SERESSA 2022

5th to 9th of December at CERN, Geneva

Accelerator Radiation Environment and Neutron Effects in Electronics

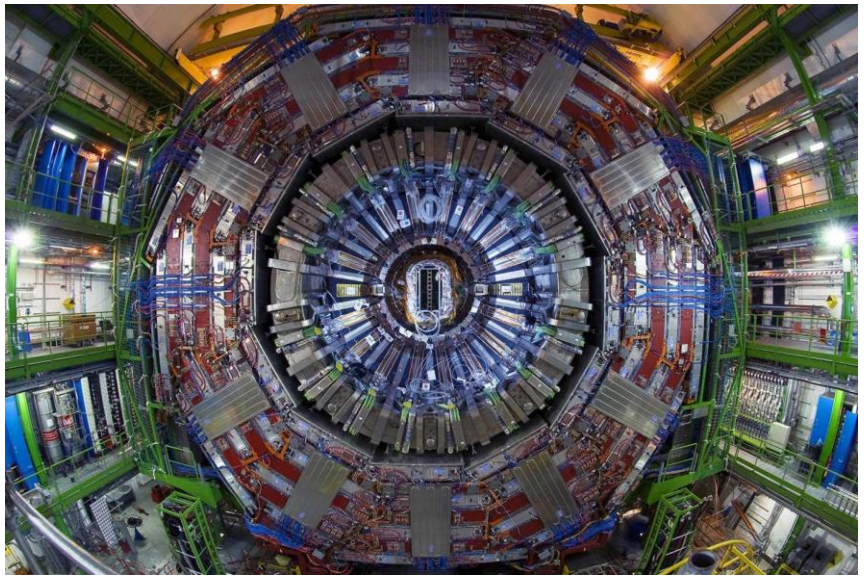
Matteo Cecchetto, CERN

Outline

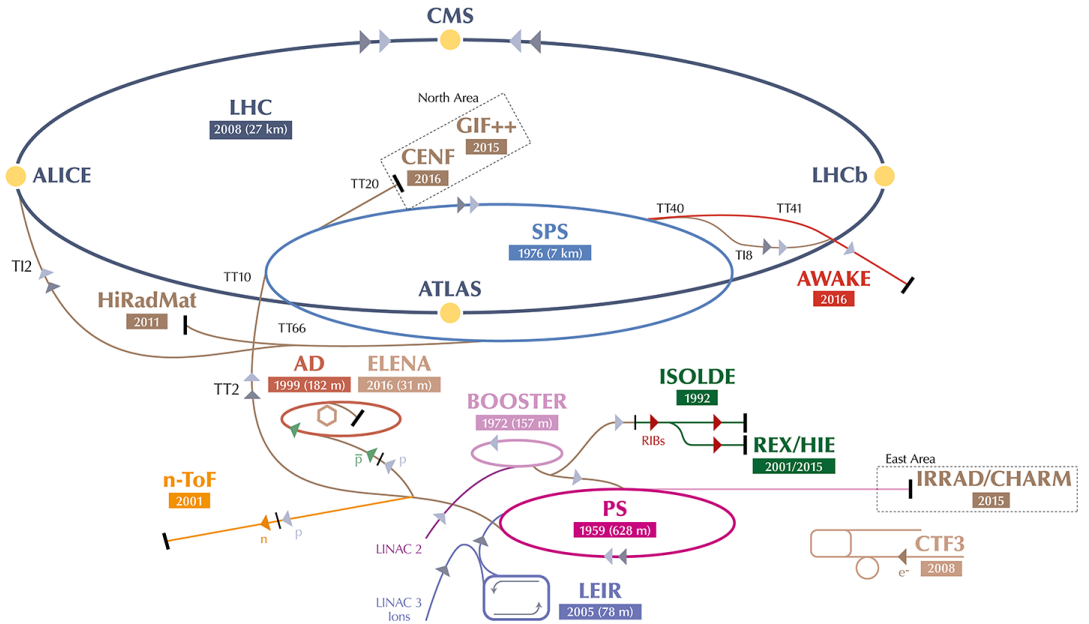
- **Introduction to CERN and the R2E project**
  - **Electronics in the LHC and R2E failures**
  - Radiation environment in the LHC and related quantities
  - Example of test facilities
- SEE estimation and RHA implications
  - SEUs induced by thermal neutrons with respect to HEH
  - SEUs induced by 0.1-10 MeV neutrons with respect to HEH
  - SEEs in atmospheric, fusion and medical environments
- Summary

CERN – European Organization for Nuclear Research

- **LHC (Large Hadron Collider)** is a 27 km long, 7 TeV beam energy, proton-proton collider.
- Four High-energy physics **experiments** (**CMS**, **ATLAS**, **ALICE**, **LHCb**) but also other facilities (CHARM, n_TOF, etc.).
- Multiple **acceleration stages** (LINAC, PSB, PS, SPS and LHC).
- Several physics **discoveries** and **technological** contributions (Higgs boson, Positron-Emission Tomography, etc.).



CERN CMS detector



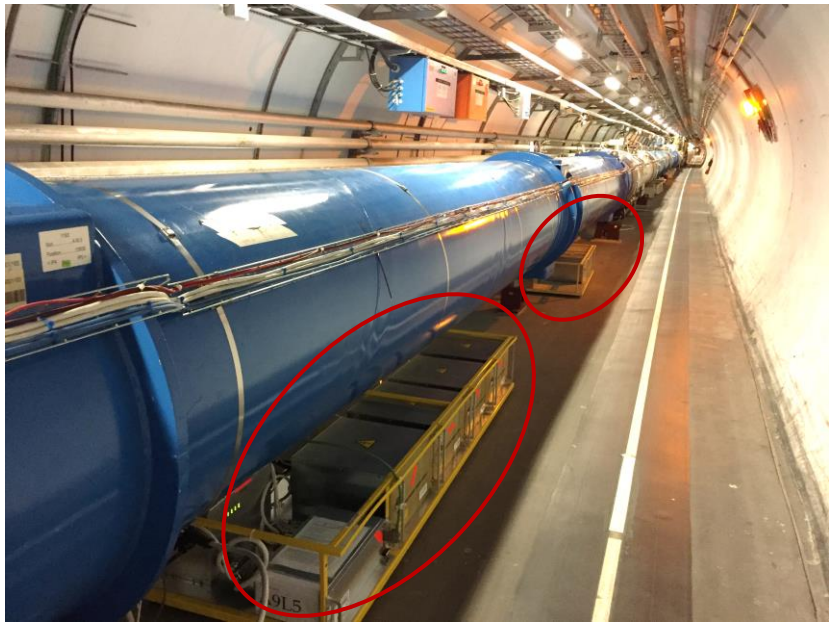
*https://cds.cern.ch/

*https://cds.cern.ch/

Electronics in the LHC

A large number of electronics operate near the accelerator and therefore is exposed to **radiation which induces many failures!**

- **Vacuum** → to allow the beam to propagate in the beam pipe unperturbed
- **Cryogenics** → to enable superconducting operation
- **Power converters** → to feed magnets with necessary currents
- **Many others** (quench protection systems, Beam instrumentation, RF systems)



Accelerator systems are mainly based on **Commercial-Off-The-Shelf (COTS)** components because of:

1) **Costs** → the very high number of system parts involved.
2) **Project timelines**
3) **Performance** → not achievable when considering rad-hard components.

Types of failures in electronics

Stochastic Effects

Single Event Effects (SEE): A **single** ionizing particle hits the sensitive area of a powered device compromising its functionality

High Energy Hadrons [cm^{-2}]

Thermal Neutrons [cm^{-2}]

- SEEs can be **non-destructive** (Soft Errors) or **destructive** (hard errors), but both can have a big impact on the LHC operation for critical systems.

Cumulative Effects

- Total Ionising Dose (TID): degradation of electronics parameters in time (MOSFETs)
- Displacement Damage (DD): displacement of lattice atoms (BJTs)

TID [Gy]

1-MeV n_{eq} [cm^{-2}]

- Not only electronics are affected but also magnets, cryogenic elements, etc.

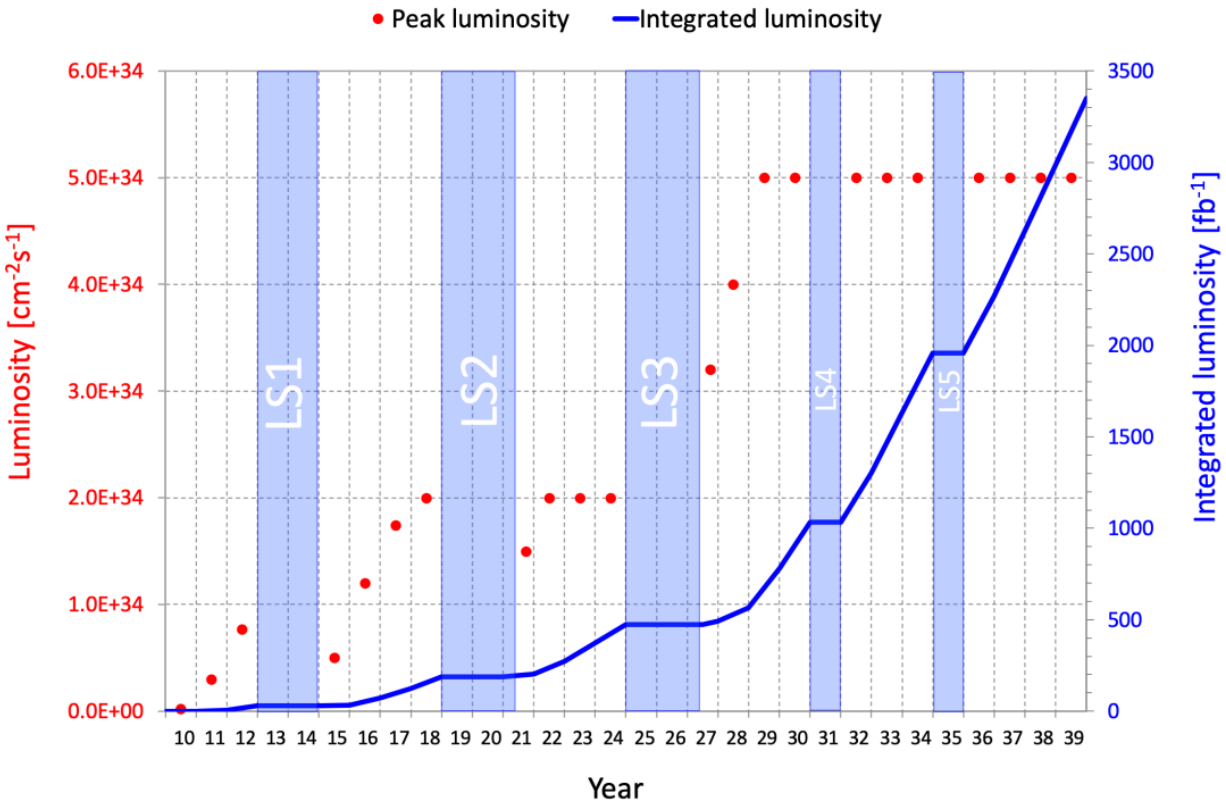
The main ingredient of HL-LHC: Luminosity

Planned upgrade to HL-LHC (High-Luminosity LHC, 2025-2035)

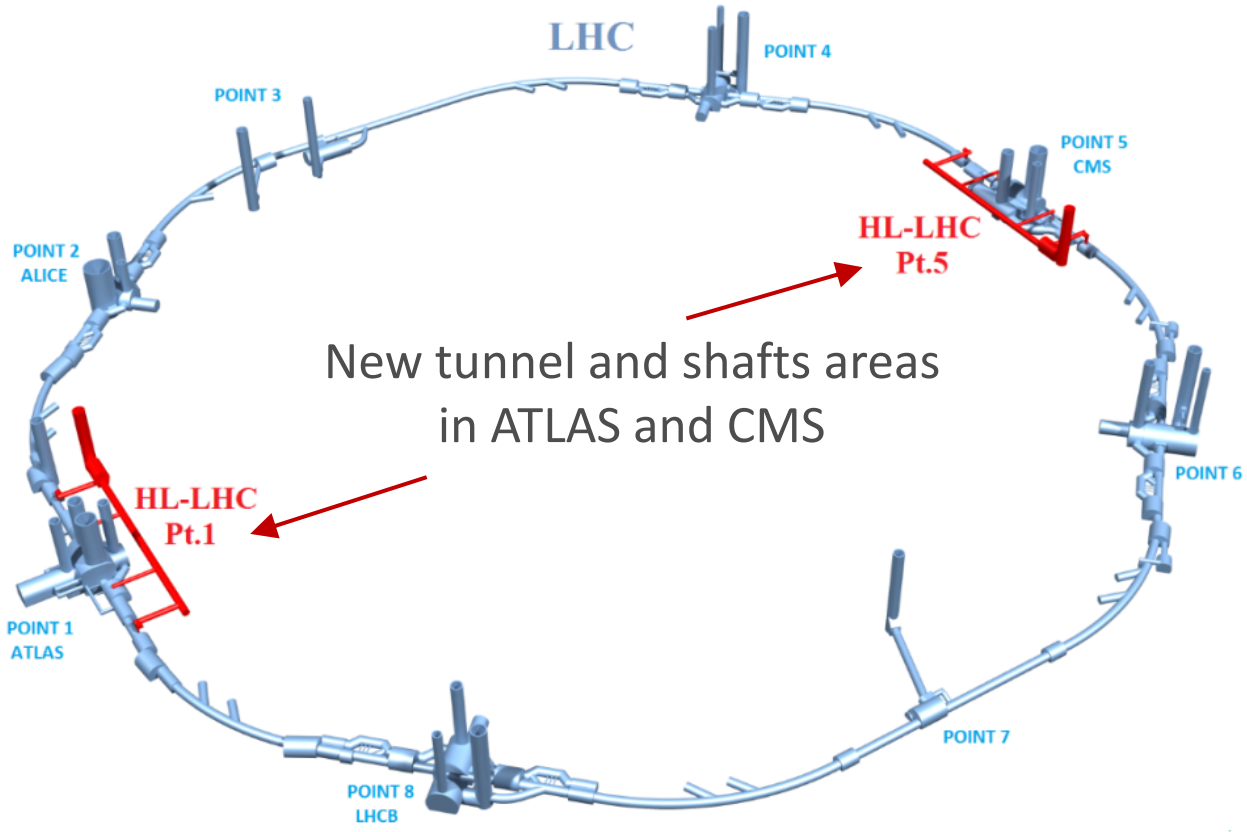
- Radiation levels mainly depend on **beam energy**, integrated **luminosity** and **intensity**

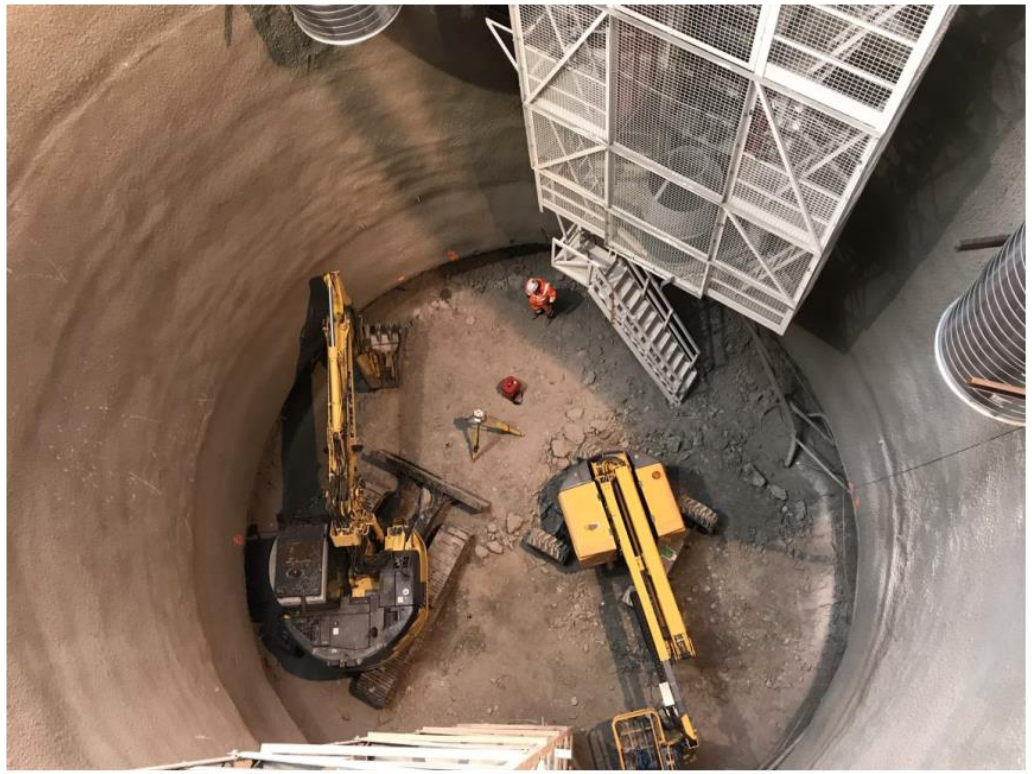
Luminosity is a critical parameter for a collider

- It is expressed in units of inverse femtobarns fb^{-1} ($1fb^{-1} \approx 10^{14}$ collisions at TeV of energies)
- The **luminosity will increase** over the years!! → **higher radiation levels** → we want to keep **R2E failures** as low as possible



HL-LHC some new constructions





*L. Rossi - A bright future for LHC: the High Luminosity collider – Talk to the CERN guides

How do R2E effects impact the accelerator performance?

R2E effects impact the accelerator performance by **reducing its availability** and compromising the related scientific program → beam sent to **dump**.

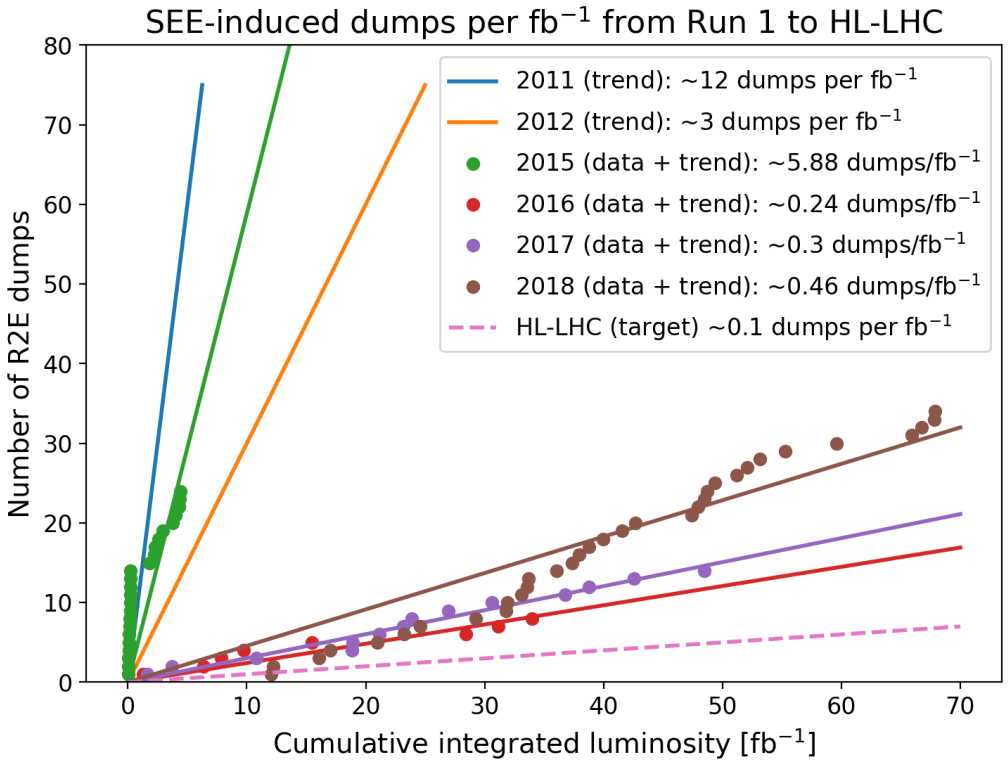
Mitigation measures for equipment already installed:

- Shielding, relocation, or replacement of sensitive elements
- Very expensive

Prevention for equipment under development (HL-LHC):
namely, make it radiation tolerant:

- Develop a **Radiation Hardness Assurance (RHA)** procedure that considers radiation constraints from the early stages of the system design
- This often involves **a lot of radiation testing** at component/system level!

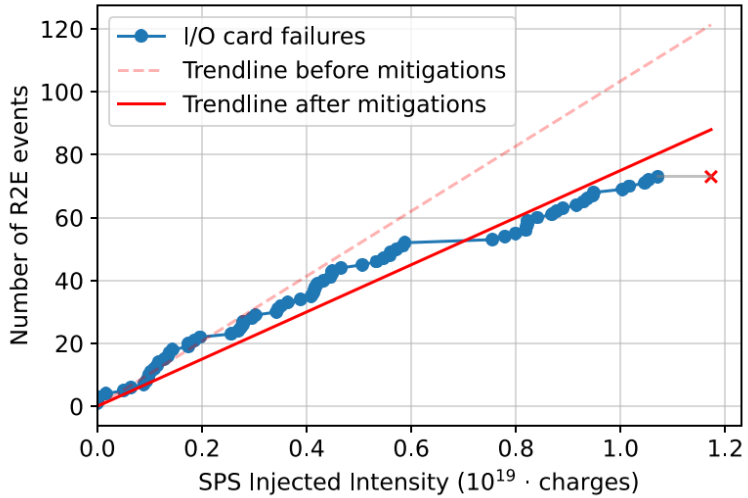
We aim at 0.1 dumps/fb^{-1} (for HL-LHC)



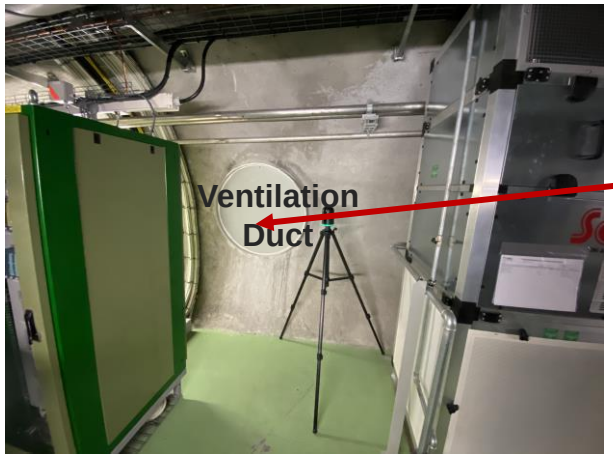
Y. Aguiar et Al., https://doi.org/10.18429/JACoW-IPAC2021-MOPAB013

Example: R2E failures in the SPS Access system

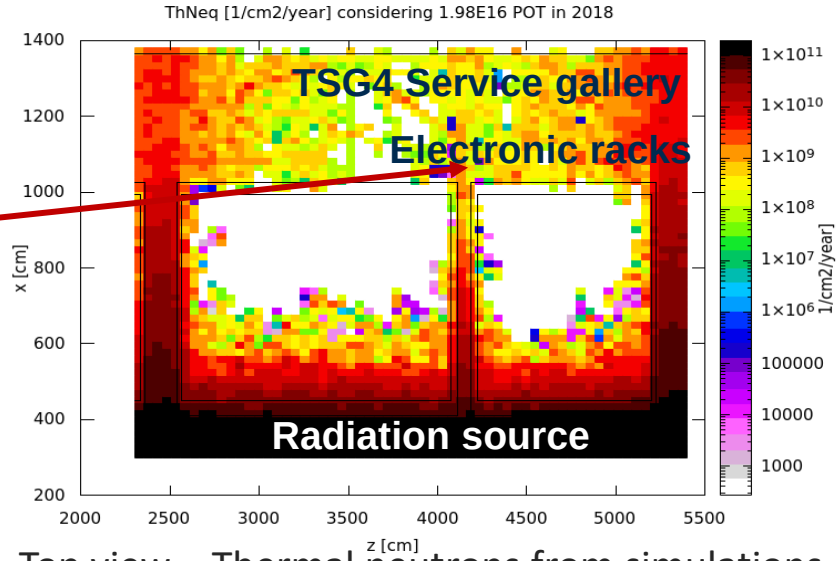
- **Access system** involves safety elements that control the access to the machine, with **relatively low neutron-dominated radiation levels** (<1e9 ThN&HEH/cm^2/year).
- Several failures have been recorded in 2021* (plot, right).
- **Shielding & Relocation** of electronic racks on the surface.
- Some racks cannot be relocated; hence, a dedicated study is needed (AWAKE-TSG4, see below, left).



*Y. Aguiar et Al, *"Implications and mitigation of radiation effects on the CERN SPS operation during the machine commissioning of Run 3"*, IPAC2022



Front view

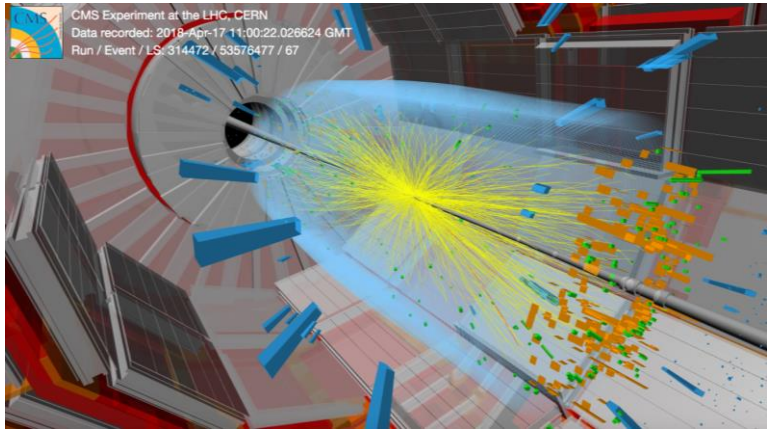


Top view – Thermal neutrons from simulations

Radiation sources in the LHC

Three main radiation sources in the LHC:

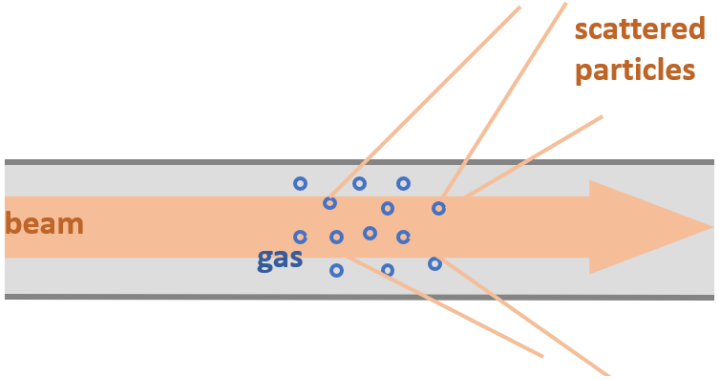
Collision debris



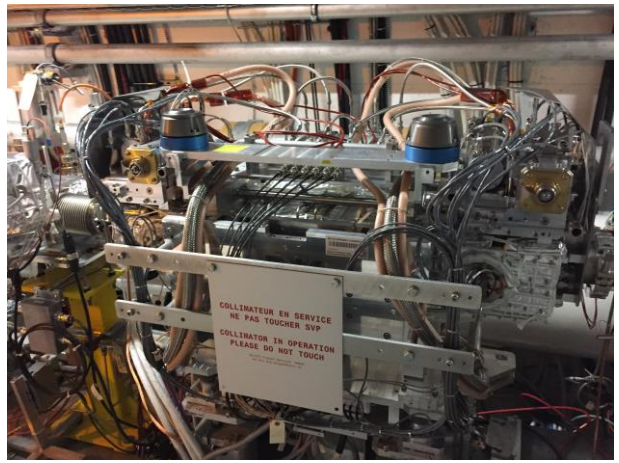
- ≈$4 \cdot 10^{15}$ inelastic collisions per year in ATLAS/CMS
- The collisions generate particles in all directions and a fraction can reach the LHC tunnel

Residual gas

The beams interact with residual gas molecules inside the vacuum pipes



Collimators



- Beam interactions with collimators generate a cascade of secondary particles
- In many areas, they can be regarded as the primary source of radiation

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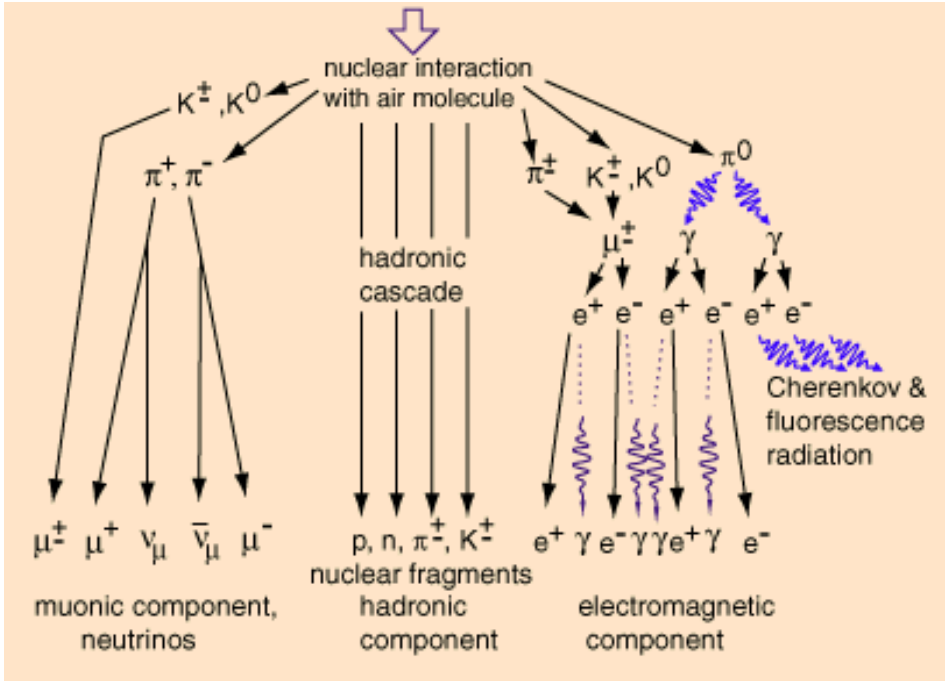
Radiation environment in high-energy accelerators

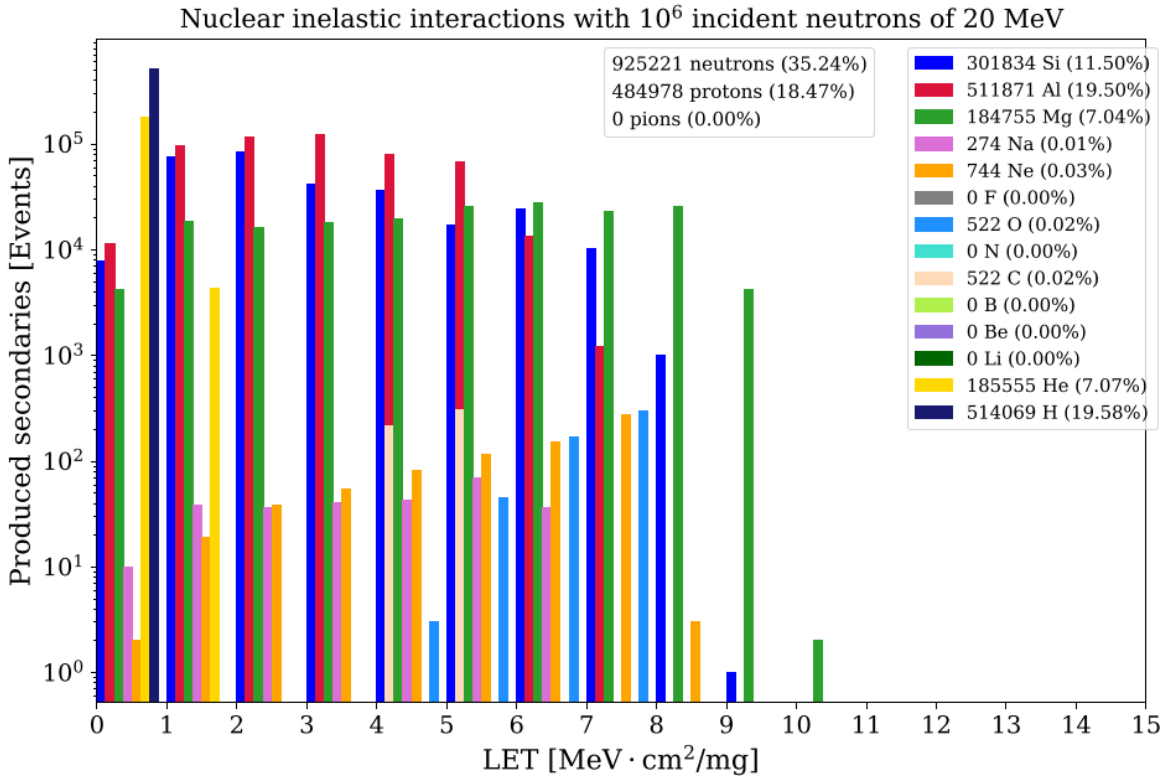
- Generations of **hadronic** (SEEs, TID, DD) and **electro-magnetic** (TID) showers with the interaction of the high-energy proton beam (or ions) with air and machine elements.
- Very similar to what happens in the atmospheric radiation environment.
- The radiation environment in the LHC varies with regards to **particle composition** and **energy spectra.**

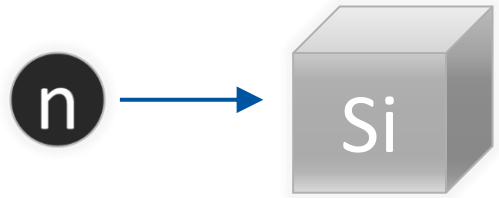


We need to characterize the radiation environment in the LHC, both through measurements and Monte Carlo simulations

What particles are inducing SEEs on electronics?

- SEEs are induced by indirect energy deposition (nuclear reactions) from **hadrons** (n, p, pi,..).
- **Neutrons are not so neutral for SEE:**
  - **Neutrons indirectly ionize atoms** by generating nuclear reactions that produce secondary ions
  - These secondary ions are then capable of releasing enough charge inside electronics and triggering SEEs

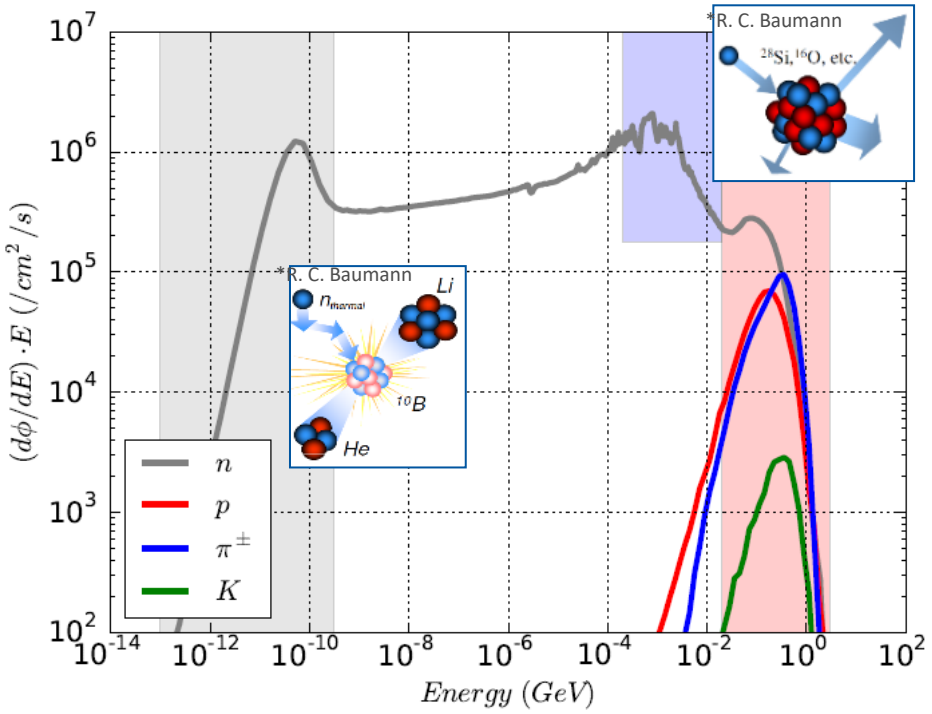




For instance, with incident neutrons of 20 MeV in silicon, many secondary ions are generated!

High Energy Hadrons and Thermal Neutrons

High Energy Hadrons (HEH):
n, p, π, K with **E ≥ 20 MeV**
Responsible for both soft and hard SEEs



HEH equivalent (HEHeq):
HEH + n between **0.2-20 MeV**

$$\varphi_{HEHeq} = \underbrace{\int_{0.2MeV}^{20MeV} w(E)\frac{d\varphi_n(E)}{dE}dE}_{\text{Intermediate energy neutrons – a major concern with scaling of technology}} + \int_{20MeV}^{+\infty}\frac{d\varphi_{HEH}(E)}{dE}dE$$

Thermal Neutrons (ThN):
n with **E ≈ 25 meV**
Only soft SEEs, interact with ^{10}B through the ^{10}B(n,α)^{7}Li reaction

$$\varphi_{ThNeq} = \int \sqrt{\frac{0.025[eV]}{E\ [eV]}}\frac{d\varphi_n(E)}{dE}dE$$

SEE: response function of electronics

The SEE rate is calculated by multiplying **fluences** (**ϕ**, in units of cm^{-2}) and **SEE cross sections** (σ, in cm^2)

$$N_{SEE} = \sigma_{ThN} \cdot \Phi_{ThN} + \sigma_{HEH} \cdot \Phi_{HEHeq}$$

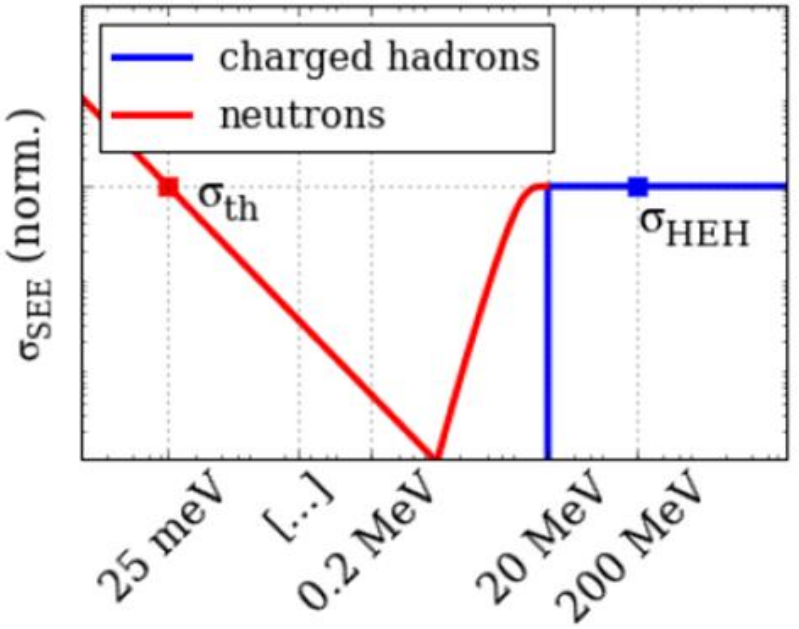
SEEs due to thermal neutrons

SEEs due to HEHeq

$$R = \frac{\Phi_{ThN}}{\Phi_{HEHeq}}$$

R-factor is the ratio between ThN and HEHeq fluences

- σ_{th} is normally measured in **nuclear reactors**.
- σ_{HEH} is measured in **monoenergetic facilities** (200 MeV protons where the cross section is typically saturated (already above 20 MeV).
- HEH above 20 MeV are assumed to equally induce SEEs, so testing with protons or a mixed field (n, p, etc.) will provide the same SEU cross section.



LHC layout

Radiation levels, which depend on beam energy, integrated **luminosity** and intensity, strongly depends on the **position along the accelerator** and can be subdivided in:

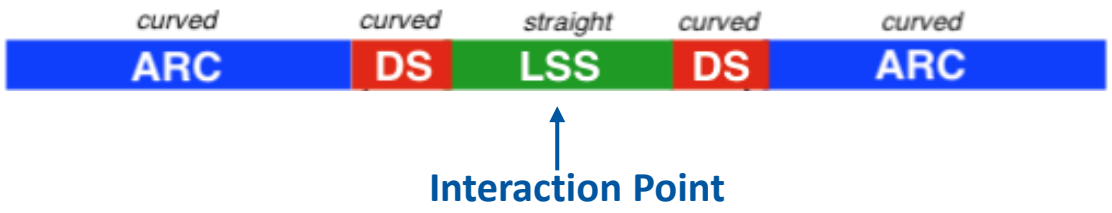
Shielded alcoves → Near Interaction Points (ATLAS, CMS)

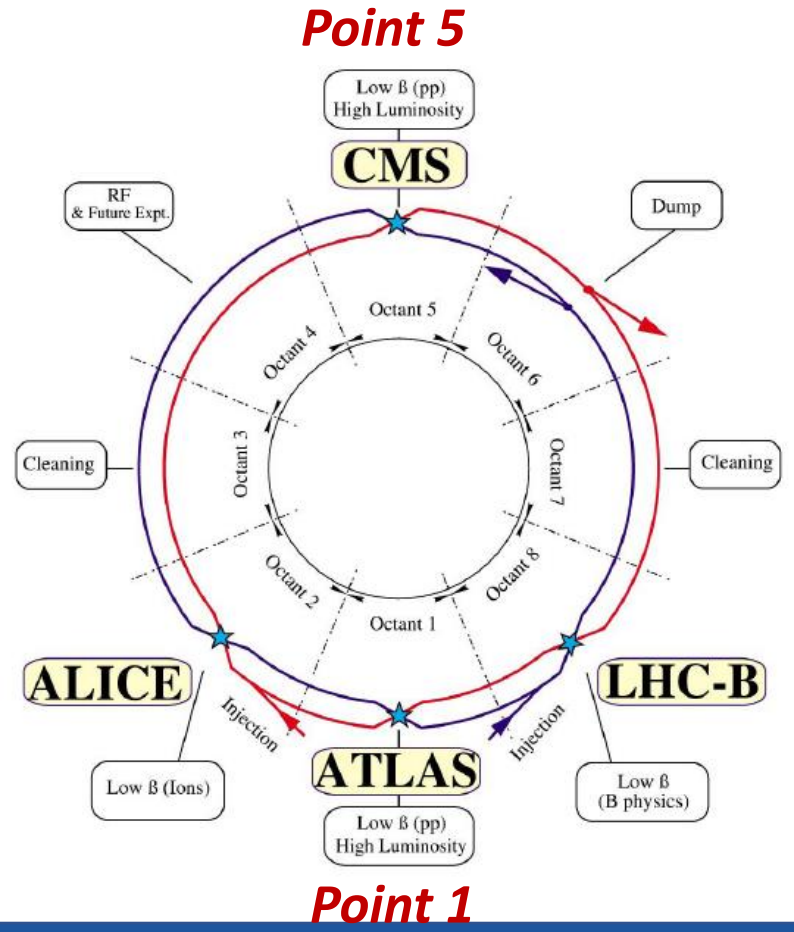
Tunnel →

Arc: Main curved section of the tunnel → beam gas interactions.

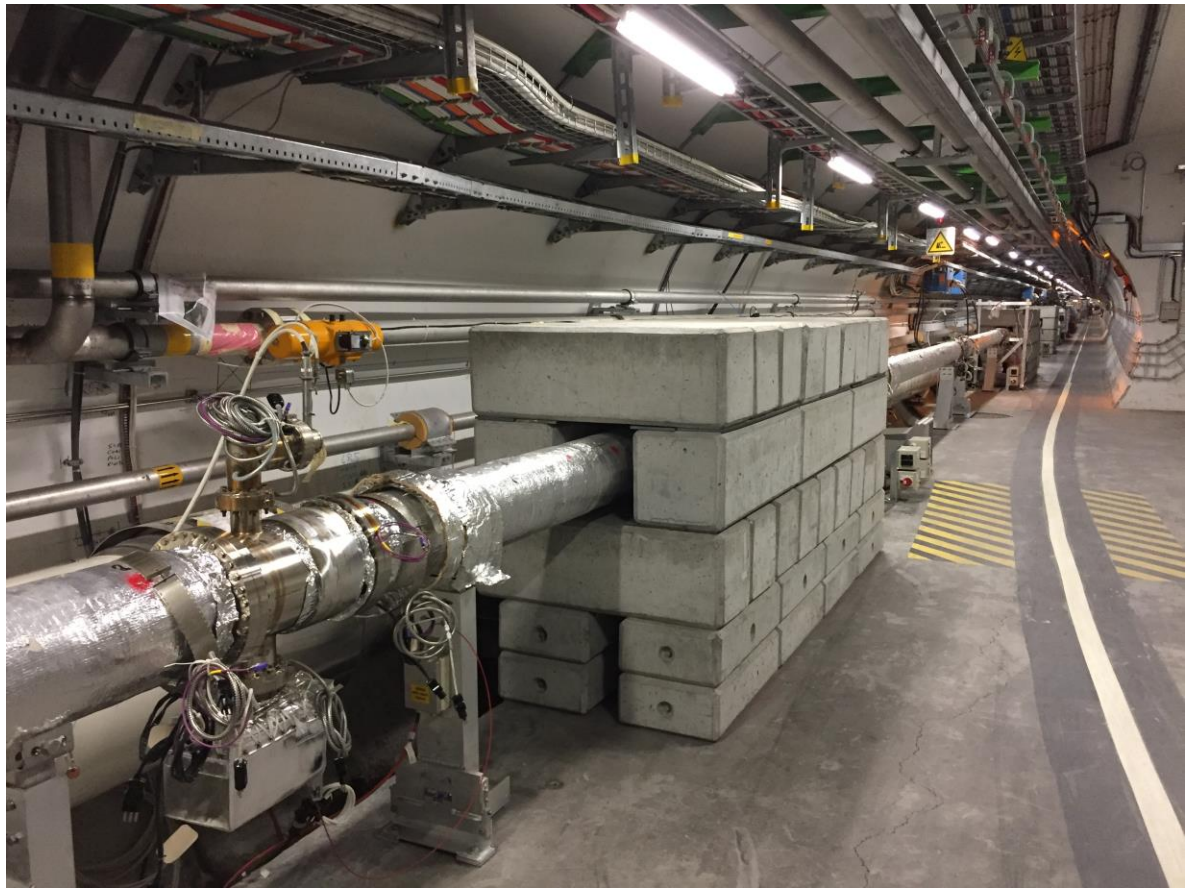
Dispersion Suppressor (DS): first curved part of the tunnel → Off-momentum protons.

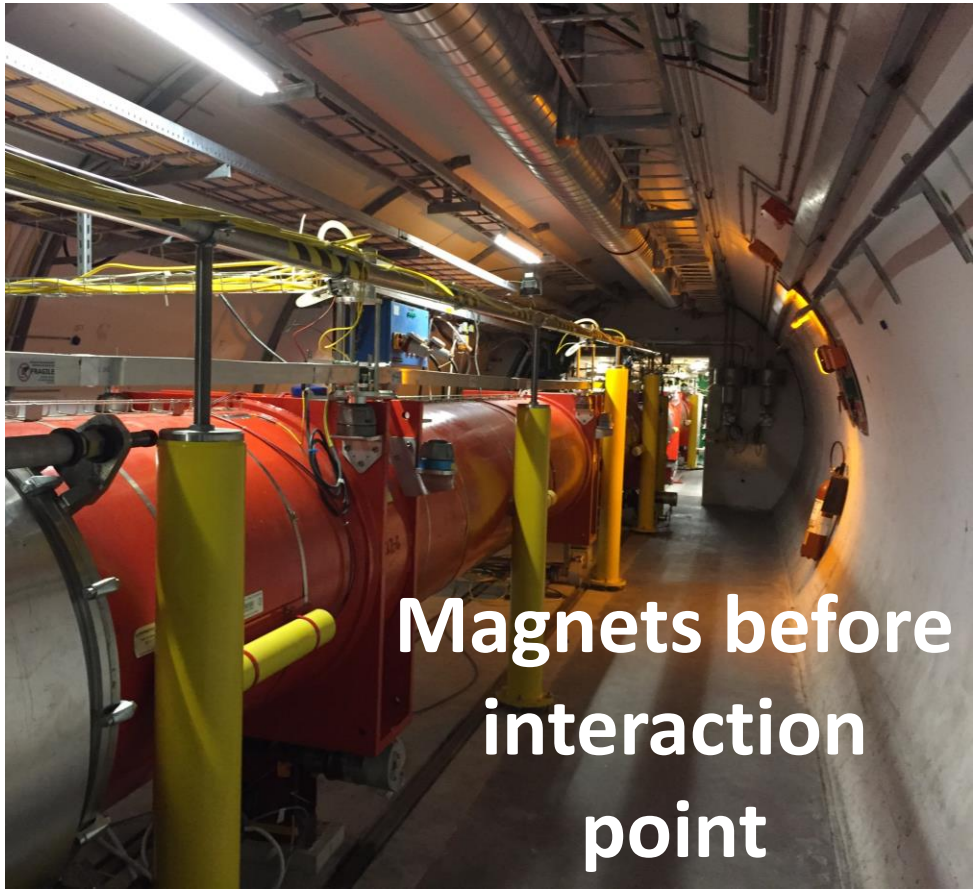
Long Straight Section (LSS): prepares beams to collide → collision and collimator debris.





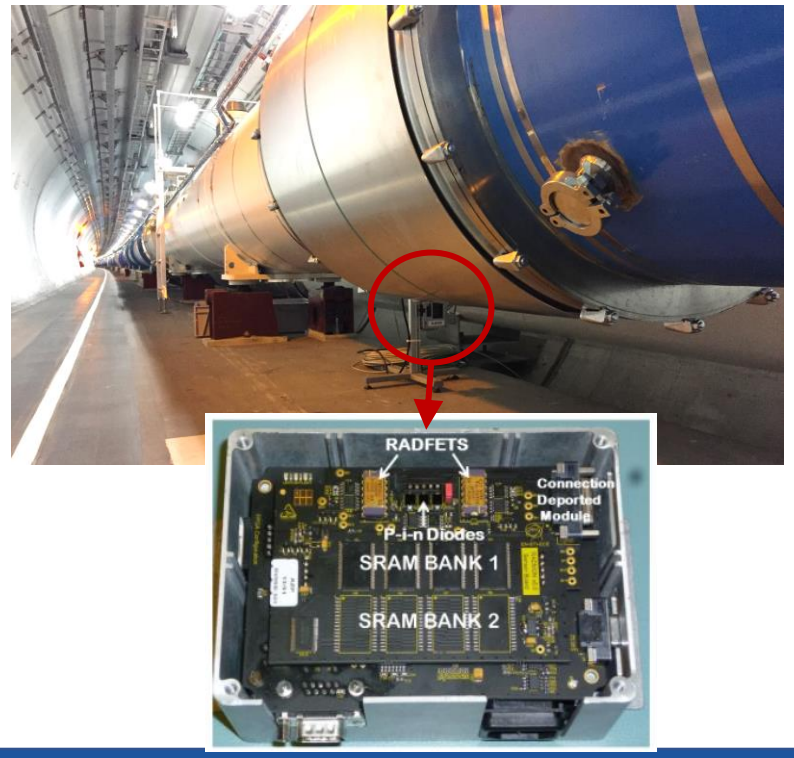
Some pictures: Long straight section (LSS)





LHC radiation monitors and simulation tools

- ***RadMon:*** a detector for ***HEHeq*** and ***thermal neutron*** fluences based on calibrated COTS, 1-MeV neutron-equivalent fluence and TID, ~400 units in the LHC.



- ***BLM:*** based on gas-filled ionization chambers, capable of measuring TID, ~4000 units in the LHC .

- ***FLUKA:*** Monte Carlo tool to simulate the interaction particles-matter and in particular the radiation levels in the LHC and the various R2E quantities (HEHeq, ThN, etc.).

FLUKA

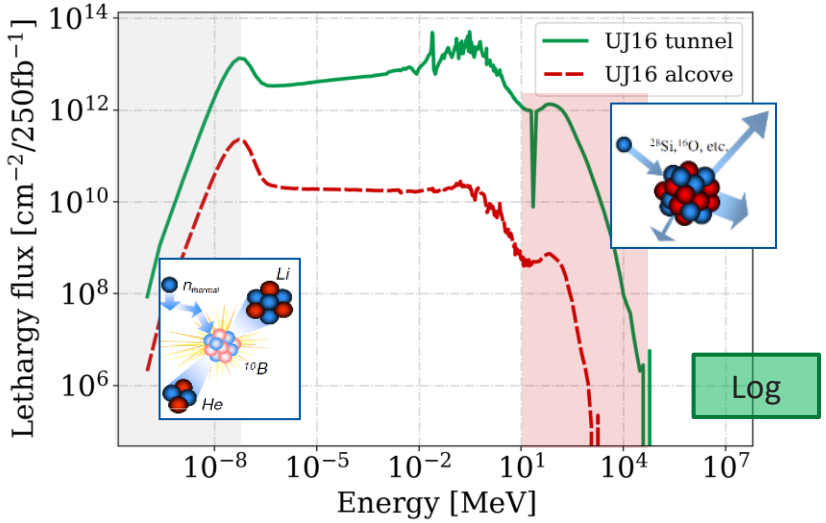
- ***G4SEE:*** Toolkit for simulating radiation effects in electronics.

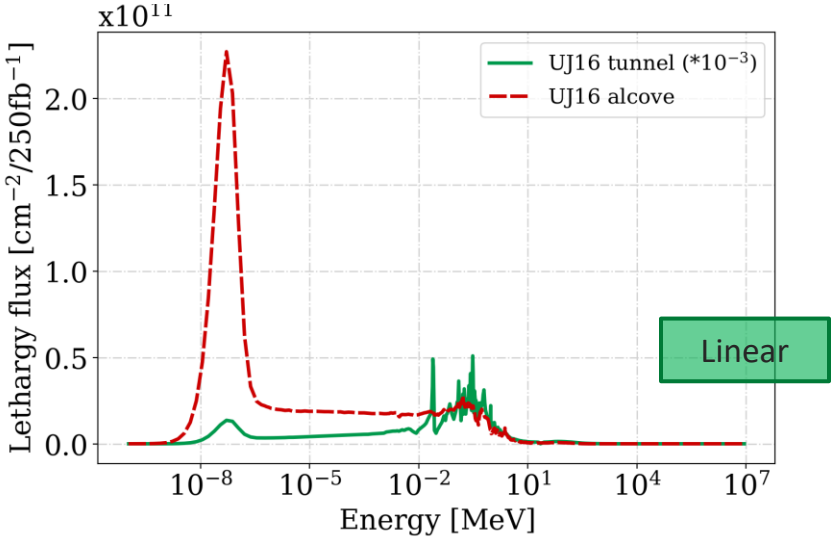
G4SEE

Shielding from collision debris UJ alcove

HL-LHC

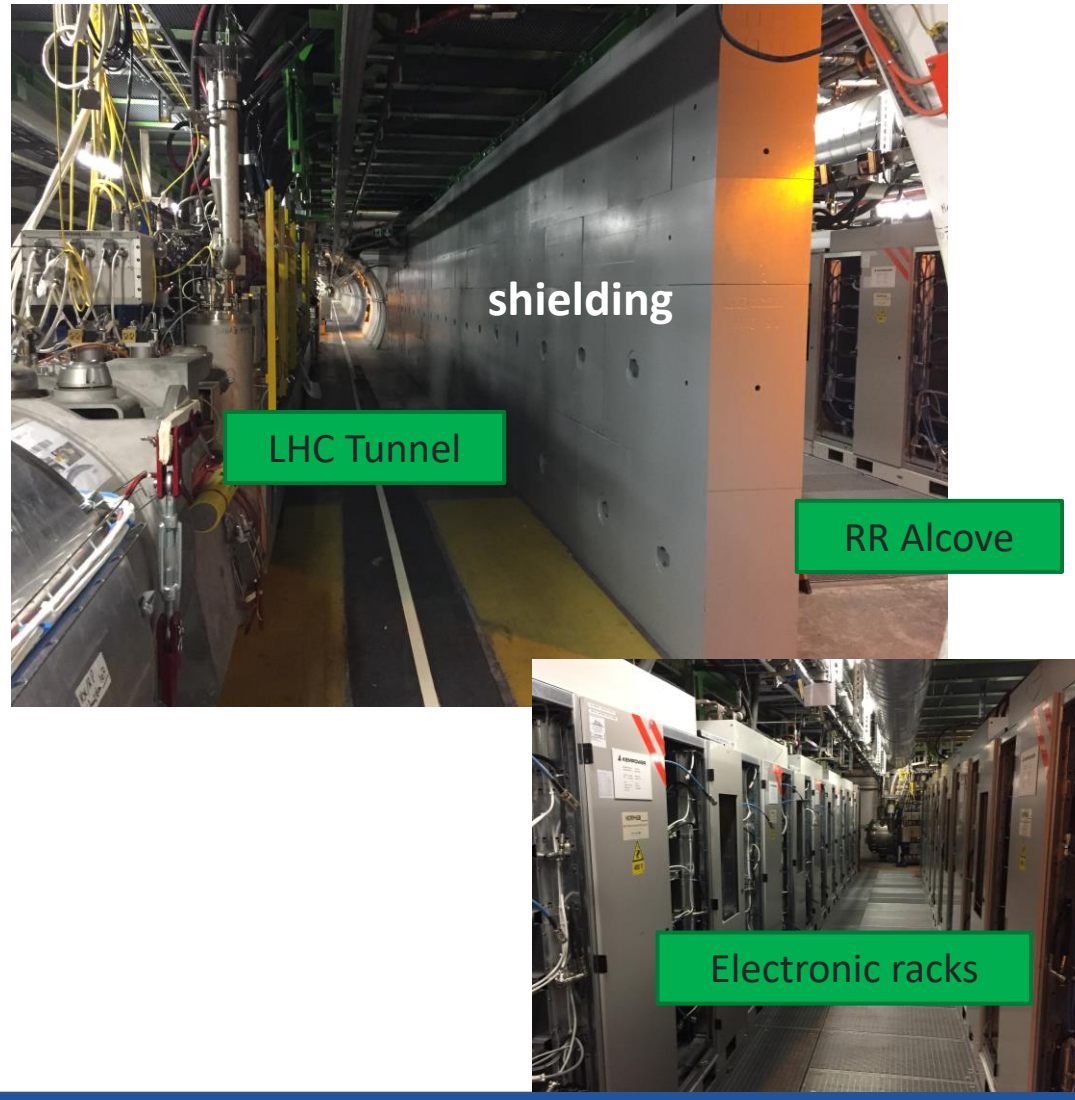
FLUKA simulations: neutrons



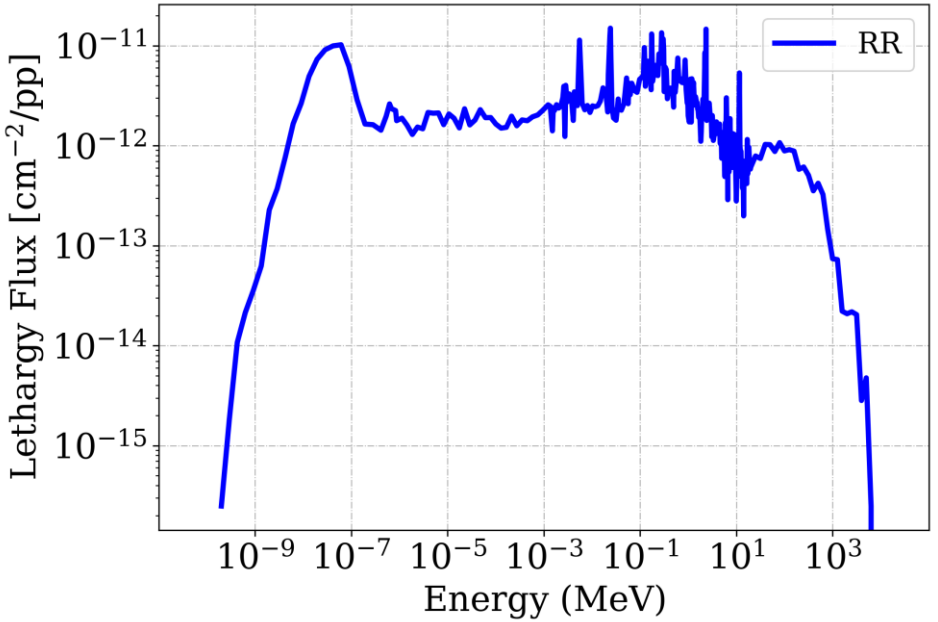


- **Heavily shielded alcove hosting electronics**, 200 cm cast iron/concrete, 50 m from the ATLAS experiment.
- **98%** of the HEH spectrum is composed of **neutrons**.
- **Large thermal neutron fluxes inside the UJ alcove** (>10^{11} cm^{-2}/y).
- Shielding reduces HEH radiation levels from **~10^{13}** (tunnel) to **~10^{9} HEH/cm^2/year**.

Shielding from collimators: RR alcove



Neutrons from FLUKA Monte Carlo simulations



- **Lightly shielded alcove**, 40 cm cast iron/concrete.
- Up to **90%** of the spectrum is composed of **neutrons**.
- Very close to the collimator which is the main source of radiation.
- Shielding reduces the radiation levels from **~10^{10}** (tunnel) to **~10^{9} HEH/cm^2/year**.

Summary of LHC radiation environment

Strongly dependent on location (within meter scale) and machine operational conditions (collimators).

Values for HL-LHC conditions

HL-LHC area	HEH fluence (cm^{-2}/year)	Lifetime TID	Lifetime 1MeV n_{eq} (cm^{-2})
Shielded alcoves	10^{9}	10 Gy	10^{11}
Tunnel ARC	10^{9}	10 Gy	10^{11}
Tunnel DS	10^{11}	1 kGy	10^{13}
Tunnel LSS	10^{13}	100 kGy	10^{15}

Shielded Alcoves and ARC: a large quantity of systems, mainly impacted by SEEs → *COTS safe*

DS: both SEE and cumulative lifetime effects (TID, DD) → *COTS safe*

Tunnel near interaction points: Use of COTS excluded; possible material damage

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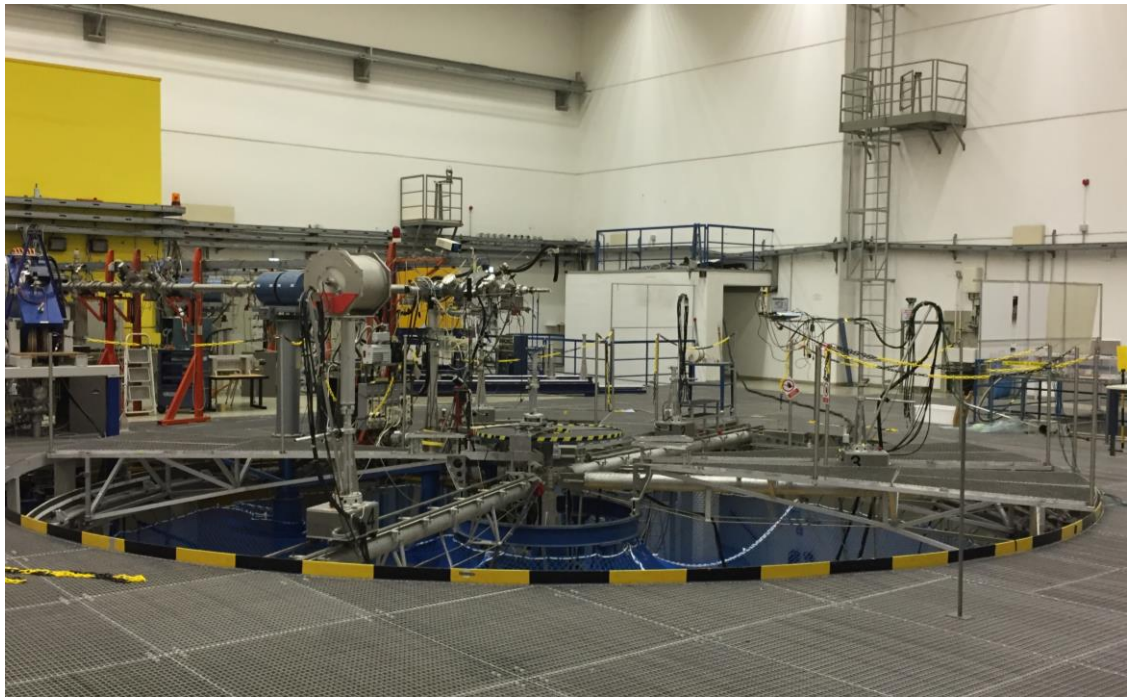
Monoenergetic neutrons - PTB

- PTB (DE) provides monoenergetic neutrons from 144 keV up to 17 MeV by combining target (**Li, D, T**) and projectile (**protons, deuteron**).



PTB irradiation hall

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
PTB	5	D(d,n)	2406
PTB	8	D(d,n)	2524
PTB	17	T(d,n)	1264

Mixed-field – CHARM facility at CERN

- CHARM provides a **mixed-field** (mainly hadrons: neutrons, protons, pions but also electrons and photons).
- Representative of the multitude of spectra found in the **LHC accelerator** and other environments (**space**, **atmospheric**, etc.).

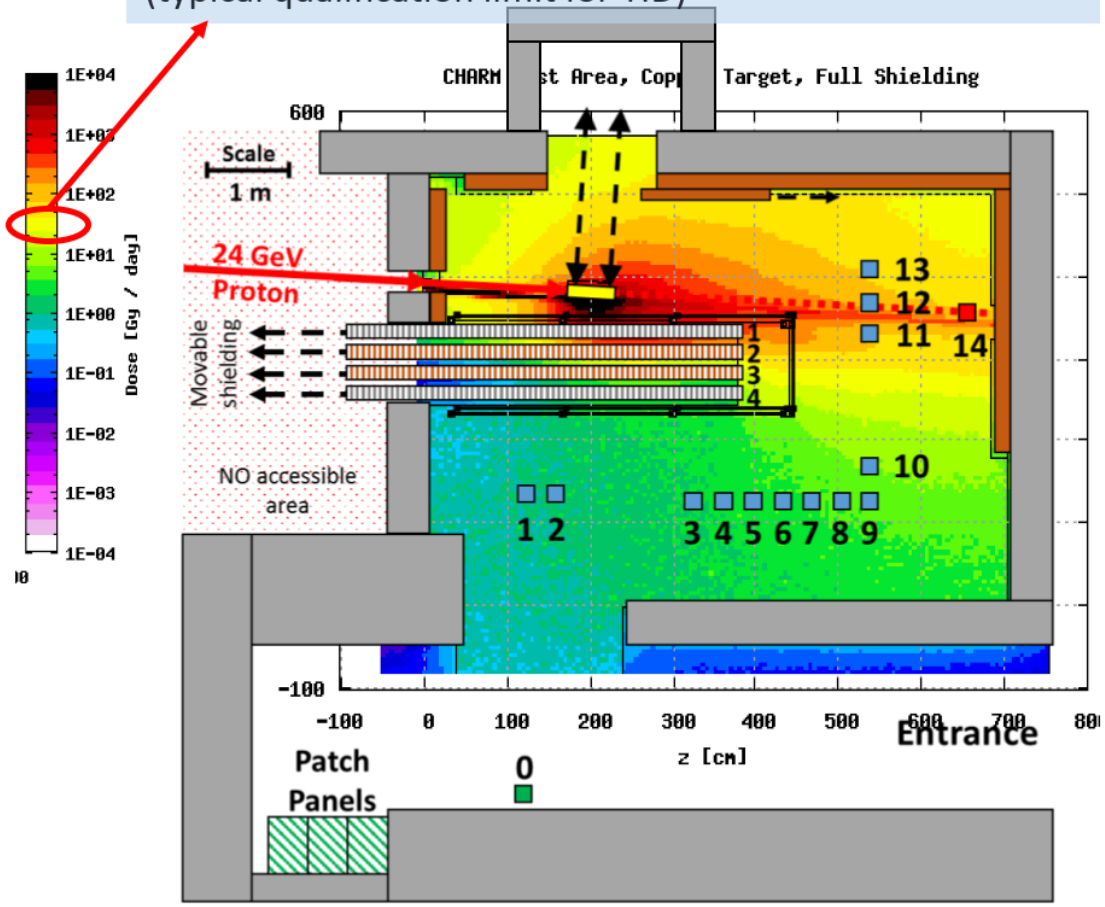
24 GeV protons impact the target

↓

A mixed radiation field is produced

System level testing for TID, SEEs and DD.
→ essential for CERN RHA assurance approach

With 40 Gy/day it is possible to achieve 200 Gy in 1 week (typical qualification limit for TID)



Dose map FLUKA simulation, top view

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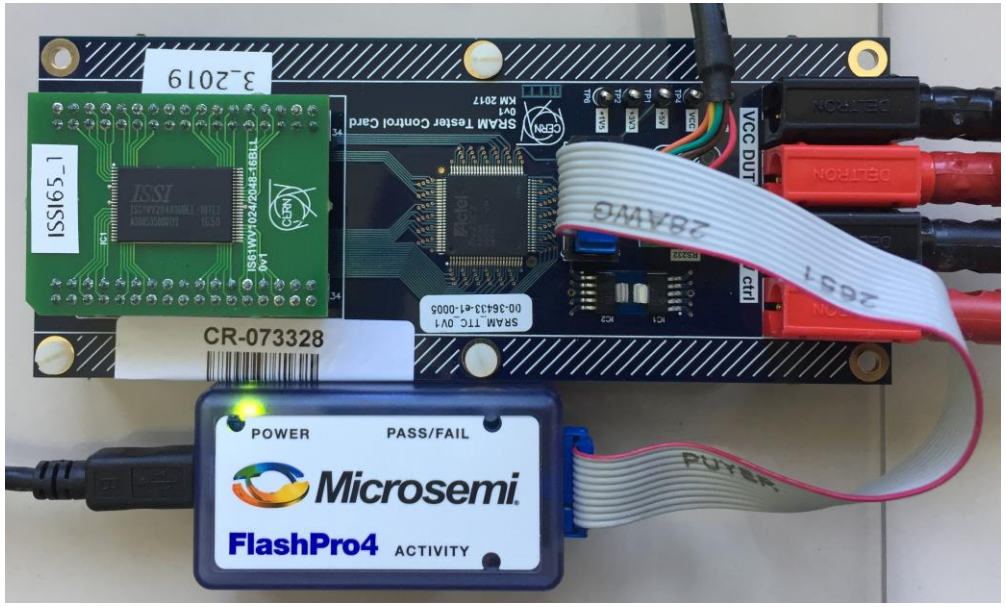
Components - Memories

SRAM | FPGA | Flash

Memory	Tech [nm]	Size	$\frac{\sigma_{HEH}}{\sigma_{ThN}}$
ESA Monitor	250	16 Mbit	5.8
ISSI	40	32 Mbit	4.6
Cypress	65	16 Mbit	157
Cypress	90	8 Mbit	106
Cypress	90	16 Mbit	107
Artix7*	28	1.4 Mbit	3.0
MLC Flash	50	4 Gbit	0.3
MLC Flash	25	8 Gbit	0.5
MLC Flash	20	16 Gbit	8.0
SLC Flash	25	32 Gbit	28

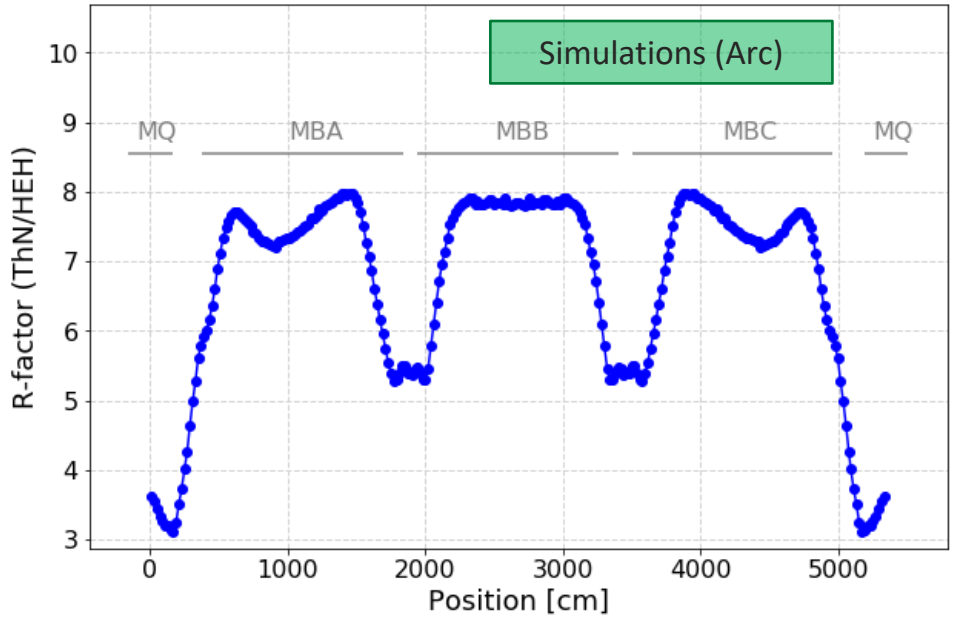


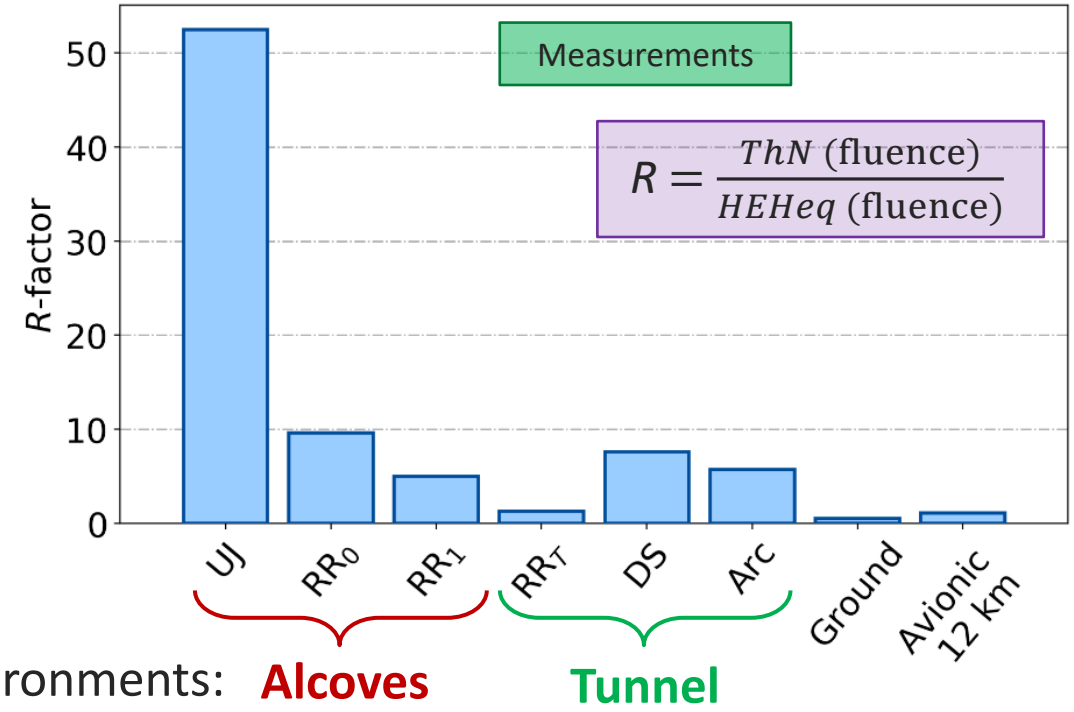
SRAM Tester

*G. Tsiligiannis et al., "*Radiation effects on deep submicrometer SRAM-based FPGAs under the CERN mixed-field radiation environment*," IEEE Trans. Nucl. Sci.

Thermal neutrons in Tunnel and Alcoves

- ***R*-factor** is defined as the **ratio between thermal neutron and HEH equivalent fluences.**





Thermal neutron fluxes dominate these LHC radiation environments:

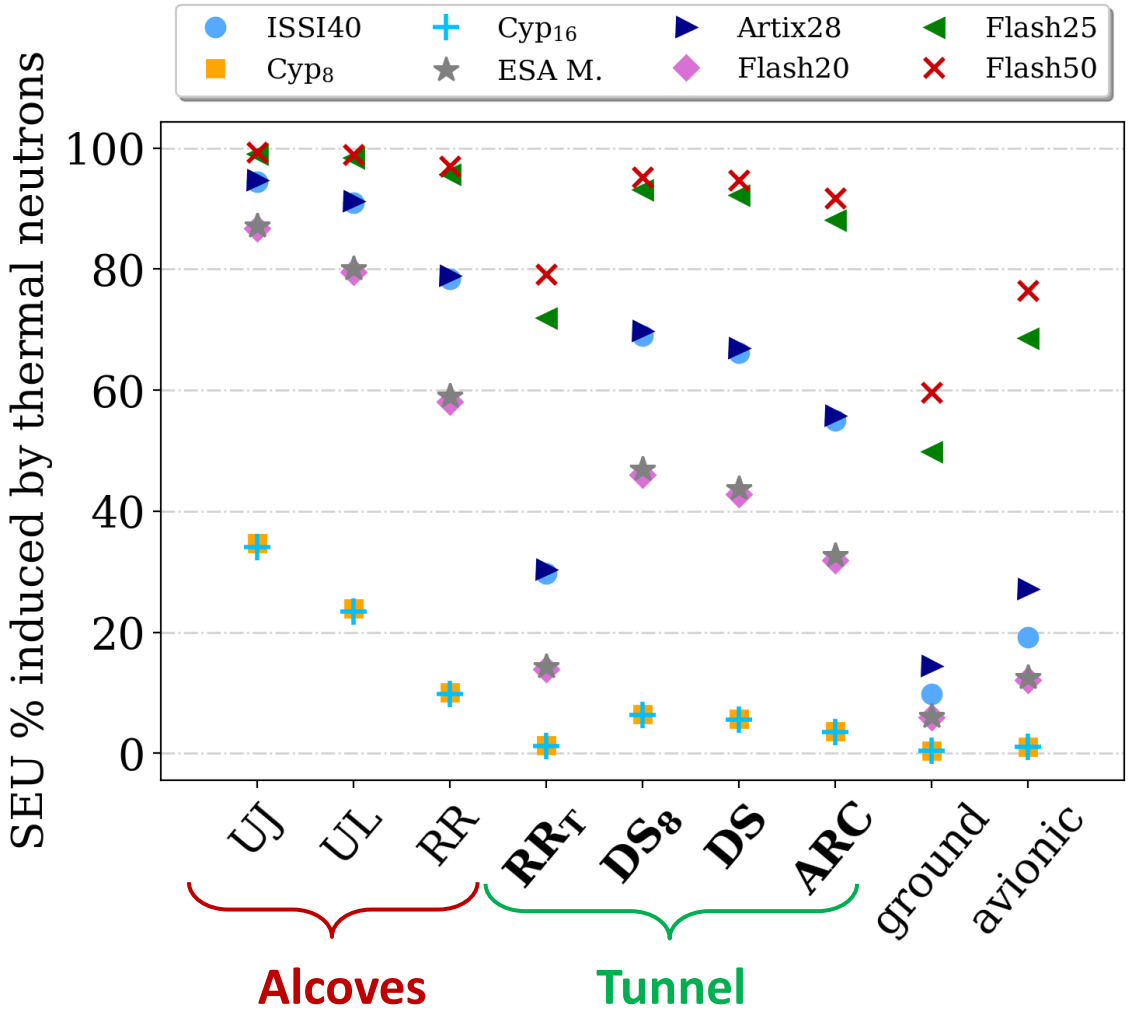
Shielded alcoves → Up to 50 times higher than HEHeq (UJ)

Tunnel → Up to 8 times higher than HEHeq (DS)

SEU induced by thermal neutrons

- Expected **SEUs due to thermal neutrons** with respect to the HEHeq are dominating in the LHC up to:

Shielded alcoves	92% SRAM
	95% FPGA
	99% Flash
Tunnel	60% SRAM
	70% FPGA
	95% Flash



- The HEH and thermal neutron sensitivities need to be carefully **qualified in dedicated facilities**

M. Cecchetto et Al,. "*Thermal Neutron-Induced SEUs in the LHC Accelerator Environment*" IEEE TNS paper

RHA considerations – thermal neutrons

- RHA approach **did not include** systematic **thermal neutron tests** at device level at CERN.
  - What happens if we neglect thermal neutrons?

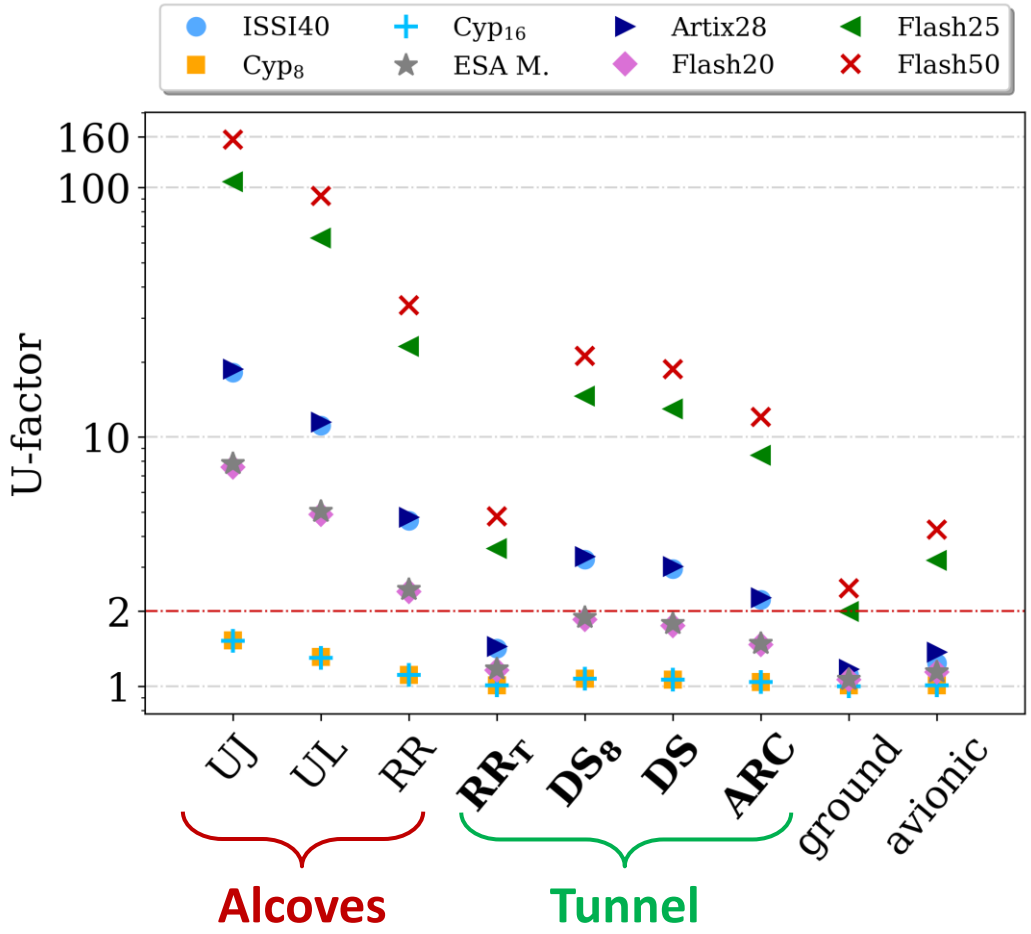
Expected events in operation (thermals + HEHeq)

$$U = \frac{N_{oper}}{N_{qual}} = 1 + R \cdot \frac{\sigma_{ThN}}{\sigma_{HEH}}$$

Expected events in qualification (HEHeq)

  - Thermals can be neglected only if U is “close to 1”, otherwise, we have SER underestimation of a factor U

U > 2 for most of the LHC environments



RHA implications – thermal neutrons

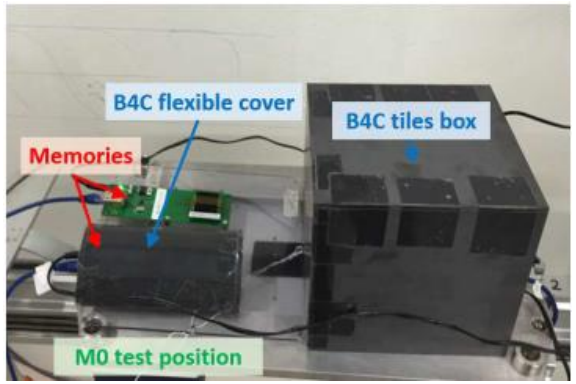
Proposed methods for thermal neutron qualification:

$$R = \frac{ThN\ (\text{fluence})}{HEHeq\ (\text{fluence})}$$

1) Thermal neutron beam (reactor)

- ✓ Only thermals, no high energy particles
- ✗ Single component, no board/system tests

2) CHARM differential measurements → Through boron carbide



- ✓ Both thermal and HEH cross sections, system tests
- ✗ Need of two devices or two runs

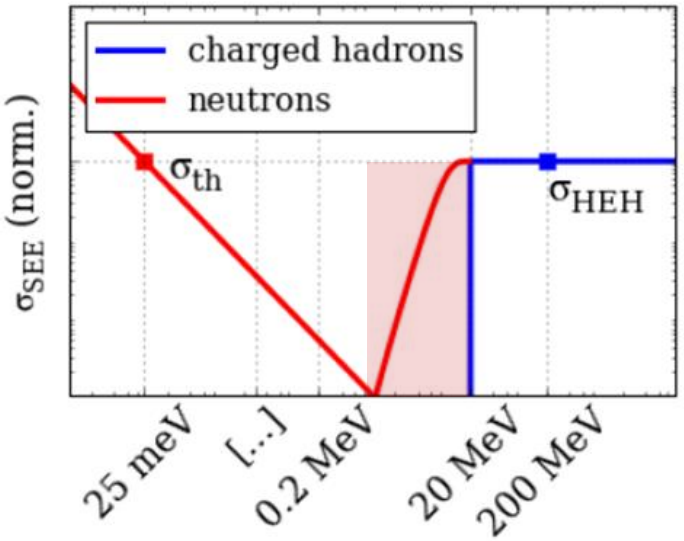
3) CHARM measurement known R (Specific R-factor in operation)

- ✓ Single measurements, system tests
- ✗ New characterization for different *R* in operation

4) Safety margin $\sigma_{ThN} = \sigma_{HEH}$

*M. Cecchetto *et al.*, "Impact of Thermal and Intermediate Energy Neutrons on SRAM SEE Rates in the LHC Accelerator," *IEEE Trans. Nucl. Sci.*

Outline



- Introduction to CERN and the R2E project
  - Electronics in the LHC and R2E failures
  - Radiation environment in the LHC
  - Example of test facilities
- **SEE estimation and RHA implications**
  - SEUs induced by thermal neutrons with respect to HEH
  - **SEUs induced by 0.1-10 MeV neutrons with respect to HEH**
  - SEEs in atmospheric, fusion and medical environments
- Summary

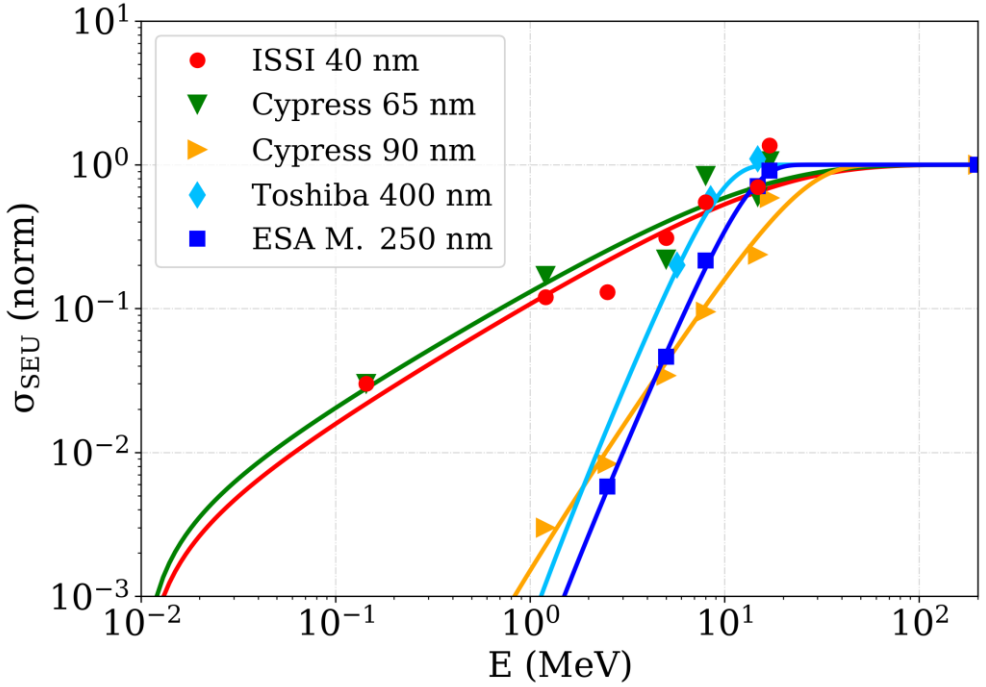
Intermediate energy neutrons – SEU cross sections

Definition based on the application, which depends on the considered threshold:

- CERN: 0.1 (0.2) – 20 MeV
- Atmospheric: below 10 MeV the neutron contribution is considered negligible (no ThN involved here)

40 and 65 nm SRAMs

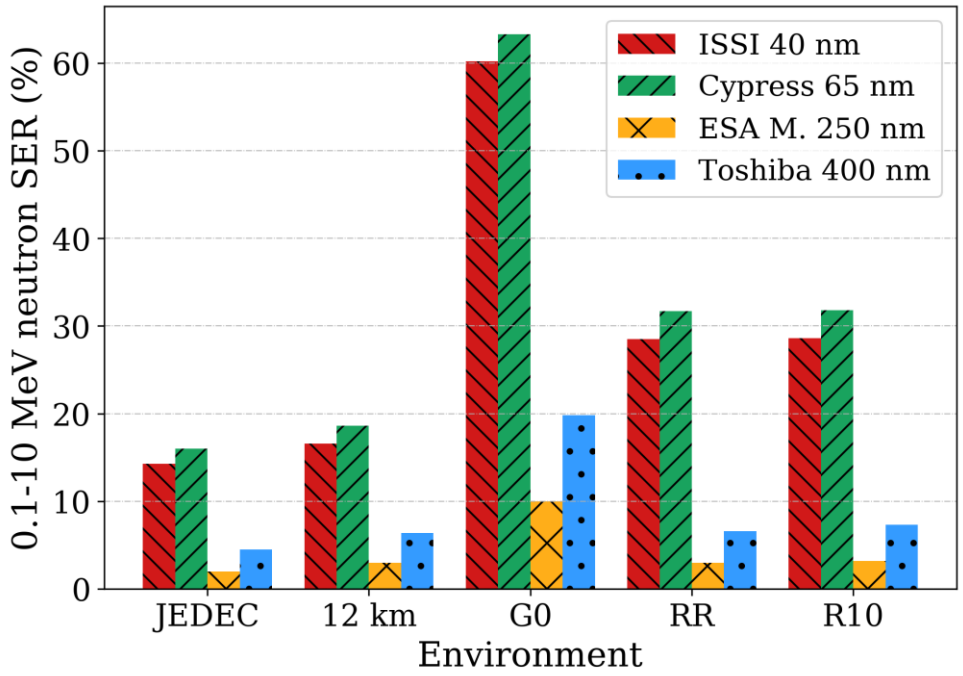
Neutron SEU cross section still relatively high at low energies!

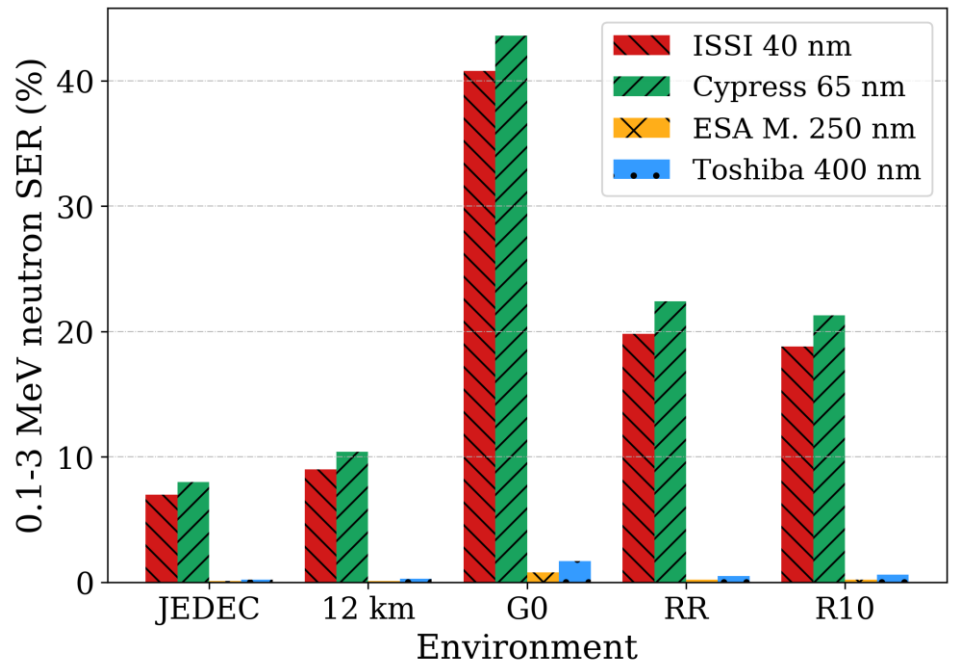


SEU cross sections measured at PTB and FNG

M. Cecchetto et Al,. "*0.1–10 MeV Neutron Soft Error Rate in Accelerator and Atmospheric Environments*" IEEE TNS paper

SEUs induced by neutrons below 10 MeV





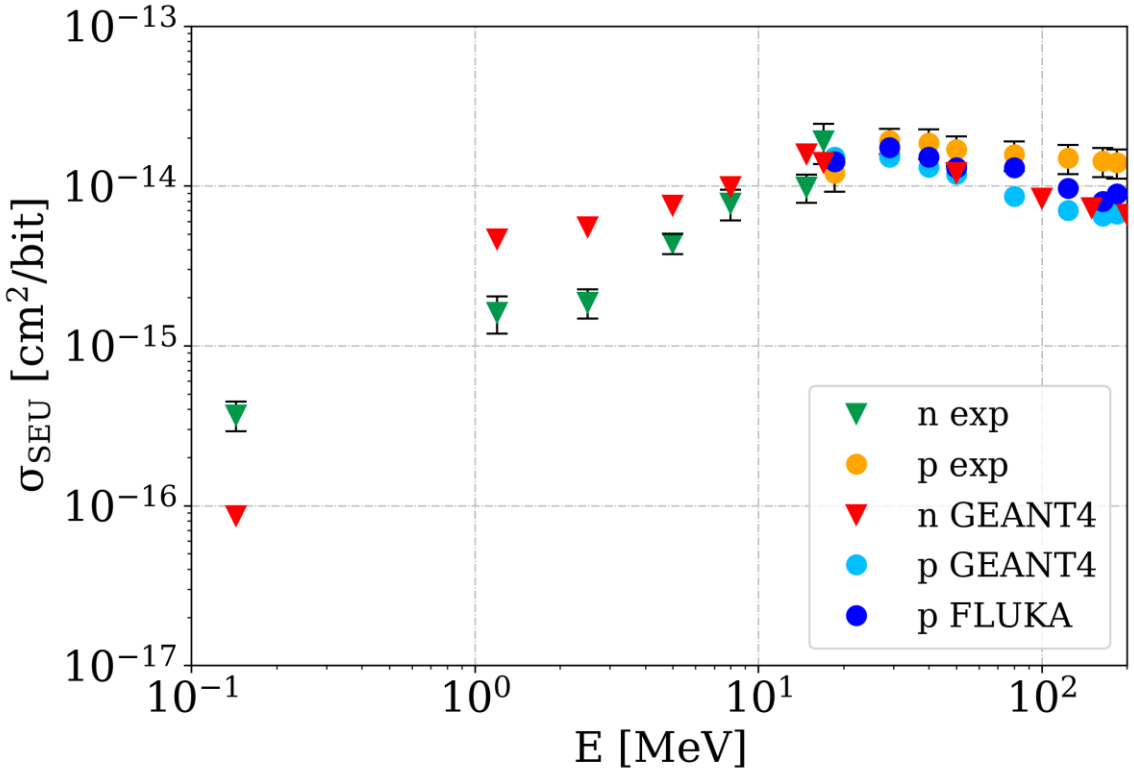
0.1-10 MeV neutrons → Up to **60%** of SEUs in accelerator; 19% of SEUs in avionics

0.1-3 MeV neutrons → Up to **44%** of SEUs in accelerator; 10% of SEUs in avionics

- Negligible contribution below **0.1 MeV**

SEU simulations – G4SEE & FLUKA

- ISSI 40 nm memory modelled in G4SEE (**GEANT4)** and **FLUKA.**
  - Si bulk 250 nm sides cubic **RPPs** - SiO_2 **BEOL** of 6 µm - **Qc = 0.72 fC**
  - Model benchmarked against proton and neutron experimental data



Simulations confirm that **neutrons can deposit enough energy to trigger SEUs even at 144 keV**

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.

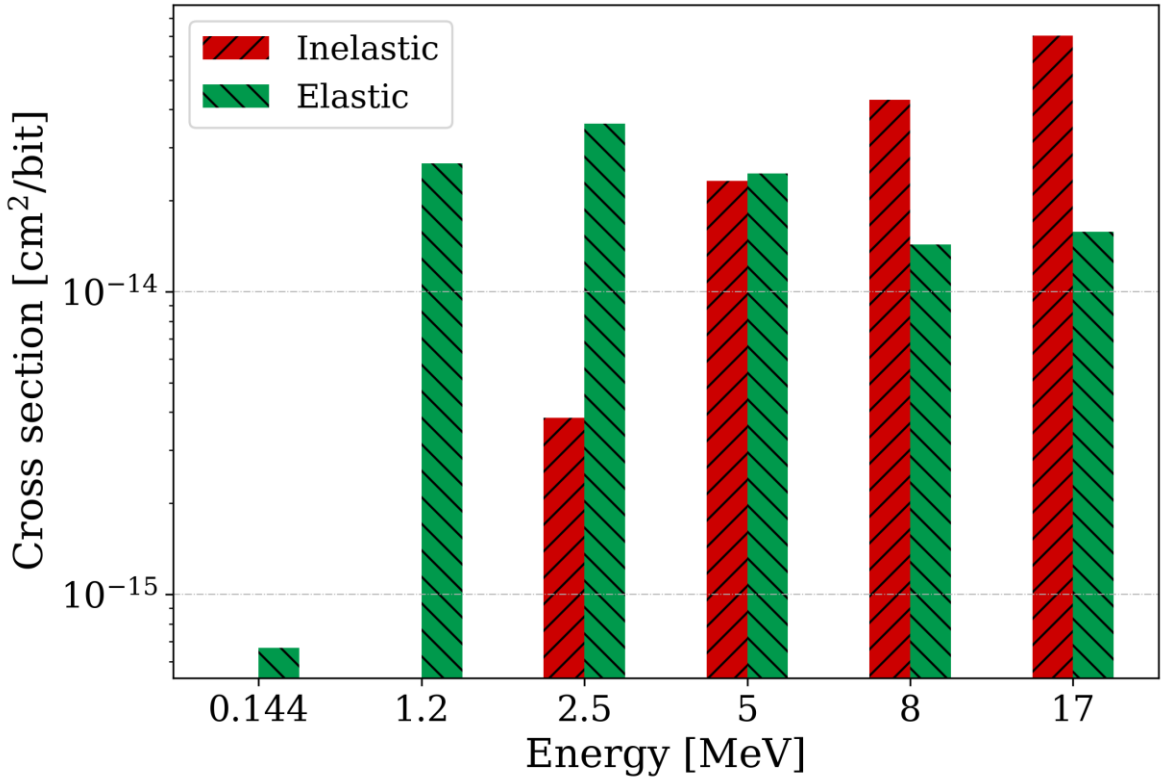
Maximum energy transferred by a neutron (**144 keV**) in elastic collisions:

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

^{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 (0.72 fC)**



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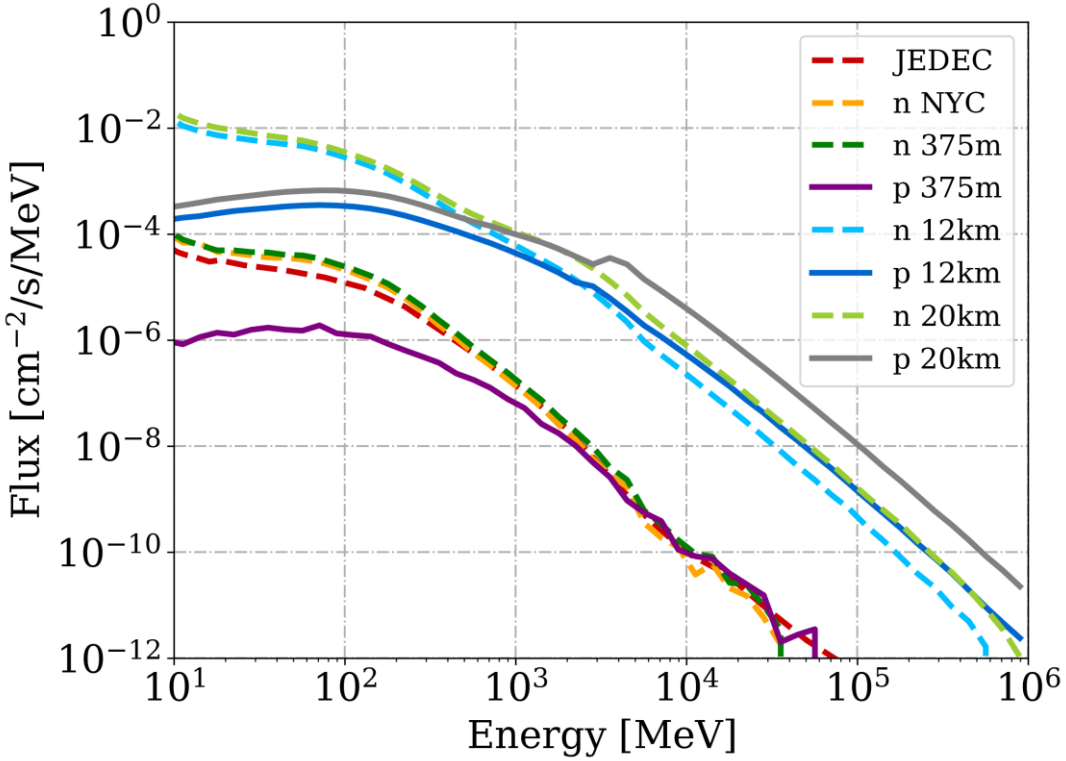
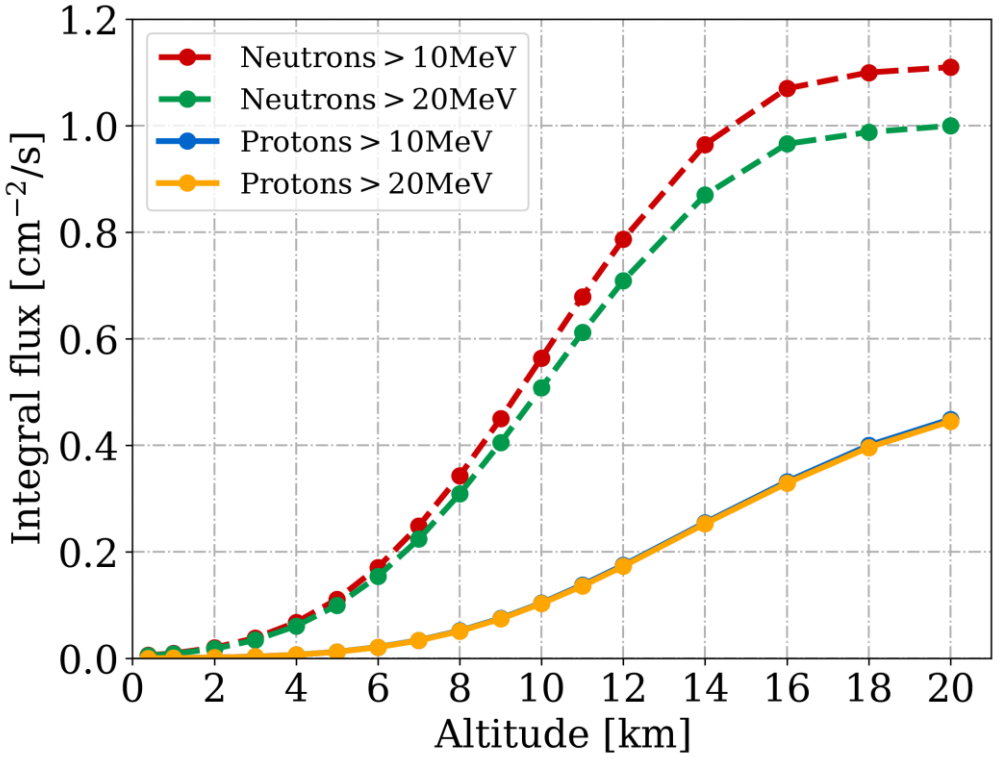
Atmospheric radiation environment

Fluxes extracted through the **MAIRE** tool (FLUKA based)

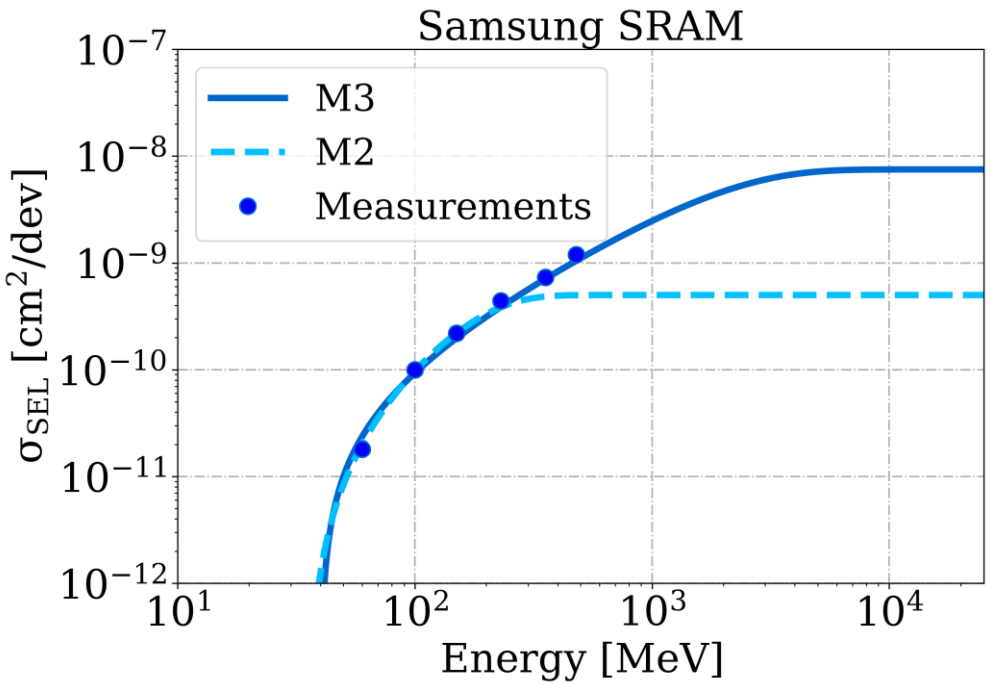




- Cosmic rays interact with the atmosphere generating a cascade of secondaries (neutrons, etc.).
- Neutrons can easily reach the lower part of the atmosphere.

SEE underestimation in atmospheric environment

Methods for component qualification:
M1) Spallation source
M2) Monoenergetic beams up to 200 MeV + Weibull fit } From JESD89A, IEC1 & IEC2 standards
M3) Monoenergetic beams/simulations up to a few GeV → From CERN



- Devices with strong SEE cross section energy-dependence saturate above a few GeV (because of **high-Z materials**)
- M1 & M2 yield significant **SEE underestimations (U)**

Memory	Altitude	U(M1)	U(M2)
Samsung	Ground level	4.4	1.7
	12 km	12.3	3.5
	20 km	23	5.4

RHA → 1) Scanning Electron Microscopy (SEM) + M3
2) Safety margin

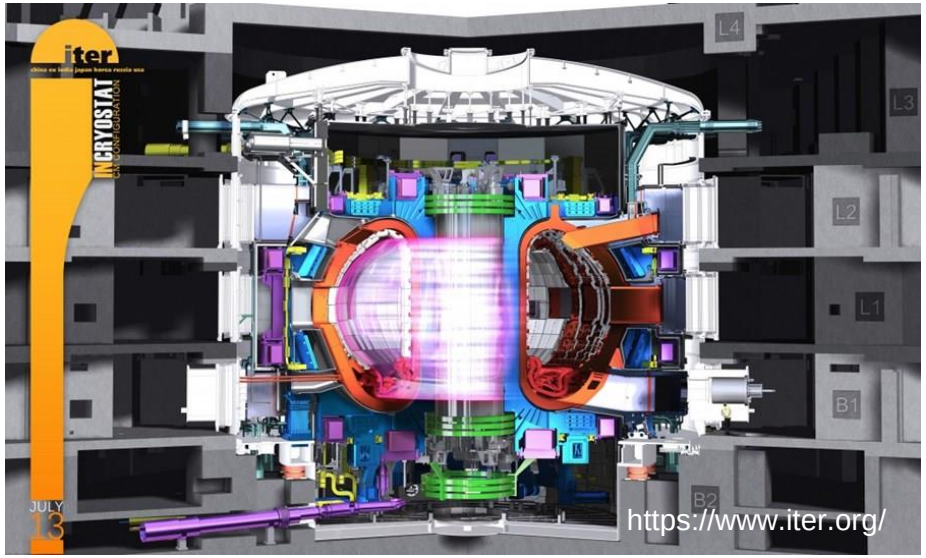
M. Cecchetto et Al,. "*0.1–10 MeV Neutron Soft Error Rate in Accelerator and Atmospheric Environments*" paper

Fusion and medical applications

- Thermal neutrons and fast neutrons (up to 14 MeV) are the main concern also in fusion and medical applications.
- Analysis/measurements were performed based on the aforementioned neutron studies at CERN.

Fusion: ITER

- Fusion reactor in southern France
- Neutrons from DD and DT reactions



Medical example: LINAC for Radiotherapy

- Neutrons mostly produced by photonuclear reactions
- Impact on electronics and patient

Conclusions

- R2E failures are critical for the LHC operation, hence we need to know the **radiation environment** in **tunnel** and **shielded alcoves** and the related effects in electronics.
  - **Neutrons** are one of the main threats, ranging from thermal up to GeV of energies.

- SEE estimation in accelerator and atmospheric environment:
  - **Thermal neutrons** up to **50 times higher than HEHeq** fluence (UJ alcove) can induce more than **90% of overall SEUs → RHA** (for accelerator).
  - **0.1-10 MeV neutrons** can induce up to **60% of overall SEUs** in accelerator (19% in avionics).
  - Potential threat for **medical** and **fusion** applications.
  - SEE underestimations in atmospheric environments when applying standard test procedures.

- **Elastic processes** can deposit enough energy to trigger SEUs even at 144 keV, as proved experimentally and via simulations.

Many thanks for your attention

Matteo Cecchetto, CERN