FRONTGRADE
Gaisler

Radiation effects on microelectronics: overview, design and testing guidelines, and Frontgrade Gaisler case examples

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big science sweden

Radiation-hard electronics – challenges, design strategies and measurements
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PUBLIC

Agenda

01 Introduction

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03 Radiation effects on electronic components

04 Radiation effects mitigation

05 Radiation hardness assurance

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01

Introduction

FRONTGRADE Gaisler

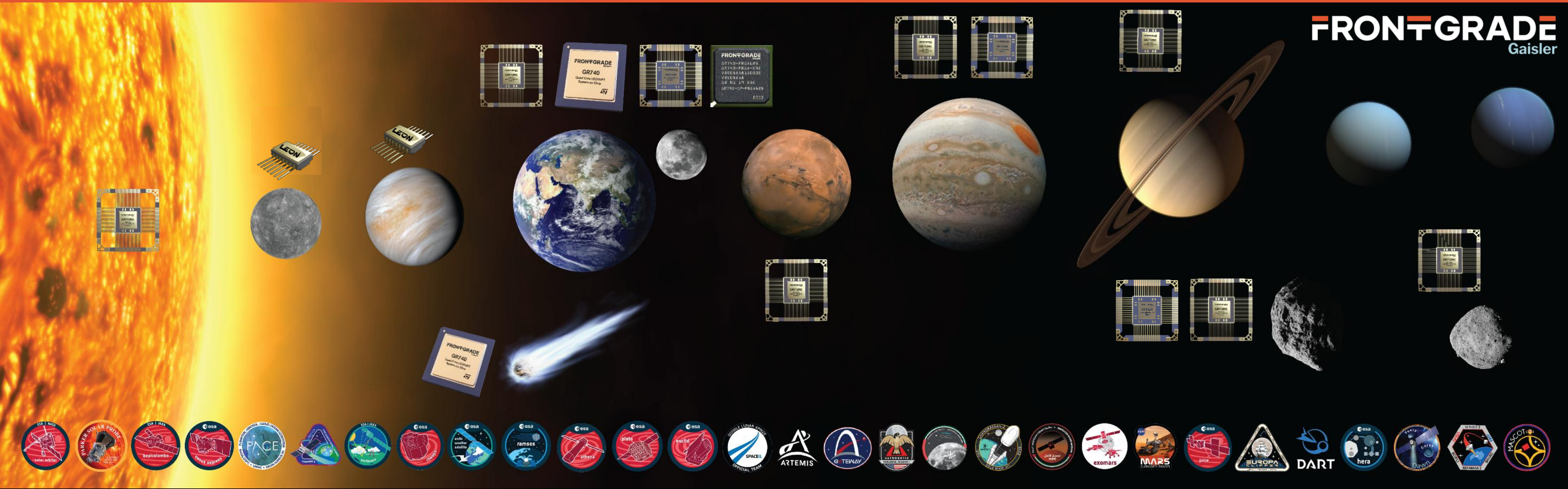
Established 2001 as a spin-off from Chalmers and European Space Agency

Located in Gothenburg, Sweden
75+ employees in Sweden, Germany, France, Spain, and United Kingdom

Experts in fault-tolerant computing

Focused mainly on

radiation hardened microprocessors



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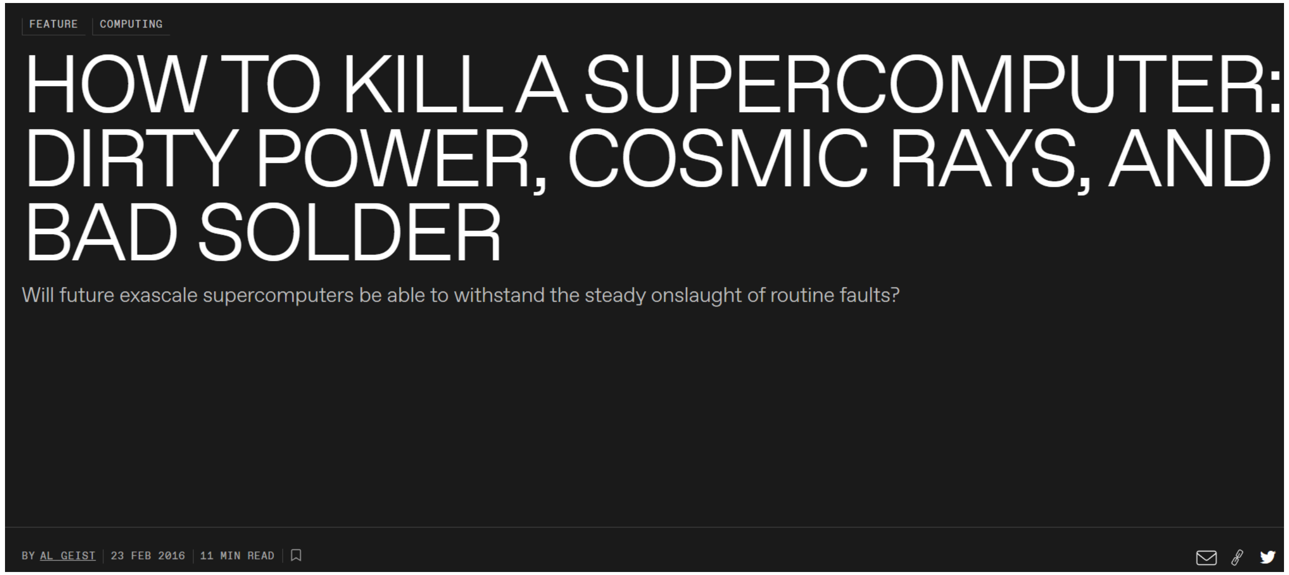
- World leader in radiation hardened space components (top three in the world) with a unique connection to ESA, EU, and NASA.
- Operating as a fab-less component supplier with manufacturing outsourced to foundries, assembly and test in Europe. In-house facilities for advanced hardware and software design.
- Customers – Airbus, Thales Group, Beyond Gravity, Lockheed Martin, Northrop Grumman, Boeing, L3Harris, Raytheon, Mitsubishi, ULA, and others.
- Applications – GPS III, Galileo, Copernicus, SDA Tranche 0, OneWeb, IridiumNEXT, Ariane 6, H3, Vulcan, Vega, ...

Introduction

Some context on radiation effects on electronic components… **Ground**

Supercomputers case(s)


FEATURE | COMPUTING

HOW TO KILL A SUPERCOMPUTER: DIRTY POWER, COSMIC RAYS, AND BAD SOLDER

Will future exascale supercomputers be able to withstand the steady onslaught of routine faults?

BY AL GEIST | 23 FEB 2016 | 11 MIN READ

https://spectrum.ieee.org/how-to-kill-a-supercomputer-dirty-power-cosmic-rays-and-bad-solder

Jaguar (2009 #1 Top 500 list):

"Just how many spurious bit flips are happening inside supercomputers already? To try to find out, researchers performed a study in 2009 and 2010 on the then most powerful supercomputer—a Cray XT5 system at Oak Ridge, in Tennessee, called Jaguar.

Jaguar had 360 terabytes of main memory, all protected by ECC. I and others at the lab set it up to log every time a bit was flipped incorrectly in main memory. When I asked my computing colleagues elsewhere to guess how often Jaguar saw such a bit spontaneously change state, the typical estimate was about a hundred times a day. In fact, Jaguar was logging ECC errors at a rate of 350 per minute.

In addition to the common case of a single cosmic ray flipping a single bit, in some cases a single high-energy particle cascaded through the memory chip flipping multiple bits. And in a few cases the particle had enough energy to permanently damage a memory location."

ECC = Error-Correcting Code

Introduction

Some context on radiation effects on electronic components… **Ground**

Toyota case

Toyota Problems Caused By Cosmic Rays? › NHTSA Supposedly Checking It Out

BY ROBERT N. CHARETTE | 16 MAR 2010 | 1 MIN READ

Robert N. Charette is a Contributing Editor and an acknowledged international authority on information technology and systems risk management.

https://spectrum.ieee.org/toyota-problems-caused-by-cosmic-rays

"The Detroit Free Press has a story today that claims the US National Highway Traffic Safety Administration (NHTSA) is investigating whether cosmic rays are the cause of Toyota's sudden acceleration problems.

According to the story, an anonymous tipster last month wrote NHTSA hypothesizing that, "It is possible that Toyota is using electronic parts that are more susceptible to SEUs [Single Event Upsets] than other manufacturers. Components such as RAM, DRAM, SRAM, FGPAs, ASICs, etc... can all be susceptible."

The tipster says that, "The automotive industry has yet to fully embrace fault-tolerant architectures and software development methods that are used widely by the avionics industry," and that the chips used by Toyota may not be hardened against interference."

Introduction

Some context on radiation effects on electronic components… **Aviation**

Airbus case

AIRBUS — Press Release

Airbus update on A320 Family precautionary fleet action

Toulouse, France, 28 November 2025 – Analysis of a recent event involving an A320 Family aircraft has revealed that intense solar radiation may corrupt data critical to the functioning of flight controls.

Airbus has consequently identified a significant number of A320 Family aircraft currently in-service which may be impacted.

Airbus has worked proactively with the aviation authorities to request immediate precautionary action from operators via an Alert Operators Transmission (AOT) in order to implement the available software and/or hardware protection, and ensure the fleet is safe to fly. This AOT will be reflected in an Emergency Airworthiness Directive from the European Union Aviation Safety Agency (EASA).

Airbus acknowledges these recommendations will lead to operational disruptions to passengers and customers. We apologise for the inconvenience caused and will work closely with operators, while keeping safety as our number one and overriding priority.

https://www.airbus.com/en/newsroom/press-releases/2025-11-airbus-update-on-a320-family-precautionary-fleet-action

Introduction

Some context on radiation effects on electronic components… **Space**

SpaceX Crew Dragon 2021 case

Fire, Fire

The SpaceX Crew Dragon dubbed Resilience, currently docked to the International Space Station after launching in November of last year, just reportedly scared the bejesus out of the station's crew.

The capsule "annunciated false emergency messages for Fire and Rapid Depress as well as other erroneous messages yesterday," *NASASpaceFlight* managing editor Chris Bergin reported in a Thursday afternoon tweet. "ISS crew ran responses for Fire and Rapid depress but stood down once stable readings were confirmed."

https://futurism.com/the-byte/emergency-alarm-spacex-dragon-space-station

According to Bergin, the ISS reported that the issue was likely a "Single Event Upset" on one of the Crew Dragon's power units, causing a processor to reset "and output data which the ISS interpreted as a collection of emergencies and off-nominal indications."

02

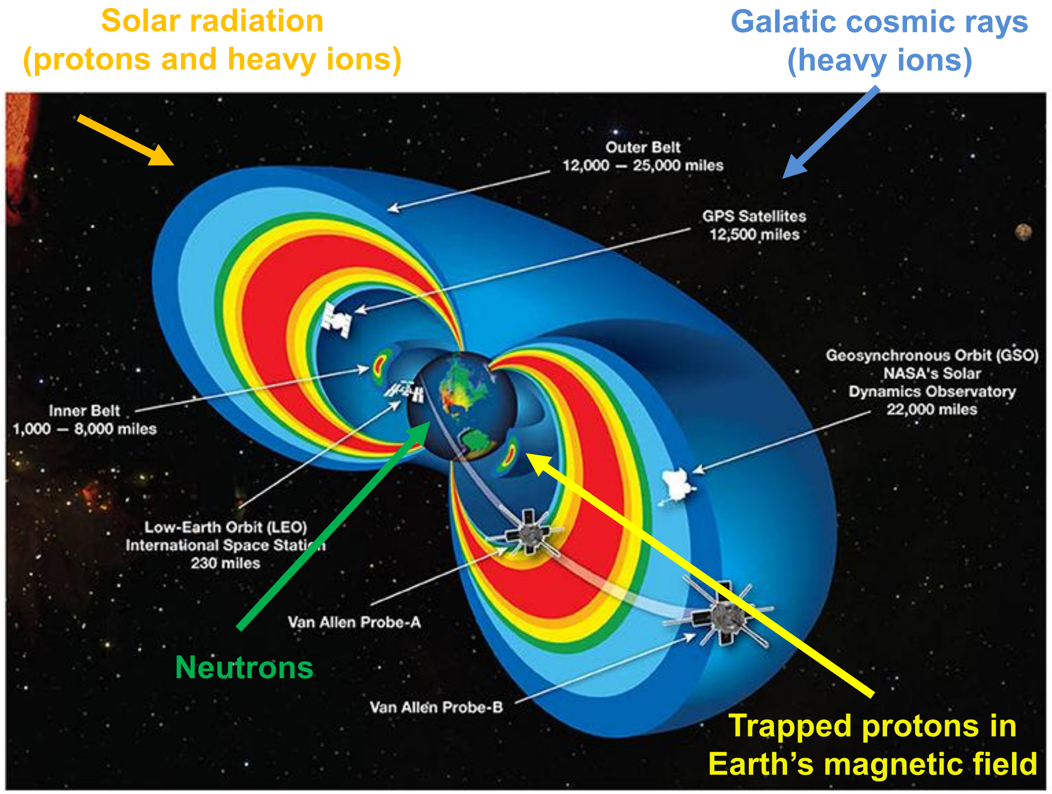
Space radiation environment

Space radiation environment

Radiation sources

Space

- Galactic cosmic rays → Heavy ions, Protons
- Solar radiation → Protons, Heavy ions
- Van Allen belts → Protons, Electrons



Credit: NASA.

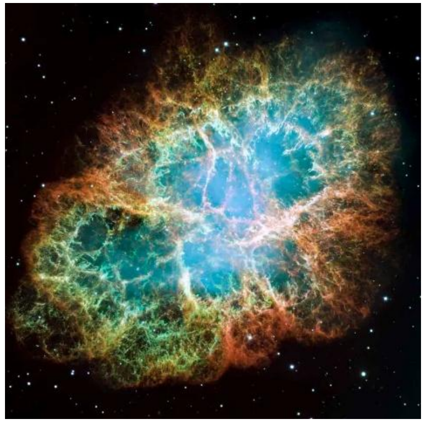
Space radiation environment

Radiation sources

Space

↓

Galactic cosmic rays	Solar radiation	Van Allen belts
↓	↓	↓
Heavy ions **Protons**	Protons Heavy ions	Protons Electrons



Credit: NASA.

Typically found in free space
(outside the Earth's magnetic field).

Originated outside our solar system by:

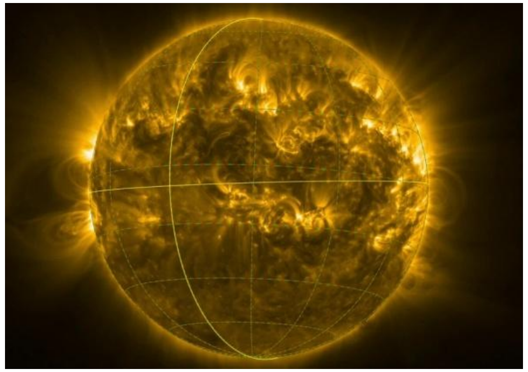
- Supernova explosions.
- Cellestial body collisions.
- Other major events.

Space radiation environment

Radiation sources

Space

Galactic cosmic rays	**Solar radiation**	Van Allen belts
Heavy ions Protons	**Protons** **Heavy ions**	Protons Electrons



Credit: ESA.

Generated by the solar activity:

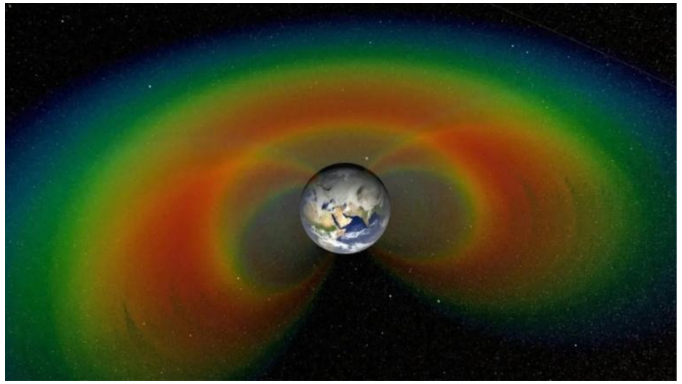
- Solar wind.
- Solar flares.
- Coronal mass ejections.

Space radiation environment

Radiation sources

Space

Galactic cosmic rays	Solar radiation	**Van Allen belts**
Heavy ions Protons	Protons Heavy ions	**Protons** **Electrons**



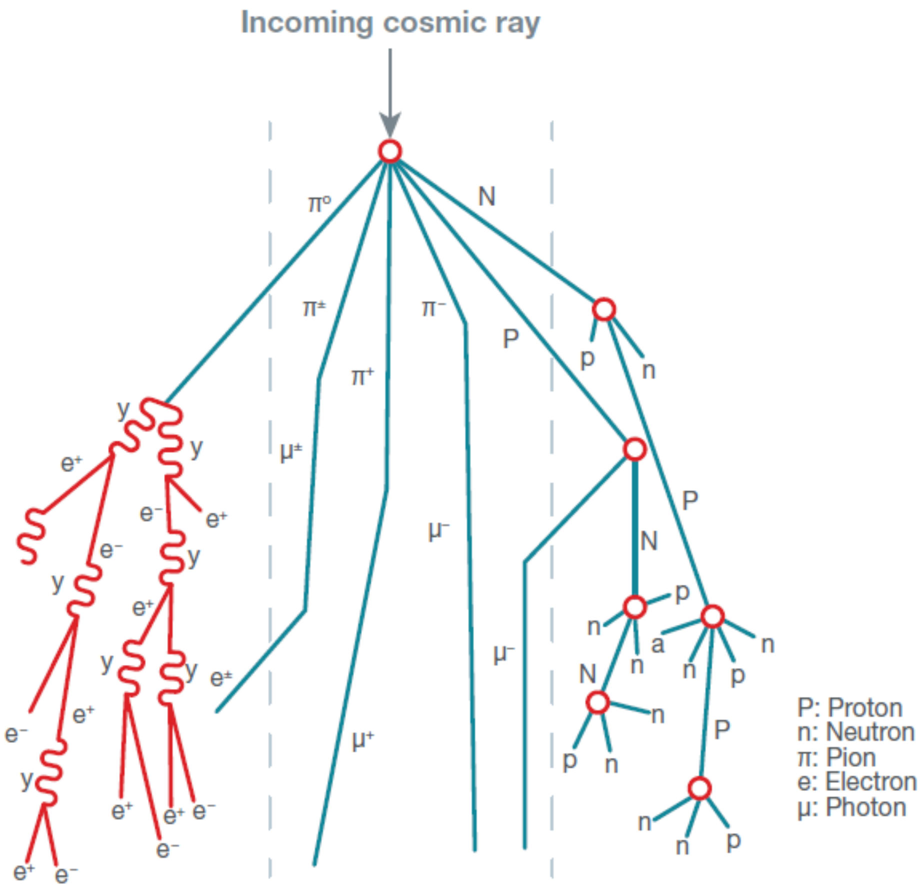
Credit: NASA.

Radiation belts can form around any planetary body that has a magnetic field (magnetosphere) of sufficient strength to divert and capture particles before they can enter the planet’s atmosphere.

The Earth’s magnetic field collects and traps protons and electrons, creating doughnut-shaped (toroidal) concentrated regions of trapped charged particles in the vicinity of Earth.

Space radiation environment

Terrestrial radiation environment



Credit: Texas Instruments.

Coulombic interactions in the upper atmosphere quickly stop heavier ions (and alpha particles), leaving only the high-energy protons to react in the upper atmosphere.

The protons undergo nuclear reactions via strong force, with oxygen and nitrogen nuclei producing huge and complex *cascades of "secondary" particles that shower down through the atmosphere to the Earth's surface*.

The *predominant particle fluxes at sea level include muons, protons, electrons, neutrons and pions*. Due to their relatively high flux and stability, the *neutrons are the most likely cosmic radiation to induce effects in devices at terrestrial altitudes*.

13 n/(cm²·h) @ sea level, according to JEDEC JESD89A.

The neutron flux increases with altitude, being hundreds of times higher at commercial flight altitudes.

Space radiation environment

Summary of environmental hazards

Environment

Mission Lifetime	LEO Equatorial	LEO Polar (Sun Sync)	GEO / Interplanetary
> 3 Years	Moderate Dose / Attenuated GCR, Trapped Proton, SAA, Some Solar Proton dependence for variation	High Dose / Higher GCR, High Energy Trapped Protons in SAA and Poles, Some Solar Proton dependence for variation	High Dose / High GCR, High Solar Proton Variability
1 - 3 Years	Manageable Dose / Attenuated GCR, Trapped Proton, SAA, Some Solar Proton dependence for variation	Moderate Dose / Higher GCR, High Energy Trapped Protons in SAA and Poles, Some Solar Proton dependence for variation	High Dose / High GCR, High Solar Proton Variability
< 1 Year	Manageable Dose / Attenuated GCR, Trapped Proton, SAA, Some Solar Proton dependence for variation	Moderate Dose / Higher GCR, High Energy Trapped Protons in SAA and Poles, Some Solar Proton dependence for variation	Moderate Dose / High GCR, High Solar Proton Variability

Credit: NASA.

Degradation has a strong dependence not only on where you go, but also how long you stay on orbit.

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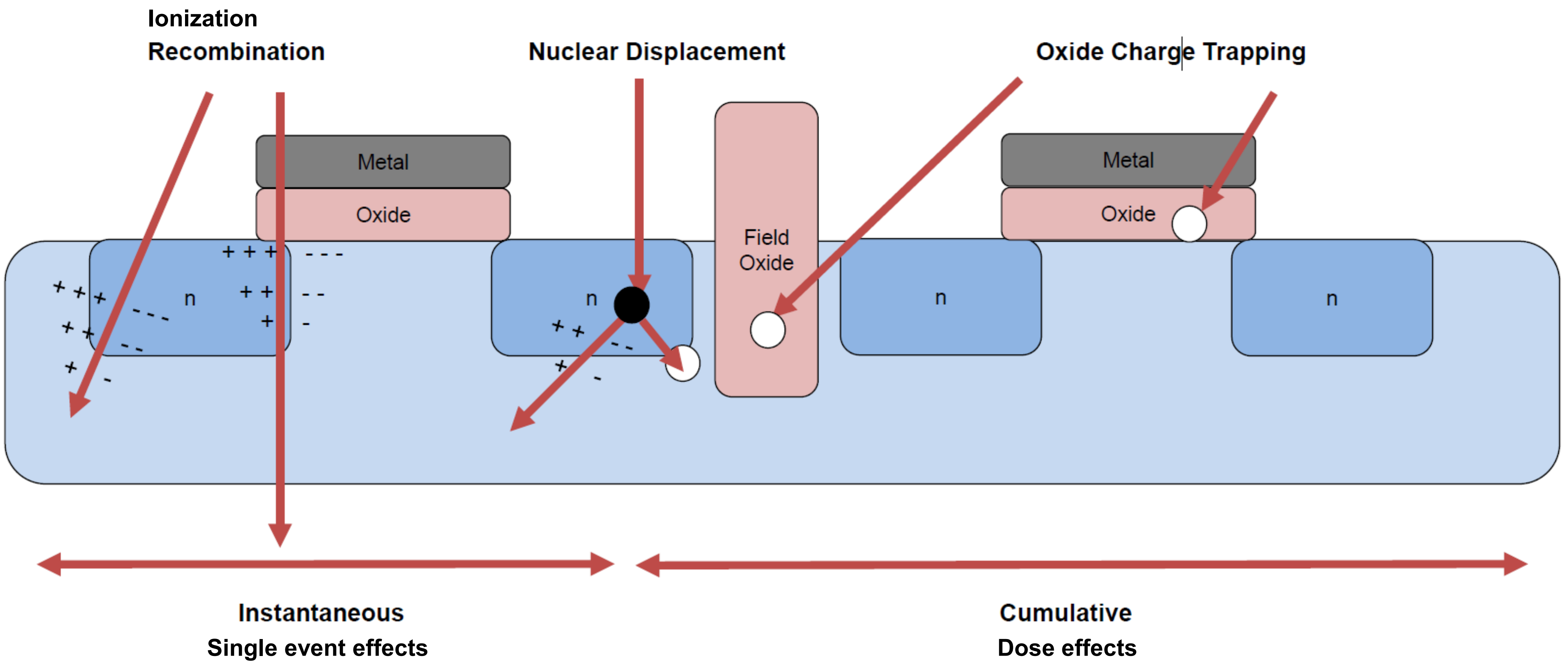
03

Radiation effects on electronic components

Radiation effects on electronic components

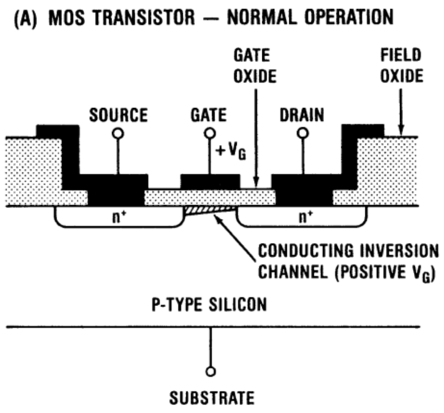
Particle and device interaction



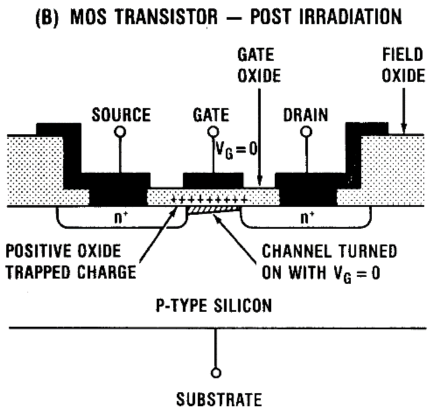
Radiation effects on electronic components

Dose effects – Total Ionizing Dose (TID)

Dose effects are characterized by *lasting parametric shifts that accumulate over time* due to chronic radiation exposure (a large number of radiation events), ultimately *leading the semiconductor device to drift out of tolerance and eventually fail*.



Applying adequate voltage on gate creates a conducting channel between the source and the drain: the device is ON!



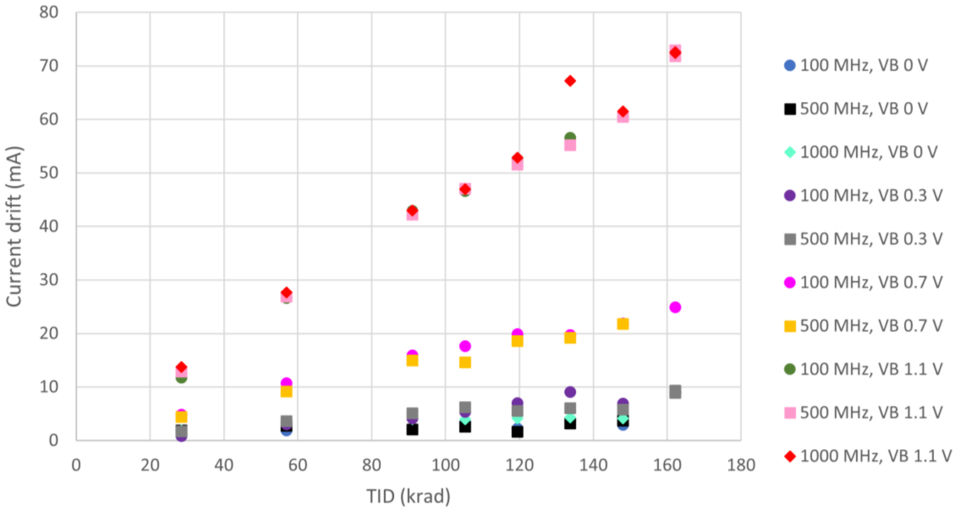
Due to ionizing radiation, the charges trapped in gate oxide cause a shift in the threshold voltage necessary to turn device ON.

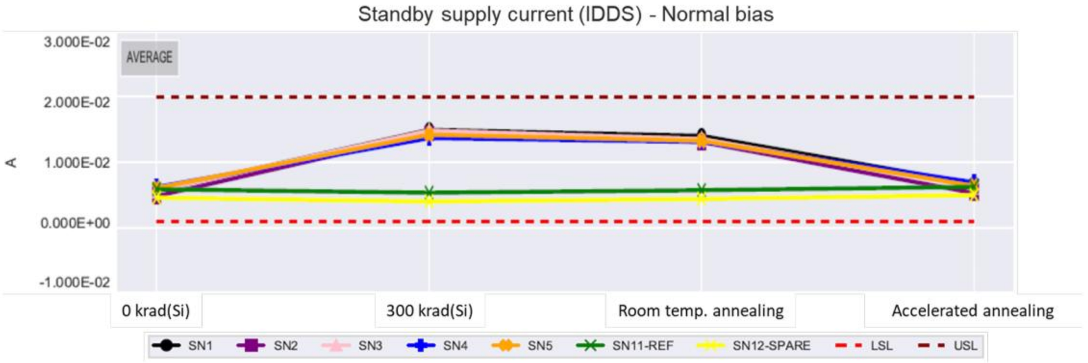
If the shift significant enough, then the transistor cannot be turned OFF even at gate voltage = 0V.

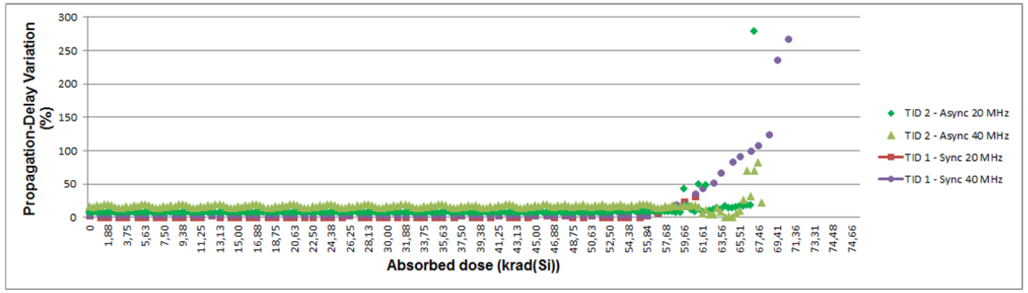
Radiation effects on electronic components

Dose effects – Total Ionizing Dose (TID)

Unit:
- Radiation absorbed dose: rad(Si)
    - 1 rad = 100 erg/g = 0.01 J/kg.
    - 100 rad = 1 Gy.
- This is not exposure (R), or dose equivalent (Sv).



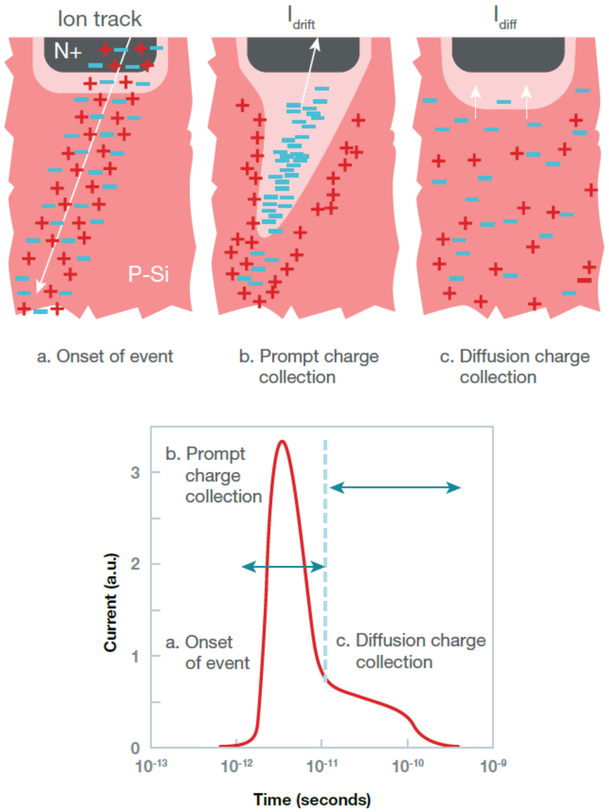




Radiation effects on electronic components

Single Event Effect (SEE)

SEEs are *random, <u>instantaneous disruptions</u> triggered by the passage of a single energetic particle*. One radiation event equals one upset occurrence. An upset could lead to failures in more than one device or bit for each individual radiation event.



Units:

- Heavy ions:
  - Linear Energy Transfer (LET), MeV·cm²/mg.
    - Stopping power normalized to target material.
- Protons:
  - Energy, MeV.

- Cross section (σ):
  - Device-particle interaction (cm²).
  - Used in calculation of rate.
  - Can be /device or /bit.

Radiation effects on electronic components

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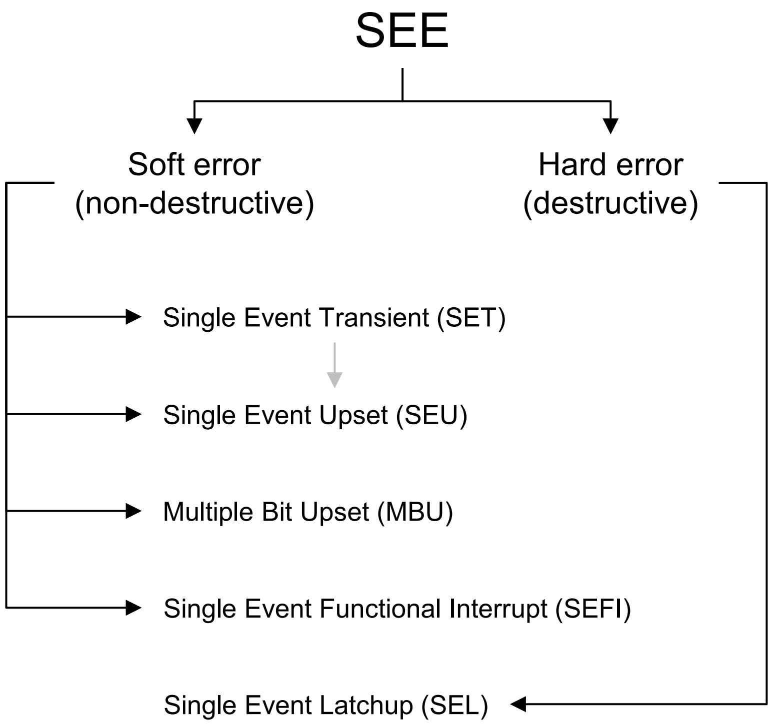
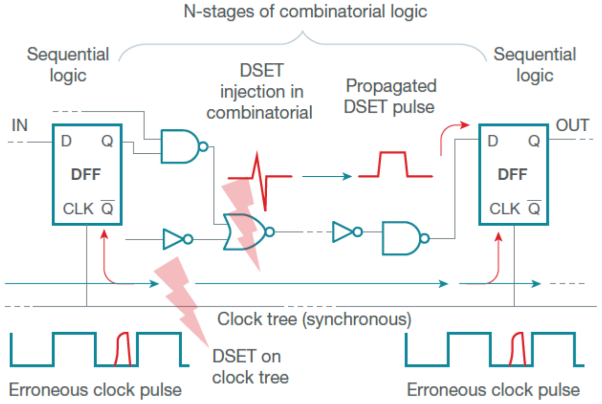
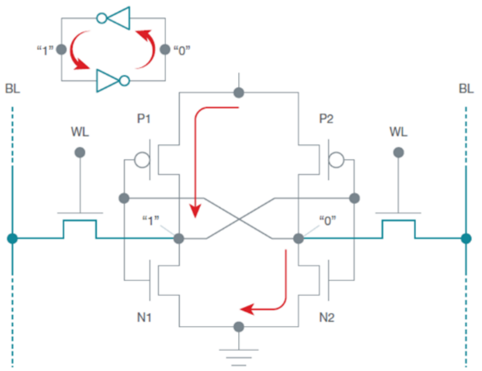
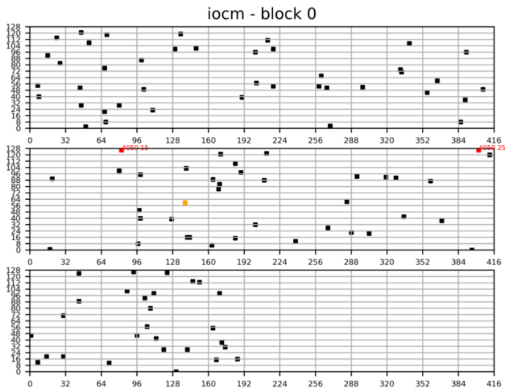






Example of SET.



Example of SEU.

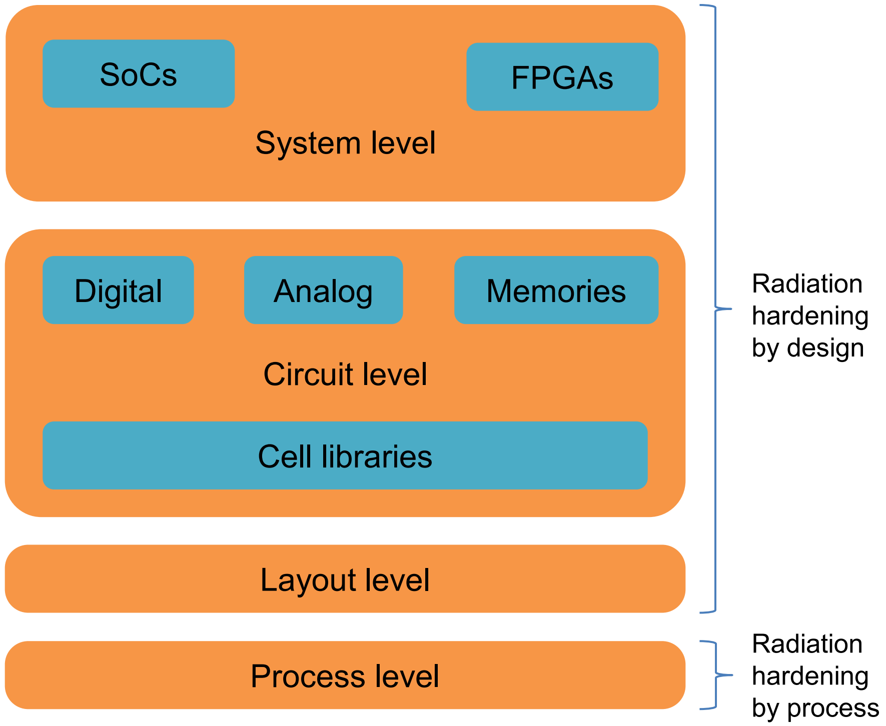
04

Radiation effects mitigation

Radiation effects mitigation

Overview

Different mitigation techniques can be applied at different abstraction levels and stages of the development of a radiation-hardened component.



Radiation effects mitigation

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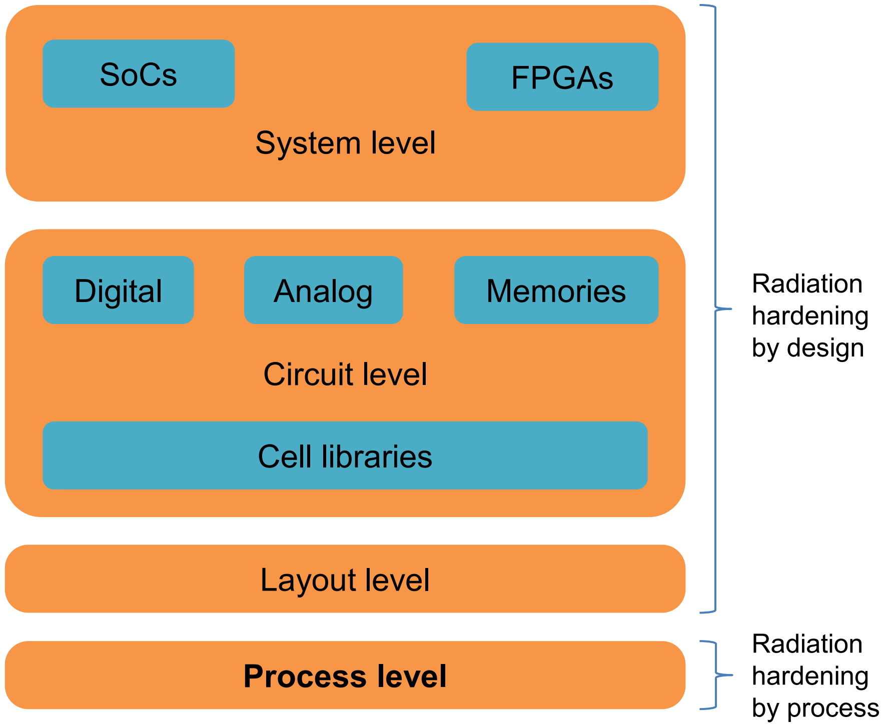


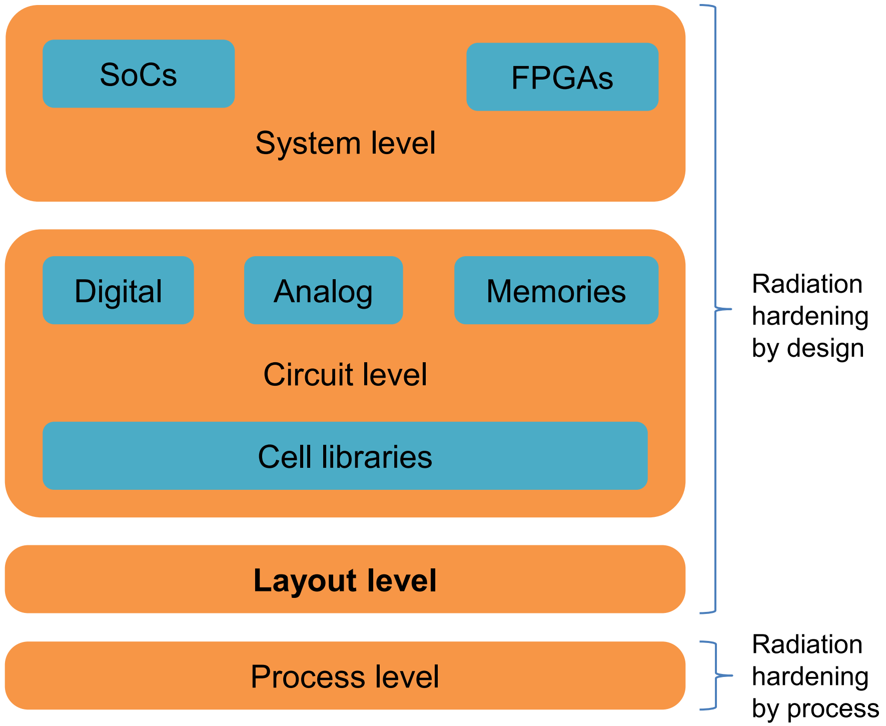
Process:

- Modification of existing semiconductor's manufacturing processes to cope with radiation effects.

Radiation effects mitigation

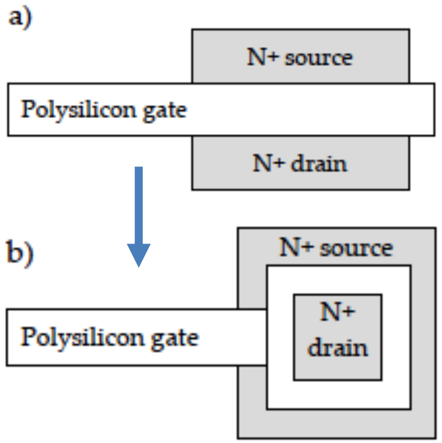
Overview

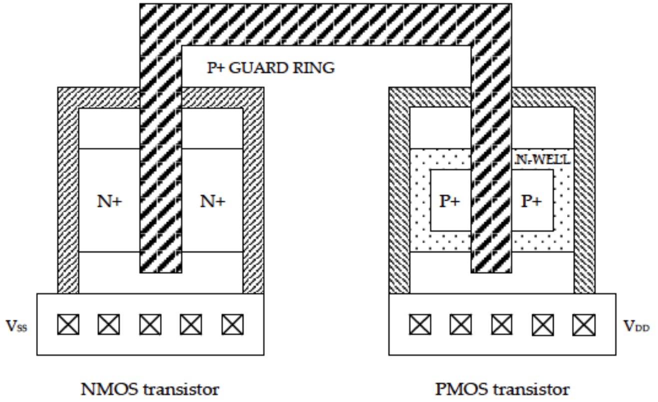
Different mitigation techniques can be applied at different abstraction levels and stages of the development of a radiation-hardened component.

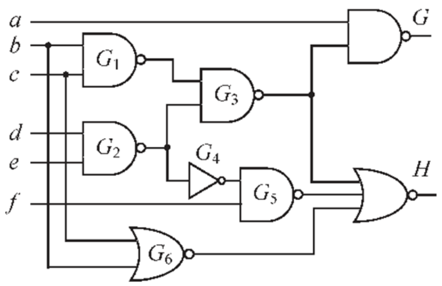


Layout:

- Modification of the transistor's shapes and insertion of protection elements to reduce mainly the effects of TID and SEL but also SET and SEU.





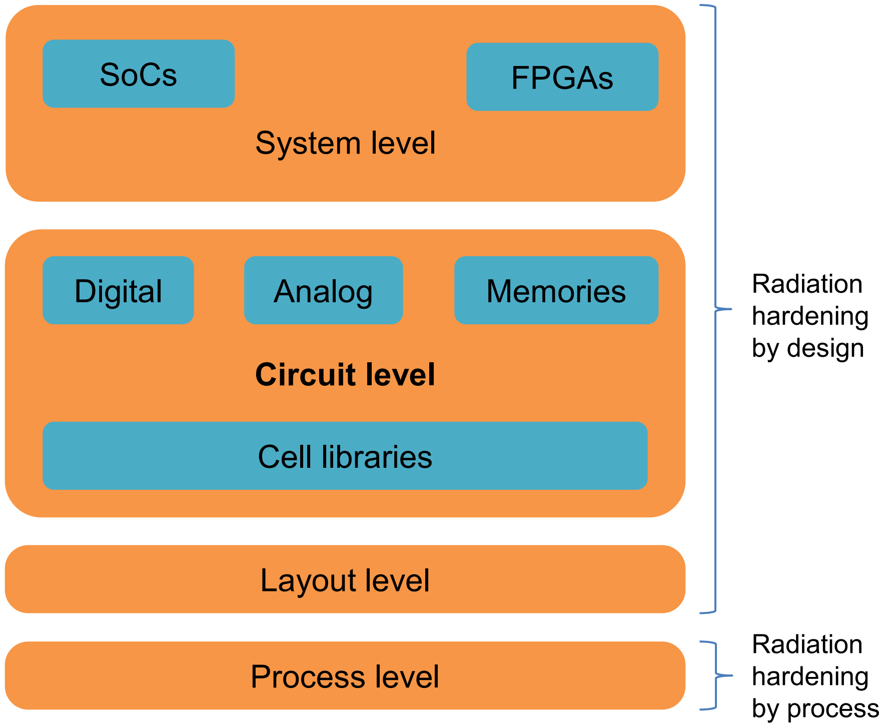


Gate	Sensitization Probability		Logical Masking Probability
	Logic 0	Logic 1	
G	0.79	0.21	0.0
H	0.81	0.19	0.0
G_3	0.38	0.56	0.06
G_1	0.56	0.19	0.15
G_2	0.47	0.16	0.37
G_6	0.19	0.12	0.69
G_5	0.19	0.09	0.72
G_4	0.09	0.05	0.86

Radiation effects mitigation

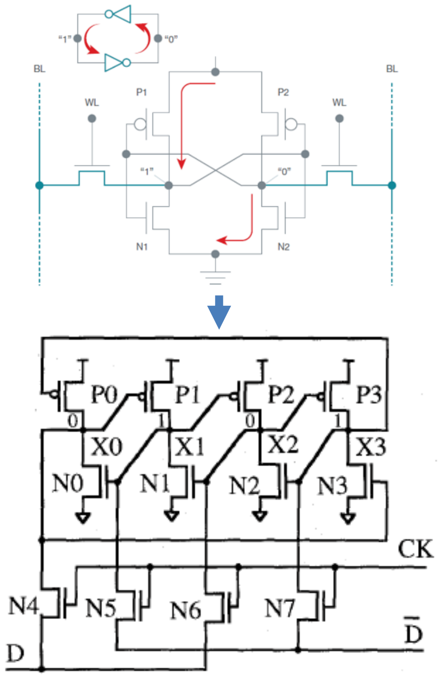
Overview

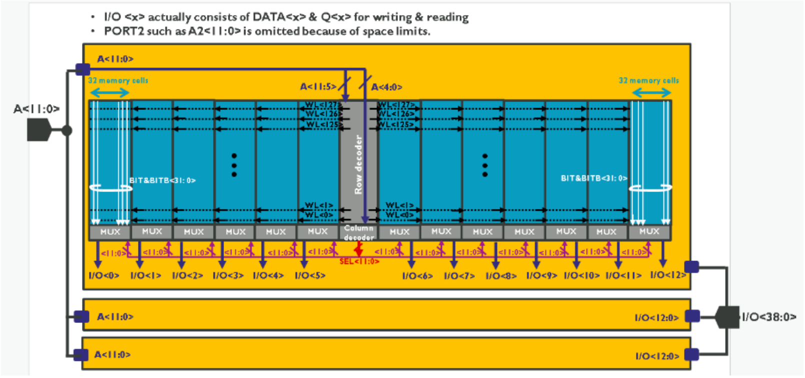
Different mitigation techniques can be applied at different abstraction levels and stages of the development of a radiation-hardened component.

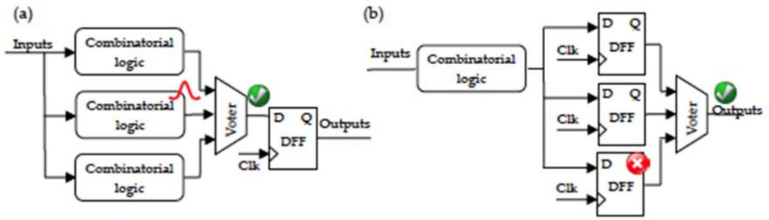


Circuit level:

- Hardening of basic functional cells and then manufacture in commercial ASIC processes.
- Hardening a library consists of combining several other techniques at process, layout, analog, digital, and memory levels.



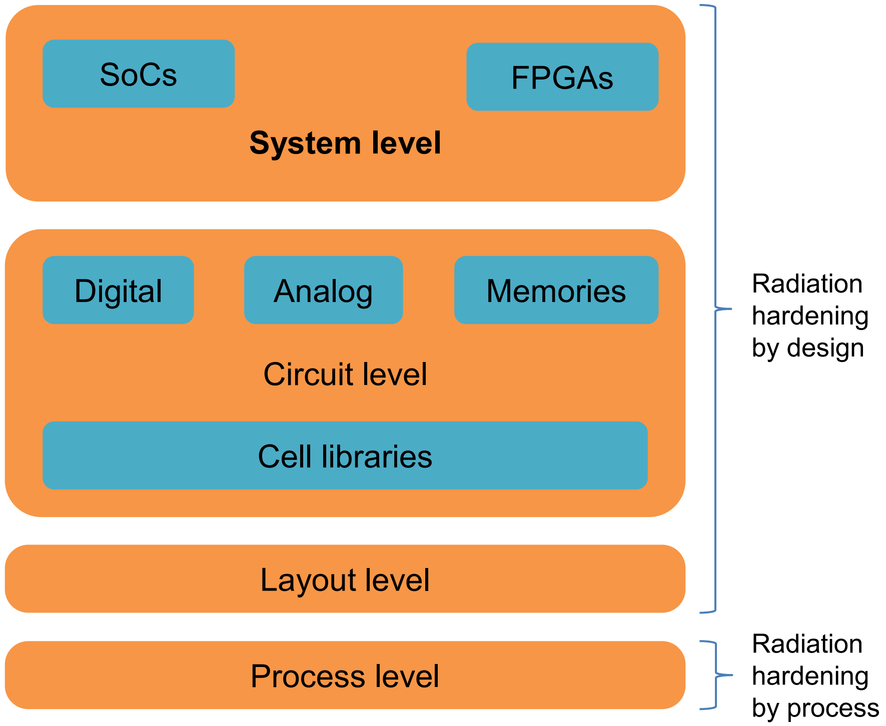




Radiation effects mitigation

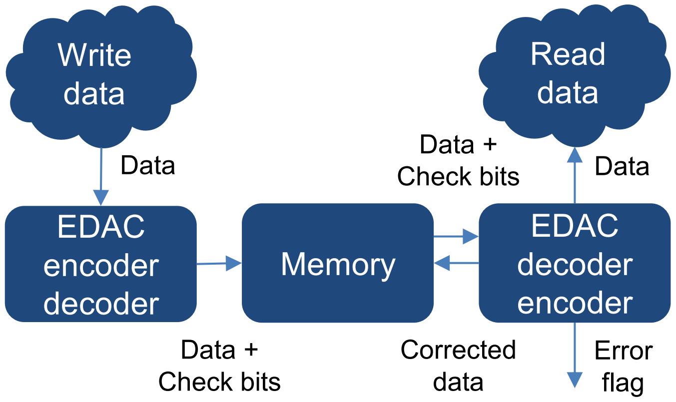
Overview

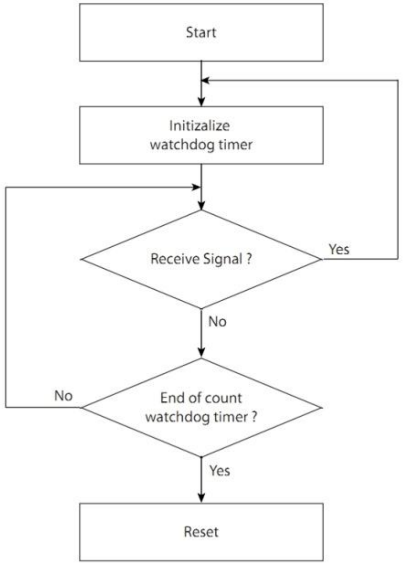
Different mitigation techniques can be applied at different abstraction levels and stages of the development of a radiation-hardened component.



System level:

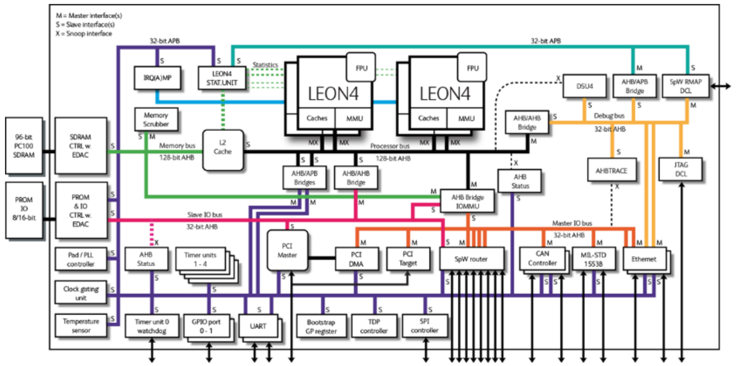
- Techniques applied to different cores (hard or soft) within a device .
- Several of them used in conjunction with lower-level techniques, such as memories.
- Needed to meet the radiation tolerance required.





Radiation effects mitigation

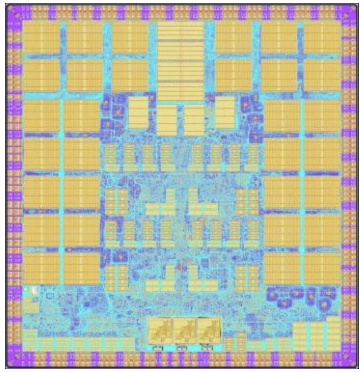
Example – GR740 – Rad-Hard Quad-Core LEON4FT System-on-Chip



SEE

Environment	Events/device/day	Mean time between events (years)
GEO	7.81E-6	350
LEO	2.09E-6	1310

TID 300 krad(Si)

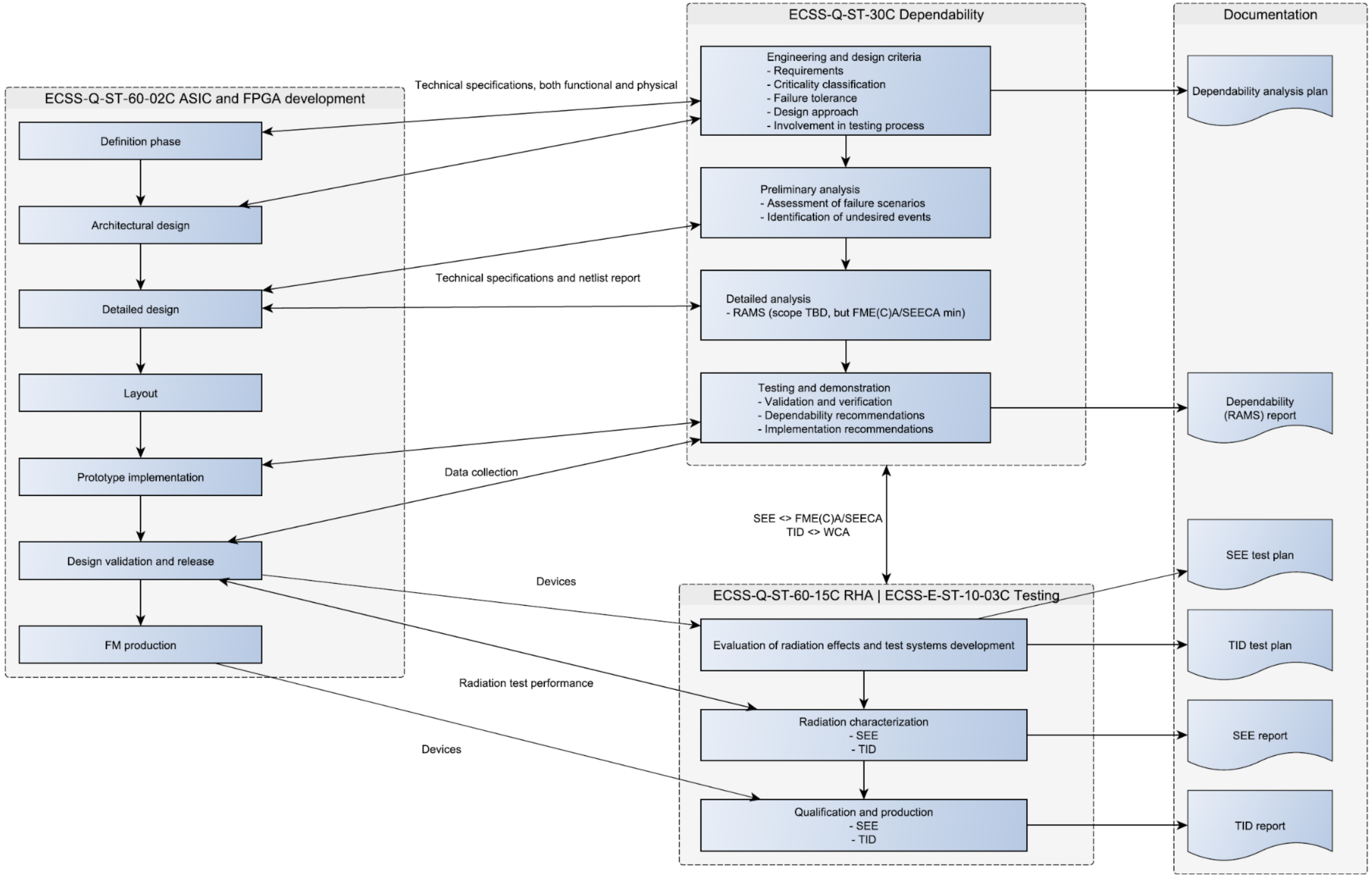


- Processor cores in the GR740 have register files containing CORELIB flip-flops (C65SPACE, non-SEU hardened).
  - Block TMR with bit-by-bit voting on the register read data outputs is implemented in the register files to mask SEUs.
  - Modules of the BTMR have adequate spacing among them to avoid sensitivity to potential uncorrectable MBUs.
- L1 cache of each processor core is composed of SRAM cells and includes an 8+1 parity error detection system with invalidation on error scheme.
- L2 cache is also composed of SRAM cells and includes a 32+7 BCH SECDED scheme.
  - Scrambling of all memory cells, one bit every four from the same word, is used to minimize the possibility of MBUs within one word.
- SpaceWire and the Ethernet core also include memory blocks implemented with SRAM cells.
  - Protected either with TMR or PDMR (Parity DMR).
- All other memory cells and sequential logic in the GR740 are composed of SKYROB flip-flops (C65SPACE, SEU hardened) that do not require additional mitigation at design level thanks to its RHBD approach at cell library level (C65SPACE).
- Three RHBD PLLs are used in the GR740 and all global clocks and reset networks are SET hardened at cell library level (C65SPACE).

05

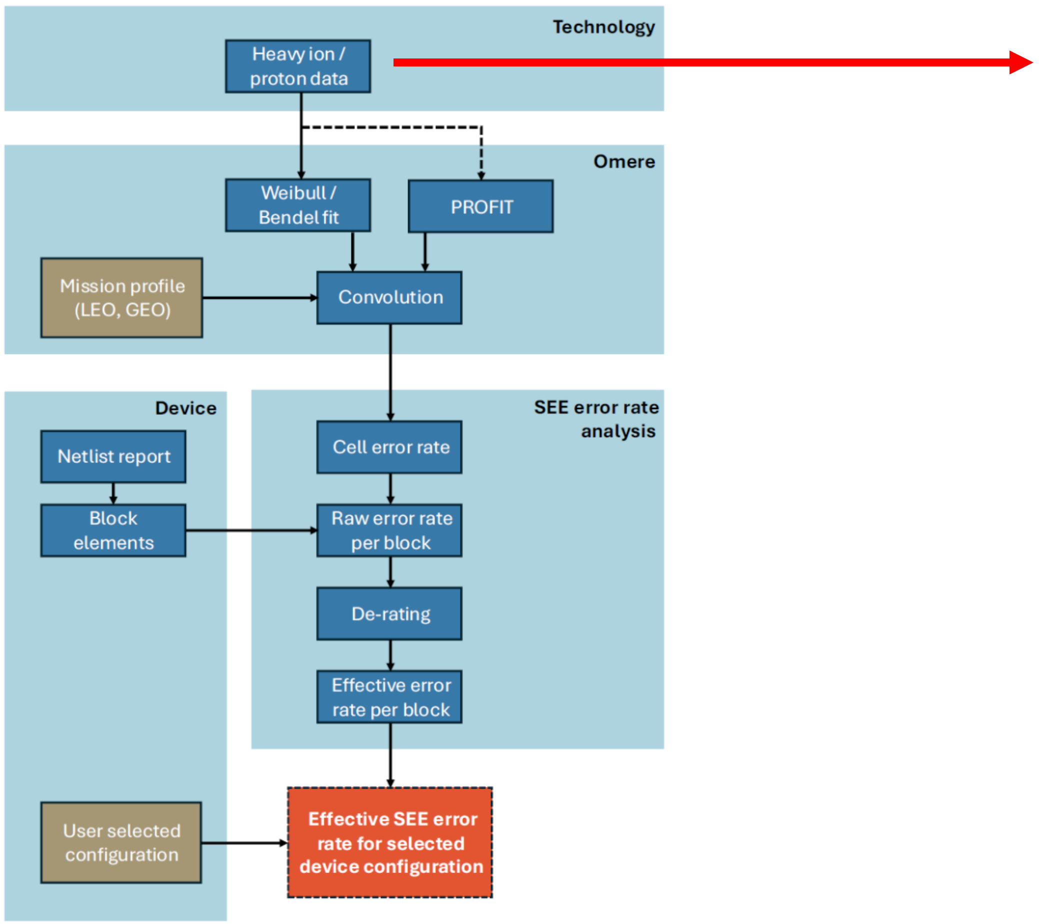
Radiation Hardness Assurance (RHA)

Radiation hardness assurance | Life cycle



Radiation hardness assurance | Analysis

How do we estimate the radiation performance of a device during its design phase?



MeV	SEU
200	4.23E-16
150	5.24E-16
100	2.68E-16
70	3.73E-16
50	2.95E-16

LET	SEU
1.87	3.43E-12
3.68	2.95E-11
10.08	1.05E-10
18.84	1.59E-10
54.95	2.72E-10

Radiation hardness assurance | Analysis

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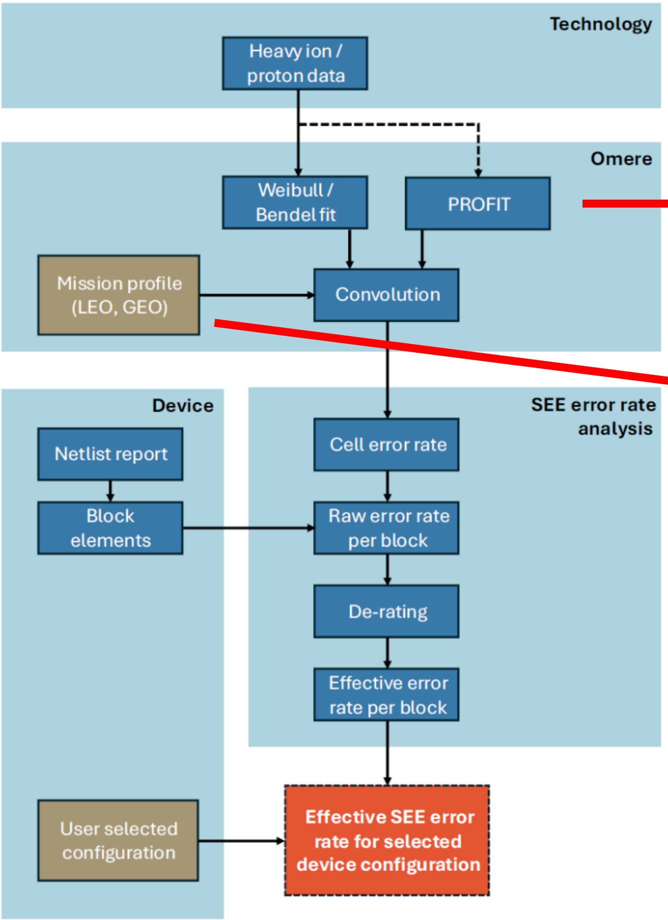
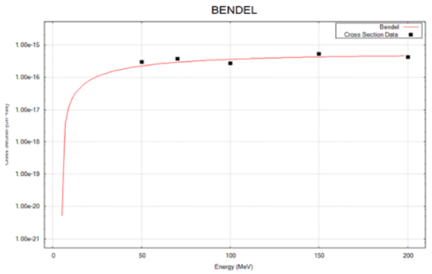
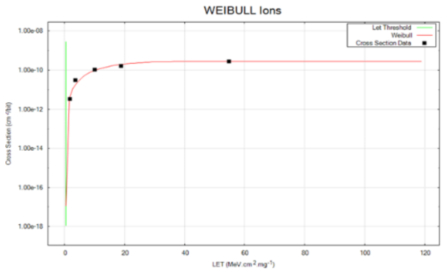
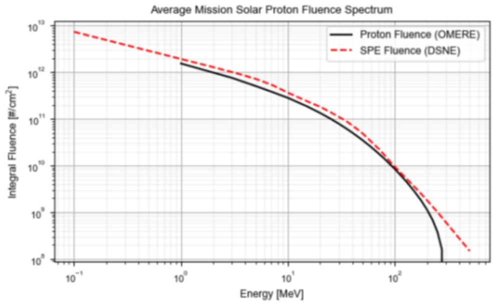
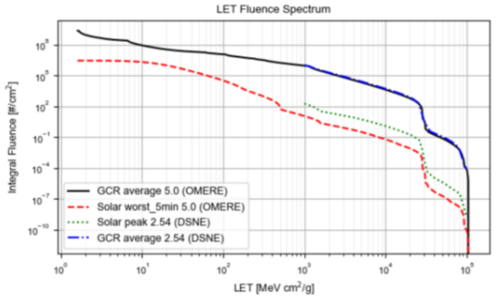




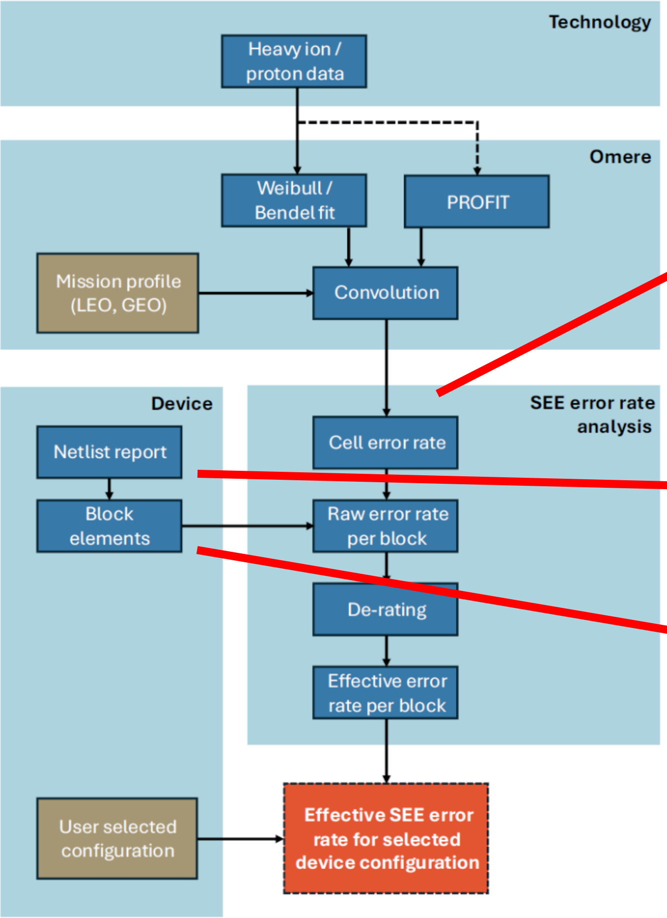






Radiation hardness assurance | Analysis

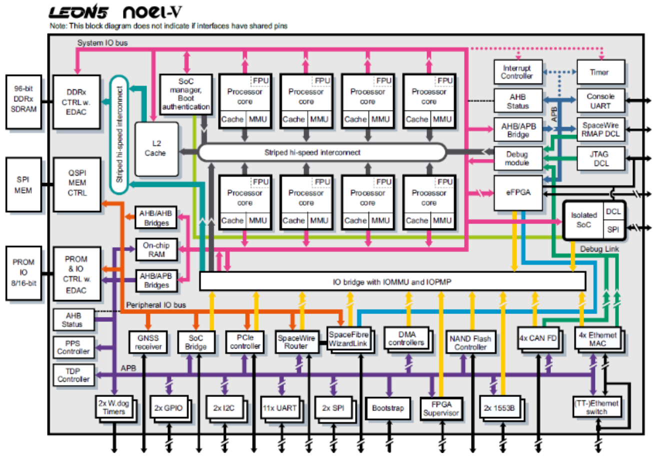
How do we estimate the radiation performance of a device during its design phase?



Cell/group name	LEO	GEO
CORE_2G_FF	2.79E-12	1.33E-12
CORE_3G_FF	2.79E-12	1.33E-12
CORHP_2G_FF	1.80E-12	6.81E-12
CORHP_3G_FF	1.80E-12	6.81E-12
SYNC_FF	4.59E-10	1.42E-09
GATE	1.44E-10	4.55E-10
DPHD	3.54E-10	1.12E-09
SPHD	5.77E-10	1.79E-09
DPREG	4.07E-09	3.81E-09
SPREG	5.05E-09	5.02E-09
CORE_LCLKG	3.07E-13	1.17E-12
PLL5000	2.52E-09	8.33E-09

Cell type	Group	List of cells in the group	Number of cells in the group	Total count of cells	Total bits/elements
RAM	ST_SPREG_BB_2048x78m4B2_baTRolmr*	ST_SPREG_BB_2048x78m4B2_baTRolmr	1	429	68530176
RAM	ST_SPREG_BB_4096x23m8B2_aTolmr*	ST_SPREG_BB_4096x23m8B2_aTolmr	1	133	12529664
RAM	ST_SPREG_BB_512x40m4B1_aTRlmr*	ST_SPREG_BB_512x40m4B1_aTRlmr	1	287	5877760
Gate	C8T28SOI_LL_*	C8T28SOI_LL_BFX13_P4; C8T28SOI_LL_BFX24	536	5331022	5331022

...



Radiation hardness assurance | Analysis

How do we estimate the radiation performance of a device during its design phase?

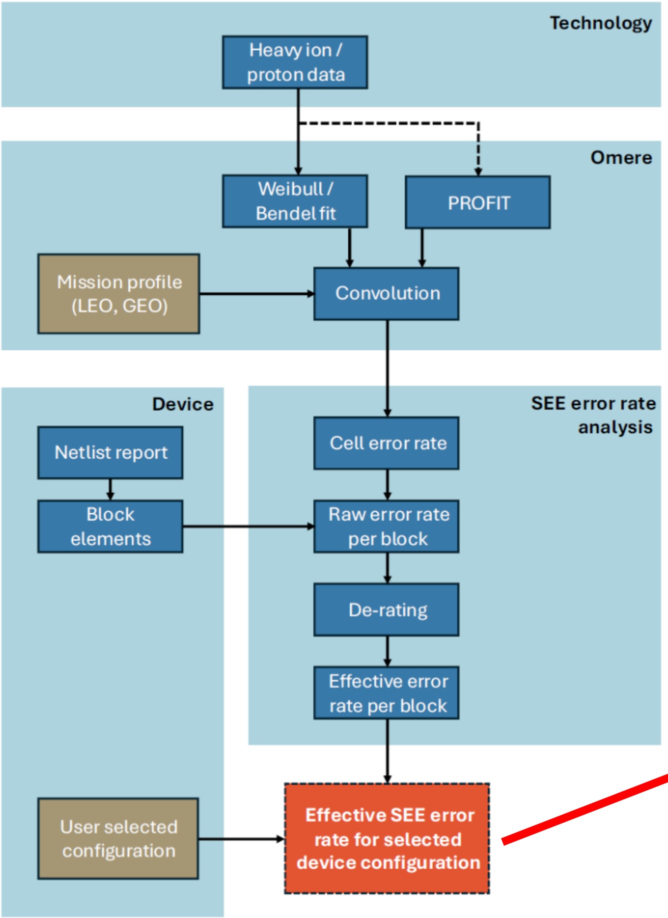


Table 6. GEO SEE error rate (error/dev/day) per GR765 block per cell group for the baseline configuration. Total and SEU effective error rates per block are also described.

GR765 block	SRAMs	Flip-flops	Gates	PLLs	Total effective error rate	SEU effective error rate
LEON5FT_SYS	0.00E+00	1.18E-10	1.75E-08	0.00E+00	1.76E-08	1.18E-10
LEON5FT_NOELVFT_SYS	0.00E+00	6.99E-09	8.03E-07	0.00E+00	8.10E-07	6.99E-09
LEON5FT_NOELVFT_CLUS	2.13E-08	1.91E-07	4.62E-06	0.00E+00	4.83E-06	2.12E-07
LEON5FT_0	1.75E-10	1.27E-08	6.68E-07	0.00E+00	6.81E-07	1.29E-08
LEON5FT_NOELVFT_0	0.00E+00	4.98E-10	2.13E-07	0.00E+00	2.14E-07	4.98E-10
AHB	0.00E+00	1.64E-09	9.29E-08	0.00E+00	9.45E-08	1.64E-09
AHBSTAT_0	0.00E+00	1.51E-11	7.37E-10	0.00E+00	7.52E-10	1.51E-11
AHBSTAT_1	0.00E+00	1.10E-11	7.37E-10	0.00E+00	7.48E-10	1.10E-11
APB	0.00E+00	8.49E-11	1.03E-08	0.00E+00	1.03E-08	8.49E-11
UART_1	0.00E+00	5.73E-11	6.67E-09	0.00E+00	6.73E-09	5.73E-11
FTMCTRL	0.00E+00	1.07E-10	8.31E-09	0.00E+00	8.42E-09	1.07E-10
GRGPIO_0	0.00E+00	2.77E-11	3.90E-09	0.00E+00	3.93E-09	2.77E-11
GRGPIO_1	0.00E+00	2.31E-11	3.79E-09	0.00E+00	3.82E-09	2.31E-11
GRHSM	1.40E-09	1.65E-08	8.08E-07	8.33E-09	8.34E-07	1.79E-08
SOCMGR[3]	1.30E-09	4.63E-09	4.71E-07	0.00E+00	4.77E-07	5.93E-09
CLOCK	0.00E+00	1.74E-10	1.11E-07	2.50E-08	1.36E-07	1.74E-10
FTADDR	0.00E+00	1.80E-08	4.75E-07	8.33E-09	5.02E-07	1.80E-08
PAD	0.00E+00	0.00E+00	1.33E-09	0.00E+00	1.33E-09	0.00E+00
GRCLKGATE	0.00E+00	1.05E-10	1.67E-09	0.00E+00	1.78E-09	1.05E-10
GRWATCHDOG	0.00E+00	3.13E-11	8.19E-10	0.00E+00	8.50E-10	3.13E-11
GPREG	0.00E+00	4.66E-12	3.59E-10	0.00E+00	3.64E-10	4.66E-12
GLOBAL	0.00E+00	0.00E+00	4.47E-07	0.00E+00	4.47E-07	0.00E+00
TOP_REMAIN	0.00E+00	1.12E-10	7.04E-09	0.00E+00	7.16E-09	1.12E-10

Table 7. LEO and GEO SEE error rates (error/dev/day) for the GR765 baseline configuration.

Environment	Total effective error rate	SEU effective error rate
LEO	2.98E-06	1.92E-07
GEO	9.09E-06	2.77E-07

Radiation hardness assurance | Testing

According to what do we test?

This document and process conversion measures necessary to comply with this change shall be completed by 1 November 2018.

INCH - POUND

MIL-STD-883K
w/CHANGE 3
3 May 2018
SUPERSEDING
MIL-STD-883K
w/CHANGE 2
22 February 2017

DEPARTMENT OF DEFENSE
TEST METHOD STANDARD
MICROCIRCUITS

AMSC N/A

DISTRIBUTION STATEMENT A. Approved for public release. Distribut

JEDEC STANDARD

Test Procedures for the Measurement of Single-Event Effects in Semiconductor Devices from Heavy Ion Irradiation

JESD57A
(Revision of JESD57, December 1996, Reaffirmed September 2003)

NOVEMBER 2017

JEDEC SOLID STATE TECHNOLOGY ASSOCIATION

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TEST STANDARD FOR THE MEASUREMENT OF PROTON RADIATION SINGLE EVENT EFFECTS IN ELECTRONIC DEVICES

JESD234

OCTOBER 2013

JEDEC SOLID STATE TECHNOLOGY ASSOCIATION

JEDEC

ECSS-Q-ST-60-15C
1 October 2012

EUROPEAN COOPERATION
ECSS
FOR SPACE STANDARDIZATION

Space product assurance

Radiation hardness assurance - EEE components

ECSS Secretariat
ESA-ESTEC
Requirements & Standards Division
Noordwijk, The Netherlands

ESCC
European Space Components Coordination

Page 1 of 22

TOTAL DOSE STEADY-STATE IRRADIATION TEST METHOD

ESCC Basic Specification No. 22900

Issue 5 | June 2016

esa

Document Custodian: European Space Agency – see

ESCC
European Space Components Coordination

Page 1 of 24

SINGLE EVENT EFFECTS TEST METHOD AND GUIDELINES

ESCC Basic Specification No. 25100

Issue 2 | October 2014

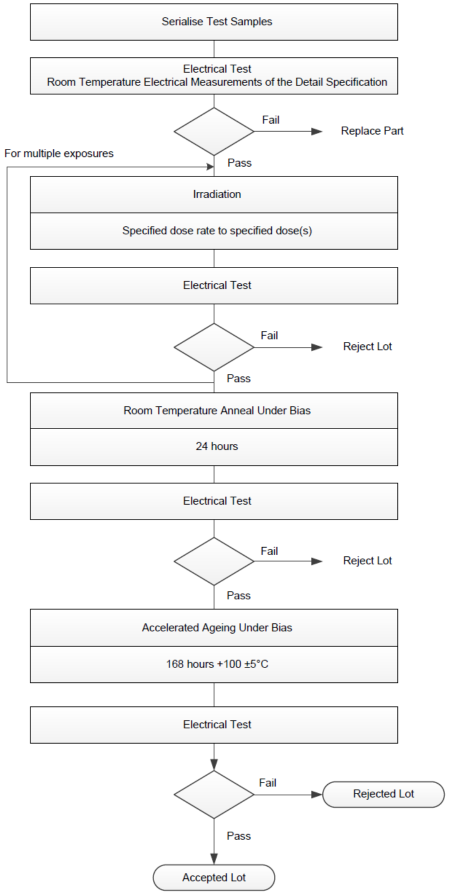
esa

Document Custodian: European Space Agency – see https://escies.org

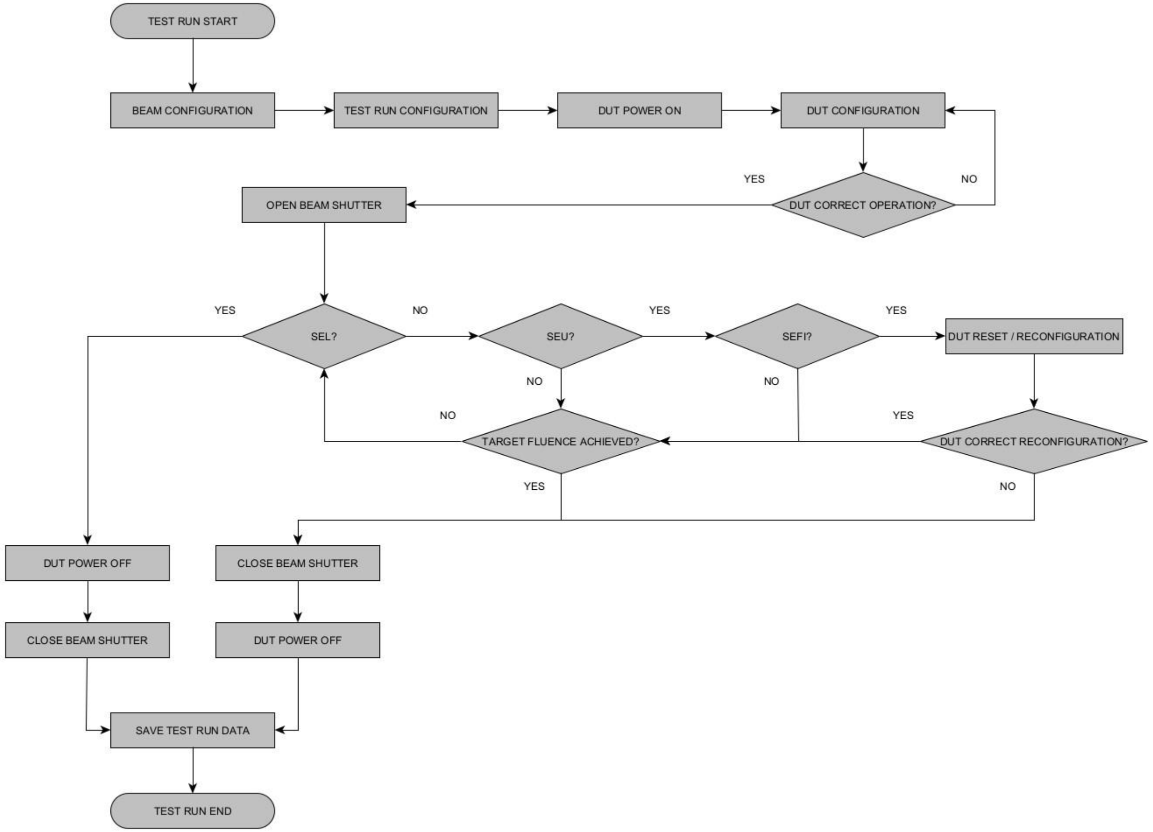
Radiation hardness assurance | Testing

How do we test?

TID:
- Accumulated dose.



SEE:
- Random events.
- Test based on:
  - Target particle fluence.
  - Number of events observed.



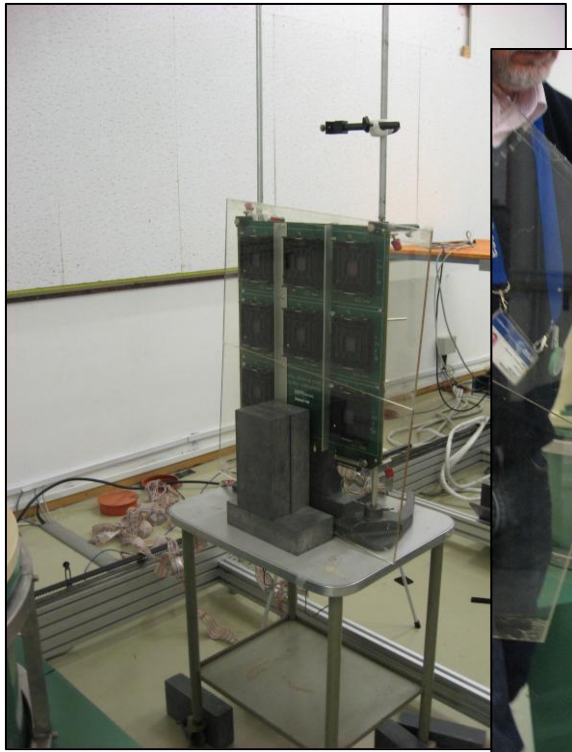
Radiation hardness assurance | Testing

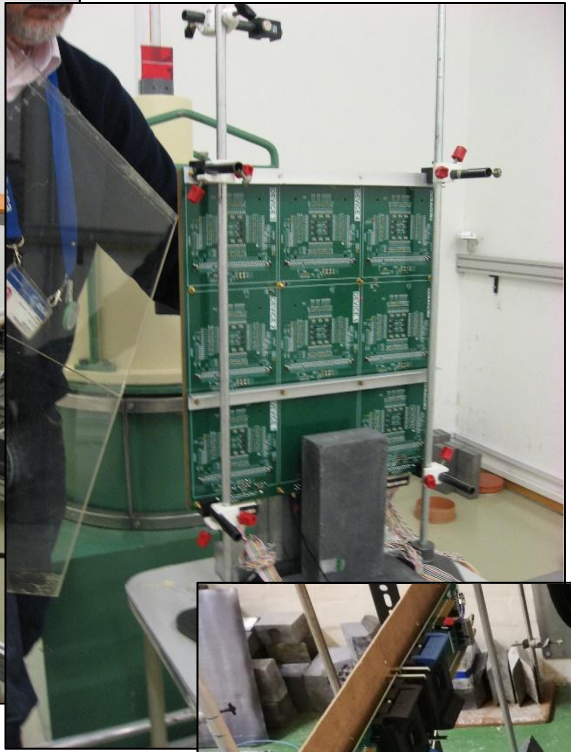
How do we test? **In practice…**

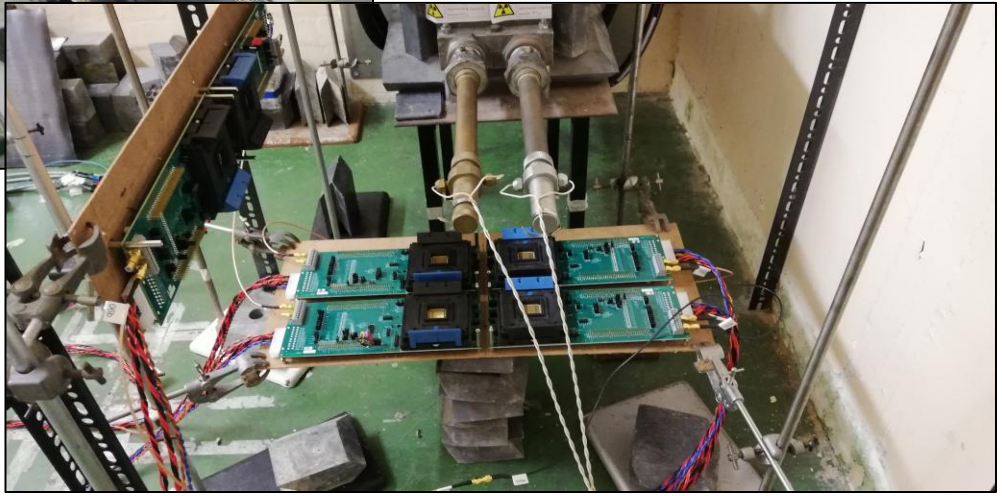
Radiation hardness assurance | Testing

How do we test? **In practice…**

TID (Cobalt-60)



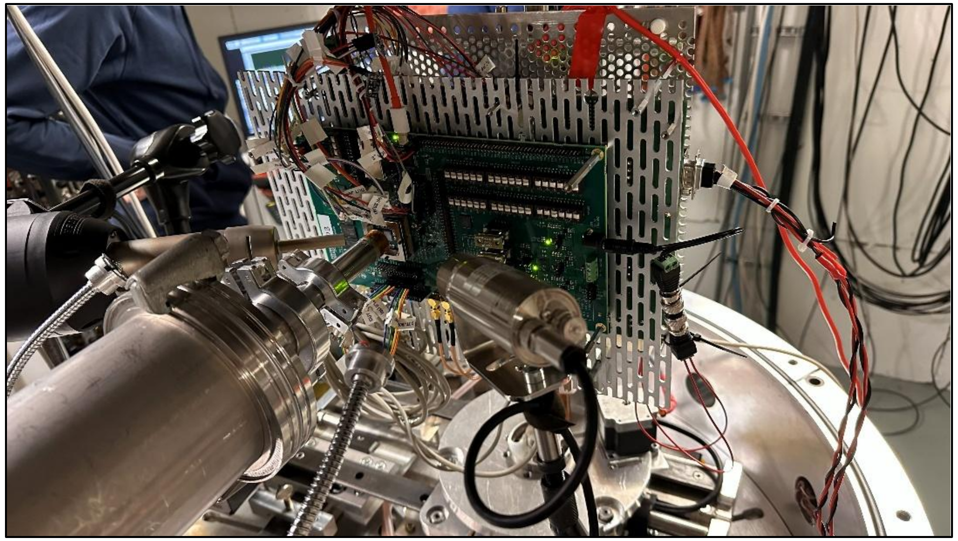


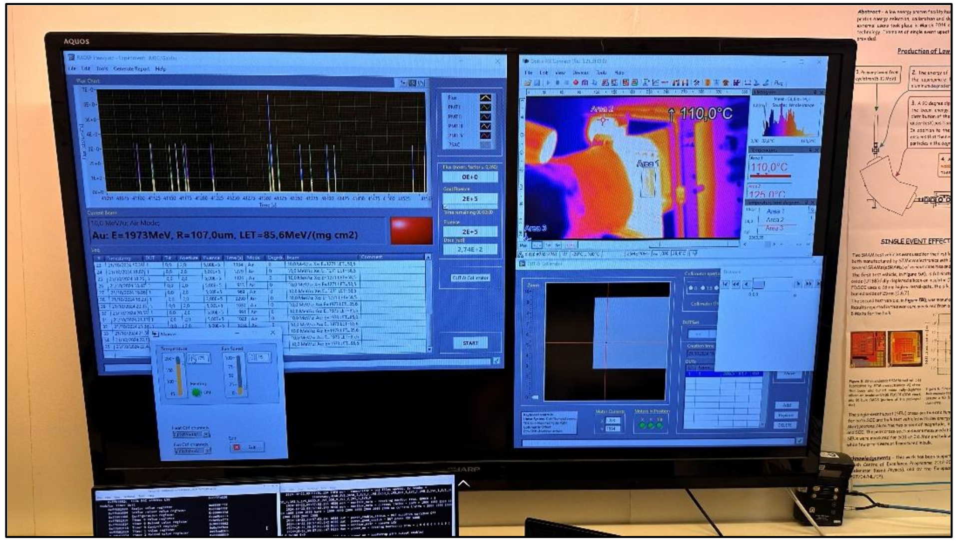


Radiation hardness assurance | Testing

How do we test? **In practice…**

SEE (heavy ions)

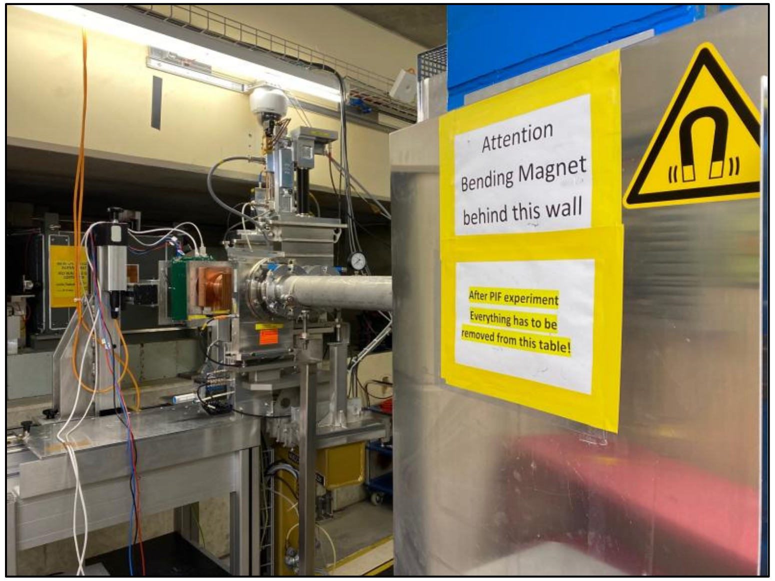


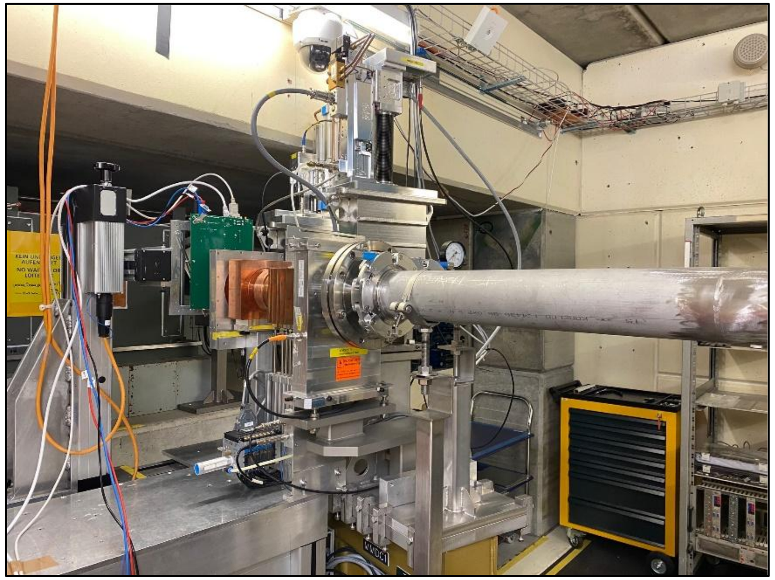


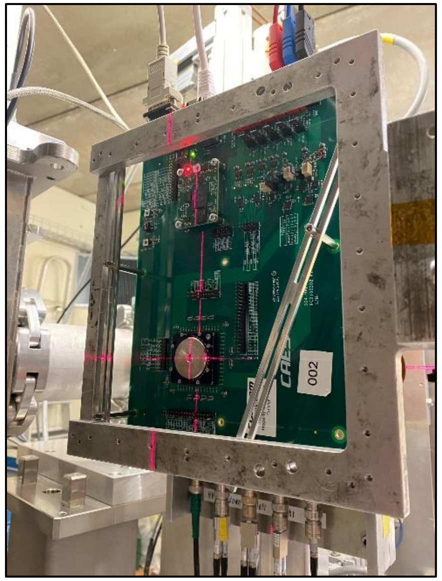
Radiation hardness assurance | Testing

How do we test? **In practice…**

SEE (protons)







06

Conclusions

Conclusions

Radiation hardness assurance consists of all activities undertaken to ensure that the electronics and materials of a space system perform to their design specifications throughout exposure to the mission space environment

Radiation effects engineering
(microelectronics component level)

Space physics
- Space weather
- Environment models/modeling
- Radiation sources

Device physics
- Material property degradations with radiation
- Charge transport
- Device process dependencies
- Charge dependency of device operation

Electrical engineering
- Device functions and operation
- Understanding circuit behavior and response

Systems engineering
- Requirements
- System level impacts
- Understanding functionality

THANK YOU!

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