Relevance and Guidelines of Radiation Effect Testing beyond the Standards for Electronic Devices and Systems

17-19 May, 2021
RADSAGA Final Conference and Industrial event

Andrea Coronetti, RADSAGA ESR 15, Work Package #4

RADiation and Reliability Challenges for Electronics used in Space, Aviation, Ground and Accelerators (RADSAGA) is a project funded by the European Commission under the Horizon2020 Framework Program under the Grant Agreement 721624. RADSAGA began in Mars 2017 and will run for 5 years.

Presentation outline

- Objectives
- System-level testing and risk acceptance
- High-energy ions and high-energy hadrons
- Pions and the HEH approximation
- Field experience and practical aspects
- Space rate from HEH data
- Conclusions

Objectives

- Develop a **handbook of guidelines** for radiation testing of components and systems with a focus on accelerator and space environments.
- Combining fundamental aspects with practical aspects.
- To serve as input to engineers working in industry and designing electronics systems on what should be considered when performing **Radiation Hardness Assurance** (RHA).

Why looking beyond the standards?

Challenges

- Standard qualification
  - Access to all sensitive volumes
  - Exhaustive coverage of radiation response
- **Inadequate facilities** for advanced packaging and large ensembles of devices
- **High costs** related to the test bench development and beam time
  - Tight schedules and low budgets

Opportunities

- State-of-the-art **COTS** devices outperforming rad-hard solutions
- Very high level of **integration**
  - More and more functionalities implemented in small volumes
- COTS **boards/sub-systems** can save development cost of new hardware
- Space missions with **high risk acceptance**
  - Opportunity for **system-level** verification

Some definitions

Component
Any electronic device that cannot be physically partitioned without affecting its capability of delivering the intended functionality

Standards available
(even if sometimes we have to distance ourselves from them)

System
Anything from a PCB to a satellite

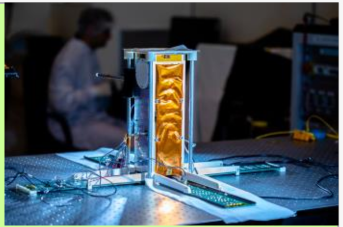
- Challenges for radiation testing do not change, they scale-up
  - Access to sensitive volumes
  - Varying worst case conditions
  - Observability of radiation effects
  - Level of confidence on results

System-level radiation testing
Verification tool for the entire assembly of devices running in operation-like conditions with the aim of getting prompt reliability and availability information (self-recovery, fault signatures and rates), verification of implemented mitigations and need for additional ones.

Achieved by testing in highly-penetrating beams

Limitations of standalone system-level testing

Space



- No perfect facility for the test
- DSEEs stimuli and coverage
- TID worst case analysis
- Part-to-part variability
- Data portability
- ELDRS
- NIEL scaling for DD
- Worst case test conditions?
- Limited level of confidence
- Pass/fail outcome on a system
- Tough to apply mitigations/redesigns

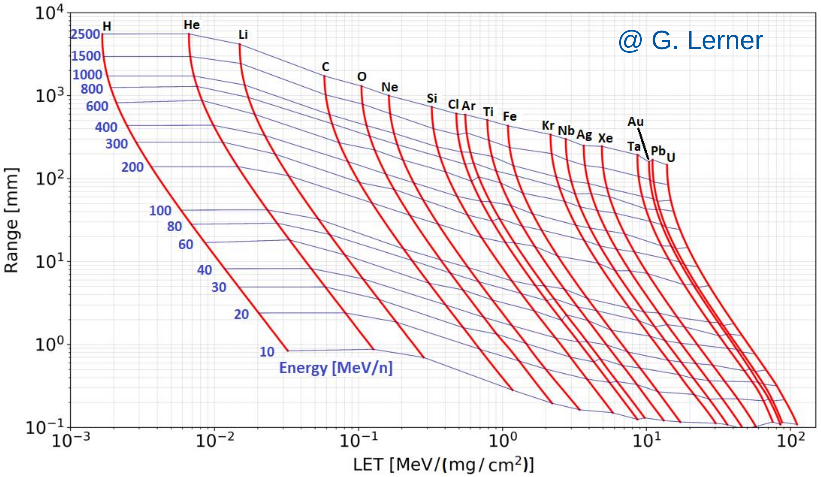
Accelerator

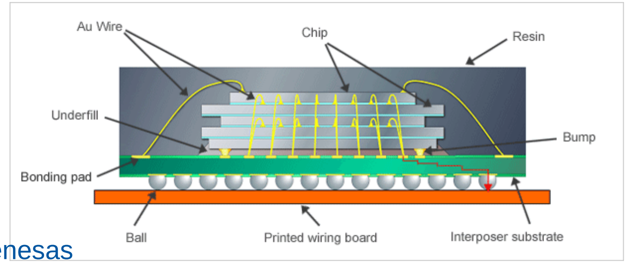
- ~~No perfect facility for the test~~
- ~~DSEEs stimuli and coverage~~
- TID worst case analysis
- Part-to-part variability
- Data portability
- ELDRS
- ~~NIEL scaling for DD~~
- Worst case test conditions?
- Limited level of confidence
- Pass/fail outcome on a system
- Tough to apply mitigations/redesigns

High-energy heavy ions

Reference satellite volume (50x50x50 cm^3)

- Main requirements are on **deep beam penetration** and **uniformity over a wide surface**
  - **Short ranges** for LET > 10 MeV/(mg/cm^2)
  - Enhanced ion **beam fragmentation** at high energy
  - **Non-homogeneities in LET** due to diverse shielding and packaging from device to device
  - Sensitive volume of devices may be shallower or deeper





@ Renesas

High-energy hadrons

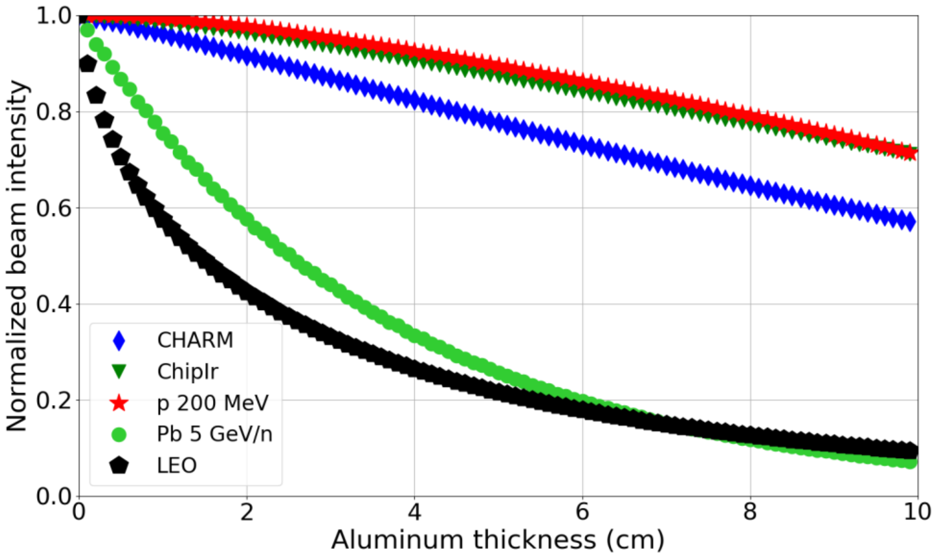
Penetration less of a problem for HEH

- High-energy protons, spallation neutrons and mixed-field are **more penetrating than the typical LEO** trapped proton spectra
- The hadron **beam intensity degrades less** in matter than HEHI

Drawback:

- Ions from indirect ionization have
  - **limited LET** (< 15 MeV/(mg/cm^2))
  - **short ranges** (low LET_{eq})
  - **TID!**

CHARM, ChipIr and NSRL offer broad enough beams (surface homogeneity > 50x50 cm^2)

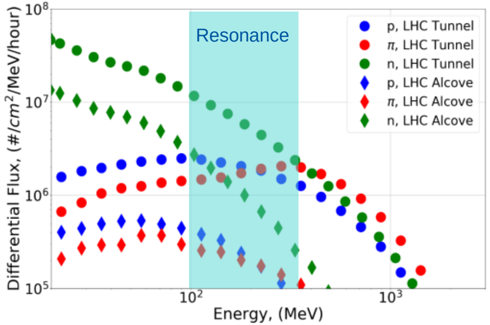


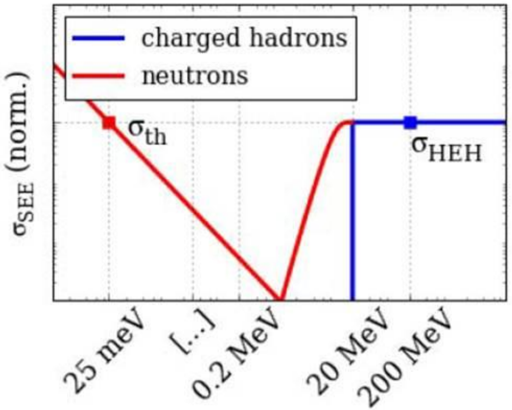
Penetration depth of LEO trapped protons (800 km, 98°) in Aluminum compared to the penetration of hadron and ion beams available at ground accelerators nowadays. Fluxes of particles (for HEH) with energy > 20 MeV.

High-energy hadrons - Pions

SEEs in Accelerator (CERN)

- Mixed-field environment
  - Composed of protons, neutrons and pions (as far as SEEs are concerned)
  - **HEHeq approximation**
    - All hadrons > 20 MeV have same cross-section
    - Which is taken as that measured from 200 MeV protons
  - Pions have special characteristics:
    - **Δ resonance**
    - **Nuclear absorption**

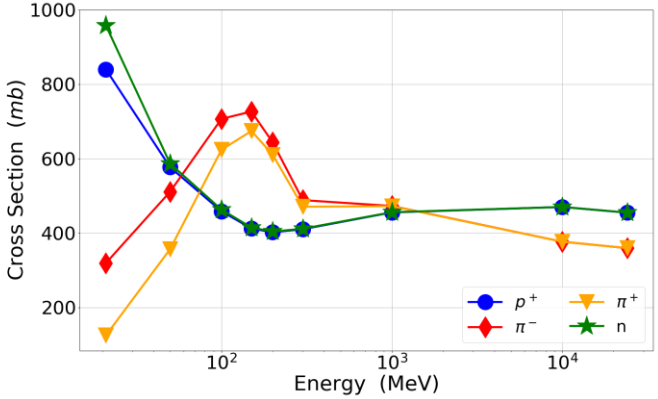


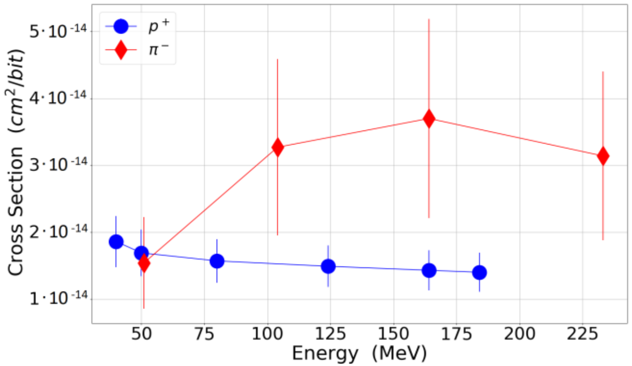


- Does the HEH approximation still stand?
- Can we use CHARM for the space environment?

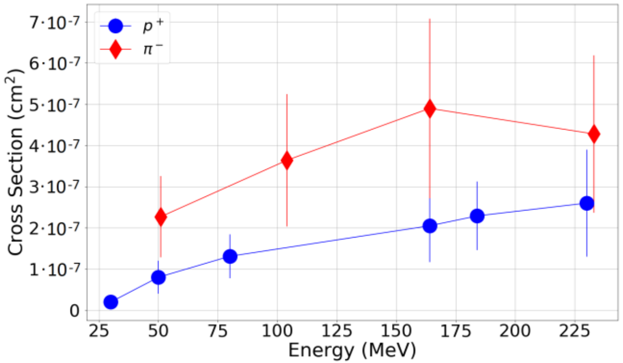
Pions

Inelastic cross-section shape (from FLUKA) is reflected in pion SEU experimental measurements





SEU



SEL

However, it does not explain alone the SEL experimental measurements at low-energy (pion absorption)

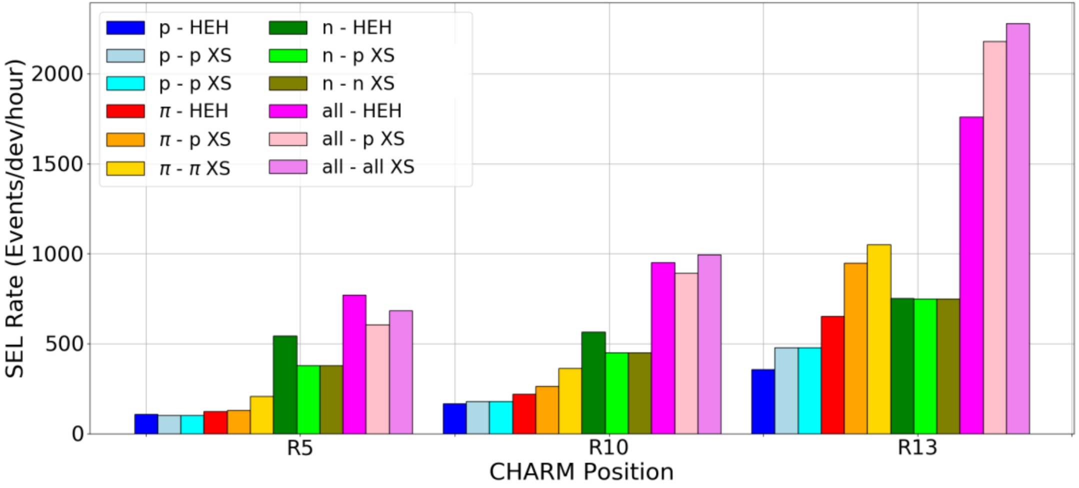
Pions

- When it comes to SEU and SEL rates pion resonance and absorption have **limited impact**
- Neutron fluxes are dominant

-> HEHeq approximation still stand

- No real difference for position R5 (used for space)

-> CHARM for space can be an option



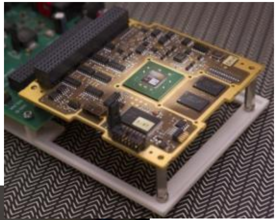
SEL rate calculated with three methods: (i) HEH approximation, (ii) proton cross-section folding, (iii) all cross-section folding for three CHARM positions representative of space (R5), shielded alcoves (R10) and LHC tunnel (R13)

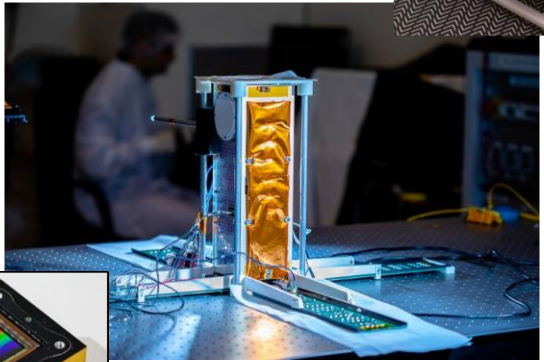
Field experience

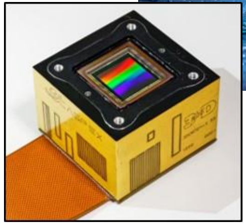
- Eyesat student nanosatellite developed by **CNES**
- All components are **COTS**
  - Tested the On-Board Computer and the CMOS Camera payload
- **High risk acceptance** space mission
- **Cost effective** qualification approach?

Requirements:
- TID tolerance > 100 Gy(Si)
- SEL/SEFI rate on OBC and Camera > 1 per 6 months

@ CNES and 3DPlus







Launched on December 18th, 2019

Top-level observability

CRITICALITY CLASSES TO DEFINE SYSTEM-LEVEL EFFECTS.

Class	Impact on the system	Action	Radiation effect naming
0	Transparent to the system functionality	No action needed	-
1	Temporary impact on functionality	No action or simple mitigation through existing equipment	Soft loss of functionality
2	Availability impacted, but no mission loss	Supervisory circuitry added to have only temporary impact	Hard loss of functionality
3	Mission reliability not achieved	May require intervention on the system design and parts	Permanent loss of functionality

Classified based on system loss of functionality

Class-0: something happens at device level, but the **effect is not propagated** to have a visible effect.

Class-1: **functionality is lost, but temporarily** (e.g., single iteration or few seconds), typically due to SEU and SET and SEFIs not requiring power cycling.
Class-2: **functionality is lost and requires an external action** to remove the bias (automatic or manual) to be restored, typically SEFI with power cycle and SEL.

Class-3: **functionality is lost and cannot be recovered** by any means, typically due to destructive SEEs, unprotected SELs, or cumulative effects of TID and TNID.

Design of the test

Testing of the **flight model 'as is',** other than macro observability, one can monitor for:

- System-level SEL
- SEFI on main control unit
- SET on output voltage/current
- Data corruption of output data streams
- Parametric variations (frequency reduction, temperature increase)
- Input voltage/current drifts

Some considerations

- Look for **more in terms of observability**, but bear in mind that the more one tries to observe the more one can affects the test outcomes
- The **facility may impose limitations** to the capabilities of the test bench (e.g., voltage drops, signal-to-noise ratio, setup accessibility)

Test logic

- What is a **‘real’ operating condition** for a system when the system can work in several different conditions?
- Is it possible to find a **single worst-case condition** considering competing parameters and diverse device sensitivity?
- And what to do, in particular, if **only one single system** can be tested?

Helpful drivers:

- Radiation effects that the system devices may be prone to and whose occurrence would set a **critical condition** for the system
- Consider the state-space envelope to find the conditions under which the system is operated the **most of the time**
- Consider the state-space envelope providing the **highest electrical and data loads** on the system

Systems usually require lower fluxes than devices (in particular digital systems to avoid being dominated by Hard Loss of Functionality)

From HEH XS to space rate

Generic fluence of high-energy hadrons (HEH) above 20 MeV:

$$\Phi_{HEH} = \sum_{i=1}^{N_p} \int_{20MeV}^{\infty} \Phi_{\mathrm{i}}(E)dE$$

Environmental similitude for stochastic events

- Between LEO environment (trapped protons + cosmic ions) and hadronic test facilities
- Need to use **volume-equivalent LET** to better describe the secondary ions from p-Si interactions:

$$LET_{eq} = \frac{E_k}{\rho t}$$

Rate during a test with HEH:

$$R_{test} = \Phi_{HEH} \times \sigma_{HEH}$$

Acceleration factor as a function of LET_{eq}:

$$Acc.factor = \frac{\Phi_{HEH}(> LET_{eq}^{*})}{\Phi_{space}(> LET_{eq}^{*})}$$

From HEH XS to space rate

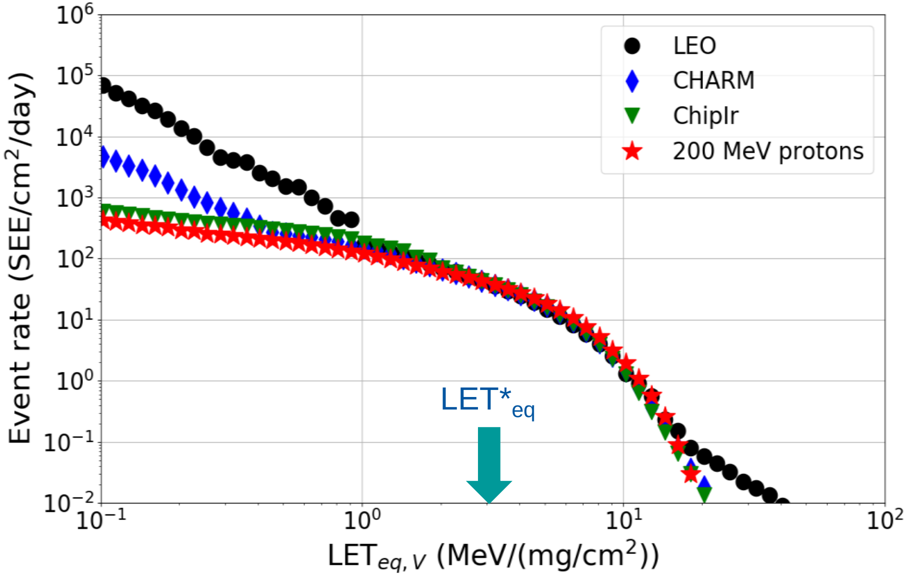
The underlying assumption is that **every particle with LET_{eq} > LET_{eq}* will induce an SEE**, the space rate is then:

$$R_{space} = \frac{R_{test}}{Acc.factor}$$
$$= \frac{\Phi_{space}(> LET^{*}_{eq})}{\Phi_{HEH}(> LET^{*}_{eq})} \times \Phi_{HEH} \times \sigma_{HEH}$$

And therefore the **scaling factor** is:

$$\alpha(LET^{*}_{eq}) = \Phi_{space}(> LET^{*}_{eq}) \cdot \frac{\Phi_{HEH}}{\Phi_{test}(>LET^{*}_{eq})}$$

Which is quite independent on the choice of LET_{eq}*



Energy deposition environmental similitude among several hadron facilities and the space environment (protons + ions) for a SEL sensitive volume of 20x4x3 μm³.

From HEH XS to space rate

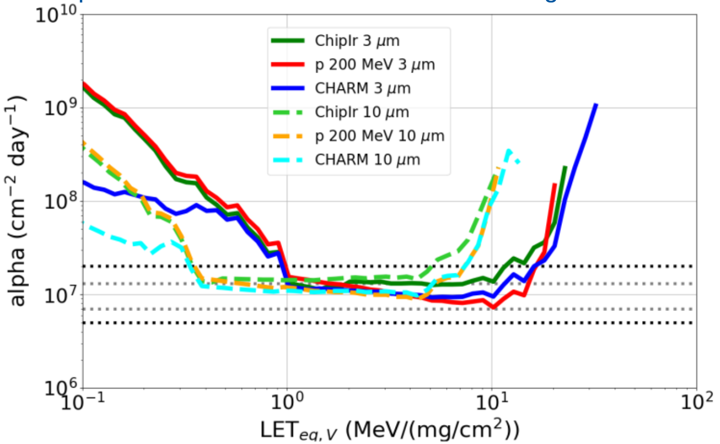
HEH beam	SEU SV	SEL 3 μm SV	SEL 10 μm SV
CHARM	9.27 x 10^6	1.14 x 10^7	1.17 x 10^7
ChipIr	7.25 x 10^6	1.35 x 10^7	1.55 x 10^7
200 MeV protons	1.05 x 10^7	1.08 x 10^7	9.92 x 10^6

A single α applies to all facilities and to different SV size (e.g., both SEU and SEL)

Applicability

- Works for soft errors (SEU)
- Works for SEL only when the LET threshold of the device is low
  - Zero events have to be bounded on WC device ion response
- Not applicable to other destructive events

Alpha factors for various facilities and SV geometries



SEU and SEL event rates (in units of events/dev/day) from standard Weibull fitting and from this method.

	Weibull ions and protons	$\alpha \cdot \sigma_{proton-200MeV}$
ISSI	6.08	5.03
Cypress	16.84	13.42
RADSAGA	1.63	1.42

	On-orbit rate	$\alpha \cdot \sigma_{HEH-CHARM}$
IS61LV5128AL-12	$1.81 \cdot 10^{-1}$	$1.46 \cdot 10^{-1}$
K6R4008V1D	$2.57 \cdot 10^{-3}$	$2.66 \cdot 10^{-3}$
AS7C34096A	$1.36 \cdot 10^{-3}$	$1.73 \cdot 10^{-3}$

Conclusions

System-level radiation testing

- **Cost-effective and time-effective** functional verification for systems that would not be tested otherwise
- **Not to be seen as replacement of component-level qualification**, more as a complementary tool
- **Risk acceptance** to be carefully assessed in order to decide on system-level testing options in the system design lifecycle
  - Several **intrinsic limitations**

Opportunities and limitations of using HEH for space

- Different response of pions and neutrons not a big deal -> **HEHeq approximation still holds**
- Possibility to use a **single conversion factor from HEH cross-section to space rate** no matter the SEE
  - Good for SEU
  - Not applicable if 0 events -> but upper bound can be low enough

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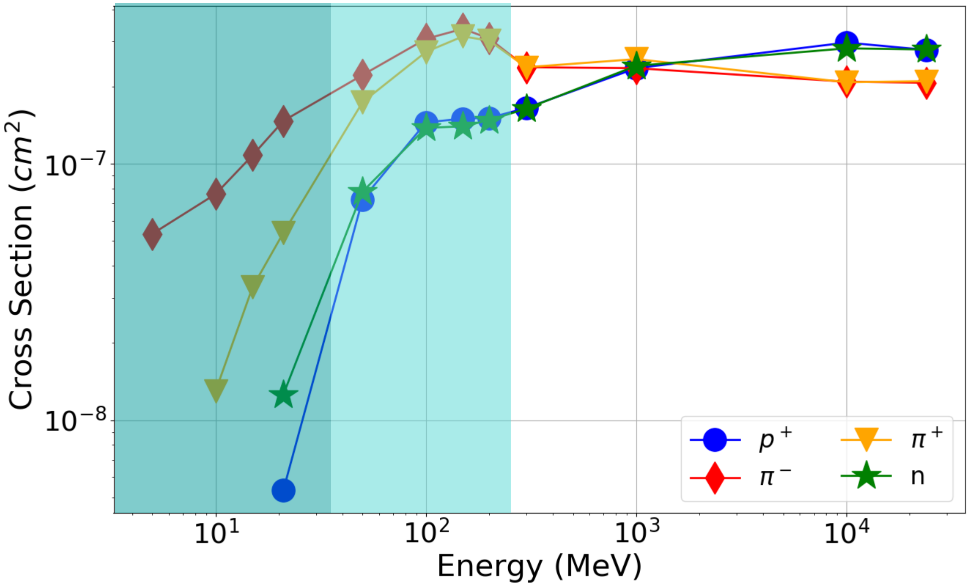
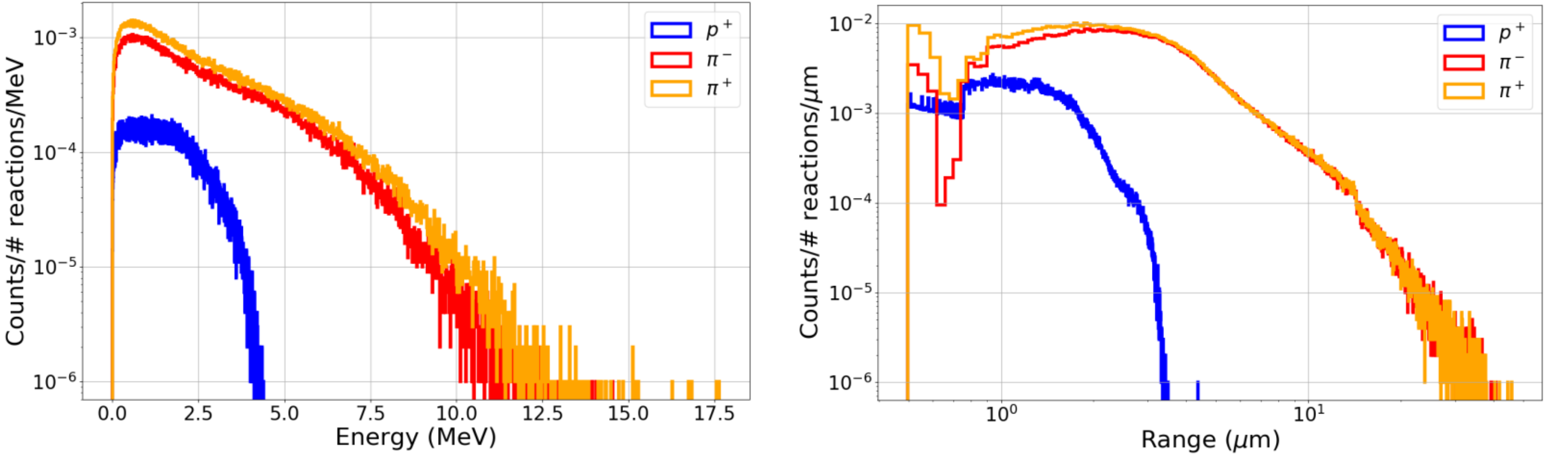
Pions

Extension to all energies and particles of mixed-field

- Pion SEL cross-sections higher for 100-1000 MeV energy
  - **Expected for the nuclear reaction cross-section resonance**
- Negative pion SEL cross-section 30 times higher than that of proton at 21 MeV and it does not fall that rapidly with decreasing energy
  - **Not aligned with nuclear reaction cross-section**



Pions



(Left) Kinetic energy distribution of magnesium from 20 MeV primary particles. (Right) Range distribution of all ions from 20 MeV primary particles with LET > LET_{th} of the SRAM (2.4 MeV/(mg/cm^2)).

Below 100 MeV

- Pion absorption yields secondary ions with higher kinetic content
- Range of ions is longer
  - -> actual deposited energy in the sensitive volume is higher
  - -> SEL cross-section is higher

$$LET_{EQ} = \frac{E_k}{\rho t}$$

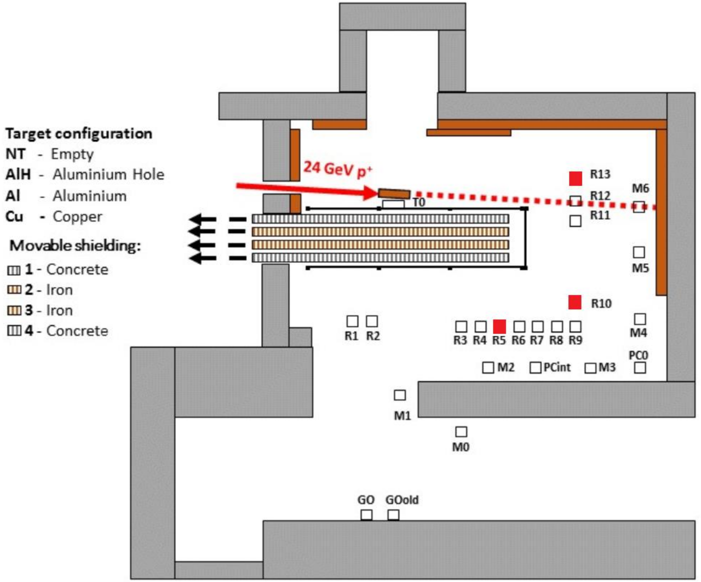
CHARM and HEH equivalence

Study case: CHARM

- Primary proton beam **24 GeV** on target
- Mixed-field generation (**pions, protons, neutrons**, etc.)
- Accelerator environment representativeness
- Use for qualification of accelerator electronics
- Use for qualification of electronics to be used in space, avionics and ground

Use of the simulated cross sections

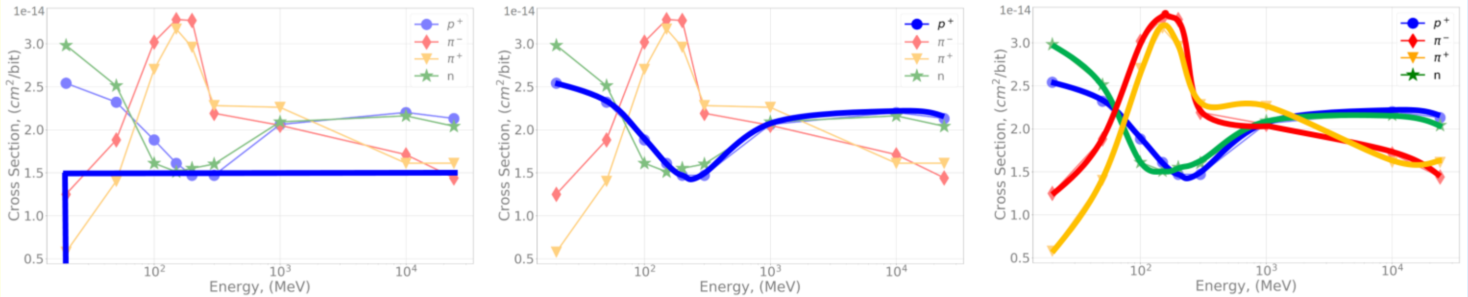
- Wider energy spectra
- All particle cross sections
- ''Worst case'' for the pions below 100 MeV

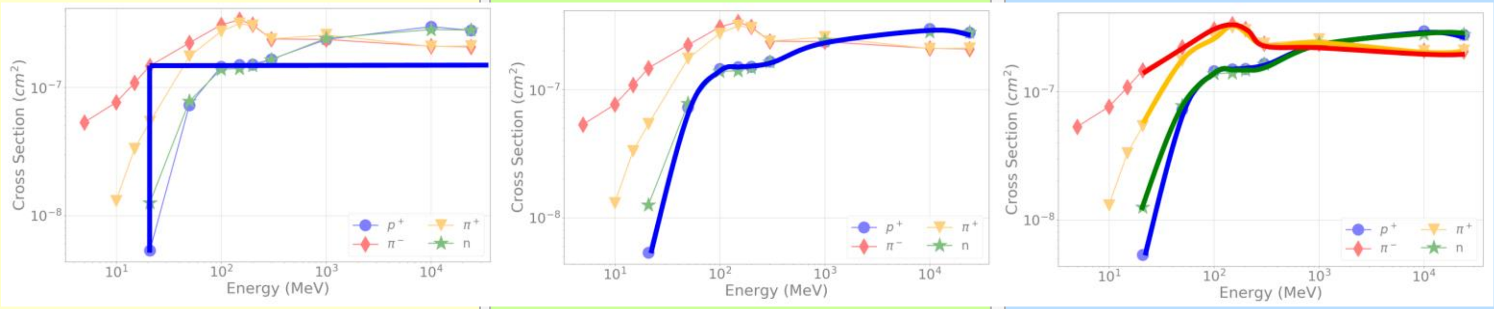


CHARM Floorplan, red squares indicate positions used for this study

HEH equivalence

HEH approximation	Proton cross-section	All cross-sections



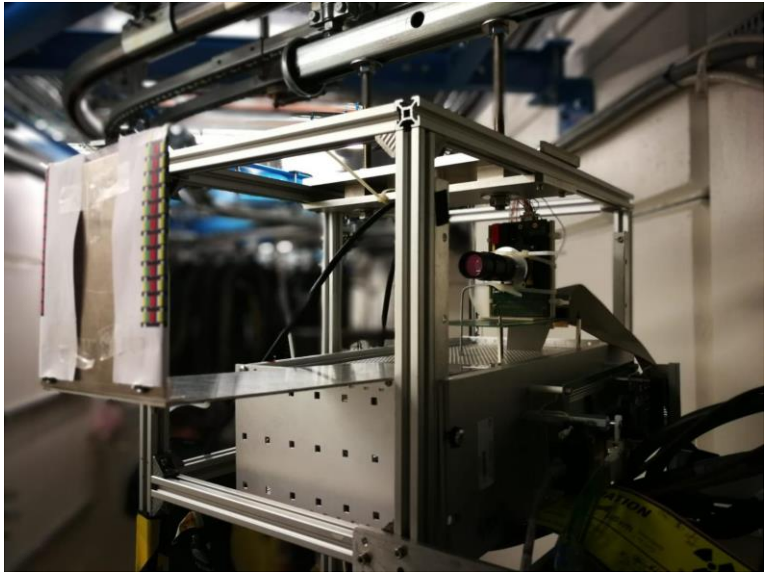


Field experience

- Pre-screen of **destructive SEEs** through heavy ion component level testing
    - **Critical** components for the system
    - Suitable for **system level hardening**
    - Suitable for system level testing **test-bench definition**

- Soft error testing of complex ICs covered through system level testing
    - **Too many tests** to be done on sub-components
    - Use of **flight SW, firmware, application**
    - Concurrent management of all peripherals

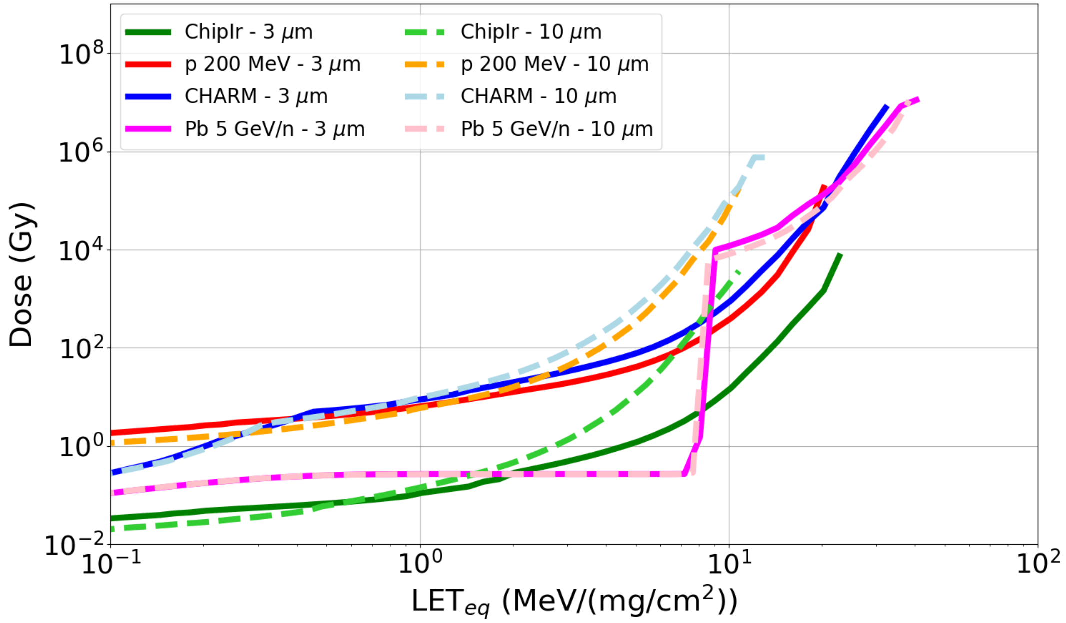
- **TID** test can be integrated in the system level test



HEH vs. HEHI

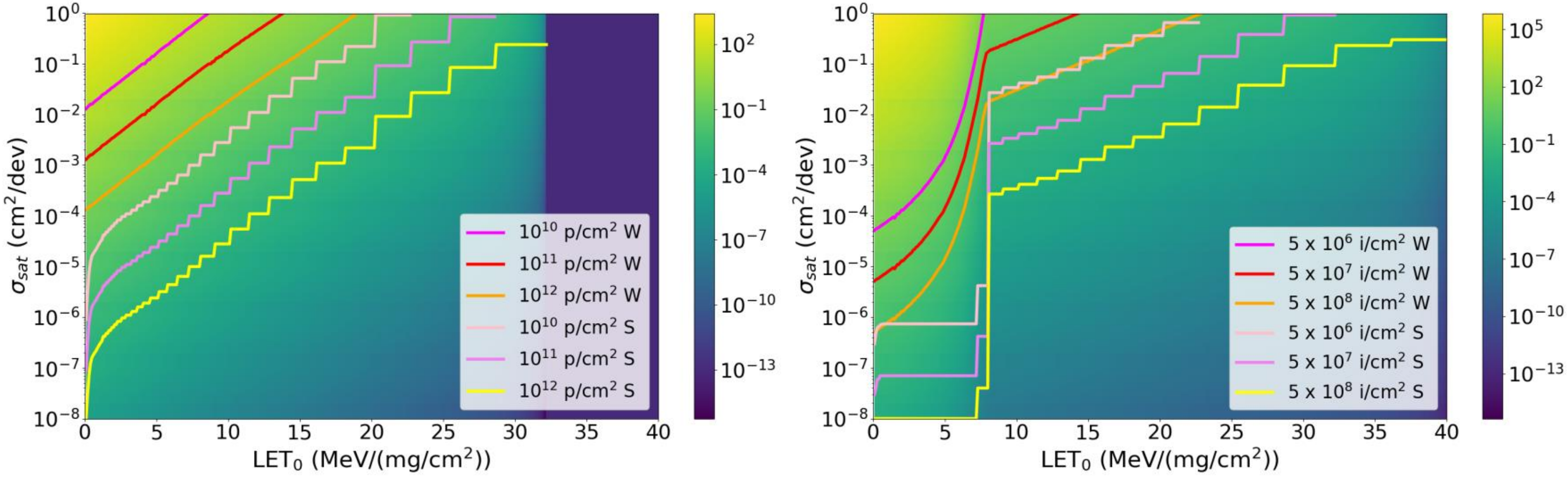
Deposited TID to have 10^4 ions/cm^2 of a certain LET_{eq} for various HEH and HEHI beams considering different SEL SVs

- Spallation neutrons deposit about 50 times less dose than CHARM and 200 MeV proton beams
- Above LETeq = 3 MeV/(mg/cm^2) there is a strong dependency with the SV size
- HEHI are either as good or better than spallation neutrons up to the primary LET of the ion



HEH vs. HEHI

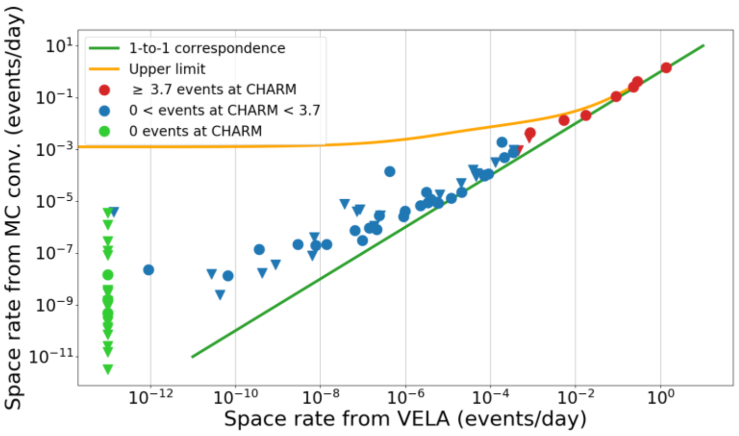
Comparison between HEH (CHARM) and HEHI (Pb 5 GeV/n) SEE susceptibilities for a SEL SV with 3 μm thickness



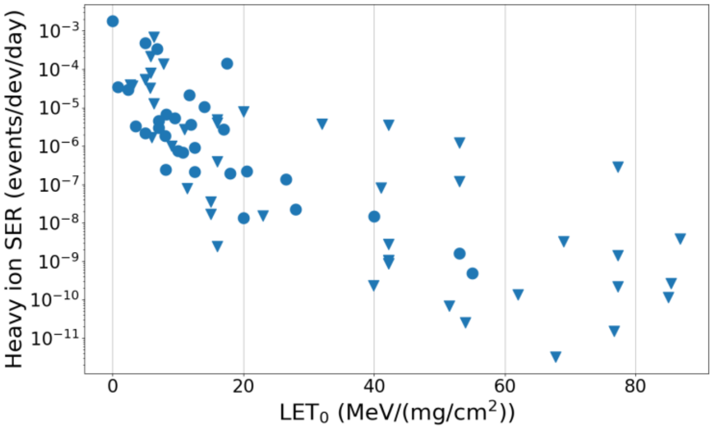
- A **HEH test** can provide **similar information** (mainly in terms of LET thresholds) about **SEE susceptibility** if compared to a **HEHI beam** after the **same TID** is delivered (still for HEHI we are also exploiting indirect ionization to settle the score)
- The picture for HEH **changes with the SV thickness**, while it does not for HEHI
- But if we compare HEHI and spallation neutrons at same dose, neutrons would be better

Zero or few events

Comparison between the predicted SEL rate from the CHARM cross-section and the actual space rate



SEL upper bound for 0 events in CHARM

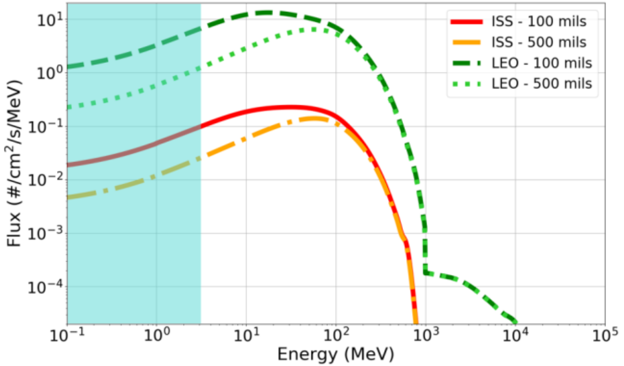


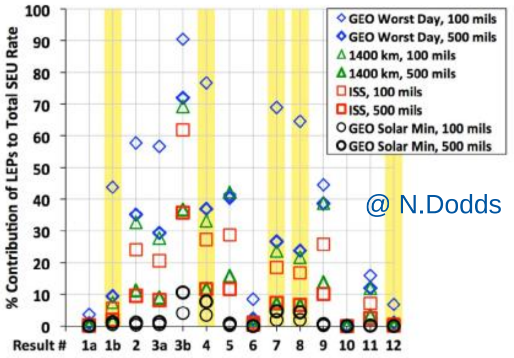
- Analysis based on actual devices
- Predictions are **very accurate** when **HEH Cross-section > 10^{-9} cm^2/dev**
- The worst case device not showing SEL in CHARM will have a SEL rate in space of **1 in 500 days** in LEO
- With no testing, the worst case device would have a SEL rate in space of **1.5 events/day**

On top of that: low energy protons

SEEs in the space environment

- **Heavy ion** biggest threat for destructive SEEs
- **High energy proton** also contribute, in particular for soft SEEs
- Testing approach:
  - Screen with heavy ion with high LET
  - Screen with protons if LET threshold is low enough
- But there are also **low-energy protons**
  - Lower fluxes than high energy protons, but cross-sections similar to low LET ions

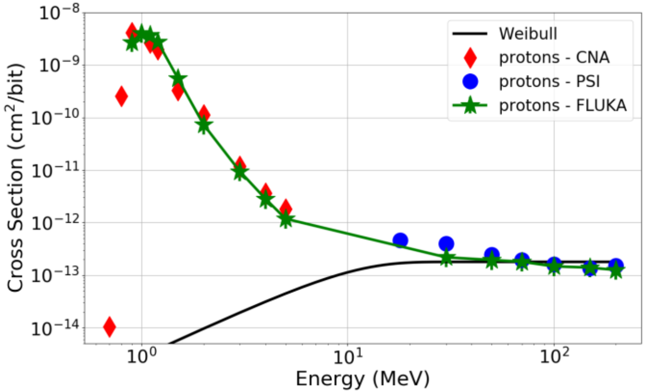


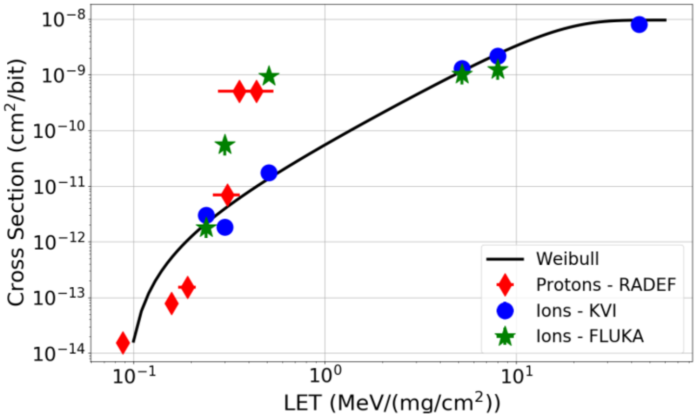


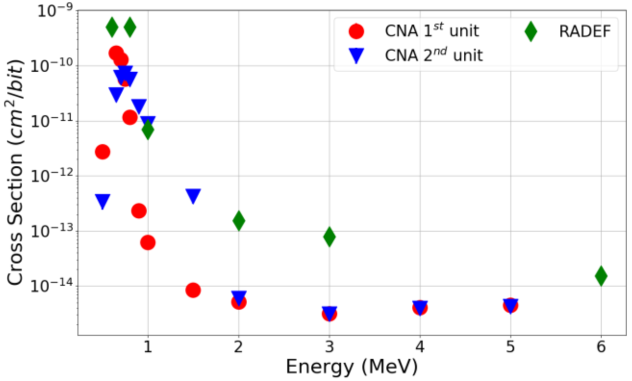
@ N.Dodds

- Can low-energy protons have an impact?
- Is a small safety margin enough or shall we test?

Low energy protons







- Even **4 orders of magnitude** higher cross-section than high energy protons
- Sometimes cross-sections **much higher** than those of **ions of similar LET**
- **Large variability for same reference, same lot**

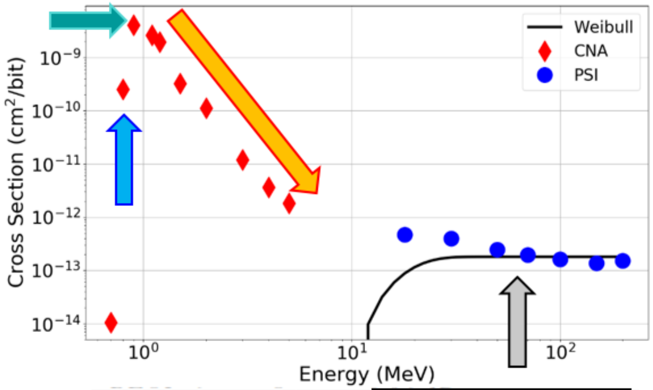
Low-energy protons

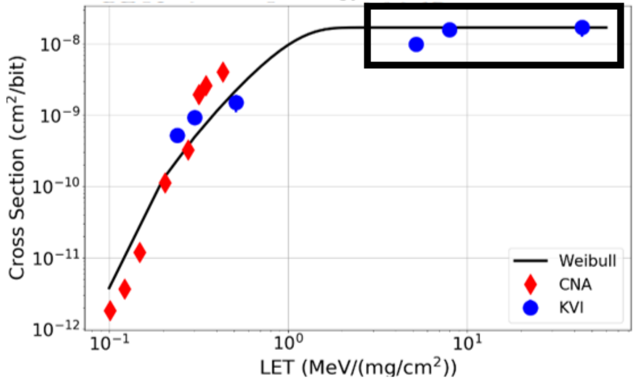
Models built with Monte-Carlo simulations with LEP and HEP

- Use of **nested RPPs** with n = 1-4
  - Better fit of HEP experimental cross-sections

Modelling criteria

- **Peak LEP cross-section** defined innermost volume surface
- RPPs ith constant thickness
  - Chosen to reflect the **slope of the fall-off** of the LEP peak
- **BEOL thickness** to represent fading at low-energy
- External RPPs based on **heavy ion** experimental data
  - Collection efficiency (alpha) calculated on previously determined LETs of LEP
- **Critical charge** based on the fitting of all the data





Low-energy protons

- Energy convolution
  - Directly on the experimental data
- Weibull
  - No LEP SER calculation
- Monte-Carlo
  - Response from the space spectra
- Dodds' method
  - Requires measuring cross-section in degraded beams (data not available)
  - Use of **mono-energetic data** to retrieve an approximated response
  - Weibull for the rest

COMPARISON OF SER PREDICTION METHODS FOR LOW- AND HIGH-ENERGY PROTONS AND HEAVY IONS FOR THE THREE SRAMS AT 0.3 V FOR THE LISTED METHODS. THE ISS ENVIRONMENT IS USED FOR ALL METHODS (500 KM, 51.6°, SOLAR MIN, 100 MILS ALUMINIUM). THE SER UNITS ARE EVENTS/BIT/DAY.

RADSAGA 65-nm SRAM			
Method	**High-E protons**	**Low-E protons**	**Heavy ions**
Energy convolution	$5.42 \cdot 10^{-7}$	$8.49 \cdot 10^{-6}$	X
Weibull	$4.57 \cdot 10^{-7}$	X	$2.65 \cdot 10^{-7}$
Monte-Carlo	$3.04 \cdot 10^{-7}$ (2%)	$1.47 \cdot 10^{-5}$ (95%)	$4.07 \cdot 10^{-7}$ (3%)
Approx. Dodds'	$4.57 \cdot 10^{-7}$ (3%)	$1.43 \cdot 10^{-5}$ (95%)	$2.65 \cdot 10^{-7}$ (2%)
ISSI SRAM			
Method	**High-E protons**	**Low-E protons**	**Heavy ions**
Energy convolution	$4.06 \cdot 10^{-8}$	$6.27 \cdot 10^{-7}$	X
Weibull	$3.81 \cdot 10^{-8}$	X	$3.90 \cdot 10^{-9}$
Monte-Carlo	$2.33 \cdot 10^{-8}$ (4%)	$5.76 \cdot 10^{-7}$ (88%)	$5.34 \cdot 10^{-8}$ (8%)
Approx. Dodds'	$3.81 \cdot 10^{-8}$ (3%)	$1.20 \cdot 10^{-6}$ (97%)	$3.90 \cdot 10^{-9}$ (0%)
Cypress SRAM			
Method	**High-E protons**	**Low-E protons**	**Heavy ions**
Energy convolution	$2.25 \cdot 10^{-7}$	$1.92 \cdot 10^{-6}$	X
Weibull	$2.03 \cdot 10^{-7}$	X	$4.02 \cdot 10^{-8}$
Monte-Carlo	$1.58 \cdot 10^{-7}$ (7%)	$1.88 \cdot 10^{-6}$ (88%)	$1.10 \cdot 10^{-7}$ (5%)
Approx. Dodds'	$2.03 \cdot 10^{-7}$ (6%)	$3.41 \cdot 10^{-6}$ (93%)	$4.02 \cdot 10^{-8}$ (1%)

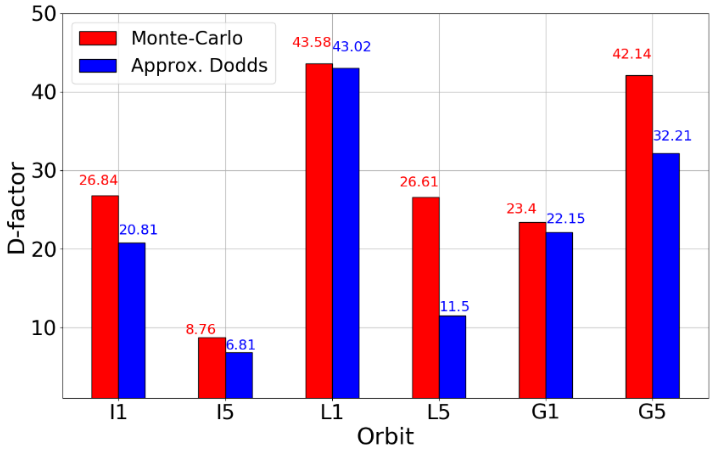
Low-energy protons

D-factor is defined as:

$$D = \frac{UR_{HI} + UR_{HEP} + UR_{LEP}}{UR_{HI} + UR_{HEP}}$$

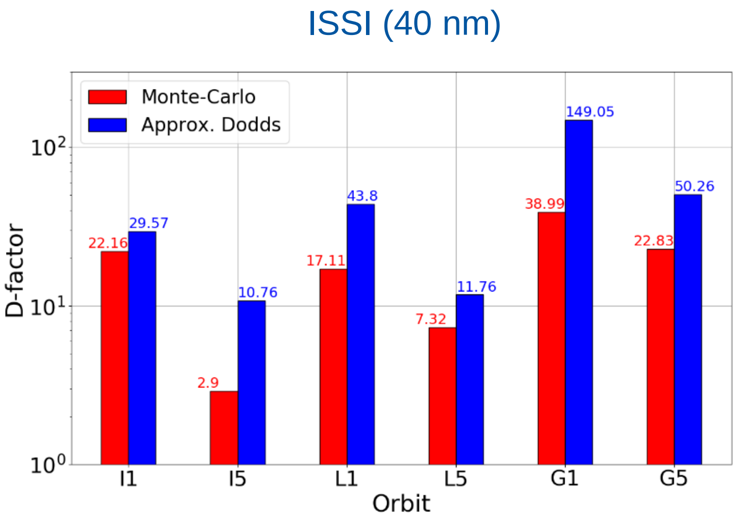
- For D = 1, LEP contribution is **negligible**
- For D = 2, LEP contribute for **as much as** heavy ions and high-energy protons
- For D > 2, LEP are the **dominant** contributor
- Can be used as a **safety margin** to bound the SER calculated from heavy-ion and high-energy proton testing

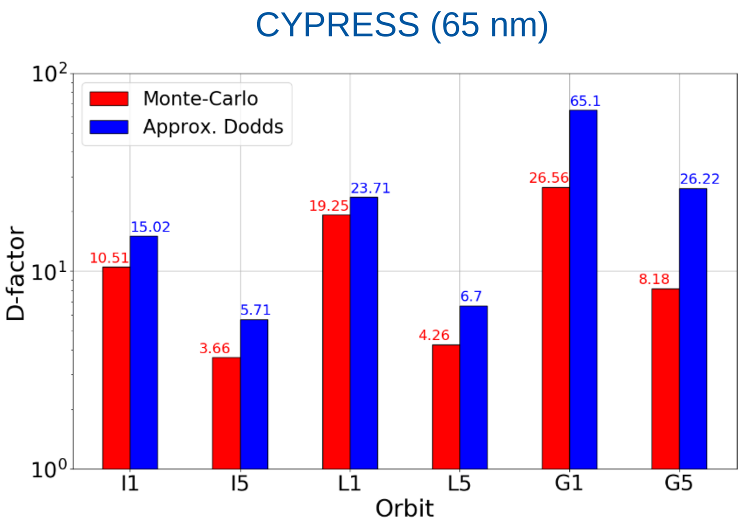
RADSAGA (65 nm) ISS, LEO and GEO 100-500 mils Al



- Devices to be tested when ion LET threshold is below 1 MeV/(mg/cm2)
- Probably no big issue otherwise
- Currently exploring whether CHARM can highlight this sensitivity

Low-energy protons



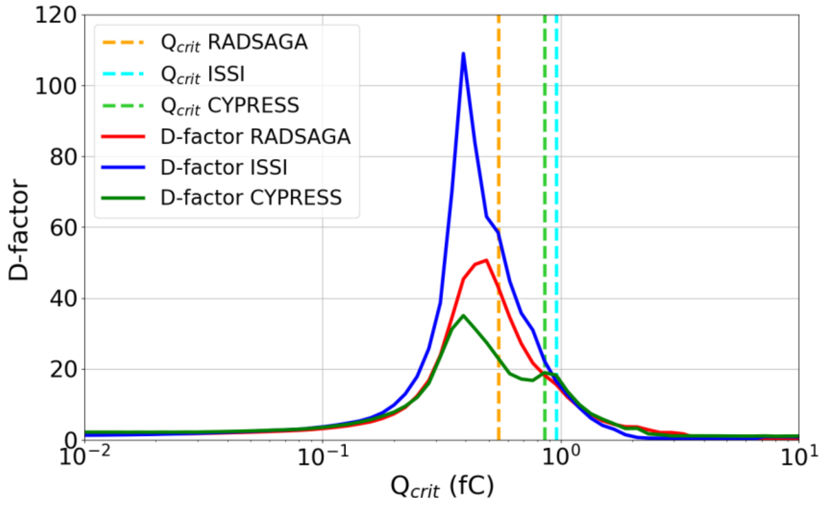


- **Agreement** between the Monte-Carlo and approximate Dodds' method:
  - Very good for RADSAGA
  - Within a factor of 2 and 4 for CYPRESS and ISSI, respectively
- **Worst cases** for orbits:
  - 1400 km and 52°, 100 mils for RADSAGA
  - GEO worst day, 100 mils for ISSI and CYPRESS

Low-energy protons

General behavior of D-factor as a function of critical charge Q_{crit}:

- -> 1 for high Q_{crit} because charge deposited by LEP **insufficient** to trigger SEU
- -> 1 for low Q_{crit} because one would have SEUs induced by **direct ionization from high-energy protons** as well
- LEP contribution is important (or even dominant) only for a **restricted range of Q_{crit}**
- Depends on the RPP models (SV dimensions, BEOL, etc.)



Low-energy protons

How close to being sensitive to direct ionization from high-energy proton the device is (based on the model)?

- RADSAGA quite **close to the peak** of LEP dominance
  - Maybe slightly sensitive to direct ionization from protons at higher energies
- ISSI and CYPRESS still at the **onset** of LEP dominance
  - But D-factor is still large (about 20)
- In general, the worst case D-factor is reached at Q_{crit} of 0.4-0.5 fC for all memories, regardless of their RPP model