SHIELDING OF ELECTRONICS IN THE TUNNEL

L.S. Esposito#, M. Brugger, F. Cerutti, A. Ferrari, R. Losito, CERN, Geneva, Switzerland

Abstract

Radiation to Electronics (R2E) represents a crucial issue to be taken into account as design criterion of any high energy and intensity machine. The different effects on the concerned equipment and the microscopic mechanisms underneath are reviewed. Evaluation and mitigation strategies are presented, based on the support of dedicated Monte Carlo calculations. In the specific context of a future e+e- HF, the relevant radiation sources and their possible impact are discussed.

INTRODUCTION TO R2E

The study of the electronics sensitivity to radiation requires a multi-disciplinary approach, spanning from the knowledge of the electronic components, to the radiation environment, and to the physics models that describe the interaction of the radiation with the matter. The goals are: (1) to define and quantify the effects of the radiation on the electronics; (2) to monitor and/or estimate the radiation levels in the concerned area; (3) to test and develop radiation-hard or sufficiently tolerant electronics; (4) to implement mitigation options.

R2E is often considered for space applications, where application design, test and monitoring standards are already well defined. However, it is important to note that the radiation environment encountered in a high energy and intensity accelerator, the high number of electronic systems and components exposed to radiation, as well as the actual impact of radiation-induced failures on the machine operation, pose challenges that might strongly differ from the context of space applications.

For a high intensity and energy machine, typical sources of radiation are luminosity debris, direct losses on collimators and dumps, and beam interactions with the residual gas inside the vacuum chamber all along the accelerator, as well as with dust fragments falling into the beam path. But, for the specific case of a lepton machine, an additional main source of radiation in the tunnel is represented by the synchrotron radiation.

In order to evaluate the impact of the radiation on the machine equipment, Monte Carlo simulations represent an indispensable tool. They need to rely both on a refined implementation of physics models of the particle interaction with matter and an accurate 3D-description of the region of interest.

Typically the mixed particle type and energy field of interest in a high-energy environment 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 [1,2] and benchmarked in detail for radiation damage issues at the LHC [3,4].

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:

- damage from the Total Ionizing Dose (TID).
- displacement damage (DD) or non-ionizing dose.
- so-called Single-Event-Effects (SEEs).

The latter ones range from single or multiple bit upsets (SEUs or MBUs), transients (SETs) up to possible destructive latch-ups (SELs), destructive gate ruptures or burn-outs (SEGRs and SEBs).

The first two groups are of cumulative nature and are measured through TID and non-ionizing energy deposition (NIEL [1], 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.

Being of stochastic nature, SEE failures form an entirely different group. They are due to the direct ionization by a single particle, able to deposit sufficient energy through ionization processes in order to perturb the operation of the device. They can only be characterized in terms of their probability of occurring as a function of accumulated High Energy (> 5 ÷ 20 MeV) Hadron (HEH) fluence. The probability of failure will strongly depend on the device as well as on the flux and nature of the particles.

For accelerator applications, the installed control systems are either fully commercial or often based on so-called COTS (Commercial-Off-The-Shelf) components, both possibly affected by radiation. This includes the immediate risk of SEE with a possible direct impact on beam operation, as well as in the long-term, cumulative dose effects (impacting the component/system lifetime) which additionally have to be considered.

As example, for the tunnel equipment in the existing LHC, radiation was only partially taken into account as design criteria prior to construction, and most of the equipment placed in adjacent and partly shielded areas was not conceived nor tested for their actual 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) [5] was then initiated to quantify the risk of radiation-induced failures and to mitigate the risk for nominal beams and beyond to below one failure a week for all exposed electronic systems together. The respective

----

#Luigi.Salvatore.Esposito@cern.ch

[1] Non-Ionizing Energy Losses.

ISBN 978-3-95450-172-4

mitigation process included a detailed analysis of involved radiation fields, intensities and related Monte Carlo calculations; radiation monitoring [6] and benchmarking; the behavior of commercial equipment/systems and their use in the LHC radiation fields; as well as radiation tests with dedicated test areas and facilities [7]. 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.

For the design of a new machine, it is therefore essential to take into account already at an early stage the impact of the radiation on the equipment in order to adopt all the necessary measures to mitigate its effect and develop radiation tolerant electronics.

In the next Section, a case study for a possible FCC-ee tunnel is presented in order to estimate the radiation levels induced by synchrotron light and evaluate its impact on the electronic equipment.

CASE STUDY

For this study, the FCC arc cell model described in [8] has been used. Table 1 summarizes the main parameters of the 80 km option considered. The geometry consists of a 25 m long half FODO cell, with five 24 cm long absorbers. The latters are shaped with an inner 25 mm copper wing (see Fig. 1). The internal dimension of the elliptical beam pipe considered is 90×30 mm (H×V).

Table 1: Key Parameters of A Possible 80 Km Long E+E- Collider

Main parameters	80 km
Beam Energy [GeV]	175
Dipole Bending Radius [km]	9.8
Critical Energy [MeV]	1.21
Energy lost per turn [GeV/turn]	8.5
Energy lost in the dipole [keV/cm]	1.375
Beam current [mA]	10
Power lost in the whole accelerator [MW]	85
Power lost in the dipole [W/cm]	13.75
Operation time per year [s]	10^7

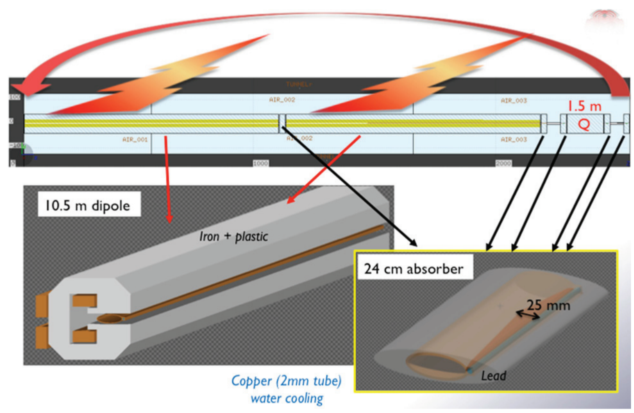

Figure 1: FLUKA geometry layout of the half FODO cell on top, details of the geometry implementation on the bottom: the 10.5 m dipole is shown on the left, while the preliminary design of a possible absorber is on the right, including an external lead shielding of 5 cm.

The synchrotron radiation as implemented in the FLUKA allows to sample from any synchrotron radiation spectrum and accounts for the photon angular distribution and polarization. A proper change of coordinates is applied to particles exiting from the end of the half FODO cell, re-injecting them back at its beginning, in order to account for the contribution of all relevant upstream cells.

The particle spectra at the height of 1 meter from the beam line in correspondence of the interconnect between the second dipole and the arc quadrupole are shown in Fig. 2. The particle fluence is dominated by the photons peaked at about few hundred keV. The spectrum of neutrons produced in photonuclear interaction ranges from about MeV down to thermal energies.

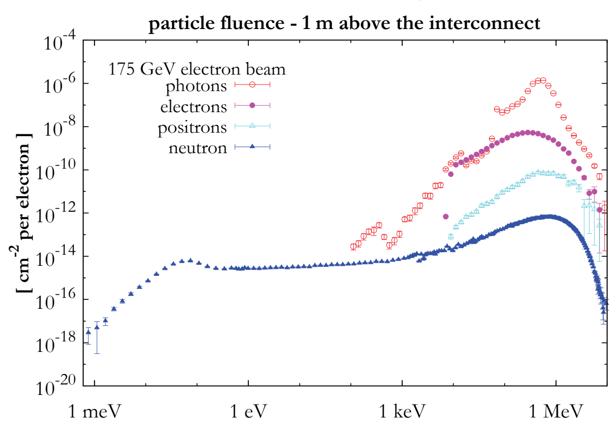

Figure 2: Energy spectra of different particle species in air at the height of 1 meter from the beam line, in correspondence of the interconnect between the dipole and the arc q-uadrouple.

Figure 3 shows HEH fluence, Silicon 1 MeV-neutron equivalent fluence and dose in the tunnel of a FCC-ee for an accumulated charge equal to 10 mA × 10^7 s. The values are azimuthally averaged.

ISBN 978-3-95450-172-4

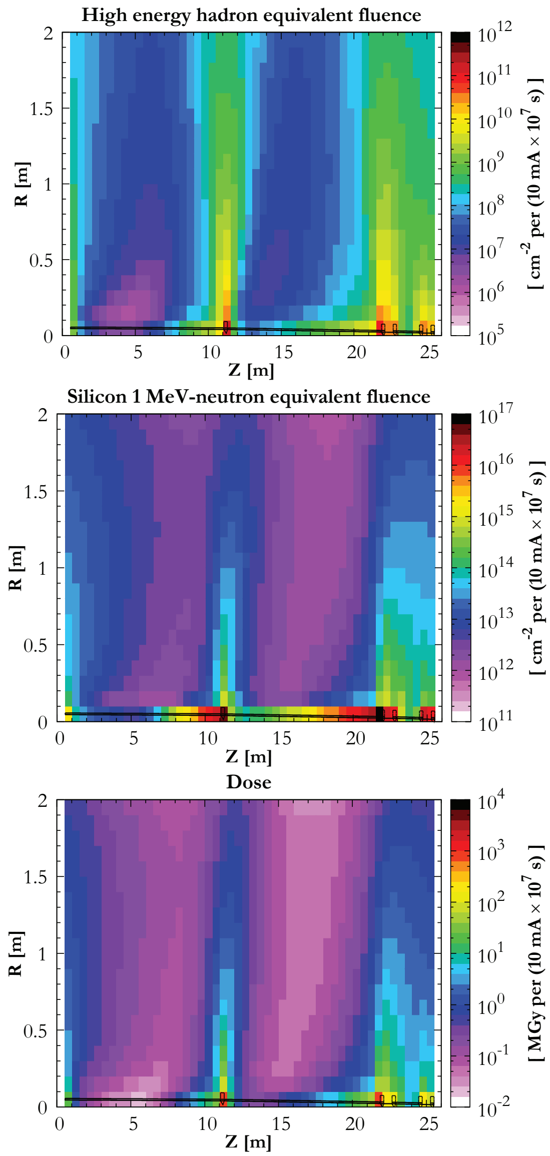

Figure 3: HEH fluence (top), Silicon 1-MeV neutron equivalent fluence (middle), dose (bottom) expected in the tunnel of a FCC-ee arc half FODO cell for an accumulated charge equal to 10 mA × 10^7 s.

The patterns present hot spots along the beam pipe in correspondence of the interconnects where the synchrotron radiation absorbers are placed.

The resulting values indicate that, depending on the location, any equipment installed in the tunnel might not only suffer SEE failures, but will mainly be heavily impacted by the TID effects thus limiting the equipment lifetime.

In particular, TID values of the order of 100 kGy ÷ 1 MGy represents a problem for the use of any active electronics. Fully commercial systems (COTS based) are to be avoided, because only after careful selection and qualification they can rarely stand more than a kGy level, while special radiation hard component might stand up to a few 10 kGy. In case they are required, their failure impact and mitigation measures have to be studied in the context of accelerator operation. Therefore, a detailed study is needed in order to coherently design the areas housing the required control electronics that can sustain significant radiation levels and mitigation measures must be addressed during the early design phase (shielding measures, minimal requirement of control electronics, maximum cable lengths, etc.).

In parallel, also with respect to material damage, a careful choice is necessary because some material, especially organic, can withstand radiation levels only in the order of ten kGy and start deteriorating afterwards.

CONCLUSION

The design of a FCC-ee machine should carefully address R2E and general radiation damage issues. The main concern is represented by the damage from TID that can eventually lead to device destruction. For the tunnel equipment (and in adjacent and partly shielded areas), a full understanding of the radiation levels is necessary. The efficient use of benchmarked Monte Carlo codes such as FLUKA is an indispensable tool to anticipate radiation issues and to implement a correct protection strategy, by means of dedicated shielding and/or electronics hardening.

REFERENCES

[1] G. Battistoni et al., “The FLUKA code: Description and benchmarking”, AIP Conf.Proc. 896 (2007) 31-49.

[2] A. Ferrari et al., “FLUKA: A multi-particle transport code (Program version 2005)”, CERN-2005-010; http://www.fluka.org

[3] M. Brugger et al., “FLUKA capabilities and CERN applications for the study of radiation damage to electronics at high-energy hadron accelerators”, Progress in Nuclear Science and Technology, PNST10184-R1 (2010).

[4] K. Roed et al., “FLUKA simulations for SEE studies of critical LHC underground areas”, Nuclear Science, IEEE Transactions on, vol. 58, no. 3, p. 932, (2011).

[5] R2E website, www.cern.ch/r2e

[6] G. Spiezia et al., “The LHC accelerator Radiation Monitoring System – RadMON”, in Proceedings of Science, 2011.

[7] M. Brugger et al., “R2E Experience and Outlook for 2012”, Proceedings of LHC Performance workshop, Chamonix 2012.

L. Lari et al. “Beam-machine Interaction at TLEP: First Evaluation and Mitigation of the Synchrotron Radiation Impact”, IPAC2014, THPRI011.

ISBN 978-3-95450-172-4