Chapter 10

The “Environmental” Challenges: Impact of Radiation on Machine Components

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The High Luminosity LHC upgrade poses demanding requirements in terms of energy deposition, in particular around the high luminosity experiments where the Inner Triplet elements and the separation dipole will be exposed to unprecedented levels of radiation, challenging their reliability and lifetime. Dedicated Monte Carlo studies have been conducted in order to characterize the debris-machine interaction and define a suitable shielding.

Moreover, also the areas adjacent to the LHC tunnel, where the installation of electronics equipment is envisaged, will be significantly impacted. In this context, cumulative damage (Total Ionizing Dose and/or Non-Ionizing Energy Loss) and stochastic effects have to be taken into account in an appropriate Radiation Hardness Assurance strategy, including the specification of the radiation environment, required test and qualification procedures, and corresponding radiation monitoring.

1. Collision Debris

Proton–proton inelastic collisions taking place in the LHC inside its four big detectors generate a large number of secondary particles, on average about 100 (120) per collision with 3.5 (7) TeV beams, but with very substantial fluctuations over different events. Moving from the interaction point (IP), this multiform population evolves, even before touching the surrounding material, because of the decay of unstable particles (in particular neutral pions decaying into photon pairs). Figure 1 illustrates the composition of the debris at 5 mm from the point of a 14 TeV center-of-mass collision, featuring a $\sim 30\%$ increase in number of particles and a clear prevalence of photons (almost one half) and charged pions ($\sim 35\%$).

Most of these particles are intercepted by the detector and release their energy within the experimental cavern. However, the most energetic ones, emitted at small angles with respect to the beam direction, travel farther in the vacuum and reach the accelerator elements, causing a significant impact on the magnets along the

Fig. 1. Number of debris particles per collision at 5 mm from the interaction point (black histogram) and at the exit of each TAS aperture (red).

Insertion Regions (IRs), in particular the final focus quadrupoles and the separation dipole. Figure 1 shows also the breakdown of the debris component going through the (future) 60 mm aperture of the TAS (Target Absorber Secondaries) absorber, a protection element consisting of a copper core 1.8 m long located at 20 m from the IP and representing the interface between the detector and the accelerator. The TAS absorbers are installed only at each side of the high-luminosity IRs, namely IR1 and IR5, hosting the ATLAS and CMS detectors respectively, since their protection role, in fact limited to the first quadrupole, is not needed for luminosities up to $0.2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ [1].

Despite the fact that the number of particles per collision leaving the TAS aperture is more that one order of magnitude lower than the total number of debris particles, they carry about 80% of the total energy, 40% per each side. At the nominal HL-LHC luminosity ($5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$), this represents about 3800 W per side that is inevitably impacting the LHC elements and is dissipated in the machine, in the nearby equipment (e.g. electronics, racks, ...) and in the tunnels walls.

It is fundamental to study how these particles are lost in order to implement all the necessary protections to shield the most sensitive parts of the LHC magnets and the most delicate components. For these purposes, Monte Carlo simulations of the particle interaction with matter play an essential role, relying on a sophisticated implementation of physics models and an accurate 3D-description of the region of interest.

A specific problem is represented by the electronics sensitivity to radiation. The above described particle debris emerging from the IP (together with an addi-

tional loss contribution from beam–gas interactions) will impact equipment being present in the areas adjacent to the LHC tunnel (UJs, RRs). Respectively installed (present or future) control systems are either fully commercial or based on so-called COTS (Commercial-Off-The-Shelf) components, both possibly affected by radiation. This includes the immediate risk of so-called Single Event Effects (SEE) and a possible direct impact on beam operation, as well as in the long-term, also cumulative dose effects (impacting the component/system lifetime) which additionally have to be considered.

For the tunnel equipment in the existing LHC, certain radiation tolerant design criteria were already taken into account prior construction. However, most of the equipment placed in adjacent and partly shielded areas was not conceived nor tested for their current radiation environment. Therefore, given the large amount of electronics being installed in these areas, during the past years a CERN wide project called R2E (Radiation To Electronics) [2] 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. The respective mitigation process included a detailed analysis of involved radiation fields, intensities and related Monte Carlo calculations; radiation monitoring and benchmarking; the behaviour of commercial equipment/systems and their use in the LHC radiation fields; as well as radiation tests with dedicated test areas and facilities [2, 3].

In parallel, radiation induced failures were analyzed in detail in order to confirm early predictions of failure rates, as well as to study the effectiveness of implemented mitigation measures. Figure 2 shows the actual number of SEE failures measured during 2011 and 2012 operation, the achieved improvement (please note that the failure rate measured during 2011 already included mitigation measures implemented during 2009 and 2010), as well as the goal for operation after LS1 and during HL-LHC.

Aiming for annual luminosities of up to 300 fb^{-1} , it is clear that machine availability has to be maximized during HL-LHC in order to successfully achieve the physics goal. This implies that existing electronic control systems are either installed in fully safe areas, sufficiently protected by shielding or adequately radiation tolerant. The last implies existing equipment, but also any future equipment to be possibly installed in R2E critical areas to be conceived in a specific way.

In the following, we will give details about the geometrical IR model developed for Monte Carlo simulation studies (Section 2), then we will describe how and where the different debris particle species are captured (Section 3), and in Section 4 we will provide estimates of the energy deposition. Finally, Section 5 summarizes the overall R2E requirements for HL-LHC and provides a first overview of design criteria and radiation levels expected in areas of concern.

Fig. 2. LHC beam dumps due to single-event effects against beam luminosity. Dots (2011 and 2012) refer to measurements, whereas lines show annual averages for both, past and future operation.

2. Beamline Model

Figure 3 shows the HL-LHC layout from the TAS to the separation dipole D1, as it is implemented in FLUKA [4–7]. The final focus quadrupoles are arranged in a triplet configuration, Q1-Q2-Q3, that is DFD (defocusing-focusing-defocusing) in the vertical plane for the outgoing beam. A corrector package (CP), that includes a skew quadrupole and eight high order correctors (from sextupole to dodecapole, normal and skew), is placed between the triplet and the D1. Two different technologies are in place to build the magnet coils: the novel Nb₃Sn for the final focus quadrupoles and the well established Nb-Ti for the corrector magnets and the D1.

To guarantee a sufficient protection of these magnets from radiation, an octagonal stainless steel beam screen equipped with 6 mm tungsten absorbers on the mid-planes is placed inside the cold bore all along the triplet, the CP and the D1, except in Q1 where the tungsten thickness is increased to 16 mm, compatible with the aperture requirements. The two beam screen versions are shown in the top insets of Fig. 3. The absorbers attached externally to the beam screen have a negligible thermal contact with the cold mass. Therefore, from the point of view of energy deposition, the beam screen function is two-fold:

- (i) it shields the coils,
- (ii) it removes a sizable part of the heat load from the 1.9 K cooling system.

Fig. 3. Prospective view of the HL-LHC geometry from TAS to separation dipole D1 as implemented in FLUKA. Bottom inset: beam line aperture. Top inset: magnet cross-section (one quadrant) showing the beam screen with 16 mm tungsten absorbers in the Q1 (a) and with 6 mm absorbers in the normal dodecapole (b). Each color corresponds to a different material.

The present HL-LHC layout foresees six cryostats: four for the triplet quadrupoles (Q1, Q2A, Q2B and Q3), one for the CP and the last one for the D1. Over the interconnects, the distance between the magnets is 1.5–1.7 m. This represents a vulnerable point in the shielding, since an interruption of the beam screen is necessary therein. As a reasonable baseline, we assume here 500 mm interruption of the beam screen in the middle of the interconnects.

3. Radiation Capture

The particles exiting from the TAS and entering the LHC vacuum pipe can be divided in two categories:

- neutrally charged particles (mainly photons, with a smaller contribution of neutrons) that travel along a straight line. They are not affected by any field and interact as soon as they hit an obstacle along their trajectory,

- positively and negatively charged particles (mainly pions and protons) that are steered and eventually captured by the magnetic fields, as their magnetic rigidity is lower than the one of the circulating protons. They first encounter the strong magnetic fields of the final focus quadrupoles.

The evolution of the differential fluences^a of the main particle species is shown in Fig. 4 at different longitudinal positions along the triplet.

The proton spectrum is characterized by the peak at the 7 TeV beam energy. This is due to single diffractive events^b at the IP, imparting to the beam protons a small angular kick and energy loss, and consequently making them to be lost farther away in the Dispersion Suppressor or cleaned out by the collimation system. Lower momentum protons in the 2–3 TeV range start to be intercepted from Q3 onwards.

Fig. 4. Energy spectra of different particle species in the vacuum pipe at the positions along the triplet indicated by the arrows in the bottom inset of Fig. 3.

^aTrack-length volume density.

^bProtons that have undergone an elastic interaction are not simulated here. They are cleaned by the collimation system.

Negatively and positively charged pions have a softer spectrum and most of them are immediately captured by the magnetic field of the first quadrupole. The increase in the lower part of the spectrum (less than few ten GeV) comes from pion production by interactions in the upstream part of the triplet.

Neutral particles, not affected by the magnetic field, are captured only when they run into a restriction of aperture. Few hundred GeV photons start to be intercepted inside the Q2B, where the shadow provided by the TAS ends. Neutrons are concentrated in the TeV region and, due to their relatively small angle, proceed farther in the machine. To stop these neutral particles, a TAN (Target Absorber Neutral) absorber is placed in front of the recombination dipole D2, at the beginning of the Matching Section.

4. Energy Deposition

For steady state losses, like the ones due to the collision debris, we can distinguish two scale sizes for the energy deposition^c:

- total power deposited on an assemble of elements that must be included in the budget of heat load to be evacuated,
- local (order of cm^3) energy deposition on sensitive parts of a magnet, namely the superconducting coils.

The first represents a crucial parameter for the design of the cryogenic system. The latter has to be evaluated in order to assure not to surpass the margin for the magnet quench, as well as to reach the desired lifetime (over a long term, radiation can deteriorate the cable electric properties and eventually damage their mechanical structure). For the purposes of quench risk evaluation, the reference quantity is the peak power density averaged over the entire radial dimension of the inner coil layer, that is the most exposed to the radiation field. As for radiation damage, one has to calculate the peak dose on a finer radial binning (~ 3 mm), since relevant material degradation can be localized with heat diffusion playing no role in this respect. Along the other dimensions, typical resolutions are ~ 10 cm longitudinally and 2-degree azimuthally.

Like the present machine, two collision schemes are foreseen at the high luminosity IRs: the protons are led to the interaction point with $295 \mu\text{rad}$ half-crossing angle either on the vertical or on the horizontal plane. This implies that the debris leaving the IP flies preferentially on the respective plane toward the IR elements. The combination of vertical crossing with the above mentioned optics configu-

^cDefinitely we are not referring to microscopic processes, that are well below the minimum millimeter scale considered throughout this chapter.

Fig. 5. Dose distribution after 3000 fb^{-1} integrated luminosity over a transverse section of the Q2A (left) and Q3 (right) coils. Vertical crossing angle pointing upward has been assumed at the IP. Geometry details (beam screen, cold bore, collar) are also shown with no respective dose estimation.

ration of the triplet (DFD) represents the worse case from the energy deposition point of view, since vertically scattered particles are more efficiently caught by the defocusing Q1 field. Figure 5 shows a couple of characteristic dose distributions over a transverse section of Q2 (IP side) and Q3 (non IP side). The energy is mainly deposited along the magnet mid-planes (particularly on the vertical one), with strong radial and azimuthal gradients. It is worth to note the inversion of the peak position from top (in Q2) to bottom (in Q3) because of the Q2 over-focusing effect while particles travel along the triplet.

Figure 6 (red curve) shows the obtained peak dose longitudinal profile. The pattern features a local maximum at the end of Q1/beginning of Q2A driven by the Q1 defocusing field. The other maxima at the IP side of the Q2B, Q3 and CP are due to the interruption of the beam screen over the interconnects. As mentioned in Section 2, a 500 mm gap has been assumed. Reducing this gap would lower these peaks, although a minimum interruption of few ten cm cannot be avoided, because it is necessary to install the beam tube bellow between two consecutive cryostats.

In the considered configuration one does not exceed 40 MGy after 3000 fb^{-1} (at the beginning of the CP). At the nominal HL-LHC luminosity, the peak power density stays within 2 mW/cm^3 all along the final focus quadrupoles and the separation dipole. This value is safely below the expected quench limit, that is assumed to be 40 (12) mW/cm^3 for Nb_3Sn (Nb-Ti) coils [8, 9].

Figure 6 shows also the case where 6 mm absorbers (instead of 16 mm) are used in the Q1 too, as for the rest of the magnet string. The maximum dose on Q1 becomes ~ 5 times higher and, moreover, there is no shadow effect on the downstream element, where a peak dose of $\sim 50 \text{ MGy}$ is reached.

Fig. 6. Longitudinal profile of the peak dose at 3000 fb^{-1} along the final focus quadrupoles, the CP and the separation dipole in case of the baseline beam screen configuration (triangles) with 16 mm tungsten absorbers in Q1 and 6 mm in downstream elements. The case with 6 mm tungsten absorbers in Q1 is also shown (boxes). Vertical crossing at the IP has been considered. Horizontal lines indicate the total magnetic lengths of the elements hosted inside the same cryostat.

The total heat load deposited is about 1300 W at the nominal HL-LHC luminosity. This load is removed by two different cooling systems (one for the magnet cold masses and the other one for the beam screen), each of them in charge to evacuate about one half of it.

5. Radiation to Electronics

Radiation damage to electronics is often considered with space applications. However, it is important to note that the radiation environment encountered at the LHC, the high number of electronic systems and components partly exposed to radiation, as well as the actual impact of radiation induced failures strongly differ from the context of 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 in the relevant LHC areas 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 and benchmarked in detail for radiation damage issues at the LHC [10, 11]. The observed radiation is due to particles generated by proton–proton (or ion–ion)

collisions in the LHC experimental areas (as previously discussed in this chapter), 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 original loss point, as well as on the amount (if any) of installed shielding material. In this environment, 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 Ionizing Dose (TID) and the SEEs.

The first two are of cumulative nature and are measured through TID and non-ionizing energy deposition (NIEL^d, generally quantified through accumulated 1-MeV neutron equivalent fluence), where the steady accumulation of defects cause measurable effects which can ultimately lead to device failure. As for 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 context of HL-LHC, several tunnel areas close to the LHC tunnel, and partly not sufficiently shielded, are or are supposed to be 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 also suffer from accumulated damage in the long-term [12].

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 [13] dedicated to the analysis of radiation levels possibly impacting installed electronic equipment. Table 1 summarizes the level of accumulated High Energy Hadron (HEH) fluence measured during 2012 for the most critical LHC areas where electronic equipment is installed and which are relevant for the HL-LHC project, together with the expected radiation levels for nominal LHC performance (50 fb⁻¹y⁻¹). 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 [14]. The results obtained during 2012 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 [15]. In a first approximation, the measured radiation levels can also be used

^dNon-Ionizing Energy Losses.

Table 1. Predicted and measured annual HEH fluence in critical shielded areas for a cumulated ATLAS/CMS luminosity of 15 fb^{-1} during 2012 operation, extrapolated to expected nominal and HL-LHC performance ($50 \text{ fb}^{-1} \text{ y}^{-1}$ for nominal and $300 \text{ fb}^{-1} \text{ y}^{-1}$ for HL-LHC performance, except for P8 where 2012 can already be considered as almost nominal and HL-LHC refers to a 5-fold increase). For HL-LHC an estimate for corresponding annual TID levels is also given.

LHC Area	Prediction (HEH/cm ²)	Measured (HEH/cm ²)	Nominal (HEH/cm ²)	HL-LHC (HEH/cm ²)	HL-LHC (Dose/Gy)
UJ14/16	1.4×10^8	1.6×10^8	5×10^8	3×10^9	6
RR13/17	2.0×10^8	2.5×10^8	8×10^8	5×10^9	10
UJ56	1.6×10^8	1.5×10^8	5×10^8	3×10^9	6
RR53/57	2.0×10^8	2.5×10^8	8×10^8	5×10^9	10
UJ76	2.1×10^7	6.0×10^7	2×10^8	1×10^9	2
RR73/77	2.9×10^7	5.0×10^7	2×10^8	1×10^9	2
UX85B	4.3×10^8	3.5×10^8	4×10^8	2×10^9	4
US85	1.3×10^8	8.8×10^7	9×10^7	4×10^8	1

to extrapolate towards HL-LHC by purely scaling with annual luminosity (see last two columns of Table 1), however keeping in mind that operational and layout parameters (beam energy, crossing angle, TAN design, absorbers, etc.) can have a not negligible impact on the final values, especially for the RRs close to the Matching Section. The resulting values clearly indicate that any equipment installed in the LHC tunnel will not only suffer SEE failures, but will also be heavily impacted by the TID effects thus limiting the respective lifetime.

To provide one specific example, based on available FLUKA calculations for the present LHC at nominal parameters and applying a simplified scaling with only cumulative luminosity, Fig. 7 shows the distribution of high-energy hadrons for LHC-P1 including the adjacent UJ, UL and RR areas (please note that the radiation levels in the UJ refer to the layout with only limited shielding, already improved along the R2E mitigation measures prior and during LS1). Any control equipment (commercial or based on commercial components) to be installed in these areas, clearly has to be proven to be sufficiently radiation tolerant. For comparison, as mentioned earlier, during the last years of operation we already had there a number of radiation induced failures on commercial equipment for radiation levels corresponding to $10^8\text{--}10^9 \text{ cm}^{-2} \text{ y}^{-1}$ (which is about 1000–10000 more than what one would get at surface due to cosmic radiation).

For the current R2E project, this allowed us deducing an acceptable limit of $10^7 \text{ cm}^{-2} \text{ y}^{-1}$ annual radiation level, leading to the definition of so-called protected areas (in terms of overall risk of radiation induced failures). Therefore, for HL-LHC any installation of non-tested (and not specifically designed) electronic equipment in the UJs, part of the ULs and RRs is clearly to be avoided or subject

Fig. 7. Annual HEH fluence expected at LHC-P1 (with the present machine layout at nominal parameters) scaled to the HL-LHC annual luminosity of 300 fb^{-1} . The radiation levels in the UJ refer to the layout with only limited shielding, already improved along the R2E mitigation measures prior and during LS1.

to a detailed analysis process prior an exceptional installation can be granted under the following conditions:

- the equipment is not linked to any safety system,
- the failure of the equipment will not lead to a beam dump,
- the failure of the equipment does not require quick access (thus lead to down-time),
- there is no any other operational impact (loss of important data, etc.).

In all other cases requiring installation in critical areas, a respective radiation tolerant electronics development must be considered from the very early stage onward. Related expertise exists at CERN within the equipment groups, the R2E project and a dedicated working group [16].

In a first approximation and limiting the total number of exposed systems, the above mentioned annual radiation design level of $10^7 \text{ cm}^{-2}\text{y}^{-1}$ can also be chosen as acceptable aiming to achieve an overall performance of less than one radiation induced failure per one or two weeks of HL-LHC operation.

For operation critical equipment, the HL-LHC project foresees respective radiation tolerant developments already at an early stage of the design phase, taking into account that:

- for the LHC-tunnel: in addition to SEEs also cumulative damage has to be considered for both existing and future equipment,
- for partly shielded areas (UJs, RRs, ULs): cumulative damage should be carefully analyzed but can most likely be mitigated by preventive maintenance (detailed monitoring mandatory), but radiation tolerant design is mandatory in order to limit SEE induced failures,
- the knowledge of radiation induced failures and radiation tolerant development within the equipment groups and in the overall A&T sector has to be maintained and further strengthened,
- the access and availability of radiation test facilities (CERN internal and external) has to be ensured providing efficient support to equipment groups,
- building on the experience obtained during the LHC R2E project and in view of the HL-LHC time-scale, it is important that the expertise of and support to radiation tolerant developments (currently available through the Radiation Working Group [16]) is maintained and ensured from the early project stage onwards.

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