R2E – EXPERIENCE AND OUTLOOK FOR 2012

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Abstract

2011 very successful LHC operation has provided valuable input for the detailed analysis of radiation levels and radiation induced equipment failures. Radiation levels around LHC critical areas and the LHC tunnel were studied in detail and compared to available simulation results, as well as put in perspective to LHC operation parameters. Observed radiation induced failures were not only analysed in detail, but already addressed through early relocation measures and patch-solutions on the equipment level. Both improvements will continue during this winter shutdown together with the installation of heavy shielding around the RBs and UJs in Point-1. Based on measured radiation levels, calculations for the shielding improvements and expected operational parameters, this paper provides an update on the expected radiation levels around LHC critical areas. It briefly summarizes the already performed mitigation measures and equipment patches and provides an estimate on expected equipment failure rates during 2012 operation. Required beam and measurement studies are highlighted in order to further improve the predictions of both radiation levels and expected equipment failures, the latter driving the chosen mitigation actions for LS1.

INTRODUCTION

Based on previous studies [1] and a respective analysis, the 2011 LHC operation was expected to be a key ingredient in the analysis of radiation induced failures on machine equipment. From the early operation onwards strong emphasis was put in the detailed analysis of equipment failures which could possibly linked to radiation. To study in detail the latter correlation, 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.*, the source of radiation being present)
- the failure(s) is/are not reproducible in the laboratory
- the failure signature was already observed during radiation tests (CNRAD, H4IRRAD and others)
- the frequency of the failures increases with higher radiation levels

This obviously still includes remaining uncertainties which can lead to failures being atributed to radiation but which are not. However, as shown in this report, the performed detailed studies over the 2011 operation time limited these uncertain cases to only a few. In addition, there is also the limitation that the analysis is likely to miss radiation induced failures which do not lead to a beam dump, as well as more complex cases where one equipment is affected by radiation and indirectly causing a problem to another one, thus leading to either longer downtimes or beam dumps.

In the following we provide a summary of the radiation levels and the induced failures for the LHC operation in 2011, including an estimate of the respective machine downtime. The impact of performed countermeasures is highlighted and the conclusion for further mitigation measures is drawn. It is shown that the detailed monitoring of the radiation levels, as well as the detailed analysis of radiation induced failures remain a high-priority for the upcoming years of LHC operation.

RADIATION LEVELS AND PARAMETERS SCALING

The radiation levels in the LHC tunnel and in the shielded areas have been measured by using the RadMon system. The major radiation-induced failures, observed during 2011 LHC operation, are Single Event Effects (SEE) on electronic equipment. The probability of having a SEE is related to the accumulated High Energy Hadron (HEH) fluence which is reported in Table 1 for the most critical areas where electronic equipment is installed. The HEH fluence measurement is based on the reading of the Single Event Upsets (SEU) of SRAM memories whose sensitivity has been previously calibrated at various facilities [2]. The results obtained during 2011 LHC proton operation show a very good agreement between the FLUKA calculations and the measurements which are given with an uncertainty factor of 2. Based on the results for 2011, the radiation levels can be scaled for the following years by using the expected machine parameters, chosen according to the main radiation sources for a given critical area. The radiation sources can be grouped into three main categories: (a) direct losses in collimators and absorber like objects, (b) particle debris from beam-beam collisions in the four main experiments, and (c) interaction of the beam with the residual gas inside the beam pipe. As far as the beam energy is concerned, according to the calculations, the operation at 7 TeV will increase the radiation levels by a factor 1.5, while an increase to 4 TeV will only lead to a marginal increase of about 10%, thus largely within the overall uncertainties.

Table 1: Predicted and measured HEH fluence in critical shielded areas based on the 2011 operation conditions.

Area	FLUKA 2011 (HEH/cm^2)	Measured 2011 (HEH/cm^2)
UJ14/16	~1.5*10^8	~2*10^8
RR13/17	~3*10^7	7.0*10^6
UJ56	5*10^7-10^8	3.5*10^7
RR53/57	~3*10^7	1*10^7
UJ76	~4*10^6	5*10^6
RR73/77	~2*10^6	~8*10^6
UX85B	~3*10^8	2*10^8
US85	~7*10^7	3.5*10^7

For the shielded areas close to the beam collision points, as well as for the Dispersion-Suppressor (DS) zones, the radiation levels are scaled with luminosity which will increase for nominal operation by a factor of 10 for the ATLAS and CMS experiments and by a factor 2 for LHCb. For the ARC of the LHC tunnel, the radiation levels depend on the beam-gas interaction whose impact is related to the beam-intensity, the bunch spacing and the conditioning of the vacuum (residual gas pressure). The scaling factor for the latter radiation source is affected by high uncertainties of the expected average residual gas pressure towards nominal LHC operation and can thus vary between 10 and 100. The scaling factor with respect to the 2011 operation for the radiation levels, due to the direct beam losses in the area of the collimators, also have associated uncertainties as both the absolute number of protons lost, as well as the loss distribution among the collimators depend on the collimator settings themselves and on the operational parameters. Dedicated beam time should be reserved during 2012 operations to have a clearer understanding of the effects of the residual beam gas as well as the collimator settings on the resulting radiation levels. On the basis of those considerations, the expected HEH fluences for the next year (2012), the nominal, and ultimate operation conditions, are reported in Table 2. The value in bracket refers to the scaling factor that is used to evaluate the radiation levels for the 2012. The scaling factor for the UJ14/16 areas is 0.5 since the benefits of the additional shielding, put in place during the winter shutdown, is already considered. As far as the ion beam operation is concerned, a preliminary analysis shows that the losses significantly increased from 2010 to 2011 operation and are localised in the DS areas and in particular in the LHC tunnel cells from 9 to 13 (point 1, 5, 7), where the radiation levels reached in a few weeks the same levels as cumulated along the year during the proton beam operation. For 2012 ion operation the impact is expected to be significantly reduced due to the proton/ion beam configuration.

Table 2: Expected HEH fluences.

Area	2011[cm^{-2}]	2012[cm^{-2}] (scaling factor)	Nominal[cm^{-2}]
UJ14/16	~2*10^8	~1*10^8 (0.5)	6.3*10^8
RR13/17	7.0*10^6	2*10^7 (3)	2*10^8
UJ56	3.5*10^7	1.1*10^8 (3)	5*10^8
RR53/57	1*10^7	3*10^7 (3)	3*10^8
UJ76	5*10^6	1.5*10^6 (3)	8*10^7
RR73/77	~8*10^6	2.4*10^7 (3)	2.4*10^8
UX85B	1.7*10^8	2.1*10^8 (1.5)	4*10^8
US85	3.5*10^7	4.4*10^7 (1.5)	9*10^7

FAILURES OBSERVED IN 2011 AND CORRESPONDING MITIGATION ACTIONS

The radiation induced failures on the LHC equipment have been analysed by organizing a weekly shift within a group of four R2E members. The main sources of information were the LHC e-logbook and the meeting on the LHC operation follow-up, daily held at 8h30 [3]. During the year, the collaboration of the groups TE/EPC, TE/MPE, TE/CRG, and EN/STI 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) [4]: 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* if a further analysis is required to understand what happened. 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 allow for a respective analysis by LHC operation [5]. In addition, a dedicated tool was developed to easily retrieve statistics on the failures type from the PM database. Fig. 1 shows the failures due to the SEEs along the year 2011. Four distinct failures cases are reported: a) events leading to beam dump, b) events leading to beam dump which are possibly due to radiation, c) failures which did not lead to beam dump, d) failures which do not lead to beam dump and are possibly due to radiation. 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. The increase of SEE failures starting from week 22 which did not lead to beam dump indicates the effectiveness of the mitigation solutions applied by the equipment groups as countermeasures to radiation effects. In fact, the active follow-up of the failures proved to be an effective and necessary task to reduce the total number of beam dumps encountered during the year.

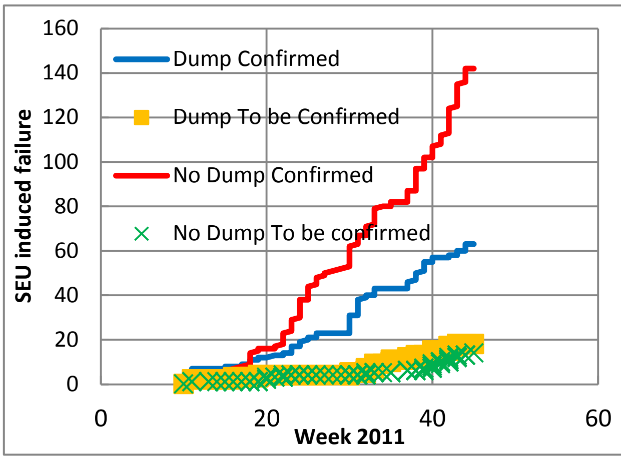
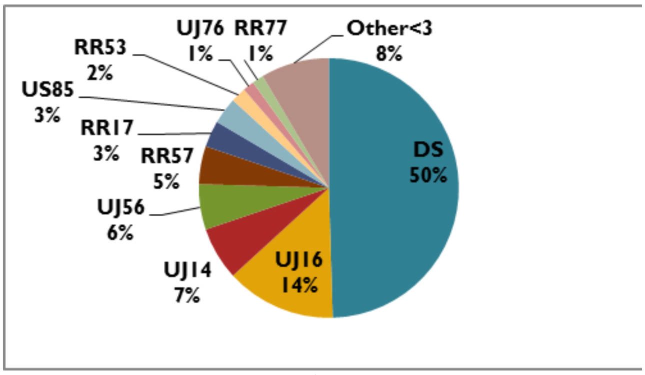
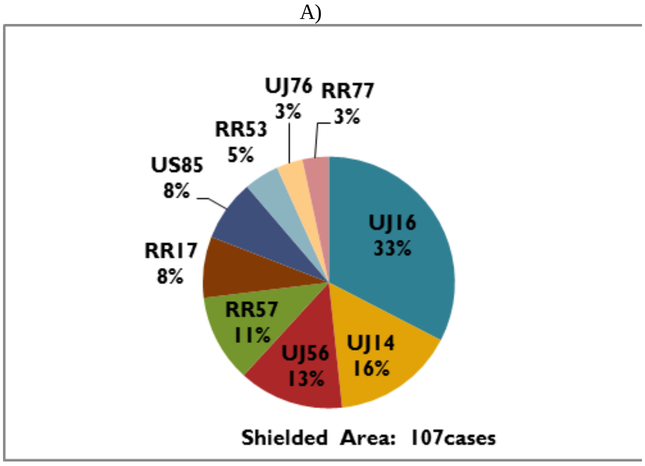


Figure 1. The evolution of the radiation induced failures along 2011 operations.

Fig.2 shows the locations of the equipment affected by SEU radiation failures. The majority of the failures related to tunnel equipment was related to the Quench Protection System (QPS) electronics and happened in the DS areas (Fig.2A). Mitigations at firmware level were applied to avoid beam dumps [6].



A)



B)

Figure 2. Locations of the equipment affected by radiation induced failures. Fig. A) reports all the cases for the tunnel and the shielded areas. Fig. B) shows the failure distribution in the shielded areas.

The shielded areas at point 1, UJ14 and UJ16, resulted to be the most critical zones (Fig.2B), both in terms of number of failures as well as observed radiation levels. It has been decided already during summer 2011 to put highest priority on those areas and improve the shielding areas already during the 2011/12 winter shutdown. The proposed solution should allow reducing the expected HEH fluence for 2012 by a factor 2 as compared to 2011 operation, and this despite the luminosity for the ATLAS experiment expected to increase by a factor of about 3 (Table 2). In the long term, the relocation of the equipment will be the definitive mitigation action and is scheduled for LS1.

In addition to the shielding and relocation actions performed during 2010/2011 and during the upcoming winter shutdown, additional effective countermeasures were applied by the groups in order to reduce the impact of radiation effects on the machine operation. In the following subsections, the failures analysis and the envisaged mitigation actions for all the affected equipment groups are briefly summarized.

QPS

Failures on the QPS systems happened both in the tunnel and in the shielded areas. Most of the failures on the tunnel equipment are due to SEU on an optical isolator (ISO150). An intermediate countermeasure at firmware level was designed to avoid beam dumps with a hardware change envisaged as long-term possibility. Other sensitive parts of the QPS system are the communication and the acquisition modules used for the protection of the magnets, the splices and the 600A converters. It is important to note that all observed SEE induced failure never compromised the safety of the machines. Various additional countermeasures are planned for the winter shutdown and for the programmed technical stops along 2012 to reduce the radiation induced failures. The details of the actions are given in [6].

Cryogenics

The cryogenic equipment also suffered various types of failures. Both destructive and non-destructive SEU failures affected the PLC (Programmable Logic Counter) in Point 1(UJs), 4(UX), 6(UX), and 8(US). A false temperature reading on the current leads triggered unnecessary beam dumps in several shielded areas. Power supplies failed due to destructive single events. The group has planned and integrated several mitigation actions. The most sensitive PLCs were or will be relocated in safer areas in the winter shutdown, the weaker power supplies were replaced with old models, more resistant to radiations, patch solutions were applied at firmware levels to avoid non-destructive single event on the PLC system and on the temperature reading circuit which could trigger beam dumps. The details of those actions are given in [7].

Collimation equipment

Abnormal controller reboots, memory corruption and power supply failures affected the control equipment of the collimation system installed in UJ14, UJ16, and UJ56. As a countermeasure, the survey of critical registers will be implemented to increase the safety of the collimator operations. The failures of the power supply were investigated in detail and are possible to be mitigated by applying a redundant system. However, this solution is not yet fully approved since the delivered monitoring card of the redundant power stage was found to be sensitive to radiations. Thus, for the 2012 restart no immediate mitigations are expected on this equipment which will mainly benefit of the shielding at point 1 to reduce radiation failures. Further actions are continued to be studied along 2012 operation.

Access system

The access doors and the iris scan systems got blocked in many LHC points, even at the surface, in 2011. As a matter of fact, the replacement of all the electronics for the access system is programmed to change obsolete systems. In addition, the failure analysis showed that the fault cases which happened at UJ14 and UJ16 are higher in number and thus expected to be partly related to radiation effects. The shielding of the UJ14 and UJ16 areas should reduce the number of those events by a factor 2 with the long-term relocation scheduled for LS1. It is important to note that newly installed system upgrades are not tested for radiation environments, thus a detailed failure analysis during 2012 operation remains mandatory. A previous proposed mitigation measure to switch off the access control during operation was not maintained as a possible failure of the equipment due to regular powering on and off could not be excluded by the equipment owner.

Beam/ Power/Warm Interlock system

The PLC used for the Power Interlock Control (PIC) system exhibited the loss of the communication with the respective deported Input/Output modules in the zones UJ14/UJ16 and UJ56. Since, in sight of possible SEE induced failures, the infrastructure for the relocation of this equipment was already prepared in the previous year, the equipment owners decided to move its system from the critical areas UJ14/16 during a scheduled technical stop of 2011. No further failures happened after the relocation. The relocation of the equipment from UJ56 and US85 is programmed in the winter shutdown. No radiation induced failures are expected anymore. The VME based part is known to be more robust, thus it’s relocation remains foreseen for LS1, with the required cabling already prepared during this winter shutdown in order to allow for higher reactivity in case the need manifests during 2012 operation.

Power converters

During 2011 operation, an auxiliary power supply of the 600A Power Converters (PC) suffered 8 destructive events. In addition, the digital filter of the Function Generator Controller (FGC) resulted to be corrupted and did not assure proper current measurements. Those events happened mainly in the UJs of Point 1, RRs of Point 1, 5, and 7, and in the UJ and UA of Point 2 and 8. The affected power supply will be tested under radiation to find out the weak components and possibly prepare a mitigation action along 2012. For the time being, the main benefit will be the shielding of the UJ14/16 (cumulative radiation levels reduced by a factor 2). In addition, the digital filter of the FGC has been improved to avoid measurement corruption and no radiation failures are expected anymore or the respective observed failure modes. At long term, both the power stage and the controller (FGC) of the PCs will be redesigned to be radiation tolerant. Moreover, the relocation of the PCs will be carried out where it is feasible.

EN/EL equipments

The Uninterruptible Power Supply (UPS) of the electrical network exhibited destructive events in the UJ56 and US85 areas. Although the failure analysis was not conclusive (dedicated tests could not be performed), the probability that those destructive faults were induced by radiations is considered as high due to the observed failure mode, the affected locations and the involved power components. On this basis, the UPS will be already relocated in the winter shutdown from UJ56, where the radiation levels are expected to increase by a factor 3 in 2012. The relocation of the UPS from US85 is foreseen for the Long Shutdown 1 (LS1).

FAILURE SUMMARY AND OUTLOOKS FOR 2012

Table 3 presents a summary of the number of dumps and failures for the 2011 operation per equipment. The number of avoided dumps is also reported to underline the effectiveness of the mitigation actions taken along the year. The last column of Table 3 presents an estimation of the machine downtime caused by the radiation induced failures. The latter analysis was performed by using the data collected on the RADWG website and on the PM database. A manual iteration on the data was required to take into account the downtime due to issues not related to SEEs which happened before or after the beam dump and led to longer downtimes than the radiation induced failure itself. Although, the analysis is preliminary, it gives a fair indication of the operation time loss due to the radiation. The downtime for the cryogenics failures considers the recuperation of the cryogenic temperatures, thus clearly dominates the overall impact.

Table 3. Summary of the SEU failures in 2011.

Equipment	2011 #dumps	2011 #failures	Avoided #Dump	Estimated downtime (hours)
QPS	23	140	150	~60 hours
Cryogenics	25	48	~25	~250
Power Converter	13	15	3-4 (FGC)	~30
Collimation control	6	8	-	~20
B/P/WIC	3	4	~2	~15
Access	~4-8	-		~10
EN/EL	2	3	-	~15
Total	72	~220	~180	~400

By knowing the cumulated radiation levels in 2011, the number of occurred failures per equipment, and the expected HEH fluence for the 2012, the failures for the 2012 operation can be estimated (Table 4). The analysis has been restricted to the failures which lead to a beam dump. Without any additional mitigation actions, about 220 beam dumps would be caused by radiation effects. If one considers the improvement of the shielding in the UJ14/16, the additional mitigation actions which have been applied towards the end of 2011 and the ones that will be applied in the winter shutdown, the total number of beam dumps can be reduced to about 30-50. Those figures show the importance of the winter shutdown operations, and suggest that each group must continue efforts to apply new patch solutions also during 2012.

Table 4. Expected SEU failures in 2012 with and without the mitigation actions.

Equipment	2012 #expected dumps (without mitigation actions)	2012 #expected dumps (with mitigation actions)
QPS	69	~20
Cryogenics	75	1-2
Power Converter	39	10-20
Collimation control	18	7
B/P/WIC	9	0
Access	-	-
EN/EL	16	~1
Total	216	~30-50

As a matter of fact, new failure signatures, which did not show up in 2011, might appear along 2012 and are important to be analyzed as they will dominate the failure scenario for after LS1. It is important that a careful evaluation is performed over the year of 2012 in order to assure that mititgation measures foreseen for LS1 fully cover the latter failure scenarios.

CONCLUSIONS

A summary of the radiation levels and the induced failures for the LHC operation in 2011 has been reported. About 70 beam dumps were provoked by radiation effects on electronic equipments causing a downtime for the machine of about 400 hours. The impact of the radiation effects would have been significantly higher without the countermeasures that were already applied in the past years [1]. Furthermore, the prompt reaction of the groups to design patch solutions for mitigating radiation effects allowed throughout the year 2011 to reduce the number of failures which could have led to a beam dump. The detailed failure analysis has permitted to identify the UJ14/16 as the most critical shielded area already at an early stage and assure that additional shielding will be installed in this winter shutdown. In addition, equipment groups have also programmed the implementation of additional mitigation actions during the winter technical stop to further improve the robustness of their equipments against radiation effects. Thanks to those efforts, the expected number of failures which can potentially dump the beam in 2012 is expected to be ~30-50, although the radiation levels will increase by a factor of 3 on average, with respect to 2011, in both the tunnel and shielded areas. 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. Dedicated beam time during MD tests is required to better understand those figures and, thus, increase the confidence on the predications of the radiation levels in the following years. The detailed follow-up and analysis of equipment failures remains crucial to assure a prompt reaction to possible new failure signatures which might appear along 2012.

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