Radiation effects in the LHC experiments and impact on operation and performance.

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Editors: M. Bindi, M. Bomben, E. Butz, A. de Cosa, I. Dawson, S. Mallows, M. Moll, B. Nachman, J. Sonneveld

Abstract
This report documents the knowledge and experience gained by the LHC experiments in running detector systems in harsh radiation environments, with focus on inner detector systems. Run 2 finished in December 2018 with unprecedented integrated luminosity delivered to the experiments. The deleterious effects of radiation is increasingly impacting detector operation and performance and measurements have been made across the LHC experiments. It is timely to review the situation and establish if the detector systems are operating and performing as expected. We would like to know how well the radiation damage is being modelled and monitored? And how accurate are the radiation background simulations? Have there been unexpected effects? What mitigation strategies have been developed? The goal of this report is to provide a major reference for future upgrades and for future collider studies, summarising the experiences and challenges of designing complex detector systems for operation in harsh radiation environments.

Keywords
Radiation, damage, simulation, LHC, experiments

Contents

1 Introduction

This report documents the knowledge and experience gained by the LHC experiments in running detector systems in harsh radiation environments, with a focus on inner detector systems. The deleterious effects of radiation is increasingly impacting detector operation and performance and measurements and observations have been made across the LHC experiments. It is timely to review the experiences of the LHC experiments and ask if the detector systems are operating and performing as expected? How accurate are the radiation damage models and predictions? Have there been unexpected effects? What mitigation strategies have been developed? Our understanding and modelling of radiation effects was originally tested in irradiation facilities, so strong motivation to cross check in-situ in the complex radiation fields of the LHC?

The goal of this report is to provide a major reference for future upgrades and for future collider studies, summarising the experiences and challenges of designing complex detector systems for operation in harsh radiation environments. In section 2 we discuss the current knowledge on the effects of radiation on detector systems. In section 3 we describe how the radiation environments ...

2 Overview of radiation effects on detector systems

Editors: M. Moll, I. Dawson, A. Nother?

A general introduction/overview on effects of radiation – we could possibly merge this section into the other sections, but my view is it's better to separate the theory from the measurements as much as possible? We could also briefly describe in this section how radiation challenges in our field differ to other industries?

2.1 Sensors

Leakage currents, depletion voltage, CCE, etc.

2.2 Electronics

SEUs etc.

2.3 Optoelectronics

Section on relevant opto/photonic (fibres, LEDs and lasers, etc.)

2.4 Services

Anything to say here apart from scattering and activation?

References

3 Simulation of radiation environments

Editors: I. Dawson, S. Mallows

Contibuting authors: I. Azhgirey, I. Dawson, M. Huhtinen, V. Ivantchenko, D. Kar, M. Karacson, S. Mallows, I. Mandic, S. Menke, P. Miyagawa, A. Di Mauro, A. Mucha, S. Pospisil, T. Szumlak, V. Vlachoudis

Write introduction discussing:

– The need of simulation for radiation background studies, starting with event generation followed by transport of particles in detector material.
– During design phase rely on radiation simulation predictions – extrapolating from lower centre of mass collision energies. Challenge in determining uncertainties on the predictions. Safety factors?
– Typical requirements of the experiments: 1 MeV neq fluence; ionising dose; hadrons $>$ 20 MeV; residual dose rates

3.1 Event generation

General discussion on event generator codes available for describing minimum bias *pp* collisions. ATLAS uses PYTHIA8, CMS and LHCb use FLUKA embedded DPMJET. (Say something about ALICE, TOTEM, LHCf ?)

3.1.1 PYTHIA

3.1.2 DPMJET

3.2 Particle transport codes

General discussion on on particle transport codes used in the LHC experiments. ATLAS uses both FLUKA and GEANT4, CMS and LHCb use FLUKA.

3.2.1 FLUKA & FLUGG

3.2.2 MARS

3.2.3 GEANT3/CALOR

3.2.4 GEANT4

3.3 Simulation frameworks

For example, ATLAS uses Git repository for shared geometry development – shared with RP. Web tools. TWikis?

3.4 Fluence and dose predictions

3.4.1 ATLAS

3.4.2 CMS

3.4.3 LHCb

3.4.4 ALICE

References

4 Measurements of radiation damage on sensors

Editors: A. De Cosa, B. Nachman
Contibuting authors: J. Agram, A. De Cosa, B. Nachman, W. Barter, J. Beyer, M. Baselga, F. Feindt, A. Grummer, J. Hunt, T. Kondo, V. Lima, K. Mochizuki, J. Sonneveld, M. Vignali

General introduction on the effects of radiation on sensors, though I propose details should go in section 2. Here we should focus on the experiment measurements, and how they compare to the predictions from simulation and modelling.
For presenting results I think easiest to summarise studies and conclusions for each experiment first, as we did in the workshops, then try to extract combined conclusions? A crude outline given below ...

4.1 Measurements

Several measurements from ATLAS can be found in Ref. [1].

4.1.1 Leakage Current

Fig. 1.

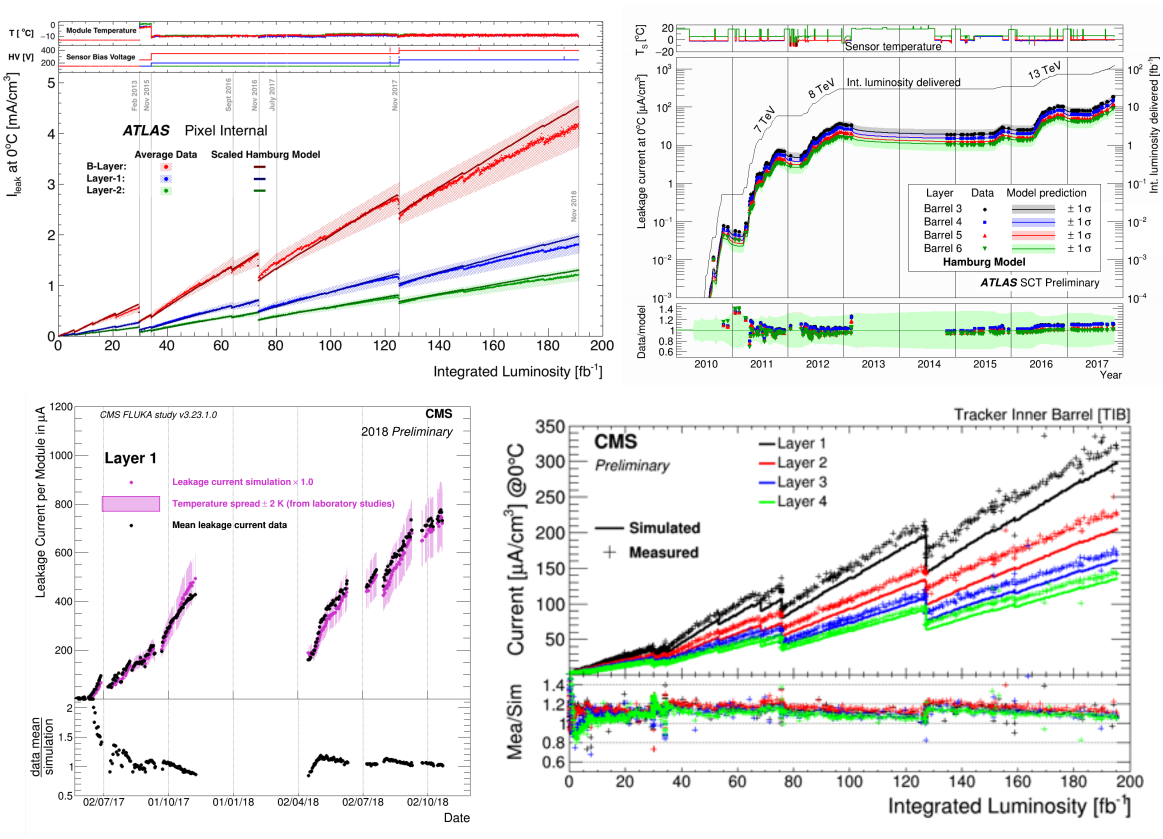

Fig. 1: Top left: ATLAS leakage current from the outer three pixel layers, from Ref. [7]. The IBL leakage current measurement can be found in Ref. [5]. Top right: ATLAS SCT, from Ref. [6]. Bottom left: CMS pixels. Bottom right: CMS strips.

4.1.2 Depletion Voltage

Fig. 2.

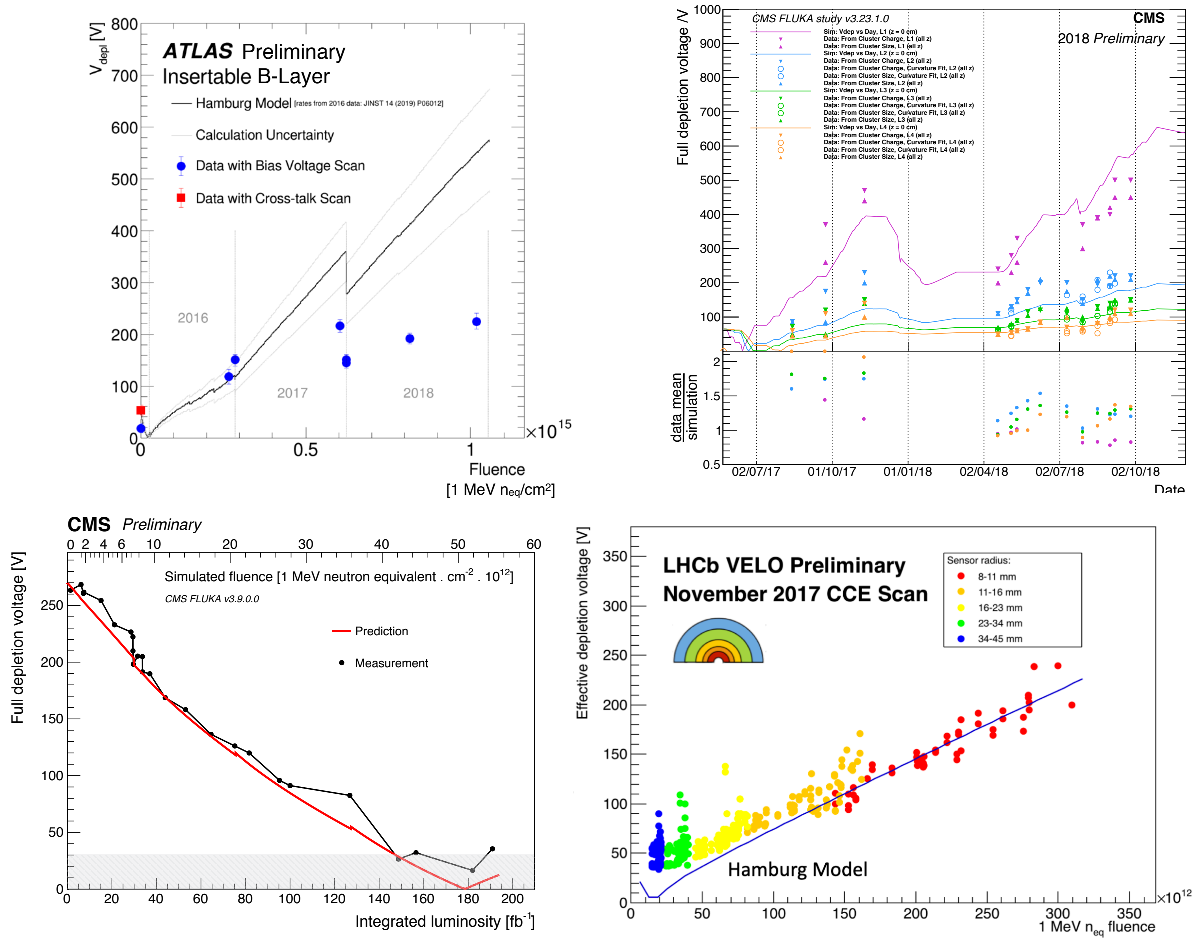

Fig. 2: Top left: ATLAS IBL, figure from Ref. [8]. Top right: CMS pixels. Bottom left: CMS strips. Bottom right: LHCb VELO.

4.1.3 Charge Collection, Hit Efficiency, and Cluster Size

Fig. 3.

4.1.4 Lorentz Angle

Fig. 4.

4.1.5 Position Resolution

Fig. 5.

4.2 Inter-experiment comparisons

4.2.1 Model Parameters

The idea of this section is to compare Hamburg model parameters.

4.2.2 Measured Fluence

Fig. 6.

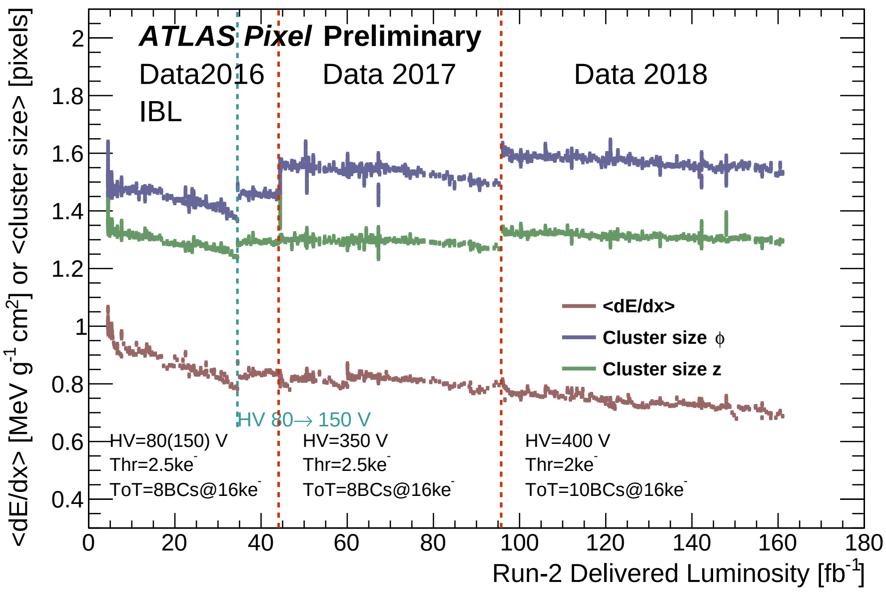

Fig. 3: Figure from Ref. [3].

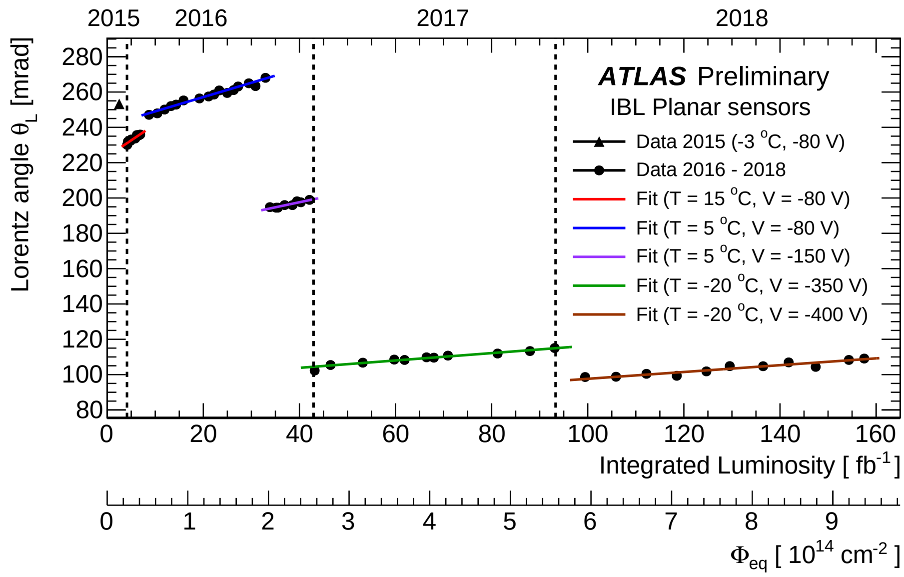

Fig. 4: Figure from Ref. [2].

4.3 Discussion

Drawing conclusions from across the experiments.

References

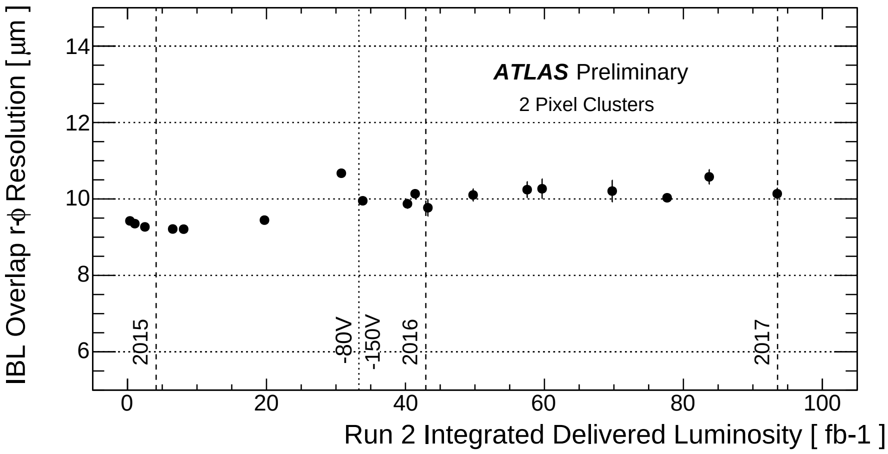

Fig. 5: Figure from Ref. [4].

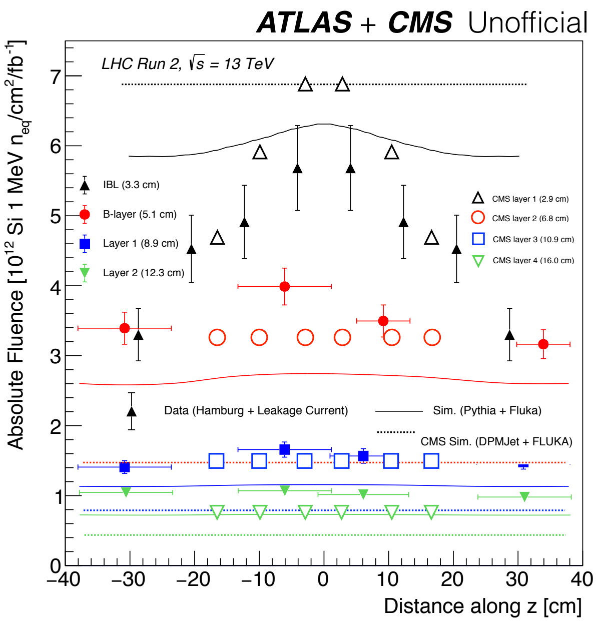

Fig. 6: blah

5 Impact of radiation on electronics & optoelectronics

Editors: M. Bindi, E. Butz
Contibuting authors: M. Backhaus; M. Bindi; P. Butti; E. Butz; W. Erdmann; R. Gerosa; B. Haney; H. Hillemanns; K. Padeken; F. Pinto; G. Pownhall; D. Robinson; A. Rozanov, J. Troska; T. Weidberg.

General introduction on the effects of radiation to electronics: ionising dose degradation, SEEs, etc.

5.1 ATLAS

5.2 CMS

5.3 LHCb

5.4 ALICE?

5.5 Inter-experiment comparisons

5.6 Discussion

Drawing conclusions from across the experiments.

References

6 Simulating radiation effects in silicon sensors and modelling charge response

Editors: M. Bomben, J. Sonneveld
Contibuting authors: M. Benoit, M. Bomben, E. Chabert, J. Merino, B. Nachman, L. Rossini, P. Sabatini, J. Sonneveld, C. Suarez, S. Swartz, T. Szumlak, A. Wang

Introduction ... TCAD etc.

6.1 ATLAS

6.2 CMS

6.3 LHCb

6.4 ALICE?

6.5 Inter-experiment comparisons

6.6 Discussion

Drawing conclusions from across the experiments.

References

7 Conclusions

References

[1] Morad Aaboud et al. Modelling radiation damage to pixel sensors in the ATLAS detector. *JINST*, 14(06):P06012, 2019.

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[8] ATLAS Collaboration. Pixel Depletion Voltage and Fluence Summary Plot for RD50. *ATL-INDET-INT-2019-016*, 2019.