RADIATION TO ELECTRONICS: REALITY OR FATA MORGANA?

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Abstract

A first year of successful LHC operation has passed reaching about $50pb^{-1}$ of integrated luminosity (1‰ of nominal, 5% of $1fb^{-1}$) and more than 1% of peak luminosity, as well as a successful ion run. It is thus time having a first look on the observed radiation levels around LHC critical areas and to compare them to available simulation results. In spite of the still very low integrated intensities and cumulative luminosities, this paper summarizes the failure rate predictions by evaluating the observed radiation levels and early electronics failures, as well as the additional results from 2010 CNRAD radiation tests. Upcoming possibly in early 2011, electron cloud and scrubbing issues and their impact on radiation levels are also briefly discussed. Based on this, updated predictions for 2011 operation and beyond will be deduced, on the base of the envisaged LHC intensity, energy and luminosity reach. Starting from these estimates, priorities for short-term improvements and beam tests are presented, as well as a brief overview of upcoming 'Radiation To Electronics (R2E)' driven mitigation actions.

INTRODUCTION

As studied and documented in detail over the past years, there is a relevant risk of occurrence of radiation damage to electronics at the LHC. A dedicated strategy is required to reduce it to a level that will allow for smooth LHC operation and maximum performance. Mitigation measures to be performed "in the shadow" of increasing LHC intensity, energy and luminosity require the thorough analysis, optimization and coordination of all related activities, the most important being:

- A thorough analysis of available monitoring data and their comparison with expected radiation levels, based on detailed simulation results and taking into account most accurate detector calibrations. This requires a detailed review of existing and required Monte-Carlo calculations together with the development of efficient monitoring tools and the constant improvement of monitor locations. For all LHC critical areas radiation levels have to be reviewed on a regular basis, assuring full monitoring coverage and the best possible understanding of their results.
- A close collaboration with the equipment groups for the assessment of radiation tolerance of presently installed (and future) electronic equipment in radiation exposed areas. Common design practices and appropriate radiation tests have to be discussed and reviewed in detail. In addition, observed radiation induced failures have to be carefully analyzed and used as direct input for (a) failure rate estimates, (b) the development of required patch-solutions, as well as (c) for the development of radiation tolerant equipment. To support (b) and (c), radiation test campaigns have to be organized on a regular basis within CERN (CNRAD, H4Irrad test areas) and at external facilities (PSI, etc.).
- The technical integration study and detailed implementation of medium-term mitigation measures such as the installation of shielding and relocation campaigns of sensitive equipment.

This paper summarizes our understanding of radiation levels, their development during the coming years of LHC operation and the consequences for electronics installed in critical areas. Finally, past and ongoing mitigation measures are briefly described and follow-up actions are identified.

RADIATION TESTS AT CNRAD

To estimate the possible implication of radiation induced failures of electronics in the LHC, three groups of information have to be known: (1) the failure mode(s) of the device, (2) the failure cross section (probability) or level at which it occurs in case of cumulative effects and (3) the expected radiation level at the point of installation. Most of the electronics systems located in the LHC tunnel, but only a few systems from the LHC shielded areas were actually tested in the CNRAD (CNGS TSG4) test area, but partly also in external facilities in 2009 [1] and earlier.

For the large number of commercial systems being installed in the shielded areas, only a representative selection of devices could be tested in 2010 and it is important to note that even for this selection no guarantee can be given that equal devices (same manufacturer and type) will also behave in an equal manner when exposed to radiation. The latter is due to fact that for 'Components of the Shelf (COTS)' no guarantee nor information is provided from the producer that in all devices the same components (manufacturer, process, batch) are used, thus variations on their behaviour under radiation have to be expected.

However, to provide a global estimate for the LHC, the test results provide the only information on the

sensitivities of the devices as well as their likely failure modes. These results are then combined with the information available in the equipment inventories of the LHC (see [2-5]) which were performed in 2010 in order to allow for a detailed analysis of all types of exposed equipment, their working principle and their impact on LHC operation in case of failures.

Numerous radiation tests were performed during 2010 with a significant fraction focusing on COTS components. For the latter, the following representative electronic systems have been selected and were available to be installed at CNRAD (equipment details provided in brackets):

- Timing and Remote Reset (custom built system as installed in the LHC)
- Cooling and Ventilation Control (Siemens S7-300, S7-200, Schneider Telemecanique Premium)
- Fire Detection (detectors of different types based on commercial components/systems)
- Control equipment of electrical installations located in LHC safe-rooms (RTU CLP500E, Ethernet Switch, DAU MAP3200, 48/24VDC, Pt100/20mA, RS232/RS485, etc.)
- Ethernet Distribution (Ethernet Switches 3Com 4400)
- Interlock Controller (PLC 315F 2 DP, Ethernet controller, 24 DI safety input modules, 2 x DO Relay modules, 2 x 32 DO module, IM153.1 - ET 200M, Boolean Processor - FM 352-5)
- Collimation (Drivers, I/O RIO, National Instruments PXI MDC + PRS, ADC, DAC, FPGA card, power supply)
- Europa crate (custom electronic for LVDTs and Resolvers excitation/acquisition, power supply)

Table 1: Equipment failure cross-sections as obtained during the 2010 CNRAD radiation test campaign on COTS systems.

Device Type	Failure Mode	Failure Cross-Section [cm^2]
PLC-S7-200	Profibus lost, reset needed	$1.8x10^{-7}$
24V DC Power Supply	Destructive failure (burned-out chip)	$1.1x10^{-8}$
PLC-S7-300	blocked, reset needed	$7.8x10^{-8}$
PLC-Schneider	PS burned	$1.1x10^{-7}$
PLC S7-300 + FM352-5	beam dump and access	$1.1x10^{-7}$
Fire Detectors	power cycle	$1.0x10^{-9}$
Ethernet Switch	blocked, reset needed	$1.4x10^{-8}$

The systems were closely monitored during the irradiation period and failures were classified into soft failures (reset allowed to continue the operation of a device) and hard failures (device was not recoverable). A selection of respective failure cross-section is provided in Table 1 with more details provided in the various radiation test reports (partly still in work) of the responsible equipment groups as collected on the RadWG website (www.cern.ch/radwg).

To illustrate the stated failure cross sections (representing the probability of failure per unit high-energy radiation fluence), one can take the result for the PLC-S7-200 and put it into perspective with the radiation levels at its installed LHC locations:

- failure cross-section: $1.8x10^{-7}cm^2$
- expected annual radiation levels in the UJ14: ~ $1x10^{9}cm^{-2}y^{-1}$ (in case no shielding/relocation is applied)
- this device would faile ~200 time per year at nominal LHC operation, leading to a beam-stop and required access

The failure cross sections obtained during the CNRAD irradiation tests can then be used together with the information collected through the equipment inventories [2-5] and can be also applied for similar electronics installed in the various areas to provide failure rate estimates (see respective chapter in this publication). However, due to the large number of different equipment types, manufacturers and components being used around the LHC critical areas, an overall uncertainty of one order of magnitude should be considered even in case when equipment types similar to the tested ones are used.

Table 1 further shows that large differences can be observed between the various equipment and depending on the failure mode. An overall suggested 'rule of thumb' for unknown equipment failure cross sections is:

- soft failures (reset required): 1 failure per equipment and a cumulated high-energy radiation fluence of 10^{6}-$10^{9}cm^{-2}$.
- hard failures (device not usable anymore): 1 failure per equipment and a cumulated high-energy radiation fluence of 10^{7}-$10^{10}cm^{-2}$.

FLUKA BENCHMARK MEASUREMENTS

Radiation levels to be expected around the LHC during nominal and ultimate LHC intensities are predominantly based on detailed and partly very complex FLUKA Monte-Carlo calculations [6, 7]. Their respective results were analyzed, updated and evaluated during the past years [8] and provided together with the equipment sensitivities the starting point for the mitigation analysis.

In order to investigate the accuracy one can obtain with Monte-Carlo calculations, it is important to distinguish between three main sources of possible uncertainties:

- level of details included in the calculation (geometry, materials)

- physics models included in the Monte-Carlo code
- operational and loss assumptions leading to the final normalisation of the results

The validity of the discrete physical models implemented in FLUKA has been benchmarked against a variety of experimental data over a wide energy range, from accelerator data to cosmic ray showers in the Earth atmosphere (see [6, 7] and references therein). LHC operation and the complexity of the final radiation field around LHC critical areas require for 'Radiation To Electronics (R2E)' purposes a detailed analysis of different levels of benchmark experiments, globally summarized in three categories:

1. dedicated experiments with LHC representative radiation fields allowing for a controlled comparison between simulations and measurements
2. controlled beam-losses and respective radiation fields in the LHC environment
3. complex beam losses and large scale simulations compared to measurements performed over an extended operation period

(1) Benchmark Measurements at the CERF Facility

In order to obtain measurements in a radiation environment similar to the LHC, however still within a well controlled setup, a set of measurements was performed at the CERF benchmark facility [9]. A layout of the CERF experimental area is shown in Figure 1. A pulsed, 120 GeV/c mixed hadron beam (60.7% π+, 34,8% p, 4.5% K+), from the Super Proton Synchrotron (SPS) accelerator, is aimed at a 50 cm long copper target creating a radiation field similar to what can be expected in the beam loss regions in the LHC tunnel. The CERF facility can therefore be used as reference field for calibrating and testing of equipment monitoring damage to electronics in a mixed radiation field. Variation in this radiation field can be achieved by placing the equipment at different positions around the copper target. These positions are indicated by labels ranging from 1 through 6, where the downstream positions (4-6) are representative for the LHC tunnel regions, whereas the other positions (1-3) are very similar to shielded areas close to the accelerator tunnel.

RadMon detectors [10, 11] were used for the benchmark at the CERF facility as the RadMon provides online measurements of the Total Ionizing Dose (TID as measured with a RadFET), the 1 MeV neutron equivalent fluence (measured with a PIN-diode) and the high-energy (> 20 MeV) hadron fluence (measured by "counting" SEUs in a memory). Each RadMon can be operated at 5V or 3V where the lower voltage effectively increases its Single Event Upset (SEU) sensitivity. During the past years and in view of their high importance for the LHC, a significant effort was made in order to improve their calibration for the various radiation components representative to the LHC radiation environment.

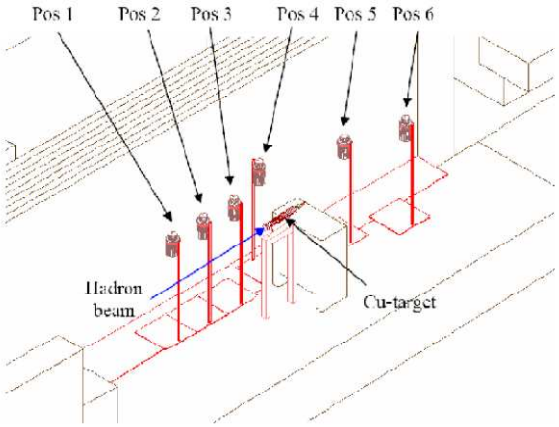

Figure 1: CERF layout with the copper target and the six measurement positions as used for the measurements.

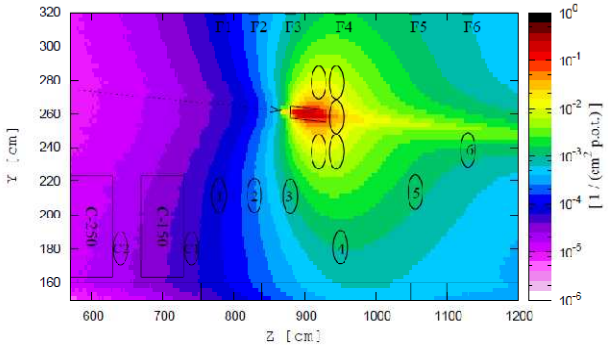

Figure 2: High-energy hadron fluence normalized per primary particle of the 120 GeV/c mixed hadron beam particle (60.7% π+, 34.8% p, 4.5% K+) impinging on the copper target.

Table 2: Comparison between FLUKA simulation and RadMon (set to 5V) measurements as performed during the CERF benchmark measurements. Results are given as high-energy hadron fluence per primary proton impinging on the CERF target. Stated errors are based on counts and calibration uncertainties for the RadMon values, as well as statistical uncertainties for the FLUKA calculations.

Location	RadMon [Error]	FLUKA [Error]	Ratio (R/F)
Pos1	3.77×10^{-4} [20.0%]	4.17×10^{-4} [5.1%]	0.90
Pos2	5.76×10^{-4} [20.0%]	5.76×10^{-4} [4.6%]	1.00
Pos3	1.99×10^{-3} [20.0%]	1.97×10^{-3} [2.8%]	1.04
Pos4	1.75×10^{-3} [20.0%]	1.71×10^{-3} [3.4%]	1.02
Pos5	1.53×10^{-3} [20.0%]	1.67×10^{-3} [3.2%]	0.92
Pos6	2.19×10^{-3} [20.0%]	2.19×10^{-3} [2.9%]	1.00

During the CERF experiment these RadMons were displaced between the different measurement positions to study their response in the various mixed radiation field which are representative for the LHC. For the same setup FLUKA simulations were performed including all relevant details (geometry, materials, source term, etc…). For all measurement locations the total ionizing dose, 1 MeV neutron equivalent and high-energy hadron fluence, as well as the particle energy spectra for the various types of particles were calculated. A horizontal cut through the layout and its respective high-energy hadron (>20 MeV) radiation field can be seen in Figures 1 and 2. The measured data and the FLUKA calculations at the different measurement positions were compared as shown in Table 2 and a very good agreement was obtained.

(2) LHC Application Benchmark during Injection Tests

Profiting from the controlled and known particle losses during LHC injection tests, monitor readings of RadMon detectors were analyzed and compared to respective FLUKA simulation results. The complex layout (see Figure 3) of this injection section into the LHC (more than 100m long) allowed for a detailed practical benchmark in order to verify the FLUKA predictions made for dedicated measurements.

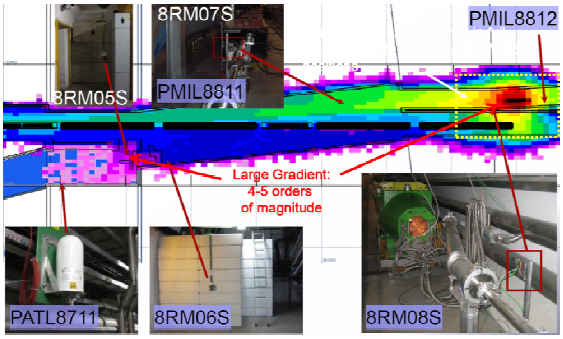

Figure 3: Layout of the LHC injection line where it enters the LHC tunnel and as implemented in FLUKA. In addition, the various monitor locations are shown.

During the first benchmark the RadMon was placed directly behind the injection dump (TED) which is situated at the end of the LHC injection line. The TED can be moved into the beam in order to allow for setup and tuning studies to be carried out in the injection line without bringing beam into the LHC. This allows for an ideal benchmarking setup where the loss term (number of protons impinging on the TED) is known in all details. The high-energy hadron fluence distribution as well as the

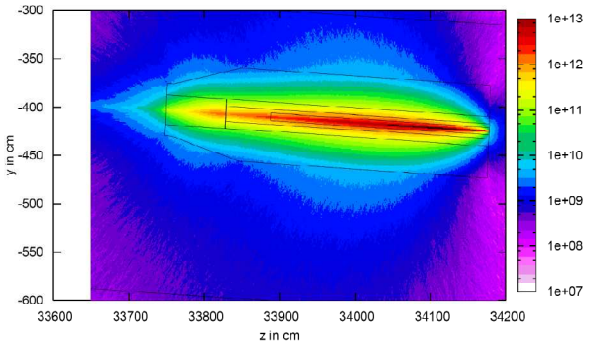

Figure 4: Horizontal high-energy hadron fluence distribution around the TI8 beam stopper (TED) for 6.8×10^{12} 450GeV/c protons impinging on the TED. The color code refers to number of particles per square-centimeter above 20 MeV [cm-2].

Table 3: Comparison between FLUKA simulation and RadMon (set to 5V) measurements performed during the injection test with direct dump on the TI8 beam stopper (TED). Stated errors are based on counts and calibration uncertainties for the RadMon values, as well as statistical uncertainties for the FLUKA calculations.

Quantity	**RadMon** [Error]	**FLUKA** [Error]	**Ratio (R/F)**
High-energy hadrons (cm^{-2})	1.2×10^{10} [20.0%]	0.96×10^{10} [3.2%]	0.80
1 MeV neutron equiv. (cm^{-2})	2×10^{10} [20.0%]	2.1×10^{10} [2.5%]	1.05
Dose (Gy)	4.73 [20.0%]	5.0 [10%]	1.06

Beam losses occur not only on the TED (during injection line setup) but also during injection when fractions of the injected beam will be lost on the injection collimator (TCDI). Electronics near the shielded area has therefore to be sufficiently protected and respective shielding improvements were already performed in 2009 [8]. Figure 5 shows the radiation field distribution in case of a beam loss on the TCDI, as well as the two monitor locations of interest.

During a setup of the TCDI collimator with a known number of protons impinging on its jaw, the two monitor locations (8RM05S and 8RM06S, see Fig.4) then served as application benchmark in order to compare the FLUKA simulations and the detector readings. The good agreement is shown in Table 4, where the results are expressed as high-energy hadron fluence per primary particle interaction on the collimator jaw.

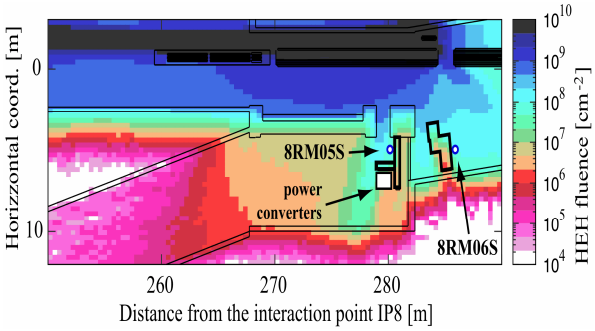

Figure 5: High-energy hadron fluence distribution around the collimator (TCDI) location originating from losses of 450GeV/c protons injected into the LHC. Fluences are normalized for an estimated cumulative annual loss on the respective collimator.

Table 4: High-energy hadron fluence (cm^{-2}) for two RadMon measurement positions close to the shielded area. Results are given as fluence per primary proton impinging on the injection collimator (TCDI). Stated errors are based on counts and calibration uncertainties for the RadMon values, as well as statistical uncertainties for the FLUKA calculations.

Location	RadMon [Error]	FLUKA [Error]	Ratio (R/F)
8RM05S (3V)	6.97. x 10^{-5} [20.0%]	7.75 x 10^{-5} [5.7%]	0.9
8RM06S (5V)	6.36 x 10^{-6} [20.0%]	6.10 x 10^{-6} [6.8%]	1.05

(3) 2010 operation and comparison of monitor readings with FLUKA simulations results

Proton losses occur distributed on the collimators during all phases of accelerator operation. During the collimation study phase and their respective design and implementation into the LHC, detailed calculations were carried out based on SixTrack [12] for particle tracking and FLUKA [6, 7] for various applications ranging from the characterisation of the radiation field, radiation protection issues and energy deposition studies. This led to a very detailed FLUKA implementation of the collimation areas (IR3 and 7) [13], which is in the following used to compare the radiation levels as predicted by the particle loss distribution based on the tracking code and the subsequent detailed FLUKA calculations with RadMon measurements as obtained during 2010 3.5TeV LHC operation.

Based on the loss distribution between the various collimators the actual loss location of the primary protons is sampled as source term in the FLUKA calculations. The secondary particle distribution is then tracked in detail along the more than 500m long geometry of the long straight section and for about half a million of primary particles in order to allow for reasonable statistics at the monitor locations (the DS/ARC sections are disabled in the case of these simulations). Strong radiation gradients exist in IR7 between the area of the primary collimators and the downstream critical areas (UJ76 or RR77) as can be seen in Figure 6 where the FLUKA results for beam-1 induced losses are shown.

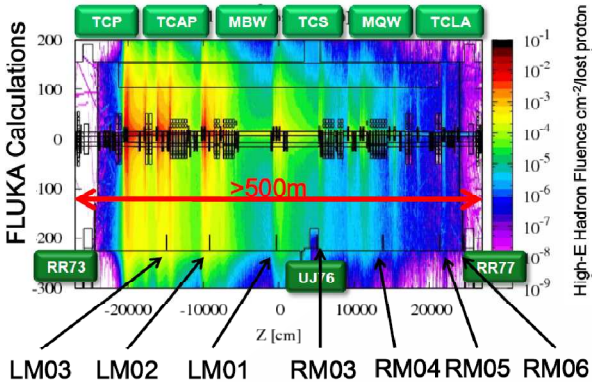

Figure 6: High-energy hadron fluence distribution along the full long-straight-section of IR7 and for primary losses occurring for beam-1 only.

In a first approximation and for the location of the RadMon detectors (see Figure 6 and detectors numbered as LM01-03, RM03-06) the particle losses between beam-1 and beam-2 can be considered as symmetric, thus allowing to mirror the radiation levels against the IP providing this way a complete radiation map for all monitor locations expressed as high-energy hadron fluence per primary lost particle.

To normalize the calculation results to the absolute values, in a next step the total number of particles lost in IR7 during 2010 LHC operation has to be determined in order to correctly compare the obtained high-energy hadron fluence to the respective cumulative monitor readings. The particle losses at the collimators being distributed and changing between the various phases of beam operation (*e.g.* ramp, squeeze, physics), together with the fact that there is no direct measurement providing the detailed number of lost particles for each collimator, the following procedure has been applied to determine the total number of protons lost in IR7 during 2010 operation (see Tables 5 and 6):

- based on the LHC BCTs as logged in TIMBER for each fill the highest intensity in the machine is considered as 'injected intensity' (see Table 5)
- right before the dump of the beam the last intensity value is considered as 'dumped intensity' (see Table 5)
- the difference between the two values is assumed to be 'lost' in the machine mainly between collisions at the experiments and collimators
- for the number of interactions in the experiments, their total luminosity is used together with an assumed total inelastic cross section of 80mb.

- the remaining intensity mainly refers to the collimators in the two collimation insertions (IR3 and IR7), and to determine the fraction of protons being lost in IR7 the BLM signals close to the collimators are used, in particular the cumulative dose at the first secondary collimator (see Table 6)

Table 5: Summary on injected, dumped and lost protons during 2010 LHC operation.

Proton Operation		
Injected & Ramped	6.02E+15	
Dumped	5.82E+15	96.70%
Lost in Machine	1.99E+14	3.30%
Of Lost protons		
Collisions	2.33E+13	11.73%
Elsewhere	1.76E+14	88.27%

Table 6: Ratio of cumulative BLM readings at the first secondary collimator in IR3 and IR7. The ratio is used to determine the fraction of the total losses as accumulated in IR7 during 2010 LHC operation.

BLM ratio IR7 / IR3		
	Ratio	% Loss in IR7
TCSG.A6L7.B1 / TCSG.5L3.B1	3.1	76
TCSG.A6R7.B2 / TCSG.5R3.B2	5.6	85

The RadMon detectors measure number of upsets in their SRAM memory which is proportional to the particle fluence. For charged particles the memory is sensitive to high energy particles (>20MeV) only, while for neutrons also intermediate energies (5-20MeV) and thermal neutrons (<0.5eV) have to be considered. In order to allow for a complete response analysis of the RadMon memory, a series of calibration measurements were carried out at CERN (CERF, CNRAD) as well as at dedicated mono-energetic facilities (PTB, NRI) [14, 15]. The particle energy spectra as obtained by the FLUKA simulation in combination with the measured thermal neutron component at a few representative locations in IR7 (based on combined 3V and 5V RadMon measurements, as well as dedicated TLD detectors) allow to predict the number of memory upsets based on the FLUKA simulations and compare them with the 2010 measurements as shown in Table 7.

As can be seen in Table 7, a very good agreement between measurements and simulations can be obtained even in situations with a very complex geometry, varying beam loss conditions and difficult particle energy fields where the calibration of detectors has to be carefully looked at.

Table 7: Comparison between FLUKA simulation and RadMon measurements for the IR7 tunnel locations. The number of measured and calculated memory upsets are compared and the contributing beams are listed.

RadMon	#SEUs Measured	Beam Contr.	#SEUs FLUKA	Ratio (M/F)
7LM03S	14401	B1	15015	1.04
7LM02S	5253	B1	9765	1.86
7LM01S	2689	B1+B2	3116	1.16
7RM03S	950	B1+B2	401	0.42
7RM04S	18727	B2	13032	0.70
7RM05S	303	B2	962	3.17
7RM06S	13	B1+B2	17	1.33

RADIATION LEVELS AROUND THE LHC

Based on the multitude of successful benchmark and 'application benchmark' measurements (a few of them briefly described in the previous chapter), it can be concluded that depending on the complexity and reproducibility of particle losses around the LHC, respective radiation levels can be very well predicted with the FLUKA Monte-Carlo code. In the following, we thus review the predictions of radiation levels for 2010 LHC operation, compare them to the predicted radiation levels and provide an outlook to the coming years of operation as well as nominal and ultimate LHC conditions.

2010 Operation

In order to provide an evaluation of the radiation levels as observed during 2010 LHC operation, all details like particle losses and distributions, operational conditions as well as monitor calibrations were carefully included in the calculation analysis and the following steps have been taken in order to obtain both, measured radiation levels around LHC critical areas, as well as correctly updated FLUKA results to be compared with:

- FLUKA predictions as based on the various source terms (*e.g.* collisions at the experiments, loss distribution in collimators, etc.) were rescaled to the actual operational conditions during 2010 (*e.g.* number of protons in the machine, accumulated luminosity for each experiment, etc.)
- RadMon monitor readings were converted into high-energy hadron fluence (>20MeV) applying updated calibration factors (this is particularly important for areas where the RadMons were operated at 3V, thus have a significant sensitivity on thermal neutrons
- To determine the thermal neutron contribution at the various measurement locations, either dedicated RadMon measurements at two voltages were used (see measurement procedure as described in [14]), or the results of dedicated TLD samples were applied (TLDs are thermo-

luminescence detectors allowing through the use of ^{6}Li and ^{7}Li to determine the dose contribution from thermal neutrons; they were further calibrated at CERF in order to improve their absolute response to mixed-radiation fields, thus allowing to determine the total thermal neutron fluence as compared to the high-energy hadron fluence (>20MeV).

Applying the above procedure to all critical areas where RadMon detectors showed a signal (at least a few counts over the LHC operation period in order to provide minimal statistics), Table 8 compares the measured radiation levels to the predicted ones.

Table 8: Radiation levels (high-energy hadron fluence above 20MeV) as predicted by FLUKA and measured at the end of 2010 LHC operation.

Critical Area	Predicted Fluence [cm^{-2}]	Measured Fluence [cm^{-2}]	Ratio (M/P)
UJ14/16	1.3E+06	1.1E+06	0.84
RR13/17	2.5E+05	6.2E+05	2.50
UJ56	1.3E+06	2.5E+05	0.20
RR53/57	2.5E+05	6.2E+05	2.50
UJ76	1.2E+06	2.1E+06	1.86
RR73/77	5.7E+05	3.1E+06	5.44
UX85b	1.3E+07	1.0E+07	0.82
US85	6.3E+06	2.9E+06	0.47
UJ23	5.6E+05	3.9E+06	6.97
UJ87	5.6E+05	2.0E+06	3.62

A generally good agreement between the predictions and the actual measurements is obtained, especially when considering the partly low radiation levels (leading to low statistics of the observed memory upsets in the RadMon where one can consider radiation levels of ~ 10^{7}cm-2 as 'good statistics'), the high dependency on LHC operation (*e.g.* higher injection losses as can be seen for the UJ23/87) and the fact that partly strong radiation gradients exist.

Prediction for 2011/2012 and Nominal Operation

Based on the before described FLUKA results we can then combine them with the predicted LHC operation parameters for 2011/2012 as well as nominal and ultimate conditions. Based on this, and again only for the selected critical areas (a full summary can be found on the R2E website [16]) Table 9 provides for the most critical areas the expected radiation levels for the coming years of LHC operation.

Table 8 and 9 nicely show that while radiation levels were generally low during the 2010 operation period (lower intensity/luminosity and beam availability), they will reach significant levels already in 2011/12 and high levels during nominal and ultimate operation if no mitigation measures are taken.

Table 9: Predicted annual radiation levels (high-energy hadron fluence in [cm^{-2}] above 20MeV) for the coming years of LHC operation. Predictions take into account the measured radiation levels as given in Table 8.

Critical Area	2011 [cm^{-2}]	2012 [cm^{-2}]	Nominal [cm^{-2}]	Ultimate [cm^{-2}]
UJ14/16	7.2E+07	1.2E+08	2.1E+09	4.2E+09
RR13/17	4.3E+07	7.1E+07	1.2E+09	2.5E+09
UJ56	1.7E+07	2.9E+07	5.0E+08	1.0E+09
RR53/57	4.3E+07	7.1E+07	1.2E+09	2.5E+09
UJ76	4.7E+07	8.0E+07	7.4E+08	8.3E+08
RR73/77	6.9E+07	1.2E+08	1.1E+09	1.2E+09
UX85b	9.4E+07	1.9E+08	3.3E+08	3.3E+09
US85	2.7E+07	5.4E+07	9.4E+07	9.4E+08
UJ23	7.2E+07	1.2E+08	2.1E+09	4.2E+09
UJ87	4.3E+07	7.1E+07	1.2E+09	2.5E+09

It shall be noted that underlying uncertainties of the here presented estimates are not insignificant and mainly connected to the actual behaviour of the LHC accelerator.

OBSERVED EQUIPMENT FAILURES DURING 2010 LHC OPERATION

As discussed in the previous chapters, radiation levels were relatively low during 2010 LHC operation. Furthermore, expected failure cross-sections for unknown equipment can range several orders of magnitudes, where an annual high-energy hadron fluence of 10^{7}cm^{-2}y^{-1} is considered as a reasonable 'threshold' level [17] where radiation induced failures start becoming visible above their standard failure modes (leading to a comparable equipment MTBF without radiation; *e.g.* without radiation the current power-converters aim for an MTBF of about 10^{5}h per equipment).

Especially during the period of early LHC operation, and respective low radiation levels, it is thus very difficult to distinguish a radiation induced equipment failure from another one which is a standard equipment failure mode. This can be further illustrated by the fact that one is observing a very large sample of electronic components in the LHC with all of them having non-radiation induced failure modes and respective probabilities. Based on partly measured failure cross sections and assuming 10^{-7}cm^{2} as conservative cross-section for unknown equipment only a few radiation induced failures were expected during the 2010 operation period [18]. It would thus be necessary analyzing in detail all occurring failures, which is not entirely possible.

R2E has thus setup a procedure where failures leading to beam-stop (as discussed during the LHC 8:30h meeting) were checked if they fulfil the following criteria:

- did the problem happen together with high radiation levels occurring in the area at the same time (radiation spike, higher losses)
- is the failure occurring in a critical area and on a possibly radiation sensitive equipment
- is the error linked to a communication problem and was resolved by a reset/power-cycle
- is the failure mode recurrent and increasing in frequency with higher radiation levels

All failure candidates were then discussed in detail with the responsible equipment groups and through the "Radiation Working Group (RadWG) [19]" in order to identify possible radiation induced failure candidates (see also the respective database available in the news section of the RAdWG website [19]). This analysis process is obviously not complete and with only a few failure candidates especially the above mentioned last criteria on the frequency of occurrence can hardly be applied.

However, the following few failures were successfully analyzed and confirmed as being very likely radiation induced:

- WIC crate failure in TI8: this failure was already observed in 2009 and is due to a communication problem of the PLC which was also tested in CNGS reproducing the same behaviour [20].
- QPS tunnel card failures: problem with a digital isolator chip (ISO150) leading to a permanent PM trigger; occurred many times and at high-loss locations (injection TCDIs, adjacent to collimation regions); was in the beginning difficult to identify as SEE induced as a similar EMC induced failure mode exists. This device was actually tested with radiation, however is used in a different way in its final implementation, thus making the electronics more vulnerable to the failure. Mitigation actions were already successfully developed in form of a firmware upgrade and partly integrated (the remaining locations will be continuously updated during the 2011 technical stops and accesses) [21] .
- µFIP communication problem: the existing controller chip is radiation tolerant, however the high number of exposed components as well as a possible batch-to-batch variation (with a possible different failure cross-section) led to three observed failures in 2010 (two on QPS equipment, one on CRYO). It shall be noted that the same failure mode was also observed during CNRAD tests.
- TE/EPC power supply: a power supply of a power converter rack situated in the UA87 close to the maze towards the TDI suffered from a burnout. The failure occurred at the same time when high injection losses at the TDI where observed. During a test at CNRAD, the same destructive failure mode was observed [22].

We can thus conclude that already a few radiation induced failures were observed, despite the relatively low radiation levels in the machine: 10^5-10^7cm^{-2} in critical areas (~10^8cm^{-2} in the tunnel) where electronics is exposed. It shall be noted that the respective LHC operation parameter correspond to only about 0.1% of nominal integrated annual luminosity, up to 2% of peak luminosity and about 1% of nominal lost beam.

Previsions provided in 2010 expected a number of radiation induced problems for the reached LHC intensities and luminosities, also in critical areas. As listed before, in the LHC tunnel 5-10 SEE events were already observed in 2010 causing the stop of the accelerator and requiring an intervention (a mitigation procedure exists for the QPS problem and is currently implemented). For the shielded areas only one failure could so far be confirmed.

Three lessons can be learned from this:

- it is (and remains) very difficult to identify radiation induced failures and quantify their risk as long as radiation levels are relatively low;
- also radiation tolerant equipment has certain weaknesses and is exposed to increasing radiation levels, thus detailed monitoring and constant analysis from all concerned equipment groups is of high importance;
- lower and higher failure rates than predicted can not be excluded as unknown equipment can be more or less sensitive (*e.g.* QPS case of the digital isolator chip ISO150), but radiation levels can also be lower or higher than expected (*e.g.* electron cloud, injection losses, life-time for ions)

Strong team efforts are required from all equipment groups and the RadWG, as no big safety margins can be taken for the R2E mitigation project and all activities have to be strongly optimized with respect to LHC operation and shutdown planning, considering the impact on installed equipment, LHC performance and final costs.

FAILURE RATE PREDICTION AND DISCUSSION ON 2011/2012 OPERATION

Based on the before presented results of radiation tests and obtained failure cross sections, as well as the expected radiation levels for LHC critical areas during 2011/2012 but also nominal and ultimate intensities, in the following we try to deduce a global radiation induced failure rate for the LHC. While performed benchmark experiments and early measurements during 2010 operation have shown that the radiation levels can be predicted with sufficient accuracy, it is important to bear in mind that strong uncertainties still remain on both, the actual sensitivity of the COTS equipment, as well as the operational behaviour of the accelerator (especially at high-loss locations or during the scrubbing period). The following estimate is thus intended to illustrate the order

of magnitude, but not the detailed number of failures to the last digit.

Based on the performed equipment inventories [2-5] and in iteration with the respective equipment responsible, the following four general failure categories were identified and included in the analysis process:

a) a failure leading to a dump of the beam and requiring access prior restart of the machine
b) as (a) but not requiring immediate access
c) a failure requiring an access which can be scheduled in the next technical stop or other access
d) other failures

Furthermore, the following procedure has been applied to determine the best possible estimate of the collective number of failures for the coming years of LHC operation:

- Based on the measured radiation levels in the various critical areas, the expected radiation levels were revised and updated as much as possible (see previous chapter).
- Wherever possible, equipment failure cross sections are based on measurements and the same are applied to similar equipments in case their sensitivity is unknown.
- For complex equipment like power-converters the expected failure cross-sections are based on the feedback as provided by the power-converter review [23].
- For unknown components a "guessed" failure cross-section is applied according to the complexity of the device and ranges from 10^{-7}cm^2 to 10^{-9}cm^2.
- An intermediate iteration used the 2010 measured and calculated radiation levels and the respective cross sections to deduce a first collective number of failures. This resulted in a higher number of failures as actually observed during the 2010 operation period (see previous chapter), thus the "guessed" failure cross sections were down-scaled accordingly to match the observed number of failures in critical areas.
- The next step is to scale the expected radiation field with the operational parameters for 2011, 2012, nominal and ultimate LHC operation. During this conference and update was provided for 2011 and 2012 [24], with nominal and ultimate conditions remaining unchanged from the original design values [25], leading to the annual radiation levels as listed for a few representative critical areas in Table 9.
- A last step then considers the total number of components/systems per area and for each equipment type their failure cross section and the expected radiation level to calculate the number of annual failures for the respective equipment. Grouping these failures by the four general failure modes (a-d) allows providing an estimate of the total number of annual failures of all equipment being installed around LHC critical areas.

Table 10 summarizes the obtained annual number of failures for the respective failure types and expresses them as mean-time between failures (MTBF).

Table 10: Predicted MTBF due to radiation induced problems in LHC electronics for the coming years of LHC operation. Levels lower than one failure per day are not realistically reachable due to machine turn-around, however listed as theoretical failure rates only.

Failure Mode	2011 [days]	2012 [days]	Nominal [days]	Ultimate [days]
Immediate Dump and Access	4	2	0.2	0.1
Immediate Dump	19	11	0.8	0.4
Scheduled Access	10	6	0.5	0.3
Other	12	7	0.5	0.3

The dominant uncertainty in the above estimate is the actual behaviour of the installed electronics. As outlined before, only a minor fraction of the equipment could be tested and partly strong assumptions had to be made on the other equipment and its failure probability. In addition, as explained in a previous chapter, the radiation levels being mainly based on measurements require a detailed evaluation of the radiation field as this impacts the monitor calibration, thus the final measured value. In order to quantify the respective uncertainty of the predicted MTBF, a sensitivity analysis has been performed on the two independent parameters:

- increasing and decreasing the failure cross-section of not tested equipment (x-axis in Figure 6);
- varying the thermal neutron contribution to the RadMon reading at the location of the radiation monitors, thus changing their calibration factors (shaded areas in Figure 6);

Combining both sensitivity studies leads to the results shown in Figure 6 which states the total MTBF as a function of the assumed failure cross-section. The shaded areas illustrate the sensitivity on the monitor calibration in the respective radiation field. It is important to note, that Figure 6 does not illustrate the other uncertainties as listed earlier (operational behaviour of the LHC or batch to batch variations of measured components/systems).

However, it is clearly shown that aiming for a MTBF of one week for ultimate LHC conditions, requires an improvement of at least two orders of magnitudes, thus considered to be outside the reach of additional uncertainties. A combination of shielding and relocation

activities, as well as radiation tolerant developments are thus required as presented in the following chapter.

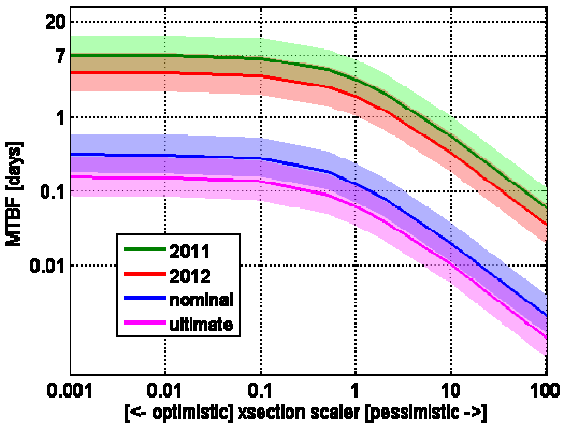

Figure 6: Sensitivity analysis of failure rate prediction as a function of the assumed failure cross sections for untested equipment, as well as the radiation field at the monitor locations.

R2E MITIGATION APPROACH AND ONGOING STUDIES

As shown in the previous chapters, estimating the detailed MTBF due to radiation damage of electronics for the entire LHC machine and all individual equipments is very difficult due to the fact that too many electronic systems are installed in areas exposed to radiation and that it will be impossible to measure the respective radiation sensitivity of all of them.

During the past almost three years the R2E study group has thus put the focus on quantifying the risk, assign priorities, propose a mid-and long-term mitigation plan and perform identified urgent actions to improve the situation and reduce the risk of radiation induced failures as much as possible already during the first years of operation.

The already implemented mitigation actions include:

- closure of holes in shielding: numerous ducts/holes in various UJs, shielding of ducts between the UAs and RAs in Point-6 (next to the TCDQ)
- installation of additional shielding in the injection areas (UJ22, UJ88) to protect adjacent power-converters; safe-room shielding in the US85 and for the UJ76; shielding of the RRs in P7;
- relocation of safety related equipment: Fire/ODH control racks in P5 and P7; UPS in P7; fire detectors in P8;
- relocation of equipment known to be very sensitive and of areas where high radiation levels are

It shall be noted that these actions have already mitigated a certain risk of radiation induced failures, however are only a first step towards a complete long-term solution. For the study and development of the latter, the following main constraints have to be considered and are briefly described in the following with their impact on the long-term mitigation approach:

a) the definition of a design criteria for acceptable annual high-energy hadron fluences and the classification of critical areas
b) an acceptable global equipment failure rate induced by radiation
c) the available time windows for mitigation actions

For (a) a design limit of $10^7 cm^{-2} y^{-1}$ high-energy hadrons is not intended to be used as an absolute value below which there is no risk of occurrence of SEE, but rather as the upper value for which normally a single non radiation tolerant electronic device, either COTS or a custom designed has good chances to have an MTBF above one year. This way it cannot be excluded that very sensitive electronics may present dramatic failures already at this level, but the R2E study group considered that the number of equipments presenting this risk is rather limited and a workaround in case of problems can be found in a reasonable time. Reducing this limit further to come close to the yearly value normally registered at ground level ($\sim<10^5$ high-energy hadrons/cm^2) would represent an investment (costs and time) well beyond what is reasonable and achievable in the given project constraints.

To reach this design goal the R2E mitigation project thus aims at minimising the number of equipment exposed to higher radiation by:

- installing additional shielding
- relocation into properly shielded areas
- directly reducing the source term of the radiation levels which is an option currently in preparation for IR7 where the installation of additional collimators in IR3 will allow to significantly reduce the radiation levels in IR7 (it remains however to be studied if this can be considered as a long-term solution or if at a certain point IR7 will again have to be used as betatron collimation area)

Unfortunately, shielding is not a sufficient option for all critical areas, thus the remaining equipment has to fulfil the second criteria (b) which was defined together with beam operation as a collective acceptable failure rate of one weekly radiation induced equipment failure under ultimate LHC conditions (intensity/luminosity/losses). This requires that for equipment not possible to be replaced and remaining in not sufficiently shielded areas alternative solutions have to be found and requiring

cables), as well as certain tunnel components which are already known to be not sufficiently radiation tolerant in the long-term (*e.g.* µFIP). Basically two mitigation options exist:

- a new radiation tolerant design to replace the existing power-converters in the critical areas remaining after relocation and shielding mitigations
- the development of new long-distance and vertical super-conducting links allowing to relocate the power-converters to the surface without having the constraint of cable lengths

Only the thorough study of all options can allow for an effective and efficient optimisation of the mid/long-term solutions to be implemented.

However, perhaps the biggest constraint in this endeavour remains (c) which significantly restricts the time windows (short stops during Christmas, long-shutdowns) available for the mitigation actions to be implemented. Furthermore, (c) has a further strong impact on the actual mitigation strategy in the sense that foreseen long operation periods between long shut-downs limit the possibilities where R2E related mitigation work can be performed in the LHC. The electronics will thus be exposed to higher radiation levels before the actual mitigation measures could be implemented. This is a particular problem for the power-converters where the development phase will be longer than the time available until the next long-shutdown.

Based on the results of the R2E study group two workshops were organised in 2010:

- 'LHC Power-Converters Workshop' [26]
- 'R2E Workshop' [27]

The first workshop studied the problematic of the existing power-converters, confirmed the high operational risk, proposed a combination of radiation tests and pointed out the importance to study immediately the possibility of a long-term radiation tolerant development. The second workshop focused on the available mid-term mitigation actions (shielding and relocation) and what actions have to be taken in order to assure a long-term mitigation plan, as well as their integration into the LHC operational schedule. The current proposal is illustrated in Figure 7.

This study and the conclusion of the R2E Workshop [27] led to the creation of the R2E mitigation project with the mandate to optimize the mitigation plan and implement all corresponding actions.

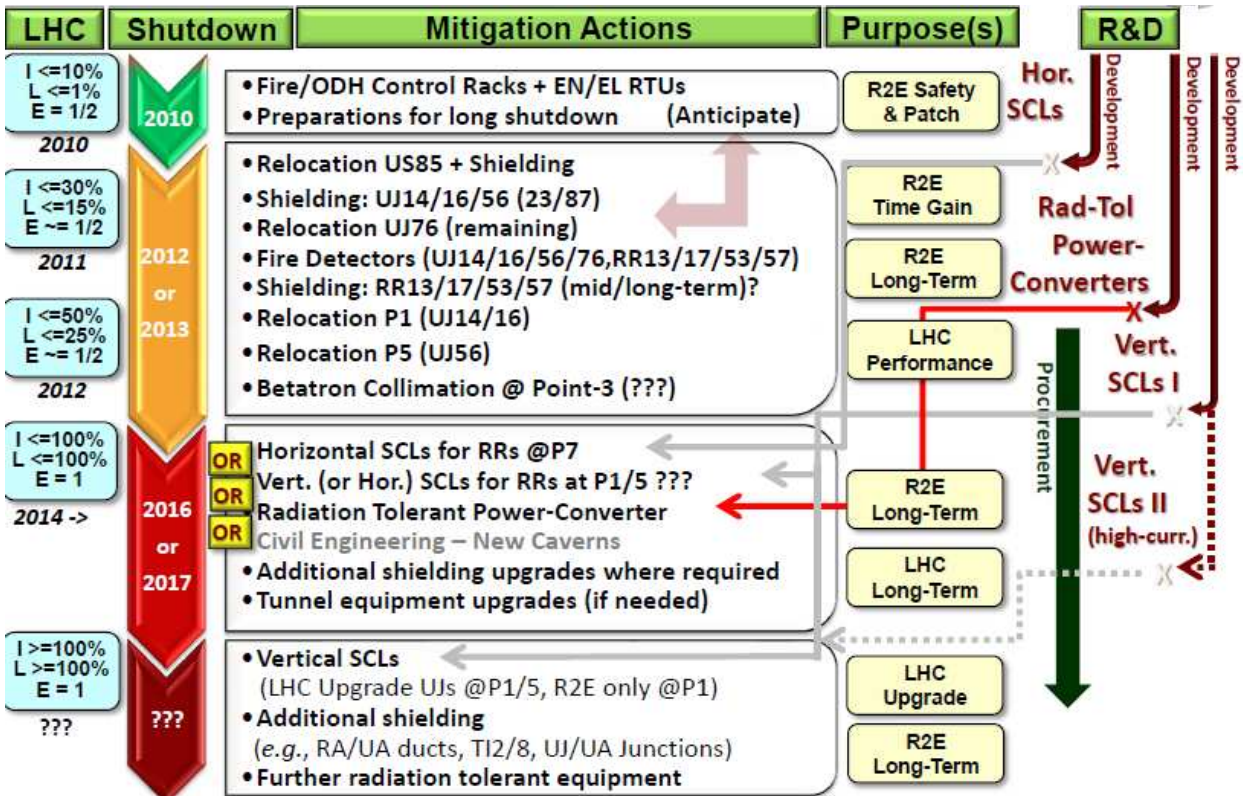

Figure 7: Proposed R2E mitigation approach including studies and actions following the LHC operation and shutdown planning.

Figure 7 illustrates that according to the available time-windows the first long-shutdown will focus on relocation and shielding actions, while the started R&D activities for the development of radiation tolerant power-converters and the design and study of super-conducting links will allow to optimize the long-term solution. In addition, civil engineering actions are kept as backup solution, knowing that such activities would most probably exceed the available length during a shutdown and also be significantly higher in total costs.

The R2E mitigation project has the mandate to minimize (avoid) any risk of radiation induced failure to electronics. It studies a detailed mitigation plan fitting into the planned shutdown periods and optimizes it with respect to planning and costs. This requires a strategy to monitor and benchmark the radiation around all critical areas, constantly review the equipment behaviour and follow-up on radiation induced problems to further refine the required mitigation actions and their respective planning. In parallel, so-called "Patch-Solutions" have to be studied and prepared wherever available. The next long shutdown will focus on shielding and relocation options, anticipating certain work already during the preceeding short stops during Christmas (*e.g.* cabling work during the 2010/11, Fire/ODH and RTU relocations). In parallel, all major long-term solutions (R&D for Superconducting Links and Radiation Tolerant Power-Converters, as well as Civil Engineering) are followed in parallel.

Besides the ongoing R&D work, implementation studies and preparations, the following questions are identified as key points to be answered towards a finalized long-term mitigation program for LHC electronics:

- what are the long-term radiation levels in the dispersion suppressors and in the arc and what does that imply for the respectively installed equipment (*e.g.* higher radiation levels during scrubbing periods);
- how can the large workload related to shielding and relocation activities be reduced and possibly fit into a shutdown of around one year [28];
- what implementation solution can be found for the safe-room equipment in Point-5 and Point-7;
- what is the radiation sensitivity of the currently installed power-converters and how does this translate into equipment failure risk once shielding and relocation measures have been applied;
- given the operation period of several years after the next long-shutdown, what intermediate solution can be found for the power-converters in accordance with the new radiation tolerant development and what is the best corresponding long-term approach;
- what additional weak-links exist in the installed tunnel-equipment and what mitigation measures can be considered.

CONCLUSION AND FOLLOW-UPS

Starting with the two questions to be answered during the 2011 Chamonix workshop, from the R2E point-of-view we can conclude that there is only a minor impact on the expected radiation levels in case the LHC energy is increased from 3.5TeV [29] to higher values, thus this is not considered as an issue for R2E.

However, shifting the long shutdown to 2013 will lead to a delay of the before described R2E mitigation measures (shielding/relocation), thus leading to a higher exposure of the installed electronics. Given the expected radiation levels and equipment sensitivities, an impact on 2012 operation can not to be excluded, however, is expected to be close to acceptable limits (MTBF >= 1 week). It is important to note that the risk of destructive failures must not be forgotten (especially for power devices) and can not be further quantified with the existing radiation test results.

For 2011, the R2E mitigation project thus puts the focus on additional radiation tests (*e.g.* full power-converter tests in the new H4IRRAD facility with representative radiation environments) and the preparation of shielding and relocation measures. The launched development for radiation tolerant power-converters will start working on the conceptual design as well as the component study and respective radiation tests.

The 2011 operational experience together with detailed monitoring and scheduled radiation tests will then allow for a further optimization step of the long-term strategy. In addition, equipment groups and the RadWG study patch solutions to be applied in case certain equipment specific failures are observed and require an early work-around.

The following related follow-up actions have been discussed and agreed upon during this workshop:

1) Prepare as much improvement as possible for 2011/12 shutdown:
- this requires a frozen layout for all points and the input from radiation tests/operation in order to select what equipment can be prioritized. The relocation work will be anticipated as much as possible (one example: the WIC crate in P8 will most likely be moved already during one of the early technical stops).

2) Change the dispersion setup of B2 (IR7 left): shorten region in the dispersion suppressor where particle losses appear due to ion beam cleaning in IR7 (ions):
- this will significantly reduce the ion induced radiation losses next to the collimation areas making the radiation levels during one month of ion operation comparable with the remaining year of proton operation.

3) Continue efforts to reduce uncertainty in equipment sensitivity:
- the new facility H4IRRAD and respective radiation tests are in preparation and will involve in 2011 multiple power-converters as installed in critical areas, EN/EL safe-room equipment and GTOs as used in Point-6.

4) Perform beam tests to improve radiation field calibration:
- two test locations (quench test location + injection region) are proposed to LHC operation and respective MD shifts are to be scheduled.

The above points together with the R&D program for power-converters, the radiation tolerant development of tunnel equipment (*e.g.* nanoFIP), the radiation test campaigns and RadWG activities shall ensure the required flexibility from the equipment point-of-view. The preparation of shielding and relocation measures

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