Test beam results for CEPC vertex detector prototype

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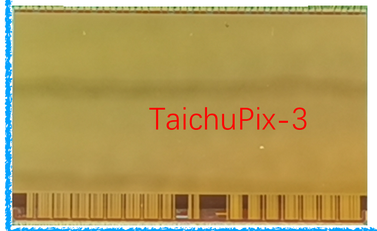
Overview of the baseline vertex detector

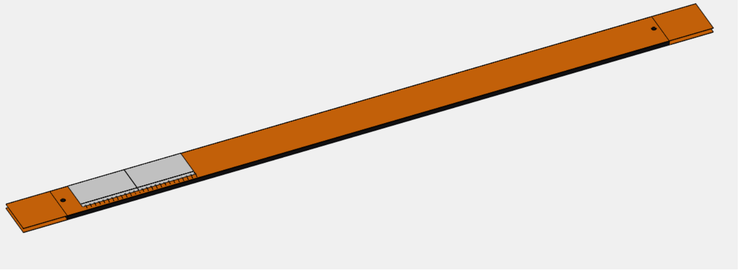
First test beam on pixel sensor prototype at DESY on 12/2022

CMOS pixel sensor prototype

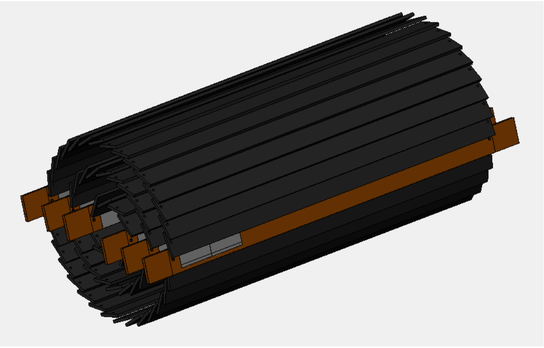


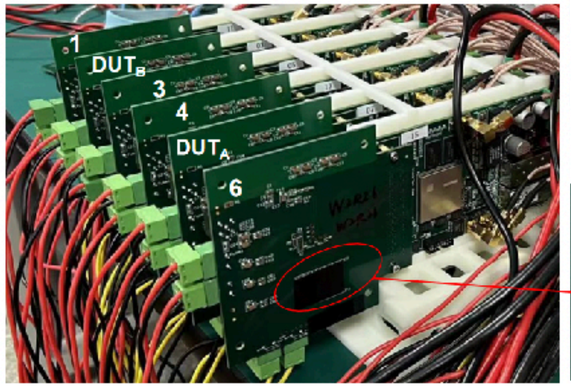
Second test beam on vertex detector mechanical prototype at DESY on 04/2023

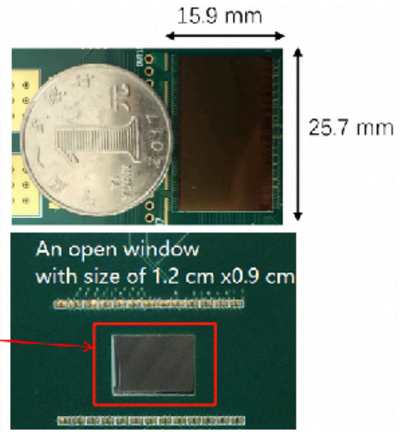
double sided ladder
2 sensors on every ladder side, read out from both ends

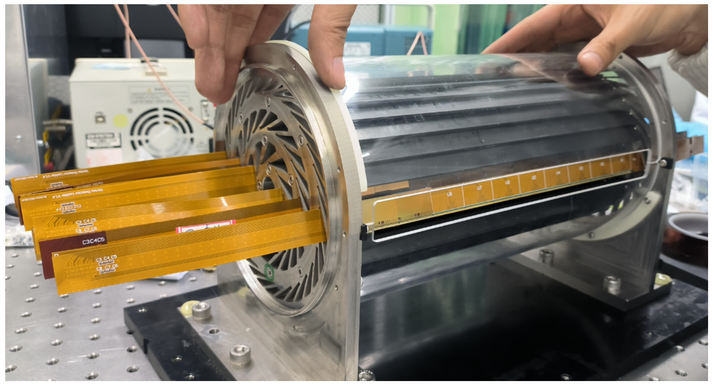


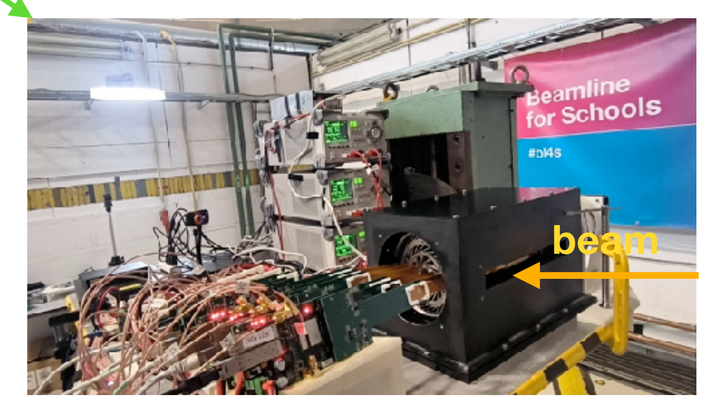
vertex detector prototype





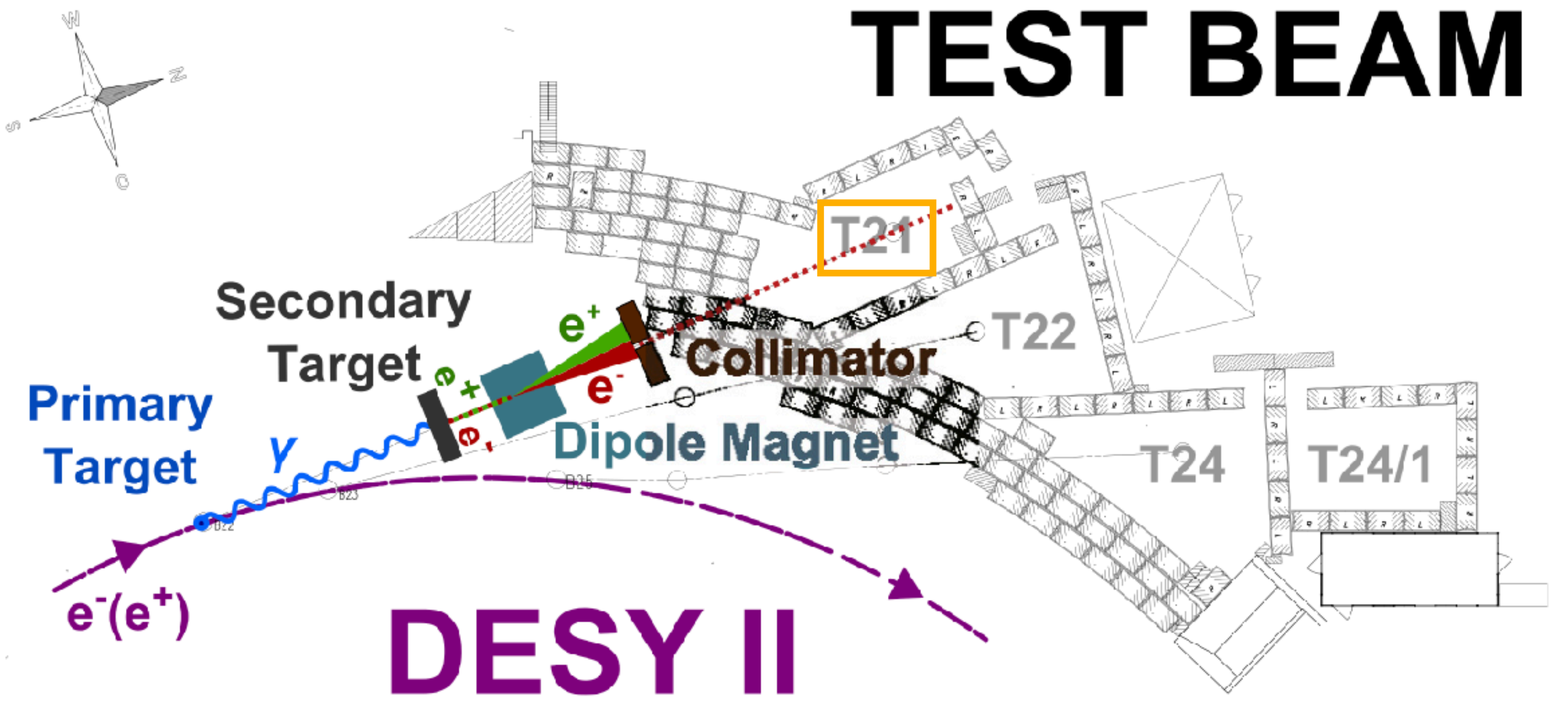






DESY TB21 beam line

- **Electron - positron** synchrotron DESY II
- Beams are converted bremsstrahlung beams from **carbon fibre target**s
- Up to 1000 particles per cm^2
- Energy from **1 to 6 GeV**
- Energy spread of ~ 5% and divergence of ~ 1mrad



Introduction of offline analysis

➡ The flow chart of offline analysis

- The data read out by a **specialised DAQ software**
- The event building by finding hits with the coincidence of time stamp
- The centre of the cluster is the **geometric centre of the gravity of the neighbouring fired pixels**
- The alignment procedure using the **Millepede** program
- **Least squares straight line fit**

➡ A dedicated offline analysis framework developed for test beam data

◉ Track finding and reconstruction

- Finding hits in every chip with time stamp coincidence
- Clustering: geometric centre of gravity of fired neighbouring pixels

◉ Track fitting

- no magnetic field
- least squares line fitting

$$\chi^2(\alpha) = \sum_{i=1}^{n} \frac{(f(m_i, \alpha) - m_i)^2}{\sigma^2}$$

m_i: measured points position (exclude the measured point at DUT)

σ: the spatial binary resolution, $25\mu m/\sqrt{12} \approx 7.22\mu m$ (the actual measured resolution would be better than 7.22 μm due to the cluster sharing effects)

α: straight line fit parameters

Alignment

- The measured hits position biased by the misaligned geometry
- Method: Millepede matrix method

$$\chi^2 = \sum_{j \in tracks} \sum_{i \in hits} \vec{r}_{ij}^{\,T}(g, l_j) V_{ij}^{-1} \vec{r}_{ij}(g, l_j)$$

g: Alignment parameters

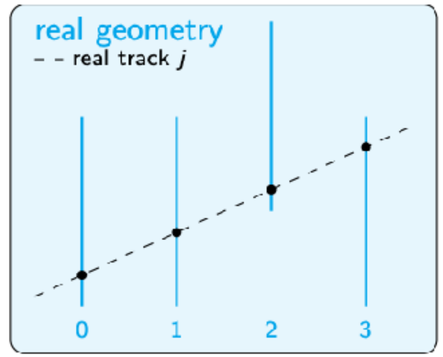
l: track parameters

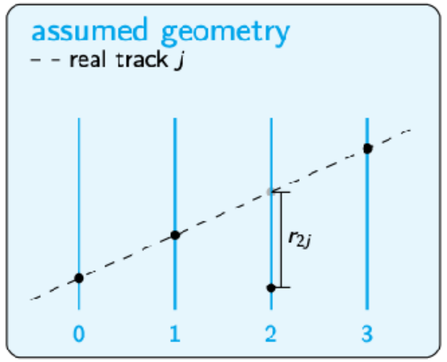
- Six alignment parameters considered for every chip position

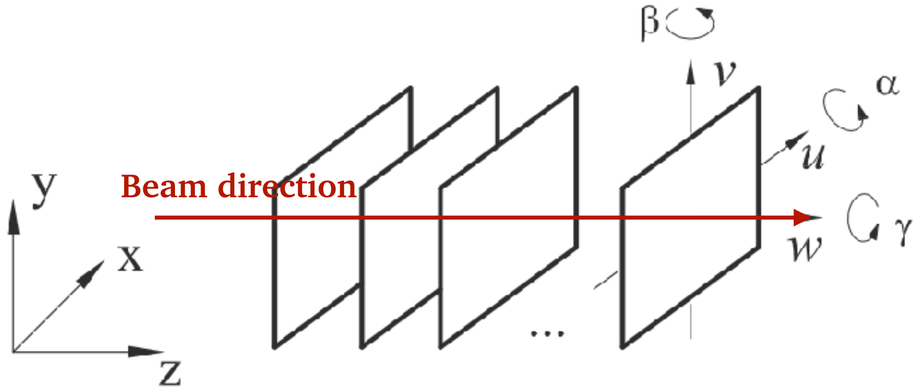
  Translation along X, Y, Z direction

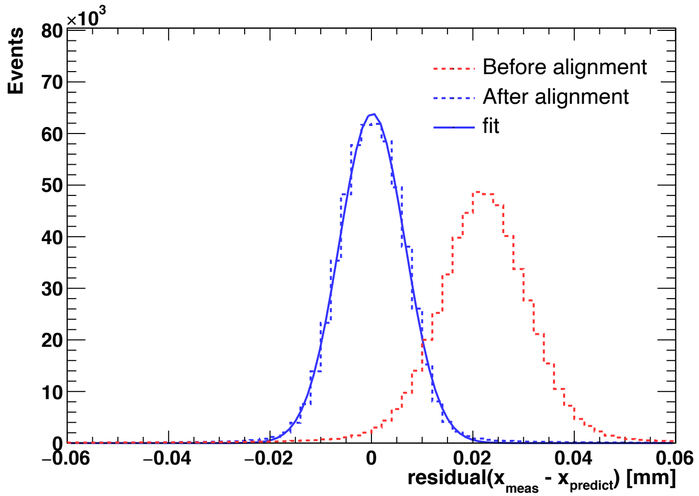
  Rotation around X, Y, Z axis

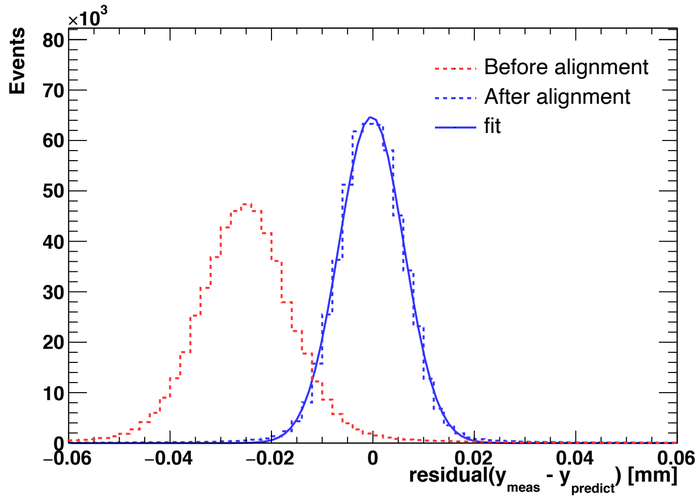
- Misalignment broadens and shifts the residual distribution

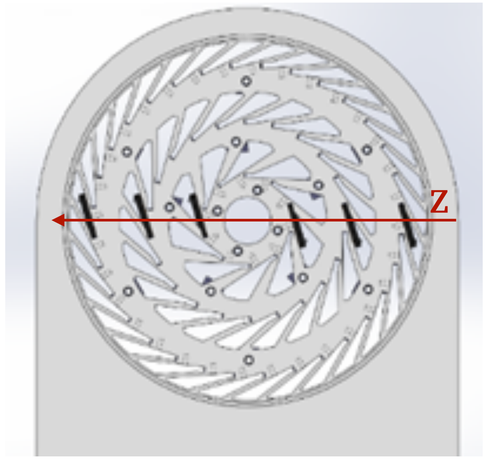












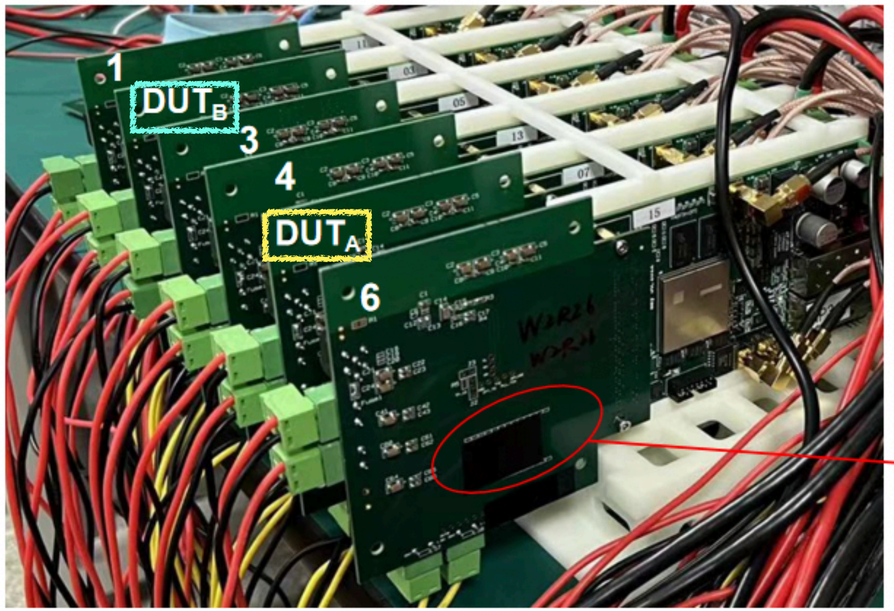
Pixel sensor prototype beam test @ DESY II

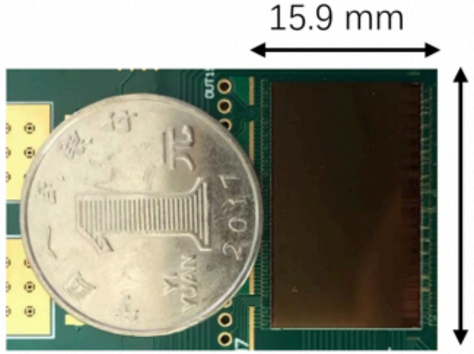
➡ Setup

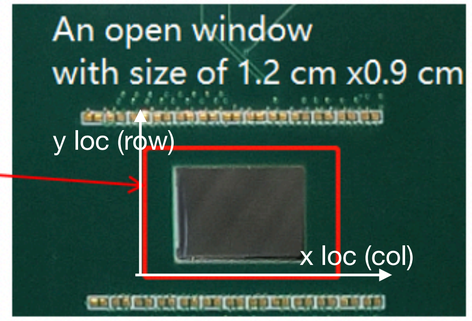
- Pixel sensor prototype beam test (09/12/2023 - 24/12/2023)
- 6 equally spaced detector module with TaichuPix3
- 2 detector under test (DUT) TaiChuPix3 with <u>different processes</u> tested

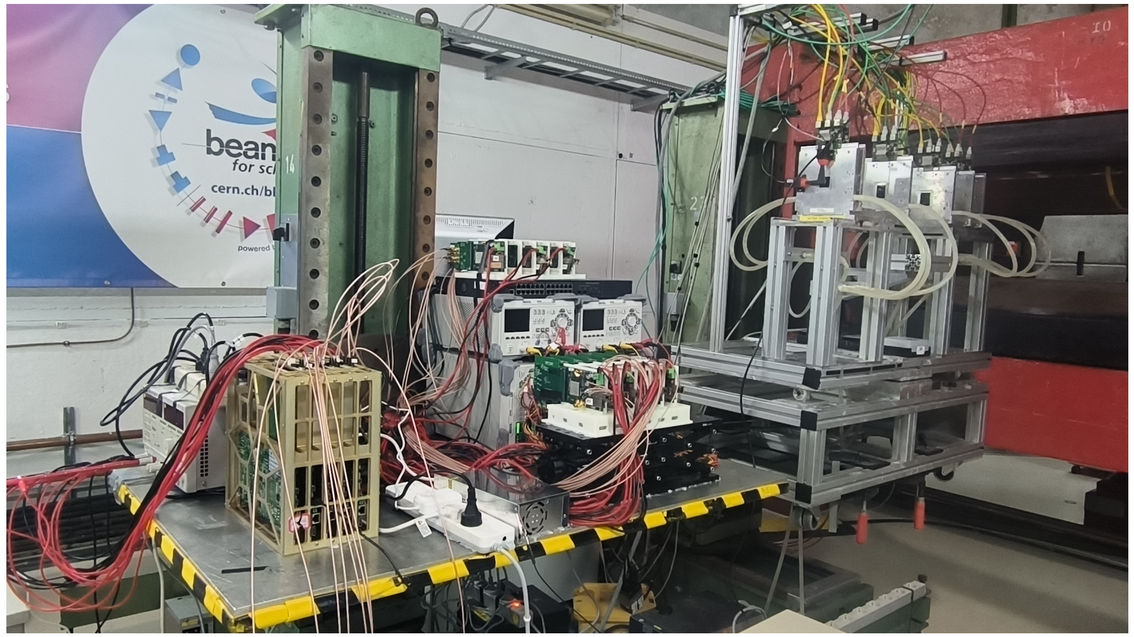
DUT_A with modified process

DUT_B with standard process







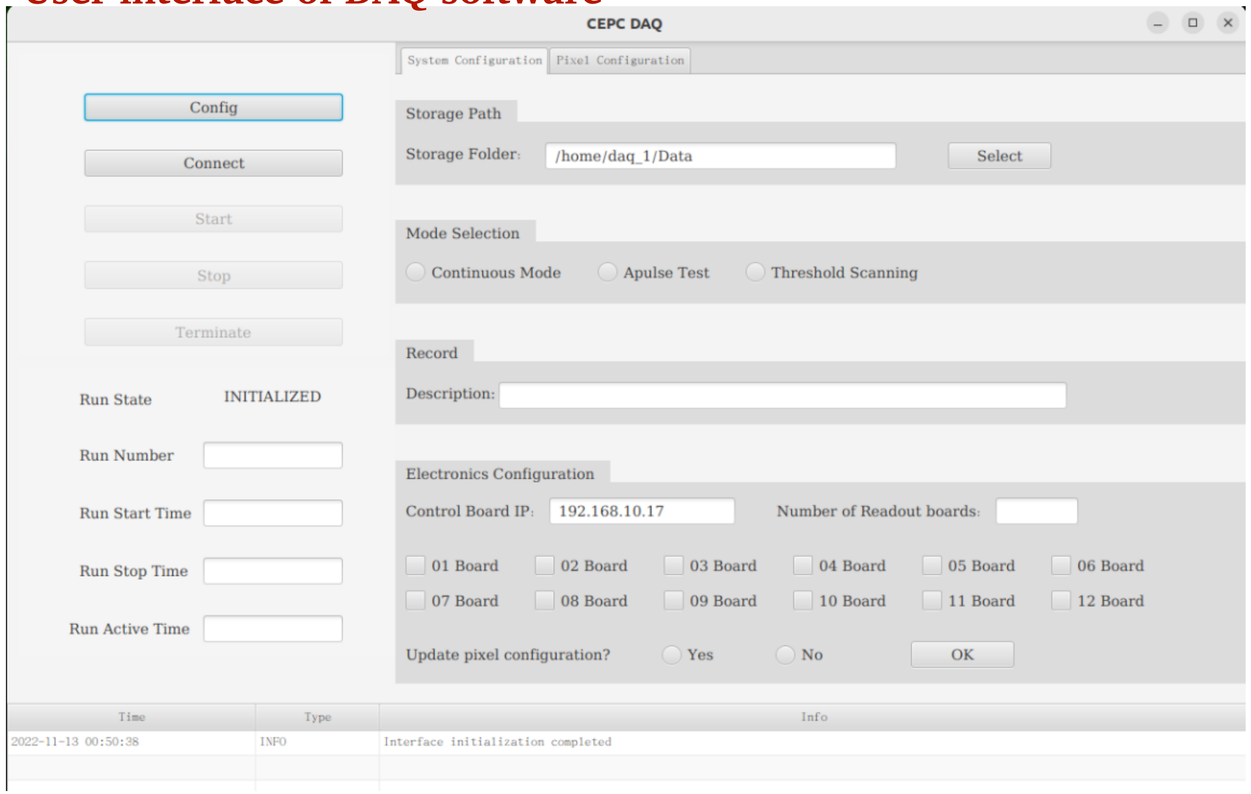


- 4 cm between each plane
- sensor size: 1024 columns x 512 rows
- sensor pitch: 25 um
- an open window used to decrease the multi-scattering from the PCB board

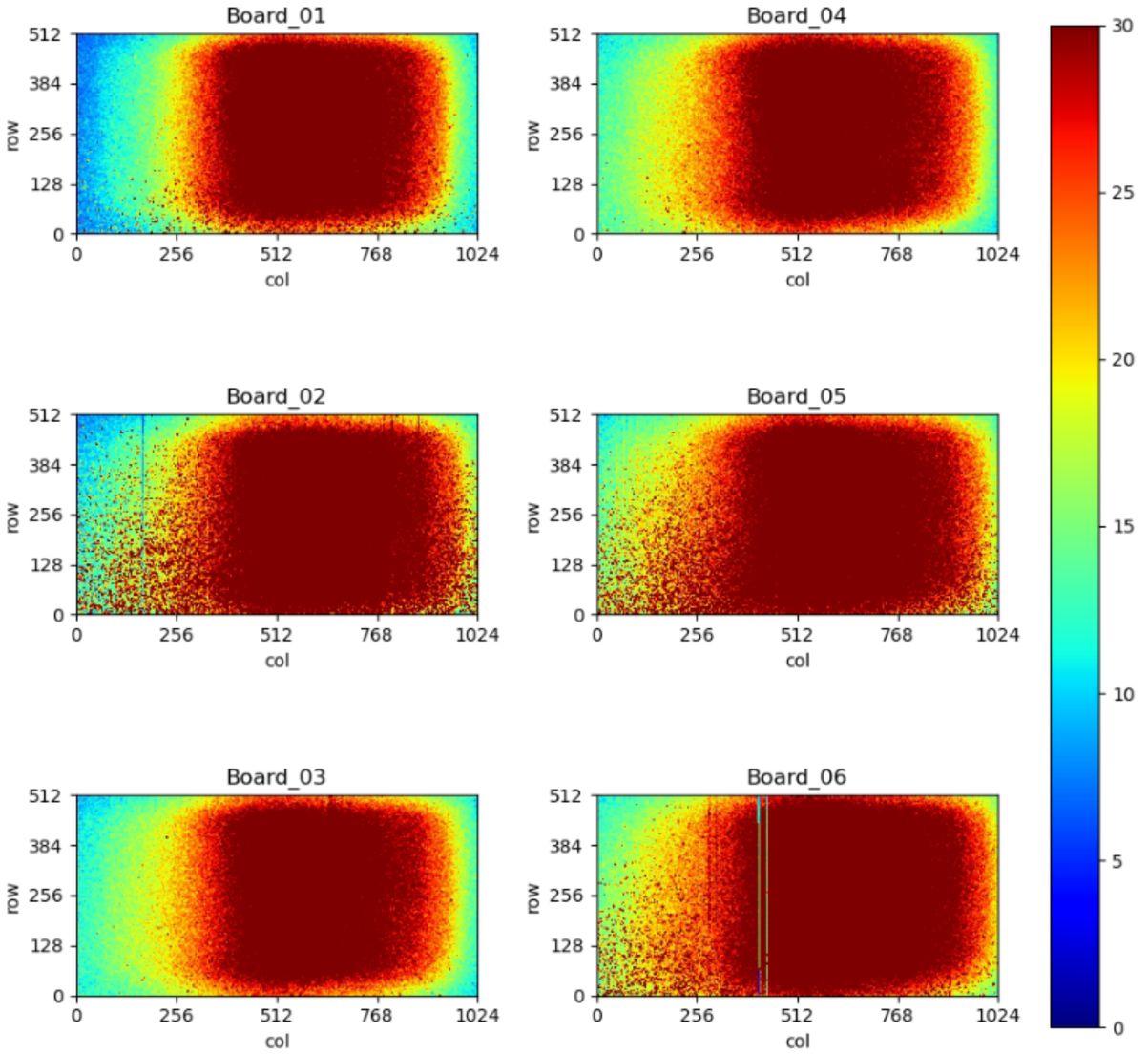
➡ Hitmap acquired by DAQ

- A specialised DAQ software is used to configure each chip in parallel
- Considering the data rate and beam performance, the main beam energy used for the first beam test was **4 GeV**

User interface of DAQ software

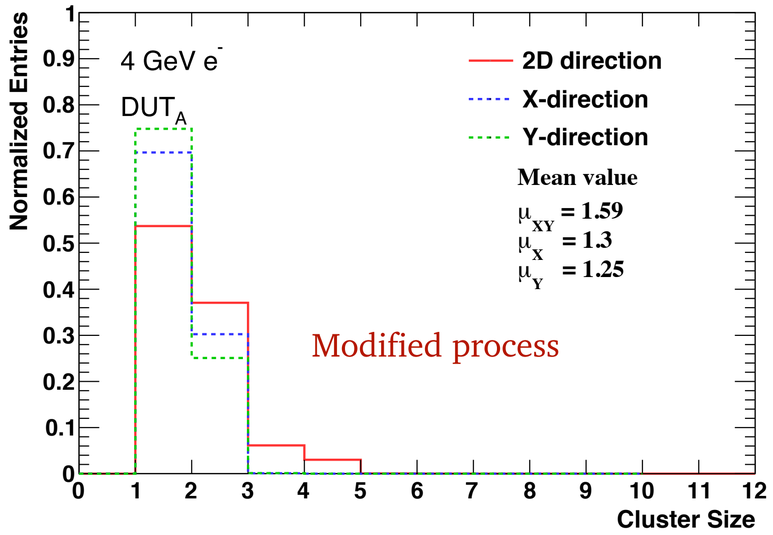


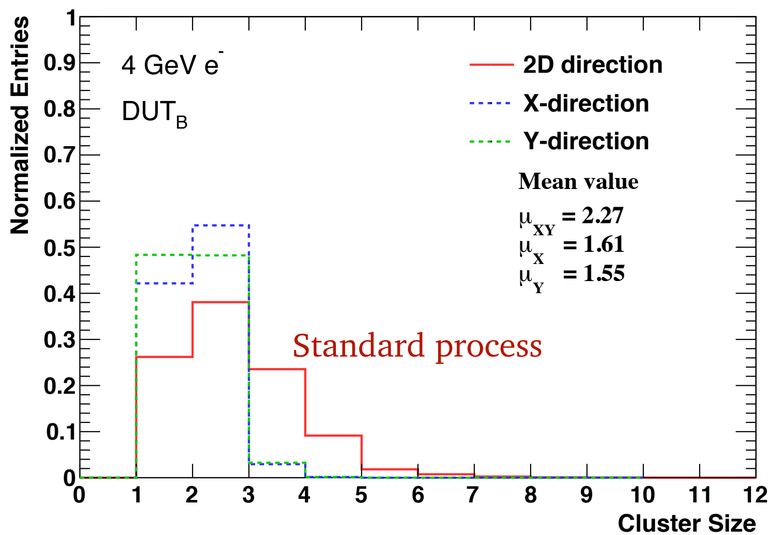
Online hitmap display



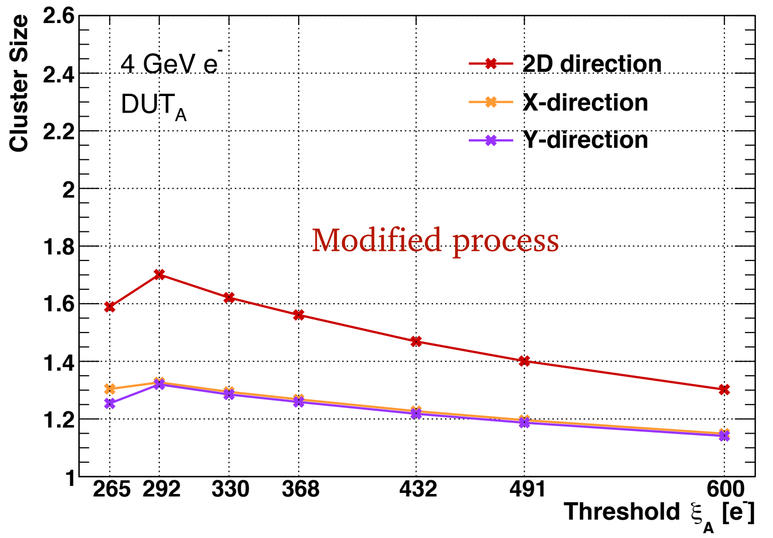
➡ Offline analysis results of first test beam

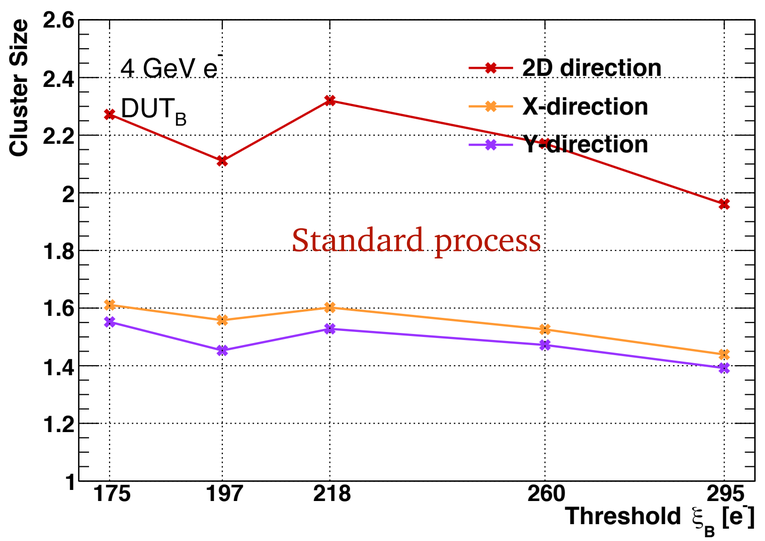
◉ Cluster size





- The peak value for DUT_A is 1 pixel, around 2 pixels for DUT_B
- Less charge sharing effects in modified process with full depletion

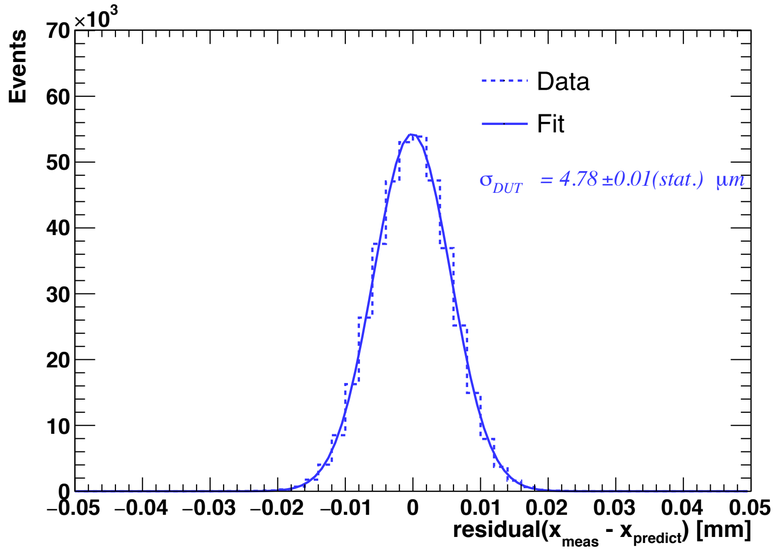


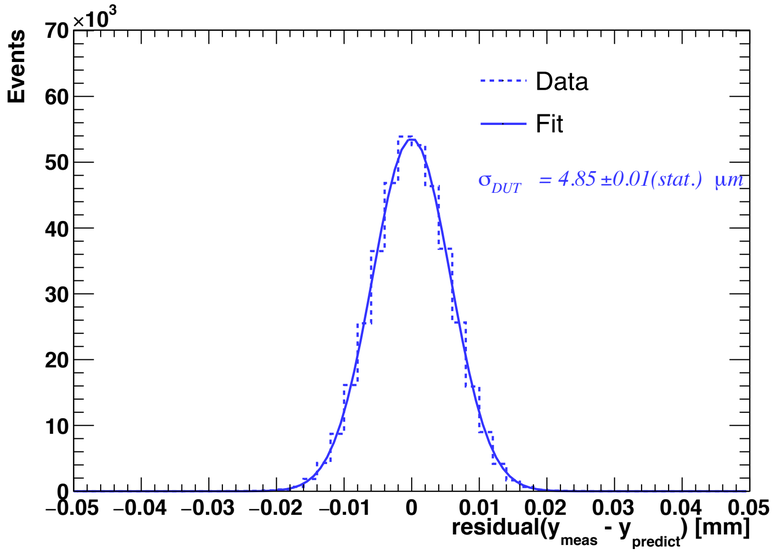


- In general, the higher the threshold, the smaller the cluster size as expected
- If lowering the threshold, cluster size will be dominated by cluster with 2 hits

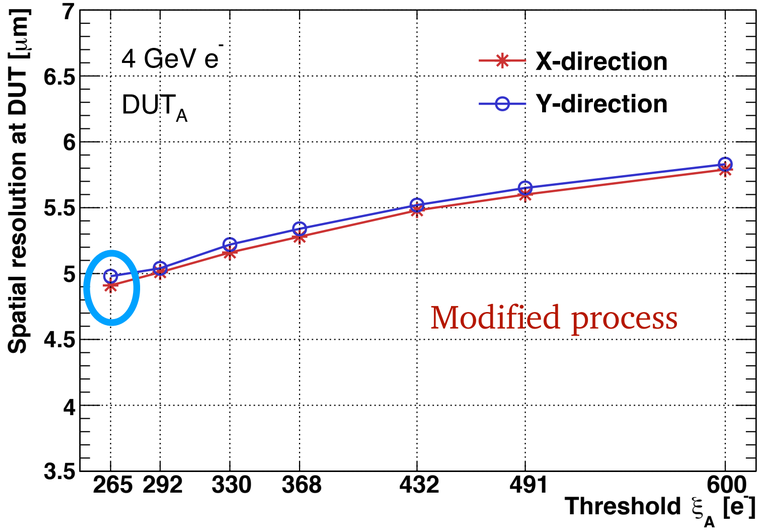
Spatial resolution (4GeV)

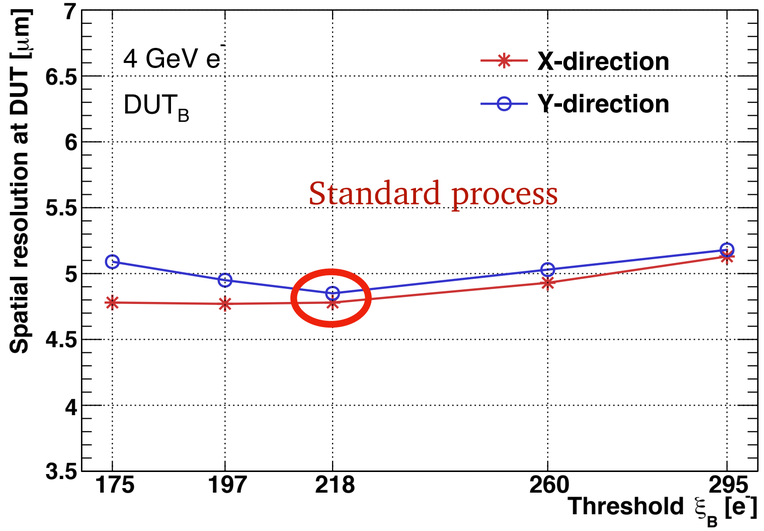
The unbiased residual distribution at 218 e- of standard process





- The spatial resolution extracted by the unbiased residual distribution after substract the track uncertainty
- **The spatial resolution less than 5 um**





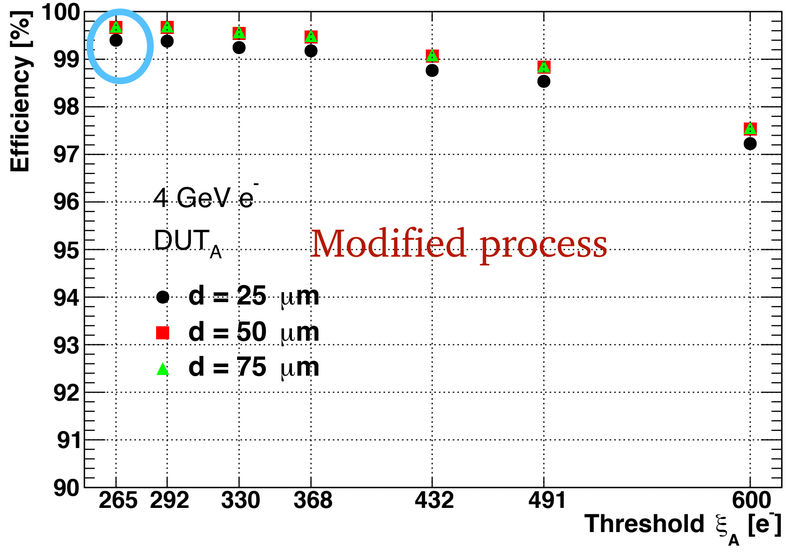
- For DUT_B with standard process, a worse resolution occurs when the threshold < 218 e- since the larger noise at lower threshold

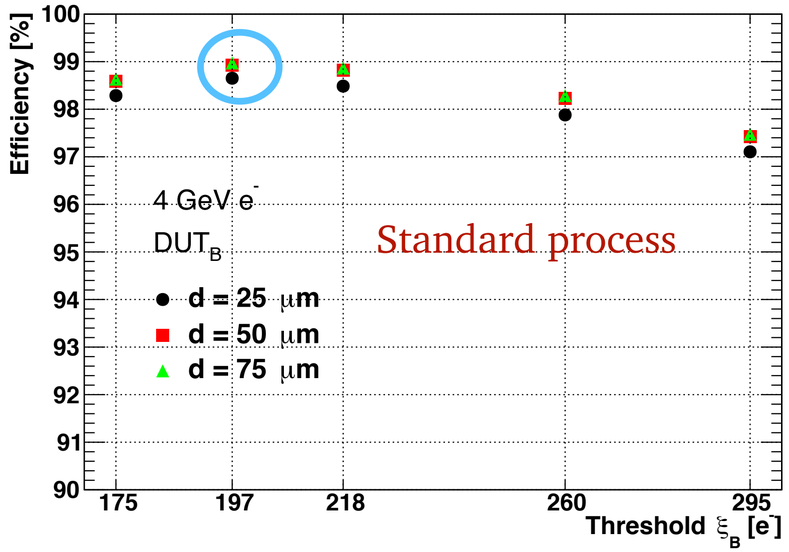
Efficiency vs. threshold (4GeV)

- Efficiency is the ratio of tracks that match the hit on the DUT within a distance d around the predicted hit from the telescope to all tracks of the telescope

$$\epsilon = \frac{N^{matched\ Tracks}_{|x_{meas},y_{meas}-x_{pre},y_{pre}|<d}}{N^{Tracks}_{tel}}$$

- With increasing threshold, the efficiency decrease
- maximum eff. for DUT_A is 99.4%, maximum eff. for DUT_B is 98.7%



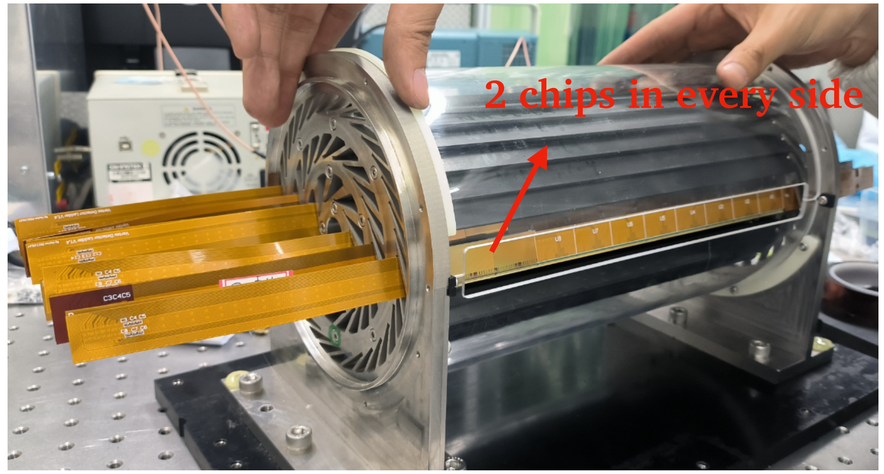


Mechanical prototype beam test @ DESY II

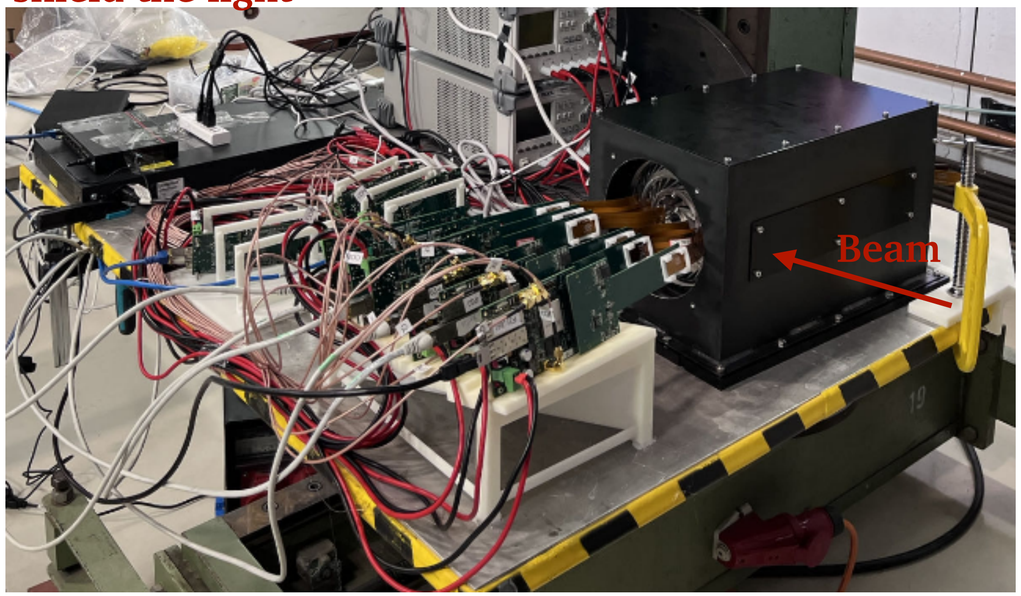
➡ Setup

- mechanical prototype beam test (11/04/2023 - 24/04/2023)
- 6 double sides ladders with 2 TaichuPix3 chips in every side (totally 24 chips installed)
- Biggest collimator available (2.5 x 2.5 cm2) used to focus on the chips on prototype

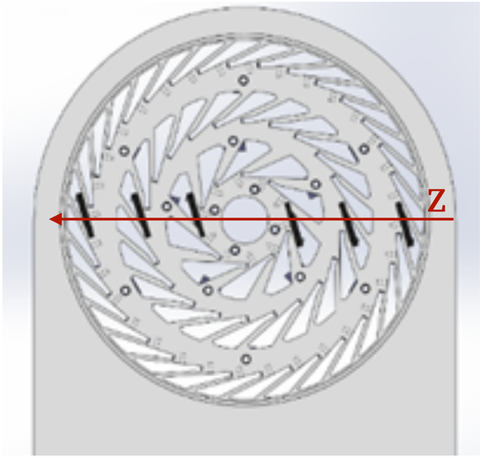
Prototype under the protection of a transparent cover



The prototype was placed in a black box to shield the light



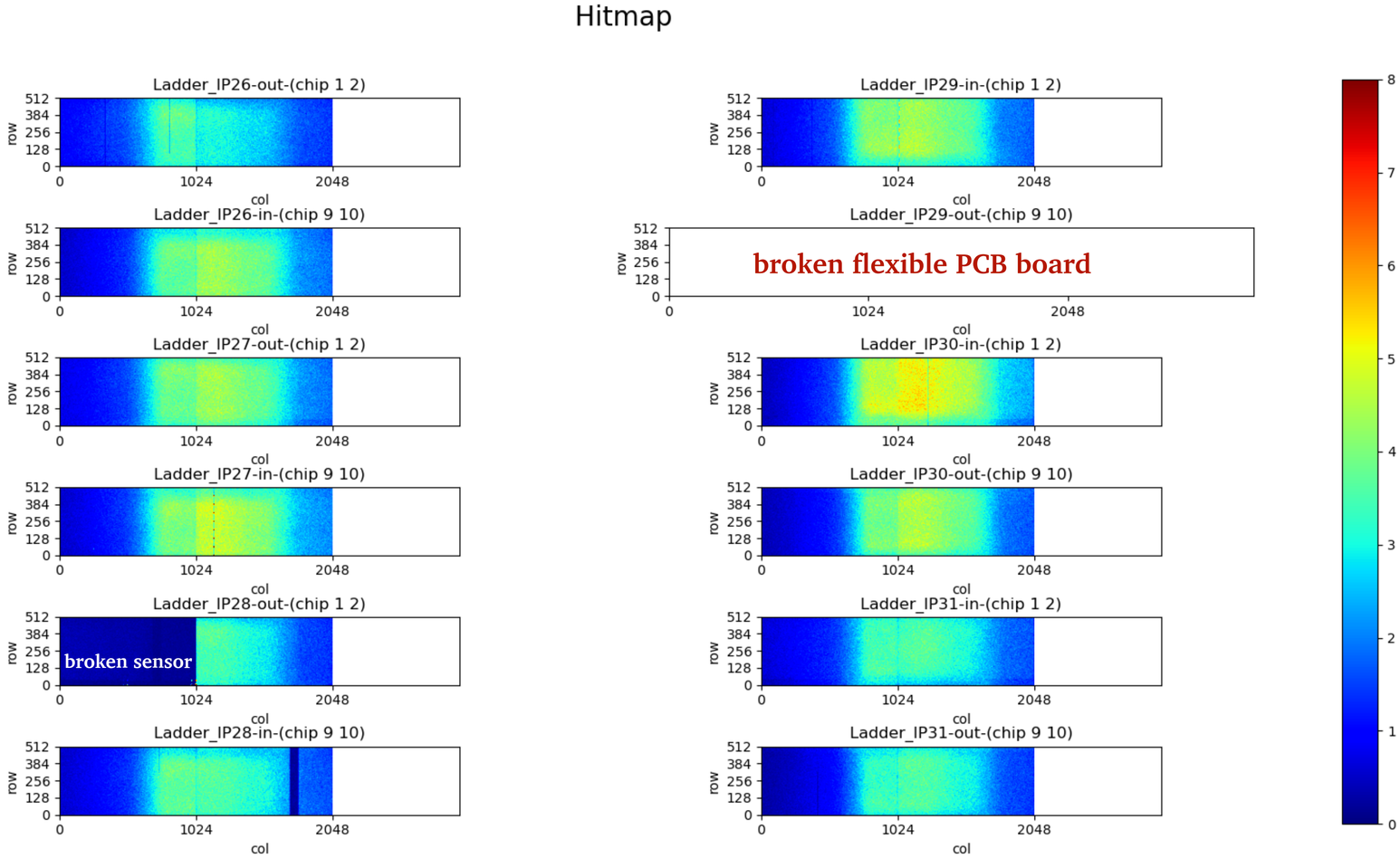
The fan or dry ice used to cool down the prototype



➡ Hitmap acquired by DAQ

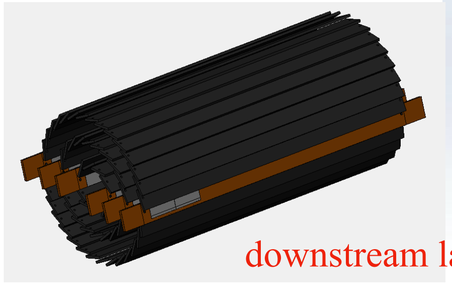
- The data rate for DAQ is ~ 12.5 MB/s
- Operating 21 sensors together with different energies and threshold

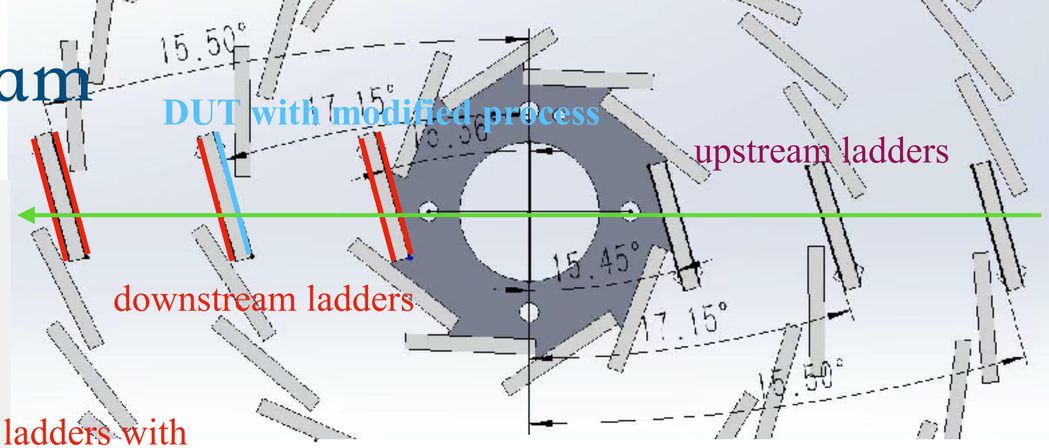
  - One flex PCB board broken and unreplaceable at DESY
  - One sensor on Ladder_IP28 sent bad data
  - **Both the prototype and the DAQ work well and stably for a long time under different energies and thresholds**



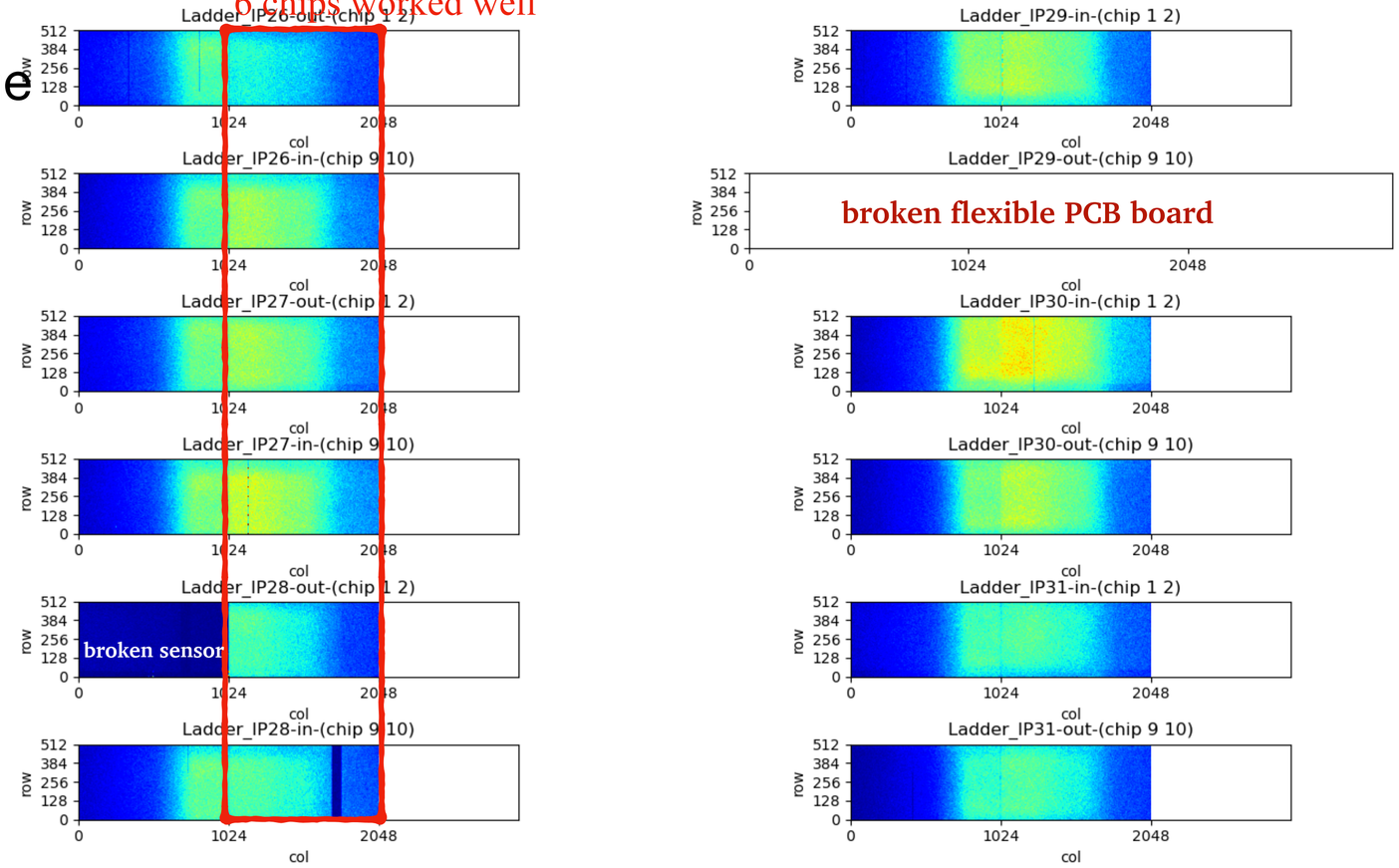
➡ Offline analysis results of second test beam

- Split up the full geometry into downstream and upstream ladders
- Considering the real vertex detector, the tracks will come from the IP. So, only 3 ladders will be transversed by the tracks.
  - It's enough to use the data from the downstream ladders with 6 chips to analyses the full prototype performance
  - Taking the chip with modified process in front of the middle layer as DUT



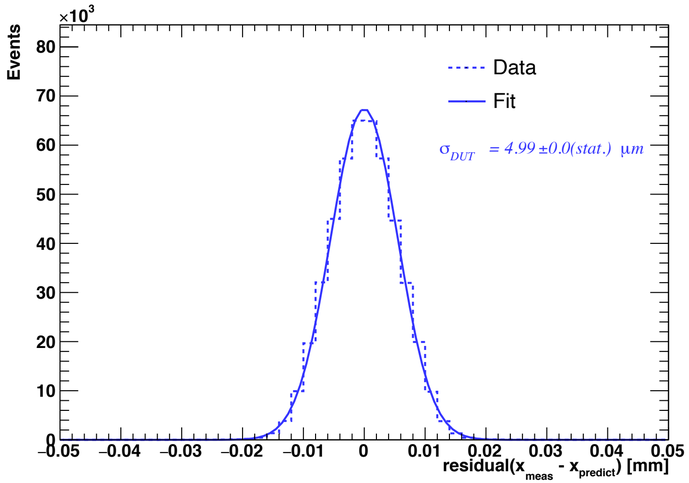


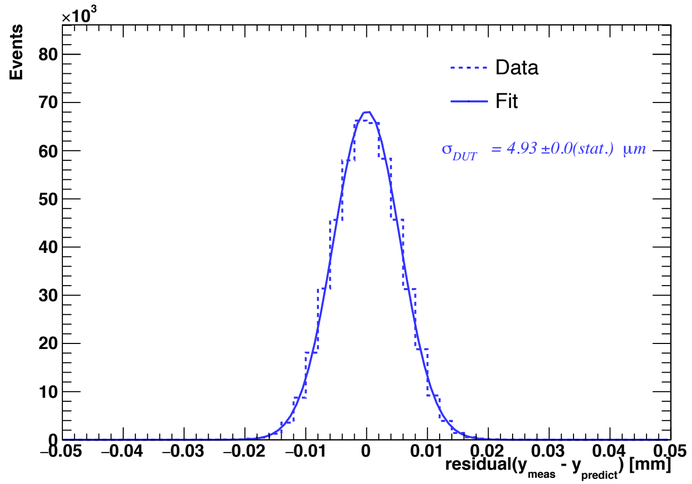
downstream ladders with 6 chips worked well

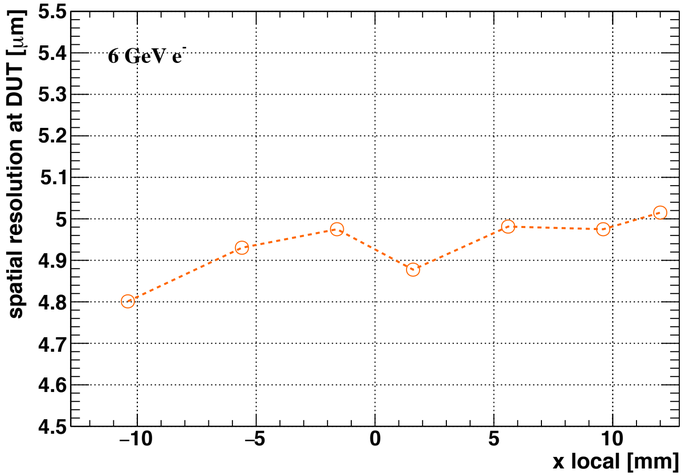


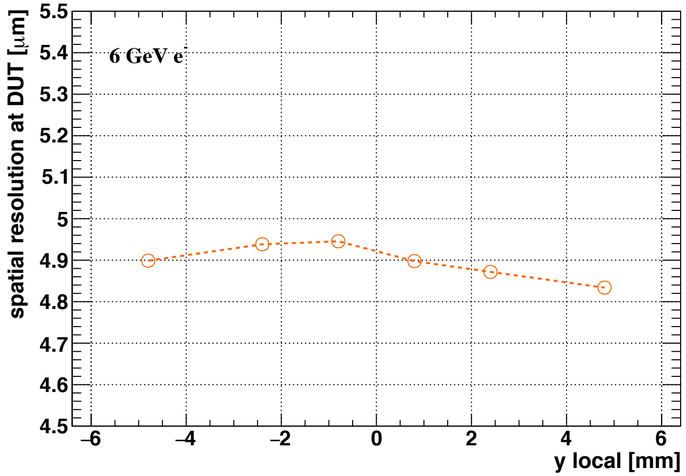
Single point resolution

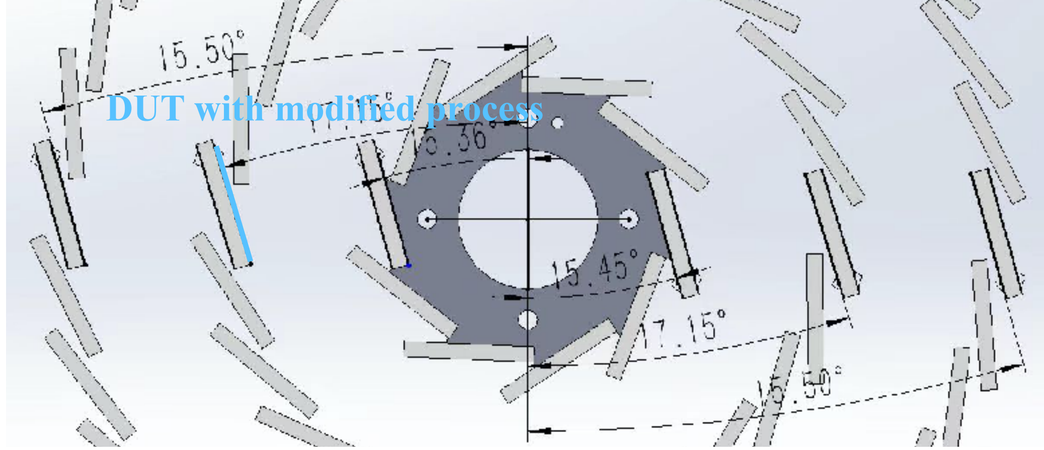
- 6 GeV electron beam
- DUT at lowest setting threshold $\xi \approx 330e^{-}$











- The unbiased residual distribution of DUT with modified process
- **The resolution < 5 um for both x and y direction**
- Split the DUT into several regions along the chip's column (x loc) and row (y loc) direction
- **The resolution in different region of chip < 5 um**
- More sophisticated alignment procedure need to be done to remove the variations as function of x and y

Summary

- The offline analysis framework developed for the test beam data
- The spatial resolution achieved the indicator goal of 3-5 μm using two test beams.

	Project indicators	Beam Test results	
Spatial resolution	3 - 5 μm	Pixel sensor prototype	Vertex detector mechanical prototype
		4.78 μm (threshold = 218 e-)	4.93 μm (threshold = 330e-)

- The different characteristics of the two TaichuPix3 chips with different processes were verified
- The prototype and DAQ can work well under different thresholds and energies
- The results of the cluster size, efficiency and resolution can be comparable between the two test beam

Backup

Spatial resolution studies

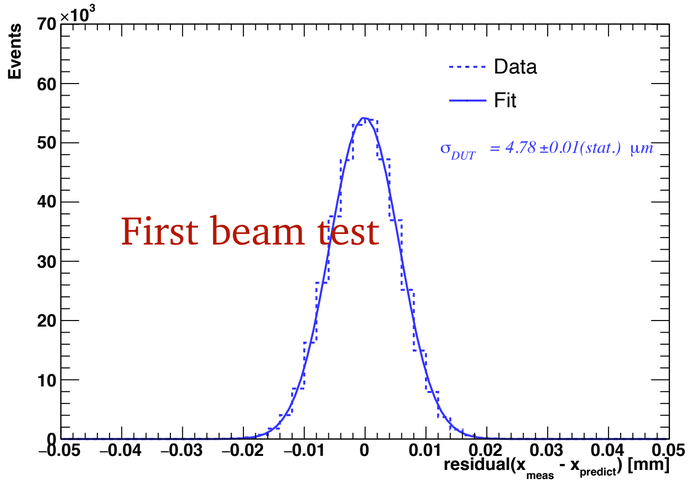
- **The spatial resolution of DUT**
  - applying the alignment parameters to the measured hit position
  - the spatial resolution of DUT evaluated from the unbiased residual distribution

$$\sigma_{DUT} = \sqrt{\sigma^2_{res,unbiased} - k\sigma^2_{tel}}$$

  - assuming same intrinsic resolution for all chips

$$\sigma^2_{DUT} = \frac{\sigma^2_{res,unbiased}}{1+k}, k = \frac{\sum_i^N z_i^2}{N\sum_i^N z_i^2 - (\sum_i^N z_i)^2}$$

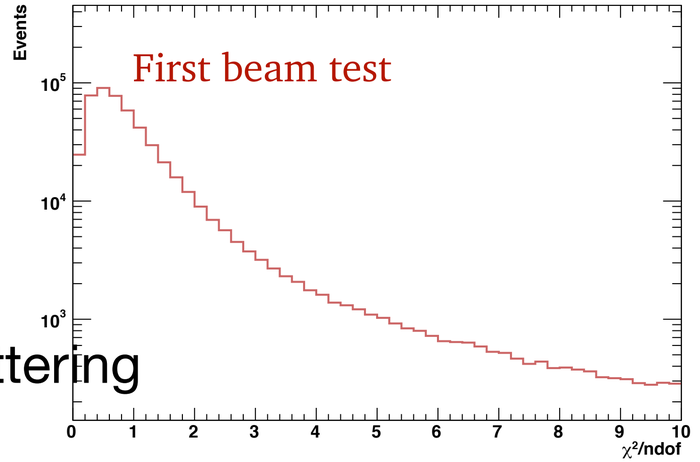
    - z_i is the z position of plane in global coordinate
    - unbiased residual $\sigma_{res,unbiased}$: the difference between measured hit position on DUT and the predicted one extrapolated from the track of telescope



  - least squares straight line fit

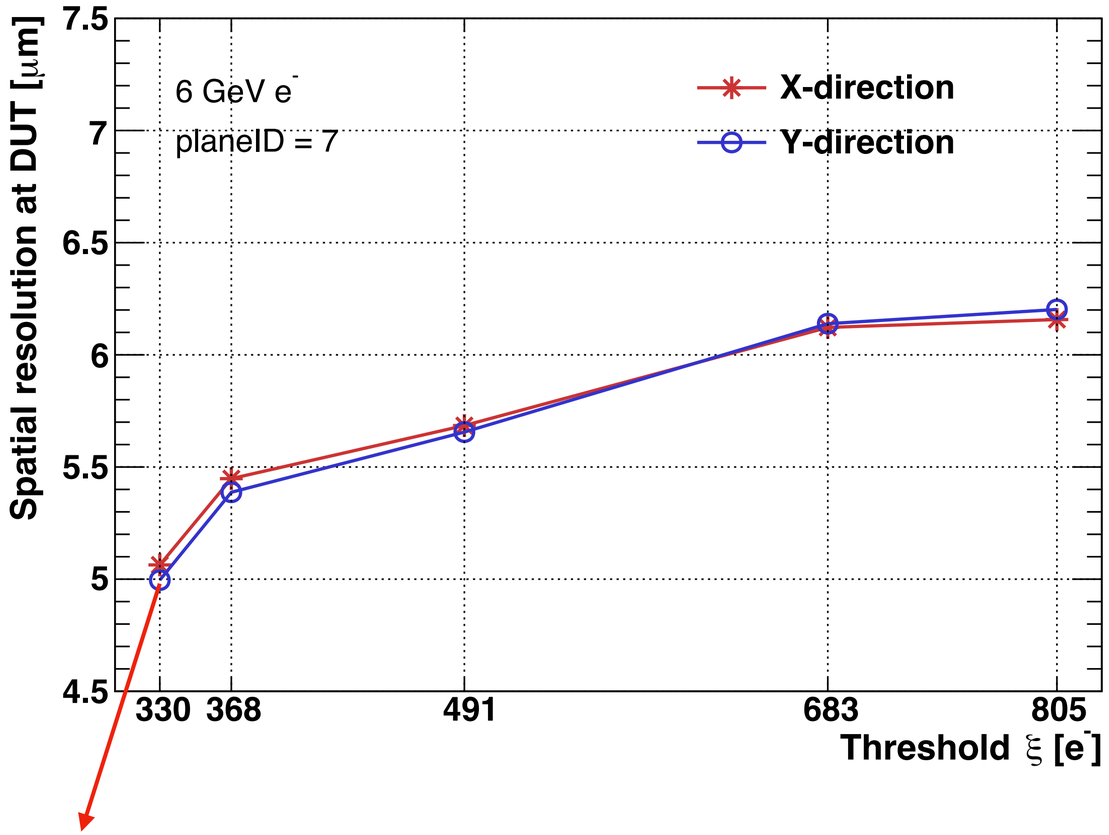
$$\chi^2 = \sum_i^n \frac{(x_{pre}, y_{pre} - x_{mea}, y_{mea})^2}{\sigma_{x,y}}$$

$\sigma_{x,y} = \frac{25\mu m}{\sqrt{12}}$, 25 um is the pixel pitch



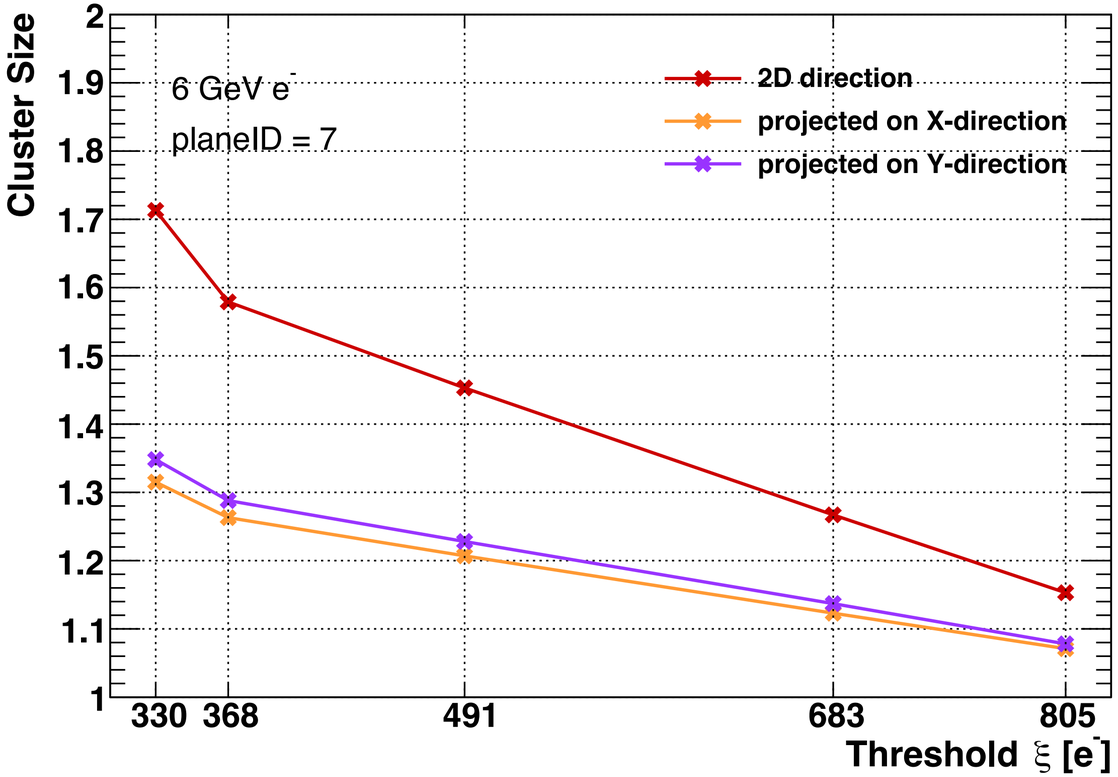
  - a track quality χ^2 cut added to decrease the effects from multi scattering

single plane resolution after subtracted track resolution

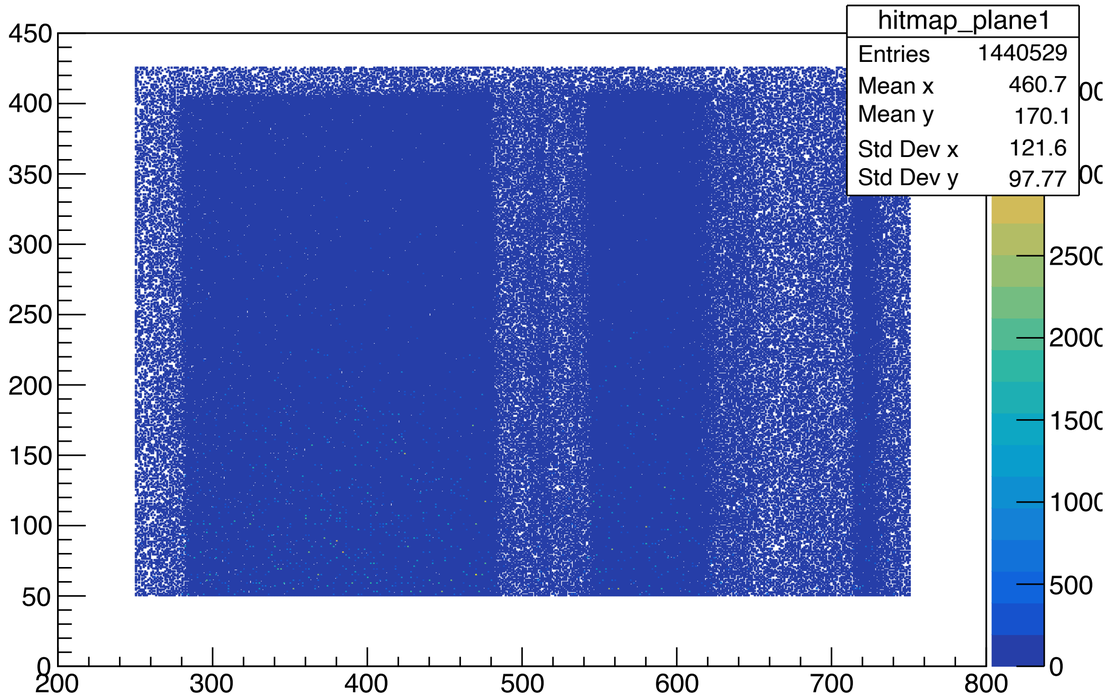


Cross checked with another run with same threshold, shows same resolution

cluster size



standard process, threshold 197 e-, eff. = 98.6%



modified process, threshold 265 e-, eff. = 99.4%