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Simulation studies for the CLIC vertex detector

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On behalf of the CLICdp collaboration

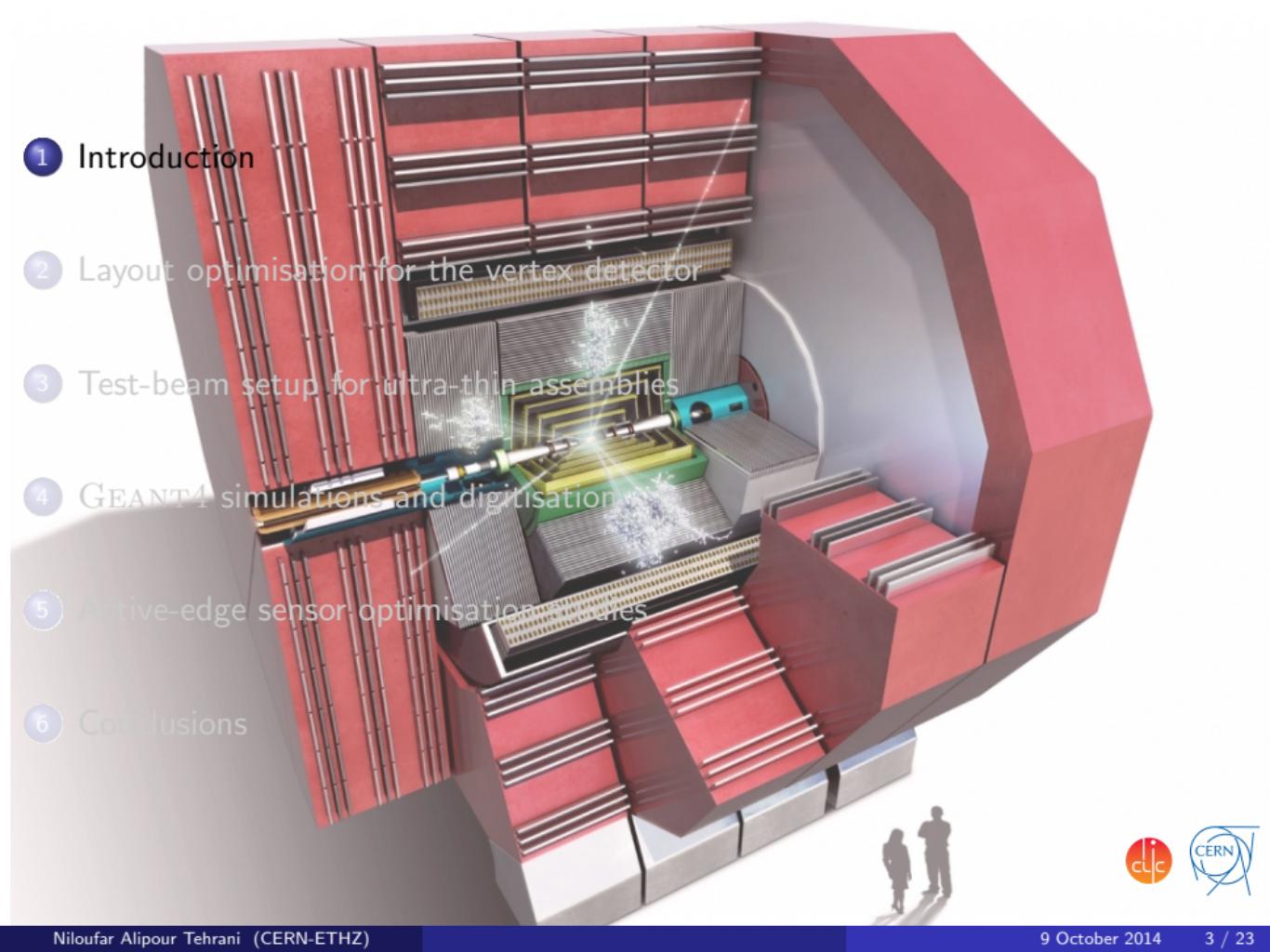
International Workshop on Future Linear Colliders (LCWS14)
Belgrade, Serbia
9 October 2014



Overview

- 1 Introduction
- 2 Layout optimisation for the vertex detector
- 3 Test-beam setup for ultra-thin assemblies
- 4 GEANT4 simulations and digitisation
- 5 Active-edge sensor optimisation studies
- 6 Conclusions





1 Introduction

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CLIC vertex detector requirements

Efficient tagging of heavy quarks:

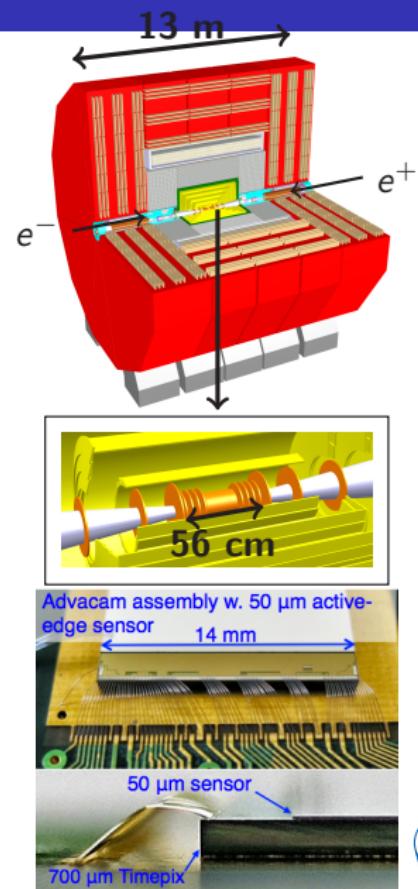
- Multi-layer VXD: 5-6 layers in the barrel and 4-6 disks. CLICdp-Note-2014-002
- Single point resolution: $\sim 3 \mu\text{m}$ \Rightarrow achievable with $25 \mu\text{m} \times 25 \mu\text{m}$ pixel pitch.
- Low material budget: $< 0.2\% X_0$ for each detection layer \Rightarrow goal: $50 \mu\text{m}$ sensor on $50 \mu\text{m}$ ASIC.

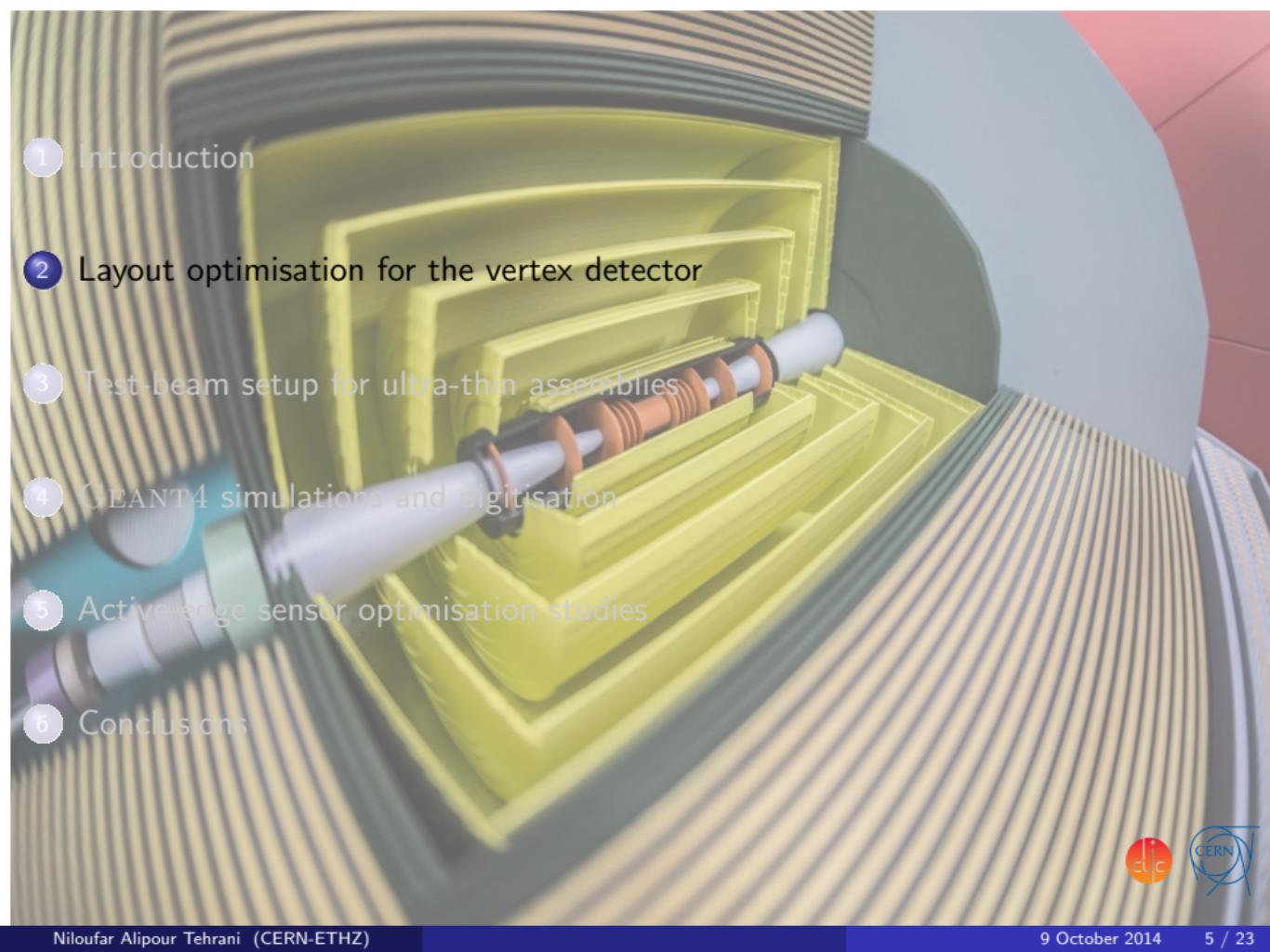
Thin-sensor R&D:

- Characterisation of thin sensor assemblies with the Timepix chip ($55 \mu\text{m}$ pitch) during testbeam campaigns at DESY.

Goal:

- Simulate the test-beam setup.
- Extrapolate results for small-pitch pixels.
- Improve digitisation models for full-detector simulation.





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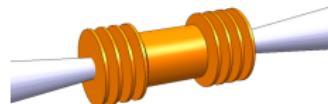
5 Active-edge sensor optimisation studies

6 Conclusions

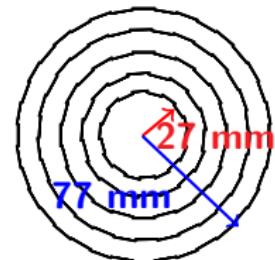
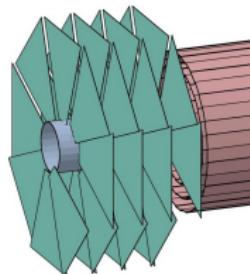


Vertex-detector layouts

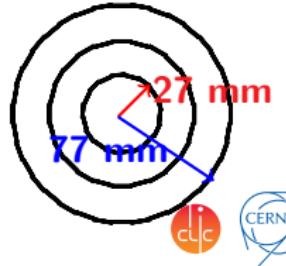
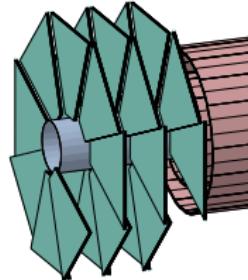
- Initial geometry containing disks in the vertex endcap (CLIC_SiD):
 - 5 barrel layers and 4 disks.



- New *spirals* geometry:
 - Spiral arrangement of the modules in the vertex endcaps (instead of disks) to allow for airflow cooling.



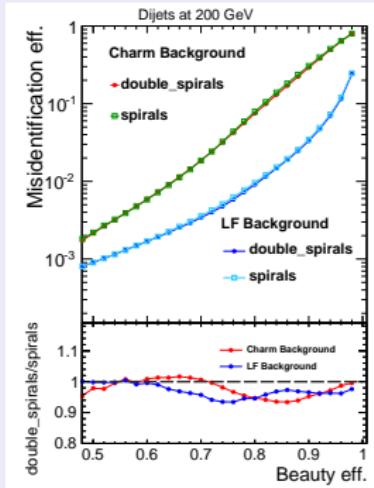
- New *double_spirals* geometry:
 - Consists of double-layered modules:
- Contains 3 layers in the barrel and 3 layers in the endcaps.



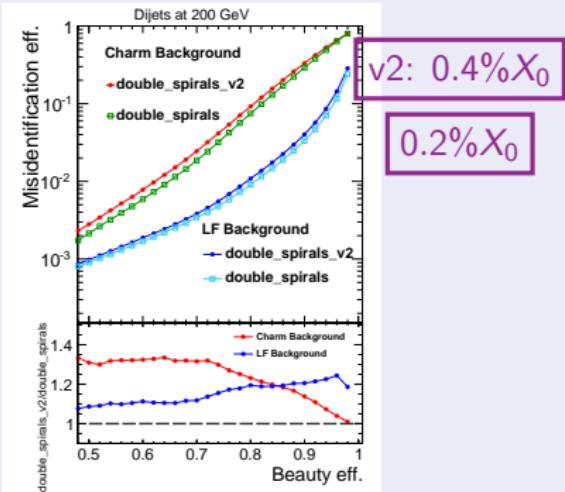
Flavour-tagging performance

- The impact of the geometries is evaluated using the flavour-tagging performance based on the full simulation of the detector.

double_spirals & spirals



double_spirals_v2 & double_spirals



- Similar performance for the *spirals* and *double_spiral* geometries.

- Increasing the material budget by a factor of 2 increases the fake rates by up to 35%.

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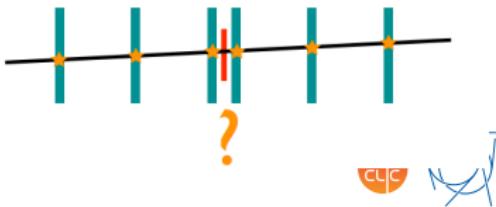
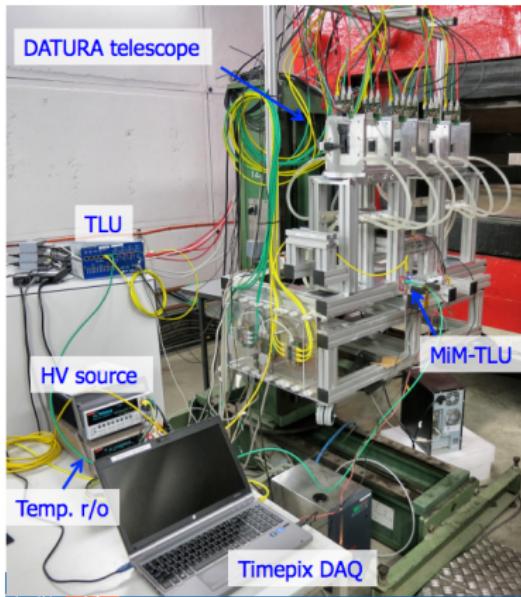
5 Active-edge sensor optimisation

6 Conclusions

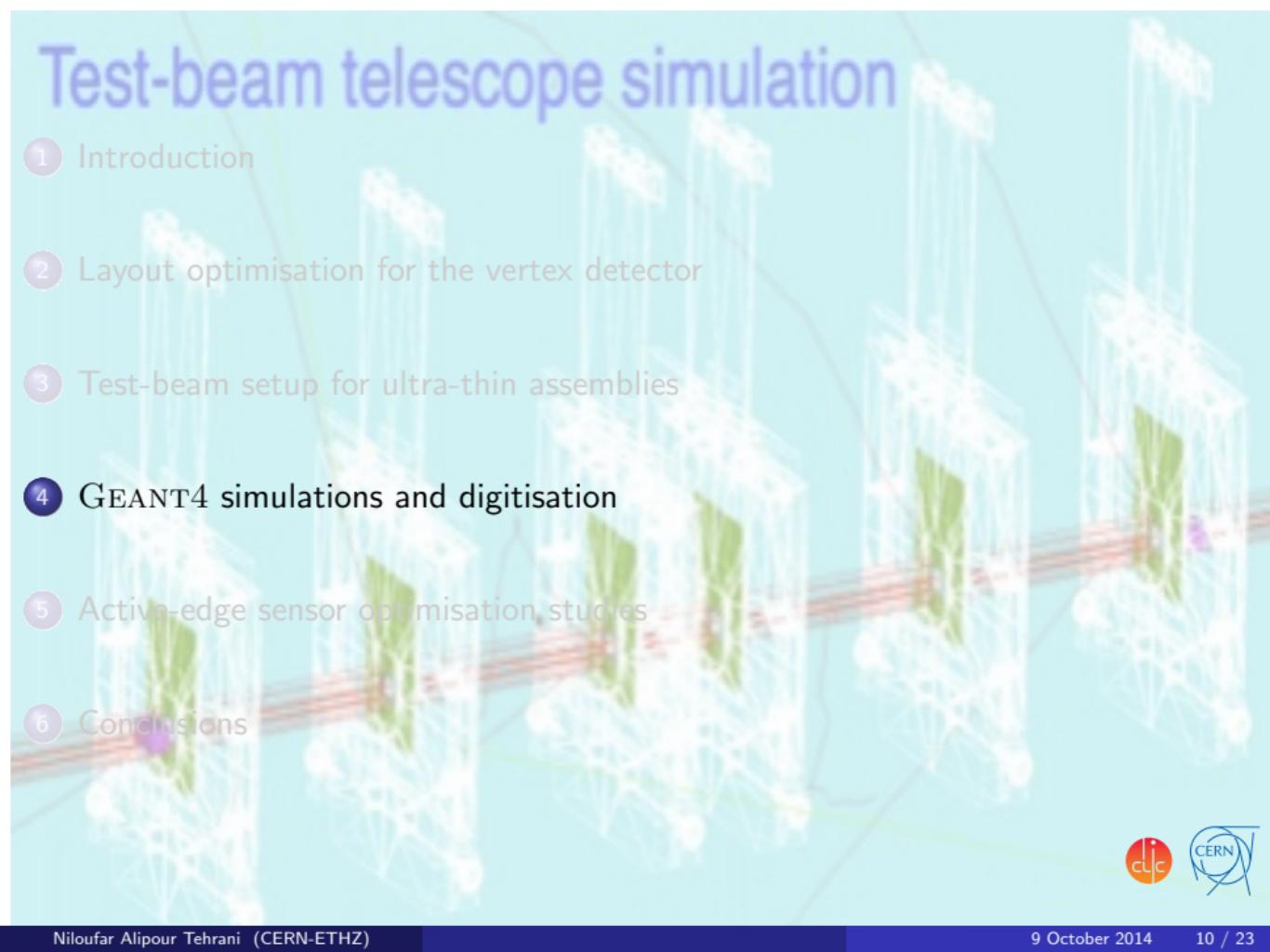


DESY test-beam setup

- Assemblies tested during the test-beam campaign at DESY in 2013-2014:
 - 50 μm -300 μm sensor thicknesses.
 - 100 μm -750 μm Timepix chip thickness.
- ▶ Talk by Sophie Redford
- 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 $\sim 3 \mu\text{m}$ at 5.6 GeV.
- The DUT is placed between layer 3 and 4 of the telescope with the possibility of rotation.



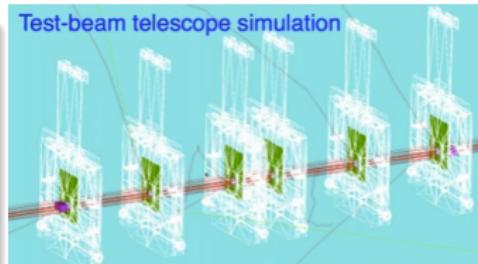
Test-beam telescope simulation

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AllPix simulation framework

AllPix

- A general purpose pixel detector simulation framework.
- Written in C/C++.
- Based on GEANT4.



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.

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.

For each chip family, users can define a digitiser which simulates:

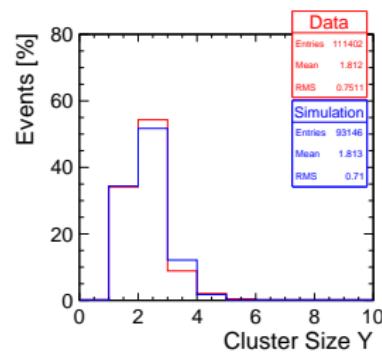
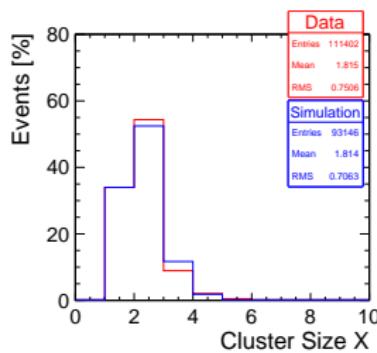
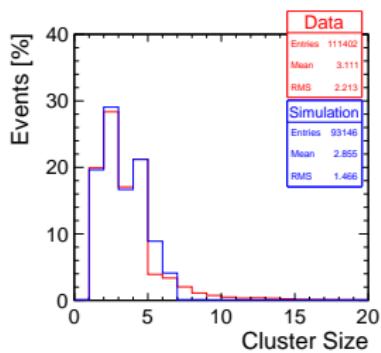
- The response of the silicon sensor to ionisation.
- The readout chip.

Provided digitisers:

- Monte-Carlo truth digitiser
- MIMOSA26 digitiser
 - Based on test-beam data.
- Timepix digitiser
 - Based on semiconductor physics \Rightarrow simulation of charge diffusion.
 - The calibration for each assembly is used to simulate the ADC and digital components of the chip.

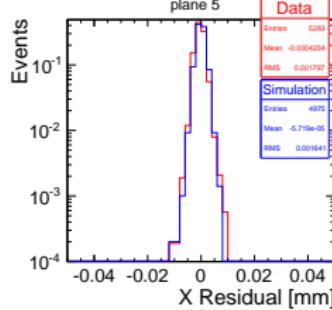
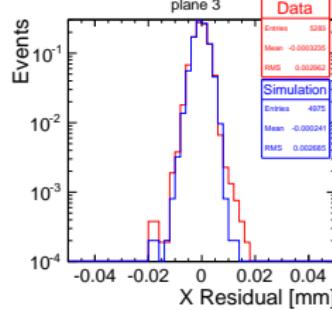
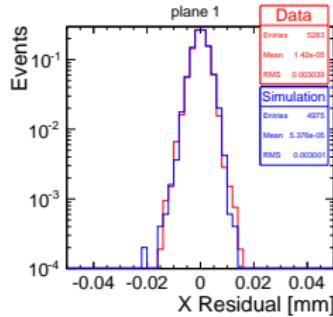
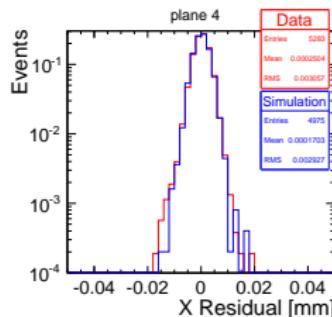
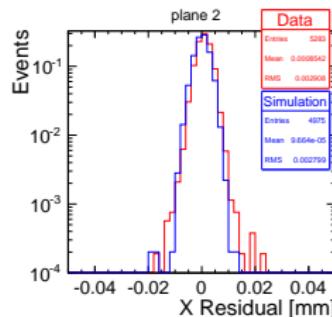
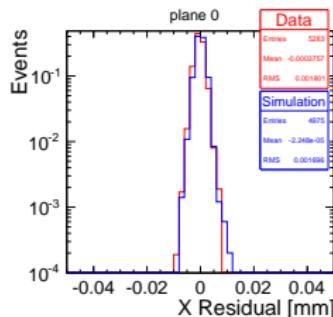
Telescope simulation in AllPix

- 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:



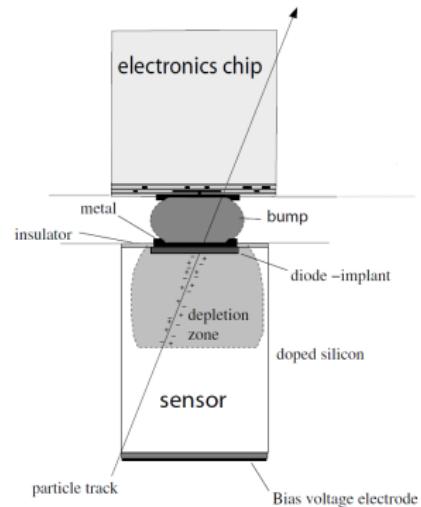
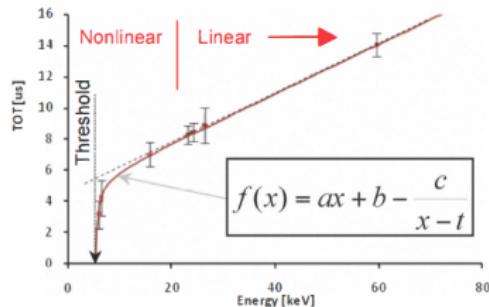
Telescope simulation in AllPix (2)

- 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.
- 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:

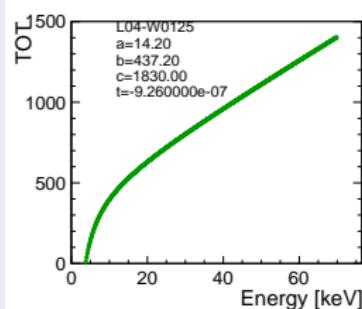


- Non-linear response of pixels in the energy range close to the threshold.

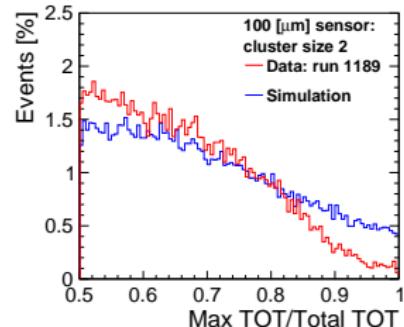
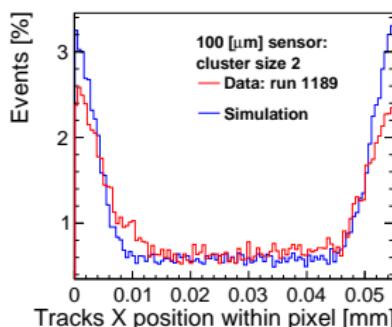
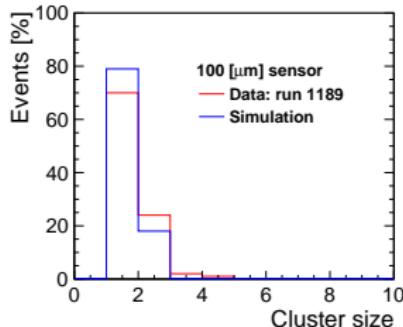
DUT simulation vs. data: 100 μm sensor

Assembly characteristics

- 100 μm sensor
- Sensor type: p-in-n
- Threshold: 1026 e^- ($\sim 3.73 \text{ keV}$)
- $V_{bias}=35 \text{ V}$, 5.6 GeV e^- beam



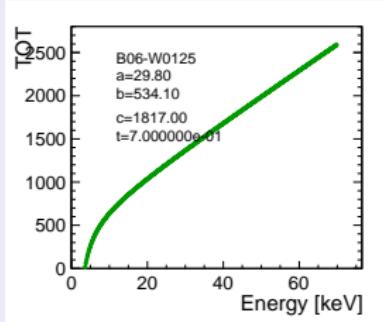
- Cluster-size distribution
- Track position: 2-hit clusters
- Charge sharing: 2-hit clusters



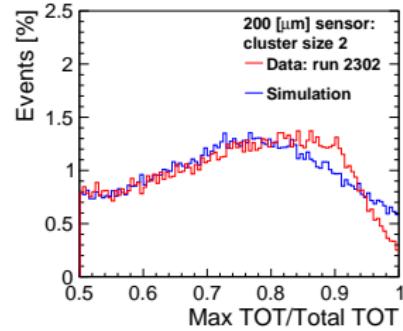
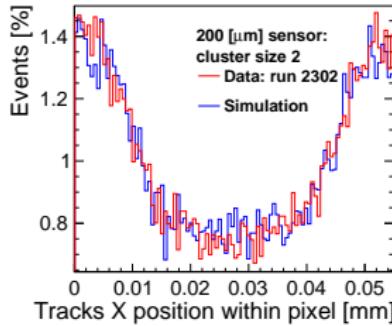
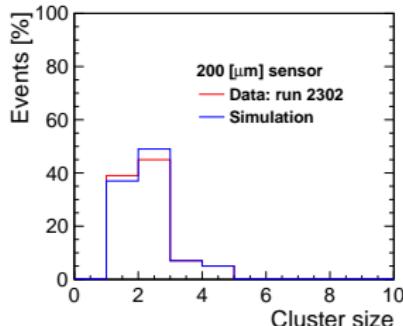
DUT simulation vs. data: 200 μm sensor

Assembly characteristics

- 200 μm sensor
- Sensor type: n-in-p
- Threshold: 973 e^- ($\sim 3.54 \text{ keV}$)
- $V_{bias} = -35 \text{ V}$, 5.2 GeV e^- beam



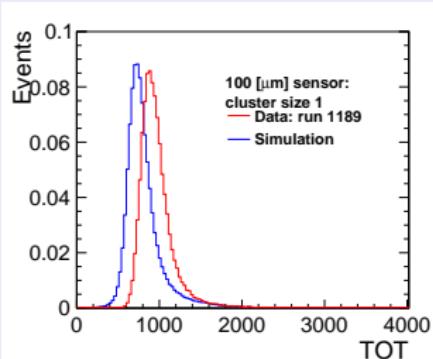
- Cluster-size distribution
- Track position: 2-hit clusters
- Charge sharing: 2-hit clusters



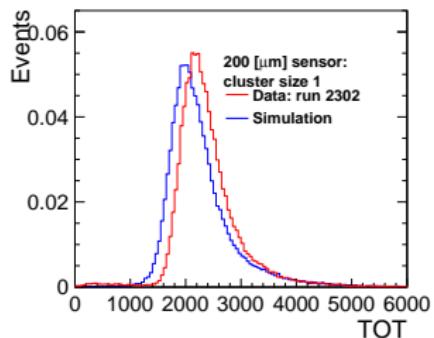
DUT simulation vs. data: TOT distribution

- Good agreement between data and AllPix simulation:
 - Charge sharing needs to be better understood in simulation (especially for low-energy hits).
- TOT distribution for cluster size 1:

100 μm sensor

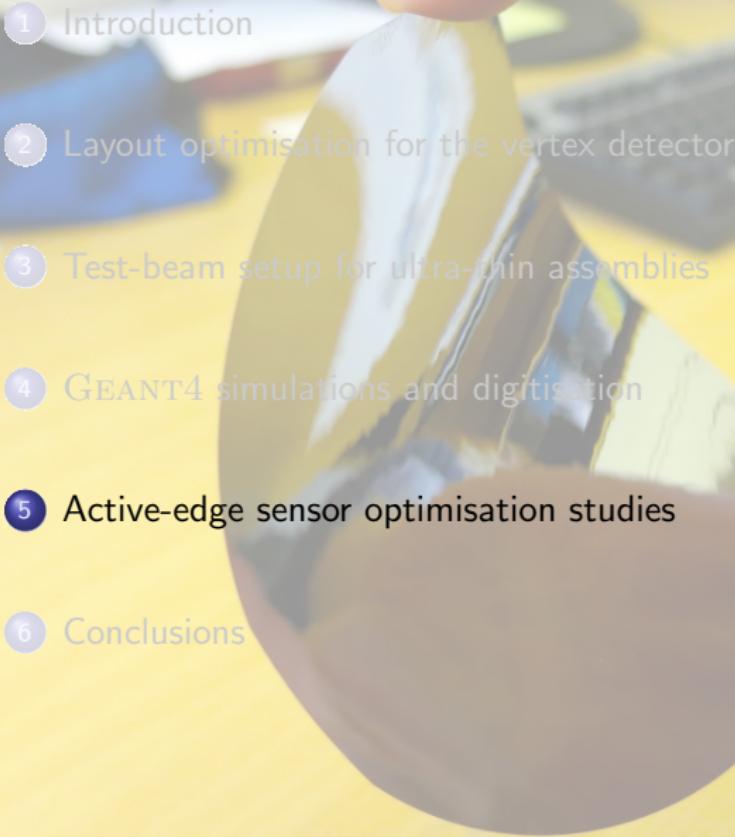


200 μm sensor



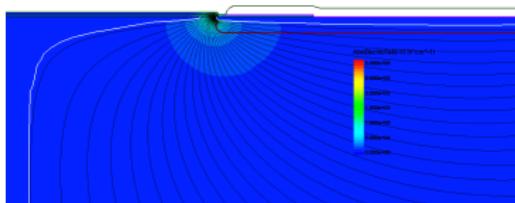
- Similar TOT distribution for simulation and data but shifted.
 - The threshold value can affect significantly the mean of the distribution.
 - Future work: find the relation between the threshold value in DAC and in number of electrons (or keV).



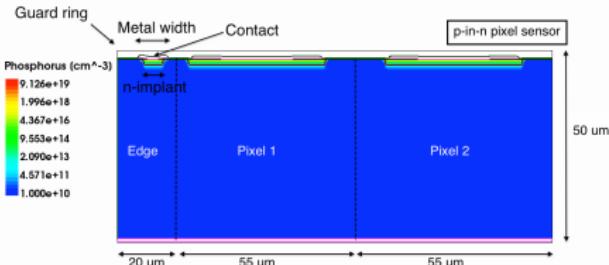
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Active-edge sensor optimisation studies

- Active edge sensors can reduce significantly the material budget and the dead areas of the detector.
- To control the voltage at the edge, an implantation is done on the sidewall
⇒ the DRIE (deep reaction ion etching) process.
 - extends the backside electrode to the edge.
 - a voltage drop between the edge and the first pixel is created ⇒ early breakdown in silicon for electric fields higher than 3×10^5 V/cm.



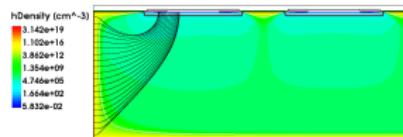
- Guard rings: establish a smooth voltage drop between the edge and the first pixel.



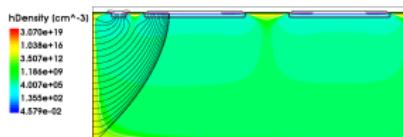
Guard ring solutions

- TCAD simulation tools are used to model semiconductor devices fabrication and device operation.

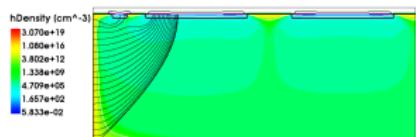
- No guard ring



- Grounded guard ring



- Floating guard ring



- No guard ring: a break down can occur for $V_{bias} = -50$ V on the edge of the first pixel.
- Grounded guard ring: the E-field is significantly reduced on the first pixel but a part of the signal in the edge region is lost (it is collected by the guard ring).
- Floated guard ring: a breakdown risk still exists for very high bias voltages but the inactive region is highly minimised.
- Assemblies with active-edge sensor from Advacam are under process.

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Conclusions

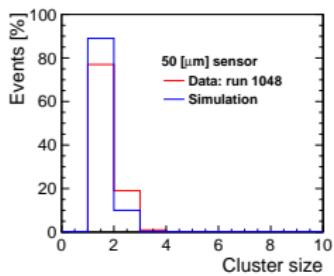
- Challenging demands on thin-sensor assemblies.
- Validation of GEANT4 simulation models with test-beam results.
- Sensor layout optimisation based on TCAD simulations.



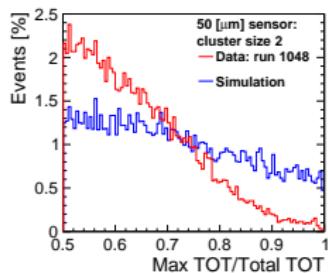
Backup slides

AllPix simulation: 50 μm sensor

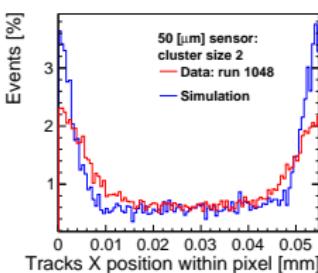
- Cluster size



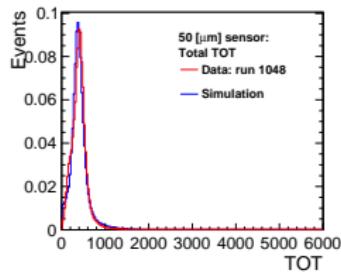
- Charge sharing:
2-hit clusters



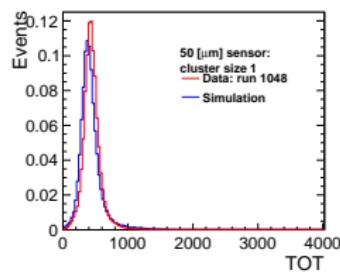
- Track position:
2-hit clusters



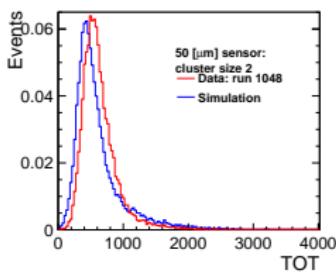
- TOT distribution:
all clusters



- TOT distribution:
1-hit cluster

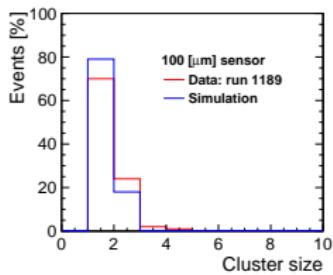


- TOT distribution:
2-hit cluster

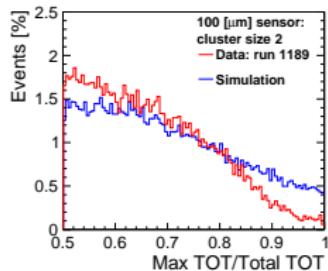


AllPix simulation: 100 μm sensor

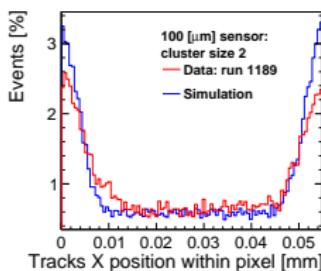
- Cluster size



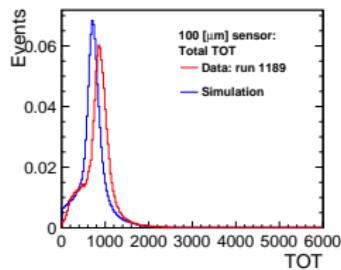
- Charge sharing:
2-hit clusters



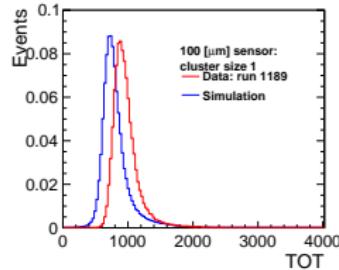
- Track position:
2-hit clusters



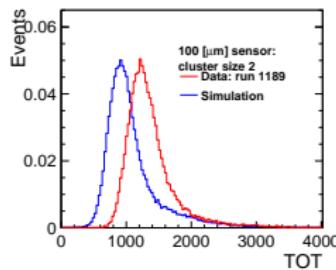
- TOT distribution:
all clusters



- TOT distribution:
1-hit cluster

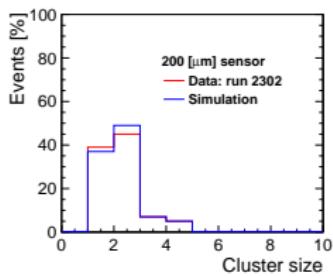


- TOT distribution:
2-hit cluster

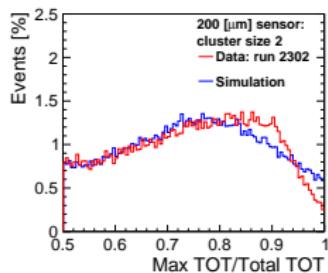


AllPix simulation: 200 μm sensor

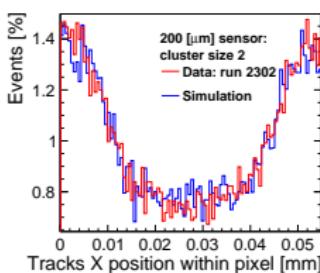
- Cluster size



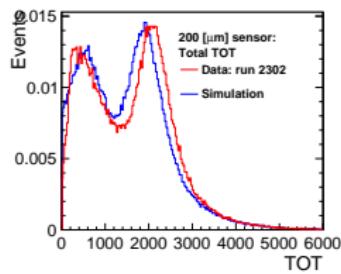
- Charge sharing:
2-hit clusters



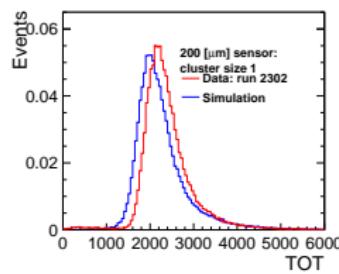
- Track position:
2-hit clusters



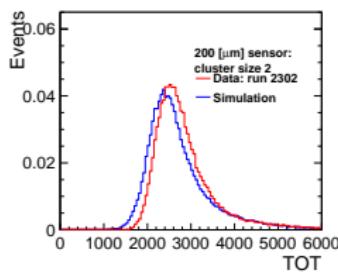
- TOT distribution:
all clusters



- TOT distribution:
1-hit cluster



- TOT distribution:
2-hit cluster



Guard ring solutions: Electric field and potential

- Grounded guard ring increases the depletion region but a part of the signal in the edge region is lost.
- Floated guard ring creates a compromise between the depletion region and the inactive region.

