

WILL WE STILL SEE SEES?

M. Calviani[#], M. Brugger, L. Losito, G. Spiezia, Q. King and Y. Thurel, on behalf of the R2E Mitigation Project

CERN, Geneva, Switzerland

Abstract

The actions taken during the first years of the Radiation to Electronics (R2E) Mitigation Project [1] enabled to drastically reduce the rate of Single Event Errors on radiation-sensitive electronic equipment installed in the LHC underground areas. Shielding and relocation activities, performed during the first Long Shutdown (LS1) in 2013/2014, will allow the resolution of the present issues concerning UJs of Points 1, 5, 7 and the cavern of Point 8. The parallel development of radiation tolerant power converters will address the remaining concerns for equipment in the RRs. Similarly R&D on super-conducting links will address the relocation of equipment away from RRs and further exposed UJs. Radiation levels in areas where luminosity is the source are under control. The questions yet remaining are related to the evolution of the beam-gas source term in the arc and dispersion suppressor (DS) region, and to the evolution of losses at the betatron and momentum insertion regions. 2012 operation will enable these points to be investigated; this will be used for a complete forecast of radiation levels and projected failures after operation is resumed in 2014/15.

INTRODUCTION

The mandate of the R2E Project is to minimize all radiation-induced failures in the LHC; in particular, to allow LHC operation with a Mean Time Between Failures (MTBF) greater than or equal to one week for a peak luminosity of $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ and a yearly integrated luminosity of 50 fb^{-1} . R2E Mitigation actions are also starting to take into account the LHC performances expected after the High Luminosity upgrade (HL-LHC), and therefore assume a peak luminosity of $\sim 5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ for a yearly integrated luminosity of 200 fb^{-1} .

Mitigation actions were foreseen in these last 3-4 years to reduce the risks of radiation-induced failures, as 2011 operation has already shown. These actions particularly consist in:

1. Relocating equipment located in areas where the high energy hadron (HEH) fluence exceeds $\sim 10^7 \text{ HEH/cm}^2 \text{ year}$;
2. Additional shielding for zones where relocation is not an option;
3. Radiation-tolerant hardware development to allow

the operation of electronics equipment in regions where solutions 1 and 2 cannot be implemented.

Some of these actions were already taken before and during 2011 operation. Others were implemented during the 2011/2012 winter shutdown and the most impacting ones will be performed during and after LS1. In any case, we can anticipate that there will still be single event errors (SEE) in the LHC after LS1, due to the fact that certain equipment will have to remain, for the foreseeable future, in the tunnel or in other exposed areas.

Despite the planned mitigation actions, as this paper explains, it is very difficult to give reliable figures on the number of failures expected in the years after LS1, due to uncertainties on the radiation-induced failure cross-section and on radiation levels in the various parts of the LHC. Moreover, the R2E Mitigation Project's goal is to guarantee a SEE-induced MTBF greater or equal than one week in post-LS1 years.

In this report we will first give a long-term overview of expected radiation levels in the LHC areas where electronics equipment is placed. Then we will analyse what will remain critical after the LS1 mitigation activities and how we are currently treating the known issues in view of nominal and ultimate LHC performances. Lastly, we will address a list of recommendations to guarantee the long-term follow-up of SEE-induced issues.

RADIATION LEVELS AND OPERATIONAL ASSUMPTIONS

Based on the operational results of 2011 [2], the radiation levels can be scaled for the next few years by using the expected machine parameters (beam energy, yearly integrated luminosity, total proton lost at IP3/7 and beam intensity), chosen according to the main radiation sources for a given critical area. This latter point can be grouped into three main categories, depending on their location in the LHC:

- Particle debris from beam-beam collisions in the main four interaction points (Points 1/2/5/8);
- Direct losses in collimators and absorber-like objects;
- Inelastic interactions of the beam with the residual gas inside the beam pipe (so called "beam-gas").

[#]marco.calviani@cern.ch

Concerning the scaling of radiation levels as a function of beam energy, according to FLUKA simulations, the operation at 7 TeV/beam will increase the radiation levels by a factor 1.5 compared to 3.5 TeV/beam operation.

For the shielded areas close to the IPs (for example UJ14/16 and RRs), and the DS regions, the radiation levels scale with luminosity; assuming 50 fb⁻¹/y for ATLAS and CMS and 2 fb⁻¹/y for LHCb, the radiation levels for nominal LHC (post-LS1) will increase by a factor 15 compared to 2011 operation (including the energy scaling) for ATLAS/CMS and by a factor 3 for LHCb. For LHC “ultimate” performance, the assumed integrated luminosity is 200 fb⁻¹/y for ATLAS/CMS and 20 fb⁻¹/y for LHCb and the increase with respect to 2011 will vary accordingly. The effect of luminosity-induced radiation levels in the IP2-neighboring alcoves (ALICE) – even in case of a luminosity upgrade – is negligible with respect to the beam-gas source.

As for the radiation levels in the momentum and betatron collimation zones, these depend both on the absolute number of protons lost as well as their distribution among the collimators (which depends on the operational configuration). For 2011 operation we have estimated, using independent monitoring systems (beam current transformers (BCT) and beam loss monitors (BLM)), that the amount of total protons lost per beam all along the collimators at IR7 is approximately 10¹⁵. The radiation level estimation for post-LS1 years was carried out using a value of lost protons which is 10 times larger, i.e. 10¹⁶ protons per beam in IR7 (and 4×10¹⁶ protons per beam in IR7 for ultimate performances). Dedicated machine development (MD) beam time should be reserved during 2012 LHC operation to improve the understanding of the effects of collimator settings (“tight settings”) on the resulting radiation levels.

A significant amount of electronic equipment is installed in the DS and arc region of the LHC tunnel (QPS, LHC60A power converters, etc.) and therefore the knowledge of the evolution of the radiation levels in that zone is of particular importance. The levels depend on the beam-gas interaction rate, which is a function of beam intensity, bunch spacing, and of the conditioning of the vacuum, i.e. the residual gas pressure. The scaling factor for this last variable is currently affected by very large uncertainties, as it is related to operation at 25 ns bunch spacing (for which no operational experience, other than MDs, exists at the moment). Based on the results of the 25ns MD performed during 2011, we have assumed it would increase by at least a factor 10 for both nominal

and ultimate operation. Due to the large number of exposed equipment, an unexpected increase of radiation levels in the arc might potentially lead to a significant increase of failures. Therefore, the HEH radiation levels should be carefully followed-up on during 2012, especially during the 25ns scrubbing run.

Taking as reference the above-listed considerations on the different LHC areas, the expected high-energy hadron fluences for post-LS1 years and for ultimate performances can be extrapolated from the radiation levels measured during 2011 (which agrees well with FLUKA simulations [2]). Table 1 reports the values of “critical” shielded areas known to house equipment prone to SEEs and for which mitigation actions have been already foreseen (among which the UJs and RRs of Points 1, 5 and 7). Similarly, Table 2 reports the HEH estimation for tunnel areas and especially for the DS and arc. Please note the different levels reached in the DS of Points 1 and 5, where the radiation levels are dominated by leakage from the high luminosity IPs, with respect to those of other points. Lastly, Table 3 shows the expectations for other, less critical areas, but which contain electronics prone to possible failures.

Table 1: HEH fluence (per cm²/y) expected in LHC critical areas during nominal and ultimate LHC conditions compared to 2011 operation. These are areas for which mitigation actions have been already foreseen. The levels in the RR of Points 1 and 5 do not yet take into account the shielding improvement (from concrete to iron) to be installed during LS1.

Areas		High-Energy Hadron Fluence		
		2011	>LS1 (nominal)	Ultimate
Critical	UJ14/16	2.10E+08	6.30E+08	2.50E+09
	RR13/17	7.00E+06	2.10E+08	8.40E+08
	UJ56	3.50E+07	5.30E+08	2.10E+09
	RR53/57	1.10E+07	3.30E+08	1.30E+09
	UJ76	5.40E+06	8.10E+07	3.20E+08
	RR73/77	8.10E+06	2.40E+08	9.70E+08
	UX85b	1.70E+08	4.30E+08	4.30E+09
	US85	3.50E+07	8.80E+07	8.80E+08

Table 2: HEH fluence (per cm²/y) and integrated dose (in Gy/y) expected in LHC tunnel areas during nominal and ultimate LHC conditions compared to 2011 operation with the conditions explained in the text (in particular, a very conservative increase of beam-gas levels by a factor 10). Please note that above a few Gy/y cumulative damage effects (total ionizing doses and displacement damages) on equipment will also become relevant.

Areas		High-Energy Hadron Fluence			Dose (Gy/y)	
		2011	>LS1 (nominal)	Ultimate	>LS1 (nominal)	Ultimate
Tunnel	DS (P1/5)	1.00E+10	1.50E+11	6.00E+11	150.0	600.0
	DS (3/7)	1.00E+09	1.50E+10	6.00E+10	15.0	60.0
	DS (other)	3.00E+08	1.40E+10	1.80E+10	13.5	18.0
	ARC	2.00E+08	9.00E+09	1.20E+10	9.0	12.0

Table 3: HEH fluence (per cm²/y) expected in other less critical LHC areas during nominal and ultimate LHC conditions compared to 2011 operation. In some cases (e.g. UX45 and UX65) radiation-induced failures have already been observed during 2011.

Areas		High-Energy Hadron Fluence		
		2011	>LS1 (nominal)	Ultimate
Investigated	UA23 (maze)	3.40E+06	2.00E+07	2.90E+07
	UA87 (maze)	1.00E+06	6.00E+06	8.40E+06
	UJ23	2.00E+05	9.00E+05	1.20E+06
	UJ87	5.00E+05	2.30E+06	3.00E+06
	UX45	2.50E+06	1.50E+07	2.10E+07
	UX65	1.00E+06	6.00E+06	8.40E+06
	REs (entry!)	5.00E+05	2.30E+07	3.00E+07

LS1 ACTIVITIES AND IMPACT ON CRITICAL AREAS

In order to reduce the extent of the effects of SEE-induced failures on the operation of the LHC, a significant amount of relocation and shielding activities will take place during LS1. An overview of the activities and more detailed explanations can be found in Ref. [3]. Almost all LHC IPs will be concerned, with the most significant activities addressing Points 1, 5, 7, and 8 (see Figure 1).

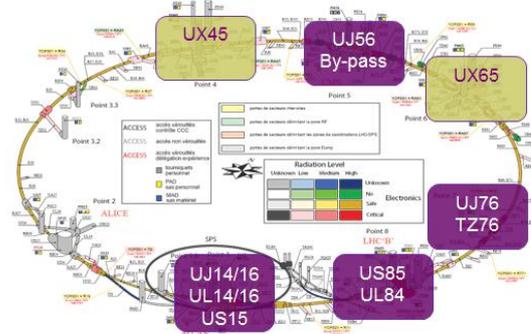


Figure 1: Overview of areas where mitigation actions will take place during LS1 [4].

Despite the huge efforts that will be concentrated during LS1, there are several systems around the LHC for which neither relocation nor shielding are possible to mitigate the effect of SEEs and, in general, cumulative radiation damage. In these cases, only radiation tolerant (“rad-tol”) hardware modifications or new developments are required. In particular, this affects systems located in the tunnel (below the MBs and MQs, see for example Fig. 3) and in the RRs (Fig. 4).

Tunnel equipment:

- QPS (nQPS splice), most exposed especially in the DS around P1/5/8. More details in Figure 2;
- LHC60A power converters (located below the MBs in the DS/ARC – see Figure 3 for an example);
- Cryogenic control equipment (below the MBs starting from cell 8);
- Beam instrumentation (below the MQs, starting from cell 12);

RRs (see Figure 4):

- QPS DQQDI/DG (global quench detector for insertion region magnets and for the 600A circuits, respectively), located in RRs and UJs (the latter to be relocated during LS1).;
- LHC120A, 600A, 4-6-8kA power converters;

System	Locations
DQQDI (IPQ, IPD, IT)	UJ14, UJ16 (2x), RR17, RR53, RR57
DQQDG (600 A)	UJ14 (2x), UJ16 (3x), RR17, RR73, RR77 (3x)
nQPS (splice protection)	B8L1, B11L5, B11R5, B9L8

Figure 2: List of tunnels and shielded areas in which QPS equipment has shown failures during 2011 operation [5].

Different strategies are being used for the different equipment under consideration (power converters, QPS, etc.). The next section gives an overview of the activities currently being pursued, estimating, whenever possible, their impact on the LHC operation.

EQUIPMENT REMAINING IN THE TUNNEL AND SENSITIVE AREAS

Power converters

There are almost ~1700 systems of this type located in the LHC underground areas. They are used to power closed orbit dipoles (COD), main dipoles, quadrupoles and inner triplet magnets.

Power converters are located in the UJ14/16, RRs of P1/5/7, UJ/UAs of P2/4/6/8 as well as in the tunnel below the MB. During 2011, several failure types were observed in PC equipment, thoroughly described in [2]; these mainly affect the auxiliary power supplies, the voltage source and some filter corruptions on the FGC ADCs. Certain mitigation actions will be already in place for 2012 LHC operation and extensive relocation activities will take place during LS1 [3]. In the medium/long-term the R2E-EPC Project [6] aims to redesign rad-tol power converters and related equipment. Due to the sensitive location of some of the PCs, an aggressive hardware rad-tol R&D is needed to guarantee minimum impact in terms of SEEs in post-LS1 years.



Figure 3: Photo of a 60A LHC power converter located below an MB.



Figure 4: Photo of the RR57 taken from the tunnel zone looking towards the IP5. Power converter racks are evident as well as the presently installed concrete shielding separating the tunnel from the alcove.

The functional gate controllers (FGC) present in all PCs are known to be prone to radiation-induced failures (their main weakness is due to latch-ups in the Xilinx CPLDs); a new rad-tol system called FGCLite is currently in the R&D phase. The total numbers of devices which will be required for the new system is roughly 1050 and the current baseline is to install them in the power converters towards the end of the LS1.

The project will also address the needs of developing patch solutions for the power supply unit of the 600A power converters, which suffered eight destructive events during 2011 operation.

The core of the R2E-EPC activities will be, however, devoted to the redesign and upgrade of the power converters installed in the RRs, namely the LHC600A and the LHC4-6-8kA – which will require a complete redesign as they have been originally engineered by external companies – as well as the LHC120A, for which only a partial redesign would be required (having internally developed at CERN). These new converters could be realistically available for installation during LS2 [7] or during intermediate stops between LS1 and LS2.

Table 4 shows the evaluation of the expected number of failures on the different types of power converters assuming the previously mentioned LHC radiation levels and based on the failure cross-section extrapolated from 2011 LHC operation and from H4IRRAD tests [8]. The extrapolations for 2012 (based on Table 1, Table 2 and Table 3) already take into account the improvement of the shielding in the UJ14 and UJ16 (~30 converters) as well as the digital filter improvements on the FGCs. For post-LS1 years, the estimate takes the presently operating power converters (not the rad-tol ones – available only towards LS2) into consideration and assumes that the EPC Group will have solved the known issues on the auxiliary power supply unit.

Recent vacuum studies, results obtained from first scrubbing runs in 2011 and respective MDs indicate

however that these levels will not be reached and that maximum levels will be reduced by at least one order of magnitude.

It is worth reminding that failures on the 60A power converters do not necessarily lead to an LHC beam dump and that the FGClite upgrades are not included in the failure estimates in Table 4. The uncertainties in the analysis are strongly affected by both the:

- Radiation-induced failure cross-section: not known with enough accuracy, due to the limited (but still highly important) statistics acquired during LHC operation and H4IRRAD tests;
- The present uncertainties related to the radiation levels in the arc during 25 ns bunch spacing operation.

Table 4: shows a tentative estimate of the number of failures in the various types of power converters installed in the LHC machine, based on the current knowledge of the equipment sensitivities and according to the assumed evolution of the LHC operational parameters.

converter	failure per year		
	2011	2012	>LS1
LHC60A-8V	4	10..30	60..200
LHC120A-10V	1	2..3	10..30
LHC600A-10V	7	7..10	1..15
LHC4-6-8kA-8V	1	1..3	1..45

Given the numbers in Table 4 and the fact that a single failure on a 120A, 600A, or 4-6-8kA will lead to an LHC beam dump, it is really important to stress the importance of the FGClite upgrade and, in general, of the R2E-EPC programme in order not to limit the availability of the LHC beam on the long-term.

It is also important to draw attention to the fact that radiation testing in mixed field facilities with particle spectra similar to those in the LHC remains mandatory before installation of the new equipment in the LHC underground areas, as it will avoid bad surprises during operation. At present there are two installations where this could take place, CNRAD and H4IRRAD [9]. The first one is linked to the operation of CNGS (currently foreseen to be discontinued after 2012) and the second one – while, in principle, available after LS1 – lacks running flexibility and cannot be considered a testing “facility”. The future PSIRRAD facility in the East Area [10] might be the answer to these needs.

Super-conducting links

As discussed during the R2E Review in November 2011, the super-conducting links (SCL) technology (developed to fully enhance the capacity of the HL-LHC Project) will realistically be fully available by LS2 [11,12]. This technology could also be used in synergy with the R2E-EPC Project. One could imagine, in fact, the installation of horizontal SCLs during LS2 to move the power converters located in the RR73/77 to the TZ76

and, for example, the installation of radiation tolerant power converters in the other RRs.

For the longer term (LS2/3) the installation of vertical SC links could be considered with the objective of completely removing the power converters from the UL14/16 (and possibly the RRs) where they will be relocated during LS1 (and where the radiation levels will again become critical during HL-LHC). It is important to underline that significant civil engineering issues will have to be solved to proceed towards this solution.

A joint R2E-SCL review will be organized in 2013 to clarify these points and define a strategy.

QPS upgrades

SEEs are responsible for most of the QPS beam dumps in stable beams during 2011. Failures on the QPS systems happened both in the tunnel and in shielded areas. Patch solutions were applied wherever possible on different equipment to reduce the likelihood of beam dumps. Various additional counter-measures have been implemented during the 2011/2012 winter stop and programmed throughout 2012 to reduce SEE-induced failures [13].

During LS1, additional mitigation measures will be taken, including the relocation of equipment (IPQ/ IPT/IT and 600A protection) from the UJ14/16/56 towards protected areas (UL14/16 and UL557) as well as a significant amount of patches and rad-tol hardware upgrades, i.e. new boards. More details are given in [14]. It is, therefore, impossible to provide, for the moment, reliable failure estimates for post-LS1 years. However, given the expertise presently acquired by TE/MPE, the goal is to no longer have any additional radiation-induced failures.

Also, in this case we would like to stress the need to perform radiation and functional tests in a mixed field spectra before installation in the LHC tunnel.

Other equipment in critical areas

The remaining Uninterruptible Power Supply (UPS) in known critical areas (US85) will be displaced in protected areas during LS1 and some control parts will be rad-tested during 2012 in the H4IRRAD area. Additional UPS will continue to stay in all the RE areas even after LS1. As these zones are directly affected by the beam-gas-induced radiation, it is important, in the long-term, to maintain a close look at the arc vacuum levels. However, given the presently observed levels, this should not be a source of problems in the long-term. More details on the radiation sensitivity of EN/EL equipment are given in [2].

Also, cryogenics equipment has suffered various types of radiation-induced failures during 2011. However, all known issues will be mitigated, thanks to rad-tol hardware development or relocation to protected areas, during the 2011/2012 winter stop and LS1 [15]. The Siemens PLCs on the compressors – presently not in the baseline of R2E activities – will be rad-tested at H4IRRAD during 2012 to avoid the observation of effects

similar to those seen on the Schneider PLC in UX45 and 65.

In conclusion, neither EN/EL nor cryogenics equipment SEE-induced LHC beam dumps are expected after LS1, if all mitigation actions proceed as planned.

CONCLUSIONS AND RECOMMENDATIONS

In this paper we have presented preliminary perspectives concerning the appearance and possible effects of radiation-induced failures in the operation of the LHC machine after LS1, highlighting the most critical components in terms of potential weaknesses as well as the projects and activities already planned to address these issues.

We cannot be more precise on the number of expected failures in post-LS1 years, basically due to:

- 1) The large uncertainties on the radiation-induced failure cross-section for both existing equipment as well as for new hardware development; and
- 2) Uncertainties on the radiation levels in the DS/ARC (due to vacuum pressure during 25ns operation) and at the betatron and momentum collimation points.

In addition, equipment groups might be required to apply on-fly patches, which mask the failure observation (similarly to the ISO150 isolator issue on the QPS system) from the beam operation teams.

SEEs are still expected to be present after LS1 but mitigation actions – hardware development, relocation and shielding – will enable their impact on the beam availability to be decreased despite a higher LHC performance. In this context, it is therefore important to pursue the R2E-EPC power converter R&D programme, the FGClite development, as well as the QPS hardware modifications, not forgetting the importance of performing radiation tests on prototypes in mixed fields facilities and test areas.

As radiation level monitoring is a primary aspect of the R2E Project, we would like to stress the importance pursuing radiation levels monitoring during 2012 as well as supporting the 2nd generation RadMon monitoring system and the BLM system, used to provide timely and accurate estimates of cumulated HEH and absorbed doses in tunnels and shielded areas.

In conclusion, the R2E Project believes that with the current plans and with continued efforts (especially in

view of the challenging operational scenarios foreseen for the HL-LHC), we could achieve an MTBF, due to SEEs, greater than or equal to one week in the years following LS1.

REFERENCES

- [1] R2E Mitigation Project website: www.cern.ch/r2e
- [2] M. Brugger *et al.*, R2E – Experience and Outlook for 2012, Proc. LHC Performance Workshop 2012.
- [3] A.-L. Perrot *et al.*, R2E strategy and activities during LS1, Proc. LHC Performance Workshop 2012.
- [4] A.-L. Perrot, J.-P. Corso *et al.*, R2E relocation & shielding activities: implementation and worksite organization, R2E Review November 2011.
- [5] R. Denz, Radiation Induced Failures in QPS Systems during the LHC run 2011, R2E Review November 2011.
- [6] R2E-EPC website: <http://te-epc-lpc.web.cern.ch/te-epc-lpc/context/radiations/general.stm>
- [7] Y. Thurel and Q. King, R2E-EPC Status, R2E Review November 2011.
- [8] Q. King and Y. Thurel, Radiation Sensitivity of LHC Power Converters and Projections, R2E Review November 2011.
- [9] B. Biskup, M. Calviani, M. Brugger *et al.*, Commissioning and Operation of the H4IRRAD Mixed-Field Test Area, CERN-ATS-Note-2011-121 PERF.
- [10] E. Lebbos *et al.*, East Area Irradiation Test Facility: Preliminary FLUKA calculations, CERN-ATS-Note-2011-082 TECH, AIDA-NOTE-2012-001.
- [11] A. Ballarino *et al.*, Super-conducting links: horizontal/vertical – Status & Possibilities, R2E Review November 2011.
- [12] R. Losito, A. Ballarino *et al.*, 2016: Radiation Tolerant Power Converters & Super-Conducting Links – Session review, R2E Review November 2011.
- [13] R. Denz *et al.*, QPS – analysis of main problems, areas to target, possible improvements, LHC Beam Operation Workshop, Evian 2011.
- [14] R. Denz *et al.*, QPS upgrade and machine protection during LS1, Proc. LHC Performance Workshop 2012
- [15] S. Claudet *et al.*, LHC Cryogenics 2011 and 2012, LHC Beam Operation Workshop, Evian 2011.