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RADIATION TO ELECTRONICS IMPACT ON CERN LHC OPERATION: RUN 2 OVERVIEW AND HL-LHC OUTLOOK

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Abstract

After the mitigation measures implemented during Run 1 (2010-2012) and Long Shutdown 1 (LS1, 2013-2014), the number of equipment failures due to radiation effects on electronics (R2E) leading to LHC beam dumps and/or machine downtime has been sufficiently low as to yield a minor impact on the accelerator performance. During Run 2 (2015-2018) the R2E related failures per unit of integrated luminosity remained below the target value of 0.5 events/fb^{-1}, with the sole exception of the 2015 run during which the machine commissioning took place. However, during 2018, an increase in the failure rate was observed, linked to the increased radiation levels in the dispersion suppressors of the ATLAS and CMS experimental insertions, significantly affecting the Quench Protection System located underneath the superconducting magnets in the tunnel. This work provides an overview of the Run 2 R2E events during LHC proton-proton operation, putting them in the context of the related radiation levels and equipment sensitivity, and providing an outlook for Run 3 and HL-LHC operation.

INTRODUCTION

The operation of the Large Hadron Collider (LHC) at CERN [1] relies on a number of complex systems performing critical functions linked to key elements of the accelerator. Examples include the Power Converter system [2], that produces and regulates the DC currents that reaches the beam line elements (e.g. magnets), the Quench Protection System [3, 4] that prevents damage to the LHC magnets due to losses of superconductivity, and many others. When a failure is detected in a critical system, the LHC Beam Interlock System [5] ensures that the beams are safely extracted from the machine in order to prevent any incident. Still, frequent premature beam aborts have a negative impact on the availability of the LHC, as after each beam dump it takes about three hours to re-establish a stable beam operation condition with collisions delivered to the experiments. During the LHC Run 1 (2010-2012), and following the observation of a significant number of failures of electronics attributed to the LHC radiation environment, the Radiation to Electronics (R2E) Project [6] was established with the objective of developing and implementing Radiation Hardness Assurance (RHA) strategies to mitigate such failures, delivering substantial LHC availability improvements already in its early phases [7]. This work focus on providing the analysis of the R2E performance during Run 2, as well as the prospects for the future LHC operation, including the High-Luminosity LHC (HL-LHC) upgrade [8].

R2E AT THE LHC

The mixed radiation field of the LHC, which includes different types of particles with broad energy ranges, can lead to radiation effects to electronics in the form of lifetime degradation and stochastic Single-Event Effects (SEEs) [9]. Depending on the position along the LHC, the main radiation source can be the inelastic collisions in the Interaction Points (IPs), the interactions of the beam with residual gas molecules in the beam pipes, or generic beam interactions with LHC elements (typically collimators). Important variations of the radiation levels in specific positions can occur due to changes in operational settings of the LHC (e.g. beam optics, collimator settings). The R2E project measures and predicts the radiation levels in all positions of interest by using different types of radiation monitors, such as the Beam Loss Monitor (BLM) [10] and RadMon [11] systems, and also by means of Monte Carlo simulations (FLUKA [12–14]). Although, the highest radiation levels are typically reached in IP1 and IP5 (hosting the high-luminosity experiments ATLAS and CMS), R2E effects can also be observed in other areas of the accelerator, depending not only on the radiation environment but also on the equipment sensitivity and the number of radiation-exposed units in the system.

LHC AVAILABILITY AND R2E PERFORMANCE

A key figure of merit quantifying the performance of the LHC is the integrated luminosity delivered to its high-luminosity experiments ATLAS and CMS, expressed in inverse femtobarns (fb^{-1}) and proportional to the number of proton collisions in the IPs. As a consequence, it is useful to measure the R2E performance by counting the R2E-induced beam dumps per unit fb^{-1}, where a smaller figure corresponds to a milder impact on the LHC physics run. Similarly, the performance targets of the R2E project are defined by performing modelling studies of the LHC availability [15] and deriving the maximum number of R2E-induced beam dumps per unit fb^{-1} that are compatible with keeping the resulting loss of integrated luminosity below a reference threshold (typically 1%).

The number of beam dumps induced by R2E faults is shown in Fig. 1 as a function of the cumulative integrated luminosity for the LHC Run 1 (with trend lines from Ref. [7]) and Run 2, for which the single R2E-induced dumps are shown individually, as further described in the next section. In general, it is clear that the R2E project has already achieved a remarkable improvement compared to the early stages of the LHC operation, with less than 0.5 dumps/fb^{-1}

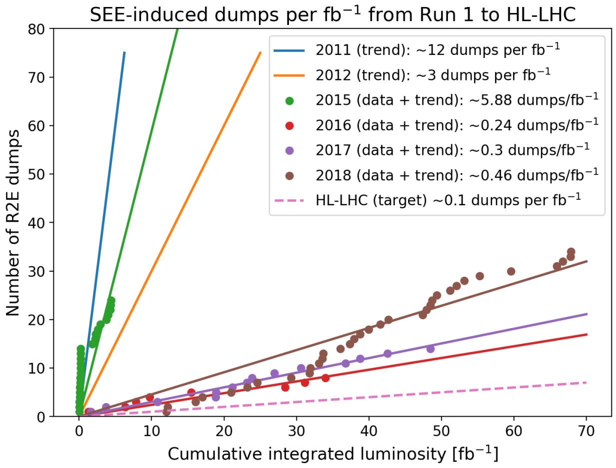

Figure 1: Number of LHC beam dumps induced by R2E failures as a function of the cumulative integrated luminosity in 2011-2012 (Run 1, trend only), 2015-2018 (Run 2, data and trend) and HL-LHC (target).

from 2016 onwards. A similar R2E performance is also targeted for the upcoming LHC Run 3, during which the performance of the LHC is expected to further improve compared to Run 2, both in terms of beam intensity and annual integrated luminosity. In addition, Fig. 1 includes the 0.1 dumps/fb^{-1} target for the HL-LHC upgrade, determined by means of machine availability simulations as described above. To be able to meet this ambitious target, the electronic systems are required to follow a dedicated RHA procedure [6], where the radiation environment is taken into account already in the early phases of the system development.

R2E FAILURE ANALYSIS IN RUN 2

The LHC faults leading to beam dumps in Run 2 are recorded in the CERN Accelerator Fault Tracking (AFT) system [16], where the teams in charge of the LHC operation and the equipment owners report, classify and validate the related information. This work focuses on the faults that are attributed to R2E, as determined by standard criteria such as the correlation with the radiation environment in the equipment position, the impossibility of reproducing the failure in laboratory conditions, or the similarity of the failure signature to those observed during irradiation tests. Table 1 presents the number of R2E events that led to a beam dump in Run 2, previously illustrated in Fig. 1, showing the breakdown of the affected systems for each year of operation. Since the Power Converters (PC) and the Quench Protection System (QPS) represent over 75% of the total R2E-induced beam dumps, with the latter being the main driver of a mild overall increase of R2E-related dumps in 2018, a more detailed analysis is provided for these two systems in the following paragraphs. The third group of failures that contributed largely to the downtime of the LHC is linked to the magnet circuits (MC) in the so-called RR regions. These failures have been observed in the temperature regulators for the current leads used in the magnet powering system, inducing the loss of its cryogenic conditions. In view of the future operations, a radiation tolerant version of the controllers has been developed and the deployment in the RR locations is in progress. The remaining events in Table 1 were attributed to the Radio Frequency (RF) system with 4 failures in 2015, and 3 SEE events in PLCs from the machine interlock system and kicker circuits.

Table 1: Number of radiation to electronics faults by system and the annual integrated luminosity (fb^{-1}) delivered to the ATLAS experiment during the LHC Run 2 (2015-2018)

System	**2015** 4 fb^{-1}	**2016** 40 fb^{-1}	**2017** 50 fb^{-1}	**2018** 65 fb^{-1}	**Total** **R2E**
PC	5	7	10	13	35
QPS	15	0	0	13	28
MC	0	0	3	7	10
RF	4	0	0	0	4
Others	0	1	1	1	3
Total	24	8	14	34	80

Concerning the PC system, a key R2E mitigation measure taken during LS1 (besides the improvement of the shielding in the alcove areas) was the relocation of the most exposed units to areas with lower radiation levels (e.g. from UJ14/16 to UL14/16) or, when possible, to radiation safe areas (from UJ56 to USC55). In terms of electronics design, a radiation tolerant power MOSFET was introduced in the auxiliary power supplies to prevent destructive Single-Event Burnouts (SEBs) observed in Run 1. These actions have successfully improved the reliability of the power converters as only 5 events were observed in the first year of Run 2, as shown in Table 1, and none was a destructive effect [17]. However, in order to achieve the HL-LHC target of 0.1 dumps/fb^{-1}, a new radiation tolerant version of the embedded function generator/controller (FGC), named FGClite, was designed and deployed in the power converters located underneath the magnets in the arcs by the end of 2016 [2]. Fig. 2a provides the distribution of the positions of the PC units whose radiation-induced failures caused beam dumps for each year. No events were observed in the arcs after the consolidation of the FGClite, but there was an increased number of failures in the RRs in 2017 and 2018 which can be linked to the increased integrated luminosity. Therefore, in view of Run 3 operation, the FGClite system was integrated to the PC units located in the RRs during LS2, along with the radiation tolerant versions of the 600A and 4-6-8 kA power converters, all tested against radiation effects at system level in the CHARM facility [18].

The QPS is one of the most complex and important systems in the LHC, as it protects fundamental elements such as the superconducting magnets. During LS1, a new version of the bus-bar splice quench detector board, known as DQQBS board, was designed and installed in the LHC to satisfy the requirements for the Copper Stabilizer Continuity Measure-

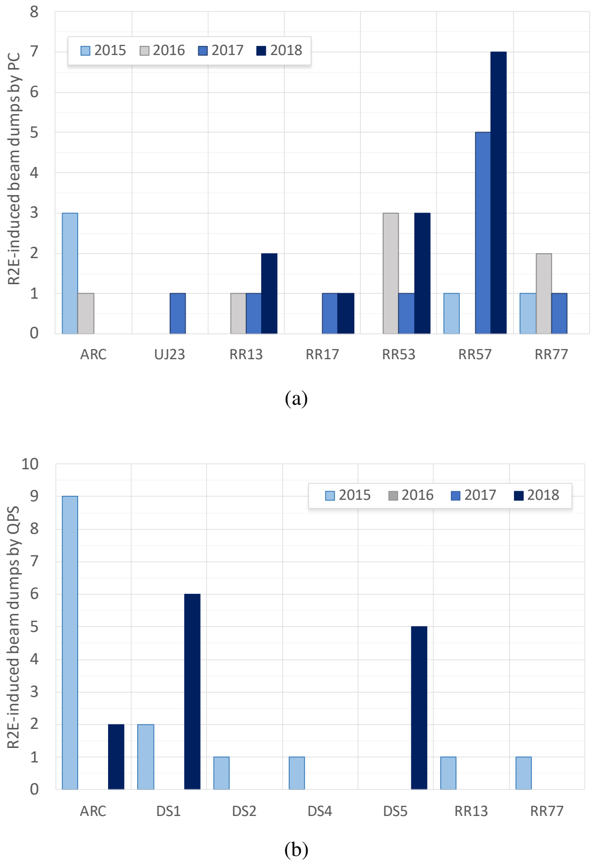

Figure 2: Distribution of R2E-induced LHC beam dumps caused by (a) the PC and (b) QPS systems.

ments (CSCM) campaign [19]. The new DQQBS board was designed specifically for the CSCM campaign and was not qualified to withstand the radiation levels during the LHC physics run. However, since such boards were not replaced by the traditional DQQBS ones before Run 2 to save operational time, many R2E-induced beam dumps were observed in the QPS system in early 2015, as shown in Table 1 and Fig. 2b. An irradiation test campaign at the Paul Scherrer Institute (PSI) demonstrated that the SRAM memory used in the new DQQBS board was indeed highly sensitive to both Single-Event Upset (SEU) and Single-Event Latchup (SEL) [20]. During the Technical Stop 2 (TS2) of 2015 radiation tolerant DQQBS boards were installed, ensuring a substantially smoother operation of the system.

Lastly, a larger number of QPS failures leading to beam dumps was observed in 2018 in the the Dispersion Suppressor (DS) region of IP1 and IP5, due to an increase of annual radiation levels mostly caused by a change in the nominal operational setting of the upstream TCL6 collimator. Fig. 3 shows the annual TID profile below the beam line in 2017 and 2018, as simulated using FLUKA for the different nominal collimator settings in each year, together with the corresponding RadMon TID measurements (in good agreement with the predictions) and showing the positions of the main LHC magnets and QPS racks. This clearly shows that the

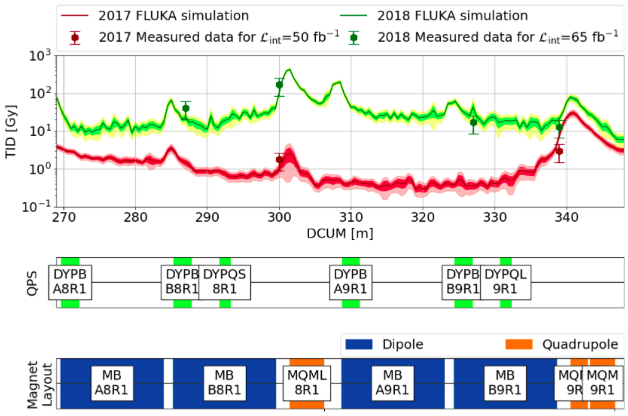

Figure 3: Annual TID vs longitudinal position below the beam line in the LHC tunnel in IP1 in 2017 and 2018, from FLUKA simulations (line) and RadMon measurements (dots).

LHC settings can have an impact on the beam losses and, as a result, on radiation-induced failures of electronic systems.

CONCLUSIONS

This work presents an overview of the R2E performance during the LHC proton-proton operation in Run 2 (2015-2018) focusing on the beam dumps that are attributed to radiation-induced failures, typically SEEs, for different systems and different years of operation. With the exception of 2015, and despite a mild increase in 2018, the number of R2E-induced dumps remained below the threshold of $0.5/\mathrm{fb}^{-1}$, which is a substantial improvement compared to Run 1. The most affected systems are the PCs and the QPS, for which the key system improvements and mitigation measures that took place since LS1 are discussed. In perspective, the R2E project aims at achieving a target of 0.1 dumps/fb^{-1} in the HL-LHC era thanks to further optimisations of the critical electronic systems, to be developed following a dedicated RHA procedure. The goal for Run 3 is to remain below the threshold of 0.5 dumps/fb^{-1}, possibly further improving towards the HL-LHC target. Lastly, as a general note, it is unlikely that systems developed according to the R2E guidelines and quality control result in radiation effects issues in the machine. However, not all systems are subject to such guidelines and quality control, hence the risk of having a significant R2E impact in the machine operation still remains for the following physics runs, mostly through (a) cumulative radiation effects (i.e. wear out part of the bathtub curve) and/or (b) installation of SEE sensitive equipment in radiation areas.

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