ATLAS ITk strip modules simulation using AllPix^2 framework

Výjezdní seminář ÚČJF Malá Skála 2019

Radek Přívara (UPOL)

April 13, 2019

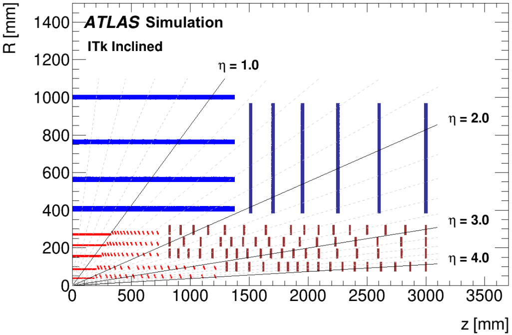
ATLAS Inner Tracker

Motivation

- Current ATLAS Inner Detector is designed for:
  - 10 years of operation
  - Instantaneous luminosity of $1.0 \cdot 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - Average pile-up $\langle\mu\rangle = 23$
  - Radiation damage equivalent to an integrated luminosity of 400 fb^{-1} for pixel detector, 700 fb^{-1} for SCT and 850 fb^{-1} for IBL (based on component technology and distance from the beam)
- Upgrade required to cope with performance of HL-LHC $\Rightarrow$ ATLAS Inner Tracker (ITk) designed for:
  - 10 years of operation
  - Instantaneous luminosity of $7.5 \cdot 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - Average pile-up $\langle\mu\rangle = 200$
  - Radiation damage of 4000 fb^{-1}

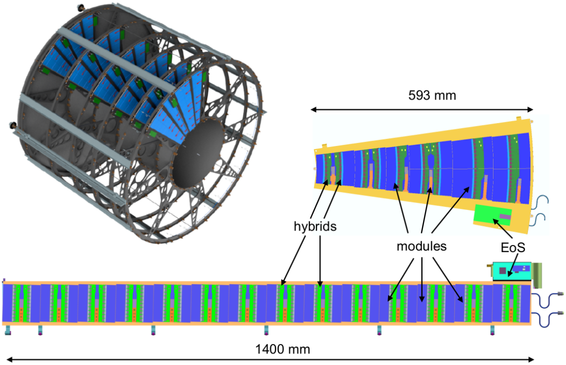
ATLAS ITk Layout

- Layout consists of a central barrel region and two end-caps.
- Pixel detector (pictured red)
  - 5 barrel module layers
  - many end-cap module rings
- Strip detector (pictured blue)
  - 4 barrel module layers
  - 6 end-cap module discs



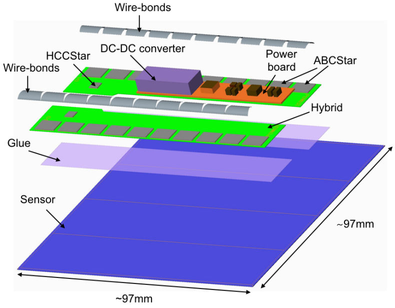
Strip detector local support structures

- Barrel strip modules (2 types) organised in staves
- End-cap strip modules (6 types) organised in wedge-shaped petals, segmented into rings (R0-R5)
- Local supports (staves and petals) provide mechanical rigidity and house the common electrical and cooling services
- Power and data links channeled through an end-of-substructure card

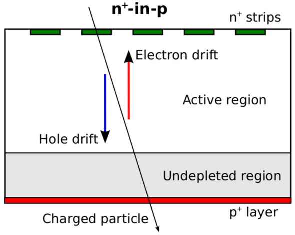


Strip module

- Strip module consists of
  - Silicon-strip sensor (type n^+-in-p)
  - Hybrid = PCB + read-out ASIC chips (ABCStar, HCCStar)
  - Power board (DC-DC converter, AMACv2 monitoring chip, HV multiplexer)
- Strips bonded to ABCStar chips
- Barrel and end-cap modules feature the same component groups, but differ in size, shape, number of chips, etc.

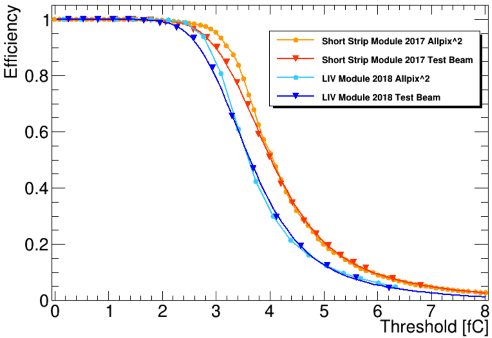


Short-strip barrel module



Module characterisation

- Threshold scan – basis for module (ABC chip) characterisation
  - Injecting a constant charge and varying the threshold value of a discriminator from 0 to max.
  - Multiple charge injections at each threshold value
  - Plotting average hit rate for each threshold value ⇒ S-curve
  - Value with 50% hit rate (Vt50) = median of the injected charge
- Gain and noise of a chip obtainable from threshold-scanning with different charges



S-curves of different modules

AllPix^2 Framework

Introduction

- Generic simulation framework for silicon tracker and vertex detectors.
- Written in C++.
- Relies on Geant4, ROOT and Eigen3 libraries.
- Modular $\Rightarrow$ easy extension to more complex simulations.
- Three configuration files required to run a simulation:
  - **Main** – global framework configuration with a list of modules to instantiate
  - **Geometry** – position, orientation and model type of detectors.
  - **Model** – parameters describing a particular type of a detector.

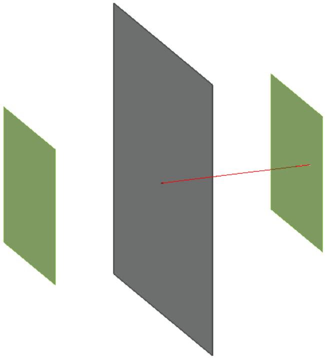
Detector model

- Very simple creation of a basic silicon pixel (strip) detector
- Allows addition of support structures to increase accuracy of a model

```
number_of_pixels = 1280 1
pixel_size = 74.5um 10cm
sensor_thickness = 300um

[support]
thickness = 1um
size = 5cm 5cm
location = "absolute"
offset = 0 0 -5cm
material = "kapton"

[support]
...
```



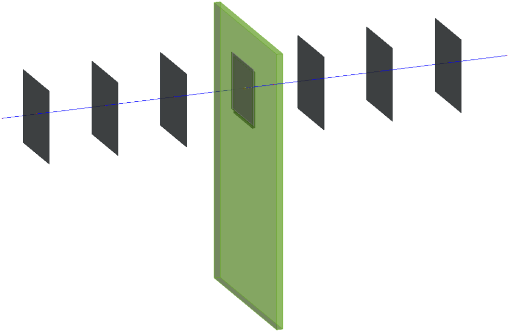
Experiment geometry

- Straightforward placement and orientation of uniquely named detectors
- Detector types must be specified

[dut]
type = "timepix"
position = 0 0 0
orientation = 0 0 0

[mimosa1]
type = "mimosa23"
position = 0 0 -6cm
orientation = 0 0 90deg

...



Main configuration

- Main configuration file in an easy-to-read format
- Consists of several modules (headers in [ ] brackets) with self-explanatory parameters (mandatory and optional)

```
[AllPix]
# Main module
detectors_file = "geometry.conf"
log_level = "STATUS"
number_of_events = 50000

[GeometryBuilderGeant4]
# Constructs the Geant4 geometry

[DepositionGeant4]
# Deposits charge carriers in the active volume of all detectors
physics_list = FTFP_BERT_LIV
particle_type = "e-"
source_energy = 4.4GeV
source_position = 0 0 -500um
beam_direction = 0 0 1
beam_size = 1mm
```

Main configuration

```
[ElectricFieldReader]
# Adds an electric field to the detector
model = "linear"
bias_voltage = -400V
depletion_voltage = -360V

[GenericPropagation]
# Simulates the propagation of charge carriers through the sensitive volume of the detector
temperature = 290K
charge_per_step = 10

[SimpleTransfer]
# Prepares sets of propagated charges for processing

[DefaultDigitizer]
# translates the collected charges into a digitized signal
electronics_noise = 643e
threshold = 1e
adc_smearing = 1e

[ROOTObjectWriter]
# Reads all messages dispatched by the framework and stores specified objects
file_name = "output.root"
```

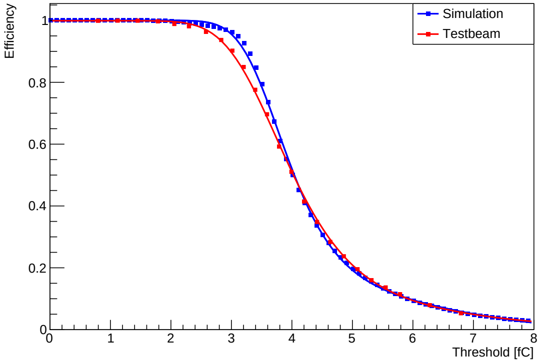
Simulation Results

Simulation

- Simulation of passage of 50 000 particles
- Efficiency and average cluster size plots obtained
- Comparison with available testbeam data from 2017
  - short-strip barrel module with ATLAS12 sensor
  - DESY – 4.4 GeV e^-
- Simulation of different angles of incidence

Efficiency

- Efficiency of the simulated module compared with testbeam data
- Good agreement except for the “efficiency drop” area



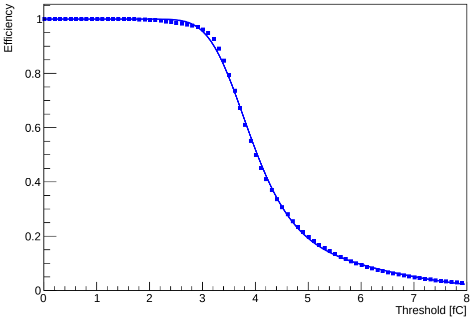
Efficiency – fit function

- Efficiency fitted with a skewed complementary error function (erfc)

$$f(x) = 0.5 \cdot [0] \cdot \text{erfc}\left(\frac{x-[1]}{\sqrt{2}\cdot[2]} \cdot \left[1 - [3]\cdot\tanh\left(\frac{[4]\cdot(x-[1])}{\sqrt{2}\cdot[2]}\right)\right]\right)$$

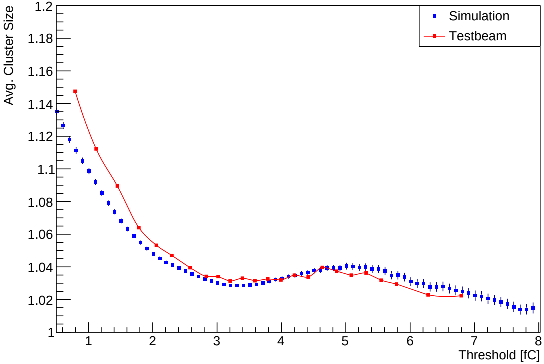
Parameter meaning:

- [0] – normalization
- [1] – median charge
- [2] – "σ"
- [3], [4] – skew parameters



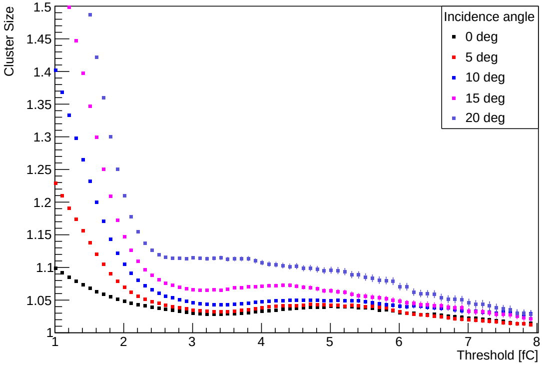
Cluster size

- Average cluster size (number of neighboring strips with a hit) compared with testbeam data
- Noticeable offset between simulation and testbeam results, although the shape of the curves is similar



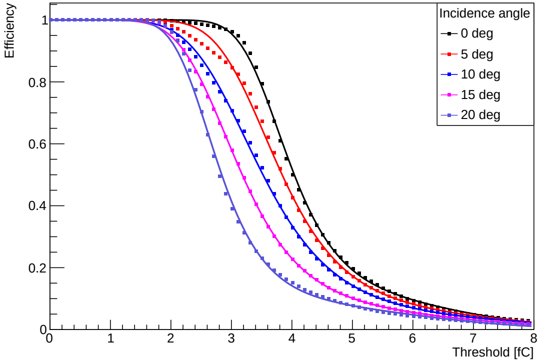
Different angles - cluster size

- Average cluster size for different incidence angles
- Higher average cluster size for larger angles, especially at low thresholds – particle itself passes through multiple strips



Different angles - efficiency

- Efficiency for different incidence angles
- For higher angles total deposited energy is split among multiple strips ⇒ harder to pass the threshold in each strip and the curve drops sooner
- Fit function doesn't accurately describe the efficiency drop area, more noticeable for some angles than others (5° and 20°)



Future work

Validation of Athena digitization

- ITk will use n^+-in-p sensor type, whereas SCT uses p^+-in-n type $\Rightarrow$ transport of different charge carriers (electrons and holes respectively)
- Unclear whether Athena can accurately simulate n^+-in-p sensor type.
- Verification possible by comparing Athena simulation results with
  - testbeam data (complicated, currently only data for perpendicular incidence and no magnetic field exist)
  - AllPix^2 simulations

References

- Technical Design Report for the ATLAS Inner Tracker Strip Detector, `https://cds.cern.ch/record/2257755`
- Design of the first full size ATLAS ITk Strip sensor for the endcap region, `https://cds.cern.ch/record/2305166`
- Allpix Squared User Manual, `https://cern.ch/allpix-squared/usermanual/allpix-manual.pdf`