IMPACTS OF SEEs

‘Radiation To Electronics’ Study Group (R2E)

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Abstract

Radiation levels expected in various LHC alcoves and more precisely the integrated flux of high-energy hadrons (multi-MeV range) pose a significant risk to all electronics not specifically designed or tested for such radiation levels. In this paper the approach to classify different electronics by their expected overall radiation sensitivity is discussed. Equipment is further grouped in terms of criticality to both, machine safety and operation efficiency. The findings are put in relation with the radiation levels based on Monte-Carlo calculations and expected in the LHC tunnel and alcoves. As equipment partly depends on other devices and installations (*e.g.*, communication) weak links were identified and redundancy issues addressed where required. Necessary modifications can then be prioritized not only by expected radiation levels but also by carefully considering respective equipment details. Long-term development of radiation-hard equipment is understood to be indispensible and the importance to efficiently and effectively steer activities related to radiation damage to electronics is underlined. Obtained results, a detailed overview and the suggested structure are presented and emphasized in this report by reviewing the 2008 activities of the ‘Radition-To-Electronics Study Group (R2E)’.

INTRODUCTION

Radiation effects in electronic devices can be divided into two main categories: cumulative effects and Single Event Effects (SEE). The steady accumulation of defects causes measurable effects which can ultimately lead to device failure. In terms of stochastical failures, so-called ‘Single Event Effects’ (SEE) 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, which will strongly depend on the device as well as on the flux and nature of the particles.

In the current configuration, LHC alcoves equipped with commercial or not specifically designed electronics are mostly affected by the risk of SEEs, whereas electronics installed in the LHC tunnel will also suffer from accumulated damage, however were already accordingly conceived (a respective review is in progress). Given the amount of electronics being installed in these areas the risk of radiation-induced damage has to be minimized as much as possible to allow for both safe and efficient LHC operation.

This report first briefly introduces the 2008 activities and conclusions of the ‘Radiation-To-Electronics Study Group (R2E)’ [1] and illustrates the chosen analysis and evaluation approach taken to address SEE related problems at the betatron cleaning insertion, in particular the UJ76. In the following, an overview is given of expected radiation levels for all LHC machine-related underground areas and a derived prioritization is presented. The same approach is suggested for equipment installed in these areas and a possible priority classification is presented. The latter was first applied to machine protection related systems and a first iteration could be performed prior to the Chamonix workshop. These findings combined with recent radiation test results let us conclude on possible SEE related problems for 2009/10, as well as summarize what is needed to develop a mid/long-term solution for SEE related problems.

R2E STUDY GROUP & 2008 ACTIVITIES

The risk of failure of the before mentioned SEEs becomes high as electronics control logic is present in a growing number of equipment. Respective failures can lead to drastic consequences: for instance, SEEs were responsible for the stop of the CNGS facility. Radiation perturbed the running of PLCs that controlled the cooling and ventilation system, as well as lead to an undetected failure of the fire detection and problems with the access system. This incident triggered an evaluation of electronics installed in all the LHC alcoves by a dedicated working group on “Radiation to Electronics in the LHC” [2]. The R2E task force [1] was subsequently created to quantify the related risk in more detail. It performed a first prioritization of the most critical areas, updated respective radiation levels and evaluated the various options for possible immediate improvements.

The R2E study group consists of experts in the various fields related to electronics damage and coordinates all respective activities for the LHC accelerator. It assists LHC operations and equipment groups with expert knowledge and assessments of radiation-induced failures in electronics of accelerator components. It directly coordinates studies of remedial actions and centralizes all related knowledge to build and form an information, coordination and evaluation contact point for ongoing as well as for future installations to minimize all risks of radiation-induced failures at CERN accelerators, starting with the LHC. Given the clear distinction of needed urgent actions as well as the requirement of a long-term implementation, activities are grouped into two parts:

Immediate:

- propose and evaluate short-term measures to reduce failure risks at existing LHC underground installations
- establish, extend and evaluate the inventory of information needed to assess radiation-induced electronics failures
- ensure accurate monitoring of radiation fields in critical areas to evaluate risks of electronics failures
- advice on irradiation tests, including calculations

Mid- and Long-Term:

- coordinate studies of radiation-induced failures, including calculations and proposals of solutions, and complement the inventory with measured data and experience gained during operation
- advice on further dedicated irradiation tests, including calculations
- assist LHC operations and concerned groups in the failure identification and their short-term mitigation
- centralise all related knowledge and make it readily available for future upgrades and new accelerators
- define procedures to minimize the risk of radiation induced failures for future projects
- create and manage a database for all electronics installed in radiation areas which is not only used as inventory but also for quality assurance to minimize radiation induced errors
- form a constant advisory contact point

After the creation of R2E first actions were divided into short/mid and long-term to both follow urgent problems as soon as possible (and effectively) as well as starting to initiate a new structure which addresses SEE and related electronics issues over the coming years.

This started with a coarse review of all LHC areas and respective available simulation data. Based on detailed updated loss assumptions [3] and an expected scaling for the coming years of operation, the simulation results were used to perform a first preliminary prioritization of areas and the analysis of related requirements and possible improvements.

During the analysis process, additional FLUKA [4, 5] simulations were performed for the most critical areas and whenever required. The latter included detailed shielding studies where applicable (*e.g.*, Point 7), and the careful analysis of possible solutions. For the betatron cleaning insertion this lead to an additional combined simulation study (detailed tracking [6] and cascade simulations) analysing a possible temporary move of the betatron cleaning to Point 3 [7].

In the iteration and analysis process simulation results and new calculations are used to continuously update the prioritization of underground radiation areas, then to be used as basis for all related iterations and evaluations.

Furthermore, during LHC injection tests and start-up, monitor readings of RadMon and RAMSES were analysed and successfully compared to respective FLUKA simulation results (see Figure 1 and Table 1). Radiation tests were continued at external facilities and started first time at the CNGS side-gallery serving as radiation test area for electronics equipment. For the latter detailed FLUKA simulations, as well as monitor readings are available to analyze equipment failure and deduce respective sensitivities.

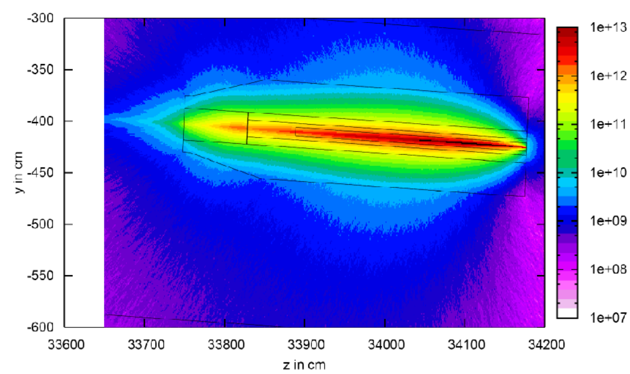

Figure 1: Horizontal high energy hadron distribution (" 20MeV " [cm^{-2}]) around the TI8 TED for $6.8x10^{12}$ protons on the TED.

Table 1: Comparison between FLUKA simulation and RadMon measurements as performed during the TI8 test.

Quantity	RadMon	FLUKA [Error]	Ratio (R/F)
High energy hadrons (cm^{-2})	1.2×10^{10}	0.96×10^{10} [3.2%]	0.80
1 MeV neutron equiv. (cm^{-2})	2×10^{10}	2.1×10^{10} [2.5%]	1.05
Dose (Gy)	4.73	5.0 Gy [10%]	1.06

Previous calibration measurements, the above successful comparison between simulation and measurements, as well as the combined knowledge of the first analysis process and numerous discussions were then used as input to plan for SEE related shutdown activities, as presented in [8] and briefly listed below:

Betatron Cleaning Insertion (IR7) [9, 10]

- (Phase 1) of the for the UJ76 proposed multiphased solution, including the preparation of the TZ76 and the first relocation of equipment as described later in this report
- UPS removal (from UJ76 into TZ76)
- installation of an additional shielding wall at the tunnel side to increase the protection of the safe room
- RR73/77 installation of final shielding

Dump Extraction (IR6)

- Shielding of ducts between the LHC tunnel and the UA63/67 next to TCDQ, TCS and TCSM

LHCb (IR8)

- UX85b installation of remote vacuum valve controllers, relocation of cryogenic racks into UL

Other Areas

- identified additional holes in shielding were already mostly closed before first start-up (*e.g.*, geometer holes at Point 7), the remaining will be closed
- for all critical areas: check for required additional monitoring, or initiate detector relocation when needed

Detailed information about performed simulations, discussed analysis, available documentation and all R2E related information can be found at [1].

In the following we describe in more detail, the chosen approach for the above mentioned collimation region and explain both the analysis process, as well as the proposed solution. It shall be noted that the latter implementation has already been started in its first phase and will be continued during the next long shutdown. In the meantime, early operation will allow us to more precisely evaluate the radiation levels and refine proposed actions.

PROPOSED SOLUTION FOR UJ76

The level of radiation expected from the collimation system at Point 7 has been simulated with FLUKA already in 2004 [11], assuming LHC design values and what is called a nominal loss scenario. The latter refers to an ideal situation where collimation efficiency is and operation performs as ideally as expected. It shall thus be noted that the below values and the details as described in the respective references and presentations are to be understood as the currently best scenario possible. Future evaluations to continue for both, measurements during early operation, and updated simulations based on more detailed loss assumptions. Based on the existing simulations [11], the integrated dose would stay below 1 Gy per year but the flux of hadrons with E>20MeV could reach up to 10^9 per cm^2 and per year (see Figure 2). At such a dose level, one does not expect any radiation damage resulting from the total ionising dose. However, single particle energy deposition can induce Single Event Errors (SEE) as outlined before.

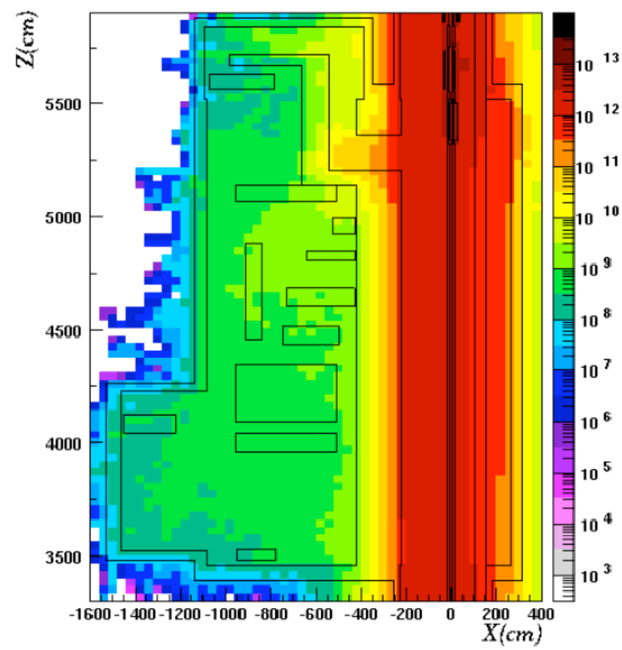

Figure 2: Annual high-energy hadrons fluence distribution (with E > 20 MeV and in $cm^{-2}year^{-1}$) in the UJ76 in a horizontal section at beam-line level [11].

Therefore, after confirmation of the above listed radiation levels with new updated simulations (in terms of layout, statistics and details), the UJ76 was given the highest area priority for the following reasons:

- expected radiation levels directly depend on the losses at the collimators, thus they might rise fast as beam intensity is increased.
- the current estimate of radiation levels highly depends on the actual distribution of losses among the collimators, introducing additional unknowns and possibly leading to values higher than assumed in the simulations, thus requiring a significant safety margin.
- the UJ76 houses a large number of electronics which is critical for machine operation and protection and often installed in the direct vicinity of the LHC tunnel (see Figure 3): *e.g.*, the uninterruptible power supply system (UPS), access control, fire detectors, as well as an important number of racks on the first floor (power converters, vacuum monitoring, RAMSES, remote cryogenics valve controllers, control equipment, etc.).

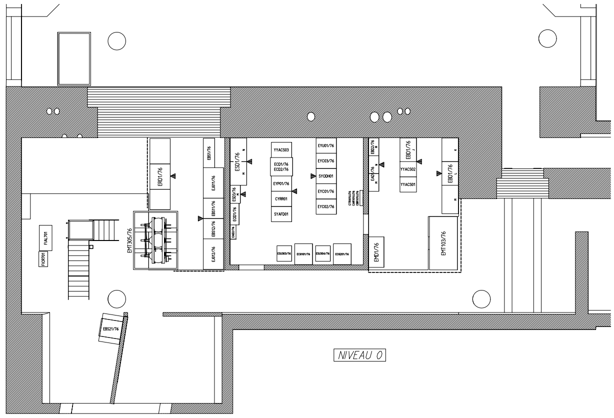

Figure 3: Rack layout on lower level of UJ76.

Many of the equipments installed in the UJ76 are expected to be highly sensitive to SEEs. In most cases, it is commercial equipment with components for which the radiation sensitivity is unknown and can significantly change between different batches of components. Thus, dedicated radiation test campaigns and the detailed quantification of reliable SEE cross sections is not realistically possible. Furthermore, their complete replacement with radiation tolerant electronics would require an important development program and cannot be envisaged within the required timescale.

It was thus proposed to minimize the possible immediate risk of SEE related problems with electronics installed in the UJ76 by planning and starting equipment relocation into the adjacent TZ76 gallery, as well as the installation of additional shielding to protect Safety related equipment. This work is planned in two phases to first address, without any delay, possible dangerous situations where the machine protection systems could become ineffective and include a potential risk for the machine elements. In addition, during the LHC start-up a more detailed knowledge of both, the actual radiation field and the component sensitivity will become available, allowing to further refine required actions during the UJ/TZ76 integration phase 2. The emphasis is first put on safety critical equipment and the preparation of the area in order to maximize flexibility.

In this respect, the TZ76 area is prepared during the current shutdown to be able to house all sensitive equipment actually installed in the UJ76. Presently the UPS is already being relocated into the TZ76. The remaining equipment could be moved during the next shutdowns. This still allows further evaluation and the optimisation of both, additional shielding options and a possible mid/long-term reduction of the SEE sensitivity of some electronic systems. Additional details and further explanations can be found in [9].

Although the present approach for the UJ76 deals with the possibly most critical area in terms of how early at LHC SEE related problems could occur, it should not be forgotten that:

- SEE in the equipment that is not immediately removed from the UJ76 may occur as soon as there is beam in the LHC and this could have an impact on LHC operation.
- A quantitative estimate of the risk of radiation induced failures and of their consequences can only be made when the equipment is exposed to radiation in dedicated test facilities. Such tests must be continued, as they will also provide guidelines for a precise planning for relocating equipment as a function of increasing beam performance in the LHC.
- The development of radiation tolerant equipment, as already achieved for the electronics in the LHC tunnel, must be generalised for the UJ and RR as the performance of the LHC will continuously increase, thus yielding higher respective radiation levels. This is particularly difficult and may take several years for standard equipment designed by commercial companies outside CERN. Effort in this direction should thus be launched without delay.
- Flux of hadrons with E>20MeV in the 10^8 per cm^2 range is expected in various areas around the ring (for instance in the UJ14/16 or UJ56), thus detailed evaluations are ongoing and a current summary is presented in the following chapter.

SUMMARY OF RADIATION LEVELS

The knowledge of radiation levels of the most critical LHC critical alcoves is currently based on simulations only, thus detailed analysis and iteration are required during early operation. It shall further be noted, that important uncertainties exist due to assumptions taken for respective loss terms (actual integrated luminosity, distribution of losses,…), as well as equipment sensitivity and effects due to actual layouts as compared to partly simplified assumptions in simulations (*e.g.*, empty alcoves).

Thus, as outlined above priorities were assigned during 2008 according to the system sensitivity and criticality, as well as the inherent uncertainty in loss assumptions (see above for UJ76). In addition, possible short-term measures which could be integrated without important constraints on shutdown activities and on costs were suggested to be integrated as soon as possible (*e.g.*, UA63/67).

The current prioritization of area with respect to expected radiation levels (presented as colour coding in Tables 2 and 3) included a further analysis and is structured as follows:

- ongoing work during this shutdown (highest-priority resulting from 2008 evaluation as described above) [yellow]
- highest priority for upcoming iterations/evaluations [red]
- second priority, cross-check with measurements [blue]
- lowest priority, layout check and evaluation [green]

Tables 2 and 3 summarize the current status of point-iterations in terms of radiation levels to be expected during 'nominal' conditions. For all LHC points, as well as the injection regions the radiation levels are given for annual dose, 1MeV-neutron-equivalent, and high-energy hadron fluences. For all presented values the respective normalisation is stated as assumed in the existing publications. This allows to easily rescaling values in case loss conditions are changing, or different annual scenarios are discussed.

To estimate the radiation levels expected during the first years of operation, the above given 'nominal' assumptions have to be rescaled to the foreseen operational scenarios, with the latest update as provided in [12]. For the high-luminosity experiments the latter gives a maximum integrated luminosity of 300 pb^{-1}, thus relatively low as compared to respective 'nominal' values of 100 fb^{-1}.

However, integrated losses in the collimation region are expected to reach already 10% of nominal. In addition, the distribution among the collimators is possibly worse in the sense that those collimators contributing most to the radiation levels in the RRs and the UJ76 would see relatively more losses [6]. At the same time for LHCb 'nominal' operation refers to 'only' 2×10^{32} $cm^{-2}s^{-1}$ in luminosity. When assuming for LHCb 1×10^{7}s as typical LHC year, this results in 2 fb^{-1}. As outlined in [12] for 2009/10 operation a limited number of bunches will be displaced for LHCb so that the experiment can get collisions before operation with 75 ns spacing. This still yields for 2009/10 about 5% (~100pb^{-1}) [12] of nominal integrated LHCb luminosity, thus an important fraction of what is used in Tables 2 and 3. Depending on the final distribution between the high-luminosity experiments (ATLAS and CMS) and LHCb, it was pointed out [13] that a reach of 300pb^{-1}, thus 15% of nominal is not to be excluded.

Table 2: Radiation levels (dose, 1MeV-neutron-equivalent and high-energy hadron fluence) for LHC Points 1 to 5 as expected during nominal operation conditions. The respective normalisation and scaling dependency are given and the derived priority levels are high-lighted (yellow: ongoing work, red: highest priority, blue: second highest priority, green: lowest priority).

LHC Point	Area(s)	Radiation Levels						Priority
		20MeV [cm^{-2}/y]	1MeV [cm^{-2}/y]	Dose [Gy/y]	Normalisation	Scaling	Comments	
Point 1	UJ14 UJ16	1.E9-1.E10	1.E10-1.E11	1. - 10.	100 fb-1	Luminosity	1st Shielding Studues performed	2
	RR13 RR17	3E7-9E7	1.5E8-4.5E8	0.01-0.2	70 fb-1	Luminosity Beam-gas	full shielding assumed in calculations (last phase as in ECR)	2
	US15 USA15	1E6-1E7		0.001-0.02	100 fb-1	Luminosity	partly based on extrapolation	4
Point 2	UX25							4
	US25							4
Point 3	UJ33	1E4-2E6	5E4-7E6	1E-6-1E-3	1E16 p/y	Direct beam losses	Cryo Equipment at Entry Point ("Worst Location")	4
	UJ32	1E7-1E8	1E8-1E9	< 0.01	1.65E11m-1y-1	Beam-gas	very conservative beam-gas assumptions	3
	RE38	2E5-1E7	1E6-5E7	5E-5-1E-3	1.65E11m-1y-1	Beam-gas	very conservative beam-gas assumptions	3
Point 4	UX45	5.0E+06	1.5E+07		2.4E10m-1y-1	Beam-gas	Different norm. for various beam-elements, dominating stated: can the density be higher?	3
Point 5	UJ56	1.E9-1.E10	1.E10-1.E11	1. - 10.	100 fb-1	Luminosity	1st Shielding Studues performed	2
	RR53, RR57	3E7-9E7	1.5E8-4.5E8	0.01-0.2	70 fb-1 2.E9-7E10m-1y-1	Luminosity Beam-gas	full shielding assumed in calculations (last phase as in ECR)	2

Table 3: Idem to Table 2 for LHC Points 6 to 8, as well as the injection regions, arcs and dispersion suppressors.

LHC Point	Area(s)	Radiation Levels						Priority
		20MeV [cm^{-2}/y]	1MeV [cm^{-2}/y]	Dose [Gy/y]	Normalisation	Scaling	Comments	
Point 6	UA63 UA67	1E6-1E9	1E7-1E10		3.4E13 p/y	Direct beam losses	Simplified simulation	1
	UD62 UD68						crane and ventilation equipment	3
	US65							4
	UX65							4
Point 7	UJ76	1E7-1E9	5E7-5E9	1E-3-1E0	1.15E16 p/y	Direct beam losses	loss dominated by secondaries interacting in lateral beampipe	1
	RR73 RR77	1E7-1E8	5E7-5E8	0.01-2	1.15E16 p/y	Direct beam losses Beam-gas	real losses to be evaluated (monitoring @start-up), strong dependency on TCLAs	1
	TZ76	<1E8			1.15E16 p/y	Direct beam losses	TZ maximum levels to be evaluated after measurements at higher intensities	4
Point 8	UX85b	5E8-2E9	1E9-1E10		3.2E14 pp/y	Luminosity	values refer to valve location	1
	US85	5E7-5E8	2E8-2E9		3.2E14 pp/y	Luminosity		2
TI2	UJ23	>5E9			1.44E16 p/y	Direct beam losses	2 shots per day on the TED crane only!!!	3
	UA23	<7E8			1.44E16 p/y	Direct beam losses	2 shots per day on the TED	3
TI8	UJ87	>5E9			1.44E16 p/y	Direct beam losses	2 shots per day on the TED crane only!!!	3
	UA87	<7E8			1.44E16 p/y	Direct beam losses	2 shots per day on the TED	3
ALL	ARC	1E9-5E12		1-1000	1.65E11m-y-1	Beam-gas	Equipment spec. designed, Issue with 60A power converters?	2
	REs	2E5-1E7	1E6-5E7	5E-5-1E-3	1.65E11m-1y-1	Beam-gas	very conservative beam-gas assumptions	4
	DS	1E9-5E12		1-1000	1.65E11m-1y-1	Direct beam losses Beam-gas	Equipment spec. designed, Issue with 60A power converters?	2

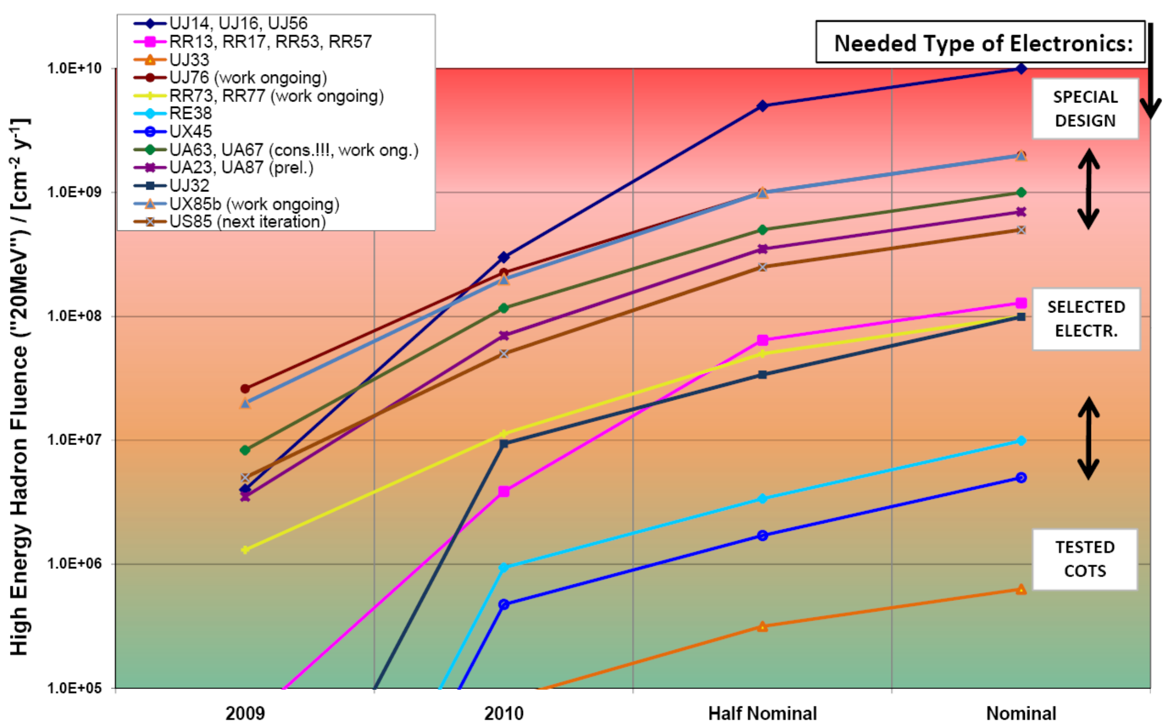

Figure 4: High-energy hadron fluences as a function of LHC operational year to be expected in various LHC alcoves based on existing simulation results and updated loss assumptions [12]. Please note that the operational year 2009/10 is based on certain assumptions, thus presented maximum fluence values define the in Tables 2 and 3 presented prioritisation, however partly include important uncertainties. It is the purpose of later described point-iterations to minimize these uncertainties.

This and similar rescaling can now be applied to all LHC critical regions and results in high-energy hadron fluences as a function of time as presented in Figure 4.

It shall be noted that such a scaling strongly depends on the expected losses, the respective distribution, and the integrated beam intensity or luminosity. As outlined above, this dependency and the inherent uncertainties in the simulations suggest to respect sufficient safety margins.

EQUIPMENT CRITICALITY

Whereas 2008 R2E activities were focused on required short-term activities and possible machine safety concerns, the required mid-/and long-term measures yields the necessity to further refine the prioritization in terms of knowledge about areas and equipment as well as required actions. This prioritization is particularly important as the current analysis shows that many of the LHC machine alcoves are affected and an important amount of equipment is concerned. It is not possible to find immediate solutions for all areas and systems of concern. An improved prioritization in terms of equipment is needed.

It is thus suggested to use an approach which is similar to the prioritization used to classify underground radiation areas (see above). With respect to equipment classes, one has to distinguish in terms of equipment criticality, as well as respective failure consequences on the machine safety, operation and efficiency. The suggested priority levels with their respective colour coding according for each equipment class and implications in case of failures are shown in Table 4.

Table 4: Equipment prioritization and colour coding according to equipment classes and respective implications in case of failure.

- 1. Machine Safety Control
  - AL3 Safety Systems
  - Beam Interlock System (BIC)
  - Damage related sub-systems (PIC, WIC, FMCM, BDS,...)
- 1.b. Systems whose input is important to assure machine protection
  - *e.g.*, BLM
- 2. Systems whose dis-functionality leads to downtime or localized damage only
  - *e.g.*, Power Converters, BTV
- 3. Impact on Beam Quality
  - *e.g.*, Vacuum
- 4. Monitoring mainly

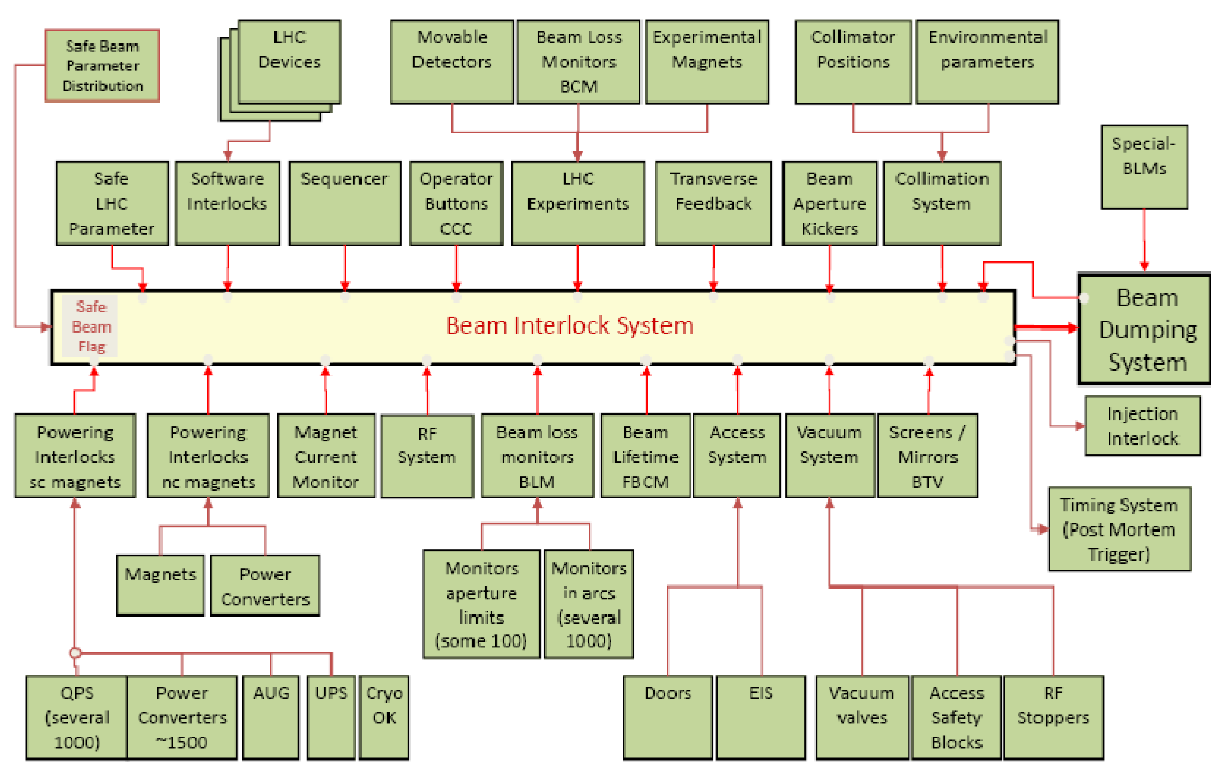

Figure 5: Schematic layout of the Machine Protection (MP) System [14].

The highest priority is given to all safety-related equipment (machine and personnel), and associated systems. This is followed by all equipment whose failure would lead to important downtime of the machine or localized damage. The last two categories then group equipment in those having an effect on the performance of the machine, and others dedicated to pure monitoring. In addition, when analysing the criticality of a system it must be taken into account that in many cases other equipment depends on the proper functionality of the former, thus respective dependencies have to be properly considered.

For illustration, this approach was first applied to the machine protection (MP) system. Being a complex system an initial iteration was performed with the aim to verify the applicability of the approach, and to identify possibly weak links where single equipment failures due to SEEs could lead to important consequences.

The MP system functionality is described in detail in [14] and references therein. An overview of the various system parts is shown in Figure 5. Some of their control electronic is situated in LHC underground areas, thus a respective evaluation was started.

Applying the suggested prioritization to the MP-related systems allows grouping the equipment in basically three layers as shown in Figure 6. Following the highest priority and neglecting those in safe areas (surface buildings or well-shielded areas) leads to a first analysis of the beam dumping, the collimation, the interlock, vacuum and access systems.

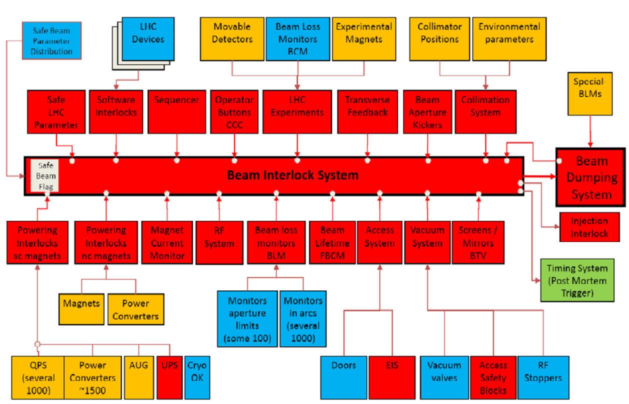

Figure 6: Prioritization levels as outlined in Table 4 and applied to the Machine Protection (MP) System [14].

The interlock-controller racks (containing PLC a based system, thus very sensitive to radiation) are mostly installed in surface areas, leaving only certain underground areas (UAs, USs, TZ76 and UJ56) to a future detailed analysis. One current concern is the 'beam interlock controller' (BIC) rack located in the UJ56 where important radiation levels are expected as the CMS luminosity increases. The system design is redundant, thus no direct impact on machine safety is expected. However, a possible reduced redundancy has to be avoided and a solution will have to be studied [15]. It shall be noted that besides the interlock-controller racks many MP related equipment is installed in certain alcoves and partly even in the tunnel (QPS), however some of which already specifically conceived and tested for the respective radiation levels.

In addition, the UA63/67 are already ready for start-up, with the connection ducts being filled during this shutdown (see above) and the UJ/UA23/87 to be monitored where access control and other equipment is installed close to the UJs. For the latter two areas no early problem is expected as radiation levels depend on the integrated intensity being sent onto the TED. The respective radiation field will be further evaluated during scheduled injection tests and direct shielding solutions are considered as possible, if required.

A further concern identified during the iteration are the collimation racks installed in UJ14/16 and UJ56. Respective solutions have to be studied, also addressing the complete equipment being installed in these areas. Current luminosity estimates suggest that the UJs next to the high-luminosity experiments are exposed to relatively low radiation during 2009/10. However, towards the end of the operational year and in case machine performance is as good as currently expected [12] it is still possibly leading to reach integrated radiation levels which are comparable to those where first CNGS failures occurred.

It shall be noted that the situation is different for LHCb, where already a significant fraction of nominal luminosity can be reached during early operation. Therefore, all sensitive equipment installed in the UX85b is scheduled to be relocated or replaced during this shutdown, and all equipment being installed in the US85 is subject to detailed monitoring during early operation.

In terms of communication the machine protection control equipment does not rely on standard components with hard wired links used where required. There are a number of additional concerns with results of radiation test being currently studied: energy extraction switches (located in the RRs); power converters (following recent tests and observed problems with the FGC controller installed in the 60A power converters located in the LHC tunnel); the new QPS system with radiation tests already being scheduled (the existing one having been tested over the last year through many radiation campaigns); solid state relays where radiation test results are currently analysed. Additional iterations are ongoing through the R2E study group and the RadWG linked with the 'Machine Protection Working Group (MPWG)'.

R2E REQUIREMENTS AND SHORT/MID/LONG-TERM MEASURES

As shown before, careful iterations are required for numerous LHC underground areas. They would possibly affect a large amount of equipment. A common and immediate solution is impossible due to several reasons, the most important ones are time and space constraints. In this context both the collection of available data as well as respective reviews are required. The latter iterations are scheduled through R2E meetings and followed by a RadWG equipment review on a regular basis.

This process includes the review of radiation levels (presently through Monte-Carlo simulations and later by comparison with measurements), the collection of global equipment information, the verification of rack locations and a detailed review of monitor locations through respective inspections. Available simulation data are evaluated and radiation levels are extrapolated to early operation, considering both respective uncertainties and aiming to define maximum fluence/dose values for each critical underground area, the latter then to be used as reference value for future equipment to be installed in these aeas.

For this purpose a general document database exists already [16] including the current knowledge of radiation levels, respective area classifications and all related documentation. A similar collection is required for the concerned equipment systems, *i.e.*, equipment classes, racks and further equipment details. Additionally, inter-dependencies have to be identified together with consequences of equipment failure/malfunctioning, as well as implications for either repair or replacement.

During this and next year's early operation the continuous evaluation of radiation levels in critical LHC alcoves will be of utmost importance. For this purpose an efficient monitoring tool will be developed allowing for a quick analysis among the different monitor systems (RadMons, BLMs, RAMSES) and combining this information with the respective machine conditions (luminosity at experiments, losses at collimators, et). For this purpose monitor locations have to be reviewed and it is suggested to concentrate during start-up on the most important areas and already prepare in advance the condensed information of expected radiation levels, concerned equipment and – if available – expected sensitivities. This approach shall be followed for all areas such as the UJ76, RRs, US85, or the UJ56. In parallel, additional FLUKA simulation studies can be performed to further refine the respective knowledge.

Furthermore, radiation testing is required for which coordinated test campaigns are organised through the RadWG. This involves mixed-field and complete system radiation testing at CNGS, certain possibilities at other CERN facilities (*e.g.*, East-Area), as well as dedicated beam time at external facilities (e.g., PSI). Last year a working group [17] started evaluating the radiation test requirements at CERN. The enquiry covers the needs for gamma, proton and mixed field irradiation facilities as well as the need for a future GIF facility ('Total Ionizing Dose (TID)' tests in combination with beam) and fast extraction tests. The report of this analysis is used to identify the current and future needs of such facilities and the respective conclusions will be summarized soon.

To improve the knowledge of radiation effects to electronics and constraints in certain LHC underground areas a further focus is put on required knowledge and development. Identified knowledge exists within the accelerator sector. With the LHC experiments having also important expertise in this domain. It is suggested to explore synergies between experiments and the LHC machine groups. For this purpose a jointly organised two-day training course on Single Event Effects (SEE) and related design issues is suggested. It will provide lectures with focus on design constraints to be followed for existing or future installed equipment. The radiation levels of concern refer to those as expected in the LHC machine alcoves and the tunnel. The school shall be organised ideally before summer 2009 and a draft program will be defined soon.

For a coherent mid- and long-term protection of electronics being installed in radiation areas a new implementation structure is suggested through the R2E study group. It shall consist of:

1. a policy for all electronics installed in areas with high radiation levels
2. the continuous evaluation of radiation levels based on both, simulations and monitoring
3. if required, the proposal of mitigating measures
4. a direct link to equipment owners and respective iterations and evaluations
5. coordinated radiation tests
6. regular control.

Such a structure (proposed in Figure 7) has to be endorsed and supported by all concerned department and group leaders. In this organization R2E forms the advisory body, is directly linked to the RadWG and reports to the management through the LHC Machine Committee (LMC). The above points are addressed through an electronics policy to be developed through the R2E study group. Thorough R2E point-iterations are performed, radiation levels evaluated and possible measures proposed. The RadWG forms the direct link to the equipment owners, organises and coordinates radiation tests as well as forms a forum for electronics development. Radiation monitors with their locations confirmed during the LHC point-iterations are then used to analyse in detail respective constraints already throughout early operation. Based on this appropriate detector threshold can be defined for long-term operation.

In addition, the LHC point-owners are the direct link to the actual LHC areas and respective installations. They are members of R2E and form an ideal control body as all planned work and installations have to include their involvement.

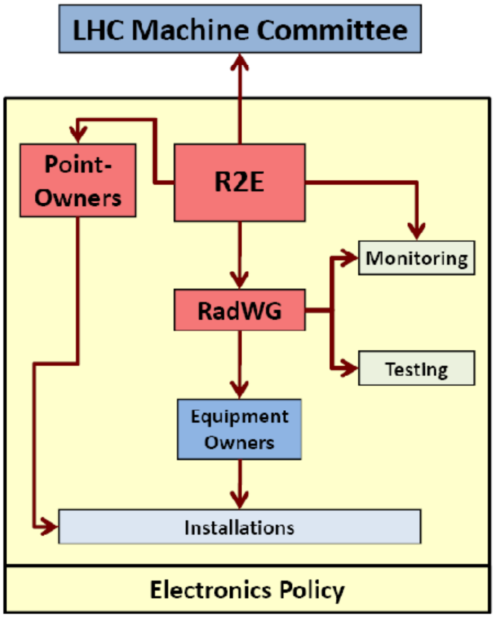

Figure 7: Suggested mid/long-term organisational structure to address radiation effects to LHC electronics.

CONCLUSIONS

In the current configuration, LHC alcoves equipped with commercial or not specifically designed electronics are mostly affected by the risk of SEEs. This paper reported on the 2008 R2E activities and conclusions. It illustrated the chosen analysis and evaluation approaches. An example was given for the UJ76, along with a detailed overview of expected radiation levels for all LHC underground areas and derived prioritizations. The same prioritization approach was suggested to be used for equipment classes installed in these areas and a possible priority classification was presented. The latter was first applied to machine protection related systems.

Based on our current knowledge no immediate showstopper has been identified for the 2009 restart. As intensity and luminosity increase SEE-related problems will arise. The detailed monitoring of radiation levels, the careful evaluation of loss assumptions and the continuous comparison between measurements and respective simulations are foreseen.

In critical areas, concerns were raised for all UPS equipment, BIC controller racks installed in the UJ56, collimation racks in UJ14/16/56 and AL3 safety related equipment in most of the areas. As radiation levels will increase fastest next to the collimation areas (Point 3 and Point 7), and at LHCb (UX/US85), monitor locations and availability have to be reviewed. A continuous detailed analysis will be of utmost importance during early operation.

A continued and more detailed review of areas and installed equipment is required, the latter emphasized due to the recent decision to run through 2009/10 without any long shutdown. For this purpose, combined R2E-RadWG LHC point-iterations are foreseen. In addition, numerous radiation tests will be required during the coming years. The respective availability of facilities has thus to be studied and coordinated.

With certain equipment functionality depending on other installations (*e.g.*, communication) possible weak links have to be analysed and carefully identified through equipment owner polls and by creating a respective database in the mid/long-term. This combined information approach allows prioritizing areas not only by expected radiation levels but also by carefully considering respective equipment details.

The above, combined with a preliminary study of risk mitigation options (shielding, replacement, relocation and re-design) clearly points to the need of a long-term strategy. The latter shall include the continued study of radiation fields for all LHC critical areas by updated Monte-Carlo calculations and complemented by detailed radiation field measurements. A continued up-to-date equipment inventory, additional test campaigns, and detailed monitoring already during early operation are considered as highly important. The long-term development of radiation hard equipment is indispensable.

The importance to efficiently and effectively steer these activities was underlined and a respective mid/long-term organisational structure was presented.

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