Radiation effects and test facilities for accelerator electronics at CERN

Matteo Cecchetto (CERN)
Rubén García Alía
with inputs from the R2E project
matteo.cecchetto@cern.ch

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Outline

1) Introduction to CERN and the Radiation to Electronics (R2E) project
   - Electronics in the LHC and R2E failures
   - Radiation environment in the LHC and related quantities
2) SEUs induced by thermal and 0.1-10 MeV neutrons in the LHC
3) Neutron test facilities employed by R2E
4) European projects and collaborations
5) Summary

CERN – Electronics in the LHC

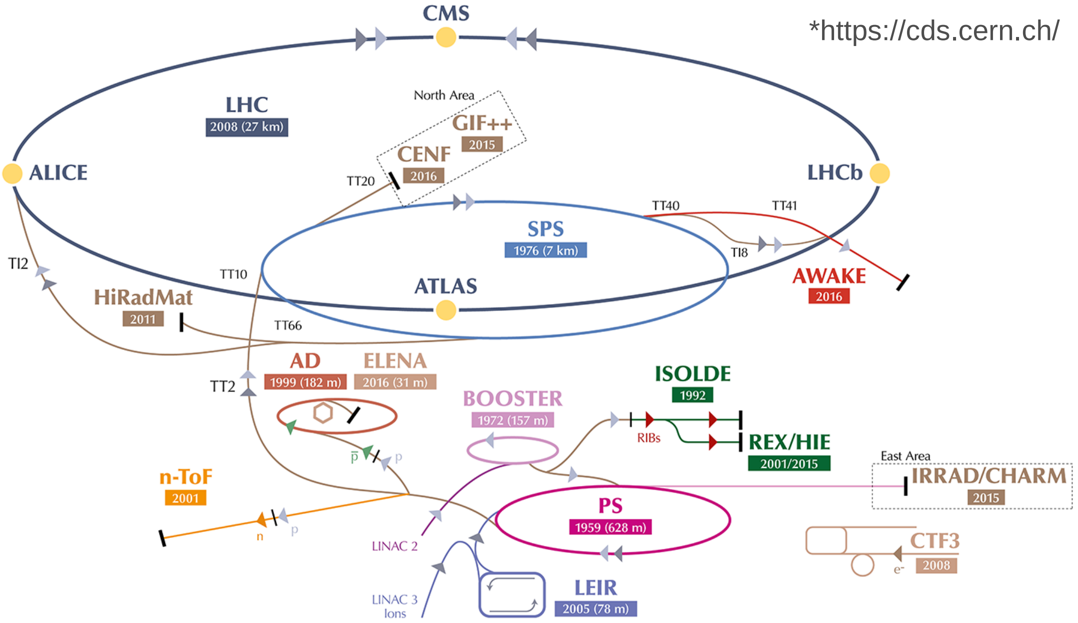
- **LHC (Large Hadron Collider)** is a 27 km long, 7 TeV beam energy, proton-proton collider.
- Four High-energy physics **experiments** (**CMS**, **ATLAS**, **ALICE**, **LHCb**).

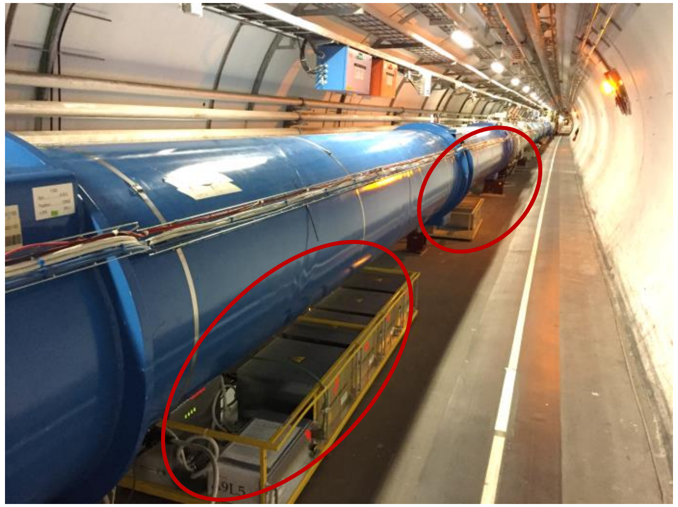
A large number of electronics operate near the accelerator (**tunnel** and **shielded alcoves**) and therefore is exposed to **radiation which induces many failures!**

- **Vacuum**
- **Cryogenics**
- **Power converters**
- **Many others**

Accelerator systems are mainly based on **Commercial-Off-The-Shelf (COTS)** components (costs, project timelines, performance).

*https://cds.cern.ch/





How do R2E effects impact the accelerator performance?

R2E effects impact the accelerator performance by **reducing its availability** and compromising the related scientific program.

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)**
- This often involves **a lot of radiation testing** at component/system level!

Shielding wall for the SPS access system

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

Type of failures in the LHC

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

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

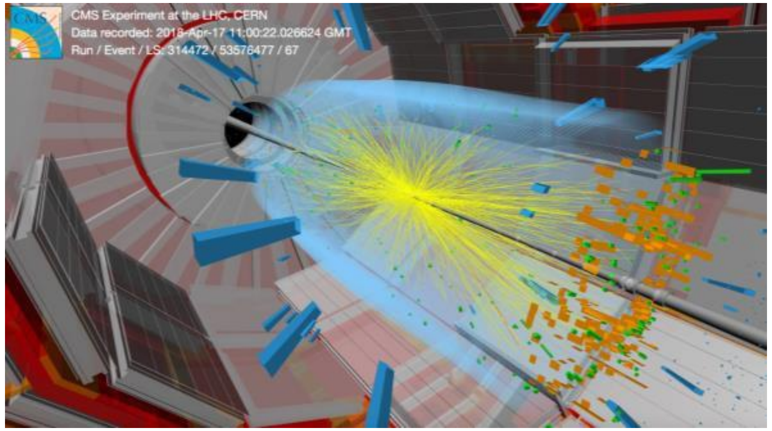
- SEEs can be **non-destructive** (Soft Errors) or **destructive** (hard errors), but both can have a big impact on the LHC operation for critical systems.

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

Radiation sources in the LHC

Three main radiation sources in the LHC:

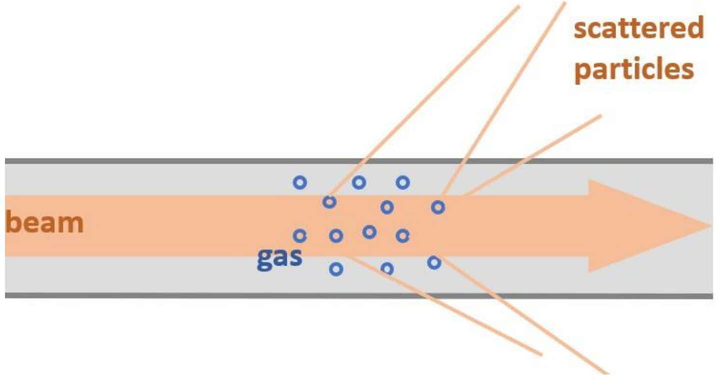
Collision debris



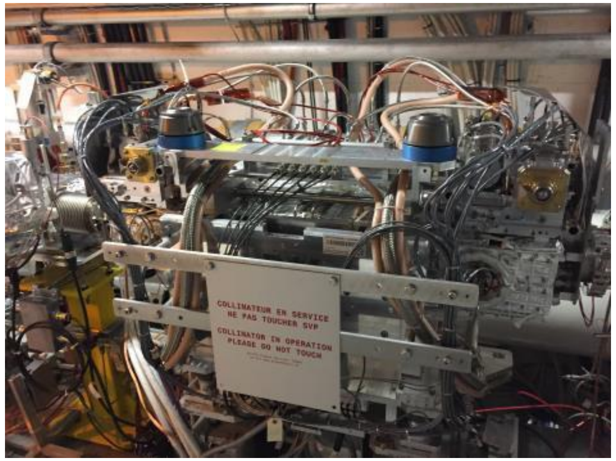
- ≈$4 \cdot 10^{15}$ inelastic collisions per year in ATLAS/CMS.
- The collisions generate particles in all directions and a fraction can reach the LHC tunnel.

Residual gas

The beams interact with residual gas molecules inside the vacuum pipes.



Collimators



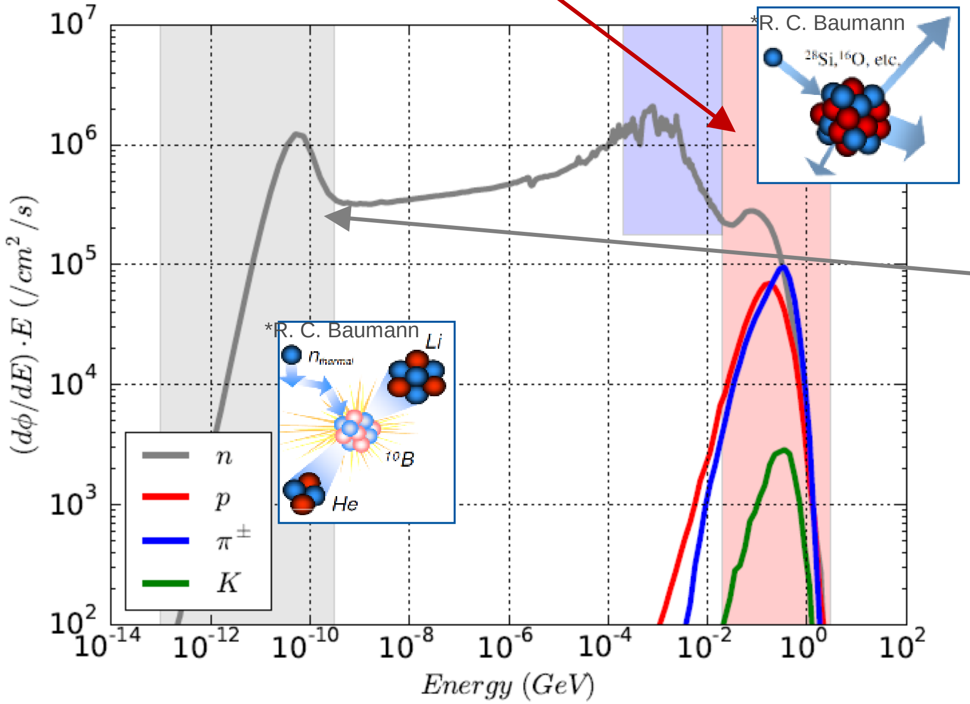
- Beam interactions with collimators generate a cascade of secondary particles.
- In many areas, they can be regarded as the primary source of radiation.

Typical hadronic radiation environment in the LHC

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**

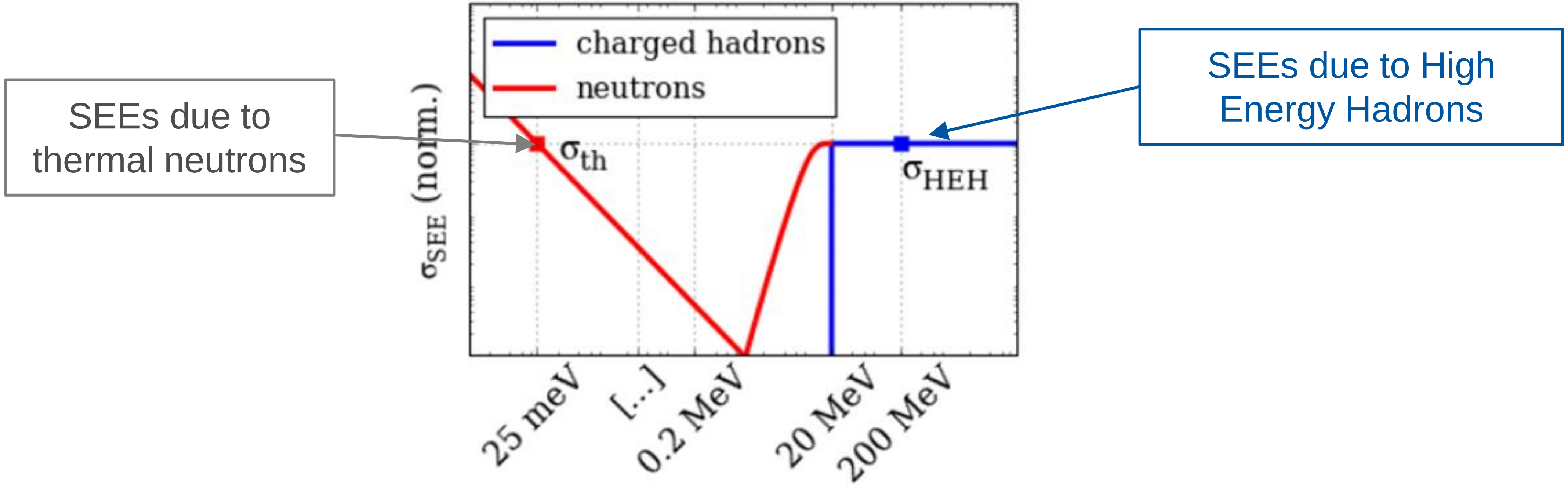
Intermediate energy neutrons are a major concern with **scaling of technology.**



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

SEE: response function of electronics and testing

Single Event Effects (SEE) depend on the particle **fluences** (**ϕ**, in units of cm^{-2}) and **SEE cross sections** (σ, in cm^2).



Electronics characterization in dedicated facilities:

- σ_{th} is normally measured in **nuclear reactors**.
- σ_{HEH} is measured in **monoenergetic facilities:** 200 MeV protons where the SEE cross section is typically saturated (often already above 20 MeV).

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Thermal neutrons in a LHC-shielded alcove

Research activity

- **Heavily shielded alcove hosting electronics**, 200 cm cast iron/concrete.
- **98%** of the spectrum is composed of **neutrons**.

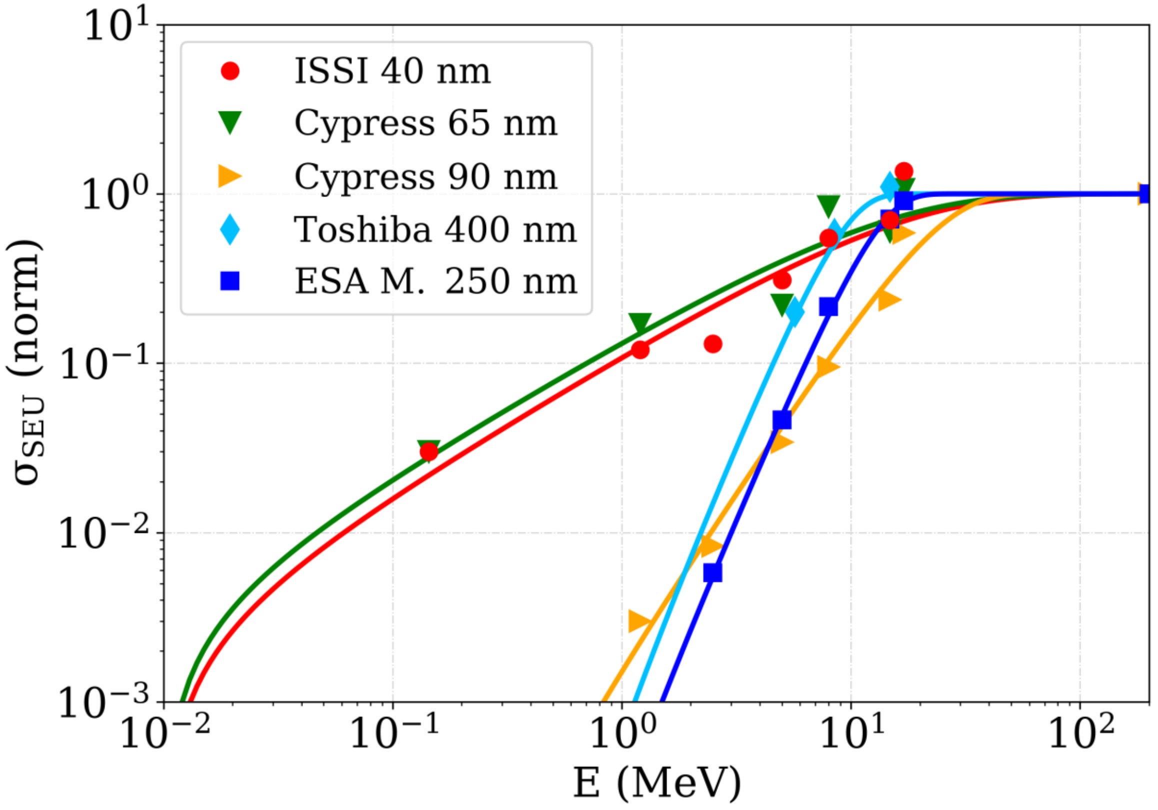
Thermal neutron fluence 50 times higher than that of all other particles inside the alcove!

Expected **SEUs in electronics due to thermal neutrons** are dominating (>**90% of overall failures** in alcoves).

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

Intermediate energy neutrons – SEU cross sections

- Focus on neutrons between **0.1 – 10 MeV** (as used in atmospheric environment).



SEU cross sections measured at PTB and FNG

40 and 65 nm SRAMs

Neutron SEU cross section still relatively high at low energies!

0.1-10 MeV neutrons

Up to

60% of SEUs in accelerator

19% of SEUs in avionics

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

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Neutron test facilities employed by R2E

Thermal neutrons → ILL (reactor)

0.1-20 MeV →
- Am-Be (spectrum 11 MeV)
- PTB (0.14 – 17 MeV neutrons)
- FNG (2.5, 14 MeV neutrons)
- LPSC (14 MeV neutrons)

High energy →
- CHARM (mixed-field)
- ChipIr (spectrum 700 MeV)
- TRIUMF (spectrum 480 MeV)
- NEAR (n_TOF, spectrum 830 MeV)
- CLEAR (electrons + target, spectrum 100 MeV)

Experimental (NEAR, CLEAR)

Mixed-field – CHARM facility at CERN

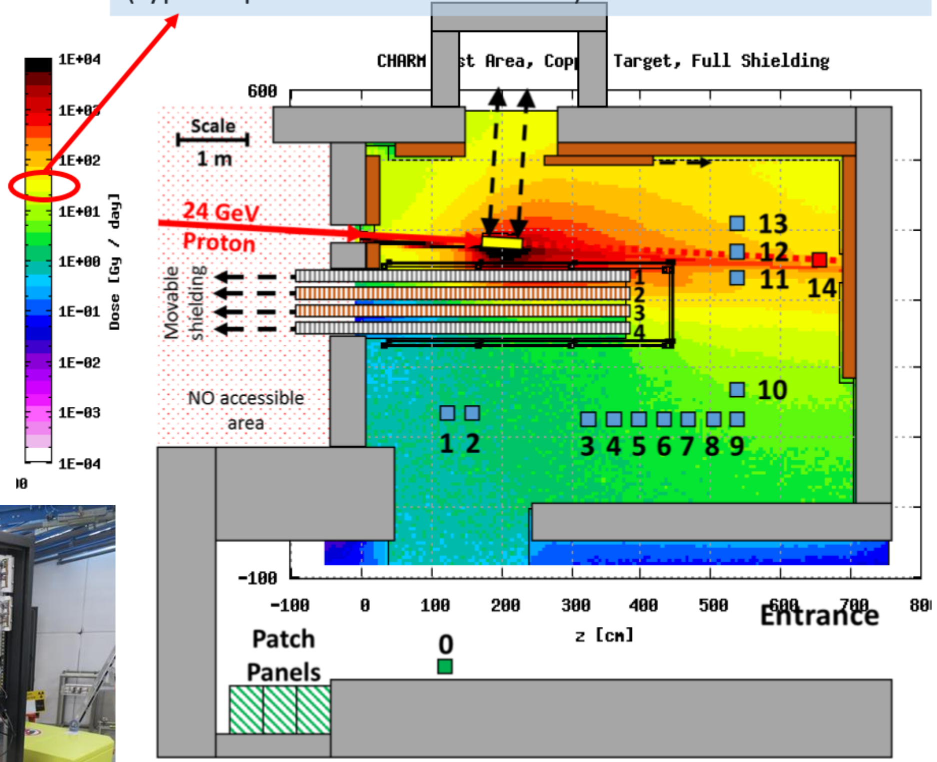
- CHARM provides a **mixed-field** (mainly hadrons: neutrons, protons, pions but also electrons and photons).
- Representative of the multitude of spectra found in the **LHC accelerator** and other environments (**space**, **atmospheric**, etc.).

24 GeV protons impact the target

⬇

A mixed radiation field is produced in the whole room

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



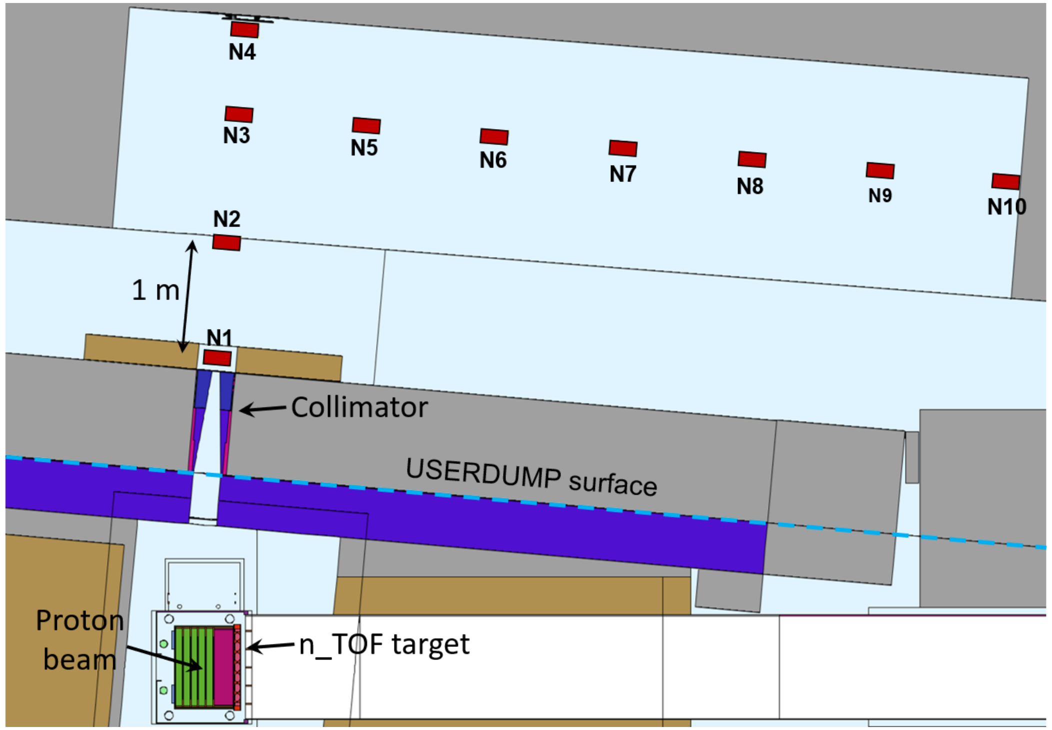
Dose map FLUKA simulation, top view

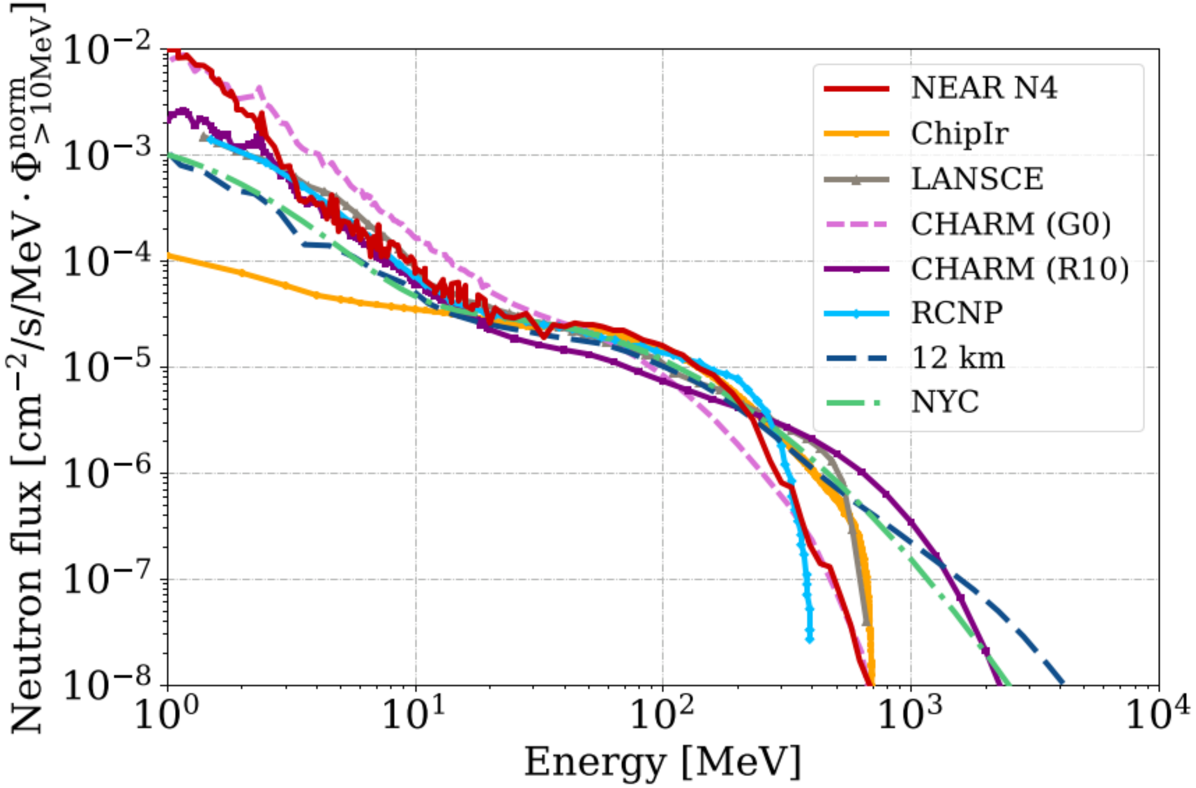

Electronics rack

System level testing for TID, SEEs and DD:
- Essential for CERN RHA assurance approach for Commercial Off The Shelf (COTS) components.

NEAR station – n_TOF facility

- Neutron spectra from thermals up to 830 MeV produced by the interaction of 20 GeV proton beam on pure lead target.

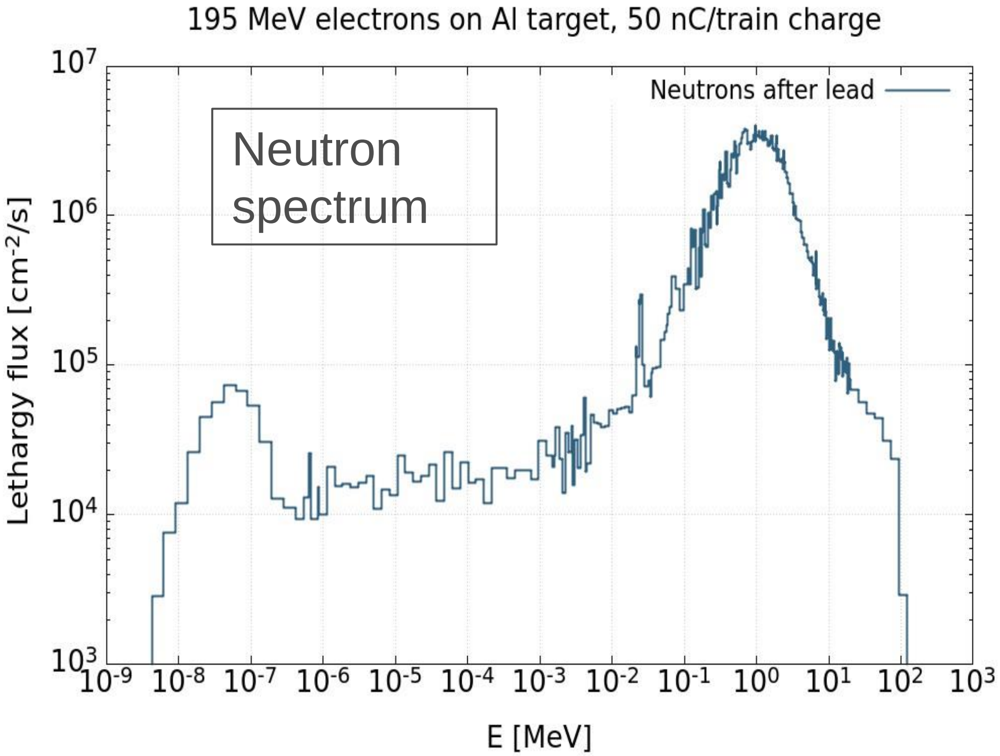




*M. Cecchetto et al., “Electronics Irradiation with Neutrons at the NEAR Station of the n_TOF Spallation Source at CERN,” IEEE link

CLEAR - neutrons through photonuclear reactions

- Experimental area.
- A **neutron spectrum** up to 100 MeV is produced by the interaction of an electron beam with an Al target.
- Similarly, neutrons are produced in **medical environments** (although with lower energies).



*G. Lerner et al., "Analysis of the radiation field generated by 205-MeV electrons on a target at the CLEAR accelerator at CERN" RADECS 2022

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RADiation facility Network for the EXploration of effects for indusTry and research (RADNEXT)

Coordination by CERN
Project Leader: Rubén García Alía
Total budget: 5 M€

https://radnext.web.cern.ch

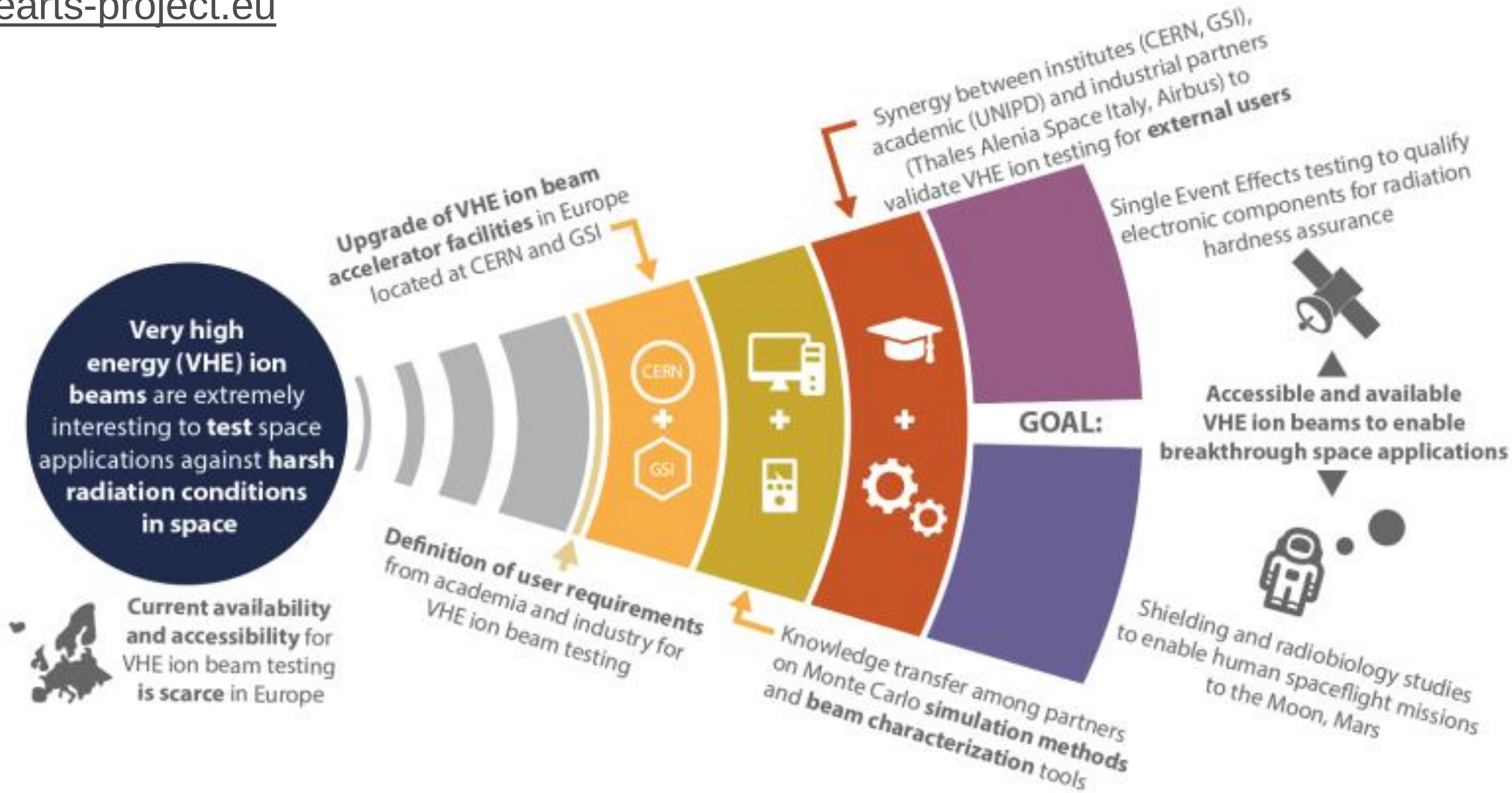
A network of European (+ TRIUMF!) **irradiation facilities** with the main purpose of **enhancing accessibility** to accelerator infrastructures:

- **6000h of beam time over 4 years**, free of cost to users, and to be awarded via a competitive proposal process
- A rich **quantity and variety of facilities**, many of the facilities you introduced before are part of the network
- Beam time for **research and industrial applications**.

HEARTS (High Energy Accelerators for Radiation effects Testing and Shielding)

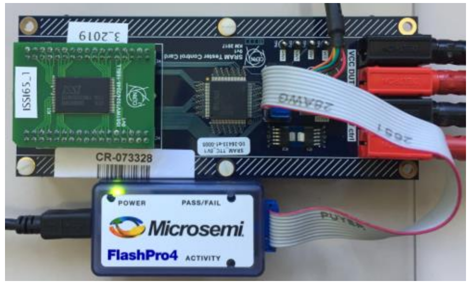
- Purpose of increasing the European autonomy for Very high energy (VHE) ion facilities.

https://hearts-project.eu



Collaborations R2E – Medical applications

Thermal neutrons and fast neutrons (up to 14 MeV) are the main concern also in medical LINAC applications.



Medical LINAC for Radiotherapy

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

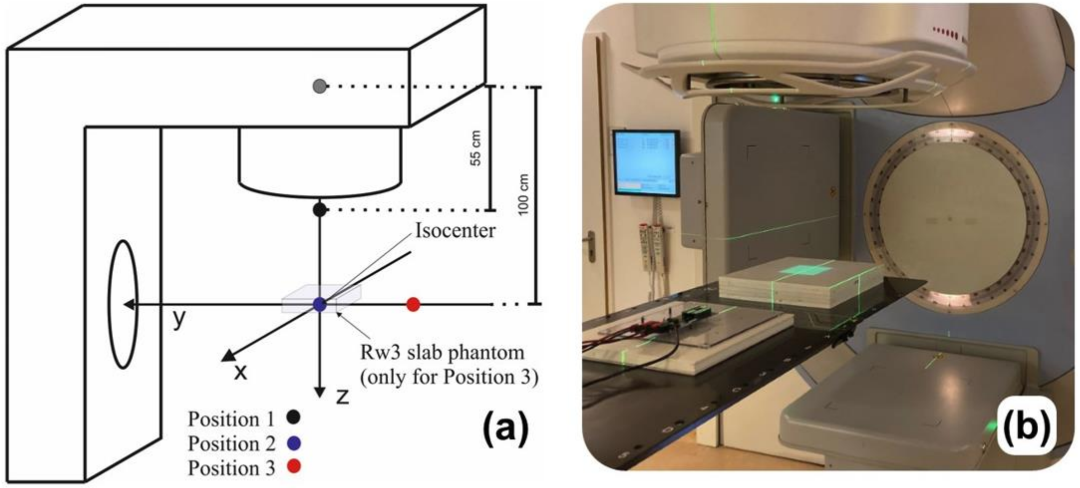


Fig. 2: (a) Schematic representation of the experimental setup including the three measuring positions 1-3. **(b)** Positioning 3 inside the Elekta Synergy linear accelerator treatment room.

*L. Gabrisch et al., "Quantification of neutron-induced SEUs in a SRAM memory by clinical 15 MV photon beam," RADECS 2023

Summary

- 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, but also protons, pions and EM showers.
- SEE estimation due to neutrons in the accelerator:
  - **Thermal neutrons** can induce more than **90% of overall SEUs** in accelerator
  - **0.1-10 MeV neutrons** can induce up to **60% of overall SEUs** in accelerator.
  - Threat for **medical** and **fusion** applications.
- COTS electronics are tested in radiation environments resembling those in the LHC.
  - **Cross section characterization** → Monoenergetic beams (protons, neutrons).
  - **System level testing** → CHARM (mixed-field).

Many thanks for your attention

https://radecs2024.org