Scope definition of HL-LHC radiation level specification document (v2)

Giuseppe Lerner, Rubén García Alía

The central purpose of the **HL-LHC radiation level specification document** (hereafter referred to as "document" or "specification document") is that of specifying the radiation levels in the various LHC locations relevant to the operation of equipment based on commercial electronics. Therefore, it should serve as definition of the radiation conditions the different systems need to be qualified against according to their location in the machine (or, alternatively, as a criterion to decide where to place/relocate the equipment, considering the rest of constraints and trade-offs).

In addition to the actual radiation level specification values as a function of location, the document will discuss the different sources and considerations applied to retrieve the expected values. In general, the input for the radiation level estimation will be a combination of (i) radiation level measurements during Run 2 (2015-2018); (ii) dedicated FLUKA simulations and (iii) the evolution of different operational quantities expected for HL-LHC. The document will also highlight locations and radiation sources for which special attention will need to be devoted during Run 3 (2021-2023) in order to endorse the predicted values.

In terms of geographical resolution, the areas of interest for electronics will be divided into tunnel and alcoves. For the tunnel and unless specified otherwise, the spatial resolution will be defined by the half-cell, i.e. the three dipole plus quadrupole structure of an extension of 54 m and repeated 68 times per sector, with the full LHC machine having 8 sectors. In the case of the alcoves adjacent to the LHC machine, the spatial resolution will be defined by the alcove name (i.e. typically a set of letters and numbers, as further detailed in the document). Therefore, the reported values will typically correspond to worst-case levels within the half-cell or alcove for radiation lifetime related quantities, and averages over the typical electronic rack locations in the case of Single Event Effect (SEE) related quantities.

Indeed, the radiation levels will be described through four main quantities. Two of them (Total Ionizing Dose and Displacement Damage) refer to cumulative radiation effects, and will therefore be quoted as expected integral values throughout the full HL-LHC operation (2025-2035) and referring to the ultimate operation scenario of 4000 fb^{-1} integrated luminosity production. The typical range of interest for TID (1-MeV neutron equivalent) levels over the full HL-LHC operation period will be 1 Gy – 10 kGy (10^{10}-10^{14} n_{eq}/cm^2), provided that below these levels, commercial electronics can be considered insensitive to cumulative radiation effects, and above it, electronic systems need to heavily rely on radiation hardened by design components. However, it is to be noted that the analysis of locations in the accelerator with TID levels in the 10 kGy – 10 MGy range is still very relevant for possible material degradation (especially in the case of polymers) and are treated outside the scope of the document.

The remaining two quantities of interest are the high-energy hadron and thermal neutron fluences, typically referred to annual levels (considering a nominal integrated annual luminosity of 250 fb^{-1}/yr), and linked in this case to the induction of Single Event Effects (SEEs). For the latter, determining a lower limit to the range relevant to possible radiation issues is more challenging, as the latter will depend on aspects such as the number of components and units a system is composed of, as well as how critical it is for the operation of the accelerator. Therefore, as a general rule, the limit for considering an area as radiation-safe for electronics will be that of having a HEH annual fluence level below $3 \cdot 10^6$ HEH/cm^2/yr. The choice of this limit is based on the fact that:

(i) It would correspond to one failure per system and year for a system with 100 units, each having a unit level SEE cross section of $3 \cdot 10^{-9}$ cm^2/unit, which can be considered as an approximate worst case;

(ii) It corresponds to a HEH fluence level roughly 30 times larger than that present at sea level due to cosmic neutrons (~10^5 HEH/cm^2/yr).

Moreover, thermal neutrons are also capable of inducing SEEs. However, provided that (i) they are only capable of inducing soft (i.e. non-destructive) errors, (ii) their associated soft error cross sections for a given component are typically at least an order of magnitude lower than those of high-energy hadrons and (iii) the fact that, if needed and as opposed to high-energy hadrons, equipment can be locally shielded against thermals with a relatively thin (several mm) layer of flexible material such as boron carbide, the lower limit for a radiation safe area with respect to thermals is considered as $3 \cdot 10^7$ n_{th}/cm^2/yr.

Thus, areas with radiation levels below $3 \cdot 10^6$ HEH/cm^2/yr and $3 \cdot 10^7$ n_{eq}/cm^2/yr (note that both conditions need to be satisfied independently) can be considered as radiation safe. In a mixed-field environment, satisfying the conditions above will also guarantee that levels are low enough with regards to possible radiation lifetime effects. Therefore, in such safe locations, electronic equipment can be designed (or purchased as a commercial module) disregarding possible radiation effects on electronics. On the contrary, equipment to be installed in areas with radiation levels above those defined above, will need to undergo the associated Radiation Hardness Assurance (RHA) procedure, which is beyond the scope of the specification document.

Indeed, the HEH and thermal neutron limits established above cannot entirely rule out encountering radiation related issues with electronic systems. However, they are considered as a reasonable (even conservative) limit to establish an adequate trade-off between the investment in designing and qualifying radiation tolerant electronics systems based on COTS and the return in terms of risk reduction related to machine unavailability.

Though strongly dependent on the related system complexity and radiation tolerance requirements, the full cycle of radiation tolerant design and qualification of a COTS based system will last in the order of 4 years. Therefore, provided the radiation level constraints needed to be considered at a very early stage of the system conception, the specification provided by this document is mainly targeted and suited for radiation tolerant system projects to start during 2020 and 2021, and targeting their deployment during LS3 (2024-25) for Run 4 operation.

Moreover, some information about the particle energy spectra will be provided, however a more complete analysis of the impact of the mixed-field hadron composition and energy dependence on aspects such as the intermediate energy (0.2-20 MeV) neutron and GeV-energy hadron influence the SEE rate beyond the HEH approximation is beyond the scope of this specification document.

Finally, it is to be noted that, if applied, safety margins on the radiation levels will be included in an explicit manner. In other words, the expected (i.e. most likely) values are quoted when first derived, and the applied margin is (if applicable) explicitly added and justified. Of course, the related margin will depend on the estimated associated uncertainty related to that specific radiation source and propagation, however as a general rule, the approach is to avoid being over-conservative, thus also avoiding over-design and over-specification with regards to the radiation tolerance. In addition, in some cases specified values might refer to upper limits as opposed to expected values. Such cases will also be pointed out explicitly. However, it is to be noted that such margins and limits only apply to the radiation levels themselves, and will not include any consideration related to the component response itself, such as part-to-part variability or Enhanced Low Dose Rate Sensitivity (ELDRS), which would therefore need to be considered and applied separately.

With regards to the radiation level specification document timeline and format, the objective is to have a first complete draft version by the end of November 2019, to be submitted to review by the respective stakeholders plus at least an external expert in a dedicated one-day review session in mid-December 2019. The objective would then be to publish the document as a ATS note during the first months of 2020.