CERN Radiation Hardness Assurance (RHA) for Accelerator Electronics

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BE-CEM-EPR

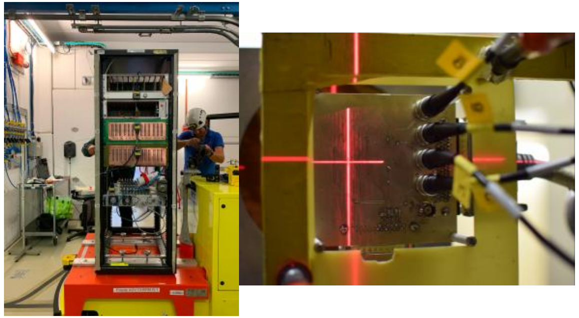
BE-CEM-EPR Section at CERN

EPR : Electronics Production and Radiation Tolerance

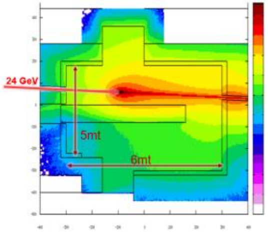
Provide CERN-wide support in the domain of Printed Circuits Boards (PCB), electronic systems assembly, radiation testing, radiation monitoring for the electronics and radiation test facilities for radiation tolerance assessment.

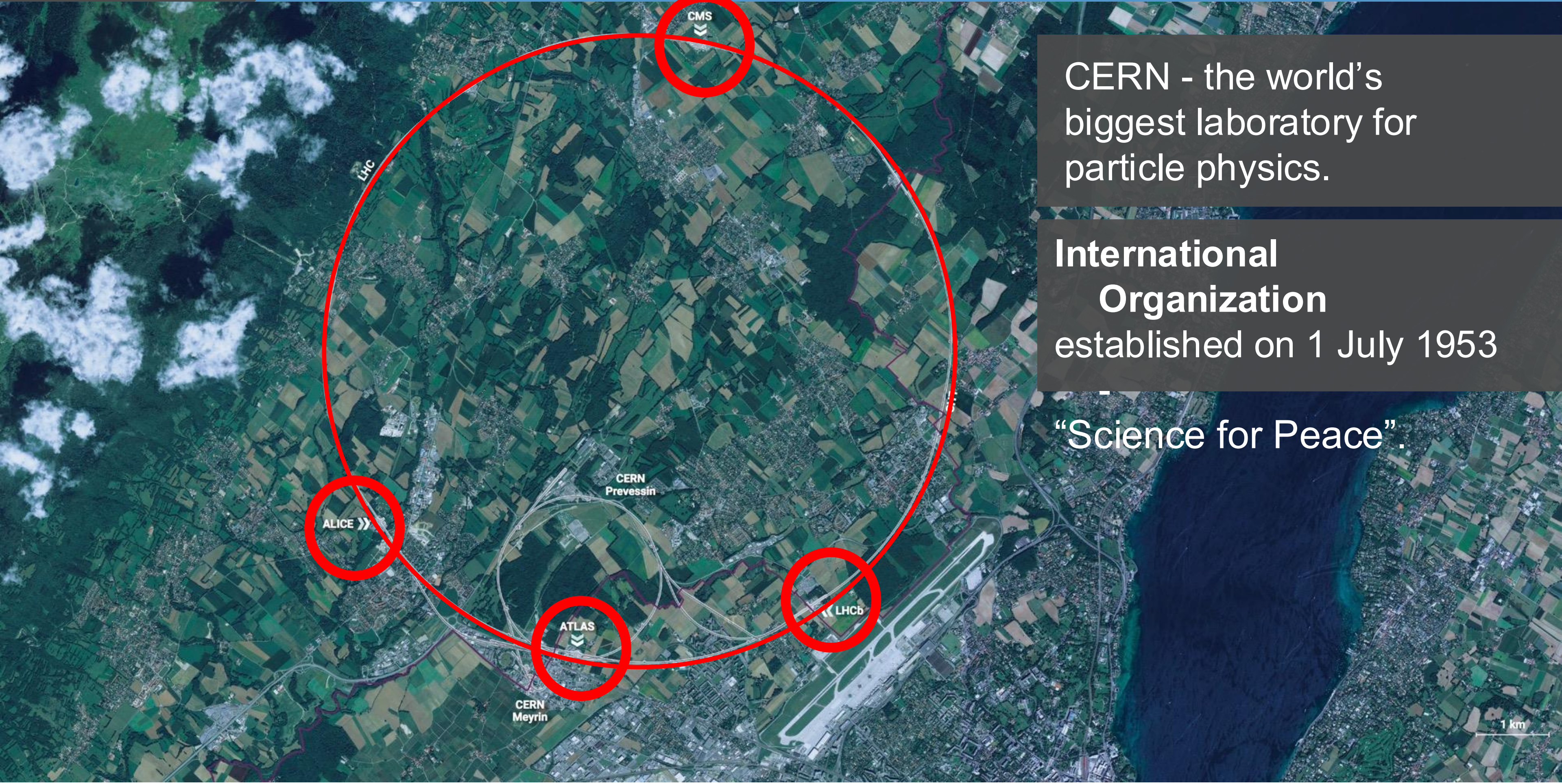
The ERP section provides:

- Service of PCB Layout design for electronic boards and crates
- Service for electronic cards assembly and cabling, internally or by subcontracting including components procurement.
- Procurement of bare PCB, manufactured internally at CERN or by subcontracting
- Manufacture and Assembly for prototypes in fast track production lines
- Service of **radiation testing on electronic components and systems**
- Coordination and the operation of **the CC60 gamma and CHARM** radiation test facilities at CERN.
- Design, installation, operation and maintenance of the RADMON and BatMon monitoring system



CHARM

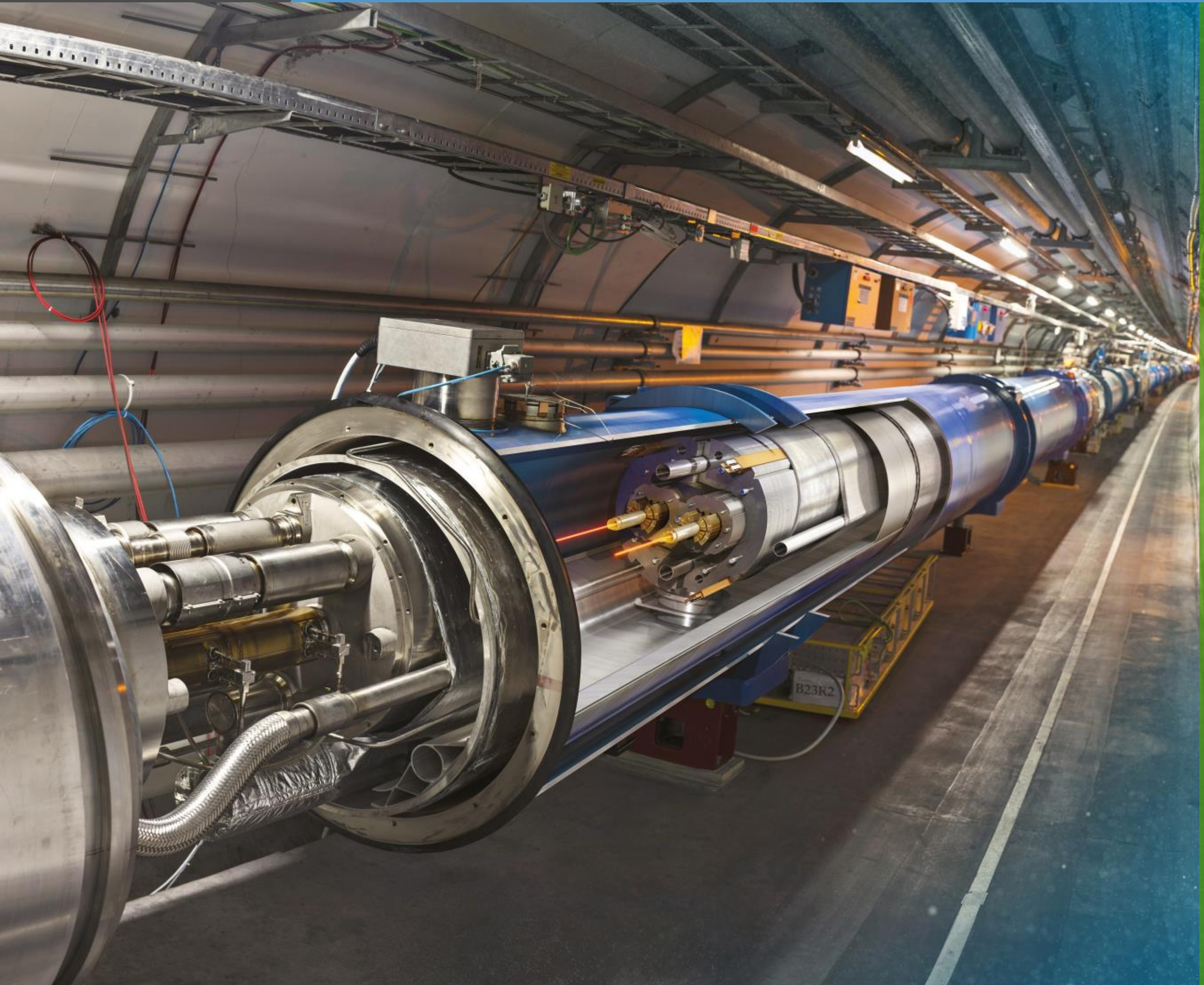




CERN - the world's biggest laboratory for particle physics.

International Organization
established on 1 July 1953

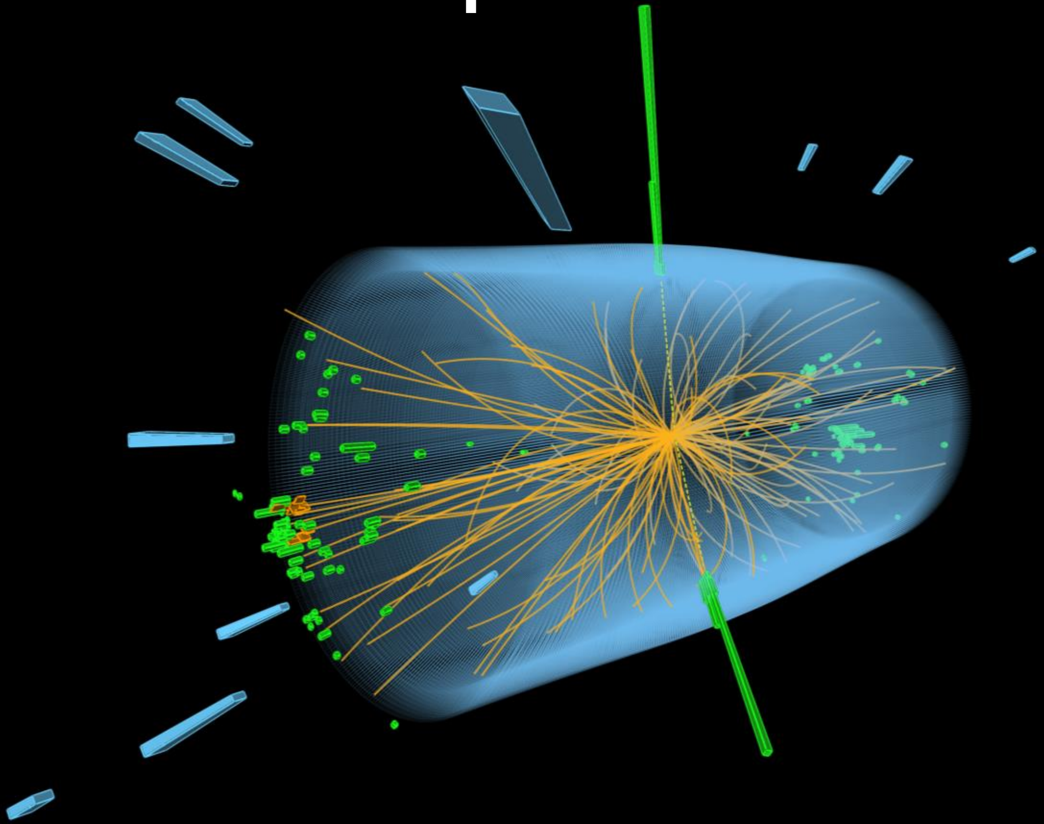
"Science for Peace".



Large Hadron Collider (LHC)

- 27 km in circumference
- About 100 m underground
- Superconducting magnets steer the particles around the ring
- Particles are accelerated to close to the speed of light

The LHC produces more than 1 billion particle collisions per second

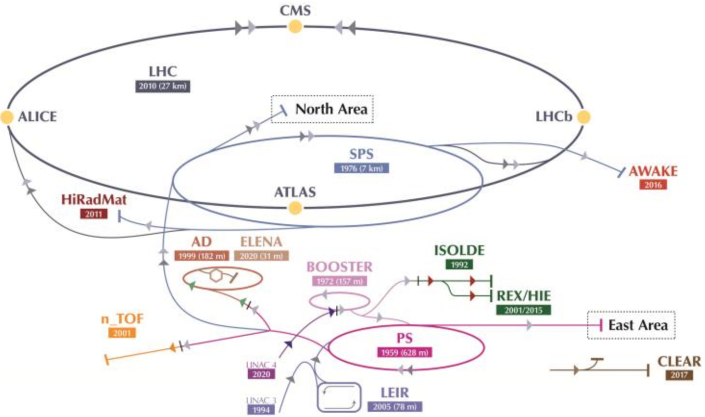


The energy of the particles in collision is converted into new particles.

The detectors measure the energy, direction and charge of new particles formed.

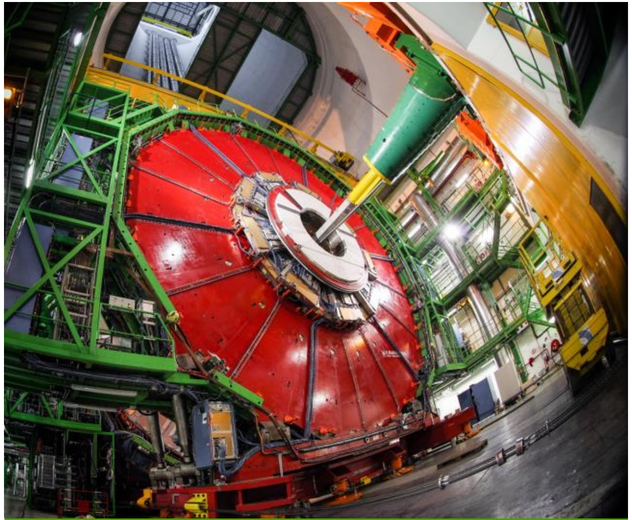
They take 40 million pictures a second. Only 1000 are recorded and stored.

CERN accelerator complex and secondary beam lines



CERN fundamental tools

ACCELERATORS



DETECTORS

Two different approaches for Electronics

Context: Accelerator Electronics

- The **reliability** is a main concern for the CERN electronic equipment
- The **criticality** of the equipment can be very high
- A large number of systems are exposed to the radiation environments induced by the LHC
- Radiation-induced failures on LHC electronics can lead to:
  - **Beam Dumps** : Lost time for physics
  - **LHC safety system failures** : Part of the machine can be destroyed

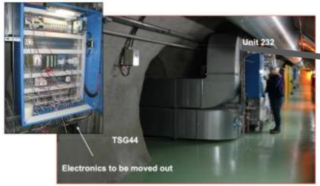
@ Courtesy of the TE/MPE Group

- Systems can be highly distributed (**up to thousand of units**):
  - Use of RadHard devices not affordable
  - Most of the systems are custom **COTS-based**
- The radiation qualification of these systems is then a major task in order to avoid failures in operation

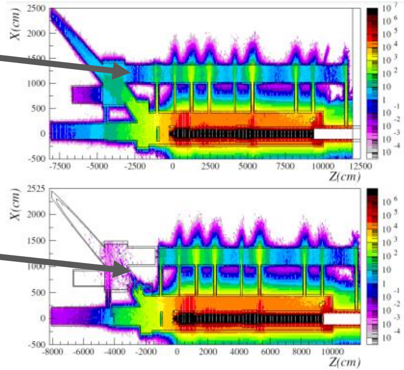
Flashback : the beginning of a decennial strategy

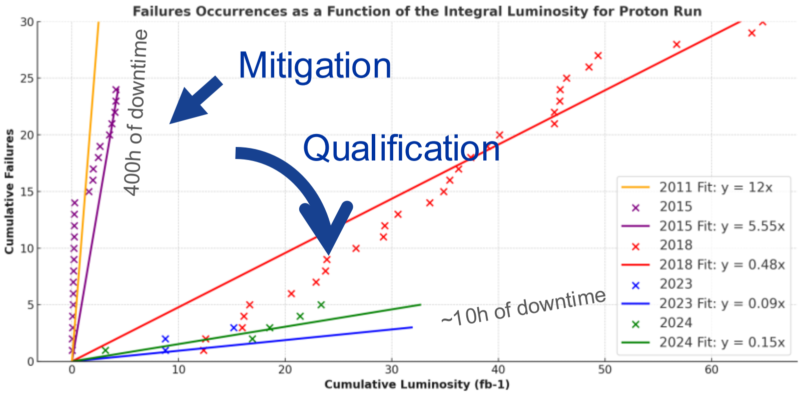
E. Gschwendtner, Ensuring safe and reliable operation of CNGS as of 2008, https://indico.cern.ch/event/22866/contributions/483136/

- **2007** Ventilation system failure in the CNGS service gallery due to radiation effects
- Task force was put in place for the LHC to face the radiation effects challenges:
  - More than **30 critical areas , 100s of racks** concerned
  - Many (Most) of them being commercial ones
- The task looked difficult
  - Strategy 1 :Relocation and Shielding
  - Strategy 2: **Qualification** : RHA
- The qualification is a collaborative effort
  - Equipment owner
  - Measurements and simulations
  - **Radiation effects testing**
  - Facilities



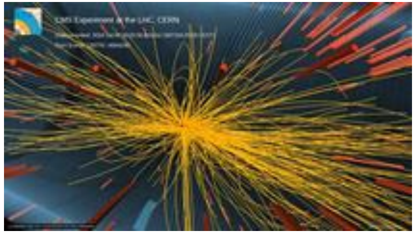
2008 Shielding



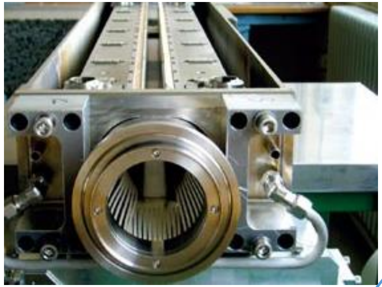


Radiation Sources at CERN

- **Collision debris**
  - Debris resulting of Beam/Beam and Beam/Target collisions
  - Scale with beam luminosity

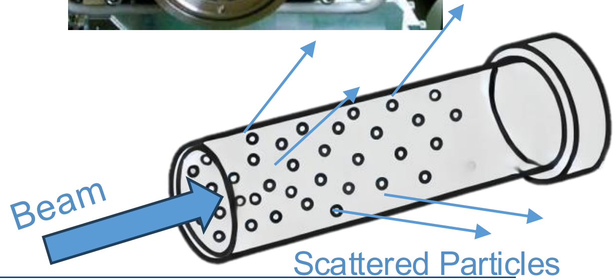


- **Direct beam losses caused by beam operations**
  - Cleaning (collimation), Extraction, Injection, Dump etc…
  - Levels usually scale with beam intensity and energy



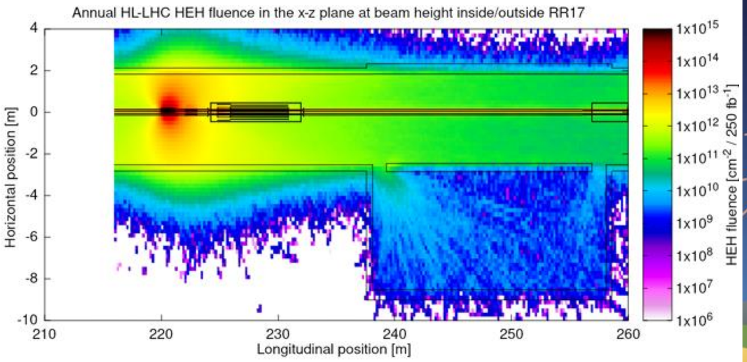
- **Beam-Residual Gas interactions**
  - Due to imperfect vacuum in the machine
  - Scale with residual gas density and beam intensity/energy

- Each interaction initiates particle showers generating a wide range of particles in terms of type (protons, pions, photons, muons, neutrons etc…) and energy (from meV up to GeV)

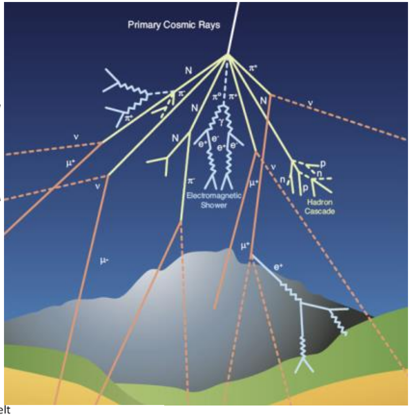


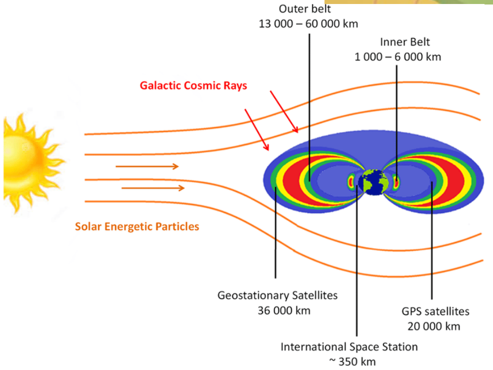
The particles zoo and other radiation environment

- Hadronic Shower
  - Hadrons
    - Protons
    - Neutrons
    - Charged and Neutral Pions
  - Photons
  - Leptons
    - Electron, Positron
    - Muons
- Terrestrial
- Space
  - GCR: protons and High Energetic Heavy Ions
  - Solar Winds: Protons, Ions
  - Radiation Belts : Protons, Electrons
- Man made: Nuclear
  - Neutrons, Gamma

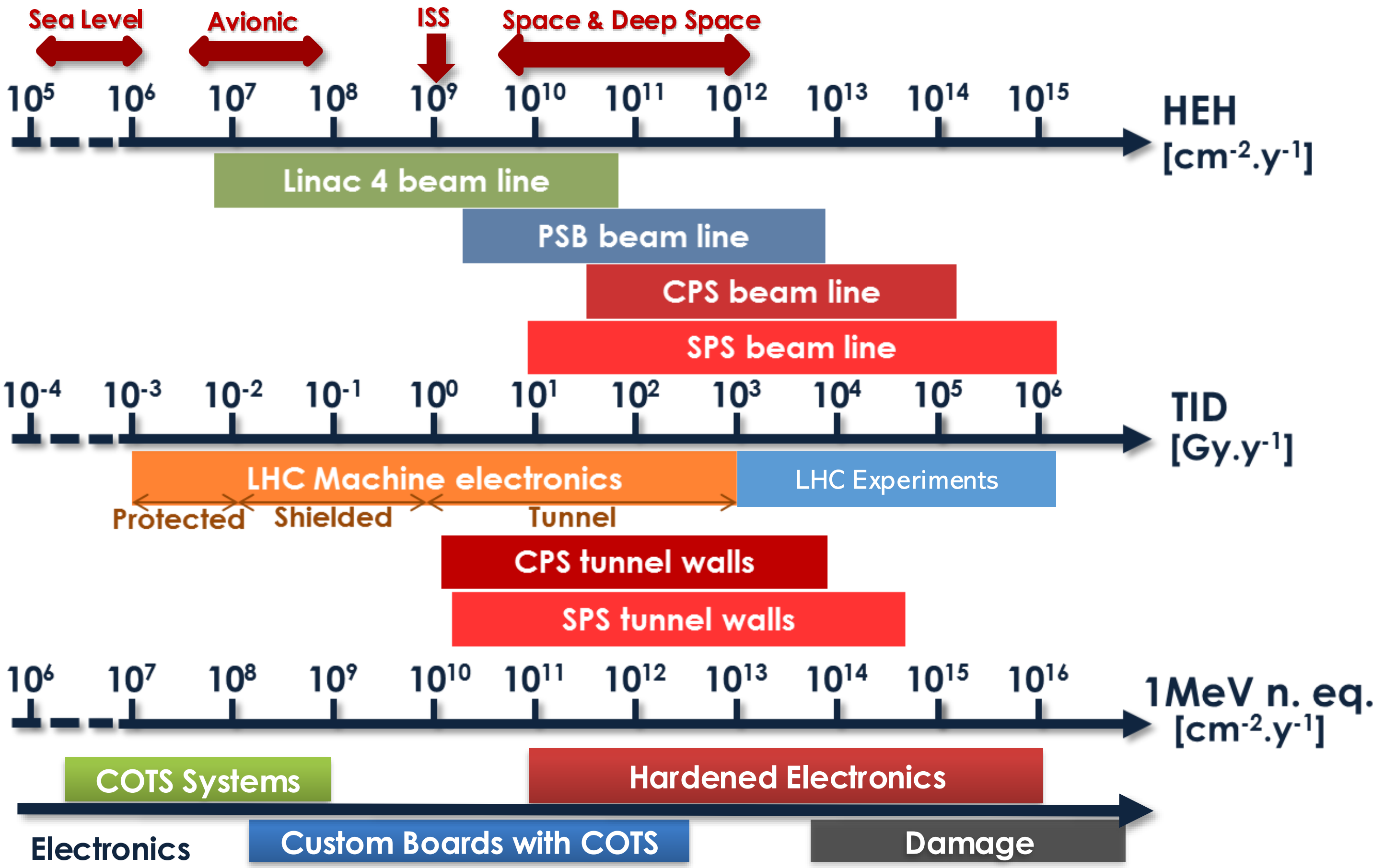


From: Radiation levels pecifications for HL-LHC

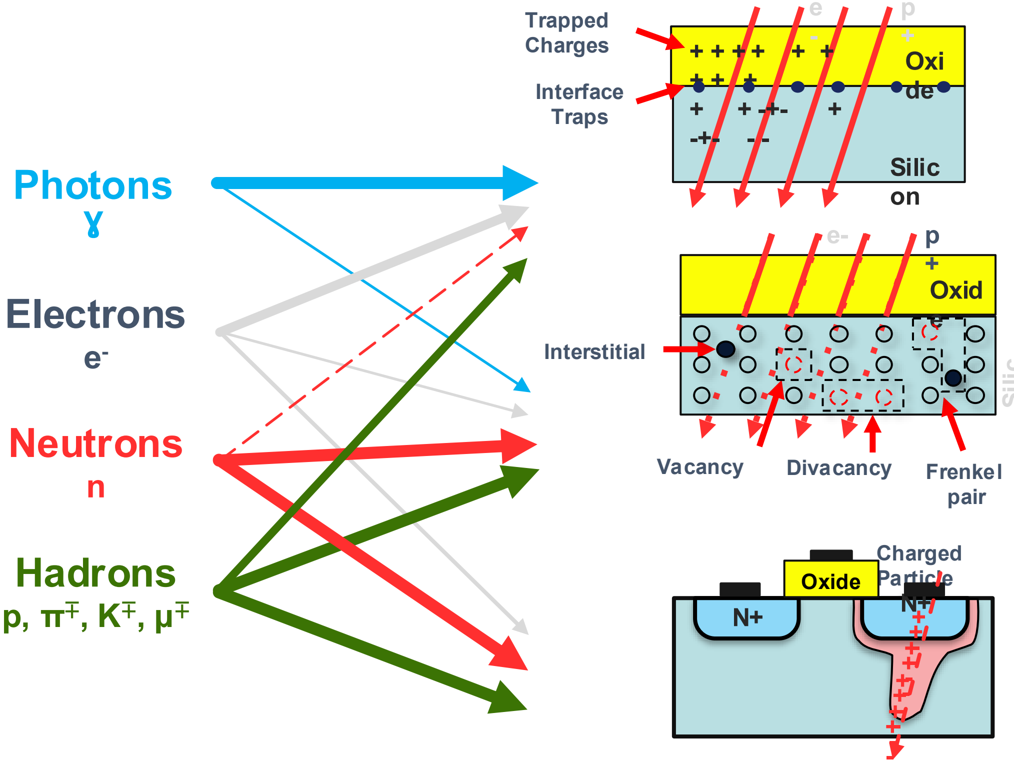




Radiation levels



Radiation Effects on semiconductors



Total Ionizing Dose (TID)

- **Effect:** electron-hole pair generation in silicon oxide
  □ positive charge trapped
- **Units**: **Gray (Gy)** □ 1Gy = 100 rad = 1J/kg
- **Device Affected:** MOSFET, Bipolar Junction Transistor (BJT),

Displacement Damage (DD)

- **Effect:** Create defect in crystal lattice by atom displacement
- **Metric:** **D**isplacement **D**amage **E**quivalent **F**luence (**DDEF**)
- **Units:** neq.cm^{-2}
  □ Amount of 1 MeV neutron fluence necessary to induce an equivalent DD to the fluence of the considered particle
- **Device Affected:** BJT, Optoelectronic

Single Event Effects (SEE)

- **Effect:** Electron hole pair generated by a single particle that can lead to a non-destructive/destructive macroscopical event
- **Metric:** High Energy Hadron Fluence (>20 MeV) (**HeH**)
- **Unit:** HeH.cm^{-2}
- **Device Affected:** MOSFET, BJT, Optoelectronic

Are radiation effects only a concern for High Energy Particle Accelerators?

E. Normand *et al.*, “First Record of Single-Event Upset on Ground, Cray-1 Computer at Los Alamos in 1976,” *IEEE Transactions on Nuclear Science*, vol. 57, no. 6, pp. 3452–3458, Dec. 2010.

2012 Cisco blog post:
"these “Single Event Upsets” are an issue even in terrestrial-based systems that must meet high reliability operating requirements” ” And despite being rare, for service providers that are building mission-critical networks, “very rare” is still too often.

Two events: Quantas flight 2008 and JetBlue Airways Flight 1230 (A320) in 2025
2008 inflight accident that included a pair of sudden, uncommanded pitch-down manoeuvres that caused severe injuries
In 2025 Airbus issued an emergency global recall of around 6000 of its A320-family aircraft - roughly half of the world's in-service Airbus fleet

Qantas Flight 72

Radiation-induced faults can also **compromise secure hardware implementations, cryptographic accelerators and AI inference systems**

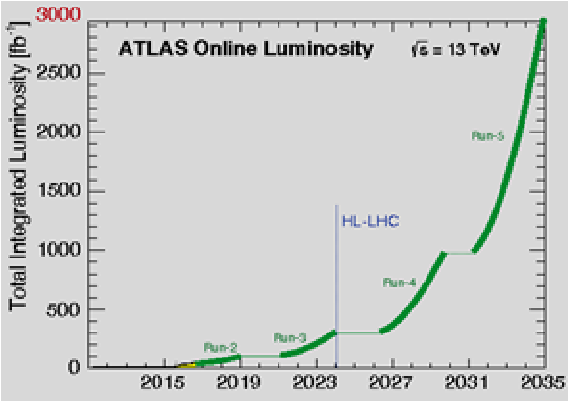
Radiation Hardness Assurance

The Radiation Hardness Assurance is a **process** that ensures electronic components and systems will meet their required performance and reliability throughout their operational lifetime in a specified radiation environment.

At CERN, all systems operating in radiation environments are required to follow Radiation Hardness Assurance (RHA) guidelines.

The objective is to ensure compliance with the target availability of the overall accelerator complex.

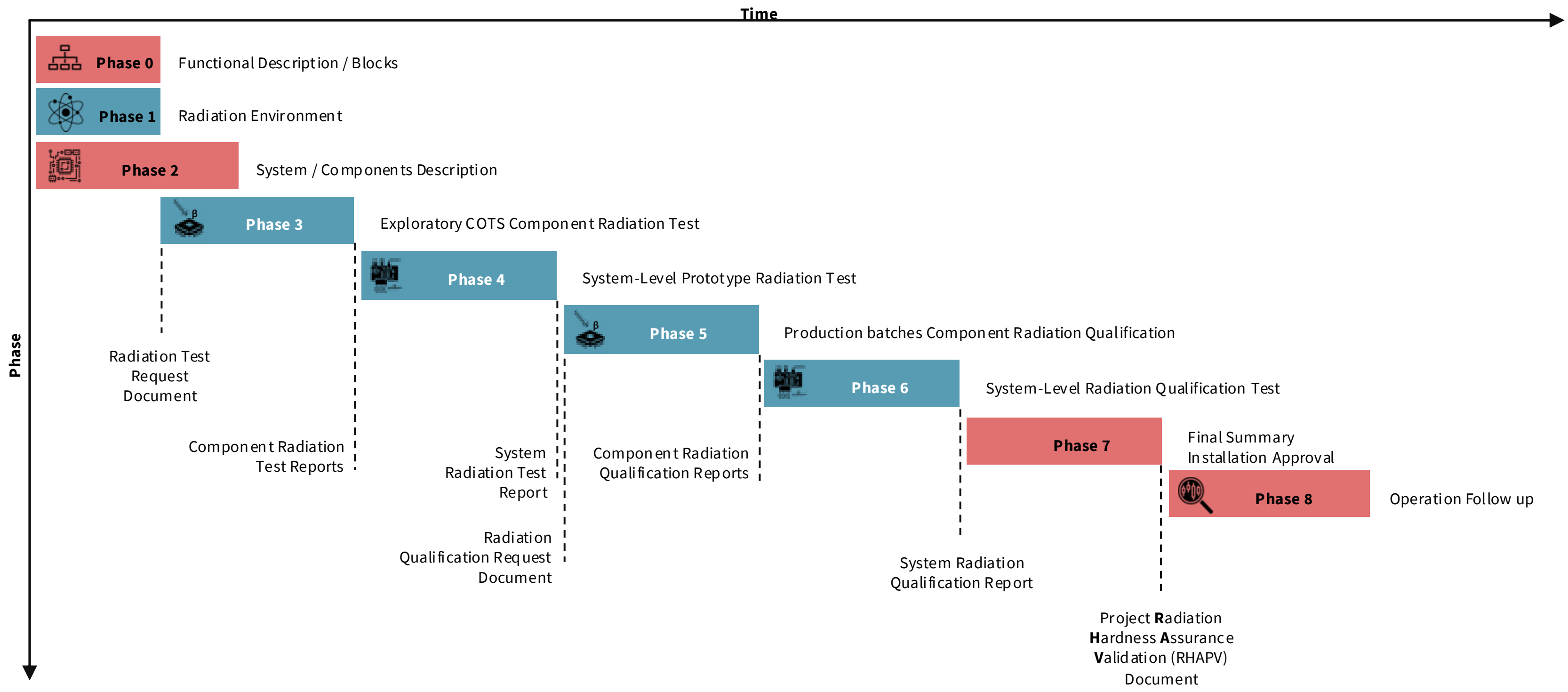
In the next 12 years, systems might be exposed to ~9 times more radiation than in the past 12 years



$$N_{SEE\_Failure} = N * \sigma * fluence$$

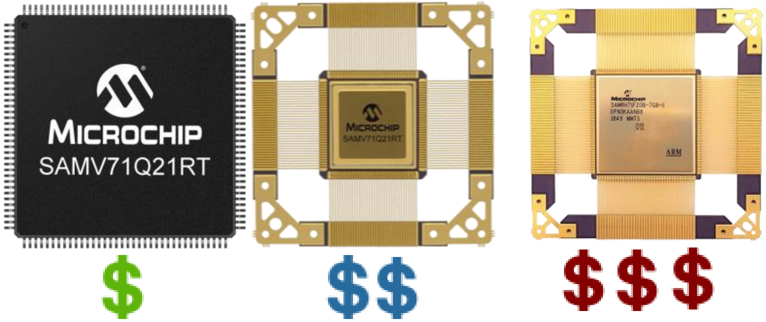
Number of systems

CERN RHA Procedure: New developments



Design choice – Radiation Tolerance

- Which components to use for the system?
  - Radiation Hard
  - Radiation Tolerant
  - Commercial Off The Shelf (COTS)



- Radiation hard:
  - Radiation hardened electronics is the electronics that have been developed, packaged, and sold to provide some level of protection against radiation in a **particular environment**
  - Rad Hard for space: Ceramic package - Fault Tolerance by Design - qualified process technology - mitigation techniques at design level – Radiation Performance: SEL immune up to xx Mev.cm2/mg TID up to yy Krad (Si).
- Radiation Tolerant
  - Rad Tol for space: Ceramic & Hermetic packages, extended temperature range -55C to 125C, extended qualification flow equivalent to QML-V or QML-Q space grade. Radiation performance: SEL LET > xx MeV.cm2/mg, and TID up to yy Krad (Si).
- COTS : Commercial Off The Shelf components
  - Plastic packages, industrial and automotive grade

COTS Radiation tolerant

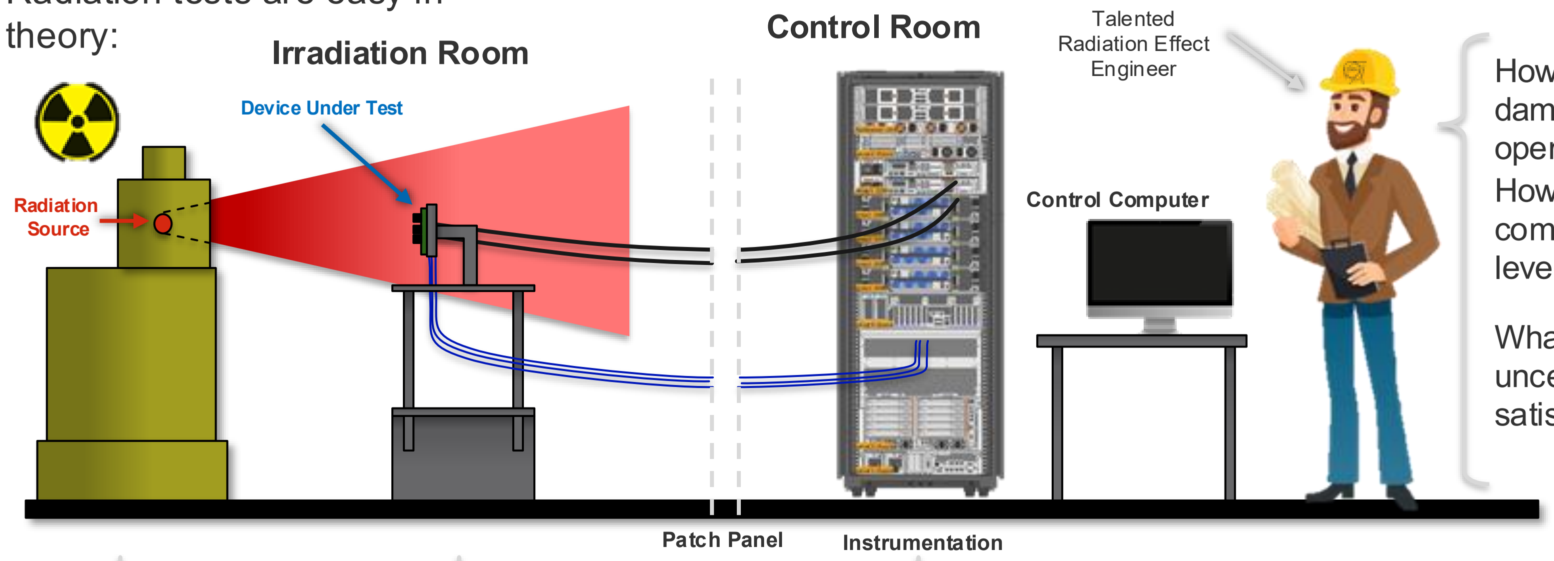
- In the 1999 P. Jarron defined a COTS Radiation tolerant as “a standard component which has by chance a good robustness against radiation effects”
- Implies: Radiation testing
- COTS RadTol are the main choice for distributed systems with hundreds/thousands devices in radiation environment
  - Higher performances compared to the RadHard
  - Cost effective
  - Lead time

Selection and Testing

- Testing all components can be a long process : how it can be possible to minimize the time ?
- Minimize the risks: **USE Radiation Data**
  - CERN: https://radwg.web.cern.ch/
  - ESA : ESCIES
  - IEEE Radiation Effects Data Workshop
  - NASA: RADHOME and NEPP
- **Three main strategies**:
  1. select unknown COTS and test
  2. test again previously selected COTS
  3. select & accept COTS with existing radiation data
- **CERN Lot qualification**
  - For critical applications: all the lots should be qualified (include strategy 1 and 2)

RHA Main activity : Radiation Testing

Radiation tests are easy in theory:



How to estimate damage in operation?
How the effects combine at system-level?

What failure rate uncertainty is satisfying?

What Radiation source(s) to use? What fluence/dose?

What to test? What to measure? What to expect?

How to test? Biased? Unbiased? Static? Dynamic? Real time monitoring or step-by-step characterization?

Single Date Lot Code workflow

COTS devices are multi-sourced and have multiple assembly lines

Although they may be electrically identical, microscopic differences inevitably exist due to variations in fabrication processes across different facilities.

We try to reduce the risk implementing a workflow for procurement where we ask distributor and suppliers to have single date lot code.

Need to verify production lot through radiation lot acceptance test (RLAT)

- Procurement and Qualification Process through EPR

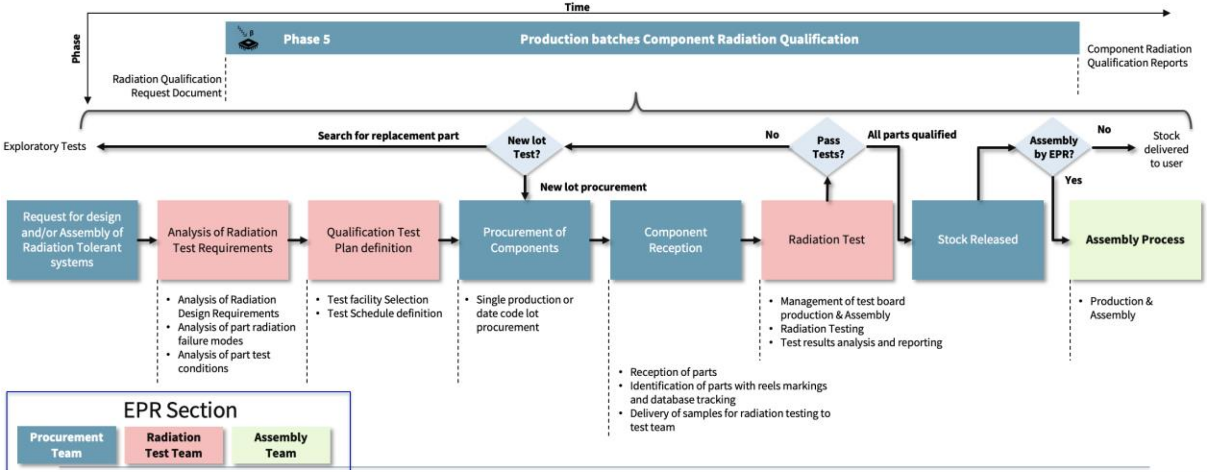


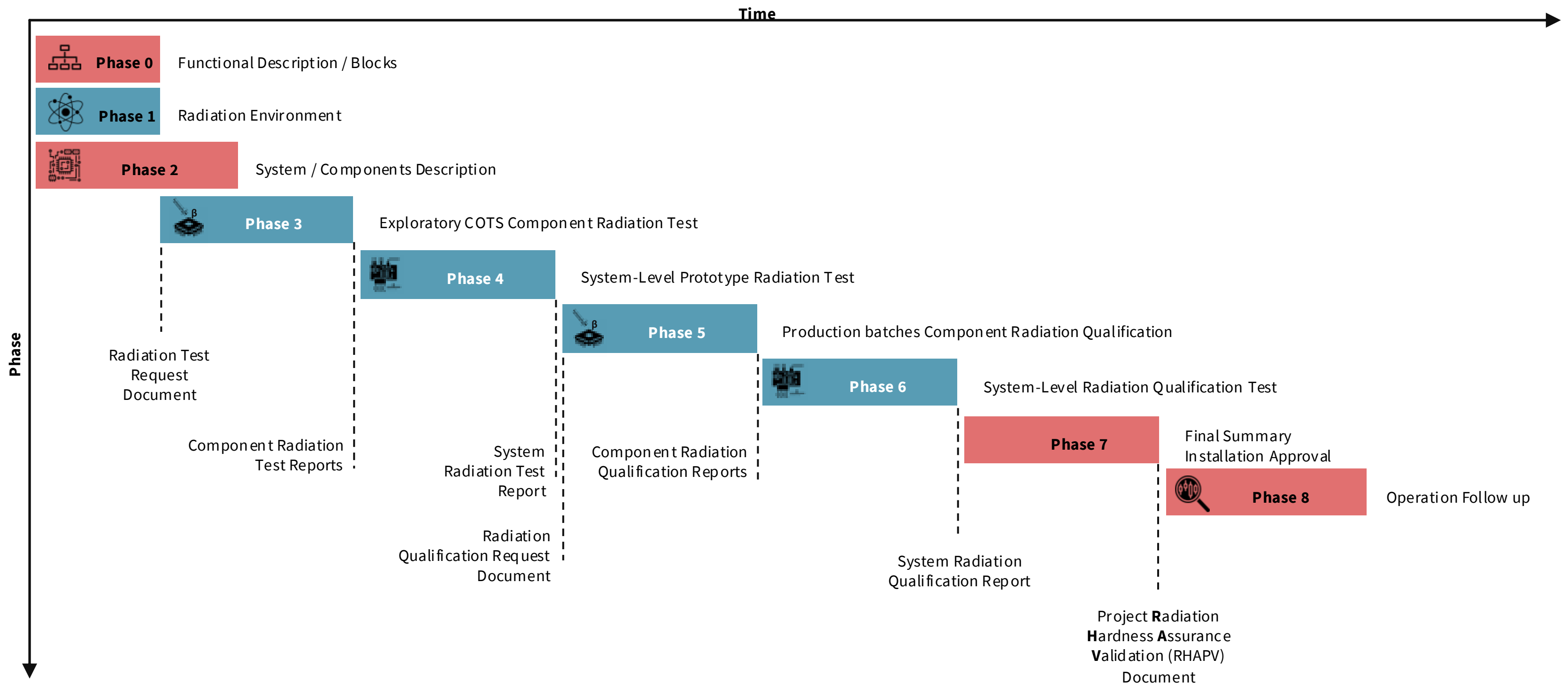
TABLE IV
INDIVIDUAL CONTRIBUTIONS TO THE BASE CURRENT DEGRADATION OF THE TESTED BJTS

Reference	Production Lot	TID Sensitivity $\left[\frac{nA}{Gy(SiO_2)}\right]$	DD Sensitivity $\left[\frac{nA}{1MeV\ n{-}eq/cm^2}\right]$
FMMT591	2301	-10.6 ± 0.9	$(-2.7 \pm 1.1) \times 10^{-9}$
	2314	-16.2 ± 1.4	$(-2.1 \pm 1.0) \times 10^{-9}$
	2315	-11.0 ± 1.1	$(-3.3 \pm 0.8) \times 10^{-9}$
2N2222	2313	3.1 ± 0.4	$(1.5 \pm 0.4) \times 10^{-9}$
	2320	5.5 ± 1.0	$(3.5 \pm 6.7) \times 10^{-10}$
2N2222AUB	2311	43.6 ± 2.8	$(2.8 \pm 3.1) \times 10^{-9}$
BCP53	2224	-1.7 ± 0.5	$(-3.2 \pm 0.3) \times 10^{-9}$
2N2907	2230	sublin.	$(-6.4 \pm 0.8) \times 10^{-9}$

4x

G. Andreetta *et al*., *"COTS BJT Radiation Qualification Methodology for Highly Distributed Systems in Mixed-Field Environments"*, **IEEE Trans. Nucl. Sci.**, vol. 72, no. 8, Aug. 2025.

CERN RHA Procedure: New developments

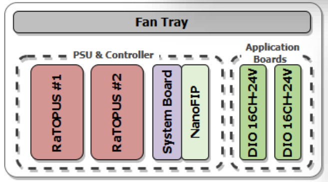


SEE Qualification Requirements Analysis and RLAT

- **Destructive Single Event Effects** (Latchups, Burnouts) affect **drastically** the **AVAILABILITY** of **the LHC**
- **The proper calculation of the part cross-section requirements** for qualification is **fundamental** to ensure it will fit the project **annual failure target**

See detailed methodology in February RadWG dedicated presentation by R. Ferraro

WIC TE-MPE Chassis [DIOT]



BOMs

LHC Risk Matrix	Recovery/Repair Time: infinite	year	month	week	day	hours	minutes
Failure Frequency: 1/hour							
1/day							
1/week							
1/month							
1/year							
1/10 years							
1/100 years							
1/1000 years							

Most common Requests

Machine Protection — **Machine Performance**

System locations
- Radiation Locations (DS, UJs, RRs)
- Number of systems

Radiation Levels
- FLUKA Simulations
- **BatMON/RadMON Radiation Monitoring**

System-Composition
- Chassis Architecture
- Redundancies
- **Bill of Materials (EDAs)**
- **Part Radiation Effects Analysis**
- **Biasing Conditions Analysis**

Target Failure Rate
- Target Maximum Failure rate according to risk analysis

Chassis Target Failure Cross-Section — Calculation of the full chassis cross-section from **locations**, **radiation levels**, **number of systems** & **target failure rate**

Board(s) Target Failure Cross-Section — Propagation of the *chassis target cross-section* to *board target cross-section*, considering **redundancy configuration** & **number of boards**

Component Target Cross-Section — Propagation of the *board target cross-section* to *part target cross-section*, considering **Radiation Sensitivity, biasing conditions** & **number of devices**

Radiation-Qualification Test Conditions — Calculation of number of test samples to use to comply with the propagated part target cross-section considering the **Facility test fluences capabilities**

Examples of Qualification Requirements

System name & Cross-Section [cm²/system]	LHC Locations	#Units	HeH Fluence [Heh/cm²/y]	System Boards	Board Cross-Section [cm²/board]	# Sensitive SEL Parts	Part Cross-Section [cm²/device]
Universal Control System Chassis (UCS) ($1.2\cdot10^{-12}$ cm²)	RR17 RR53 RR57	32	$1.40\cdot10^{10}$	DC/DC Power Supply	$9.66\cdot10^{-14}$	15	$6.44\cdot10^{-15}$
				Analog Outputs	$1.93\cdot10^{-13}$	54	$3.58\cdot10^{-15}$
				FPGA System Board	$1.29\cdot10^{-13}$	24	$5.36\cdot10^{-15}$
	RR13	8	$1.00\cdot10^{10}$	Power Interlock	$3.81\cdot10^{-13}$	60	$6.35\cdot10^{-15}$
				General Interlock	$3.26\cdot10^{-13}$	107	$3.05\cdot10^{-15}$
	RR73 RR77	24	$2.00\cdot10^{9}$	Contactor Control	$6.44\cdot10^{-14}$	4	$1.61\cdot10^{-14}$
				Driver Board	$1.45\cdot10^{-13}$	21	$6.90\cdot10^{-15}$
				Universal Control System	$1.69\cdot10^{-13}$	11	$1.54\cdot10^{-14}$
Warm magnet Interlock (WIC) Chassis ($9\cdot10^{-12}$ cm²)	TI2	17	$2.69\cdot10^{8}$	2x DIO 16ch opt. 24V	$9.64\cdot10^{-13}$	7	$1.38\cdot10^{-13}$
	TI8	18	$1.49\cdot10^{8}$	DC/DC Power Supply	$4.13\cdot10^{-12}$	20	$2.07\cdot10^{-13}$
	TT40/41	7	$6.37\cdot10^{9}$	FPGA System Board	$4.13\cdot10^{-12}$	30	$1.38\cdot10^{-13}$
Wire Positioning Sensor (WPS) Chassis ($3\cdot10^{-10}$ cm²)	UJ, UL	8	$3.00\cdot10^{9}$	6x WPS Conditioning	$3.05\cdot10^{-11}$	27	$1.13\cdot10^{-12}$
				DC/DC Power Supply	$3.39\cdot10^{-11}$	20	$1.69\cdot10^{-12}$
	UPS	20	$1.05\cdot10^{9}$	FPGA System Board	$3.39\cdot10^{-11}$	30	$1.13\cdot10^{-12}$

400 Test Samples
- 1 Week in CHARM

Minimum 10 Test samples for CHARM/PSI

Less than 5 test samples required for CHARM/PSI

R. Ferraro - SEL Qualification Methodology for ATS Rad-Tol Control Systems

Radiation Test Facilities used for Qualification

PSI-PIF – Switzerland, Viligen
- 30-220 MeV Proton beam
- Combined **SEE**, **TID**, **DD** Test

ILL – Genoble, France
- Thermal Neutron Beam
- Thermal neutron sensitivity Tests

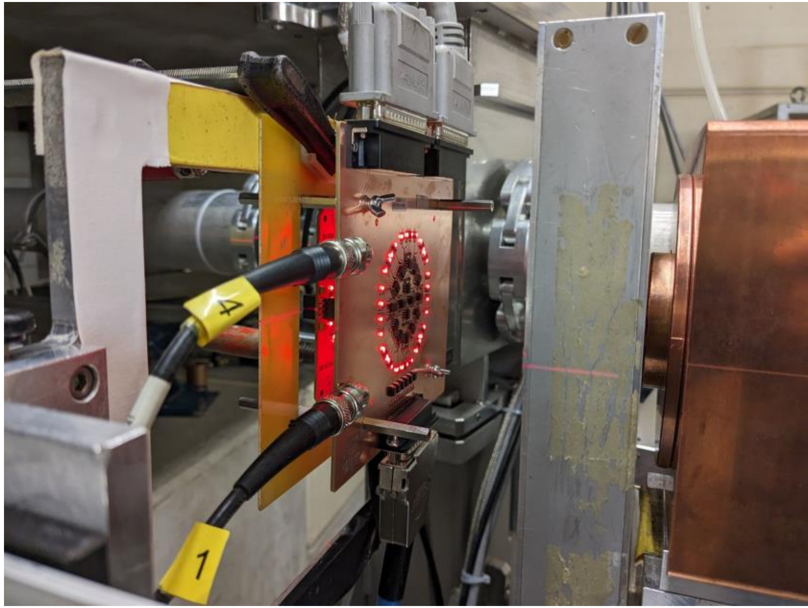
CC60 – Switzerland, CERN
- 10 & 110 Tb Cobalt 60 Sources
- **TID** Tests

JSI – Slovenia, Ljubljana
- Triga Mark II Nuclear Reactor
- **DD**, TID

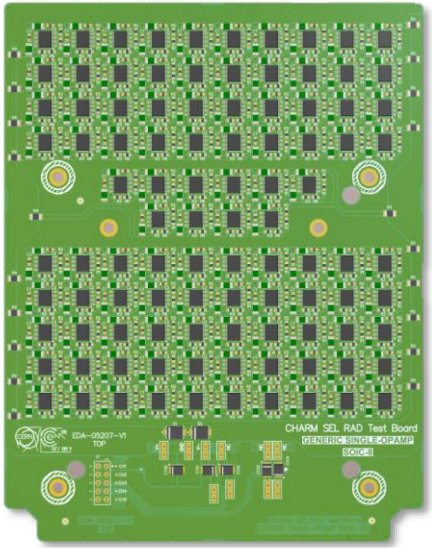
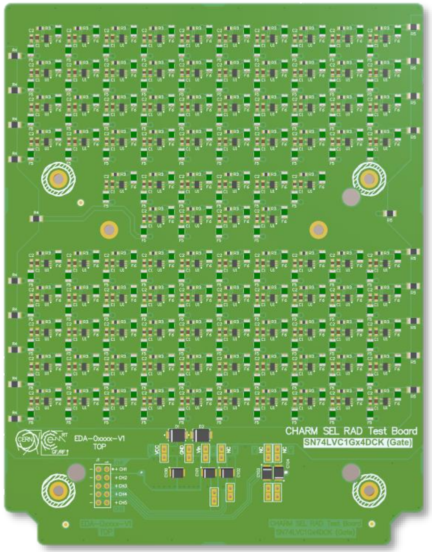
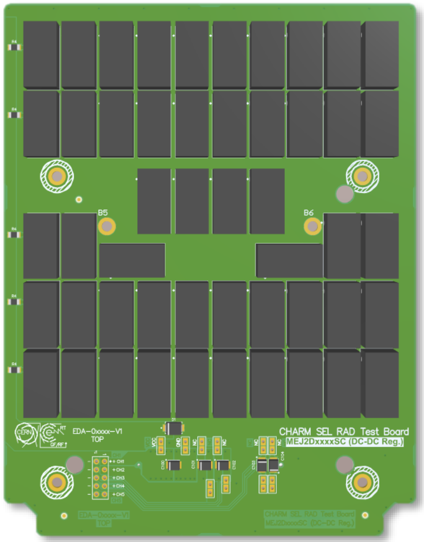
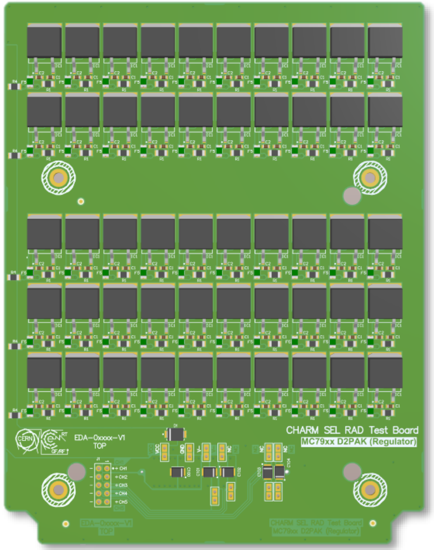
CHARM – Switzerland, CERN
- Representative LHC Radiation mixed-fields
- SEE, TID, DD

Limit of a proton facility for some CERN qualifications

- In most cases, hundreds of devices should be tested for CERN systems
- Usually proton facilities have small beam size (i.e 5x5 cm)
  - Few components can be placed in-beam
- Energy spreads if multiple boards are stacked
- The use of a large volume facility allow to test hundreds of components in a single radiation campaign



SEL Test Board Examples:

Dual Opamps	Logic Gates	DCDC Converters	Voltage Regulators
			
100 samples	100 samples	50 samples	50 samples

R. Ferraro - SEL Qualification Methodology for ATS Rad-Tol Control Systems

CERN CHARM Facility

CHARM

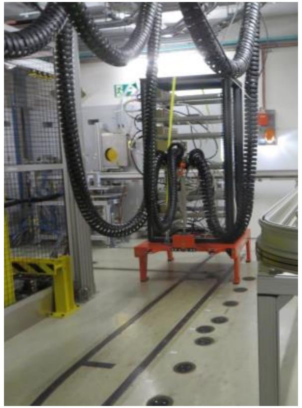
CHARM = CERN High energy AcceleRator Mixed field facility

Main mission: Radiation tests of electronic equipment and components

in a radiation environment similar to the one of the accelerator

Large dimension of the irradiation room
- Large number of devices
- Large volumes electronic equipment
- Full systems

Numerous representative radiation fields
- Mixed-Particle-Energy: Tunnel and Shielded areas
- TID, DD, Soft and Hard Single Event effects testing



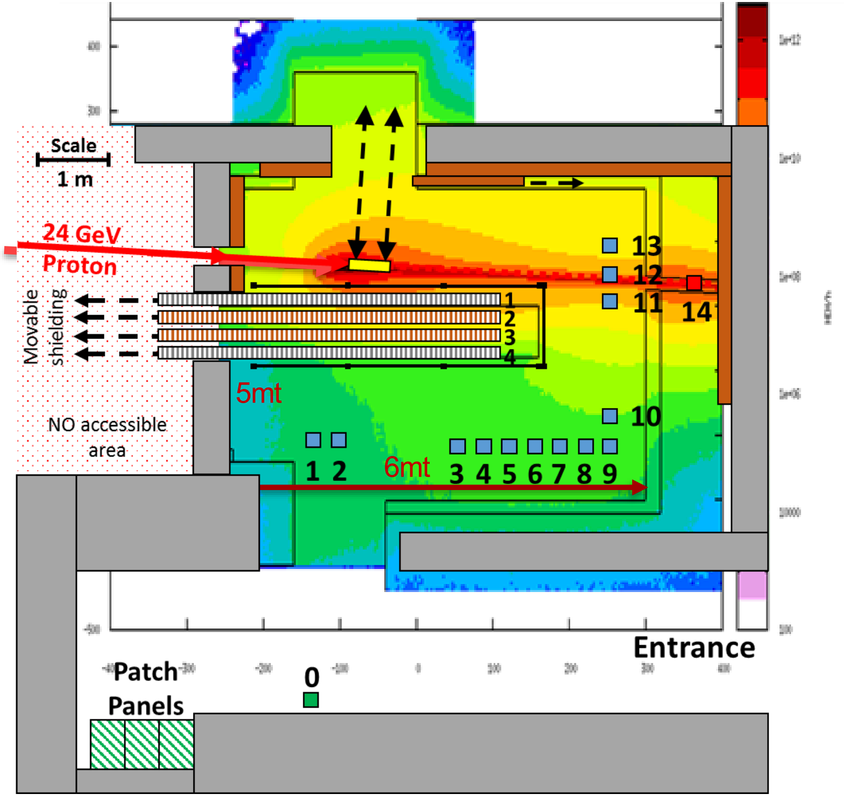
CHARM!

How CHARM works

PRIMARY PROTONS IMPINGE THE TARGET: A SECONDARY RADIATION FIELD IS CREATED

3 KEY ELEMENTS:

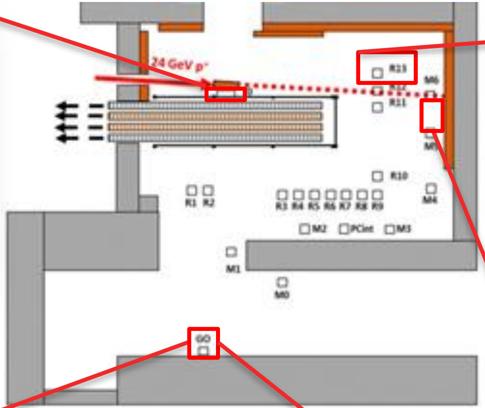
1. **Target** — Target
2. **Movable Shielding** — Concrete, Iron
3. **Positions** — Conveyer, Montrac



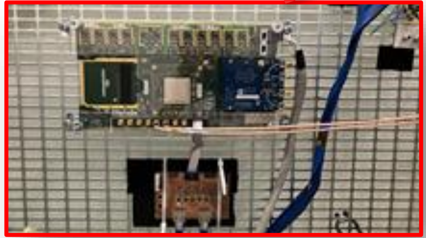
CHARM Test Position

Target Table Test Position

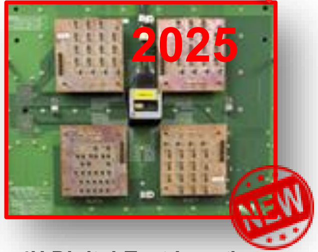
- **MOSFET SEB Test location**
- Will allow reaching high test fluences on GaN or other new MOSFET technologies



G0 Test Positions



- **Very High-Speed Digital Test location**
- Allows to test high-speed / complex digital devices/systems (FPGA, RF front-end)



- **4U Digital Test Location**
- Allows testing digital device with lower SEE requirements

MONTRAC Test Position

- **4U Permanent SEL Test location**
- Allow performing dedicated SEL tests for very low SEL cross-section requirements

RACK Test Position

- **4U Cumulative TID+DD & SEE tests**
- Allows testing & monitoring & applying complex test vectors on large number of parameters on several part numbers

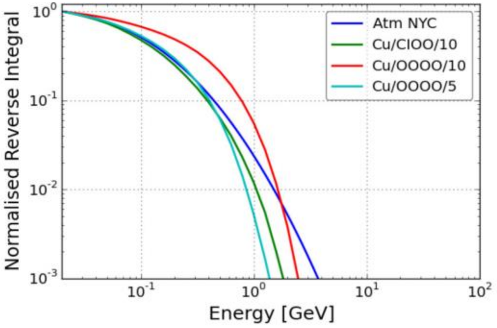
CHARM for ground application

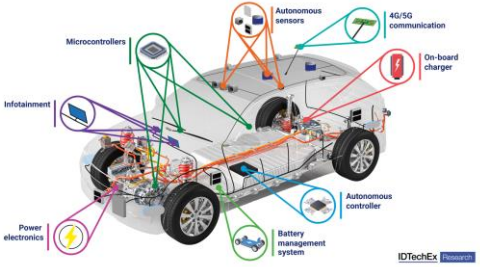
SiC Mosfet Tests

GTO Tests

Courtesy of Viliam Senaj and David Cabrerizo (TE/ABT)

- CHARM can be used also for ground application well representing the ground radiation environment (JESD89)

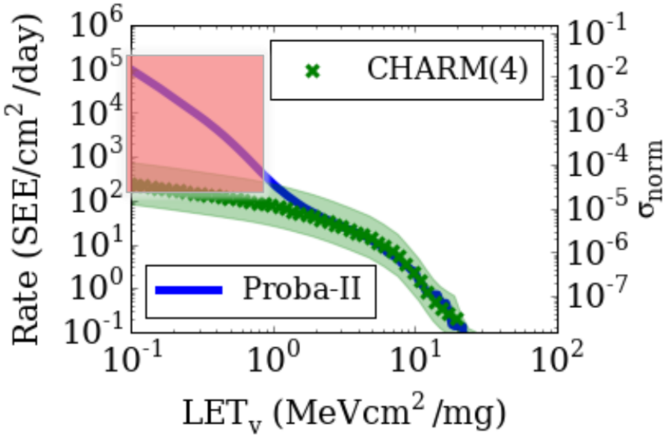




- We use the facility to test high voltage components used in the accelerator and in many other power circuit at ground level
- We use the facility to accelerate the tests on digital electronics (such as SRAM, DRAM, FPGA, MCU) to expose all the possible failures that can have during operation (also at ground level)

CHARM for Space

Proba-II (LEO) environment



- Volume-equivalent LET spectrum (LET$_v$) for Proba-II environment (800 km, 98°)
- CHARM LET$_v$ spectrum for HEH
- Very similar distribution as hadrons above ~20 MeV interact with silicon weakly depends on the hadron type and energy
- Direct ionization interval: present at CHARM but not included in plot as only hadrons >20 MeV are considered (direct ionization at CHARM is treated in *Infantino, IEEE TNS 2016*)

RadGateX

The most challenging tasks in radiation testing are: Coping with irradiation facilities infrastructures, Long cables, Beam Time availability

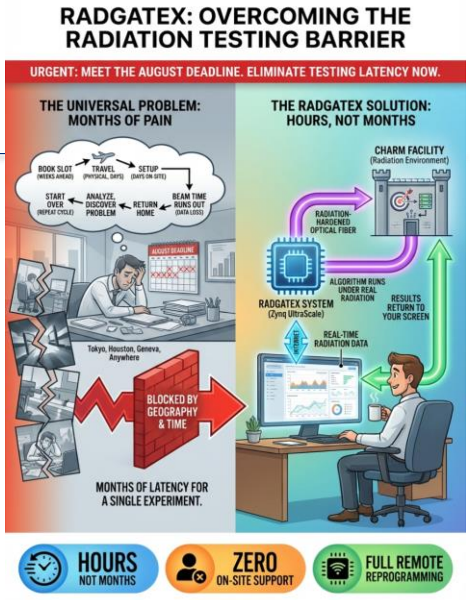
Everything I have shown so far requires expensive facilities, long beam times and specialized infrastructures. **RadGateX** was developed to drastically reduce these barriers:

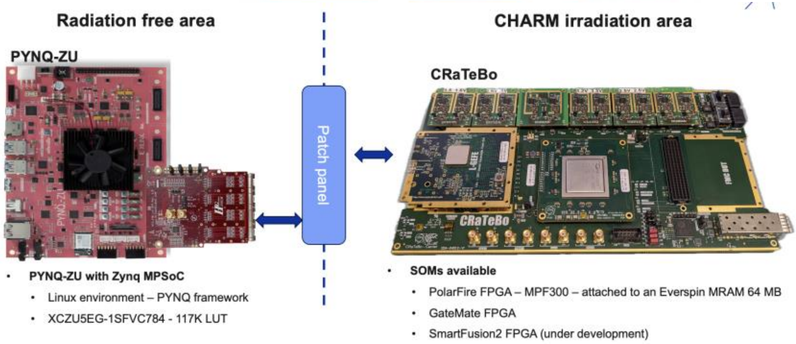
- Remote testing of (but not limited to) FPGA-based system
- No facility access required!
- Testing in radiation environments

How?

- With a radiation tolerant reconfigurable platform, i.e., CRaTeBo
- Rad-hard optical link - up to 3.2 Gbit/s (protected with FEC as well)
- Reconfigurable FPGA back-end with Linux environment running PYNQ framework
- Enable use of Python code for data processing or DUT control

https://radgatex.web.cern.ch/

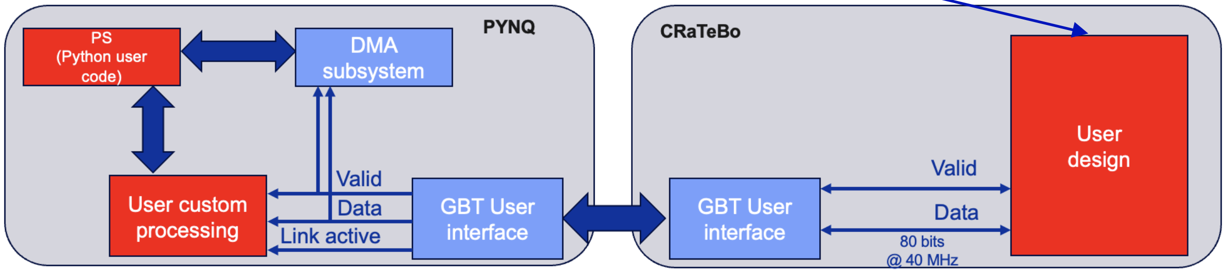




Synergies and Possibilities

- What can happen to my crypto core under radiation?
- What happen to my ADAS system under radiation?
- What happen to my ML algorithm under radiation?

- We can deploy gateware and hardware with minimum effort thanks to this platform
- Currently testing an opensource AES-128 core: 2 days of working (from home)



Conclusions

- **Accelerator design choice**
  - Qualified COTS for accelerator systems.
- **Radiation Hardness Assurance**
  - A complete engineering process, from design to operation.
- **Representative radiation testing**
  - Essential to predict reliability in real operating environments.
- **CHARM as a unique capability**
  - Mixed-field testing for components, systems and large-scale electronics.
- **Looking ahead**
  - New technologies and platforms such as **RadGateX** will enable faster, more accessible radiation qualification.

Thank you for your attention!

Controls
Electronics &
Mechatronics