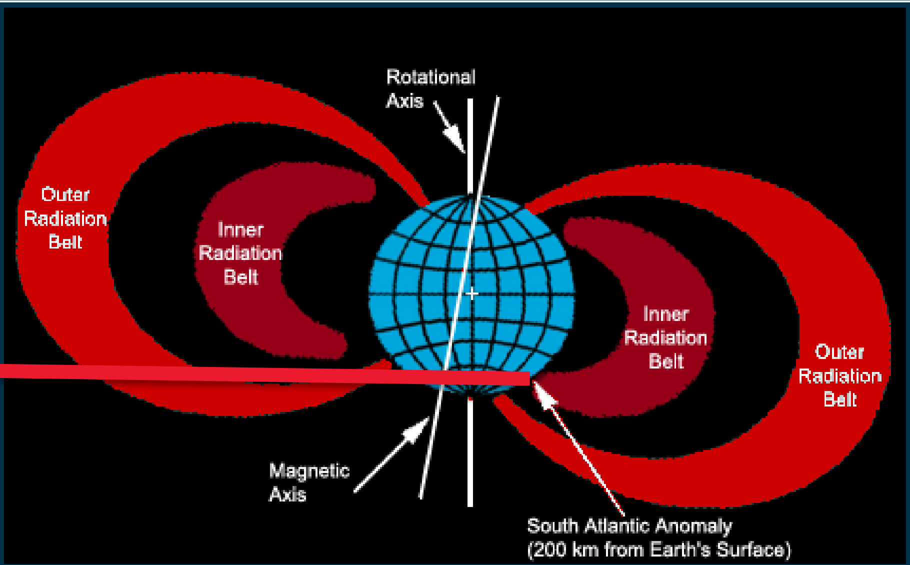


(Richard Bertram Horne Nature Physics 3, 2007)

The South Atlantic Anomaly (SAA)



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

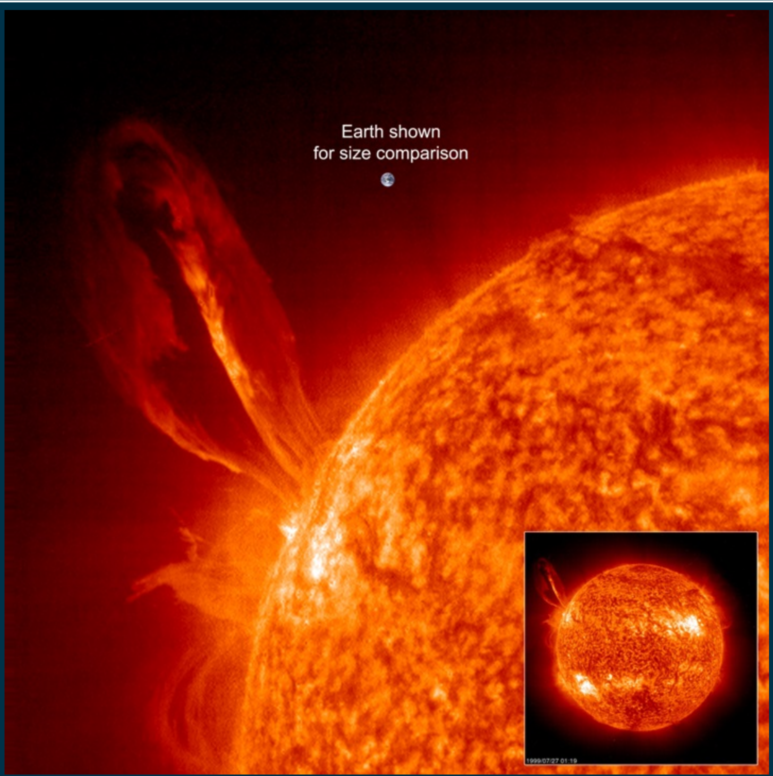


(Wikimedia Commons, the free media repository)

The South Atlantic Anomaly is observed as the magnetic axis is not aligned with the Earth rotational axis. The inner radiation belt thus is closer to earth above the South Atlantic.

2 - Solar Event Particles

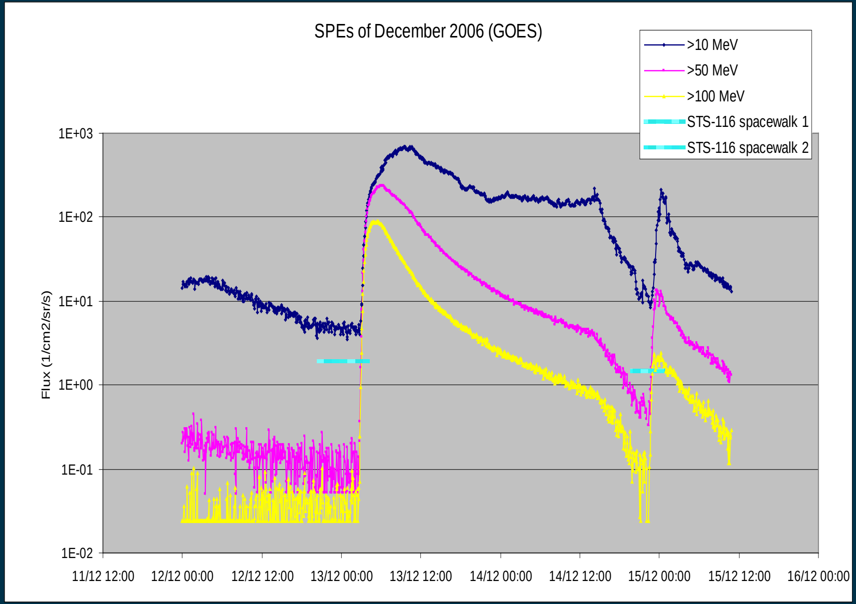
- Solar Events (Solar Flares or Coronal Mass Ejection) represent emission of a broad spectrum of particles and very high energy release.
- The electrons, protons and heavier ions ejected reach Earth in a couple of days. Radiation fluxes can be high for several days during solar flares
- The energy spectra 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.



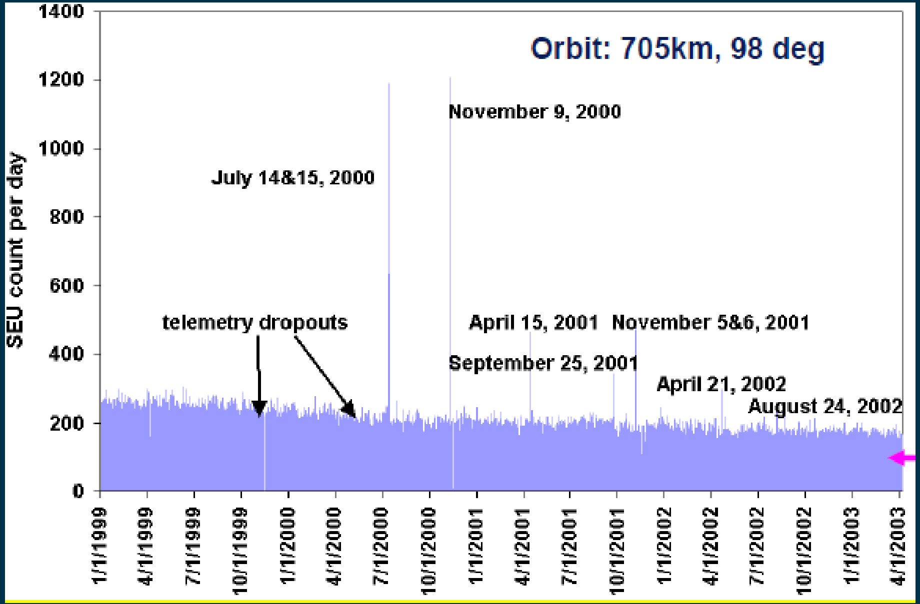
Large solar eruption captured by SOHO on the 27 July 1999. The eruption is larger that Earth.

Observation of Solar Particle Events

Single Event Effect rates increase significantly during a Solar event



GOES data (https://www.ngdc.noaa.gov/stp/satellite/goes/)

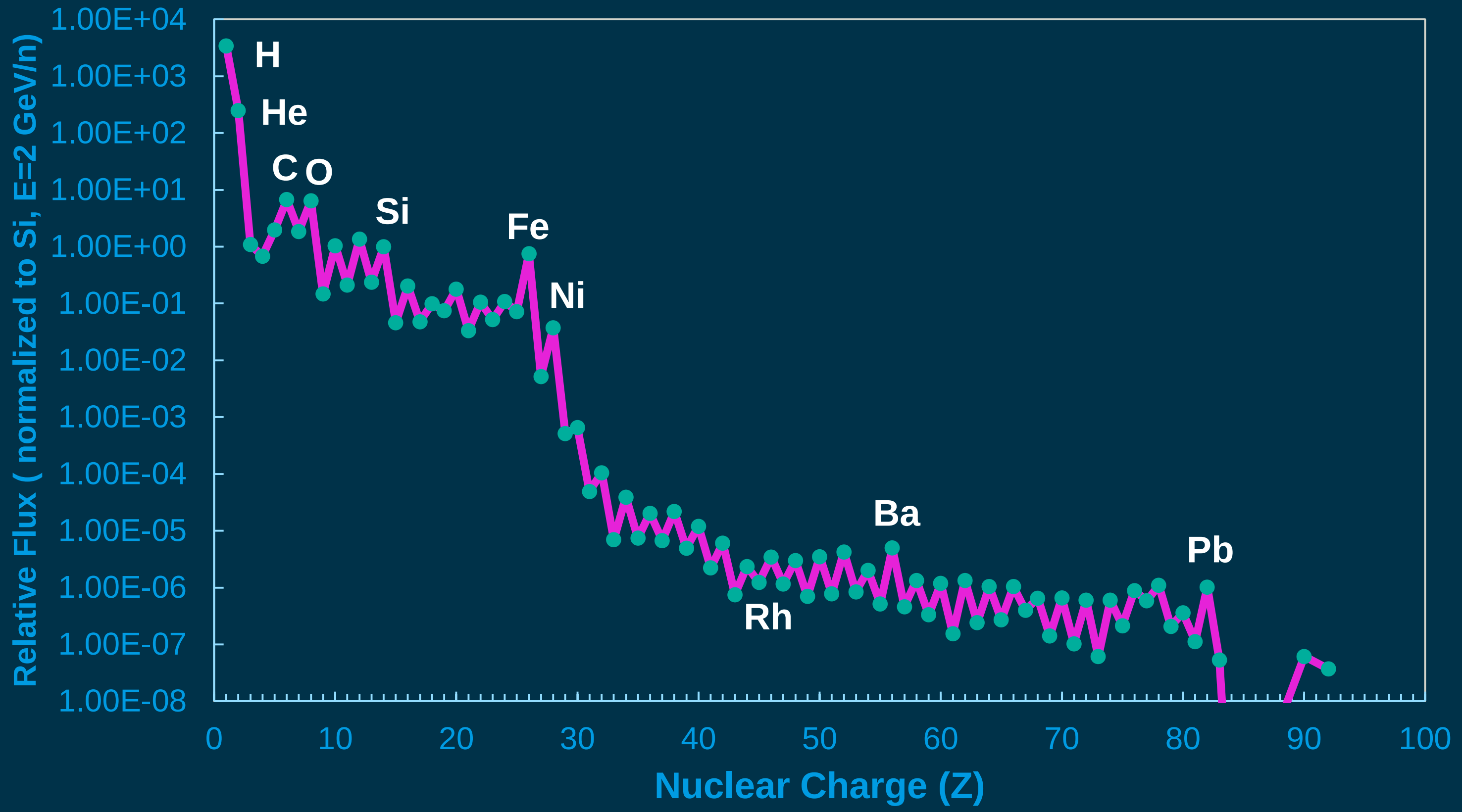


SEUs on SEASTAR SSR (Poivey, NSREC REDW 2003)

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



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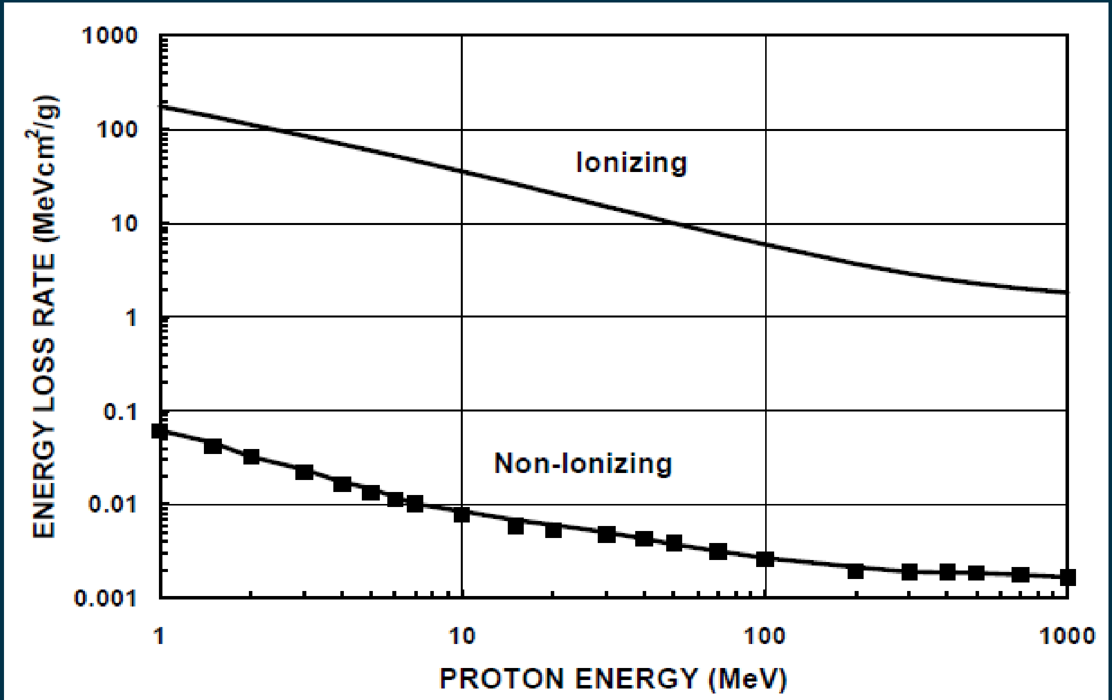
Interactions of Radiation with Electronic Devices

- 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)**

Ionizing and Non-Ionizing Energy Loss



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

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

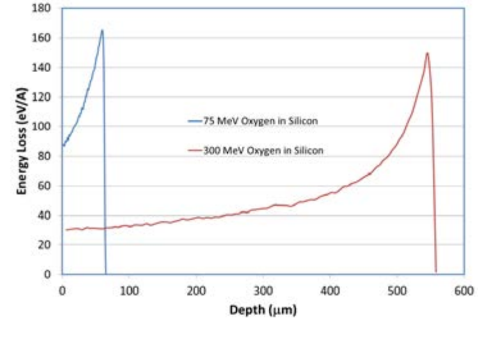
NIEL: energy loss rate through displacements, (about 0.1% of total energy)

Ionizing Radiation Units

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

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

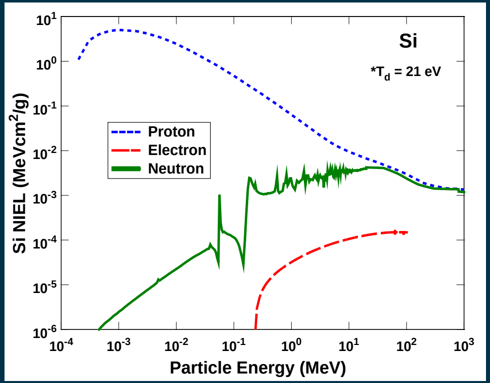
(ρ = material density)



    - 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 = Kinetic Energy Released to MAtter)*
  - In $MeVcm^2/mg$ or $keVcm^2/mg$
  - Depends on target material, particle type and energy
  - **NIEL is a mean parameter**



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

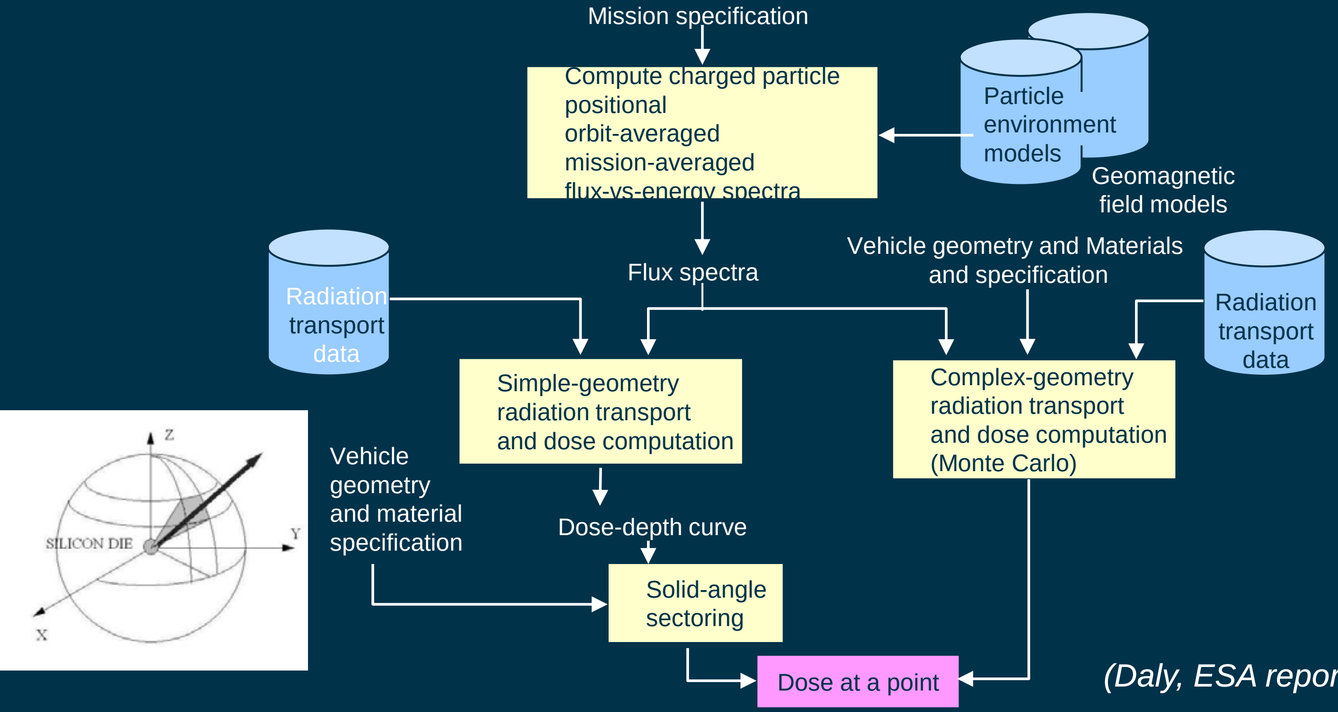
$$DDD = \int_{Emin}^{Emax} \left(\frac{\partial \emptyset}{\partial E}\right) NIEL(E)\,dE$$ (keV/g or MeV/g)

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

$$F_{E0} = \int_{Emin}^{Emax} \left(\frac{\partial \emptyset}{\partial E}\right) \frac{NIEL\,(E)}{NIEL\,(E0)}\,dE$$ ($\#/cm^2$)

  - e.g. 10 MeV $protons/cm^2$ or 1 MeV $neutrons/cm^2$

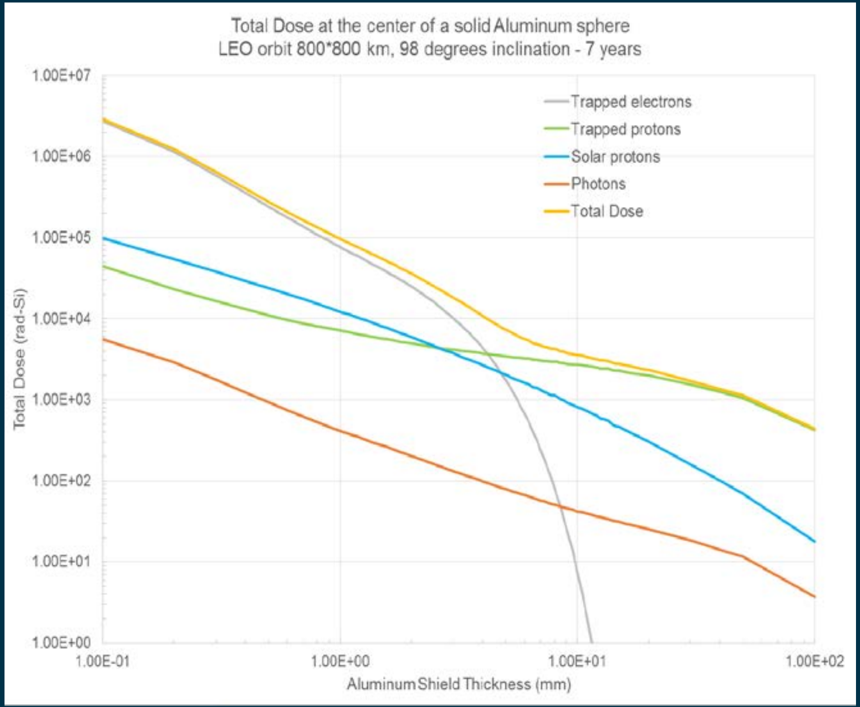
Computer Methods for Particle Transport

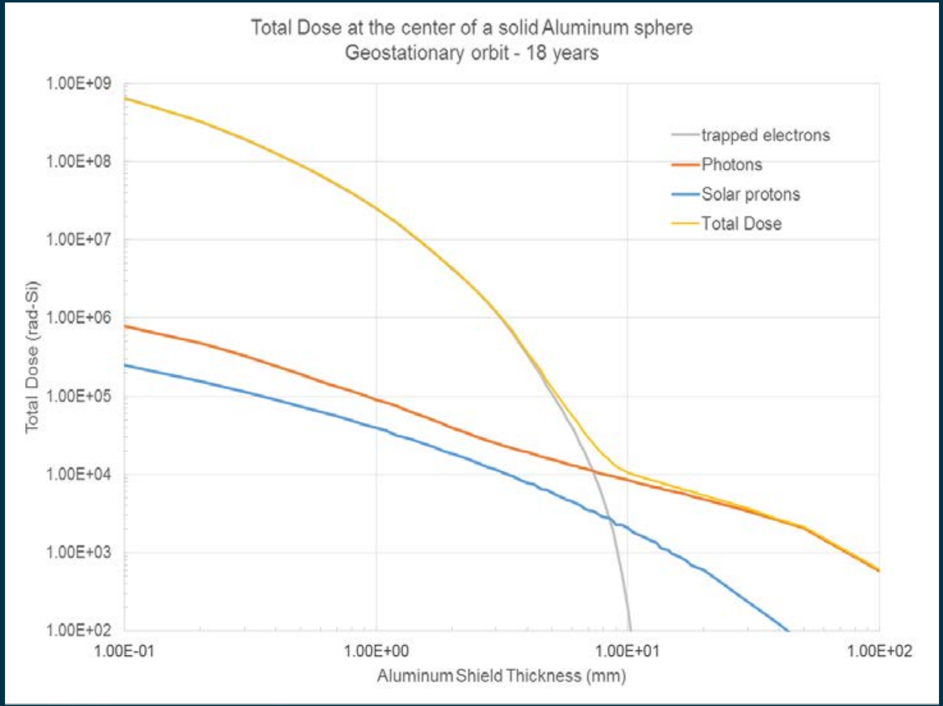


Particle Environment models and simple geometry transport tools are available in **SPENVIS** (ESA supported webtool, https://www.spenvis.oma.be) or **OMERE** (CNES supported application, http://www.trad.fr)

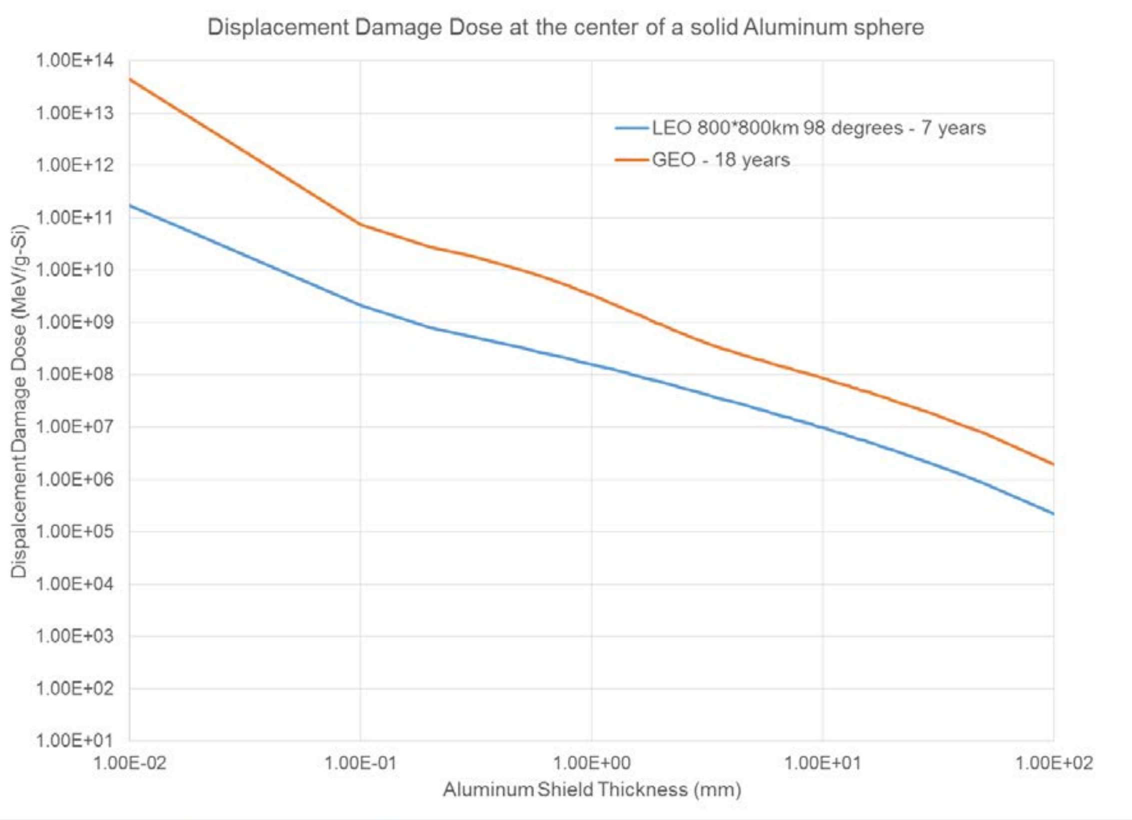
(Daly, ESA report 1989)

Dose versus depth curve - Examples

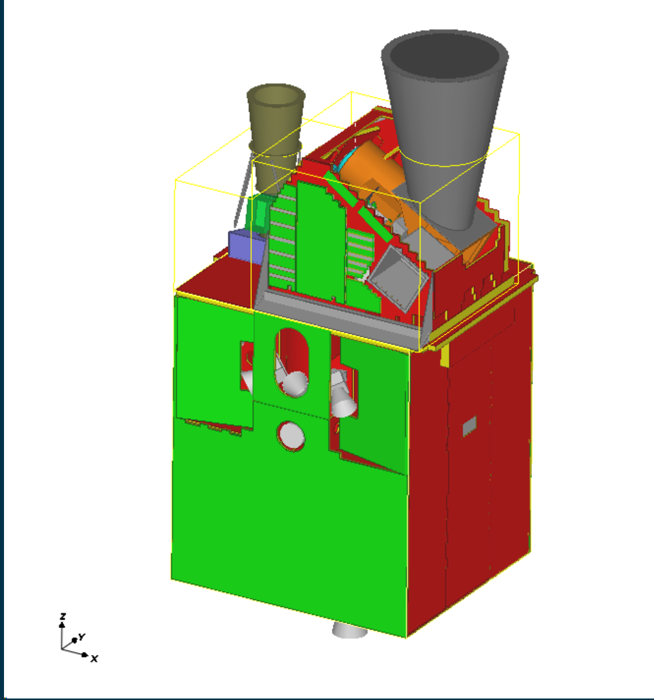


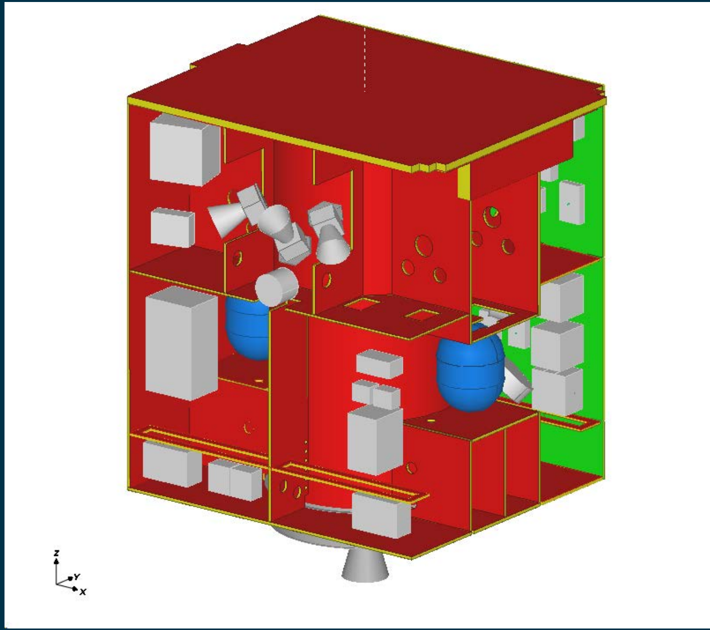


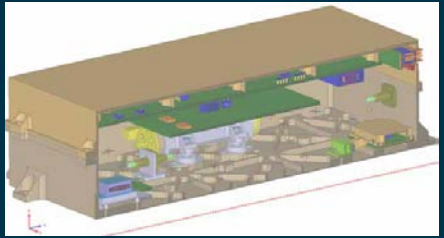
DD equivalent Fluence versus Depth Curve - Example

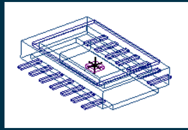


Accurate TID/DD Levels Estimation in Electronic Parts

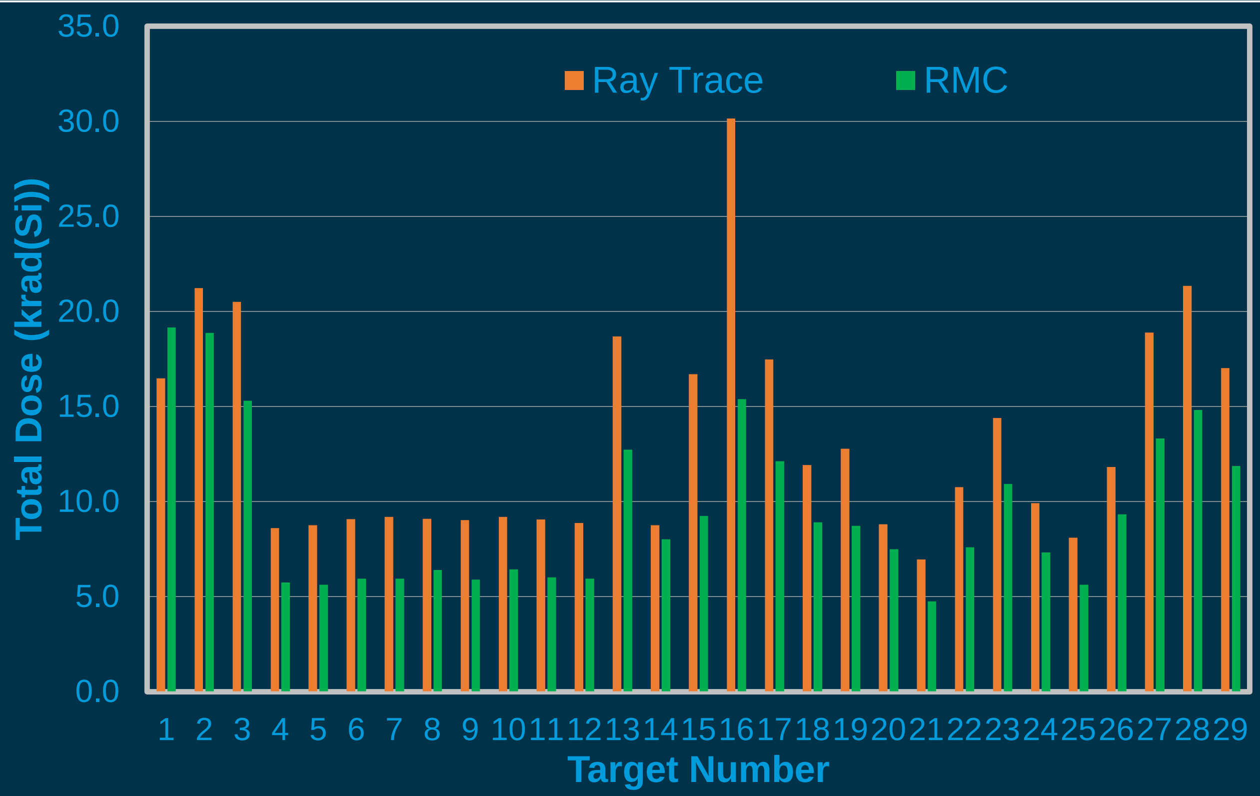








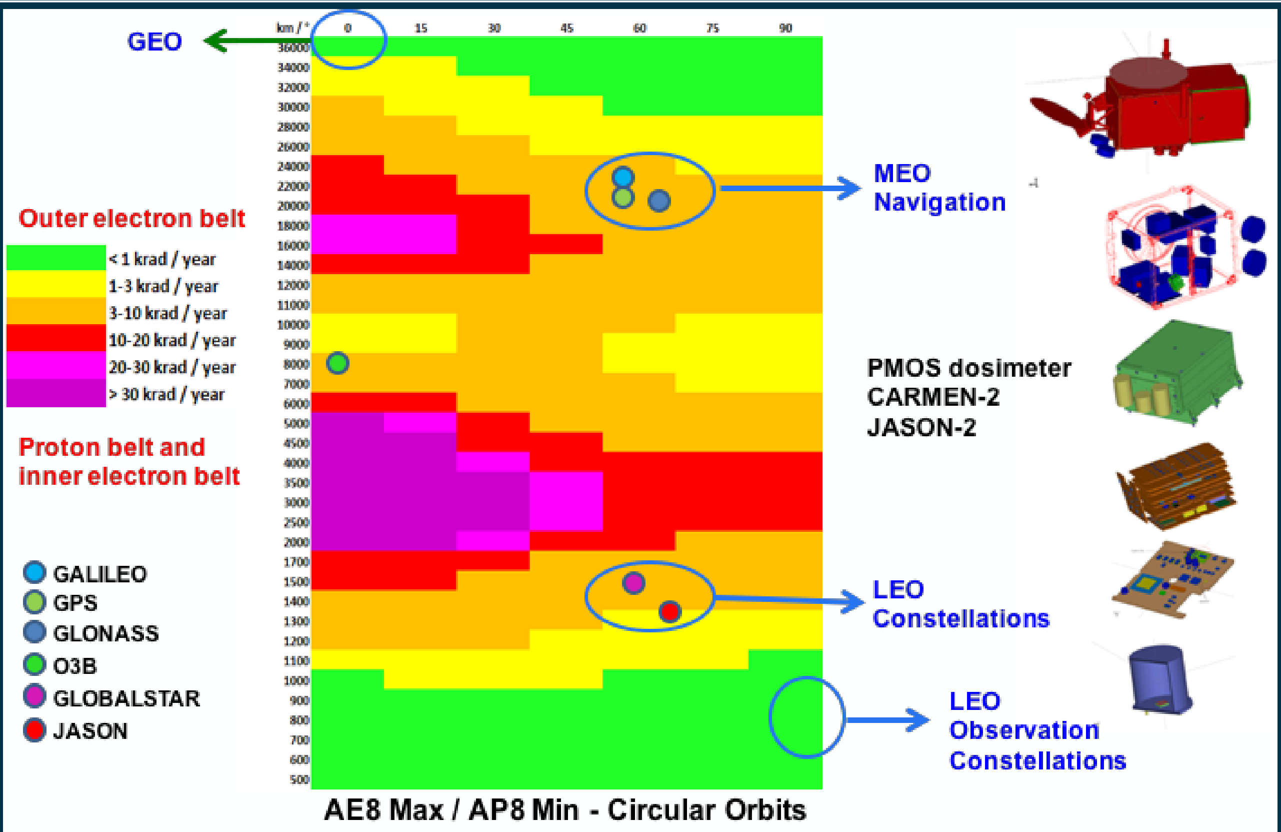
TID Levels, Ray Trace versus Monte Carlo Analysis – GEO orbit 18 years



Ray Trace analysis overestimate dose levels for electron dominated orbits

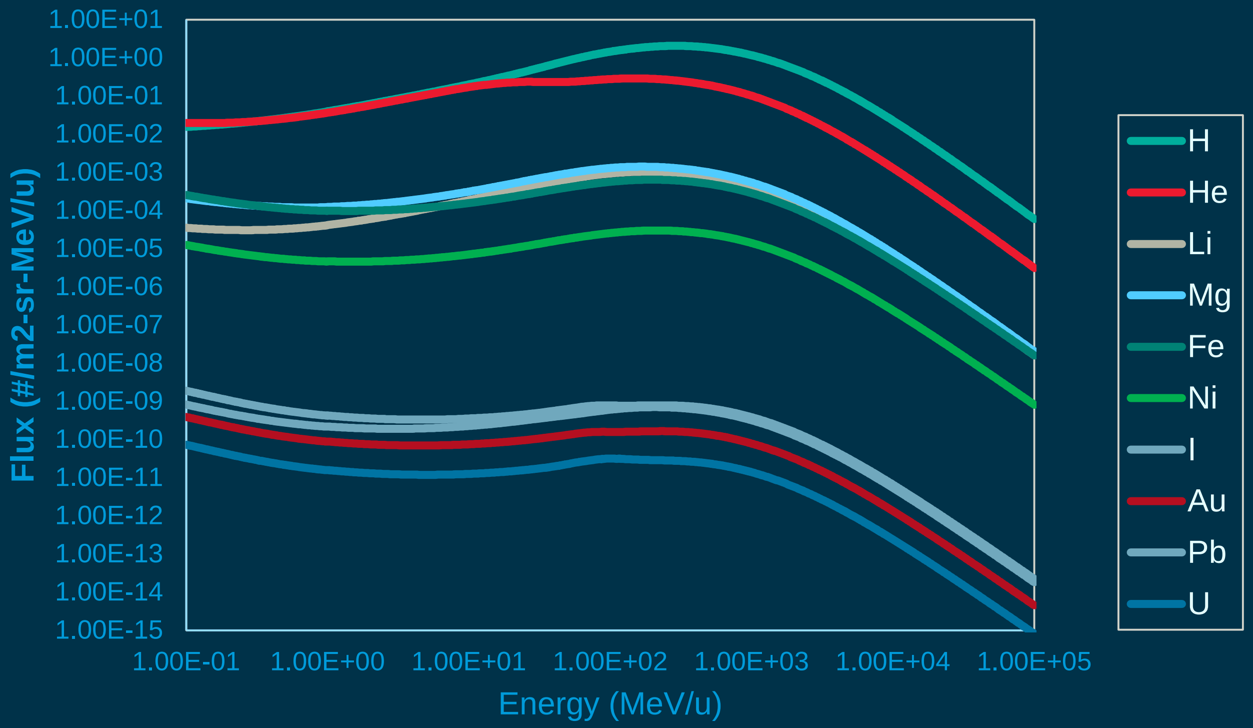
(After A. Varotsou, GTTREF study)

Examples of Missions TID Levels

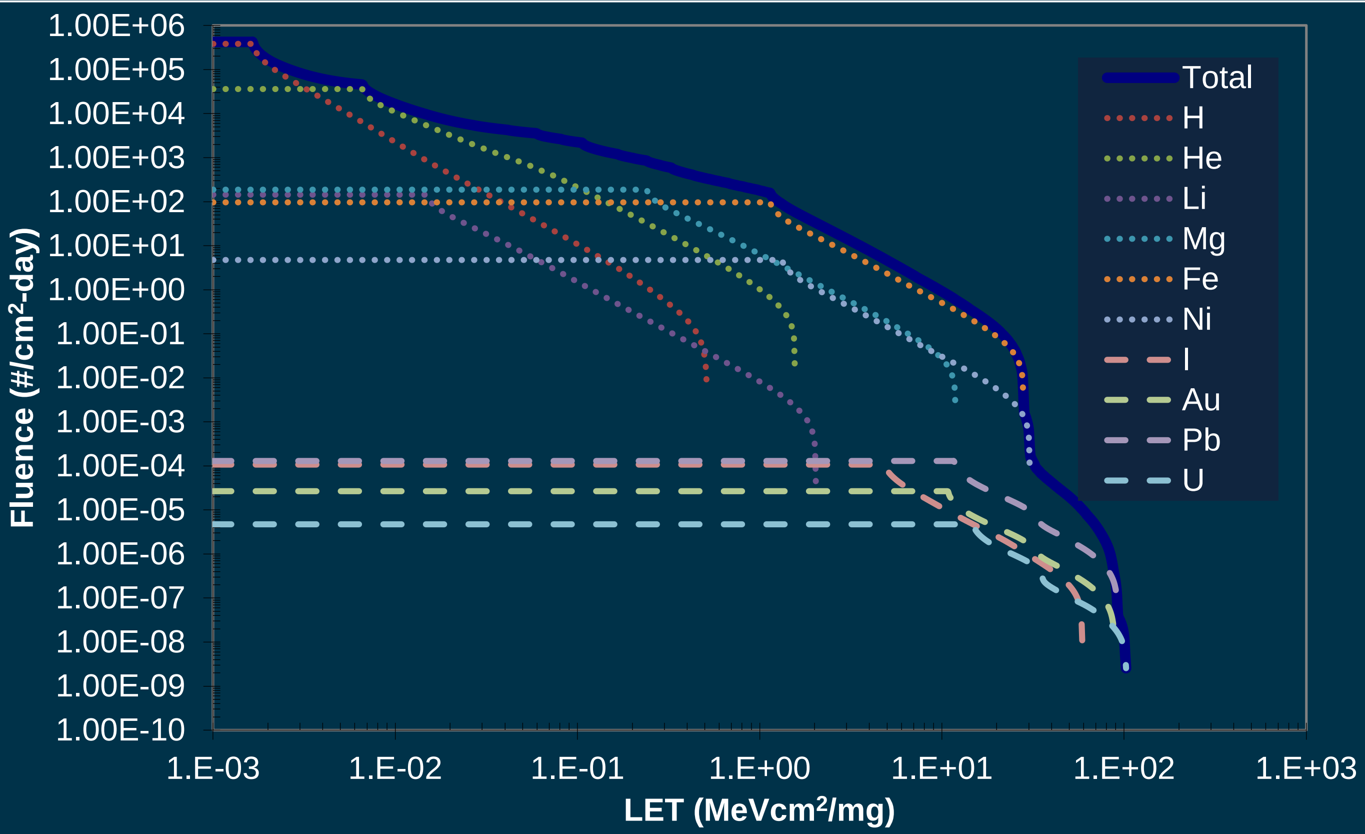


After Ecoffet & Gerardin, RADECS 2015

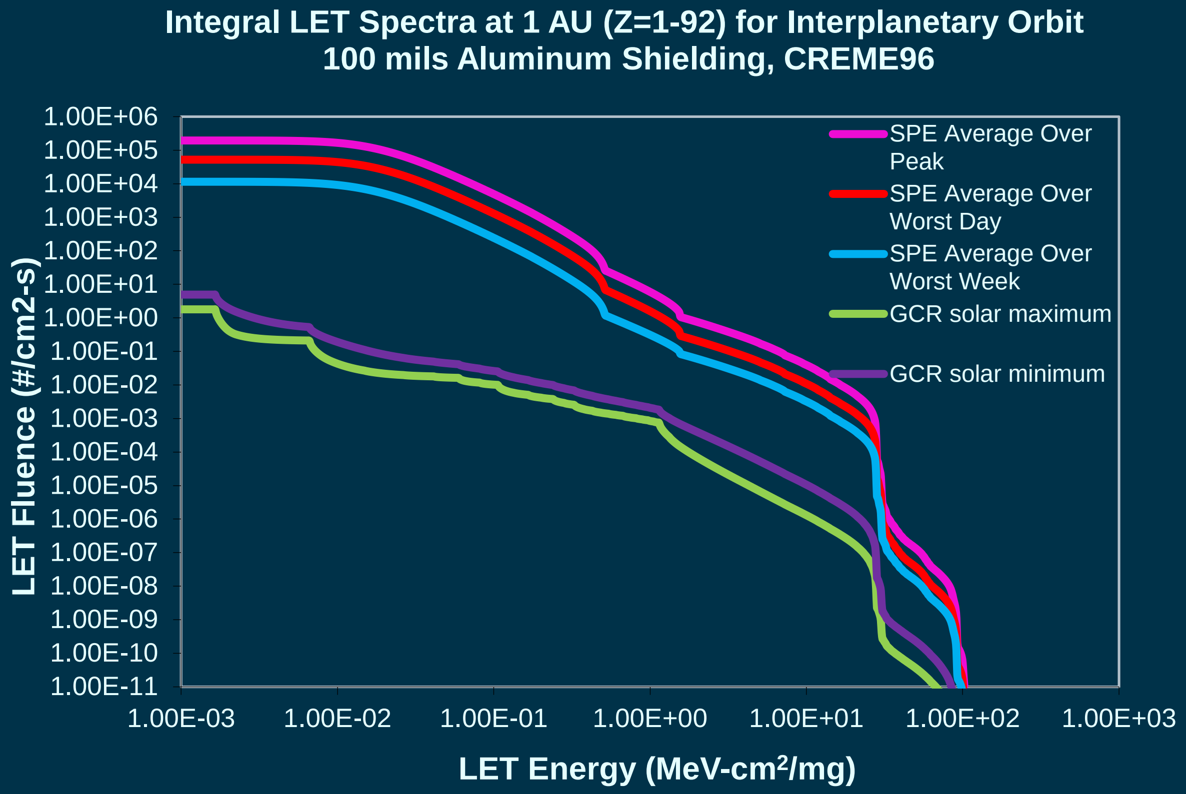
SEE ion environment



Integral LET Spectra at 1AU (Z=1-92) for Interplanetary GCRs
100 mils Aluminum Shielding, CREME96, Solar minimum

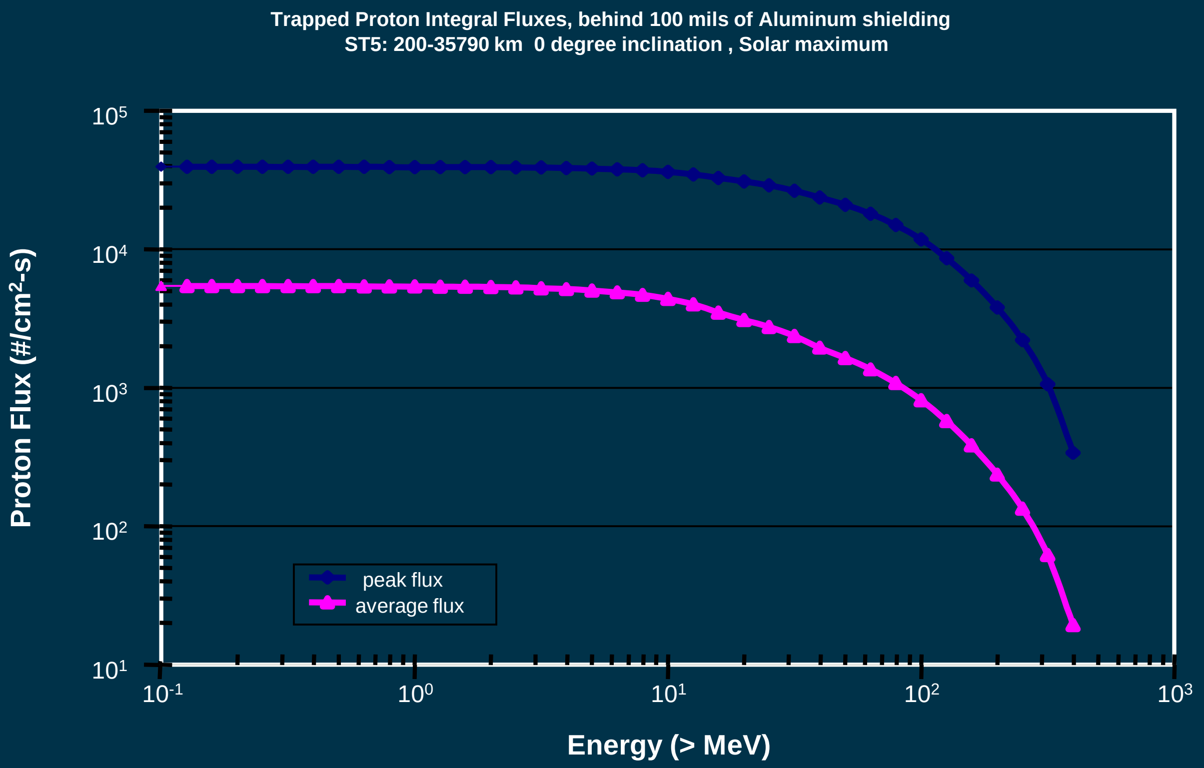


Ion SEE environment - GCRs and Solar Particles



- 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

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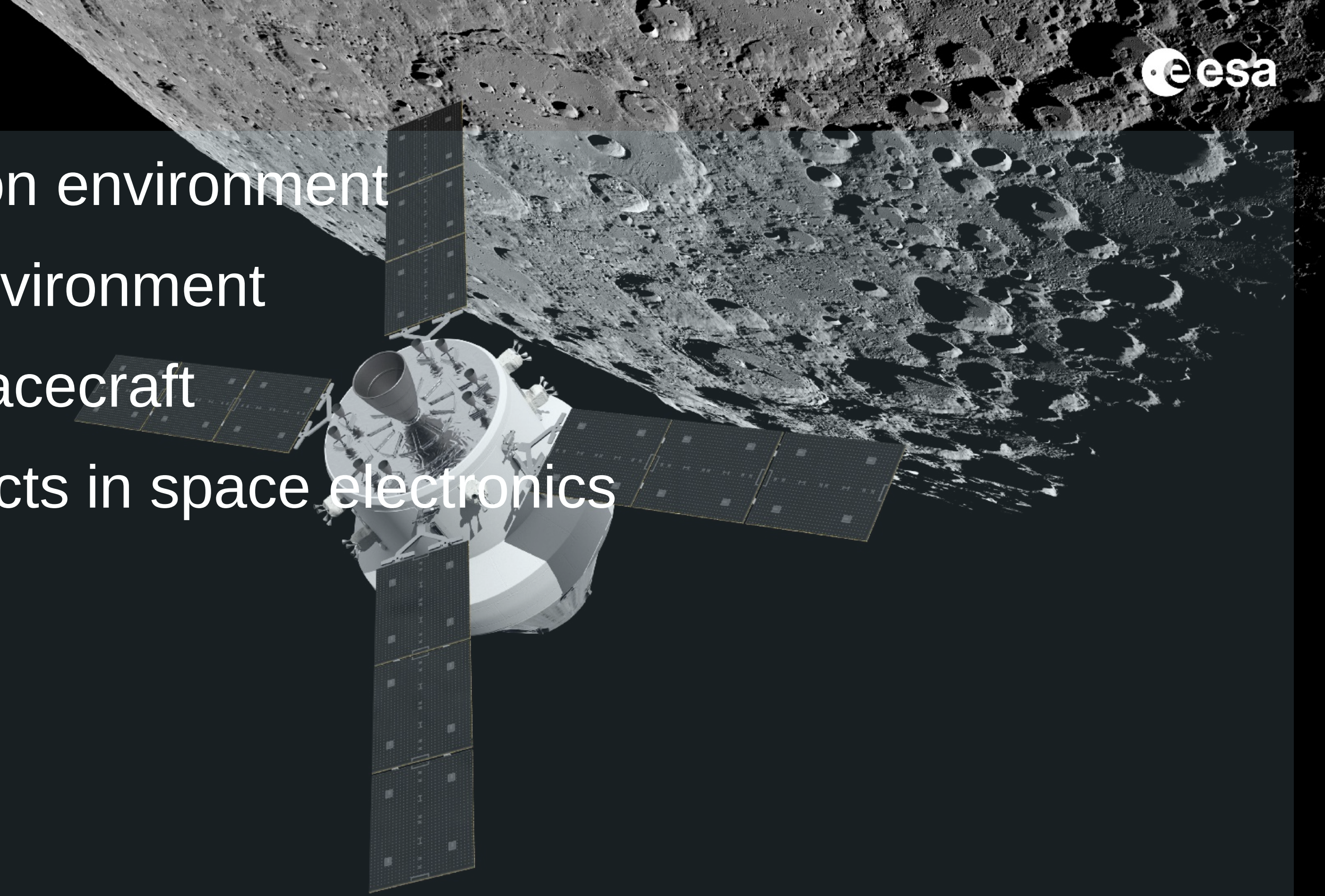
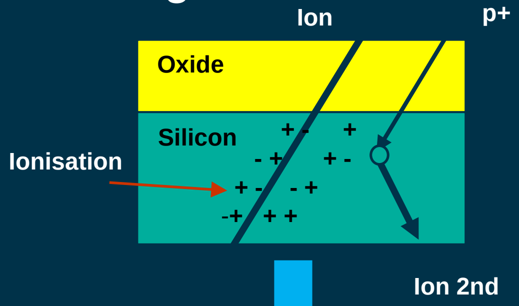


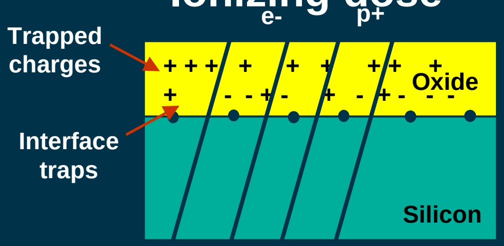
MAIN RADIATION EFFECTS

Single event effects

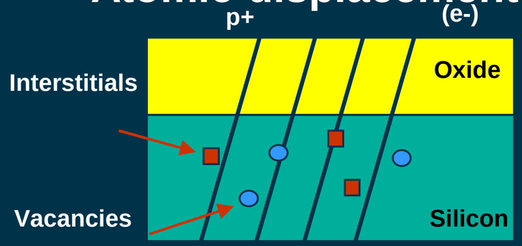


SET : transient
SEU : upset
SEL : latch-up
SEB : burn-out
SEGR : rupture

Ionizing dose



Atomic displacement



Parametric drift
Function loss

Lifetime

Hot pixels
RTS

Operating safety
Dependability/Availability
Performances

(S. Gerardin, RADECS2015 short course)

TID effects - Summary

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

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

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

Radiation Effects Testing – In a Nutshell

(*Adapted from Muschitiello & Costantino, SERESSA 2018*)

Total Ionizing Dose	Displacement Damage	Single Event Effects

Cumulative effect:
Gradual global degradation of device parameter

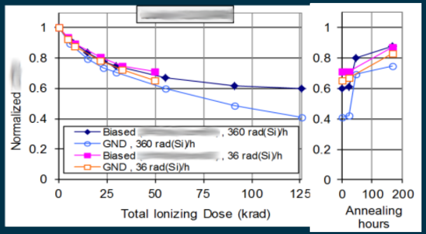
PERFORMANCE DEGRADATION
as function of :

Probabilistic effect:
transient, permanent or static errors.

CROSS SECTION
(=Probability of SEE occurrence)
as function of:

Total Ionizing Dose

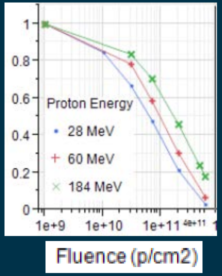
Total dose [rad(Si)] [Gy(Si)] – **Co-60**



Other irradiaton test parameters:
Dose rate [rad(Si)/s] [Gy(Si)]

Displacement Damage

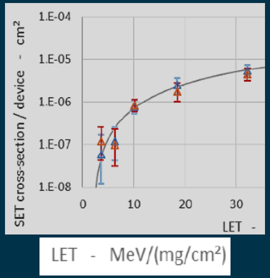
Fluence [p/cm^2] – **protons**
Displacement Damage Dose [MeV/g]



Other irradiation test parameter:
Proton Energy [MeV], Flux [p/cm^2/s]

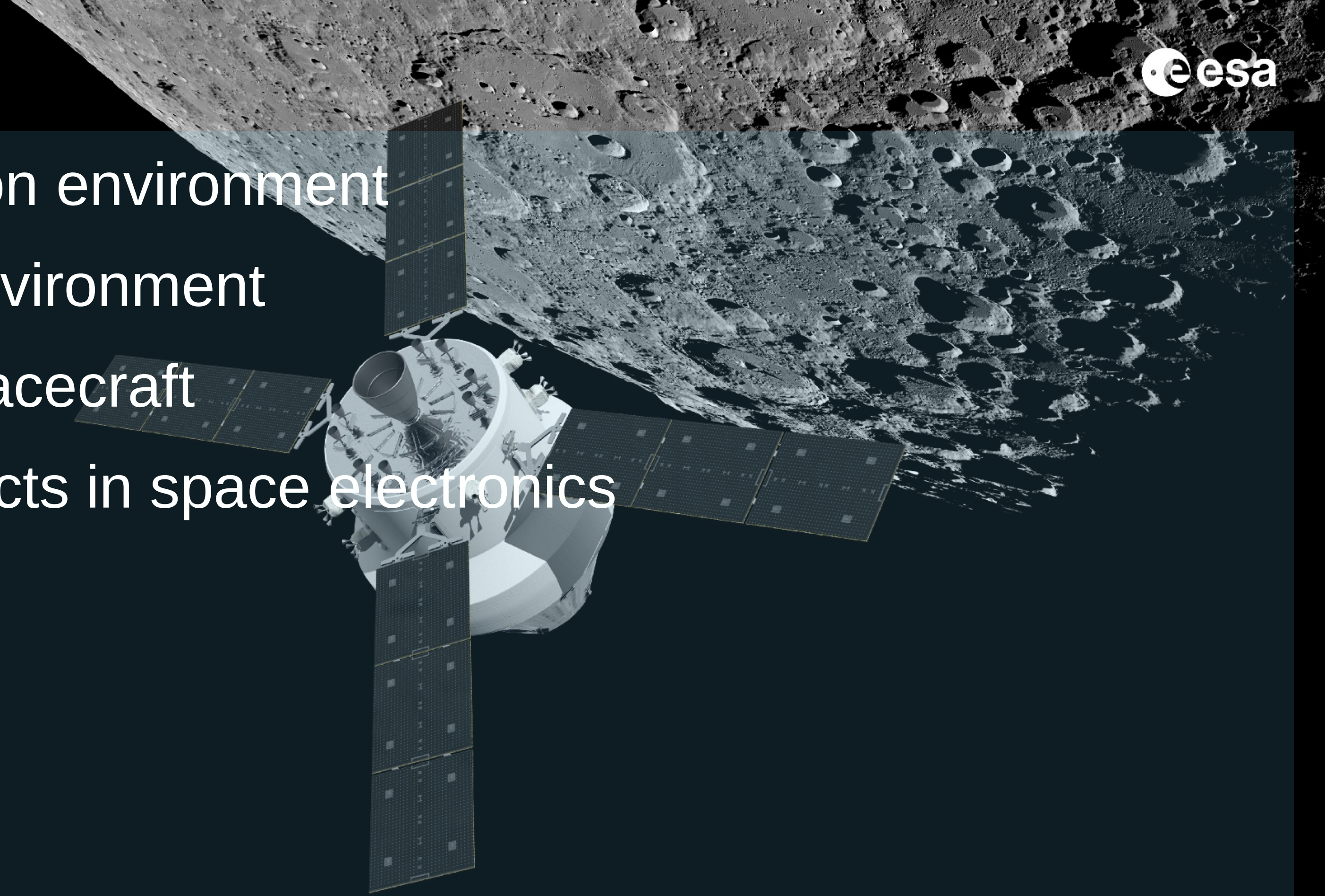
Single Event Effects

Linear energy transfer [MeV/mg/cm^2] – **ions**
Energy [MeV] - **protons**



Other irradiation test parameters:
Fluence [p/cm^2], Flux[p/cm^2/s] , particle range [um]

OUTLINE



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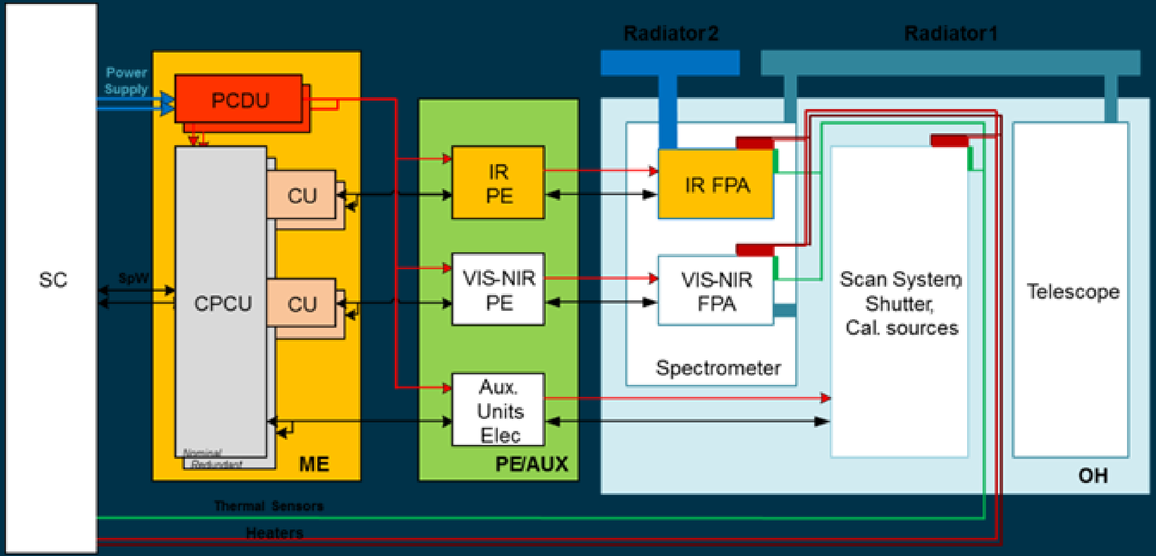
Typical Instrument Structure

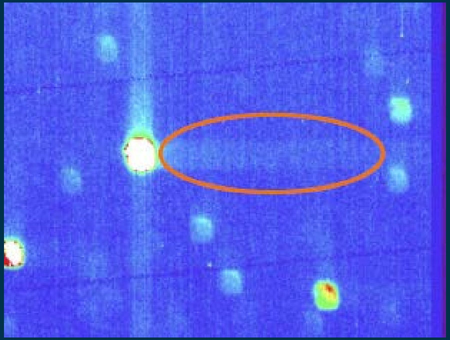


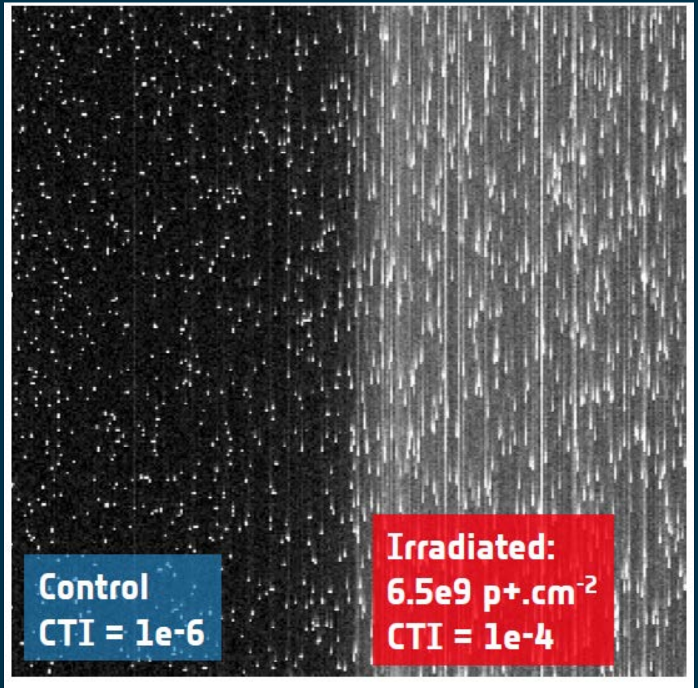
- Focal Plane
  - Sensor
- Proximity Auxiliary Electronic
  - Data Acquisition
  - AD Conversion
- Main Electronic
  - Digital Processing
  - Power Conditioning

Imager DD and TID – CCDs

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

Sensor degradation is a significant constraint for payloads

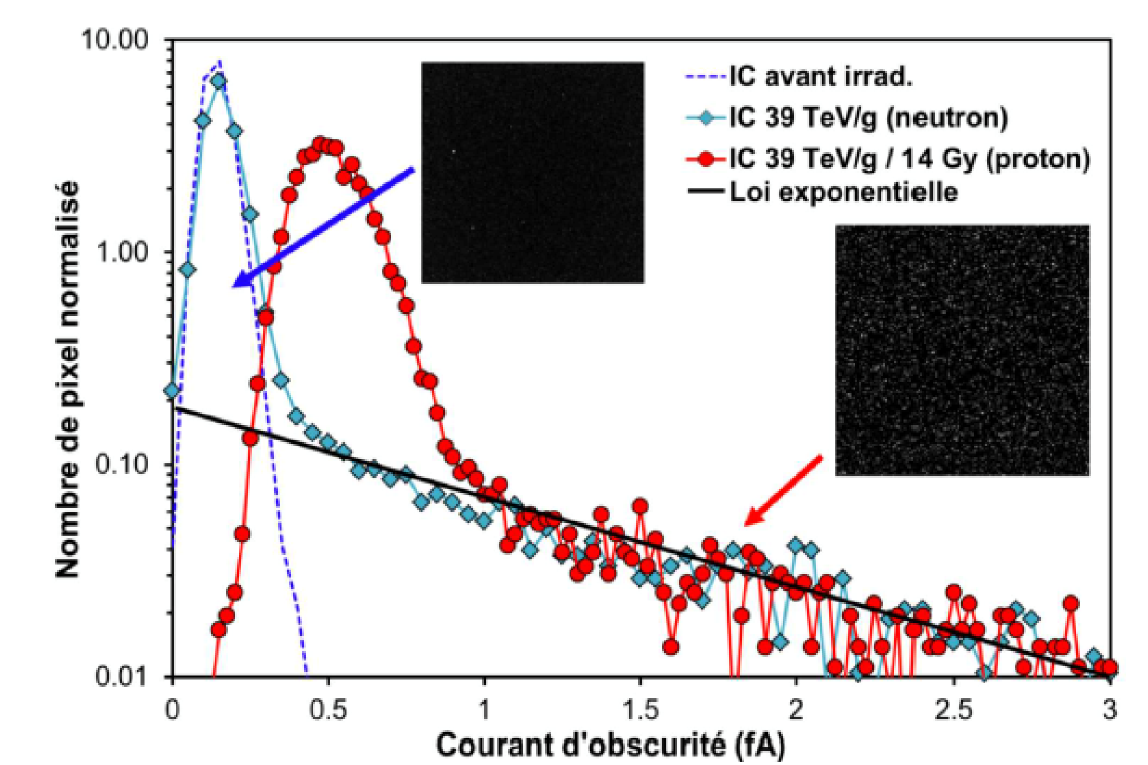




PLATO E2V CCD270, Image acquired while Illuminated by Fe55 X-ray source

(Prod'homme ESWW2016)

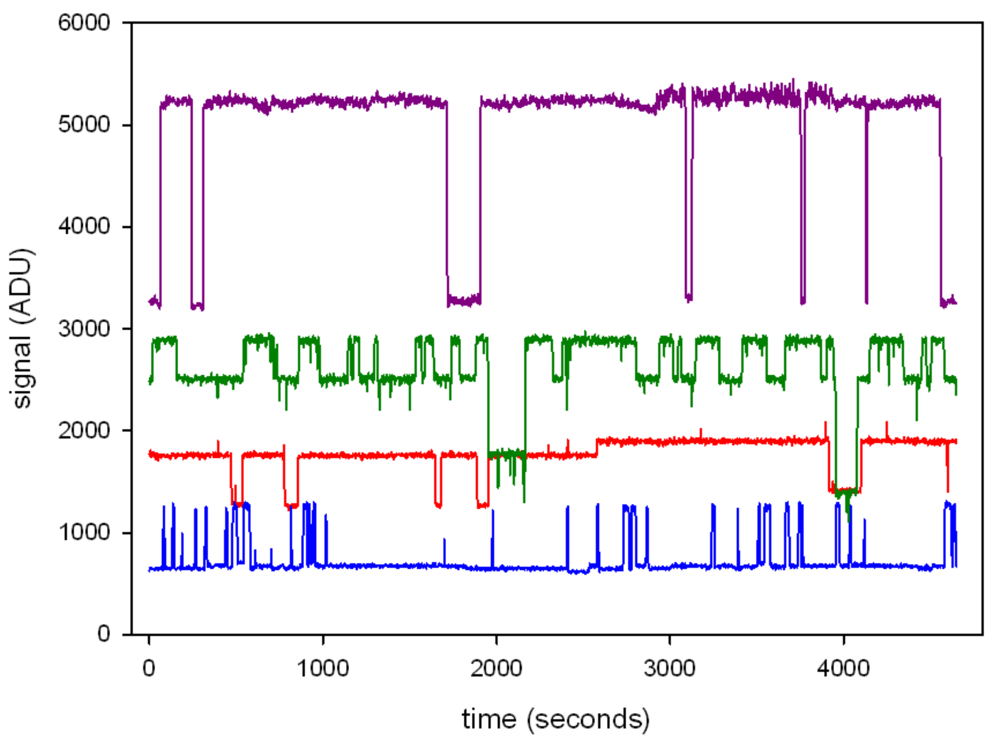
Imager Displacement Damage Effect – Hot Pixels



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

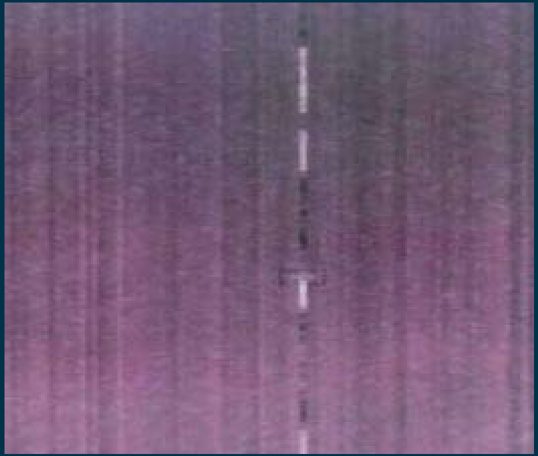
- Number of hot pixels is reduced at low temperature
- Hot pixels can be eliminated by software treatment of images.

Imager DD – Random Telegraph Signal (RTS)

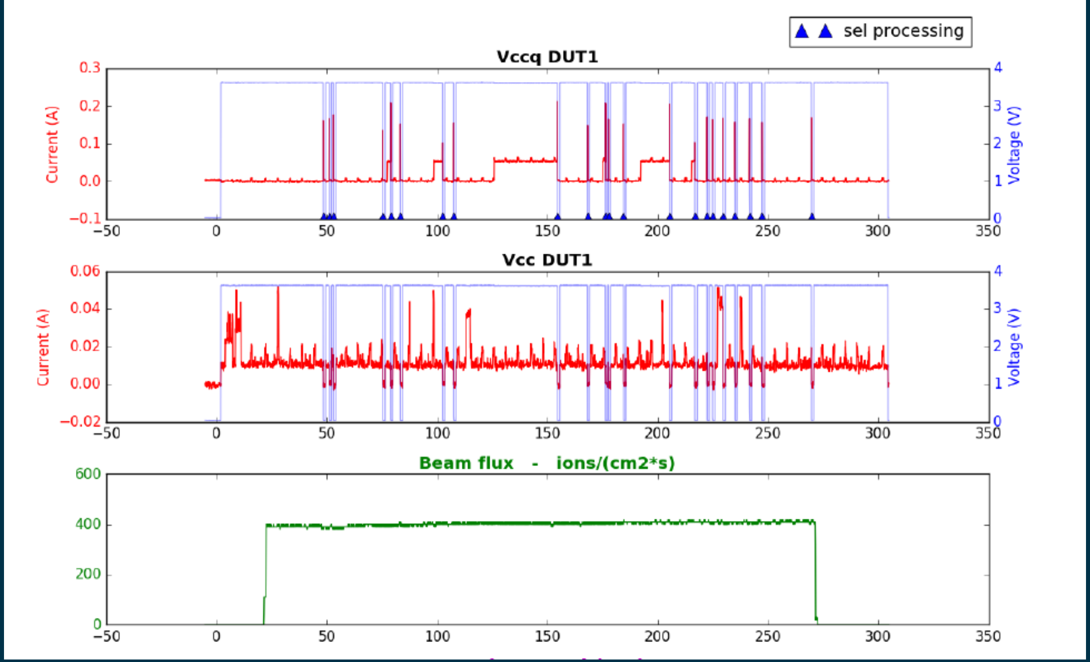


Sample of 4 CCD pixels showingRandom Telegraph Signal (RTS) behaviour at 23°C

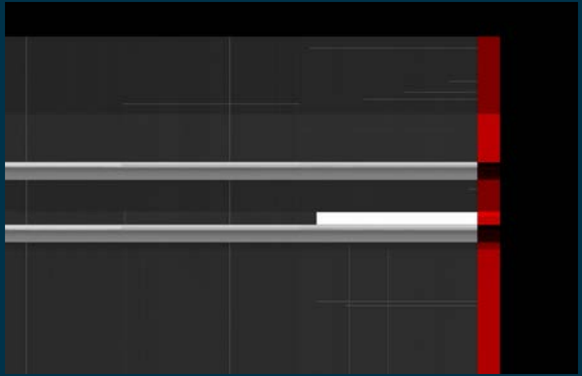
RTS disappears at low temperature

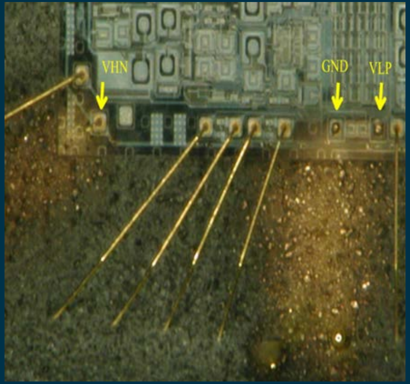


Imager + Readout - SEL



(Vermeiren, REODW 2012)

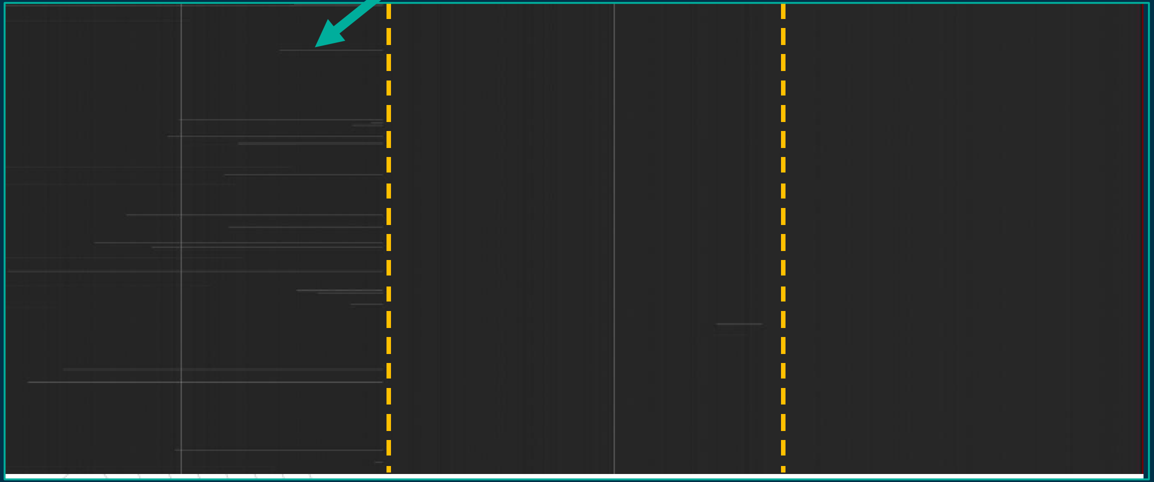




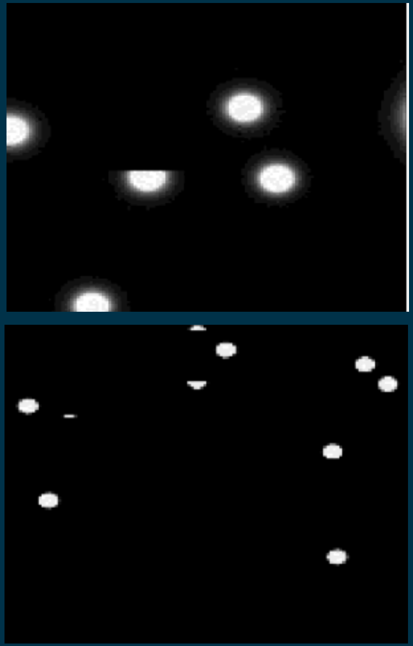
- High current condition during SEL can damage a part
- SEL sensitivity is reduced at low temperature

Imager + Readout - SEFI, SET

(Vermeiren, REODW 2012)



(Lalucaa, REODW 2012)



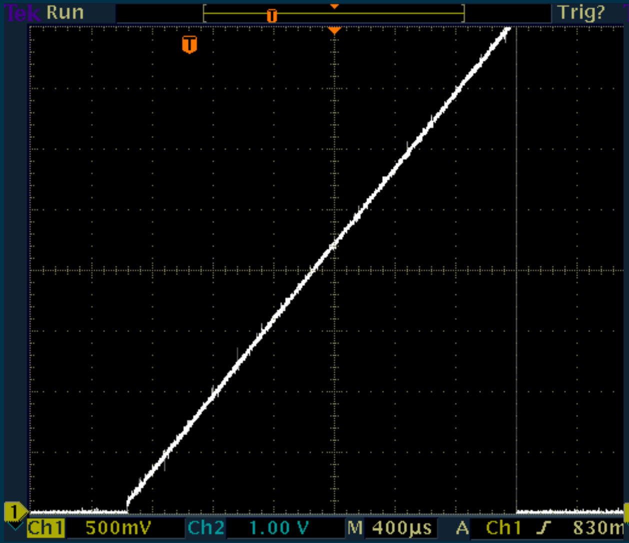
RESET and even Power Cycle is necessary to remove a SEFI condition

SET: Saturation of the pixels and sometimes blooming
SET last only one frame and can be removed by treatment of images

ADC – TID degradation

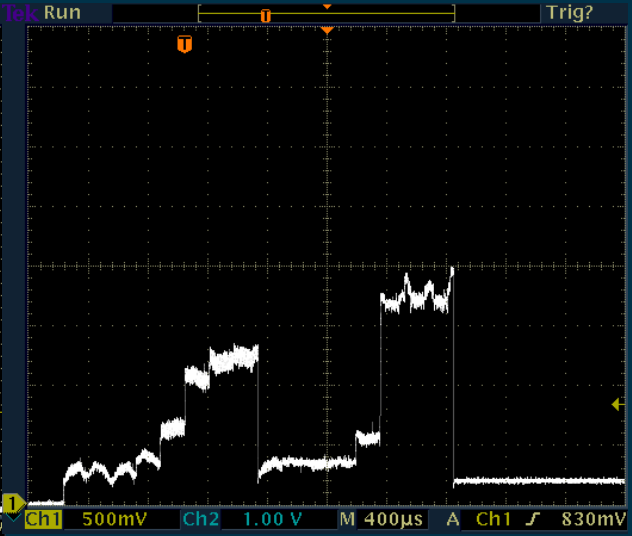
Significant loss of information

Complete loss of information



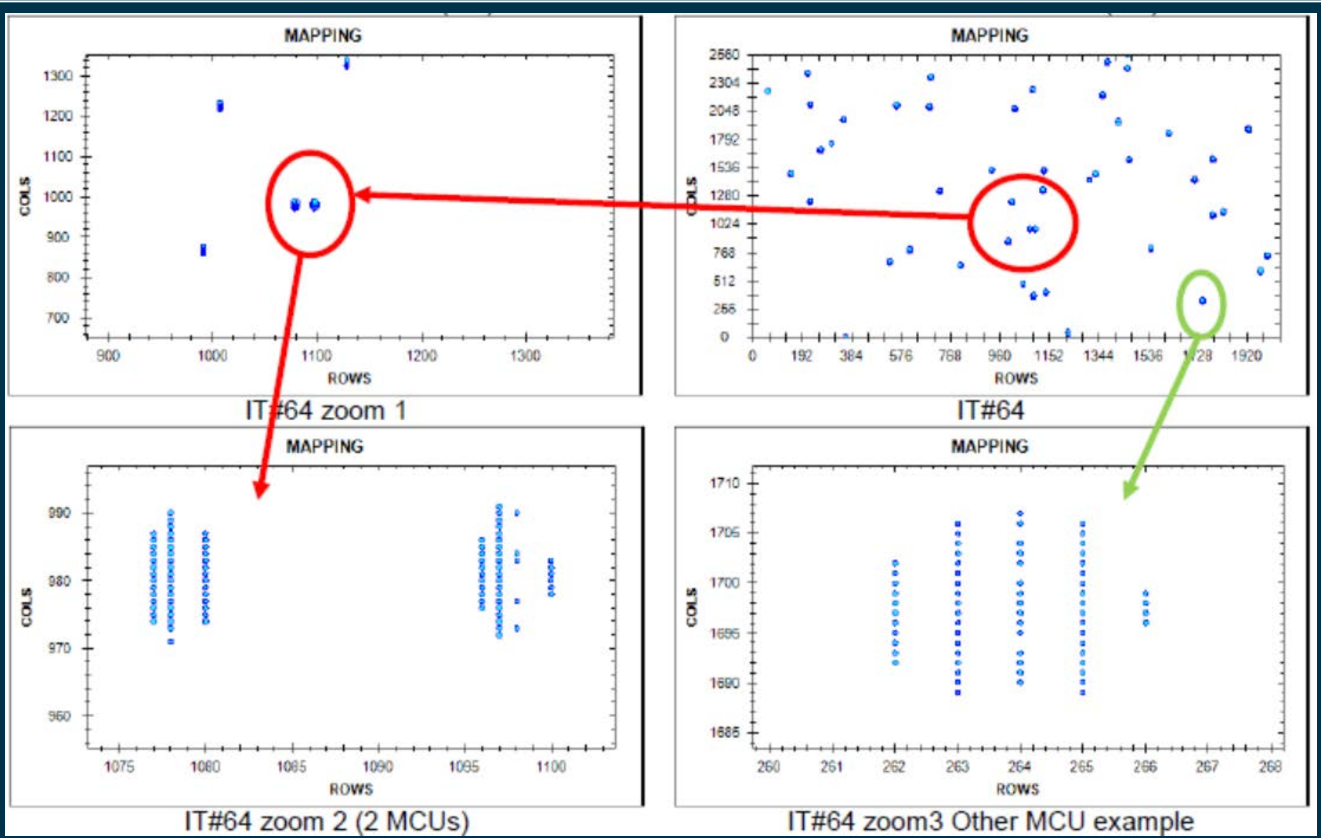
Before irradiation

5 Krad-Si
(50 Gy-Si)



10 Krad-Si
(100 Gy-Si)

Digital Devices - Memory - Multiple Cell Upsets (MCU)

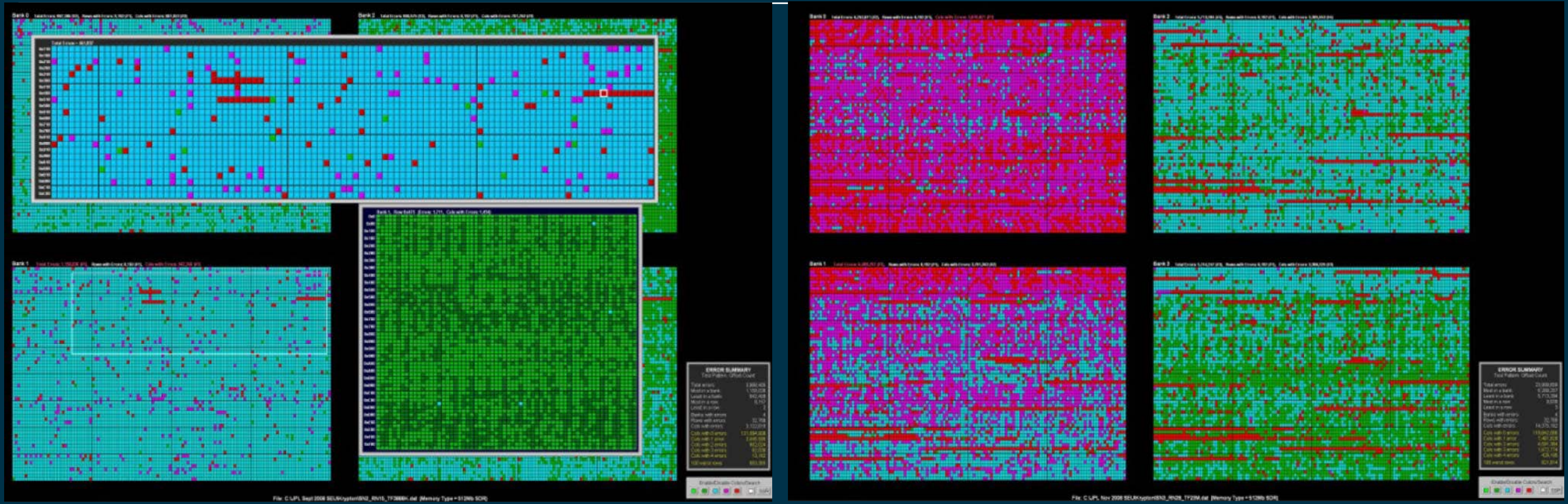


One ion strike can induce more than 100 cell SEUs in memories

MCUs are not an issue as long as impacted bits do not belong to the same data word

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

Digital Devices – SDRAM - SEFI



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)

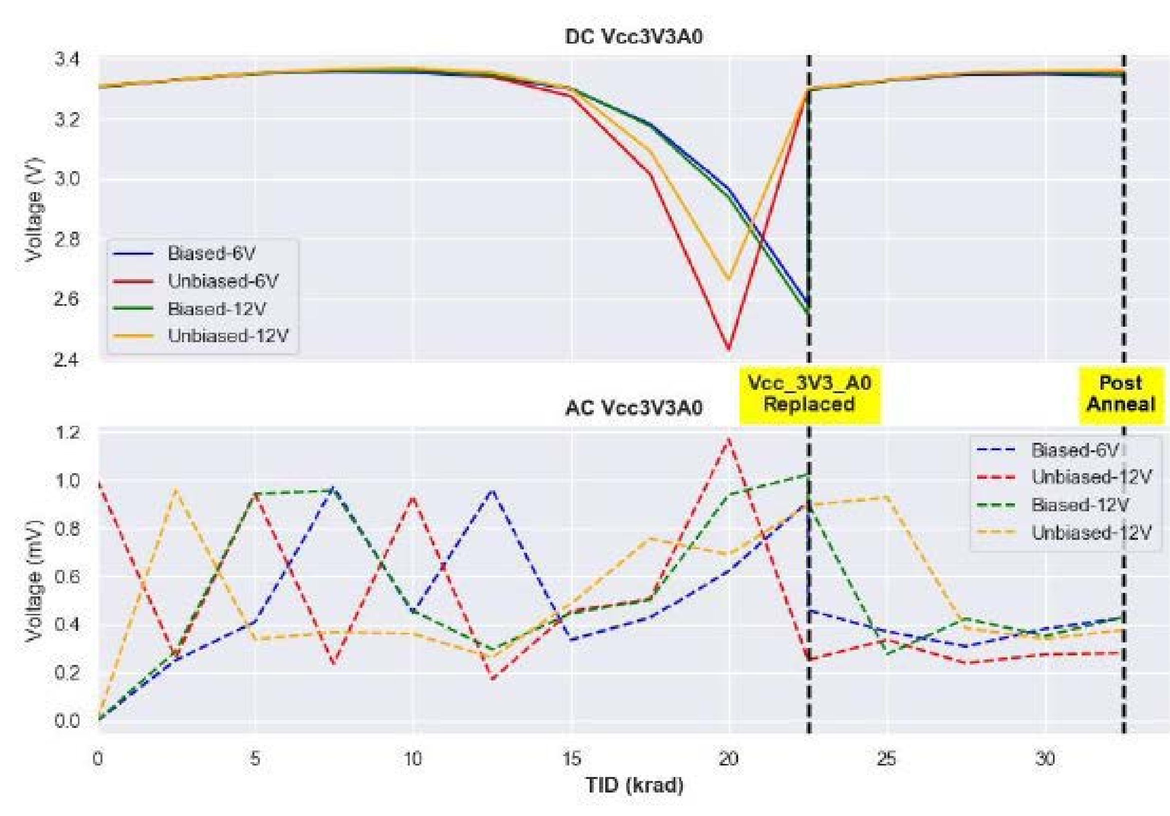
Reinitialisation or a power cycle are necessary to recover from SEFI. Memory content is lost in most cases

Digital Devices – Microcontroller, SoC – SEFI mitigation

MCU, SoC heartbeat
Watchdog output
MCU, SoC supply voltage
MCU, SoC supply current

When the processor hangs, no heartbeat is sent to the watchdog. Watchdog initiates a power cycle

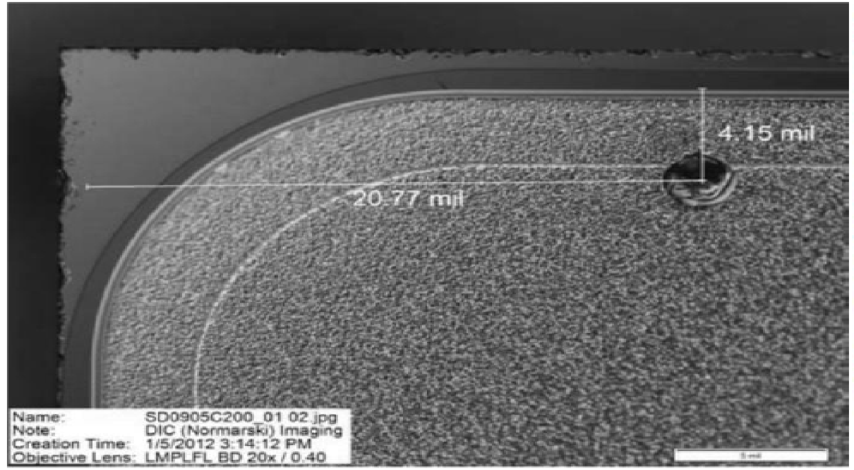
Power Device - DC-DC converter, Low Dropout Voltage Regulator TID Degradation

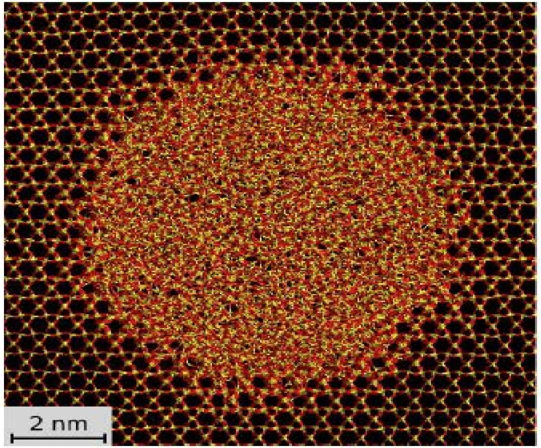


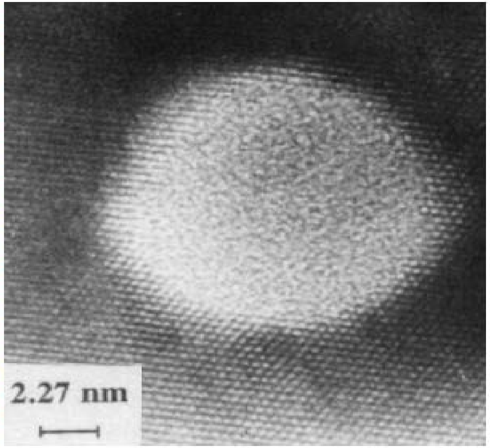
Output Voltage

When output voltage gets below 3V, parts supplied by this device will not work properly

Power Devices - 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)]

Destructive events in power diodes and FETs are avoided by derating the voltages applied to these devices (ie. a 100V transistor can only be used up to 50V)

Power Device – DC-DC converter – SEFI (shutdown event)

Input voltage

Input current

Output voltage

Self recovery

No recovery
(power cycle is needed for recovery)

Power Device – DC-DC converter, LDO - SET

Input voltage

Input current

Output voltage

Parts powered by this device will not work correctly during the SET

OUTLINE

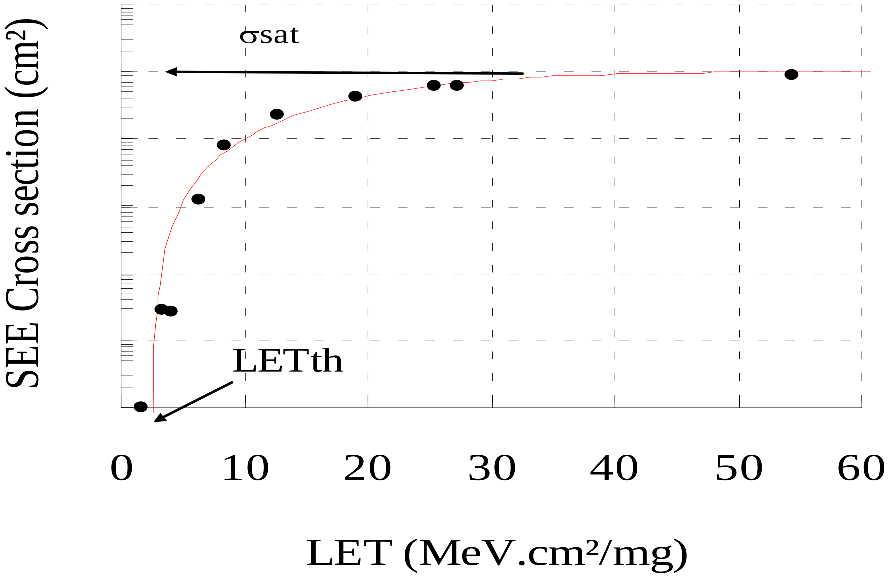
- Space radiation environment
  - External Environment
  - Inside a spacecraft
- Radiation effects in space electronics
  - Summary
  - Examples
- Conclusion

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.

BACK-UP SLIDES

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



- n
- t

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

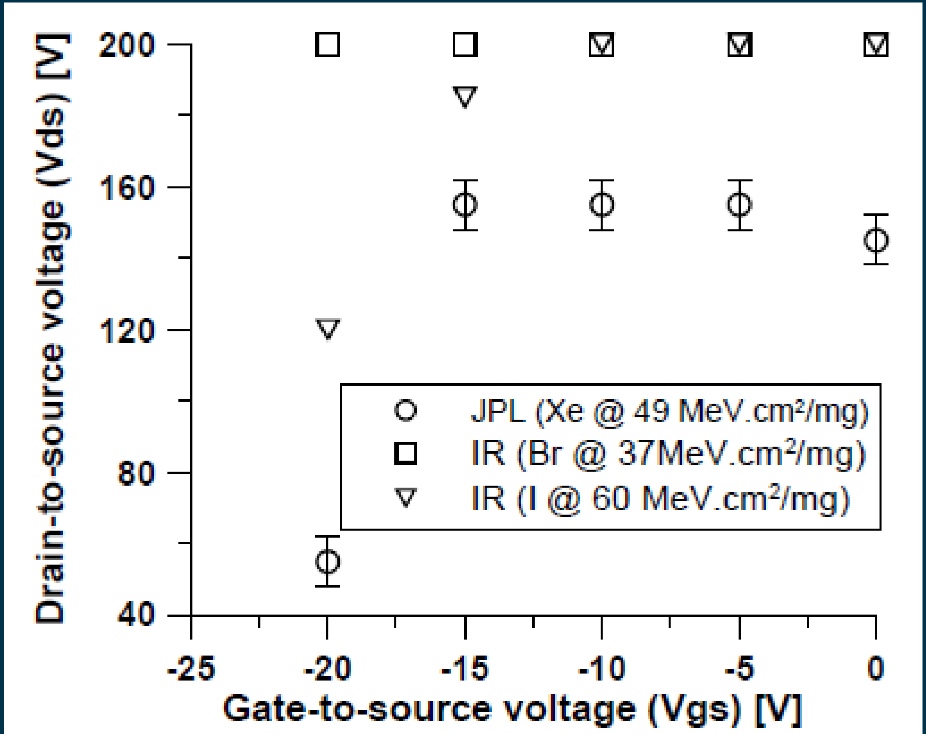
$$\sigma = \sigma_{sat}\left(1 - \exp\left(\frac{LET - LET_{th}}{W}\right)^{S}\right)$$

W and S are fitting parameters

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

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

Power MOSFETs, SEE Safe Operating Area, Example



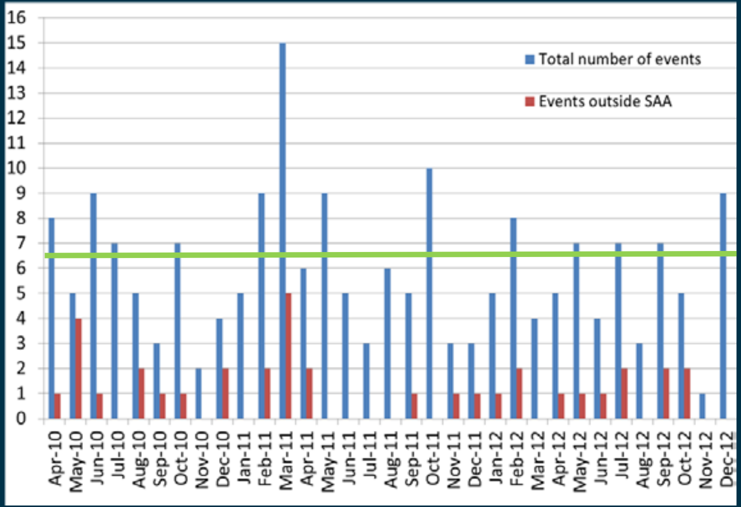
Manufacturer's data with short range ions

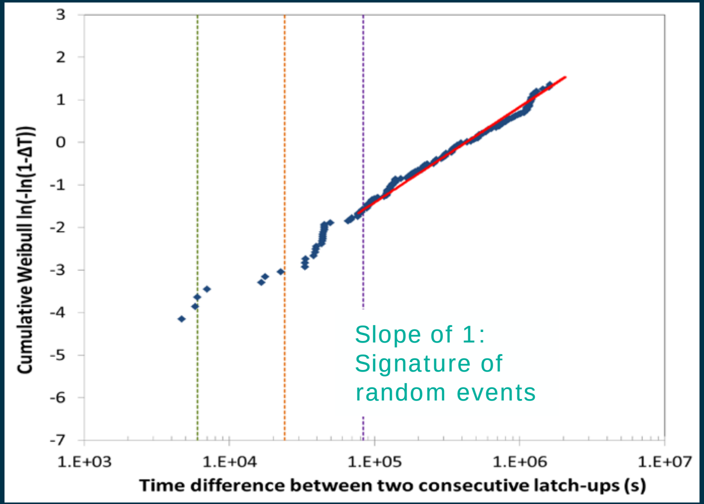
JPL data with long range ions

(L. Scheick, NSREC DW 2009)

SEEs are Random Events

Rate of occurrence is not steady, it varies randomly





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