Multifunctional Shielding Polymer (MSP)/Plasteel™ for Space Applications

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WRMISS, Cologne, Germany, Sept. 2-4, 2025

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Content

Risks to Electronics and Materials in Space

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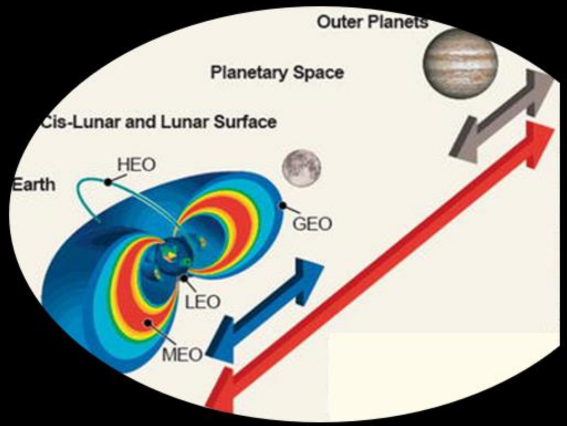
- Atomic oxygen
- Ionizing radiation
  - Trapped particles
- Debris
- Micro Gravity
- UV radiation
- Ionizing radiation
  - SEP
  - GCR
- High vacuum
- Solar wind/plasma
- Micrometeoroids
- Severe temperature cycles
- Abrasion
- Dust

Low Earth Orbits:
160 – 2000 km altitude



In planetary space

On the Moon and on Mars

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Materials Requirements in Space

The material must fulfill mechanical & thermal requirements according to space qualifications, incl.:

- **Survive the launch (vibration) and deployment into space without performance loss.**
- **Material compatibility in space, not degrade or cause a threat to humans, (flammability, toxicity, outgasing, etc.) and other systems.**
- **Withstand large temperature variations and vacuum.**
- **Provide thermal conductivity enough to mitigate possible heat stresses.**
- **Provide protection against:**
  - UV radiation
  - Ionizing radiation
  - Extreme heat when re-enter the Earth´s atmosphere
  - Degradation/corrosion from atomic oxygen at LEO
  - Micrometeroids and space debris
- **Achieving full performance over the whole duration of the space mission.**
- **…**

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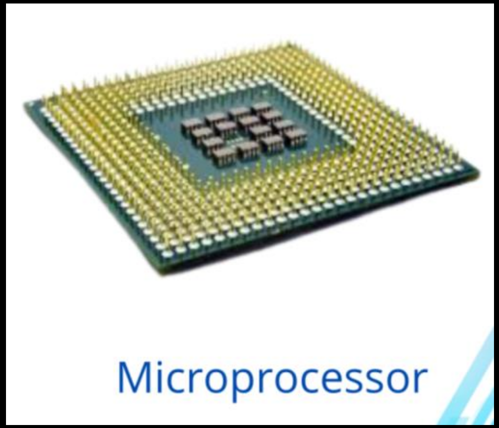
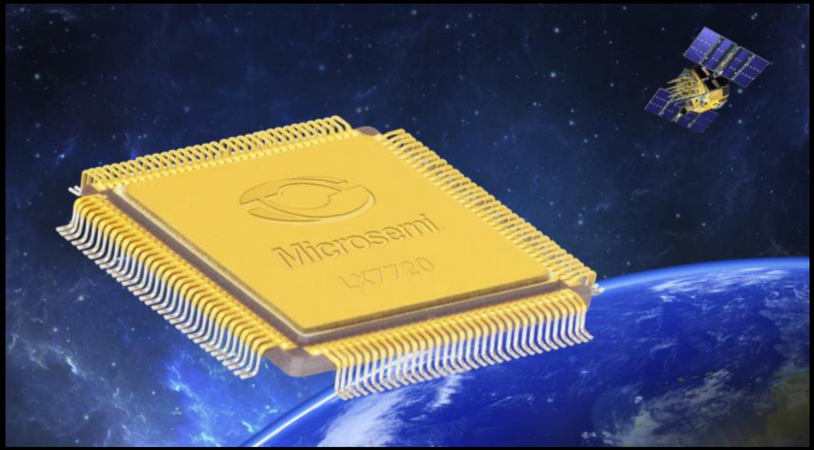
In Space Data Handling and Analysis

Data transfer from space to Earth takes too much time so to enable On orbit Servicing, Assembly, and Manufacturing (OSAM), surveillance, data servers for Internet and communication, etc., there is a need for in space data handling and analysis, using microprocessors/microcontrollers that fast can execute complex AI algorithms.





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In Space Data Handling and Analysis

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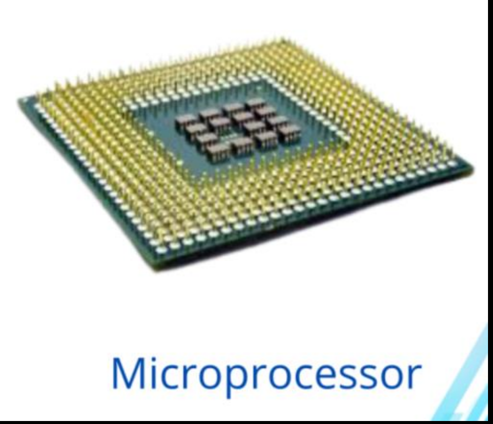
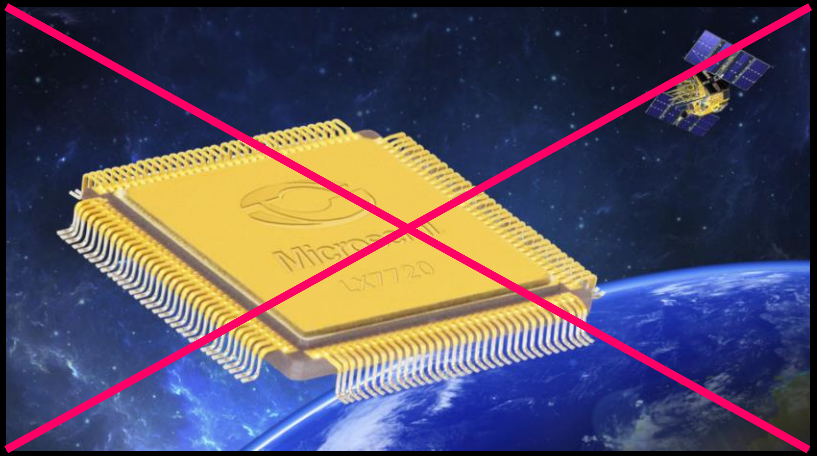


Rad hard microprocessors/microcontrollers do not fulfill all the needed requirements!



COTS components are needed!

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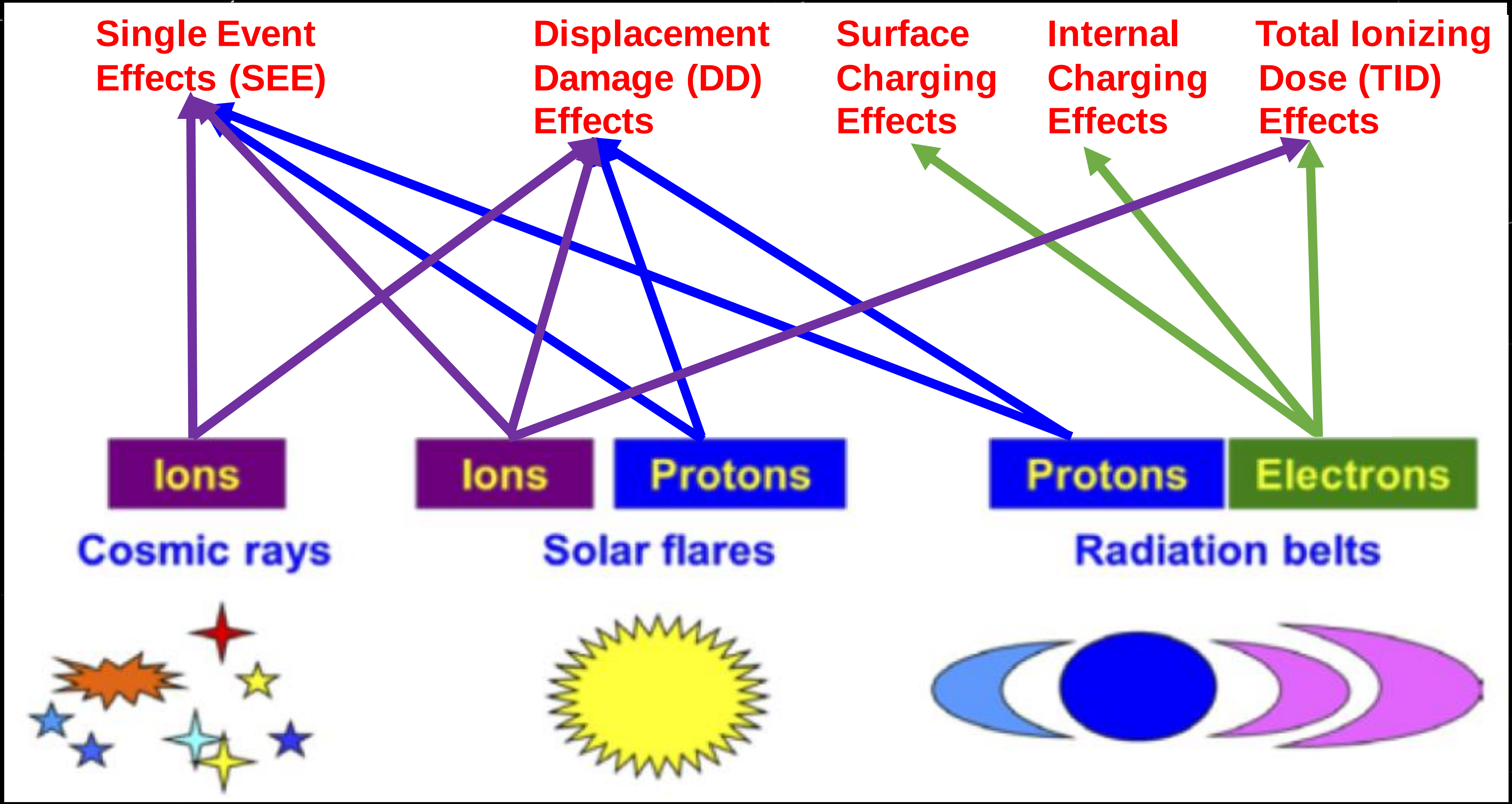
Radiation Effects to Electronics



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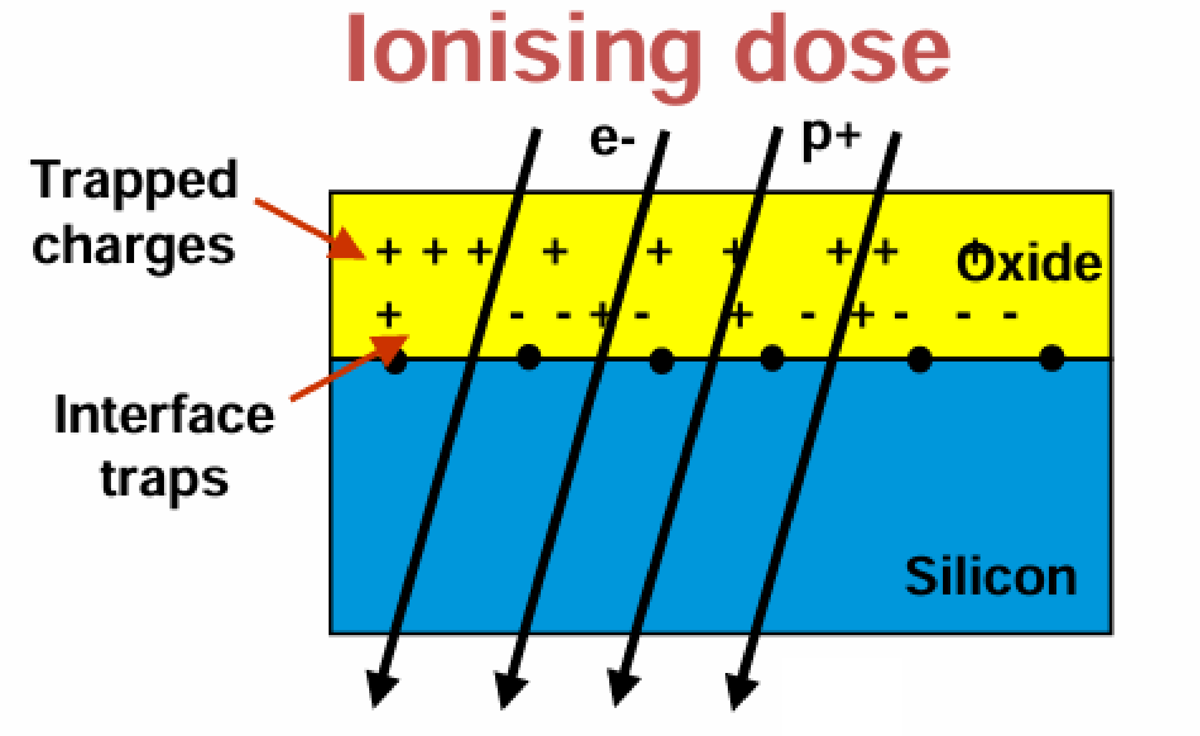
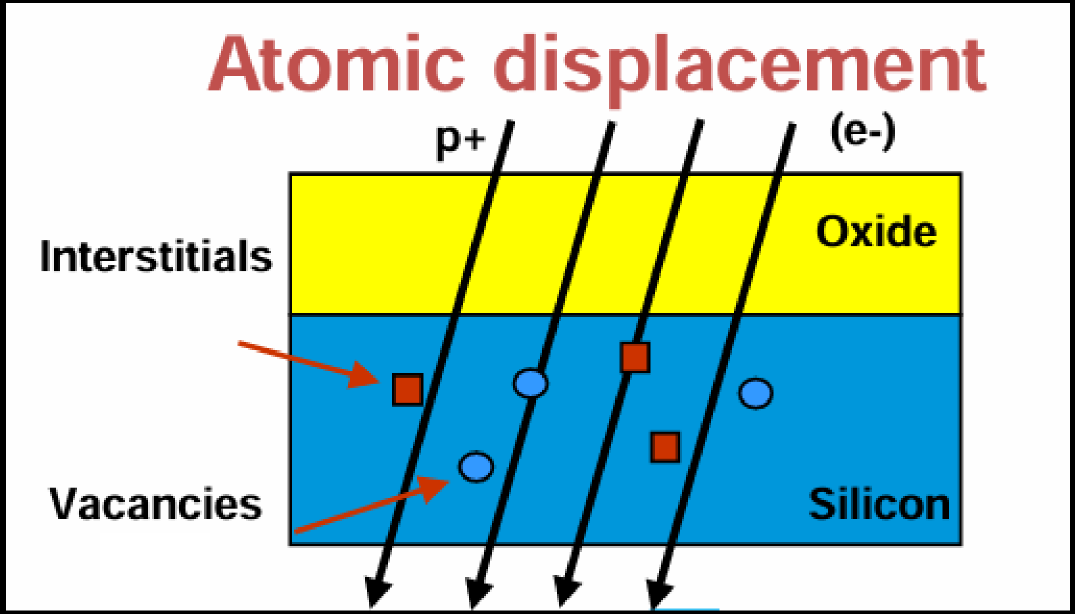
Total Ionizing Dose (TID) Effects

- Cumulative long term ionizing damage mainly due to charged particles.
- At Earth's orbits, TID is mainly caused by protons and electrons.
- Leads to:
  - Threshold Shifts
  - Leakage Current
  - Timing Changes
  - Functional Failures



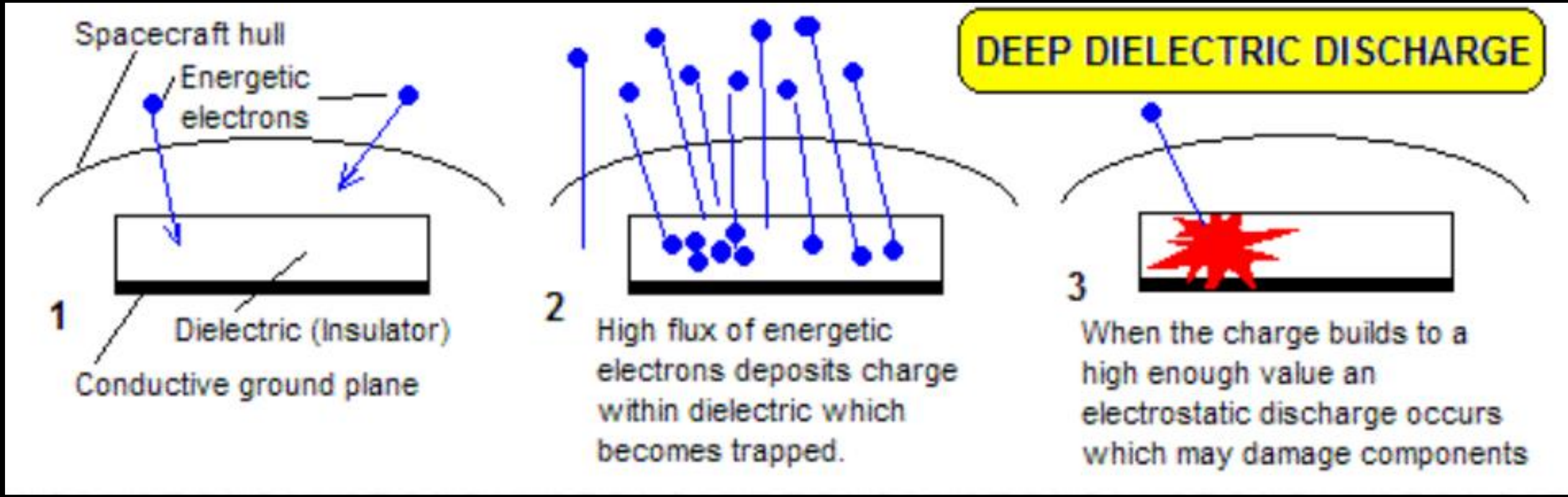
Non-ionizing Radiation Effects/Displacement Damage (DD) Effects

- Caused by DD dose, which is the nonionizing energy loss (NIEL) in each material resulting from a portion of energy deposition by impinging radiation.
- Is a cumulative parametric degradation that can lead to functional failures.
- In space, DD dose is mainly caused by protons and secondary neutrons.



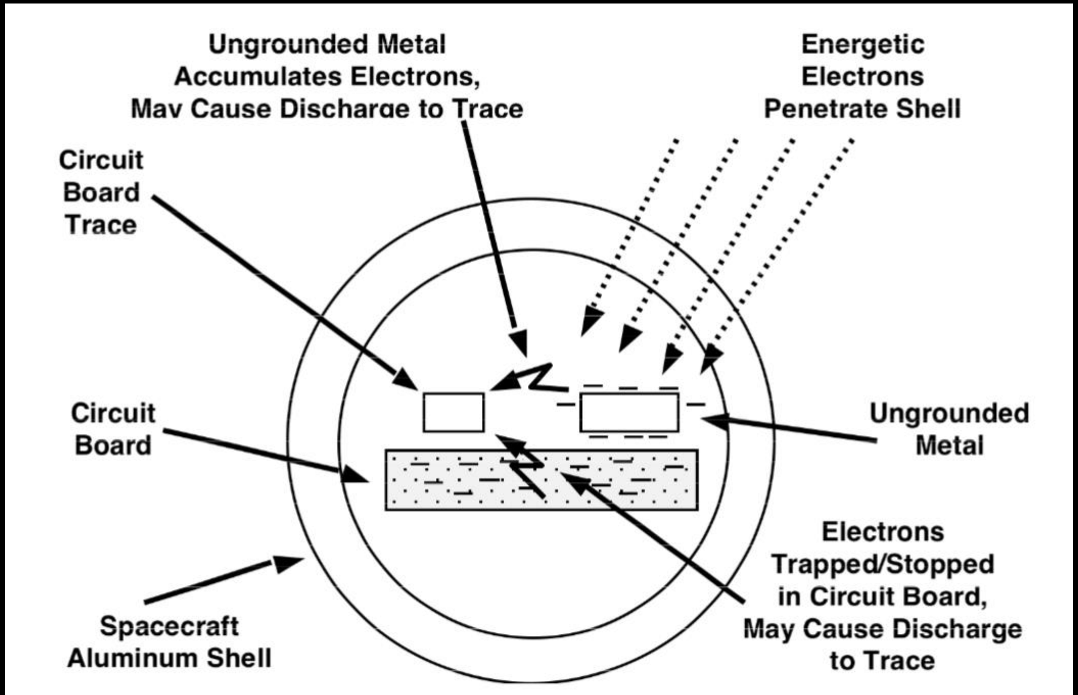
Surface Charging

- Charging of conductive surfaces of a spacecraft.
- Mainly occur when a spacecraft is exposed to a high electron flux, but can also be caused by plasma, solar radiation and magnetic fields.
- If neighboring surfaces of the spacecraft are at very different potentials, sudden discharge might occur, which may cause severe damage to the electronics in the spacecraft.



Internal Charging

- Also called bulk charging, or deep dielectric effects, occurs when high-energy electrons & ions penetrate satellite shielding materials and deposit charge on internal spacecraft components, which can damage spacecraft components.



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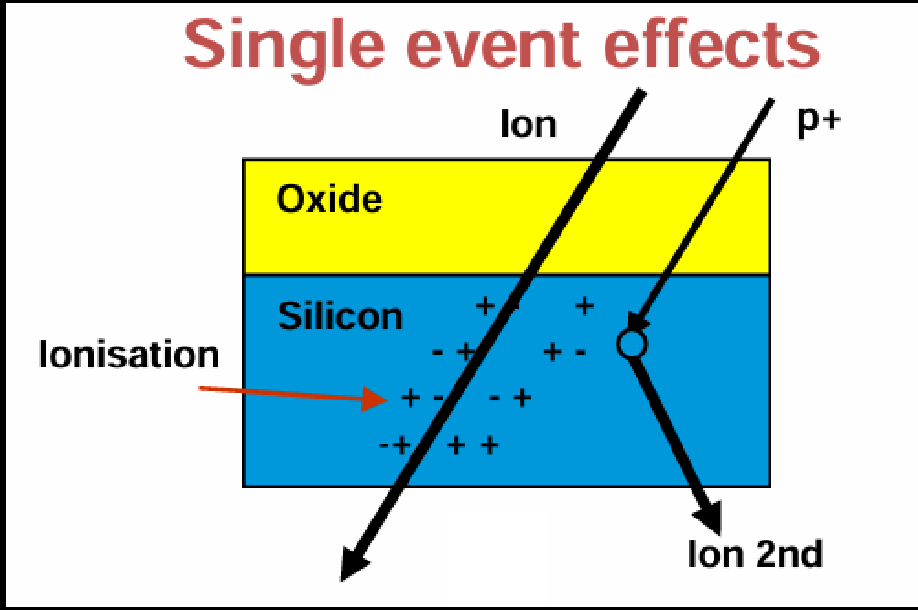
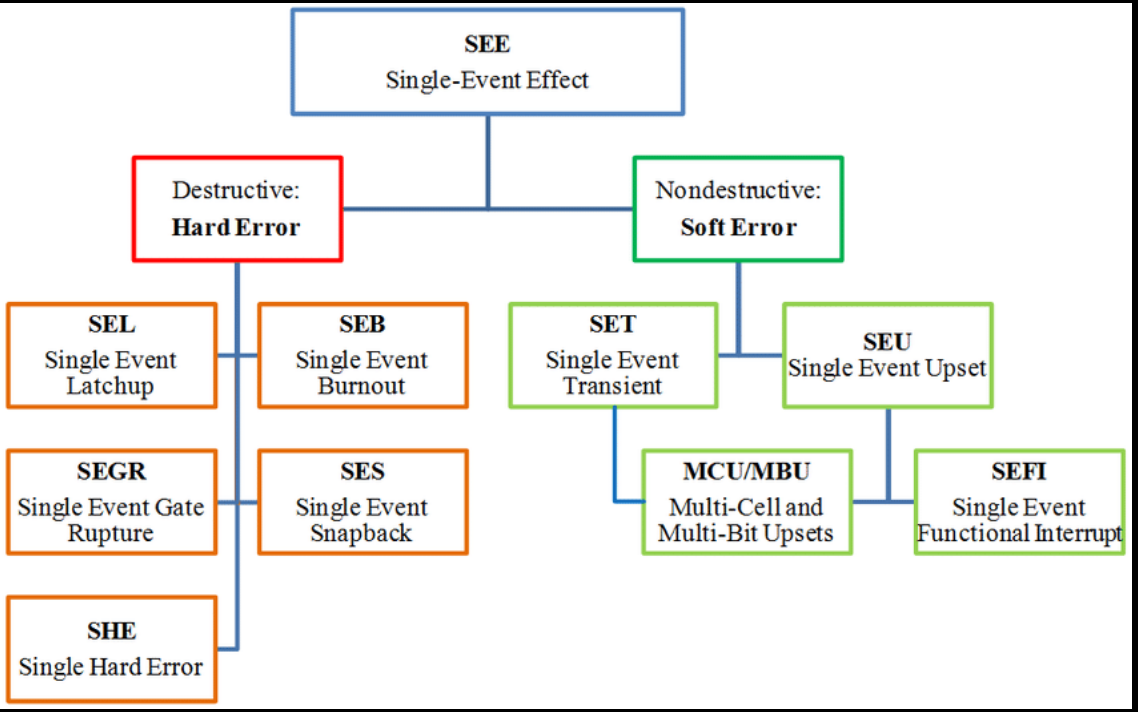
Single Event Effects (SEE)

- The most severe radiation effects in electronics exposed to space radiation caused by a single particle when it passes through the semiconductor material.
- Require particles with enough ionization density to deposit enough localized energy in the electronic component.
- Mainly caused by protons, neutrons, and heavy ions traversing sensitive volumes inside the electronics.





A permanent damage to one or more elements of the circuit or the device (gate oxide rupture, destructive latchup events).

Reversable effects/non permanent Damage.

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Radiation Shielding Requirements

- **The shielding material shall**
  - **Maximize the energy loss of incoming particles**
  - **Minimizing the creation of dangerous secondary radiation**
  - **Minimize the number of high LET particles**
  - **Fulfill materials requirements in space**

From the launch of the first satellite over 50 years ago, aluminum (Al) has been the first choice of materials.

TID Behind Al Shielding

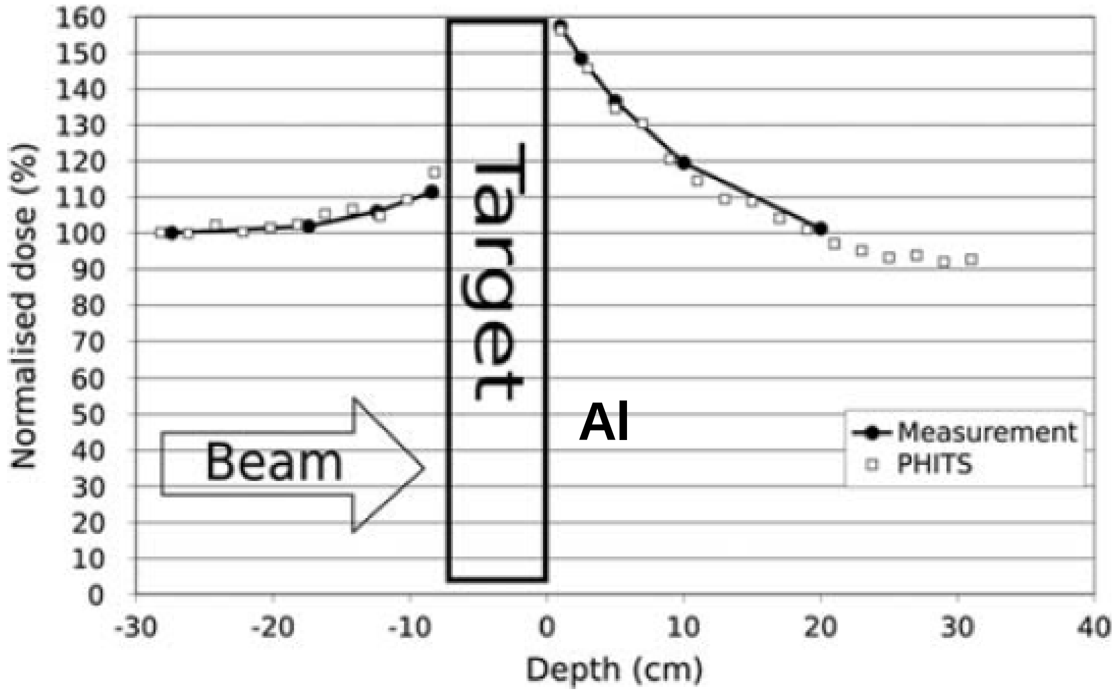

Fig. 1 Measured (*closed symbols*) or calculated (*open symbols*) dose as a function of the distance along the 1 GeV proton beam axis z in the presence of a 20 g/cm^2 Al target. The dose is normalized to the value at $z = -30$ cm

Experiment at NASA´s Space Radiation Laboratory (NSRL) 2007!

Radiat Environ Biophys (2007) 46:107–111
DOI 10.1007/s00411-006-0088-6

PROCEEDINGS OF THE 4TH IWSRR

Shielding of relativistic protons

A. Bertucci · M. Durante · G. Gialanella · G. Grossi · L. Manti · M. Pugliese · P. Scampoli · D. Mancusi · L. Sihver · A. Rusek

The dose increases already in front of Al shielding (i.e., on the side exposed to the beam), and is then strongly increased behind the shield.

Radiation Shielding Requirements

Energy loss should be as high as possible in the shielding!

- **Electromagnetic energy deposition in material**
  - **Bethe-Bloch formula for Electronic Stopping Power**

$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\ln\frac{2m_e c^2\beta^2\gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

$$\frac{S}{\rho} \propto \frac{Z_T}{A_T}$$

S = - dE/dx∞

The electromagnetic energy deposition per unit target mass (A_T) increase by decreasing atomic weight

➡ *Better with hydrogen rich shielding material!*

- **Nuclear energy deposition in material**
  - **Total Nuclear Reaction Formula**

$$\frac{\sigma}{A_T} \propto A_T^{-\frac{1}{3}}$$

$$\sigma = \pi r_0^2 c_1(E)\left(A_P^{1/3} + A_T^{1/3} - c_2(E)\right)^2$$

The nuclear energy deposition per unit target mass (A_T) increase by decreasing atomic weight

➡ *Better with hydrogen rich shielding material!*

Radiation Shielding Requirements

Incoming HZE particles should fragment into low Z particles in the shielding material, to reduce the LET and the dose!

- **The number of atoms/weight should be as high as possible in the shielding material to get as many nuclear reactions as possible**

Material	No of Atoms/g x 10^{22}
Aluminium:	2.2
Solid hydrogen (1 atm, 4.2 K):	59.7
Liquid hydrogen (1 atm, 20 K):	59.7

→ ***Hydrogen rich material is best!***

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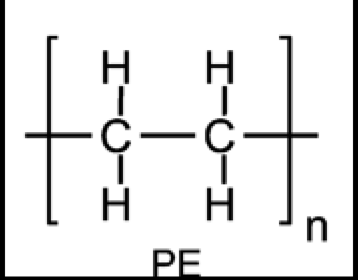
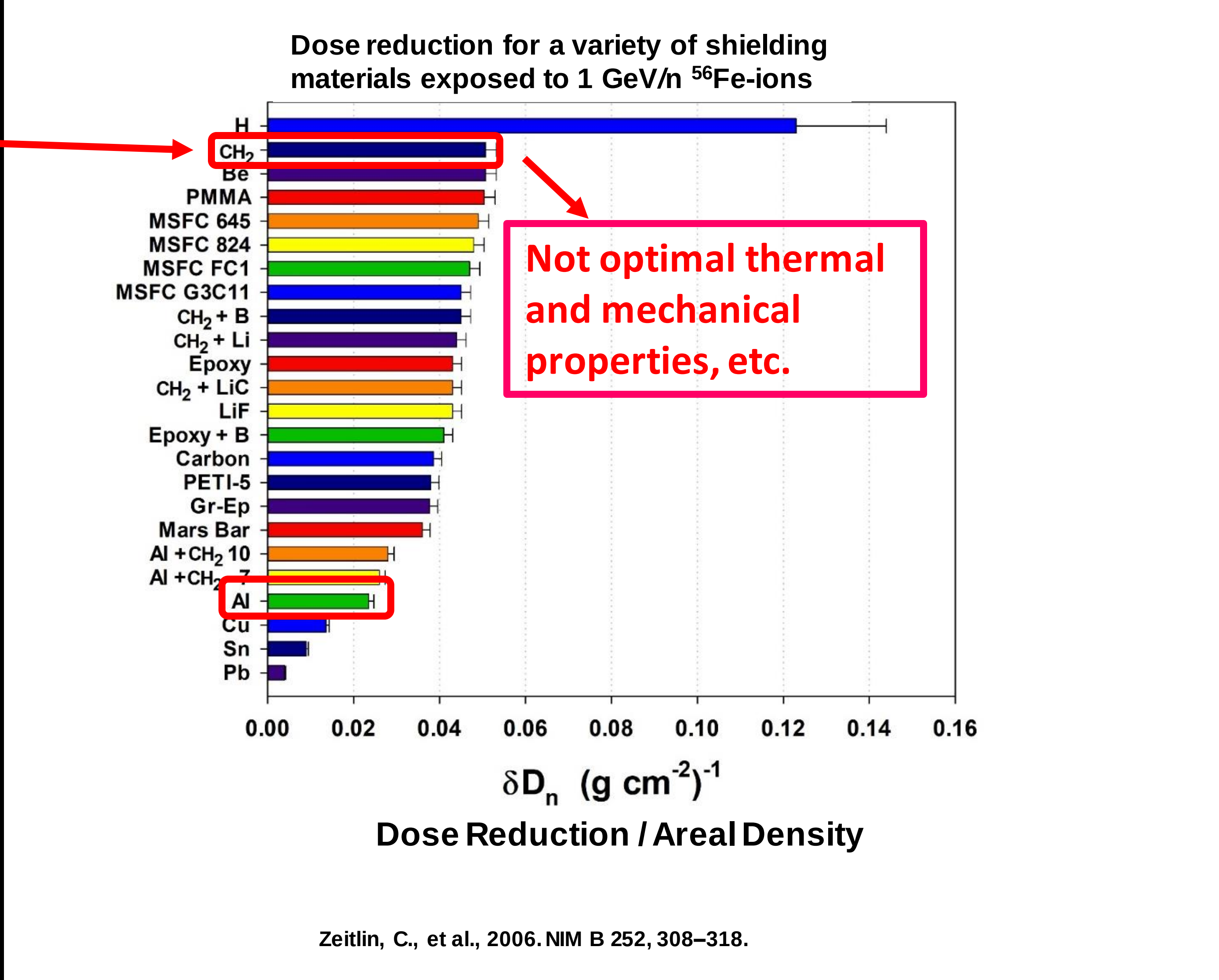
Dose Reduction for Shielding Materials



Polyethylen (PE)



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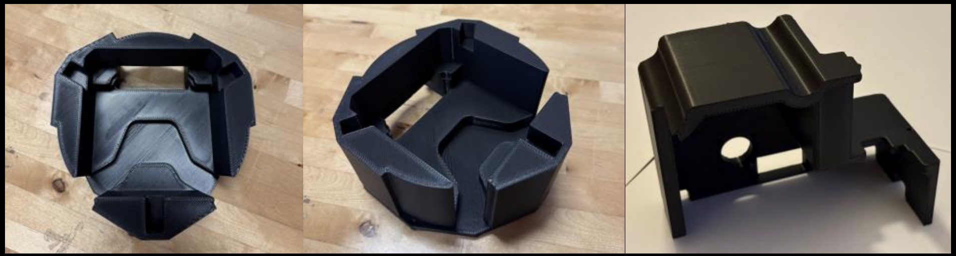
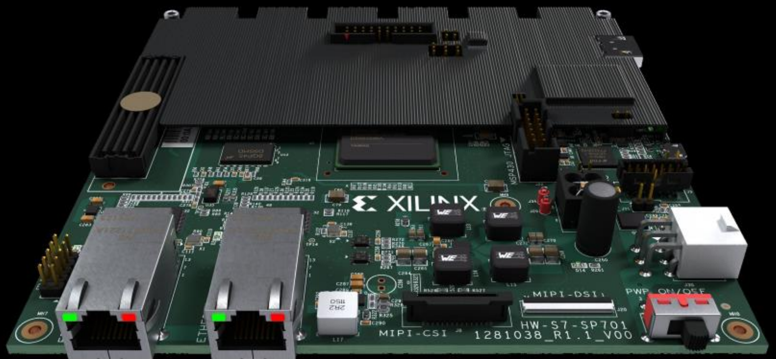
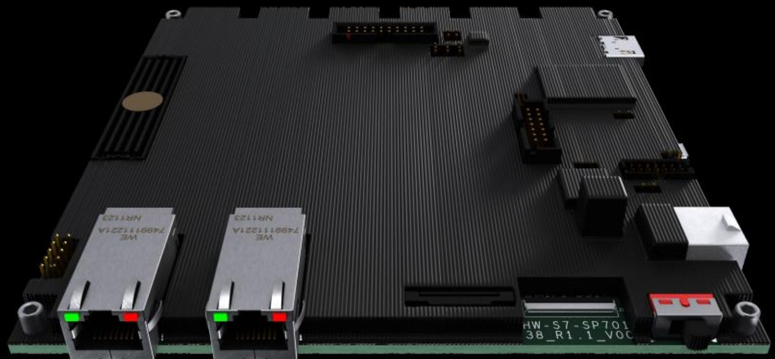
Multifunctional Shielding Polymer (MSP)/Plasteel™

- Nano-doped hydrogen rich polymer with good radiation protection, mechanical and thermal properties.
  - $\rho \approx 0.96\ g/cm^3$, emissivity as machined/printed = 0.96, melting Temp = 168 °C …
- Can be used as conformal/spot shielding of electronic boards/COTS components, shielding plates or larger subsystems.
- Can be 3D printed, moulded and thermoformed in any form factor.
- Up to 40x mass saving compared to conventional shielding.
- Significant dose reduction compared to conventional shielding.
- 10x - 15x cheaper than Rad Hard systems.







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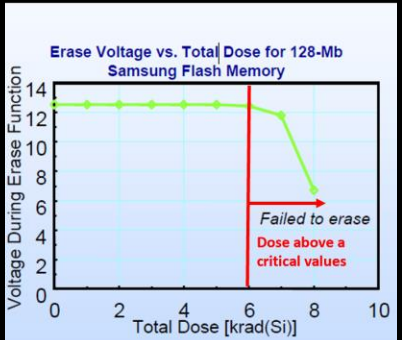
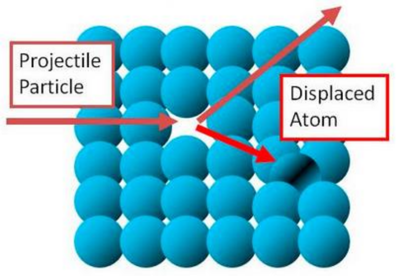
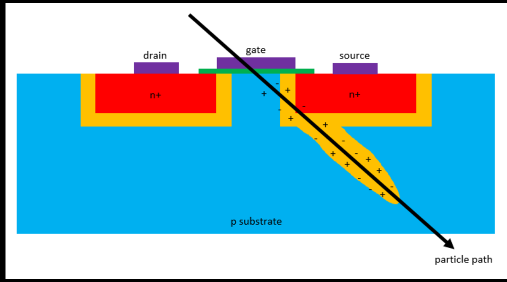
Quantities of Interest

- **Quantities of Interest**

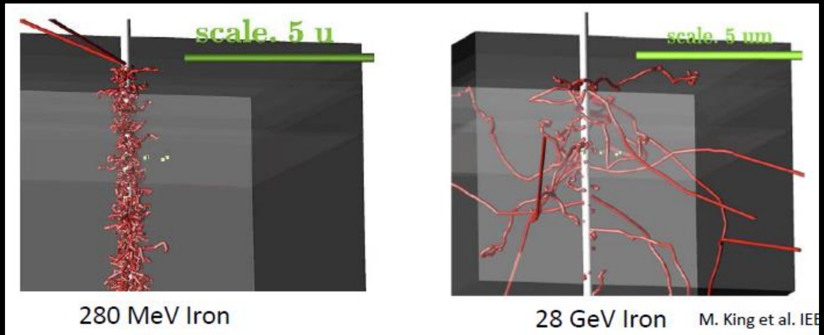


  - **Total Ionizing Dose (TID), dE/dm**





  - **Particle Fluencies, dθ/dt**



  - **LET (linear energy transfer/ionization density) dE/dX**

Quantities of Interest

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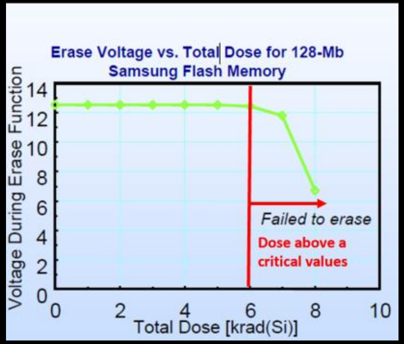
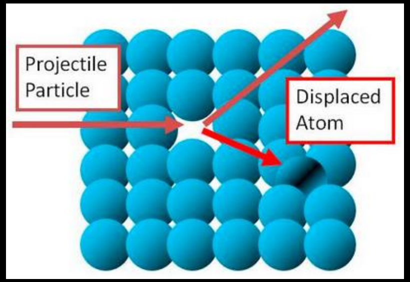
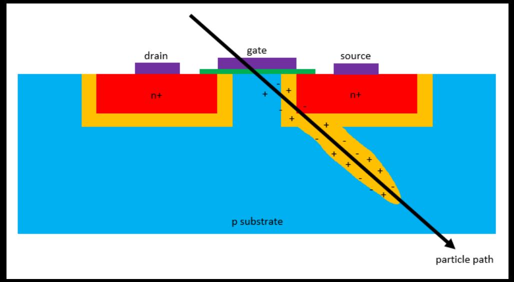


➢ **Total Ionizing Dose (TID), dE/dm**





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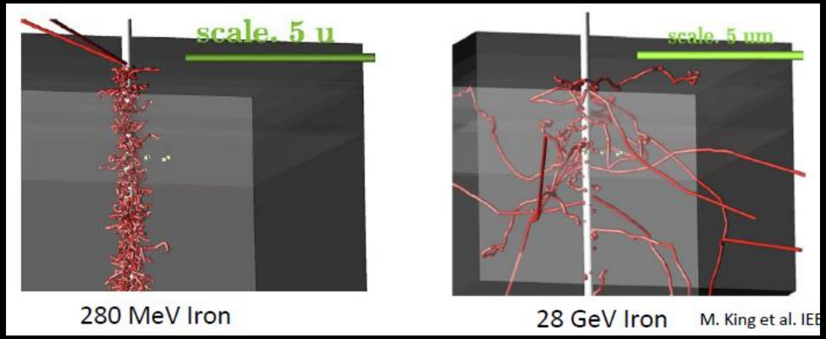
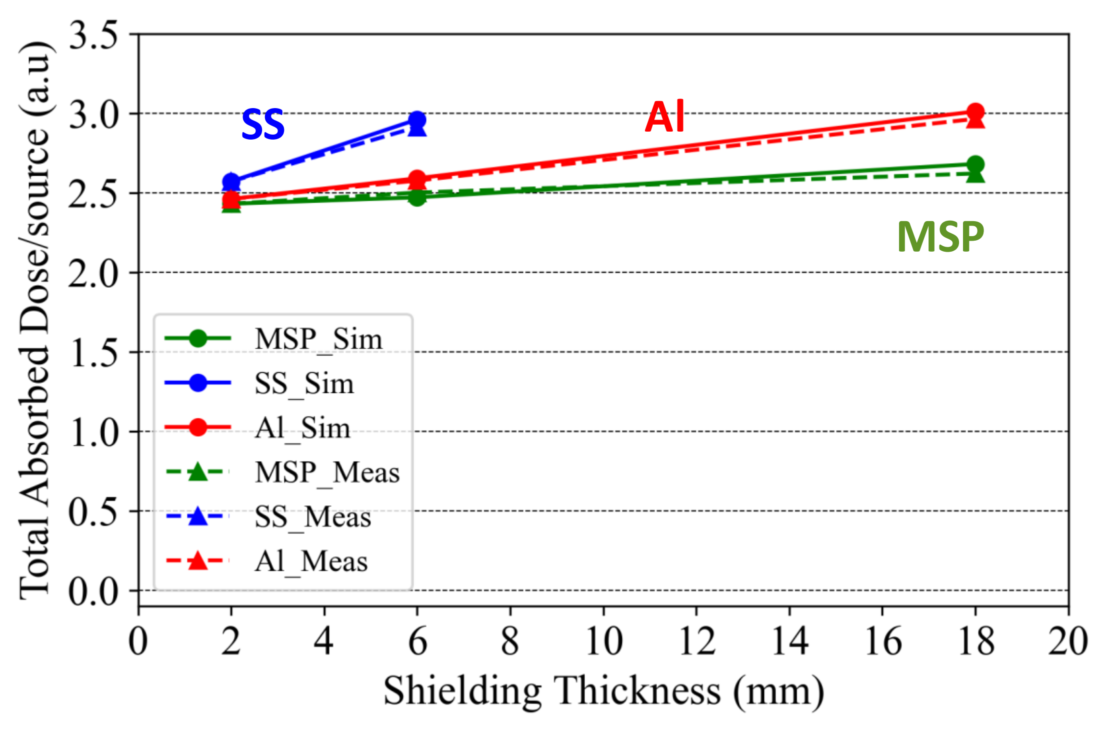


➢ **LET (linear energy transfer/ionization density) dE/dX**

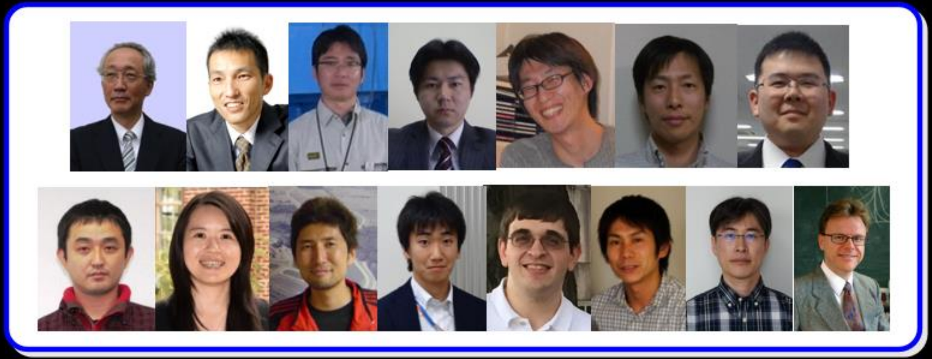
Dose Si behind SS, Al and MSP/Plasteel™

The dose in Si behind Stainless Steal (SS), aluminum (Al) and MSP/Plasteel™

Incident particles: 100 MeV proton



- Experiments done at Loma Linda University Medical Hospital, CA, USA
- Simulations done with PHITS*



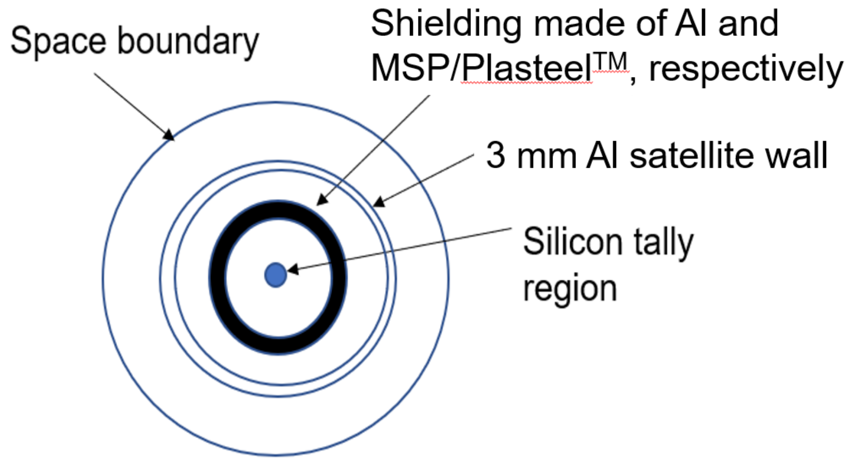
* T. Sato, …, L. Sihver and K. Niita J., J. Nucl. Sci. Techn. 61:1, 127-135, DOI: 10.1080/00223131.2023.2275736.

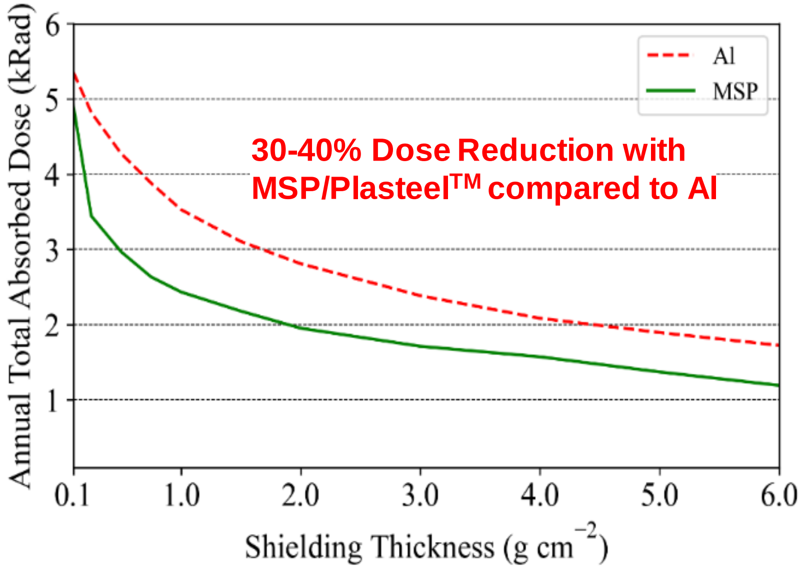
Al Density = 2.7 g cm^{-3}
Multifunctional Shielding Polymer (MSP) Density ≈ 0.96 g cm^{-3}

TID Behind Shielding

Space Simulations*

A spherical satellite with 3 mm Al walls & a radius of 50 cm, at 1400 km (LEO) and 51.6° inclination.
Shielding with Al and MSP/Plasteel™, respectively. TID in Si detector in the middle.





Simulation geometry

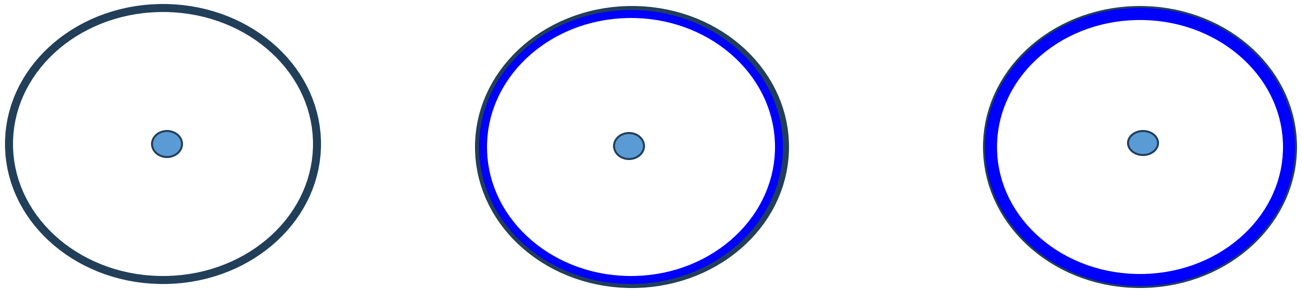
Comparison of TID in Si after Al and MSP/Plasteel™, respectively

* T. Sato, …, **L. Sihver** and K. Niita J., J. Nucl. Sci. Techn. 61:1, 127-135, DOI: 10.1080/00223131.2023.2275736.

TID Behind Shielding

Space Simulations*

A spherical satellite with 2 mm Al walls & a radius of 50 cm, at 35,786 km (GEO)
Shielding with Al and Al + MSP/Plasteel™, respectively. TID in Si detector in the middle.



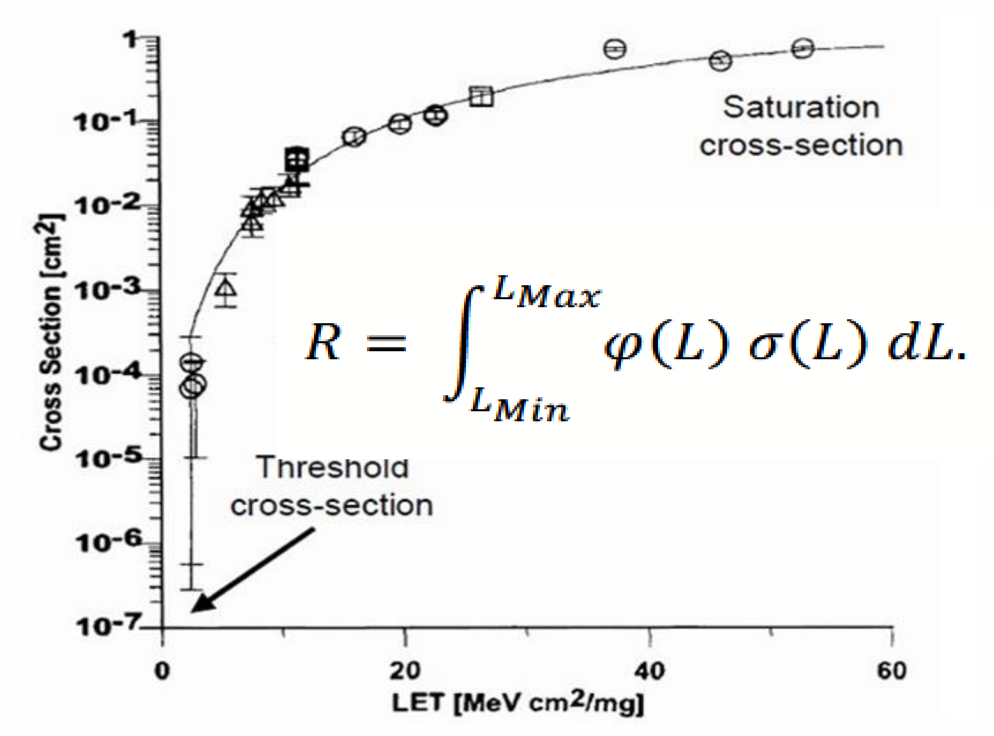
	Unshielded Al (only 2 mm Al)	Al+10 mm MSP/Plasteel™	Al+14 mm MSP/Plasteel™
TID from e^- [krad/year]:	**83.2 +/- 3.7**	**1.2 +/- 0.05**	**0.4 +/- 0.02**
TID from GCR + SPE (Aug. 1972 event) [Gy/event]:	**4.7 +/- 0.02**	**1.1 +/- 0.01**	**0.8 +/- 0.00**

* T. Sato, …, **L. Sihver** and K. Niita J., J. Nucl. Sci. Techn. 61:1, 127-135, DOI: 10.1080/00223131.2023.2275736.

Single Event Effects (SEE) - Simplified

Important parameters:

- Particle Fluencies
- LET (ionization density / lineal energy transfer)



$$R = \int_{L_{Min}}^{L_{Max}} \varphi(L)\, \sigma(L)\, dL.$$

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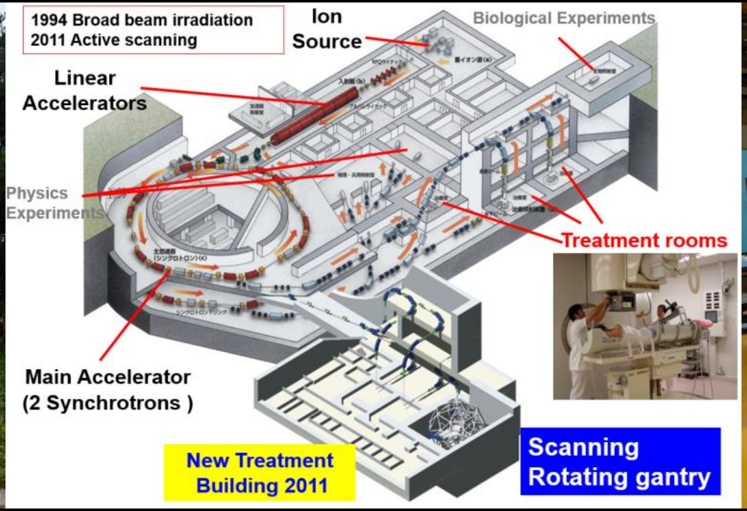
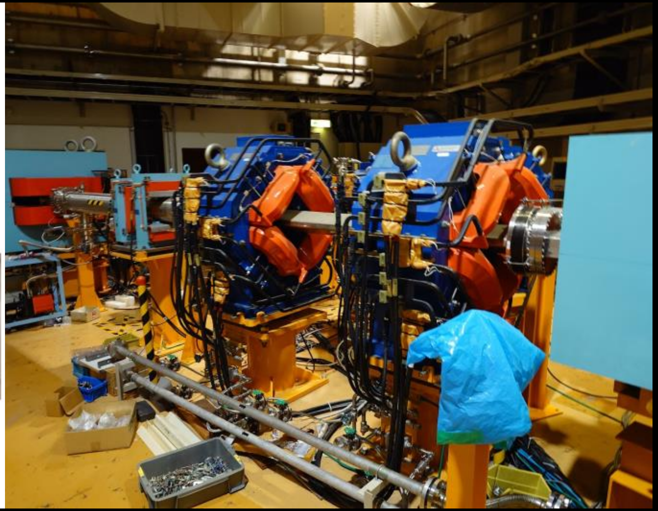
SEE Measurements together with Aethero Space

AETHERO

- **63 MeV protons: TRIUMF, Vancouver, Canada**

- **180 MeV/u Xe: HIMAC, Chiba, Japan**





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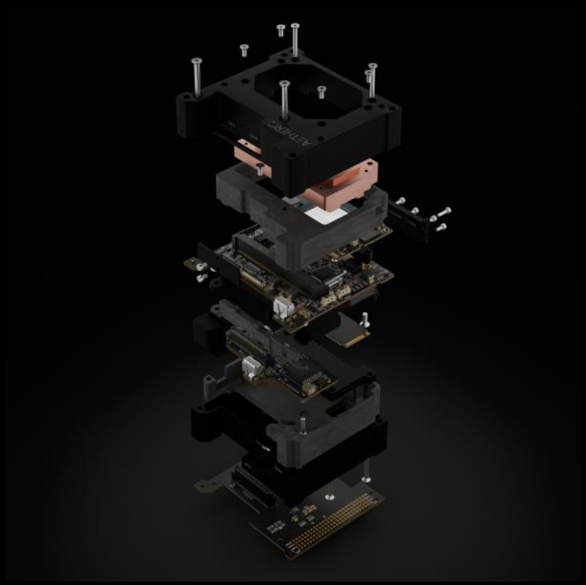
Goal of the Measurements

Determine Single Event Effects (SEEs) on edge computing modules running on COTS NVIDIA Jetson Orin NX System-On-Chip (SOC) ***– the world's most powerful AI edge computer*** **- behind Cosmic Shielding Corporation´s MSP/Plasteel and Aluminum exposed to 63 MeV protons and 180 MeV/u Xe ions.**



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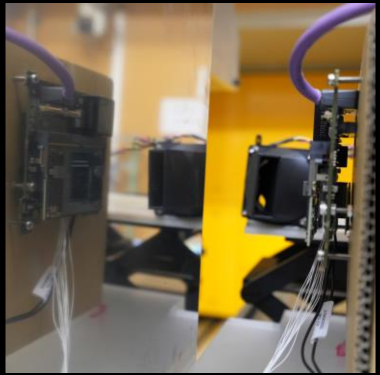
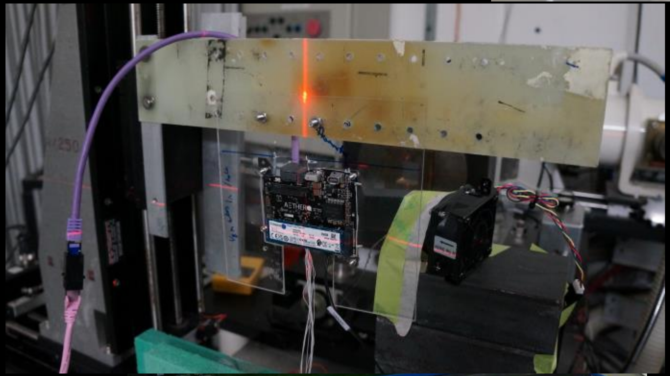
Experimental Setups at TRIUMF and HIMAC

- **The SOMs was connected via UART and SSH simultaneously, which allowed for:**
  - **Remote data logging to the lowest debug level using UART connection to the SOM, provided with a USB-C to UART adapter connected to the a host computer in the control room.**
  - **Transfer the onboard data log using a fast SSH connection over ethernet.**



- **A DC power supply was also connected to the host machine to digitally monitor and log the output of the power supply.**



- **The behavior of:**
  - **CPU/GPU cores on chip processors, and memory**
  - **temperature**
  - **power**
  - **watchdog/radiation mitigation software**

were continuously monitored and logged on the host computer.

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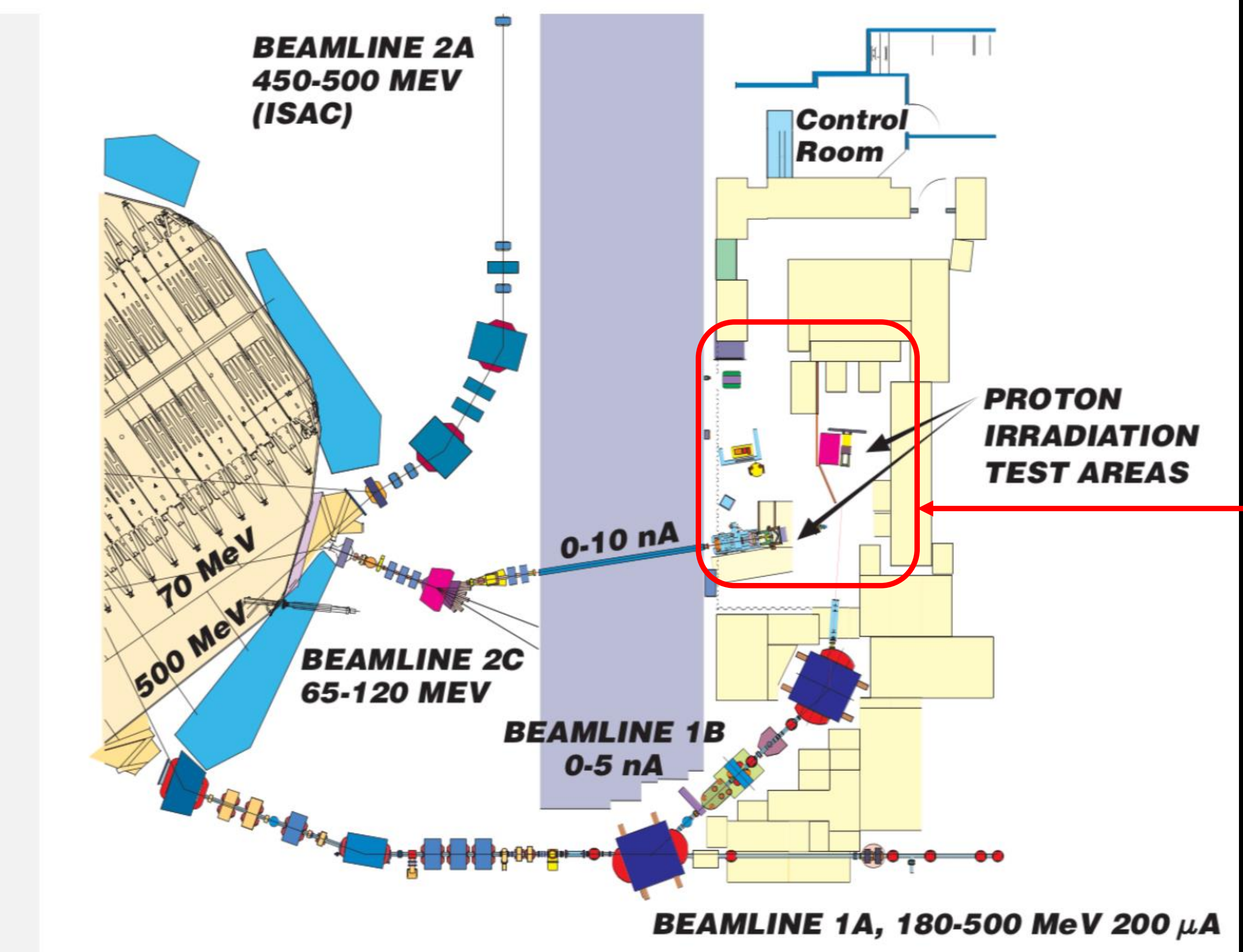
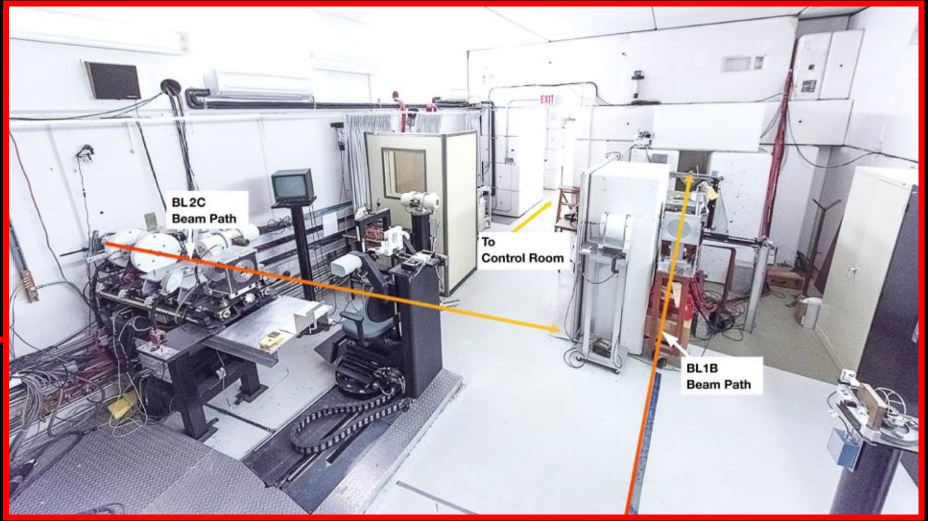
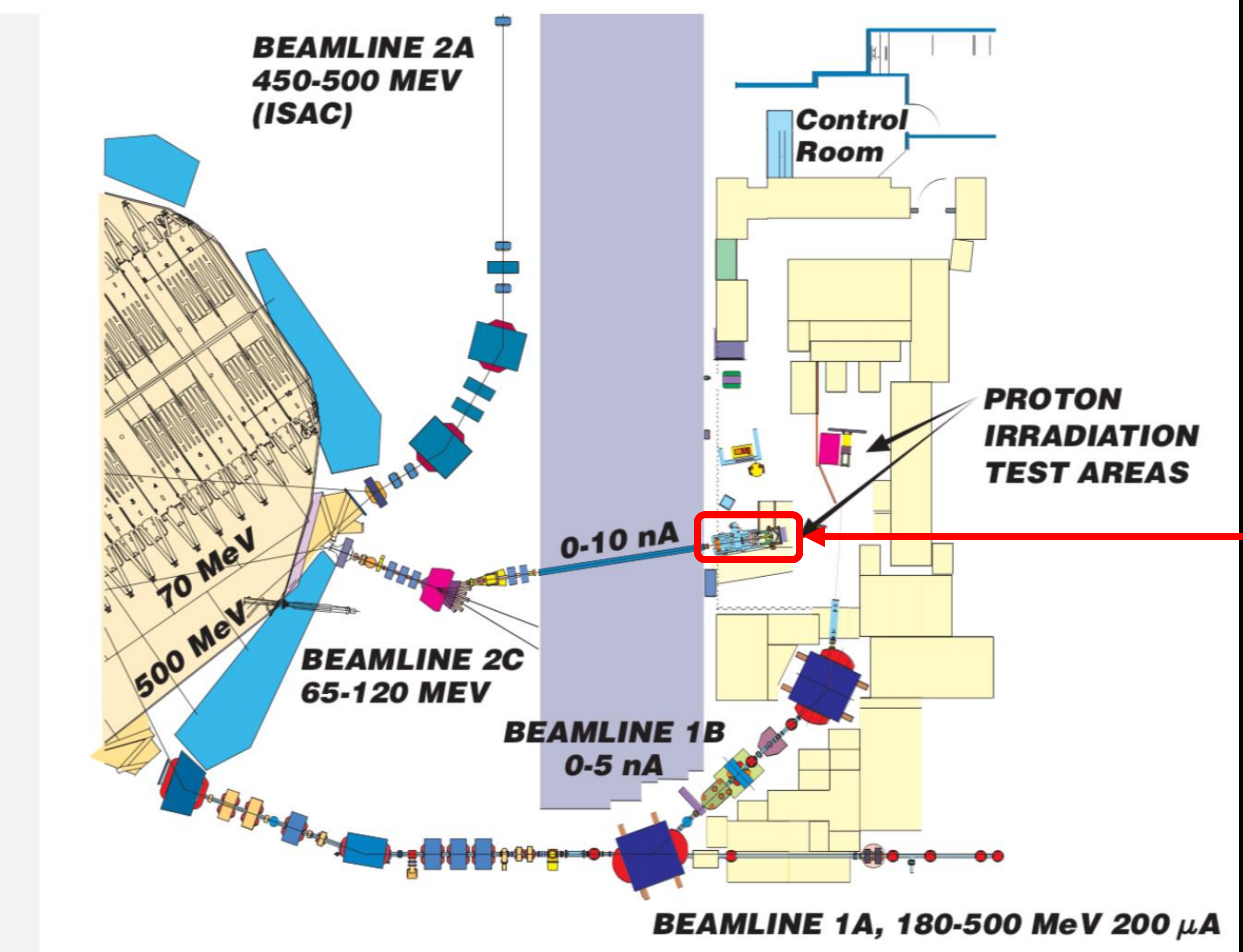
Experimental Setup at TRIUMF
(BL2C Beam Line)

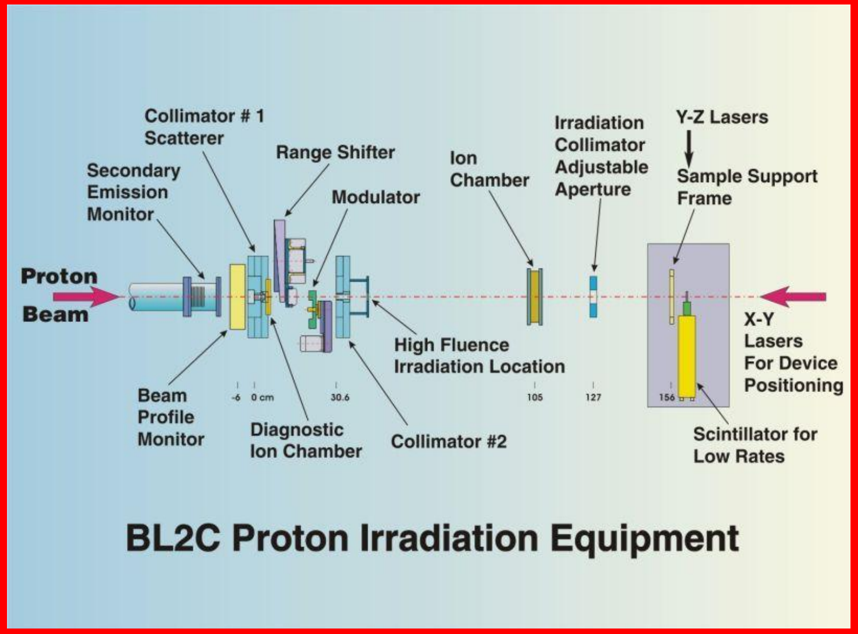




Experimental Setup at TRIUMF
(BL2C Beam Line)



The beam intensity is monitored by an air ionization chamber (IC) which has been calibrated against plastic scintillators and other ICs.



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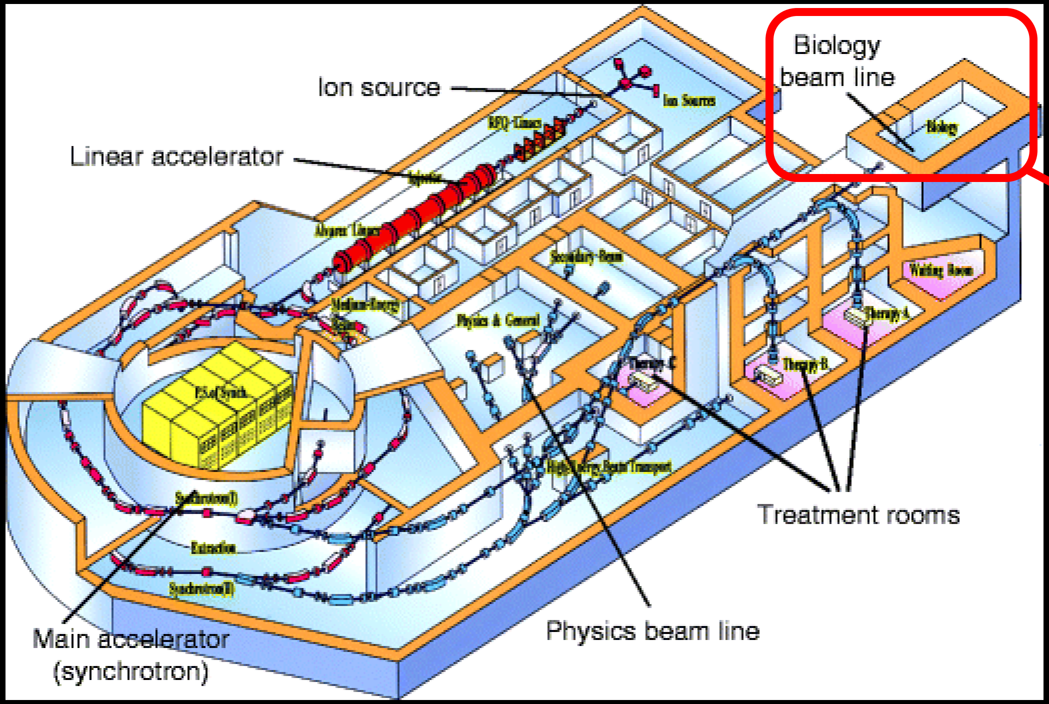
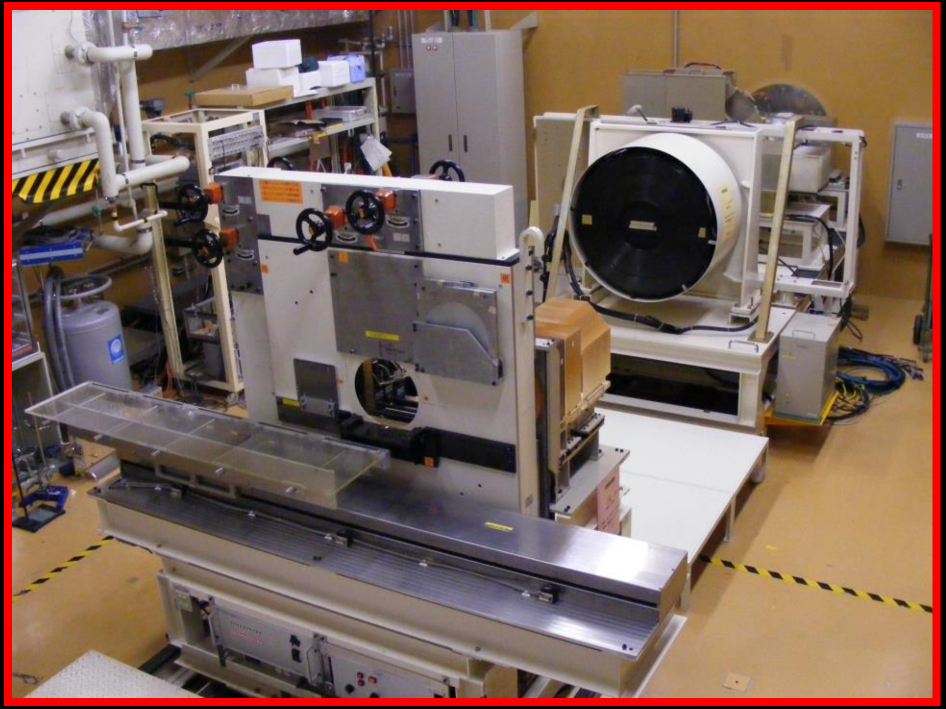
Experimental Setup at TRIUMF
(BL2C Beam Line)

A 3 cm x 3 cm collimator was used at TRIUMF so only the system-on-modules (SOMs) were irradiated.

Experimental Setup at HIMAC
(BIO Room)





3 cm x 3 cm and 6 cm x 6 cm collimators were used at HIMAC so we could both irradiate:

- **Only the system-on-modules (SOMs)**
- **The whole boards**

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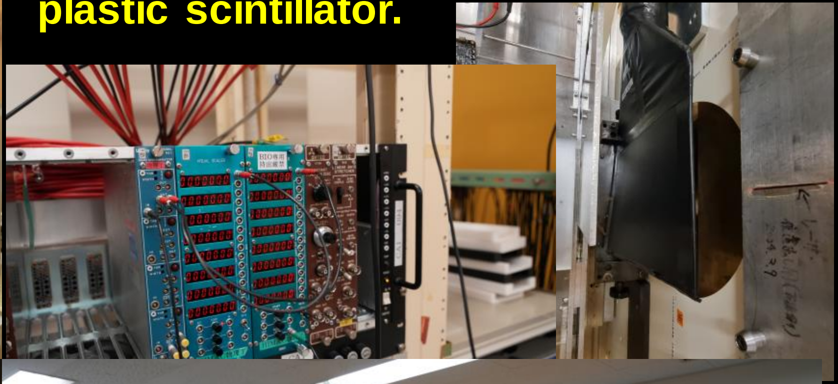
Experimental Setup at HIMAC
(BIO Room)

The beam intensity is monitored by a plastic scintillator.



Classification of Non-Destructive Severe SEEs:

- **Single Event Upsets (SEUs) and Multi-Bit Upsets (MBUs)**
  - **Errors that are self-corrected and allow the device to continue operate, which means that the watchdogs/radiation fault mitigation software fix the errors.**
  - **Errors that are NOT self-corrected and cause the watchdog on the NVIDIA SOM to self-reboot.**
- **Single Event Functional Interrupts (SEFI)**
  - **When the watchdog uses the companion chip onboard to reset the NVIDIA SOM under some conditions when the NVIDIA chip latches up.**
  - **In extreme cases when the companion chip also latches up and the watchdog fails at resetting the system which requirs a manual power cycle.**

Classification of Semi-Destructive Severe SEEs:

- **Single Event Hard Errors**
  - **NVMe SSD failures where sections of the drive do not work due to stuck memory.**
    - ✓ **This can be mitigated to some extent by using page file skipping by the onboard radiation fault mitigation software.**
- **Single Event Burnout**
  - **NVMe SSD failures where sections of the drive do not work due to burned out transistors.**
    - ✓ **This can be mitigated to some extent by using page file skipping by the onboard radiation fault mitigation software.**

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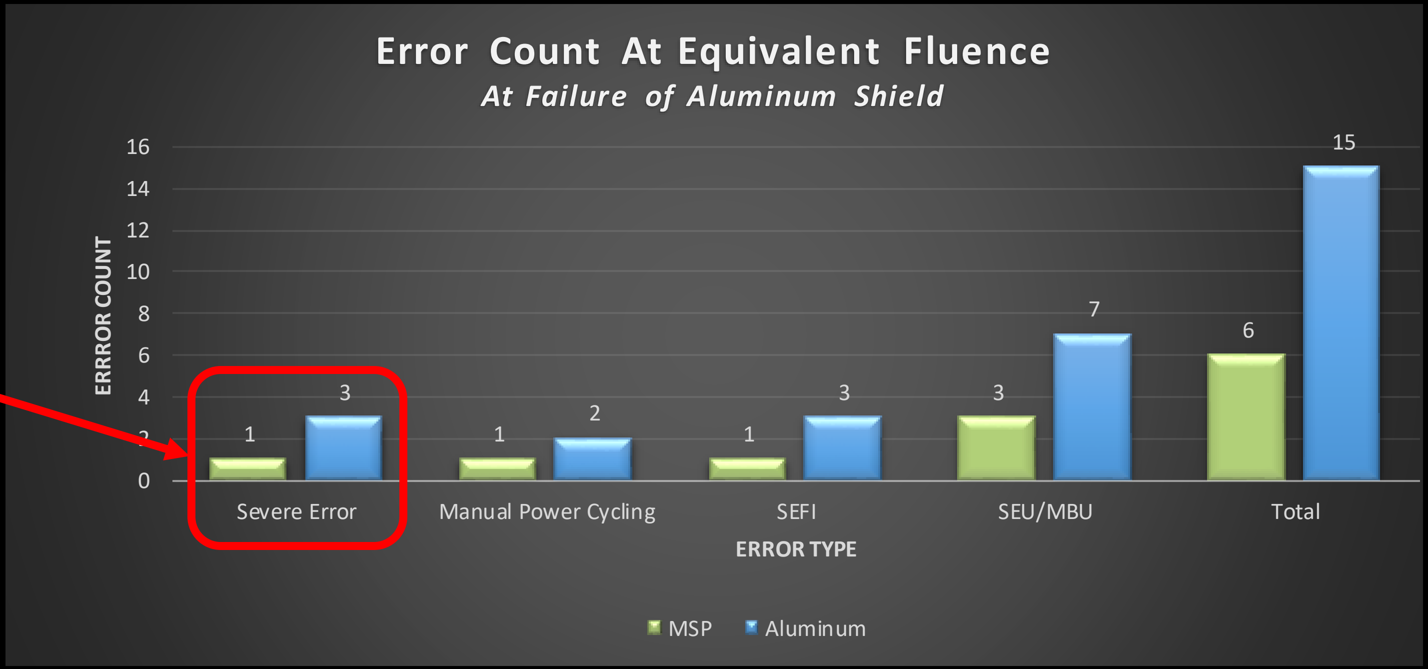
Classification of Destructive Severe SEEs:

- **Single Event Gate Rupture (SEGR)**
  - **Needs to be verified by reflashing. If the SOMs recover after reflashing then there are no (SEGR).**
- **Single Event Dielectric Rupture (SEDR)**
  - **Needs to be verified by reflashing. If the SOMs recover after reflashing then there are no (SEDR).**

Results from 63 MeV Proton Irradiations

- **At a flux of around 7×10^6 p/cm^2/s, 3 cm x 3 cm collimated, the SOMs worked until exposed to a total fluence of:**
  - **4.0×10^{10} p/cm^2 behind 1.15 g/cm^2 (12 mm) MSP**
  - **6.4×10^9 p/cm^2 behind 1.30 g/cm^2 (4.4 mm) Al**

Watchdog rebooting
and/or Manual Power Cycling



Number of errors of each error type in the SOM behind MSP and Al at $\theta = 6.4 \times 10^9$ fluence (at which the SOM behind Al stopped working)

Results from 63 MeV Proton Irradiations

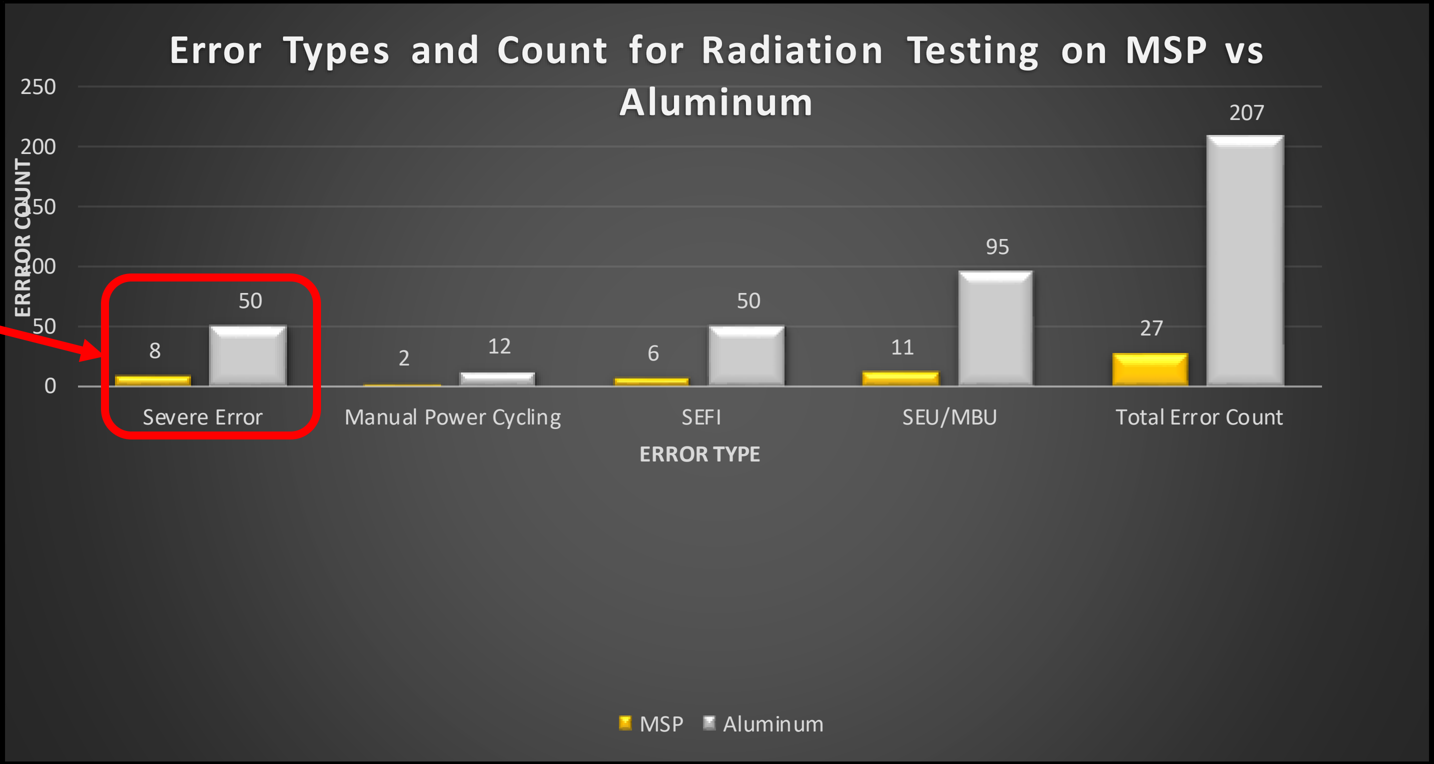
- **Significantly more failures behind Al then behind MSP at the same fluence.**
- **The SOMs failed behind Al at a significantly lower total fluence than behind MSP even if Al had 13 % higher areal density.**
- **Cause of failures the same behind the MSP and behind Al.**
  - **As expected non radiation hardened Kingstone SSDs were the first to fail.**

The SSDs behind the MSP could easily be recovered by flashing and rewriting the sectors while there were destructive errors in the SSDs behind Al so they could not be recovered by reflashing/rewriting!

Results from 180 MeV/u Xe irradiations

- At a flux of around $1x10^3$ p/cm^2/s, 3 cm x 3 cm collimated, the SOMs had the following errors when exposed to a total fluence of:
  - 1.2 x 10^6 p/cm^2 behind 1.16 g/cm^2 (12 mm) MSP
  - 6.4 x 10^5 p/cm^2 behind 1.30 g/cm^2 (4.4 mm)

Watchdog rebooting and/or Manual Power Cycling



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Results from 180 MeV/u Xe irradiations

- At a flux of around $1x10^3$ p/cm²/s and 6 cm x 6 cm collimated beams.
- After $1.2x10^5$ p/cm², the SOM behind 0.42 g/cm² (4.4 mm) MSP had experienced 11 severe errors, which all required manual power cycling, but it was still operating without any problem.
- After $3.2x10^4$ p/cm², behind 0.43 g/cm² (1.6 mm) Al, the radiation hardened Exascend PR4 SSDs broke and had to be replaced.
- After $7.8x10^4$ p/cm², behind 0.43 g/cm² (1.6 mm) Al, the SOM itself broke, and it could not be recovered so that was the end of the measurement.

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On Orbit Testing

CUSTOMER MISSION	SYSTEM	TIME IN-ORBIT
Axiom ISS Multishield	Active & passive Detectors	Returned after 8 months
Quantum Space Scout-1	TIMEPIX, Flight Computer	Currently In-Orbit
Deimos	NVIDIA Jetson AGX	Currently In-Orbit
DROID.002	Multiple optical & electrical components	Currently In-Orbit
HOLMES-008	Camera backplane shield	Currently In-Orbit
ALDER-002	Camera backplane shield	Currently In-Orbit

Cosmic Shielding Corporation (CSC) - AXIOM Ax2 exp.

COSMIC SHIELDING CORPORATION

6 months exp. inside the ISS to test CSC´s Multifunctional Shielding Polymer

Launched on the top of the SpaceX Falcon9 Rocket to the ISS on May 21, 2023
Landed on Earth with Ax3, Feb. 9, 2024

PI: Lembit Sihver

Detector systems: customized versions of SPACEDOS in Collaboration with NPI, Prague, Czech Republic

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“Near Future” SEE Testing

At TRIUMF:

105 and 480 MeV protons & neutrons if needed

At NSRL:

147 & 380 MeV/n Bi with and without degrader

At HIMAC:

180 MeV/u Xe
500 MeV/u Fe

At CERN:

275 MeV/u & 900 MeV/u Pb with and without degrader

Summary and Conclusions

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The new Space Era is Happening NOW!

COTS components are needed, but ionizing radiation is a "Show Stopper" if no efficient shielding!

- **MSP/Plasteel™**
  - **Can be used as conformal/spot shielding of electronic boards/COTS components, shielding plates or larger subsystems.**
  - **Can be 3D printed, moulded and thermoformed in any form factor.**
  - **Reduces the dose more than other conventional shielding materials.**
  - **Significantly reduces all kinds of SEEs, incl. the "severe errors".**
  - **Gives up to 40x mass saving compared to conventional shielding.**
  - **Is 10x - 15x cheaper than rad hard systems.**

Acknowledgements

I thank Aethero Space for performing the SEE measurements together with me, and all the staff at TRIUMF and HIMAC, especially:

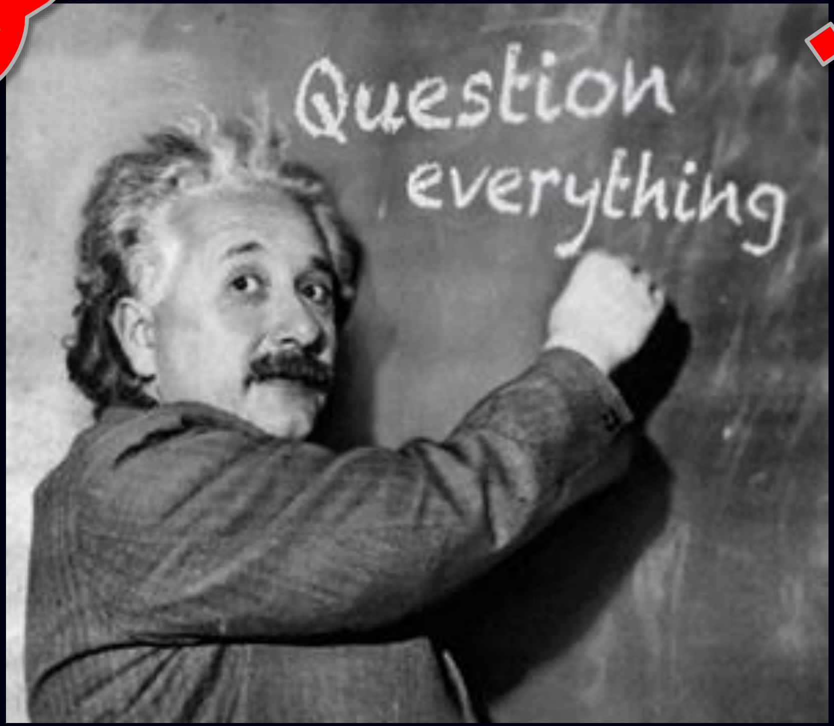
Dr. Camille Belanger-Champagne and Dr. Alex Hands at TRIUMF

Dr. Satoshi Kodaira and Mr. Hisashi Kitamura at HIMAC

We also acknowledge the US DoD for funding CSC´s STTR and TACFI projects, and the US AFRL and US Space Systems Command (Space Force) for their support.


Thank you for your attention!

Questions?



Comments?