PROCEEDINGS OF SCIENCE

Including radiation damage effects in ATLAS Monte Carlo simulations: status and perspectives

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Signal reduction is the most important radiation damage effect on performance of silicon tracking detectors in ATLAS. Adjusting sensor bias voltage and detection threshold can help in mitigating the effects but it is important to have simulated data that reproduce the evolution of performance with the accumulation of luminosity, hence fluence. ATLAS collaboration developed and implemented an algorithm that reproduces signal loss and changes in Lorentz angle due to radiation damage. This algorithm is now the default for Run3 simulated events. In this paper the algorithm will be briefly presented and results compared to first Run3 collision data. For the high-luminosity phase of LHC (HL-LHC) a faster algorithm is necessary since the increase of collision, event, track and hit rate imposes stringent constraints on the computing resources that can be allocated for this purpose. The philosophy of the new algorithm will be presented.

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1. Introduction

Vertexing and tracking detectors at the CERN Large Hadron Collider (LHC) experiments, being the closest instruments to particle collisions, are exposed to high radiation fields; as an example, at the end of Run2 the innermost ATLAS [1] Pixel Detector layer - Insertable B-Layer (IBL) [2] - integrated a radiation damage fluence of about 9×10^{14} $\mathrm{n_{eq}/cm^2}$ [†] and a dose in excess of 50 Mrad. Radiation damage to Si sensor bulk [3] determines change of operation conditions and of physics performance; increasing the bias voltage, operating the detector at low temperature and adjusting the hit-detection threshold can help in coping with these effects, but is it important to have simulated events that can mimic the evolution of physics performance with the accumulation of radiation damage. For this reason the ATLAS collaboration developed an algorithm [4] to simulate radiation damage effects in Si bulk; this algorithm is activated by default for the generation of Monte Carlo (MC) events for Run3.

In this report the main effects of radiation damage to sensors will be summarised in Section 2; the algorithm to simulate the modification of performance with fluence will be presented in Section 3. Comparison of collision and simulated data in ATLAS IBL and Pixel Detector will be shown in Section 4; the challenges of the High-Luminosity phase of LHC (HL-LHC) [5] and the strategy for a new algorithm will be discussed in Section 5. Section 6 will conclude the report.

2. Radiation Damage to Sensor Bulk

The collisions of LHC protons produce radiation fields which induce damage into the Si bulk of pixel sensors. At microscopic level the high energy hadrons from the protons collisions create energy levels in the forbidden gap, which can trap carriers and/or generate extra electron-hole pairs. Due to these mechanisms the detector behaviour change, with operation and performance degradation; the former include increase of the leakage current and of the operational voltage, the latter a reduction in charge collection efficiency. Moreover the charged defects alter the distribution of space charge in the bulk, hence the electric field profile. For in-depth discussion of radiation damage to silicon detectors for example see [3]. In the next Section the modelization of such radiation damage effects in ATLAS MC events will be presented.

3. Radiation Damage Digitizer

The IBL and Pixel Detector are the closest measuring instruments of the entire ATLAS experiment, with IBL - in operation since 2015 - at only 3.3 cm from the beam axis. The detector [2, 6] comprises four barrel layers and 3+3 disks of pixels modules; sensors are all planar n^+-on-n, apart from 3D n^+-on-p sensors in the forward part of IBL. The pitch of IBL sensors is $50{\times}250$ $\mu\mathrm{m}^2$, while all other layers feature $50{\times}400$ $\mu\mathrm{m}^2$ pitch. IBL planar (3D) sensors are 200 (230) μm thick, while outer layers and disks feature 250 μm thick sensors. For details on ATLAS IBL and Pixel Detector performance please see [7].

In order to follow closely the evolution of its IBL and Pixel Detector the ATLAS collaboration developed an algorithm to simulate radiation damage effects in MC events [4]. To calculate the signal induced on electrodes the algorithm makes the carriers produced by ionising particles drift by

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[†] Fluence is normalised to the damage produced by neutrons of 1 MeV

taking into account several effects. The carriers speed is calculated using the product of mobility [8] and electric field. The latter is simulated using TCAD [‡] tools. A limited number of effective defects are used in the simulations to reproduce the effects of radiation damage; for planar sensors the Chiochia model [9] was choosen, the LHCb model [10] for 3D. In Figure 1 an example of simulated electric field profiles in IBL planar sensors is shown.

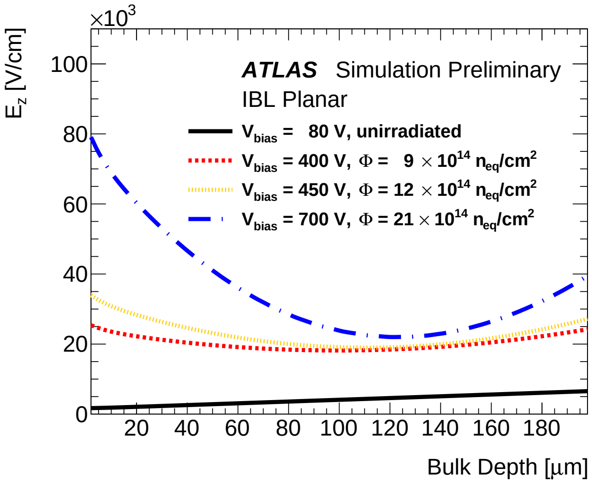

Figure 1: TCAD simulated electric field profile of IBL planar sensors in Run2 and Run3. The electric field projection along the bulk is presented as a function of the bulk depth; the electrons drift towards lower z values [11]. The Chiochia model [9] was choosen to simulate the radiation damage effects.

It is interesting to note that with irradiation the electric field features two maxima with a deep minimum in the middle. From these simulated profiles the average deflection due to Lorentz force is calculated; the combined effect of electric and magnetic field is then used to estimate the time for a carrier to reach the respective collecting electrode. If the expected collection time is lower than a randomly generated trapping time then the carrier is considered trapped and its induced signal will be calculated using a pre-computed weighting potential [12] map of the sensor. The algorithm is now the default for the simulation of events in ATLAS MC.

4. Results

The radiation damage digitizer has been validated on collision data in several data taking conditions and looking at different cluster observables. A first example can be found in Figure 2 where the measured cluster charge distribution for IBL planar and 3D sensors is shown and compared to MC simulation; a study of long clusters (> 3 pixels) is also reported.

The agreement in cluster charge distribution is remarkable, at the 1% level when the Most Probable Value (MPV) of the distributions are compared. It is worth noting that planar and 3D sensors differ not only in technology but also in material bulk and TCAD radiation damage model. In the Figure the result from simulated events without radiation damage effects is reported for planar sensors; it is evident the inadequacy of such description. The study of long clusters indicate that the agreement is excellent even looking at charge deposition at different depths; this is a signal of the precise modelization of the electric field profile in the bulk.

[‡] Technology Computer Aided Design

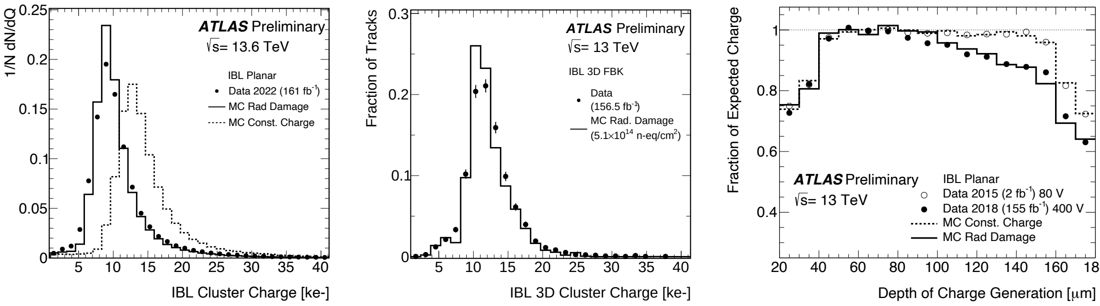

Figure 2: Comparison of cluster charge distribution in data (points) and MC (histograms) for IBL (left) planar sensors and (center) 3D sensors [13, 14]. The dashed (continuous) histogram is for simulated events with (without) radiation damage effects. The fluence for IBL planar is estimated to be of about 9×10^{14} n_{eq}/cm^2. (right) Relative charge collection efficiency as a function of charge deposition depth in the bulk for IBL planar sensors. Here the data from pristine sensor (open points) are reported too.

The MPV of the cluster charge distribution is studied also as a function of the integrated luminosity; results for data and MC events are presented in Figure 3 again for IBL planar and 3D sensors. The results are reported as charge collection efficiency (CCE), having normalised the MPV to the value before irradiation.

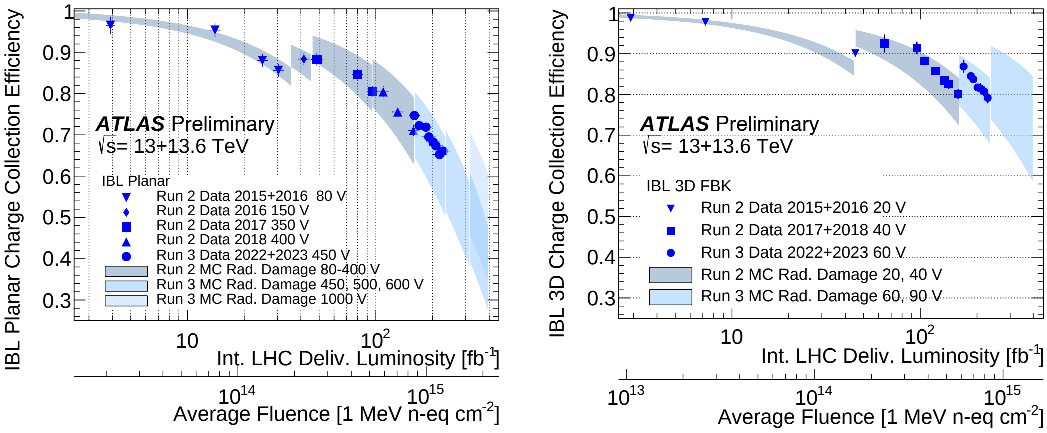

Figure 3: Comparison of the evolution of CCE with integrated luminosity for IBL (left) planar and (right) 3D sensors in data (points) and MC events (bands) [15]; the corresponding radiation fluence is also indicated. The vertical bands include the estimated uncertainty affecting the input parameters of TCAD radiation damage model and of the trapping constants.

The MC predictions follow closely the data on almost two order of magnitude of radiation fluence. Thanks to this excellent agreement the tool is used to predict expected CCE as a function of additional integrated luminosity, to prepare operation conditions and calibrate reconstruction tools.

5. High Luminosity: Challenges and Strategies

The High Luminosity phase of LHC will deliver an instantaneous luminosity 5 to 7 times larger than the nominal LHC one (1×10^{34} /cm^2/ns) with the goal to integrate up to 4000 fb^{-1}. Particle, hit and occupancy rate will increase accordingly; the radiation fluence will reach a value ten times higher than today in the innermost pixel layer. All these challenges require a new vertexing and tracking detector, the ATLAS Inner Tracker [5]. The new detector will be installed in 2028 and will consist at the core of 5 pixel barrel layers plus several rings in the forward region. 3D sensors will be used in the innermost barrel and ring, the former with a 25×125 μm^2 pitch, the latter with a 50×50 μm^2 pitch. All the other pixel detectors will be based on planar sensors, either 100 μm or 150 μm thick, always with a 50×50 μm^2 pitch.

The high rate of events at HL-LHC will impose strict requirements also on computing resources for the simulation of MC events. Despite the excellent performance of the actual radiation damage digitizer the algorithm is considered too slow for HL-LHC. Hence a faster - yet as performant as possible - algorithm is being designed. The basic idea of it is sketched in Figure 4.

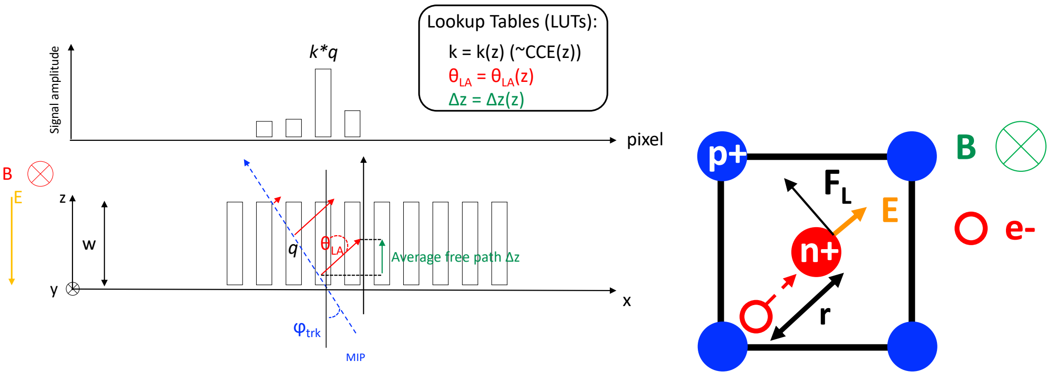

Figure 4: Sketch of the algorithm for the radiation damage digitizer at HL-LHC. (Left) in planar sensors LUTs as a function of the depth z in the bulk will be used to determine the final position of carriers and also the relative induced signal. (Right) for 3D sensors the expected signal will be calculated as a function of the radial distance r from the central electrode; for a sensor in a ring module the orientations of electric field E, the magnetic field B and of the Lorentz force F_L are also indicated.

The final position of a carrier produced at depth z will be determined using Lookup Tables (LUTs) containing the average path $\Delta z(z)$ and Lorentz angle $\theta_{LA}(z)$; another LUT will be used to scale with a factor $k(z)$ the induced signal as a function of the carrier generation depth z in the bulk. LUTs will be calculated using the Allpix^2 [§] simulation tool with TCAD simulations of the electric field as input. For 3D sensors the radial distance r of the carrier with respect to the centre of the n$^+$ column will be used instead of deposition depth. For 3D sensors in the barrel layer the Lorentz force is negligible due to the electric and magnetic field being parallel. For 3D sensors in the rings the effect of Lorentz force is to make carriers drift in a curved path; preliminary results indicate that the effect is again negligible.

6. Conclusions and Outlook

Radiation damage effects in ATLAS Pixel Detector are sizeable, charge collection reduction being the most notable effect. The radiation damage digitizer developed by ATLAS collaboration is able to reproduce - and anticipate - the effects with a precision of 1%. Despite the success the algorithm will be upgraded for HL-LHC with a faster version based on LUTs.

[§] https://allpix-squared.docs.cern.ch/

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