



An overview of the radiation environment at the LHC in light of R2E irradiation test activities

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Summary

The main objective of this report is to present a brief overview of the radiation environment that can be expected in areas where electronics are installed in the LHC. This covers particle energy spectra in addition to nominal integrated values of the High Energy Hadron (HEH) fluence, relevant for Single Event Effects (SEEs), Total Ionizing Dose (TID), and the 1 MeV (Si) neutron equivalent, relevant for displacement damage. The risk of thermal neutrons is considered by introducing the risk factor R_{th} . This report is presented as part of the R2E project and should create a foundation from which appropriate irradiation test criteria can be evaluated and determined.

1 Introduction

The radiation environment encountered at the Large Hadron Collider (LHC) at CERN will differ strongly from the environment relevant for space applications. The mixed field expected at the LHC as well as its experiments is composed of charged and neutral hadrons (protons, pions, kaons and neutrons), photons, electrons and muons. This complex field, which has been extensively simulated by the FLUKA Monte Carlo codes [1, 2, 3, 4], 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 the 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 the amount of (if any) 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, Single Event Effects (SEEs) and damage from the Total Ionising Dose (TID).

At the LHC various areas are partly equipped with commercial electronic devices not specifically designed to be radiation tolerant. In order to ensure safe and acceptable operation of this equipment and potential new development, it is therefore important to determine the expected radiation levels in these areas. This document will present particle energy spectra and nominal integrated values of the radiation levels at the LHC. The main objective is to create a

foundation from which appropriate irradiation test criteria can be evaluated and determined. It is important to point out that failures in the equipment installed at LHC can be tolerated below a given rate. This may adjust the emphasis more towards the need to determine the expected failure rate rather than a fail/no fail criterion.

2 Useful definitions

Throughout this report a few expressions or abbreviations are repeatedly used and are they therefore defined in table 1. High energy hadrons are defined as all hadrons (p, n, $\pi\pm$, $K\pm$)

Table 1: Definitions.

High Energy Hadrons	HEH	p, n, $\pi\pm$, $K\pm$ of $E_{kin} \geq 20$ MeV
Thermal neutrons	Th.n.	Neutrons of $E_{kin} \leq 0.5$ eV.
Thermal neutron risk factor	R_{Th}	Ratio of the thermal neutron fluence to the high energy hadron fluence, see Eq. 1

with a kinetic energy above 20 MeV. For the purpose of irradiation test criteria hadrons above 20 MeV (high energy hadrons) are considered to be equally effective in inducing SEUs due to their approximately similar nuclear interaction cross section. The cut-off from 20 MeV and below is justified by that rapid decrease in the charged hadron nuclear interaction cross section from about 20 MeV and below. Also, as the energy decreases the charged hadrons will no longer be able to penetrate the device package to reach the sensitive area. Below 20 MeV the contribution from charged hadrons is therefore considered to be insignificant. This threshold does on the other hand not apply to neutrons which may contribute down to the nuclear interaction threshold of the respective materials. However, their effectiveness in inducing for example SEU will decrease with energy. They can therefore not be counted as equal to a neutron at higher energies. For simplicity these neutrons are therefore not included in the definition of high energy hadrons for this report. This approximation holds because, for most cases, their contribution to the total high energy hadron fluence is in the order of 10-30%, a contribution that will not change any conclusions with respect setting the requirements for irradiation testing. Further details concerning the contribution from these neutrons can be found in [5].

Due to the various shielding configurations (e.g. concrete and/or iron walls) separating the LHC alcoves from the beam line and tunnel, a significant thermal neutron fluence is expected. For the majority of devices installed in the alcoves, the sensitivity to thermal neutrons is unknown. In [6] it is shown how the thermal neutron SEU cross sections can vary orders of magnitude between different types of devices. A so-called ‘risk-factor’, R_{Th} , giving the ratio of the thermal neutron fluence to the high-energy hadron fluence, has therefore been introduced in order to identify thermal neutron critical areas. Thermal neutrons are here defined as neutrons with a kinetic energy below or equal to 0.5 eV

$$R_{Th} = \frac{\Phi_{Th.n.}}{\Phi_{HEH}} \quad (1)$$

3 The radiation environment at LHC

Depending on the location of the electronics in the LHC, the composition and levels of the radiation fields, and consequently the main radiation effects of concern, can be very different.

The majority of electronic equipment at the LHC is installed in alcoves separated from the beam line by various shielding configurations, e.g. concrete and iron blocks/walls. These alcoves are distributed around the LHC in the various insertion regions. In addition some equipment is also installed directly below or in the vicinity of the beam line inside the LHC tunnel itself. When evaluating the radiation field in light of irradiation test criteria we therefore distinguish between two main categories of areas respectively referred to as shielded areas and tunnel areas. The purpose of this report is to present integral values of the radiation levels and particle energy spectra representative of these two categories of areas. There will of course be local variation due to different loss distributions and shielding configurations, but the values and spectra presented here are chosen to illustrate the span of radiation levels being present in the LHC. More detailed studies are available in [7, 8, 9].

3.1 Sources of radiation

The main sources of radiation relevant for radiation effects in electronics at the LHC are direct losses in collimator and collimator like objects, particle debris from proton-proton or lead-lead collisions in the four main experiments, and interaction of the beam with the residual gas inside the beam pipe. The radiation levels are expected to correlate with the beam intensity and collimator settings for direct losses, scale with luminosity for collision debris, and be in relation to both beam intensity and residual gas density for beam-gas interactions. While direct losses or collisions debris typically are the dominating sources for the majority of the LHC areas, significant contribution from beam-gas interactions are expected only in a few areas.

3.2 The FLUKA Monte Carlo code

The simulation results presented in this report have been performed using the FLUKA Monte Carlo code (version 2008.3d.1). FLUKA is a well benchmarked [1, 2, 3, 4] general purpose tool for calculations of particle transport and interactions with matter, covering an extended range of applications like for example proton and electron accelerator shielding, target design, calorimetry, activation and dosimetry, cosmic ray studies, and radiotherapy.

The evaluation of the LHC radiation environment has until 2010 mainly been based on Monte Carlo simulation. However, after 2010, the first year of operation has provided the first benchmark measurements. These measurements are in good agreement with the simulations and have provided valuable feedback and input for adjustments to improve the forecast of the expected radiation levels for nominal operation.

3.3 Overview radiation levels

There are two main categories of radiation effects that need to be considered when operating in a radiation exposed area. These are cumulative effects and Single Event Effects (SEE). Both categories are again sub-divided into various groups according to either their physical effect or respective failure mechanism. For both the cumulative effects and SEE it is important to determine the expected integral values in order to set the envelope or limits of the irradiation test. For example, if a device is expected to be exposed to a certain dose over its life time in the LHC, it is important that the device is exposed at least an equivalent dose during the irradiation test. Similar conditions apply to displacement damage and 1 MeV neutron equivalent. For SEEs the integral values are important to determine the expected failure rate, typically expressed for a nominal year of LHC operation. Also, combined with the knowledge of the particle energy spectra, the integral value can be important determine the exposure

time/fluence needed to define/investigate the significance of rare effects. For example, Single Event Latch-up (SEL) caused by fission products due to the presence of heavy material in the device (e.g. Tungsten).

Table 2: Overview of expected annual radiation levels for each of the overall LHC areas.

ANNUAL DESIGN VALUES (ROUGH & PRELIMINARY)					
NOMINAL	Tunnel			Shielded Areas	'Safe Areas'
	DS		ARC		
	High	Low		RR (Power-Converters)	REs,UAs,UJs (rem.)
HEH [$\text{cm}^{-2} \text{y}^{-1}$]	$1.0 \cdot 10^{11}$	$2.0 \cdot 10^{10}$	$1.0 \cdot 10^9$	$2.0 \cdot 10^8$	$1.0 \cdot 10^7$
1 MeV eq. [$\text{cm}^{-2} \text{y}^{-1}$]	$4.0 \cdot 10^{11}$	$8.0 \cdot 10^{10}$	$4.0 \cdot 10^9$	$8.0 \cdot 10^8$	$4.0 \cdot 10^7$
Dose [$\text{Gy} \text{y}^{-1}$]	200	40	2	0.4	0.02
ULTIMATE	Tunnel			Shielded Areas	'Safe Areas'
	DS		ARC		
	High	Low		RR (Power-Converters)	REs,UAs,UJs (rem.)
HEH [$\text{cm}^{-2} \text{y}^{-1}$]	$4.0 \cdot 10^{11}$	$8.0 \cdot 10^{10}$	$4.0 \cdot 10^9$	$8.0 \cdot 10^8$	$1.0 \cdot 10^7$
1 MeV eq. [$\text{cm}^{-2} \text{y}^{-1}$]	$1.6 \cdot 10^{12}$	$3.2 \cdot 10^{11}$	$1.6 \cdot 10^{10}$	$3.2 \cdot 10^9$	$4.0 \cdot 10^7$
Dose [$\text{Gy} \text{y}^{-1}$]	800	160	8	1.6	0.02

Table 2 provides an overview of the expected annual radiation levels for each of the overall LHC areas. It shall be noted, that these values are meant as a global overview of peak radiation levels in order to provide a general classification, while local radiation levels are made available through regular radiation reports available through the R2E mitigation project [9]. Values are given for two LHC operational conditions:

- Nominal operation: corresponding to a cumulative LHC luminosity of 50 fb^{-1} , an average luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ and annual collimation losses of the order of 10^{16} protons.
- Ultimate operation: providing LHC operation to improve by an overall factor of four, here assuming a linear scaling of all relevant radiation source terms, except for safe areas

The radiation levels are split in the following way:

- LHC tunnel areas (affected equipment: 60A power converters, quench protection, cryogenics and beam instrumentation):
 - dispersion suppressor (DS): valid from the start of the cold section up to cell 13 and providing an expected lower and upper limit of radiation levels which mainly refer to locations close to the dipole (lower limit) and quadrupole magnets (higher limit).
 - arc: the cold section larger than cell 13 where the stated value refers to a currently assumed maximum average dose which will significantly depend on the residual gas pressures finally present under nominal LHC operation conditions (these are still not fully known, thus future update of this value is probable, however likely to reduce)
- Areas adjacent to the LHC tunnel:
 - shielded areas: areas close to the LHC tunnel with a certain amount of shielding being installed, however excluding extensive use of commercial electronic systems without prior radiation tests and design/operation considerations (examples are : UJ14, RR73, RE38, etc.)

- so-called ‘safe areas’: remaining underground areas where radiation levels are sufficiently shielded in order not to yield an acceleration factor of more than a few hundreds as compared to surface conditions (examples are: USC5, UA63, US15, etc.)

3.4 Particle energy spectra for shielded areas

Within the category of shielded areas there are two important types of alcoves housing electronic equipment. These are referred to as UJs and RRs where typically the UJs are closer to high loss points and consequently will be exposed to the highest levels of radiation. A more extensive shielding configuration has therefore been implemented for the UJs compared to the RRs. Examples of representative particle energy spectra are shown in figures 1 and 2 for respectively a UJ and RR alcove in the LHC insertion point 1.

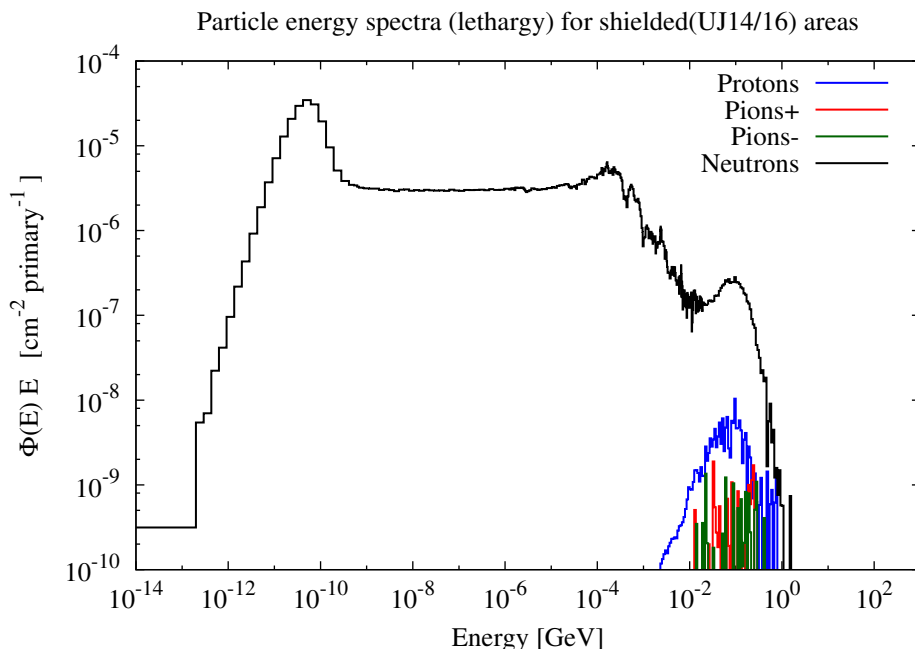


Figure 1: Particle energy spectra (lethargy) representative for shielded(UJ) areas in the LHC for a nominal operation (7 TeV). The spectra are normalized one proton-proton collision (referred to as a primary in the label).

For these locations the radiation levels scale mainly with the luminosity for the adjacent experiment. The particle energy spectra are therefore normalized to one proton-proton collision (referred to as a primary in plots). The impact of the different shielding configurations can clearly be seen when comparing the two plots. For the UJ the shielding configuration is both thicker and composed of different materials compared to the shielding configuration of the RR. The shielding configuration of UJ is therefore more effective in attenuating charge particles and high energy part of the spectra. Nevertheless, even though the high energy hadron fluence in general is lower in the RRs, it contains particles of higher energies compared to the UJs. This is due to the thinner shielding and is important to keep in mind when considering the risk of for example Single Event Latchups (SELs). A more detailed discussion concerning SEL testing is presented in Section 3.6.

A suggested method to quantify the fraction of high energy particles in a radiation environment is to generate the inverse cumulative probability curve as shown in figures 3 and 4. For

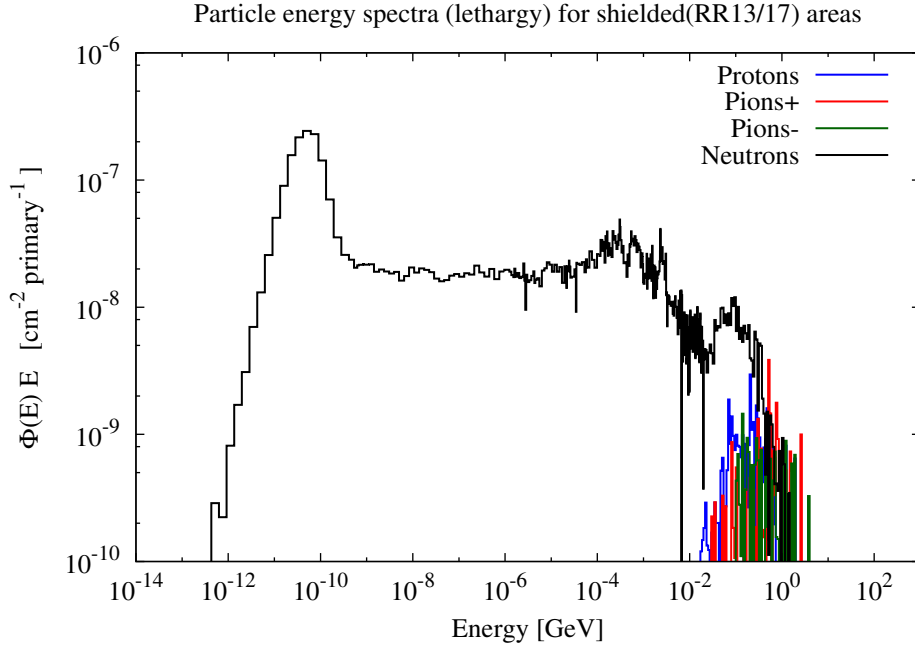


Figure 2: Particle energy spectra (lethargy) representative for shielded(RR) areas in the LHC for a nominal operation (7 TeV). The spectra are normalized one proton-proton collision (referred to as a primary in the label).

each particle type included in the high energy hadron fluence, this curve can be used to determine the probability that a given particle has an energy equal to or higher than a given energy value. The high energy hadron fluence in shielded areas is typically dominated by neutrons with a fraction of charged hadrons ranging from 2-10%.

3.5 Particle energy spectra for tunnel areas

Tunnel areas are defined as areas around, close to and in direct line of sight of the beam line. The composition of the particle energy spectra shown in figures 5 and 6 are consequently very different from those of the shielded areas. The high energy hadron fluence is typically orders of magnitude higher and the particle energy spectra are shifted towards higher energies. For tunnel areas the electronic equipment of interest is located on the floor directly below the beam line. This equipment can potentially be exposed to a high energy hadron fluences in the order of 10^{10} [$\text{cm}^{-2} \text{y}^{-1}$] with energies reaching up to 100 GeV. The fraction of charge hadrons is also higher compared to shielded areas ranging from 10-30% depending on the location.

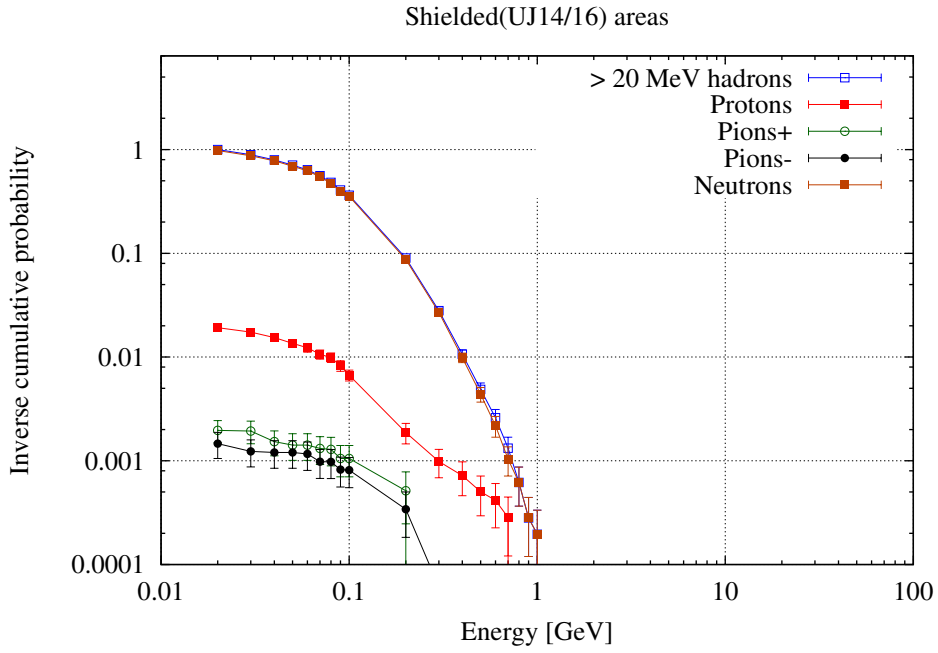


Figure 3: Inverse cumulative probability plots representative for shielded(UJ) areas in the LHC. The curves are normalized to the high energy hadron fluence.

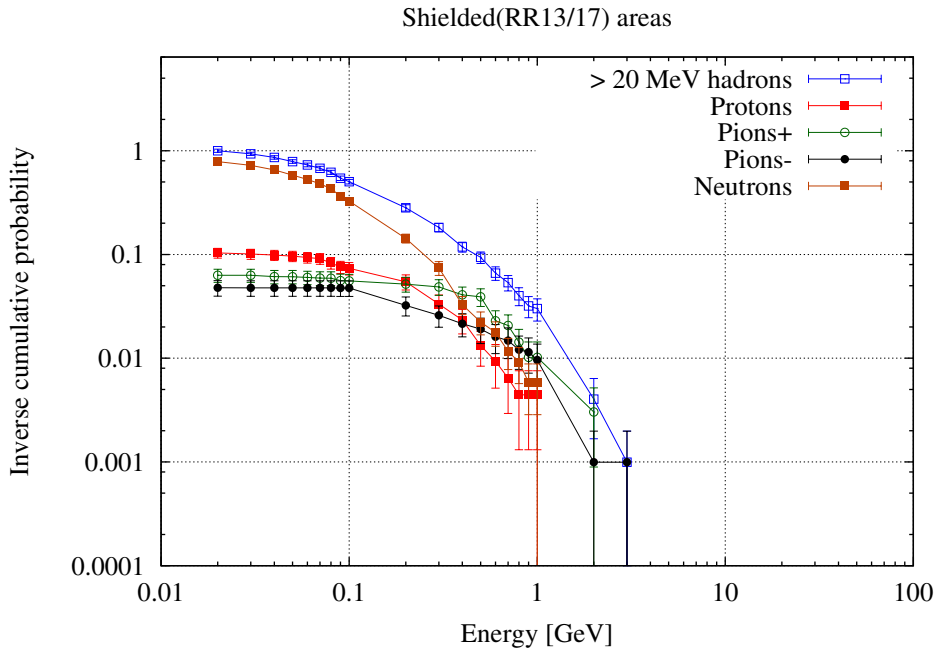


Figure 4: Inverse cumulative probability plots representative for shielded(RR) areas in the LHC. The curves are normalized to the high energy hadron fluence.

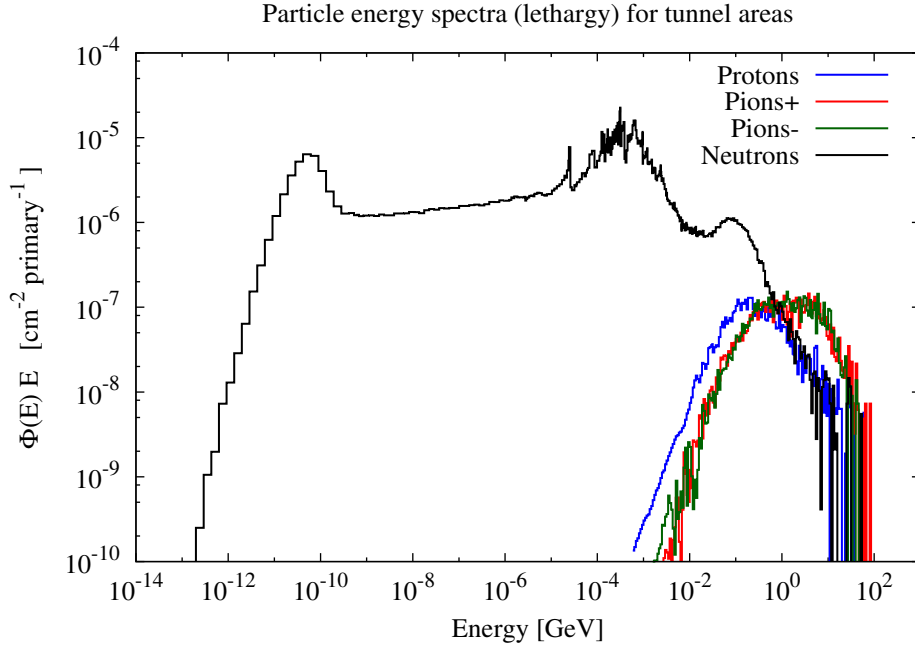


Figure 5: Particle energy spectra (lethargy) representative for tunnel areas in the LHC for a nominal operation (7 TeV). The spectra are normalized one proton-proton collision (referred to as a primary in the label).

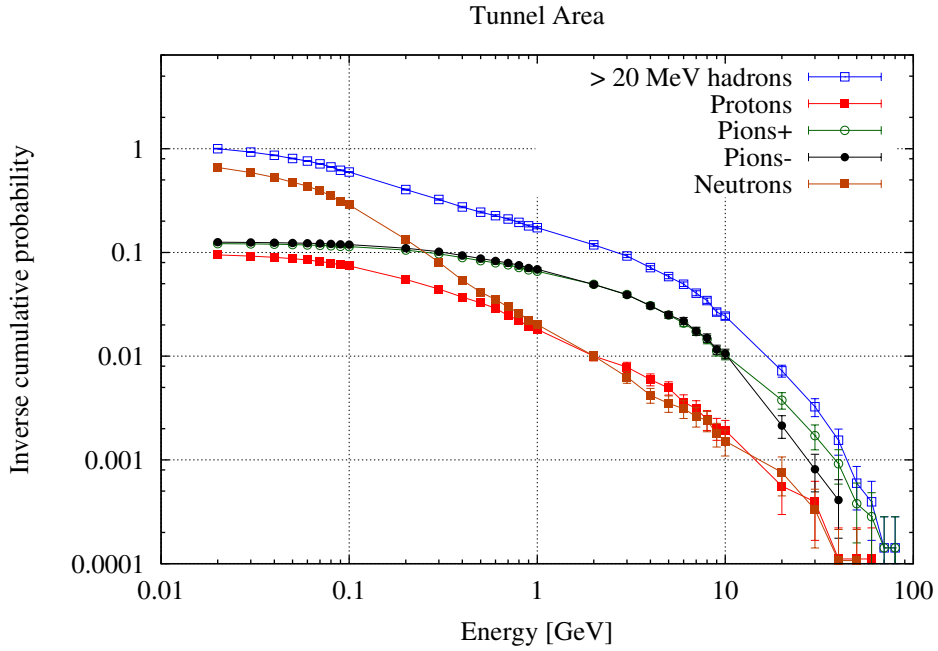


Figure 6: Inverse cumulative probability plots representative for tunnel areas in the LHC. The curves are normalized to the high energy hadron fluence.

3.6 Particle energy spectra for available test areas

As the electronics will operate in mixed particle fields it is also desirable and in some cases needed to perform irradiation testing in representative of real operating conditions. It is important to point out that mixed field tests do by no means fully replace the characterization of the SEE response in mono-energetic beams, dose calibration in for example a Co-60 source, or displacement damage testing in a 1 MeV neutron source. These tests are important in order to achieve a good understanding of a device's response to a particular particle type and energy, and through this to determine the full energy or LET response curve of the device. Mixed field testing on the other hand, will provide an extremely valuable validation of the individual irradiation test results for real operating conditions. In some cases, mixed field testing at CERN may also be the only available option due to time, budget and practical constraints. If one consider the example of the various types of power converters that are installed at the LHC today, they may contain several hundreds of components, weigh hundreds of kilos, and fill up 2 meter high racks. Until today these converters have been considered to be installed in safe areas exposed to an insignificant amount of radiation. As the knowledge of the LHC radiation levels have improved this is no longer the case and it is therefore important to investigate their sensitivity to radiation. The only practical method of testing these power converters is to bring them into a representative mixed radiation field where the whole system can be exposed and tested. This will provide an indication of their sensitivity but not a complete analysis due to the above listed limitations and also expected batch variations. Of course, for new developments, components will be finally be chosen based on the result single component testing. Mixed radiation field testing will then provide a primary screening of candidate components and a final system validation. SEL testing is another scenario where radiation test areas/facilities

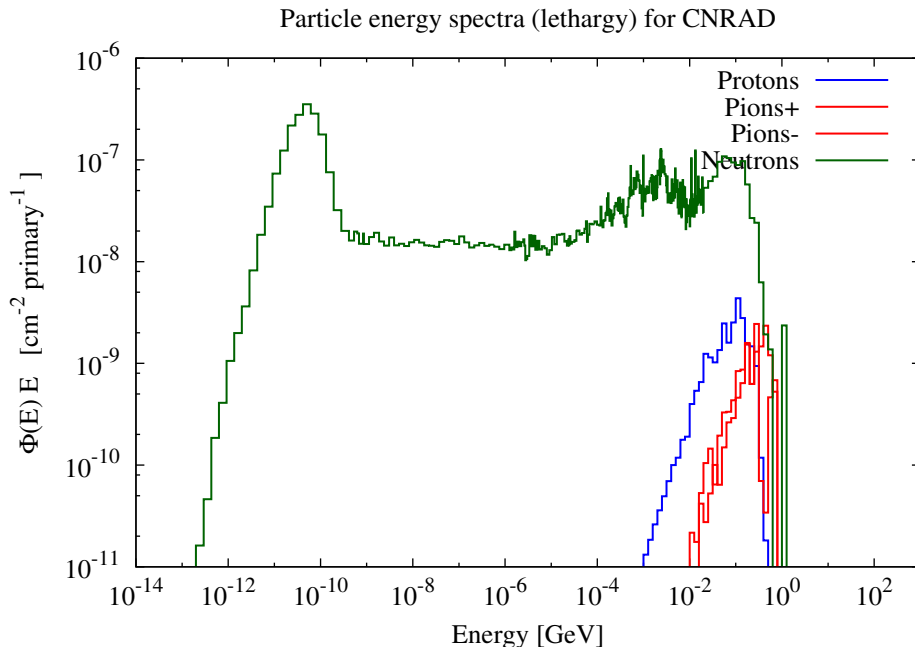


Figure 7: Particle energy spectra (lethargy) for line of sight location at CNRAD. The spectra are normalized per particle on target (p.o.t.) (referred to as a primary in the label).

at CERN can prove valuable and possibly also be the only method of representative testing. In [10] it is shown how the production cross section of high LET fragments increases when the energy of the incoming particle increases. It is therefore recommended that that SEL testing

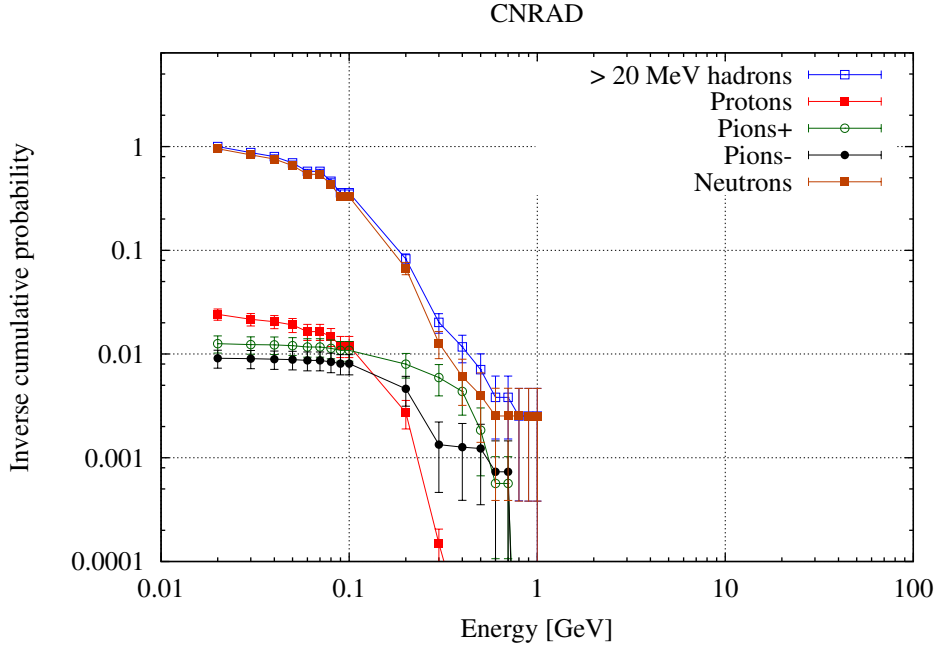


Figure 8: Inverse cumulative probability plots for line of sight location at CNRAD. The curves are normalized to the high energy hadron fluence.

should be performed at the maximum particle energy of the radiation environment. When considering that particle energies in the order of GeVs can be reached in some LHC areas, this recommendation may prove difficult and even impossible to fulfill. With respect to the LHC radiation environment, the limitation of the work in [10] is that only incoming proton energies of up to 500 MeV were studied. It is therefore important to improve our understanding of how the production cross section of high LET fragments behaves at higher energies. We know that for example the proton and neutron induced fission reactions in Tungsten starts to saturate with increasing energy [11]. How does this impact the LET value of the fragments? Will this also saturate, and at which energy? The answer to these questions could help to identify the maximum energy needed to test for SELs in LHC like environments.

At CERN there are two available areas dedicated for mixed field irradiation testing of electronic equipment, CNRAD [12] and H4IRRAD[13]. Both these areas are based on the principle of having a primary proton beam impinging on target in order to create a mixed particle field around the target. The corresponding particle energy spectra and cumulative probability curves is shown in figures 7 and 8 for CNRAD [12], and figures 9 and 10 for H4IRRAD. In figures 11 and 12 these test areas are compared to the neutron energy spectra and the inverse cumulative probability curve (HEH) representative of the LHC shielded and tunnel areas. As can be seen the various areas share the main features with respect to the shape of the spectra. They all have the thermal neutron peak, the resonance peak around 1 MeV and the high energy peak around a 100 MeV and extending to a few hundred MeV. However, there are important differences such as the ratio of thermal neutrons to high energy hadrons (R_{th}), and the extension or tail of the high energy peak towards the higher energies. Considering only the high energy hadron fluence and in particular SEL testing, the main conclusions that can be drawn from these simulation results are:

- the CNRAD facility covers only the test conditions needed for the shielded(UJ) areas,
- the H4IRRAD covers the test conditions needed for both main types of shielded areas,

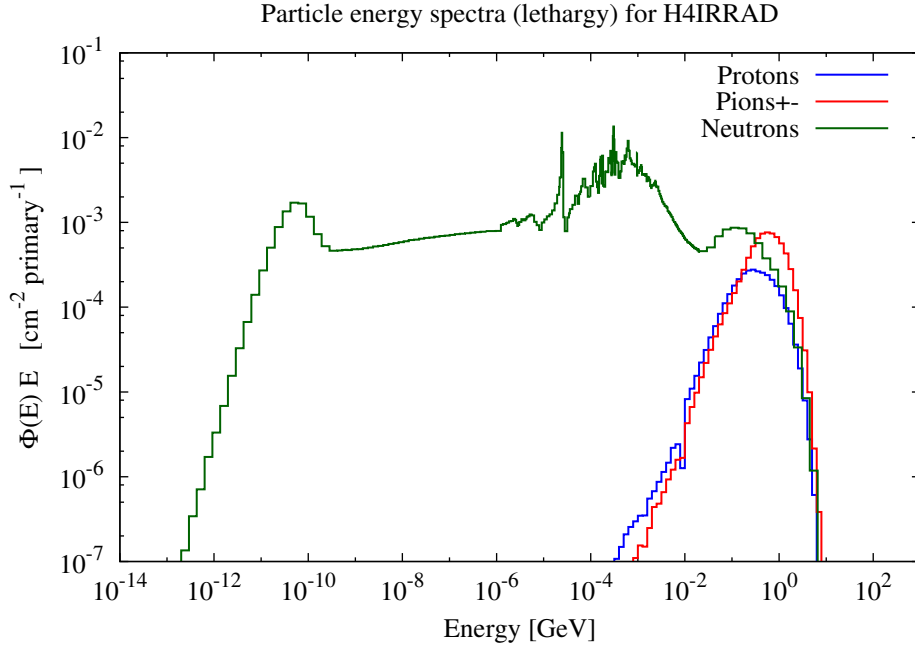


Figure 9: Particle energy spectra (lethargy) for H4IRRAD. The spectra are normalized per particle on target (p.o.t.) (referred to as a primary in the label).

- the H4IRRAD does not fully cover the test conditions needed for the tunnel areas as it does not reach high enough energies.

At present investigations are undergoing to both identify other potential test areas that can provide higher energy beams, and to understand their actual need due to the expected saturation of the production cross sections.

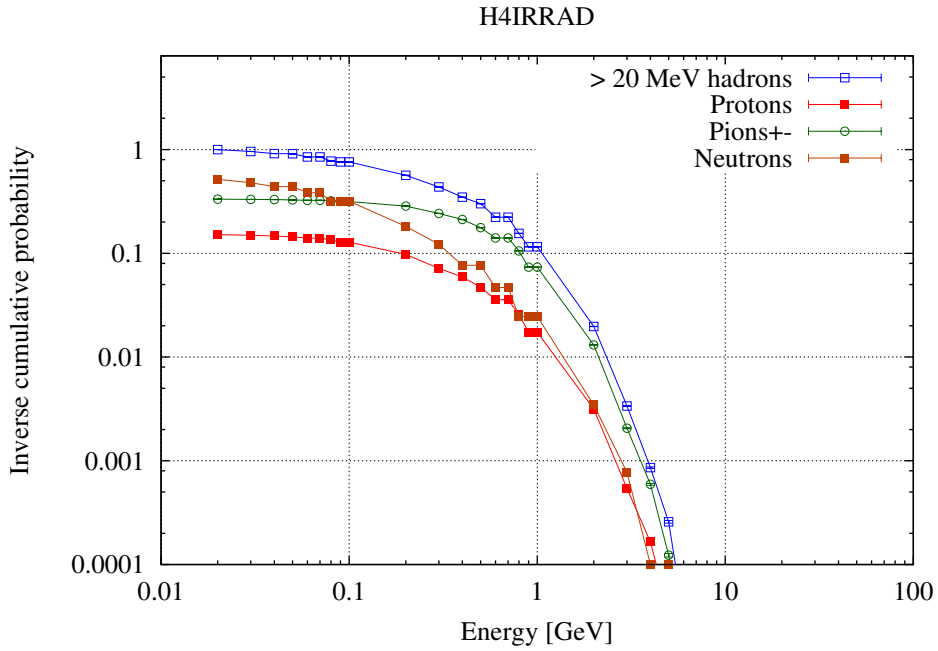


Figure 10: Inverse cumulative probability plots for H4IRRAD. The curves are normalized to the high energy hadron fluence.

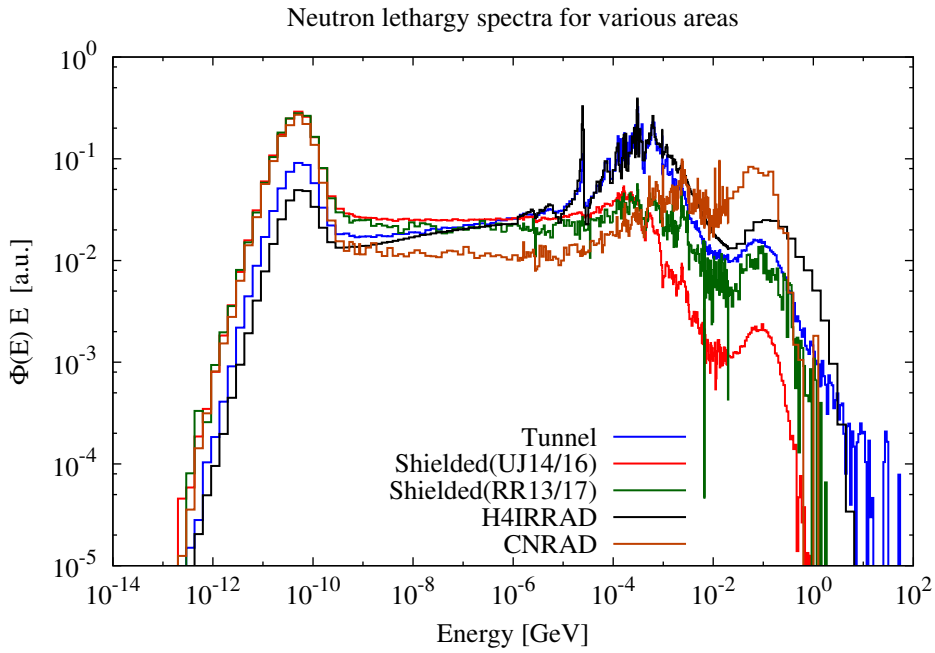


Figure 11: Neutron energy spectra for various LHC equipment and test areas. Each spectra is normalized by its individual total integral over the full energy range.

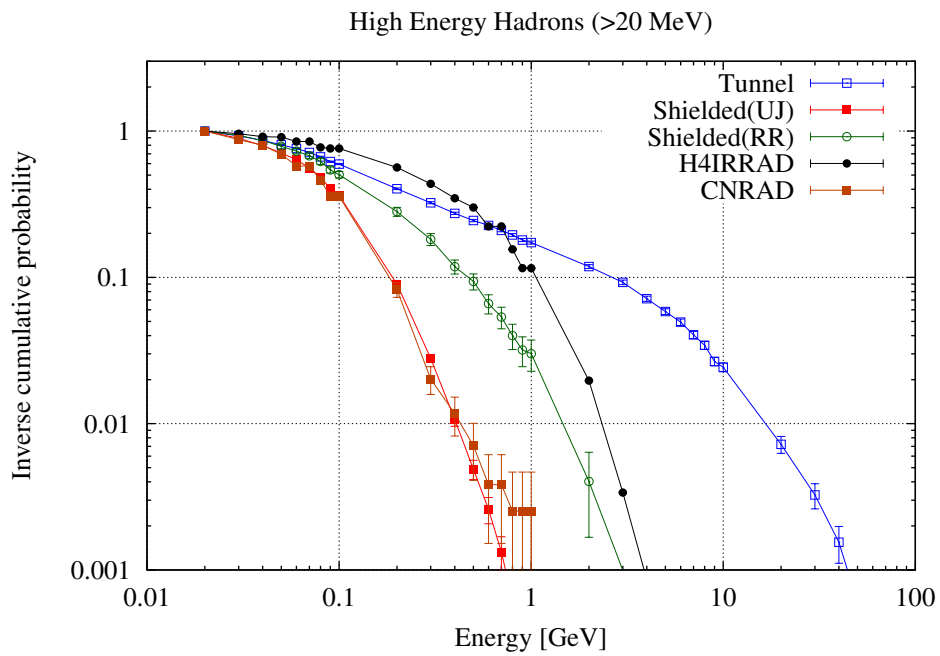


Figure 12: Inverse cumulative probability for various LHC equipment and test areas. The curves are normalized to the high energy hadron fluence.

3.7 Predictions for nominal operation in UJ-14/16 and RR-13/17

Two areas of great importance for the LHC power converters are the UJ's and RR's of insertion point 1. These areas are different both in terms of absolute radiation levels and in terms of the ratio of the thermal neutron fluence to the high energy hadron fluence. This is illustrated in figure 13 where the neutron lethargy spectra is normalized to a nominal year of operation. A nominal year of operation refers to a total of $8 \cdot 10^{15}$ collisions¹ at beam energies of 7 TeV. A comparison of inverse cumulative high energy hadron fluence curve of the UJ and RR are shown in figure 14.

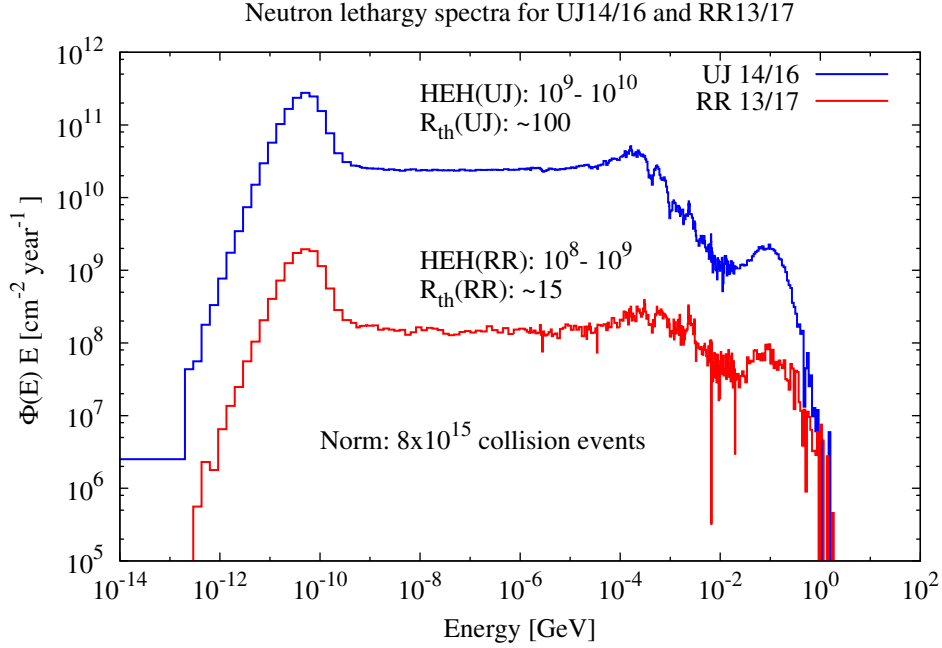


Figure 13: Neutron energy spectra for UJ-14/16 and RR-13/17 normalized to a nominal year of operation.

¹ $\mathcal{L}=1e34 \text{ cm}^{-2}\text{s}^{-1}$, 1 year = $1 \cdot 10^7$ sec, $\sigma_{pp} = 76 \text{ mb}$

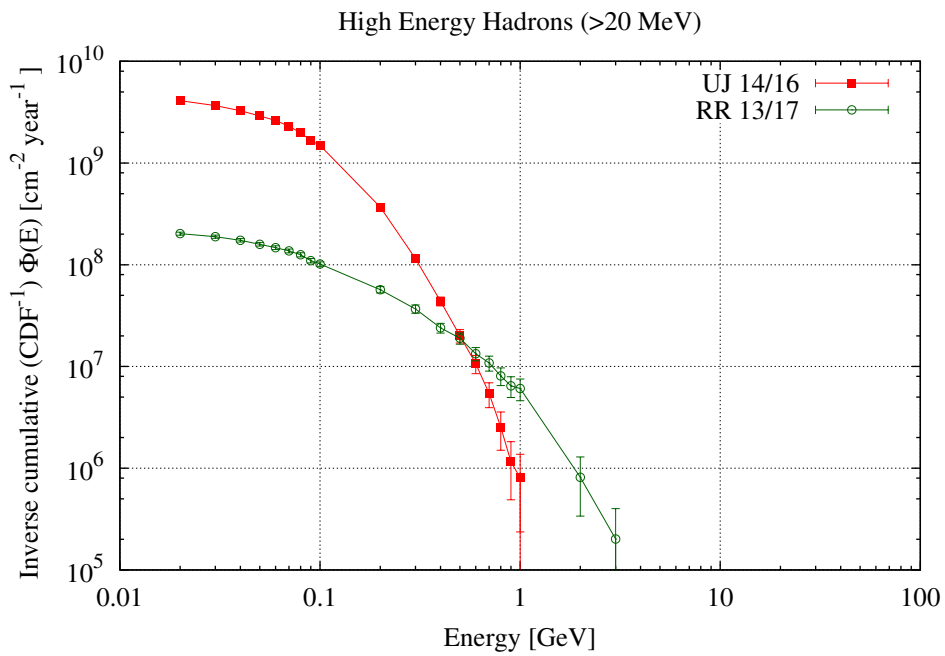


Figure 14: Inverse cumulative high energy hadron fluence for UJ-14/16 and RR-13/17 normalized to a nominal year of operation.

4 Summary

At the LHC the electronic equipment will be exposed to mixed radiation field composed of charged and neutral hadrons, photons, electrons and muons. Monte Carlo simulations have been performed to determine the expected radiation levels for nominal operating conditions in addition to the particle energy spectra. These results will create a foundation from which appropriate irradiation test criteria can be evaluated and determined. There are two main categories of areas to be considered, shielded alcoves and tunnel areas. For each category the upper limit of the respective radiation levels to be considered are listed in table 3.

Table 3: Table of expected radiation levels (upper limit) for the shielded alcoves and tunnel areas. Integral values are normalized to one nominal year of LHC operation.

Area	High-energy hadron fluence [cm ⁻² y ⁻¹]	$\frac{\Phi_{Ch.had.}}{\Phi_{HEH}}$ [%]	E _{max} [GeV]	R _{Th}	Dose [Gy y ⁻¹]	1 (Si) MeV n. eq. [cm ⁻² y ⁻¹]
Tunnel	$\leq 1.0 \cdot 10^{10}$	≤ 30	100	≤ 8	≤ 100	$\leq 3.0 \cdot 10^{10}$
Shielded	$\leq 2 \cdot 10^9$	≤ 10	5	≤ 20	≤ 1	$\leq 6 \cdot 10^9$

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