RADIATION DAMAGE TO ELECTRONICS AT THE LHC

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Abstract

Control systems installed in LHC underground areas using COTS (Commercial Off The Shelf) components are affected by the risk of 'Single Event Effects'. In the LHC tunnel, in addition, cumulative dose effects have also to be considered. While for the tunnel equipment certain radiation tolerant design criteria were already taken into account during the LHC construction phase, most of the equipment placed in adjacent and partly shielded areas was not conceived nor tested for their current radiation environment. Given the large amount of electronics being installed in these areas, a CERN wide project called R2E ('Radiation To Electronics') has been initiated to quantify the danger of radiation-induced failures and to mitigate the risk for nominal beams and beyond to below one failure a week. This paper briefly summarizes the analysis and mitigation approach chosen for the LHC, highlights a few of the encountered difficulties and the obtained experience in the following aspects: radiation fields & related calculations, monitoring and benchmarking; commercial equipment/systems and their use in the LHC radiation fields; radiation tests with dedicated test areas and facilities.

INTRODUCTION

The mandate of the R2E Project [1] is to minimize all radiation-induced failures in the LHC; in particular, to allow LHC operation with a *'Mean-Time Between Failures'* (MTBF) greater than or equal to one week for a peak luminosity of 2×10^{34} $cm^{-2}s^{-1}$ and a yearly integrated luminosity of 50 fb^{-1}, but also taking into account the LHC performance expected after the High Luminosity upgrade (HL-LHC), therefore assuming a peak luminosity of $\sim5\times10^{34}$ $cm^{-2}s^{-1}$ for a yearly integrated luminosity of up to 200 fb^{-1}. Given the large number of LHC electronic control and power equipment being exposed to radiation a continuous effort is required in order to keep the risk of radiation induced failures and their impact on the accelerator operation as low as possible.

THE LHC RADIATION ENVIRONMENT AND RADIATION EFFECTS TO BE CONSIDERED

It is important to note, that both the radiation environment encountered at the Large Hadron Collider (LHC) at CERN, the high number of electronic systems and components, as well as the actual impact on radiation induced failures strongly differ from the environment relevant for space applications. While for the latter application design, test and monitoring standards are already well defined, additional constraints, but in some cases also simplifications have to be considered for accelerator environment.

The mixed particle type and energy field encountered at the LHC is composed of charged and neutral hadrons (protons, pions, kaons and neutrons), photons, electrons and muons ranging from thermal energies up to the GeV range. This complex field has been extensively simulated by the FLUKA Monte Carlo code benchmarked in detail for radiation damage issues at the LHC [2, 3]. The observed radiation is due to particles generated by proton-proton (or ion-ion) collisions in the LHC experimental areas, distributed beam losses (protons, ions) around the machine, and to beam interacting with the residual gas inside the beam pipe. The proportion of the different particle species in the field depends on the distance and on the angle with respect to the interaction point, as well as on the amount (if any) of installed shielding material. Electronic components and systems exposed to a mixed radiation field will experience three different types of radiation damages: these are displacement damage, damage from the Total Ionising Dose (TID) and so-called Single Event Effects (SEEs).

The first two being of cumulative nature (measured through 'Total Ionizing Dose (TID)' and non-ionizing energy deposition (generally quantified though accumulated 1-MeV neutron equivalent fluence), where the steady accumulation of defects cause measurable effects which can ultimately lead to device failure. In terms of stochastic SEE failures, they form an entirely different group as they are due to the direct ionization by a single particle, able to deposit sufficient energy through ionization processes in order to disturb the operation of the device. They can only be characterized in terms of their probability to occur as a function of accumulated High Energy (>5÷20 MeV) Hadron fluence. The probability of failure will strongly depend on the device as well as on the flux and nature of the particles. In the current configuration, several tunnel areas close to the LHC tunnel, and partly not sufficiently shielded, are equipped with commercial or not specifically designed electronics which are mostly affected by the risk of SEEs, whereas electronics installed in the LHC tunnel will in the long-term also suffer from accumulated damage [4].

For this purpose, during the first years of LHC operation, the radiation levels in the LHC tunnel and in the shielded areas have been measured by using the CERN RadMon system [5] dedicated to the analysis of radiation levels possibly impacting installed electronic equipment. Major calibration campaigns were recently performed in order to minimize all related measurement uncertainties.

The major cause of radiation-induced failures observed during 2011 LHC operation are due to SEEs on electronic equipment. Table 1 summarises the level of accumulated High Energy Hadron (HEH) fluence during 2011 for the most critical LHC areas where electronic equipment is installed. The HEH fluence measurements are based on the RadMon reading of the Single Event Upsets (SEU) of SRAM memories whose sensitivity was extensively calibrated in various facilities. The results obtained during 2011 LHC proton operation show that the measurements very well compare with previously performed FLUKA calculations and observed differences can actually be attributed to changes of operational parameters not considered in the calculations.

Table 1: Predicted and measured HEH fluence (cm^{-2}) in LHC critical areas (see also area overview in [1]) based on 2011 operation conditions.

Area	FLUKA	Measured
UJ14/16	~2x10^8	2x10^8
RR13/17	~3x10^7	7x10^6
UJ56	5x10^7 - 1x10^8	4x10^7
RR53/57	~3x10^7	1x10^7
UJ76	~4x10^6	5x10^6
RR73/77	~2x10^6	8x10^6
UX85b	~3x10^8	2x10^8
US85	~7x10^7	4x10^7

LHC OPERATION AND R2E MITIGATION MEASURES

The for the LHC required R2E mitigation actions to be implemented during the first Long Shutdown of 2013/2014 (LS1), were analysed and prepared in detail over the last three years. These actions particularly consist in:

1. Relocating commercial equipment located in areas where the high-energy hadron (HEH) fluence does not exceed ~10^7 HEH/cm^2/year, whenever possible;
2. Installing additional shielding for zones where relocation is not an option;
3. Radiation-tolerant hardware development to allow the operation of electronics equipment in regions where solutions 1 and 2 cannot be implemented.

Some actions affecting the most critical and exposed equipment were already taken before as well as partly during 2011 operation, also taking into account the observation of unexpected failures during operation.

Given the extended amount of equipment to displace, shield or redesign, a prioritization of mitigation measures was defined and consistently followed throughout the R2E mitigation project:

- 1st Priority – critical personnel and machine safety equipment: envisage/prepare for immediate relocation (performed at the earliest stage of all R2E related activities);
- 2nd Priority – shielding options: aim for fast and overall improvement of a large number of equipment (continuously performed taking into account the criticality of the concerned area and the time available during machine stops);
- 3rd Priority – most sensitive equipment and areas: relocation and shielding measures selecting the equipment/area with the highest impact on operation (as started during 2011 operation and continued during the last operational stop with a strong focus on radiation-tolerant patch-solutions for equipment design);
- 4th Priority – remaining critical equipment/areas: prepare long-term mitigation actions including additional shielding, consequent relocation and radiation-tolerant design for the remaining equipment.

Following the agreed list of priorities and as a consequence of already implemented mitigation measures, it was possible to limit the number of radiation induced accelerator stops. Consistent with Table 1, Figure 1 shows the locations of the equipment most affected by SEE radiation induced failures during 2011 operation. The majority of failures related to tunnel equipment were related to the so-called Quench Protection System (QPS) electronics and happened in the LHC tunnel, more precisely in the Dispersion Suppressor (DS) areas (Fig. 2a). This weakness already known from early operation onward, allowed for mitigation measures to be applied at firmware level already during the 2010/2011 Winter Break in order to avoid a non-acceptable number of beam dumps.

During 2011, in total, about 70 beam dumps were provoked by radiation effects on electronic equipment causing an important downtime for the machine of about 400 hours. The impact of the radiation effects would have been significantly higher without the countermeasures that were already applied in the past years and the numerous patch solutions implemented during 2011.

As it can be seen in Figure 1b, the shielded areas at LHC Point 1 (UJ14 and UJ16), were confirmed as being the most critical zones both in terms of the number of failures as well as observed radiation levels. In summer 2011, it was thus decided to improve the shielding of equipment already during the 2011/12 winter break. In addition, the relocation of the equipment will be the definitive mitigation action and is scheduled for LS1.

Thanks to the mitigation measures taken before the restart of LHC operation in 2012, the expected number of failures which can potentially dump the beam in 2012 is expected to be around 30-50, although the radiation levels will increase by a factor of 3 on average, with respect to 2011, in both the tunnel and shielded areas.

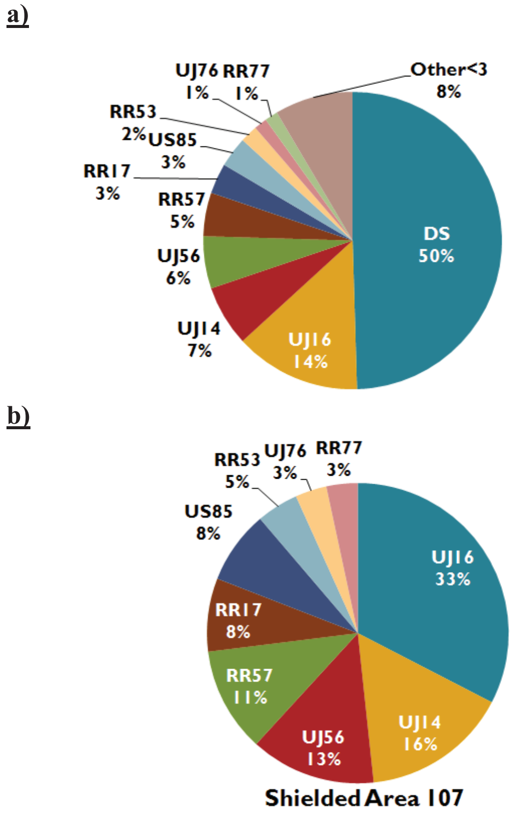

Figure 1: Locations of the equipment affected by radiation-induced failures. Figure (a) reports all the cases for the tunnel and shielded areas; Figure (b) shows the failure distribution in the so-called shielded areas (*i.e,* not LHC tunnel areas).

Both, the accurate monitoring of the radiation levels and the detailed follow-up and analysis of equipment failures are key to ensure an efficient LHC operation.

CONCLUSIONS AND FUTURE REQUIREMENTS

In order to reduce the impact of the effects of SEE-induced failures on the operation of the LHC, a significant amount of relocation and shielding activities has been or will be continued to be implemented. However, there are several systems around the LHC for which relocation or shielding is not possible or sufficient to mitigate the effect of SEEs and in the long-term also cumulative radiation damage. In these cases, only radiation tolerant hardware design can guarantee an efficient accelerator operation. In these cases modifications on existing systems, as well as new equipment developments have been foreseen. In particular, this affects systems located close to the beam, like the quench-protection, cryogenics and beam-instrumentation system, as well as the 'low-current' power-converters, all critical in order to achieve the highest possible LHC operational efficiency.

All radiation fields encountered around the LHC beams are mixed radiation fields. It is therefore important to perform the required irradiation tests in mixed radiation fields being as similar as possible to the ones encountered during LHC operation. However, for the moment many required radiation tests are performed at the proton facility of PSI as well as at two ad-hock mixed-beam irradiation areas at CERN (CNRAD [6] operated parasitically to the CNGS facility; and H4IRRAD [7] operated in the CERN North Area) providing however limited testing capacity. A new radiation test facility ideally serving both the accelerator and the physics community has thus been studied and is considered as high priority in order to assure radiation tolerance requirements for the LHC and beyond. Besides large irradiation volumes, easy accessibility and design, a new radiation test facility should also foresee enough flexibility in order to allow tests also in neutron dominant and low-dose exposures conditions. A combined radiation test facility has thus been proposed, the requirements have been analysed [8] and a first set of design calculations [9] have shown its feasibility.

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