1 Introduction

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This report documents the knowledge and experiences gained by the LHC experiments in running vertex and tracker detector systems in extreme radiation environments and concludes a series of workshops held at CERN [1–3]. By the time of the workshops, the last one held on February 2019, the LHC machine had delivered a large fraction of the design luminosity to the experiments and the deleterious effects of radiation on detector performance and operation were being observed and measured. It was timely to review the situation across the LHC experiments and answer questions such as: Are the detector systems operating and performing as expected? How reliable are the radiation damage models and predictions? How accurate are the Monte Carlo simulation codes? Have there been unexpected effects? What mitigation strategies have been developed? Since the workshops, additional radiation studies have been undertaken and published, the results of which are also referenced in this report.

Our understanding and modelling of radiation effects in the LHC detector systems was originally tested in irradiation facilities. However, such facilities do not reproduce the more complex radiation reality of the LHC experiments and there is strong motivation to cross-check and validate. Previous collider experiments were designed for operation in much less severe radiation environments and extrapolating their experiences to the LHC experiments has been limited, partly due to the higher collision energies of the LHC, but mainly because of the much higher proton–proton collision rates.

The scope of the report is focused on the measurements and observations made in Run 1 (2010–2012) and Run 2 (2015–2018), and, where feasible, their comparison with predictions. We discuss predictions for Run 3 (2022–2024) and the Phase II upgrades only in the context of where lessons learned from Runs 1 and 2 have directly impacted design or strategy. The many crucial LHC Phase II upgrade design studies currently being qualified in irradiation test facilities are not considered in this report.

A major goal of this report is to provide a reference for future upgrade and collider studies, summarizing the experiences and challenges of designing complex detector systems for operation in harsh radiation environments. We begin in Section 2 with a general introduction into the physics of radiation effects on silicon sensors and electronic systems. In Section 3 a brief description of the LHC detector systems relevant for this report is given, along with the important machine parameters, such as the collision luminosity delivered to the experiments. In Section 4 we describe how the experiments simulate their complex radiation backgrounds, crucial in the design of experiments, using Monte Carlo event generators and particle transport codes. From such simulations radiation quantities of interest, such as particle fluence and ionizing dose, can be determined. Also included in this section are the results of validation studies to establish the accuracy of the simulated predictions. In Sections 5 and 6 we give a detailed description of the many radiation related measurements and observations made by the detector sensor and electronic systems, respectively, along with comparisons with simulated predictions. In Section 7 we show how the LHC radiation damage measurements are being integrated into detector simulation and digitization software to allow increasingly accurate predictions of sensor design and performance. Finally, we present the conclusions of this inter-experiment work in Section 8.

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CERN Yellow Reports: Monographs, CERN-2021-001, DOI: 10.23731/CYRM-2021-001, p. 1.

References

[1] Radiation effects in the LHC experiments and impact on operation and performance, CERN, 11–12 February 2019, https://indico.cern.ch/event/769192/.

[2] Radiation effects in the LHC experiments and impact on operation and performance, CERN, 23–24 April 2018, https://indico.cern.ch/event/695271/.

[3] 31st RD50 Workshop, CERN, 20–22 November 2017, https://indico.cern.ch/event/663851/.