R2E AND AVAILABILITY

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Abstract

The Radiation to Electronics (R2E) Project is responsible for the development and the implementation of mitigation actions to minimize the radiation induced failures in the electronics and thus to optimize the availability of the Large Hadron Collider (LHC). Significant shielding and relocation mitigation actions, coupled with a large number of equipment upgrades are being implemented during the first LHC Long Shutdown of 2013/2014 (LS1) in five LHC Points (Points 1, 4, 5, 7 and 8) and for electronics deployed in the remaining critical areas such as the LHC tunnel and adjacent RRs. This report first provides a brief summary of the radiation levels, the observed failures during Run-1, the LS1 R2E activities with particular focus on the expected improvements on the overall system failures. The last part of the report focuses on the qualification strategy, including radiation hardness assurance procedures and test facilities.

INTRODUCTION

Particle debris emerging from the experiments, secondary showers from collimators or other beam intercepting devices, as well as beam–gas interactions impact equipment being present inside and areas adjacent to the LHC tunnel (UJs, RRs). Respectively installed (present or future) control systems are either fully commercial or based on so-called COTS (Commercial-Off-The-Shelf) components, both possibly affected by radiation. This includes the immediate risk of so-called Single Event Effects (SEE) and a possible direct impact on beam operation, as well as in the long-term, also cumulative dose effects (impacting the component/system lifetime) which additionally have to be considered.

For the tunnel equipment in the existing LHC, certain radiation tolerant design criteria were already taken into account prior first LHC operation. However, most of the equipment placed in adjacent and partly shielded areas was not conceived nor tested for their current radiation environment. Therefore, given the large amount of electronics being installed in these areas, during the past years a CERN wide project called R2E (Radiation To Electronics) [1] has been initiated to quantify the danger of radiation-induced failures and to mitigate the risk for nominal beams and beyond to below one failure a week. The respective mitigation process included a detailed analysis of involved radiation fields, intensities and related Monte-Carlo calculations; radiation monitoring and benchmarking; the behaviour of commercial equipment/systems and their use in the LHC radiation fields; as well as radiation tests with dedicated test areas and facilities [2, 3].

In parallel, radiation induced failures were analysed in detail in order to confirm early predictions of failure rates [4, 5], as well as to study the effectiveness of implemented mitigation measures. Figure 1 shows the actual number of SEE failures measured during 2011 and 2012 operation, the achieved improvement (please note that the failure rate measured during 2011 already included mitigation measures implemented during 2009 and 2010), as well as the goal for operation after LS1 and later during HL-LHC.

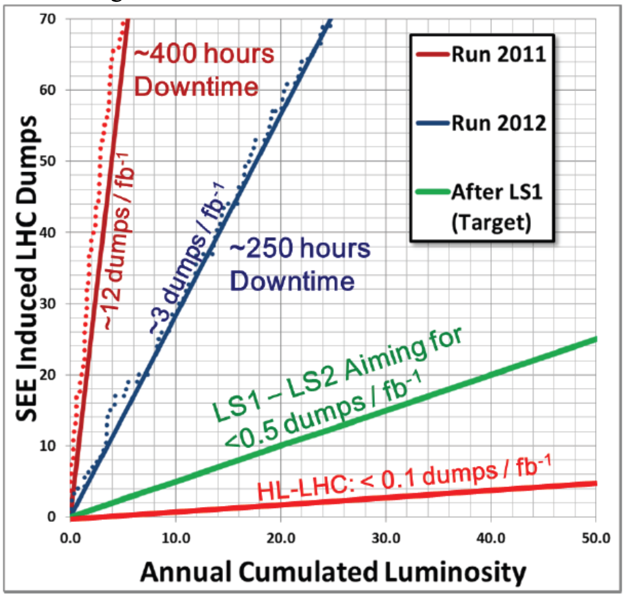

Figure 1: LHC beam dumps due to single-event effects against beam luminosity. Dots (2011 and 2012) refer to measurements, whereas lines show annual averages for both, past and future operation.

This implies that electronic control systems are either installed in fully safe areas, sufficiently protected by shielding or adequately radiation tolerant. The last implies existing equipment, but also any future equipment to be possibly installed in R2E critical areas to be conceived in a specific and qualified way – a procedure usually referred to as ‘Radiation Hardness Assurance (RHA)’ [6].

RADIATION ENVIRONMENT AND CRITICAL AREAS

Radiation damage to electronics is often considered with space applications. However, it is important to note that the radiation environment encountered at the LHC, the high number of electronic systems and components partly exposed to radiation, as well as the actual impact of radiation induced failures strongly differ from the context of space applications. While for the latter application design, test and monitoring standards are already well defined, additional constraints, but in some cases also simplifications have to be considered for accelerator environment. The mixed particle type and energy field encountered in the relevant LHC areas is composed of charged and neutral hadrons (protons, pions, kaons and neutrons), photons, electrons and muons ranging from thermal energies up to the GeV range [7].

Over the past years, this complex field has been extensively simulated by the FLUKA Monte Carlo code and benchmarked in detail for radiation damage issues at the LHC [8-11]. The observed radiation is due to particles generated by proton–proton (or ion–ion) collisions in the LHC experimental areas, distributed beam losses (protons, ions) around the machine, and to beam interacting with the residual gas inside the beam pipe. The proportion of the different particle species in the field depends on the distance and on the angle with respect to the original loss point, as well as on the amount (if any) of installed shielding material. In this environment, electronic components and systems exposed to a mixed radiation field will experience three different types of radiation damages: these are displacement damage, damage from the Total Ionising Dose (TID) and the SEEs [11]. The first two are of cumulative nature and are measured through TID and nonionizing energy deposition (NIEL, generally quantified through accumulated 1-MeV neutron equivalent fluence), where the steady accumulation of defects cause measurable effects which can ultimately lead to device failure. As for stochastic SEE failures, they form an entirely different group as they are due to the direct ionization by a single particle, able to deposit sufficient energy through ionization processes in order to disturb the operation of the device. They can only be characterized in terms of their probability to occur as a function of accumulated High Energy (>5–20 MeV) Hadron fluence. The probability of failure will strongly depend on the device as well as on the flux and nature of the particles. In the context of HL-LHC, several tunnel areas close to the LHC tunnel, and partly not sufficiently shielded, are equipped with commercial or not specifically designed electronics which are mostly affected by the risk of SEEs, whereas electronics installed in the LHC tunnel will also suffer from accumulated damage in the long-term.

For this purpose, during the first years of LHC operation, the radiation levels in the LHC tunnel and in the shielded areas have been measured by using the CERN RadMon system [12] dedicated to the analysis of radiation levels possibly impacting installed electronic equipment. Table 1 summarises the level of accumulated High Energy Hadron (HEH) fluence measured during 2012 for the most critical LHC areas where electronic equipment is and will be installed. The HEH fluence measurements are based on the RadMon reading of the Single Event Upsets (SEU) of SRAM memories whose sensitivity was extensively calibrated in various facilities [13-16]. The results obtained during 2012 LHC proton operation show that the measurements very well compare with previously performed FLUKA calculations and observed differences can actually be attributed to changes of operational parameters not considered in the calculations [5].

EQUIPMENT FAILURE ANALYSIS

2012 LHC operation was a key period for the analysis of radiation induced failures on machine equipment. As briefly shown in the previous section, the very successful LHC operation has confirmed the estimates of the radiation levels provided in Chamonix 2012 and successfully confirmed the strategy of early mitigation measures taken in previous years. During 2012 a strong emphasis was put in the detailed analysis of equipment failures which could possibly be linked to radiation effects and to verify if all of them are addressed throughout the LS1 mitigation measures. To study the correlation with radiation in detail, a number of criteria have been set, implying one, several and, ideally, all of the following conditions to be fulfilled:

- equipment failure occurs during periods with beam-on/collisions/losses (*i.e.*, source of radiation)
- the failure(s) is/are not reproducible in the laboratory
- the failure signature was already observed during radiation tests (CNRAD, H4IRRAD and others)
- failure frequency increases with higher radiation

For rare cases this implies remaining uncertainties which can lead to failures being incorrectly attributed to radiation. However, the performed detailed studies over the 2012 operation period limited these uncertainty cases to only a few. In addition, there is the complementary limitation that the analysis is likely to miss radiation induced failures which do not lead to a beam dump. In addition more complex events where a particular unit is affected by radiation, then in turn indirectly causing a problem to another one, thus eventually leading to either longer downtimes or beam dumps.

The radiation induced failures on the LHC equipment have been analysed by organizing a weekly shift within the R2E project team. The main sources of information were the LHC e-logbook and the meeting on the LHC operation follow-up, daily held at 8h30. During the year, the collaboration of all the equipment groups was highly appreciated and permitted to improve the performed failure analysis. Once a failure is suspected to be related to radiation effects, the following information is collected and stored on the web page of the RADiation Working Group (RADWG) [6]: a) equipment, b) type of failure, c) location, d) consequence of the failure, e) number of beam fill. In some cases, it is not straight forward to understand if a failure was effectively due to radiation effects. Thus, the event is marked as *to be confirmed (TBC)* if a further analysis is required to understand what happened. In addition, the number of the beam fill was used as a direct link to insert information also in the Post Mortem (PM) database and in order to track the beam dumps that were due, or possibly due (*to be confirmed*), to radiations and require a respective detailed analysis by the operators and the equipment groups. Table 2 shows the failures due to SEEs.

Table 1. Overview of critical areas and respective radiation levels (please note that local distributions can vary according to the detailed location – values refer to worst case locations).

ANNUAL RADIATION LEVELS	Assumptions for various periods:	based on measurements as reported in 2012 summary then used with calculations for scaling				similar to 2012 bit less lumi higher energy 25ns +scrubbing (x2 for ARC/DS)		50fb-1y-1 6.5TeV IR3/7: ~1x10^{16} ~2-3x10^{14} p.	
Location	Area Assumptions	HEH Fluence [cm^{-2}y^{-1}]	Dose [Gy y^{-1}]	HEH Fluence [cm^{-2}y^{-1}]	Dose [Gy y^{-1}]	HEH Fluence [cm^{-2}y^{-1}]	Dose [Gy y^{-1}]	HEH Fluence [cm^{-2}y^{-1}]	Dose [Gy y^{-1}]
		RUN-1				RUN-2			
		2011		2012		2015		[2016; 2018]	
Tunnel ARC MQ	beam-gas ~10^{15}			3E+08	0.5	5E+08	1.0	5E+08	1.0
Tunnel ARC MB	beam-gas ~10^{15}			1E+08	0.2	2E+08	0.4	2E+08	0.4
Tunnel DS MQ				3E+09	5.0	5E+09	10.0	5E+09	10.0
Tunnel DS MB				1E+09	2.0	2E+09	4.0	2E+09	4.0
Tunnel DS Worst	worst RadMon/BLM			5E+09	10.0	1E+10	20.0	1E+10	20.0
RRs (P1/5)	shielding >LS1	1E+07	NIL	3E+07	NIL	3E+07	NIL	8E+07	0.1
RRs P7		1E+07	NIL	4E+07	NIL	4E+07	NIL	1E+08	0.1
UJs P1	full shielding	1E+08	0.1	2E+08	0.3	2E+08	0.3	5E+08	1.0
UJ/RE32	based on RadMon on tunnel side			1E+06	NIL	2E+06	NIL	2E+06	NIL
UJ56		3E+07	NIL	2E+08	0.1	2E+08	0.1	5E+08	0.9
UJ76		1E+07	NIL	8E+07	0.1	8E+07	0.1	2E+08	0.5
ULs P1 start equ.	where 1st PCs are					2E+06	NIL	6E+06	NIL
ULs P1 end equ.	towards US								
UPS P1/5 Corner	no equipment					2E+09	5.0	6E+09	12.0
UPS P1/5 Behind	+UX contribution								
UX45		2E+06	NIL	2E+07	NIL	4E+07	NIL	4E+07	NIL
UX65						1E+06	NIL	1E+06	NIL
UX85(b)		2E+08	0.2	3E+08	0.3	3E+08	0.3	6E+08	0.6
US85	lumi scaling diff.!	2E+07	NIL	1E+08	0.1	1E+08	0.1	1E+08	0.2
UW85	shielding as efficient as designed					2E+06	NIL	4E+06	NIL
US45								1E+06	NIL
REs	shielding as is							1E+06	NIL
UJ23 (next UA23) UJ87 (next UA87)	injection losses remain comparable	2E+06	NIL	3E+06	NIL	6E+06	NIL	6E+06	NIL
Mazes (e.g, UA23, UA83)	streaming based on RadMon reading			1E+06	NIL	2E+06	NIL	2E+06	NIL
TZ76 (1st 15m), UA63/67 (behind ducts) UJ33	ok, but to be monitored during operation					1E+06	NIL	2E+06	NIL
All Other	ok								

Colour Codes				
HEH			TID	
low	1.00E+06		low	0.1
mid	1.00E+07		mid	1.0
high	1.00E+08		high	10.0

Table 2: Number of failures due to radiation. A detail view of the destructive events is given below.

Dump Confirmed	**Dump TBC**	**No Dump**	**No Dump TBC**
58	10	36	7
Destructive Failures			
17	1	4	0

Four distinct failure cases are reported:

a) Events leading to beam dump (Dump confirmed).
b) Events leading to beam dump which are possibly due to radiation (Dump TBC).
c) Failures which did not lead to beam dump (No Dump).
d) Failures which do not lead to beam dump and are possibly due to radiation (No Dump TBC).

The second part of Table 2 highlights the observed destructive failures, i.e. failures which triggered an intervention in the machine to replace a component/system. They represent ~30% of the total number of events leading to a beam dump. It is important to note that the number of events to be confirmed represents only a small fraction and will thus not affect the overall conclusion. Figure 2 shows the distribution of the failures per area (a) and per equipment (b). The failures per area are almost equally distributed among the alcoves which were known to be prone to radiations.

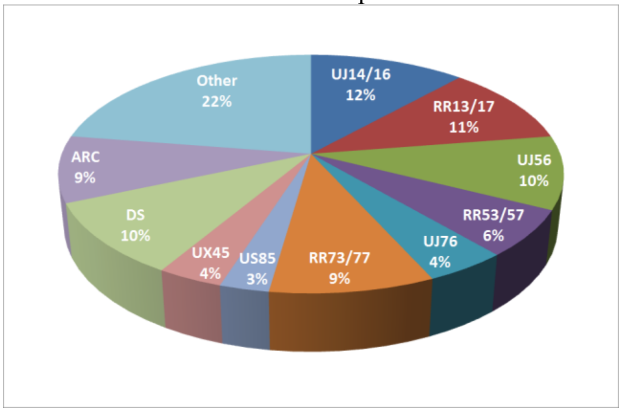

Figure 1a: Failure distribution per area

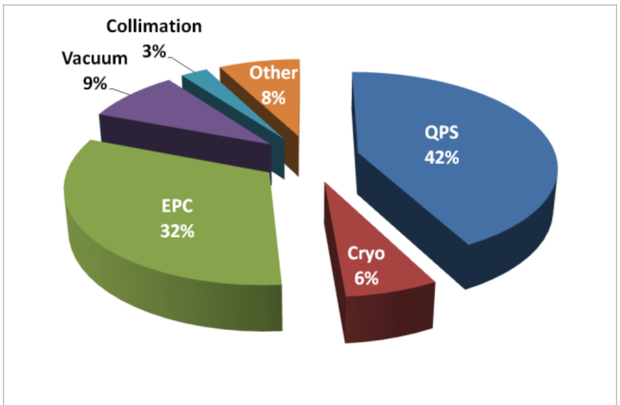

Figure 1b. Failure distribution per equipment.

As compared to 2011 operation and the respective observed SEE related failures [4], this also reflects the successful implementation of R2E countermeasures where the focus was put on the most exposed areas, thus bringing all of the critical areas more or less to the same exposure level (also visible in the reported radiation levels for 2012). I.e, the number of failures in the UJs of Point 1 is not as dominant as along 2011, showing the effectiveness of the shielding that was put in place in the 2011-12 xMasBreak [2, 3]. The majority of the failures that occurred in the tunnel was related to the Quench Protection System (QPS) electronics. The EPC equipment, installed in the RR areas, presented a recurrent failure due to a destructive event on an auxiliary power supply. In addition to the shielding at point 1, the relocation of a few sensitive equipment (Cryogenic, Beam, Power interlocks, and UPS devices), as well as the patch solutions applied on the equipment that could not be moved yet, allowed to significantly decrease the overall number of failures with respect to 2011.

LS1 RELOCATION & SHIELDING ACTIVITIES

During 2012 operation, monitored radiation levels as well as in parallel carried out Monte-Carlo simulations (FLUKA) have motivated additional actions to be performed in Point 4, in addition to those already scheduled in Points 1, 5, 7 and 8 (see Figure 3) and the respective implementation involves fifteen groups across the different CERN Departments [17-19].

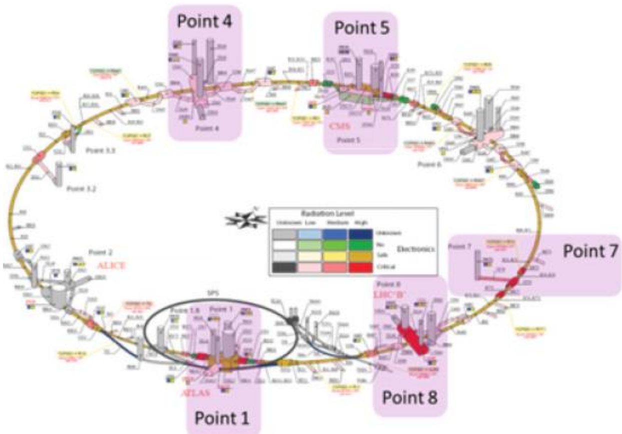

Figure 3: LHC critical areas considered for shielding and relocation activities.

The foreseen improvements to mitigate the effects of radiation to electronics were studied in detail. This will allow the beam dumps caused by SEEs to be further reduced according to the requirements for nominal LHC operation (from originally ranging in the few hundreds to only a few tens). As mentioned above, already only for the relocation activities, in total fifteen groups are involved in the relocation of a total of 90 racks, ranging from power converters, electrical equipment, to safety control units located in Points 1, 4, 5, 7 and 8. The existing concrete shielding of the RRs located in Points 1 and 5 is at the same time replaced by cast iron. Additional shielding is installed at Point 8 and major civil engineering works are carried out at Point 5 and Point 7 (ducts, removal of walls).

Point-4

During 2012 LHC operation, only very few failures (but major as impacting cryogenics control equipment) were observed on the cryogenics equipment located in

LHC Point 4. A possible future increase of the radiation levels could not be excluded during future changes in beam operation, however at first the relocation of the cryogenics equipment was put on hold, mainly due to the cable length limitation of special existing cables (15 metres) avoiding the equipment relocation outside the close surrounding area. In parallel, the cryogenics team (TE/CRG) successfully collaborated with firms to develop longer cables which resulted in the first production and test of longer cables (40 m) during the first semester of 2013. This provided us the opportunity to study together with the cryogenics team and other impacted equipment groups the relocation options for all critical equipment installed in Point 4. It turned out that several months were required for the relocation activities that could thus only be carried out during a Long Shutdown (LS). After a preliminary planning and the confirmation of the availability of required resources, by the end of May 2013 the LHC LS1 Committee gave its approval to perform these relocation activities during LS1.

The work towards implementation followed three main phases. The first phase was the identification/definition of the sensitive equipment to be relocated [20]. In addition to one Personal Access Door (PAD) and one fire detection control unit the following cryogenics equipment was identified as equipment to be relocated: the cold compressor system, the cold box 1.8 K, the cryogenics distribution box 4.5 K, the associated SIPART valves positioners and the control system of the cryogenics RF cavities. The second phase was the study of the activities to be performed with their associated technical and integration issues. The third phase was the definition of the activities sequence and then the definition of the baseline planning. The mitigation activities started in January 2014. They were scheduled over 26 weeks with only two weeks of margin with the start of the 'flushing' activity in the adjacent sectors.

Safe Rooms

The electrical services dedicated to personal safety as general emergency stop, safety lighting etc., are installed underground in dedicated 'safe - rooms' ensuring the functionality of their inner equipment during two hours in case of external fire. Part of this equipment was found to be sensitive to radiation (Single Event Effects (SEE)) and in the Points 5 and 7 the 'safe - rooms' were located in areas identified as critical in terms of radiation. It was thus decided to relocate the sensitive parts respectively, to the UL557 and in the TZ76 galleries. Due to space constraints, a classical implementation of a 'safe room' (constructed through walls, etc.) in the TZ76 gallery was not possible. The only respective way would have implied long and costly civil engineering work. The alternative solution was to relocate the equipment inside several individual and certified fire resistant enclosure with a dedicated and integrated ventilation system (see Figure 4).

In Point 5, due to safety constraints linked to the CMS experiment emergency exit path and due to integration issues, the optimal solution was to build a new 'mini safe room' in the UL557 with reduced dimensions. The associated ventilation system had to be located in the adjacent UL558 gallery. The design and implementation of this ventilation system were not trivial and required to solve several technical and safety issues (e.g., the respective ventilation control system allowing for highly reliable and fully redundant cooling during LHC operation).

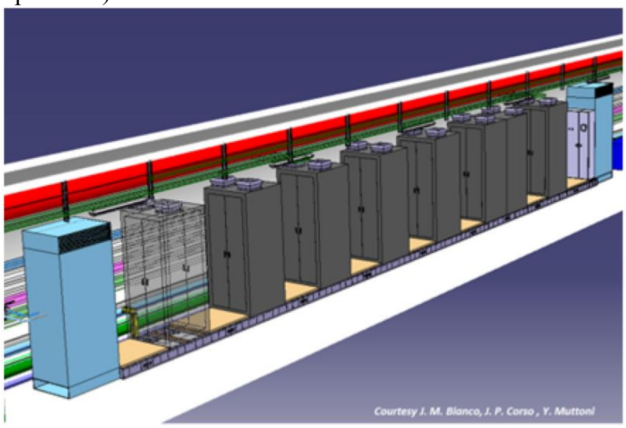

Figure 4: Relocation of Point 7 safe room equipment inside individual fire resistant enclosure.

EQUIPMENT UPGRADES & DEVELOPMENTS

To provide an example for very complex accelerator control systems and respective design/mitigation constraints to be carried out during LS1, we give a brief description of two key systems for the LHC machine: the Quench Protection System and the Power Converters, and how radiation tolerant strategies are applied taking into account the criticality of the system, the location, the impact of its failure on machine operation and the available timeline for developments and required upgrades.

For both cases, a review of the initial design with radiation tolerant constraints was required because a large number of individual units are installed in locations exposed to various radiation levels. In particular, the QPS case study provides an example of radiation tolerant development where a trade-off and simplifications had to be considered because of tight time line constraints (as upgrades were required in a very short available time-frame). The power converter case study provides an example of a radiation tolerant development over a longer time period where design and mitigation measures can be included and tested for at various levels.

QPS

The protection systems for the LHC main dipole, lattice quadruple magnets, and the corresponding bus-bars are located in racks placed underneath the main dipoles inside the accelerator tunnel (ARC) together with the data acquisition system and the associated quench heater power supplies. In case of a quench the latter energize the heater strips mounted on the magnet coils. Annual radiation levels of more than 10 Gy or $1x10^{10}cm^{-2}$ high-energy hadrons have to be considered. In addition, the electronics for protecting the dipoles and the quadrupoles of the insertion region, and the inner triplets is located in partly shielded areas where radiation levels are lower, but still a factor of 100-10000 times higher than at surface.

The QPS equipment consists of custom boards, developed at CERN by using COTS ("Components Of The Shelf) components. The equipment to be installed in the tunnel was conceived to be radiation tolerant up to a total dose of 200 Gy, which corresponds to a high-energy hadron fluence of $\sim 2x10^{11}cm^{-2}$, considered for the evaluation of the SEE cross section, however, not all components were qualified according to the system requirements as implemented in the final installation. In addition, no radiation constraints were imposed for the design of the electronics of the partly shielded areas. With those requirements, the QPS team designed the tunnel equipment with robust solutions based on classical analogue and digital circuitry, which were tested individually against radiations. Conversely, more sophisticated components such as micro-controllers and digital signal processors (DSP) were used for the shielded area boards.

A strict radiation test and qualification strategy could not be followed due to production time-line constraints. The main critical components of the tunnel boards were tested but the component lots were not individually qualified, neither a systematic tests of the entire boards in its actual functioning mode could be carried out prior installation. This was acceptable due to the expected continuous increase of LHC performance, thus a respective increase also in terms of radiation exposure, in this way allowing for corrective measures to be taken during early operation [21].

As expected, the first years of LHC operation confirmed the very good system design, nicely showing that the QPS system never compromised the safety of the machine and of the superconducting magnets. Faults which could damage the machine permanently, causing significant down-time (months of stop) never happened and were protected for at several levels. However, as anticipated, radiation-induced operational failures did happen on both the boards of the tunnel and shielded areas causing beam dumps and thus downtime to the accelerator, requiring mitigation measures to be implemented.

Concerning the tunnel equipment, most SEEs have been observed on a digital isolator linking the detection electronics to the supervising data acquisition system (DAQ). While not causing beam dumps the malfunction required initially machine access to restart the DAQ but could be eventually mitigated by a firmware upgrade. The incriminated component was tested against radiation using a setup which checked the output while the input of the isolator was fed with a square wave. However, the digital isolator is finally used in static mode in the real application and having a fixed input made it thus more vulnerable to SEEs. Radiation-induced failures also happened on the data acquisition system and were, due to a loss of communication on the field bus, provoked by a SEFI on the chip which manages the bus. The vulnerability of the device was known but accepted since this fault only provoked a loss of the monitoring data; however, it turned out to be still a limiting factor since the post-mortem data, transmitted after the activation of an interlock signal, were lost, making impossible the diagnostic of the fault which triggered the interlock.

Concerning the shielded area equipment, the radiation levels turned out to be higher than originally anticipated during the system design and especially the DSP based digital quench detection systems suffered SEEs causing spurious system triggers.

In this way, the operation of the machine put in evidence the vulnerability of the system to SEEs. At that stage, with the machine in operation (2010-2012), a new design or the replacement of the vulnerable components were not possible due to the large number of impacted electronic cards. Still, prompt mitigation actions were required in order to allow for acceptable operation conditions until 2013. According to the strategy described above, two solutions were adopted. Additional shielding was added to the galleries in order to decrease the radiation levels. In addition, firmware modifications were deployed to the system, limiting the impact of the SEEs on the optical isolator and on the microcontroller. By doing so, the failure rate was decreased to an acceptable level for the operation.

The analysis of the pitfalls, the efficiency of the mitigation actions formed then the basis to plan a suitable mid/long-term solution to be applied during the first Long Shutdown (LS1) of the machine (2013) and also afterwards. For the LS1 it was decided to

- relocate the equipment or parts of it in more protected areas wherever possible. These measures concern in particular the inner triplet protection systems formerly located in partly shielded areas.
- re-design the DSP based quench detection boards by replacing its functionality with a radiation tolerant FPGA and an ADC, properly tested. During LS1 this is applied to the protection systems for insertion region magnets and 600 A corrector magnet circuits installed in partly shielded areas.
- apply power cycle functionality to the microchip which manages the fieldbus to restore its functionality.

This is an intermediate measure, which will be superseded by a fully radiation tolerant DAQ system at a later stage.

For LHC operation after LS2 more systems upgrades will become necessary in order to comply with the increasing radiation load especially in the dispersion suppressor areas. This is subject to a dedicated design study within the LHC high luminosity project.

Power Converters

The 60 A converter had to be installed in the tunnel ARC while all the other converters types were placed in adjacent shielded areas. Table 3 lists the total number of units per converter types, specifying the number of parts which are in safe areas (radiation levels comparable to the surface) and those which are not. This poses a clear design challenge given the high number of exposed systems and respective annual cumulated radiation levels: up to some 10 Gy for TID and up to a few 10^{10} $cm^{-2}y^{-1}$ for high-energy hadrons (about 10^{11} cm^{-2} of 1MeV neutron equivalent fluence) for the tunnel areas and about a factor of 10 less for the worst exposed shielded areas.

At the design stage, some of these power converters, the 60 A type, were known to be operated in a radioactive environment, thus this has been taken in consideration from their initial conception phase, however also not following component or device batch-control, system tests or individual checks for the high-energy radiation environment. In addition, there is a large number of standard design Power Converters that were not foreseen for installation in irradiated areas and are still exposed to significant radiation levels. Moreover some converter types were not designed or constructed at CERN [22].

Table 3: Overview of the number of power converter units in the various radiation critical LHC locations.

Converter Type units	Safe Area Units	Irrad. Area Units	Rad-Tol Design	Rad. Location	
Tunnel					
60A-08V (752 Units)	000	752	yes	ARC	
Shielded areas					
120A-10V (290 Units)	183	107	no	RR1x RR5x RR7x UJ1x UJ56	(36) (36) (20) (10) (05)
600A-10V (400 Units)	272	128	no	RR1x RR5x RR7x UJ1x UJ56	(28) (28) (48) (16) (08)
600A-40V (37 Units)	025	012	no	UJ76	(12)
4..8kA-08V (189 Units)	123	066	no	RR1x RR5x UJ1x UJ56	(30) (30) (04) (02)

When it became clear that several power converters of the shielded areas will be impacted by radiation effects and that also the power converters of the tunnel, although tested under radiation, could still suffer destructive events and not be radiation tolerant to the TID level expected for the nominal LHC conditions, different mitigation proposals were evaluated in a dedicated R2E review in 2010. Additional shielding and in some cases relocation actions helped (Point-7) and will help (Point-1 and Point-5) to reduce the number and level of exposed equipment. However, a significant number of systems remain not sufficiently protected because they are not easily to be relocated. Mitigation actions applied at the system level are only possible within certain limits since the design of many converters was outsourced in the past and partial upgrade options are limited.

On this basis, it was decided to study a re-design the power converters which could not be moved respecting the radiation tolerant criterions fixed after the reviewing of the radiation levels of the areas where the converters are installed. Based on this, a long term plan was developed. The long term plan for the power-converter upgrades foresees first and most urgently the redesign of the controller part (FGClite and Rad-DIM), ready for installation right after the first long shutdown, and the power part for the 600 A, and 4-6-8 kA to install the new parts during the second long shutdown of the LHC machine.

In addition, the choice of redesigning the 600A as well as the 4-6-8kA was based on the fact that these converters were initially directly developed by and purchased from industry, thus are considered as highly critical regarding any (even not radiation related) patch or other crash solution to be put in place without having the full knowledge of the detailed design and electronic boards. Furthermore, the 600A is intended to be redesigned as a fully redundant converter which can then re-used as well for the 60A and 120A converter in the context of the LHC High Luminosity project.

The power converter group organized the project to have the maximum efficiency in dissociating the already demanding and challenging power design phase from the rad-tolerant aspects. By doing so, different teams (see Figure 5) work in parallel and limit the delay of each one on the other. It was possible to follow this approach since it was assumed that a power converter designer shall focus on the circuit topology, keeping in mind radiation tolerant requirements and suggesting the use of simple techniques and robust components of a few families and types, but not necessarily having any special constraints on the specific reference of the single components.

Figure 5: The radiation tolerant design of the power converters is based along three teams: the converter design, radiation test and management/documentation.

Thus, the converter design team focuses on the electrical design of the different converter types and associated functional controller; the radiation test team carries out the tests on the components, the management/documentation team leads the projects and assures the link between the former two teams.

The project aims at having the power converters designed at CERN based on COTS components. Provided the available timing a full radiation test strategy can be adopted by foreseeing

- the screening test for the component selection
- the purchase of the component lot and respective radiation qualification
- the test of the system (or parts) according to the qualification procedure outlined in the following section.

RADIATION TESTING & FACILITIES

The first important element required for an efficient and successful qualification procedure is the knowledge of the radiation environment. The peculiarities of the LHC radiation environment and the differences among the different areas, shielded zones and tunnel, are described in more detail in [6], where the respective critical radiation effects on electronics have been described as well. Electronic components and systems exposed to a mixed radiation field will experience three different types of radiation damages: Displacement Damage (DD), damage from the Total Ionising Dose (TID) and so-called Single Event Effects (SEEs). The first two are of cumulative nature, where the steady accumulation of defects causes measurable effects which can ultimately lead to device failure. In terms of stochastic SEE failures, they form an entirely different group as they are due to the direct ionization by a single particle, able to deposit sufficient energy through ionization processes in order to disturb the operation of the device. They can only be characterized in terms of their probability to occur as a function of accumulated High Energy (>few MeV) Hadron fluence. The failure probability will strongly depend on the device as well as on the nature of the particles and its energy [15, 16].

As shown earlier, several areas close to the accelerator tunnel and partly not sufficiently shielded, are equipped with commercial or COTS based systems which are mostly affected by the risk of SEEs, whereas electronics installed in the accelerator tunnel, based on custom design, will in the long-term also suffer from additional cumulated damage (TID and DD).

On this basis, all three types of radiation effects must be considered for testing although they will not impact in the same way the electronic systems. This implies having the appropriate facilities where two, partly parallel, strategies can be pursued:

- The first one consists in selecting and using external facilities which are recognized by the radiation community [23]: e.g., a) the Paul Scherrer Institute (PSI) providing a monochromatic proton beam, b) the Centre Energie Atomique (CEA) providing a neutron environment at ~1 MeV, c) Fraunhofer INT institute offering a ^{60}Co or neutron source, d) the European Space Agency (ESA) offering a ^{Co}60 source and several others. In addition, specific facilities, such as the PTB (Physikalisch-Technische Bundensanstalt), the Nuclear Research Institute (NRI in Rez), and the nuclear reactor in Kijeller can be exploited for calibration purposes (e.g., for the RadMon project).
- The second strategy aims at building a mixed radiation facility capable of reproducing the representative accelerator environments (e.g., of both the shielded and tunnel areas). In the past, two test areas, CNRAD and H4IRRAD, have been used for this purpose, although their operation was not fully optimized for radiation testing (limited availability, intensity, etc.). On the basis of this experience, a dedicated new radiation facility (CHARM) is being built during LS1 and will be briefly described in a later section of this paper.

As for the radiation qualification procedure, in a first stage, the design team specifies the list of components required for making a converter defining the type of the components, the main electrical performance, and possibly indicating a couple of references. The radiation test team then takes the list of components and organized the setup for the tests, trying to match as much as possible the bias conditions in which the component will be used. If this information is not available, the test setup is organized to evaluate the generic characteristics of the device under test.

Given the high number of components to be tested, they are classified into one of three different classes (C0, C1, and C2) presented in detail in Table 4. Based on this, Table 5 shows the respective radiation test methodology applied for the screening test. The classification takes into account the overall failure impact level of individual components [24].

Table 4. Component classification.

Class	Radiation response	Sourcing	Components
Class-0 (potentially sensitive)	Quite resistant or moderate sensitivity to radiation	Easily replacement Different manufacturers and types on the market	Diodes, Transistors
Class-1 (potentially critical)	Potentially susceptible to radiation, not on system's critical path	Substitution possible (list of preferable replacements is defined)	Voltage regulators/references, DACs, memory
Class-2 (highly critical)	Potentially susceptible to radiation, on system's critical path	Difficult to replace as no equivalents on the market	ADCs, FPGA mixed circuits for field bus

Class-0 (C0) components are tested with mixed-field radiation environment at CERN which is equivalent to LHC tunnel conditions, thus showing the direct functioning of the device in the final application. These tests can be done using a dedicated test setup for component tests or done on the electronic card level with components implemented and fulfilling their function in the design. The drawback of these tests is the very long irradiation time due to the relatively low fluence that can be obtained. In addition, CERN's complex is in a shutdown period during 2013 and 2014 and the mixed-field facility is not available during this time. A new test facility (CHARM) is thus under construction to be able to overcome these limitations and is presented in the last chapter of this document.

Table 5. Test methodology per class of components.

Class	Mixed-Field	Proton (PSI)	Heavy-ion
Class-0 (potentially sensitive)	**Mandatory** Component tests or tests of the complete board for SEE and TID	N/A	N/A
Class-1 (potentially critical	**Optional** Component tests or tests of the complete board for SEE and TID	**Mandatory** Component tests for SEE and TID (margin to account for >1GeV)	N/A
Class-2 (highly critical)	**Optional** Component tests or tests of the complete board for SEE and TID	**Mandatory** Component tests for SEE and TID (margin to account for >1GeV)	**Mandatory** Component tests for better SEL assessment

Class-1 (C1) components have to be irradiated with mono-energetic protons at the PSI radiation facility to measure their susceptibility to SEE and TID. Dedicated component tests are required for C1. In the LHC tunnel the particle energies range up to several tens of GeV, so the 230 MeV mono-energetic protons at PSI cannot reveal the component's response to such energies. On the other hand, for many components, the proton cross-section saturates already for energies in the range of tens of MeV. One has thus to take either a safety margin factor into account for the high energies not possible to test at PSI, or in some cases, foresee an additional test to be performed within a mixed-field radiation facility to study in detail its response to LHC radiation environment.

Class-2 (C2) components are to be tested exactly in the same way as the C1 components and additionally the heavy-ion radiation campaign has to be performed in order to better assess their Single-Event-Latch-up cross-section already during the component selection process. As all C2 components are highly critical to the project design, their destructive event cross-section is the biggest concern while the other non-destructive SEEs can be mitigated on the design level (e.g, using Error Correcting Codes (ECC), Triple Modular Redundancy (TMR) or other adapted mitigation methods). As all C2 components are highly critical to the design, their destructive event cross section is the biggest concern and needs to be verified through dedicated tests in a mixed-radiation facility.

The targets limit for the high-energy hadron fluence, 1-MeV eq. neutron fluence, and TID is fixed according to the expected radiation levels of the critical areas where the components will be installed for a minimum lifetime of 10 years.

Once the components are selected, they are bought per lot. The lot is qualified by testing 5-10 samples per lot. The lot will be tested in the same facility where the screening test was performed. If a TID test at low dose rate (100-400 rad/h) is to be performed for critical bipolar devices, a Co-60 source will be used.

Finally, at least three samples of the entire system or subsystems are tested in a CERN test area where the mixed radiation field is reproduced.

Therefore, any installation of non-tested (and not specifically designed) electronic equipment in the UJs, part of the ULs and RRs is clearly to be avoided or subject to a detailed analysis process prior an exceptional installation can be granted under the following conditions:

- the equipment is not linked to any safety system,
- the failure of the equipment will not lead to a beam dump,
- the failure of the equipment does not require quick access (thus lead to downtime),
- there is no any other operational impact (loss of important data, etc.).

In all other cases requiring installation in critical areas, a respective radiation tolerant electronics development must be considered from the very early stage onward. Related expertise exists at CERN within the equipment groups, the R2E project [1] and a dedicated working group [6]. In a first approximation and by limiting the total number of exposed systems, the above mentioned annual radiation design level of 10^7 $cm^{-2}y^{-1}$ can also be chosen as acceptable upper limit aiming to achieve an overall performance of less than one radiation induced failure per one or two weeks of operation.

THE NEW FACILITY: CHARM

As explained in the previous sections, within the framework of the Radiation to Electronics (R2E) project, the testing of electronic equipment in a radiation field similar to the one occurring at CERN accelerators (e.g. in the Large Hadron Collider (LHC)) in order to study the respective equipment sensitivity is an important condition to assure mid/long-term operation requirements. High intensity and high-energy radiation fields are needed for realistic radiation tests. For this purpose, a new irradiation facility called CHARM (Cern High-energy AcceleRator Mixed field/facility) is currently being constructed [25, 26]. The commissioning of this unique mixed field facility will be carried out during summer of 2014 in order to be ready for standard operation after LS1.

This facility is not only useful for testing devices within accelerator representative environments, but its available radiation fields will also be characteristic for ground and atmospheric environments (neutron energy spectra) as well as the space environment (representative for the inner proton radiation belt). In addition, the size of the available test area is such that also larger objects can be irradiated and ultimately even objects requiring special services (power, cooling, etc.) to be connected for operation.

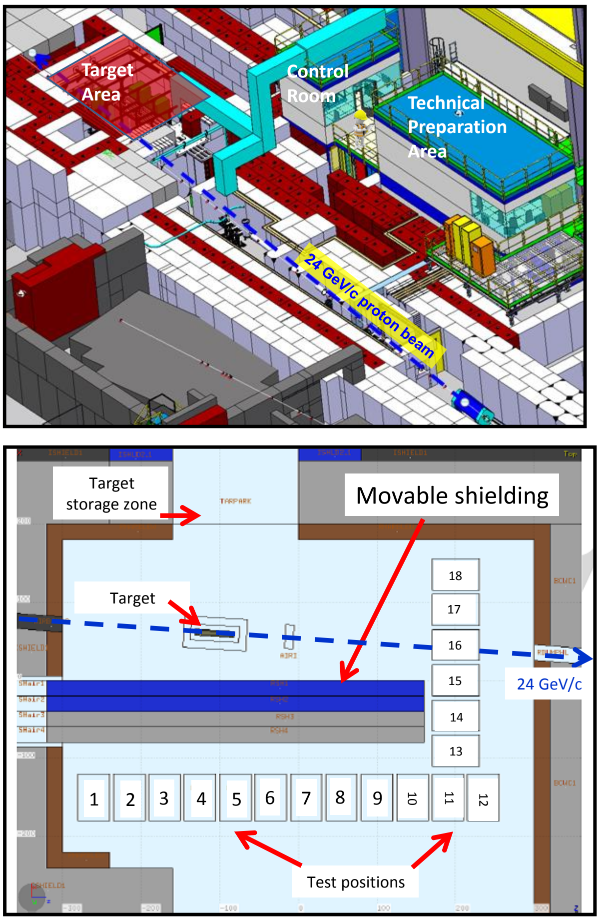

Figure 6: (top) 3D view of the facility and (bottom) FLUKA geometry for the target area. Racks 1 to 18 are the regions representing the test locations. The blue, grey and brown plates are respectively iron, concrete and marbles blocks.

The CHARM facility will be located in one of the experimental halls at CERN (East Area, T8 beam-line). Figure 6: (a) 3D view of the facility and (b) FLUKA geometry for the target area. Racks 1 to 18 are the regions representing the test locations. The blue, grey and brown plates are respectively iron, concrete and marbles blocks.

Its surrounding layout is composed of iron and concrete blocks in order to reduce at maximum the radiation outside of the shielding structure. A 3D view of the facility and a horizontal cut of the inner target chamber are shown respectively in Figure 6 (a) and (b). As it can be seen from Figure 6(a), the target chamber is large enough to host bulky and complete systems (e.g. full power converter or UPS units) since around 70 m3 of space will be available for radiation tests.

Within the facility, a 24 GeV/c proton beam extracted from the Proton Synchrotron (PS) accelerator impacts on a cylindrical copper or aluminium target (see Figure 6 (b)), and the created secondary radiation field is used to test electronic equipment installed at predefined test positions. Copper and aluminium as material's choices for the primary beam target are good compromises not only because of their mechanical and thermal properties, but together with the mobile shielding configuration they also allow the creation of a secondary particle spectrum representative for the source term of those present in the atmospheric, space and accelerators environment.

To model and choose between the various representatives spectra, different shielding configurations are available in the facility. Four movable layers of an individual thickness of 40 cm made out of concrete and iron can be placed between the target and the test locations in different combinations (see movable shielding in Figure 6 (b), thus allowing to modulate the test spectra and adopt them as closely as possible to the radiation field (energy and intensity) aimed for during the tests. The shielding plates are motorized with remote control.

The intensity of the radiation field can be further modulated by varying the primary beam intensity, the choice of target head, e.g. two massive ones (Al or Cu – the yield of the massive Al target is about 2.5 times smaller than for the massive Cu target) or one with reduced effective density (Al target with holes – it gives an additional reduction by a factor 4), allowing for an overall reduction factor of the primary radiation field of 10-100 in total.

It is important to note that even for large volumes and also when including the shielding configuration, even a full year of exposure e.g., in the LHC (a few 10^{11} HEH/cm^2) can be easily emulated within a few days of exposure in this facility (see Figure 7).

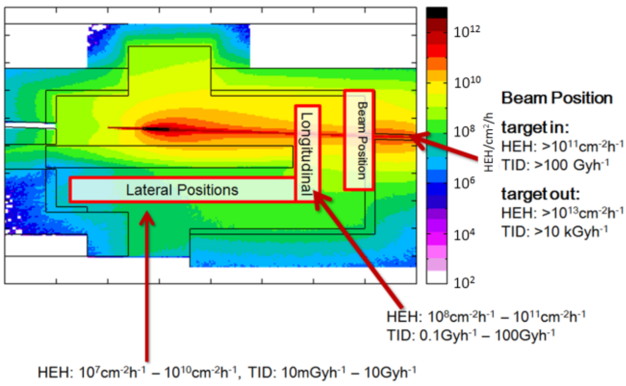

Figure 7: HEH flux (cm^{-2}/h) inside the radiation zone.

The dose rate ranges for the various test positions are shown in a qualitative way. For that hourly radiation values are provided for overall longitudinal, lateral, or direct exposure positions shown. The beam is impinging on the target from the left. "Target in" and "Target out" correspond to test at "beam position" with and without target respectively.

The installation of equipment inside the target chamber will be mostly automatized with remote controlled transporters. Two transporter systems will be used, one to carry heavy and bulky equipment (called "large transporter") and one to transport small samples to the test position in direct line of sight with the beam axis (usually referred to as "small train").

CONCLUSIONS

In this report we summarized the radiation environment and levels encountered during the first years of LHC operation high-energy accelerators and their particularities at critical LHC areas. The energy distribution, as well as the proportion of the different particle species depends on the distance and on the angle with respect to the interaction point, as well as the amount of installed shielding material. Electronic components and systems exposed to a such mixed radiation field thus experience at once all three different types of radiation damages: Single Event Effects (SEEs), damage from Total Ionizing Dose (TID) and displacement damage (DD), where in all cases, not only the particle type, but also the respective energy distribution are to be considered, especially if high-Z materials are present near the device's sensitive region, as well as that the impact of thermal neutrons can not to be neglected for several cases.

A summary of the induced failures for the LHC operation in 2012 has been given with about 60 beam dumps which were provoked by radiation effects on electronic equipment during 2012 operation and causing a downtime for the machine of about 250-300 hours. The impact of the radiation effects would have been significantly higher without the countermeasures that were already applied in the past years. Furthermore, the prompt reaction of the groups to design patch solutions for mitigating radiation effects allowed throughout the year 2012 to reduce the number of failures which could have led to a beam dump. In total, the radiation induced failures were reduced by a factor 4 with respect to the 2011 operation.

Additional mitigation actions are planned for the LS1 period to further reduce the radiation vulnerability of the equipment. Thanks to those efforts, the expected number of radiation induced dumps per fb^{-1} is expected to be <1. This objective will permit to classify the radiation induced failures as minor, and to operate the LHC smoothly without any significant number of stops related to radiation.

The monitoring of the radiation levels will be a continuous work which aims at reducing the uncertainty factors, mainly related to the beam gas effects and the losses in the collimation areas, as well as to closely monitor the long-term radiation impact on exposed electronic systems. This will allow verifying design assumptions, as well as scheduling preventive maintenance actions when required. The detailed follow-up of the system upgrades and developments remains crucial to reach the above goal.

Both the requirement as well as the challenge of using commercial components for accelerator applications have be highlighted and respective mitigation measures have been illustrated together with the requirements and solutions for radiation monitoring and radiation test facilities.

For operation critical equipment, the r2e project foresees respective radiation tolerant developments already at an early stage of the design phase, taking into account that:

- for the LHC-tunnel: in addition to SEEs also cumulative damage has to be considered for both existing and future equipment,
- for partly shielded areas (UJs, RRs, ULs): cumulative damage should be carefully analyzed but can most likely be mitigated by preventive maintenance (detailed monitoring mandatory), but radiation tolerant design is mandatory in order to limit SEE induced failures,
- the knowledge of radiation induced failures and radiation tolerant development within the equipment groups and in the overall A&T sector has to be maintained and further strengthened,
- the access and availability of radiation test facilities (CERN internal and external) has to be ensured providing efficient support to equipment groups, building on the experience obtained during the LHC R2E project and in view of the HL-LHC time-scale, it is important that the expertise of and support to radiation tolerant developments (currently available through the Radiation Working Group) is maintained and ensured from the early project stage onwards.

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