Modeling Radiation Damage to Pixel Sensors in the ATLAS Detector

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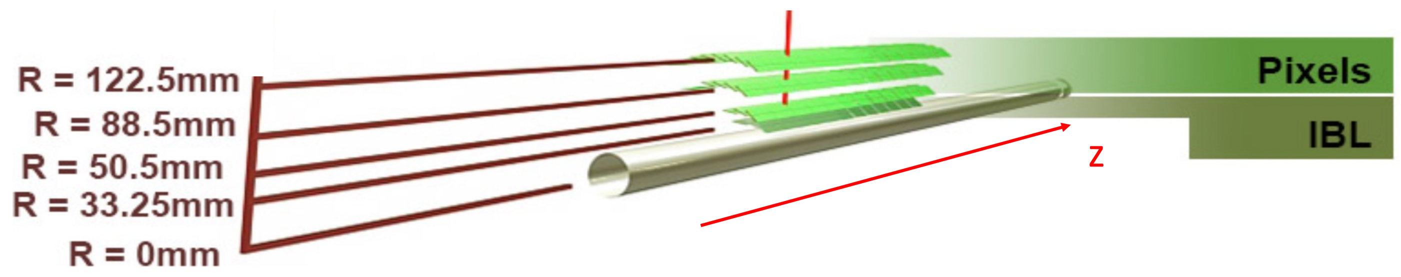
ATLAS Pixel detector

In Run 2 and Run 3, ATLAS Pixel detector[1,2] is made of 4 barrel layers and 3 disk layers at each end cap.



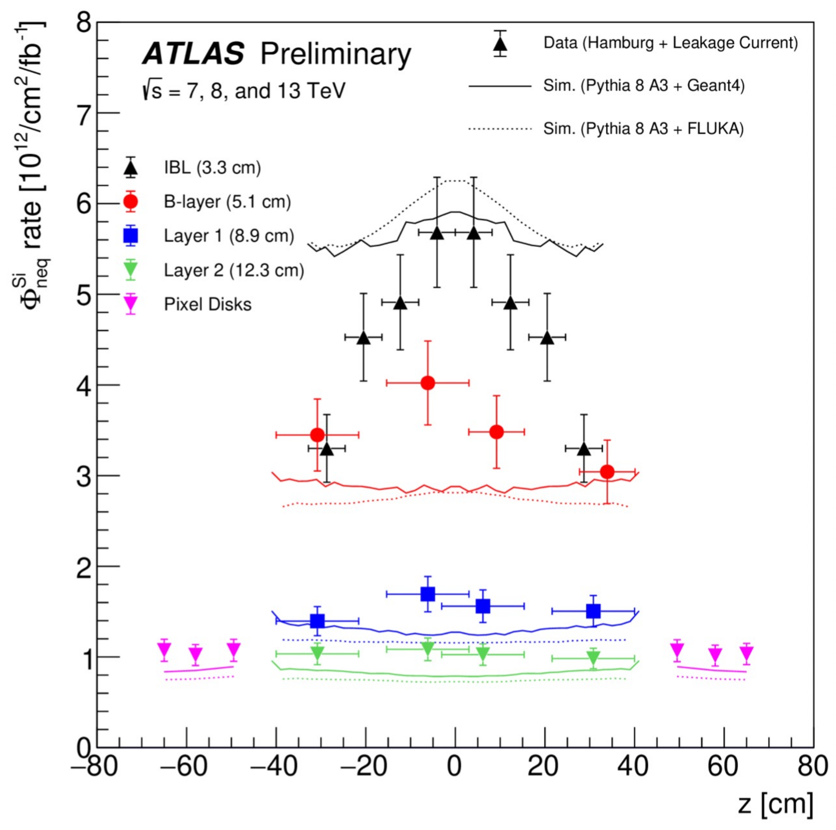
3 outer layers (planar)

- B-Layer, Layer 1 and 2
- Pixel size 50 x 400 μm^2
- 250 μm thickness (n-in-n)
- FEI3 readout

1 innermost Layer (planar + 3D)

- Insertable B-Layer (IBL)
- Pixel size 50 x 250 μm^2
- planar: 200 μm thickness (n-in-n)
  3D: 230 μm thickness (n-in-p)
- FEI4 readout

Radiation damage



Non-ionizing interactions from heavy particles and nuclei lead to radiation damage, which modifies the sensor bulk and can alter the detection of minimum-ionizing particles (MIPs).

As the closest detector component to the interaction point, pixel detectors are subjected to a significant amount of radiation over their lifetime.

The innermost layer has received a fluence Φ of ~ $\mathbf{1 \times 10^{15}}$ **1 MeV n_{eq}/cm^2** at the end of Run 2, and it will receive a fluence of ~ $\mathbf{1.8 \times 10^{15}}$ **1 MeV n_{eq}/cm^2** at the end of Run3.

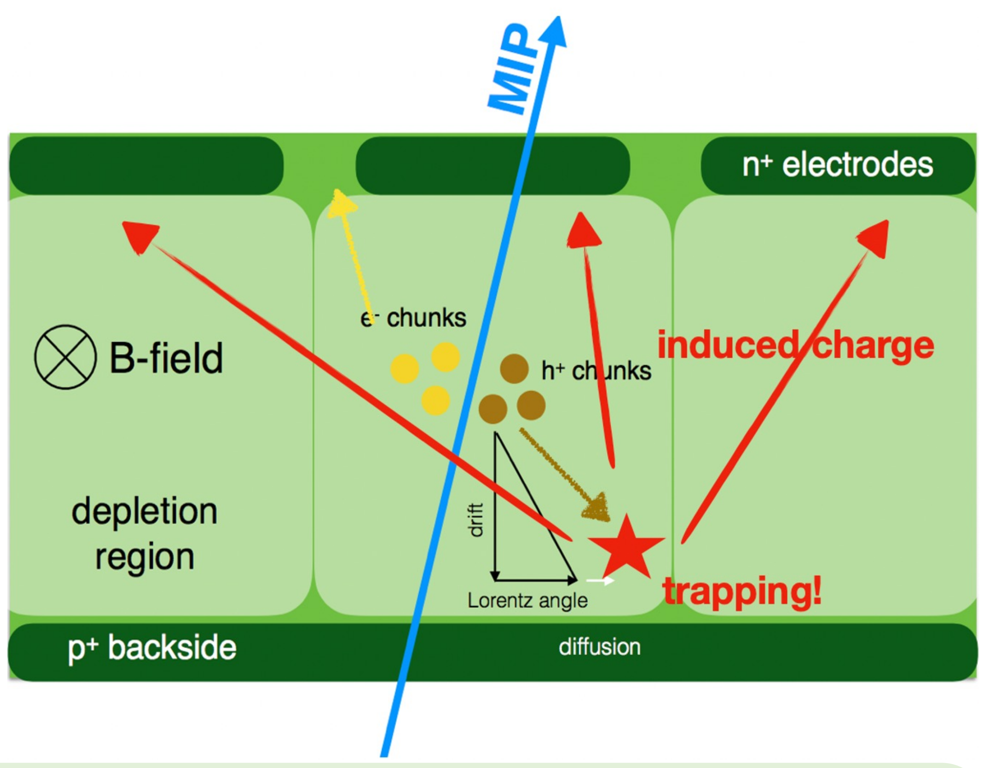
Stronger fluence dependence on z than predicted by simulations on IBL and B-Layer.

ATLAS Pixel detector digitizer

Radiation damage effects are implemented in the digitization step of the simulation[3], where the energy depositions of charged particles are converted into digital signals sent from module front ends to the detector readout system.

Digitizer accounts for:

- Grouping the charges in “chunks” to speed up the simulation
- Drift of charges
- Electric field simulation
- Lorentz angle deflection from E/B fields
- Charge trapping
- Ramo potential to account for induced charge
- Charge conversion to Time-over-Threshold (ToT)

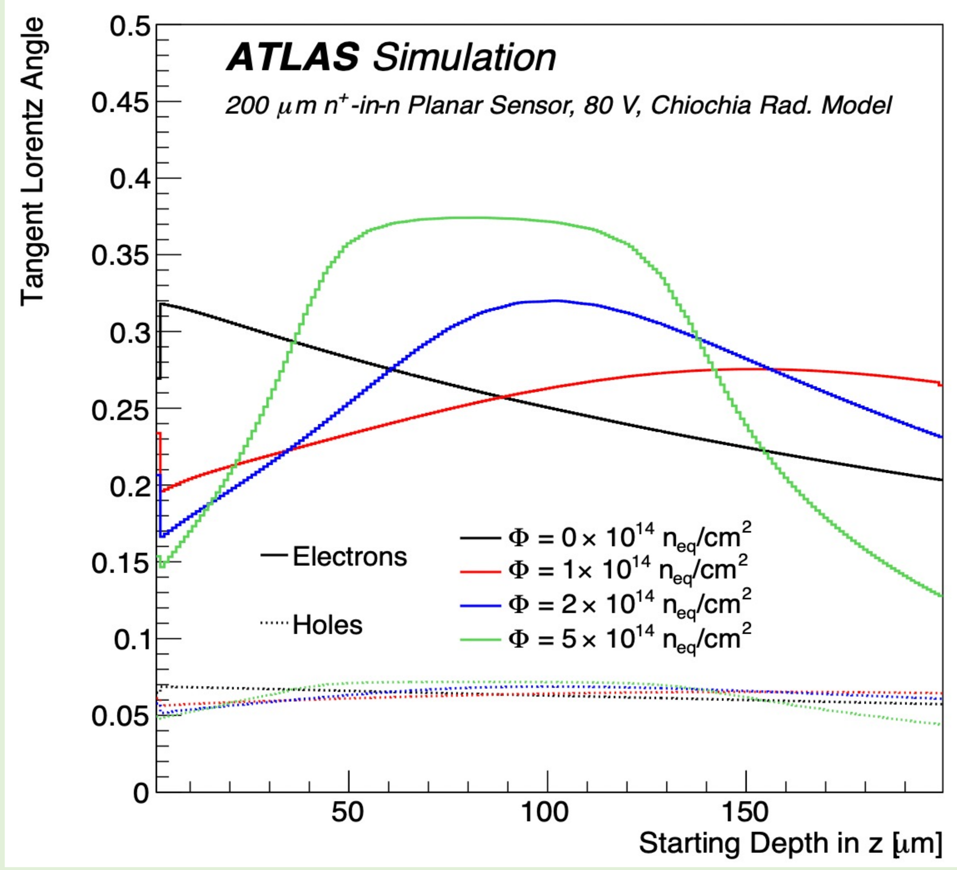


Lorentz angle deflection

Radiation damage modifies the electric field shape and therefore the Lorentz angle θ_L.

Lorentz angle depends on the initial and final positions of the charge carriers and needs to be integrated over path

$$\tan\theta_L(z_{initial}, z_{final}) = \frac{\overbrace{rB}^{\text{Hall scattering factor}}}{|z_{final} - z_{initial}|}\int_{z_{initial}}^{z_{final}} \underbrace{\mu(E(z))}_{\text{Mobility}}\,dz$$



Electric field simulation

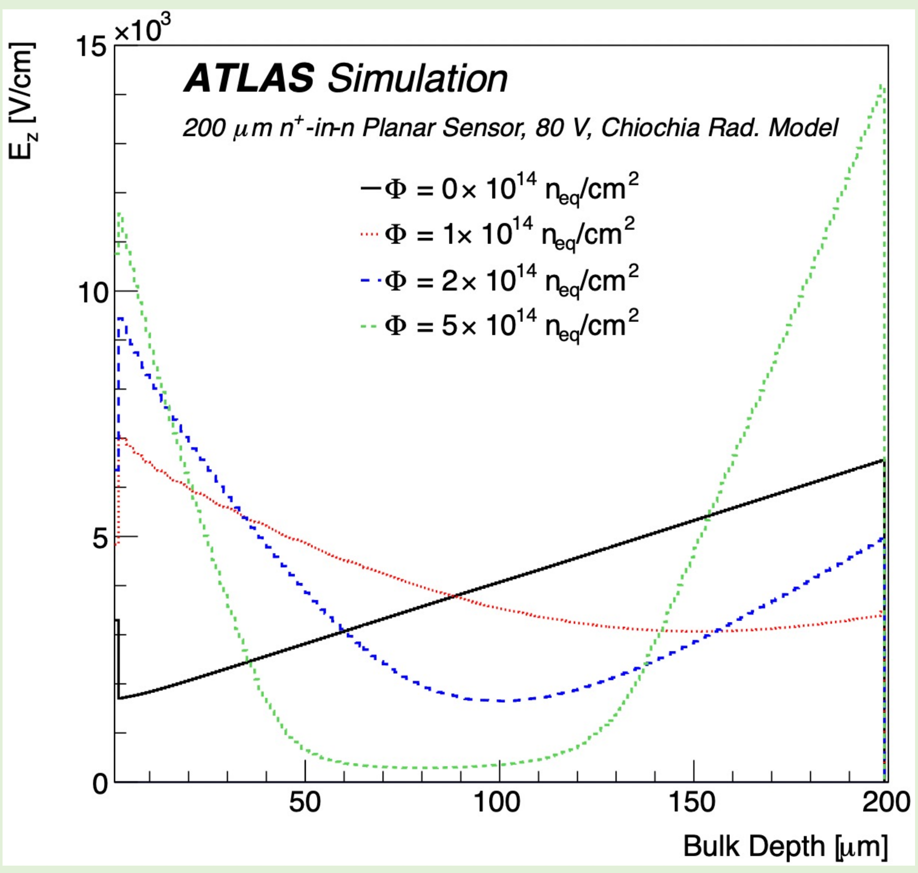
Radiation damage produces defects in the sensor that change the effective doping concentration.

Electric field profile (E_z) depends on:

- Fluence
- Type of irradiation
- Operation temperature
- Time and temperature during detector lifetime (annealing)

Simulations of electric field profiles using TCAD tool. Typical “U” shaped electric field for the planar sensors (double junction effect).

Chiochia model[4] used for planar irradiated sensors.



Charge trapping

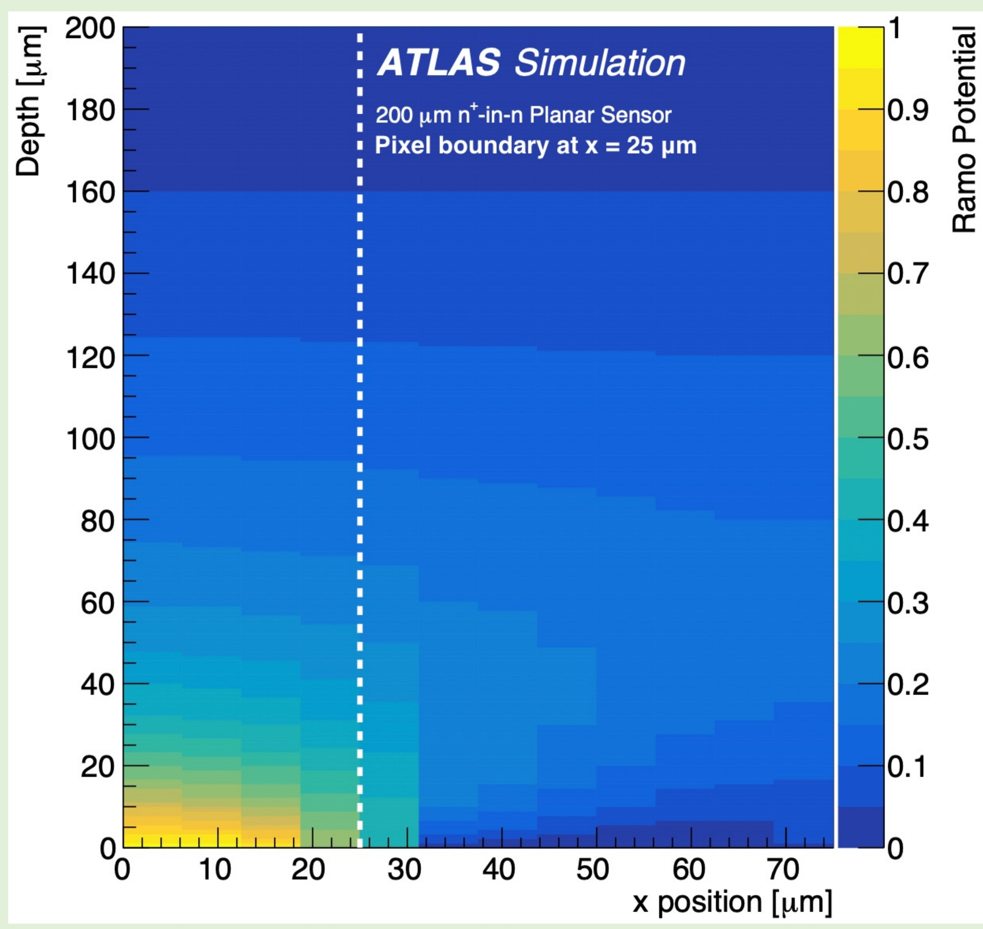
Defects formed in the silicon sensors are sites for charge trapping.

Charges are trapped if the time to reach the electrode exceeds a trapping time τ, which is exponentially distributed with mean value $1/(\beta_{e/h}\Phi)$, where $\beta_{e/h}$ is the trapping constant dependent on the type of charge carriers.

Trapped charges q induce a partial signal on the electrode, given by

induced charge = - q (R_f - R_i)

where R_f and R_i are the Ramo potential in the final and initial positions.

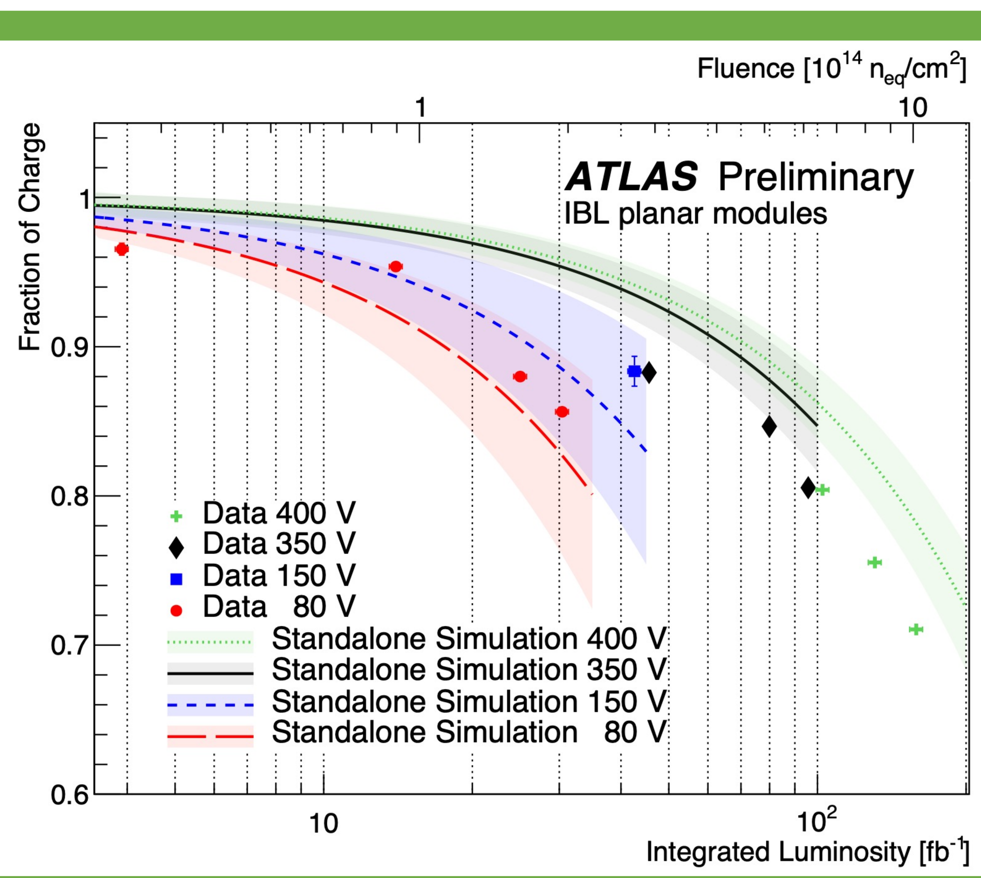


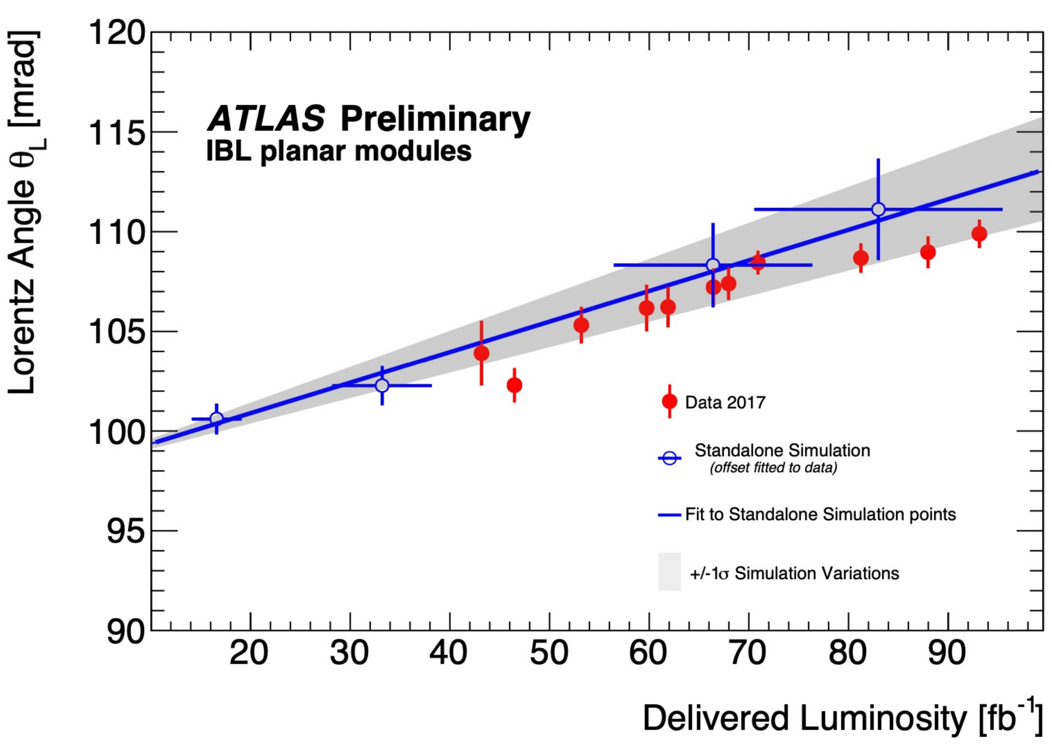
Simulation & Validation

Simulation and validation of the radiation damage effects throughout the ATLAS Run 2.

Direct way to see the impact of radiation damage: charge collection efficiency. More fluence means more trapping so less charge collected. The charge collection efficiency gradually decreases with integrated luminosity until there are regions of the sensor with a small electric field, at which point there are significant losses. After switching the bias voltage in the IBL from 80 V to 150 V for detector operation, the charge collection efficiency increased.

As a consequence of the “U” shaped electric field, the Lorentz angle shows an increasing trend as a function of the integrated luminosity, as confirmed from the simulation.





Conclusions

Comparisons between simulations using the radiation damage model and collision data indicate that within the current precision, the fluence-dependence of charge collection and the Lorentz angle are well-reproduced. These quantities are quite sensitive to variations in the radiation damage parameters, and further collision data may even be used to constrain the radiation damage models.

Sensors designed for the High Luminosity LHC (HL-LHC) will need to cope with about an order of magnitude more fluence. The experience developed in Run 2 and Run 3 from the continued monitoring and modeling the radiation damage effects will feed pixel operation at HL-LHC.

References

[1] ATLAS Collaboration, “*ATLAS pixel detector electronics and sensors*”, JINST 3 (2008) P07007.
See also poster n. 416 “*Operational Experience and Performance with the ATLAS Pixel detector at the Large Hadron Collider at CERN*” for further details.
[2] ATLAS Collaboration, “*Production and Integration of the ATLAS Insertable B-Layer*”, JINST 13 (2018) T05008.
[3] ATLAS Collaboration, “*Modelling radiation damage to pixel sensors in the ATLAS detector*”, JINST 14 (2019) P06012, DOI: 10.1088/1748-0221/14/06/P06012.
[4] V. Chiochia et al., “*A double junction model of irradiated silicon pixel sensors for LHC*”, Nucl. Instr. and Meth A 568 (2006) 51-55.