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Modelling radiation damage effects to pixel sensors for the ATLAS Detector

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Summary. — 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 the ATLAS Pixel Detector.

1. – The ATLAS Pixel Detector and radiation damage effects

The innermost layer of the ATLAS Pixel Detector [1] is the Insertable B-Layer (IBL) [2], is located at just 3.3 cm from the beam pipe and is made of n^+-in-n planar oxygenated silicon sensors pixels of $50 \times 250\,\mu\text{m}^2$ in size and $200\,\mu$m thick. The IBL has received a total fluence of $\sim 6 \times 10^{14}\, n_{eq}/\text{cm}^2$ until the end of 2017 (corresponding to a luminosity delivered by LHC of $92\,\text{fb}^{-1}$), while a total fluence of $18 \times 10^{14}\, n_{eq}/\text{cm}^2$ is estimated by the end of Run 3 in 2023 (with a total estimated integrated luminosity of $300\,\text{fb}^{-1}$).

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 induced charge. In simulations deposits of energy in the detector from particles (taken from Geant4 [3]) are transformed into digital signals using a specially developed software based on Allpix [4]. This simulation takes into account effects due to radiation damage and to Lorentz angle, mobility, and charge drift. 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 [5] model.

When drifting, the charge carriers are considered trapped if the estimated time to reach the electrode is larger than a random trapping time τ exponentially distributed

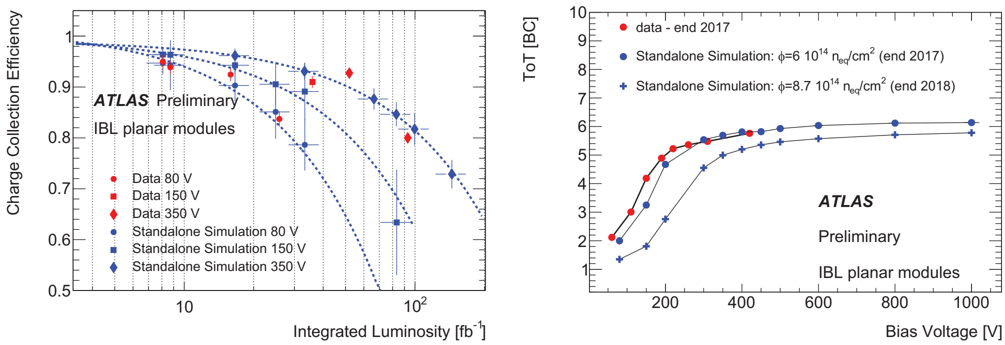

Fig. 1. – Left: charge collection efficiency as a function of luminosity. Right: most probable value of ToT as a function of bias voltage (taken from [6]).

as $1/k\phi$, where ϕ is the fluence and k is the trapping constant. In the simulation two distinct k are used for electrons and holes: $k_e = 4.5 \pm 1.5 \times 10^{-16}\,\mathrm{cm}^2/\mathrm{ns}$ for electrons and $k_h = 6.5 \pm 1.0 \times 10^{-16}\,\mathrm{cm}^2/\mathrm{ns}$ for holes. Uncertainties on the model are considered by varying the parameters in the TCAD simulation for the electric field and the trapping probabilities. Standalone simulations with Allpix are used to predict the evolution with fluence of the performance of the detector. This allows to validate the radiation damage model using collision data, and predict future performance and plan operating conditions change to maintain a high detection efficiency. The charge collection efficiency (CCE), defined as the ratio of the most probable value at a certain fluence with respect to the value for unirradiated sensors, is shown in fig. 1 on the left as a function of the delivered luminosity for central IBL modules. 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, is shown in fig. 1 on the right. In both cases the simulations are in good agreement with data in both trend and absolute value, within uncertainties.

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