Telescope and Timepix DUT simulation with Allpix/Geant4

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Overview

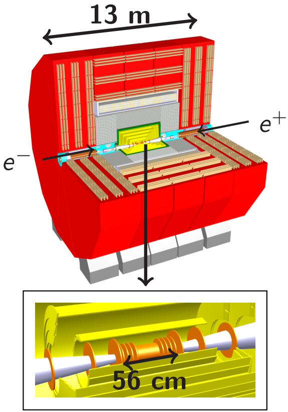
- Introduction
- R&D on sensor for CLIC
- Testbeam setup for thin assemblies
- GEANT4 simulations and digitisation
- Conclusions

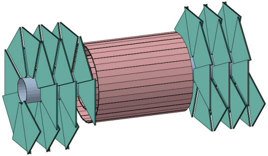
CLIC vertex detector requirements

- Efficient tagging of heavy quarks:
  - Multi-layer VXD: 3 double layers in barrel and endcap regions (31 mm inner radius).
  - Single point resolution: $\sim 3\,\mu\text{m} \Rightarrow$ achievable with $25\,\mu\text{m} \times 25\,\mu\text{m}$ pixel pitch.
  - Low material budget: $< 0.2\%\ X_0$ for each detection layer $\Rightarrow$ goal: $50\,\mu\text{m}$ sensor on $50\,\mu\text{m}$ ASIC.

- Thin-sensor R&D:
  - Characterisation of thin sensor assemblies during testbeam campaigns at DESY.

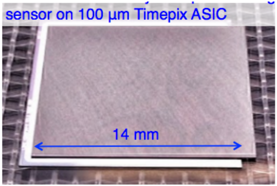
- Goal:
  - Simulate the testbeam setup.
  - Extrapolate results for small pitch pixels.
  - Improve digitisation models for full detector simulation.

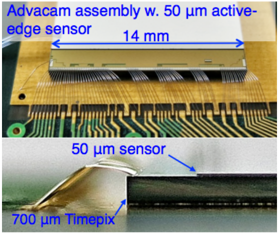




R&D on sensor

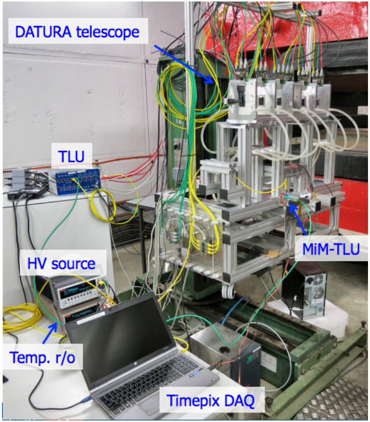
- The ultimate goal for CLIC:
  - low material budget and small pitch: 50 μm sensor on 50 μm ASIC with 25 μm pixel pitch.
- Thin-sensor R&D:
  - Timepix chips (55 μm pixel pitch) are used to study the feasibility of thin sensors.
  - use simulations to extrapolate to pixels with a pitch of 25 μm.

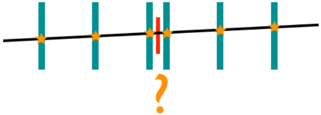




DESY testbeam setup

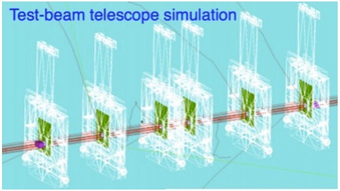
- Assemblies tested during the testbeam campaign at DESY in 2013-2014:
  - 50 μm-300 μm sensor thicknesses.
  - 100 μm-750 μm Timepix chip thickness.
- DESY II beam: 1-6 GeV electron.
- The EUDET telescope is used to reconstruct the tracks and extrapolate them on the device under test (DUT).
- The telescope contains 6 planes of Mimosa26 pixel sensors with a tracking resolution of $\sim$3 μm at 5.6 GeV.
- The DUT is placed between layer 3 and 4 of the telescope with the possibility of rotation.





AllPix simulation framework

- AllPix:
  - A general purpose pixel detector simulation framework.
  - Written in C/C++, based on GEANT4.
  - https://twiki.cern.ch/twiki/bin/view/Main/AllPix



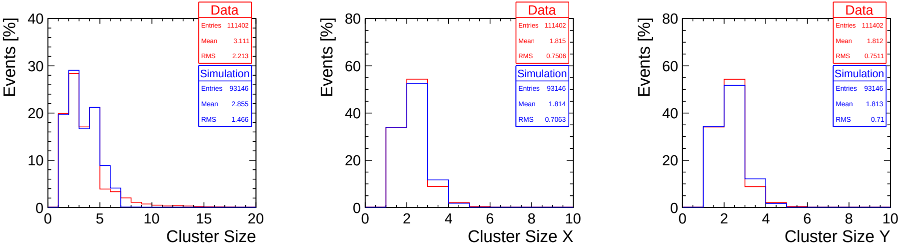
- Inputs:
  - Pixel detector geometry: i.e. number of pixels, thickness, pitch, bump geometry and material.
  - Test structure: i.e. support and cabling.
  - Simulation scenario: i.e. nature of particles, geometric and energy distribution, number of trials.
- Output:
  - Raw data: text files containing the pixels hit and the energy deposited.
  - ROOT files: containing the MC truth data.
  - Possibility to convert the raw data into LCIO format and use the EUTelescope software chain.

Digitisation in AllPix

- AllPix provides:
  - World construction and positioning of the pixels and detectors.
  - GEANT4 simulation of the passing of particles in sensitive volumes and the energy deposited by ionisation.
- Digitisers (defined by the users) simulate:
  - The response of the silicon sensor to ionisation.
  - The readout chip.
- Existing digitisers:
  - Monte-Carlo truth digitiser
  - MIMOSA26 digitiser
    - Based on testbeam data.
  - Timepix digitiser
    - Based on semiconductor physics $\Rightarrow$ simulation of charge transport and diffusion in electric field.
    - The calibration for each assembly is used to simulate the Timepix response.

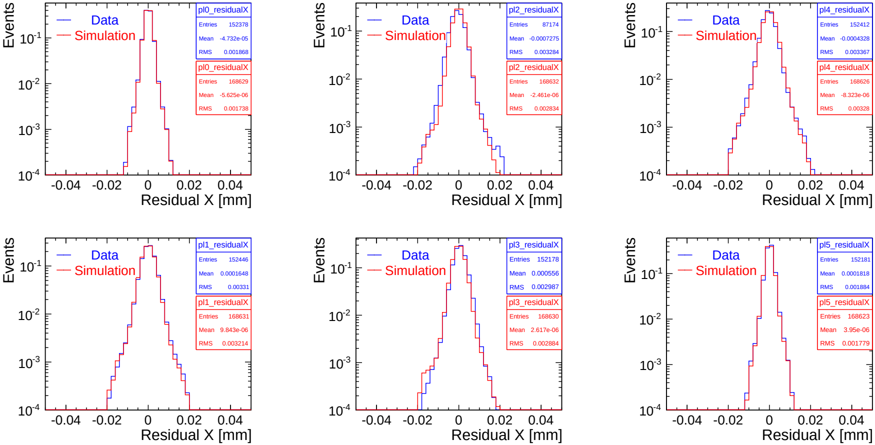
EUTelescope simulation in AllPix: cluster size distribution

- Simulation of the telescope (without DUT).
- The digitiser for the telescope sensors (Mimosa26) takes into account the crosstalk between the pixels (based on data).
- Cluster-size distribution:



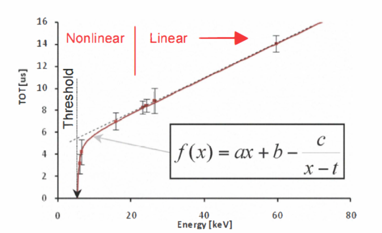
EUTelescope simulation in AllPix: tracking resolution

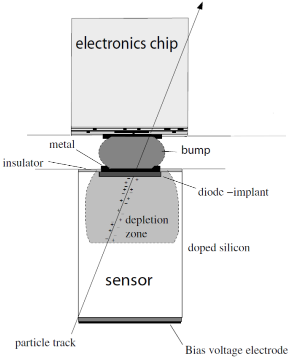
- The simulation and the data have very similar tracking resolution after the tuning of the simulation.



DUT simulation

- Semiconductor physics simulated by theoretical models for drift and diffusion.
- The electronic noise: $\sim$100 e^- rms.
- Timepix chip simulated by the calibration of each assembly which allows to convert the energy (given by GEANT4) to Time Over Threshold (TOT).
- Pixel-by-pixel calibration using monoenergetic radiation $\Rightarrow$ TOT surrogate function:

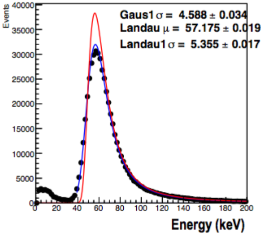


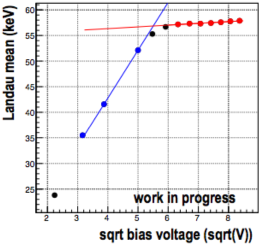


- Non-linear response of pixels in the energy range close to the threshold.

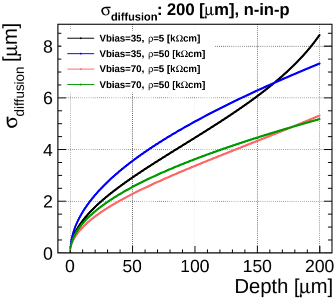
Resistivity of the sensors

- Bias voltage affects collected charge $\Rightarrow$ use bias scan to determine the depletion voltage.
- Determine the resistivity ρ:
  $V_{depletion} = \frac{d^2}{2 \cdot \epsilon \cdot \mu \cdot \rho}$
- For 200 µm sensor: $V_{depl} = \sim 30\,\text{V}$ and thus $\rho = \sim 5\,\text{k}\Omega\,\text{cm}$



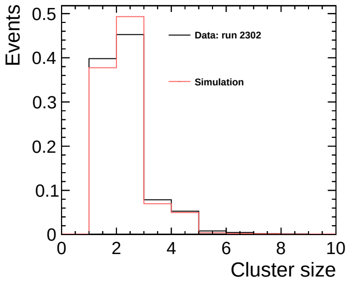


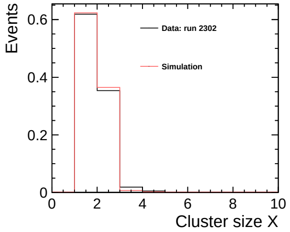
- Theoretical values for $\sigma_{diffusion}$ for low and high resistivity and bias voltages:

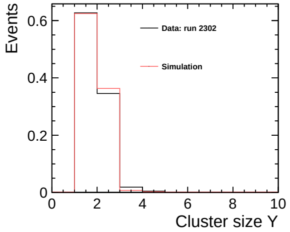


DUT Simulation: cluster size distribution

- Assembly characteristics:
  - 200 μm planar silicon sensor (assembly B06-W0125).
  - Sensor type: n-in-p.
  - Bias voltage: −35 V.
  - Threshold: 3.54 keV (∼960 electrons).
  - 5.2 GeV e^{-} beam.
  - Sensor resistivity used for the simulations: $\rho = 5\ \mathrm{k\Omega\,cm}$.





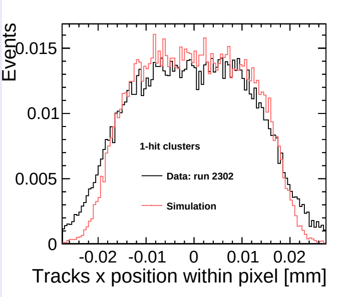


- Good agreement between data and simulation of the cluster-size distribution.

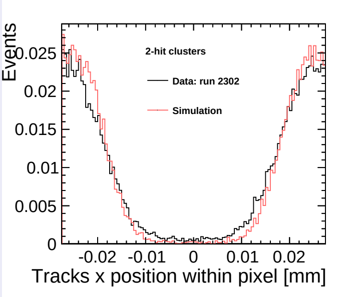
DUT Simulation (2): track position

- 200 µm sensor, $V_{bias} = -35\,\mathrm{V}$
- The telescope is also simulated and the tracks are found using the EUTelescope reconstruction software.
- The simulation shows a better tracking resolution.
- More investigation needed.

1-hit clusters

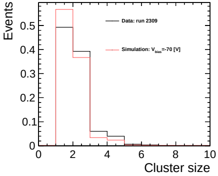


2-hit clusters

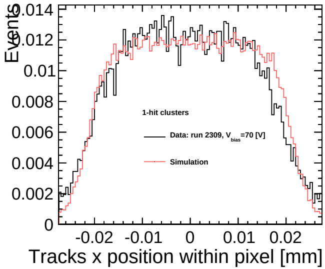


DUT Simulation (3): increase in bias voltage

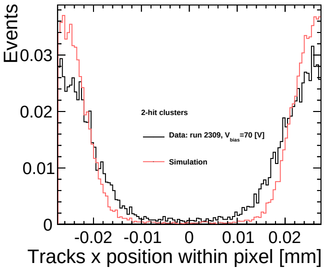
- 200 μm sensor and $V_{bias} = -70\,\mathrm{V}$.
- Less agreement between data and simulation for the higher bias voltage.
- More investigation needed.



1-hit clusters



2-hit clusters

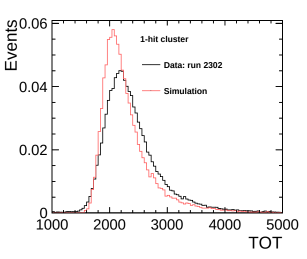


DUT Simulation (4): TOT distribution for 200 µm

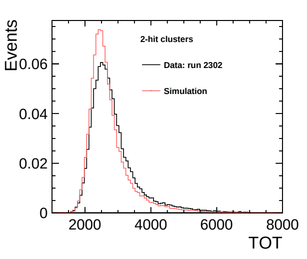
- The simulation shows a lower TOT peak than the data. The low energy part shows a poor agreement with the data.
- How well GEANT4 describes the energy loss in thin silicon? What about the TOT calibration?

- For $V_{bias} = -35\,\mathrm{V}$

1-hit clusters

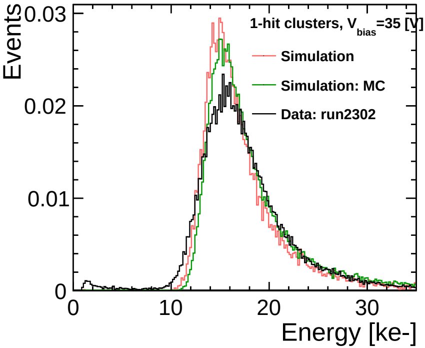


2-hit clusters



Landau distribution in simulation

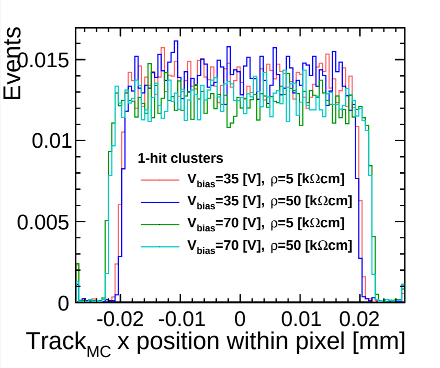
- 200 µm sensor and $V_{bias} = -35\,\mathrm{V}$
- Energy distribution of 1-hit clusters:
  - The MC truth energy, shows the same MPV (most probable value) and high energy tail as the data but the low energy part is not well described. $\Rightarrow$ more investigation is needed on the data quality and also calibration.
  - The charge diffusion, tends to shift the distribution to lower energy values.



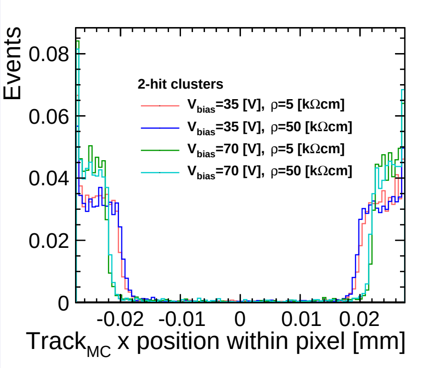
DUT Simulation: MC track position

- MC track position within the pixels:

1-hit clusters



2-hit clusters

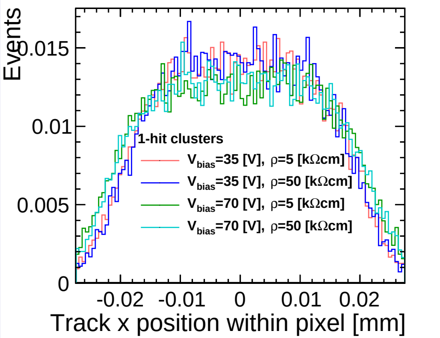


- In data, the track resolution is $\sim 3\,\mu m$
  $\Rightarrow$ Smear the MC track position with a gaussian.

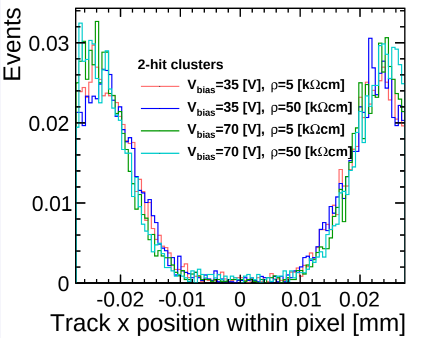
DUT Simulation: MC track position smeared with a gaussian

- MC track position smeared with a gaussian distribution with σ=5 µm.

1-hit clusters



2-hit clusters



- The distribution becomes more similar to the data ⇒ more investigation on the tracking resolution in the simulation and data is needed.

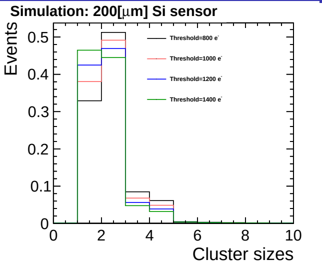
Conclusions

- Challenging demands on thin-sensor assemblies.
- AllPix simulation framework is a flexible tools for pixel detector simulations and provides an interface to EUTelescope.
- Validation of GEANT4 simulation models with testbeam results is ongoing.
  - The DUT needs a better understanding to disentangle different parameters.

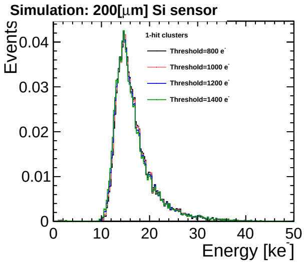
Backup slides

Threshold scan in simulation

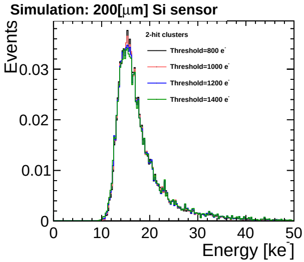
- By varying the threshold in the simulation the cluster size is more affected than the energy distribution for 1 and 2-hit clusters.
- 200 μm sensor
- n-in-p
- −35 V bias voltage



- 1-hit clusters

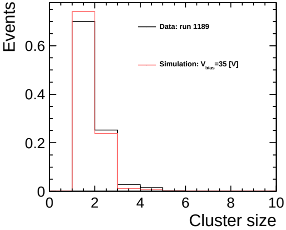


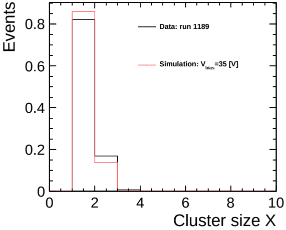
- 2-hit clusters

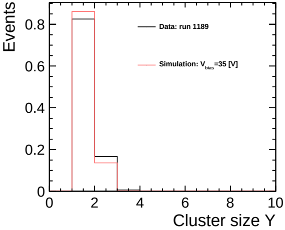


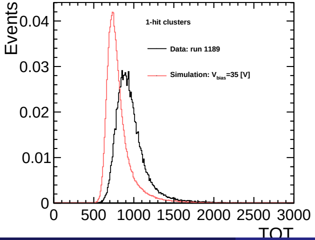
DUT Simulation for 100 µm sensors

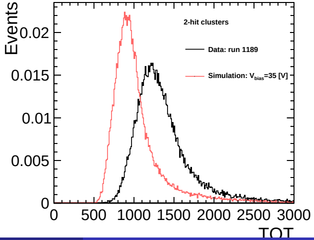
- 100 µm sensor
- p-in-n
- 35 V bias voltage











DUT Simulation for 200 µm sensors