Modeling Radiation Damage to Pixel Sensors in the ATLAS Detector

EPS online, 2021

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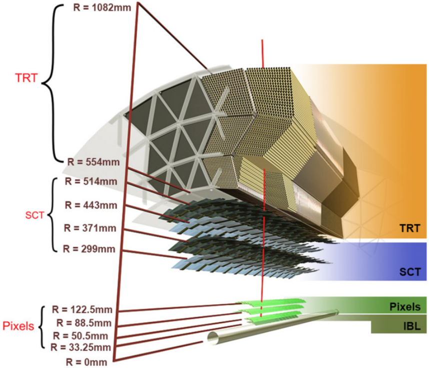
July 27, 2021

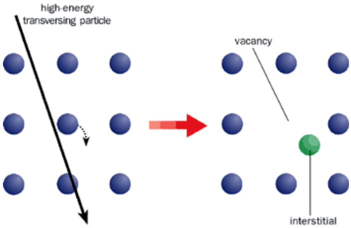
Pixel detectors in ATLAS

- ATLAS Inner Detector: **Pixel**, SCT and TRT
- Pixel: 4 barrel layers + 3 disks
- Innermost layer: IBL (installed between Run 1 and 2)
- Sensors
  - n^+-in-n **planar** sensors
  - IBL planar: 200 μm thick
  - IBL high $|z|$: n^+-in-p **3D**
    - 230 μm thick
  - Other pixel layers: 250 μm
- Pixel pitch
  - IBL: $50 \times 250 \mu m^2$
  - Other: $50 \times 400 \mu m^2$



Radiation damage effects

- Radiation damage to bulk
  - Displacing a silicon atom
  - Change in effective doping concentration
  - Charge trapping
  - Increase in sensor leakage current
- **Annealing** effects - depend on irradiation and temperature history

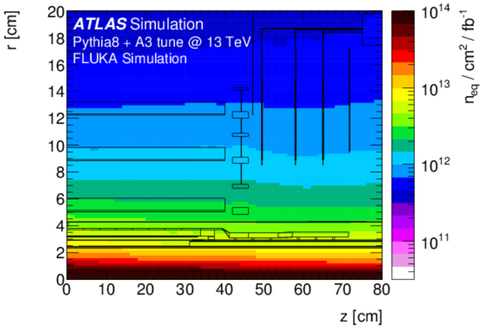


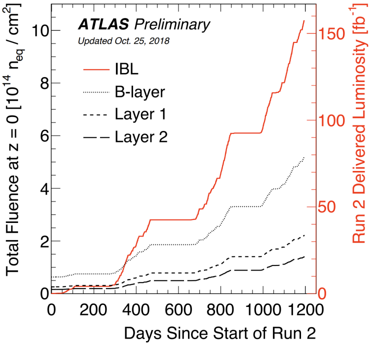
Macroscopic effects

- Change in doping $\rightarrow$ change in depletion voltage, and E profiles
- Charge trapping $\rightarrow$ reduced signal collection efficiency

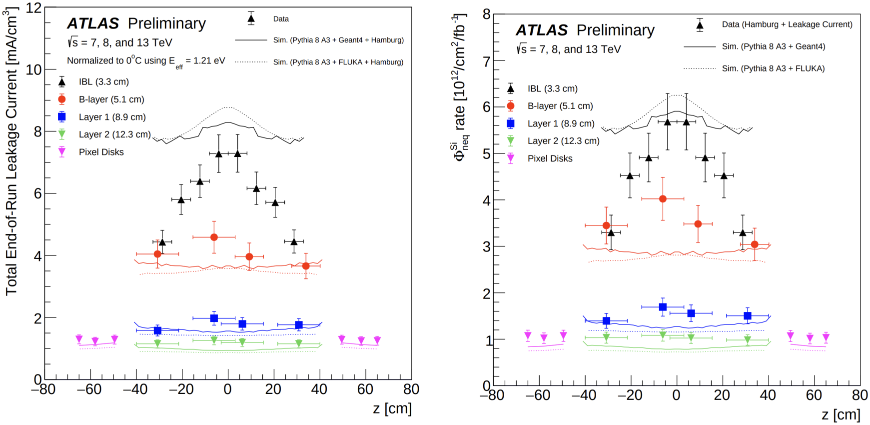
Fluence estimation

- 1 MeV n_{eq} cm^{-2} per fb^{-1} estimated with Pythia8 + FLUKA
- **Fluence/fb**$^{-1}$ for IBL $z = 0$: 6.2×10^{12} $n_{eq}/cm^2/fb^{-1}$(mostly pions)
- Luminosity measured using dedicated sub-detectors





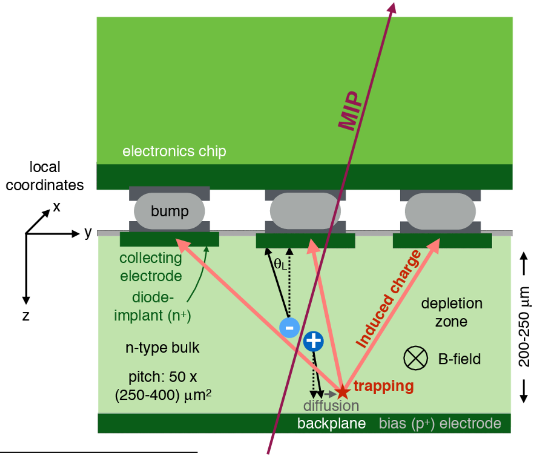
Fluence from leakage current measurement



- **Stronger** $|z|$ dependence in data than predicted in IBL
- Discrepancy origins: temperature, depletion voltage, modeling of particles, transport/radiation/annealing models

Digitizer scheme

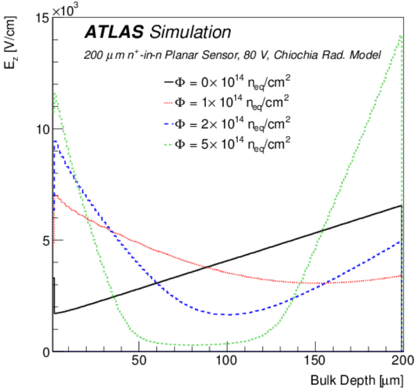
- Reflects the microscopic changes - impact on charge collection
- **Simplified** model[1] due to CPU requirements



[1] JINST 14 (2019) P06012

Electric field

- Simulated using the default two-trap **TCAD** model
- Irradiation effects simulated using **Chiochia** model[2]
- Field no longer linear with the bulk depth
- Uncertainties of up to 30% (parameter variation)



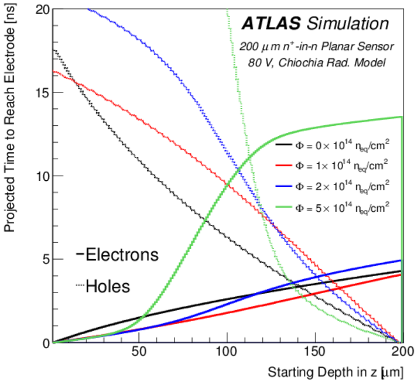
Annealing effects

- Difficult to incorporate in TCAD, Hamburg model - trivial space-charge dependence on depth
- Effective scenario: minor impact (3%) on acceptor trap concentration - negligible

[2] Nucl. Instrum. Meth. A 568 (2006) 51

Trapping time, position

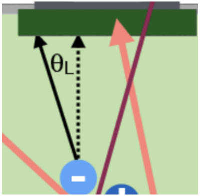
- Propagating charges CPU expensive - **pre-computed** once per geometry
- $t_{\text{collection}}(x_{\text{initial}}) \approx \int_C \frac{ds}{\mu(E)E}$
- Reduces to 1D integral for planar sensor
- $x_{\text{trap}}(t_{\text{trap}}) \approx \int_0^{t_{\text{trap}}} \mu(E)E\,dt$
- Trapping time: random exponentially distributed with mean value $1/\beta\Phi$

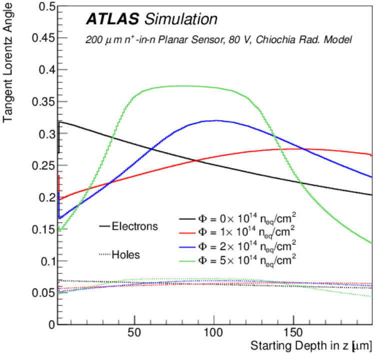


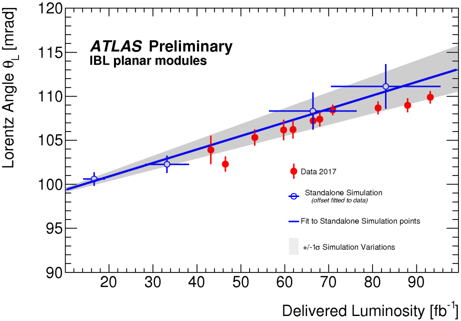
- $\beta_e = (4.5 \pm 1.5) \times 10^{-16}\text{cm}^2/\text{ns}$, $\beta_h = (6.5 \pm 1.5) \times 10^{-16}\text{cm}^2/\text{ns}$

Lorentz angle

- Change in E field → change in mobility → change in Lorentz angle
- $\tan \theta_L^{\text{integrated}} = \frac{rB}{|z_{\text{final}} - z_{\text{initial}}|} \int_{z_{\text{initial}}}^{z_{\text{final}}} \mu(E(z))\, dz$

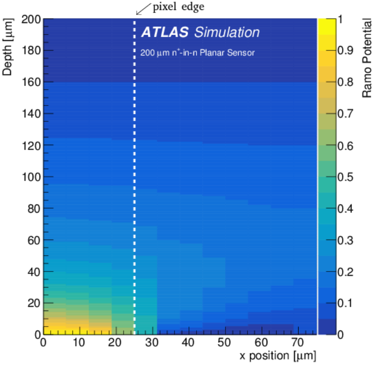


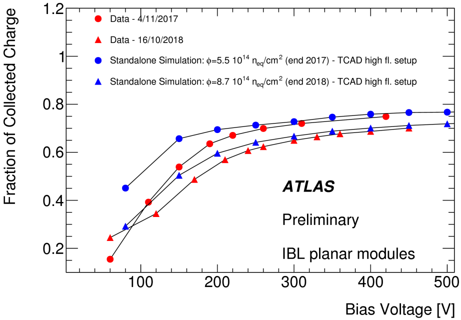




Ramo potential

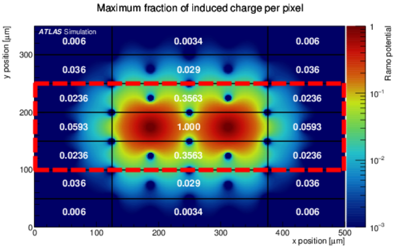
- Signal induced even for trapped charges
- $Q_{\text{induced}} = -q\left(\phi_W(\vec{x}_{\text{end}}) - \phi_W(\vec{x}_{\text{start}})\right)$
- Ramo potential: use TCAD to solve Poisson equation
- Planar: mostly in z directions, need x, y for neighboring sensors

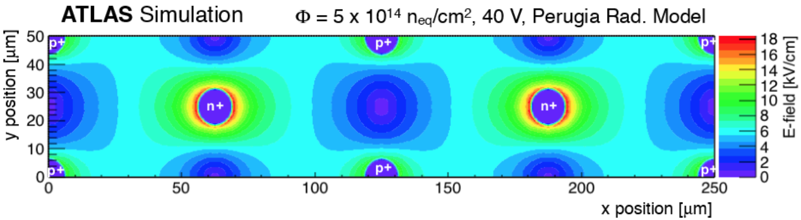




3D sensors

- Charges drift laterally ($x - y$ plane)
- Radiation effect simulated using **Perugia** model[3] (p-type)
- E field independent of z
- The computation of times more complex - integrate over path
- E field parallel to B $\rightarrow$ Lorentz angle negligible





[3] IEEE Transactions on Nuclear Science 63 (2016) 2716

Summary

- Significant impact of irradiation on pixel performance in Run 2
- Presented ATLAS pixel radiation damage simulation
- Combines multiple microscopic models
- **Improves** prediction wrt observed data
- Radiation damage paper: JINST 14 (2019) P06012
- Leakage current measurement paper: Accepted by JINST
- Operation experience of Pixel by Tobias Bisanz (today at 4pm)

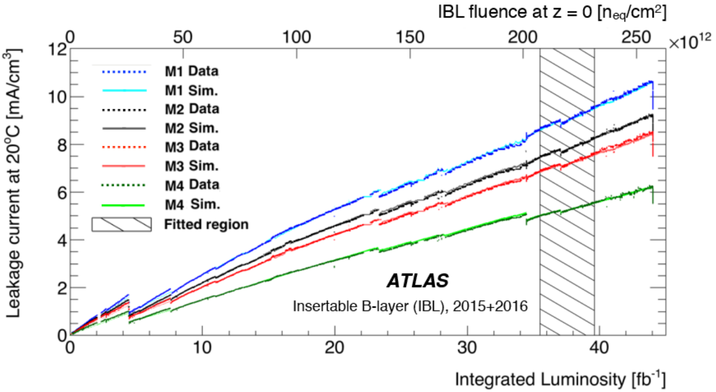
Run 3 and beyond

- More irradiation/larger fluences in **Run 3** and **HL-LHC** - 10x more
- Some assumptions may need to be revisited
  - Effects of **annealing**
  - Charge **trapping constants**

BACK UP

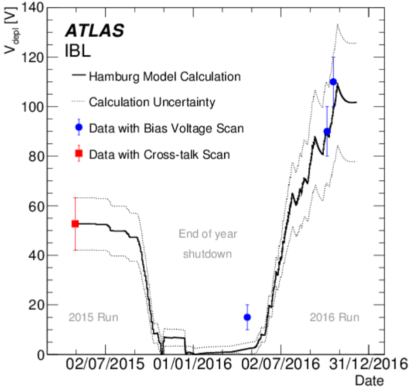
Fluence estimation validation

- Cross-checking the estimated FLUKA fluence with leakage current measurements
- Hamburg model - provides leakage curent as a function of fluence



Effective doping concentration

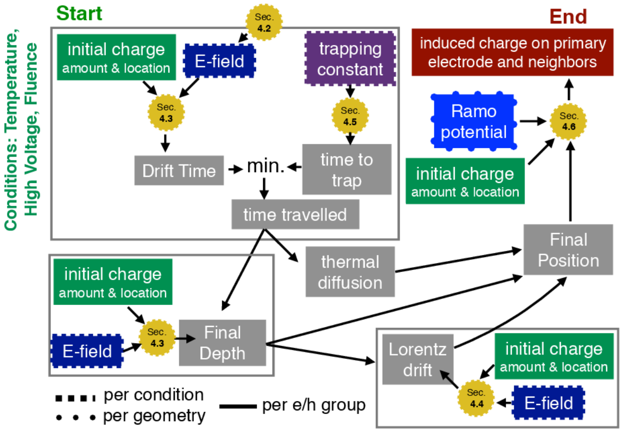
- Using Hamburg model, taking into account irradiation and thermal history
- Predicted impact on depletion volume compared with measurements
  - Using cross-talk between pixels (only before space-charge inversion)
  - Using bias voltage scans



- Uncertainty estimated by varying input parameters and 20% uncertainty on the initial doping concentration

Digitizer scheme full

- Reflects the microscopic changes - impact on charge collection
- **Simplified** model[4] due to CPU requirements



[4]JINST 14 (2019) P06012

Digitizer

The algorithm

1. Get magnitude and position of energy deposit from GEANT4
2. Get e-h pairs, group them
3. Drift electrons and holes
4. For each group, calculate fluence-dependent time-to-trap (randomly generated)
5. If drift time $>$ trap time $\rightarrow$ trap the charge group (find position)
6. Induced charge = difference in weighting (Ramo) potential of the final and initial position
7. Also apply the charge on neighboring pixels
8. Convert charge to ToT, proceed with reconstruction