The COTS Use in the Harsh Radiation Environment of the CERN Accelerators Complex

Ruben Garcia Alia, Salvatore Danzeca (for the CERN R2E Project)

R2E

ACCEDE COTS2019

SEVILLE – SPAIN 6-8 NOVEMBER

Outline

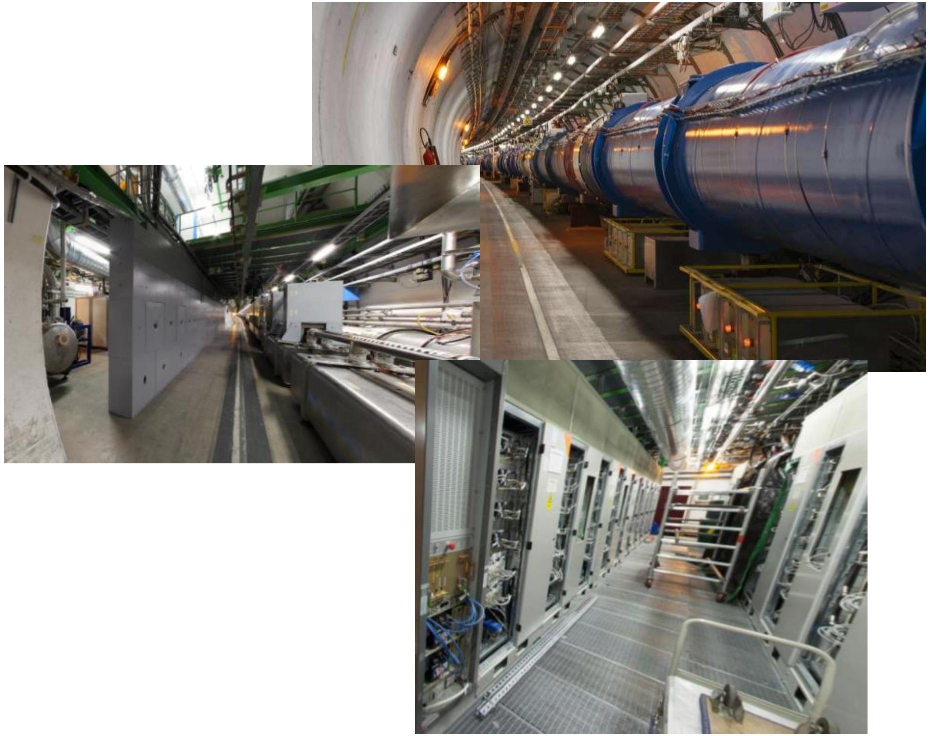
- Introduction to R2E problematic in accelerators
- Accelerator radiation environment
- Radiation Hardness Assurance approach
- RADSAGA and RADNEXT
- Main takeaways

Outline

- **Introduction to R2E problematic in accelerators**
- Accelerator radiation environment
- Radiation Hardness Assurance approach
- RADSAGA and RADNEXT
- Main takeaways

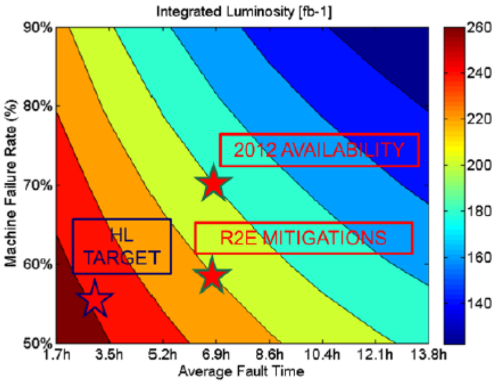
COTS-based critical equipment near accelerator

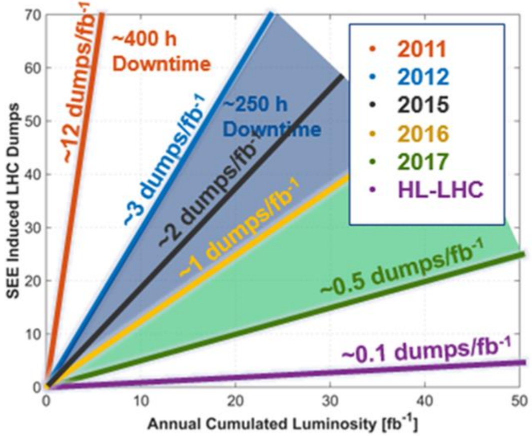
- Main reason requiring operation near accelerator:
  - Cable distance to accelerator elements (magnets, vacuum, cryogenics, RF, beam instrumentation…)
  - Lack of radiation-safe areas around accelerator (underground machine)
- Main drivers for use of COTS:
  - Cost
  - Performance
  - Availability and timeline
- Typical example of system level SEE requirement: one R2E failure per critical system per year



R2E impact on accelerator performance

- Critical LHC systems are interlocked: their main function is to protect the machine integrity, therefore in case of fault/spurious signal, the beam will be dumped (i.e. extracted from LHC in controlled manner)
- An R2E event (soft/hard) can result in the loss of beam (turn-around time of 2-3 hours) and/or the need of access (further 3-4h of downtime)
- 0.1 dumps/fb^{-1} involves an upper limit of 25 R2E dumps/year, or roughly one per week of operation
- Given the amount of critical systems exposed to radiation, this translates into an R2E failure budget of a few (2-3) per system and year – we consider one per year as design requirement.
- If we consider the (realistic) case of 1000 units exposed to 10^9 HEH/cm^2/year, one failure per system and year involves:
  - A unit failure rate of one in 1000 years* (MTBF of $2.8 \cdot 10^6$ hours, or 350 FITs)
  - A system-level SEE cross section upper limit of 10^{-12} cm^2/unit



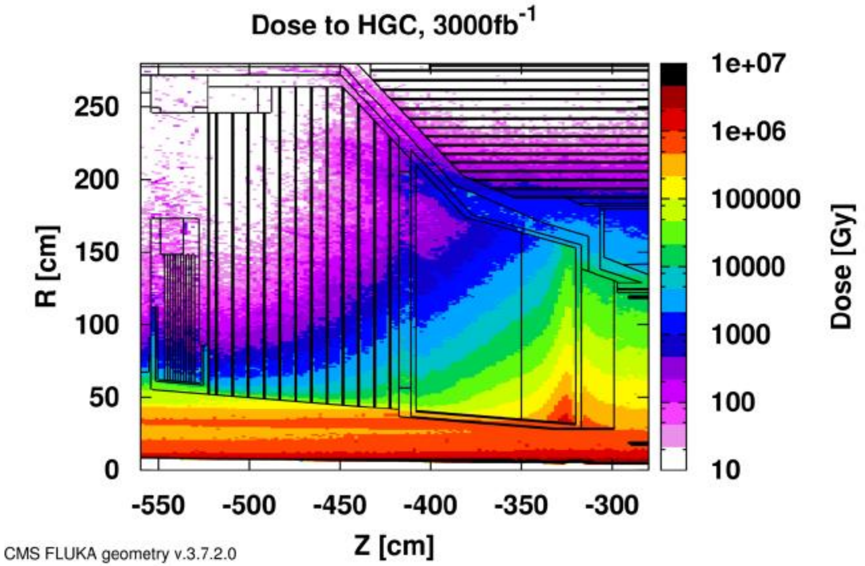


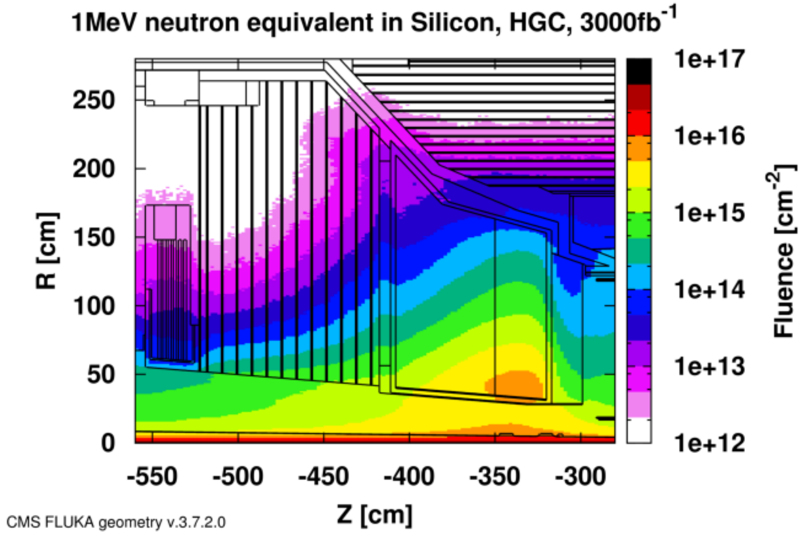
*LHC operation years, corresponding to 2800h

Outline

- Introduction to R2E problematic in accelerators
- **Accelerator radiation environment**
- Radiation Hardness Assurance approach
- RADSAGA and RADNEXT
- Main takeaways

Detector environment and electronics

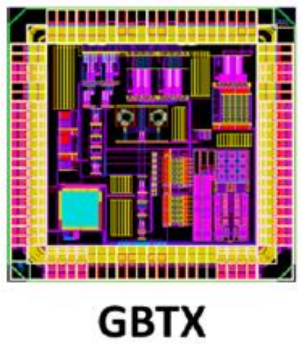




*For the **HL-LHC** (High-Luminosity LHC) detector electronics, to operate between 2025 and 2035, radiation levels of up to **10 MGy (1 Grad)** and **10^{16} n_{eq}/cm^2** are expected, thus requiring the use of **rad-hard by design electronics***

Detector environment and electronics

- Example of rad-hard design for high-energy accelerator detector electronics: Giga-Bit Transceiver (**GBT**)
  - Started in 2007 as a rad-hard bi-directional optical link for the LHC detector upgrade program
  - Data transmission between front-end detector, exposed to radiation, and back-end, in radiation safe area
  - Radiation constraints: **SEE-free**, **1 MGy TID** (and no DD limit as it can be neglected for CMOS)
  - Qualification: **X-rays** for TID, **heavy ions** for SEE
  - Timeline and cost for development & qualification are beyond the scope of systems for the accelerator sector

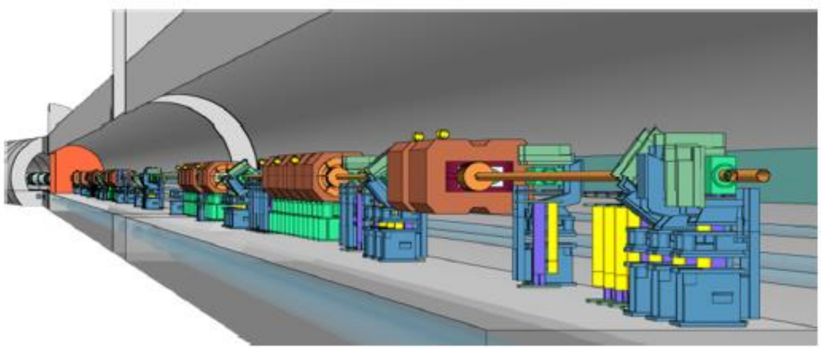


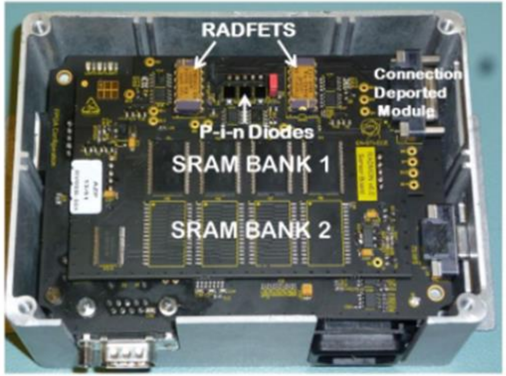
ASIC designed in framework of GBT program

Uznanski, RADECS Short Course 2017

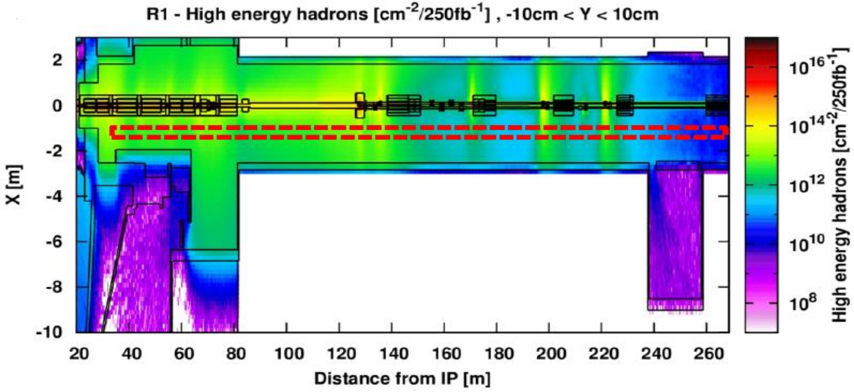
Accelerator environment

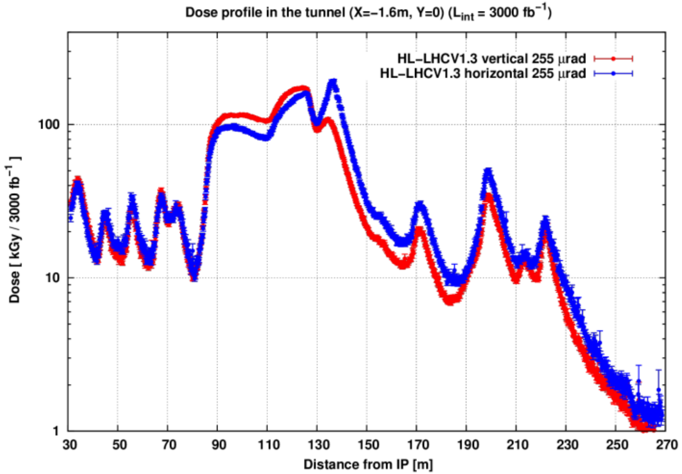
- The radiation levels in the accelerator span over many orders of magnitude (e.g. GGy irradiation of beam screens for material damage) but typically COTS-based systems are foreseen to operated in areas with levels below 200 Gy for ~20 years operation
  - The 200 Gy limit is mainly motivated by (i) the relatively large amount of areas near the accelerator fulfilling this condition, (ii) the fact that selected COTS can be used up to such levels
- Importance of monitoring and simulating radiation levels in order to provide specifications for equipment groups designing and qualifying radiation tolerant systems





Accelerator environment – areas near Interaction Points



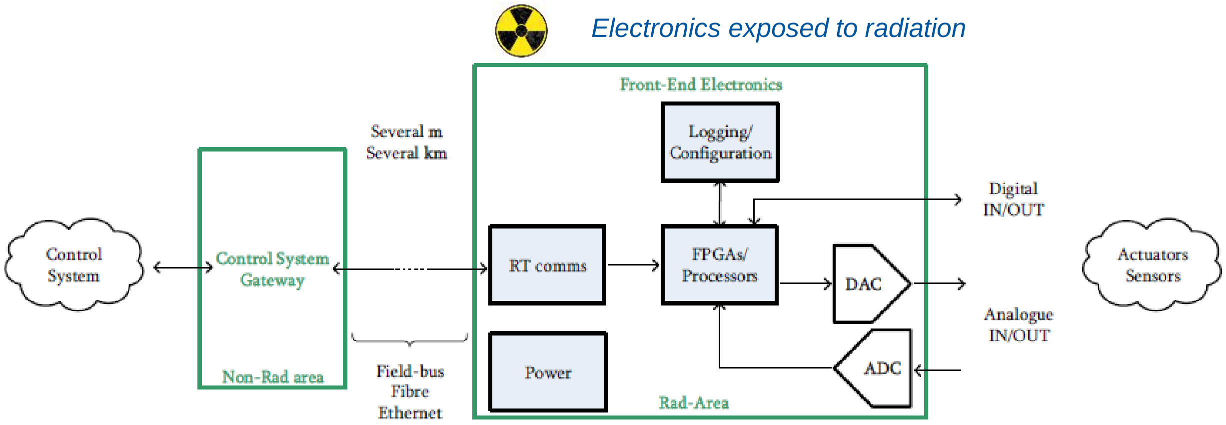


- Radiation levels near interaction points dominated by collision debris
- Expected TID and DD levels in the accelerator tunnel for system lifetime (~10-20 years) can reach **100 kGy** and **10^{15} n_{eq}/cm^2**, therefore **excluding use of COTS**
- Shielded alcoves (~40-200 cm of concrete/iron shielding) host electronic systems in this part of the accelerator, with HEH_{eq} levels of **10^7-10^9 HEH/cm^2/year**, therefore posing a threat in terms of SEEs

Outline

- Introduction to R2E problematic in accelerators
- Accelerator radiation environment
- **Radiation Hardness Assurance approach**
- RADSAGA and RADNEXT
- Main takeaways

Accelerator COTS system architecture



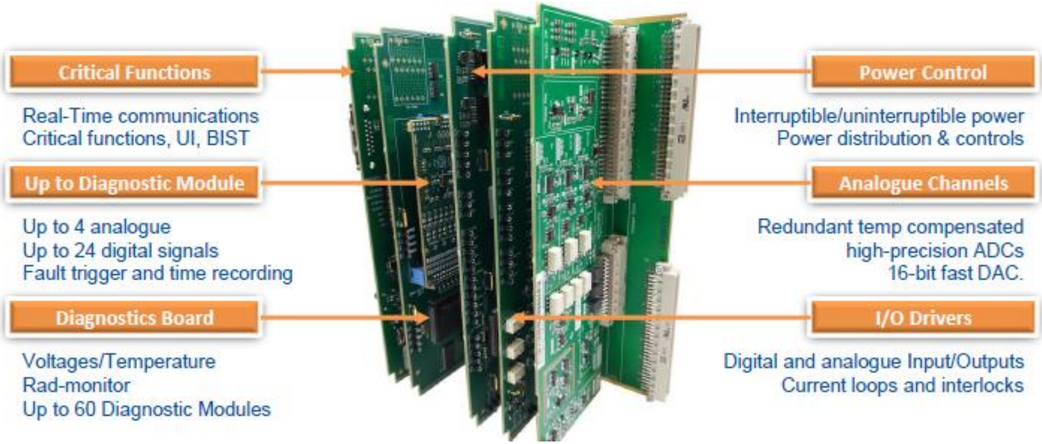
Uznanski, MAPLD'18

- *COTS-based, but custom design (i.e. full control of schematics and part selection). Use of COTS modules (black boxes) for critical applications in radiation is excluded.*
- ***Front-end:*** *no microcontrollers/DSP performing computationally intensive tasks, which are moved to control system through gateway,* ***high availability rad-tol communication*** *between front-end and gateway required*

FGClite power converter controls system

- Critical system to accurately control power converter current provided to LHC magnets
- Replacement of FGC2 system, which was radiation sensitive
- Main design concept: lighter front-end, pushing part of the digital processing to radiation-safe areas (i.e. importance of rad-tol, high-performance communication link)
- Modularity with clear definition of critical/diagnostic functions

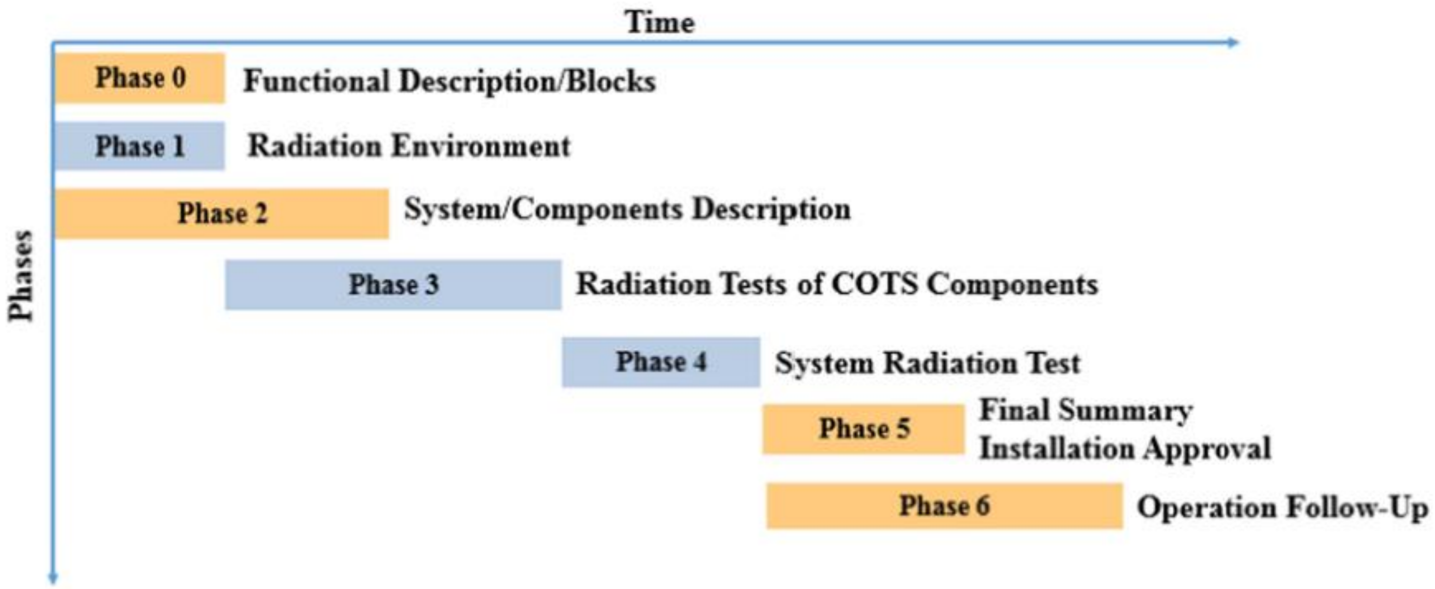
Full system: ~1000 units, 14k PCBs, ~50 different semiconductors, ~ 0.5M active components



***Radiation qualification** for HL-LHC targets:*

- *>200 Gy and $5{\cdot}10^{12}$ 1MeV n_{eq}/cm^2 lifetime*
- *<10^{-13} cm^2 SEE failure cross section*

RHA for COTS-based systems



- *Considering radiation tolerance constraints at very early stage of design*
- *Validation of radiation tolerance at system level before final production*

RHA for COTS-based systems

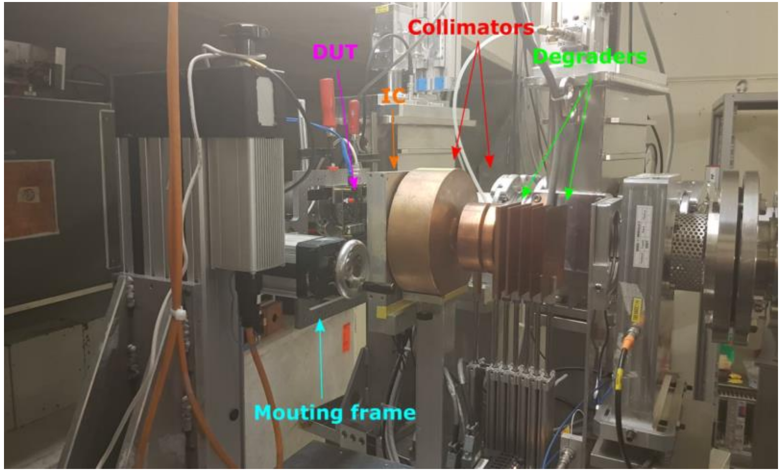
Class	Radiation response	Sourcing	Test methodology
Class-0 (potentially sensitive)	Resistant or moderately sensitive	Easily replaceable, different manufacturers available	Selection of already tested component when possible. Only integrated in system test.
Class-1 (potentially critical)	Potentially susceptible to radiation, not in system's critical path	Substitution possible (list of preferable replacements defined)	Sensitivity screening, if possible of several candidates. If passed, integrated in system test.
Class-2 (highly critical)	Potentially susceptible to radiation, on system's critical path	Difficult to replace, no equivalents on the market	Sensitivity screening and if passed, lot/batch testing. If accepted, integrated in system test.

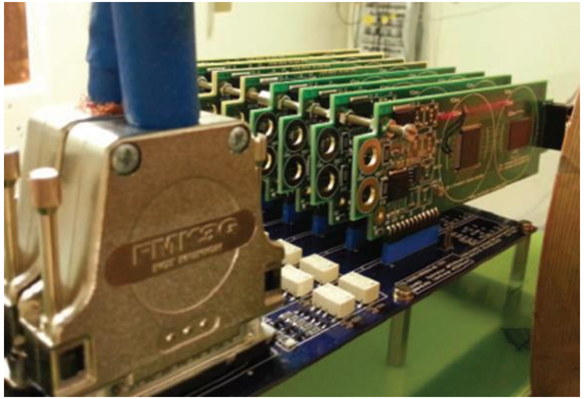
+ *impact of component failure at system level*

Not possible to test all parts at same level, therefore different classes according to criticality need to be considered

Component level testing (at PSI)

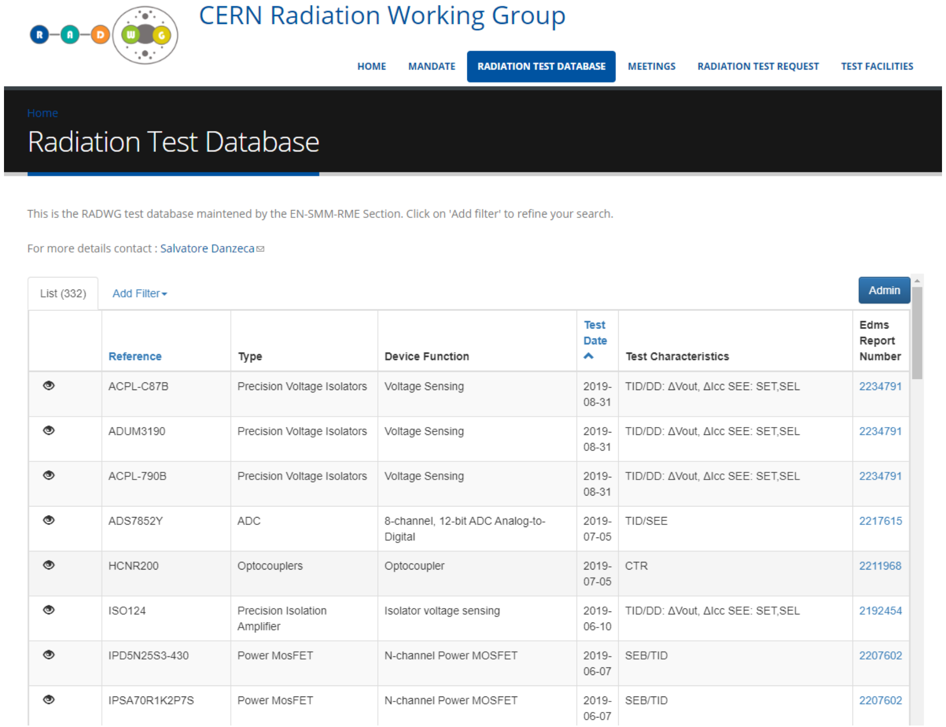
- Component level tests typically carried out at PSI (200 MeV protons), covering all three effects (SEEs, TID, displacement damage)
- Typical annual figures for R2E at PSI: ~500h beam time, ~50-80 different COTS references tested
- Standard component level requirements: Destructive SEE free, lifetime of 200 Gy and $2{\cdot}10^{12}$ n_{eq}/cm^2





Component level testing: database

- Database with over 300 COTS component test report (mainly PSI: proton SEE, TID and DDD)
- Work-in-progress for defining and implementing access to reports for academic and commercial use
- CERN R2E mid-term strategy: being able to provide accelerator equipment groups with parts from tested lots (common batch procurement of components, appropriate storage, etc.)



CERN Radiation Working Group

HOME MANDATE RADIATION TEST DATABASE MEETINGS RADIATION TEST REQUEST TEST FACILITIES

Home

Radiation Test Database

This is the RADWG test database maintened by the EN-SMM-RME Section. Click on 'Add filter' to refine your search.

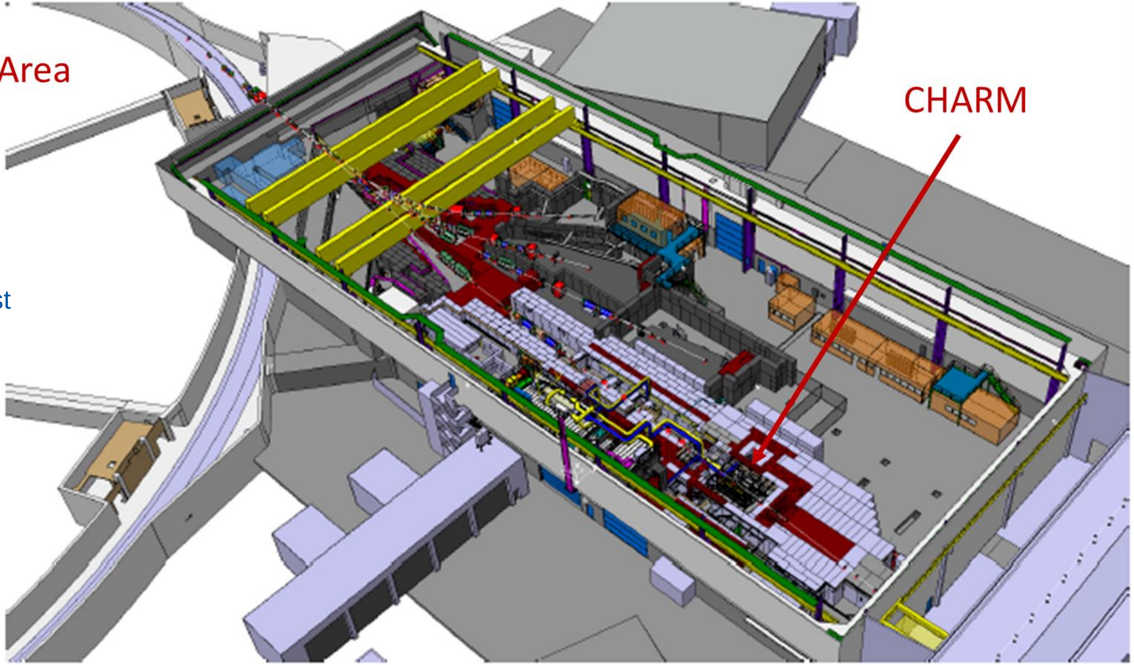
For more details contact : Salvatore Danzeca

List (332) Add Filter Admin

	Reference	Type	Device Function	Test Date	Test Characteristics	Edms Report Number
	ACPL-C87B	Precision Voltage Isolators	Voltage Sensing	2019-08-31	TID/DD: ΔVout, ΔIcc SEE: SET,SEL	2234791
	ADUM3190	Precision Voltage Isolators	Voltage Sensing	2019-08-31	TID/DD: ΔVout, ΔIcc SEE: SET,SEL	2234791
	ACPL-790B	Precision Voltage Isolators	Voltage Sensing	2019-08-31	TID/DD: ΔVout, ΔIcc SEE: SET,SEL	2234791
	ADS7852Y	ADC	8-channel, 12-bit ADC Analog-to-Digital	2019-07-05	TID/SEE	2217615
	HCNR200	Optocouplers	Optocoupler	2019-07-05	CTR	2211968
	ISO124	Precision Isolation Amplifier	Isolator voltage sensing	2019-06-10	TID/DD: ΔVout, ΔIcc SEE: SET,SEL	2192454
	IPD5N25S3-430	Power MosFET	N-channel Power MOSFET	2019-06-07	SEB/TID	2207602
	IPSA70R1K2P7S	Power MosFET	N-channel Power MOSFET	2019-06-07	SEB/TID	2207602

http://radwg.web.cern.ch/content/radiation-test-database

System level testing (at CHARM)



Proton Synchrotron accelerator:
- 24 GeV/c protons
- Circumference of 628m
- Injects beam into SPS (which in turn injects into LHC) but also provides beam to PS East Experimental Area

CHARM:
- Slow-extracted beam from PS (350ms spills every ~10s, i.e. quasi-continuous)
- Roughly $5{\cdot}10^{11}$ protons per spill
- Generation of mixed radiation field through interaction of proton beam with 50 cm copper target
- Access to facility once per week; flux can be varied through shielding and target

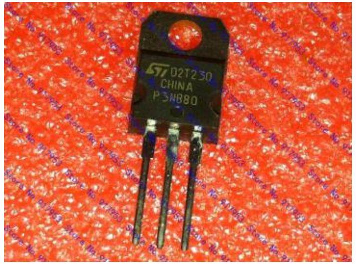
System level testing (at CHARM)

- System level testing at CHARM:
  - System level testing is applied as validation under operational conditions and in representative radiation environment (i.e. the part selection & qualification, plus system level mitigation have already been carried out beforehand, therefore system level validation is expected to be successful)
  - Systems are built modularly and with self-diagnose capability, therefore in case of failures or errors at a rate larger than that specified, re-design without major changes is typically possible
- Typical weekly radiation levels (considering position R10 and $1.5 \cdot 10^{16}$ protons on target): 350 Gy, $2.5 \cdot 10^{12}$ n_{eq}/cm^2, $7.5 \cdot 10^{11}$ HEH/cm^2

Risk of use of COTS modules (black boxes)

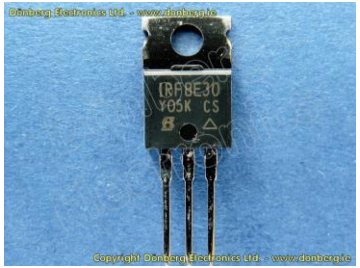
- "Black box" approach, very low observability and no re-design possibilities
- Power MOSFET used in pre-regulator of power converter AC-DC
- Two MOSFETs of similar electrical specs but very different sensitivity

Courtesy of Yves Thurel, TE-EPC-LPC



STP3NV80
(N-channel, 800V)

22 destructive events before LS1



IRFBE30
(N-channel, 800V)

One destructive event before LS1

Outline

- Introduction to R2E problematic in accelerators
- Accelerator radiation environment
- Radiation Hardness Assurance approach
- **RADSAGA and RADNEXT**
- Main takeaways

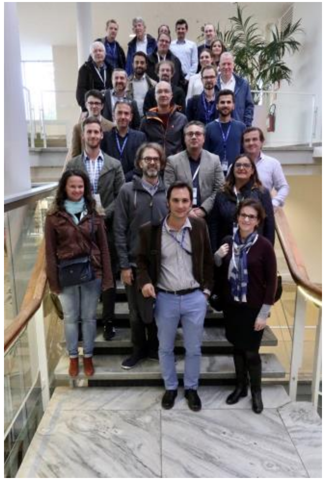
RADSAGA and RADNEXT

***RADSAGA:** an on-going Marie Curie training network of 15 student projects across Europe working on radiation effects for space, avionic, ground level and accelerator applications*

RADSAGA

http://radsaga.web.cern.ch/

***RADNEXT:** an EU proposal in preparation for enhanced service and accessibility to irradiation beam time for research applications in academia and industry*



Interested partners and users can contact radnext-proposal-coordination@cern.ch

Outline

- Introduction to R2E problematic in accelerators
- Accelerator radiation environment
- Radiation Hardness Assurance approach
- RADSAGA and RADNEXT
- **Main takeaways**

Presentation takeaways

- The CERN accelerator sector makes **extensive use of COTS-based custom systems, operating successfully in radiation environment and with challenging availability and lifetime constraints**
- High-reliability operation of COTS-based systems in radiation environments is possible in a cost-efficient manner, but relies heavily on:
  - Consideration of radiation environment and specification of required tolerance at a **very early stage of system definition** (otherwise, a strong price is paid in terms of machine performance and mitigation measures)
  - **Centralized support** for part selection, architecture definition and component & system level radiation testing

Recent R2E publications

- M. Brucoli et al., "Investigation on Passive and Autonomous Mode Operation of Floating Gate Dosimeters," in IEEE Transactions on Nuclear Science, vol. 66, no. 7, pp. 1620-1627, July 2019.

- M. Brucoli et al., "Investigation on Passive and Autonomous Mode Operation of Floating Gate Dosimeters," in IEEE Transactions on Nuclear Science, vol. 66, no. 7, pp. 1620-1627, July 2019.

- R. Ferraro et al., "Study of the Impact of the LHC Radiation Environments on the Synergistic Displacement Damage and Ionizing Dose Effect on Electronic Components," in IEEE Transactions on Nuclear Science, vol. 66, no. 7, pp. 1548-1556, July 2019.
- M. Cecchetto et al., "SEE Flux and Spectral Hardness Calibration of Neutron Spallation and Mixed-Field Facilities," in IEEE Transactions on Nuclear Science, vol. 66, no. 7, pp. 1532-1540, July 2019.
- P. Fernández-Martínez et al., "SEE Tests With Ultra Energetic Xe Ion Beam in the CHARM Facility at CERN," in IEEE Transactions on Nuclear Science, vol. 66, no. 7, pp. 1523-1531, July 2019.
- R. G. Alía et al., "Ultraenergetic Heavy-Ion Beams in the CERN Accelerator Complex for Radiation Effects Testing," in IEEE Transactions on Nuclear Science, vol. 66, no. 1, pp. 458-465, Jan. 2019.
- C. Martinella et al., "Current Transport Mechanism for Heavy-Ion Degraded SiC MOSFETs," in IEEE Transactions on Nuclear Science, vol. 66, no. 7, pp. 1702-1709, July 2019.

Further References

- “FLUKA Simulations for SEE Studies of Critical LHC Underground Areas”, K. Roed et al, IEEE TNS, 2011
- “LHC RadMon SRAM Detectors Used at Different Voltages to Determine the Thermal Neutron to High Energy Hadron Fluence Ratio”, D. Kramer et al, IEEE TNS 2011
- “Method for Measuring Mixed Field Radiation Levels Relevant for SEEs at the LHC” K. Roed et al, IEEE TNS, 2012
- “SEU Measurements and Simulations in a Mixed Field Environment”, R. Garcia Alia et al, IEEE TNS, 2013
- “Qualification and Characterization of SRAM Memories Used as Radiation Sensors in the LHC”. S. Danzeca et al, IEEE TNS, 2014
- “SEL Cross Section Energy Dependence Impact on the High Energy Accelerator Failure Rate”, R. Garcia Alia et al, IEEE TNS, 2014
- “A New RadMon Version for the LHC and its Injection Lines”, G. Spiezia et al, IEEE TNS, 2014
- “SEL Hardness Assurance in a Mixed Radiation Field”, R. Garcia Alia et al, IEEE TNS, 2015
- "CHARM: A Mixed Field Facility at CERN for Radiation Tests in Ground, Atmospheric, Space and Accelerator Representative Environments,“ J. Mekki et al, IEEE TNS 2016
- "Monte Carlo Evaluation of Single Event Effects in a Deep-Submicron Bulk Technology: Comparison Between Atmospheric and Accelerator Environment," A. Infantino et al, IEEE TNS, 2017.
- “Single event effects in high-energy accelerators”, R. Garcia Alia et al, Semicond. Sci. Technol, 2017
- “High-energy Electron Induced SEUs and Jovian Environment Impact”, M. Tali et al, IEEE TNS, 2017
- “Simplified SEE Sensitivity Screening for COTS Components in Space”, R. Garcia Alia et al, IEEE TNS, 2017
- "LHC and HL-LHC: Present and Future Radiation Environment in the High-Luminosity Collision Points and RHA Implications,“ R. Garcia Alia et al, IEEE TNS, 2018

Thanks for your attention!