8 Conclusions

The LHC experiments have been running successfully and taking data since 2010. Much experience has been gained in running detector systems in challenging radiation conditions, and the impact on operation and performance has been assessed in this report. In general, we find the impact of the radiation effects to be in accordance with initial design expectations. While some unexpected effects have been observed with challenging consequences, these were in general successfully mitigated against.

The simulation of radiation environments is crucial in the design phase of new hadron collider experiments or upgrades. We showed in Section 4 how the proton–proton collisions are now well described by Monte Carlo event generators such as PYTHIA, with inelastic cross-sections and particle productions rates described at levels of precision typically less than 10%. The measurements made by the experiments, along with cosmic ray data, constrain significantly the predictions for particle production in future hadron colliders, such as the proposed 100 TeV Future Circular Collider at CERN. We also showed how Monte Carlo particle transport codes such as FLUKA and GEANT4 are being used to accurately simulate radiation backgrounds in and around the LHC experiments. In the initial design phase, factors of two to five were applied by some of the experiments to reflect the uncertainty in the simulations. Intensive benchmarking of the simulated predictions against detector measurements has led to a drastic reduction in such simulation 'safety factors'. For example, today the ATLAS experiment applies a factor 1.5 on its simulated predictions of fluence and dose. This has big implications on the choice of technologies that can be used in the LHC experiment upgrades, which in turn has enormous cost benefits. An important caveat to this, however, is that the reliability and accuracy of the simulation results is highly dependent on the geometry and material description of the experiment implemented in the simulations. For radiation background studies, fine detail is often not required, but it is crucial to reproduce accurately the radiation and interaction lengths. A final comment on 'lessons learned' is relevant for detector upgrades in an experiment. It is vital to study the impact of introducing new detector systems and services into an existing experiment, otherwise unintended increases in radiation background levels can occur in some of the other systems leading to a reduction in detector lifetime.

In Section 5, we showed the many measurements related to radiation damage performed by the experiments. A variety of probes have resulted in a detailed diagnostic information that can be used for modifying models, guiding operation and upgrades, as well as improving the quality of offline reconstruction. For leakage current, existing models that were mostly developed at independent irradiation facilities describe the existing data reasonably well, while other probes like depletion voltage are less well modelled. Expanding and enhancing this measurement program into Run 3 and the HL-LHC will be critical for preserving and possibly enhancing physics analysis as radiation damage becomes even more prominent. Further developments of the existing models will be required to make the most use of future measurements and the existing data may provide powerful constraints on these models, including estimating uncertainties.

In Section 6, we discussed how the effects of radiation have impacted the electronic and optoelectronic systems. Several of the observed phenomena like single event effects and threshold or current increases are expected. For many of them the magnitude or probability is in line with simulations or pre-installation tests. Still, owing to the complexity of the systems there were surprises either due to unanticipated effects or larger than expected magnitude or probability of occurrence. The root cause in most cases has been identified and mitigating actions have been applied. It is still evident that even with the rigorous testing applied to any device installed in the detectors, surprises are always possible, and a

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detailed understanding of the system is necessary to identify and compensate for these effects.

In Section 7, we showed how radiation damage measurements are being integrated into sensor simulation software by the LHC experiments to allow increasingly accurate sensor design and performance predictions. ATLAS and CMS both use TCAD simulations to model the non-linear electric fields created in the sensor by radiation induced defects. Trapping rates and defects are modelled, with ATLAS using parameters taken from the literature, and CMS preferring to fit their parameters to match their measured LHC data. This is then used as input into the sensor charge collection and digitization software. On the contrary, LHCb adopts a simpler and more direct strategy by assuming a linear electric field in the silicon sensor and correcting the signal collection according to the depth of the depleted region after radiation damage. Also discussed in Section 7 was the fact that models fitted to test beam data do not always accurately describe sensor performance after radiation damage in operation at the LHC. It is also unclear if the currently used fitting parameters can be used to extrapolate to the highest radiation levels of the HL-LHC and to perform accurate simulations of sensors for future predictions. Further investigations and modelling studies will likely continue well into the Phase II Upgrade.