Modeling Radiation Damage to Pixel Sensors in the ATLAS Detector

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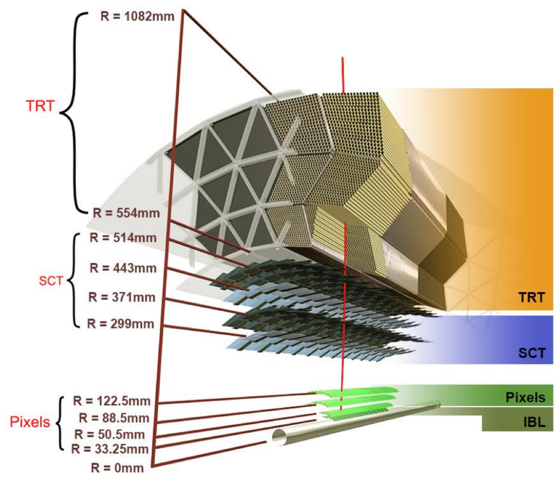
The ATLAS Pixel detector

The **ATLAS Pixel** [1][2] detector is the innermost part of the Inner Detector (ID). 4 Barrel + 2x3 Disk Layers.

Three outer layers
- B-Layer, Layer 1 and 2
- 50 x 400 μm²
- 250 μm thickness
- FEI3 readout - 8 bit ToT

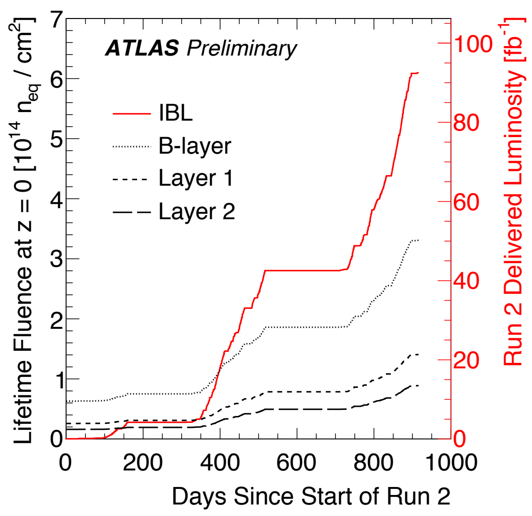
Innermost Layer: **IBL** (planar and 3D)
- 50 x 250 μm²
- planar: 200 μm thickness
- 3D: 230 μm thickness (n-in-p)
- FEI4 readout - 4 bit ToT
- **3.3 cm from beam pipe**



Fluence Levels

IBL is the most sensitive layer to radiation damage, already with a measurable impact on tracking.
Total **IBL cumulated fluence** and corresponding LHC delivered luminosity. Values referring to 2023 are estimates and correspond to the end of Run 3.

year	2016	2017	2023
Fluence $[\times \mathbf{10^{14}} n_{eq}/\mathrm{cm}^2]$	2.4	6	18
Total LHC delivered luminosity $[\mathrm{fb}^{-1}]$	42	93	300

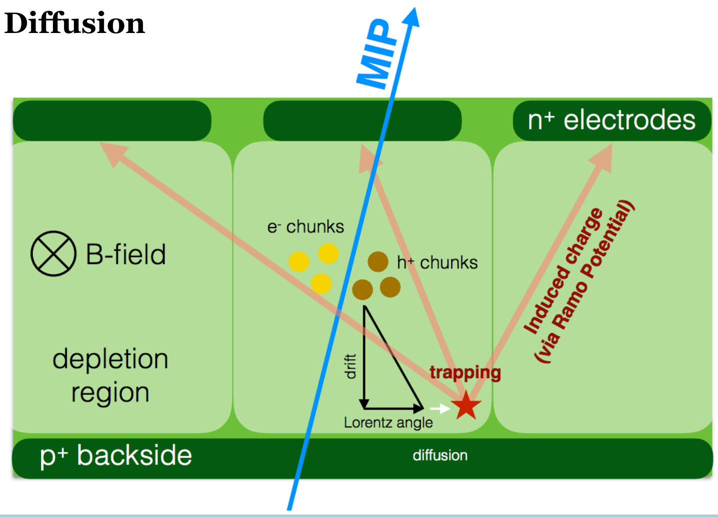


Simulation Scheme

A software based on Allpix[3] that **simulates the charge induced on the electrodes by the deposit of energy in the detector from particles** (taken from Geant4) has been developed. The various components are illustrated in the figure below.

Drift and diffusion model have been augmented to include effects such as:

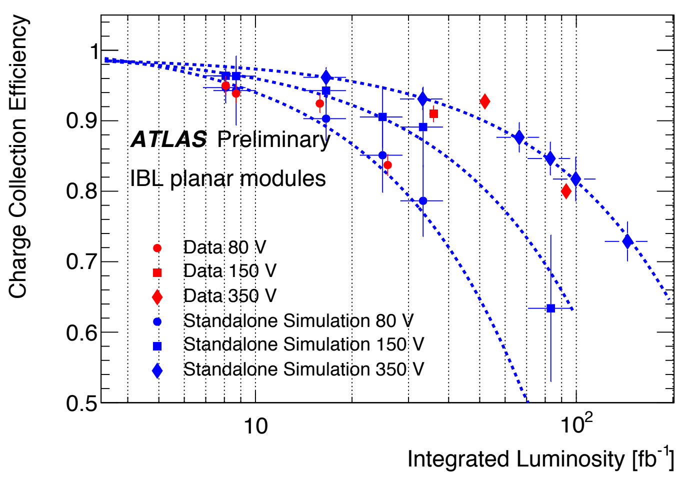
- Modification of the Electric field (Simulated with **TCAD** technology and with radiation damage effects based on model [4])
  - Charge **drift**
  - **Lorentz Angle**
- Trapping **probability**
- **Ramo Potential** to account for induced charge
- **Diffusion**



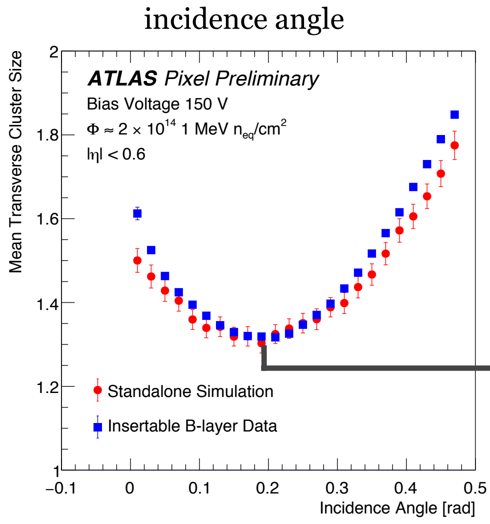
Results

Simulations based on Allpix have been developed to predict the evolution of the performance parameters of the detector with fluence, such as: **charge collection efficiency** (CCE), the fraction of charge with respect to the non-irradiated case, and **Lorentz Angle**, the angle minimizing the transverse cluster size. Comparisons with data from 2016 and 2017 with 80, 150, and 350 V are shown in the figure. Simulation error bars account for radiation damage model parameter variations (trapping constant, introduction rates, and capture cross-sections).

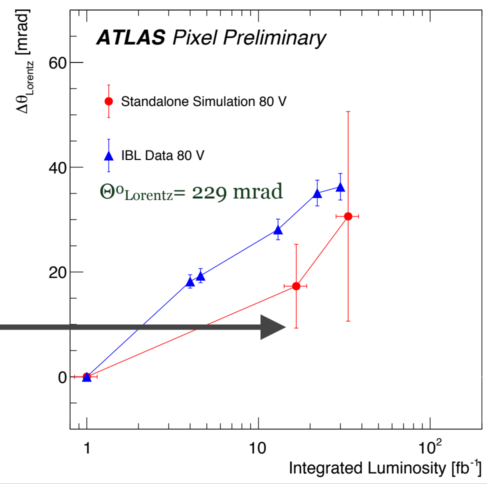
CCE as a function of integrated luminosity



Average pixel cluster size as a function of incidence angle



Lorentz angle as a function of integrated luminosity

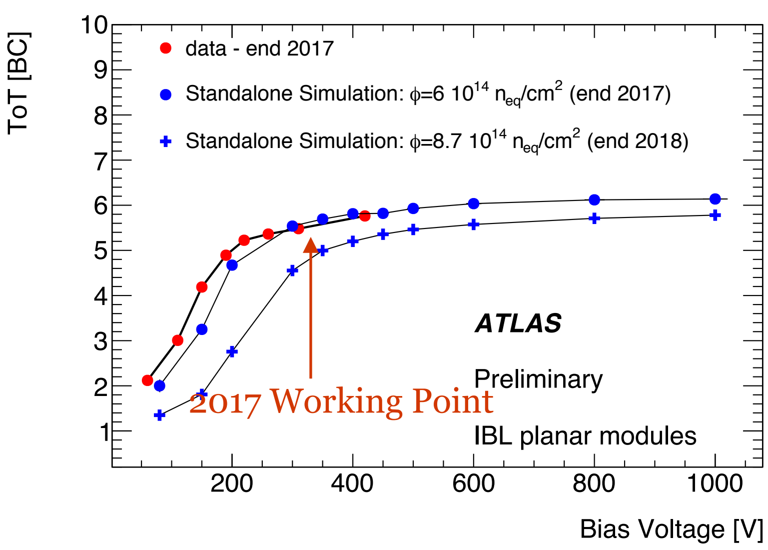


Future Operations

Simulation is also used to predict future operational conditions, allowing to change them in time to maintain a high detection efficiency.

The **most probable value of ToT** (Time over Threshold) of the **IBL** pixel clusters as a function of the Bias Voltage working point is shown in the figure.

In order to have the same ToT we will need to increase the Bias Voltage working point.



Conclusions

Effects of radiation damage are already visible in the pixel detector:

- Simulation is in **good agreement** with data within the systematic uncertainties on simulation - need to constrain these in the future.
- Predictions allow to set a **new working point** in order to maintain a high detection efficiency.

Bibliography

[1] ATLAS Collaboration. "The ATLAS Experiment at the CERN Large Hadron Collider". In: JINST 3 (2008), S08003.
[2] G. Aad et al., ATLAS pixel detector electronics and sensors, JINST 3 (2008) P07007.
[3] Allpix: https://twiki.cern.ch/twiki/bin/view/Main/AllPix
[4] V. Chiochia et al. A Double junction model of irradiated silicon pixel sensors for LHC. Nucl. Instrum. Meth., A568:51–55, 2006.