TCAD Simulation of Electrical Characteristics and Irradiation Modeling for ATLAS ITk-Strip Sensors

2nd DRD3 week on Solid State Detectors R&D
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on behalf of the ATLAS ITk Strip Sensors community

Overview

- **The HL-LHC upgrade will increase luminosity by a factor of 7.5, leading to:**
  - **Higher pile-up.**
  - **Increased radiation levels.**

- **ITk Strip Sensors are designed for the ATLAS Tracker Upgrade** to maintain tracking performance under HL-LHC conditions:
  - n-on-p sensors with thousands of strips.
  - Designed to withstand extreme radiation levels (up to 1.6E16 neq/cm^2).

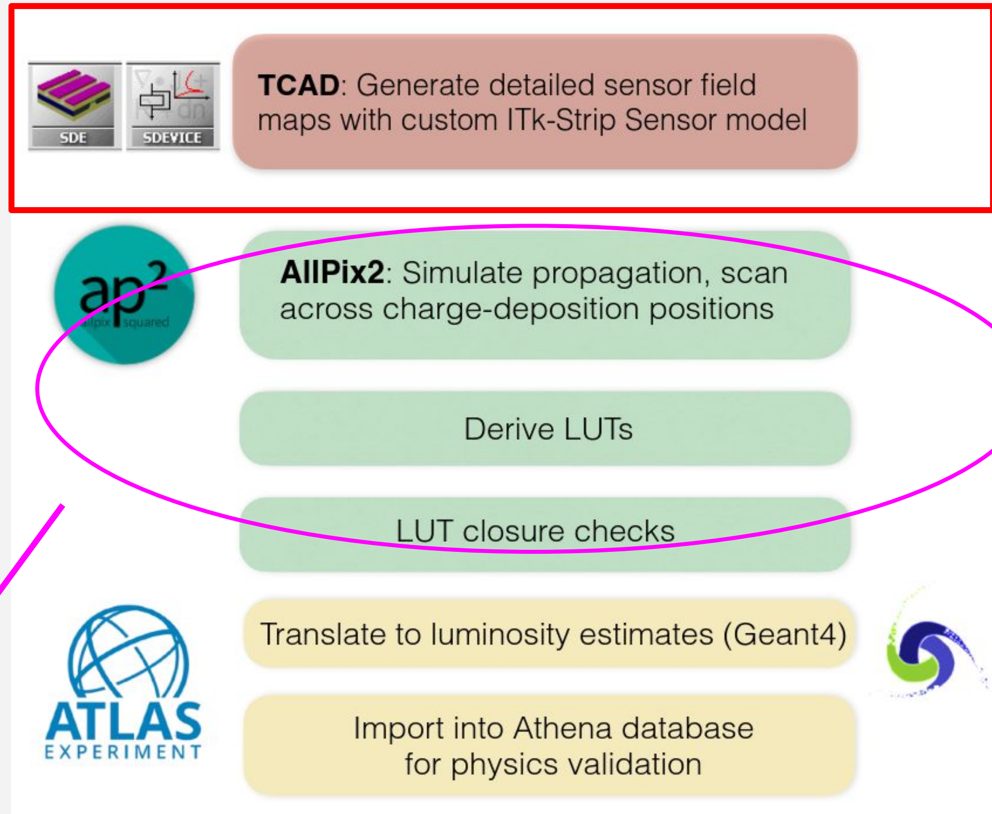
- Precise modeling of the ITk sensors is essential for:
  - **Optimizing electronics operational setting.**
  - **Ensuring accurate particle tracking and physics performance.**
  - **TCAD simulations** offer a cost-effective and efficient way to study and characterizing sensor performance:
    - **But, a full ITk strip sensor simulation is computationally impractical.**

Overview

- Hence, **a streamlined 2D TCAD simulation pipeline has been developed, with Python integration for flexible parameter scans.**

In this talk, we present the preliminary studies of the sensor electrical behavior before and irradiation using this streamlined TCAD process

- **Previous established Perugia & LHCb model.**
- **A preliminary DLTS-based model. (from Christoph's measurement)**

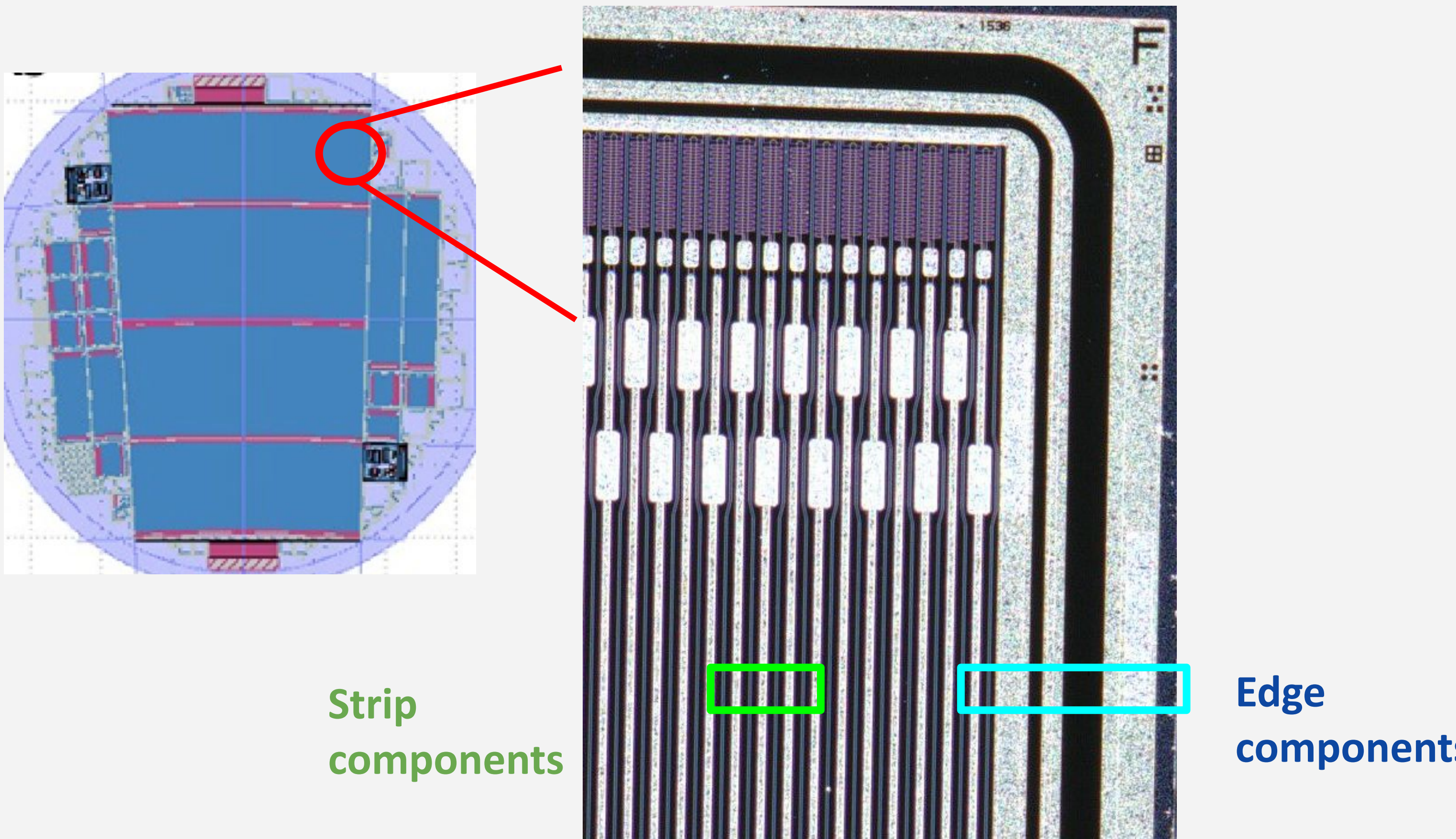


More details on Jeff's talk

TCAD Simulation Setup

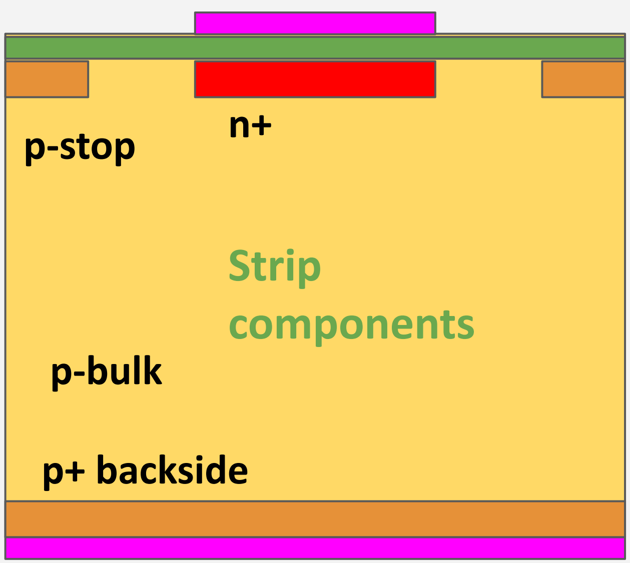
Simulation Setup

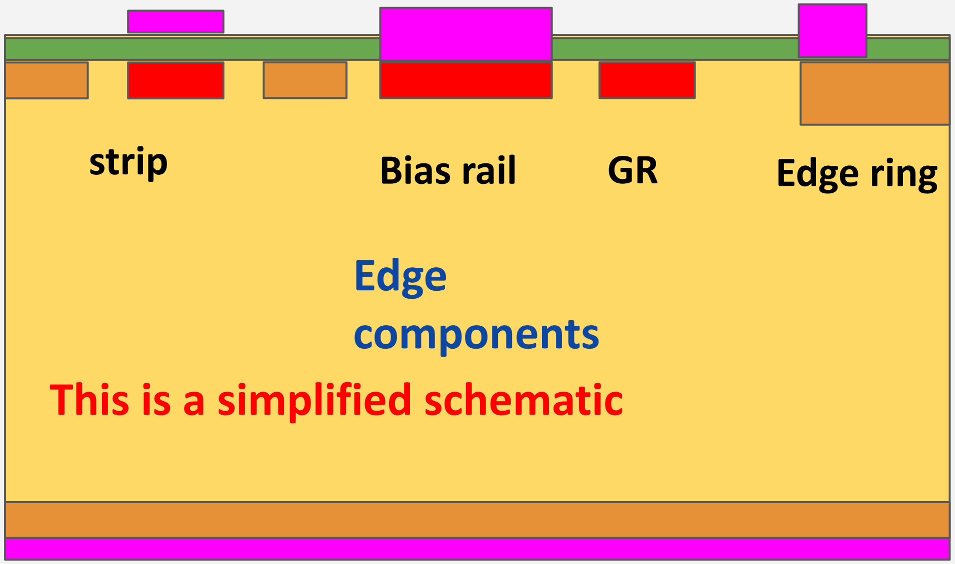
- To map the real sensor geometry and structure, custom ITk strip sensor model implemented in TCAD simulation.
  - Parameters are derived from C-V and metrology measurements.
- Symmetric and periodic structure ⇒ 2D simulation with basic components:



Simulation Setup

- **Symmetric and periodic structure ⇒ 2D simulation with basic components:**
  - **Strip component**: a single strip with halved p-stops on both sides.
  - **Edge component**: a single (or multiple) strip(s) with the full edge structure.
- **Stitching multiple of these basic components ⇒ larger sensor structure**
  - E.g. the MD8 test sensors have area:
    - 0.47 cm^2 for bulk region.
    - 0.11 cm^2 for edge region.
  - **In our streamlined TCAD process, only essential components, with equivalent area less than 1 mm^2, are simulated.**





Validating Stitched Structures

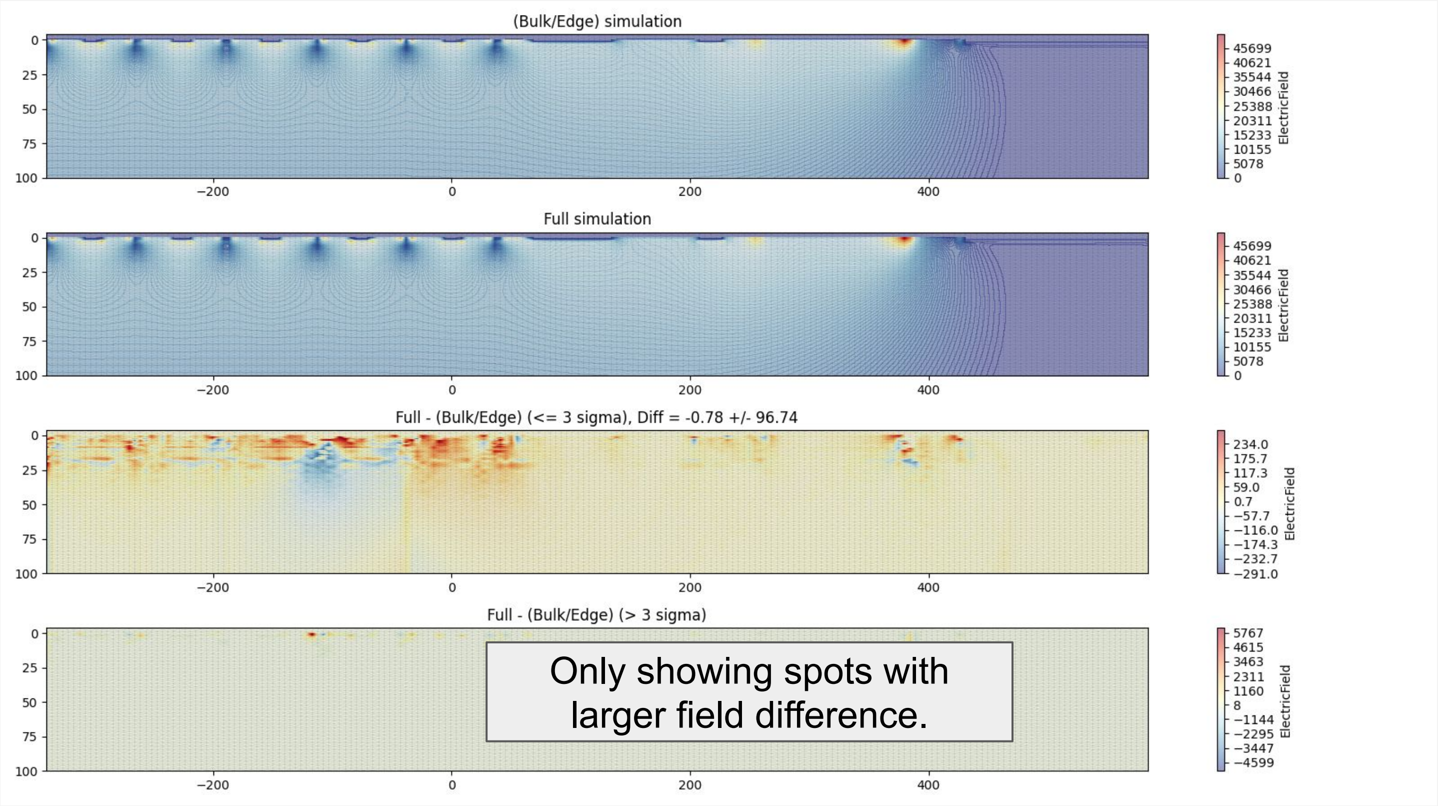
- **Can we accurately reproduce larger structures by stitching basic components?**
    - **Simulate a standalone larger structure (e.g., 5 strips with edge structure).**
    - Reconstruct the same structure with basic components:
        - **Stitch together 4 strip with 1 edge components.**

- **Validation Through Key Comparisons:**
    - Microscopic **Quantities** (not directly measurable):
        - **Example: Electric field/potential distribution.**
            - **Critical input for tools like Allpix.**
        - Additional quantities can also be explored.
    - Macroscopic **Quantities** (measurable):
        - Example: I-V characteristics.

Validation: Electric Field

When comparing electric fields, two difference were observed:

- **Primarily due to numerical uncertainty.**
    - Can be improved with higher precision and finer mesh size, but with cost of higher computational resources.



Stitched large structure using components

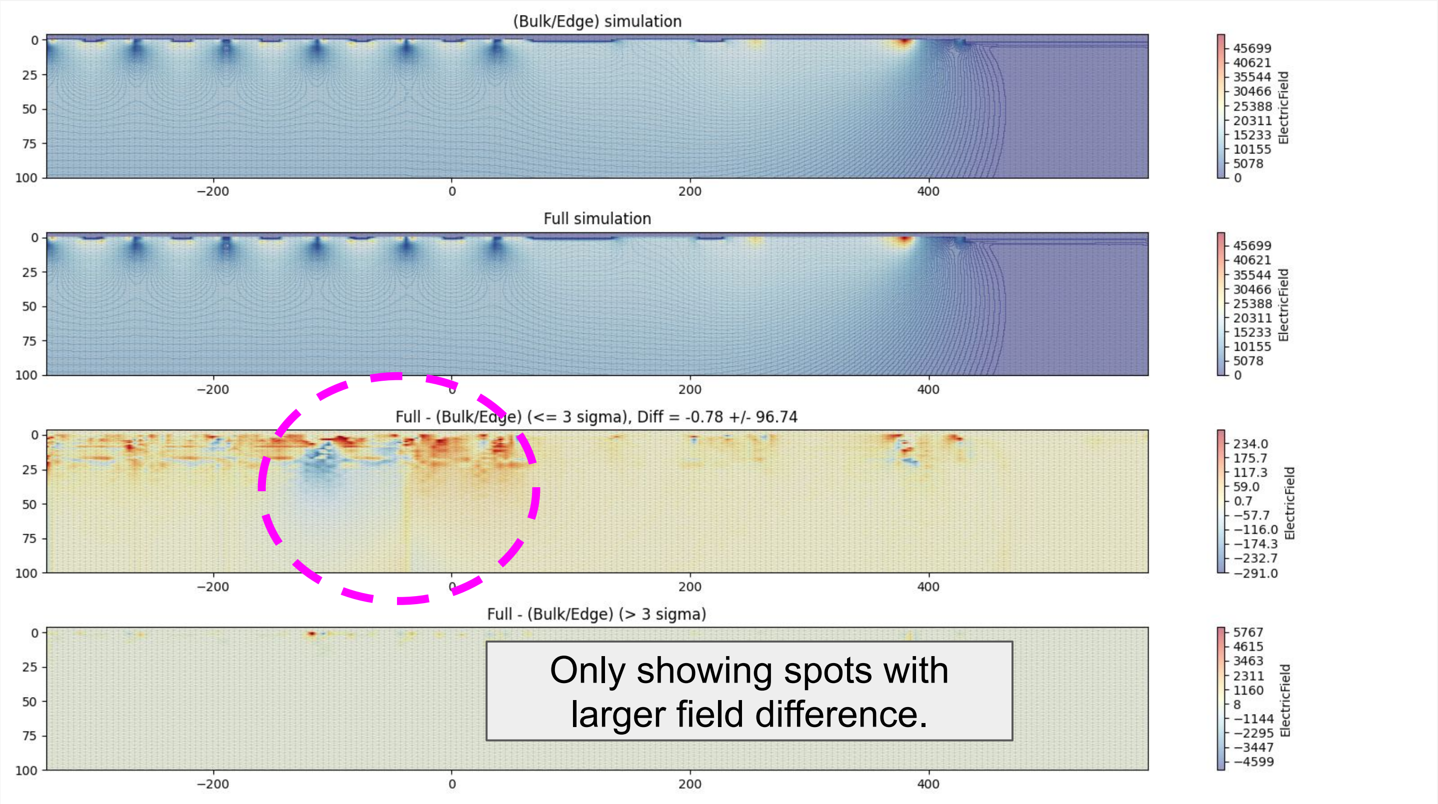
Standalone large structure

The overall difference in the electric field is small

Validation: Electric Field

When comparing electric fields, two difference were observed:

- Difference in boundary condition when transition from strip to edge region
  - Can be improved with adding more strips into the edge structure element.



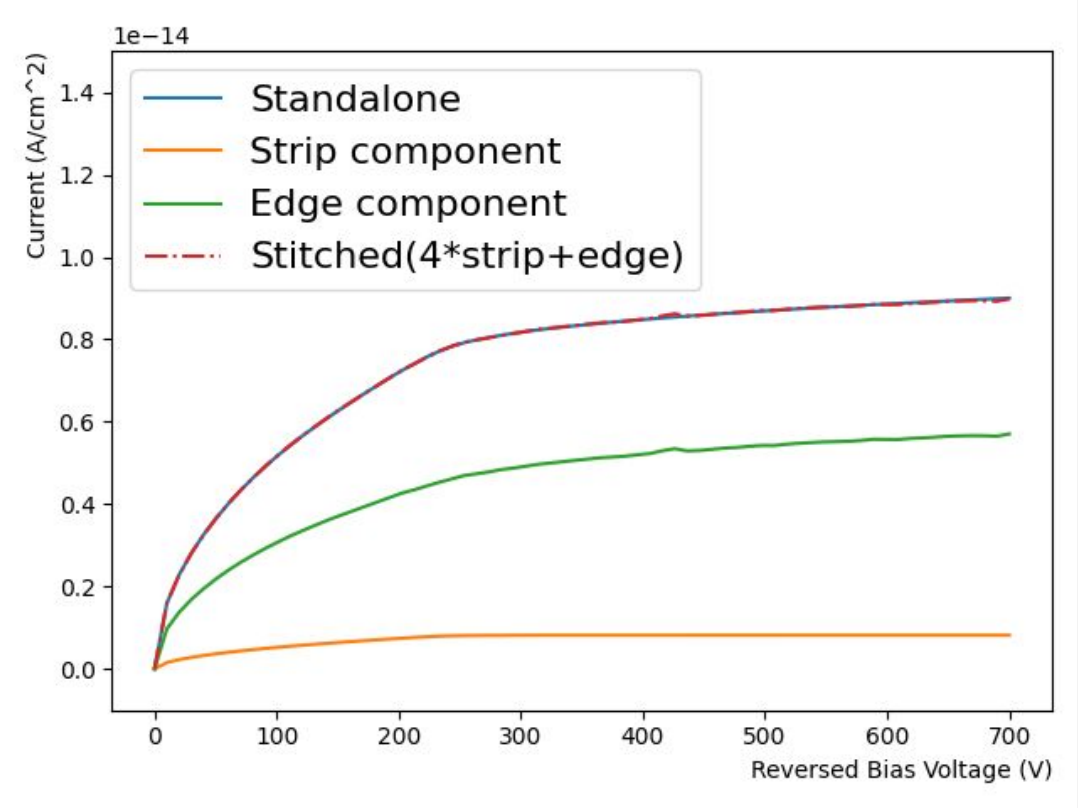
Stitched large structure using components

Standalone large structure

The overall difference in the electric field is small

Validation: I-V

- The simulated I-V for a larger structure can be accurately reproduced using basic components.
- **Only the essential basic components, representing critical regions of the strip sensors, are required for simulation.**
  - **Larger sensor structures can be reconstructed by appropriately scaling and combining these components.**



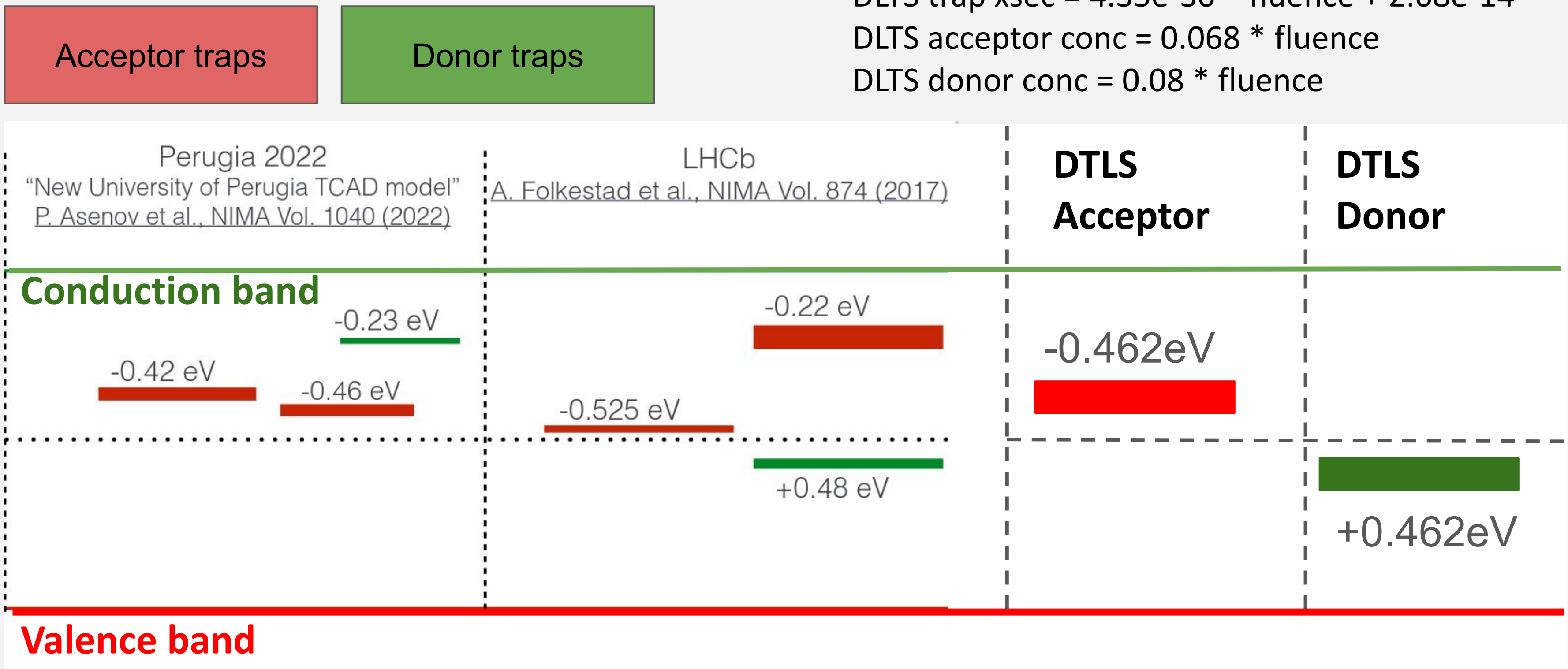
Case Study:
Irradiation Model for Strip Sensors

Trap Models

- **Previously established Perugia and LHCb trap models were simulated using the presented TCAD setup and compared with DLTS measurements (see Christoph's talk).**

This DLTS model is very preliminary. Further investigation is required.

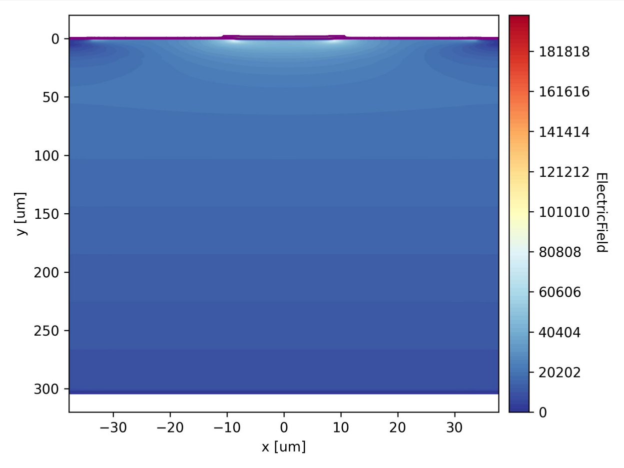
DLTS trap xsec = 4.35e-30 * fluence + 2.08e-14
DLTS acceptor conc = 0.068 * fluence
DLTS donor conc = 0.08 * fluence



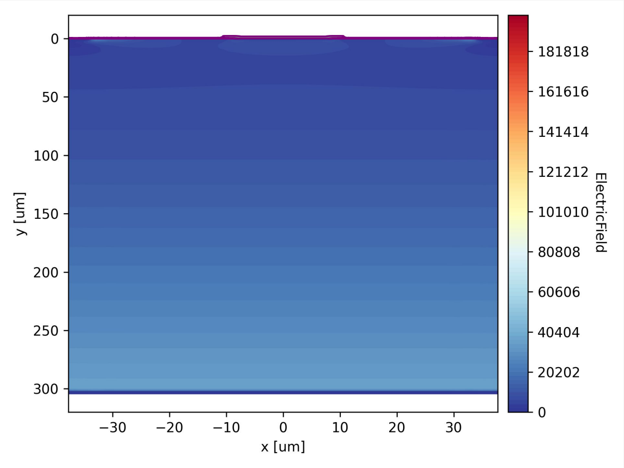
E-Field: Strip components

- Electric field maps are shown for a bias voltage of 500V and a radiation fluence of 1.5×10^{15} neq/cm^2
- DLTS model shows minimal changes, with the electric field remaining similar to the pre-irradiation state.
- The Perugia model: noticeable increase in the electric field on the sensor's backside, and field reduction near the surface.
- The LHCb model has much stronger field developed near the strip

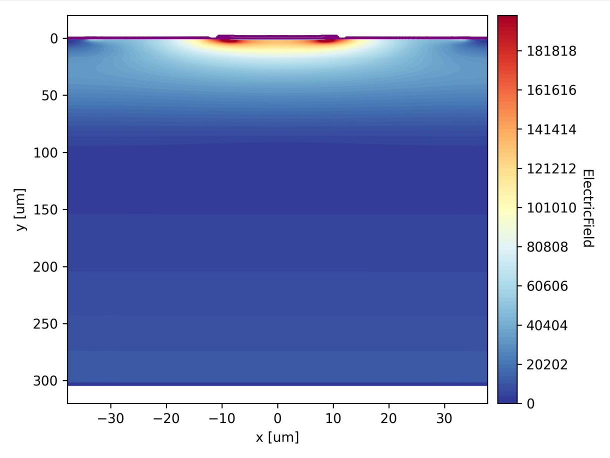
Before Irradiation



Perugia Model
(no surface traps)



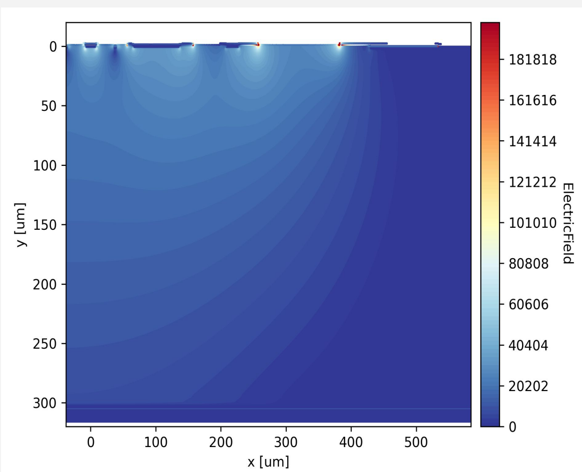
LHCb Model



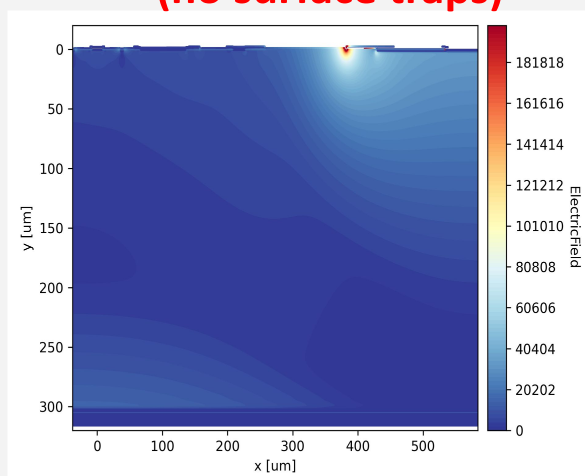
E-Field: Edge components

- Electric field maps are shown for a bias voltage of 500V and a radiation fluence of 1.5×10^{15} neq/cm^2
- DLTS model shows minimal changes, with the electric field remaining similar to the pre-irradiation state.
- The Perugia model: significant changes in the edge region after irradiation, with a high field developing near the edge rail.

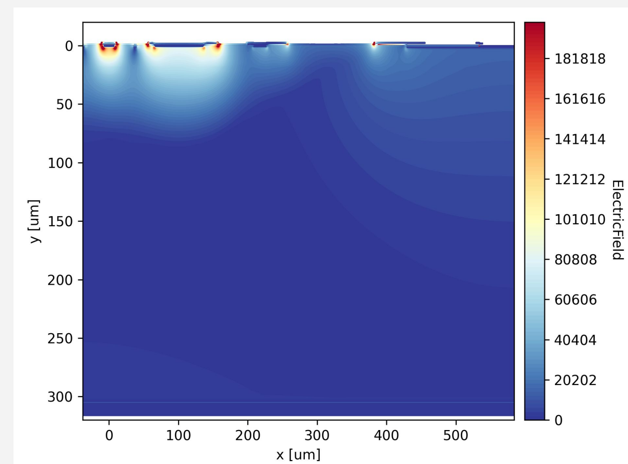
Before Irradiation



Perugia Model (no surface traps)

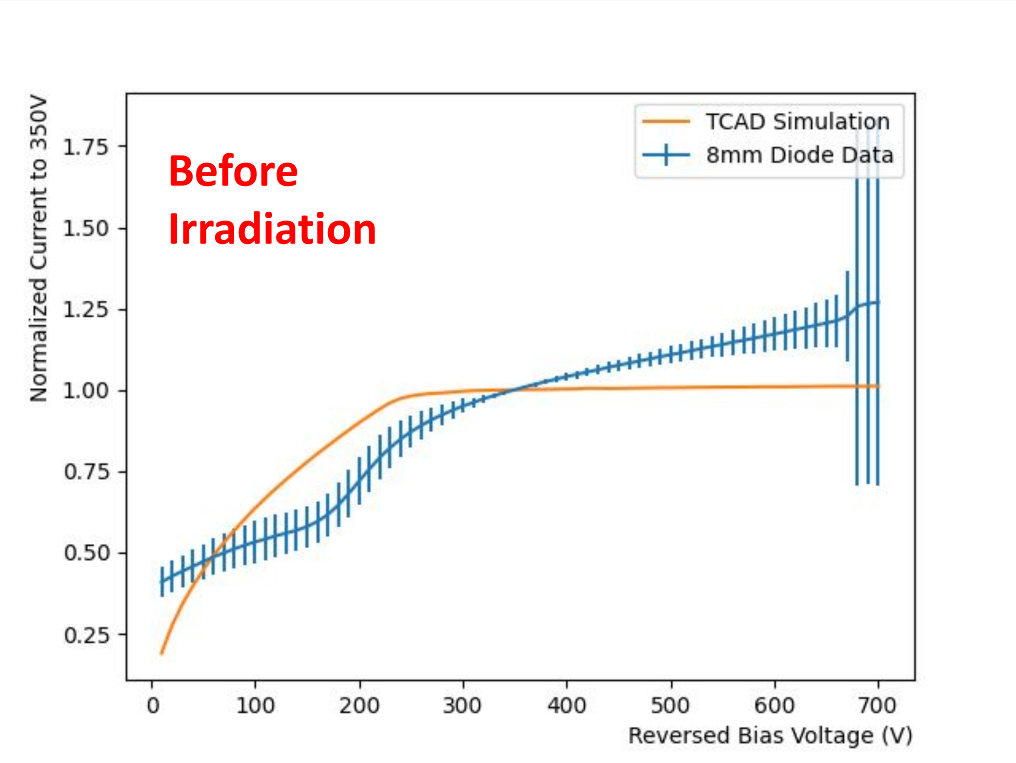


LHCb Model



I-V Comparison to Data

- The simulated I-V is compared to 8 mm test diodes:
  - The simulated current is scaled to match the 8 mm test diode area and normalized to the value at 350 V.



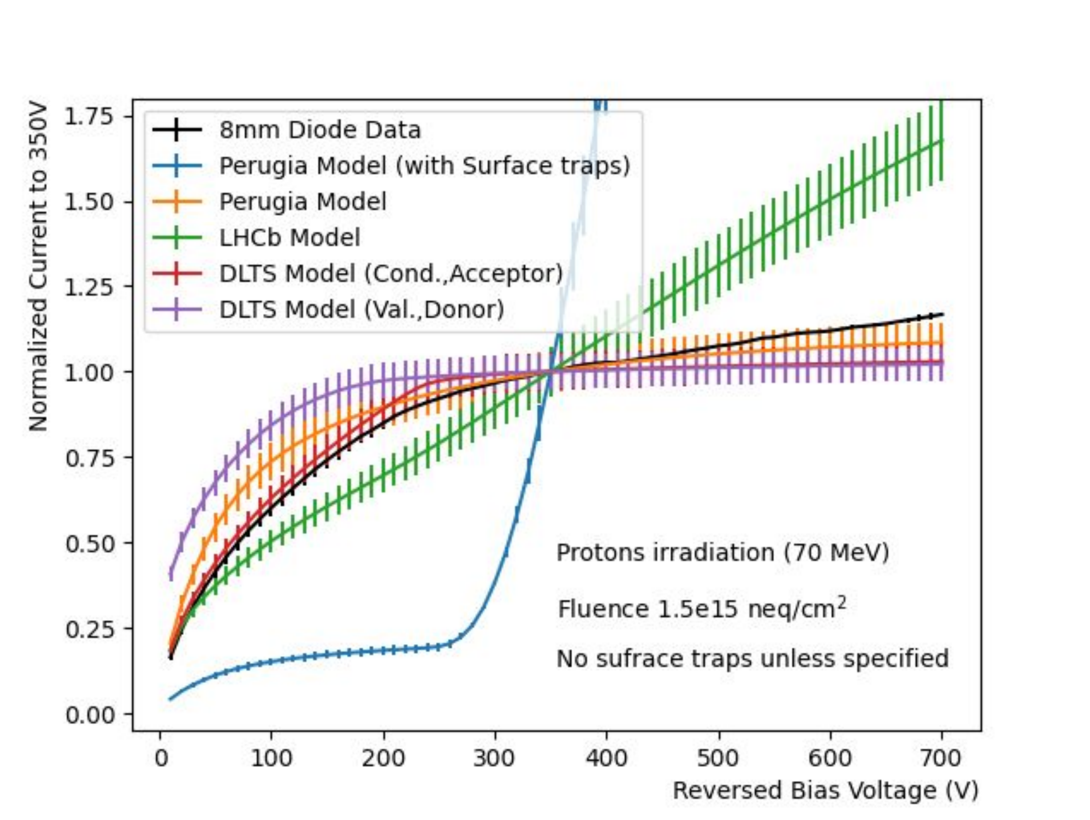
- Missing inherent trap model introduced from fabrication process.
- Surface trap model for Si-Oxide interface.
- Around 200V, potentially inaccurate doping profile from the bulk to backside that cause difference in depletion.

Requires further model tuning.

I-V Comparison to Data

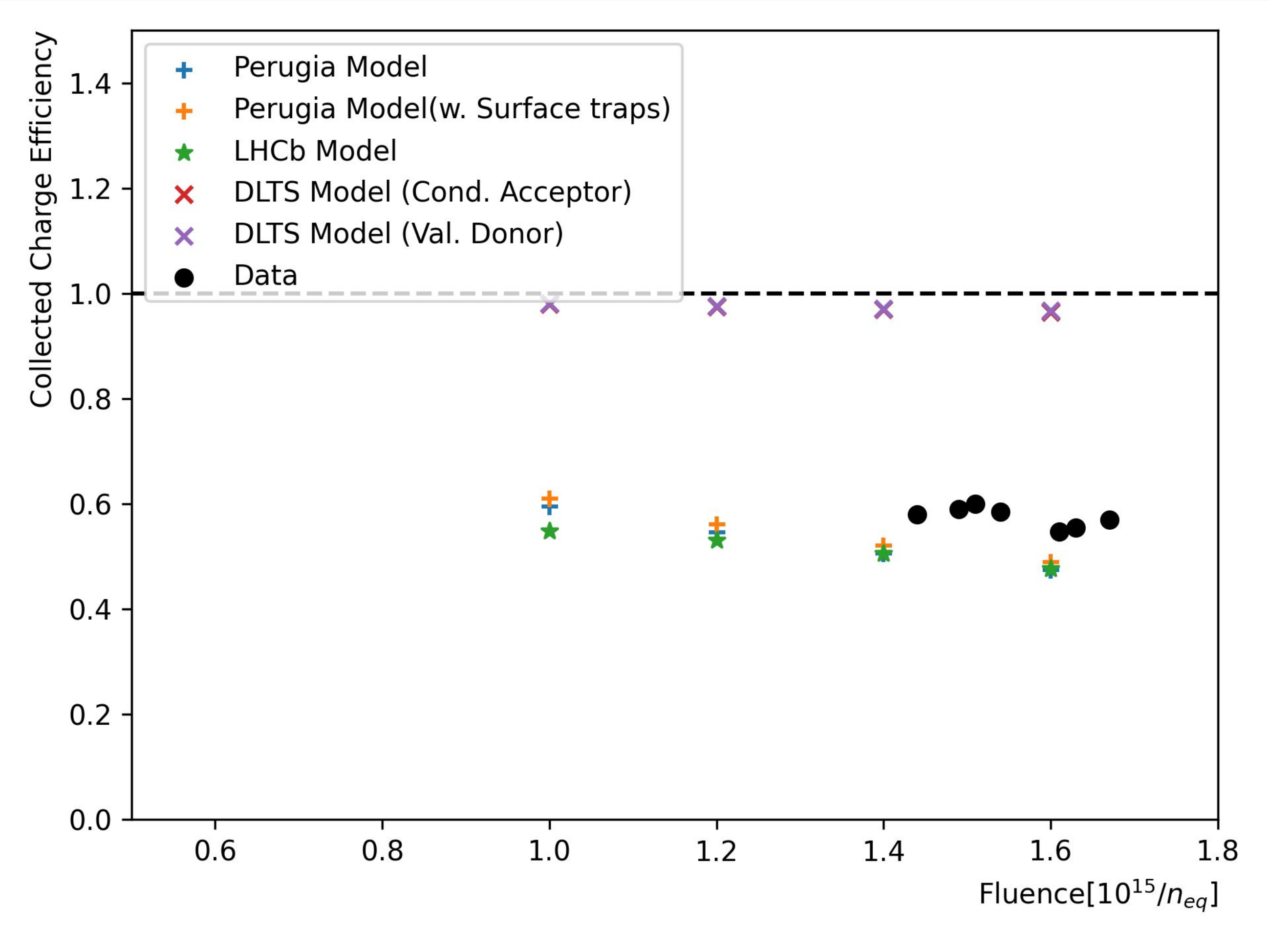
- The simulated I-V is compared to 8 mm test diodes:
  - The simulated current is scaled to match the 8 mm test diode area and normalized to the value at 350 V.
  - The simulations error are 10% area scaling uncertainty. (but ideally the area are well measured, so the error bar is overestimated)

- None of the models fully capture the data across all bias voltages.
- Surface traps contribute significantly at higher bias voltages.
- The Perugia model provides the best overall agreement with the data.
- The DLTS model (Cond. Acceptor) performs better at lower bias voltages.



Charge Collection

- **Minimum ionizing particles were simulated to study charge collection.**
  - CCE was evaluated using pre-irradiation data and simulations.
- **Bias voltage applied: 500V.**



the DLTS model tends to overestimate the CCE, with extremely slow degradation ⇒ Need further investigation

The Perugia model demonstrates better alignment with the data.

- **Including surface traps causes significant deviations in the I-V curve.**
- **However, the CCE remains largely unaffected.**

Summary

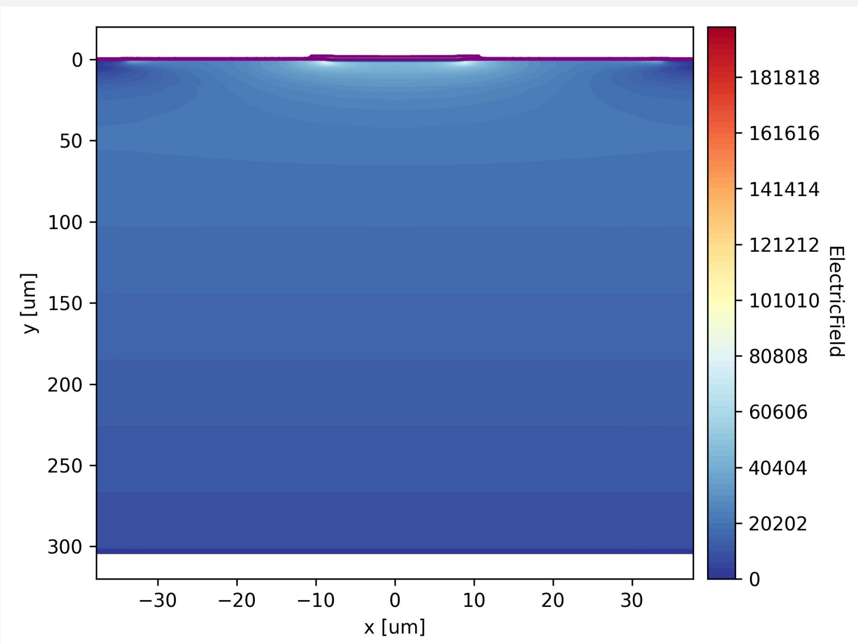
- **Streamlined TCAD Pipeline for ITk Strip Sensors:**
  - Developed a 2D simulation approach using basic components to represent essential regions of the strip sensors.
  - Reconstructed larger test structures by combining basic elements with appropriate area scaling.
- **Irradiation Model Studies:**
  - Explored various irradiation models within the TCAD pipeline.
  - None of the models fully capture both I-V and charge collection characteristics.
  - The Perugia model provides the closest overall match to data.
- **Future Work:**
  - Further refine the TCAD model for ITk strip sensors
    - Investigate significant differences in the pre-irradiation I-V shape.
    - Improve irradiation modeling with insights from DLTS measurements.
  - Develop a model capable of describing multiple measurable parameters (I-V and CCE.)
  - Extend validation to different irradiation types (e.g., neutron and gamma).
  - Incorporate environmental effects such as humidity into the simulations.

Backup

E-Field: Strip components

- Electric field maps are shown for a bias voltage of 500V and a radiation fluence of 1.5×10^{15} neq/cm^2
- DLTS model shows minimal changes, with the electric field remaining similar to the pre-irradiation state.

Before Irradiation



DLTS Model
(Cond. Acceptor)