TCAD + AllPix2 pipeline for the ATLAS ITk-Strip Digitization Model

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on behalf of ATLAS ITk Strip Sensors community

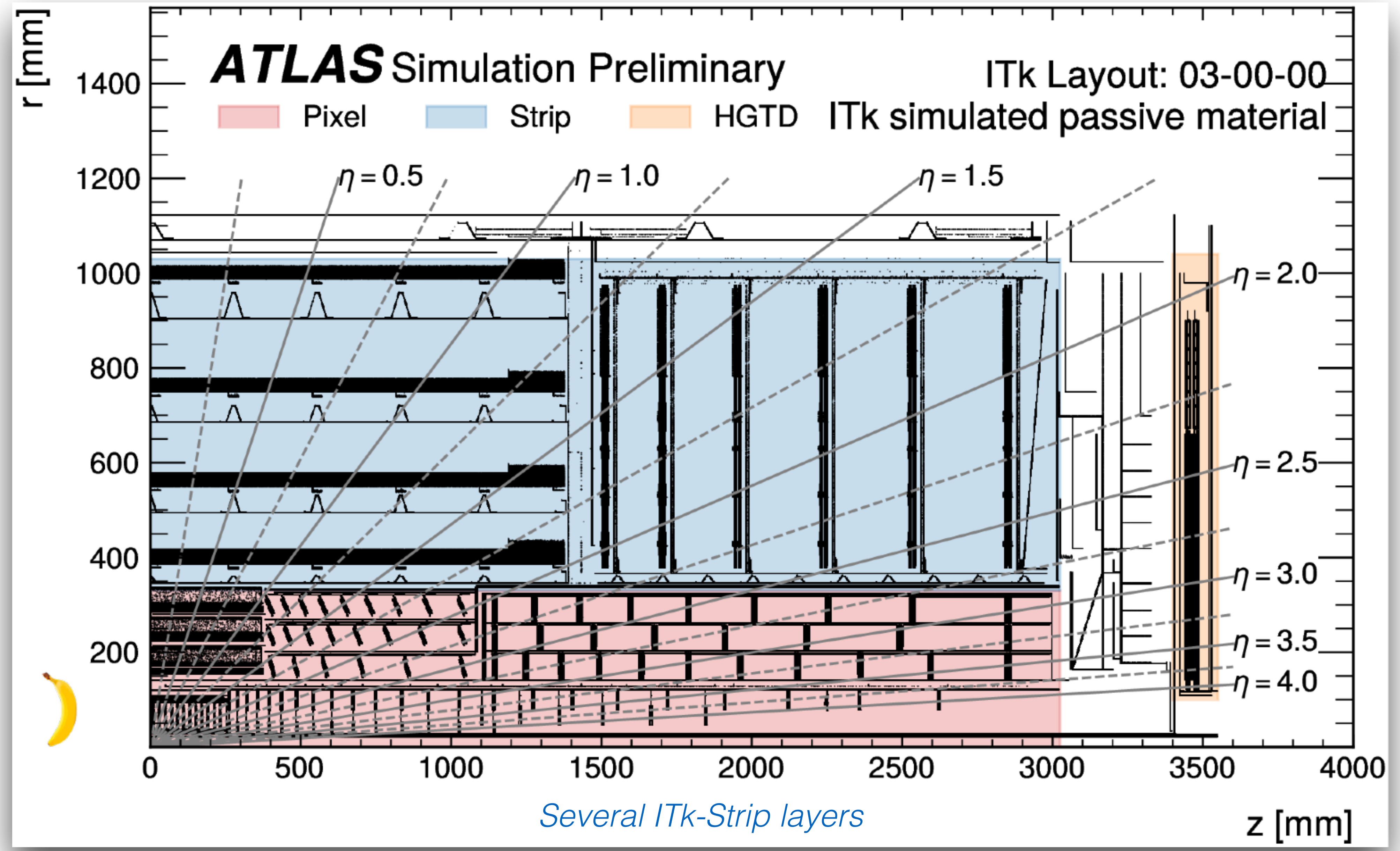
2nd DRD3 week on Solid State Detectors R&D
4 Dec 2024

ATLAS EXPERIMENT

Carleton University

ITk-Strip Basics

- For HL-LHC, new ATLAS charged-particle tracker (ITk) with inner **Pixel** and outer **Strip** detectors
- **ITk-Strip**: 4 barrel layers and 6 endcap disks of paired strip sensors



ITk-Strip Basics

- Sensors are AC-coupled **n-type** implants in a **p-type** bulk, separated by **p-stops**
- Expect lifetime fluences of ~50 MRad, or 1.6×10^{16} 1-MeV n_{eq}/cm^2
  - Nominally biased to ~300V, increasable to ~700 V to counteract radiation damage

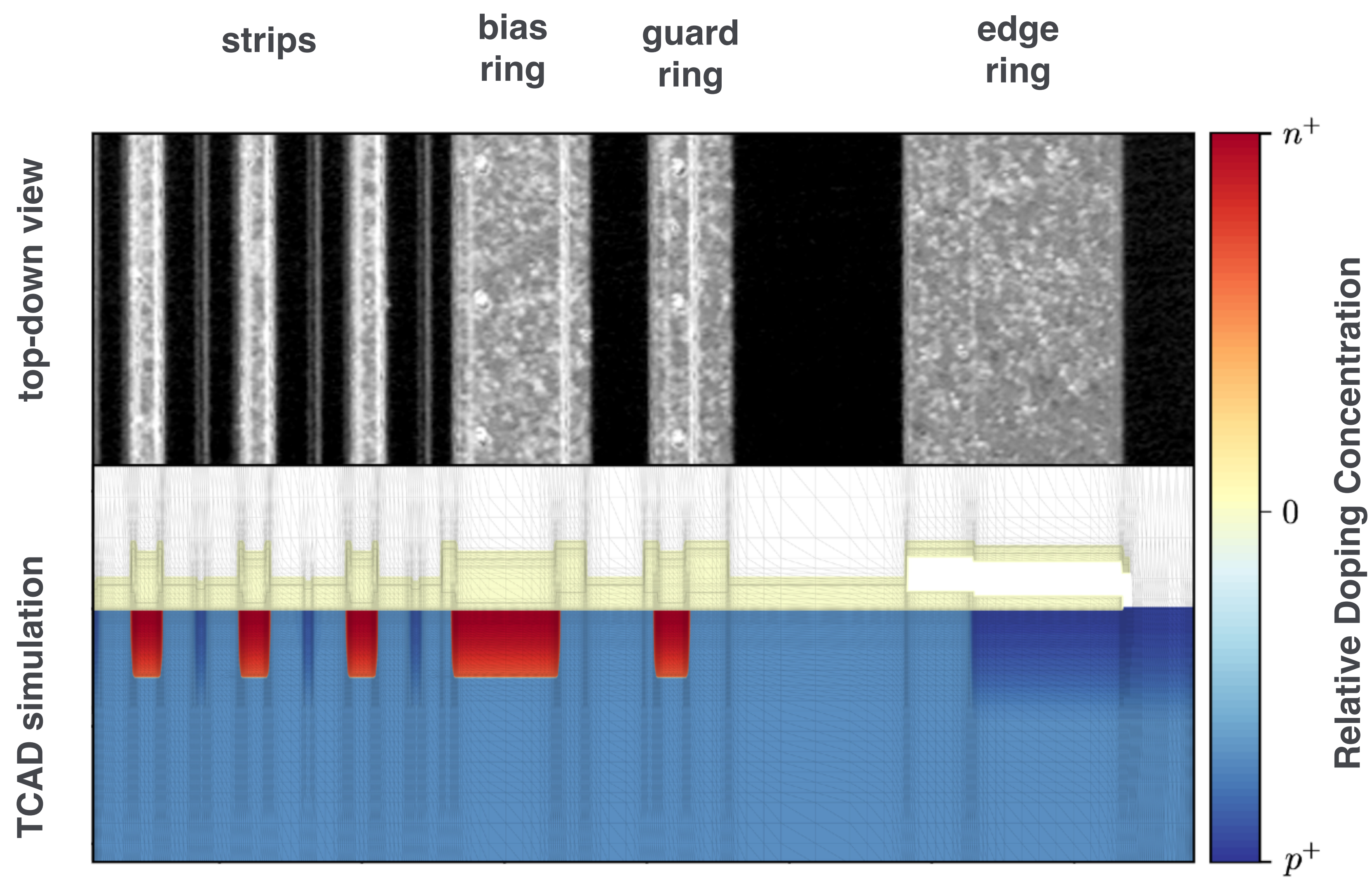


Photo & simulation of sensor strips & edge

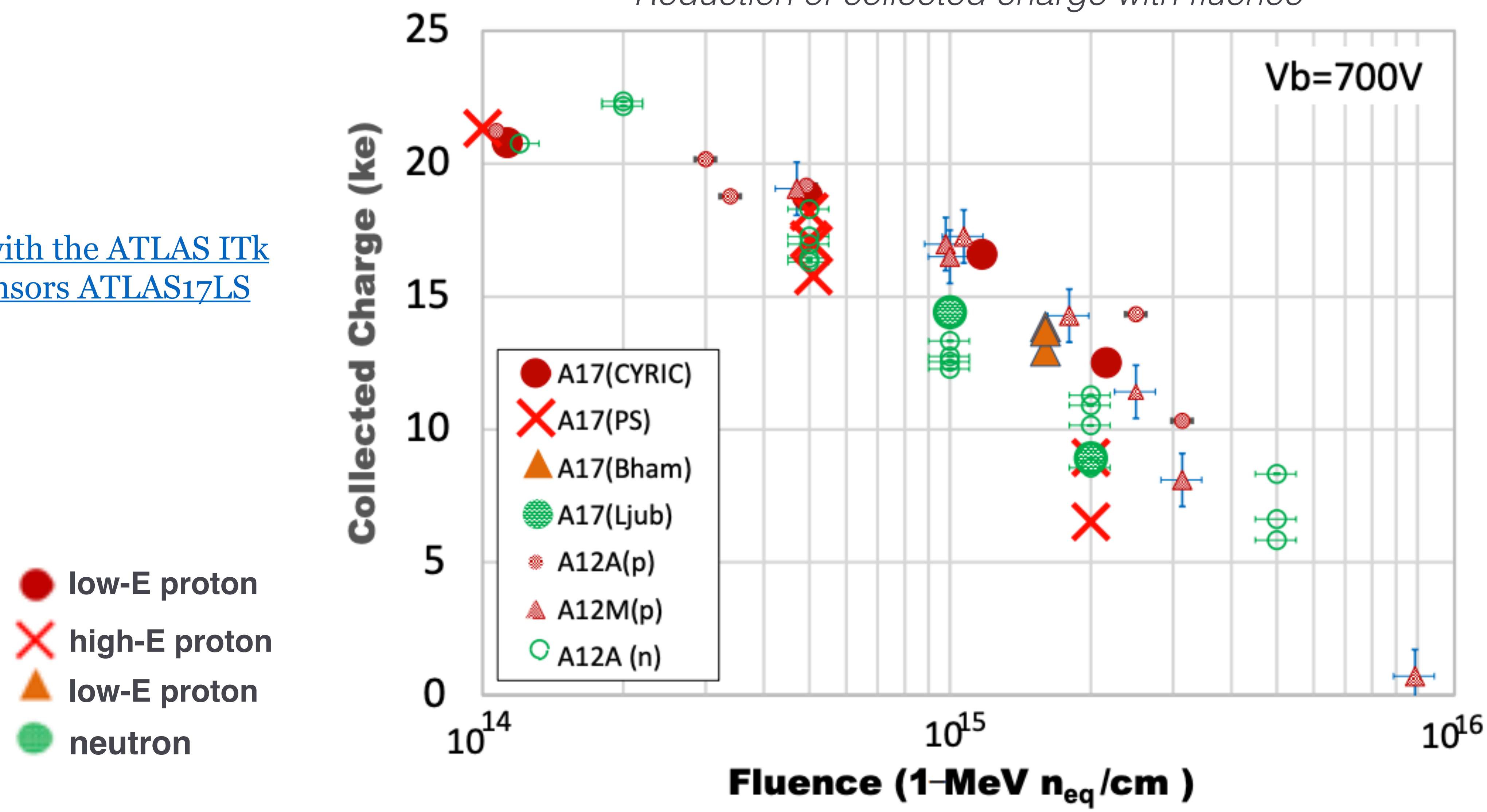
Motivation for Precise Digitization Model

Extreme radiation fluences will degrade performance of silicon sensor

- Operational: How to adapt? When & how high should we increase bias voltage?
- MC Simulation: Tracker modeling of charge-collection inefficiency & charge sharing between sensors

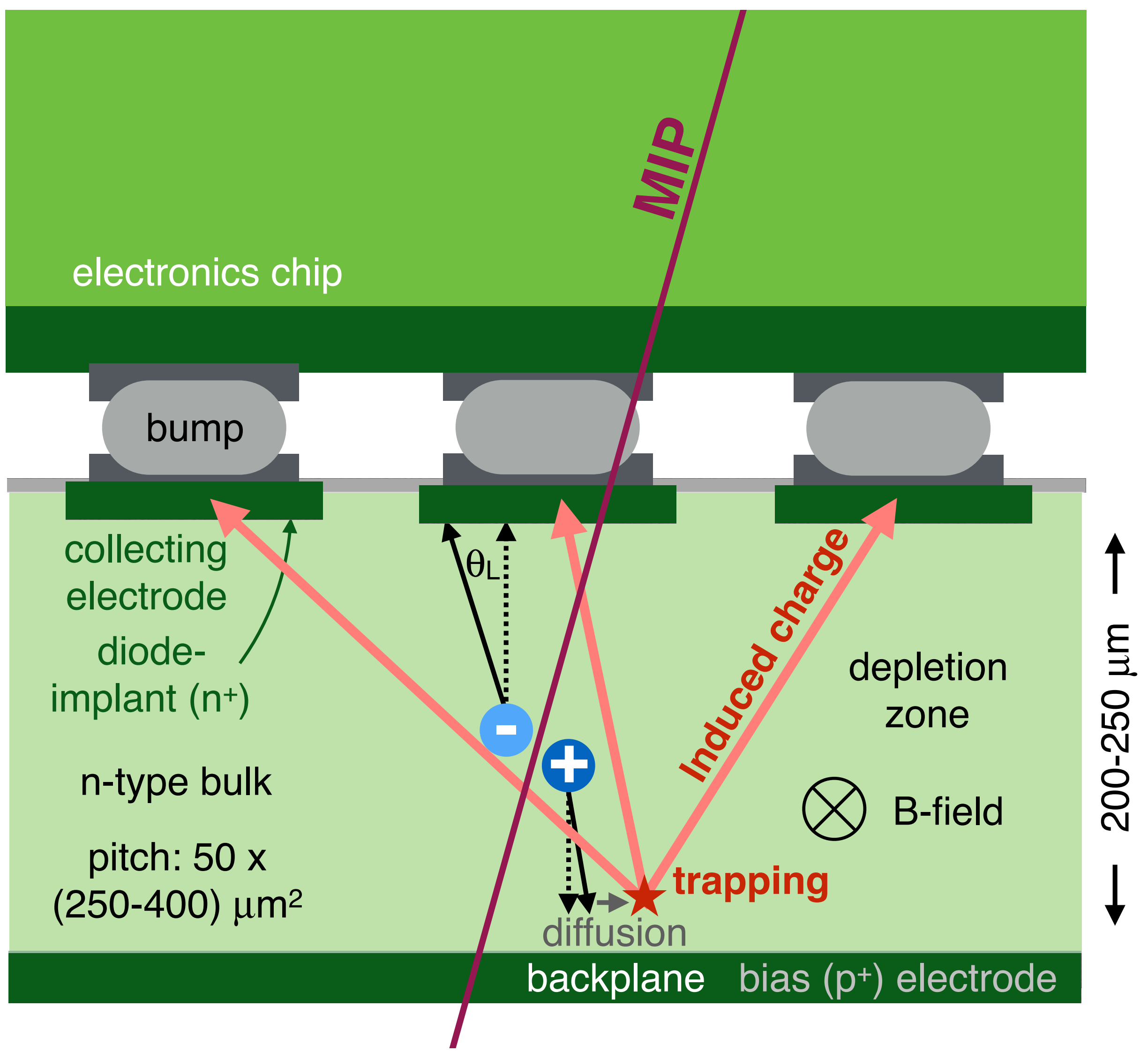
Charge collection study with the ATLAS ITk prototype silicon strip sensors ATLAS17LS

Reduction of collected charge with fluence



Current Digitization Strategy

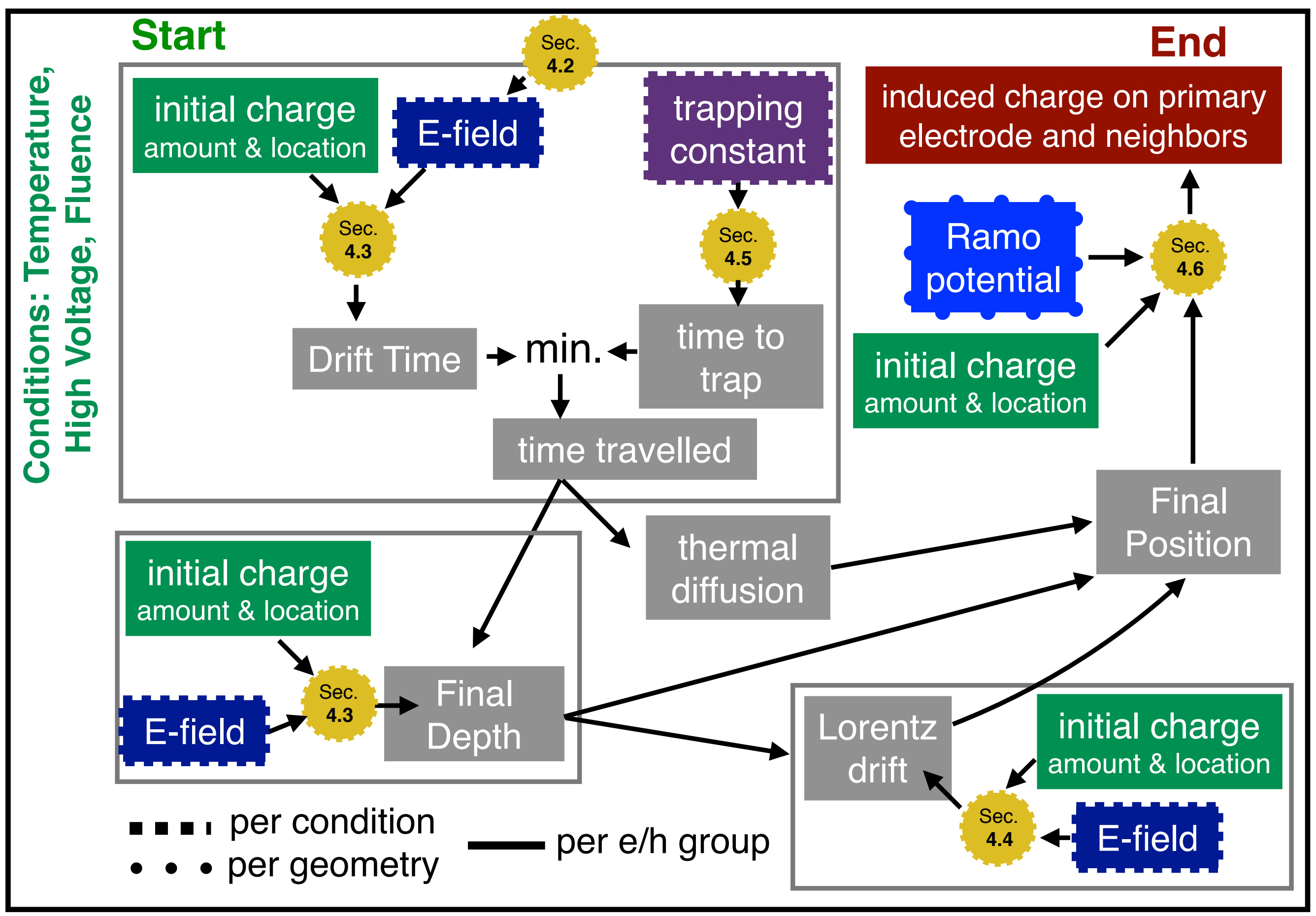
- For current ATLAS tracker, only Pixel layers simulate performance after radiation damage
  - For HL-LHC, radiation damage of outermost strip detector will be significant & needs simulation
- Simulation propagates groups of deposited charges calculates induced readout signal from drift & trapping



[Modelling radiation damage to pixel sensors in the ATLAS detector](#)

Current Digitization Strategy

- Complex simulation utilizes fluence-specific inputs at several points:
  - **Electric field**
  - **Weighting (Ramo) potential**
  - **Trapping constant**
- Slow to run, not tenable in HL-LHC conditions



[Modelling radiation damage to pixel sensors in the ATLAS detector]

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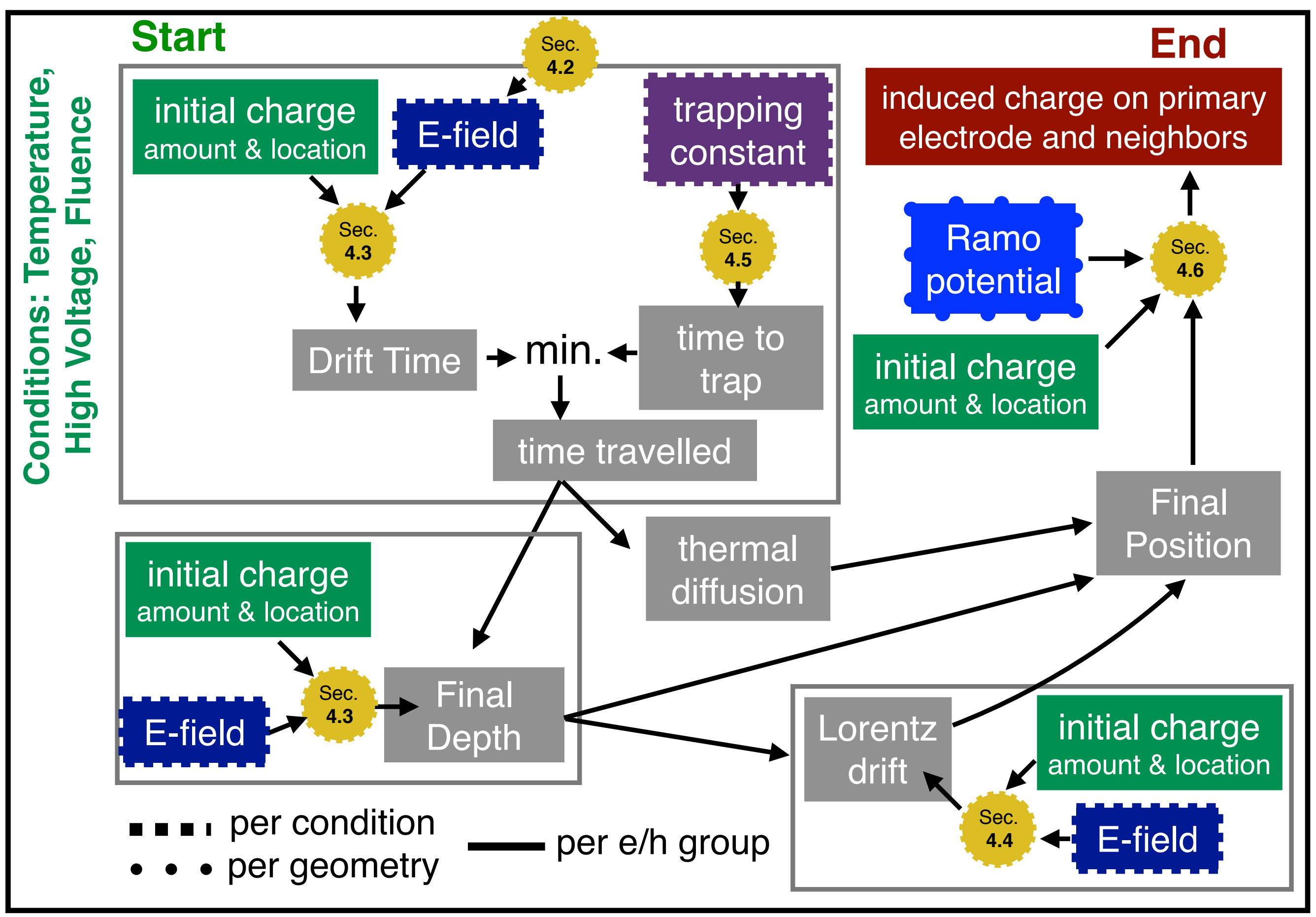
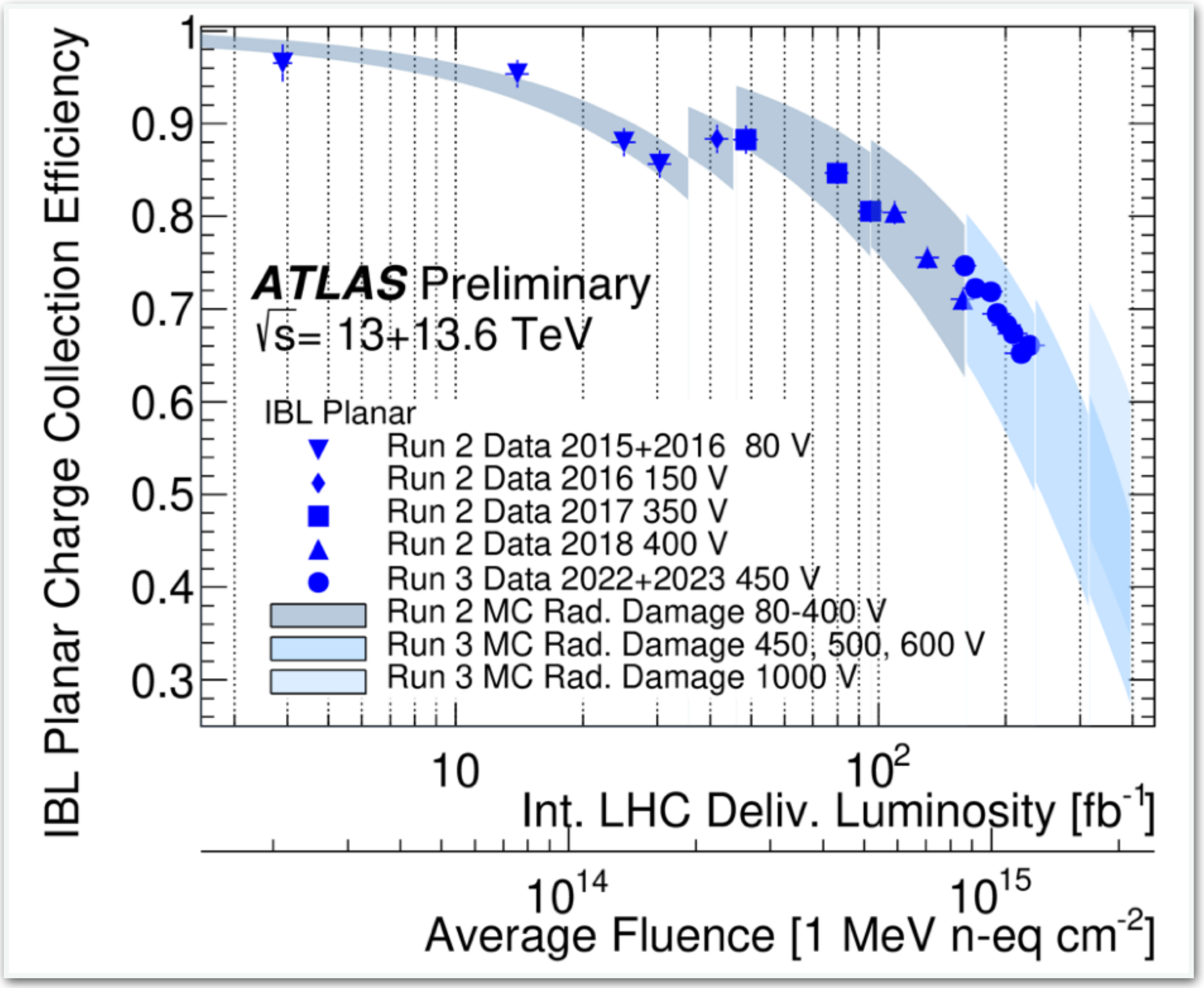
But gives very accurate predictions!



[Modelling radiation damage to pixel sensors in the ATLAS detector]



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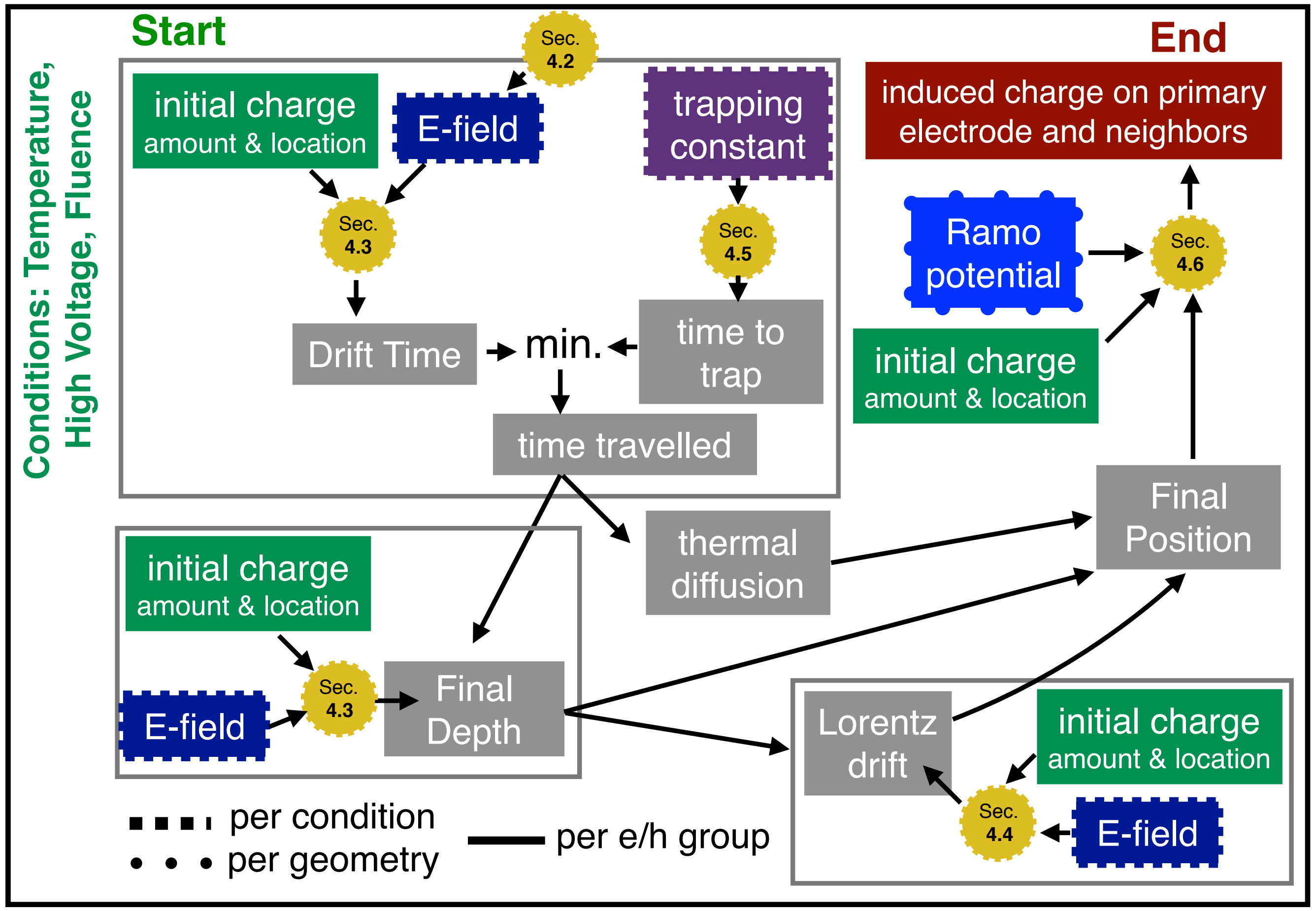
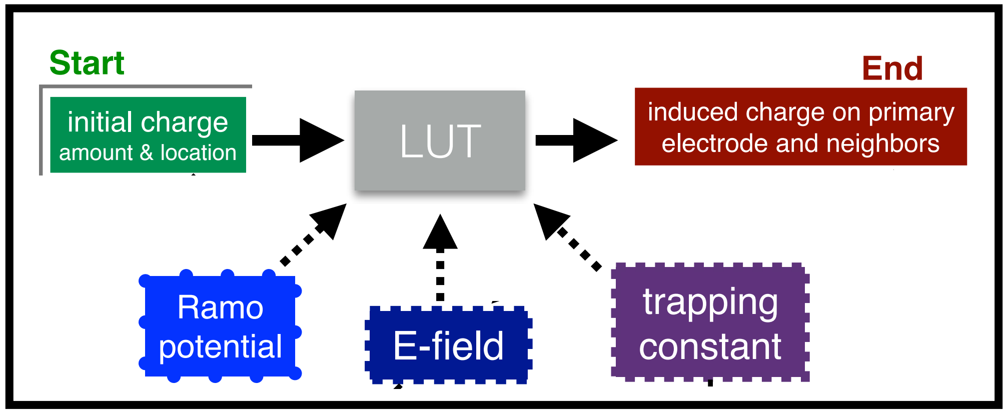
Simplified Digitization Strategy

- Complex simulation utilizes fluence-specific inputs at several points:
  - **Electric field**
  - **Weighting (Ramo) potential**
  - **Trapping constant**
- Slow to run, not tenable in HL-LHC conditions



Modelling radiation damage to pixel sensors in the ATLAS detector

- Exploring simplified method using look-up tables (**LUTs**) to parameterize charge propagation vs deposition depth
  - Simple implementation
  - Faster simulation (~3x speedup for Run 3)
  - Also gives accurate predictions!



- Working with Université Paris Cité (Marco Bomben & Keerthi Nakkalil) who created proof-of-concept for ITk-Pixel
  - See recent talk at Pixel2024 & paper describing method

LUT Pipeline

Streamlined simulation infrastructure for ITk-Strip
to generate look-up table (**LUT**) models fairly easily in ~1 day

TCAD: Generate detailed sensor field maps with custom ITk-Strip Sensor model

AllPix2: Simulate propagation, scan across charge-deposition positions

Derive LUTs

LUT closure checks

Translate to luminosity estimates (Geant4)

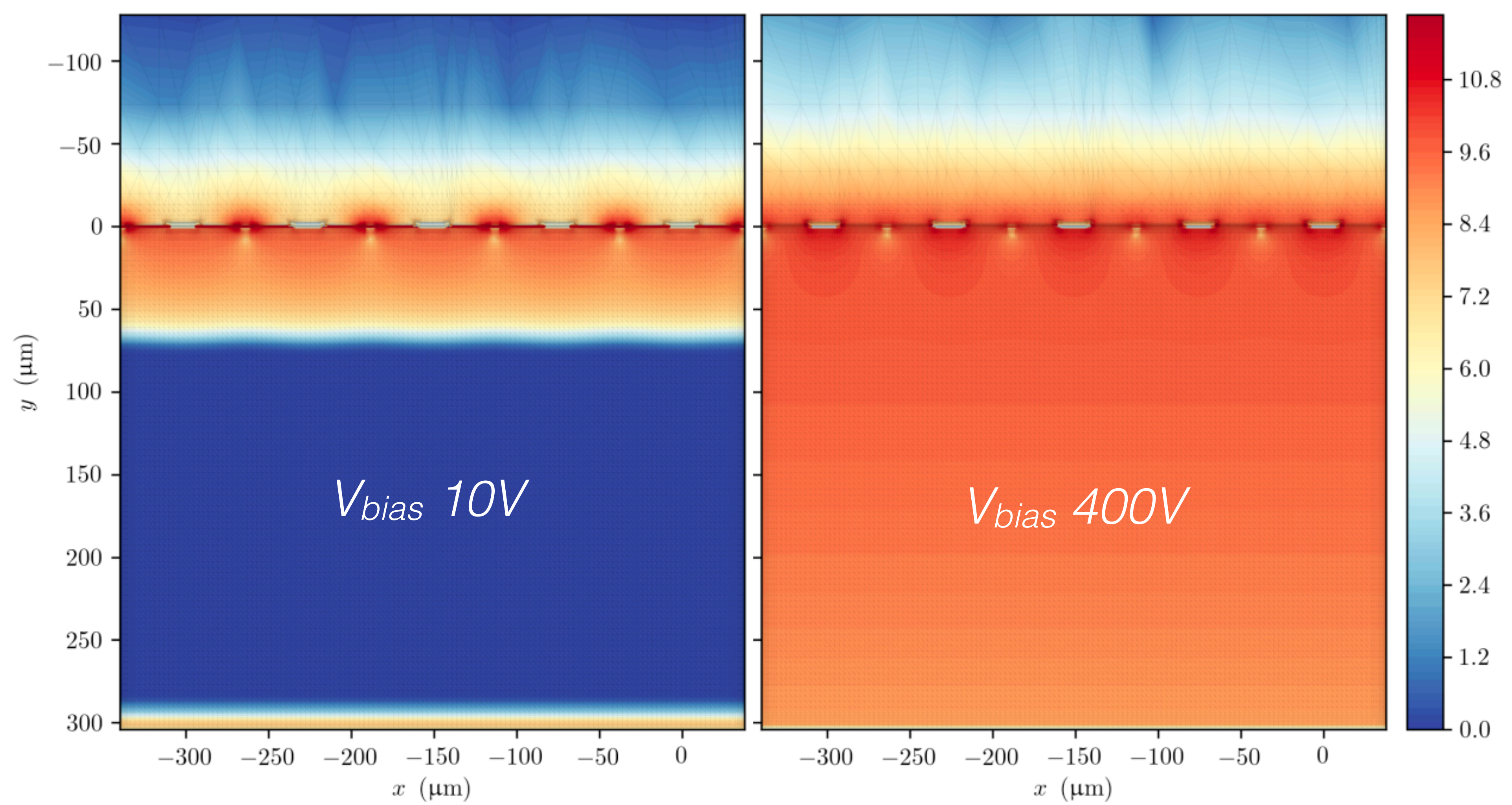
Import into Athena database for use & physics validation

ITk-Strip TCAD model

TCAD: Generate detailed sensor field maps with custom ITk-Strip Sensor model

- TCAD simulation of ITk-Strips being tested with various public models of radiation-induced trapping (see TCAD talk by Yuzhan Zhao)
  - Custom python integrations to greatly increase flexibility for massive parameter scans

Unirradiated Electric Field evolution across 5 strips (log scale)



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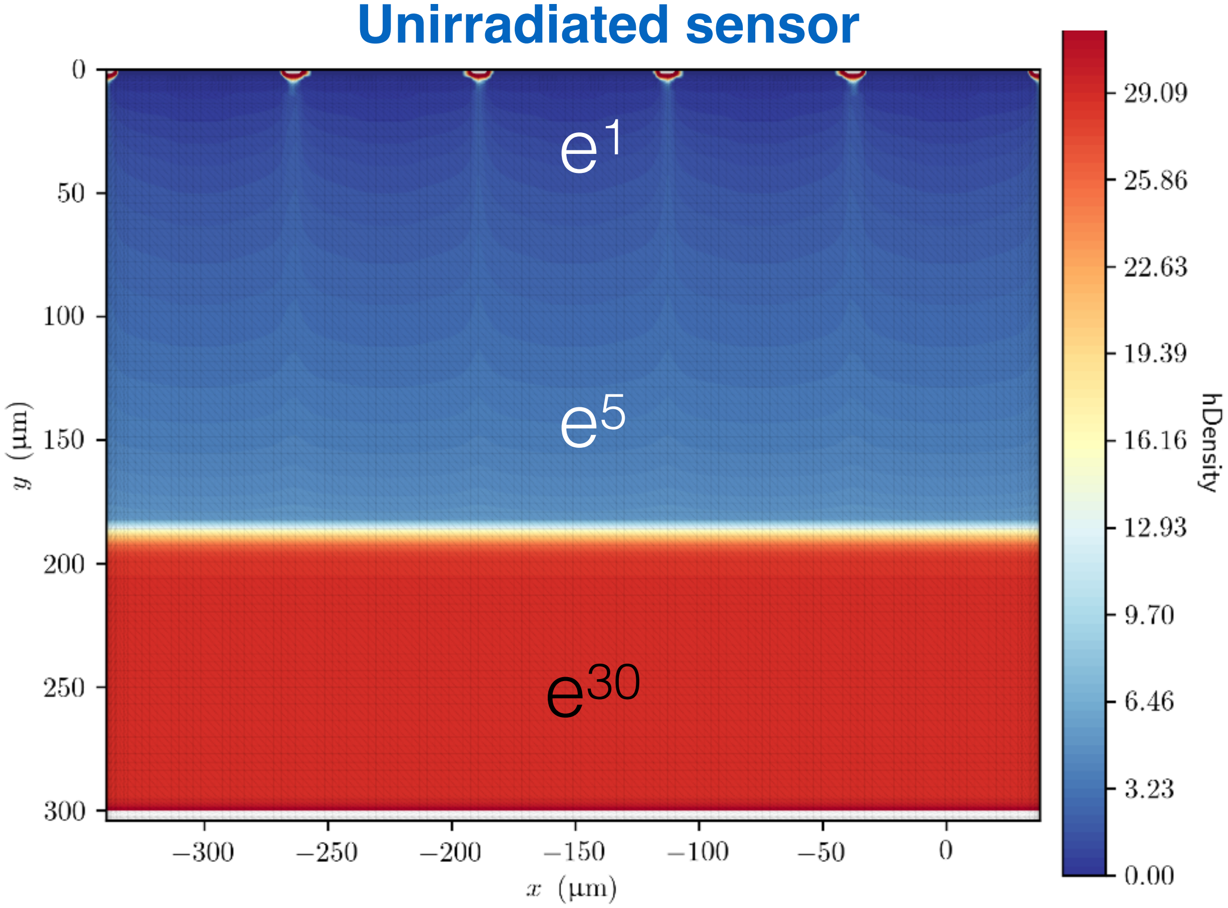
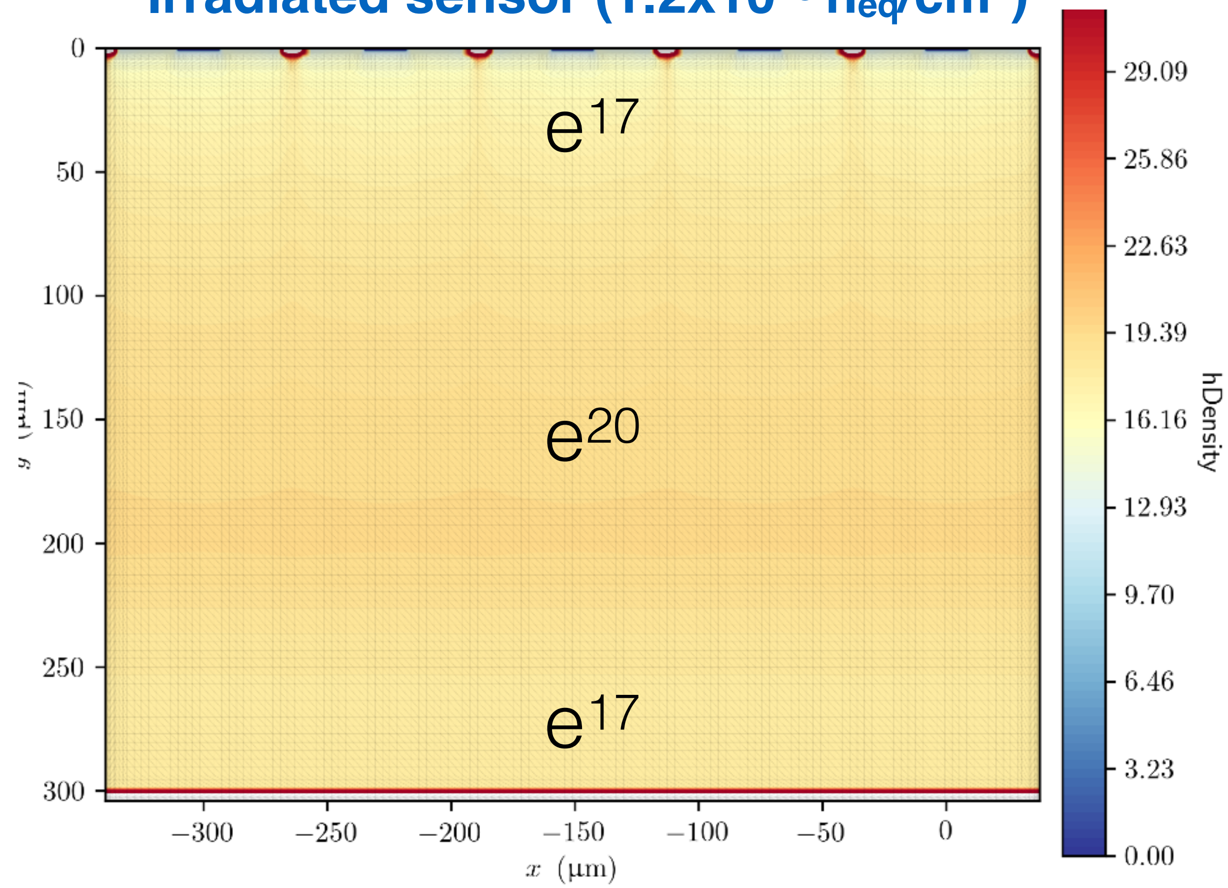
Density of hole carriers @ 100V

Unirradiated sensor



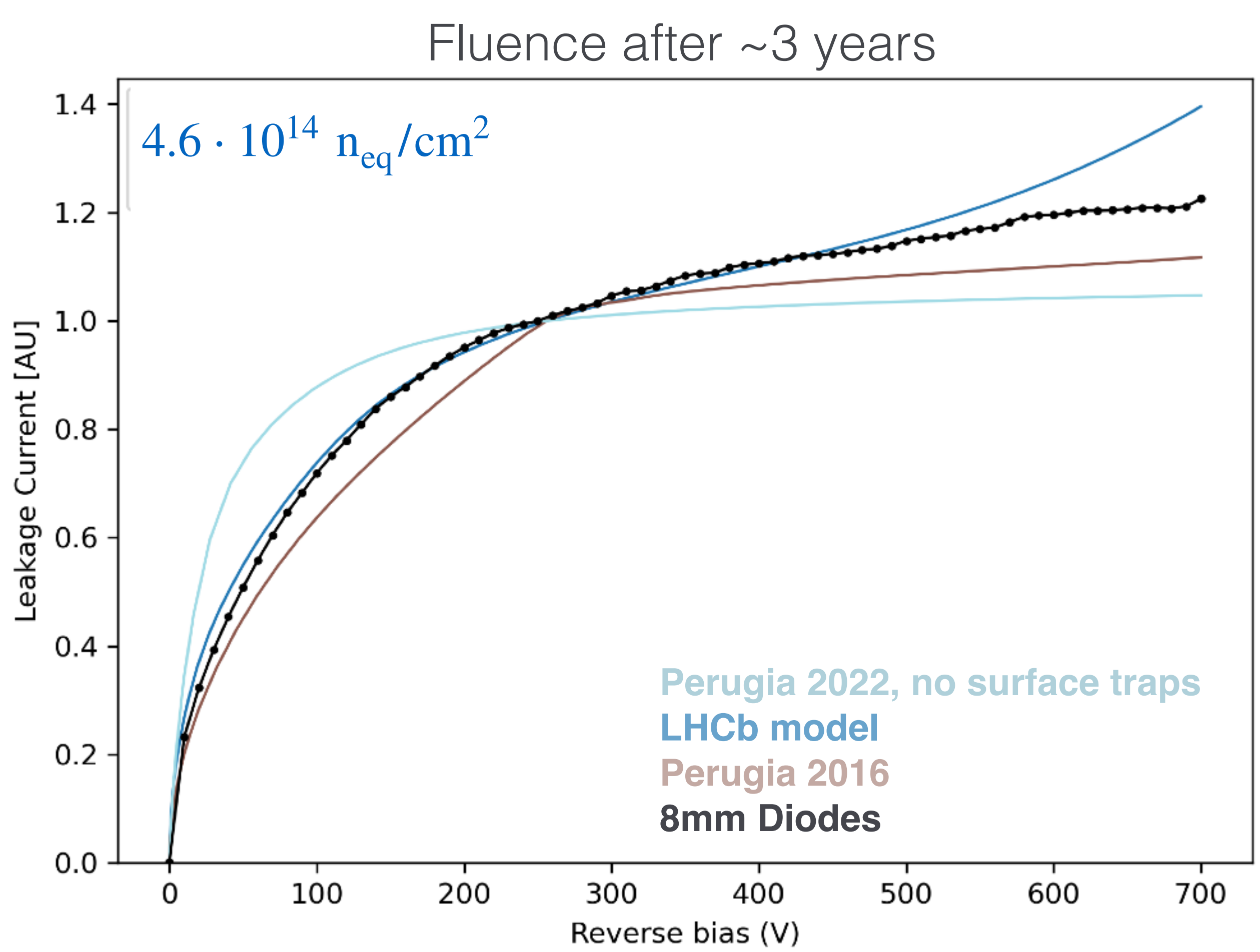
Irradiated sensor ($1.2x10^{15}$ n_{eq}/cm^2)

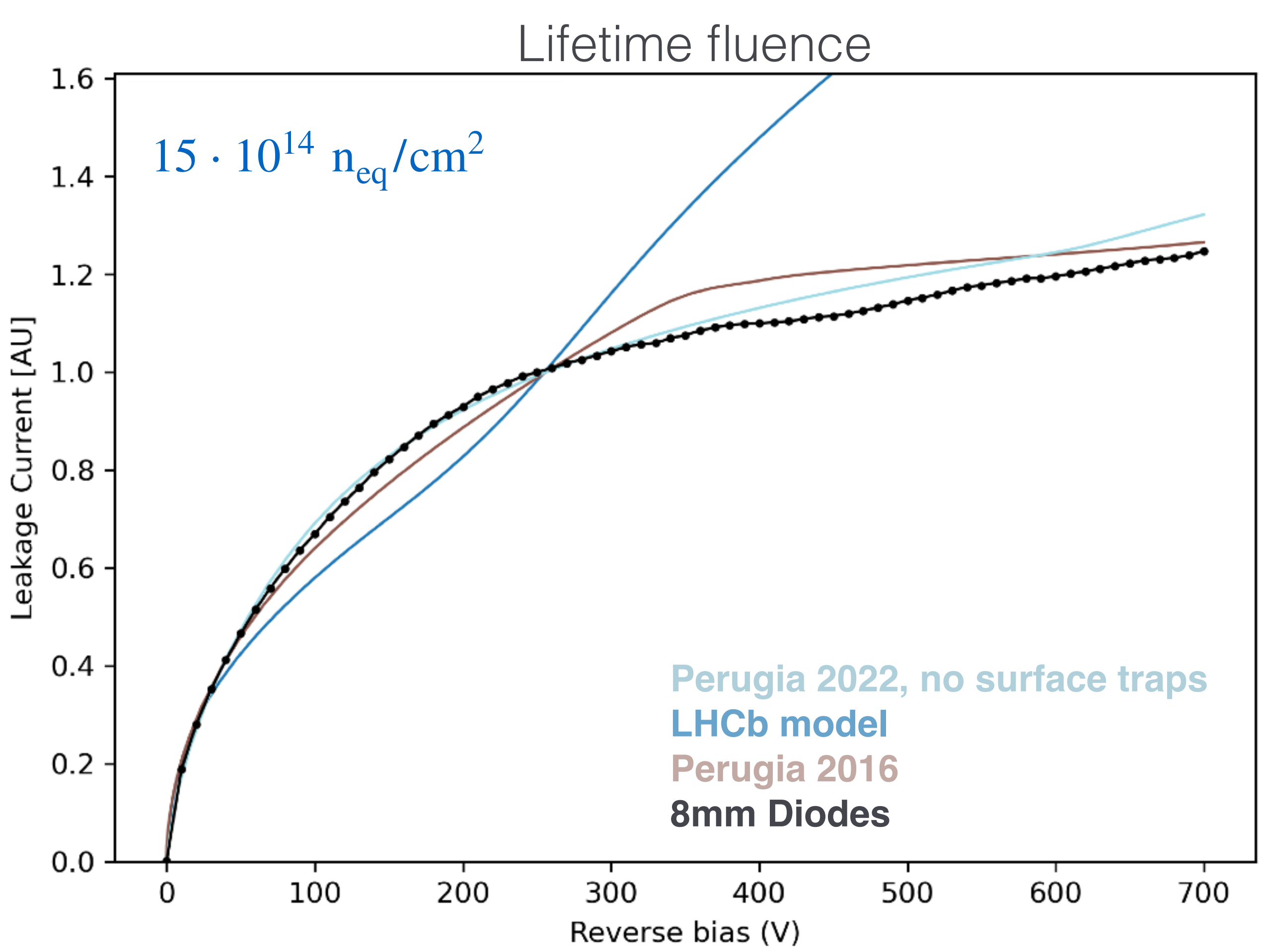


ITk-Strip TCAD model

TCAD: Generate detailed sensor field maps with custom ITk-Strip Sensor model

- TCAD simulation of ITk-Strips being tested with various public models of radiation-induced trapping (see TCAD talk by Yuzhan Zhao)
  - Custom python integrations to greatly increase flexibility: massive parameter scans & automated plotting
- Validate models with QC (unirradiated) & QA (irradiated) test-structure data from ITk-Strip sensor community
  - No existing model is consistently performant across fluences, bias voltages, temperatures
  - Pursuing custom ITk Strip model at Carleton, informed by direct measurements of silicon defects (see DLTS talk by Christoph Klein)



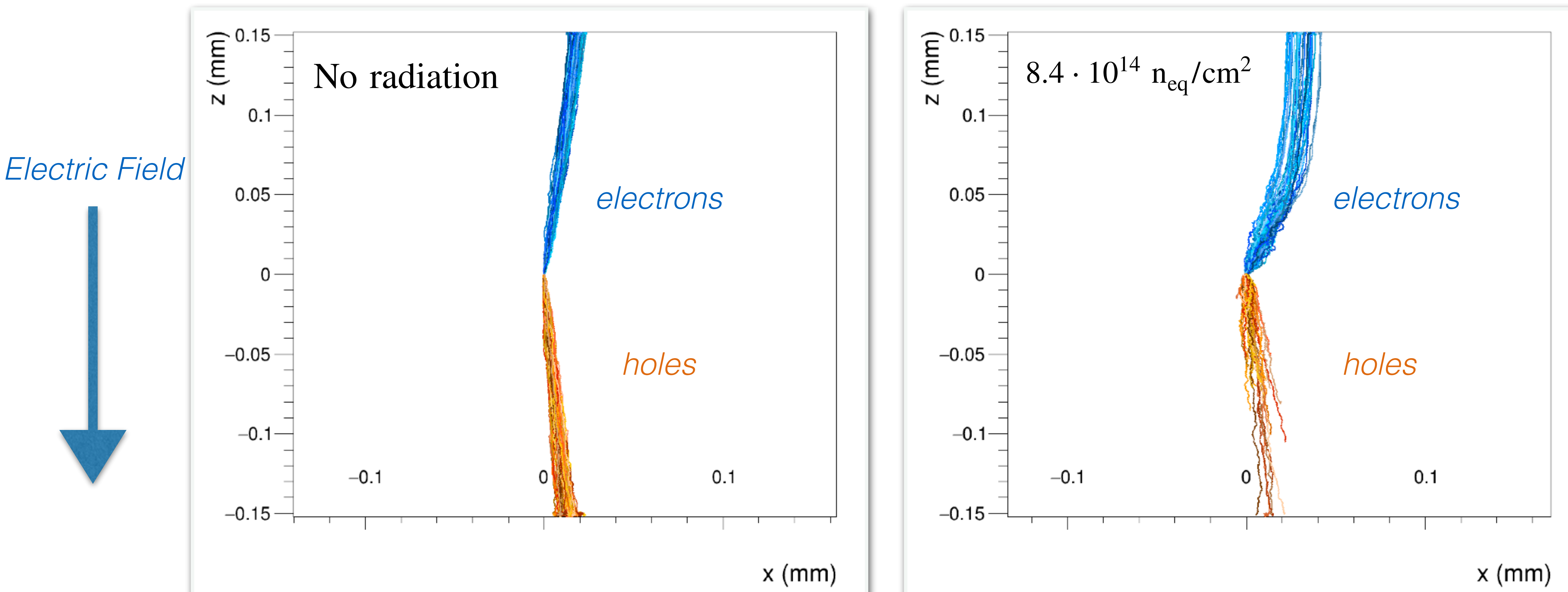


Leakage current data & simulated models, normalized at 250 V

Charge Propagation Simulations

AllPix2: Simulate propagation, scan across charge-deposition positions

- AllPix2 strategy to convert TCAD fields into human-readable AllPix2 format, derive Weighting Potential from ΔElectrostaticPotential
- Simulate charge propagation via AllPix2 **TransientPropagator**
- Scan across various depths of deposited charge



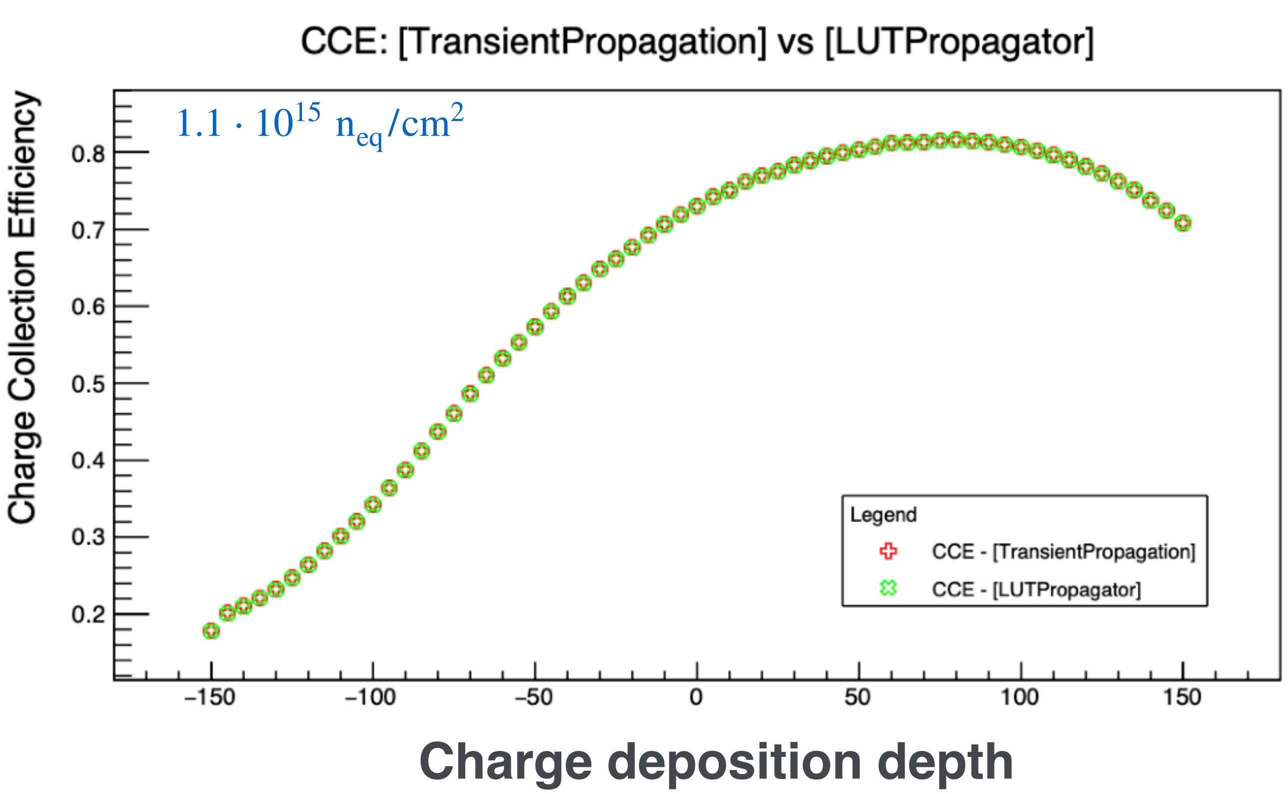
Charge propagation from center of sensor without / with radiation

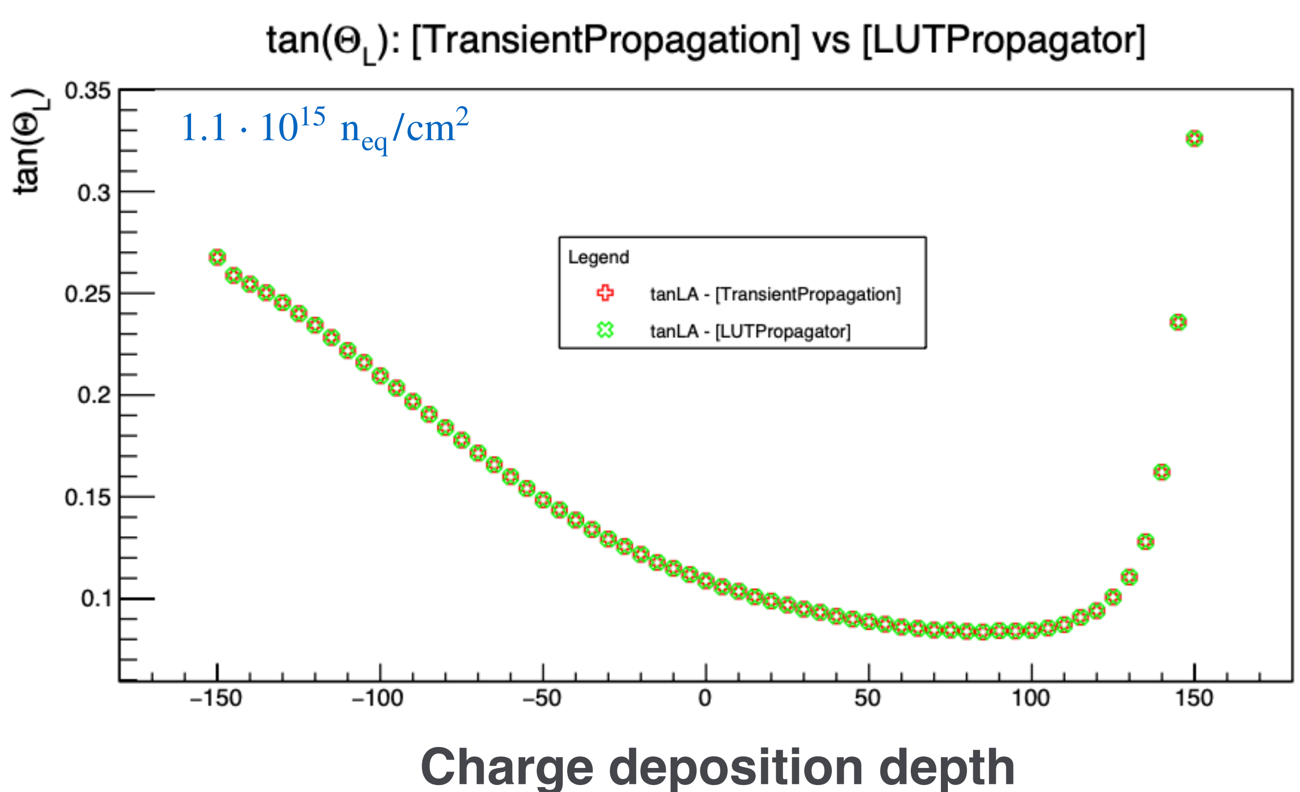
Building Look-up Tables

Derive LUTs

LUT closure checks

- Developing unified framework across ITk-Strip & ITk-Pixel for deriving LUTs
  - Fit or interpolate TransientPropagator results vs. charge deposition depth
  - Key distributions are Charge Collection Efficiency & Lorentz Angle
- New **LUTPropagator** module implemented in AllPix2 utilizes LUTs for fast validation against TransientPropagator

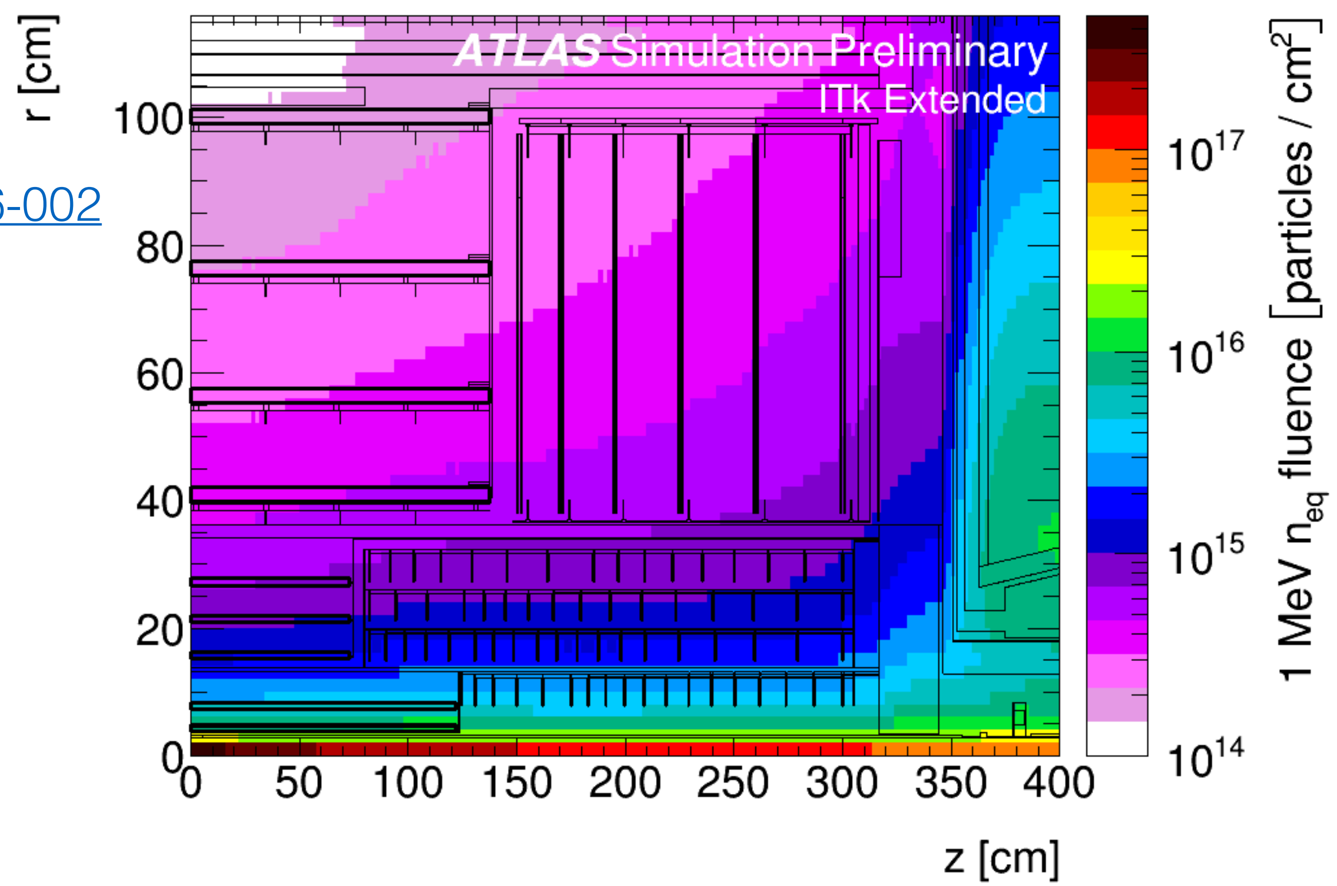




ATLAS Software Integration

ATLAS EXPERIMENT

ITK-2016-002



Translate to luminosity estimates (Geant4)

Import into Athena database for use & physics validation

- TCAD+AllPix2 pipeline repeated for various fluence estimates (in steps of ~5×10^{14} n_{eq}/cm^2)
- ATLAS MC generated in "campaigns" to match single year of data
  → different fluences for different layers at a specific integrated luminosity
  - Fluences of each layer estimated from Geant4 / Fluka simulations
  - Predicts < 30% variation across length of barrel layers → use average estimate for each layer
  - No endcap implementation yet due to complex geometry & fluence profile
- Strategy allows digitization model re-calculation as data collected without rerunning TCAD+AllPix2

Conclusion

- Exploring custom TCAD models of irradiated ITk-Strip sensors, including DLTS-measured lattice defects
- Automated pipeline builds LUTs from sensor simulations utilizing TCAD & AllPix2
  - Straightforward to run: Template for running TCAD followed by python framework connecting simulations
  - Pre-produce LUT models at various fluences (& voltages) → as HL-LHC progresses translate to luminosity-specific estimates on the fly
- LUTPropagator module & example LUT calculation scripts will be made available via AllPix2