Test Beam Results of planar pixel quad modules and spatial resolution of 3D pixels for the Phase-2 CMS Tracker

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On behalf of the CMS Tracker Group

CMS

UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA

INFN Istituto Nazionale di Fisica Nucleare

18th 'Trento' Workshop on Advanced Silicon Radiation Detectors

The CMS Inner Tracker upgrade for the High Luminosity-LHC

HL-LHC operation conditions	Sensor design constraints
Luminosity $7.5\text{x}10^{34}/(\text{cm}^2\bullet\text{ s})$ ➜ up to 200 events/25 ns bunch crossing	Maintain occupancy at ‰ level and increase spatial resolution ➜ pixel size x6 smaller than present pixels ➜ $25\text{x}100\ \mu\text{m}^2$ (current detector in CMS $100\text{x}150\ \mu\text{m}^2$)
CMS baseline choice: at least one replacement of innermost layer of TBPX (at integrated fluence ≈ $1.9\text{x}10^{16}\text{n}_{\text{eq}}/\text{cm}^2$, end of “Run 5”, i.e. after ≈6 years of operation) and inner ring of TEPX	Reduce electrodes distance to increase electric field and thus the signal ➜ thin planar or 3D columnar technologies

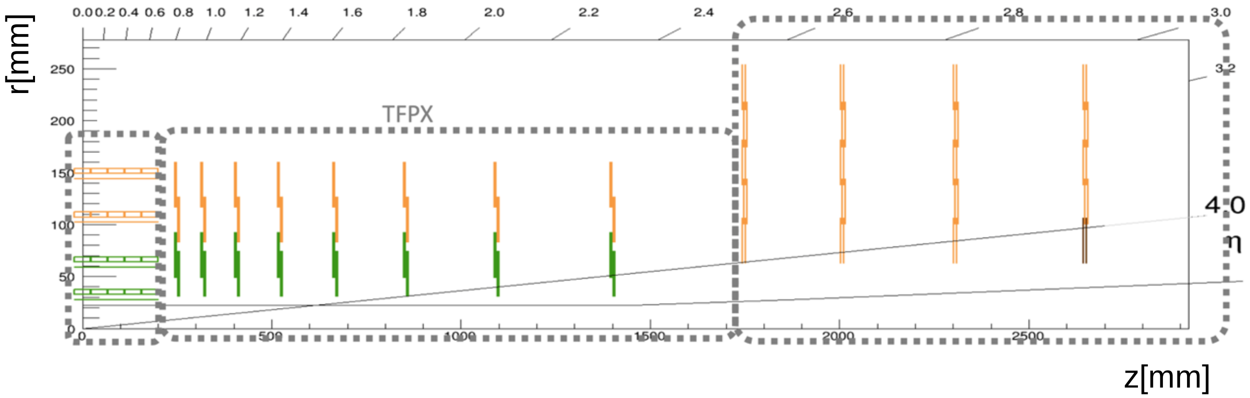
Sensor main features:

- Two types of hybrid pixel modules: 1x2 and 2x2 **CMS readout chips (CROCs)** per module

- **Planar sensors** $25\text{x}100\ \mu\text{m}^2$ x $150\ \mu\text{m}$ active thickness, sensors baseline choice for whole Inner Tracker except for barrel layer 1

- **3D sensors** $25\text{x}100\ \mu\text{m}^2$ x $150\ \mu\text{m}$ active thickness, baseline choice for barrel layer 1 (better thermal performance than planar)

See talk by Massimiliano Antonello



Planar quad module cell geometry

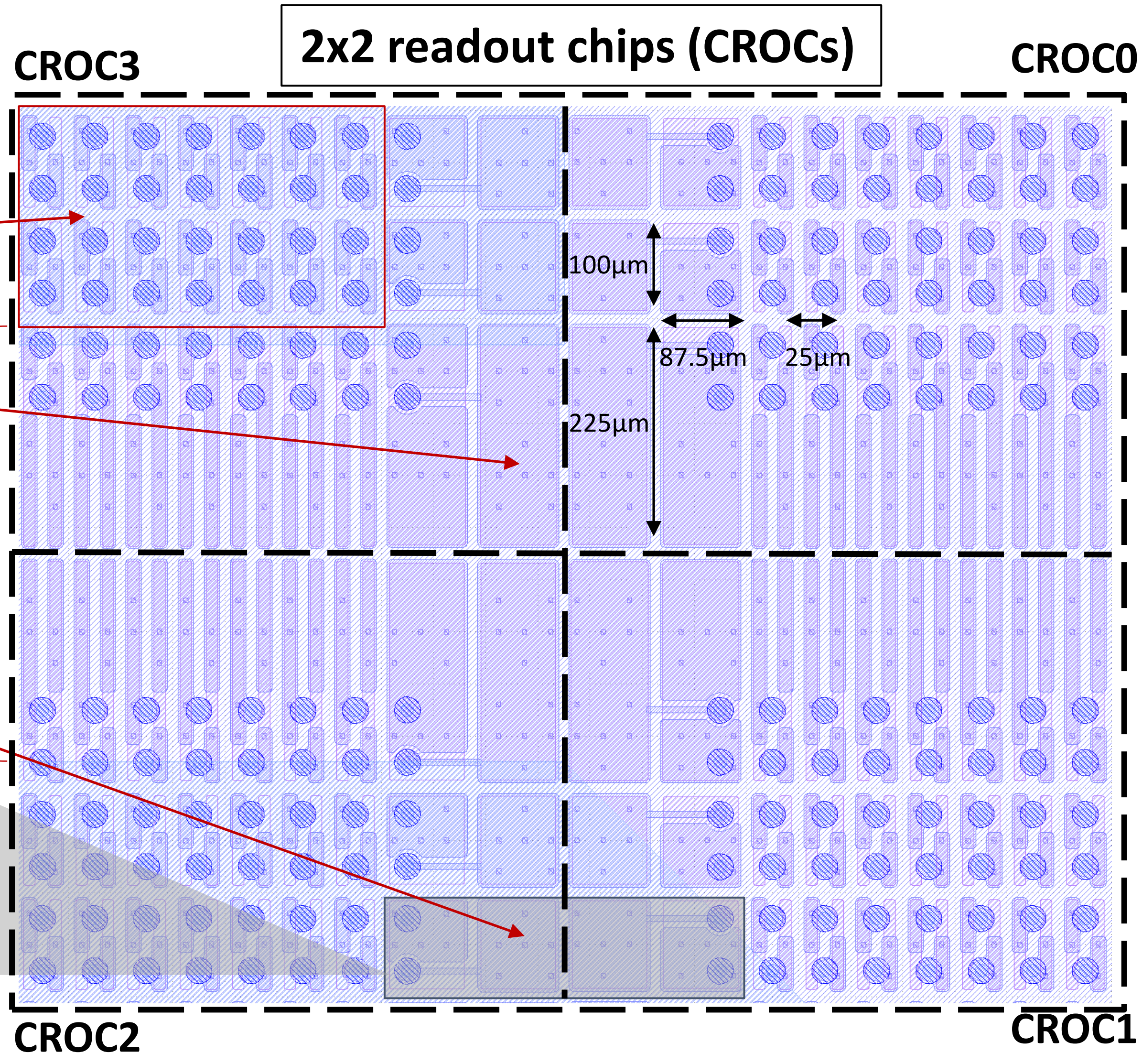
Planar Hamamatsu quad module (active thickness $150\ \mu m$) read out by **2x2 CROCs**

Standard cells ($25 \times 100\ \mu m^2$)

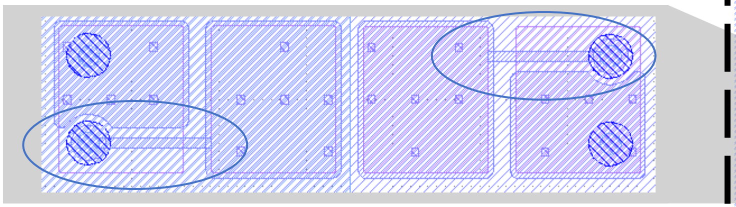
8 non-standard central cells ($87.5 \times 225\ \mu m^2$)

2 non-standard rows ($225 \times 25\ \mu m^2$)

4 non-standard columns ($87.5 \times 100\ \mu m^2$)



Rail that passes over the neighbour pixel cell



MAIN GOAL: study of **non-standard** cells of the module

FNAL Test Beam December 2022

Beam test performed at Fermilab Test Beam Facility with 120 GeV protons

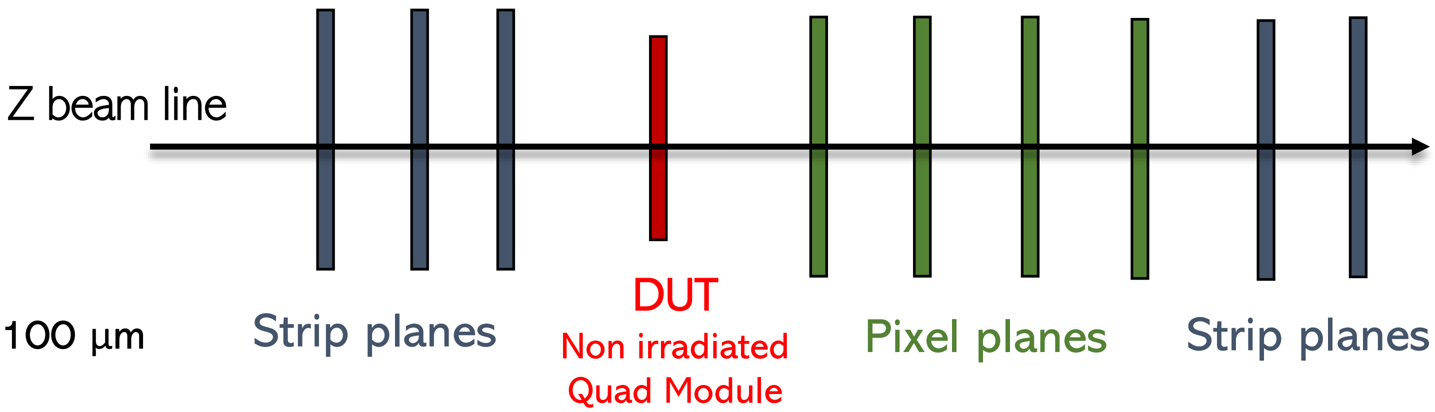
We took data with a planar quad barrel module.
<u>The sensor was NOT irradiated</u>

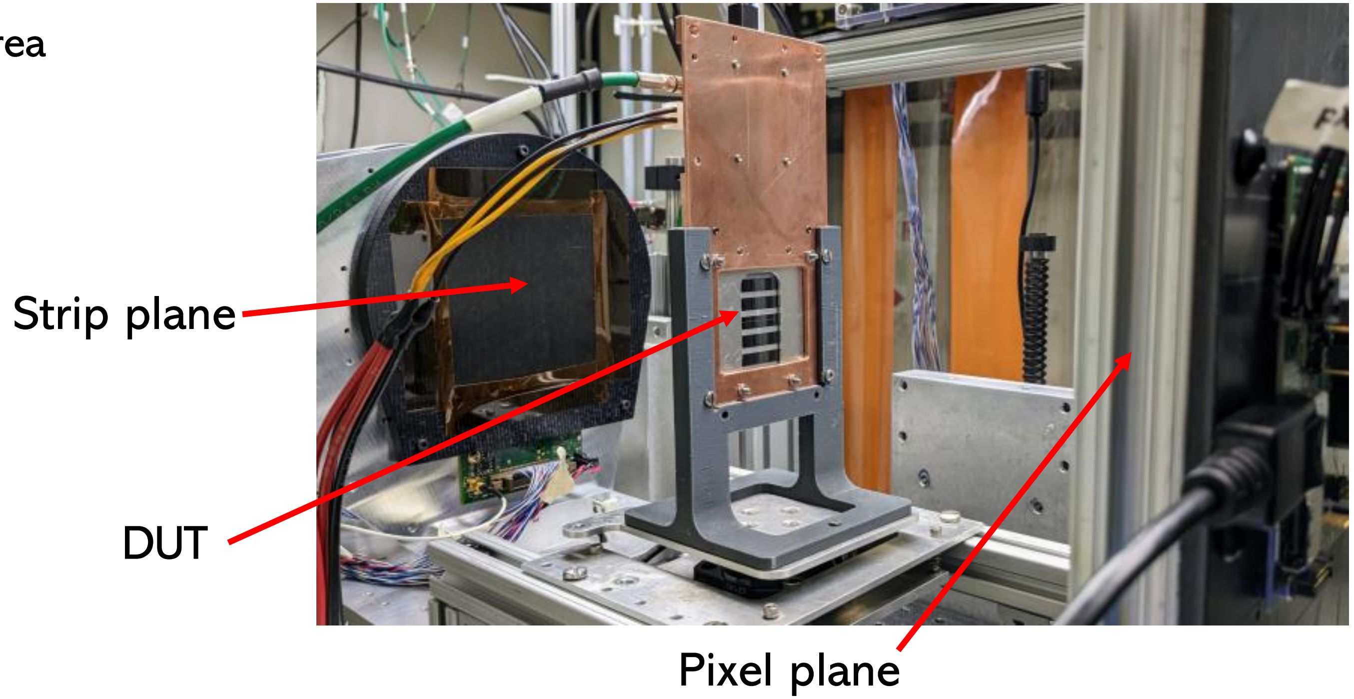
TELESCOPE SET UP:

- 5 Strip planes (60 μm pitch) and 4 Pixel planes (25x100 μm pitch, read out by RD53A→ only linear front end)
- Telescope resolution ($\sigma_{TEL} \approx 4\mu m$)
- Device Under Test (DUT) quad module (illuminated area $7x7mm^2$)
    - Planar Hamamatsu quad module (active thickness 150 μm) read out by 2x2 **CROCs**
    - CROCs operated in sync mode and using external accelerator clock (for the first time)

TRACK SELECTION AND HIT ASSOCIATION:

- tracks with hits on all strip planes and hits on 2 pixels planes at least
- track fit χ^2/dof<5
- hits associated with tracks on DUT within 300 μm

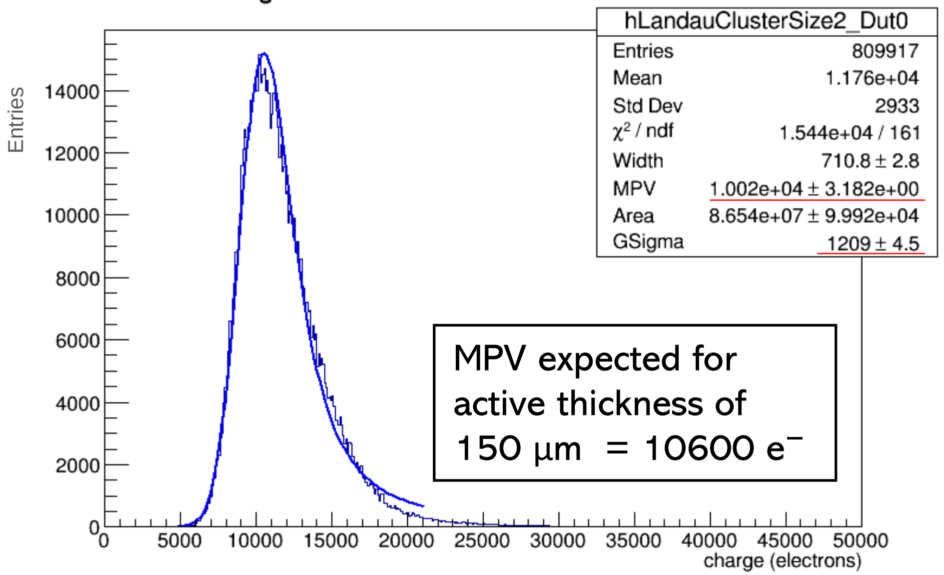




Calibrations

- Performed calibration and equalization of the thresholds of all pixels within a CROC
- Pulse height curves fitted with a linear fit below saturation
- Threshold and noise were determined by performing a charge injection scan (S-curve)
  <threshold> ≈ 1100 - 1200 electrons
  <noise> ≈ 90 - 100 electrons

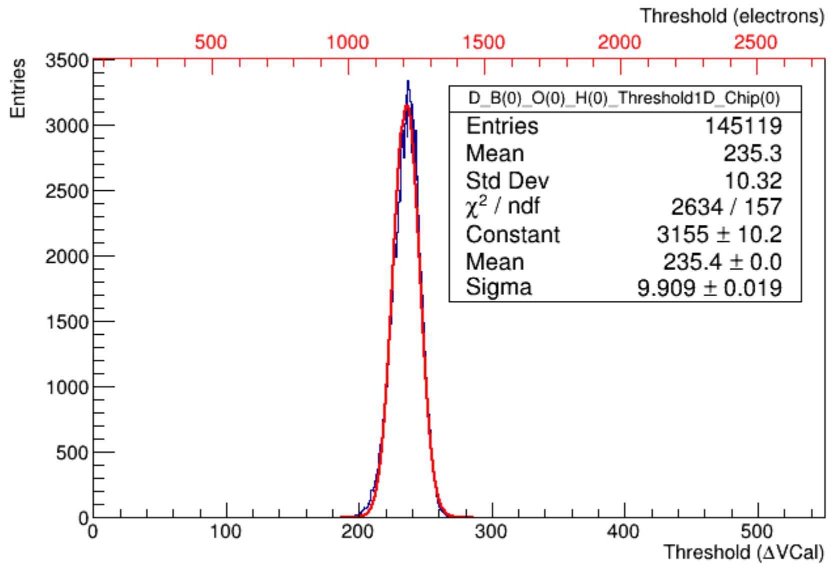
Charge distribution for clusters of size 2 Dut



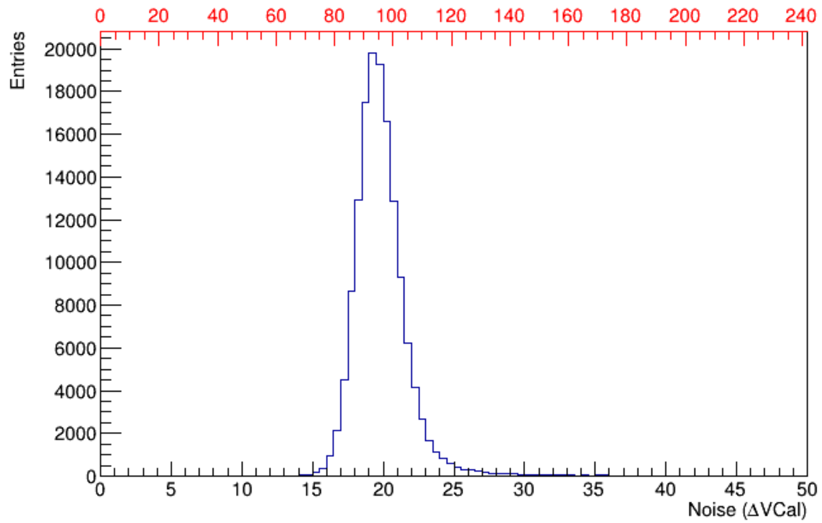
The fit function is a Landau convoluted with a Gaussian

Operated at 100V (overdepleted)

Threshold distribution CROC0



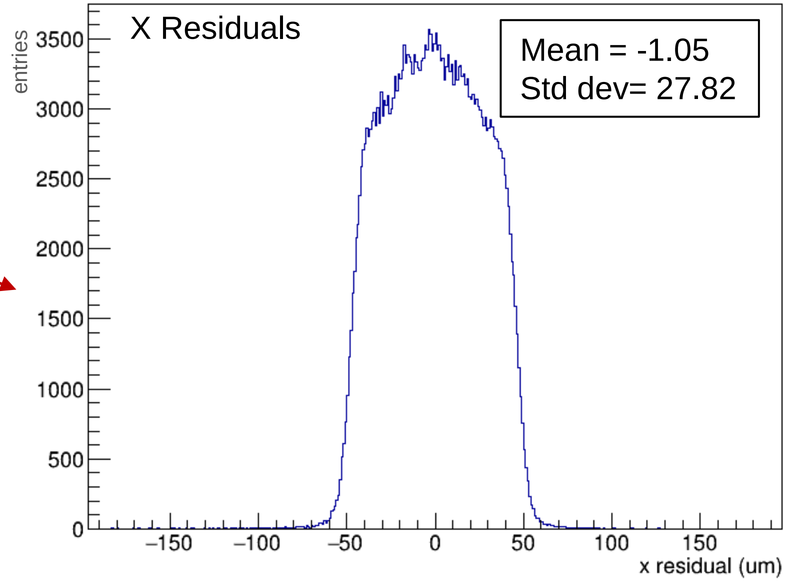
Noise distribution CROC0



Residuals 25x100 μm^2 cells

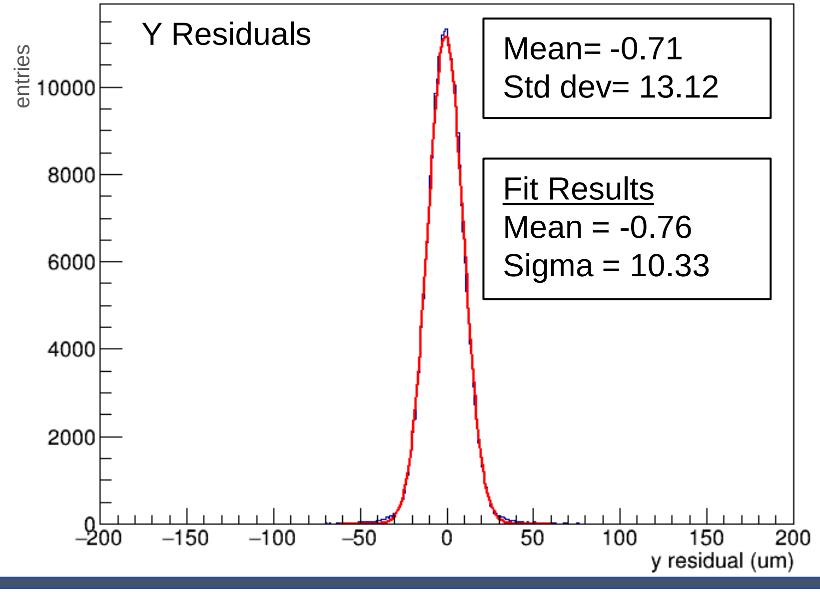
Results for **X residuals (long pitch)** are in agreement with expectations

- Digital resolution for the long pitch: $100\ \mu\mathrm{m}/\sqrt{12} = 28.9\ \mu\mathrm{m}$

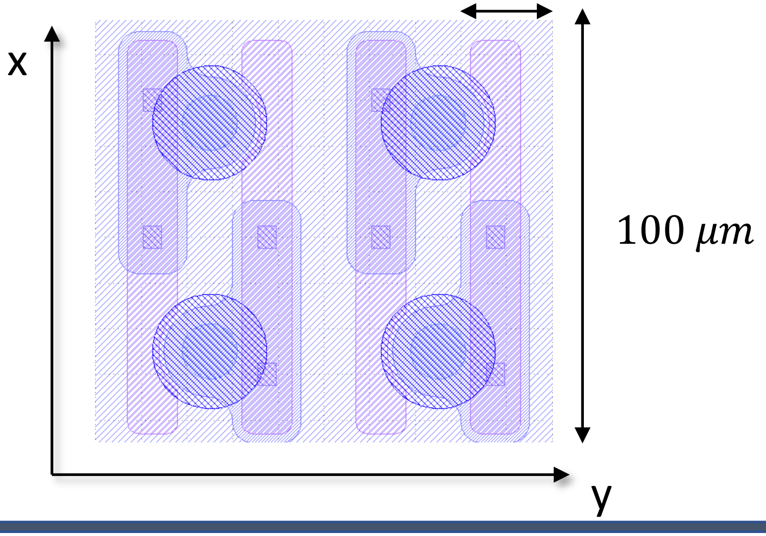


Results for **Y residuals (short pitch)** show discrepancies with the expected resolution

- Rough estimate of the DUT resolution : $\sqrt{\sigma_{DUT}{}^2 - \sigma_{TEL}^2} = 9.5\ \mu\mathrm{m}$
- Digital resolution for the short pitch: $25\ \mu\mathrm{m}/\sqrt{12} = 7.2\ \mu\mathrm{m}$



Residuals = associated cluster position - interpolated track intercept

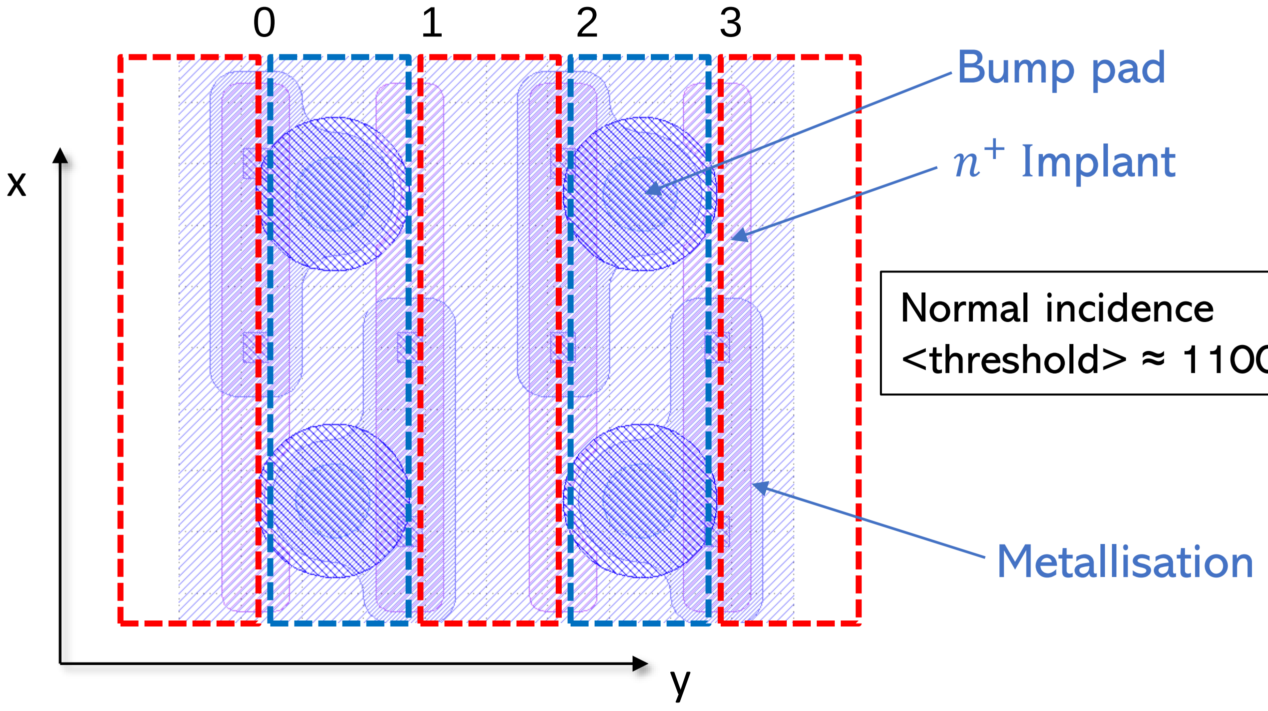


Y residuals 25x100 μm^2

Study of Y residuals for areas between coupled and non coupled pixels

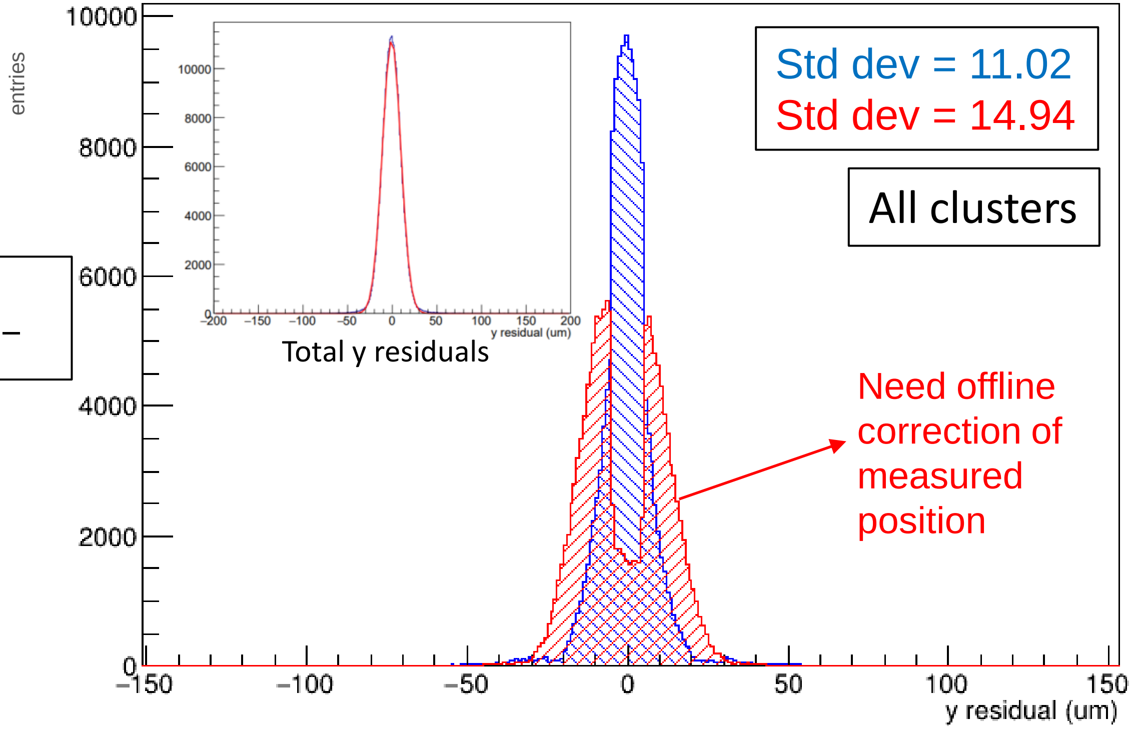
When tracks pass trough the area where pixels are coupled we expect regular charge sharing.
The residual distribution evaluated between pixel 0 and 1 (or 2 and 3) show a single peak as expected.

When tracks pass trough the area where pixels are not coupled (between pixel 1 and 2) the residuals are pushed outwards because the neighbors cells (cell 0 and 3) also lights up.
This results in a double peaked distribution.



Normal incidence
<threshold> ≈ 1100 e^-

Schematic drawing of a 1x4 pixel grid of the DUT for 25x100 μm^2 pixel cells



The residuals distributions evaluated on the corresponding areas of the same color

Cluster size 25x100 μm^2

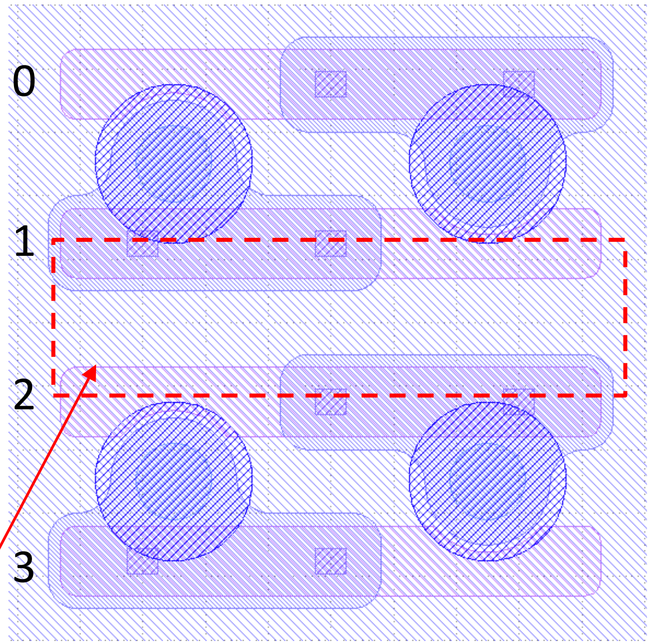
At high bias voltage the **cluster size is higher** at the intersection of **non coupled pixels**

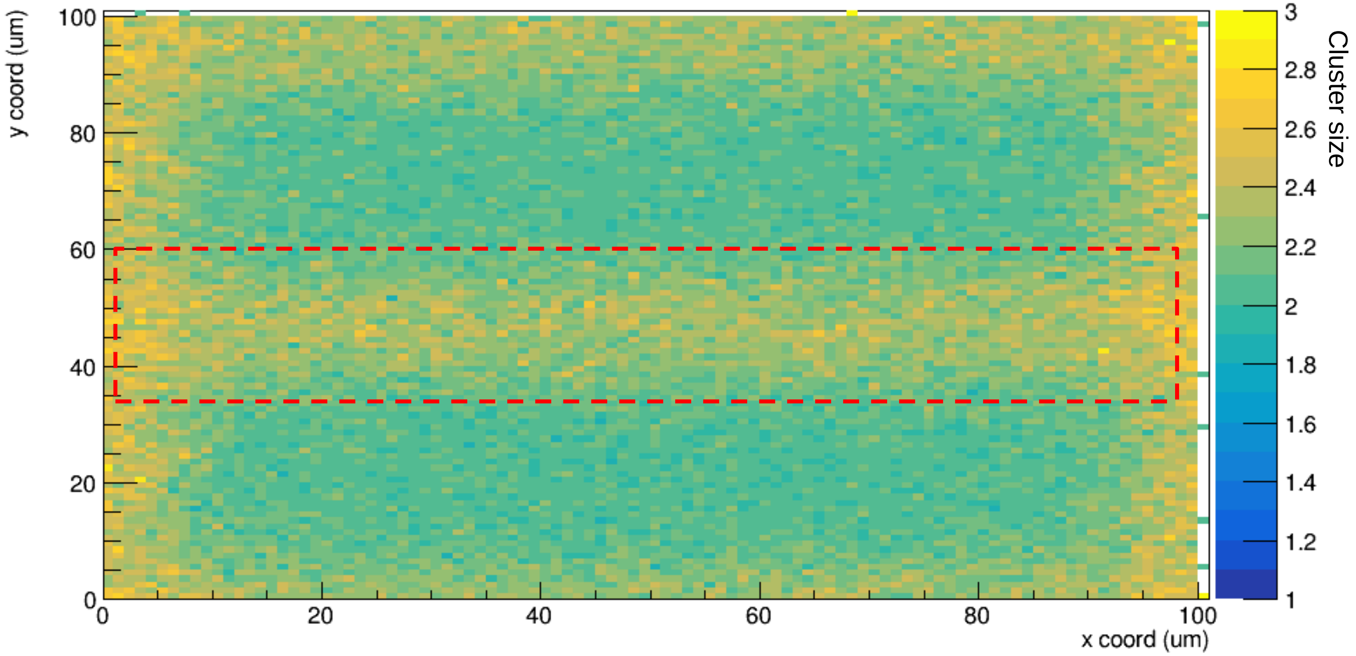
Cluster size 2 hits are ≈ 78% of the total

When a particles passes through the area where the <u>pixels are not coupled</u> there is regular charge sharing between pixels 1 and 2

On top of regular charge sharing adjacent pixels might light up as a result of **cross talk**

This results in an increased cluster size in this area





Schematic drawing of a 1x4 pixel grid of the DUT (left) and corresponding cluster size map (right)

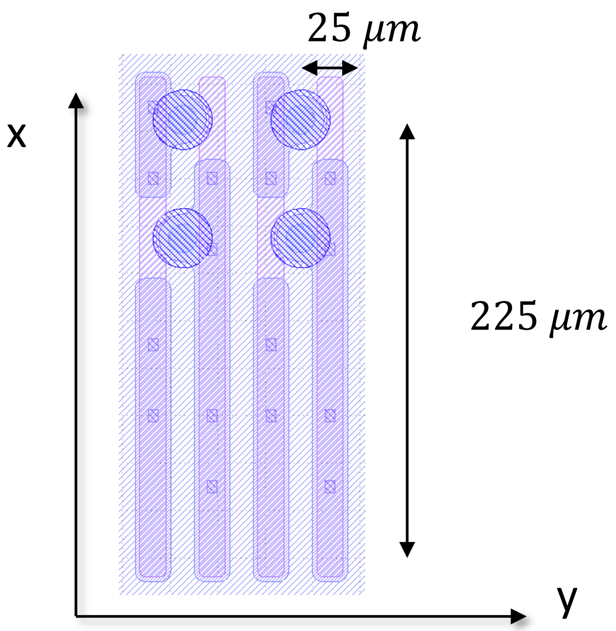
Residuals 25x225 μm^2

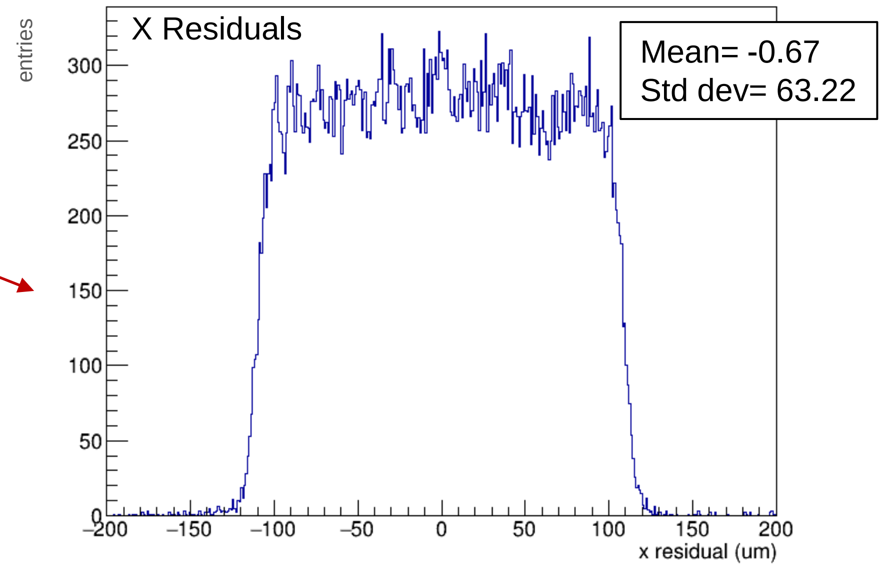
Results for **X residuals (long pitch)** are in agreement with expectations.

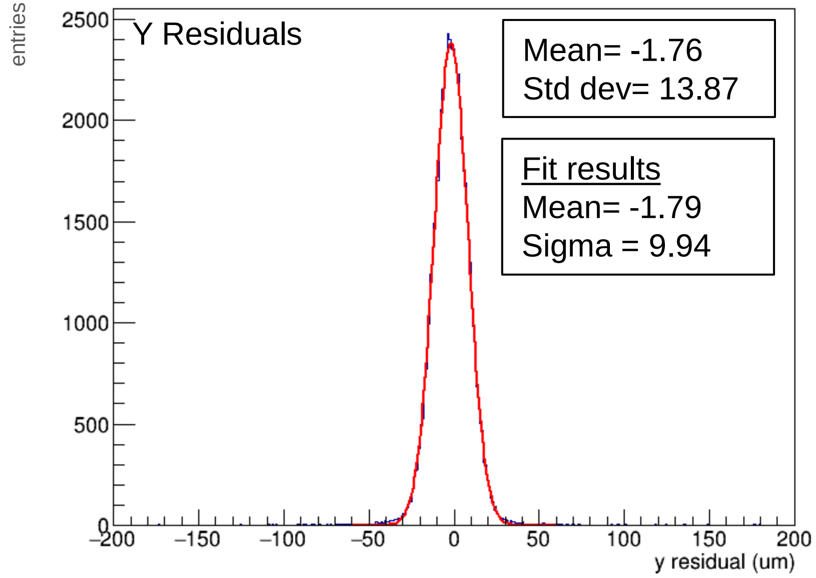
- Digital resolution for the long pitch: $225\ \mu m\ / \sqrt{12} = 64.9\ \mu m$

Results for **Y residuals (short pitch)** show discrepancies with the expected resolution.

- Rough estimate of the DUT resolution: $\sqrt{\sigma_{DUT}{}^2 - \sigma_{TEL}^2} = 9.1\ \mu m$
- Digital resolution for the short pitch: $25\ \mu m\ / \sqrt{12} = 7.2\ \mu m$





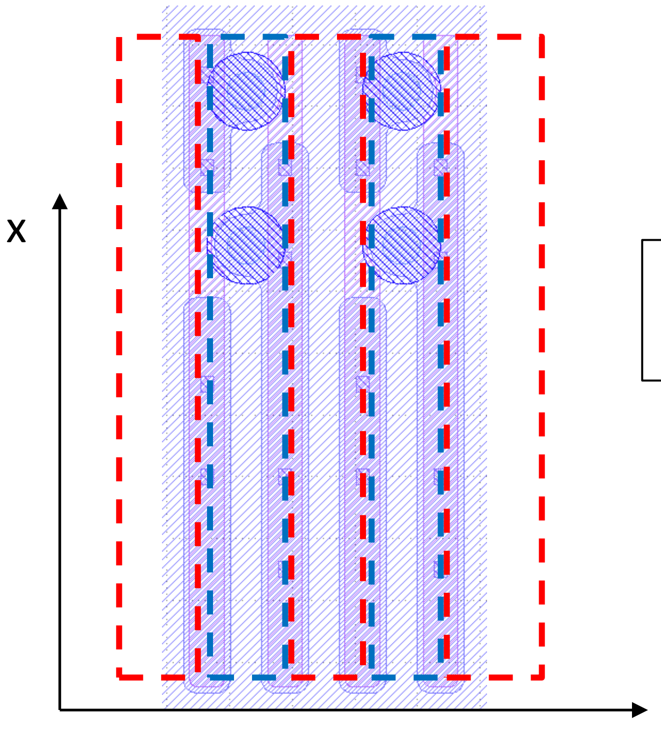


Y residuals 25x225 μm^2

Study of Y residuals for areas between coupled and non coupled pixels

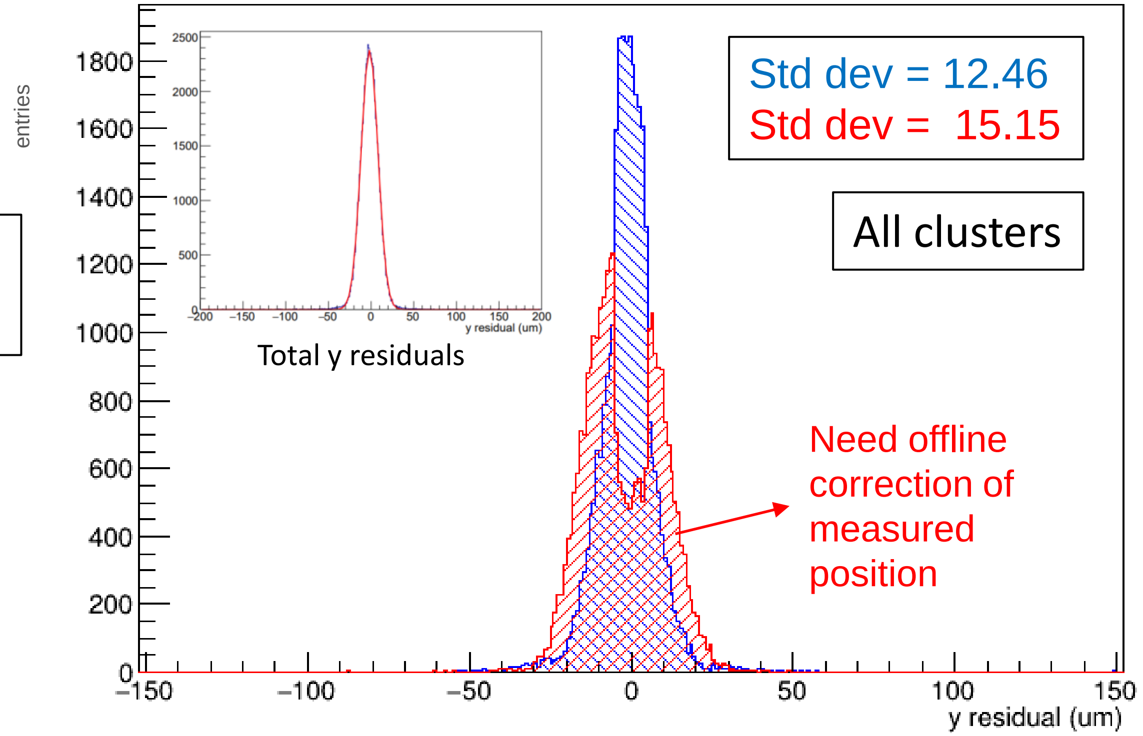
When tracks pass trough the area where pixels are coupled we expect regular charge sharing.
The residual distribution evaluated between pixel 0 and 1 (or 2 and 3) show a single peak as expected.

When tracks pass trough the area where pixels are not coupled (between pixel 1 and 2) the residuals are pushed outwards because the neighbors cells (cell 0 and 3) also lights up.
This results in a double peaked distribution.



Schematic drawing of a 1x4 pixel grid of the DUT for 25x225 μm^2 pixel cells

Normal incidence
<threshold> ≈ 1100 e^-



The residuals distributions evaluated on the corresponding areas of the same color

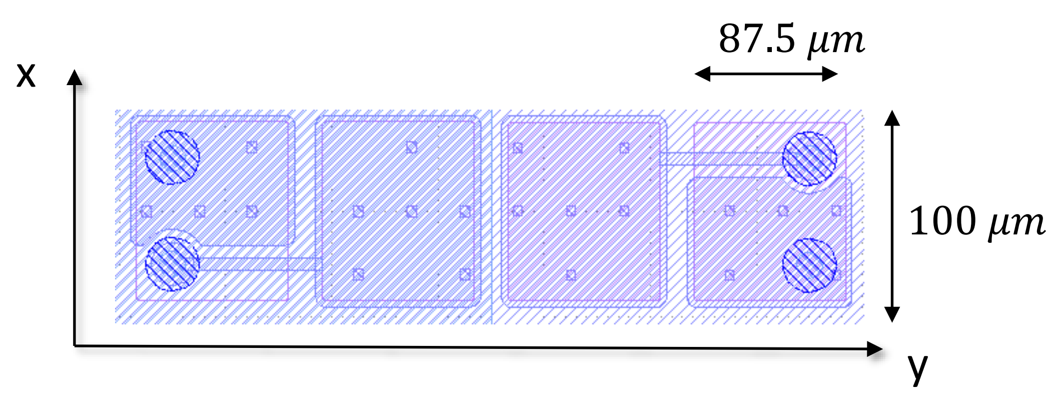
Residuals 87.5x100 μm^2

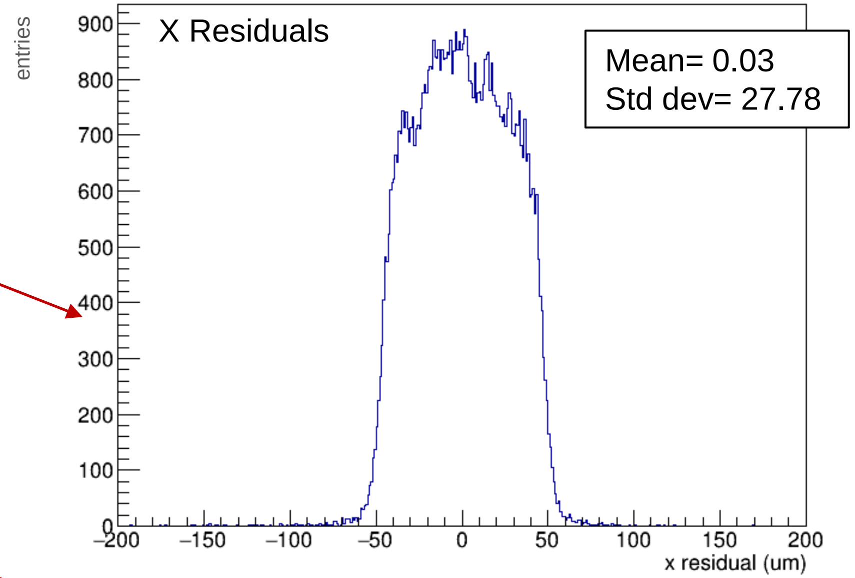
Results for **X residuals (long pitch)** are in agreement with expectations.

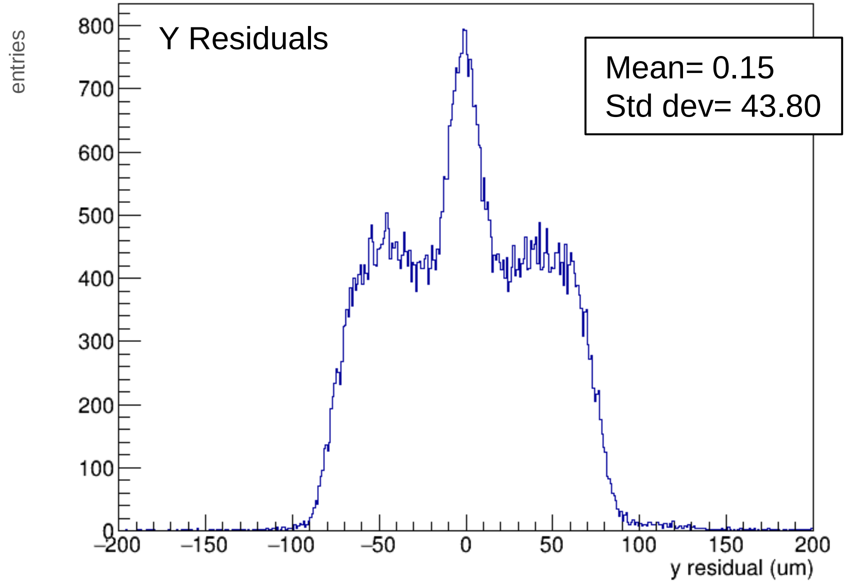
- Digital resolution for the long pitch: $100\ \mu\text{m}\ /\sqrt{12} = 28.9\ \mu\text{m}$

Results for **Y residuals (short pitch)** show discrepancies with the expected resolution.

- Digital resolution for the short pitch = $87.5\ \mu\text{m}\ /\sqrt{12} = 25.3\ \mu\text{m}$

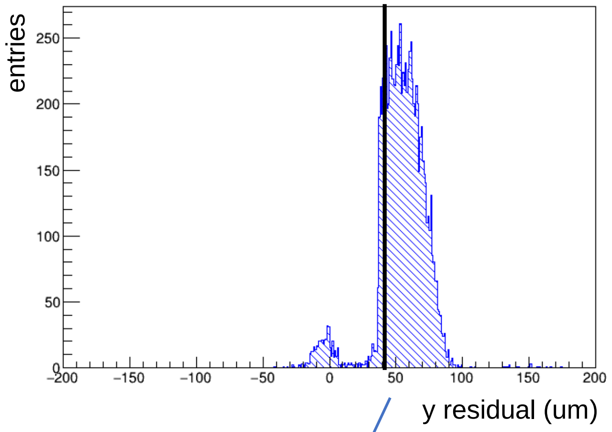


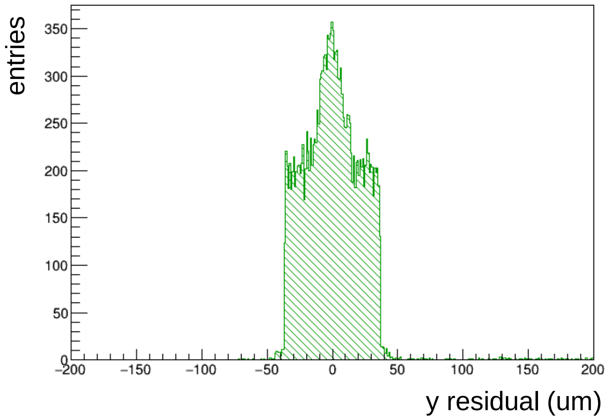


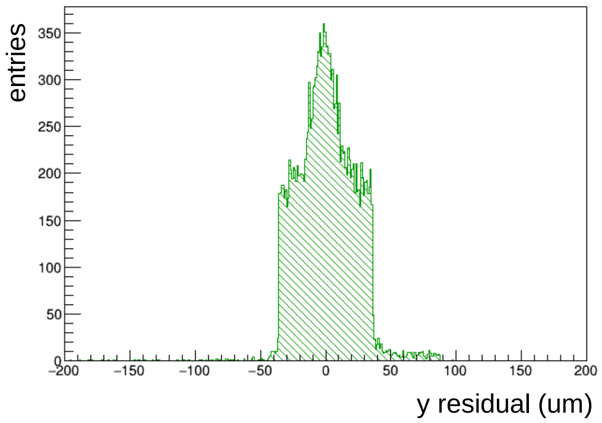


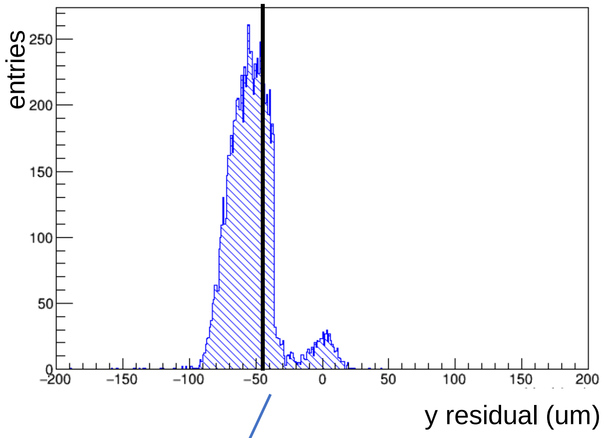
Cluster size 2 hits are ≈ 84% of the total

Y residuals 87.5x100 μm^2



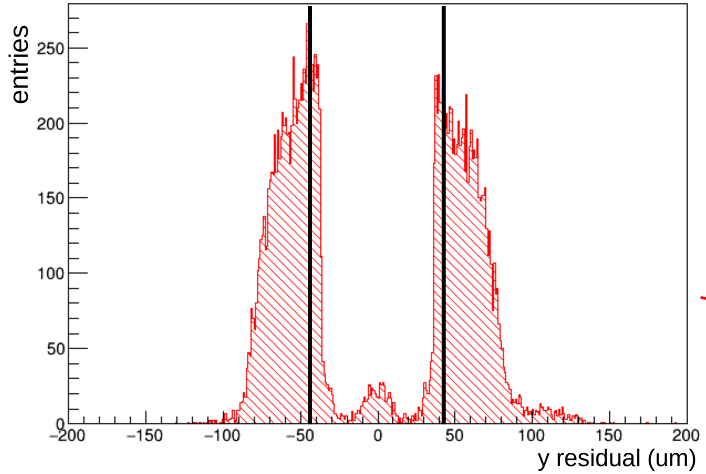






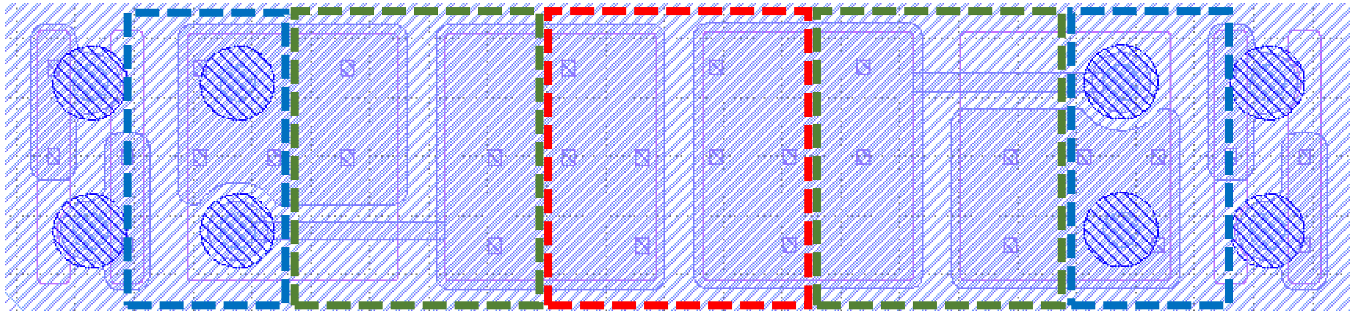
Residuals > 87.5/2 µm are mainly due to cross talk

Residuals <- 87.5/2 µm are mainly due to cross talk



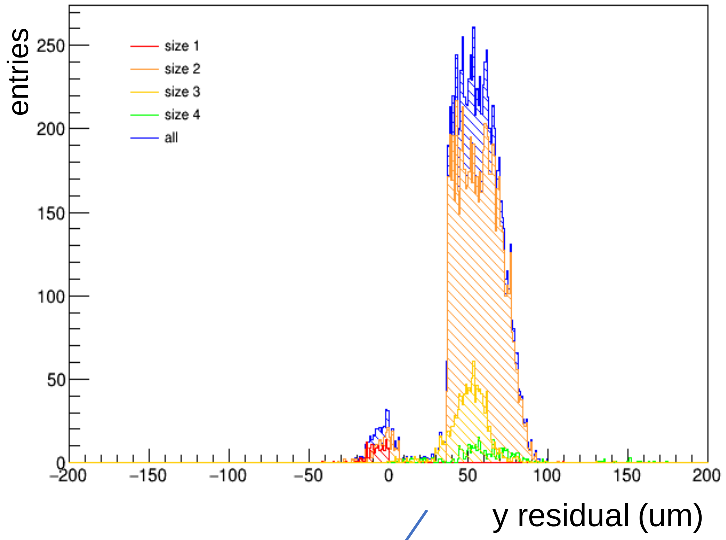
Residuals distributions evaluated on the corresponding areas of the same color

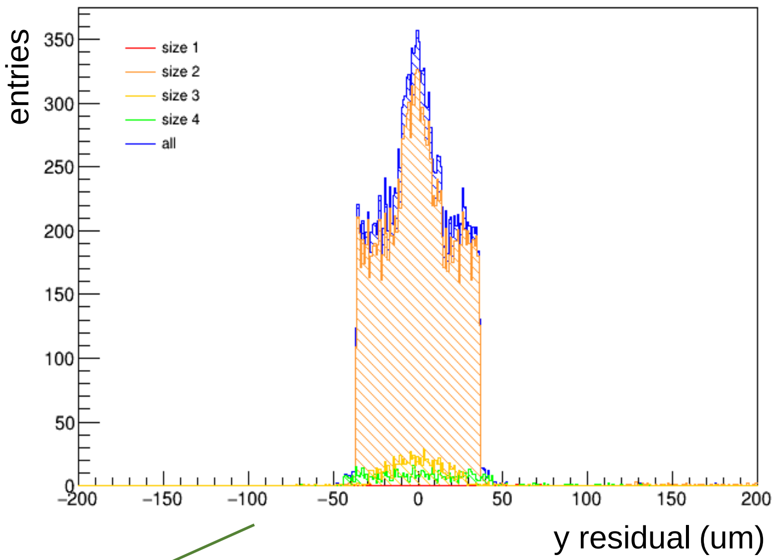
Residuals > 87.5/2 µm and < -87.5/2 µm are mainly due to cross talk

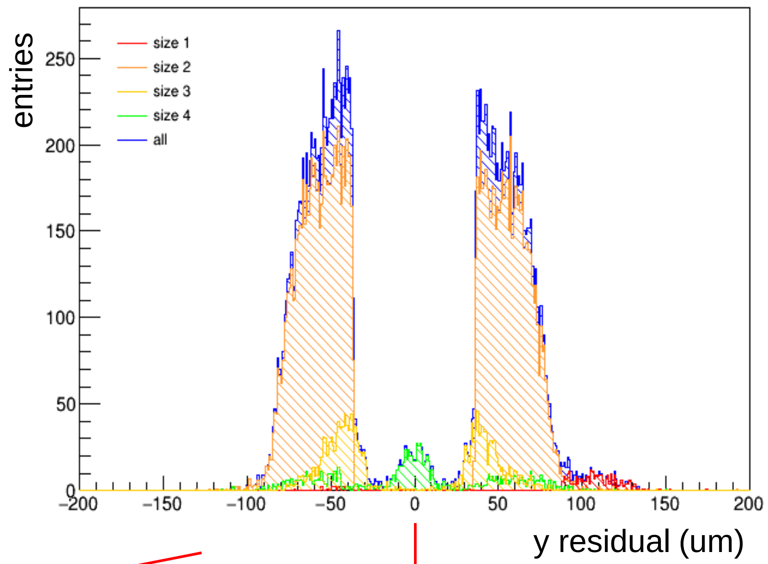


Schematic drawing of a 1x6 pixel grid of the DUT with 4 cells 87.5x100 μm^2 and 2 cells 25x100 μm^2

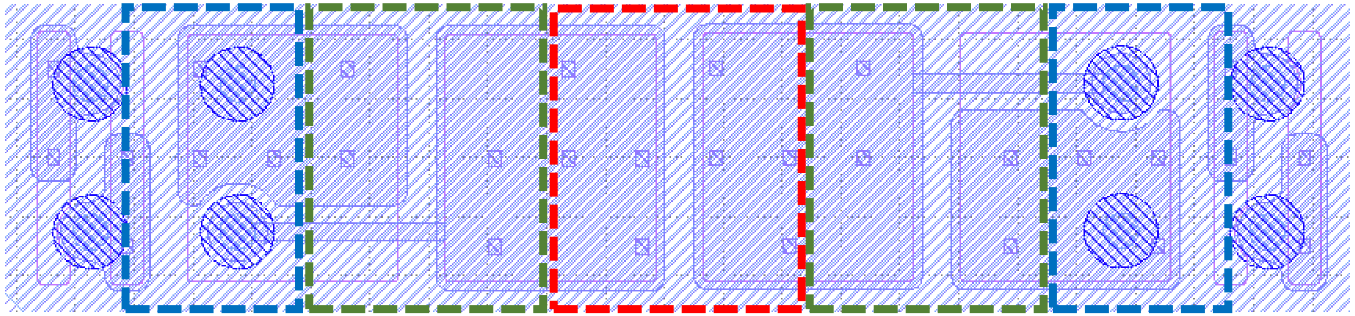
Y residuals split by cluster size 87.5x100 μm^2







- residuals of cluster size 4 around 0 caused by the lighting up of all 4 cells 87.5x100 μm^2
- no residuals of cluster size 2 around 0



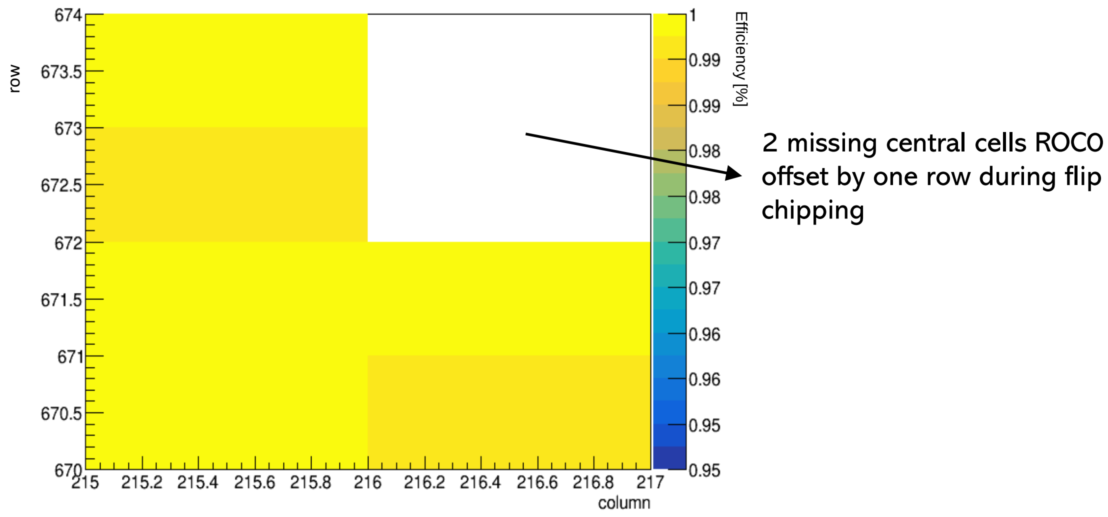
Normal incidence
<threshold> ≈ 1100 e^-

Cluster size 2 hits are ≈ 80% of the total

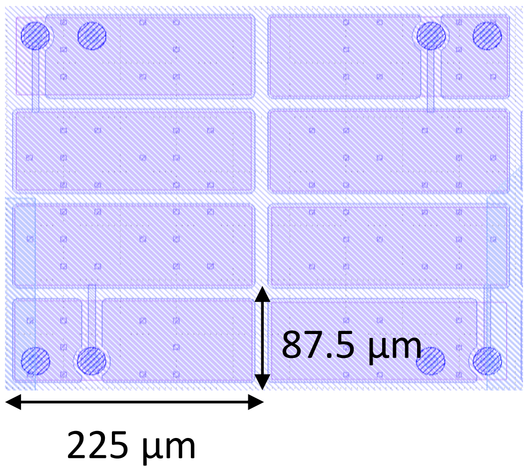
Hit efficiency studies

Efficiency for the 8 special central cells (87.5x225 μm^2)

2D efficiency map for the 8 central cells



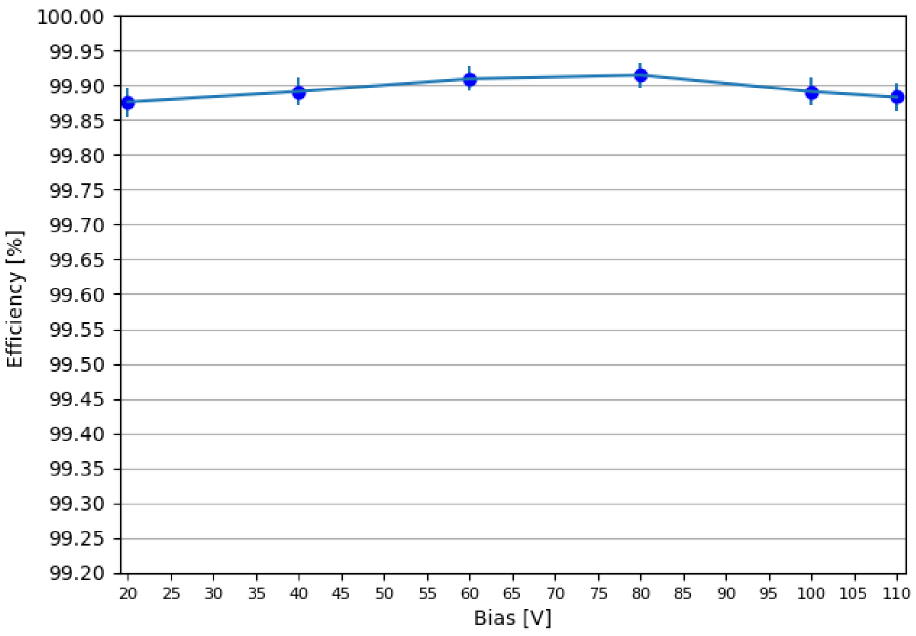
Schematic drawing of the 8 central cells of the DUT



Efficiency of all illuminated area of the module

- Mean efficiency for quad module averaged **over all illuminated area**: **99.895 ± 0.003 %** at **100 V** bias

Efficiency as a function of V_{bias}



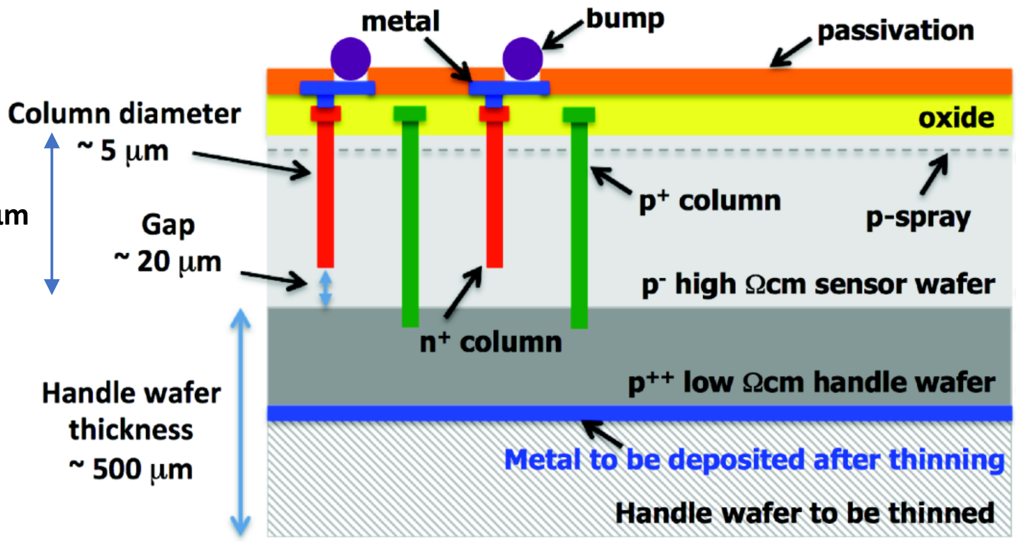
The efficiency is > **99.8%** even with V_{bias} = 20V

3D sensors - CERN Test Beam November 2022

3D pixel sensors (25x100 μm^2)

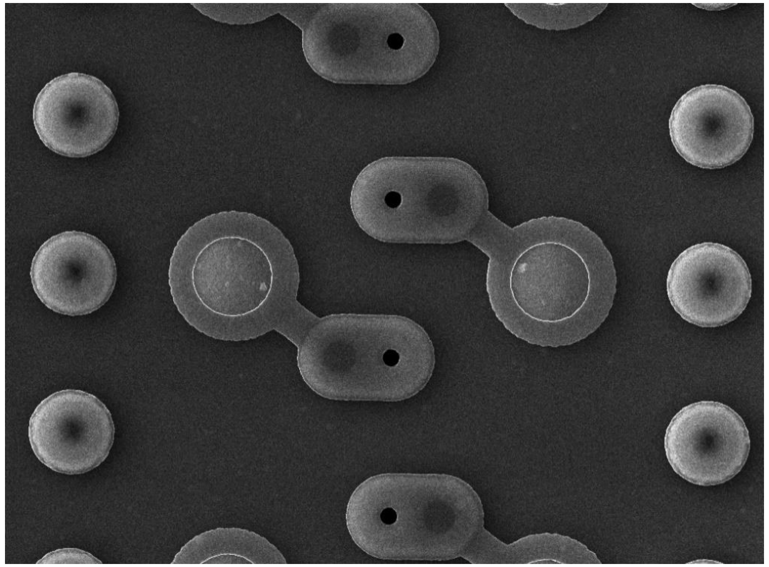
- Made by the **FBK** foundry in Trento, Italy, in collaboration with INFN
- Sensors equipped with the CROC
- Modules irradiated up to an equivalent fluence of 1 x 10^{16} n_{eq}/cm^2

Test Beam performed at CERN test beam facility with 75 GeV protons



TELESCOPE SET UP: See talk by Clara Lasaosa

- 5 planar pixels telescope planes (13x13 μm^2), 3 DUTs planes (3D pixel sensor with 25x100 μm^2 pitch read out by CROC) and 1 reference plane

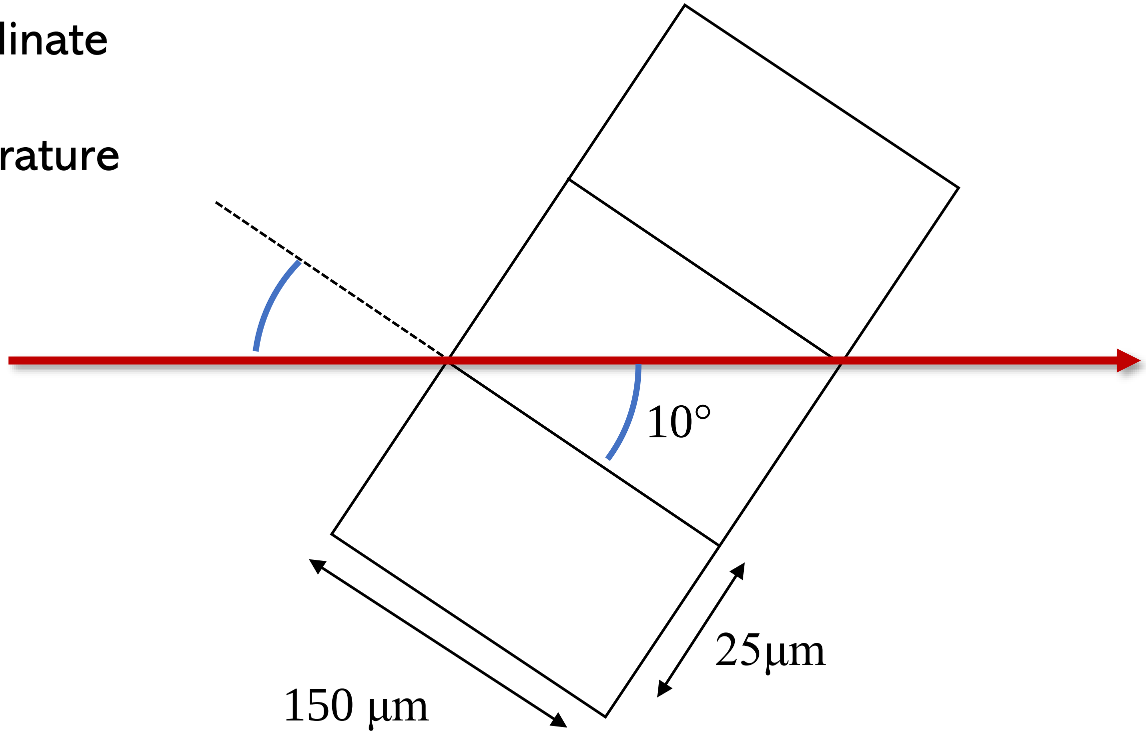


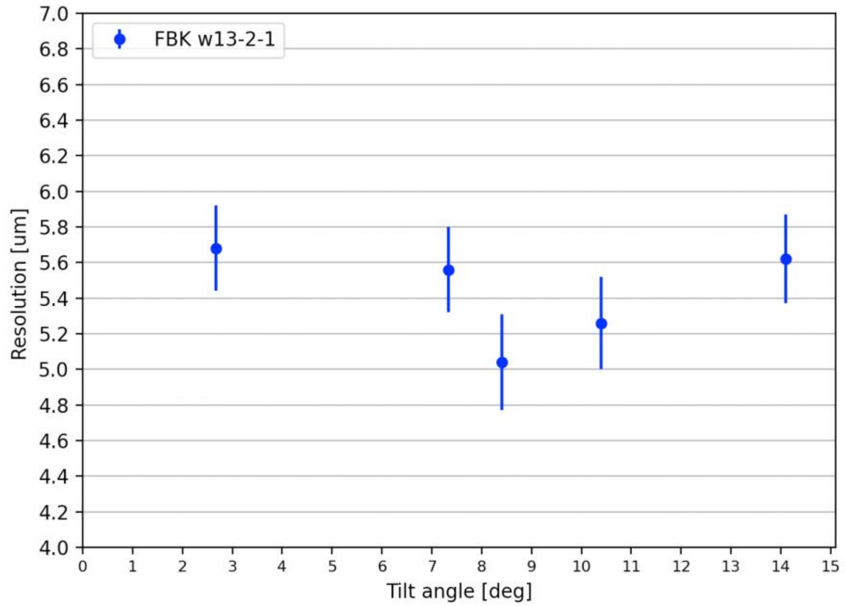
TRACK SELECTION AND HIT ASSOCIATION:

- tracks with hits on 5 (4 mimosa26+reference) telescope planes
- hits associated with tracks on DUT within 135x35 μm^2 ellipse
- track fit χ^2/dof<10

3D sensors - Resolution vs. Turning Angle

- The module was turned around the short pitch 25 µm coordinate
- Telescope resolution σ_{TEL} (≈ 6.9 µm) was subtracted in quadrature from the DUT residual
- Reached ≈ 5 µm for all tested modules→ well below digital resolution
- Minimum of spatial resolution obtained around 9° tilt angle





CROC Spatial Resolution: about 5 µm at 1 x 10^{16} n_{eq}/cm^2

Summary

The **quad planar module** read out by 4 CROCs is the first module of its kind to be tested for CMS phase 2

- Very encouraging efficiencies performances even for **non-standard pixels cell** in the inter-chip region
- Studied biases of position estimates due to cross talk in standard and non-standard pixel cells→ offline correction foreseen
- These studies will be complemented with laboratory measurements to evaluate the cross-talk of standard and non-standard cells

Future plans:

- More double and quad modules will be tested in the near future, before and after irradiation
- More accurate efficiencies studies are foreseen to better understand the performances

3D pixels modules are confirmed to be used for the inner layers of the silicon trackers to be built for the HL-LHC.

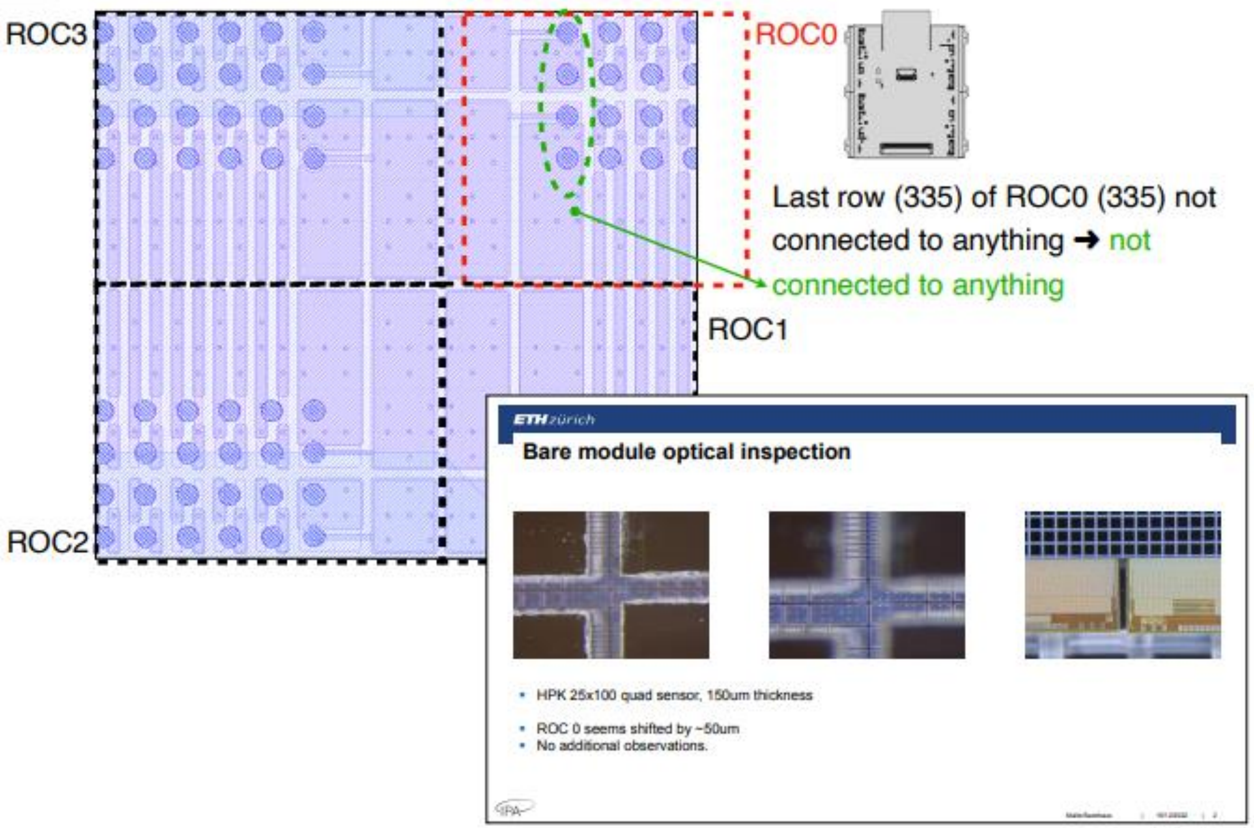
- After irradiation up to a fluence of $1 \text{ x } 10^{16}\ n_{eq}/cm^2$ we measured an hit resolution of about 5 μm

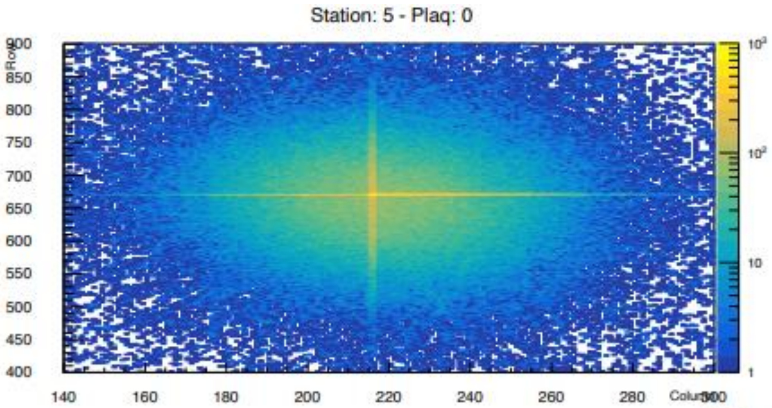
Future plans:

- New test beam campaigns are foreseen with sensors irradiated at higher fluences

BACK UP SLIDES

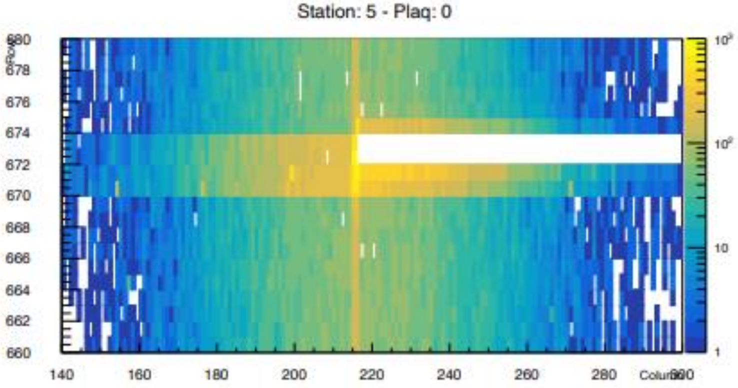
Quad module cell Geometry



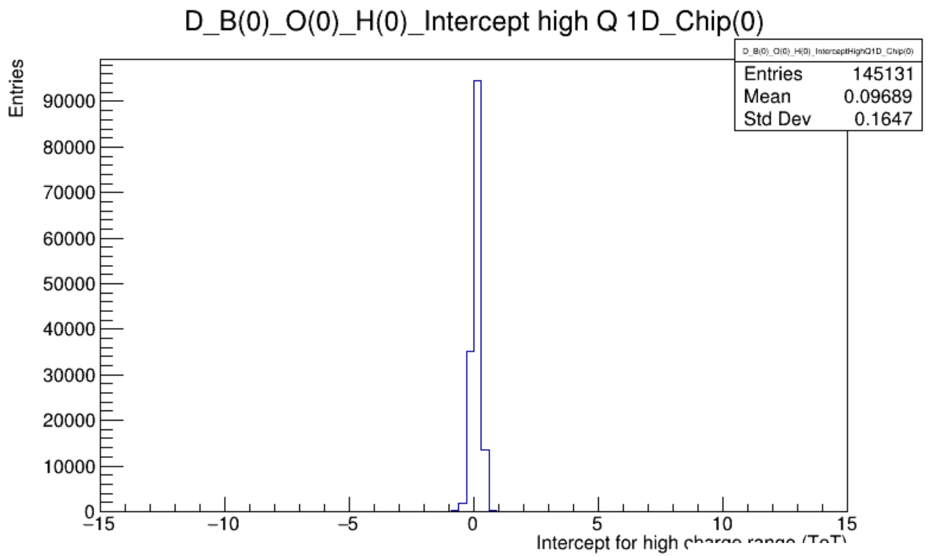


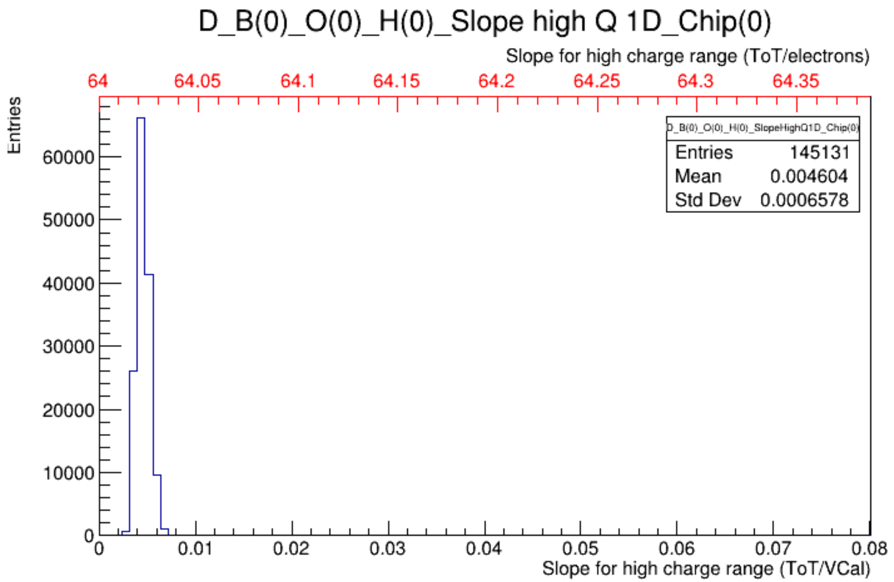
Beamspot from all hits in December FNAL data

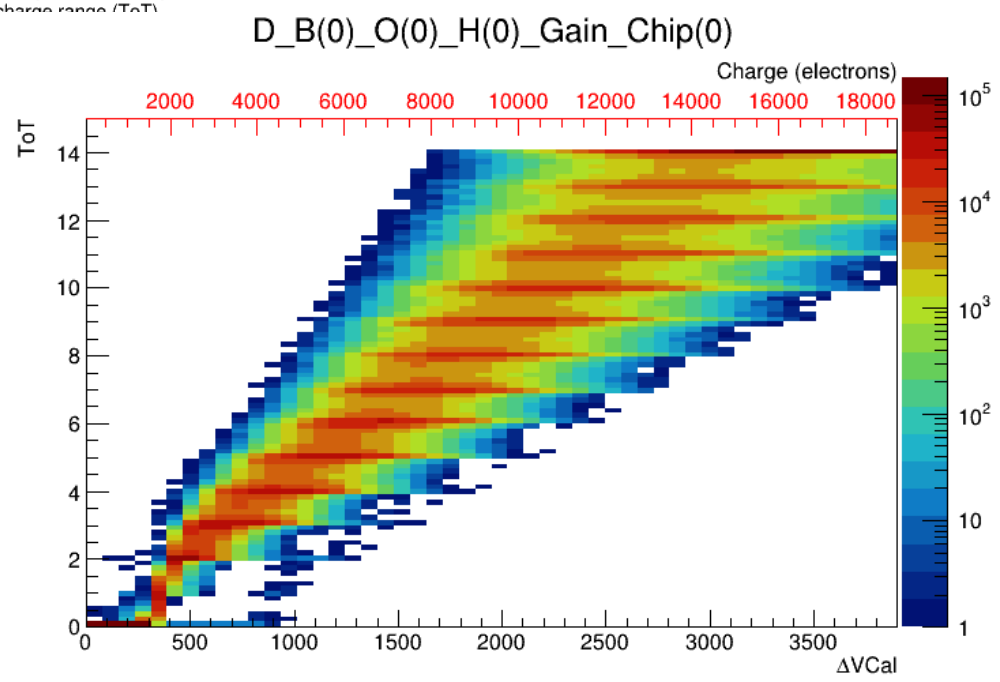
Zoom-in on previous plot



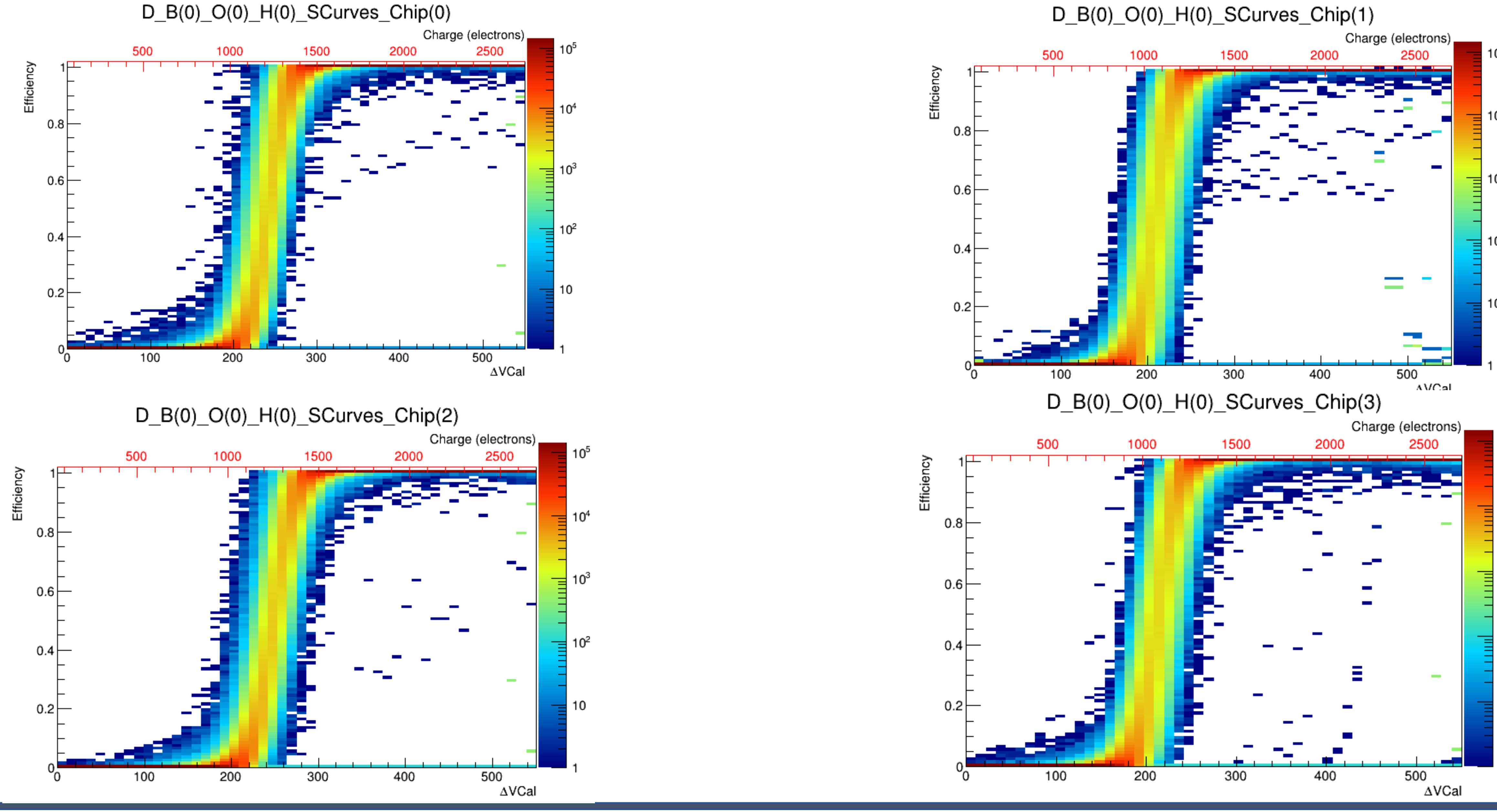
Calibrations





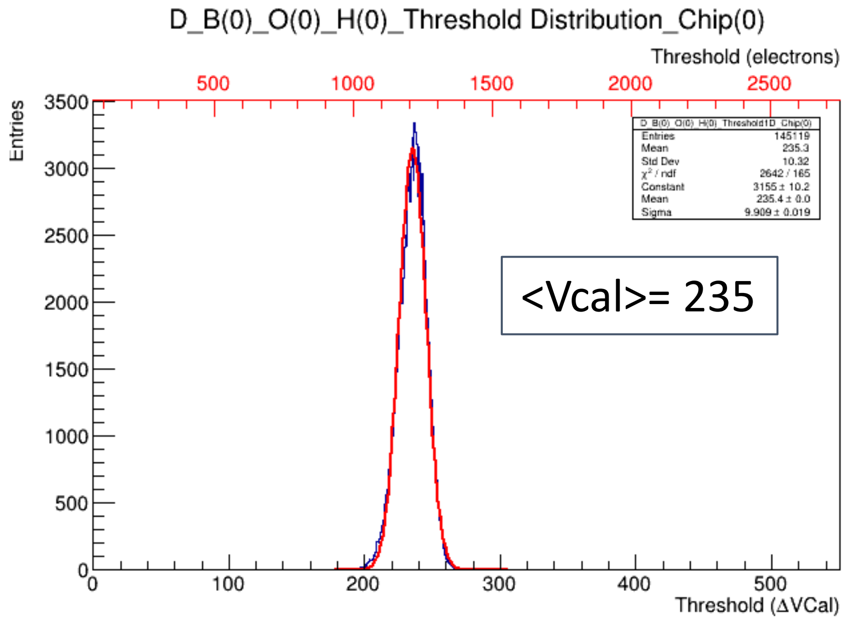


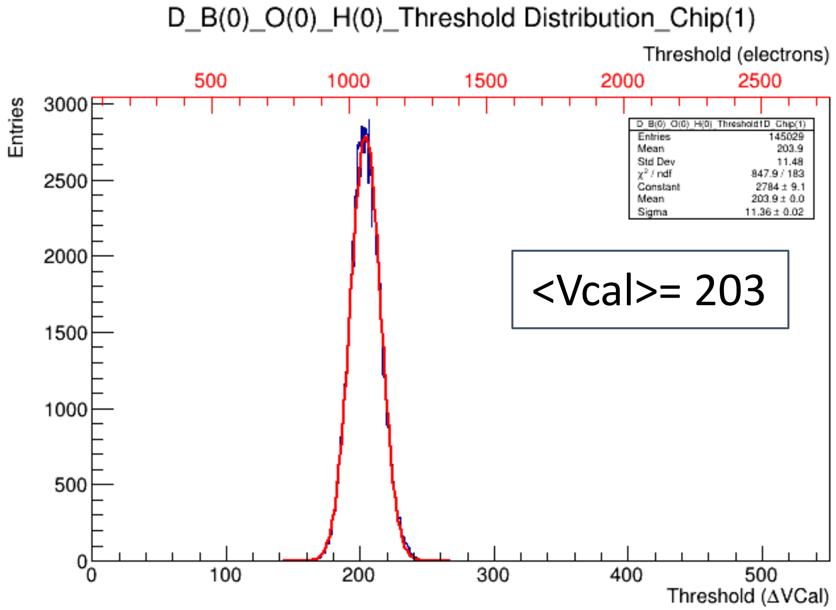
Calibrations

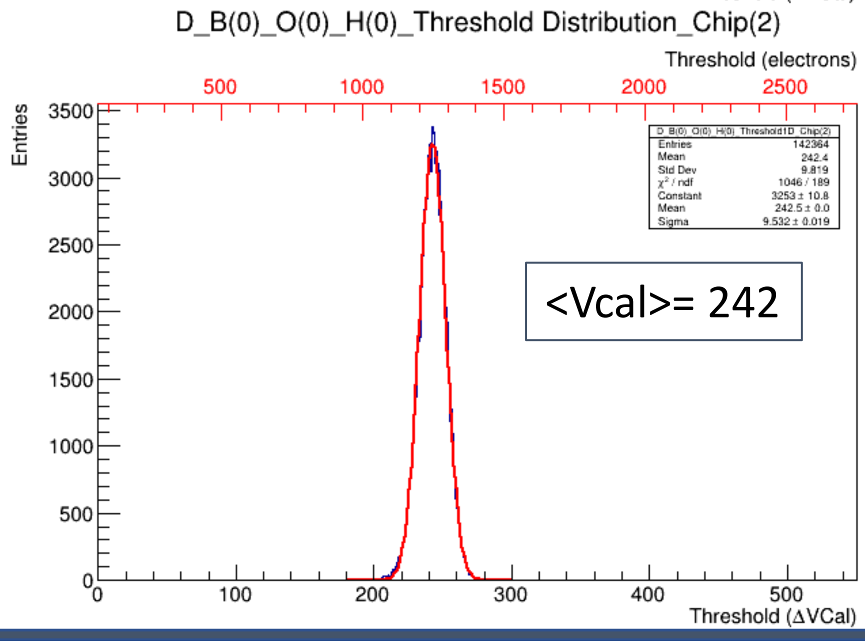


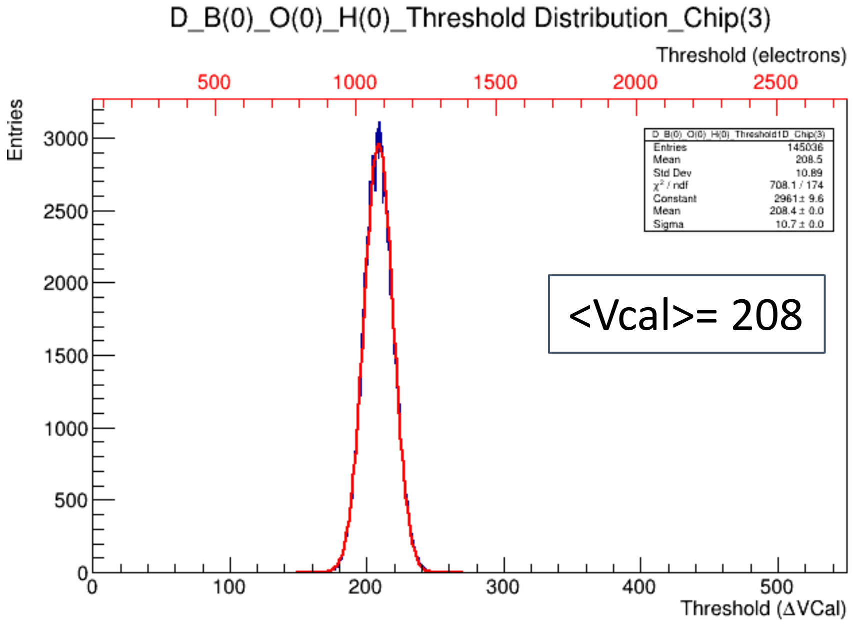
Calibrations

1 Vcal ≈ 5 electrons

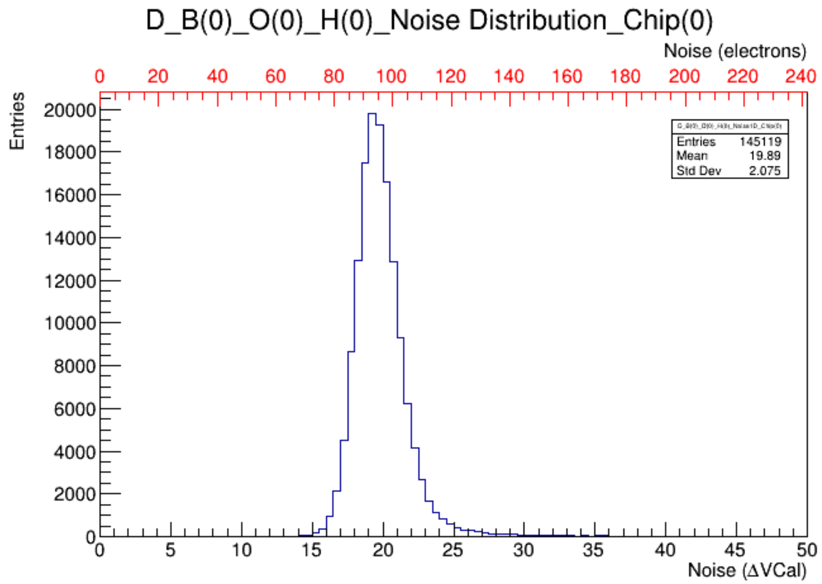


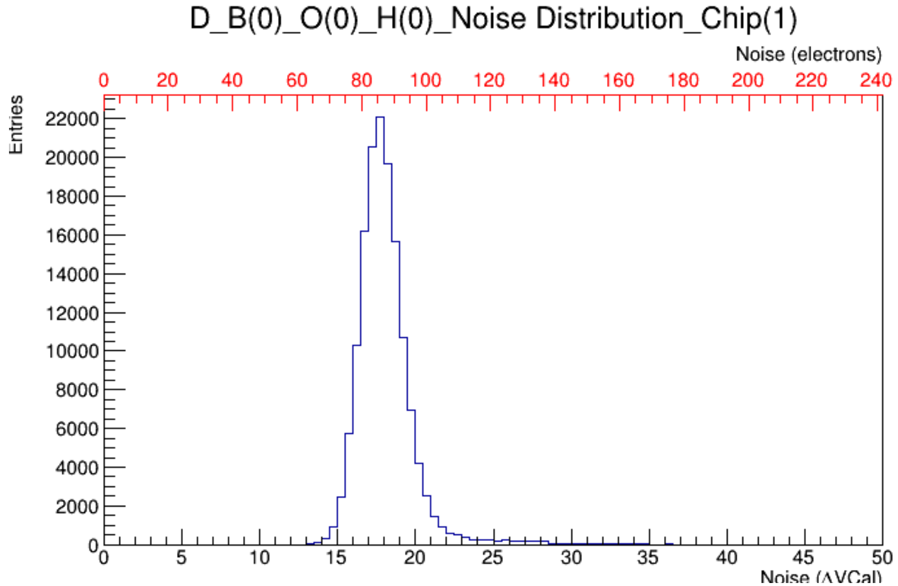


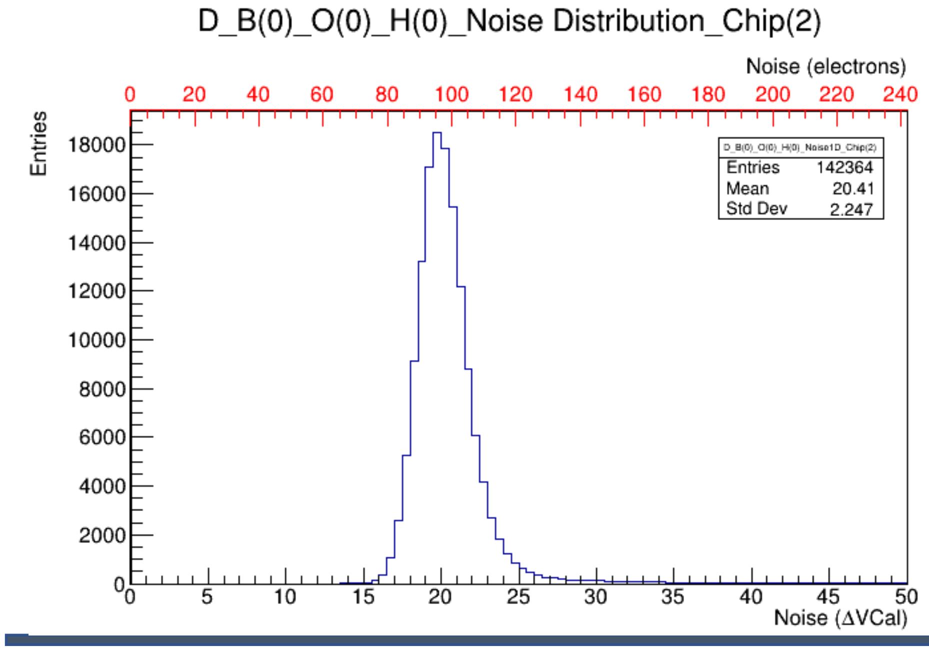


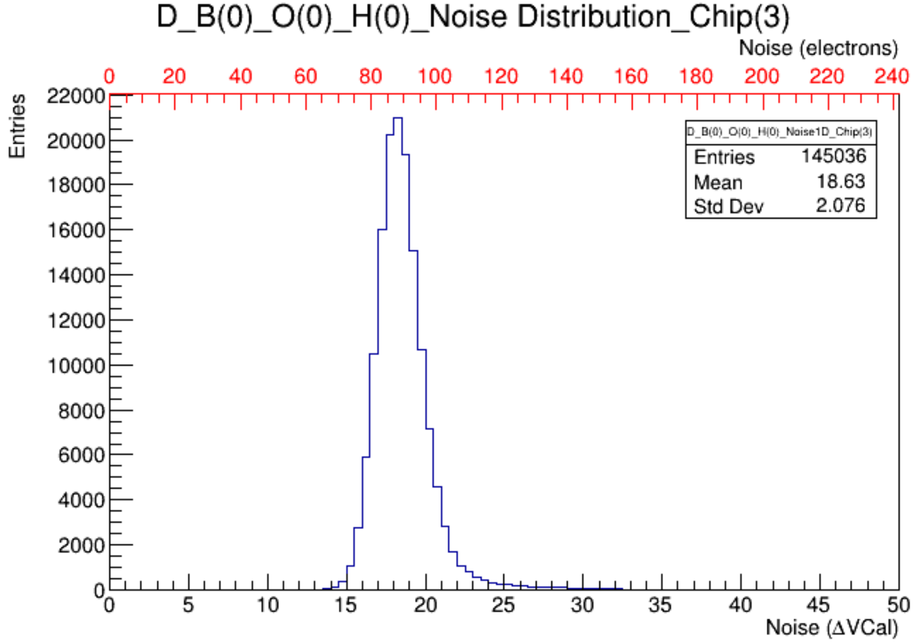


Calibrations



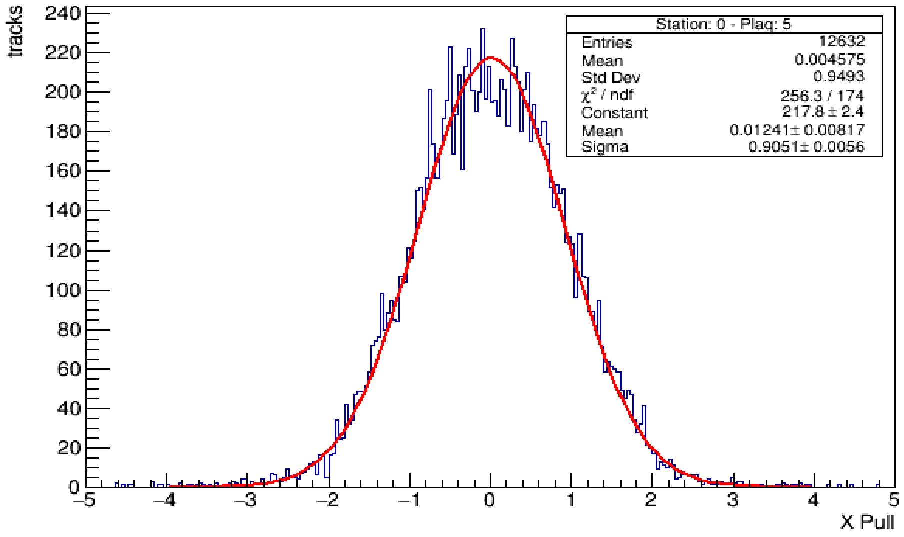




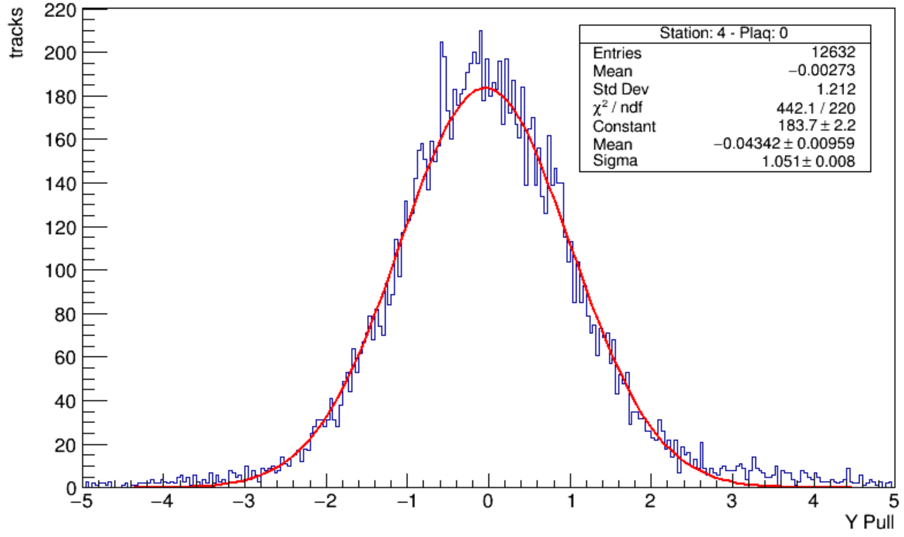


Alignment

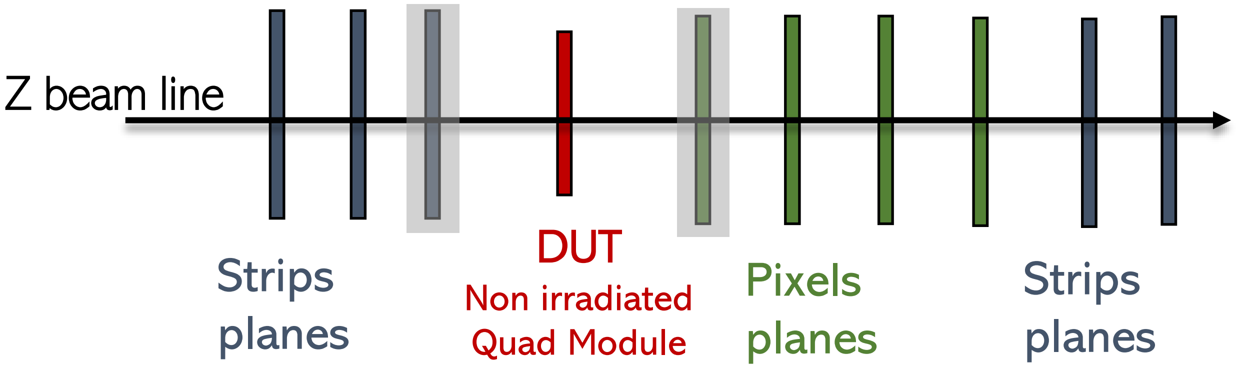
Strip Telescope Upstream Pulls



Pixel Telescope Downstream Pulls



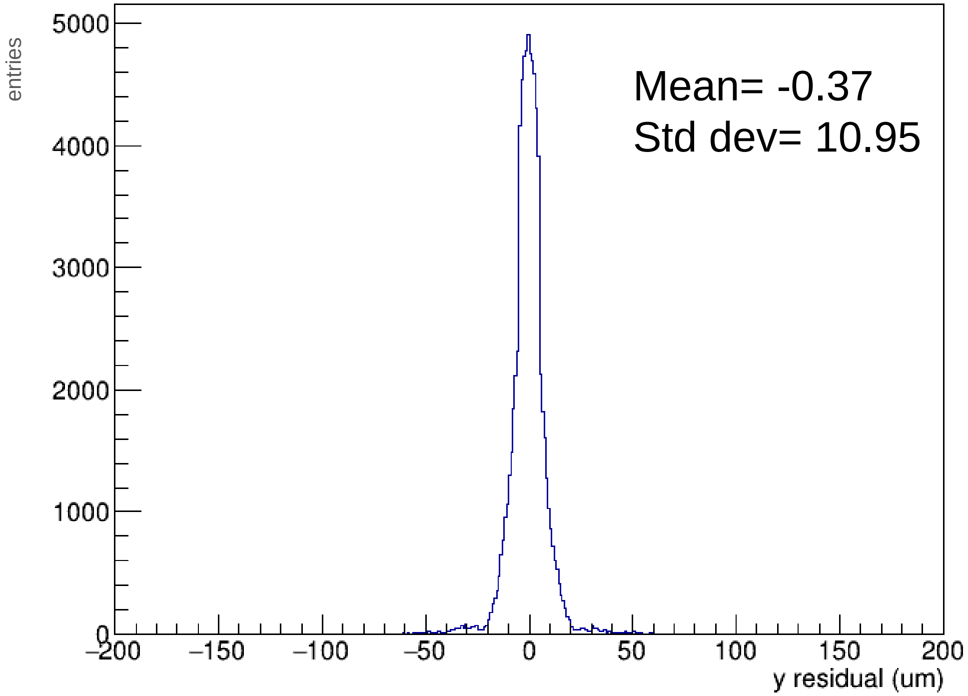
Pulls for telescope strip plane
and pixel plane closer to the DUT

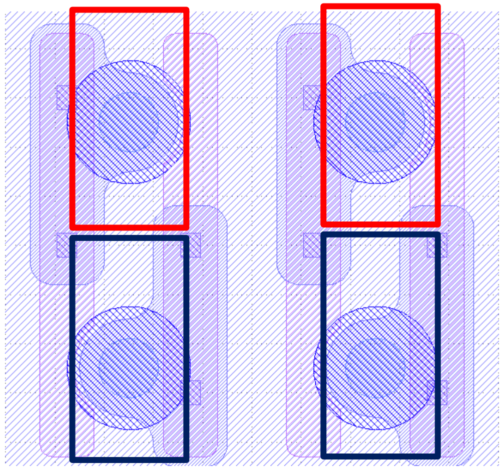


25x100 μm^2

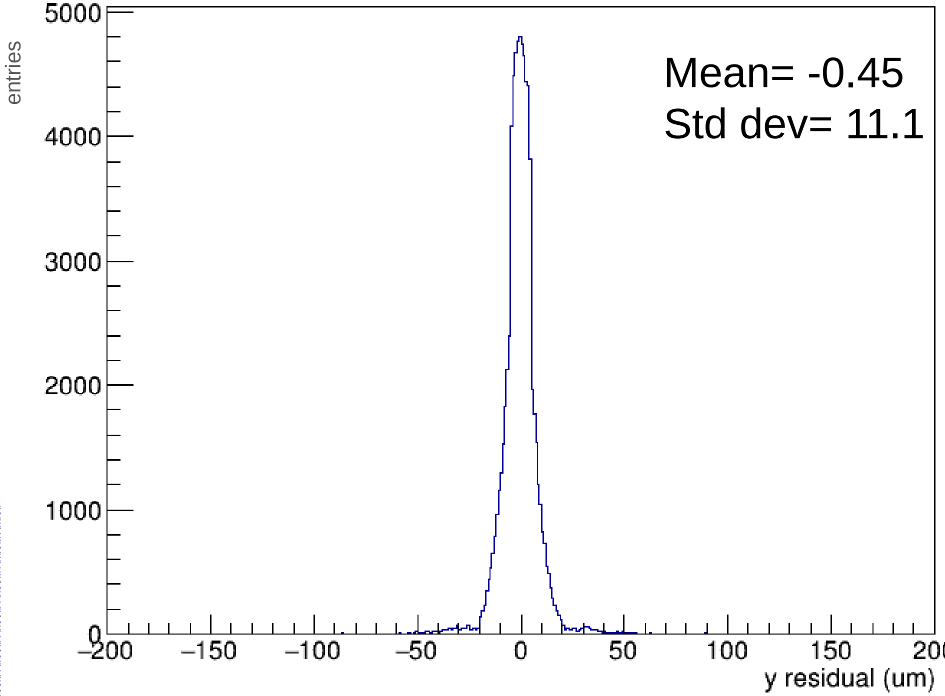
No asymmetry observed for Y residual distribution for the top half and bottom half of the cells

Top half Y residuals in-between bumps





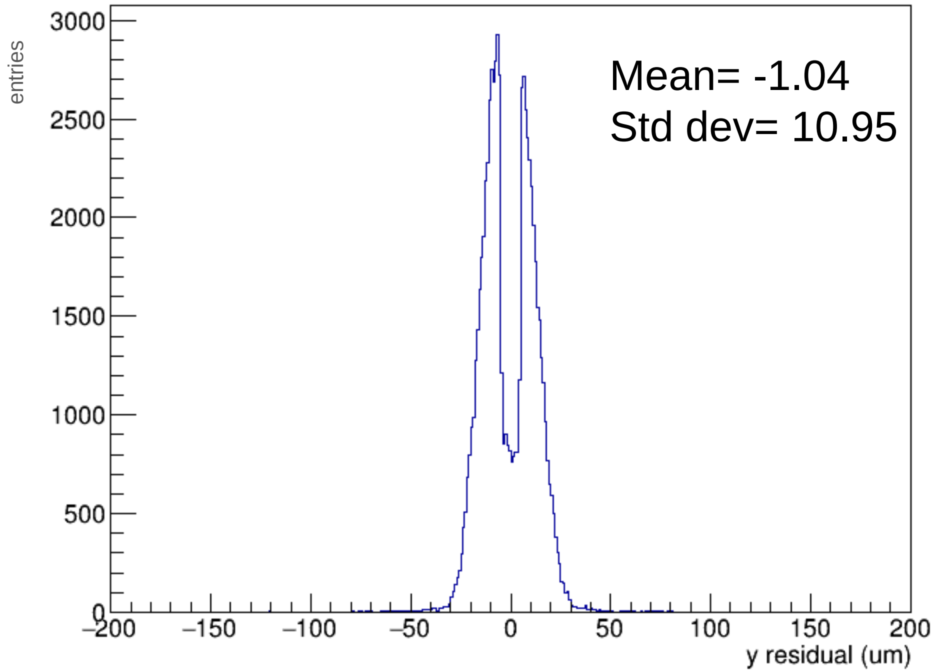
Bottom half Y residuals in-between bumps



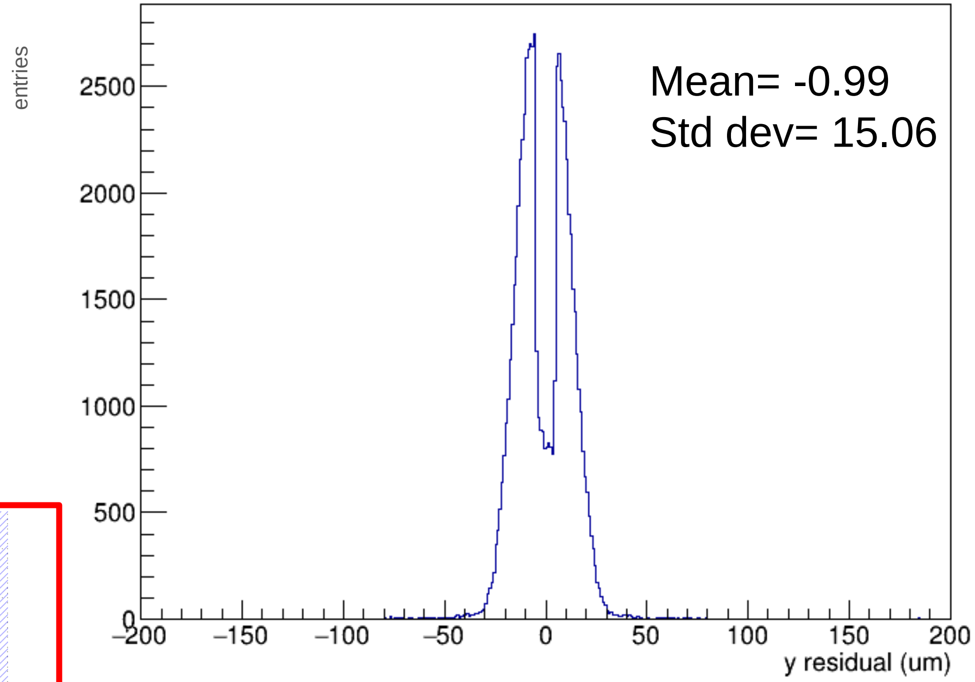
25x100 μm^2

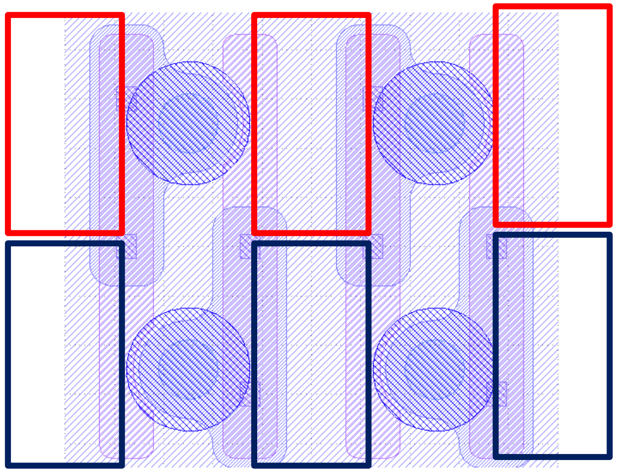
No asymmetry observed for Y residual distribution for the top half and bottom half of the cells

Top half Y residuals not in-between bumps



Bottom half Y residuals not in-between bumps

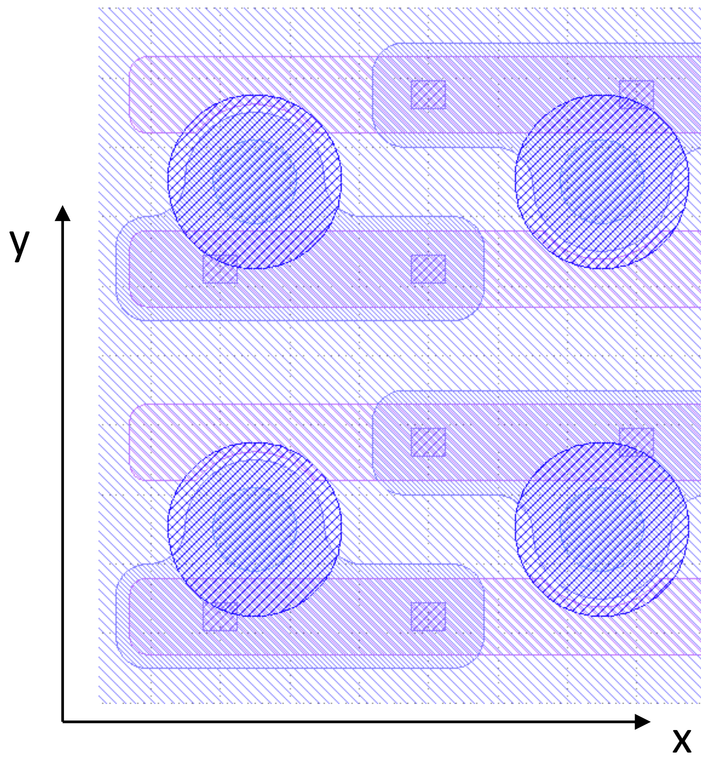


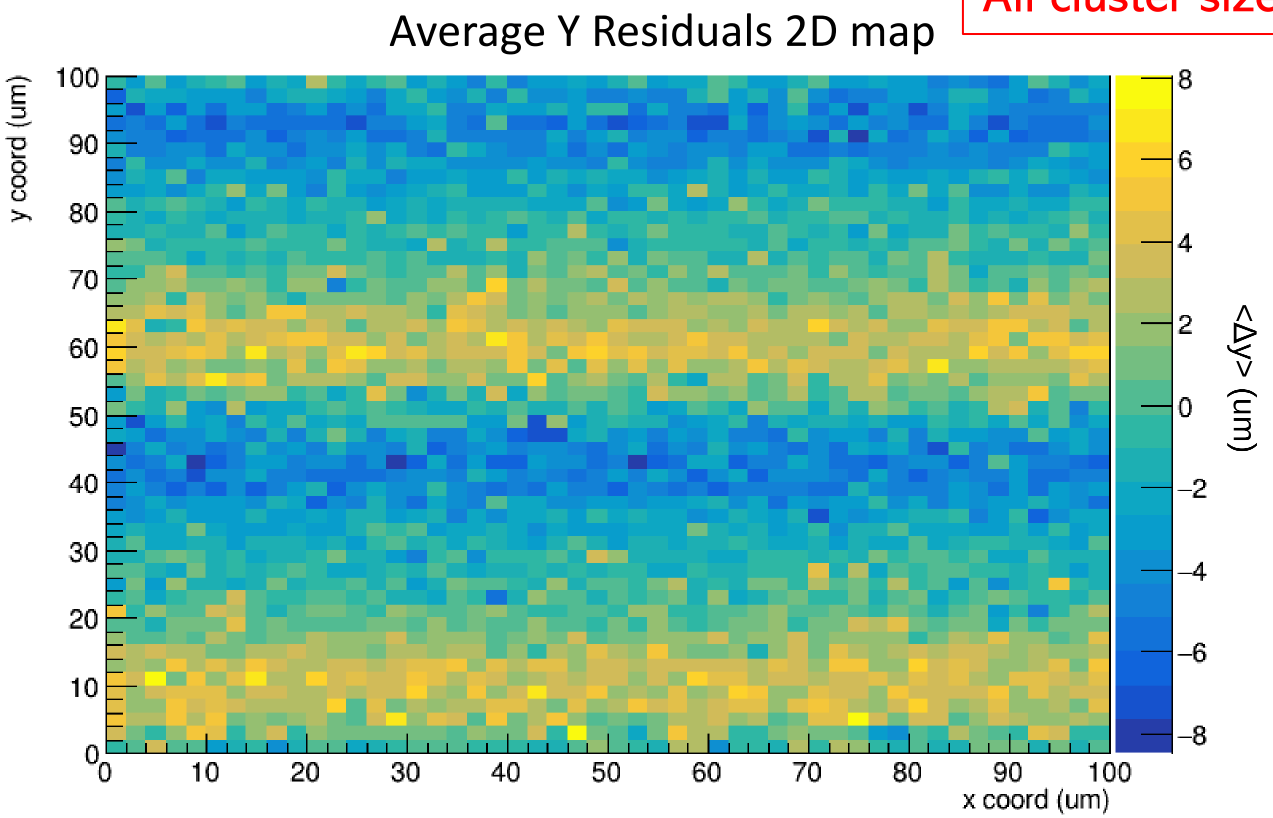


2D map of Y Residuals 25x100 μm^2

Confirms the absence of asymmetry for Y residual distribution for the top half and bottom half of the cells

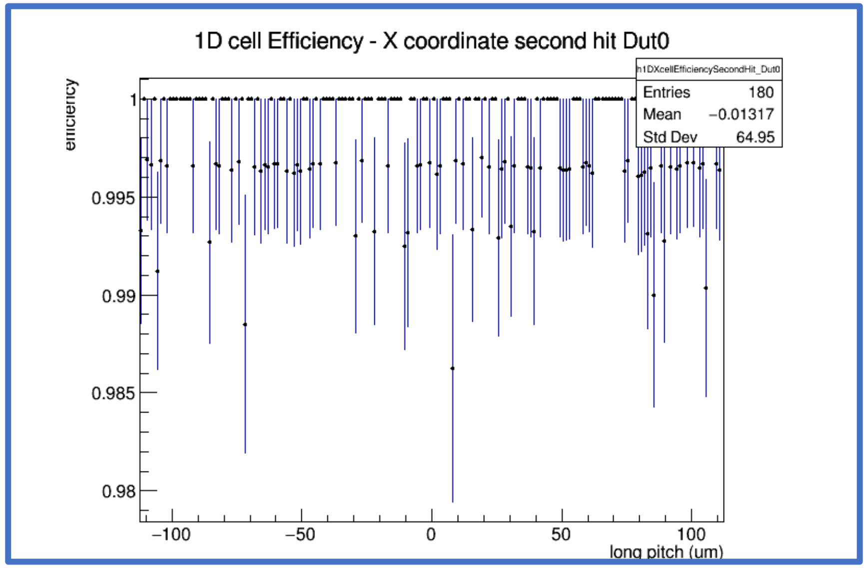
All cluster sizes

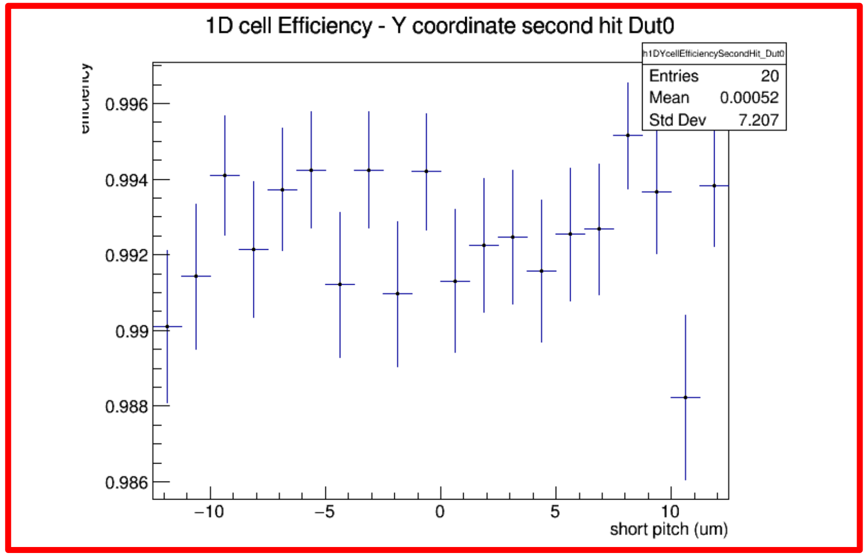


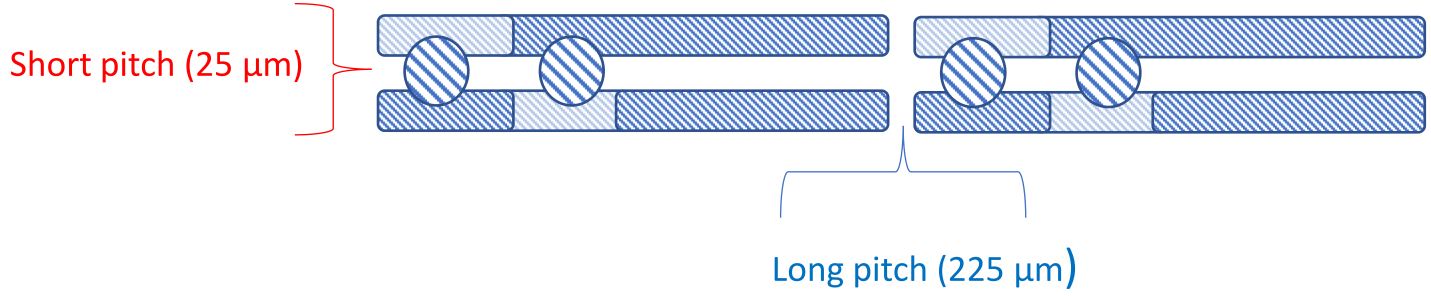


Schematic drawing of a 1x4 pixel grid of the DUT (left) and corresponding average Residuals map (V bias=100V) (right)

Efficiency studies 25x225 μm^2

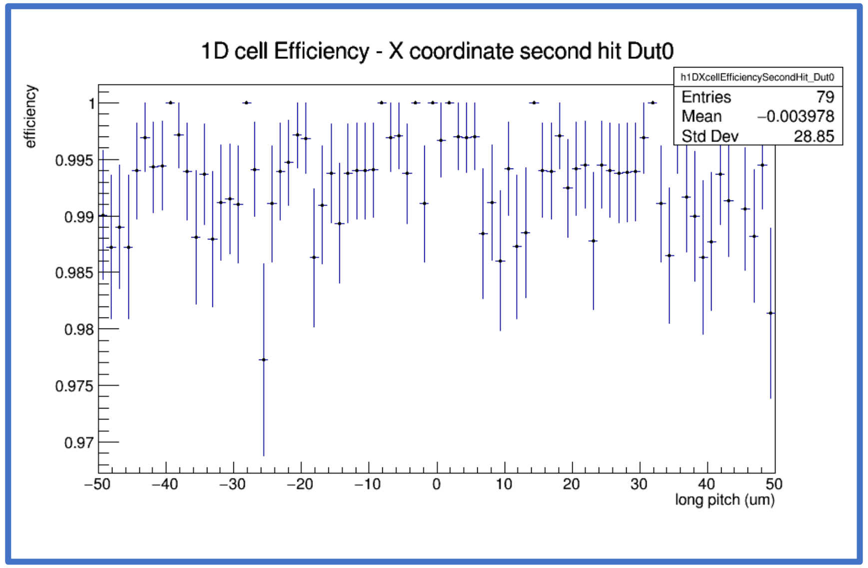


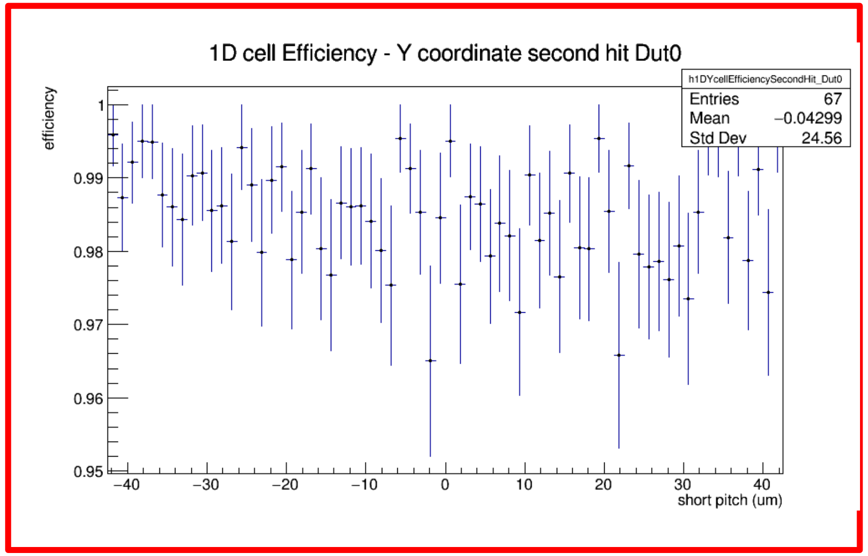


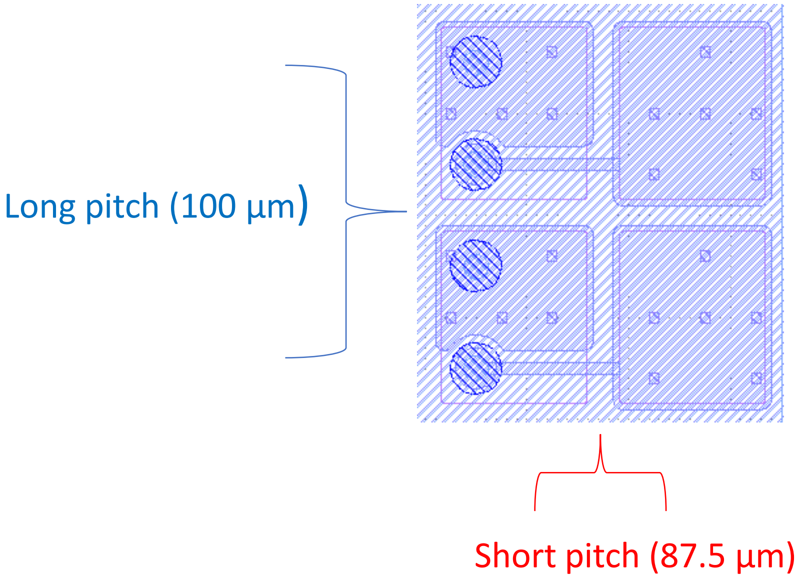


Efficiency as a function of the track impact point form the divide between two pixel cells along the short and long pitch

Efficiency studies 87.5x100 μm^2







Efficiency as a function of the track impact point form the divide between two pixel cells along the short and long pitch

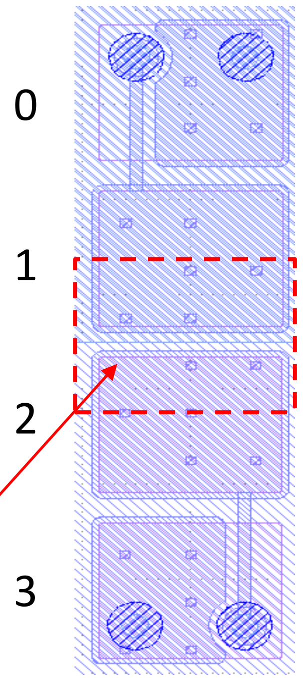
87.5x100 μm^2

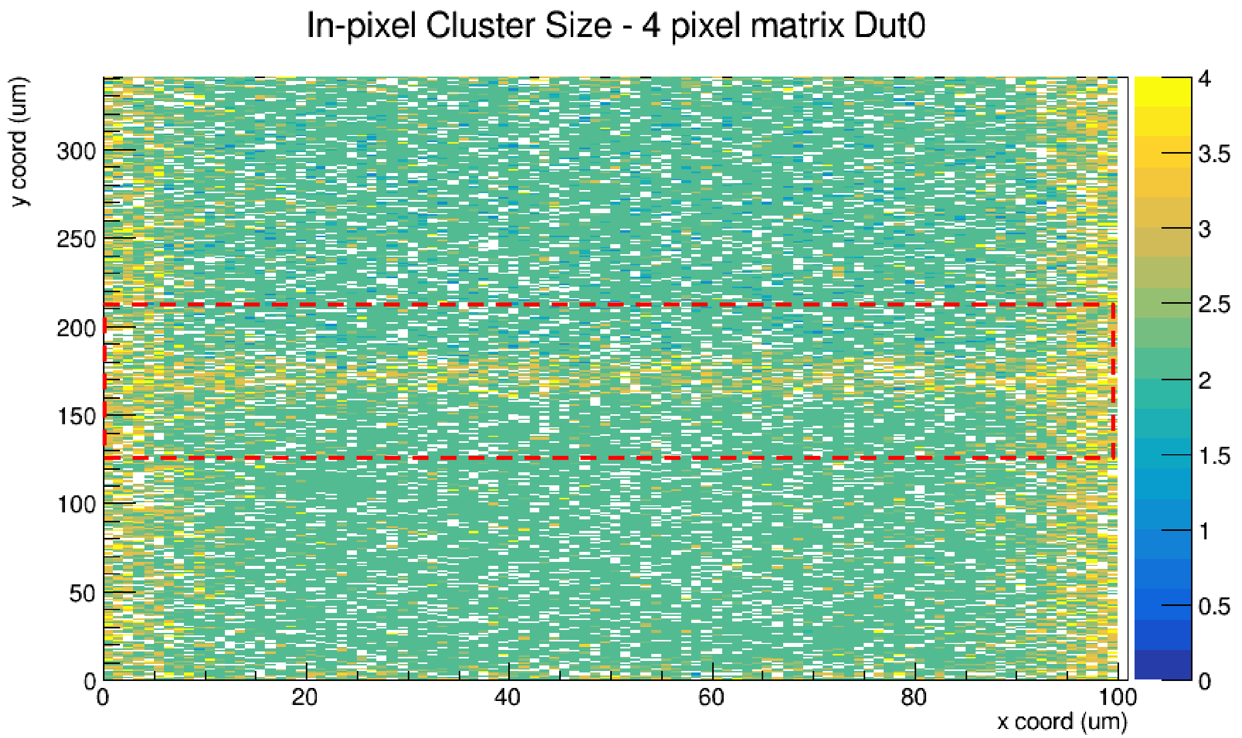
At high bias voltage (100V) the **cluster size is higher** at the intersection of **non coupled pixels**

When a particles passes through the area where the <u>pixels are not coupled</u> there is regular charge sharing between pixels 1 and 2.

On top of regular charge sharing adjiacent pixels might light up.

This results in an increased cluster size in this area.



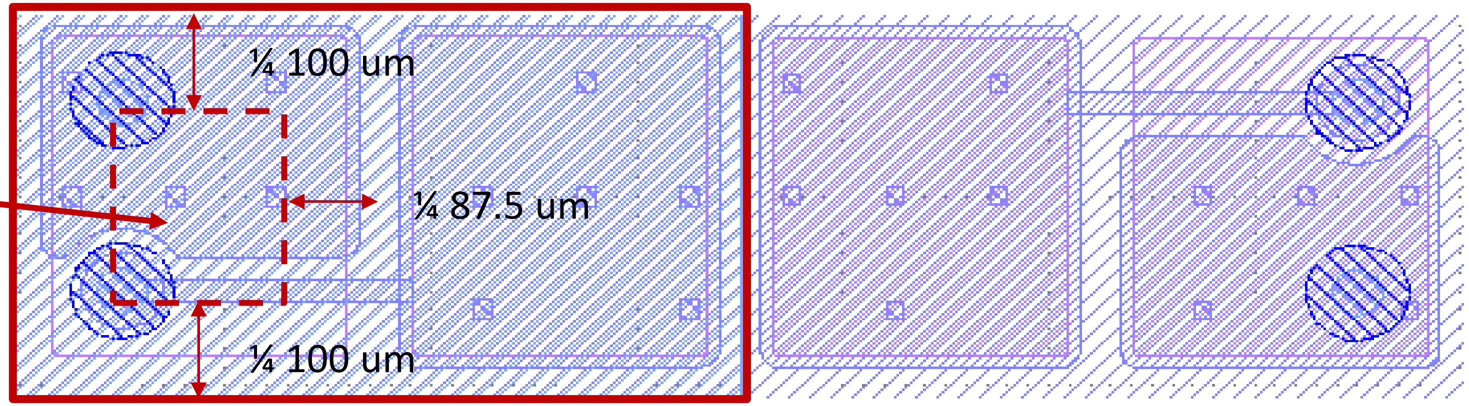


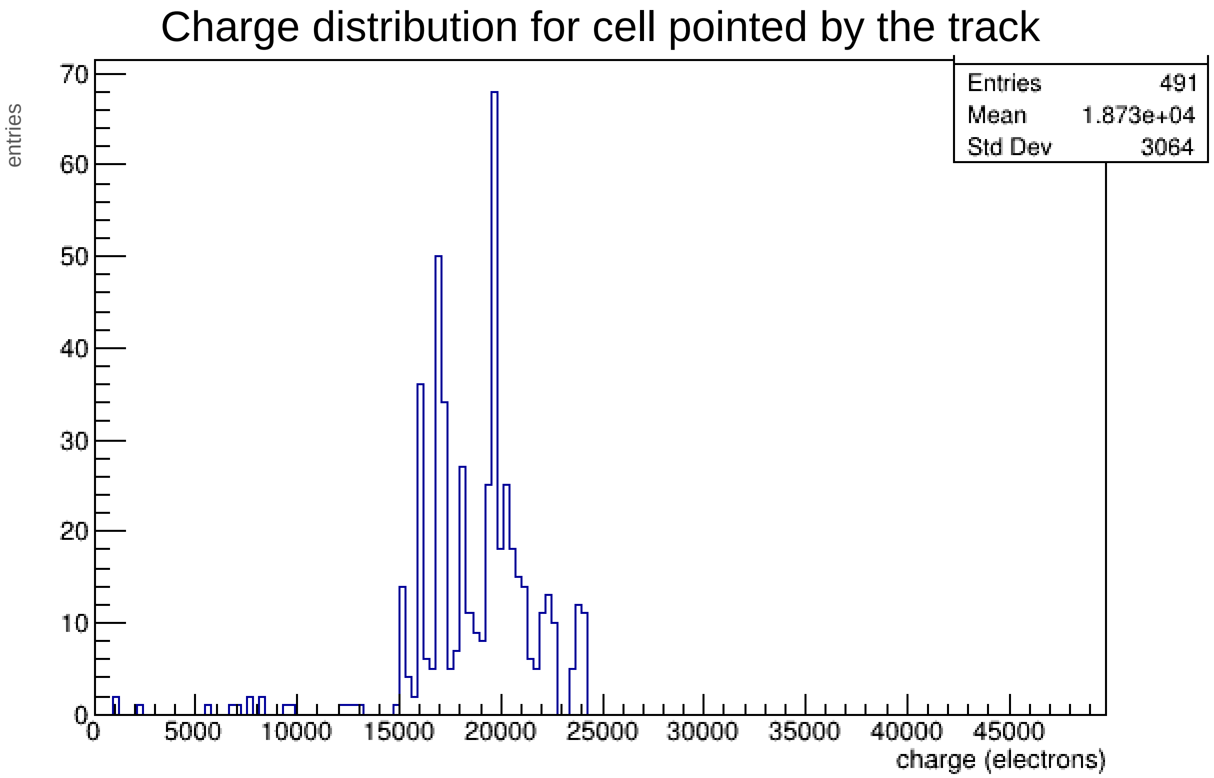
Schematic drawing of a 1x4 pixel grid of the DUT (left) and corresponding cluster size map (**V$_{bias}$=100V**) (right)

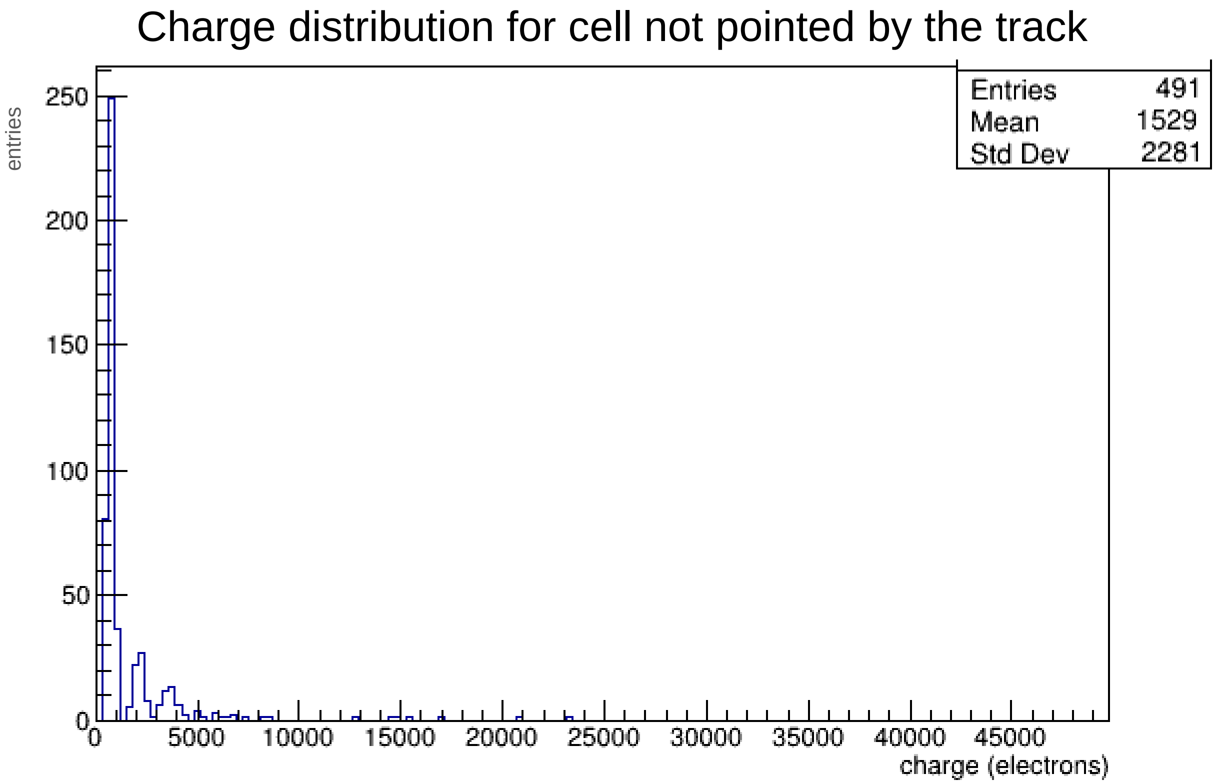
Charge spectrum 87.5x100 μm^2

Fiducial area inside the cell defined as a rectangle of 50 µm x 43.75 µm

Cluser size 2

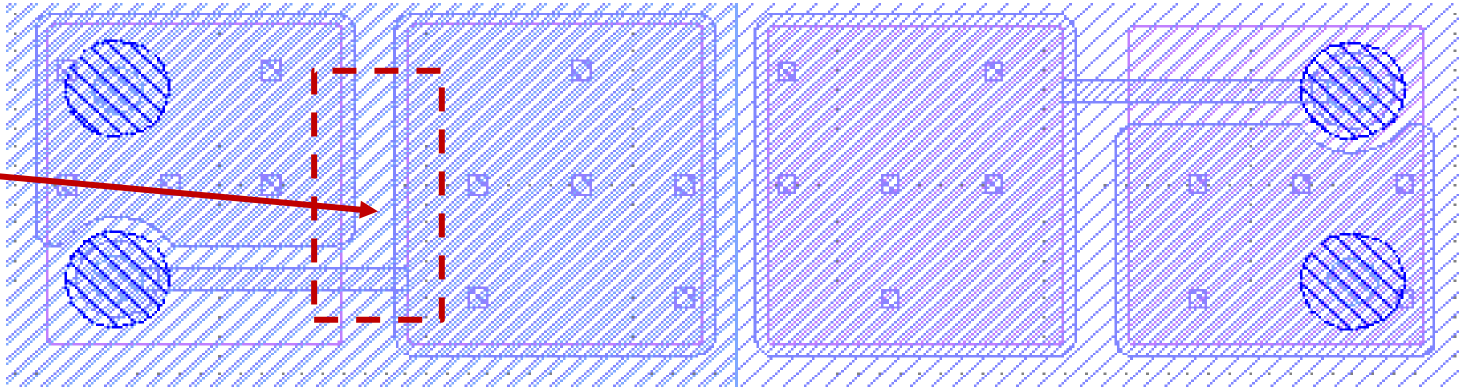




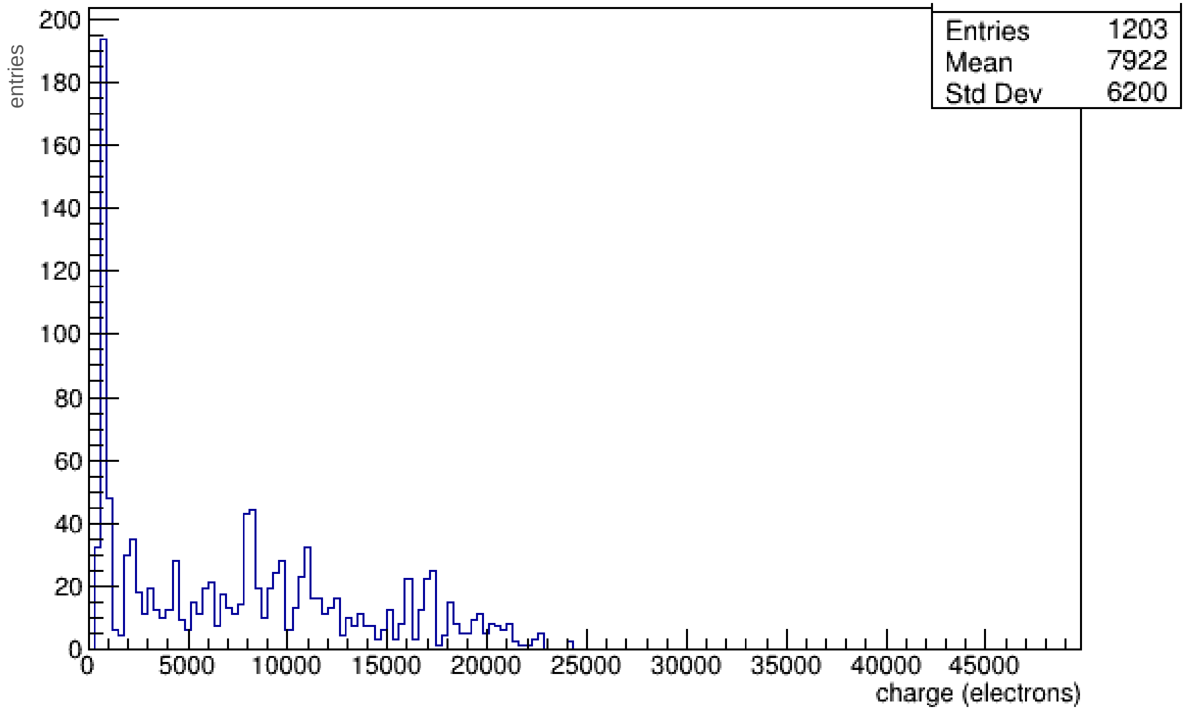


Charge spectrum 87.5x100 μm^2

Fiducial area inside the cell defined as a rectangle of 70 µm x 30 µm



Charge distribution for cell on the left



Charge distribution for cell on the right