0.1-10 MeV Neutron Soft Error Rate in Accelerator and Atmospheric Environments

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on behalf of the R2E project

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https://indico.cern.ch/event/971222/

Introduction: radiations in the LHC

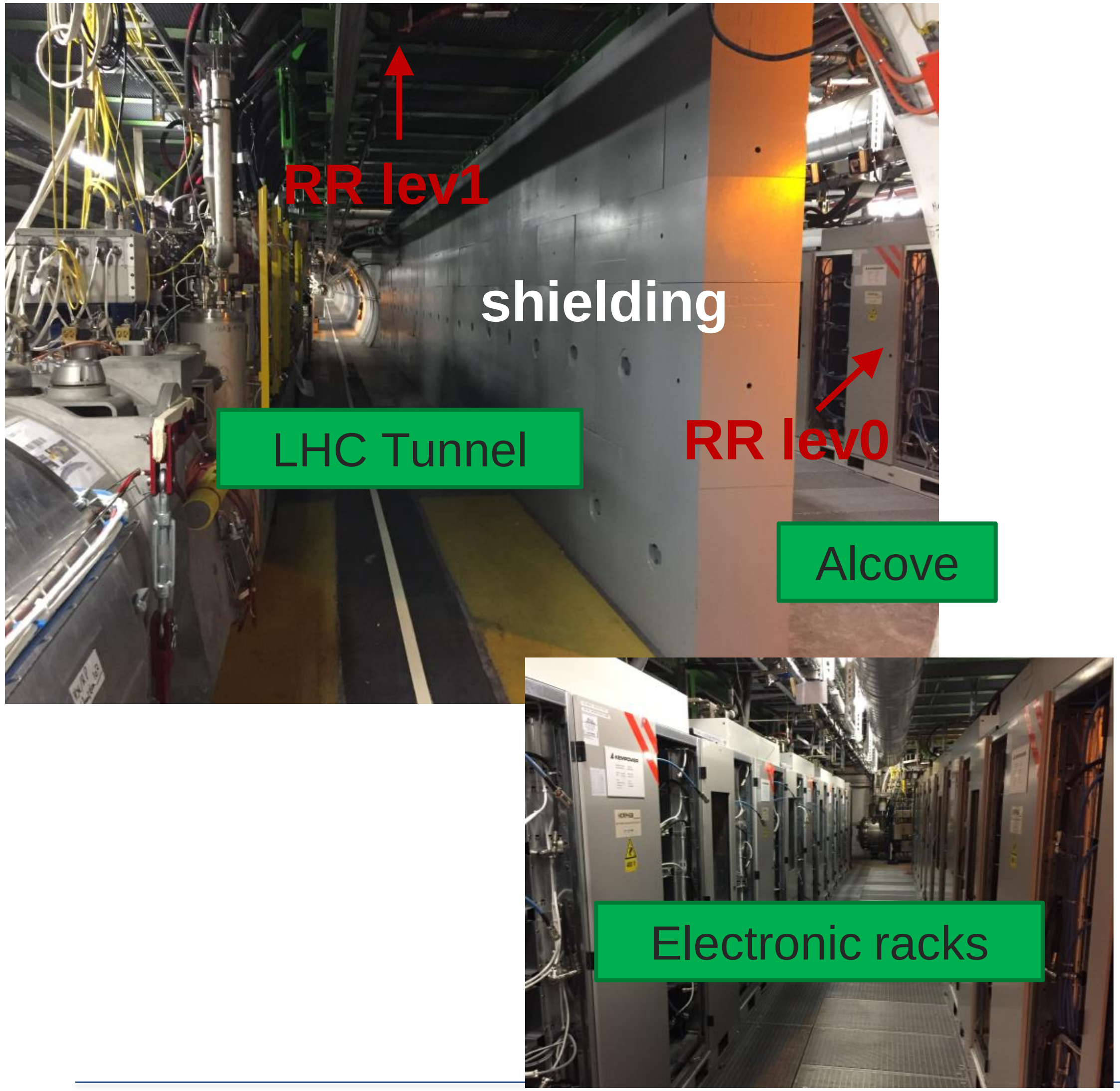
Radiation sources ➡ Collision debris | Residual gas | Collimators

Radiation environment mainly composed of **neutrons** in

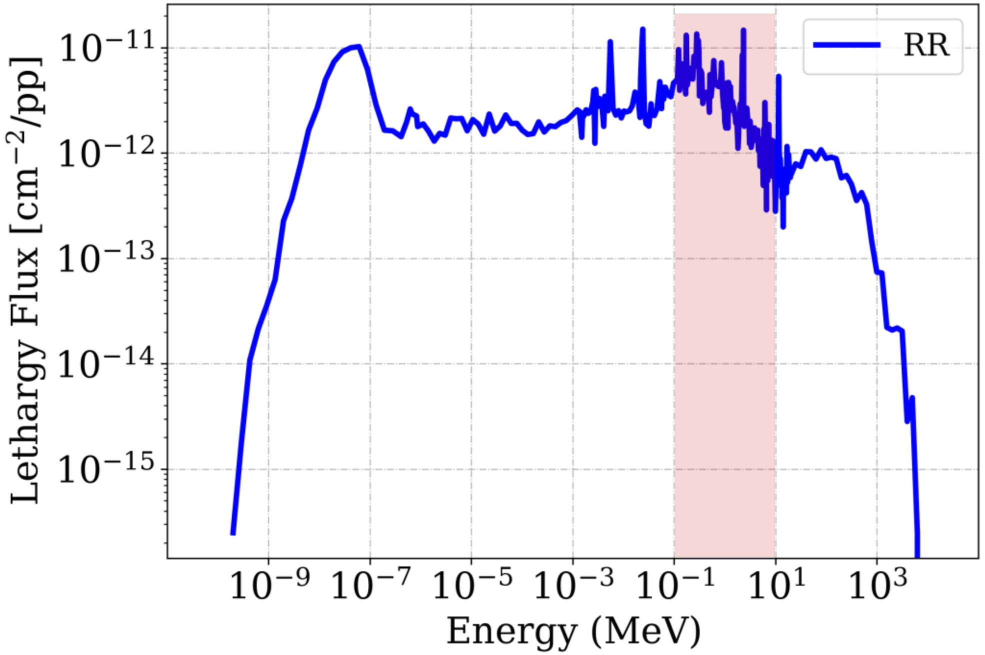
Tunnel | Shielded alcoves

A large number of electronics (mainly **COTS**) operate near the accelerator and are exposed to **radiation inducing SEEs**

Example - Neutron spectrum in the RR alcove



From FLUKA Monte Carlo simulations

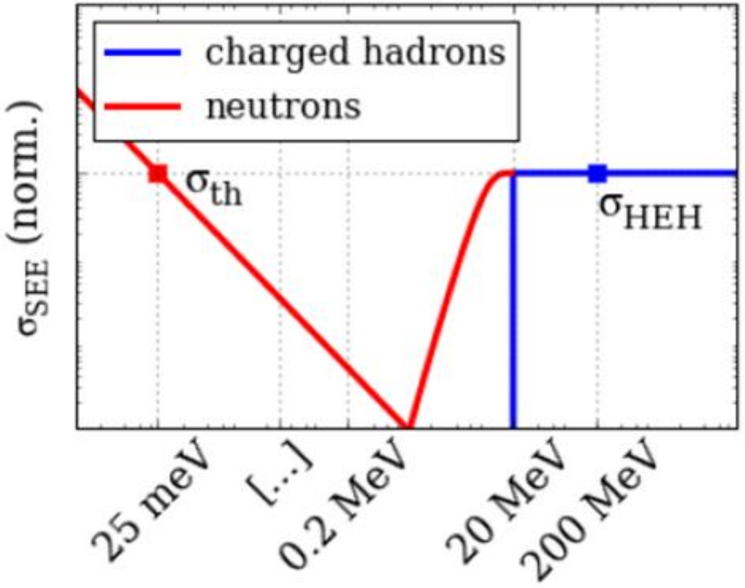


- **Lightly shielded alcove**, 40 cm cast iron/concrete
- Up to **90%** of the HEH (hadrons > 20 MeV) spectrum composed of **neutrons**
- Shielding reduces HEH radiation levels from **~10^{10}** (tunnel) to **~10^{9} HEH/cm^{2}/year** (HL-LHC)

SEEs: response function

Intermediate energy neutrons

from 0.2 to 20 MeV, the device (SRAM) cross section is strongly energy dependent



$$\varphi_{HEHeq} = \underbrace{\int_{0.2MeV}^{20MeV} w(E)\frac{d\varphi_n(E)}{dE}\,dE}_{} + \int_{20MeV}^{+\infty} \frac{d\varphi_{HEH}(E)}{dE}\,dE$$

- Intermediate energy neutrons - major concern with scaling of technology
- Memory response w(E) so far considered from 400 nm Toshiba SRAM

Components – Neutron test facilities

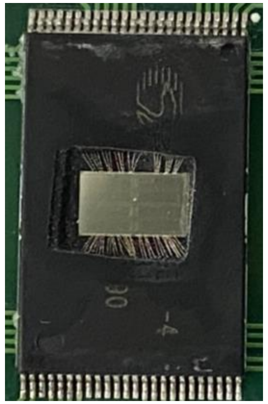
- Test performed at **PTB** (Germany) and **FNG** (Italy)
- Mono-energetic neutron irradiations, from **0.144 to 17 MeV**

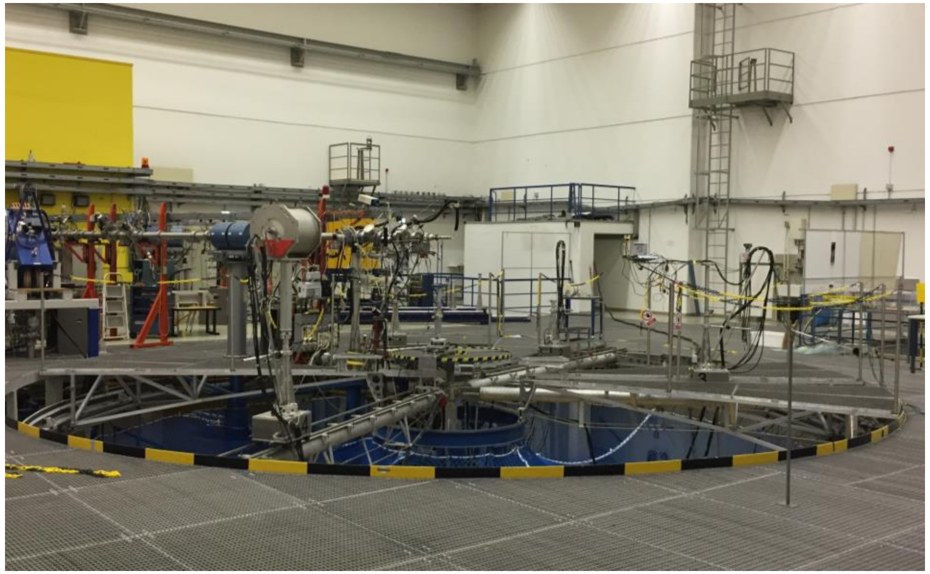
➡ SRAMs of different technologies

➡ SEU tests with **package** and **delidded**

Memory	Tech [nm]	Size [Mbit]
ISSI	40	32
Cypress	65	16
Cypress	90	8
ESA Monitor	250	16

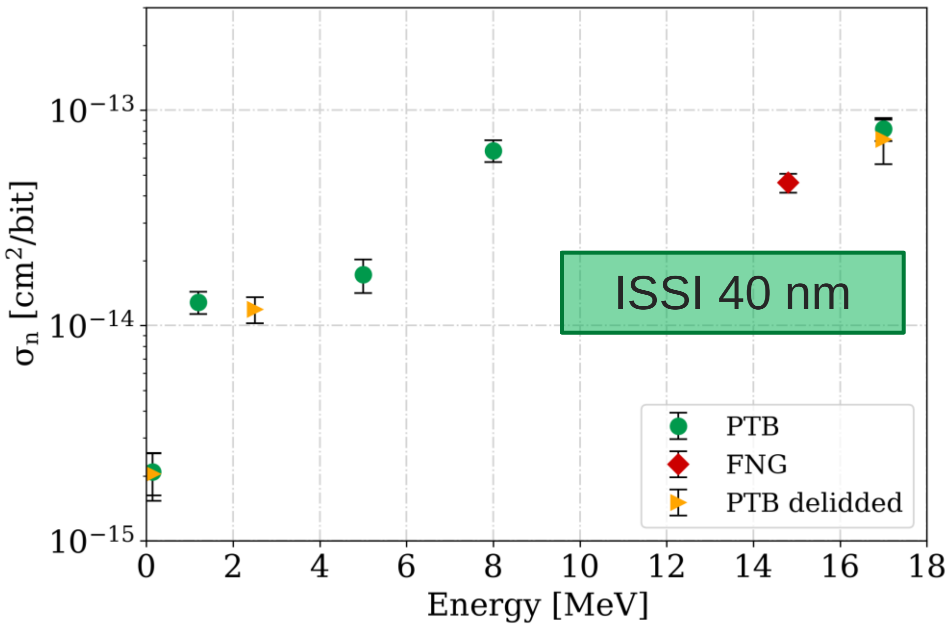
Facility	E_n [MeV]	Reaction	E_{proj} [keV]
PTB	0.144	Li(p,n)	1943
PTB	1.2	T(p,n)	2047
PTB	2.5	T(p,n)	3356
FNG	2.5	D(d,n)	300
PTB	5	D(d,n)	2406
PTB	8	D(d,n)	2524
FNG	14.8	T(d,n)	300
PTB	17	T(d,n)	1264

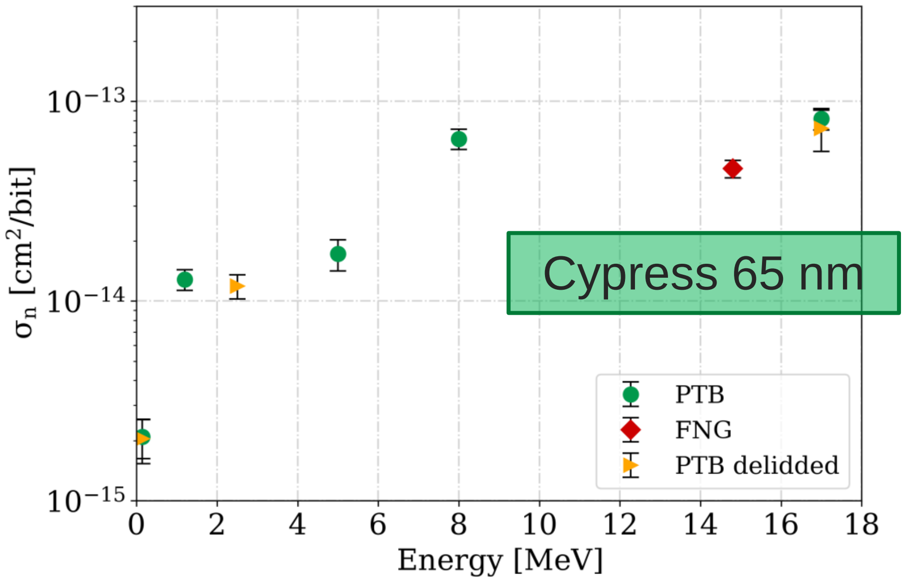


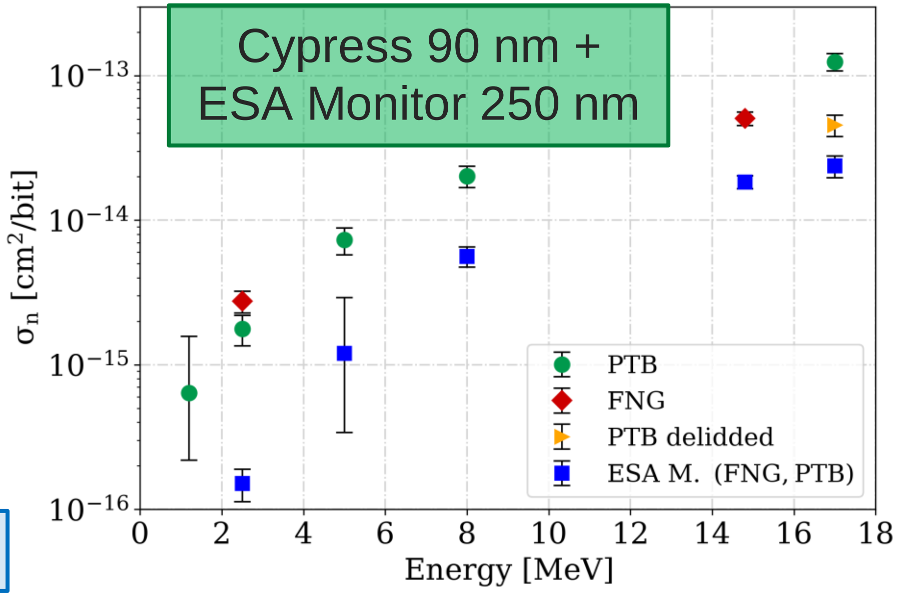


PTB irradiation room

SRAM neutron cross sections





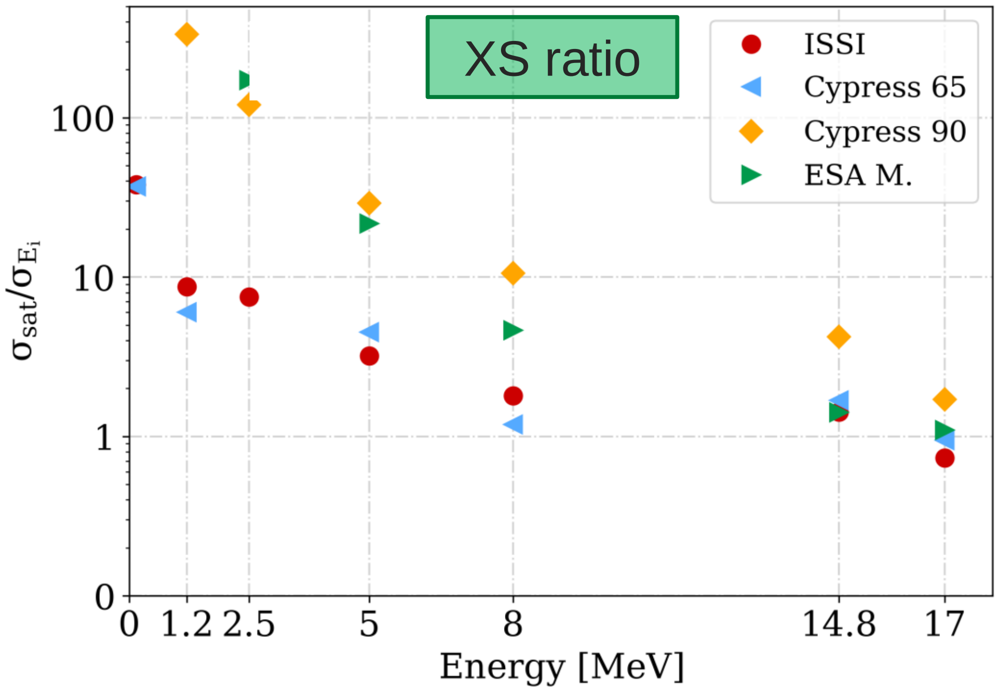


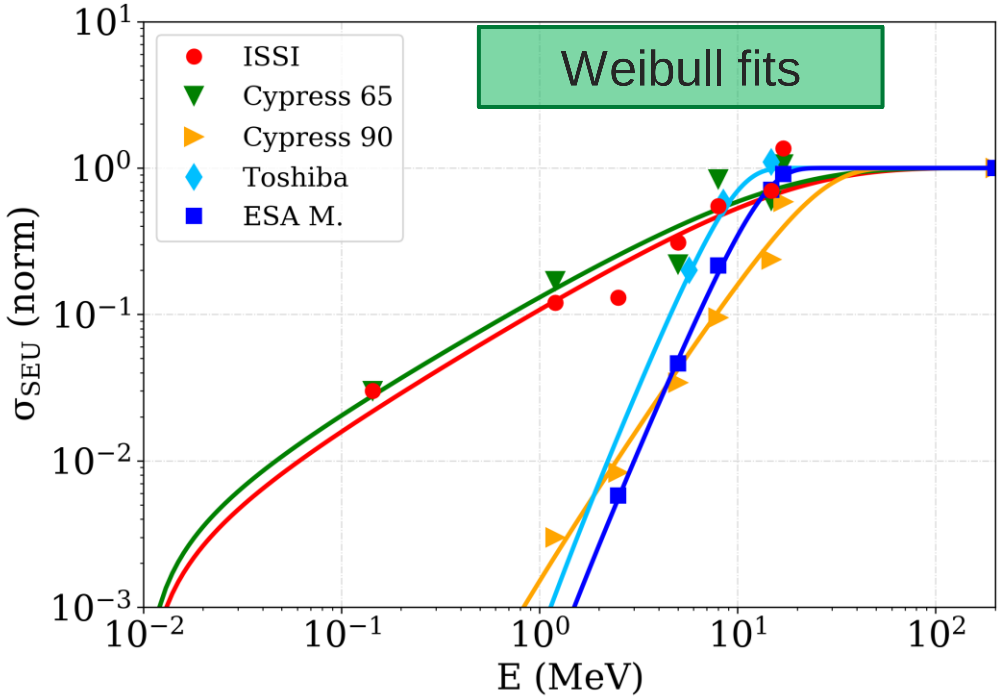
40 and 65 nm SRAMs → Neutron SEU cross section still very high at low energies!

90 and 250 nm SRAMs → Typical behaviour

No significant difference between package/delidded tests

Cross section comparison to saturated value





- Ratio between high energy proton (saturated) and neutron cross sections of :

40 and 65 nm → 6 at 1.2 MeV

37 at 0.144 MeV

90 and 250 nm → >100 below 2.5 MeV

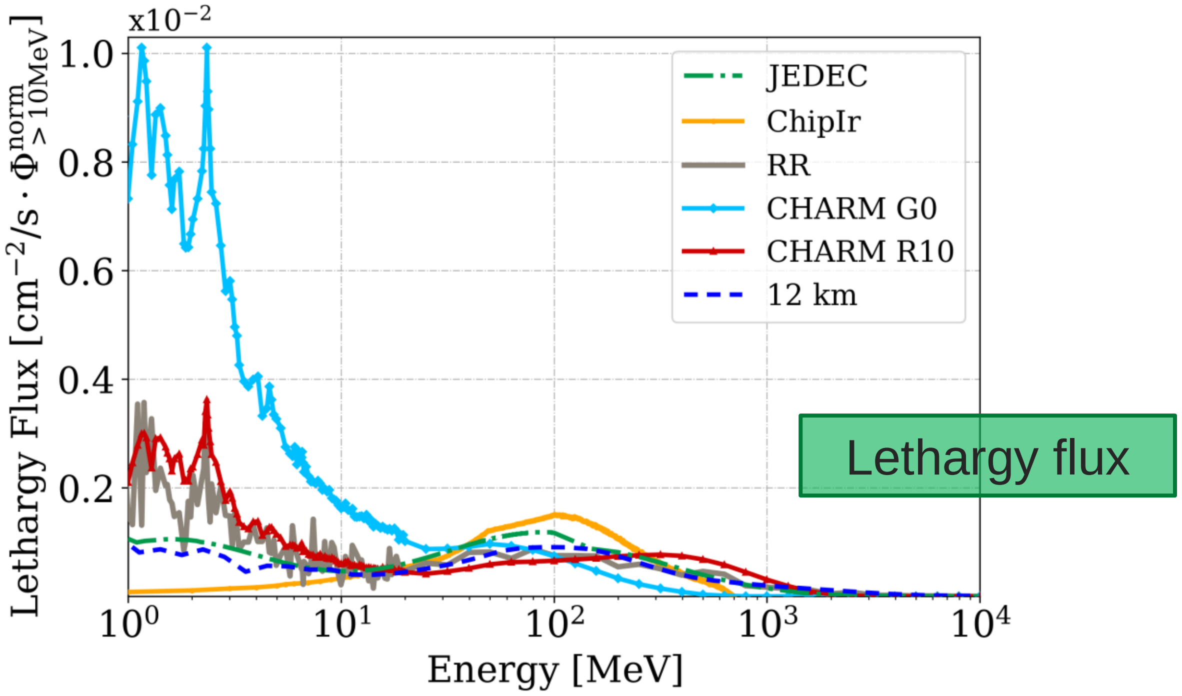
Neutron spectra of different environments

Accelerator

- Hard spectra → **RR** alcove, **R10**
- Soft spectrum → **G0** - **highest flux below 10 MeV**

Atmospheric

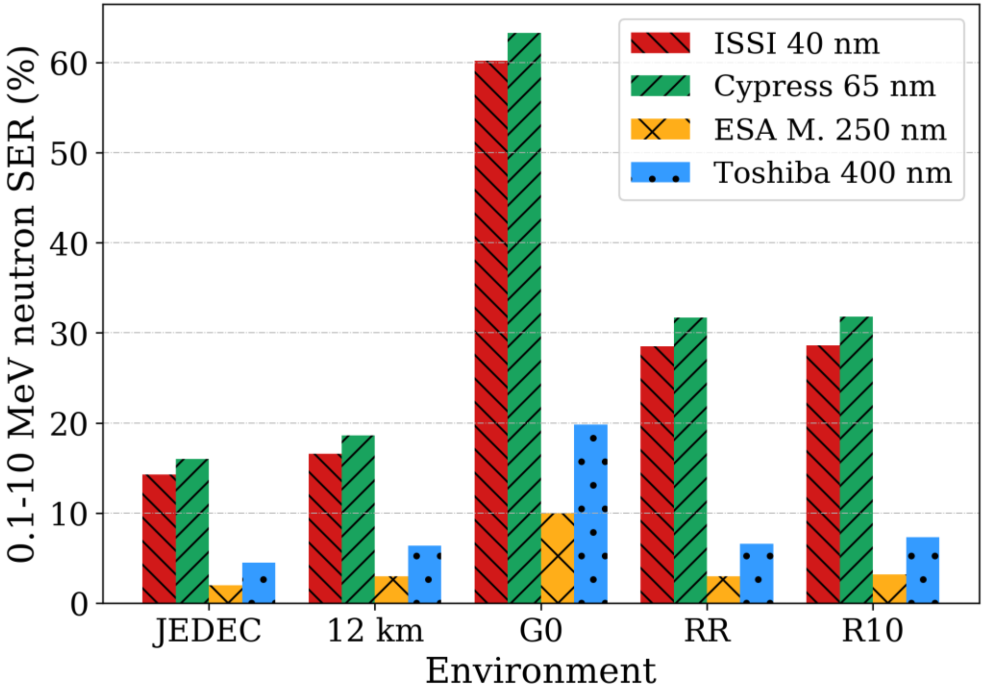
- Ground level → **JEDEC** (1 m)
- Avionic → **12 km** altitude above Geneva

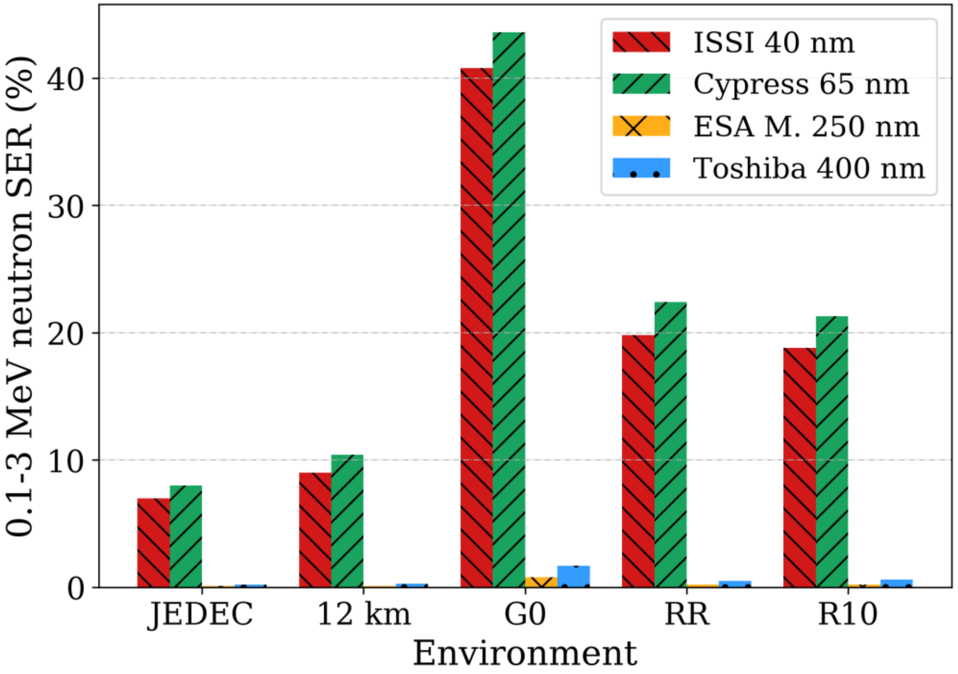


Lethargy flux

Spectra normalized to the JEDEC New York City fluence above 10 MeV

SEUs induced by neutrons below 10 MeV on the overall rate





0.1-10 MeV neutrons

Up to

60% of SEUs in accelerator

19% of SEUs in avionics

0.1-3 MeV neutrons

Up to

44% of SEUs in accelerator

10% of SEUs in avionics

- Neutrons **<1 MeV** → **21%** of SEUs in Cypress 65 nm in accelerator
- Negligible contribution below **0.1 MeV**

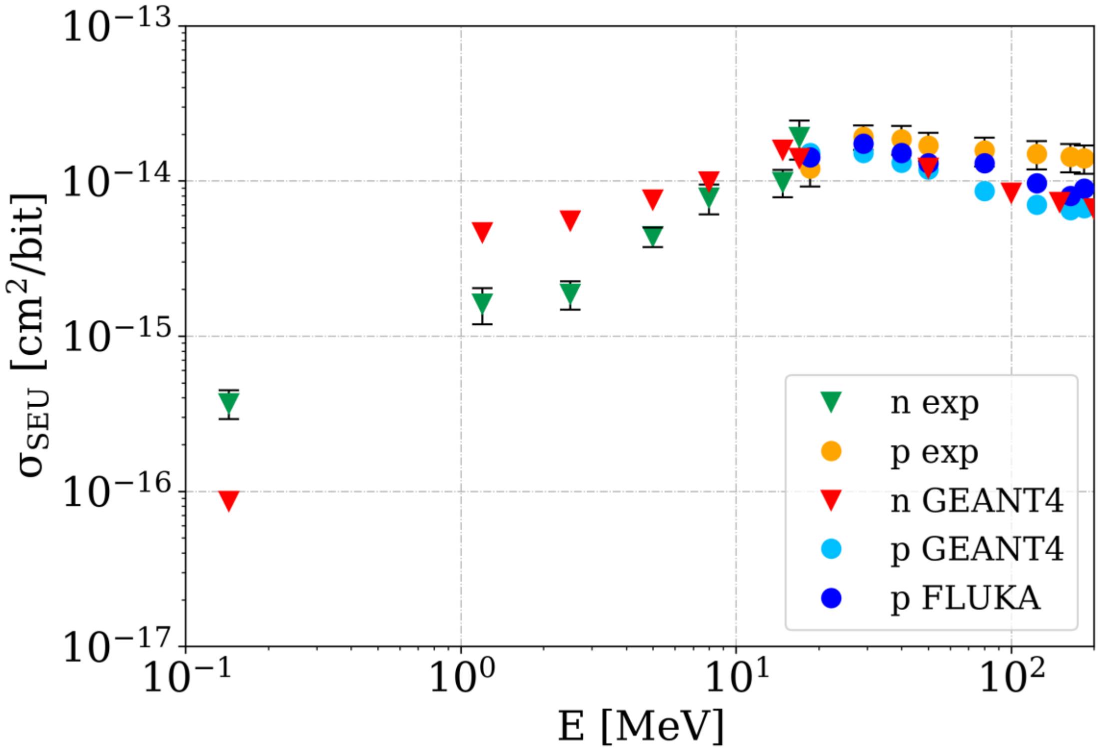
SEU simulations – GEANT4

ISSI 40 nm memory modelled in **GEANT4** (G4SEE, *see David's presentation*) and **FLUKA**

- Si bulk 250 nm sides cubic **RPPs** - SiO_2 **BEOL** of 6 um - **Qc = 0.72 fC**
- Model benchmarked against proton (18 – 200 MeV) and neutron (0.144 – 17 MeV) experimental data

⬇

- **Satisfactory agreement** considering the broad range of energies and particle species
- Simulations confirm **neutrons can deposit enough energy to trigger SEUs even at 0.144 MeV**



Energy deposition – Elastic vs inelastic processes

- Energy threshold for (n,a) **inelastic interactions** in ^{28}Si is **2.75 MeV**
- Below this threshold mostly **elastic processes** take place

Maximum energy transferred by a neutron (**144 keV**) in elastic reactions:

$$E_{max} = E_n \cdot \frac{4A}{(A+1)^2}$$

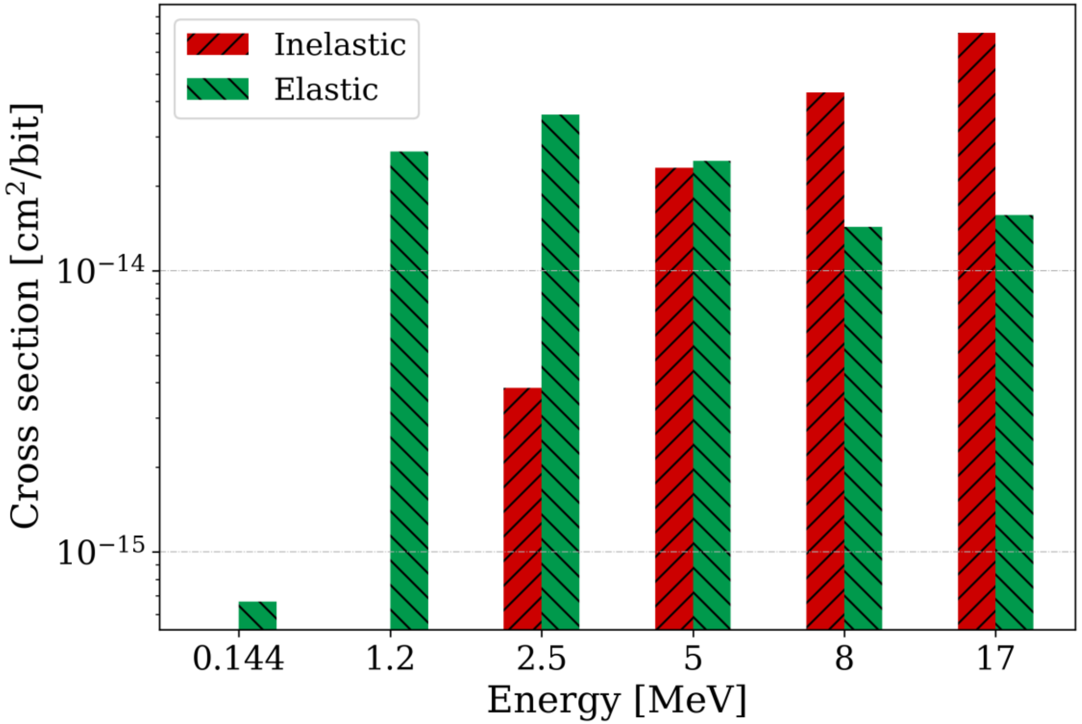
^{28}Si ➡ E_{max}=19 keV ➡ $Q_{c\text{-}max}$=0.84 fC

^{16}O ➡ E_{max}=32 keV ➡ $Q_{c\text{-}max}$=1.42 fC

Both **above memory Qc**

More energy transferred to lighter nucleus

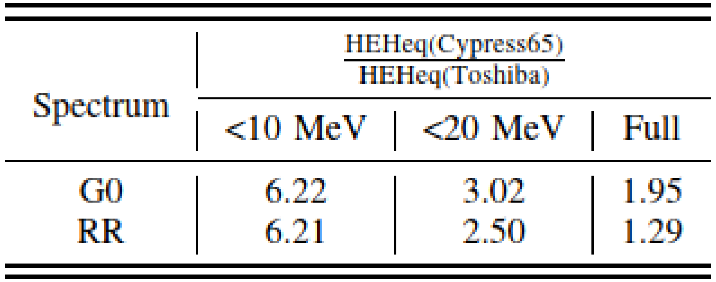
→ oxygen



Radiation Hardness Assurance (RHA) implications

Toshiba reference memory used for the HEHeq fluence calculation not anymore the worst-case response

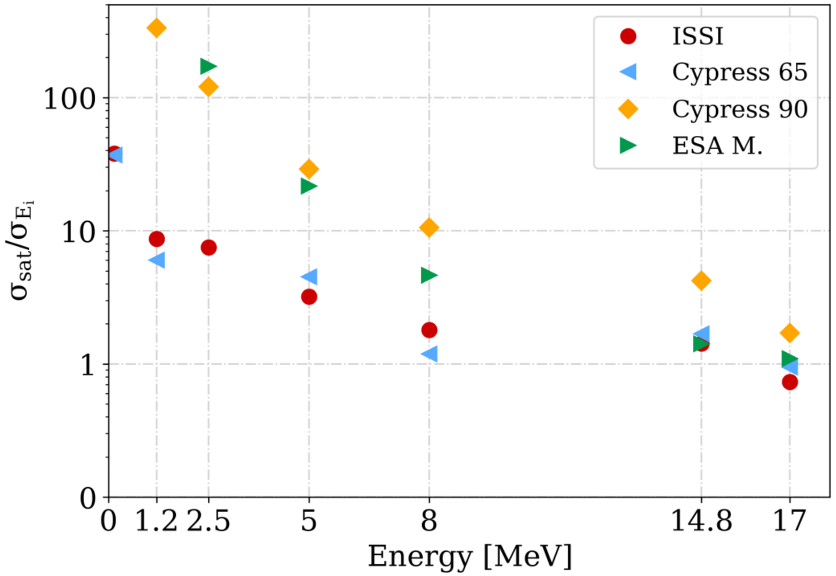
→ Possible SER underestimations



Spectrum	$\frac{\text{HEHeq(Cypress65)}}{\text{HEHeq(Toshiba)}}$		
	<10 MeV	<20 MeV	Full
G0	6.22	3.02	1.95
RR	6.21	2.50	1.29

RHA solutions:

1. **Safety margin** to the HEHeq fluence (at least factor 2)
2. Implement **Cypress 65 nm response** for the HEHeq fluence calculation
3. Component **qualification with 2.5 MeV neutrons** and comparison to saturated cross section



Conclusions

- In the commercial SRAMs studied in this work, neutrons between 0.1-10 MeV can induce up to:

60% of SEUs in accelerator	**19%** of SEUs in avionics

- RHA (for accelerator)→ Neutrons between **0.1 – 10 MeV** yield dominating SEU contribution
- Potential treat for **medical** and **fusion** applications
- Toshiba 400 nm response for HEHeq flux not anymore the worst case
- **Elastic processes** can deposit enough energy to trigger SEUs even at 144 keV, as proved experimentally and via simulations

This presentation: M. Cecchetto et Al, “0.1-10 MeV Neutron Soft Error Rate in Accelerator and Atmospheric Environments” IEEE TNS

Thermal neutrons: M. Cecchetto et Al, “Thermal Neutron Induced SEUs in the LHC Accelerator Environment” , IEEE Trans. Nucl. Sci., 2020

Thank you for your attention!