RadMon: a versatile, integrated radiation monitoring system for accelerators and experiments electronics at CERN

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CERN

Controls
Electronics &
Mechatronics

Radiation to electronics at CERN

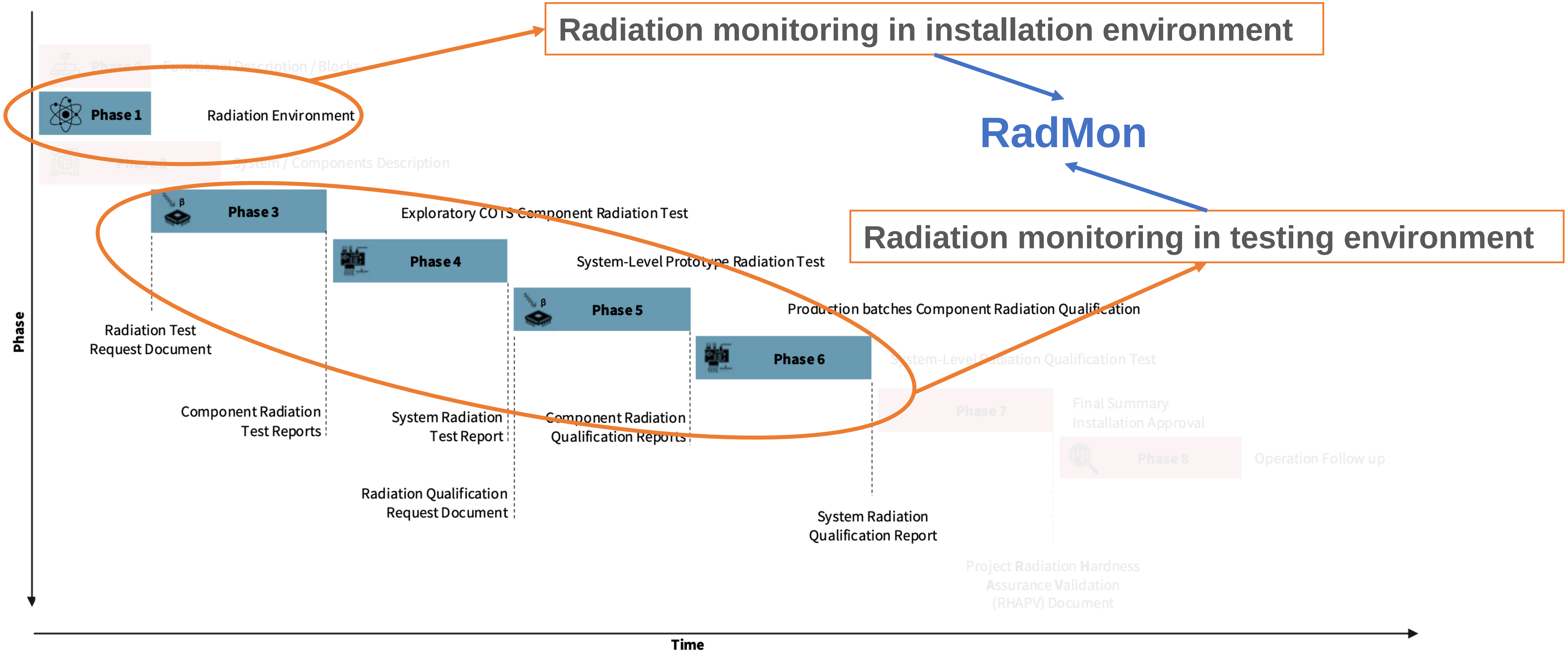
A reliability challenge in LHC:

- 2 proton beams at 6.5 TeV of ~3×10^{14} p+ each, stored 0.7 GJ
- fractions of the stored beam suffice to **quench a superconducting** LHC **magnet** or damage parts of the accelerator → Machine Protection Systems
- Protections are Electronic systems → radiation effects should be minimised!

Twofold problem:

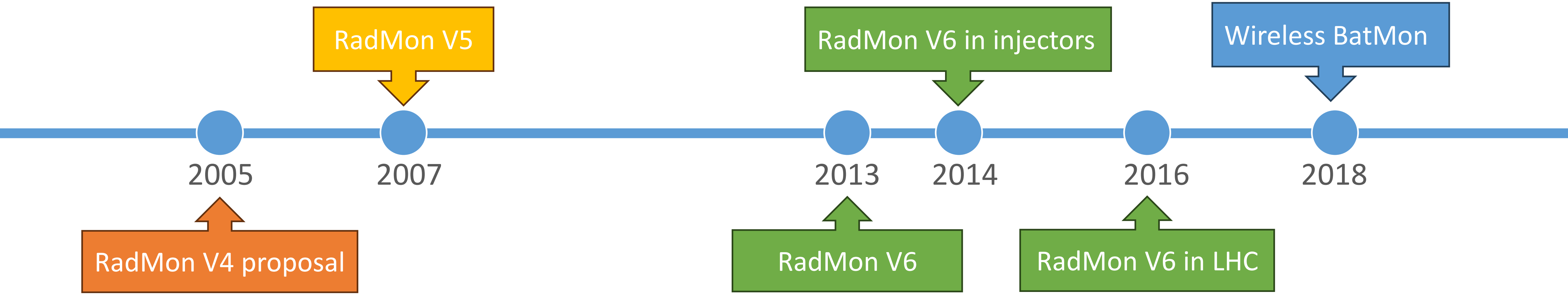
- electronics must remain live to react to real dangers
- false reactions should be avoided
- The radiation effects on a critical system can lead to lose the beam (**beam dump**)
- Lost time for physics, and time is money

Radiation Hardness Assurance at CERN



Introduction to RadMon System

- **The RadMon system measures radiation levels** for the purpose of evaluating and anticipating radiation effects on electronics in CERN's accelerator complex.
- It operates in CERN **accelerator tunnels, shielded galleries, and experimental areas**.
- **Over 500 RadMon** devices are in use, acquiring data every second.



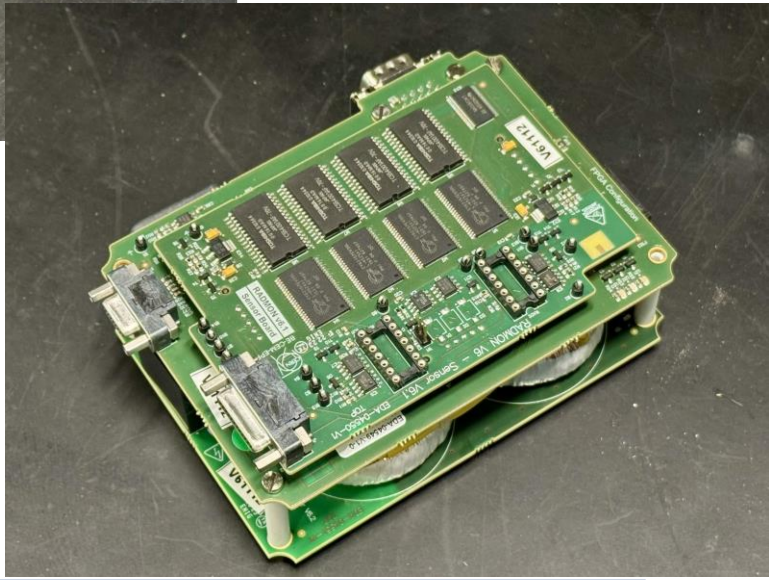
- Evolution of RadMon V5 deployed in LHC early years (~200 units)
- V5 replaced by V6 in 2014-2018, increased number from 200 to 500

RadMon radiation detectors

RadMon V6 Hardware Overview

RadMon onboard detectors:

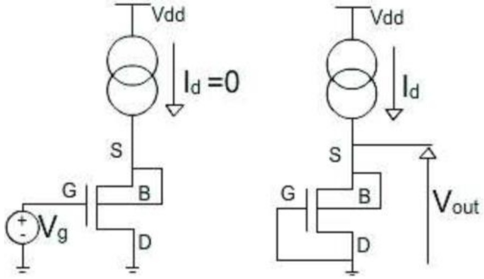
- **Total Ionising Dose (TID): RADFET**
- **High-Energy Hadron fluence (HEH): SRAMs**
- **1-MeV equivalent neutron fluence (1MeVeqN): p-i-n diodes**
- **Thermal Neutron fluence (ThN): SRAMs**
- Communicate through WorldFIP to Front-End computer (FEC) infrastructure in CERN accelerator complex,
- store data in NXCALS



Total Ionizing Dose (TID) Measurement

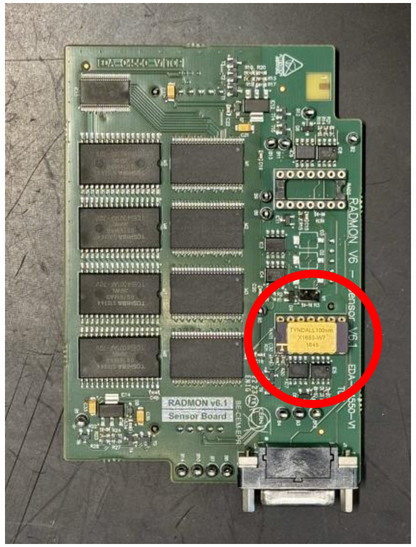
- In a MOSFET, Ionizing radiation causes **charge development in gate oxide** near silicon interface. This causes a **threshold voltage shift (V_{th})**, proportional to absorbed dose
- **RADFET devices are MOSFET** with specifically processed and biased oxide for dosimetry purposes
- ***Method:*** *measure threshold voltage Vth by current injection*

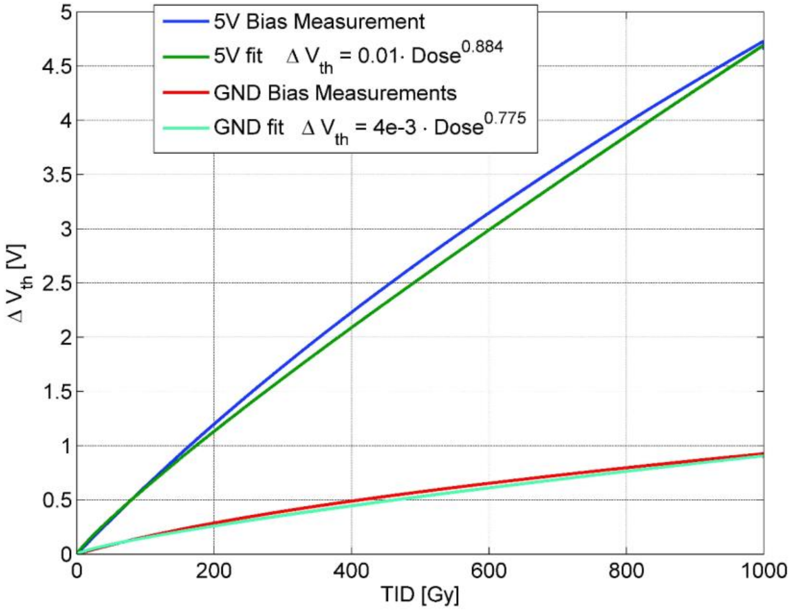
	Resolution @ 10 Gy	Resolution @ 1 kGy	Range
0V bias	0.2 Gy	0.7 Gy	>100 kGy
5V bias	0.06 Gy	0.2 Gy	3 kGy



$$V_{out} = V_{sg} = |V_{tp}| + \sqrt{\frac{I_d}{\frac{1}{2}\frac{W}{L}\mu_p C_{ox}}}$$

$$\Delta V_{sg} = V_{sg1} - V_{sg2} = |V_{tp1}| - |V_{tp2}|$$



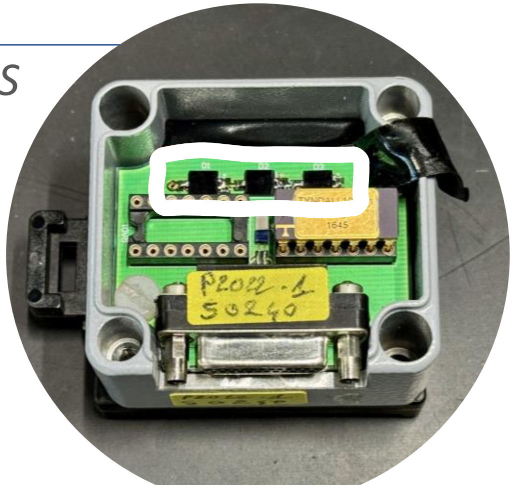


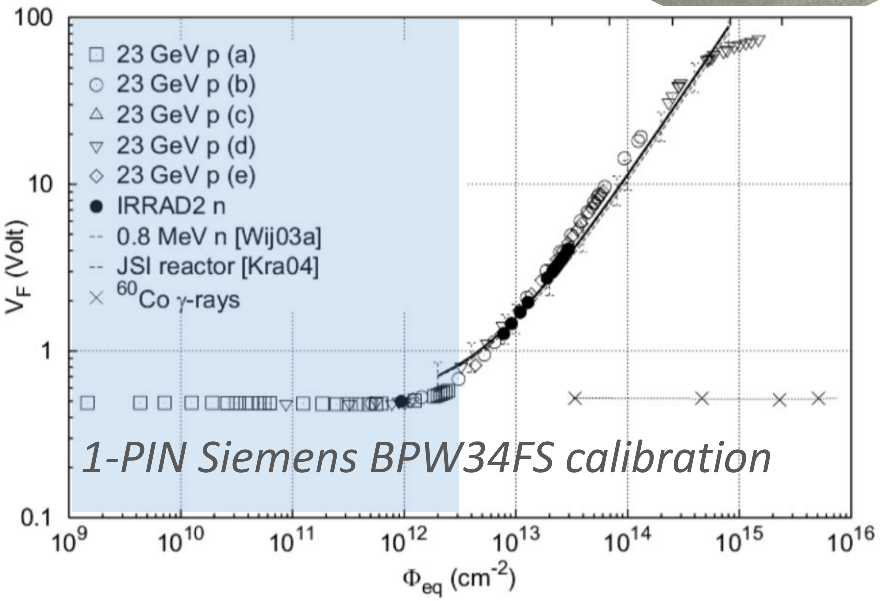
Displacement Damage (DD) Measurement

- **Silicon p-i-n diodes** measure Displacement Damage (DD) from particle interactions.
- Monitors **1-MeV equivalent neutron fluence** (Φeq).
- Detected by **changes in forward threshold voltage V_f caused by defects**.
- ***Method:*** *inject a constant current to measure forward voltage of one or three-series diodes*
- *three-series increases sensitivity ($\Delta V = 3V_f$)*

	Resolution	Range
1 PIN	2E10 n/cm^2	5E14 n/cm^2
3-series PIN	6E9 n/cm^2	1E13 n/cm^2

Siemens BPW34FS
Pre-irradiated at
2E12 n/cm^2
Sensitivity:
1E10 n/cm^2 mV

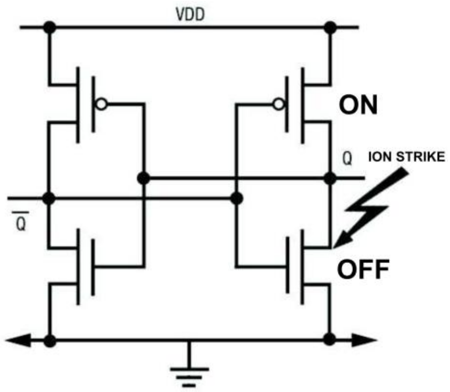




1-PIN Siemens BPW34FS calibration

High Energy Hadrons and Thermal Neutrons

- high-energy hadrons (HEH) (proton, neutron) and thermal neutrons, cause Single Event Upsets (SEUs) (bit-flip) in SRAM
- main mechanism: proton/neutron undergo nuclear interaction with nucleus of Si lattice -> recoil/alpha/fragment ejected -> indirect ionisation
- **SEU in SRAM cells proportional to fluence: fluence=SEU/xsect**
- >20 MeV p-Si comparable with n-Si x-sect
- Thermal neutrons (ThN) special case: $^{10}B(n,alpha)^{7}Li$ (for devices containing B traces)

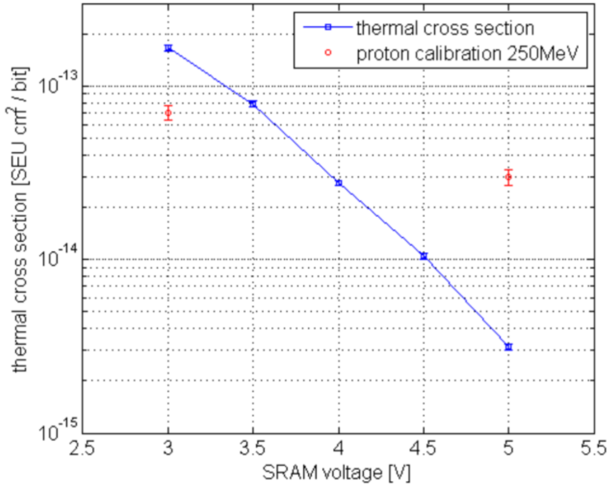


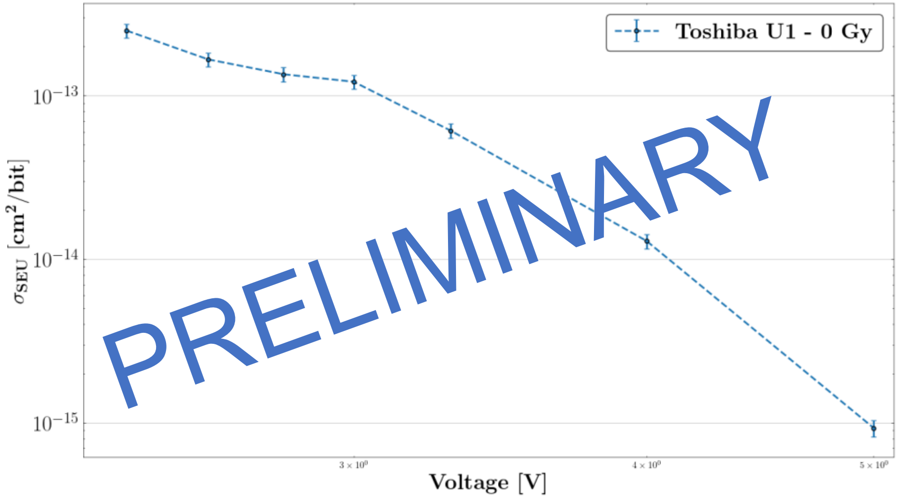
High Energy Hadrons and Thermal Neutrons (II)

- Method: count SEU in two different sets of SRAMs, one more sensitive to HEH and one to ThN, and compute the two fluences by analytical calculation

$$\begin{cases} SEU^{SRAM1} = \sigma_{HEH}^{SRAM1} \cdot \Phi_{HEH} + \sigma_{Th}^{SRAM1} \cdot \Phi_{Th} \\ SEU^{SRAM2} = \sigma_{HEH}^{SRAM2} \cdot \Phi_{HEH} + \sigma_{Th}^{SRAM2} \cdot \Phi_{Th} \end{cases}$$

- Calbrations: using protons and neutrons of known energy on both SRAM types
- cross-section depends on V_{bias} too





RadMon radiation tolerance

RadMon V6 system radiation tolerance

Sensitive elements:

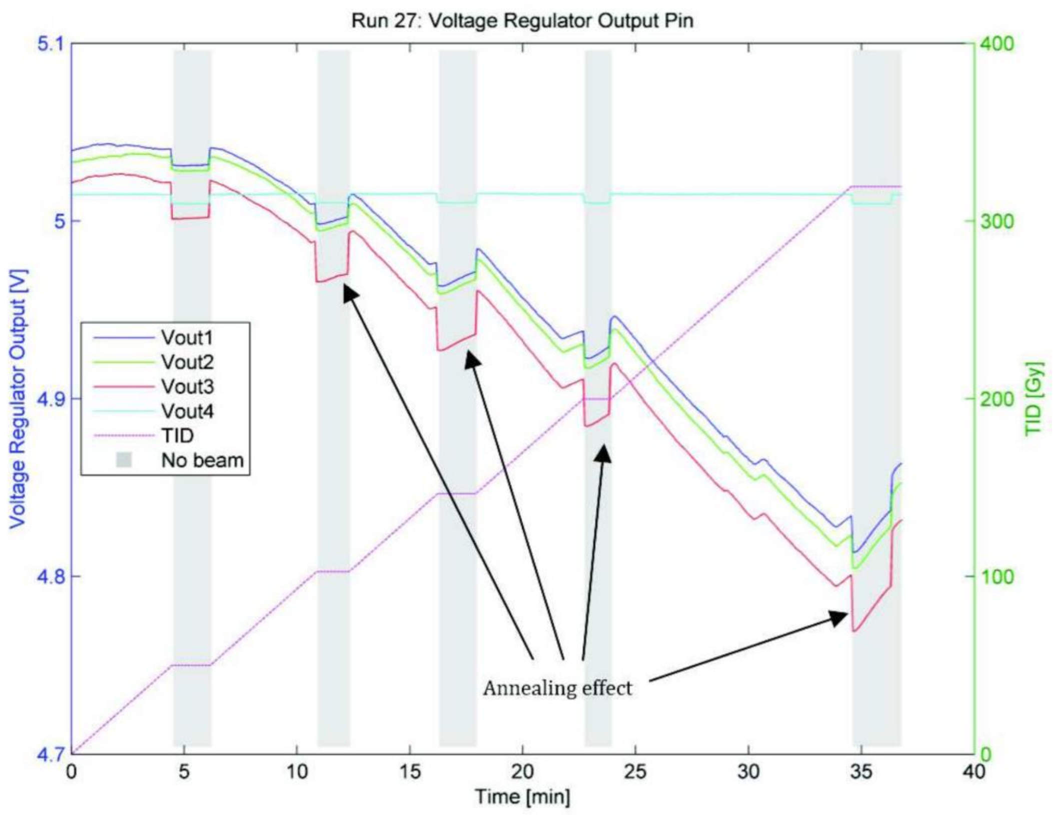
FPGA, Voltage regulator, ADC

V regulator:

- LM317D2T, 5% drift at 300 Gy, working properly beyond 3E12 n/cm2

FPGA:

- Microsemi ProAsic3E (FLASH based)
- 400 Gy theroretical limit for programmed device but 200 Gy limit for programming



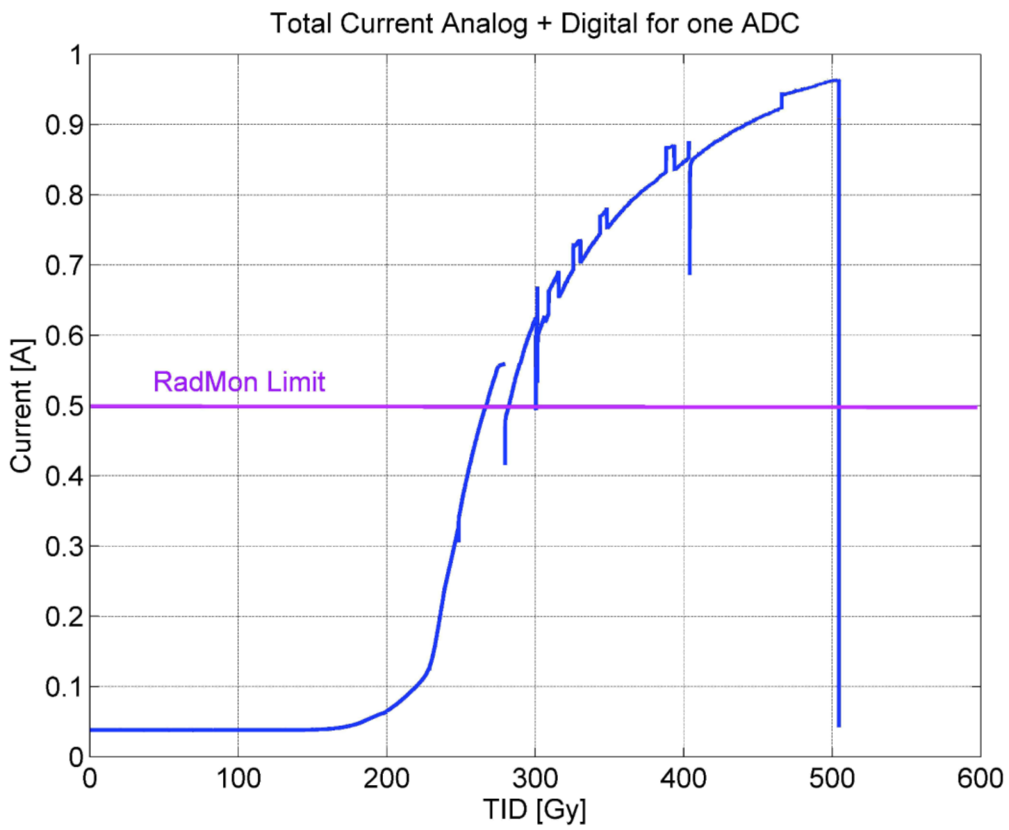
RadMon V6 system radiation tolerance (II)

Sensitive elements:

FPGA, Voltage regulator, ADC

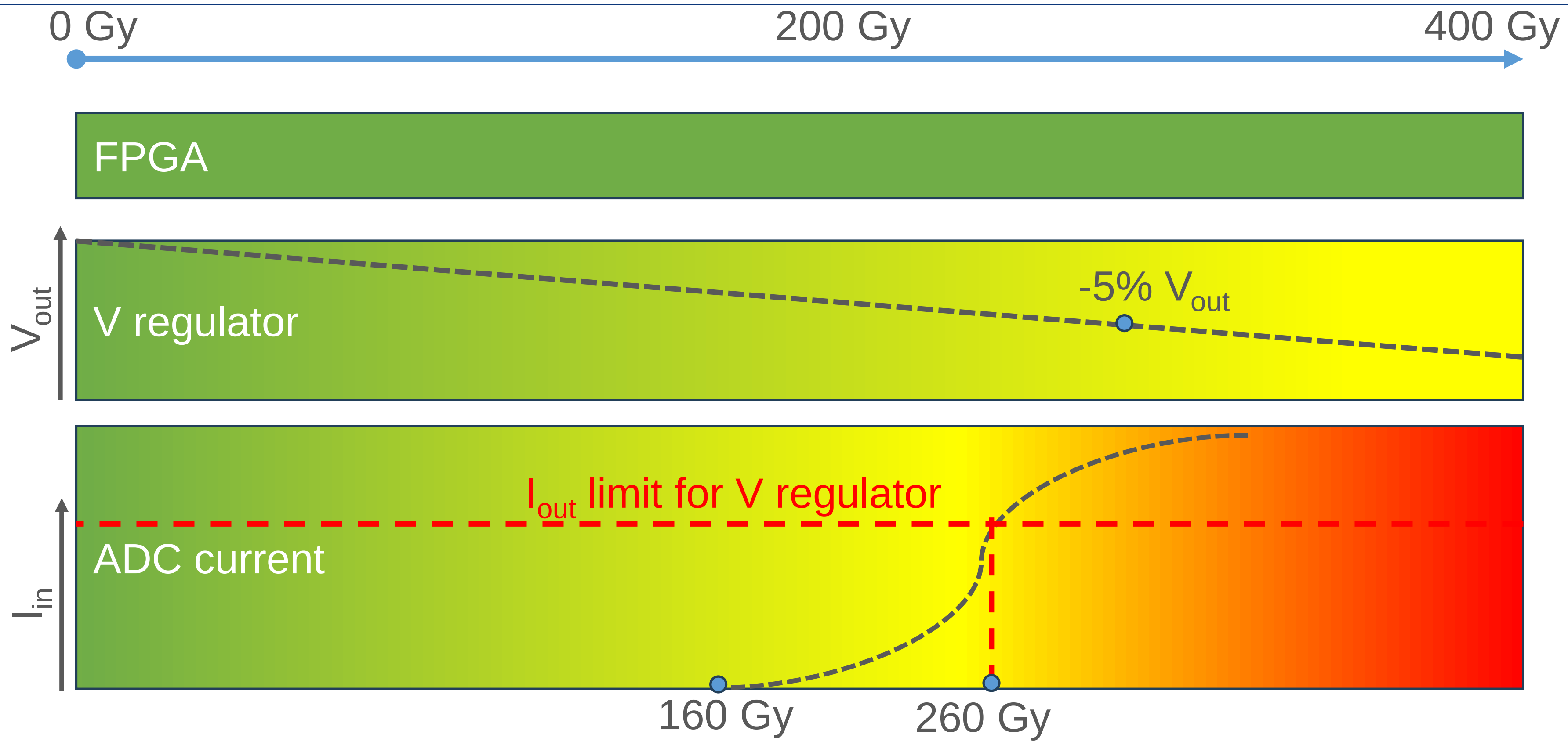
ADC:

- MAX11046, 8ch, 16 bit
- Main fault: increase of current consumption (max allowed budget from regulators 500 mA)
- At 160 Gy current increase, at 240 slope increases, at 260 Gy ADC fails (current consumption explodes, V_{ref} drifts)



→ RadMon V6 limit: 240 Gy vs 80 Gy for V5: x3 increase of MTBM

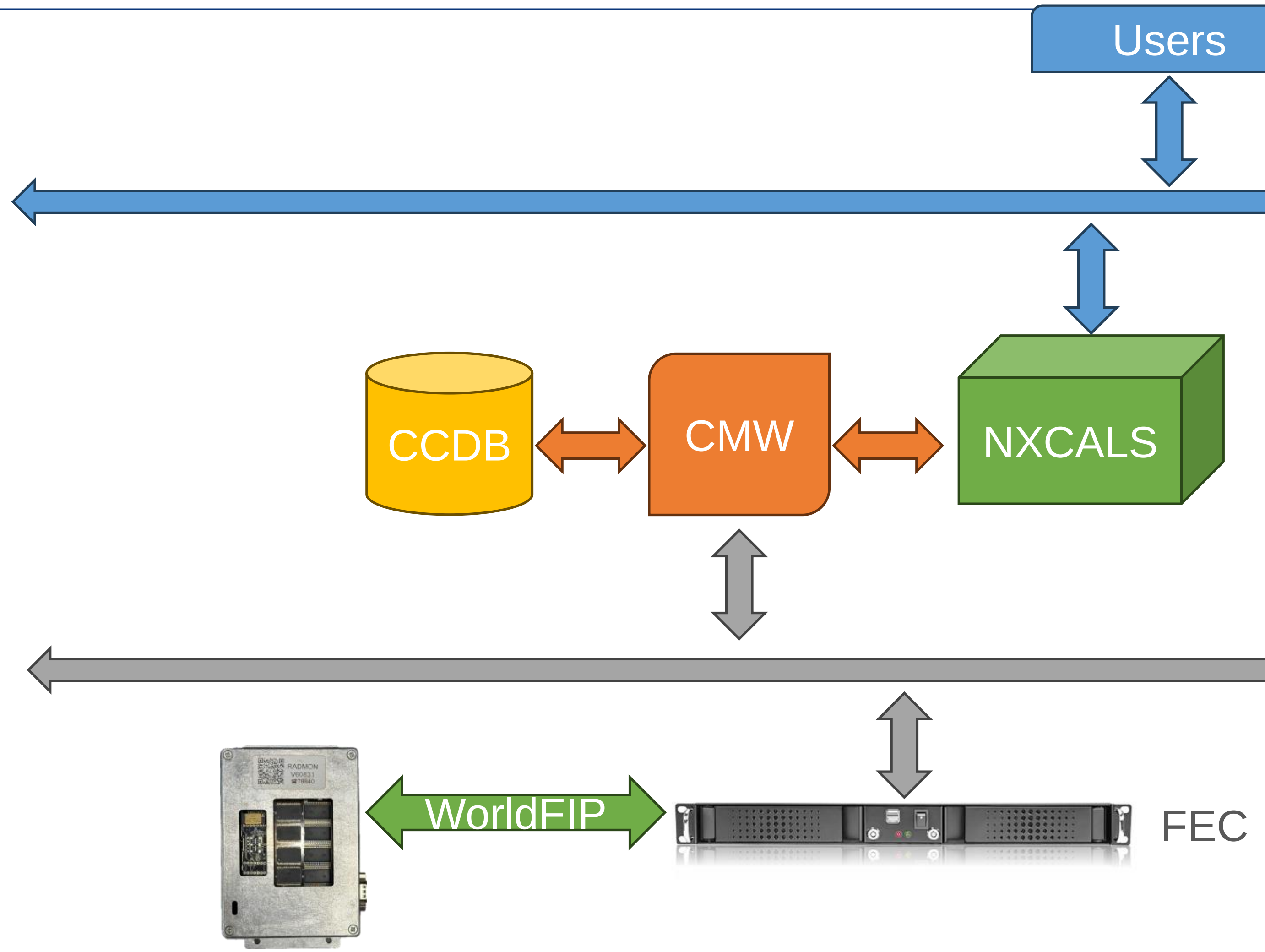
RadMon V6 radiation failure mode



At 160 Gy ADC I_{in} increase, at 260 Gy ADC fails (current consumption explodes, V_{ref} drifts)

→ RadMon V6 limit: 260 Gy vs 80 Gy for V5: x3 increase of MTTF

RadMon control and data flow architechture



RadMon V6 System Architecture

- RadMon V6 devices consist of a **main detection system** and **optional remote sensor module**.
- **Remote modules with RadFETs and p-i-n diodes** extend **up to 50 meters away**. Can withstand 10^{14} 1MeVeqN/cm^2 and 3 kGy (higher limit achievable in different configurations)
- This flexibility supports radiation **monitoring in areas otherwise inaccessible** for the full device (available space, radiation levels, magnetic field).

RadMon System for LHC and injectors

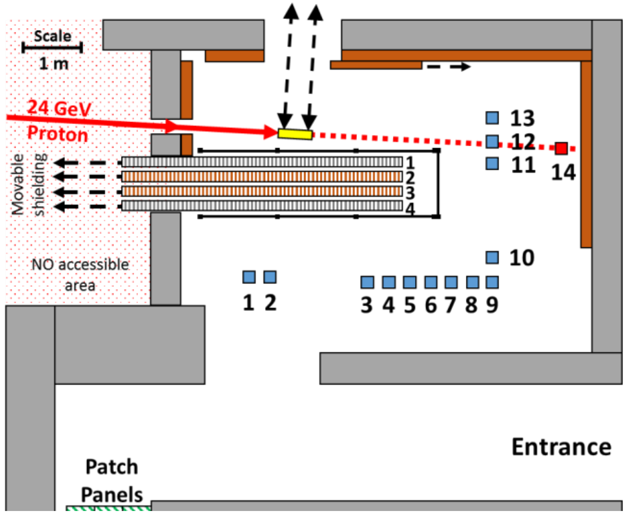
- RadMon main purpose is to monitor radiation levels in harsh environment around LHC, for fault troubleshooting and simulation validation
- Most concerned areas:
  - QPS racks below dipoles in half cells 8-13
  - RR shielded alcoves for Power Converters
  - UJ and UL galleries
  - Also injectors profit from RadMon monitoring

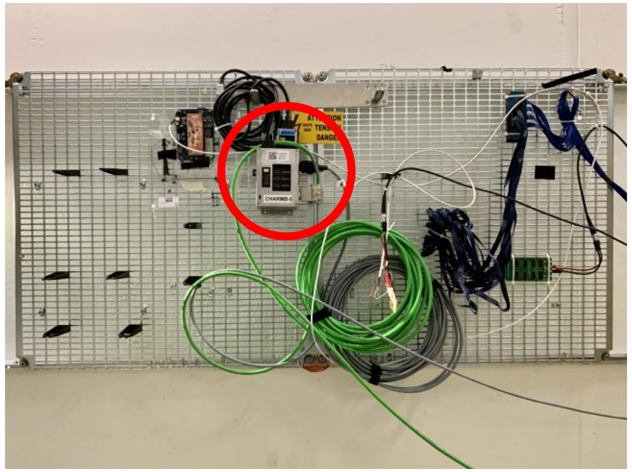
RadMon Deployment in LHC experiments

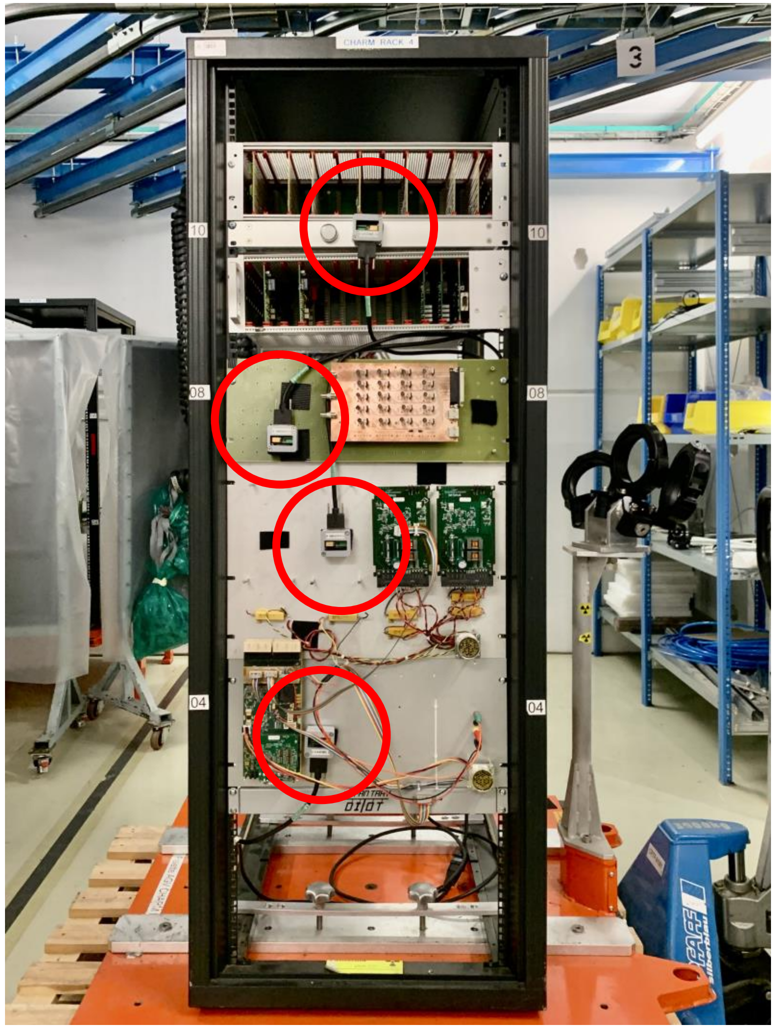
- **RadMon systems are installed around LHC experiments**
- Monitoring radiation levels for electronics racks around the detector
- **ATLAS, CMS, ALICE, LHCb** use RadMon for fault troubleshooting and radiation levels monitoring in DAQ, HV, LV, controls racks in the caverns
- **Cryogenics and Vacuum** also profit from RadMon data for monitoring and design of upgrades for HL-LHC
- **NA62, AWAKE, HIRADMAT** covered
- Collaboration with JPARC

RadMon in CHARM facility for test dosimetry

- RadMons are used in **CHARM mixed field test facility**
- Radiation **dosimetry during user tests**
- A **continuous testbench** to develop the system and push it to the limit:
  - **>500 Gy and few E12 HEH,1MeVn/cm^2 per week**

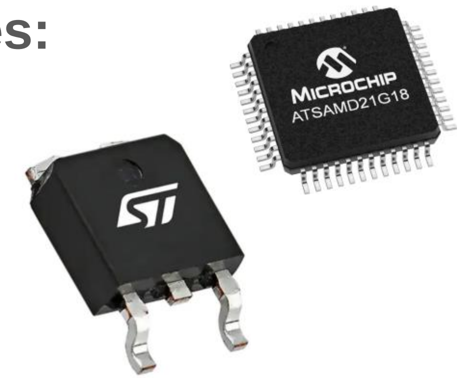






Future Prospects and Developments

Continuous development of RadMon for expanding monitoring capabilities:



- **Improved radiation tolerance** for HL-LHC installations
  - ➢ Exploring and testing new sensitive parts: ADC, V regulators, FPGAs, uControllers
- **Improved B-field tolerance** for experimental caverns
  - ➢ Separate sensitive parts out of B field, redesign, testing
- **Wireless communications platform**
  - ➢ ”BatMon” low consumption, battery powered device with LoRa IOT wireless transmission
- **New technologies for embedded detectors**
  - ➢ Floating Gate Dosimeter, new SRAM,

→ Towards a RadMon V7

Conclusions

- RadMon system provides extensive and continuous radiation monitoring all around sensitive electronics locations at CERN
- RadMon device integrates different detector technologies to cover the whole spectrum of interest for radiation effects on electronics
- Radmon installations extend from injectors, to the LHC, and all around the experiments
- Data is accessible through standard diagnostic database and tools
- Continuous evolution of the system will keep it up-to-date with the new challenges of HL-LHC, and beyond

Thank you for your attention!

References

- Danzeca
- Ravotti
- Kramer