Simulations of ATLAS ITk strip detectors

2nd Allpix^2 User Workshop

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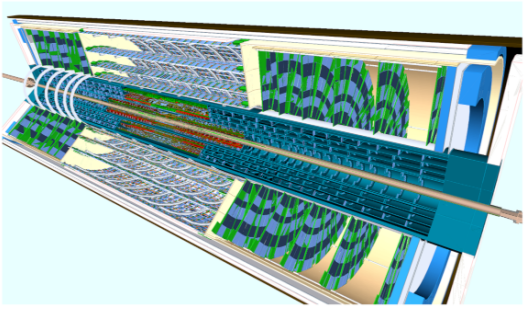
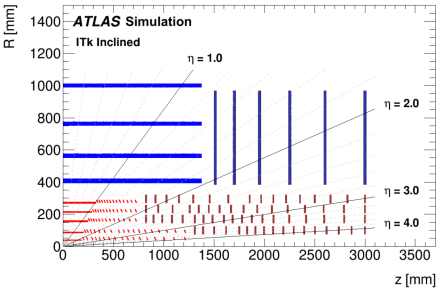
Content

ATLAS Inner Tracker

- ATLAS Inner Tracker (ITk) is the innermost (future) part of the ATLAS Detector.
- Critical for particle track and vertex reconstruction.
- Divided into two regions – barrel and end-cap.
- Utilizes two types of detectors – ITk Pixel and ITk Strip segments.

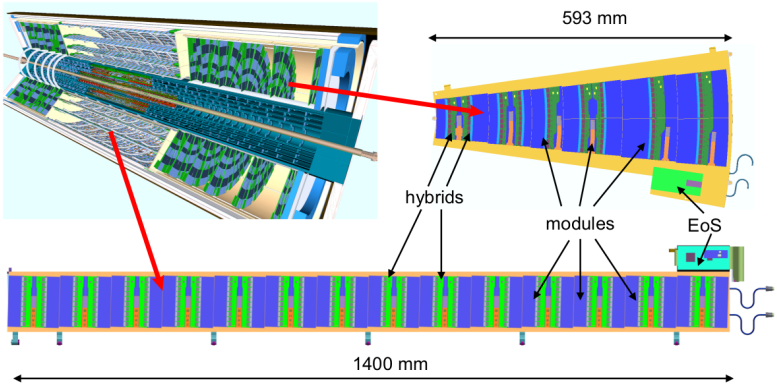


ATLAS ITk visualization.



ATLAS ITk layout: pixel modules in red, strip modules in blue.

- Barrel and end-cap strip modules differ in size and shape.
  - Barrel modules are rectangular and placed on "staves."
  - End-cap modules are trapezoidal, have various shapes (R0–R5) to fit onto a "petal."



Barrel and end-cap regions of the ITk. Barrel modules on a stave, end-cap modules on a petal.

ITk Barrel modules

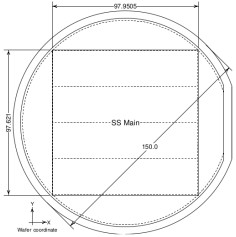


Fig.2 Barrel wafer layout: Short-strip (SS)

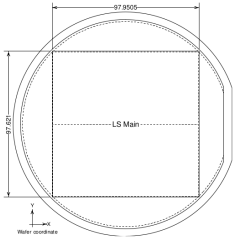


Fig.3 Barrel wafer layout: Long-strip (LS)

ITk End-cap modules

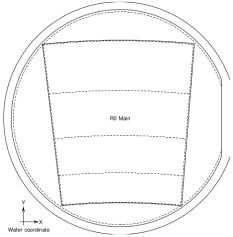


Fig.4 Endcap wafer layout: R0

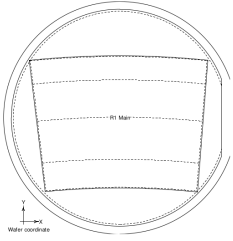


Fig.5 Endcap wafer layout: R1

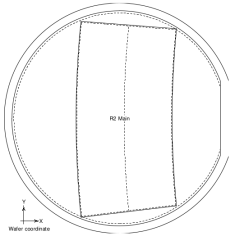


Fig.6 Endcap wafer layout: R2

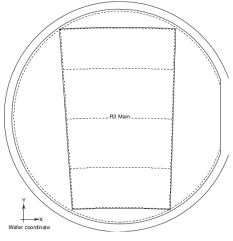


Fig.7 Endcap wafer layout: R3

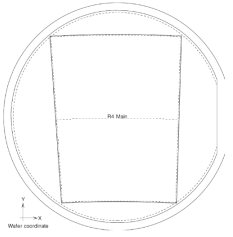


Fig.8 Endcap wafer layout: R4

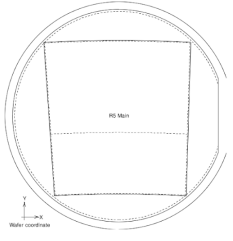
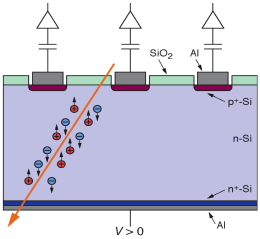
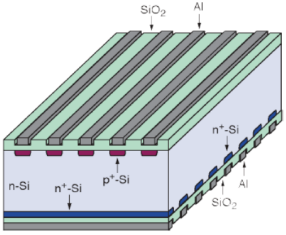


Fig.9 Endcap wafer layout: R5

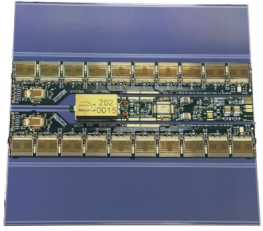
- Strip detectors based on P-N junctions with applied high voltage.
- Passage of a charged particle → free charge carriers.
- Charge propagation to electrodes according to the applied voltage.
- Monitoring of collected charge on electrodes → position of the particle.



Strip module cross section.

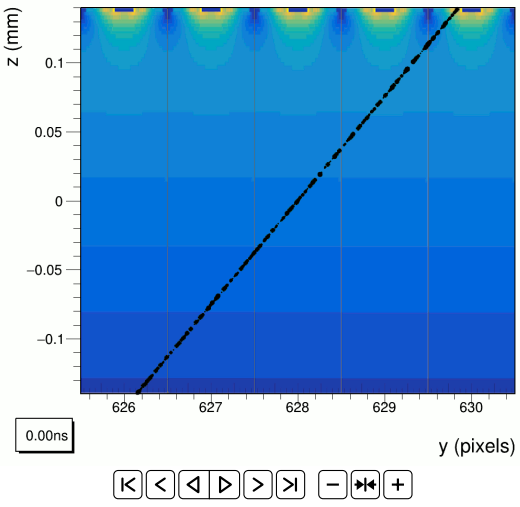


Top view of a strip module.



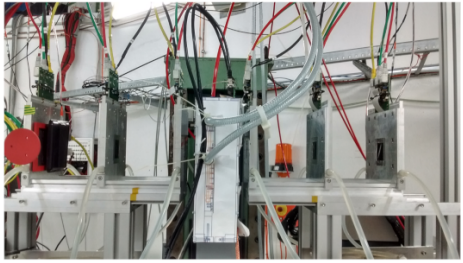
Barrel strip module prototype.

- Animation of charge propagation in a strip sensor in Allpix^2.
  - Region-of-interest spans 5 strip cells.
  - Electric field generated in TCAD.
  - Only electrons propagated.

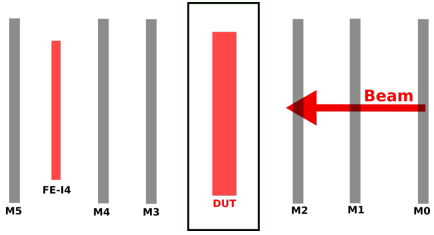


Module testing

- Module prototypes characterized using test beam measurements.
- EUDET-type beam telescopes: six Mimosa planes and FE-I4 timing plane.
- Telescope reconstructs particle tracks $\Rightarrow$ reference hit position in the DUT, compared to recorded position.

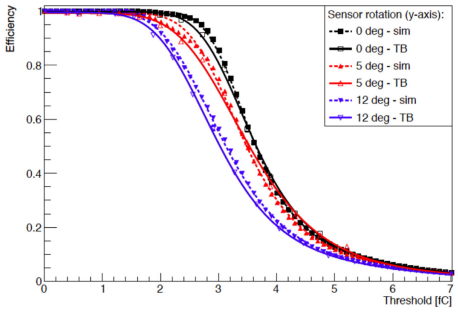


DURANTA Telescope at DESY.

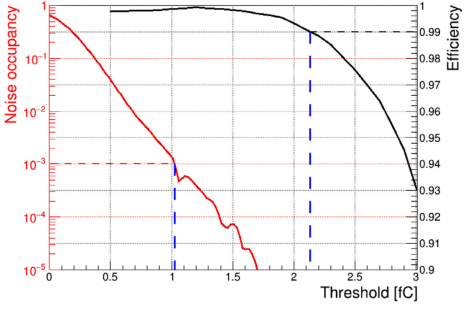


Telescope layout.

- Interest primarily in detection efficiency and noise occupancy.
- Results obtained by performing threshold scans.
- ATLAS ITk Collaboration requirement for an end-of-life module – a threshold range with:
  - efficiency over 99%,
  - noise occupancy under 0.1%.



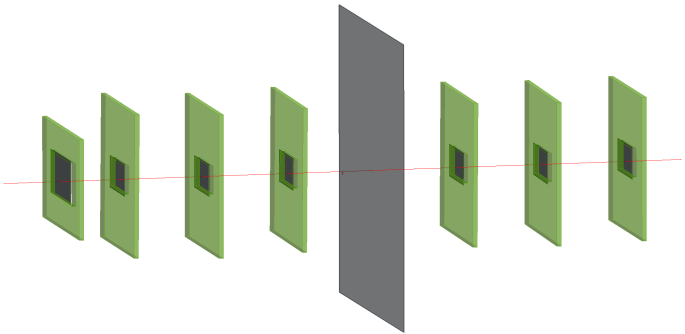
Efficiency comparison of test beam data and Allpix^2 results for various incidence angles.



Efficiency and noise occupancy for an irradiated module. Blue horizontal lines denote the threshold range where performance requirements are satisfied.

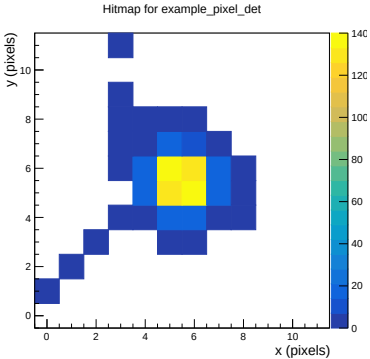
Allpix^2 simulations

- Focus mostly on recreation of test beam measurements in simulations.
- Reconstruction and analysis using the Corryvreckan framework or Python scripts.
- Efforts to find optimal simulation parameters that give the best agreement with test beam data.



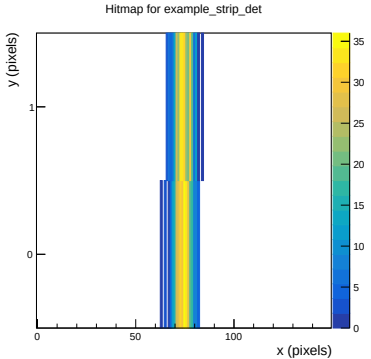
Telescope simulation in Allpix^2.

- Strip modules can be simulated in Allpix^2 without any modifications to the framework.
- A strip is simply a long pixel.



Example pixel detector hitmap.

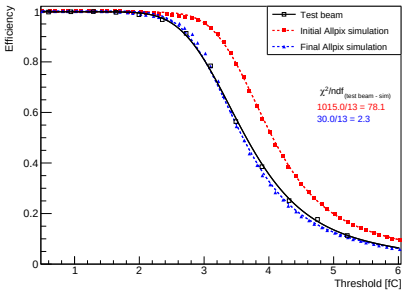
```
number_of_pixels = 12 12
pixel_size = 50um 50um
```



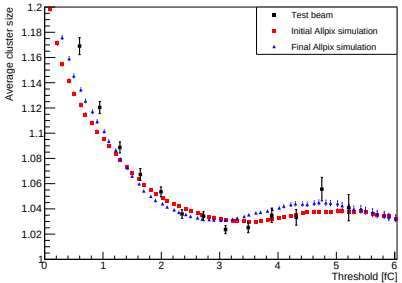
Example strip detector hitmap.

```
number_of_pixels = 150 2
pixel_size = 74.5um 5mm
```

- Number of configuration parameters optimized to find the best agreement between Allpix^2 and test beam data. Their effect varied:
  - ✓ active sensor thickness
  - ✓ electric field model
  - ✓ cross-talk effect
  - × physics lists



Efficiency curve from Allpix^2 before and after parameter optimization.



Average cluster size from Allpix^2 before and after parameter optimization.

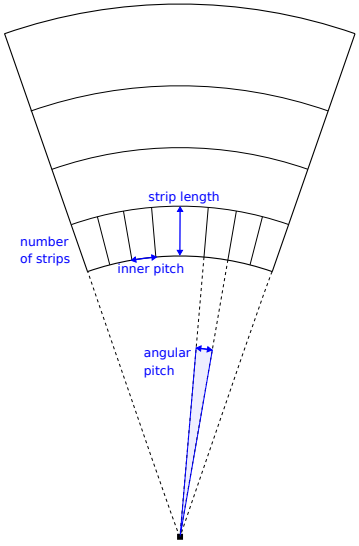
Radial geometry in Allpix^2

- Rectangular strip detectors can be simulated, but radial end-cap detectors currently cannot.
- Simulation studies thus limited to only the ITk barrel modules.
- Implementation of radial geometry into Allpix^2 currently in progress.
  - Simulations are essentially functional, some features are missing/not yet implemented.

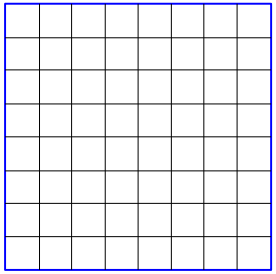
- Radial detector model defined using 4 parameters for every strip row:
  - number of strips,
  - angular pitch,
  - inner pitch,
  - strip length.
- Model type defined as `radial_strip`.

ATLAS ITk R0 model definition:

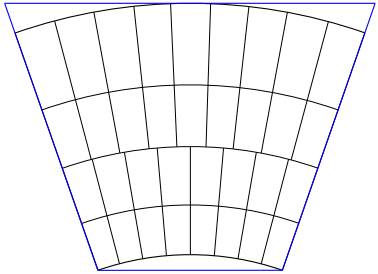
```
type = "radial_strip"
number_of_strips = 1026, 1026, 1154, 1154
angular_pitch = 0.193mrad, 0.193mrad, 0.171mrad, 0.171mrad
inner_pitch = 74.4um, 78.1um, 73.6um, 78.5um
strip_length = 19mm, 24mm, 29mm, 32mm
```



- Every detector is internally represented by a single volume wrapper (+ support structures).
- Straightforward for rectangular detectors, less trivial for radial detectors.
- Assignment of propagated charge to an individual pixel handled by the `DetectorModel::getPixelIndex` method.
  - This allows for model-specific implementation.

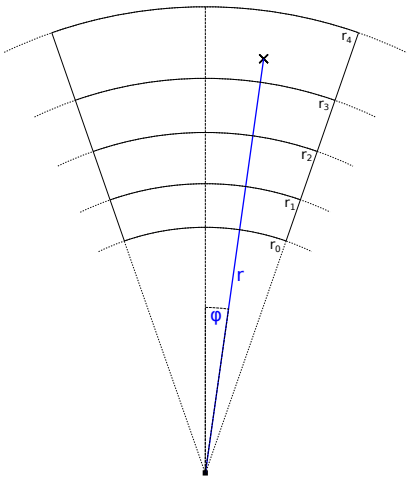


Example pixel detector (volume wrapper in blue).

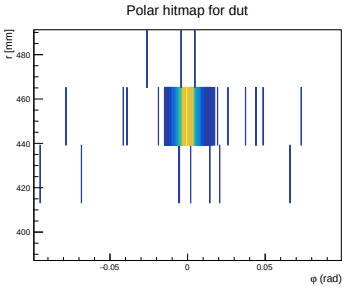


Example radial strip detector (volume wrapper in blue).

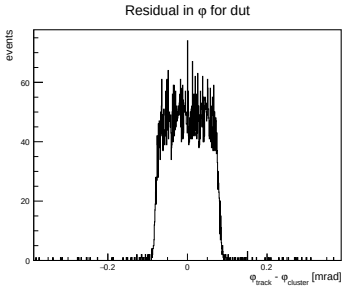
- Local coordinate centre defined in the sensor focal point.
- Hit positions converted from cartesian to polar (r, φ) coordinates, used to:
  - evaluate if a hit is inside a sensor.
  - assign collected charge to a strip.
  - create relevant outputs (polar hitmap, residuals in r, φ).



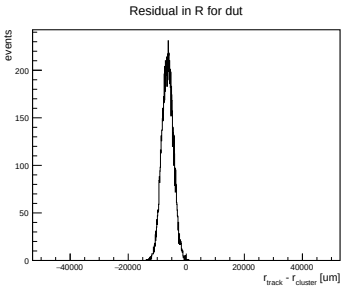
- Radial geometry implementation tested on an ITk R0 detector model.
  - Correct dimensions and geometry.
  - Linear electric field.
  - Cross-talk effect via the `CapacitiveTransfer` module.
- Standard output plots available, more added specifically for radial detectors.



ITk R0 polar hitmap.



ITk R0 angular residuals.



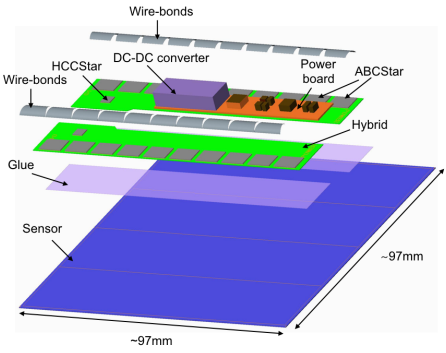
ITk R0 radial residuals.

Summary

- Allpix^2 has been used for performance studies of ATLAS ITk strip modules.
- Great agreement of simulation results with real measurements of prototypes.
- Recent developments enable simulations of strip modules with radial geometry.
  - Work in progress.
  - This extends the simulation studies to the entire ITk strip detector.

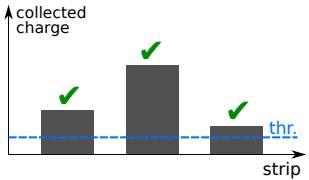
Backup

- A strip module has a number of components:
  - Silicon strip sensor.
  - Read-out ASICs.
  - Hybrid Controller Chips (HCC).
  - Power board: low-voltage DC-DC converter, high-voltage circuit.
  - Autonomous Monitor and Control (AMAC) chip.
- Barrel and end-cap modules have the same component groups.

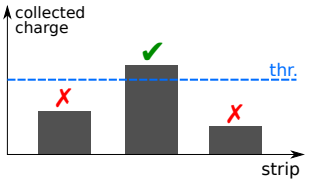


A barrel strip module layout with components.

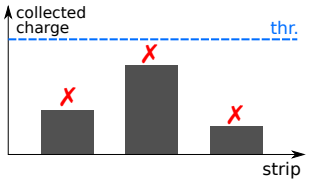
- Module characterization by performing threshold scans:
  - Systematically varying a charge threshold (for a hit to be called).
  - Observing several parameters as a function of the threshold.
- At low thresholds, noise creates a lot of false hits.
- At high thresholds, real hits are ignored.



Low thresholds are noisy.

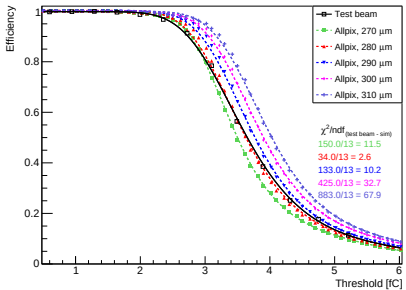


Medium thresholds are fine.

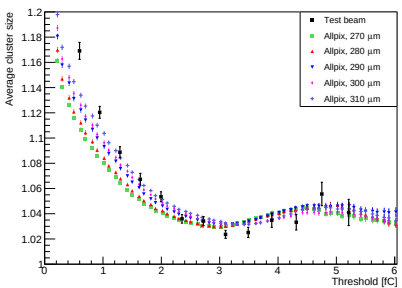


High thresholds have no hits.

- Generally active sensor thickness can be smaller (up to $\sim$ 10%) than the physical thickness.
- The effect of active thickness was studied for various values.
- Active thickness of 280 μm was the best fit based on efficency agreement.



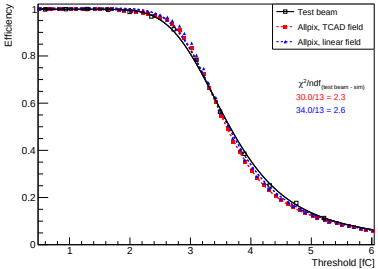
Efficiency curves for various active thickness values.



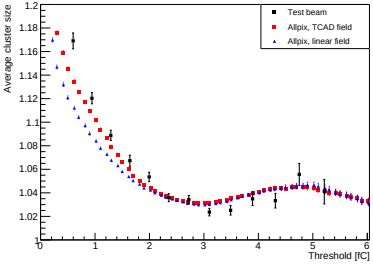
Average cluster size for various active thickness values.

- Comparison of simulation results when using a linear EF model and a TCAD-generated EF.
- Some effect on average cluster size at lower thresholds.
- Negligible effect on efficiency curves.

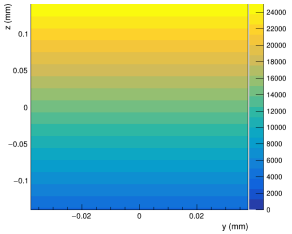
$\Rightarrow$ We are using the linear model, simpler and much faster.



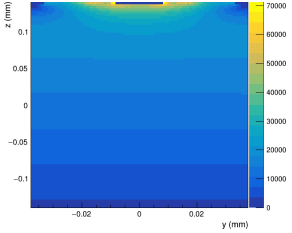
Efficiency when using different electric field models.



Average cluster size when using different electric field models.



Linear electric field magnitude.



TCAD-generated field magnitude.