CERN Radiation Hardness Assurance: Challenges and Solutions for Large-Scale Distributed System Exposed to High-Energy Particle Accelerator Environments

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TWEPP 2023 – 2-7 October 2023

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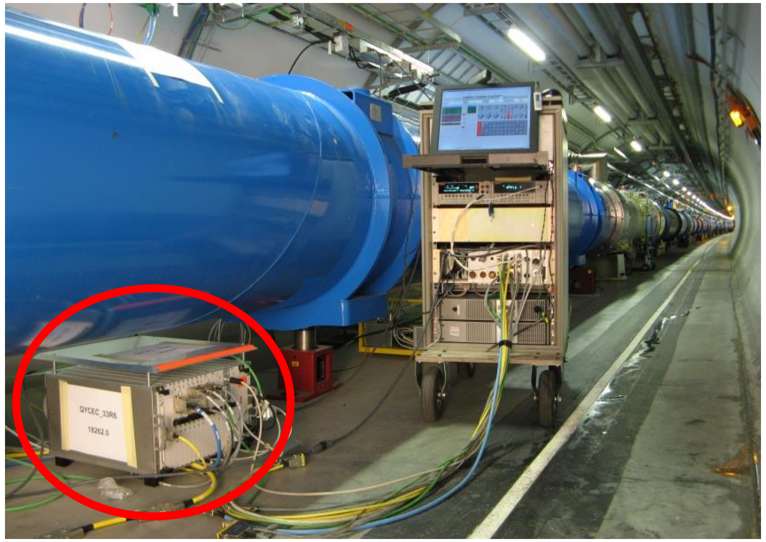
Introduction

- At CERN, a large number of **COTS-based** systems are exposed to the LHC radiation environments
- The **reliability** and the **availability** are a main concern for the CERN electronic equipment located in radiation areas
- The **criticality** of the equipment can be very high, the radiation effects can lead to:
  - **Beam Dumps** → Lost time for physics
  - **LHC safety system failures** → Part of the machine can be destroyed
- In the LHC systems are affected by all radiation effects:
  - **TID and DD:**
    - → Affect system lifetime (permanent failure)
    - → Same failure probability for all units
  - **SEE:**
    - → Stochastic system failure rate
    - → **Failure probability depends on number of systems**



@ Courtesy of the TE/MPE Group

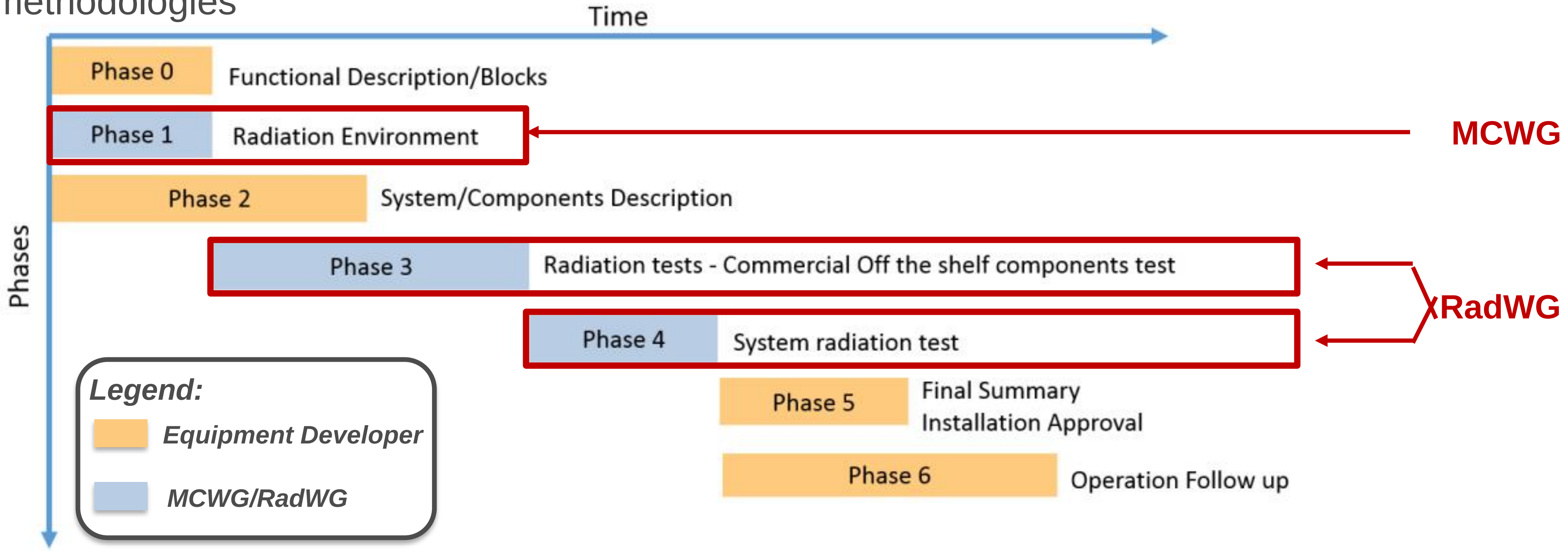
$$N_{SEE\_Failure} = \boldsymbol{N} * \sigma * fluence$$

Number of systems

Example:
DQLPU = 530 units
(Quench Protection unit system)

ATS-CERN RHA Guideline for COTS-based system

Radiation Hardness Assurance (RHA) Procedure for CERN AcceleraTor Sector (ATS) was developed to ensure reliability of radiation-tolerant developments and is based on ESA RHA and reliability methodologies



- Provide advices in early development stages for component choice
- Help analyze system failure observed in operation or during system-level tests and propose mitigation techniques or part replacement candidates

Phase 1: Radiation Environment

- Radiation levels at the electronic equipment locations are provided by the MCWG, in different way:

Previous Analysis

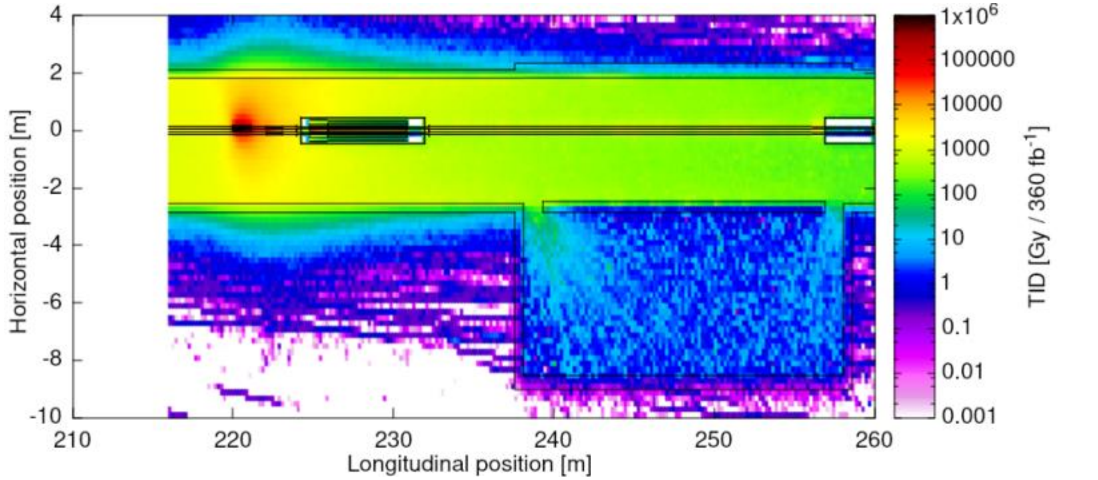
The values of radiation expected for HL-LHC are known for the most important locations of the machine and are available in released documents.

Measurements

Dosimeters are employed to carry out the measurements in the position of interest

Simulation

When monitoring devices are not available, Expected radiation levels are evaluated through simulations

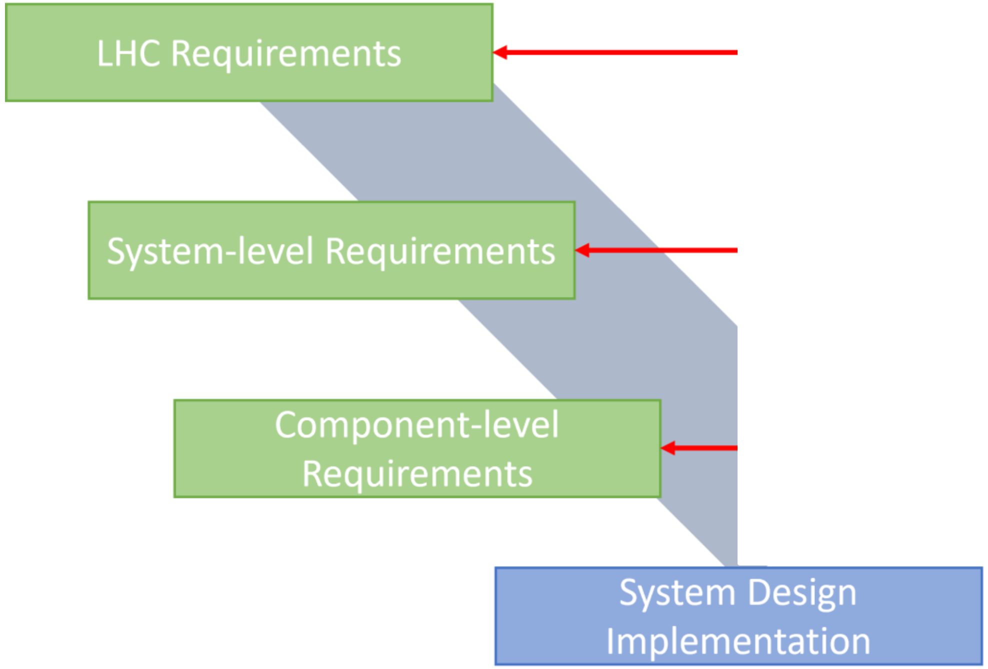


Expected TID for HL-LHC in the x-z in RR17 G. Lerner. Radiation level specifications for hl-lhc. Technical report, CERN EDMS document, https://edms.cern.ch/document/2302154/1.0, Geneva, CH, 2020.

- This information is the initial input that defines all primary requirements and the next qualification phases.

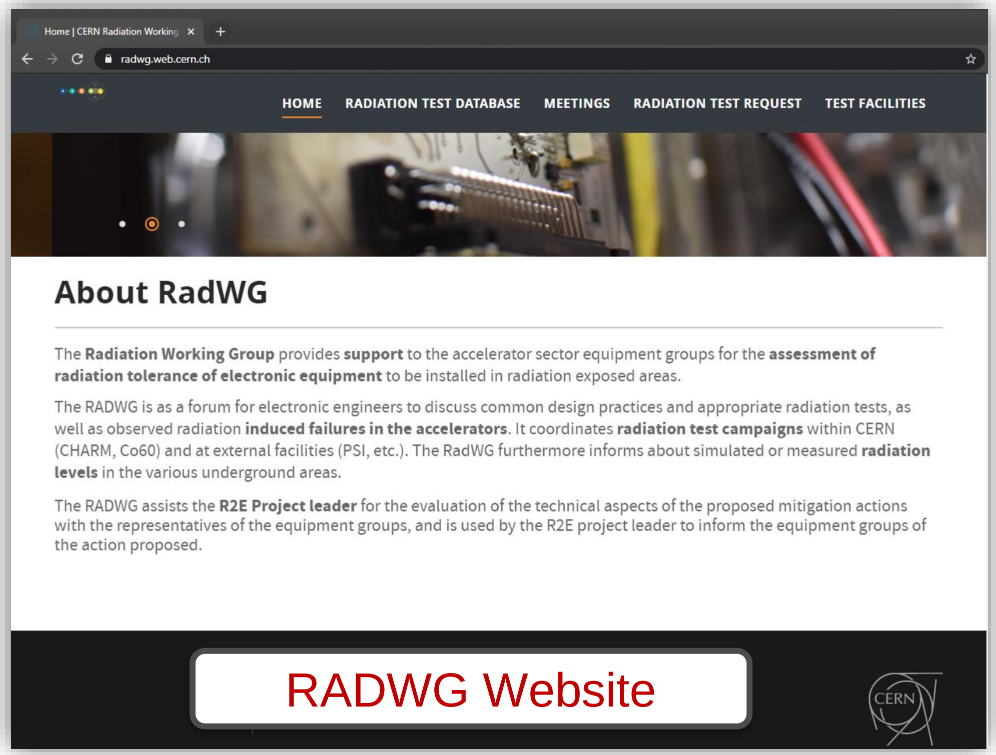
Phase 2: System/Components description

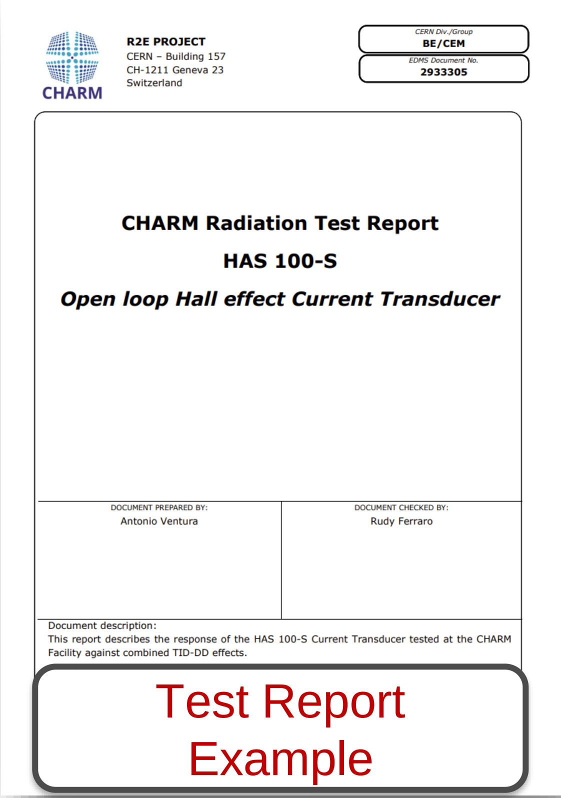
- In Phase 2, availability and reliability requirements at the system and component-level are defined based on the LHC Requirements established also through Phase 1.
- The definition of the requirement tailors the design choices but **not only!**
- The component and system-level qualification phase are strictly interconnected with this Phase: the requirements defined during this step define the constraints that will be necessary to meet during the qualification stages.



Phase 2: System/Components description

A database of Radiation-Tolerant components maintained by the Radiation Working Group (RadWG) is made available to the Equipment groups to select the component meetings their project and radiation tolerance requirements:




CHARM

R2E PROJECT
CERN – Building 157
CH-1211 Geneva 23
Switzerland

CERN Div./Group: BE/CEM
EDMS Document No.: 2933305

CHARM Radiation Test Report

HAS 100-S

Open loop Hall effect Current Transducer

DOCUMENT PREPARED BY:	DOCUMENT CHECKED BY:
Antonio Ventura	Rudy Ferraro

Document description:
This report describes the response of the HAS 100-S Current Transducer tested at the CHARM Facility against combined TID-DD effects.

If no components fits the system's requirements new candidates should be qualified

Phase 2: System/Components description

- The target availability for HL-LHC is 0.1 dumps/fb−1 → whole machine.
  - A conservative approach is followed defining the dumps/fb−1 allowed for each system. It has been estimated that the number of units capable of inducing a beam dump is in the order of ten thousand and thus, its unit should produce 10−5 dumps/fb−1 .
  - The environment that the system will have to withstand is known from Phase1 and can be used to evaluate the respect of the margins.

ID	Requirements
LHC-R001	Each system in the LHC can cause 10^{-5} dump$\cdot fb$

By multiplying the corresponding expected fluence per fb by system Th and HEH cross-sections → expected failure rate per fb is obtained.

Within the specs, DEV-A003 best choice

Phase 2: System/Components description

- The assessment of compliance with the reliability constraints is simpler.The TID and DDEF margins are adjusted by taking into account the expected radiation value of the operating area foreseen in Phase 2 for the whole lifetime of the accelerator (12 years).
- The radiation design margins, where RDM >2 is possible, are taken into account to reflect the statistical distribution of radiation responses of equipment of the same LOT.

ID	Requirements
LHC-R001	In UJ16 are expected 144 Gy in 12 years of operation of HL-LHC
LHC-R002	In UJ16 are expected $6 \cdot 10^{11}$ MeV neq. cm^{-2} in 12 years of operation of HL-LHC
SYS-R001	Considering RDM of 3, all the components have to remain within the defined specs after absorbing 432 Gy and $1.8 \cdot 10^{12}$ MeV neq. cm^{-2}
SYS-R002	The 1.2 V DC-DC converter shall not deviate more than ±10% to not compromise the functionalities of the system
DEV-A001	This DC-DC converter stopped working after cumulated 200 Gy and $3.2 \cdot 10^{11}$ MeV neq. cm^{-2}
DEV-A002	At the RDM, the device was functional but the output was deviated of -12 %
DEV-A003	At the RDM, the device did not exhibit any degradation remaining within the specs

Phase 3: COTS components level testing

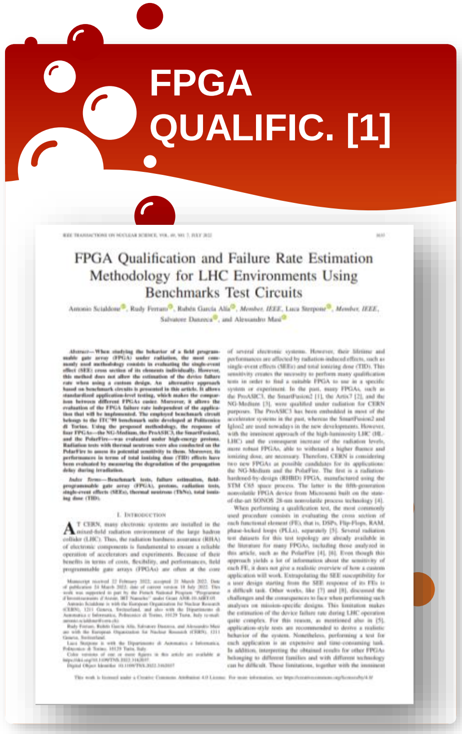
			SEE	TID	DD
Semiconductor Materials	**Si / SiO2** **III-V Compounds (GaAs…)**		Charge collection Carrier drift Depletion area extension	ΔNOT, ΔN_{IT}	Minority carrier decrease Carrier removal Current leakage…
Active Elementary Devices	**Transistor:**	MOSFET	SET, SEB, SEGR, SEL…	ΔV_{TH}	-
		Bipolar…	SET	$\Delta H_{CE}, \Delta I_{CE}, \Delta I_{BE}, \Delta V_{BE}$	$\Delta H_{CE}, \Delta I_{CE}, \Delta I_{BE}, \Delta V_{BE}$
	Diodes:	Zener	SET	$\Delta V_F, \Delta I_L$	$\Delta V_F, \Delta I_L$
		LED	SET	$\Delta V_F, \Delta P, \Delta I_L$	$\Delta V_F, \Delta P, \Delta I_L$
		Schottky…	SET, SEB	$\Delta V_F, \Delta I_L$	$\Delta V_F, \Delta I_L$
Integrated Circuits	**Digital:**	Memory	SEU, SEFI, SEL, MBU…	ΔI_{CC}	-
		FPGA		$\Delta I_{CC}, \Delta t_{PD}$, programmability	-
		µController		$\Delta I_{CC}, \Delta V_{REF}$ …	-
	Analog:	Opamp	SET, SEL	$\Delta v_{off}, \Delta I_{BIAS}, \Delta G, \Delta I_{quiescient}$ …	$\Delta v_{off}, \Delta I_{BIAS}, \Delta G, \Delta i_{quiescient}$
		Regulators		$\Delta I_{CC}, \Delta V_{REF}, \Delta V_{START}$ …	$\Delta I_{CC}, \Delta V_{REF}, \Delta V_{START}$ …
	Mixed:	ADC	SEU, SEFI, SEL, MBU,SET	$\Delta I_{CC}, \Delta V_{REF}, \Delta_{ENOB}$ …	-
		DAC		$\Delta I_{CC}, \Delta V_{REF}, \Delta_{ENOB}$ …	-
		Smart Power		$\Delta I_{CC}, \Delta T_P$	ΔT_P
	Optronics:	Optocoupler	SET	$\Delta CTR, \Delta I_{TH}$	$\Delta CTR, \Delta I_{TH}$
		PhotoMOS		ΔI_{TH}, Switch capability	ΔI_{TH}
SoC Systems	**Can contains all the above**		Destructive events Temporary failures Permanent fault states	Performance degradation Parametric degradation	

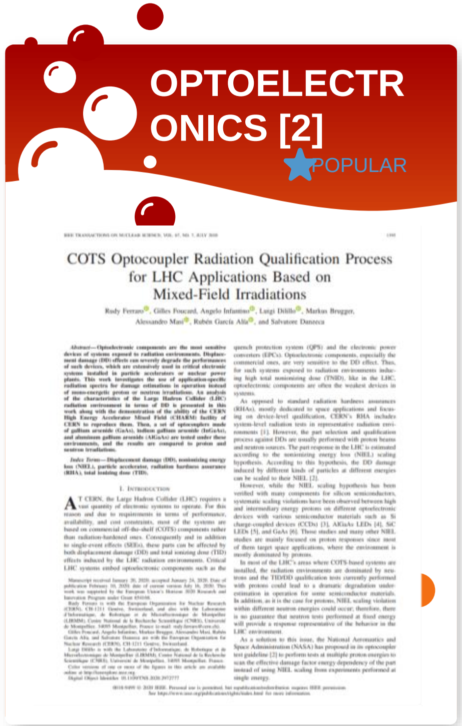
Phase 3: COTS components level testing

		SEE	TID	DD
Active Elementary Devices	**Transistor:** MOSFET Bipolar… **Diodes:** Zener LED Schottky…	MIL-STD-750, SEB/SEGR ESCC25100	ESCC22900 (ELDR) MIL-STD 883 1019.8 MIL-STD750E 1019.5 ASTM F 1892-06	No standard yet but guidelines
Integrated Circuits	**Digital:** Memory FPGA µController **Analog:** Opamp Regulators **Mixed:** ADC DAC Smart Power **Optronics:** Optocoupler PhotoMOS	**Guidelines, conferences, journals, literature etc..:** *“Guideline for Optocoupler Ground Radiation Testing and Optocoupler Usage in the Space Radiation Environment”*, NASA *“Field Programmable Gate Array (FPGA) Single Event Effect (SEE) Radiation Testing”*, NASA *“SEE Testing of ADC and DAC”*, ESCIES *RADECS* Short courses *NSREC* Short courses		
SoC Systems	**Can contains all the above**	**No standards but Guidelines exist (with a big contribution from CERN/R2E):** H. Quinn, "Challenges in Testing Complex Systems,"in IEEE TNS, April 2014 A. Coronetti et al., "Radiation Hardness Assurance Through System-Level Testing: Risk Acceptance, Facility Requirements, Test Methodology, and Data Exploitation,“ IEEE TNS 2021 T. Rajkowski et al., “Comparison of the Total Ionizing Dose Sensitivity of a System in Package Point of Load Converter Using Both Component- and System-Level Test Approaches,” Electronics 2021		

Phase 3: CERN Specific Radiation Qualification Challenges

- In order to obtain more realistic results and to improve the qualification phase at component level, CERN has developed its own guidelines specific to its radiation environment.



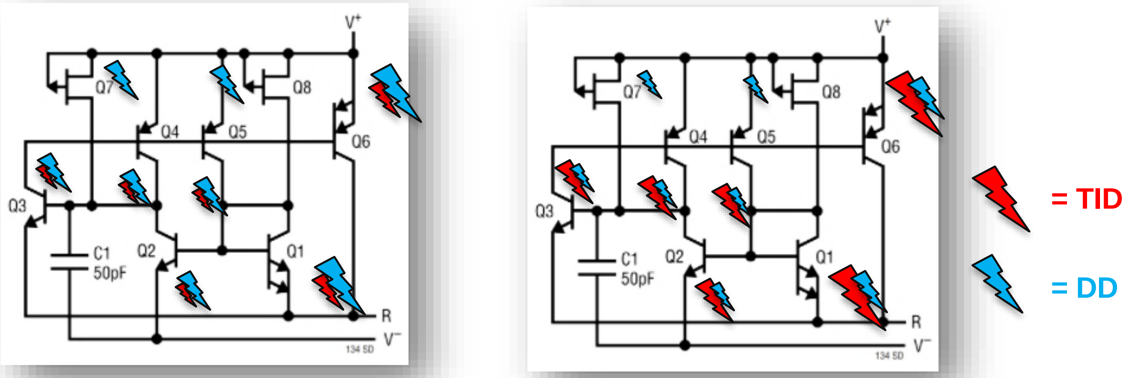


Phase 3: Challenge Example - Impact of LHC TID/DD levels

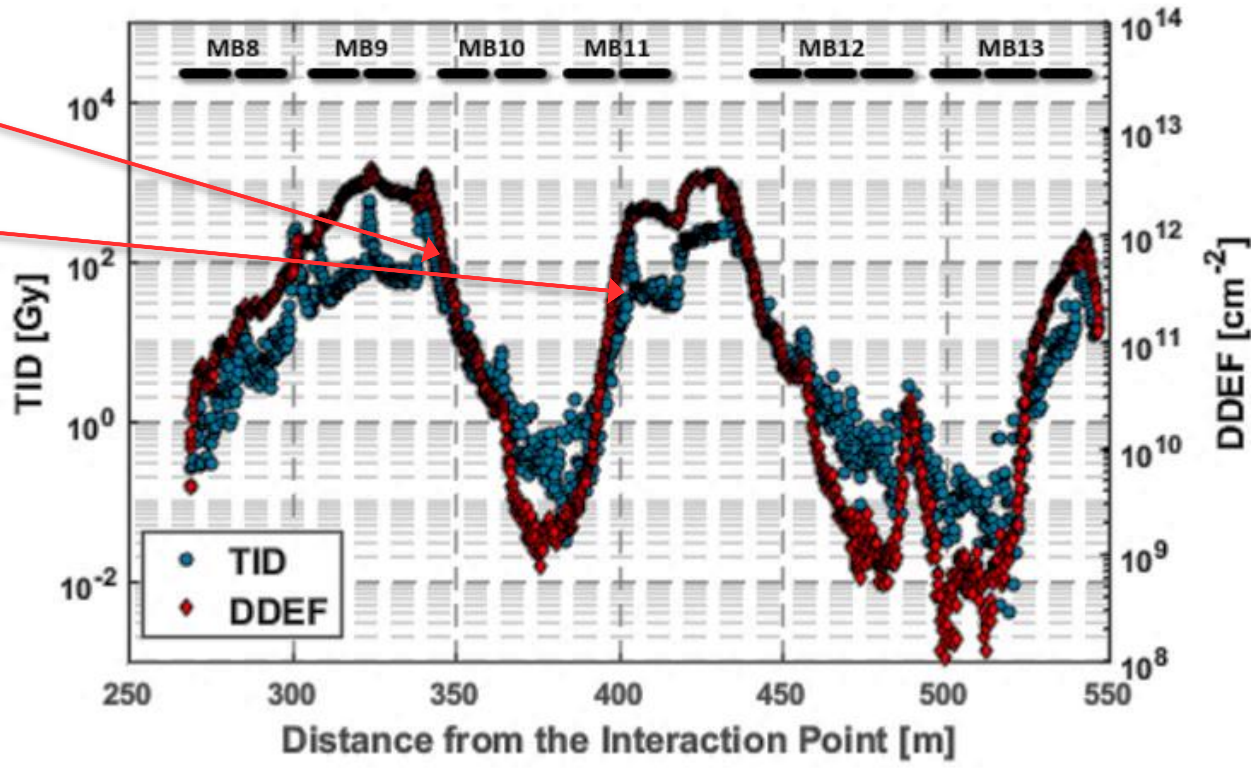
- **In terms of TID-DD effects, the LHC environment present a unique challenge:**
  - **Depending on the areas, a same system can experience different radiation levels:**
    - **Below MB10 for 10 years:**
      - **TID:** 700 Gy
      - **DDEF:** 1 x10^{12} neq. cm^{-2}
    - **Below MB11 for 10 years:**
      - **TID:** 700 Gy
      - **DDEF:** 2x10^{13} neq. cm^{-2}

    → 20 times more DDEF for the same TID

    → Can have strong impact on circuit-effect:



LM334 internal design



DS area Fluka simulation of Radiation levels

Phase 3: Challenge Example - Impact of LHC TID/DD levels

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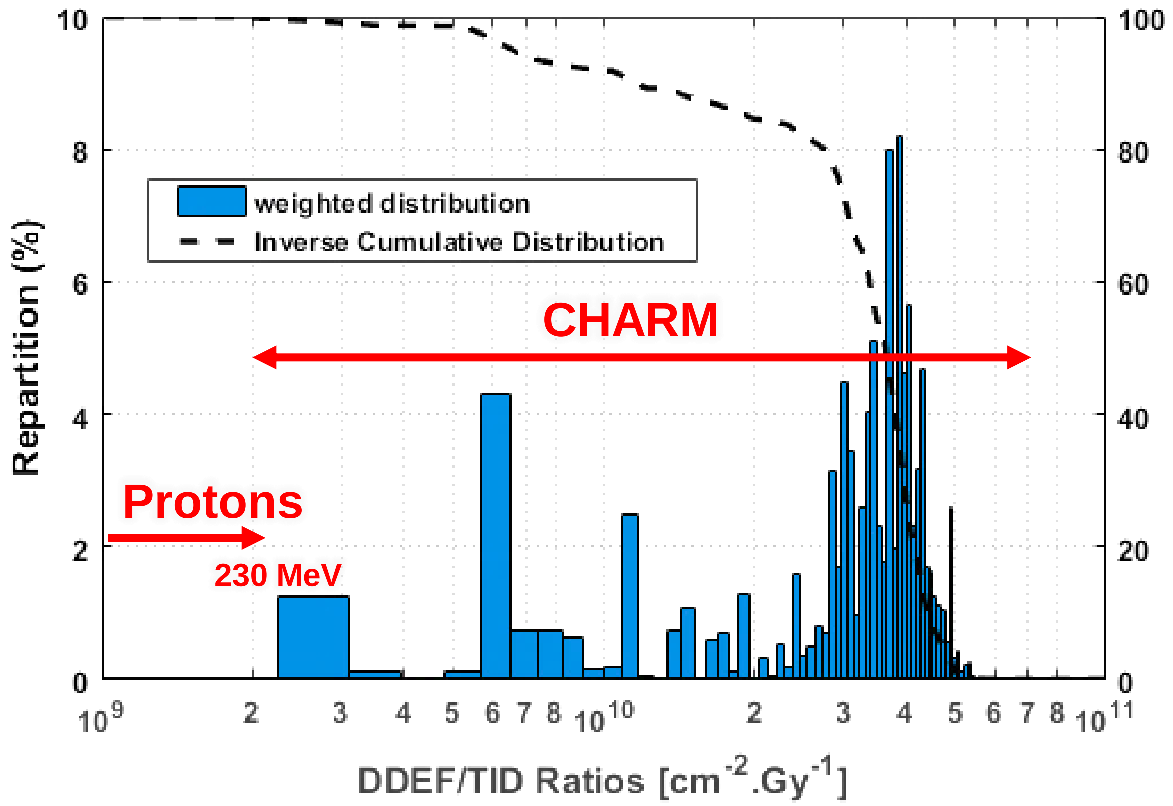
      - **TID:** 700 Gy
      - **DDEF:** 2x10^{13} neq. cm^{-2}

      → 20 times more DDEF for the same TID

- **Wide variety of DDEF/TID Ratio:**
  From **10^9** up to **10^{11} $cm^{-2}.Gy^{-1}$**
  → Can lead to various degradation profiles for devices sensitive to combined TID-DD



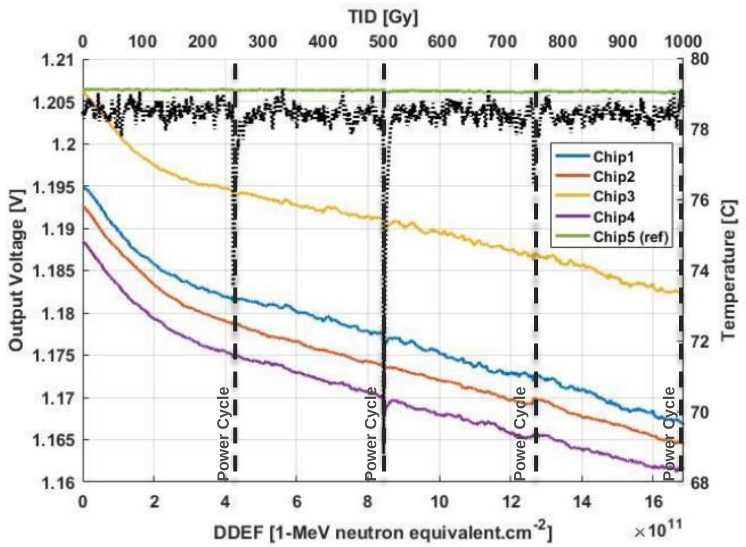
R. Ferraro *et al.*, "Study of the Impact of the LHC Radiation Environments on the Synergistic Displacement Damage and Ionizing Dose Effect on Electronic Components," in *IEEE Transactions on Nuclear Science*, link

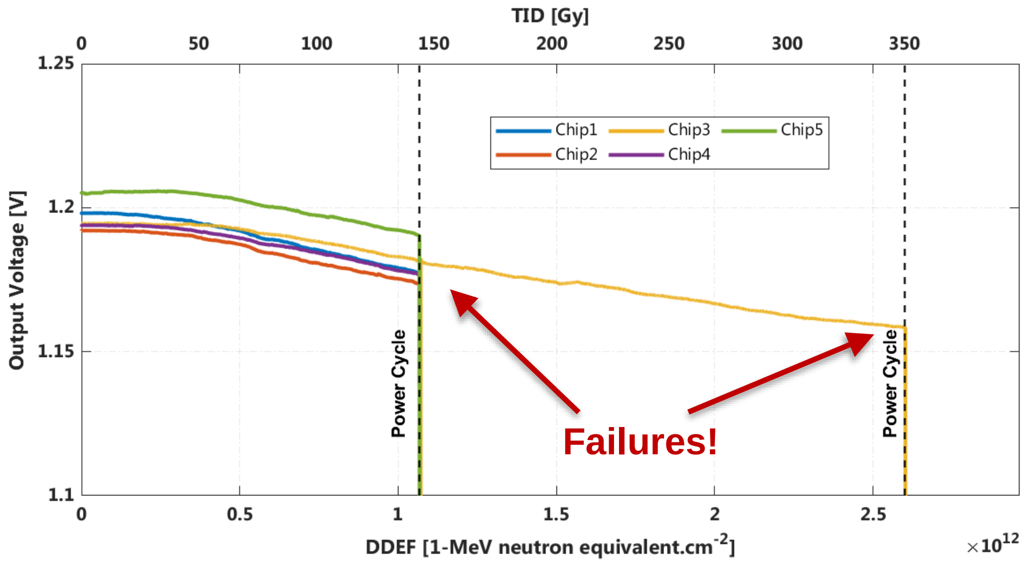
Phase 3: Challenge Example - Impact of LHC TID/DD levels

- Example of a regulator exhibiting different failure degradation rate in different DDEF/TID ratio conditions:

- **LM3083 Adjustable Positive Voltage Regulator:**

  - DDEF/TID = 1.69 x 10^9 neq.cm^{-2}.Gy^{-1} → x 4.5 → DDEF/TID = 7.3 x 10^9 neq.cm^{-2}.Gy^{-1}



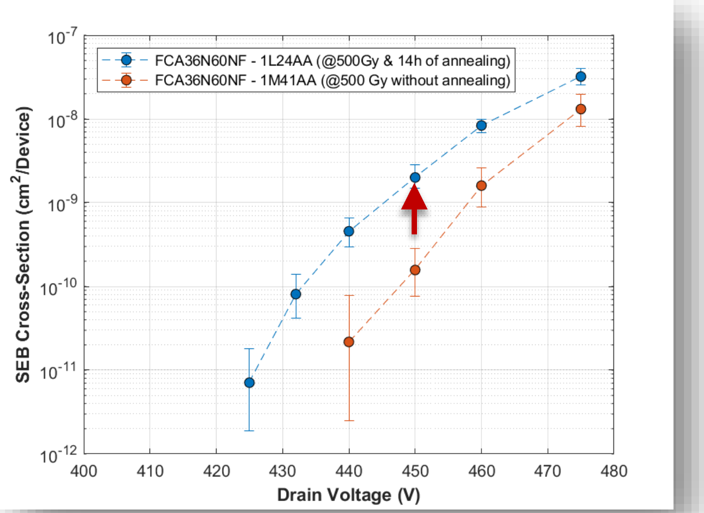


- Negligible output drift up to 1kGy & 1.6 x 10^{12} neq.cm^{-2}
- Complete failure as low as 150 Gy & 1.05 x 10^{12} neq.cm^{-2}

Phase 3: Challenge Example – lot-to-lot variation

Devices can exhibit different radiation sensitivities from lot to lot:

➢ **Single Event Effects:**

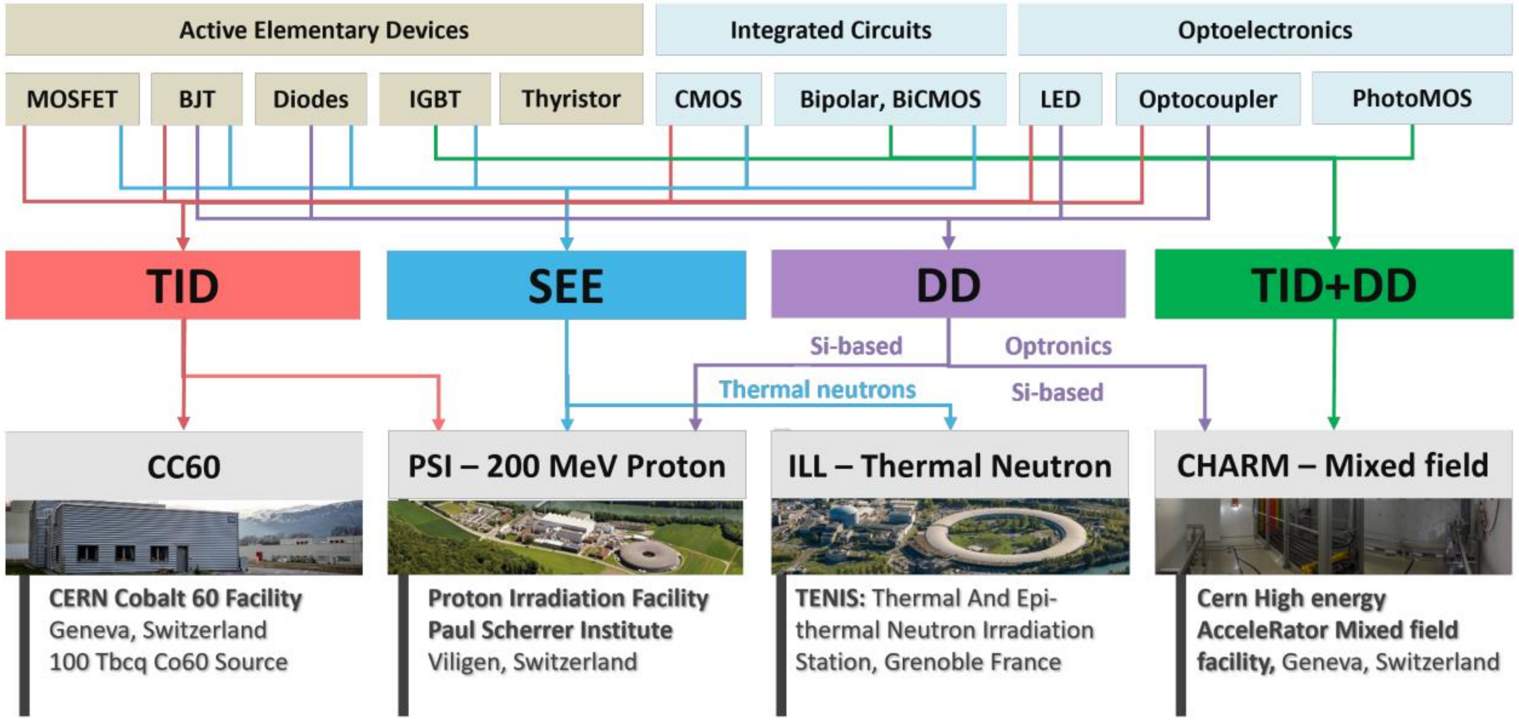


For same drain voltage, cross section 10 times higher!

- If enough samples are tested a single lot variability is usually small enough to meet Radiation Design Requirements (RDR)
- Every production lots should be qualified against radiation
- Procuring single lots for multiple projects allow for reducing overall qualification cost, resources and efforts

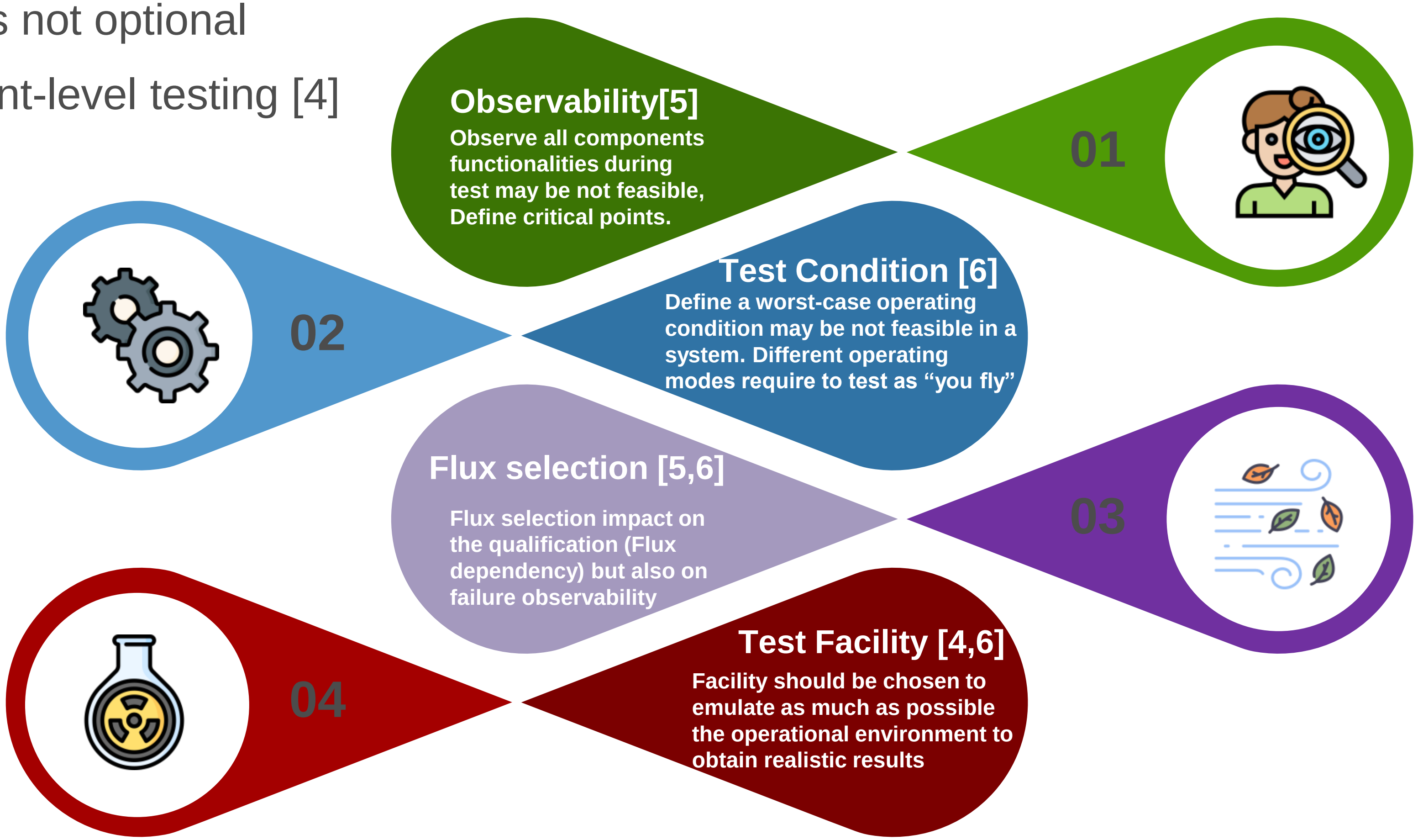
Phase 3: COTS components level testing

All specific challenges and methodologies are combined and address in the CERN RHA procedure and the overall facility selection methodology for the different kinds of components is the following:



Phase 4: COTS System level testing - challenges

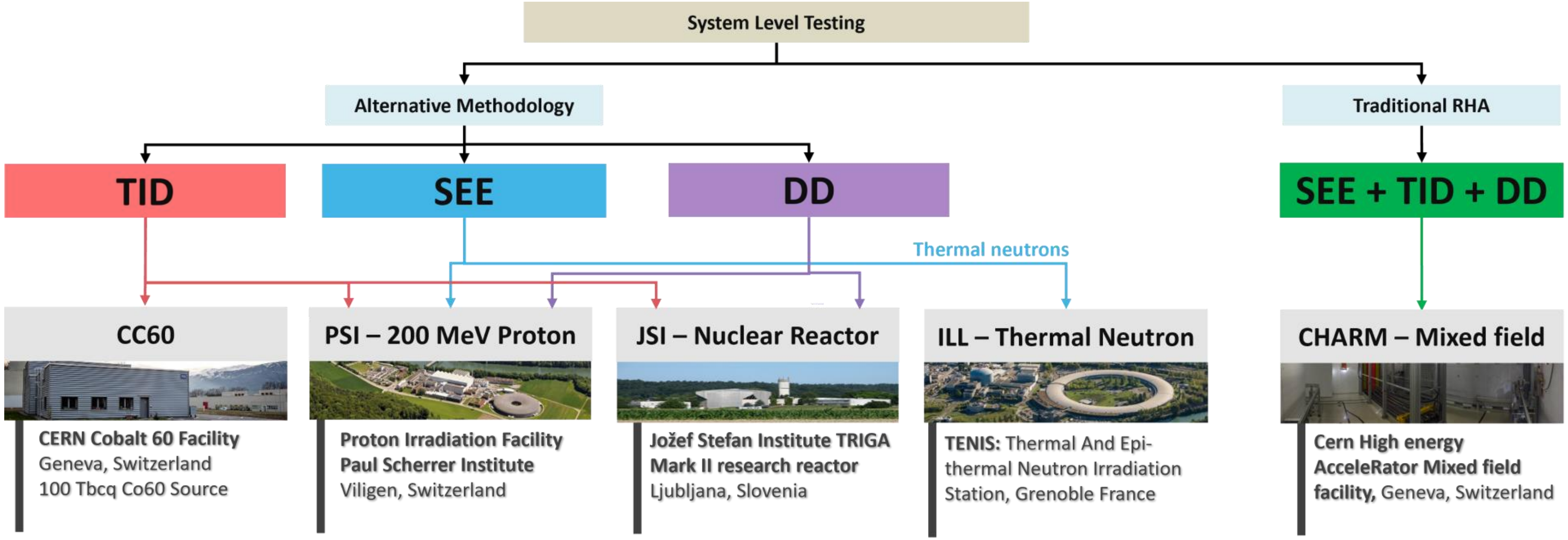
- For CERN system-level testing is not optional
- It is complementary to Component-level testing [4]

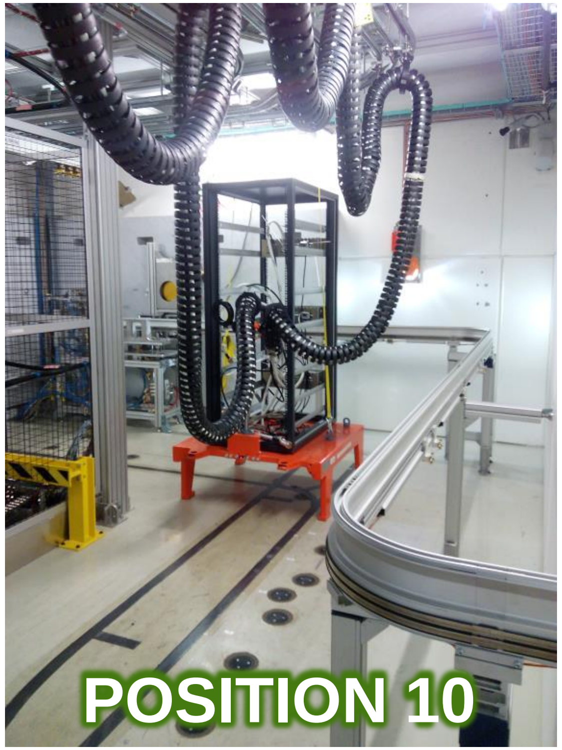


The different publications developed in recent years make it possible to improve this phase and provide guidelines on how to overcome these challenges.

Phase 4: COTS System level testing - strategies

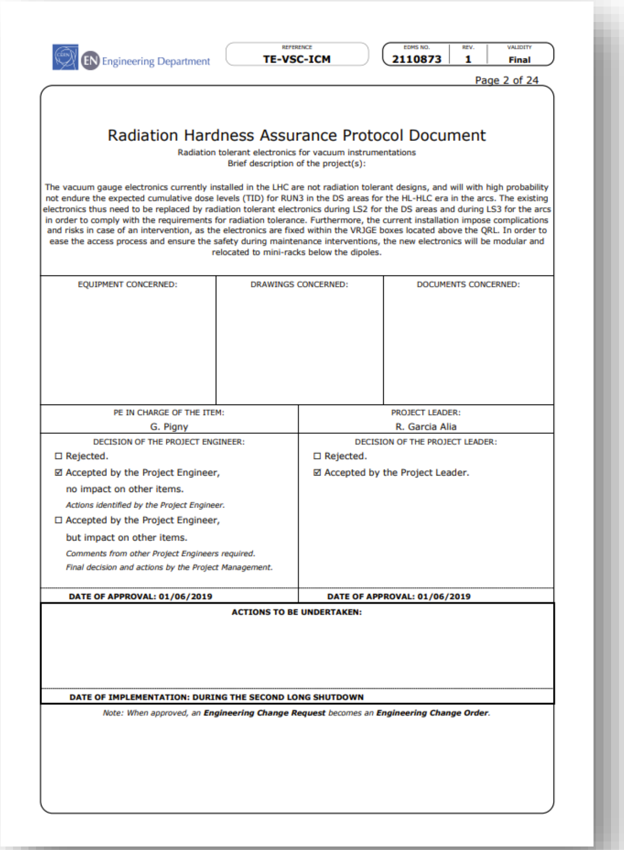
- CERN RHA foresees qualification of system in CHARM-facility. This facility offers the possibility of testing complete electronic systems in a realistic field, fully representative of the mixed-field environment of the high-energy accelerator.
- Its unavailability during LHC Long Shut-down (LS) pushed to the development of alternative methodology capable to provide the advantages of system-level testing.





Phase 5: Installation Approval

- Once all the qualification is performed, a System Radiation Hardness Project Validation document is filled to demonstrate the system reliability against Radiation:



Engineering Department

REFERENCE	EDMS NO.	REV.	VALIDITY
TE-VSC-ICM	2110873	1	Final

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Radiation Hardness Assurance Protocol Document

Radiation tolerant electronics for vacuum instrumentations

Brief description of the project(s):

The vacuum gauge electronics currently installed in the LHC are not radiation tolerant designs, and will with high probability not endure the expected cumulative dose levels (TID) for RUN3 in the DS areas for the HL-HLC era in the arcs. The existing electronics thus need to be replaced by radiation tolerant electronics during LS2 for the DS areas and during LS3 for the arcs in order to comply with the requirements for radiation tolerance. Furthermore, the current installation impose complications and risks in case of an intervention, as the electronics are fixed within the VRJGE boxes located above the QRL. In order to ease the access process and ensure the safety during maintenance interventions, the new electronics will be modular and relocated to mini-racks below the dipoles.

EQUIPMENT CONCERNED:	DRAWINGS CONCERNED:	DOCUMENTS CONCERNED:

PE IN CHARGE OF THE ITEM:	PROJECT LEADER:
G. Pigny	R. Garcia Alia
DECISION OF THE PROJECT ENGINEER: ☐ Rejected. ☑ Accepted by the Project Engineer, no impact on other items. *Actions identified by the Project Engineer.* ☐ Accepted by the Project Engineer, but impact on other items. *Comments from other Project Engineers required.* *Final decision and actions by the Project Management.*	DECISION OF THE PROJECT LEADER: ☐ Rejected. ☑ Accepted by the Project Leader.
DATE OF APPROVAL: 01/06/2019	**DATE OF APPROVAL: 01/06/2019**

ACTIONS TO BE UNDERTAKEN:

DATE OF IMPLEMENTATION: DURING THE SECOND LONG SHUTDOWN

*Note: When approved, an **Engineering Change Request** becomes an **Engineering Change Order**.*

Example of RHAPV Document

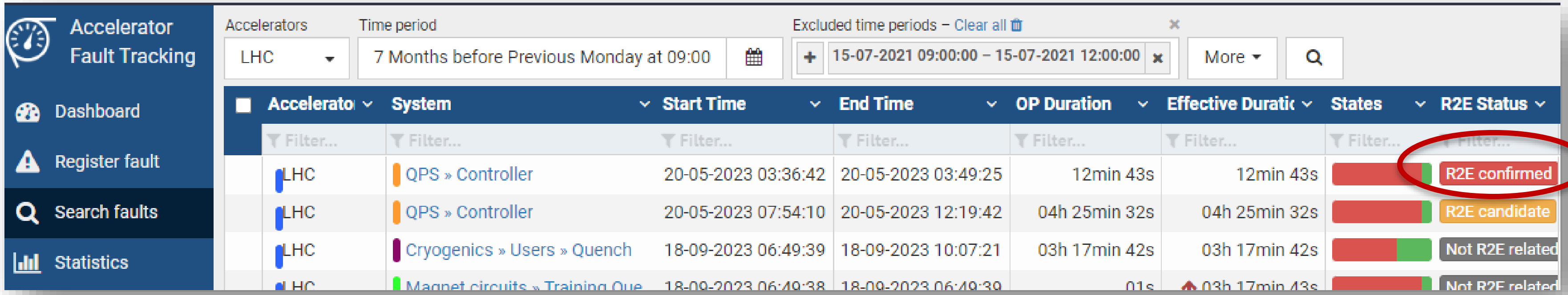
The Document contains:

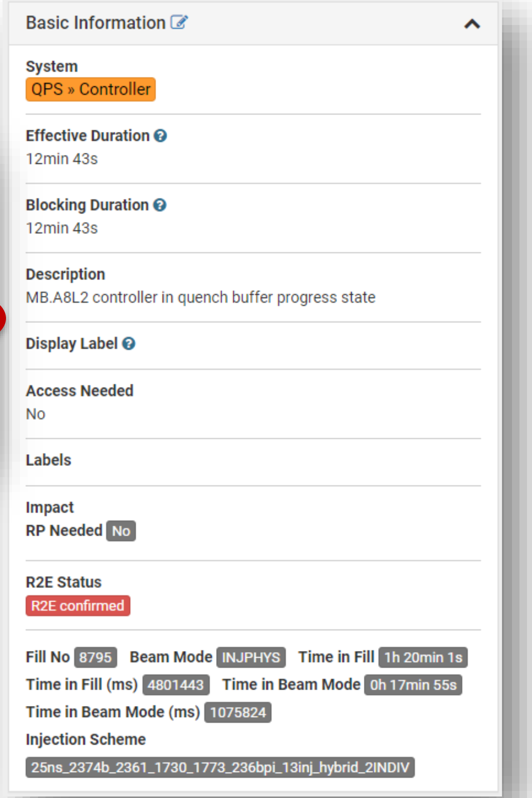
- **Project Description**
  - Technical requirements
  - Criticality
  - Architecture
  - Equipment EDAs
- **Equipment Locations & Radiation Environments**
- **Radiation Tolerance**
  - System/Components Radiation failure modes
  - Component-level qualification
  - System-level qualification

- Linked to the Engineering Change Request (ECR) as final validation
  - **Check-box in ECR** template for electronics installed in possible radiation area

Phase 6: Operation Follow-up

- During operation RHA activities are still ongoing, confirmed or suspected radiation-induced failures are reported on the Accelerator Fault Tracking webtool (aft.cern.ch) and are follow-up with mitigation actions, such as replacement, new system revision etc…





- The failure rate and degradation observed during operation are continuously compared with the estimated values.
- These comparisons allow the validation of the RHA process, but also its extension if unexpected anomalies are observed.

Conclusion

- In this presentation the **CERN Radiation Hardness Assurance (RHA) Procedure was introduced** through an overview of the different Phases constituting it.
- The **different approaches** used to perform the radiation analysis of the LHC environment (Phase 1) were presented.
- The definition of the **system requirements** (phase 2) and **CERN Radiation Database** were outlined.
- The different **challenges related to the LHC radiation environment** required the development of specific **methodologies** to obtain more **realistic possible results**.
  - An example of these methodologies (DDEF/TID ratio impact on degradation rates) was given.
- The **importance of system-level** testing from a CERN perspective was discussed:
  - The challenges are addressed by CERN's approach. However, ongoing studies will improve this phase.
- Once qualified, the system is followed up to verify the effectiveness of the approach.
- The CERN RHA is nowadays a mandatory procedure for all systems installed in no-safe areas

Reference

1) A. Scialdone, R. Ferraro, R. G. Alía, L. Sterpone, S. Danzeca and A. Masi, "FPGA Qualification and Failure Rate Estimation Methodology for LHC Environments Using Benchmarks Test Circuits," in *IEEE Transactions on Nuclear Science*, vol. 69, no. 7, pp. 1633-1641, July 2022, doi: 10.1109/TNS.2022.3162037.

2) R. Ferraro *et al*., "COTS Optocoupler Radiation Qualification Process for LHC Applications Based on Mixed-Field Irradiations," in *IEEE Transactions on Nuclear Science*, vol. 67, no. 7, pp. 1395-1403, July 2020, doi: 10.1109/TNS.2020.2972777.

3) R. Ferraro, R. G. Alía, S. Danzeca and A. Masi, "Analysis of Bipolar Integrated Circuit Degradation Mechanisms Against Combined TID–DD Effects," in *IEEE Transactions on Nuclear Science*, vol. 68, no. 8, pp. 1585-1593, Aug. 2021, doi: 10.1109/TNS.2021.3082646.

4) A. Coronetti *et al*., "Radiation Hardness Assurance Through System-Level Testing: Risk Acceptance, Facility Requirements, Test Methodology, and Data Exploitation," in *IEEE Transactions on Nuclear Science*, vol. 68, no. 5, pp. 958-969, May 2021, doi: 10.1109/TNS.2021.3061197.

5) Alessandro Zimmaro, Rudy Ferraro, Jérôme Boch, Frédéric Saigné, Rubén García Alía, Alessandro Masi, and Salvatore Danzeca. Radiation test flux selection methodology to optimize see observability on systems with different operating modes. In 2022 22th European Conference on Radiation and Its Effects on Components and Systems (RADECS), pages 1–8, 2023

6) A. Zimmaro *et al*., "Testing and Validation Methodology for a Radiation Monitoring System for Electronics in Particle Accelerators," in *IEEE Transactions on Nuclear Science*, vol. 69, no. 7, pp. 1642-1650, July 2022, doi: 10.1109/TNS.2022.3158527..

Thank you for your attention!

Controls
Electronics &
Mechatronics

CHARM Mixed Field Facility

- Primary 24 GeV proton beam coming from PS impinges a target
- Secondary radiation fields similar to the LHC radiation fields.
- Radiation field can be modulated with:

➢ **Target:**

Cu - Copper
Al - Aluminium
AlH - Aluminium Hole

➢ **Shielding:**

C – Concrete **(1,4)**
I – Iron **(2,3)**

➢ **Positions:**

Lateral **(1:9)**
Longitudinal **(9:13)**