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Report

RADIATION LEVELS AT CERN's INJECTORS AND THEIR IMPACT ON ELECTRONIC EQUIPMENT

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Abstract

Electronic devices operating in hostile radiation environments, such as those found close to high-energy particle accelerators, can suffer from different types of radiation induced failures. At CERN, the mixed particle and energy radiation fields present at the Large Hadron Collider (LHC) and its injector chain can give rise to both stochastic and cumulative effects causing radiation induced failures of exposed electronics and materials, thus directly impacting component and system lifetimes, as well as maintenance requirements. With its original focus on the LHC, the Radiation to Electronics (R2E) project has been successfully implementing mitigation actions in order to avoid accelerator downtime due to radiation induced failures on active electronics. In a next step, the emphasis is put on CERN's injector chain, collecting the respective available information about radiation levels, the definition of additional monitoring requirements and a critical analysis of present and future equipment installations. This paper provides a first overview of the work performed and presents two case studies including respective FLUKA Monte-Carlo calculations concerning electronic devices installed or to be installed in the injector chain.

Keywords: CERN PS, CERN PS Booster, CERN SPS, R2E project, Injector Chain, Radiation Environments, Dosimetry, Monte Carlo Calculations.

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Electronic devices operating in hostile radiation environments, such as those found close to high-energy particle accelerators, can suffer from different types of radiation induced failures. At CERN, the mixed particle and energy radiation fields present at the Large Hadron Collider (LHC) and its injector chain can give rise to both stochastic and cumulative effects causing radiation induced failures of exposed electronics and materials, thus directly impacting component and system lifetimes, as well as maintenance requirements. With its original focus on the LHC, the Radiation to Electronics (R2E) project has been successfully implementing mitigation actions in order to avoid accelerator downtime due to radiation induced failures on active electronics. In a next step, the emphasis is put on CERN's injector chain, collecting the respective available information about radiation levels, the definition of additional monitoring requirements and a critical analysis of present and future equipment installations. This paper provides a first overview of the work performed and presents two case studies including respective FLUKA Monte-Carlo calculations concerning electronic devices installed or to be installed in the injector chain

RADIATION TO ELECTRONICS (R2E)

The Radiation to Electronics (R2E) project [1] started in 2007 with the aim of increasing the LHC mean time between failures (MTBF) above 1 week for electronic failures caused by radiation [2], i.e. below 0.5 beam dumps per inverse femtobarn (fb^{-1}) for the nominal LHC peak luminosity: $\sim 10^{34}$ $cm^{-2}s^{-1}$ and a yearly integrated luminosity around 50 fb^{-1}. Due to mitigation actions performed during the last years, the annual LHC operation downtime has been successfully decreasing as depicted in Fig. 1.

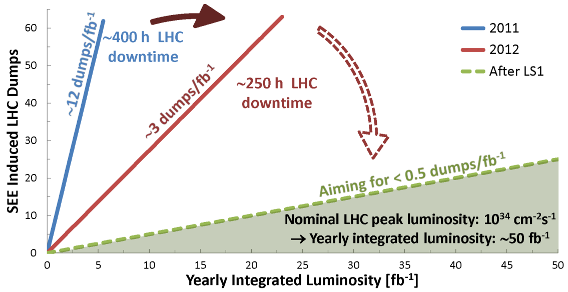

Figure 1: R2E downtime.

After several years, for the LHC detailed information is now available, based on an exhaustive monitoring program combined with extensive set of Monte-Carlo simulations. As from 2012, the emphasis was put on the LHC injector chain since a lower injector downtime should also contribute to the reduction of the LHC downtime. In this context, in a first step an inventory of the existing information on radiation levels and monitoring in the injectors was created. Additional dosimeters were installed in areas of interest and their analysis combined with available Monte Carlo calculations in order to perform first benchmark studies, as further described below.

R2E Activities

The different activities of the R2E project can be summarized as follows:

- Perform radiation tests in a radiation field representative to the one present in the LHC (tunnel & shielded areas), such as at the Paul Scherrer Institute (PSI) and at CERN mixed-field irradiation facilities (H4IRRAD that will be replaced in mid-2014 by the CHARM facility [3] in the PS East Area).
- Carry out Monte Carlo simulations, monitoring and benchmarking studies of radiation levels in critical areas.
- Develop an inventory of existing and future electronic systems to be installed in critical areas.
- Implement mitigation measures: equipment relocation, insertion of additional shielding and hardware R&D of radiation tolerant electronics.

In 2012 and in accordance with the diverse activities assigned to the R2E project, several studies regarding radiation levels in the injectors and their impact on electronics were carried out for different users interested in installing electronic devices in specific locations along the injector chain.

LHC INJECTOR CHAIN & RADIATION LEVELS

With a total tunnel extension of around 45 km, the LHC injector chain consists of a succession of accelerators that increase the energy of particle beams before injecting them to the next accelerator in the chain until the LHC. Besides

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the LHC injection sequence, the accelerators deliver particle beams to a set of dedicated experiments taking place in parallel at CERN.

An extended analysis of the different inputs available for the injection chain was performed to obtain detailed information about the corresponding radiation levels. Maximum exposure levels of the main LHC injectors (PSB, PS and SPS) are summarized in Tab. 1. These values correspond to very specific locations of the accelerators, close to the respective vacuum chambers, where electronics cannot stand.

Acc.	TID [kGy.y^{-1}]	dH*(10)/dt [mSv.h^{-1}] (t_{cool}: 32h)	HEH fluence [h.cm^{-2}.y^{-1}]	1 MeV eq fluence [n.cm^{-2}.y^{-1}]
PSB	70	1.8	10^{13}	10^{14}
PS	600	6.6	10^{14}	10^{15}
SPS	> 1 MGy.y^{-1}	17.2	10^{15}	10^{16}

Table 1: Maximum radiation levels in the injectors attained a few centimeters from the respective beam lines.

For the analysis process it is very important to have a detailed understanding of the radiation source term, thus the respective beam loss fractions and distribution. An example of prompt versus residual dose measurements in the PS accelerator can be seen in Fig. 2. The plot depicted in this figure shows the comparison between the available values for the PS of the annual Total Ionizing Dose[1] (TID) and the ambient dose equivalent rate (dH*(10)/dt) measured after 32 hours of cooling time[2]. Despite few incoherence seen comparing both graphs, in part probably due to the fact that the comparison is based from inputs obtained on different time scales, the plot allows us to clearly identify the different locations where most of beam losses occur around the PS accelerator and where, as far as possible, the presence of electronic equipment should be avoided. Nevertheless, when no other alternatives are available, radiation shielding can be installed to protect electronic devices.

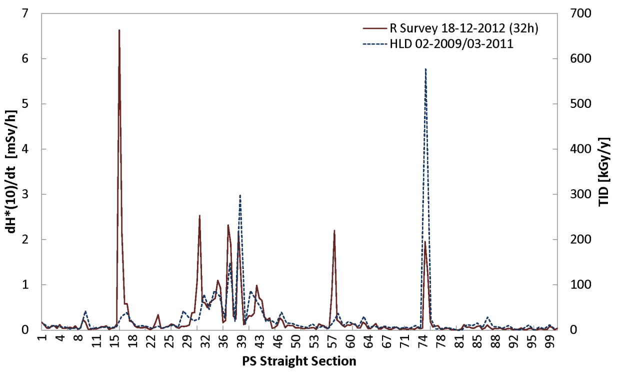

Figure 2: Prompt dose vs. residual dose at CERN-PS.

RADIATION EFFECTS ON ELECTRONICS

This section summarizes briefly the different radiation effects that have to be taken into account when installing electronic devices in the CERN injector chain. Electronic components exposed to mixed radiation fields, as the ones present at CERN, can experience 3 different types of radiation damages [2] [4]:

- Single Event Effects (SEE): due to the energy deposition of a single incident ionizing particle in the semiconductor structure and function of the integrated value of the High Energy Hadron (HEH, E > 20 MeV) fluence.
- Total Ionizing Dose (TID): damage due to cumulative long-term ionization, e.g. the threshold voltage (V_{th}) drift observed in a MOS-structure.
- Displacement damage: caused by accumulation of lattice defects and measured through the integrated 1 MeV (Si) neutron equivalent fluence.

Fig. 3 summarizes the stochastic and cumulative effects of radiation on electronics, as well as the respective devices, quantities and units usually used to quantify them.

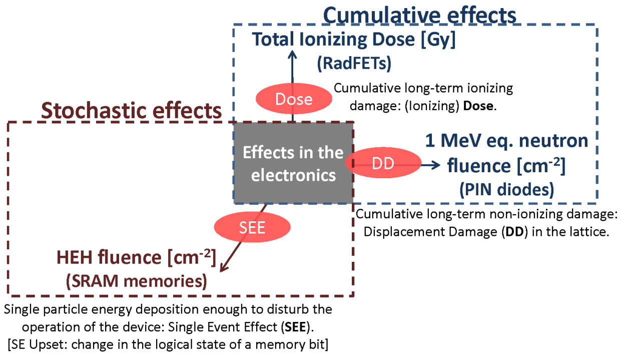

Figure 3: Radiation effects on the electronics.

MONITORING & FLUKA MONTE CARLO SIMULATIONS

Two different levels of inputs are used by the R2E project to assess the different radiation levels in the injection chain. The first one is based on dosimetry/monitoring surveys performed periodically along the injection sequence while the second, is based on FLUKA Monte Carlo simulations [8] [9] either for benchmark studies or to estimate exposure levels for instance in critical areas where no detectors are available.

Listed below are some of the different types of detectors used for radiation monitoring along the injectors. The respective pictures can be seen in Fig. 4.

i Beam Loss Monitors (BLM) in the SPS: 257 Ionization chambers (15 bits ADC, V∼1L, N_2 filled). [TID]

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[1] Measured with Radio-Photo Luminescent glass dosimeters (RPL) located at few centimeters of the PS beam line.

[2] Measured 32h after beam stop (18-12-2012) at 40 cm of distance of the PS vacuum chamber.

ii BLMs in the PSB and PS: ACEM (Aluminum Cathode Electron Multiplier) detectors: enhanced sensitivity photomultiplier to ionizing radiation achieved by replacing the photocathode by an aluminum foil. [TID]

iii Radio-Photo Luminescent (RPL) glass dosimeters: passive solid-state dosimeters (silver activated phosphate glass) used in all the injector chain [5]. [TID]

iv Radiation surveys[3]: Automess AD6 (Geiger Muller) measurements performed in all the injector chain during beam off, usually with a cooling time of 32 hours and 2 months, at a distance to the vacuum chamber around 40 cm [6]. [Ambient dose equivalent rate, dH*(10)/dt]

v Radiation Monitors (RadMons) [7]: online[4] measurements by three different detectors: Radiation-sensing Field-Effect Transistors (RadFETs) [TID], PIN diodes [1-MeV equivalent neutron fluence] and SRAM memories [HEH and thermal neutron fluence]. The deported unit measures the TID and the 1-MeV eq neutron fluence while the main board measures the same quantities as well as the HEH fluence.

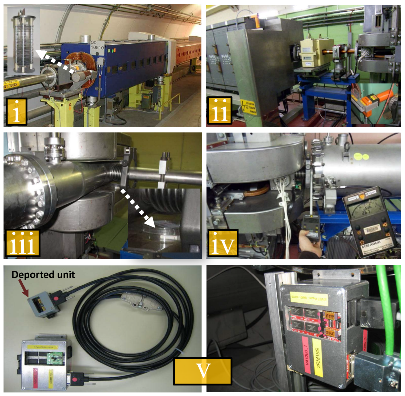

Figure 4: Radiation monitoring in the injectors.

In the next two sections, two different case studies are presented. The first one corresponds to the situation when the location of the electronics cannot be set far away from the correspondent detector that, in its turn, stands usually very close or even lies inside the vacuum chamber of the accelerator. This is the case for the electronics used by Beam Position Monitors (BPM) in the PS complex (case study I) since the signal-to-noise ratio does not allow distances between electronics and the respective detector higher than ∼8m for the Linac 4 and ∼15m for circular machines. The second case corresponds to a benchmark study between a FLUKA simulation performed in sector 08 of the PS and the monitoring survey carried out with additional detectors installed in this region in 2012.

CASE STUDY I - BPM ELECTRONICS AT THE PS COMPLEX

As previously mentioned, new electronics for Beam Position Monitors (SEM Grids & Wire Scanner) are being installed in the PS & Linac 4 during the present first Long Shutdown (LS1). To reach the specifications, the electronics should be as close as possible to the detectors. Therefore, a FLUKA simulation was performed in order to estimate the reduction of the radiation levels that one should expect installing the electronics in the 5 cm gap below the PS floor level at only few meters of distance to the accelerator (see Fig. 5).

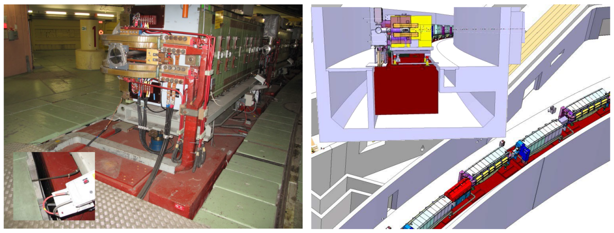

Figure 5: CERN-PS layout.

For this simulation the beam loss distribution along the vacuum chamber was done assuming the same loss profile than the one obtained from the radiation survey performed ∼2 months[5] after the beam stop of December 2012 (considering only the proton run). Inelastic nuclear interactions of primary beam particles with residual gas nuclei in the vacuum chamber were the source of losses used in this simulation [10]. With a proton beam momentum of 14 GeV, the primaries were then forced to interact, along their trajectories in the vacuum chamber, with a given number of residual gas nuclei per volume, which in turn was distributed as a function of the empirical beam loss profile mentioned above.

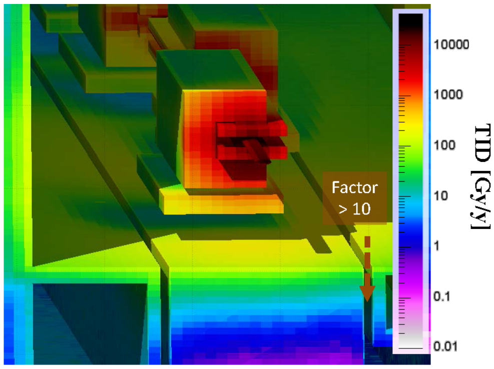

Figure 6: FLUKA simulation for the SEM Grids.

According to the results shown in Fig. 6, one can expect a dose reduction by a factor higher than 10 setting the elec-

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[3] Related to the induced activation of the surroundings but also correlated with beam losses.

[4] Active dosimeters being installed in the injector chain (LS1).

[5] Despite being dependent on the induced activation, the choice of a higher cooling time allows us to be as less as possible sensitive/dependent to the losses occurring during the last operation period of the accelerator.

tronics inside the 5 cm gap below the floor level instead of being placed on the floor. With a lifetime dose limit of the BPM electronics around few hundreds of grays (Gy), it is even possible to estimate the approximate life expectancy of the electronics, depending on the radiation field present at the location chosen for the electronics.

CASE STUDY II - RF ELECTRONICS IN SECTOR 08 (PS)

In the framework of the R2E project, FLUKA Monte Carlo simulations and monitoring surveys are combined to perform benchmark studies then used to predict future radiation levels in the LHC injector chain.

In 2012, additional detectors (RadFETs and Batmons) were installed in sector 08 of the PS accelerator to assess the radiation levels in the surroundings of two racks with electronics for the Radio-Frequency system. Subsequently, the dosimeter readout was combined with Monte Carlo calculations in order to perform a first benchmark study of this critical accelerator region.

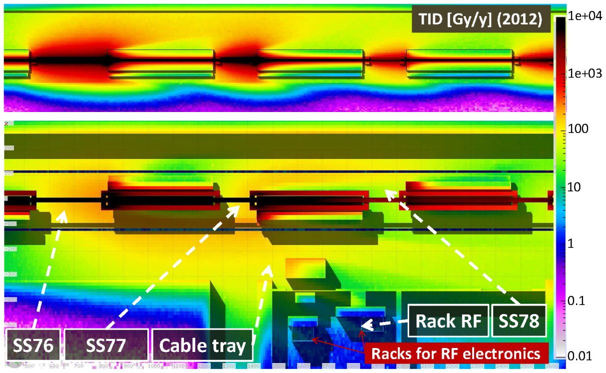

Figure 7: FLUKA simulation vs. dose measurements in 5 different points of sector 08 - PS accelerator. (top to bottom: side and top views)

Location	TID [Gy.y^{-1}]		Ratio
	FLUKA	RadFET	
SS76	553	408	1.4
SS77	2217	2651	0.8
SS78	951	466	2.0
Cable tray	137	91	1.5
Rack RF	3.1	5	0.6

Table 2: FLUKA simulation vs. dose measurements.

According to the results shown in Fig. 7 and Tab. 2, a very good agreement was found between simulation and measurements. All the ratios between FLUKA calculation and the performed monitoring survey were found to be within a range from 0.6 to 2.0. As described in the previous section, inelastic beam-residual gas interactions were the source of losses along the vacuum chamber. The beam loss profile was done according to the radiation survey measured in February 2012. Moreover, a factor of normalization was applied to the FLUKA results, multiplying the FLUKA output by an estimation of the total beam losses in the PS accelerator due to the Continuous Transfer (CT) extraction that is the most contributing process to the overall ring activation[6] [11] (~8% × 5.4x10^{19} protons CT extracted in 2012).

The underestimation of the simulation for the RF rack location may be easily explained by an iron shielding installed mid-2012 directly in front of the rack. The measurements from the detector located close to this rack were collected before setting up the iron shielding, while the results from the simulation were obtained including the shield in the geometry. Finally, the following assumptions, that had to be taken for beam loss distribution, monitors and layout contributed to the overall uncertainties:

- The beam loss distribution profile used is based on residual dose surveys, hence dependent on induced activation.
- Difficulties were found in establishing the exact location of the detectors installed in sector 08 (problematic when close to strong gradients has the ones observed close to the vacuum chamber).
- Not all the details of the complex geometry of some straight sections were included in the simulation.

CONCLUSION

The R2E project has been working during the last years to avoid electronics failures caused by radiation in the LHC. Since 2012, a special attention was paid to the LHC Injector Chain with the intent of further reducing the global downtime, due to radiation induced failures on electronics, to the lower possible level. In this paper, an overview of the existing information on radiation levels and monitoring in the LHC injectors was shown. Additional dosimeters were installed in areas of interest and their analysis combined with available Monte Carlo calculations in order to perform a first set of successful benchmark studies here presented. A second case study carried out for the BPM electronics being installed at only few meters of the PS accelerator was also described.

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