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Modelling radiation damage effects to pixel sensors for the ATLAS detector

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A B S T R A C T

Silicon pixel sensors are at the core of the current ATLAS detector at the Large Hadron Collider (LHC), and as the detector component closest to the interaction point, they are exposed to a significant amount of radiation during operation. This paper presents a digitization model incorporating radiation damage effects to the pixel sensors. Predictions for basic pixel cluster properties such as the charge collection efficiency are also presented alongside validation studies with Run 2 collision data in ATLAS Pixel Detector.

Contents

1. The ATLAS Pixel Detector and Radiation Damage effects 677
2. Digitizer model 677
3. Validation with data 678
4. Conclusions 678
References 678

1. The ATLAS Pixel Detector and Radiation Damage effects[1]

The ATLAS [1] Pixel Detector [2] is the innermost component of the Inner Detector. It consists of four barrel layers and three disk layers per each end cap. The barrel layers are composed of n^+-in-n planar oxygenated silicon sensors and n^+-in-p 3D pixel sensors. The innermost layer, the Insertable B-Layer (IBL) [3,4], is located at just 3.3 cm from the beam pipe and is made of pixels of 50×250 μm^2 in size and 200 μm in thickness, while in the region with high $|z|$[2] of the IBL there are the 3D pixel sensors of 50×250 μm^2 in size and 230 μm in thickness. The other barrel layers are respectively at 5.05 cm, 8.85 cm, and 122.55 cm from the beam pipe and consist of pixels of 50×400 μm^2 in size and 250 μm in thickness. IBL was installed in ATLAS in May 2014 before the start of LHC Run 2, while the other three layers have been there since the beginning of Run 1. The IBL has received a total fluence of $\sim 6\times10^{14}$ n$_{eq}$/cm^2 until the end of 2017 (corresponding to a luminosity delivered by LHC of 92 fb^{-1}), while a total fluence of 18×10^{14} n$_{eq}$/cm^2 is estimated by the end of Run 3 in 2023 (with a total expected integrated luminosity of 300 fb^{-1}). The other three layers have received lower fluence from 0.8×10^{14} n$_{eq}$/cm^2 to $\sim 3.5\times10^{14}$ n$_{eq}$/cm^2.

2. Digitizer model

Charged particles crossing a sensor create electron–holes pairs that travel towards the electrodes due to the combined effects of the electric and magnetic field. They induce a signal in the collecting electrodes that is processed by the electronics. Exposition to high fluence induces defects inside the silicon sensor bulk that modify the electric field profile and enable charge carriers to be trapped with a certain probability inside the sensor, therefore reducing the collected charge. In this paper the simulated deposits of energy in the detector from particles (taken from Geant4 [6]) are transformed into digital signals with a specially developed software based on Allpix [7]. This simulation takes into account radiation damage effects, and also effects due to Lorentz angle, mobility, charge drift, and electric field. The electric fields inside the bulk of the sensor are obtained with a TCAD (Technology Computer Aided Design) tool with the addition of radiation damage effects, parametrized according to the Chiochia [8] model. When drifting, the charge carriers are considered trapped if the estimated time to reach the electrode is larger than a value extracted from an exponential distribution with lifetime tau. The lifetime is inversely proportional to

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[2] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis coinciding with the axis of the beam pipe. The x-axis points from the IP towards the centre of the LHC ring, and the y-axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z-axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$.

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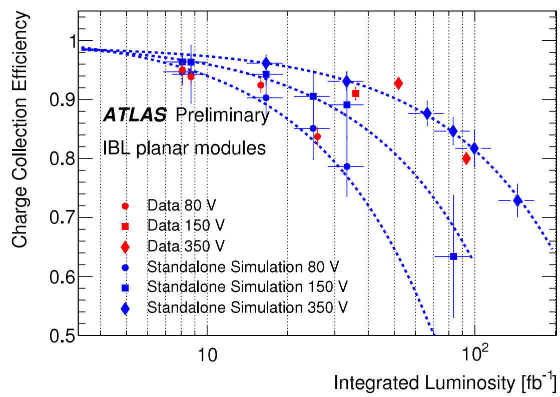

Fig. 1. Charge collection efficiency as a function of integrated luminosity. From [5].

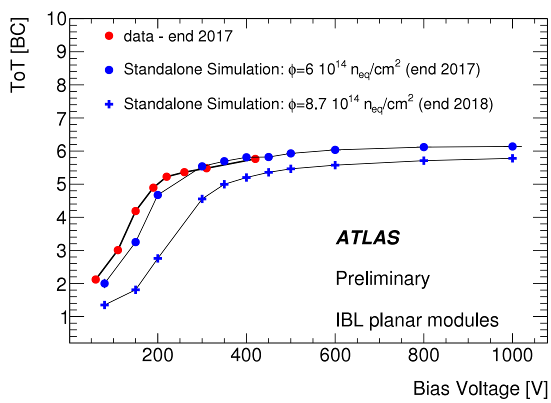

Fig. 2. Most probable value of ToT as a function of bias voltage. From [5].

the fluence with the proportionality constant being called k : $\tau = 1/k\phi$. In the simulation two different k are used for electrons and holes: $k_e = (4.5 \pm 1.5) \times 10^{-16}$ cm^2/ ns for electrons and $k_h = (6.5 \pm 1.0) \times 10^{-16}$ cm^2/ ns for holes. Uncertainties on the model are considered by varying the parameters in the TCAD simulation for the electric field and for the trapping probabilities.

3. Validation with data

Standalone simulations with Allpix are used to predict the evolution with fluence of the detector performance. This allows to validate the radiation damage model using collision data, and to predict future performance and plan operating conditions change to maintain a high detection efficiency. Simulation results are compared to data from Run 2 collected with the ATLAS IBL detector. During this time the bias voltage has been increased to cope with radiation damage: the IBL sensors have operated at 80 V in 2015, 150 V in 2016, and 350 V in 2017. One important observable to monitor is the collected charge, which is reported as the most probable value of the charge distribution. The charge collection efficiency (CCE) is defined as the ratio of the most probable value at a certain fluence with respect to the value for unirradiated sensors. The charge collection efficiency as a function of the delivered luminosity for central ($|\eta| < 0.8$) IBL modules is shown in Fig. 1. The agreement between data and simulation is good within the simulations uncertainties. Fig. 2 shows the evolution of the collected charge, expressed in Time over Threshold (ToT) as a function of the bias voltage for data from the end of 2017, and simulation for two fluences, corresponding respectively to the end of 2017 and end of 2018 for IBL modules. Again the simulation is in good agreement with data in both trend and absolute value, within uncertainties.

4. Conclusions

A modelling of the effects of the radiation damage in the ATLAS Pixel Detector has been presented. TCAD simulations with effective traps in the silicon bulk are used to model distortions to the electric field. Comparison between simulation and collision data have been shown to be in good agreement. The effects of the radiation damage in the ATLAS Pixel Detector are already measurable and the simulation framework presented here can be used to help to make decisions that ensure good online and offline performance and to guide the design of the future detector at the HL-LHC.

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