Modeling Radiation Damage to Pixel Sensors in the ATLAS Detector

Lorenzo Rossini¹
on behalf of the ATLAS Collaboration

¹University of Milano - INFN
Pixel detector is the innermost layer of the ATLAS detector: High flux of particles!

4 Barrel layers + 6 Disk Layers (3 at each end) with different geometry and technology

- 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!
High flux of particles means high radiation dose on the sensor

Radiation damage effects in the sensor already visible! See also Hongtao Yang talk!

Correct Monte Carlo prediction that accounts for radiation damage is essential for physics
High flux of particles means high radiation dose on the sensor

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Correct Monte Carlo prediction that accounts for radiation damage is essential for physics
Digitization: the conversion from energy depositions of charged particles to digital signals sent from module front ends to the detector readout system.

Develop digitizer that models inside effects of radiation damage.

“Chunks” of charges are drifted to the electrodes. Digitizer accounts for:

- Charges drift
- E/B Field simulations from **TCAD**
- Lorentz Angle (function of E/B fields and distance in the detector)
- Trapping probability
- Ramo potential to account for induced charge
- Charge conversion to ToT

Digitizer for planar sensors! *(3D in back up)*
Fluence prediction taken from FLUKA + Pythia

- FLUKA prediction validated with leakage current and Hamburg model:
  - Assign 15% uncertainties in the central region (|z|~0)
ATLAS Pixel Detector Digitizer: E-field

- B-field
- E-field
- depletion region
- p+ backside
- n+ electrodes
- induced charge
- trapping!
- MIP
- drift
- Lorentz angle
- e- chunks
- h+ chunks
Electric Field simulations

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

- Depletion voltage and Electric Field profile depends on:
  - Fluence
  - Type of irradiation
  - Temperature during and after irradiation (annealing)

- Electric Field is simulated with TCAD technology
  - more information in Marco Bomben talk
  - TCAD first step on which build the simulations

- Typical double junction effect well described →”U” shaped E-Field

Annealing

TCAD simulation doesn’t account for thermal history: no annealing effects included

Use Hamburg Model to model annealing

- Set the average charge distribution in the sensor to match the \( N_{\text{eff}} \) concentration predicted by Hamburg model

- No 1-1 correspondence between TCAD and Hamburg model
  - We only match the total effective concentration
ATLAS Pixel Detector Digitizer: Lorentz Angle

- **B-field**
- **E-field**
- **depletion region**
- **p⁺ backside**
- **n⁺ electrodes**
- **MIP**

- **e⁻ chunks**
- **h⁺ chunks**
- **induced charge**
- **trapping!**

**Lorentz angle**

\[ \theta_L \]
Lorentz Angle: $	an \theta_L^{\text{integrated}}(z_{\text{initial}}, z_{\text{final}}) = \frac{rB}{|z_{\text{final}} - z_{\text{initial}}|} \int_{z_{\text{initial}}}^{z_{\text{final}}} \mu(E(z)) \, dz$

- Intrinsic dependence on the E field
- Radiation damage modifies E field shape and therefore $\theta_L$
  - depends on final and initial positions
  - integrate over path

$\theta_L$ drift

\[ B \times \text{MIP} \]

\[ \theta_L \]

\[ \text{Hall scattering factor} \]

\[ \mu \ (	ext{Electrons}) \]

\[ \mu \ (	ext{Holes}) \]

\[ \mu \ (	ext{Unirradiated}) \]

\[ \mu \ (1 \times 10^{14} \text{ cm}^{-2}) \]

\[ \mu \ (2 \times 10^{14} \text{ cm}^{-2}) \]

\[ \mu \ (5 \times 10^{14} \text{ cm}^{-2}) \]

\[ \text{Pixel Depth in Z [\mu m]} \]

\[ \text{Lorentz Angle [rad]} \]
ATLAS Pixel Detector Digitizer: Trapping Probability

- E-field trapping
- induced charge
- trapping!
Trapping probability

Defects form in the silicon and are sites for charge trapping.

Charges are trapped if the time to reach the electrode is larger than a trapping time $\tau$.

- $\tau$ is a random variable exponentially distributed with mean value $1/(\beta_{h/e}\Phi)$.
  - $\Phi$ is the fluence.
  - $\beta_{h/e}$ is the trapping constant: different for electrons and holes.
  - $\beta_e = 4.5 \pm 1.0 \times 10^{-16} \text{ cm}^2/\text{ns}$
  - $\beta_h = 6.5 \pm 1.5 \times 10^{-16} \text{ cm}^2/\text{ns}$
  - Average of neutron and proton irradiation studies.

- Trapped charges induce a partial signal on the electrode, given by:
  - $-q(R_f-R_i)$:

$R_f$ and $R_i$ are the Ramo potential in final and initial positions.
Trapping probability

Different trapping constant for electrons and holes

- Trapping probability depends on time of annealing
- Different results for type of irradiation (protons vs neutrons) and temperature
- Two main sources for these values
  - G. Kramberger et al., NIM A481 (2002) 297. Plot: trapping constant as a function of annealing time
- In simulation use average of two values
- Errors account for:
  - differences between two groups
  - annealing effects
  - measures uncertainties
Model Prediction and Data Comparison

Charge Collection Efficiency as a function of Luminosity for IBL with data from Run 2

- Simulation points error bars
  1. x: 15% on fluence-to-luminosity conversion
  2. y: radiation damage parameter variations

- Data points error bars
  1. x: 2% on luminosity
  2. y: ToT-charge calibration drift

Good agreement with data!
Essential to understand what operational condition to use in the future
Lorentz Angle depends on the fluence

Lorentz angle as a function of integrated Luminosity

Mean cluster size as a function of particle incident angle
Conclusions

• A new digitizer for the ATLAS pixel detector has been presented
  ▶ Many features that account for most of the effects involving radiation damage
  ▶ Based on TCAD maps for E-fields
• We produced simulations that are in good agreement with Run 2 data, in terms of
  ▶ Charge collection efficiency
  ▶ Lorentz angle
• Predictions useful for:
  ▶ Decide pixel detector operation condition
  ▶ Improve our modeling of data for physics analysis
• We are now prepared to model the radiation degradation for Run 2+3 and for HL-LHC
• Similar approach of digitizer
  ▶ Charges are drifted towards electrodes
• Charge collection efficiency
  ▶ Only simulation results
  ▶ higher fluences than IBL results