Modelling radiation damage to pixel sensors in the ATLAS detector

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On behalf of the ATLAS Collaboration

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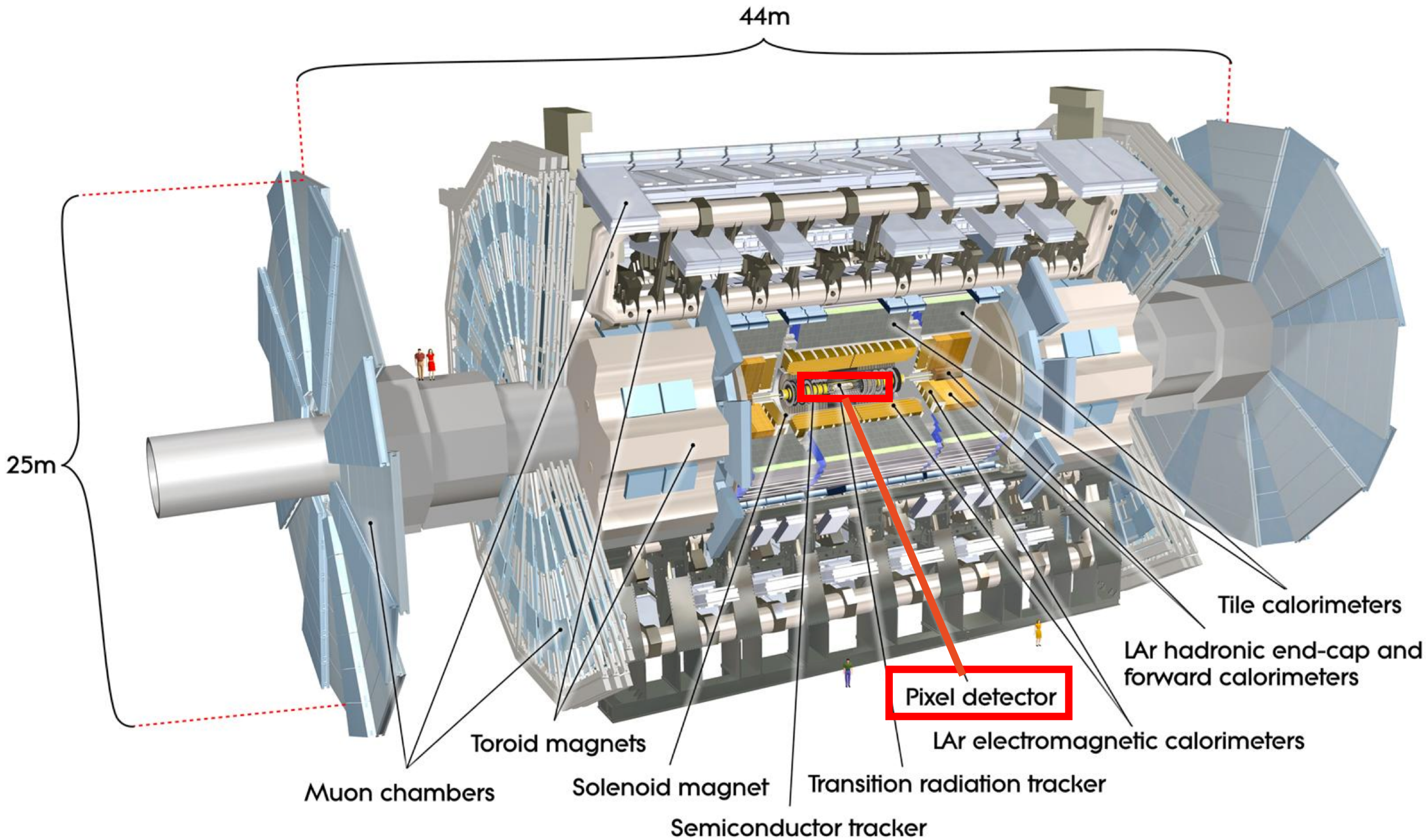
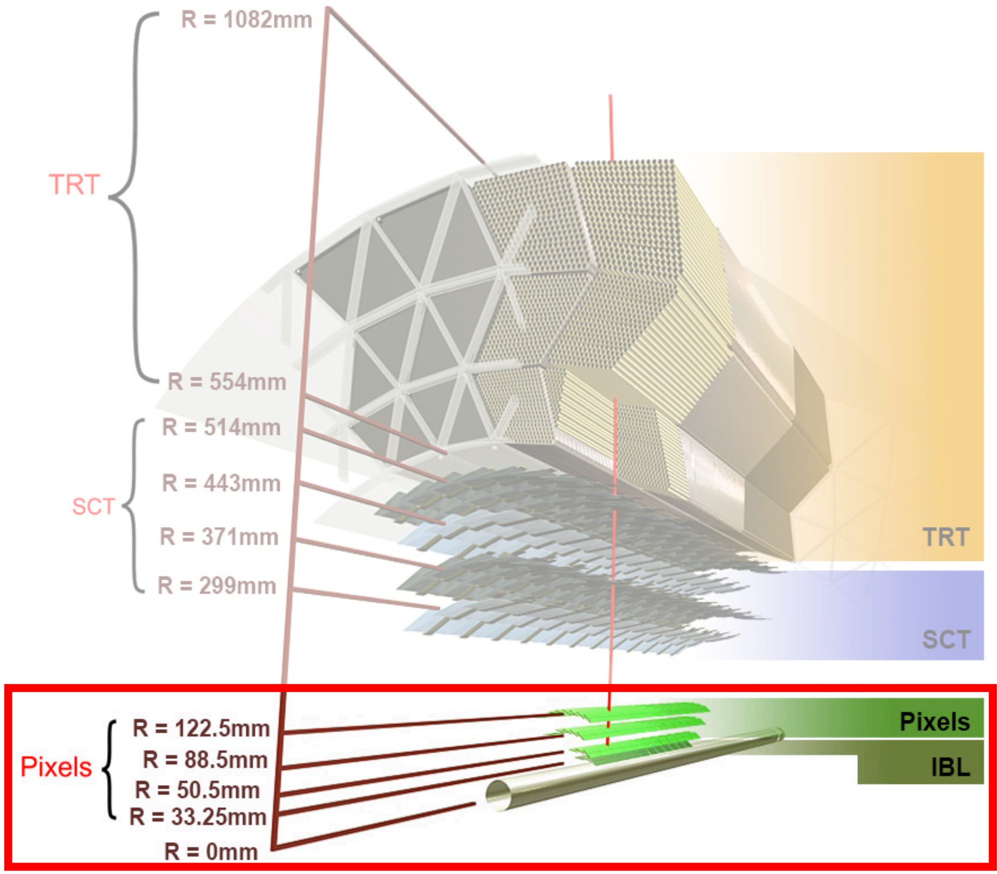
The ATLAS Detector

- Silicon pixel detectors are at the core of the current and planned upgrades of the ATLAS Pixel detector



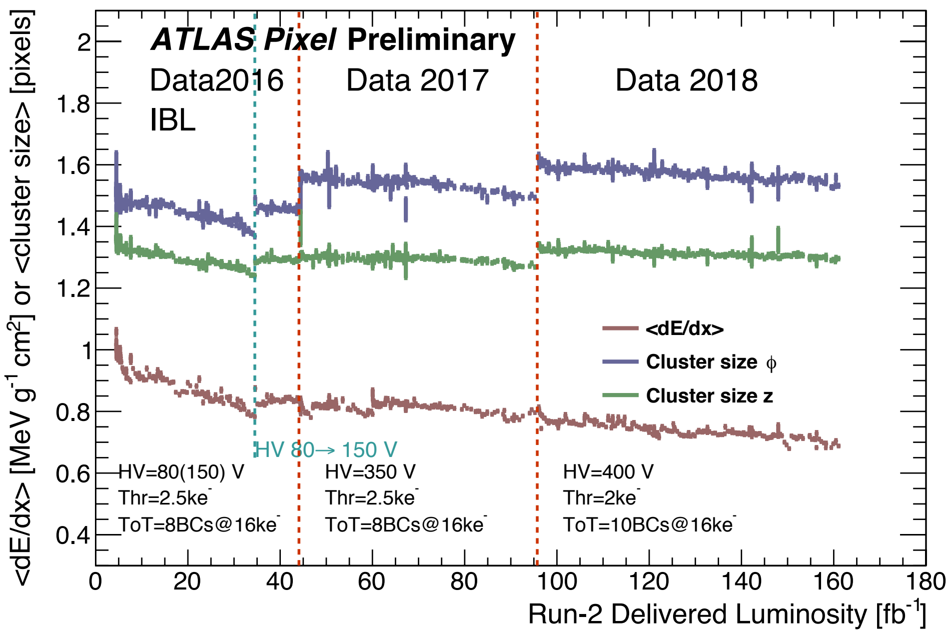
ATLAS Pixel Detector

- The ATLAS Pixel detector consists of four barrel layers and 2 × 3 disks
- The innermost barrel layer (the Insertable B-Layer or IBL) is located 3.3 cm from the LHC beam line
- By the end of LHC Run 2, the integrated fluences for the two layers closest to the beam line were:
  - IBL: 1×10^{15} 1 MeV n_{eq}/cm^2
  - B-Layer: 5×10^{14} 1 MeV n_{eq}/cm^2

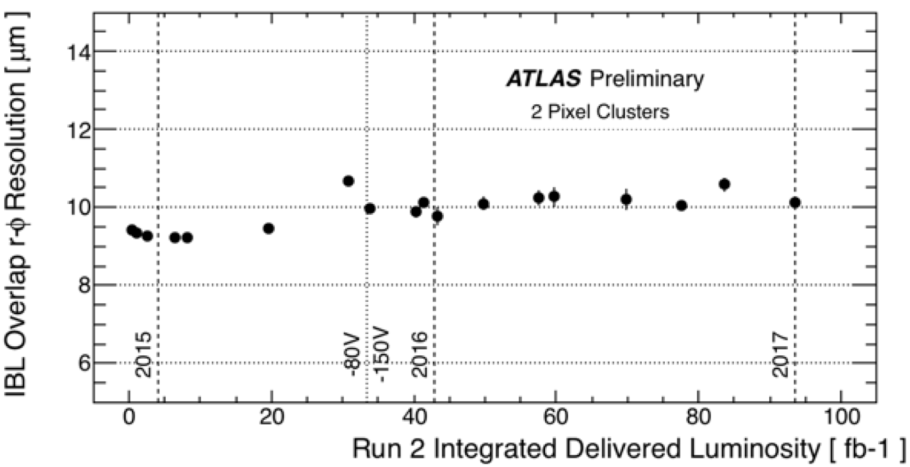


Impact on Physics and Performance

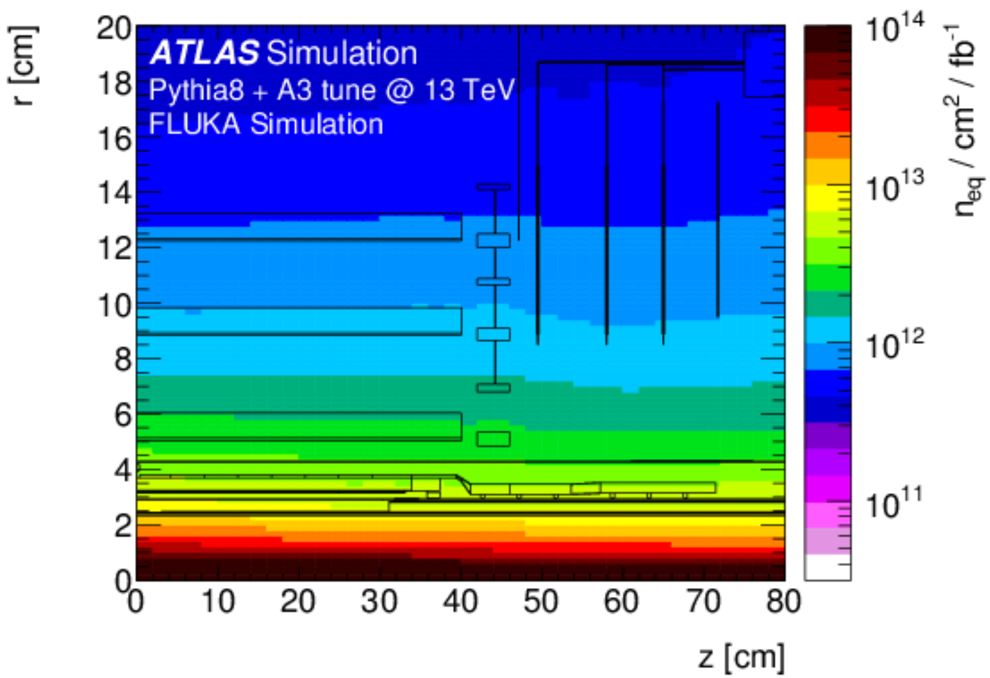
- It is imperative that radiation damage effects be quantified to **inform operations**, **offline analysis**, and **future detector design**
- Significant decrease of dE/dx and cluster size for IBL with delivered luminosity
- Possible degradation in position resolution

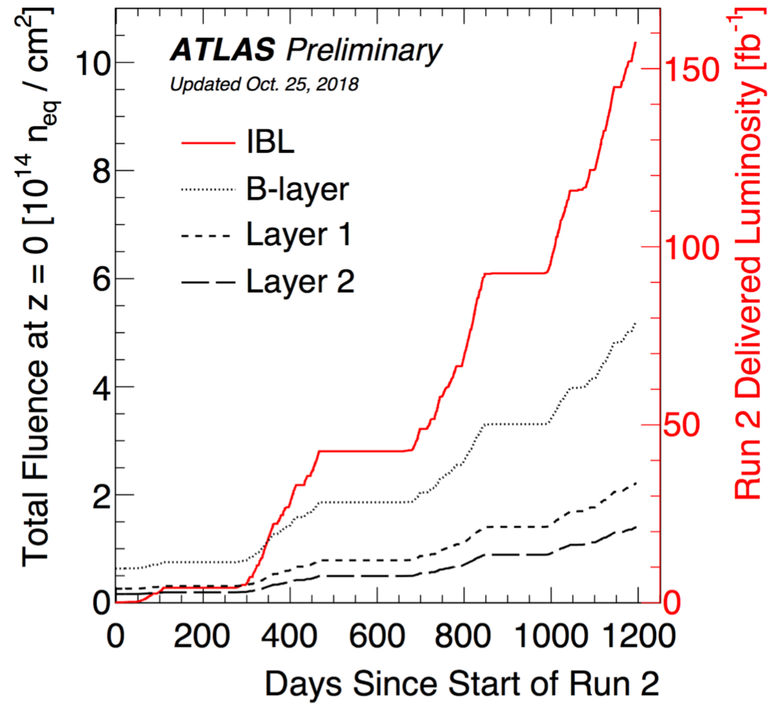


Pixel Position Resolution



Fluence Predictions



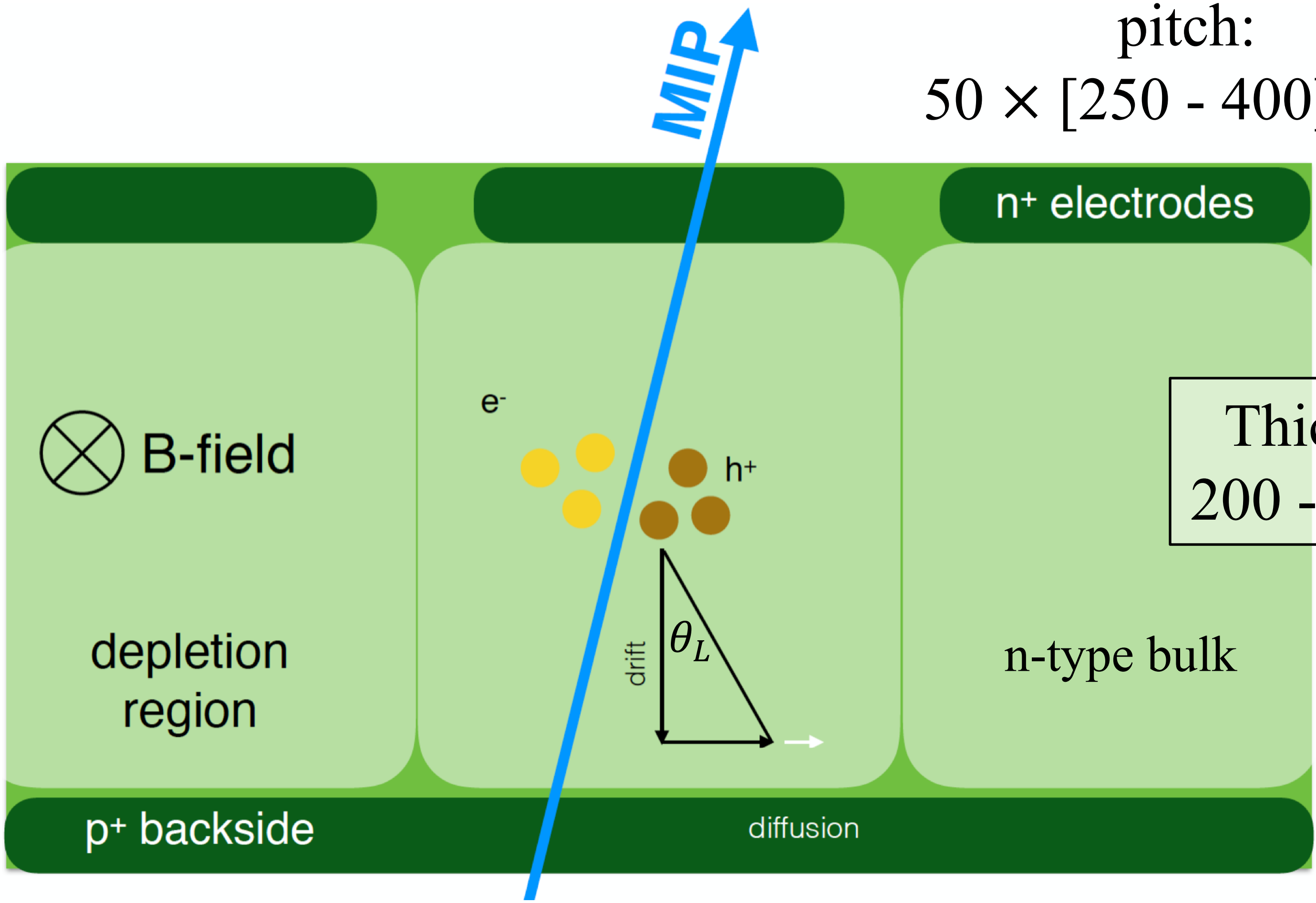


- Simulated 1 MeV n_{eq} fluence predictions made through the ATLAS FLUKA geometry on the left
- Lifetime fluence predictions for the ATLAS Pixel Detector layers are shown on the right (since the start of Run 2 on June 3, 2015)
- These simulations are used to check how much radiation damage the sensors have been exposed to and can be compared to data

Silicon Sensors

- The ATLAS Pixel Detector layers consist of n^+-in-n planar oxygenated silicon sensors

pitch:
$50 \times [250 - 400]\ \mu m^2$

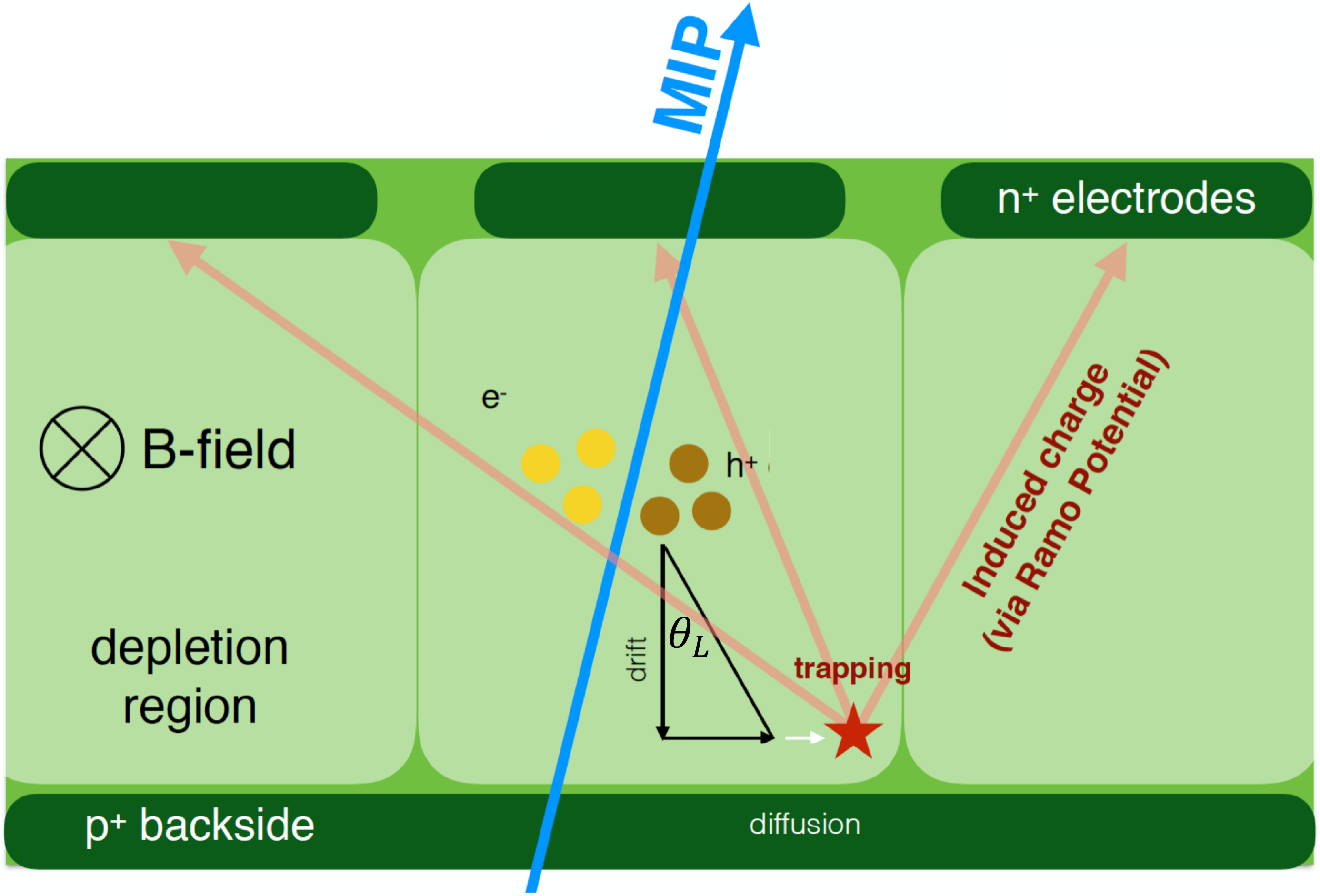


Thickness:
200 - 250 μm

MIP: Minimum Ionizing Particle, θ_L: Lorentz Angle

Radiation Damage

- Radiation introduces traps in the bulk by displacing a silicon atom from its lattice site, resulting in an interstitial and a vacancy (Frenkel pair)



MIP: Minimum Ionizing Particle, θ_L: Lorentz Angle

Part I

- Monitoring of radiation damage effects
  - Use the Hamburg Model* to validate sensor conditions data: fluence and depletion voltage

For more detail see:
The ATLAS Collaboration, JINST 14 (2019) P06012

*M. Moll, 'Radiation damage in silicon particle detectors: Microscopic defects and macroscopic properties', PhD thesis: Hamburg U., 1999, http://www-library.desy.de/cgi-bin/showprep.pl?desy-thesis99-040

Hamburg Model

- The Hamburg Model simulates leakage current and depletion voltage

Leakage Current

$$\Delta I = \alpha \cdot \Phi_{\mathrm{eq}} \cdot V$$

difference in leakage current before and after irradiation

radiation damage coefficient

fluence

Depletion Voltage

$$V_{\mathrm{depl}} = |N_{\mathrm{eff}}| \cdot \frac{ed^2}{2\epsilon\epsilon_0}$$

effective doping concentration

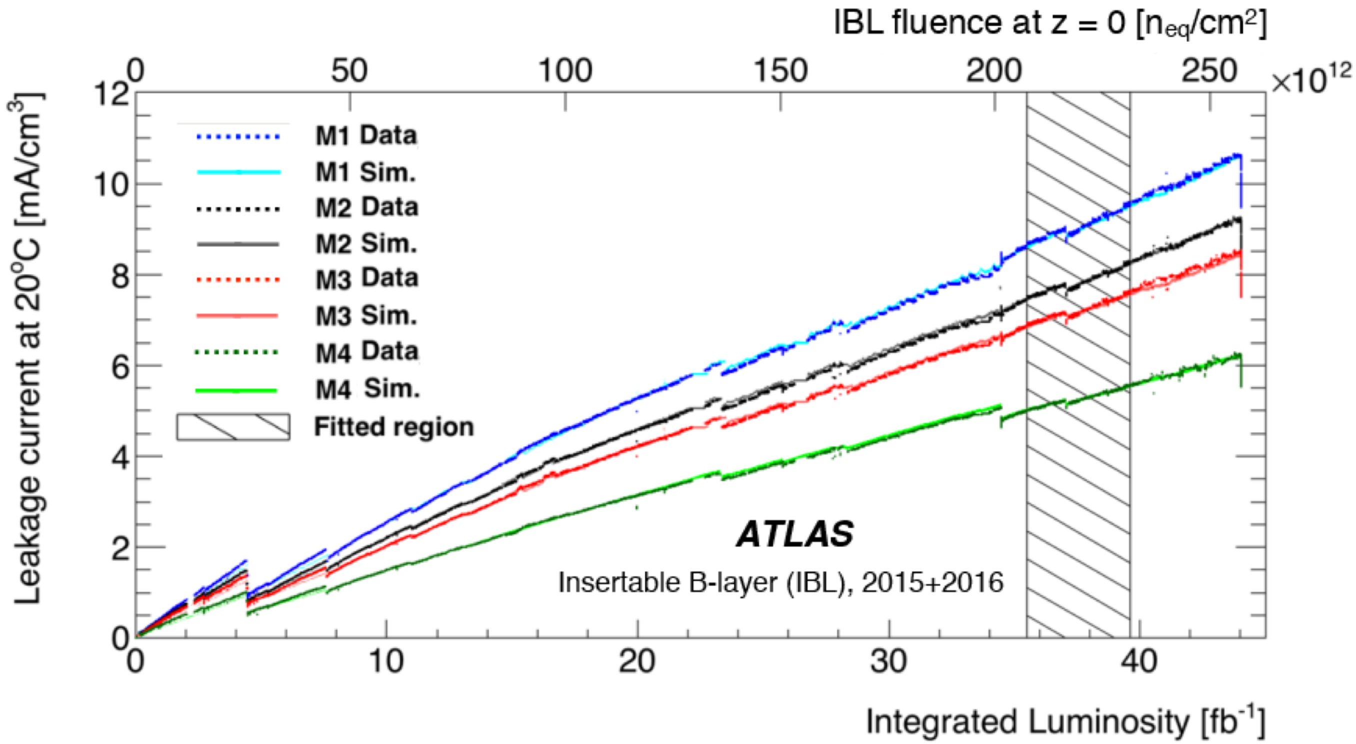
time and temperature dependent and include annealing characterization

Other variables: V is the depleted volume, d is the sensor thickness, e is the charge of the electron, ϵ is the dielectric constant, and ϵ_0 is the vacuum permittivity

Fluence Monitoring

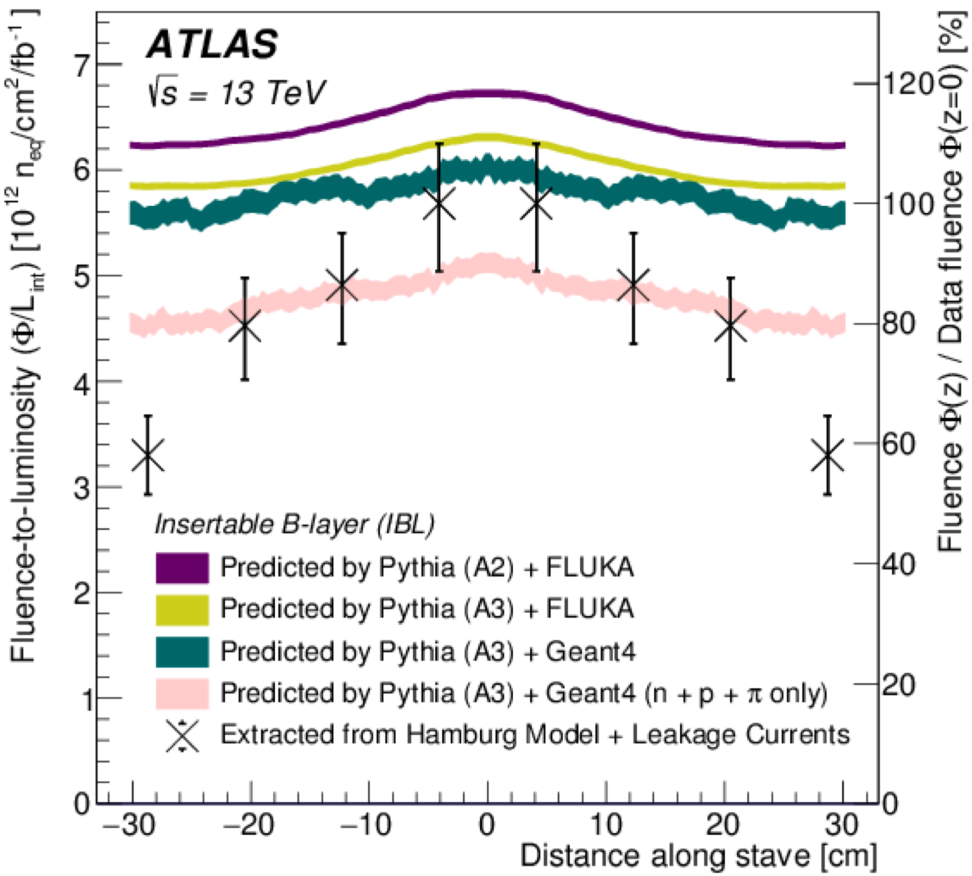
- The measured ("Data") and predicted ("Sim") leakage current as a function of integrated luminosity for IBL
- Leakage current is predicted using the Hamburg Model and by fitting the data in the dashed region to determine the fluence-to-luminosity factor, Φ/L_{int}
- Leakage currents for the other layers : ATL-INDET-PUB-2019-001

Module Group	|z|-Range
M1	[-8,8] cm
M2	[8,16] cm
M3	[16,24] cm
M4	[24,32] cm



Fluence-to-luminosity

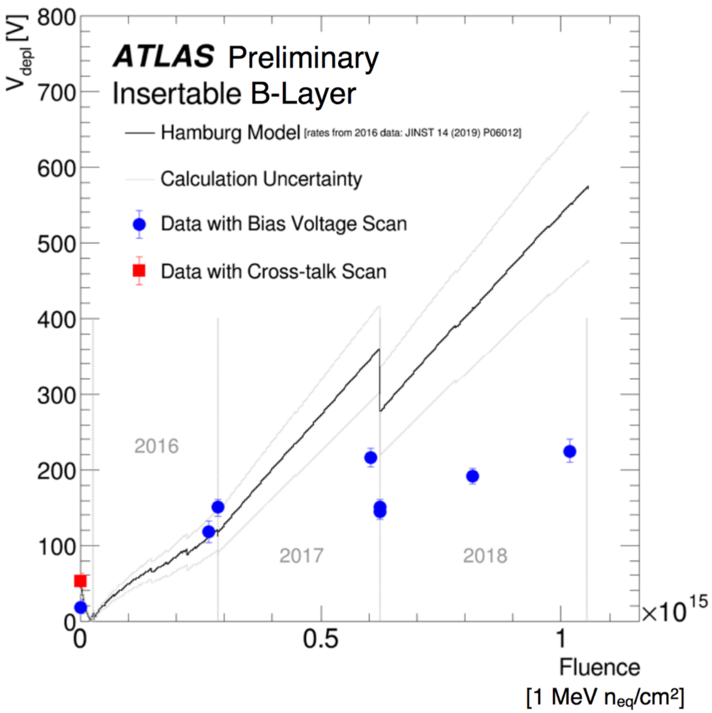
- Fluence-to-luminosity conversion factors (extracted from the leakage current fits) as a function of z on IBL
- The conversion factors are compared to those predicted with
  - Pythia + FLUKA
  - Pythia + Geant4
- Two different minimum bias tunings are are also investigated*
- Differences between measured and predicted Φ/L_{int} are most likely due to damage factors or input particle spectra

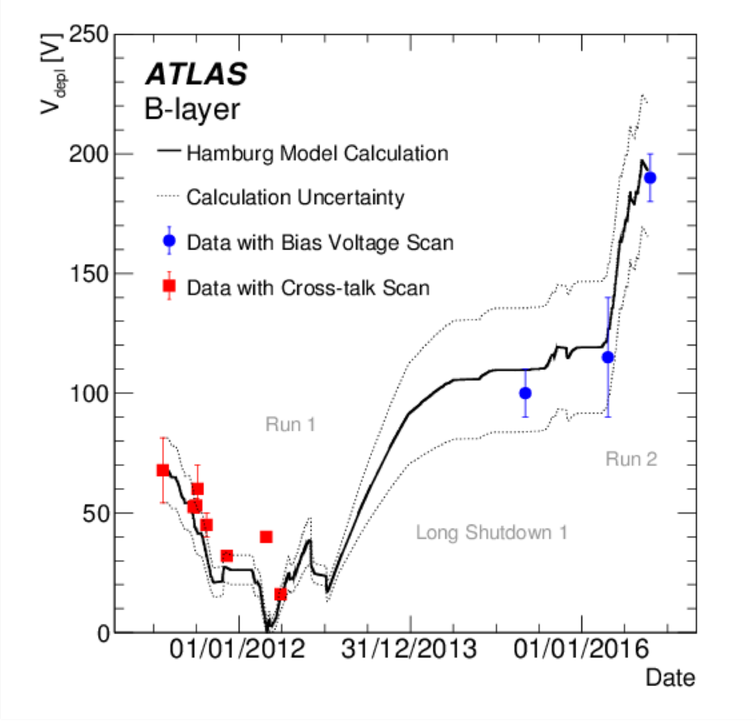


*ATLAS Collaboration, A study of the Pythia 8 description of ATLAS minimum bias measurements with the Donnachie-Landshoff diffractive model, ATL-PHYS-PUB-2016-017, https://cds.cern.ch/record/1474107

Depletion Voltage

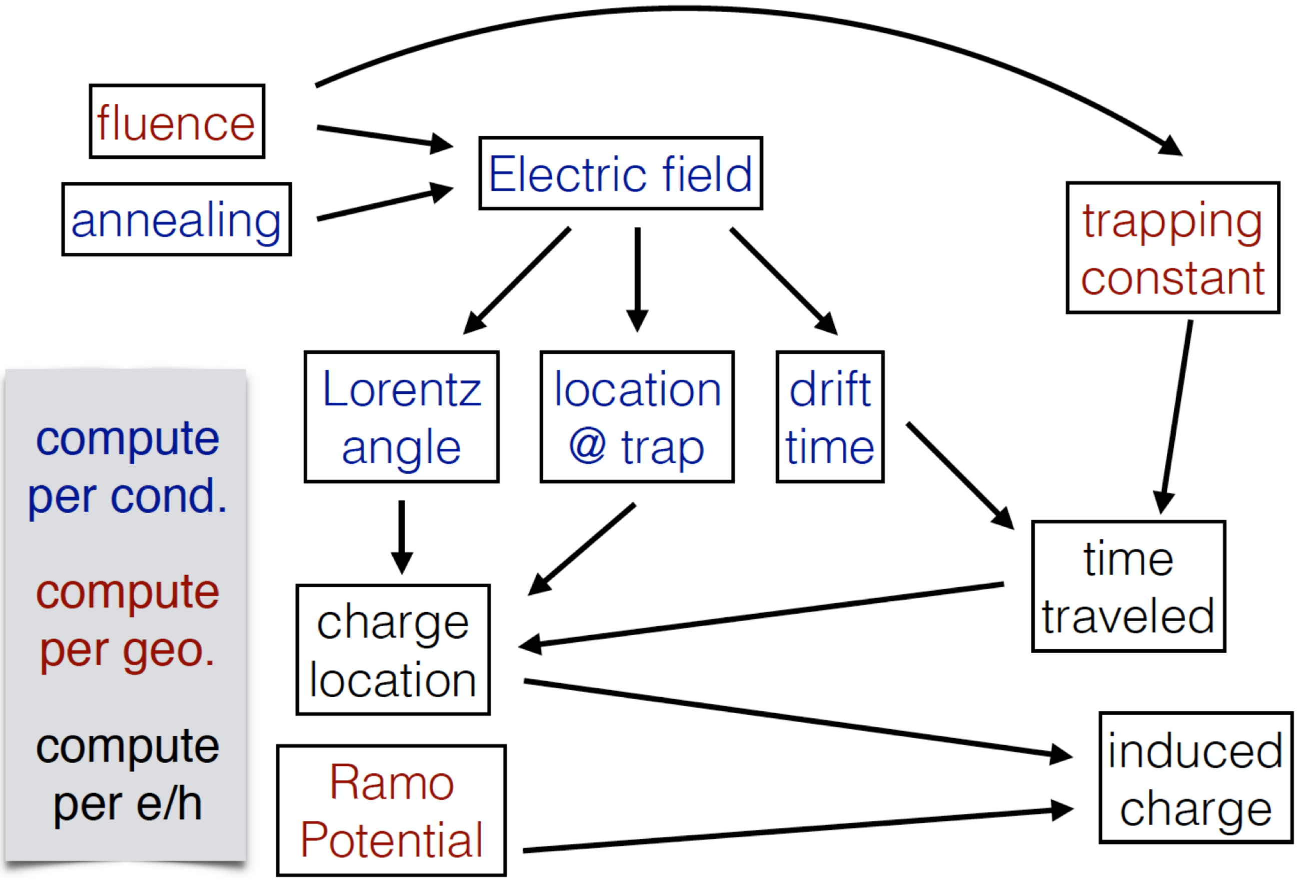
- Calculated depletion voltage according to the Hamburg Model for IBL (on the left) and the B-Layer (on the right)
- Depletion voltage data is determined through two techniques: cross talk scans and bias voltage scans
- Full depletion is well predicted by the Hamburg Model at lower fluences and over predicted at higher fluences





Digitizer Model

- A schematic of the digitizer model is shown here – start with fluence and annealing input and produce induced charge at the electrode as output



Part II

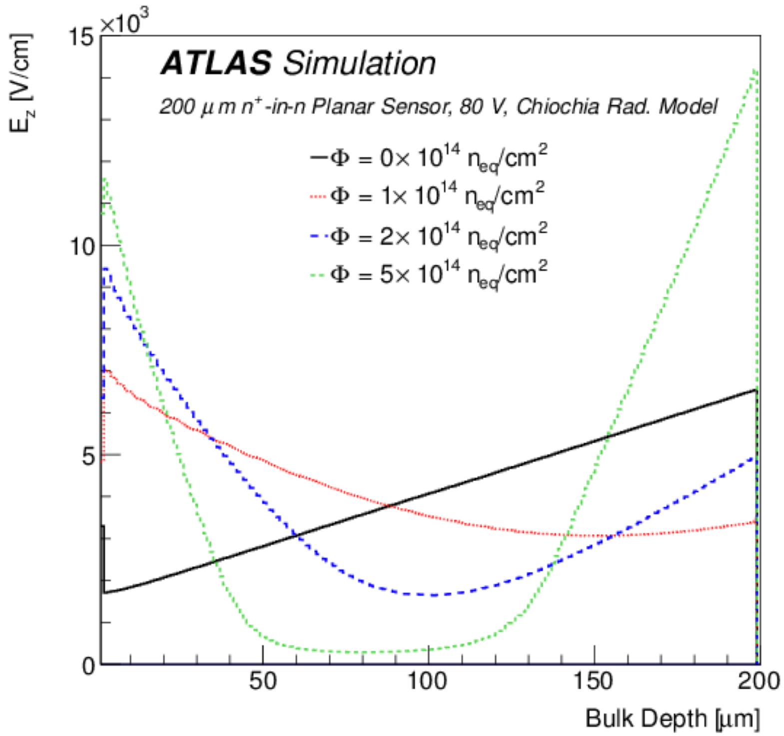
- <u>Modelling</u> of radiation damage effects
  - ➢Use Technology Computer Aided Design (TCAD) to implement a non-uniform electric field and compute charge propagation inside the sensor bulk
  - ➢Implements the Chiochia double trap model* (one acceptor trap and one donor trap)

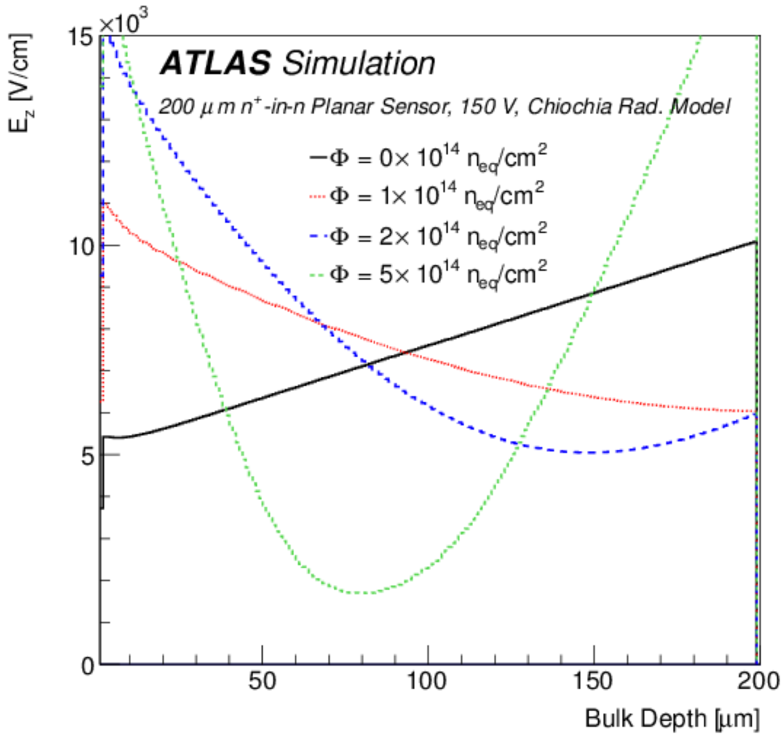
For more detail see:
The ATLAS Collaboration, JINST 14 (2019) P06012

*V. Chiochia et al., *A double junction model of irradiated silicon pixel sensors for LHC*, NIMA 568 (2006) 51

Electric Field

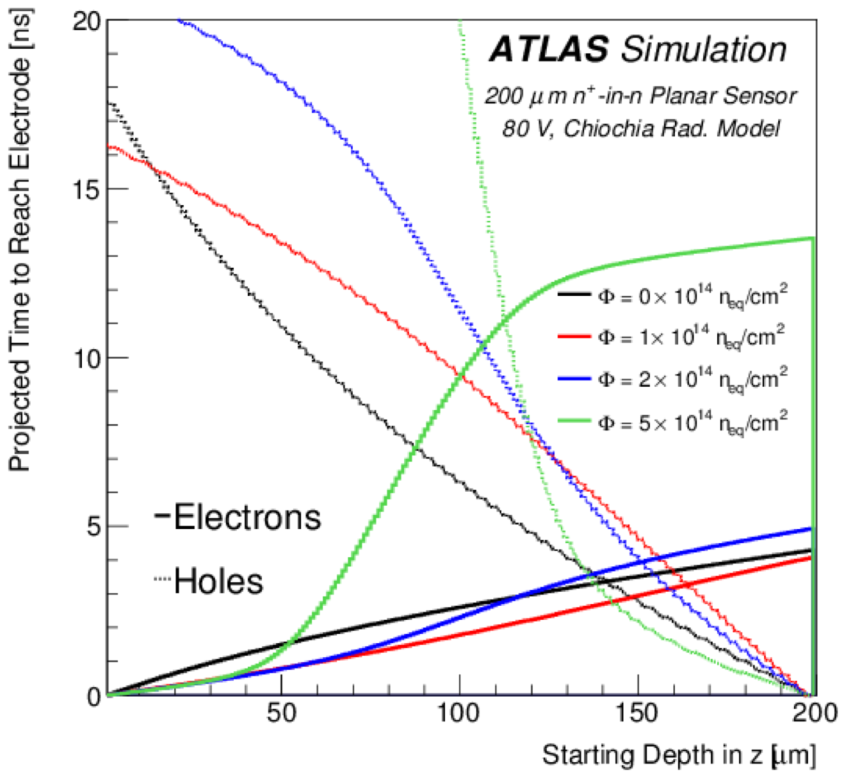
- The simulated electric field magnitude in the z direction along the bulk depth of an ATLAS IBL sensor
  - Simulation uses the Chiochia Radiation Model through TCAD
  - The electric field is averaged over x and y
- The E field at various fluences is shown for the sensor biased at: 80 V (on the left) and 150 V (on the right)





Time-to-Electrode

- The projected time - in the absence of trapping – for an electron or hole to drift from the point of generation to the collecting electrode (for electrons) or back plane (for holes)
- Using E fields predicted by Chiochia model through TCAD simulation

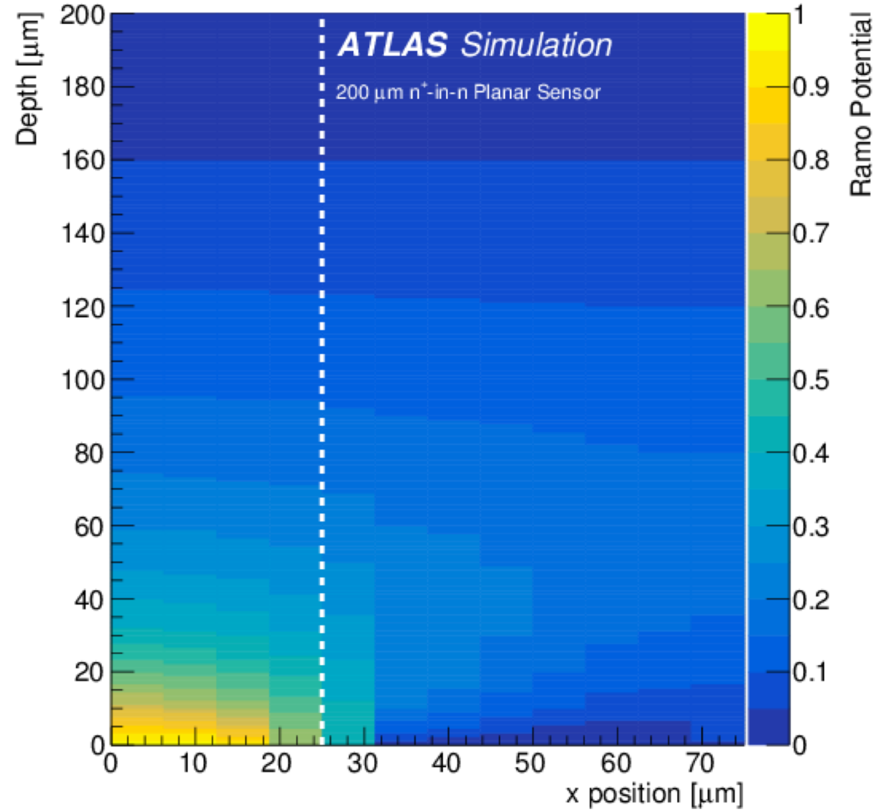


- An exponential distribution, with mean value $1/\beta\Phi$, is used to set the random charge trapping time
  - β is the trapping constant and Φ is fluence

Ramo Potential

shown at y = 0

- The Ramo potential is calculated using TCAD to solve the Poisson equation ($\nabla^2\phi_W = 0$) and from the geometry of the sensor
  - Here ϕ_W is the Ramo potential
- Slice of the full three-dimensional ATLAS IBL planar sensor Ramo potential is shown
  - The dashed vertical line (at 25 μm) indicates the edge of the primary pixel



- Induced charge on the electrode is computed with the Ramo potential and the charge trapping location:

$$Q_{\text{induced}} = -q[\phi_{\text{w}}(\vec{x}_{\text{end}}) - \phi_{\text{w}}(\vec{x}_{\text{start}})]$$

Part III

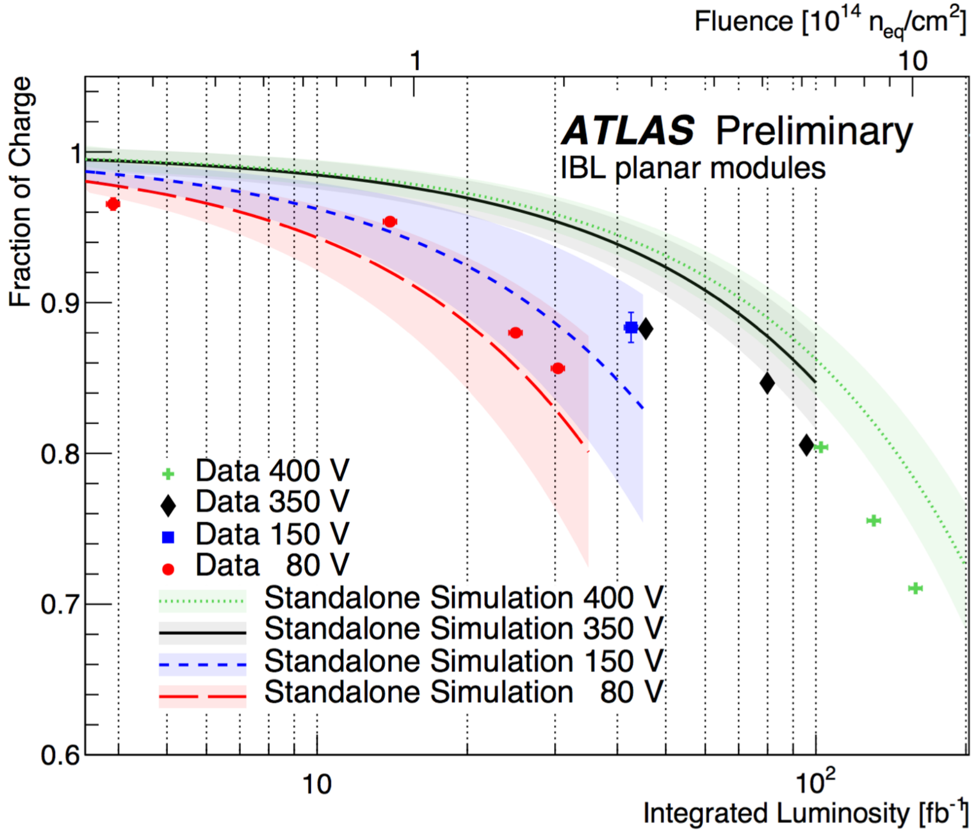
- Model validations
  - Comparing simulations with data for: charge collection efficiency and Lorentz angle

For more detail see:

The ATLAS Collaboration, JINST 14 (2019) P06012

Charge Collection Efficiency

- Charge collection efficiency as a function of integrated luminosity for 80 V, 150 V, and 350 V bias voltage
- The bias voltage was increased during data-taking, so the data points are only available at increasing high-voltage values

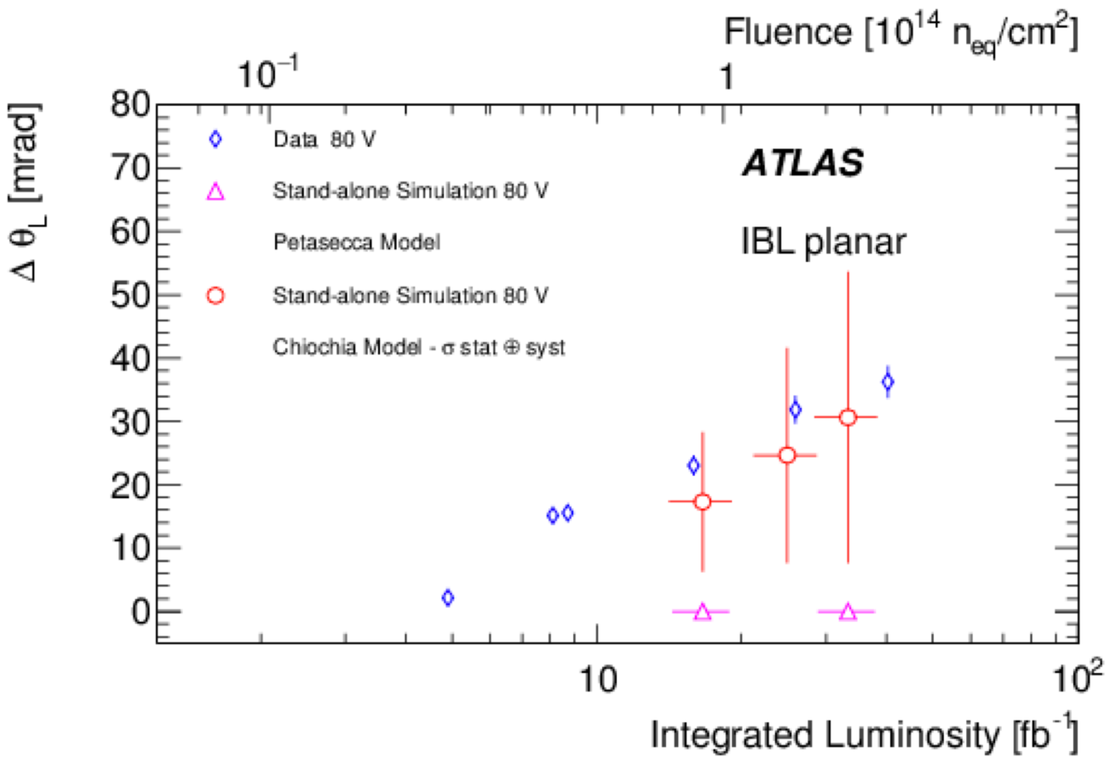


- The uncertainty on the simulation is due to model parameters as well as the uncertainty in the fluence-to-luminosity conversion
- Uncertainties on the data are due to charge calibration drift (vertical) and luminosity uncertainty (horizontal)

Lorentz Angle

- The change in the Lorentz angle (θ_L) from the unirradiated case as a function of integrated luminosity

- Two TCAD radiation models are considered: Chiochia and Petasecca*
  - The Petasecca model predicts a linear electric field profile
- Due to the deformation of the E field, the mobility and Lorentz angle increase with fluence



*M. Petasecca et. al., Numerical Simulation of Radiation Damage Effects in p-Type and n-Type FZ Silicon Detectors, IEEE Transactions on Nuclear Science 53 (2006) 2971

Conclusions

- Measurements and simulations of radiation damage to the ATLAS pixels have been presented
- The updated digitization model is now in ATLAS software and is aiming to be default in LHC Run 3
    - The digitization model is being used for ATLAS upgrade (ITk) design studies
- Modeling radiation damage in the ATLAS software is critical to maintain physics performance in Run 3 and for the HL-LHC
    - The aim is to improve the model accuracies for input to operations, offline analysis, and future detector design

Additional Slides

Hamburg Model: Leakage Current

- The Hamburg model is based on this relationship:

$$\Delta I = \alpha \cdot \Phi_{\mathrm{eq}} \cdot V$$

- And by replacing α (the radiation damage coefficient) the equation becomes:

$$I_{\mathrm{leak}} = (\Phi_{\mathrm{eq}}/L_{\mathrm{int}}) \times V \cdot \sum_{i=1}^{n} L_{\mathrm{int},i} \cdot \left[\alpha_{\mathrm{I}} \exp\left(-\sum_{j=i}^{n} \frac{t_j}{\tau(T_j)}\right) + \alpha_0^* - \beta \log\left(\sum_{j=i}^{n} \frac{\Theta(T_j) \cdot t_j}{t_0}\right)\right]$$

- Where the variables are:
  - Φ_{eq} is the fluence, L_{int} is the integrated luminosity, V is depleted volume of the sensor, t_{i} is the time, and t_0 = 1min
  - $\alpha_I = (1.23 \pm 0.06)\times10^{-17}$ A/cm
  - $\tau^{-1} = (1.2^{+5.3}_{-1.0}) \times 10^{13}\ \mathrm{s}^{-1} \times e^{(-1.11\pm0.05)\ \mathrm{eV}/k_{\mathrm{B}}T}$
  - $\alpha_0^* = 7.07 \cdot 10^{-17}$ A/cm
  - $\beta = (3.29 \pm 0.18) \times 10^{-18}$ A/cm
  - and $\Theta(T) = \exp\left[-\frac{E_{\mathrm{eff}}}{k_{\mathrm{B}}}\left(\frac{1}{T} - \frac{1}{T_{\mathrm{R}}}\right)\right]$

Hamburg Model: Depletion Voltage

$$N_{\text{eff}}(t) = N_{\text{D}}^{\text{non-removable}}(0) + N_{\text{D}}^{\text{removable}}(t) - N_{\text{A}}^{\text{stable}}(t) - N_{\text{A}}^{\text{beneficial}}(t) - N_{\text{A}}^{\text{reverse}}(t), \quad (3)$$

$$\frac{\mathrm{d}}{\mathrm{d}t} N_{\text{D}}^{\text{removable}}(t) = -c\phi(t) N_{\text{D}}^{\text{removable}}(t) \quad \text{removal of donors for } n\text{-type during irradiation,} \quad (4)$$

$$\frac{\mathrm{d}}{\mathrm{d}t} N_{\text{A}}^{\text{stable}}(t) = g_{\text{C}}\phi(t) \quad \text{addition of stable acceptors during irradiation,} \quad (5)$$

$$\frac{\mathrm{d}}{\mathrm{d}t} N_{\text{A}}^{\text{beneficial}}(t) = g_{\text{A}}\phi(t) - k_{\text{A}}(T) N_{\text{A}}^{\text{beneficial}}(t) \quad \text{beneficial annealing,} \quad (6)$$

$$\frac{\mathrm{d}}{\mathrm{d}t} N_{\text{N}}^{\text{reverse}}(t) = g_{\text{Y}}\phi(t) - k_{\text{Y}}(T) N_{\text{N}}^{\text{reverse}}(t) \quad \text{reverse annealing – neutrals,} \quad (7)$$

$$\frac{\mathrm{d}}{\mathrm{d}t} N_{\text{A}}^{\text{reverse}}(t) = k_{\text{Y}}(T) N_{\text{N}}^{\text{reverse}}(t) \quad \text{reverse annealing – acceptors,} \quad (8)$$

Parameter	IBL [$\times 10^{-2}\text{cm}^{-1}$]	*B*-layer [$\times 10^{-2}\text{cm}^{-1}$]	ROSE Coll. [$\times 10^{-2}\text{cm}^{-1}$]
g_{A}	1.4 ± 0.5	1.4 ± 0.5	1.4 (*n*)
g_{Y}	6.0 ± 1.6	6.0 ± 1.6	2.3 (*p*), 4.8 (*n*)
g_{C}	1.1 ± 0.3	0.45 ± 0.1	0.53 (*p*), 2.0 (*n*)

$$V_{\text{depl}} = |N_{\text{eff}}| \cdot \frac{ed^2}{2\epsilon\epsilon_0},$$

where d is the sensor thickness, e is the charge of the electron, ϵ is the dielectric constant, and ϵ_0 is the vacuum permittivity

Full Run 2 IBL Leakage Current

- The IBL Leakage current for the full Run 2 data is shown here: