REVIEW OF CRITICAL RADIATION AREAS FOR LHC ELECTRONICS AND MITIGATION ACTIONS. RADIATION MONITORING AND FIRST RESULTS

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Abstract

This paper provides an update of the radiation levels in the critical LHC areas, both based on updated FLUKA simulations as well as on early measurements. Furthermore, a detailed analysis of the respective particle energy spectra is given and put in contrast to present and possible future radiation sensitivities. The radiation monitoring improvements as performed during the 2009 shutdown are illustrated and conclusions for the actual impact on LHC operation and the measured shielding effectiveness are presented wherever available. Based on this, the 2008/2009 applied mitigation actions will be preliminary evaluated together with additionally foreseen short- and medium term measures.

INTRODUCTION

A large spectrum of equipment and electronics is exposed to radiation around the various LHC areas. The preparation and study of long-term mitigation actions requires a careful analysis of various aspects:

1. radiation levels and their evolution with LHC operation (based on detailed Monte-Carlo simulations, as well as measurements when available)
2. inventory of installed electronics (designed, COTS) and failure consequences
3. expected radiation sensitivity, failure cross-section and possible failure rates
4. early monitoring and optimization possibilities
5. analysis of mitigation options
    a. early actions
    b. shielding (simple + complex)
    c. relocation
    d. radiation tolerant by design
    e. civil engineering options
    f. other options
6. evaluation and comparison of required resources (costs, time and man power)

This report focuses on points (1), (4) and (5). A first evaluation of (6) is further given in [3]. Point (2) is covered in reference [1] and reference [2] summarizes the 2009 CNGS radiation tests for specifically designed electronics (partly addressing also point (3).

MONITORING IMPROVEMENTS

The LHC radiation field varies between the different locations where electronics is installed (tunnel, shielded areas). Depending on the location, either cumulative damage or single event effects will be the main source of radiation induced problems to electronics. The continuous monitoring as well as a detailed analysis of the radiation field (particle type and energy) are considered as important, in order to study and optimize the various mitigation options. This chapter summarizes recent monitor improvements and gives further updates on the radiation fields.

RadMon Improvements

In 2009 dedicated benchmark experiments were carried out at the CERF facility in order to analyse the RadMon [4] SEU detector response to mixed fields as expected in LHC critical areas. A detailed FLUKA [5, 6] benchmark, analysed the dependency of the RadMon reading as a function of voltage settings (3V and 5V are used in the LHC according to the installation location of the RadMon). This is of particular importance as the voltage setting strongly influences the SEU sensitivity to thermal neutrons. This is important for both, RadMon readings in LHC shielded areas, as well as measurements carried out during the CNGS equipment tests. Based on a detailed analysis of both measurement campaigns [7, 8], as well as a dedicated calibration at a reactor in Prague [9] the following calibration is proposed for the RadMon high-energy hadron fluence estimate:

Table 1: RadMon high-energy hadron and thermal neutron SEU sensitivities for two voltage settings as installed in the LHC (3V: shielded areas, 5V tunnel areas). The listed fluences correspond to one equivalent RadMon SEU count.

Voltage	**High-E Hadrons**	**Low-E Neutrons**	$\sigma_{h>20MeV}/\sigma_{\text{low-E}}$
3V	8.47×10^{5} cm^{-2}	3.56×10^{5} cm^{-2}	0.42
5V	2.00×10^{6} cm^{-2}	1.90×10^{7} cm^{-2}	9.5

In addition, the following actions were taken in order to improve the early RadMon measurements in the LHC:

- numerous detectors were relocated in order to allow for a better coverage around LHC critical areas (*e.g.*, US85)
- additional detectors were added in certain locations (*e.g.*, LHC Point-6 next to TCDQ)
- when available, one of the detectors located in critical areas was placed towards/in the LHC tunnel to allow for non-zero readings during commissioning (*e.g.*, RRs in P7)
- voltage settings were updated consistently to 5V for all tunnel locations (except ARC) and 3V for all shielded ones (as well as ARC).

Inventory and Additional Monitoring

Through dedicated R2E iterations of critical LHC areas, shielding configurations and monitor locations were checked and documented. This included not only the RadMon locations, but also installed RAMSES monitors (*e.g.*, PMIs in the LHC tunnel, IG5 chambers in shielded areas). For this year, a monitor location visualisation tool is proposed to be developed, in order to allow for an easier interpretation of monitor readings during LHC operation.

In addition, more than 200 passive detectors (‘Thermo Luminescence Detectors’ TLDs) detectors were placed around critical LHC areas [10]. They will allow for an early analysis of integrated dose levels at low beam-intensities where RadMon readings would be below threshold or at very low statistics. They will be removed from the tunnel and analysed during late-summer in order to allow for a refined prediction for the remaining operation time.

Combined Monitoring Tool

In collaboration with the LHC operations group a combined monitoring tool was developed and a beta-version was released recently [11]. The tool allows acquiring radiation detector readings installed in the LHC in an easy and combined way. A graphical interface provides a detector selection by area, LHC coordinate (DCUM) or machine element search. An user friendly interface allows easy navigation around the LHC layout to select the desired areas, get information about the detailed detector location, as well as set timing and other required input information.

The fast retrieval of multiple detector data for the critical areas is a powerful tool to understand the radiation fields around the ring and alcoves. The tool is able to display multiple detector information including: BLMs, RADMON, RAMSES, collimator settings and beam intensity. The readings are combined in one framework only and easily allow for data extraction and combined visualisation.

This way the various detectors measurements can be related to operational information like, for example, beam intensity or collimator settings, important to compare previous simulation results to the actual measurements.

The monitoring tool interfaces to the measurement or logging database and provides an analysis GUI, as well as the correct time correlation. Detector readings can be displayed as rates as well as integrated over time intervals and the results can be directly displayed, as well as exported for further analysis. A dedicated inspector tool allows searching for detectors exceeding predefined thresholds, as well as making a first statistical analysis.

It shall be noted that the combined monitoring tool is considered as useful not only for the purpose of radiation to electronics, but could be of general interest for all LHC monitoring or equipment groups.

THE RISK OF THERMAL NEUTRONS

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 that can ultimately lead to device failure. Stochastic failures, so-called ‘Single Event Effects’ (SEE) form an entirely different group as they are due to the direct ionization by a single particle (from nuclear reaction in the electronics itself), 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.

Mixed radiation fields of various particle types and a large range of energies are the source of radiation effects in both areas. Especially in shielded areas (*e.g.*, UJs, RRs) an important contribution to the total particle fluence is coming from low-energy or thermal neutrons (*e.g.*, UJ76, see Figure 1).

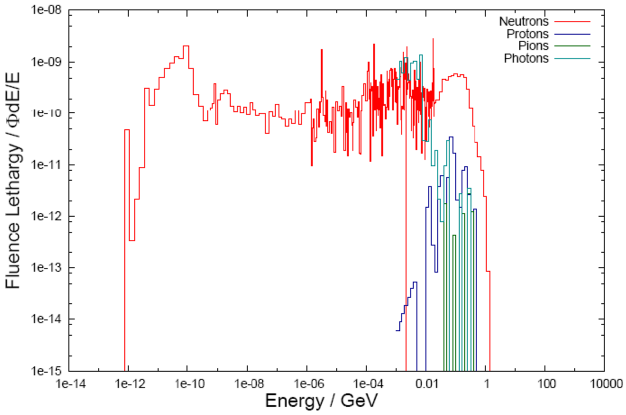
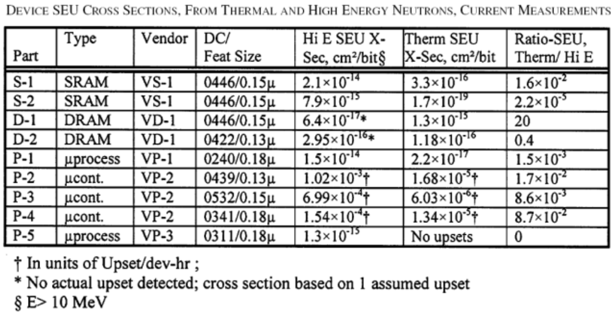


Figure 1: UJ76 representative particle energy spectra.

Usually high-energy hadrons above a certain threshold energy (*e.g.*, ~20MeV for protons and a few MeV for neutrons) are the main source of SEEs. However, depending on the device electronics, low-energy neutron capture reaction (*e.g.*, n-alpha) can create highly ionizing secondary particles that are then also the source of SEEs. The capture reaction cross-sections, exponentially increasing with decreasing energies, lead to a possible high sensitivity for low-energy and thermal neutrons. This fact is illustrated in Table 2, showing device sensitivities to both, high-energy and thermal neutrons [12].

Table 2: Comparison of high-energy and thermal neutron SEU-cross sections [12].



DEVICE SEU CROSS SECTIONS, FROM THERMAL AND HIGH ENERGY NEUTRONS, CURRENT MEASUREMENTS

Part	Type	Vendor	DC/ Feat Size	Hi E SEU X-Sec, cm²/bit§	Therm SEU X-Sec, cm²/bit	Ratio-SEU, Therm/ Hi E
S-1	SRAM	VS-1	0446/0.15µ	2.1×10^{-14}	3.3×10^{-16}	1.6×10^{-2}
S-2	SRAM	VS-1	0446/0.15µ	7.9×10^{-15}	1.7×10^{-19}	2.2×10^{-5}
D-1	DRAM	VD-1	0446/0.15µ	6.4×10^{-17}*	1.3×10^{-15}	20
D-2	DRAM	VD-1	0422/0.13µ	2.95×10^{-16}*	1.18×10^{-16}	0.4
P-1	µprocess	VP-1	0240/0.18µ	1.5×10^{-14}	2.2×10^{-17}	1.5×10^{-3}
P-2	µcont.	VP-2	0439/0.13µ	1.02×10^{-3}†	1.68×10^{-5}†	1.7×10^{-2}
P-3	µcont.	VP-2	0532/0.15µ	6.99×10^{-4}†	6.03×10^{-6}†	8.6×10^{-3}
P-4	µcont.	VP-2	0341/0.18µ	1.54×10^{-4}†	1.34×10^{-5}†	8.7×10^{-2}
P-5	µprocess	VP-3	0311/0.18µ	1.3×10^{-15}	No upsets	0

† In units of Upset/dev-hr ;
* No actual upset detected; cross section based on 1 assumed upset
§ E> 10 MeV

It can be seen that the thermal neutron sensitivity ranges over order of magnitudes depending on the tested device. For equipment exposed in shielded areas this means that depending on the actual thermal neutron fluence (as opposed to the high-energy hadron one) and the device characteristics (unknown), a SEE contribution from thermal neutron will range from being a negligible up to being the dominant contribution.

For this purpose, various critical LHC areas where analysed for the particle fluence ratio between thermal neutrons and high-energy hadrons (see Figure 2). This allows defining a so-called 'risk-factor (R)' for each area which shall be considered for the early analysis of monitor readings and possible mitigation actions.

$$R_{th} = \frac{\Phi_{th}}{\Phi_{20MeV}} \qquad (1)$$

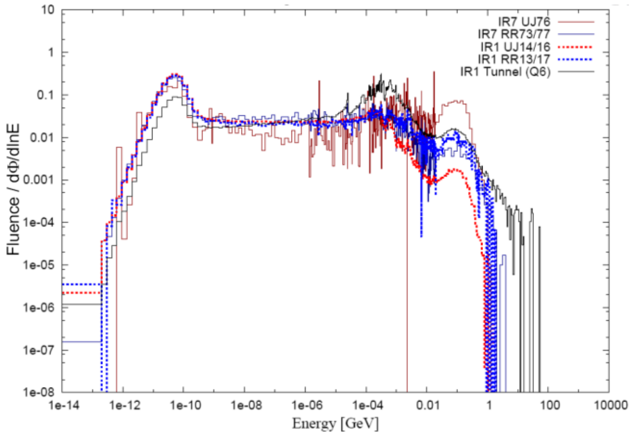


Figure 2: Comparison of various representative spectra of LHC critical areas. The 'risk-factor (R)' for thermal neutrons is defined by dividing the integrated thermal neutron fluence by the high-energy hadron fluence.

A summary for all LHC critical areas of the expected 'R-factor' is given in Tables 4 and 5. The respective 'risk-factor (R)' as listed in the column 'Thermal Ratio' ranges from a few to a few hundred. This underlies the importance in closely monitoring and analysing the radiation fields of critical areas also for their low-energy neutron contribution.

OVERVIEW OF LHC CRITICAL AREAS

Given the so far short time of operation at low intensities and luminosities, the knowledge of radiation levels of the most critical LHC critical alcoves is mainly based on simulations. Continuous analysis and iterations are required during early operation to have detailed updates for all critical areas. It shall further be noted, that important uncertainties exist due to assumptions taken for respective scaling of loss terms (*e.g.*, actual integrated luminosity, distribution of losses,…) as summarized in Table 3, as well as equipment sensitivity and effects due to actual layouts as compared to partly simplified assumptions in simulations (*e.g.*, empty alcoves).

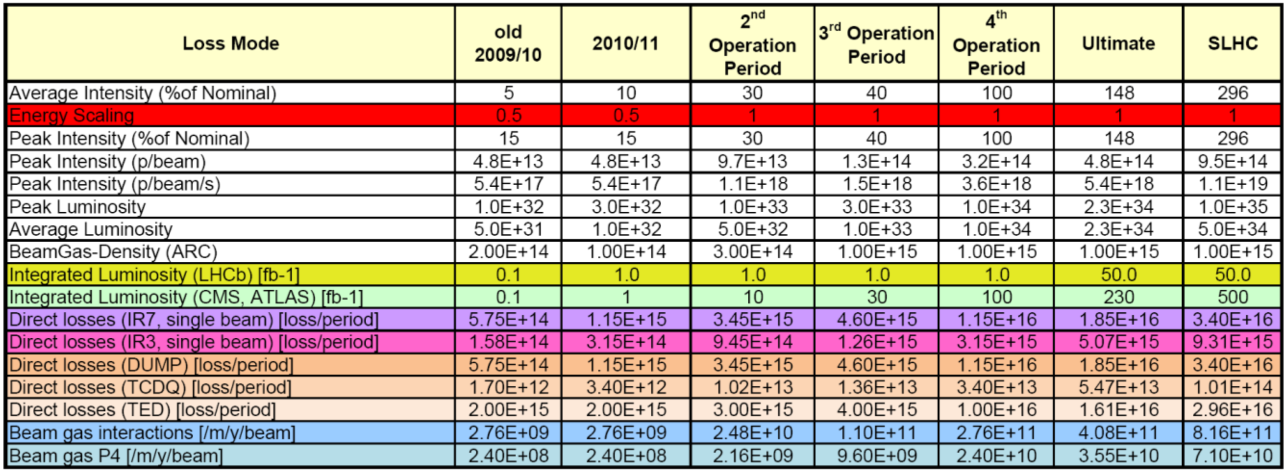
Area priorities were assigned already in a previous Chamonix workshop [13] according to the radiation levels, the system sensitivity and criticality, as well as the inherent uncertainty in loss assumptions. The current prioritization of areas with respect to expected radiation levels (presented as colour coding in the last column of Tables 4 and 5) remains unchanged and is structured as follows:

- started/finished work during past shutdowns (highest-priority which required immediate action) [yellow]
- highest priority for ongoing/upcoming iterations/evaluations [red]
- second priority, cross-check with measurements and preparation for mid/long-term planning [blue]
- lowest priority, layout check and continuous evaluation [green]

For all LHC critical areas and for the respective considered operation period, radiation levels are given for high-energy hadron fluences. For each operational period the values refer to the respective normalisation for each operation period as summarized in Table 3. For each operational period an additional colour coding indicates whether integrated high-energy hadron fluences remain below 10^{6}cm^{-2}(dark green), 10^{7}cm^{-2}(light green), 10^{8}cm^{-2}(orange), 10^{9}cm^{-2}(light red) and 10^{10}cm^{-2}(dark red).

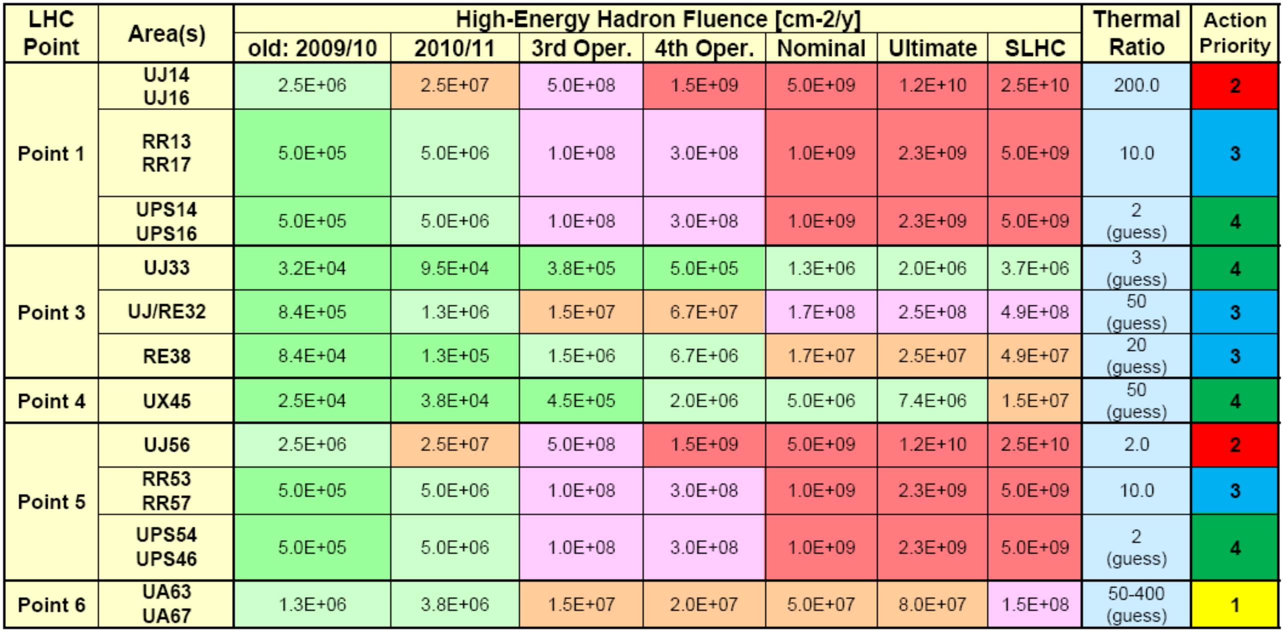
The chosen normalisation allows to rescale values in case loss conditions are changing, or different annual scenarios are discussed in the future. It shall be noted that such a scaling strongly depends on the expected losses, the respective loss distribution, and the integrated beam intensity or luminosity. As outlined above, this dependency and the inherent uncertainties in the simulations suggest respecting sufficient safety margins when mid/long-term mitigation options are discussed. The presented scaling assumptions are predominantly used to indicate a possible evolution of radiation levels in time. Continuous analysis is required in order to refine these predictions.

Table 3: Loss and luminosity assumptions used for the analysis of expected radiation levels [14].



Loss Mode	old 2009/10	2010/11	2nd Operation Period	3rd Operation Period	4th Operation Period	Ultimate	SLHC
Average Intensity (%of Nominal)	5	10	30	40	100	148	296
Energy Scaling	0.5	0.5	1	1	1	1	1
Peak Intensity (%of Nominal)	15	15	30	40	100	148	296
Peak Intensity (p/beam)	4.8E+13	4.8E+13	9.7E+13	1.3E+14	3.2E+14	4.8E+14	9.5E+14
Peak Intensity (p/beam/s)	5.4E+17	5.4E+17	1.1E+18	1.5E+18	3.6E+18	5.4E+18	1.1E+19
Peak Luminosity	1.0E+32	3.0E+32	1.0E+33	3.0E+33	1.0E+34	2.3E+34	1.0E+35
Average Luminosity	5.0E+31	1.0E+32	5.0E+32	1.0E+33	1.0E+34	2.3E+34	5.0E+34
BeamGas-Density (ARC)	2.00E+14	1.00E+14	3.00E+14	1.00E+15	1.00E+15	1.00E+15	1.00E+15
Integrated Luminosity (LHCb) [fb-1]	0.1	1.0	1.0	1.0	1.0	50.0	50.0
Integrated Luminosity (CMS, ATLAS) [fb-1]	0.1	1	10	30	100	230	500
Direct losses (IR7, single beam) [loss/period]	5.75E+14	1.15E+15	3.45E+15	4.60E+15	1.15E+16	1.85E+16	3.40E+16
Direct losses (IR3, single beam) [loss/period]	1.58E+14	3.15E+14	9.45E+14	1.26E+15	3.15E+15	5.07E+15	9.31E+15
Direct losses (DUMP) [loss/period]	5.75E+14	1.15E+15	3.45E+15	4.60E+15	1.15E+16	1.85E+16	3.40E+16
Direct losses (TCDQ) [loss/period]	1.70E+12	3.40E+12	1.02E+13	1.36E+13	3.40E+13	5.47E+13	1.01E+14
Direct losses (TED) [loss/period]	2.00E+15	2.00E+15	3.00E+15	4.00E+15	1.00E+16	1.61E+16	2.96E+16
Beam gas interactions [/m/y/beam]	2.76E+09	2.76E+09	2.48E+10	1.10E+11	2.76E+11	4.08E+11	8.16E+11
Beam gas P4 [/m/y/beam]	2.40E+08	2.40E+08	2.16E+09	9.60E+09	2.40E+10	3.55E+10	7.10E+10

Table 4: Radiation levels (dose, 1MeV-neutron-equivalent and high-energy hadron fluence) for LHC Points 1 to 5 for expected operational periods. In addition, an estimate for the 'risk-factor' of thermal neutrons is given and priority levels are high-lighted (yellow: advanced/partly finished work, red: highest current priority, blue: second highest priority, green: lowest priority). This table is continuously updated on the R2E website (www.cern.ch/r2e).



LHC Point	Area(s)	High-Energy Hadron Fluence [cm-2/y]							Thermal Ratio	Action Priority
		old: 2009/10	2010/11	3rd Oper.	4th Oper.	Nominal	Ultimate	SLHC		
Point 1	UJ14 UJ16	2.5E+06	2.5E+07	5.0E+08	1.5E+09	5.0E+09	1.2E+10	2.5E+10	200.0	2
	RR13 RR17	5.0E+05	5.0E+06	1.0E+08	3.0E+08	1.0E+09	2.3E+09	5.0E+09	10.0	3
	UPS14 UPS16	5.0E+05	5.0E+06	1.0E+08	3.0E+08	1.0E+09	2.3E+09	5.0E+09	2 (guess)	4
Point 3	UJ33	3.2E+04	9.5E+04	3.8E+05	5.0E+05	1.3E+06	2.0E+06	3.7E+06	3 (guess)	4
	UJ/RE32	8.4E+05	1.3E+06	1.5E+07	6.7E+07	1.7E+08	2.5E+08	4.9E+08	50 (guess)	3
	RE38	8.4E+04	1.3E+05	1.5E+06	6.7E+06	1.7E+07	2.5E+07	4.9E+07	20 (guess)	3
Point 4	UX45	2.5E+04	3.8E+04	4.5E+05	2.0E+06	5.0E+06	7.4E+06	1.5E+07	50 (guess)	4
Point 5	UJ56	2.5E+06	2.5E+07	5.0E+08	1.5E+09	5.0E+09	1.2E+10	2.5E+10	2.0	2
	RR53 RR57	5.0E+05	5.0E+06	1.0E+08	3.0E+08	1.0E+09	2.3E+09	5.0E+09	10.0	3
	UPS54 UPS46	5.0E+05	5.0E+06	1.0E+08	3.0E+08	1.0E+09	2.3E+09	5.0E+09	2 (guess)	4
Point 6	UA63 UA67	1.3E+06	3.8E+06	1.5E+07	2.0E+07	5.0E+07	8.0E+07	1.5E+08	50-400 (guess)	1

Table 5: see caption of Table 4, LHC Points 7 to 8 and ARC/DS.

LHC Point	Area(s)	High-Energy Hadron Fluence [cm-2/y]							Thermal Ratio	Action Priority
		old: 2009/10	2010/11	3rd Oper.	4th Oper.	Nominal	Ultimate	SLHC		
Point 7	UJ76	5.0E+07	1.5E+08	6.0E+08	8.0E+08	2.0E+09	3.2E+09	5.9E+09	2.0	1
	RR73 RR77	5.0E+06	1.5E+07	6.0E+07	8.0E+07	2.0E+08	3.2E+08	5.9E+08	50.0	1
	TZ76 (start)	5.0E+05	1.5E+06	6.0E+06	8.0E+06	2.0E+07	3.2E+07	5.9E+07	10 (guess)	4
Point 8	UX85b	1.0E+08	1.0E+09	2.0E+09	2.0E+09	2.0E+09	1.0E+11	1.0E+11	0.2	1
	US85	2.5E+07	2.5E+08	5.0E+08	5.0E+08	5.0E+08	2.5E+10	2.5E+10	2 (guess)	2
	UW85	5.0E+06	5.0E+07	1.0E+08	1.0E+08	1.0E+08	5.0E+09	5.0E+09	10 (guess)	3
	UA83/87	2.5E+06	2.5E+07	5.0E+07	5.0E+07	5.0E+07	2.5E+09	2.5E+09	5 (guess)	4
TI2	UJ23	6.9E+06	1.0E+07	2.1E+07	2.8E+07	6.9E+07	1.1E+08	2.1E+08	5 (guess)	3
	UA23	3.5E+06	5.2E+06	1.0E+07	1.4E+07	3.5E+07	5.6E+07	1.0E+08	10 (guess)	3
TI8	UJ87	6.9E+06	1.0E+07	2.1E+07	2.8E+07	6.9E+07	1.1E+08	2.1E+08	5 (guess)	3
	UA87	3.5E+06	5.2E+06	1.0E+07	1.4E+07	3.5E+07	5.6E+07	1.0E+08	10 (guess)	3
ALL	ARC: MBs	3.2E+07	4.8E+07	5.7E+08	2.5E+09	6.4E+09	9.4E+09	1.9E+10	4.0	3
	ARC: MQs	3.2E+08	4.8E+08	5.7E+09	2.5E+10	6.4E+10	9.4E+10	1.9E+11	2.0	3
	DS: MBs	2.5E+09	7.5E+09	3.0E+10	4.0E+10	1.0E+11	1.6E+11	3.0E+11	4.0	3
	DS: MQs	2.5E+10	7.5E+10	3.0E+11	4.0E+11	1.0E+12	1.6E+12	3.0E+12	2.0	3
	REs	8.4E+04	1.3E+05	1.5E+06	6.7E+06	1.7E+07	2.5E+07	4.9E+07	20 (guess)	4

EARLY MEASUREMENTS

In this chapter, a selection of first measurement results from injection and beam tests, as well as early operation is presented. A continuous check of radiation levels around critical areas is mandatory and has to include a detailed analysis not only of the RadMon readings, but also of the corresponding observed beam loss pattern and intensity or luminosity, as well as other adjacent radiation monitors (*e.g.*, RAMSES, BLMs).

In this sense, expected losses during operation and operational constraints could be compared to measured ones, ideally through a dedicated controlled test setup where losses are provoked on critical collimators leading to increased radiation levels in adjacent critical areas. These results could then be used to compare with simulations and possibly allow defining ‘safe’ operation limits (*e.g.*, collimator setups).

Figure 3 shows a first example of the TI8 collimator setup (TCDIH.87904, 25.10.2009) where the losses on the collimators lead to streaming of radiation into UJ87 and where the respective monitors show an immediate signal.

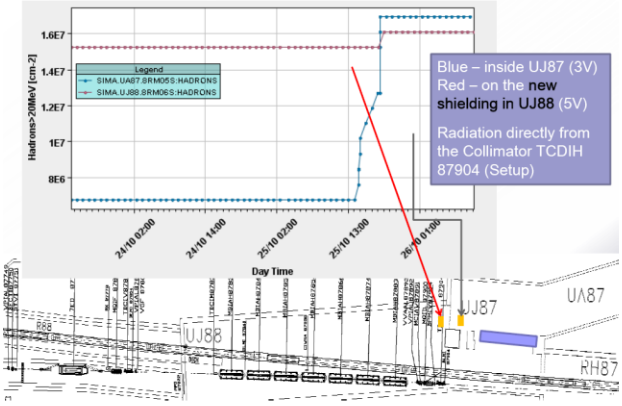


Figure 3: Radiation levels as observed on RadMons in UJ87 and UJ88 during collimator (TCDIH.87904) setup.

Furthermore, during the setup of the TCDQ, dedicated loss studies allowed not only to verify possible streaming through the ducts between the tunnel and the UA (see sketch of Figure 4), but also to compare the RadMon readings with existing FLUKA simulation results (see Figure 5). For the purpose of these tests on either side of Point-6 during the last shut-down a RadMon was relocated next to the mask downstream of the TCDQ in order to allow for an early measurement at the tunnel side.

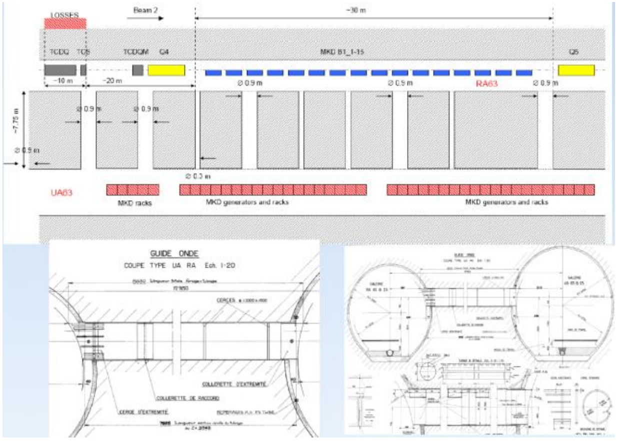


Figure 4: Layout of the RA/UA areas at Point-6 showing the TCDQ position. [16]

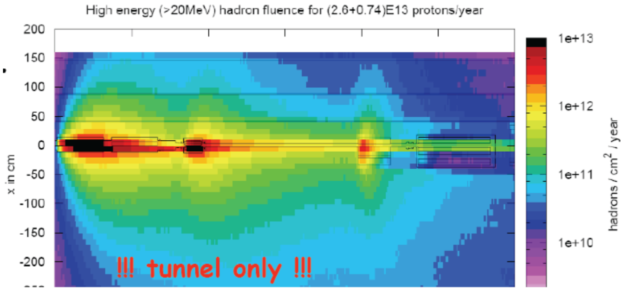


Figure 5: FLUKA results for nominal losses on the TCDQ and downstream elements [32].

The respective FLUKA simulations were originally performed for 7 TeV and assuming a nominal impact on the TCDQ (see Figure 5). For this comparison between measurements and simulations, the results had to be renormalized according to the observed injected intensities and to 450GeV. This comparison obviously includes significant uncertainties, however allows for an overall evaluation of the situation around the TCDQs in Point-6.

Within these uncertainties, the simulation results compare well with the obtained measurements ($5.6\text{x}10^{7}\text{cm}^{-2}$ as obtained by the RadMon reading on the tunnel side as compared to FLUKA at the same location: ~$2\text{-}3\text{x}10^{7}\text{cm}^{-2}$). Furthermore, the RadMon placed on the UA side (and set to 3V, thus higher sensitivity) confirmed the expected attenuation through the duct of at least 1000 as no single count was observed.

This shows that beam-losses initiated on purpose during early operation would allow for an efficient analysis in order to draw important conclusions for R2E critical areas. Therefore, during early operation, controlled losses are suggested for all critical areas where monitors allow for an analysis during early operation. The radiation levels can then be cross-checked by the RadMon (or other monitor) being closest to the loss location and by then applying a respective scaling towards the critical area (based on simulations). As a consequence, a list of possible test-locations was derived (see [15]) and is available to the operations group and whenever beam-time is available beam losses around critical areas could be initiated and the respective detector measurements be analysed.

In addition, during extended injection tests during the summer of 2009 an equipment failure (‘Warm Interlock Controller, WIC) was observed in the TI8 injection line. This led to a stop of both CNGS operation and LHC injection. An immediate analysis of available measurement data and FLUKA simulations lead to a first estimate of expected radiation levels leading to the failures ($10^{8}\text{-}10^{9}\text{cm}^{-2}$). A detailed review of WIC layout and available test measurements indicated that the equipment shows a much lower failure cross section, thus suggesting that the event not being an impossible, but very unlikely incident. To verify the latter, an additional injection test with higher intensities was carried out and about $4\text{x}10^{13}$ protons were lost on the same injection collimator. No further WIC failure was observed, however as only one rack is concerned by possible upstream losses on injection collimators, it was recommended to relocate it when time becomes available.

MITIGATION OPTIONS

In the following an overview of possible mitigation options is given together with a few examples where dedicated studies already exist. The full list of possible mitigation options (short/mid- and long-term) are continuously updated on the R2E website (www.cern.ch/r2e).

As outlined earlier, for the most exposed areas the radiation levels may reach very soon values leading to radiation induced failures and therefore could affect the operation of the LHC. It was shown that for nominal conditions, annual fluences can reach up to a fluence of 10^{9} high-energy hadrons/cm^{2} and therefore present a considerable risk for the operability of the LHC.

‘Easy’ Options

It shall be noted that for a few cases already minor actions can significantly improve or solve possible radiation induced problems. One example is the access-gate in UJ14/16/23/87 which can be switched off during operation. A respective procedure is in preparation together with the operations group [17].

Furthermore, equipment already developed and tested for the tunnel area is sufficiently radiation tolerant and can remain mostly in place (details can be found in [1,2,18]), *e.g.*:

- QPS (further development possible)
- BPM (mostly ok)
- BLM

- Certain cryogenics control (which is similar to the one installed in the tunnel).

Radiation Tolerant Design

For equipment which could or is already based on a custom design, possible radiation tolerant redesign options can be considered, *e.g.*:

- replacement of remote-valve-controllers in US85 where the solution is already known from other areas (see [13])
- certain types of power-converters with a possible proposal discussed the first time in [18]
- possible options for new FIP development as described in [19]

In addition, possible pathways of common developments could be identified and studied further (*e.g.*, collaboration with PH/ESE for a common development of FPGA or micro-processors to be used in generic field-bus application, or as acquisition module for temperature, pressure, and low-precision voltage measurement).

Shielding

For certain critical areas local shielding can reduce the radiation levels for concerned equipments. The shielding is of highest importance for areas where the relocation of equipment is difficult and the reduction of expected radiation levels would allow gaining time for preparing relocations. Therefore, for many areas additional FLUKA simulation studies were (or are currently) performed to define and optimize the shielding layout for various operational assumptions.

Even though the installation of many of the considered shielding integrations can only mitigate SEE related problems in time, the actual attenuation of radiation levels in the critical areas is still considered as an important improvement for later local relocation options or requirements (*e.g.*, relocation from the UJs into the ULs where higher radiation levels in the ULs would otherwise further limit the available space). The shielding walls once put in place will reduce the radiation levels not only in the respective critical areas, but also in the adjacent ones, thus allowing for a more effective use of the available space in the adjacent areas.

For a few locations additional shielding is expected to fully mitigate radiation induced problems. Especially for the areas close to the injection lines (UJ23/87) additional shielding was already put in place before LHC startup (*e.g.*, as shown in Figure 6 the improved shielding wall of UJ88/87, for details please refer to [21])

Figure 6: Shielding improvement of areas downstream the LHC injection lines [21].

During injection tests and early LHC operation the achieved shielding efficiency in UJ88/87 could actually be verified. The analysis confirmed the expected improvement of about a factor of 10 less radiation in high-energy hadron fluence. This allowed for a significantly relaxed situation for the current operation period. A long-term solution will first require further measurements during which possible issues with low-energy neutrons have to be analysed and then possibly considered for shielding improvements.

Further shielding improvements already performed during 2009 included the finalisation of the mobile shielding plugs in Point-7 (close to RRs), the shielding of the safe-room in the US85, as well as the lateral shielding wall of the UJ76.

Based on a first shielding layout proposed by the integration team, a detailed study of shielding options was carried out for the UJs close to the high-luminosity experiments (UJ14/16/56). For the current layout nominal annual radiation levels of a few $10^9 cm^{-2} y^{-1}$ are expected (*e.g.*, see Figure 7 for the UJ16). Updated FLUKA simulation studies [23] allowed defining the respective weak points of the existing layout (*e.g.*, limited shielding thickness or entrance maze geometry).

Various shielding options were discussed together with the integration team. For the UJ56 a first pre-study was performed [24] in order to verify possible shielding constraints (see Figure 8 for a transversal cross-section of the LHC tunnel showing the maximum shielding thickness). For UJ14/16 a shielding enforcement of the plug (concrete/iron) was proposed, however the FLUKA simulations showed only a minor improvement due to the remaining weak-points towards the entrance maze (UJ17/16 junction), as well as the shielding weakness next to the UL/UJ junction (towards the LHC tunnel). Especially, due to the configuration of the two caverns (UJ13/14 and UJ16/17 respectively) a much larger shielding is required to significantly reduce the radiation levels in the UJs.

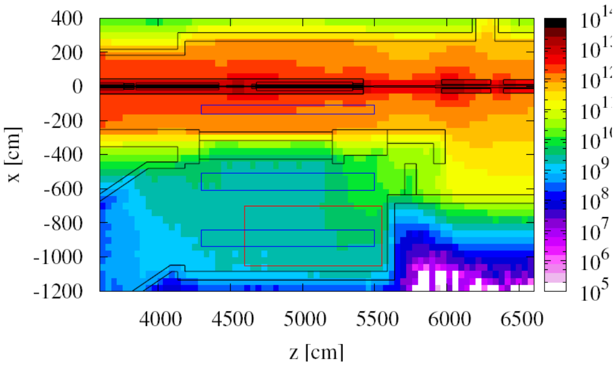


Figure 7: UJ16 radiation levels (nominal annual high-energy hadron fluence given in [$cm^{-2}/100fb^{-1}$) as calculated with FLUKA. Two weak-points can be observed: (1) the shielding thickness next to the UL/UJ boundary, as well as the streaming through the entrance maze.

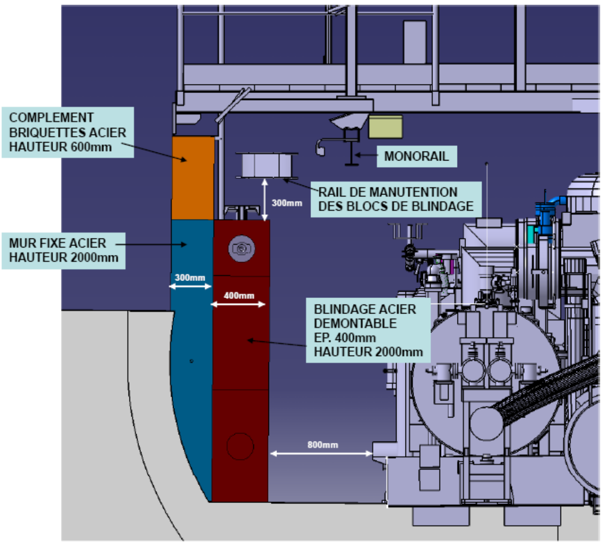


Figure 8: Maximum shielding thickness (30/70cm of iron) which can be integrated on the tunnel side of the UJ56.

Including a heavy iron and concrete shielding for the UJ14/16 can eventually lead to significant improvement with a reduction factor of 10-20. This is also important in order to possibly use parts of the UL for later relocations. For this heavy shielding a staged implementation is considered as possible and a detailed integration study is to be launched as soon as possible. Further optimizations are required for the current study (so far requiring about $60m^3$ iron and $40m^3$ concrete) before a possible integration proposal can be finalized. The above listed UJ56-shielding is however only effective at the lower-floor (reduction of up to a factor of 10), thus considered as useful either for the protection of equipment installed in the safe-room, or in case a restructuring of the UJ56 has to be considered (*e.g.*, reshuffling with power converters).

Other areas where shielding improvements could be considered are:

- UJ76: the already installed safe-room shielding could be improved; however, the safe-room equipment remains at risk
- UJ/UA/23/87: as described above, the installed shielding is already improved and further steps are possible; combined simulation/integration study required
- RR/13/17/53/57 shielding similar to RR73/77 is considered as possible; a more complex shielding around the beam-pipe could be envisaged
- UA63/67: RA/UA connection ducts are already shielded and additional rods could be added if required
- UJ32 (RE32): only required in case early monitoring shows that beam-gas could be a long-term issue
- UJ84/86 – UA83/87: to be considered due to the weakened plug shielding (magnet transport zone) depending on downstream losses from LHCb, as well as possible TDI contributions.

Equipment Relocations

The following possibilities for early relocations have been identified:

- fire/ODH control racks: relocations are already performed in UX/US85, but still pending for UJ76, UJ56. As this might have a possible impact on safety, the relocations are to be scheduled as soon as possible
- fire detectors: might have a possible impact on the safety chain during operation, however without posing a safety risk as detectors are redundant and the failure will be observed. For the detectors most areas affected and relocations might have to be considered (already performed for UX/US85 and partly required long distance tests are ongoing)
- it shall be noted that for other equipment groups scenarios are studied and partly prepared for:
    - BIC, PIC, WIC
    - Timing/Remote-Reset

In absence of other mitigation options, for the US/UW85 a complete relocation might have to be considered. They might be required rather early given the fact that expected radiation levels next to LHCb will reach nominal values rather soon (due to the significantly lower nominal luminosity of LHCb). Therefore, a detailed relocation study has been started, a first iteration with the equipment owners is completed and possible new equipment locations were identified [25].

Even though a solution exists it must be noted that the envisaged relocation campaign would require significant resources (costs, time and man-power). Most of the installed equipment would have to be relocated including cryogenics, WIC, timing and remote-reset, UPS, access control, network, AUG control, electrical distribution (control), GSM. For this, cabling and installations need to be prepared with sufficient lead time (about 4-6 months).

Therefore, respective emphasize must soon be given to planning and coordination.

Other areas where shielding improvements could be considered are:

- UJ76: preparations are in place to transfer the equipment to the TZ76. It's important to note that if it is required to house also the equipment from the adjacent RRs, a decision is required soon and before any further relocations are put in place.
- UJ14/16: relocation possibilities exist in the US15 (3rd floor) and adjacent ULs. First studies were performed for the upgrade installations; however have to be studied further in order to verify remaining radiation levels, as well as other constraints (*e.g.*, cable lengths of existing power-converters).
- UJ56: relocation options towards the UP/USC-bypass were also studied for the LHC upgrade.

Civil Engineering

Local enlargements of caverns are considered as hardly feasible solutions due to strong impact on adjacent installed equipment (*e.g.*, dust during work), as well as the non-accessibility during LHC operation [26].

A first feasibility study has been performed for civil engineering work to build new relocations caverns next to the RRs at Point-1 and Point-5 [27]. Here relocation of the power converters is difficult to envisage as besides the 120A and 600A also the heavy 4-6 kA converter are installed. The latter cannot be easily displaced nor redesigned. Therefore, the option to drill new shafts from surface and create a side gallery protected from radiation was considered (see Figure 9).

A pre-study exists [27] with estimated high cost of civil engineering to which one has to add the cost for all the infrastructure and actual relocation. The study has confirmed that most of the civil engineering work can be performed even with beam in the LHC. However, it remains to be evaluated what level of vibrations can be accepted by the machine without perturbing the beam conditions.

It shall be noted that the shafts would also be used as a possible escape path in case of a massive discharge of helium in the tunnel [28]. In addition, it would be possible to further extend these new caverns to have new UA galleries in P1 and P5, which would then also allow a comfortable relocation option for all the equipment in the UJ14/16/56 and give in addition sufficient space for all the new equipment necessary for the later LHC upgrade scenarios.

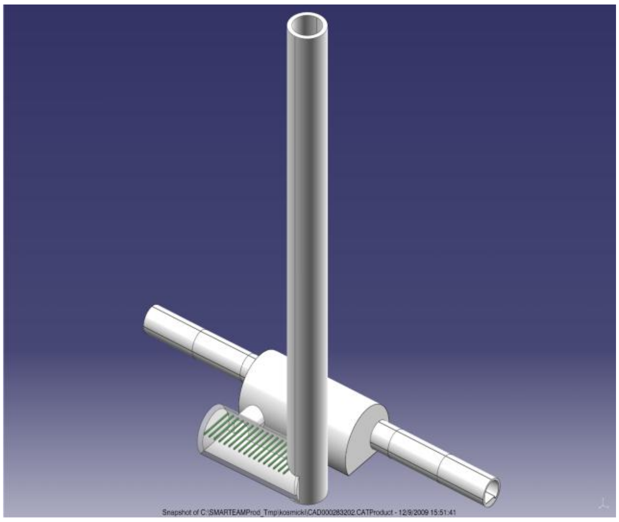


Figure 9: Preliminary layout proposal for new shafts and caverns for the RRs in P1 and P5 [29].

Other Mitigation Options

R&D work is currently being carried out at CERN for the development of new super-conducting (HTS) links:

- the development of semi-flexible MgB_2 link for the powering of the triplets for the upgrade phase-1 (up to 100m length and about 120 kA in multiple circuits) [30].
- the development of gas-cooled HTS links operating at higher temperatures and suitable also for vertical transfer of current [31]

Both options and their possible impact on long-term R2E mitigation options have to be further studied before any conclusion can be drawn.

Furthermore, for the UJ76 and RR73/77, several collimation options have to be considered:

- the temporary operational move of the betatron collimation to Point-3 as proposed and studied in [32]. Especially with the newly discussed cryogenic collimators, the parameters for the relocation have changed, thus a possible long-term solution would have to be investigated [33].
- the installation of phase-II collimators as additional absorber in order to reduce the radiation levels in the critical areas .

CONCLUSION

The radiation monitoring improvements as performed during the 2009 shutdown were illustrated and some examples for the actual impact on LHC operation were presented. An update and overview of the radiation levels in the critical LHC areas were given together with a detailed analysis of the respective particle energy spectra. Since radiation levels are still mainly based on simulation results, early measurements will have to be intensively carried out over the coming months.

So far applied mitigation actions were briefly summarized together with additionally foreseen short- and medium term measures. Local shielding is supposed to improve the situation for several critical areas and even if not being a long-term solution for most areas, the reduction in radiation levels can allow to sufficiently gain time until other long-term solutions can be implemented.

Early relocation options have to include all sensitive equipment focusing first on safety related equipment (*e.g.*, Fire/ODH control rack in P5/7). For all relocation campaigns, first a complete relocation plan must be studied in detail, thus allowing for early relocation only when all final equipment locations have been identified.

Civil engineering or other alternative mitigation options have to be studied in detail for areas where other solutions cannot be found or their implementation remains questionable. Whenever possible, long-term optimizations shall not only consider issues related to radiation damage to electronics, but also take into account other possible future requirements (*e.g.*, accidental Helium release or upgrade scenarios).

Due to the partly long lead time, first decisions are soon required, not for a final implementation plan, but rather to allow for gaining time through parallel preparation studies. Only this detailed planning and the analysis of all mitigation options can allow to properly optimize the solutions for all critical areas. This implies an important inter-departmental effort to verify possible mitigation scenarios with respect to their feasibility, long-term sustainability as well as resource requirements.

Due to the stringent time constraints work in parallel is required and it will not be enough to do things ‘sequentially’ in the sense that if one would first observe and then react, the time required to implement most of the mitigation options, would lead to important constraints for LHC operation.

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