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Bundesministerium für Bildung und Forschung

Characterization of prototypes for the CMS Phase II pixel sensors

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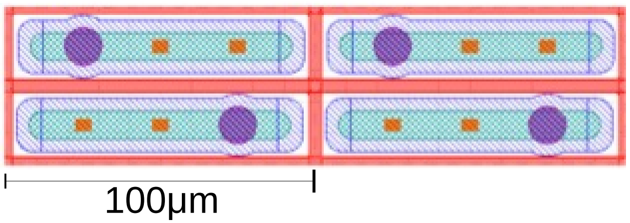
Sensor design studies

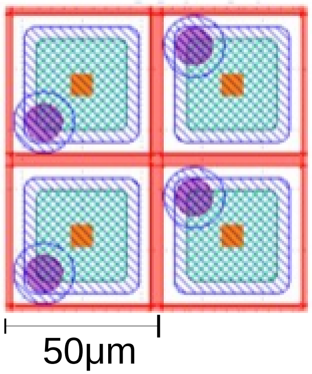
High-Luminosity LHC expectations:

- Luminosity of 7.5x10^{34} cm^{-2}s^{-1}, up to 200 events / 25 ns bunch crossing
- Radiation level for 1st pixel layer after 3000 fb^{-1}: 2 x 10^{16} neq/cm^2

➡ **CMS Phase II Upgrade**

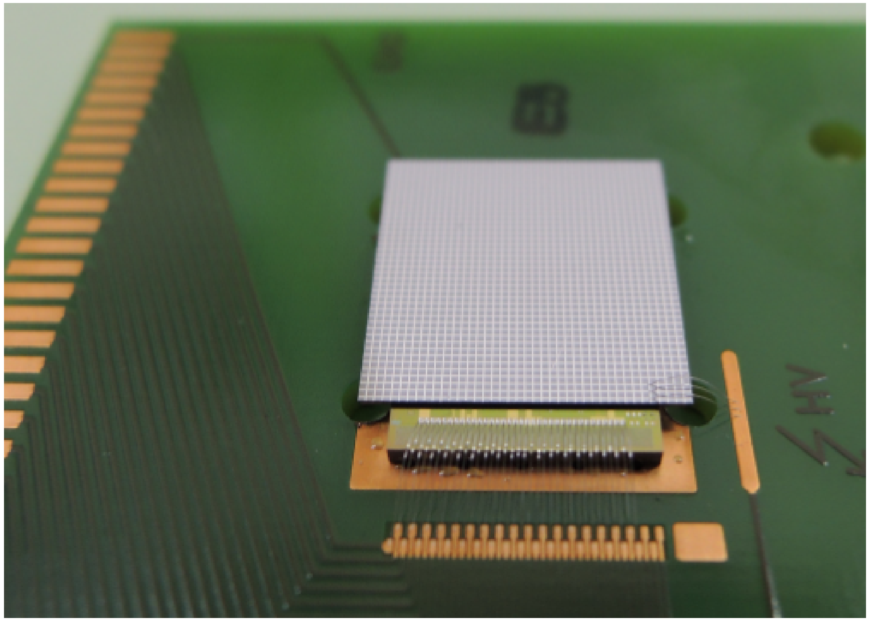
→ **CMS R&D** to decide on final sensor design





- **Sensors**
  - produced by HPK
  - 50x50 µm^2 and 100x25 µm^2 pixel size
  - 150 µm active thickness
  - n-in-p with p-stop and p-spray isolation

- **Readout by ROC4SENS (PSI R&D chip)**
  - Staggered 50x50 µm^2 pitch
  - ~25k pixels
  - 12-bit analog pulse height
  - No zero suppression



8x8 mm active area

Methods & Observables

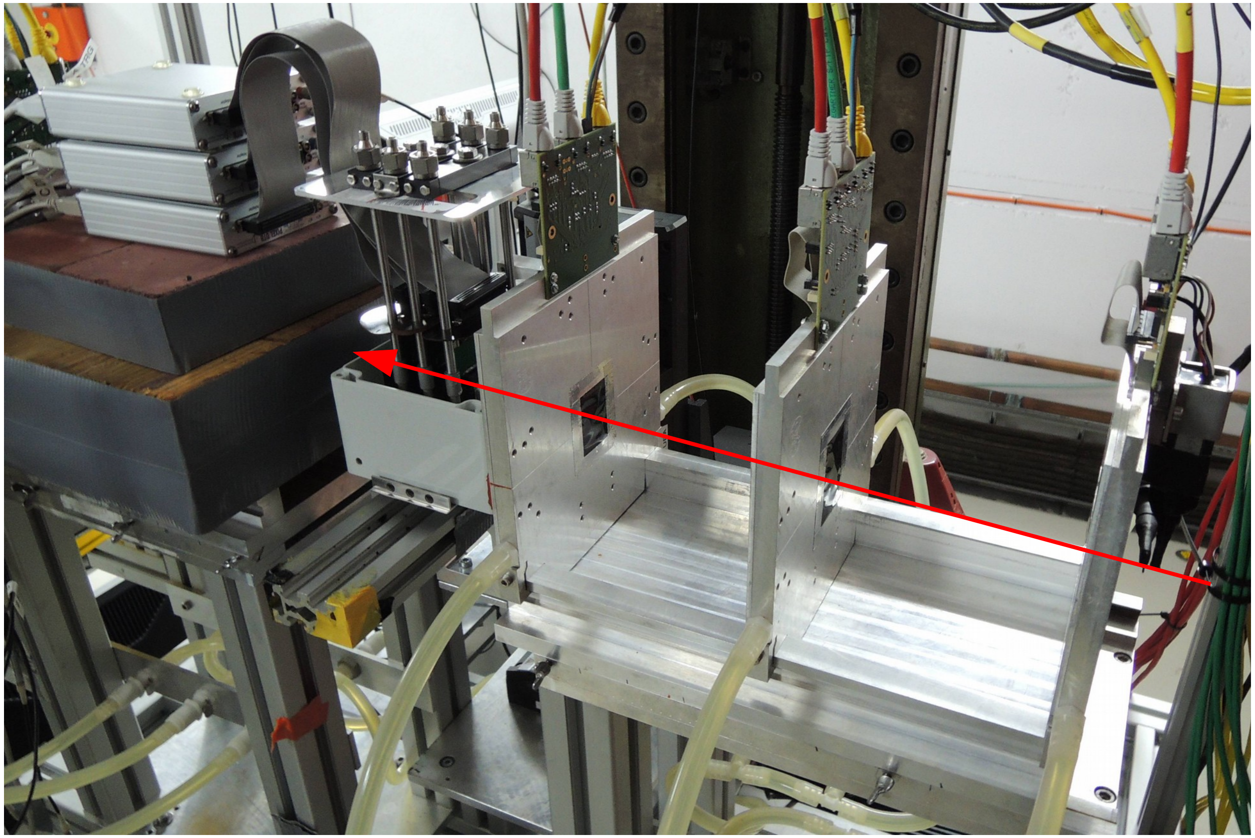
We need different measurement and analysis methods to obtain the key observables of the individual sensor designs:

- **Efficiency**
- **Charge Collection**
- **Charge Sharing**
- **Resolution**

We need to establish analysis methods on the non-irradiated sensor data in order to investigate the influence of irradiation on these observables.

Beam Tests setup

- DESY test beam facility
  - Electron / positron beam
  - 1 – 6 GeV
  - a few kHz rate
  - 5 µm beam resolution
- DAQ based on CMS - DTB
- EUDET DATURA telescope



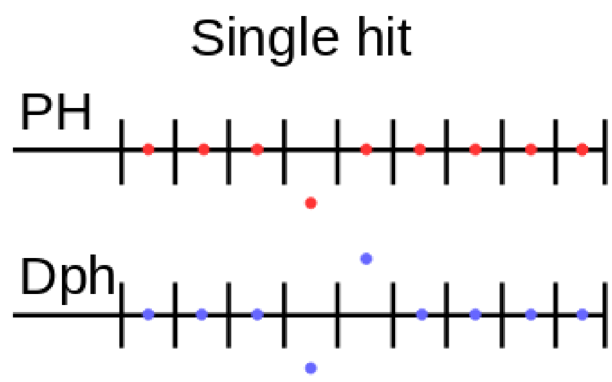
- Dreimaster setup
  - Support frame for 3 planes
  - 20 mm spacing
  - Turn angle (around vertical axis) 0°- 30°

Online data storage

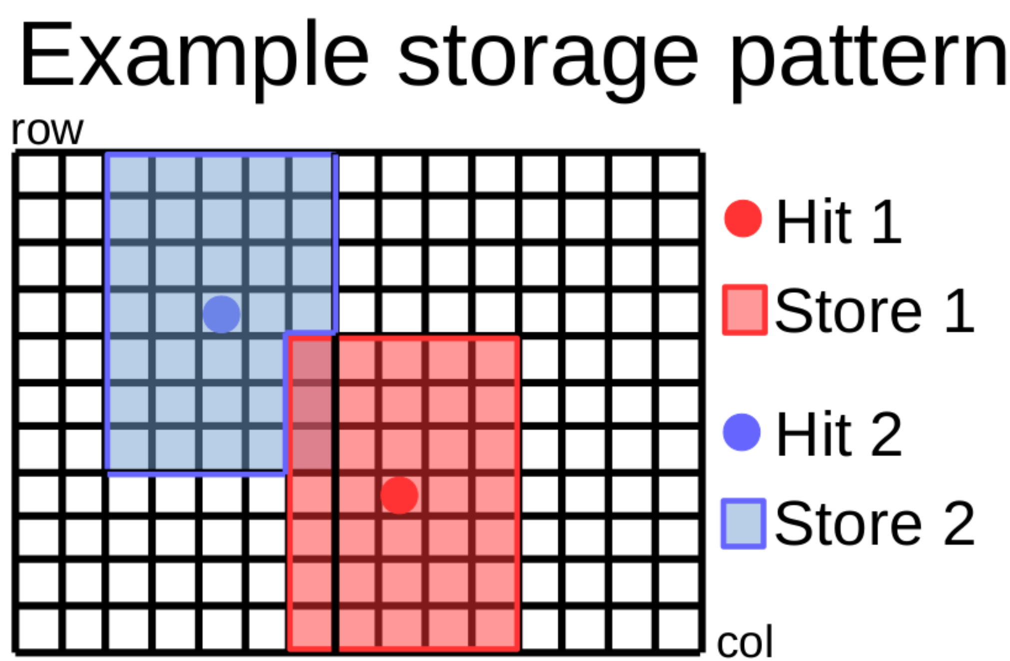
We have **no zero suppression** → data reduction necessary:

→ Perform zero suppression by **hit finding**

- Correct for pedestal $PH_i = ADC_i - PED_{i-1}$ (i event index)
- Correct for common mode fluctuation
  $Dph_j = PH_j - PH_{j-1}$ (j pixel index)
- Method:
  - Set a negative threshold th
  - Pixel j marked as **hit** if $Dph_j < th$
  - Pixel j-1 marked as **hit** if $Dph_j > -th$
  - Mask rows < 6 and one pixel on each edge



- Define **Region Of Interest (ROI)**
  - Area of 5 x 7 (column x row) pixels
  - Centered around each hit
- Store **hit position** (column, row)
  and **trigger number**
- Store **position** and **PH** of all pixel in ROI (if not stored in any previous hit of the same trigger number)



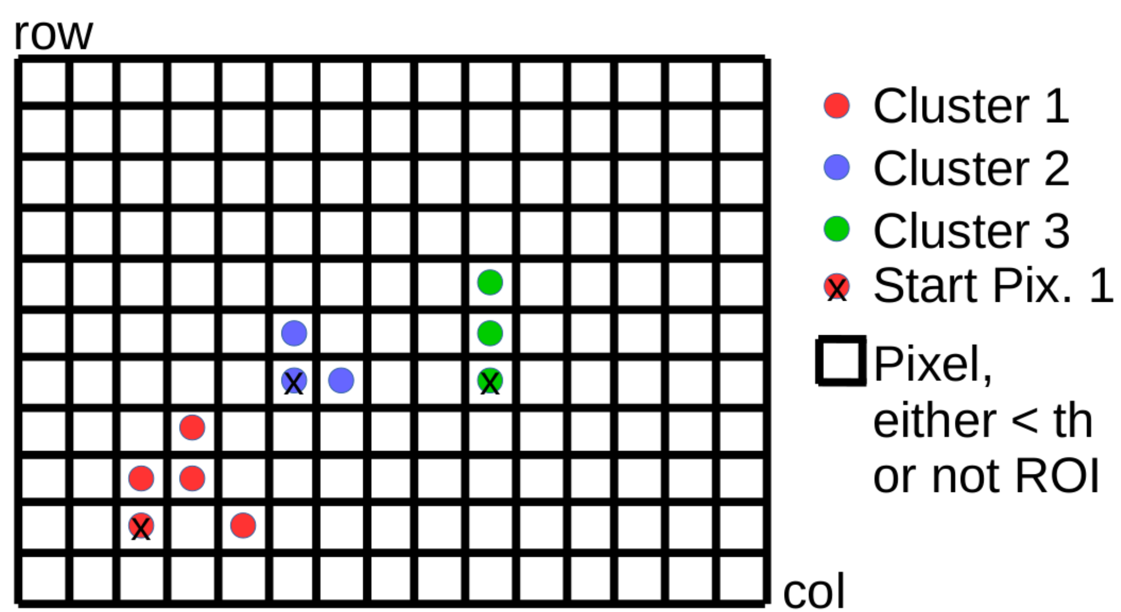
Clustering

Clustering

- Take any not yet clustered pixel over threshold (10 ADC ~ 0.7 ke)
- Add all neighbors to cluster

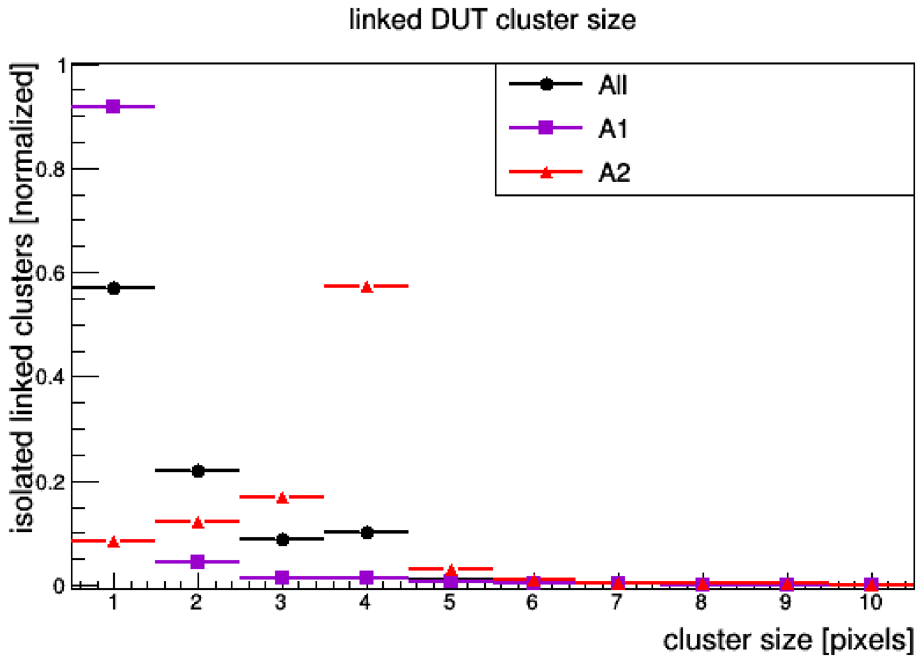
Center of gravity

- Calculate charge-weighted center of gravity
  → Cluster position **(c_x,c_y)**
- Start next cluster



Cluster charge $Q_c = \sum_{j=0}^{n} q_j$, where n is the number of pixels in a cluster and q_j the charge of the j^{th} pixel

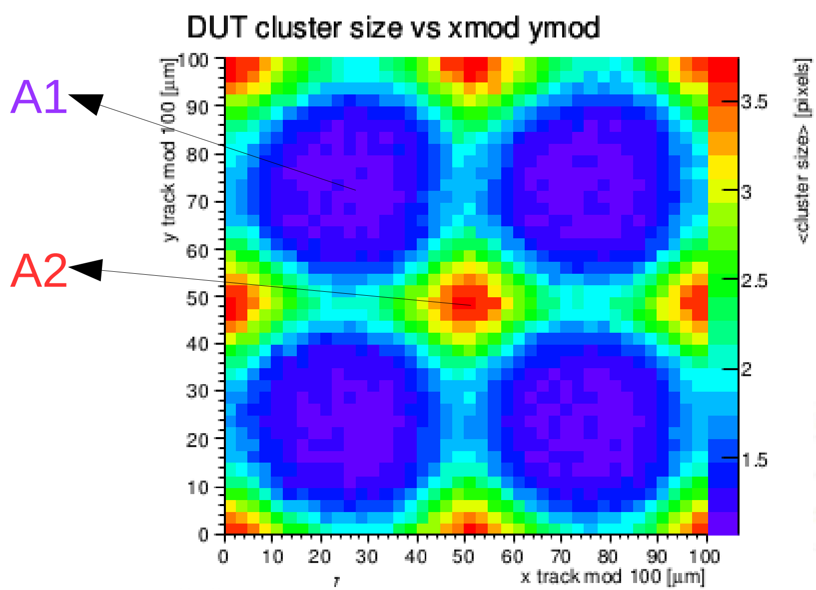
Clustering Control Plots



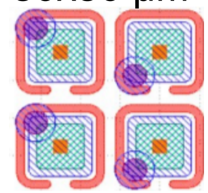
Normal incidence

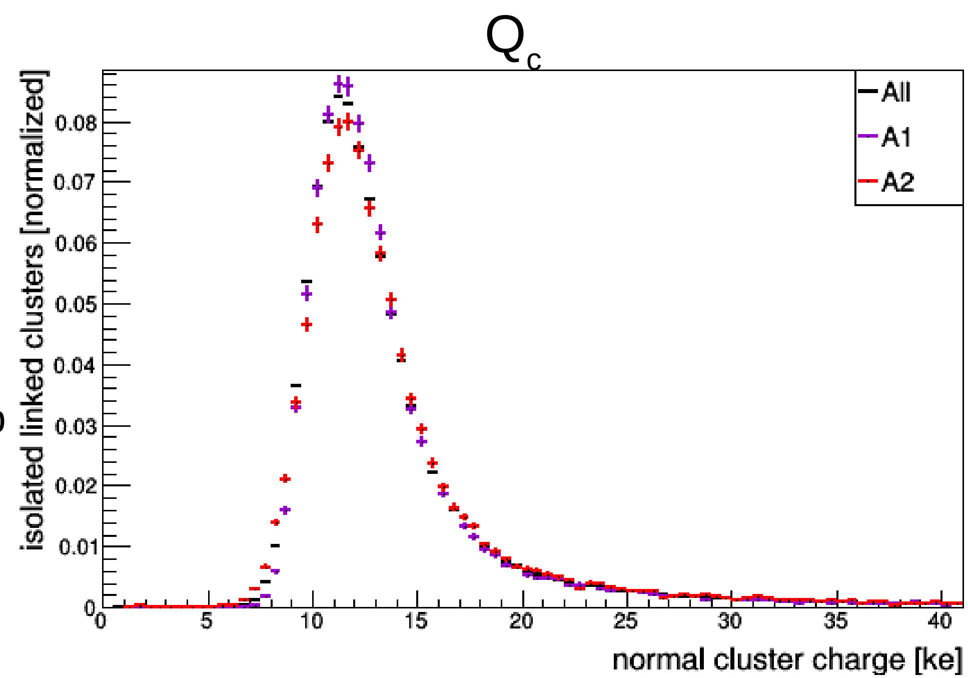
- Mostly 1-pixel clusters
- Bethe-Bloch: in 300 μm silicon ~ 22 ke
- DUT thickness 150 μm

→ We calibrated the charge scale to 11 ke

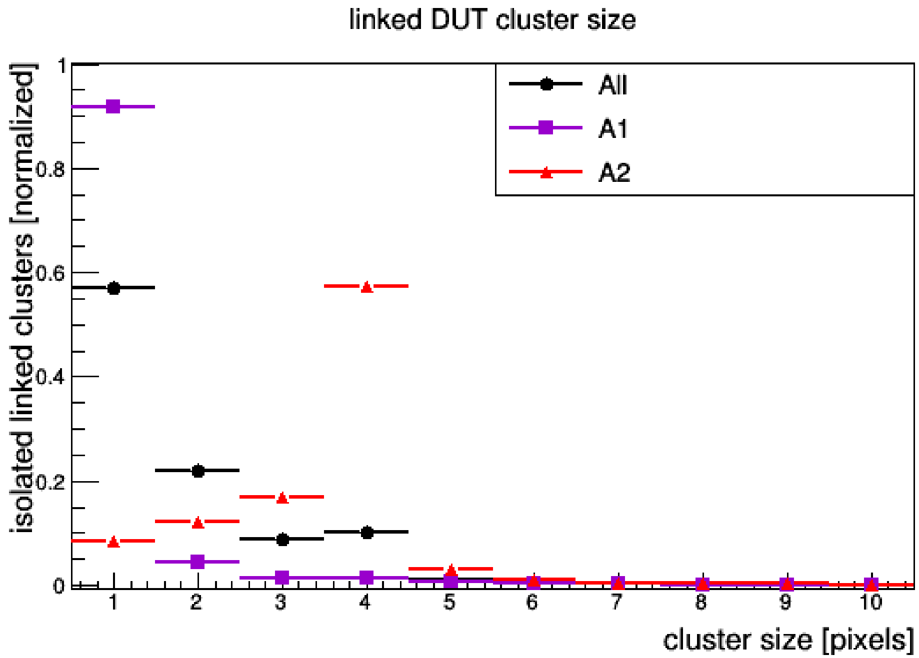


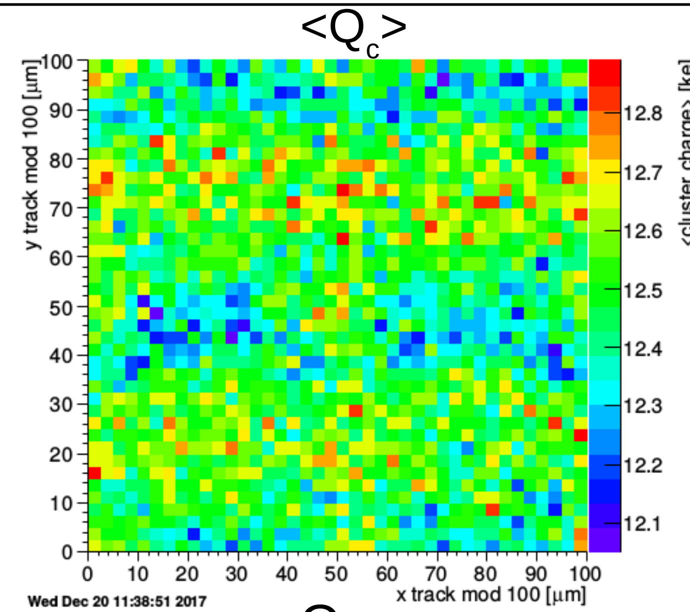
open p-stop
50x50 μm²

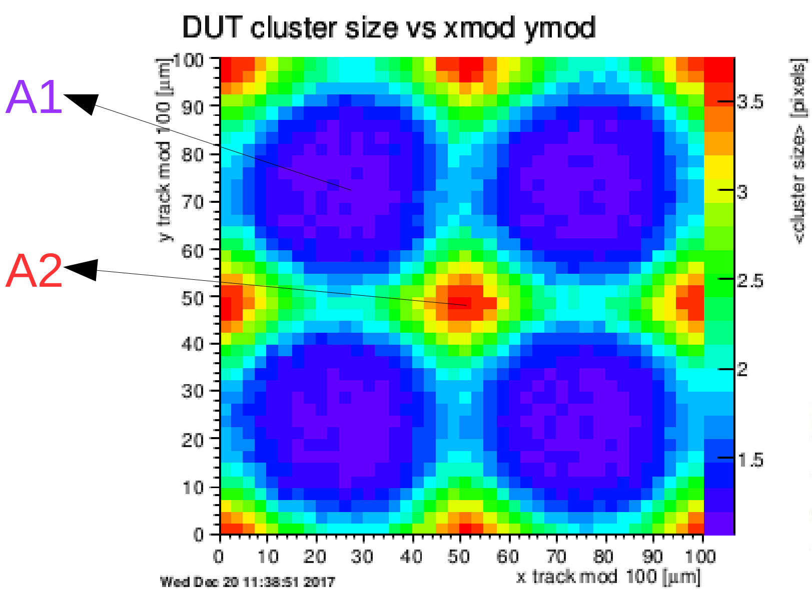




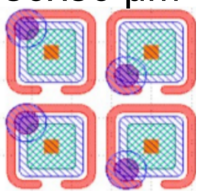
Clustering Control Plots

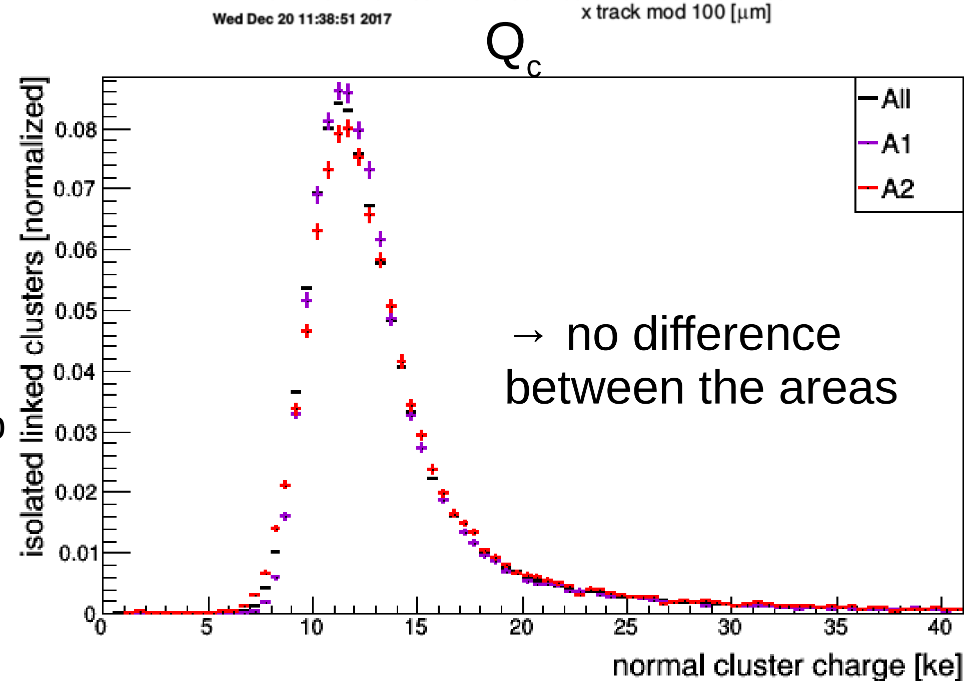






open p-stop
50x50 μm^2

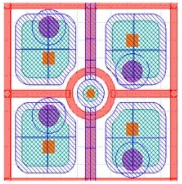




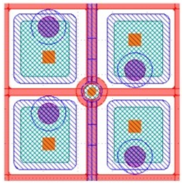
→ no difference between the areas

Cluster charge

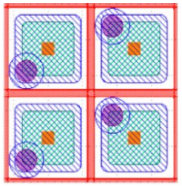
Normal incidence, using telescope, DUT: T= 20 °C, V_{bias}= -120 V



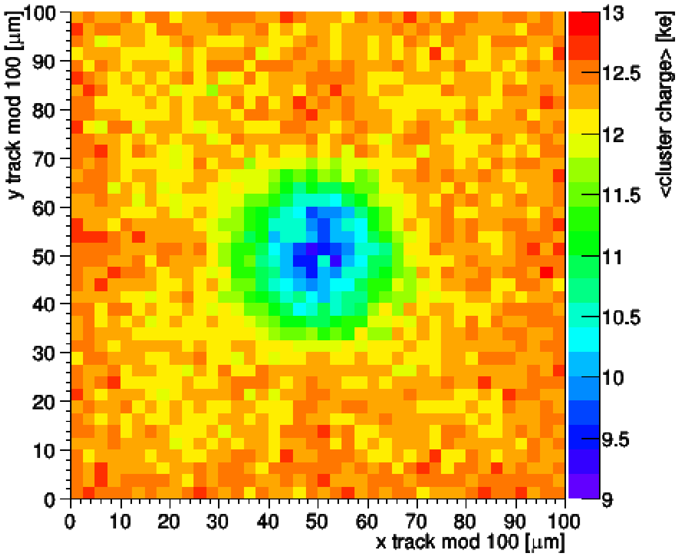
p-stop
Large bias dot
(d= 25 μm)
50x50 μm²

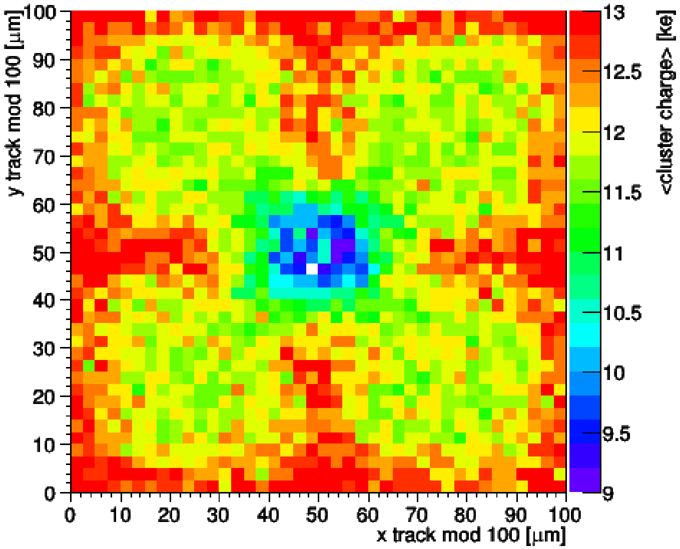


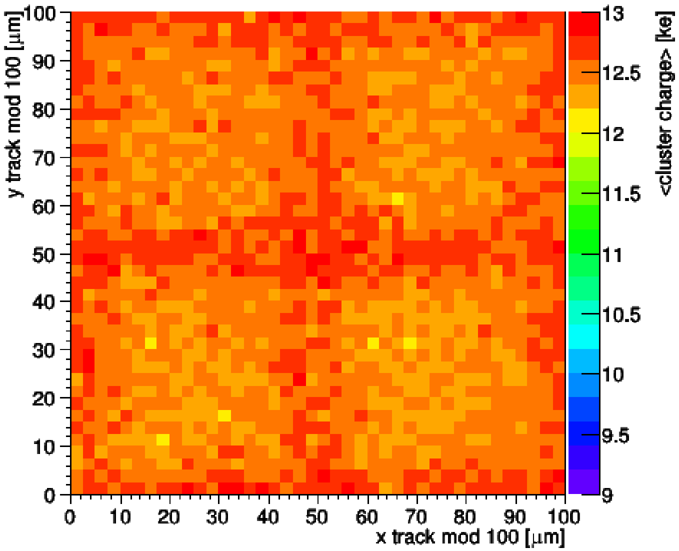
p-stop
Small bias dot
(d= 15 μm)
50x50 μm²



p-stop
default
50x50 μm²

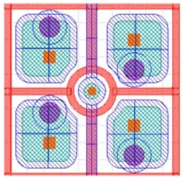




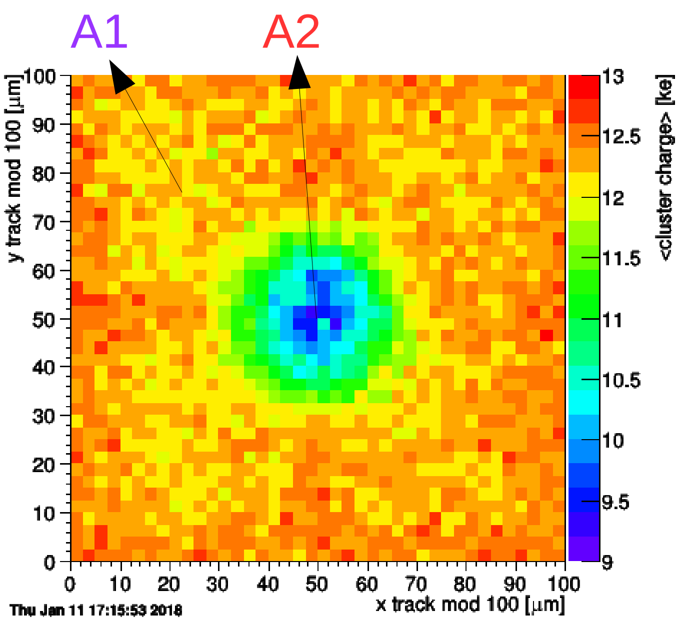


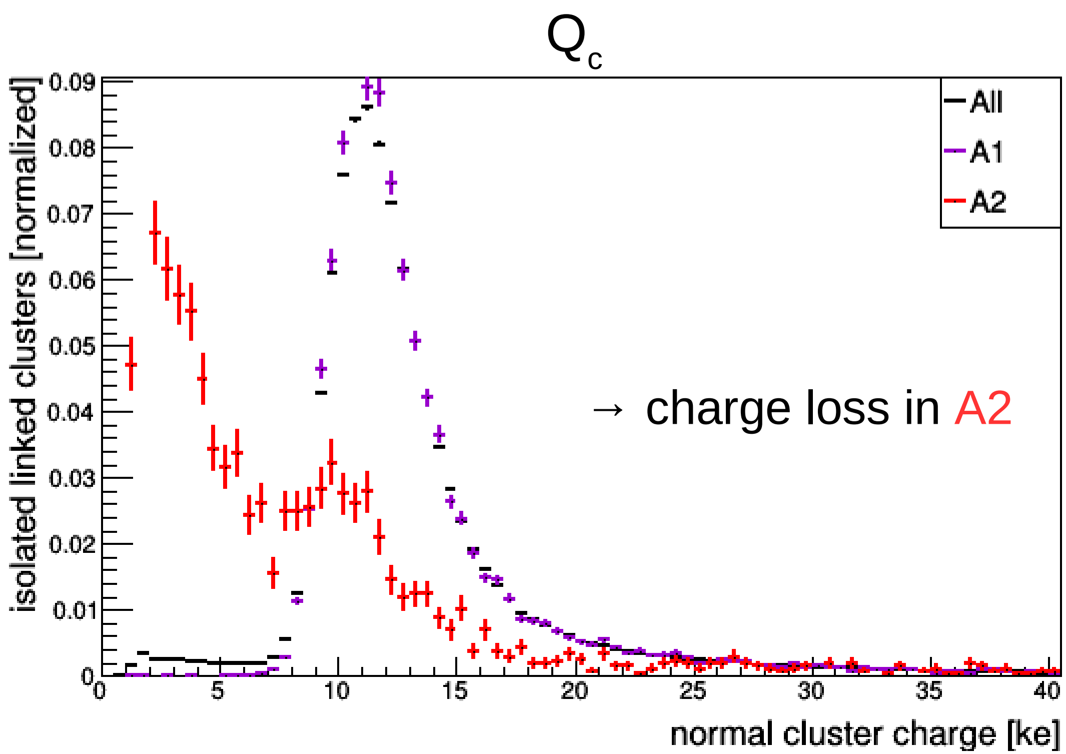
Cluster charge

Normal incidence, using telescope, DUT: T= 20 °C, V_{bias}= -120 V

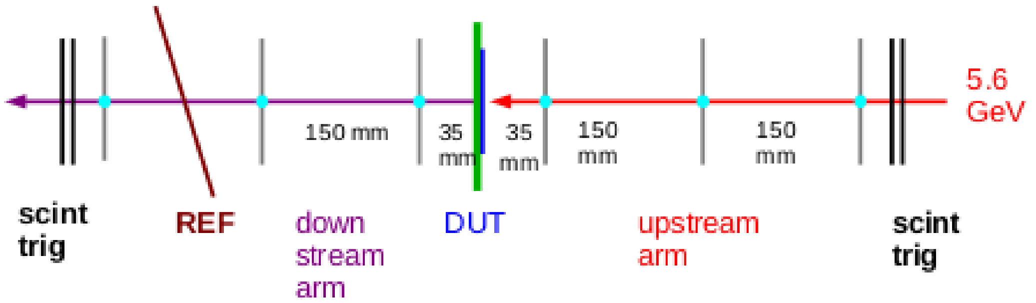


p-stop
Large bias dot
50x50 µm²

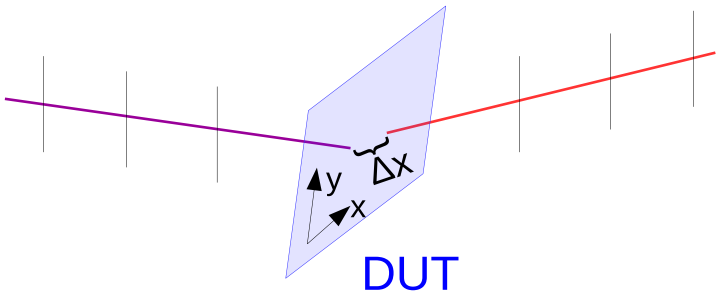




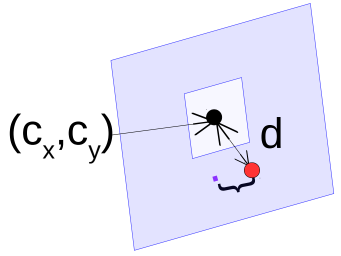
Hit efficiency definition



- **Efficiency = N_{hits}/N_{tracks}**
- Track definition:
  - Match upstream and downstream triplets using box cut in x,y ($\Delta x=|x_u-x_d| < 0.1$ mm, $\Delta y=|y_u-y_d| < 0.1$ mm)
  - REF link; box cut in x,y (0.15 mm)
  - Double track rejection: 0.6 mm isolation at REF



- Hit definition (Hit on track):
  - Connect DUT cluster to upstream track projection loose radial cut (d < 0.49 mm)

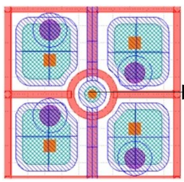


- Fiducial region 0.2 mm to sensor edges

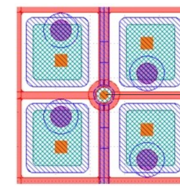
Efficiency

Normal incidence, using telescope, DUT: T= 20 °C, V_{bias}= -120 V

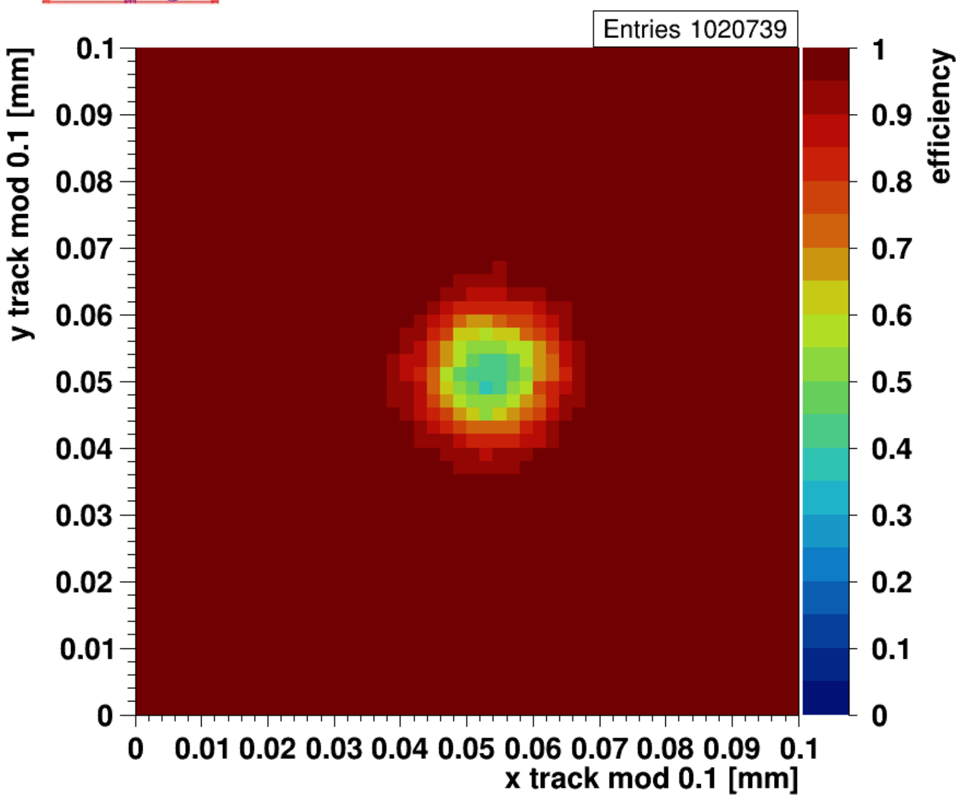
→ Overall very high hit efficiency
→ as expected: smaller bias dot has better efficiency than large bias dot

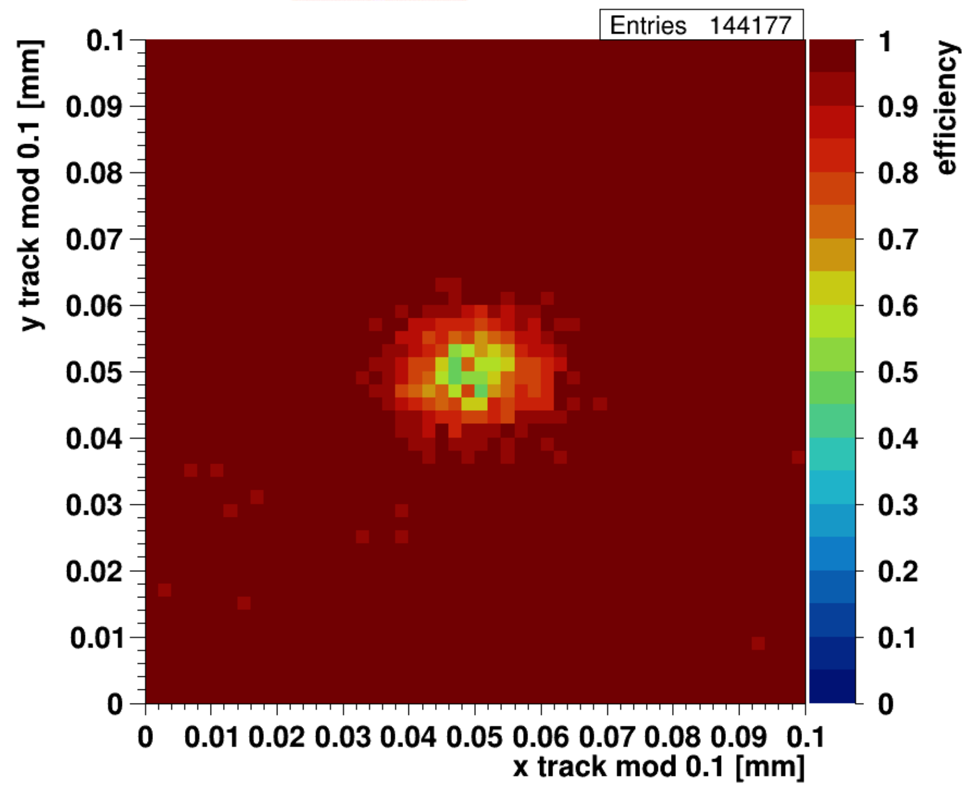


p-stop
Large bias dot (d= 25 µm)
50x50 µm²



p-stop
Small bias dot(d= 15 µm)
50x50 µm²



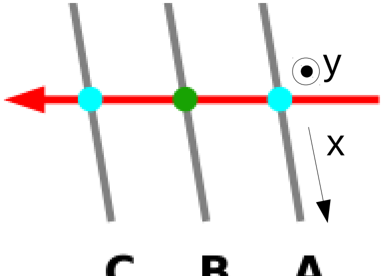


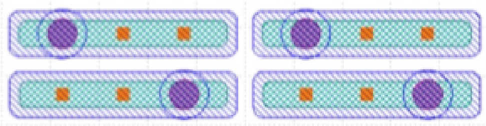
Position resolution with Dreimaster

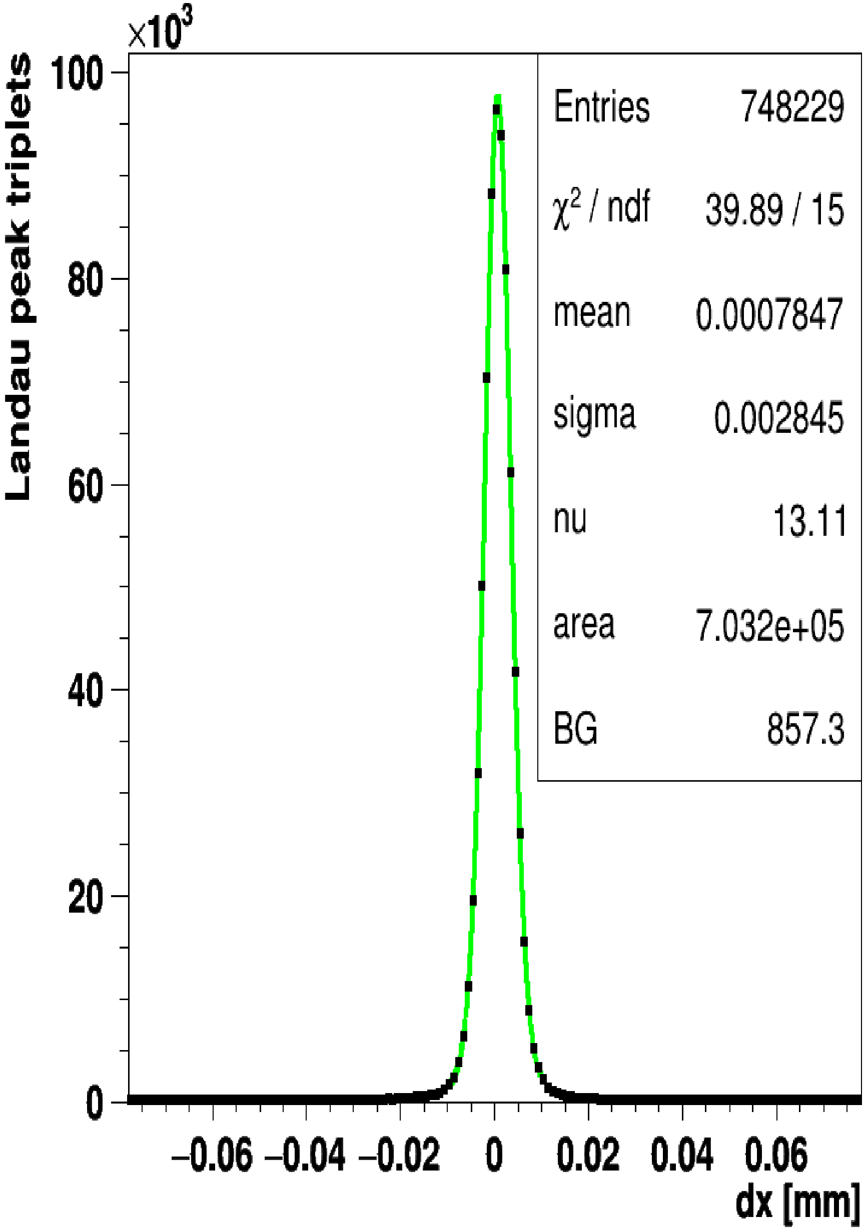
- 8° turn (optimal incidence)
- 6 GeV electrons
- Cut on the Landau distribution
- Triplet residuals

$$\Delta x = x_B - \frac{x_A + x_C}{2}$$

- Hit Resolution
  - 2.85 μm from the fit
  - **1.8 μm** by unfolding tracking and scattering





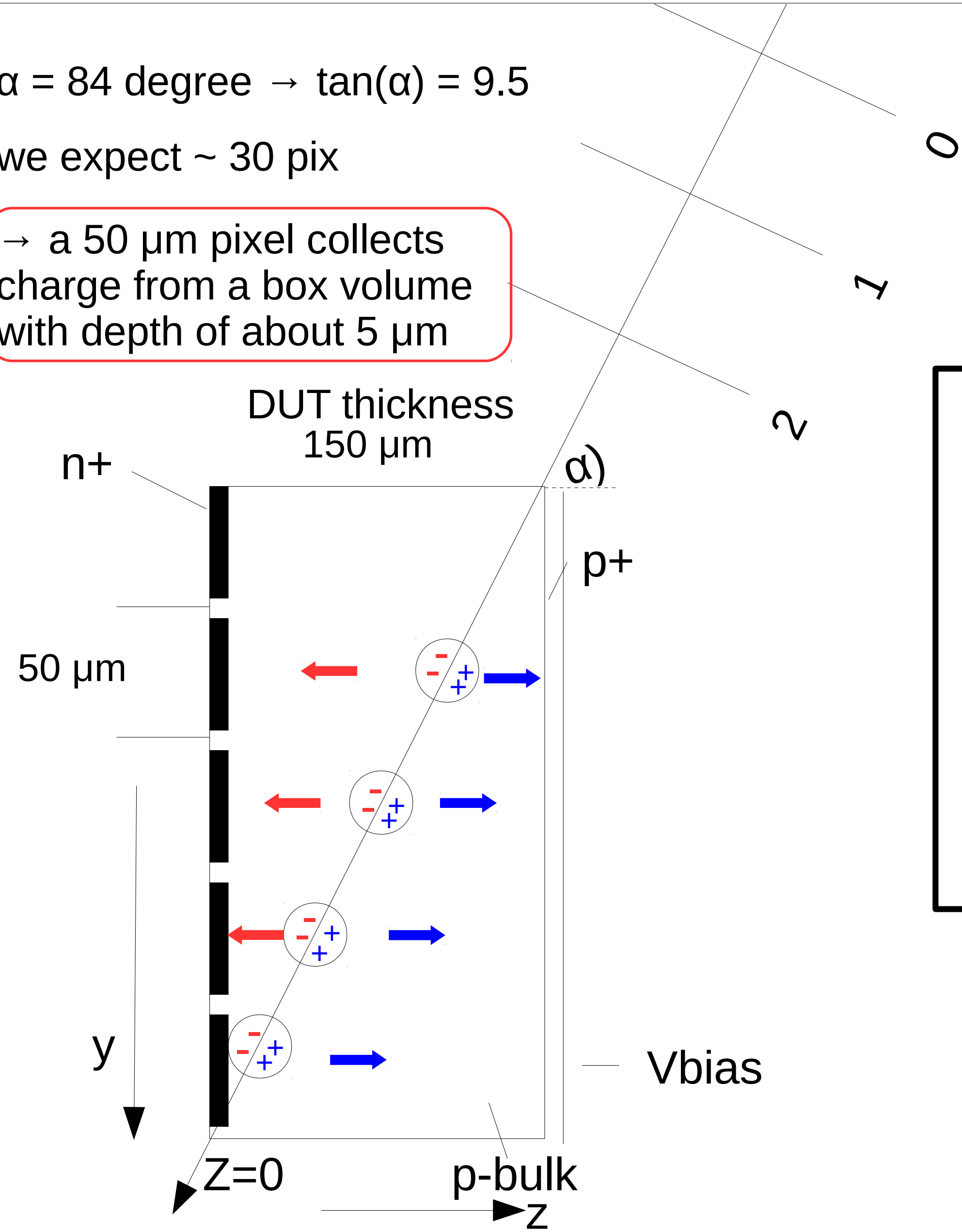


Shallow angle measurement

α = 84 degree → tan(α) = 9.5

we expect ~ 30 pix

→ a 50 µm pixel collects charge from a box volume with depth of about 5 µm



The idea:

- Measuring the depletion profile
- Charge collection efficiency as a function of the distance from the readout pixels

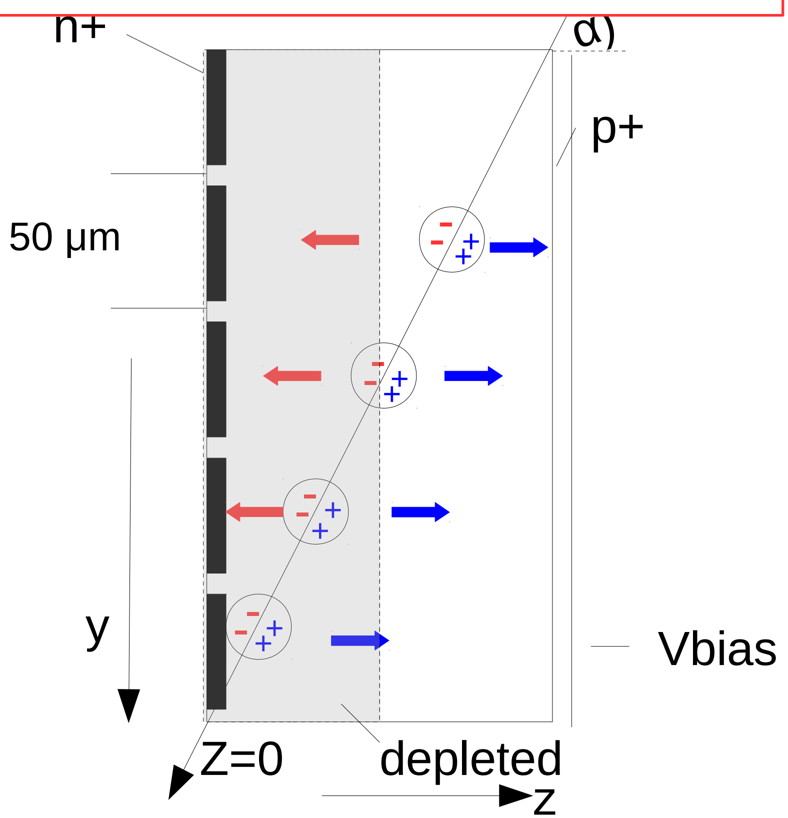
Shallow angle measurement

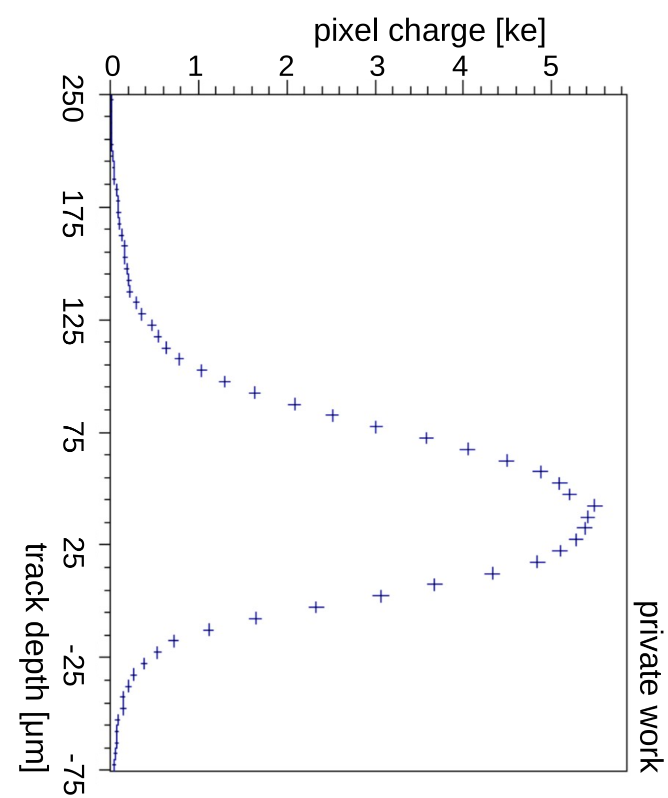
We expect:

- The same charge distribution in each pixel for **non-irradiated** sensors
- ~5ke charge in 50 µm silicon

For **irradiated** sensors we expect:

- **Trapping**
  → Charge that is induced further from the electrodes is more likely to be trapped
  → the charge distributions may vary for each pixel





Bias voltage scan

DUT pixel charge from shallow angle analysis for different bias voltages:

- Sensor thickness 150 µm
- 65 ns integration time
- Below the depletion voltage the active region grows from the pixels to the backside with increasing voltage

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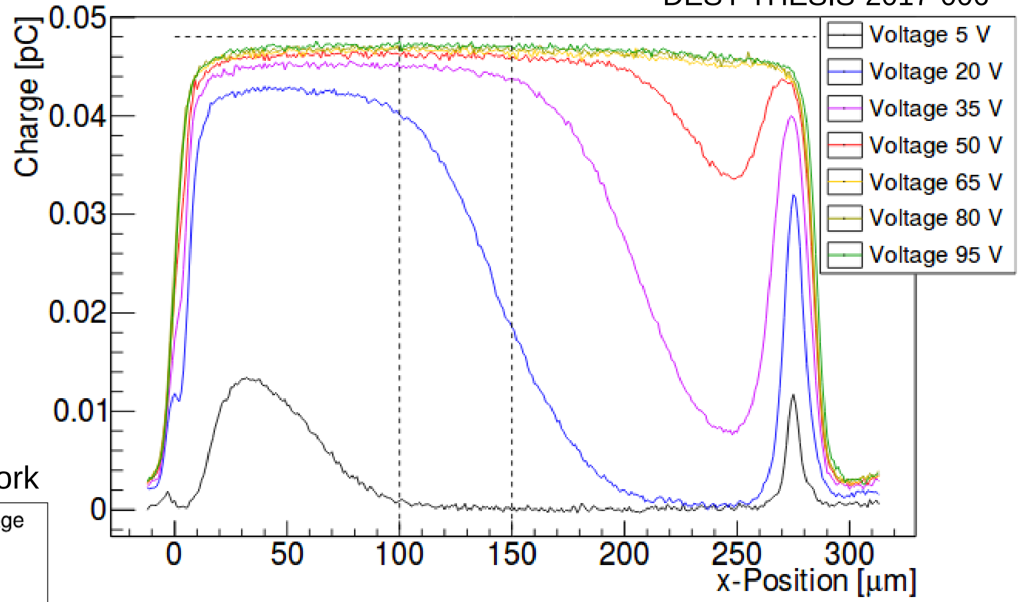
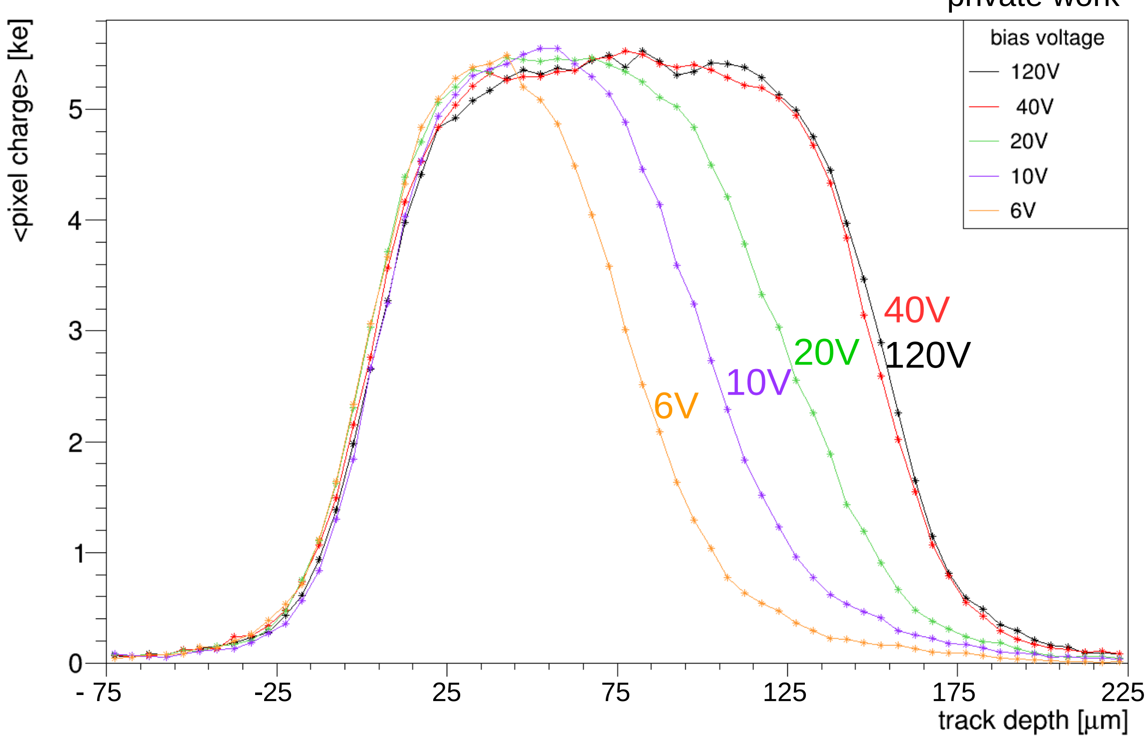


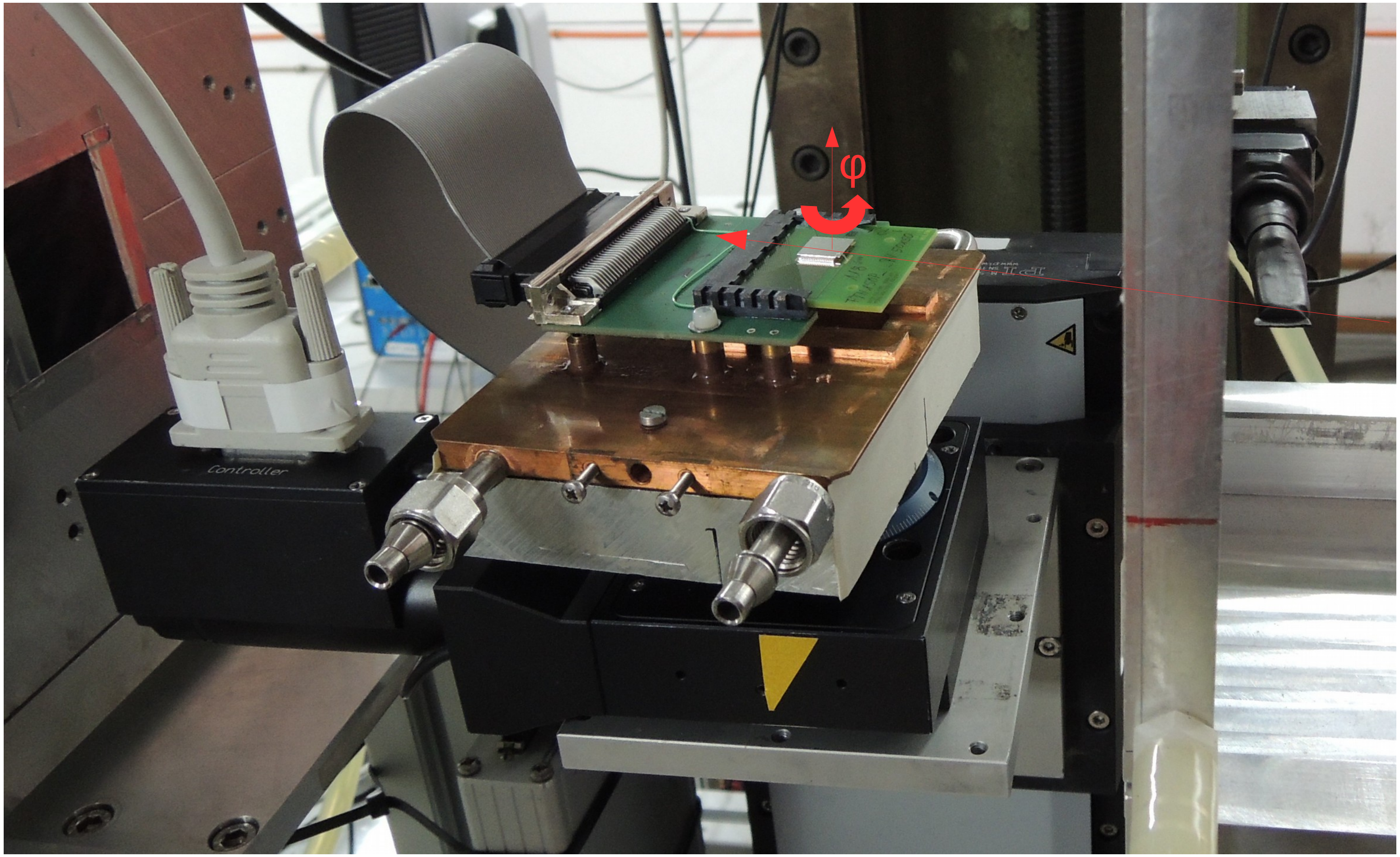
private work

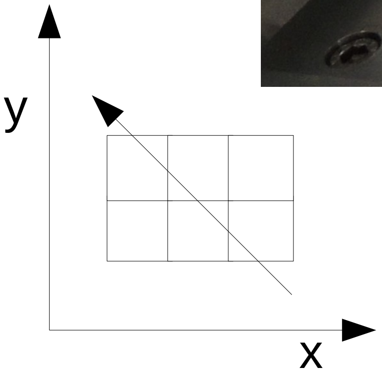


Charge collection from Edge-TCT for different bias voltages:

- Sensor thickness 285 µm
- Below the depletion voltage the active region grows from the pixels to the backside with increasing voltage

Edge-on tracking





Edge-on → in-silicon tracking
Rotated → position resolution for charge sharing

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Edge-on tracking

- 50x50 μm² pixels
- Add charge from 8 columns

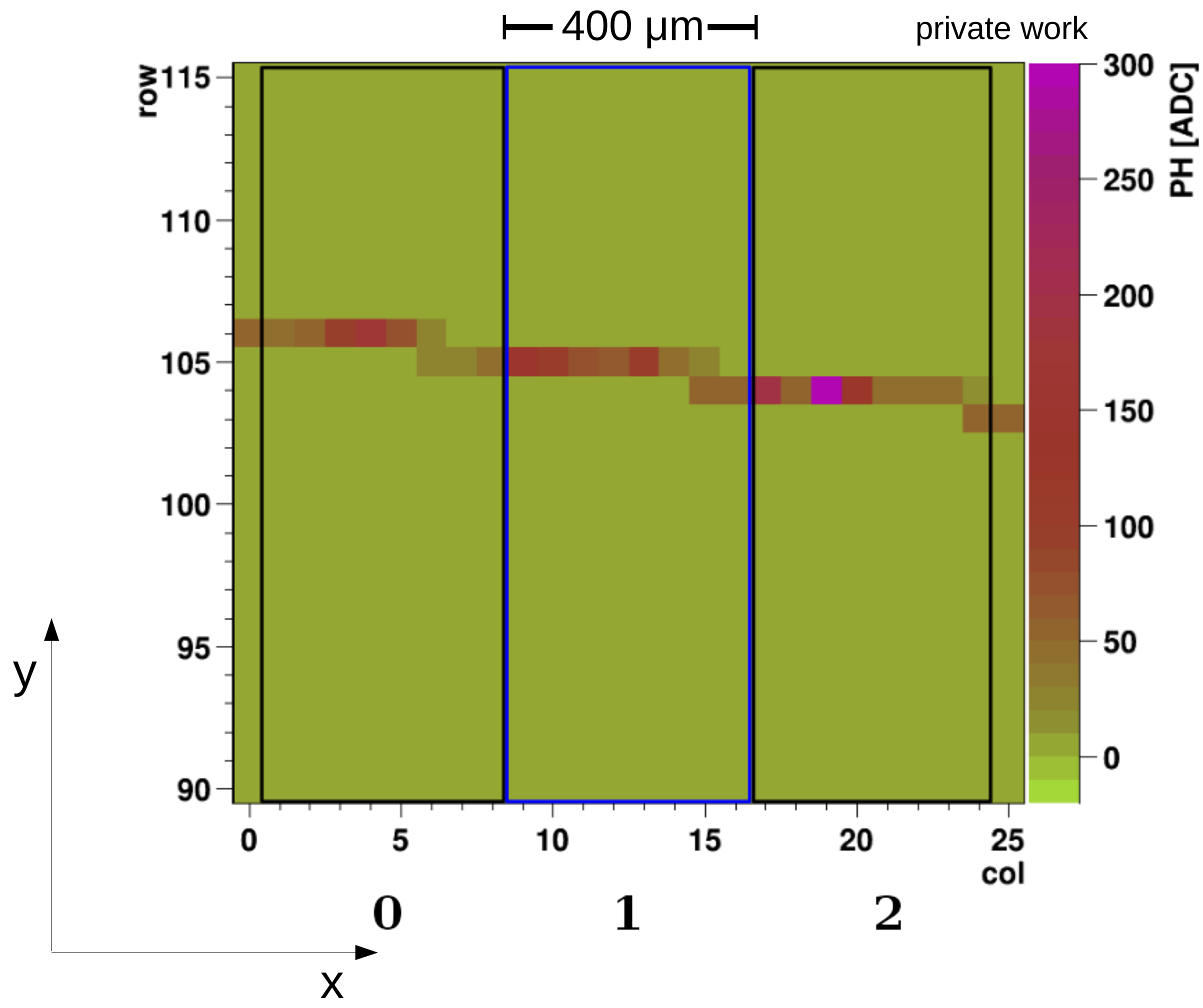
  → equivalent to 400 μm thick sensor

$$atan\left(\frac{50}{400}\right)=7.1^{\circ}$$

→ 7.1° angle for charge sharing every 8 columns

- Triplet tracking on 8-column planes

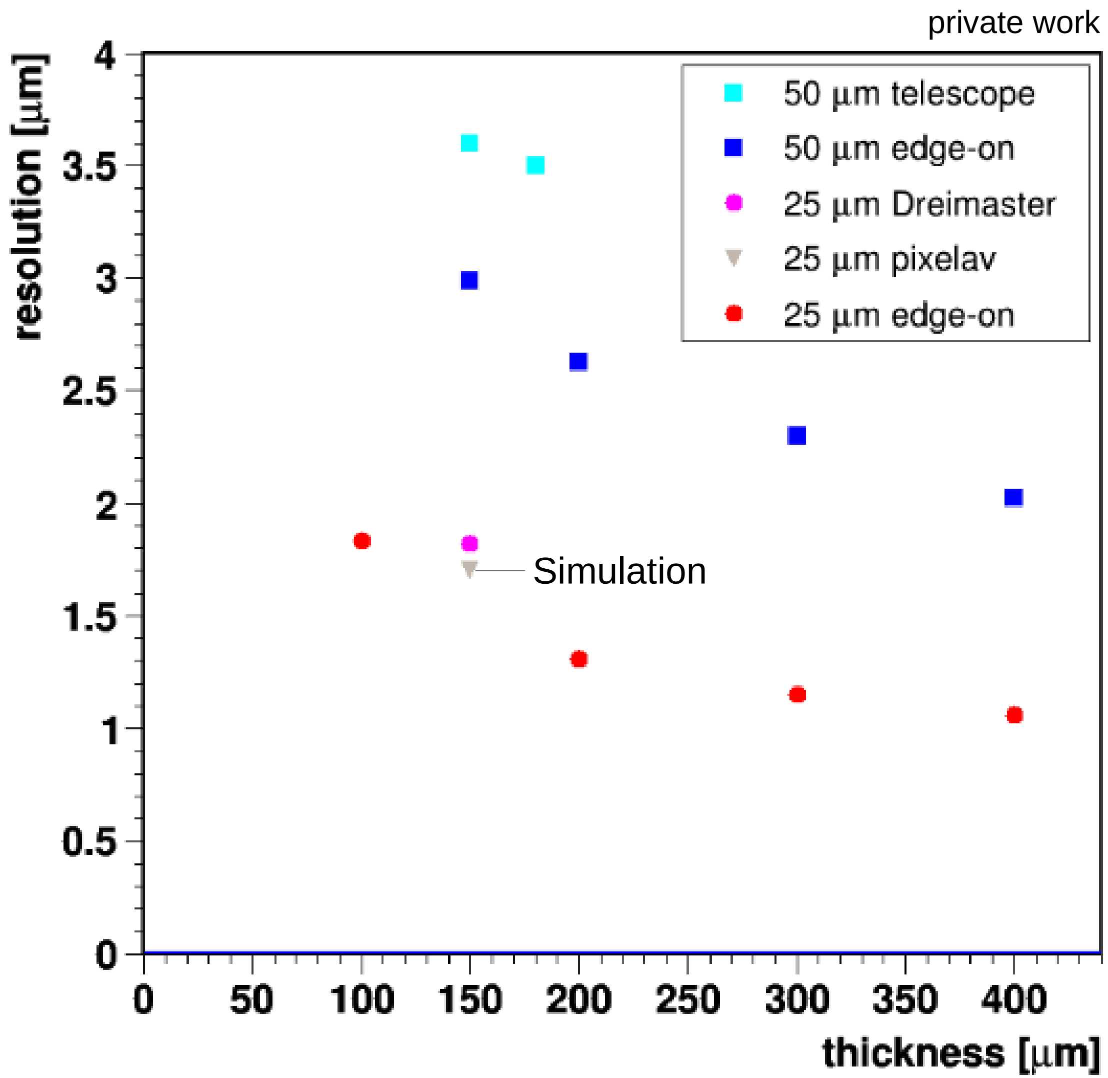
$$\Delta y = y_1 - \frac{y_0 + y_2}{2}$$



Resolution

- Edge-on measurement
  - optimal incidence angle
  - internal triplet residual
- Telescope / Dreimaster
  - external triplet residual
  - track contribution subtracted
- **Resolution**:
  - edge-on internal residuals better than inclined angle external residuals

➞ Difference to be understood



Summary

- **Various sensors successfully tested at DESY**

- **Analyses for efficiency, charge collection, charge sharing and resolution developed**
  - Analyzed under several conditions:
    - **normal**, **inclined**, **shallow** and **edge-on** incidence
    - Mimosa telescope and Dreimaster,
    - momentum and bias scans

- **First Results**
  - Smaller bias dot has better efficiency than large
  - Before irradiation p-spray isolation works fine
  - Edge-on tracking for sensor thickness studies
    - 1.1 µm resolution with 25 x 100 x 400 µm^3

Outlook

Next Steps

- Sensors have been irradiated at CERN to 2E15 neq/cm^2
  - Irradiated ROC4SENS is know to work
  - Cooling with Peltiers in the telescope is ready
  - Lab tests ongoing in January
  - Dreimaster insulation to be done
  - **Next test beam starting mid February**

- Irradiation to higher fluences in May 2018