Radiation Hardness Assurance for COTS used on low-cost missions

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- The goal of this work package was to define a **radiation hardness assurance (RHA)** methodology compatible with the requirements of **small missions**
- Two critical points
  - Use of COTS components
  - Restricted budget
- We incorporated ideas from the literature and lessons learned during the project

Methodology

- **Simplified flow**
  - Steps skipped or simplified when reasonable to do so
- Use of **available information** to the maximum extent possible, to assess radiation sensitivity
  - Radiation test databases
  - Technological information
- **Reduction of Testing Costs**
  - Number of samples
  - Radiation sources
  - Board-level testing

Proposed Flow

- Radiation Environment
- Criticality Analysis
- Evaluation of radiation performance of selected parts
  - Use of Existing Radiation Data
  - Use of Information on Manufacturing Technology
    - Total Ionizing Dose
    - Single Event Effects
  - Radiation Testing
    - Total Ionizing Dose
    - Single Event Effects
- Part Suitability Assessment

1. Radiation Environment

Tool		URL
SPENVIS	Space ENVironment Information System	https://www.spenvis.oma.be/
CRÈME	Cosmic Ray Effects on Micro-Electronics	https://creme.isde.vanderbilt.edu/
OMERE	Outil de Modélisation de l'Environnement Radiatif Externe	https://www.trad.fr/en/space/omere-software/
Fastrad		https://www.fastrad.net/
NOVICE		https://empc.com/novice-software/

- The user should input trajectory data and the epoch of the mission and obtain information about the radiation environment, also considering reasonable amounts of shielding
- Radiation sources typically taken into consideration are:
  - Trapped protons and electrons in the radiation belts
  - Solar particles
  - Galactic cosmic rays

- The main outputs of this analysis are:
  1. The total dose curve, usually expressed as received TID as a function of spherical Al shielding
  2. The displacement damage equivalent fluence curve, usually expressed in terms of 10 or 50 MeV protons
  3. Trapped protons and electrons fluxes
  4. Solar particle fluxes and fluences
  5. LET spectra for nominal solar environment (i.e. galactic cosmic rays) and for solar events (Worst Week, Worst Day and Peak 5 minutes scenarios)
- **A detailed analysis might be waived for Low Earth Orbits at low altitude** (< 500 km) **in low inclination** (< 30°) **and relatively short duration** (< 1 year)
  - Radiation exposure is limited and reasonably low (100-1000 rad(Si)/year), provided some form of mitigation is implemented for SEE
  - Awareness of critical areas, such as the South Atlantic Anomaly, where the proton radiation belts extend to lower altitude, is necessary, though

- As a second step, a **criticality analysis** should be performed to point out the devices involved in the most important mission functions and the most dangerous radiation effects
  - **Not all parts have the same criticality**. Failures in parts that will end the mission should be addressed first
  - Once the list of critical part has been done, **the most critical effects** should be highlighted
- The following radiation effects should be always considered
  - **Destructive SEE**
    - Single Event Latchup, Single Event Gate Rupture or Single Event Burnout
  - Less likely to induce mission-ending critical failures, but still important to consider are:
    - TID-induced failure
    - DD-induced failure
- Consideration should also be given to the effects causing **single event functional interrupts (SEFIs)**
  - no physical damage to the devices, but loss of information which may seriously put a mission at risk

Evaluation of Criticality

- The goal is to **assess the risk** associated with the usage of the COTS parts selected the specific mission.
  - Based on this analysis: (1) accept the part, (2) reject the part, or (3) perform additional radiation tests
- Mission
  - Mission Parameters: orbit, launch date, radiation design margins, etc.
  - Mission Environment: radiation environment
- Satellite Geometry
  - A detailed description to assess the radiation environment inside the satellite at the location of specific components, sub-systems or systems
  - As an alternative, a **simplified approach which considers an approximate shielding** of 1 or 2 mm of Aluminum provided by the equipment box, and an extra of 0.5 or 1 mm from the spacecraft can be used, together with dose-depth curves
- Parts
  - Technology
  - Flight heritage
  - Test heritage

Severity Categories and Levels

Severity Category	Severity Level	Failure Effects	
		Dependability Effects (as specified in ECSS-Q-ST-30)	Safety Effects (as specified in ECSS-Q-ST-40)
Catastrophic	1	Failure propagation	Severe detrimental environmental effects
			Loss of system
Critical	2	Loss of mission	Major detrimental environmental effects
			Major damage to interfacing flight systems
Major	3	Major mission degradation	
Minor or Negligible	4	Minor mission degradation or any other effect	

- Severity Categories and Levels according to ECSS-Q-ST-30-02C

Probability Levels

Probability Level	Limits	PN
Probable	$P > 10^{-1}$	4
Occasional	$10^{-3} > P > 10^{-1}$	3
Remote	$10^{-5} > P > 10^{-3}$	2
Extremely remote	$P \leq 10^{-5}$	1

- For the derivation of the probability level the following aspects are considered:
  - **Test heritage**: test data are considered for the assessment of the failure mode probability level if available.
  - **Flight heritage**: flight data are considered for the assessment of the failure mode probability level if available.
  - **Statistical Models**: in case test or flight heritage is available from different lots statistical models are used for the assessment of the influence of Lot-to-Lot variation
  - **Engineering judgment**: if data are not available a qualitative approach for determination of the probability level shall be used.

3. Part Radiation Performance

- The use of existing test data is key to lower RHA costs
- Various **publications** dealing with radiation effects:
    - the IEEE Transactions on Nuclear Science,
    - the Nuclear Space Radiation Effects Conference data workshop proceedings
    - RADiation and its Effects on Components and Systems data workshop proceedings
- The use of **radiation test databases** that serve as a data compendium of previously performed tests, appears to be of great value:
    - ESA Radiation Test Database
    - GSFC Radiation Data Base
    - JPL Radiation Effects Database
    - CERN Radiation Test Database
    - DOEET web-page by ALTER

Use of Existing Data: Limitations

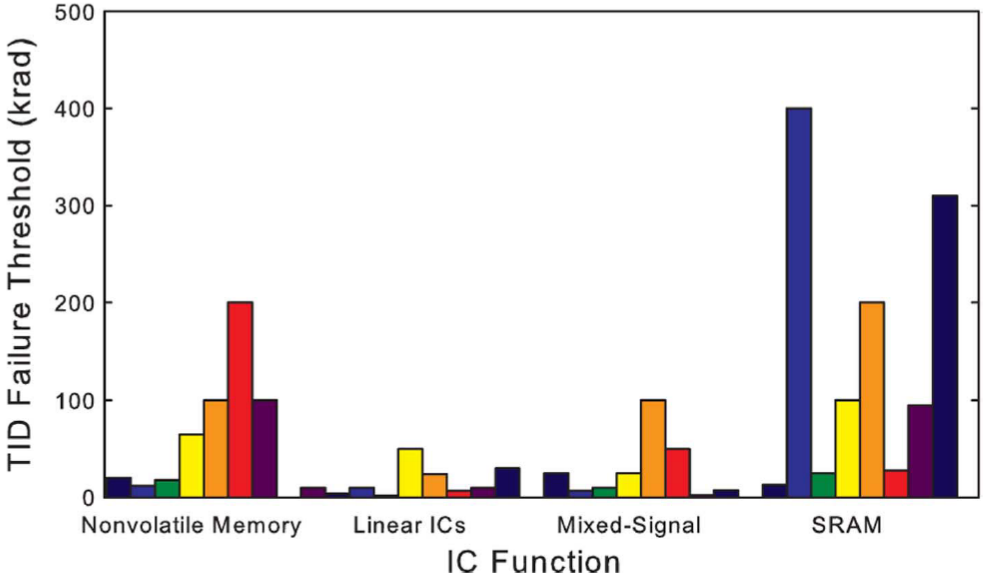
- **Part-to-part/Lot-to-lot variability** may be extreme in COTS
  - **Lack of traceability** seriously limits the use of existing data
  - Even if available data is recent and on the same part number, there is no guarantee that the part is the same as that which will be used in flight
  - Tested devices might come from a different lot than flight devices, if procured at some distance in time
    - It might be difficult to procure parts from a single lot, even in one go

Use of Information on Manufacturing Technology

- When no test data are available and testing is not a possibility, an **analysis of the manufacturing technology** should be performed
- Concerning **Total Ionizing Dose**
  - **Scaling** and in particular the reduction of the gate oxide thickness and the replacement of LOCOS with STI, have led to an **increase in the tolerance of devices with small feature size operating at low voltage**
  - In general, **the larger the supply voltage, the more likely the device is to suffer from total ionizing dose effects**
    - Digital devices are more aggressively scaled than their analog counterparts. However, these considerations should not be taken too far, as variability is large especially among COTS
    - Devices with a low supply voltage may have internal circuitry working at higher voltages, which might determine the overall sensitivity. This is the case of non-volatile devices

Categories of Parts and TID Sensitivity

- Some general trends as a function of device category are visible
- In general, **linear parts** bring more risk than an untested digital device, from the perspective of total ionizing dose tolerance
- It must be noted that failure doses as low as 1 krad can be found in particularly sensitive devices, which may cause mission failure even in relatively benign environments.
- Below 1 krad, the probability of failure due to total dose is very small



From Dodd et al. IEEE TNS 2008

CORHA TID Results: Memories

Category	Device	Parametric Failure Level (krad)		Functional Failure Level (krad)		TID Pass Level (krad)		Comment
		biased	unbiased	biased	unbiased	biased	unbiased	
NVM	MT28EW128ABA	50	50			15	15	Standby current increases over spec.
NVM	CY14V101PS	50	100			15	50	Supply current increases overs spec.
NVM	MB85RS256TY	50		**100**		15	100	
NVM	CY15B102QN	15		**50**		10	100	Standby current increases over spec, then functional failure.

- Results obtained by the CORHA project
  - **Functional failures** tend to occur at relatively **high doses** in all tested components,
  - **Parametric failures** may occur at doses as low as 2 krad in some analog components, but this should not be taken as a general rule.
- As the number of used parts increases, the chances that a part with poor TID tolerance is present in the bill of material increases
- It must be remarked that moderate parametric failures can be tolerated by some designs and applications, therefore this type of degradation should be addressed on a case-by-case basis

CORHA TID Results: Misc

Category	Device	Parametric Failure Level (krad)		Functional Failure Level (krad)		TID Pass Level (krad)		Comment
		biased	unbiased	biased	unbiased	biased	unbiased	
µC	STM32F103RGT6			54.1	100.1	25.1	54.1	
µC	STM32L152RET6			100.1	168h, 100°C	25.1	24h, RT	
OpAmp	LT1499HS#PBF-ND	10.0	10.0	> 100	> 100	2.0	2.0	
OpAmp	LTC6240HVCS#PBF-ND	10.3	10.3	> 100	> 100	2.0	2.0	
OpAmp	MAX44248ASA+T	> 100	> 100	> 100	> 100	100	100	
Analog Mux	CD74HC4051M96	11.0	54.0	> 100	> 100	2.0	25.0	Truth Table Test fails after 24h, RT anneal and recovers after 168h, elevated temperature annealing
Analog Mux	ADG5408TCPZ-EP	2.0	11.0	> 100	> 100	0.0	2.0	Truth Table Test fails at 2 krad for the biased and at 100 krad for the unbiased device
ADC	ADC128S102CIMTX	11.0	11.0	> 100	> 100	2.0	2.0	

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- As the number of used parts increases, the chances that a part with poor TID tolerance is present in the bill of material increases.
- It must be remarked that moderate parametric failures can be tolerated by some designs and applications, therefore this type of degradation should be addressed on a case-by-case basis

Recommendation for TID

Priority	Devices
Very High	High-voltage components, bipolar devices
High	Analog components, non-volatile memories
Medium	Low-voltage digital components
Low	Devices based on III-V semiconductors

Type	Process	Tech Node	Failure TID [krad]
CMOS	Bulk	>1000	30-50
CMOS	Bulk	250-1000	30-100
CMOS	Bulk	90-250	100-300
CMOS	Bulk	<90	100-1000
CMOS	SOI	<90	100-1000
CMOS	Bulk	FinFET	100-1000

Based on published data, results collected during the project and the scientific literature, the **guidelines** above have been proposed

Displacement Damage

Priority	Devices
High	Solar cells, Imaging Devices (CCDs, Active Pixel Sensors), Optocouplers
Medium	Bipolar devices
Very low	Low-voltage CMOS-based digital components Devices based on III-V semiconductors

- Displacement damage was not addressed in CORHA
- The simple guidelines above have been derived from the scientific literature and existing standards
- List of priority when dealing with displacement damage

- The evolution of single event effects with scaling is much less straightforward
  - Latchup increases with temperature and voltage
    - Strong dependence on doping levels and geometry
  - Threshold LET for SEU decreases
  - MBU increases
  - SEFIs become more and more complex and difficult to diagnose
- Reliance on technological information may be difficult
  - Mitigation is always recommended

Single Event Latchup: CORHA results

Category	Device	SEL	Comments
Non-volatile Memory	MT28EW128ABA	Yes	Small probability
Non-volatile SRAM	CY14V101PS	Yes	@ room temperature and also with protons
Non-volatile Memory	MB85RS256TY	No	
Non-volatile Memory	CY15B102QN	Yes	@ room temperature and also with protons
Microcontroller	STM32F103RGT6	No	
Microcontroller	STM32L152RET6	Yes	Intense latching @ Room temperature and also with protons
OpAmp	LT1499HS#PBF-ND	No	
OpAmp	LTC6240HVCS#PBF-ND	No	
Analog Mux	CD74HC4051M96	No	
Analog Mux	ADG5408TCPZ-EP	No	A single latch up was observed @ room temperature
ADC	ADC128S102CIMTX	Yes	

- Wide variety of observed behaviors
- Single Event Latchup is a common threat

Single Event Latchup: Guidelines

Type	Process	Tech Node	SEL
CMOS	Bulk	>1000	possible
CMOS	Bulk	250-1000	Possible
CMOS	Bulk	90-250	Likely
CMOS	Bulk	<90	Possible
CMOS	SOI	<90	Impossible
CMOS	Bulk	FinFET	Likely

- Due to the reduction in supply voltage, sensitive volume shape, and doping levels, CMOS technology exhibits some trends in the SEL sensitivity
  - Beware of FinFET technologies!

Single Event Upsets: CORHA Results

Category	Device	SEU
Non-volatile Memory	MT28EW128ABA	Sensitive only at high LET (large feature size)
Non-volatile SRAM	CY14V101PS	Non-volatile storage is immune, volatile one is sensitive
Non-volatile Memory	MB85RS256TY	Immune
Non-volatile Memory	CY15B102QN	Immune

- One of the focus of CORHA was on non-volatile memories
  - Some storage technologies are harder than others: ferroelectrics, SONOS, but also Flash with large feature size are almost immune
- Single Event Upsets are common in volatile storage

Radiation Testing

- When existing data and considerations on manufacturing technology do not provide sufficient information for a reliable assessment, **radiation testing** should be performed
- Some approaches are available to reduce costs
  - Total Ionizing Dose
    - Reduction of Tested Parts
    - TID Testing at board/system level
  - Single Event Effects
    - Reduction of radiation sources
    - SEE Testing at board/system level

TID: Reduction of Tested Parts

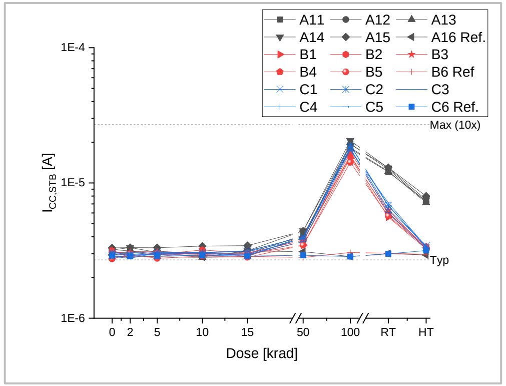
- Any approach aiming at reducing the number of tested parts has to cope with the **large variability** and **lack of traceability** that characterize COTS
- When reducing the number of tested parts, the **radiation design margin** should be increased
- CORHA results actually do not show extreme variability, especially on digital components, but literature data are much more worrying

CORHA Results: Lot-to-Lot Variability

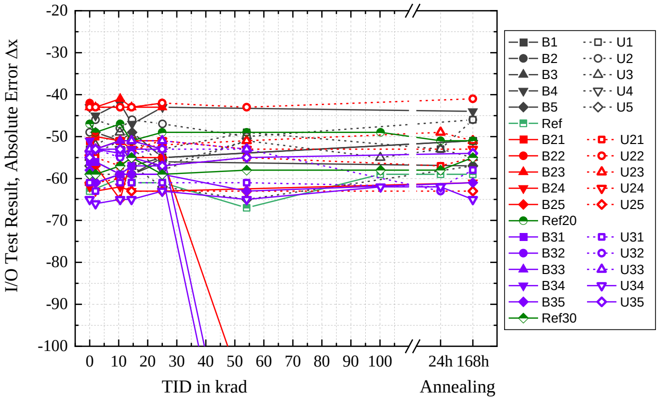
Device	Lot	Parametric Failure Level (krad)		Functional Failure Level (krad)		TID Pass Level (krad)	
		biased	unbiased	biased	unbiased	biased	unbiased
CY15B102QN	Lot 1	15		50		10	100
	Lot 2	15		50		10	100
	Lot 3	15		50		10	100
STM32F103RGT6	Lot 1			54.1	100.1	25.1	54.1
	Lot 2			54.1	100.1	25.1	54.1
	Lot 3			54.1	100.1	25.1	54.1
LTC6240HVCS#PBF-ND	Lot 1	10.3	10.3			2.0	2.0
	Lot 2	14.4	54.4			10.5	25.0
	Lot 3	10.5	25.0			2.0	14.4

- In general, the lot-to-lot variability observed in CORHA was minor
  - Lots were procured from the same sources at some months of distance in time
  - No worst-case
  - Analog devices again more critical (OpAmp)

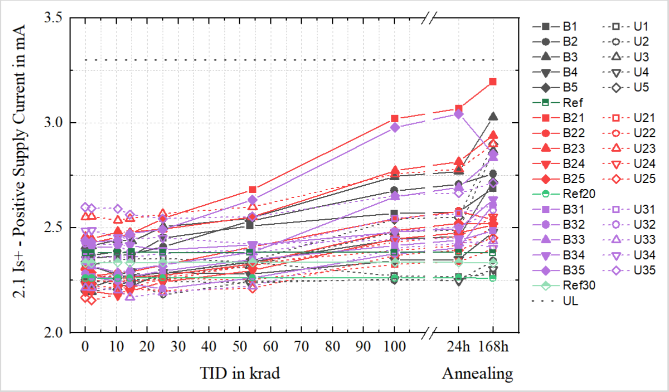
CORHA Results: Lot-to-Lot Variability



FRAM
CY15B102QN



µC
STM32F103RGT6



OpAmp
LTC6240HVCS8

- In general, the lot-to-lot variability observed in CORHA was minor, especially in digital devices

TID Testing at Board/System Level

- Radiation testing may be performed at board/system level
- TID board level testing offers some advantages:
  - a quick and cheap **go / no-go test**
  - identification of the **weakest components** on the board, provided that proper test vectors are used
  - assessment of the TID margin of the board
- The tests shall be conducted in conformance with the relevant standards (ESCC22900 or MIL-STD 883 Method 1019).
- The dose rate shall be chosen in such a way to account for ELDRS effects if applicable

- TID board tests performed in the frame of CORHA were consistent with component level testing

TID Proposed Guidelines

Scenario	Shielding used	Recommendation
Mission dose < 1krad$_{(Si)}$	**Yes / No**	**No testing**
Mission dose 1 – 5 krad$_{(Si)}$	**No**	**Decision for testing at component, board or equipment level shall be made by the mission engineers.**
Mission dose > 5krad$_{(Si)}$	**No**	**Perform testing at component, board or equipment level.**
Mission dose > 1 krad$_{(Si)}$	Yes	In case shielding decreases the dose level below 1 krad$_{(Si)}$ radiation testing may be omitted.
Mission dose > 1 krad$_{(Si)}$	Yes	In case shielding decreases the dose level in a range from 1 krad$_{(Si)}$ to 5 krad$_{(Si)}$ the decision for testing at component, board or equipment level shall be made by the mission engineers.
Mission dose > 5 krad$_{(Si)}$	Yes	In case shielding cannot decrease the dose level below 5 krad$_{(Si)}$ radiation testing shall be performed at component, board or equipment level.

- These recommendations are valid for low-cost missions only
  - There are always risks associated with no testing

TID Proposed Guidelines

Data available	RDM
TID Tests on 10 parts in flight lot	1.2
TID Tests on 2 parts in flight lot	1.5
Recent TID Tests on different lot	1.8
TID data from recent literature	2
NO TID data, technology considerations only	3

- If a statistical analysis is performed, a RDM of 1.0 could even be used, but such an analysis is not foreseen in the frame of a low-cost mission

SEE Testing

- **SEE testing** should be focused on **destructive events**, since soft events can usually be handled at the system level, with **proper mitigation**
  - Simplified heavy-ion tests might be performed with the goal of verifying the occurrence of destructive SEE
    - **a single high-LET heavy ion** may be used to save beam time and rule out possible destructive events
  - In order to implement effective mitigations against non-destructive events, **one must know the SEE types a part can exhibit**.
    - A simple ECC or CRC is ineffective against SEFIs on complex devices
    - Modern, complex devices can have unexpected SEFIs

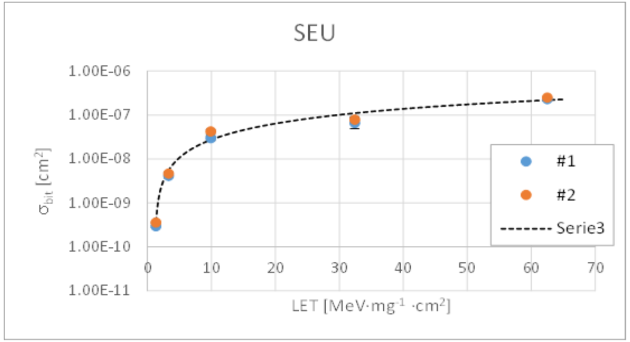
SEE: Models to Predict Proton Sensitivity

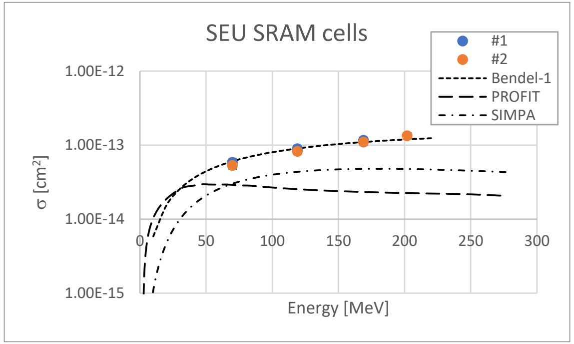
- **Proton sensitivity** can be derived **from heavy-ion sensitivity**
  - Concern for electronics with a threshold LETth smaller than 15 MeV·cm^2 ·mg^{-1}
  - Analytically (PROFIT, SIMPA, FOM) or by means of simulation, thus reducing the amount of testing required. The opposite is usually not possible.
  - If the target environment is proton rich, heavy-ion tests can be skipped
- **CORHA** data show that the predictions can be underestimated or overestimated by a **more than one order of magnitude**.
  - Sufficient margin should therefore be considered when using such models
  - This is not unexpected since these models were developed a few decades ago [Cal96] [Dou95], when feature sizes were very different and the number of used materials limited to a few elements.
  - Work is ongoing to update them, keeping into account the latest developments in semiconductor technology

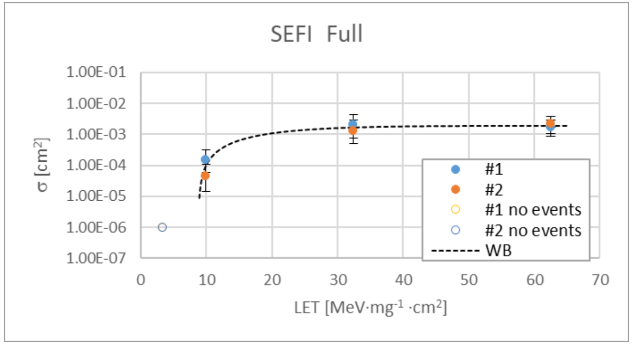
Proton Models: CORHA Results (1)

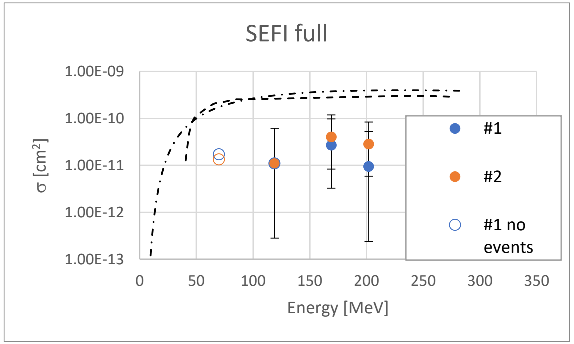
Memory (CY14)

- Underestimation for SEU
- Overestimation for SEFI (PROFIT and SIMPA were never intended for SEFIs)
- Difficult to draw general trends

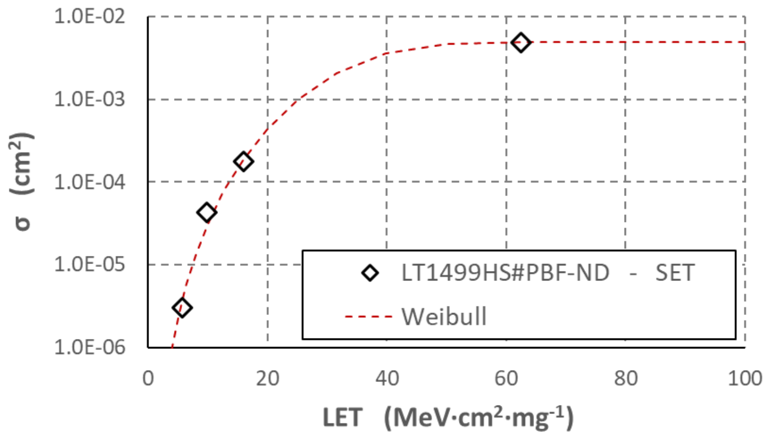


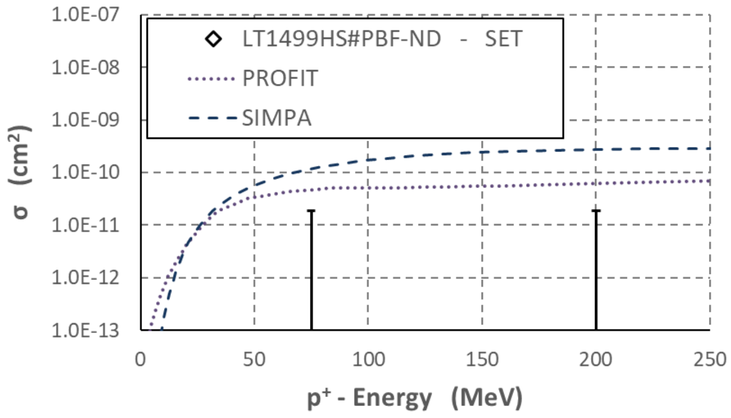






Proton Models: CORHA Results (2)





- OpAmp
- Events with protons predicted from heavy-ion data…
- …but none observed.

SEE:Testing at board/system level

- Radiation tests at **board level** performed with **protons** offer the possibility to test a **complete board** or system at one time
  - Time efficient
  - Can be used as a simple **Go / No-Go test**
- To consider
  - The exposure shall be performed at a high particle energy, greater than 150 MeV
  - The focus should be on the occurrence of destructive events – i.e. SEL – and functional tests
  - Selection of test vectors is critical to expose weaknesses

SEE:Testing at board/system level

- **Beam size constraints** for board-level tests
  - Typical proton beam sizes are circular with a **diameter** of approximately **10 cm**
  - A uniform exposure of a board bigger than the beam is not possible and **separate exposures** for different segments of the board are necessary
  - One may profit by segmenting the exposure, by the use of beam collimators
    - This allows for the possibility to identify the SEE susceptibility for various parts of the board / system individually
    - Increased exposure time

SEE:Testing at board/system level

- Within CORHA, board level testing has been performed on a **system** which makes use of a **STM32F micro-controller**
  - The system has been monitored for two effects:
    1. SEL
    2. Functional errors
  - The overall size of the board was approximately 10 x 10 cm^2
  - Due to limitations of the beam size, the board had to be irradiated **in two halves**

SEE:Testing at board/system level , CORHA results

Proton Energy (MeV)	Comment	DUT	Φ (cm^{-2})	SEFI	SEL
230	upper half	3	10^{10}	25	0
230	upper half	3	10^{11}	N/A^{+}	0
230	lower half	3	10^{10}	3	0
230	lower half	3	10^{11}	N/A^{+}	0
230	upper half	6	10^{10}	22	0
230	lower half	6	10^{10}	2	0
230	upper half	6	10^{11}	N/A^{+}	0
230	lower half	6	10^{11}	N/A^{+}	0

- Observed effects:
  - Occurrence of SEFI in the STM32F microcontroller chip
  - The **results** are **in line with heavy ion and proton test data** being available for the STM32F at component level.

SEE Testing Recommendations

Scenario	Criticality Level	Recommendation
LEO, low altitude and small inclination	Low	No testing
	High	Perform at least board-level testing with protons
LEO, MEO, GEO	Low	Perform at least heavy-ion testing for destructive events (single high LET) in critical components
	High	Full component level testing with heavy ions and optionally protons. If proton testing is waived, consider sufficient margin on modeling results.

- General SEE testing recommendations

Conclusions (1)

- A **radiation hardness assurance** methodology suitable for low-budget missions, focused on COTS, has been proposed, leveraging the scientific literature and the experimental data collected in the frame of the CORHA project
- The proposed methodology includes:
  - An **assessment of the radiation environment**, at least for mission in less benign orbits, expecting a few krads of total ionizing dose
  - An **evaluation of the radiation sensitivity** of the parts selected for the mission, which keeps into account
    - Criticality of the performed function and possible radiation effects
    - Availability of past radiation test data and technological information
    - Implemented mitigation strategies
  - A **final assessment of the suitability** of the parts

Conclusions (2)

- **Guidelines** for exploiting in the best possible way **existing data or technological information** about the EEE parts under consideration have been illustrated, together with suggestions to reduce costs, when radiation testing is needed
- Some of the highlights are:
  - reduction of tested parts with increased design margin;
  - simplified SEE testing targeting only destructive events, assuming mitigation for soft events is implemented;
  - use of models to calculate proton sensitivity from heavy-ion one;
  - board-level testing
- It must be noted, however, that the **complexity of modern devices** which can feature hundreds or even thousands of operating modes, demands for more extensive testing rather than less
  - This should be carefully considered, also when devising mitigation strategies.
- The suggested approach makes it possible for designers of space systems **to reduce costs, allowing for increased risks of mission failures**