Beam test experience with small pitch 3D pixel sensors

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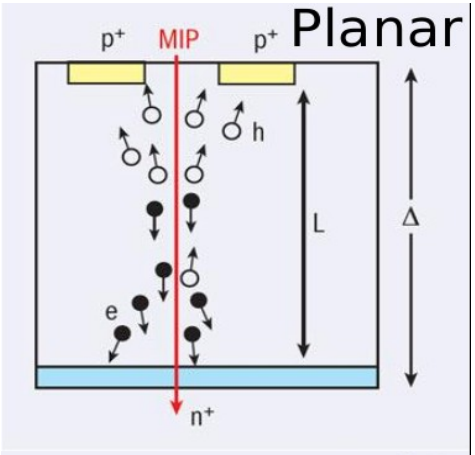
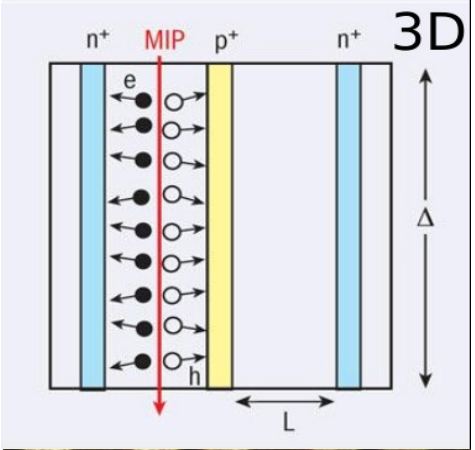
Index

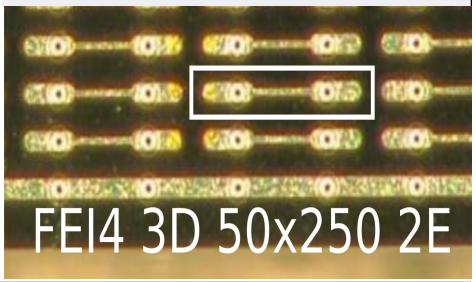
- Introduction
- Small pixel 3D structures: pixel size of 50x50 and 25x100 μm²
- Summary of Beam Tests with small pitch sensors
- The custom made 3D FEI4 Telescope + Judith reconstruction (not irradiated devices)
- EUDET + EUTelescope reconstruction + TBmon 2 analysis (irradiated devices)
- Conclusions

Introduction

- Current innermost layer (IBL) of ATLAS detector made of planar + 3D silicon sensors on FEI4 chip
  - Array of 336x80 pixels
  - Pixel size 50x250 µm²
  - Radiation hardness proven at least up to 9e15 n_{eq}/cm² (2016 JINST 11 C11024)
- **Planar**: electrodes implanted on the surfaces
- **3D**: column-like electrodes penetrating silicon bulk
- **Advantages** of 3D vs planar
  - Allows to reduce electrode distance (decoupled of sensor thickness)
  - Lower depletion voltage (lower power dissipation)
  - Increased radiation hardness
- **Upgrade** for high luminosity LHC
  - 3D pixel sensor good candidate for innermost layers
  - Need **smaller pixel size** to cope with higher occupancy and increased radiation levels (up to 2e16 n_{eq}/cm²)
  - Proposed pixel sizes 50x50 and 25x100 µm²

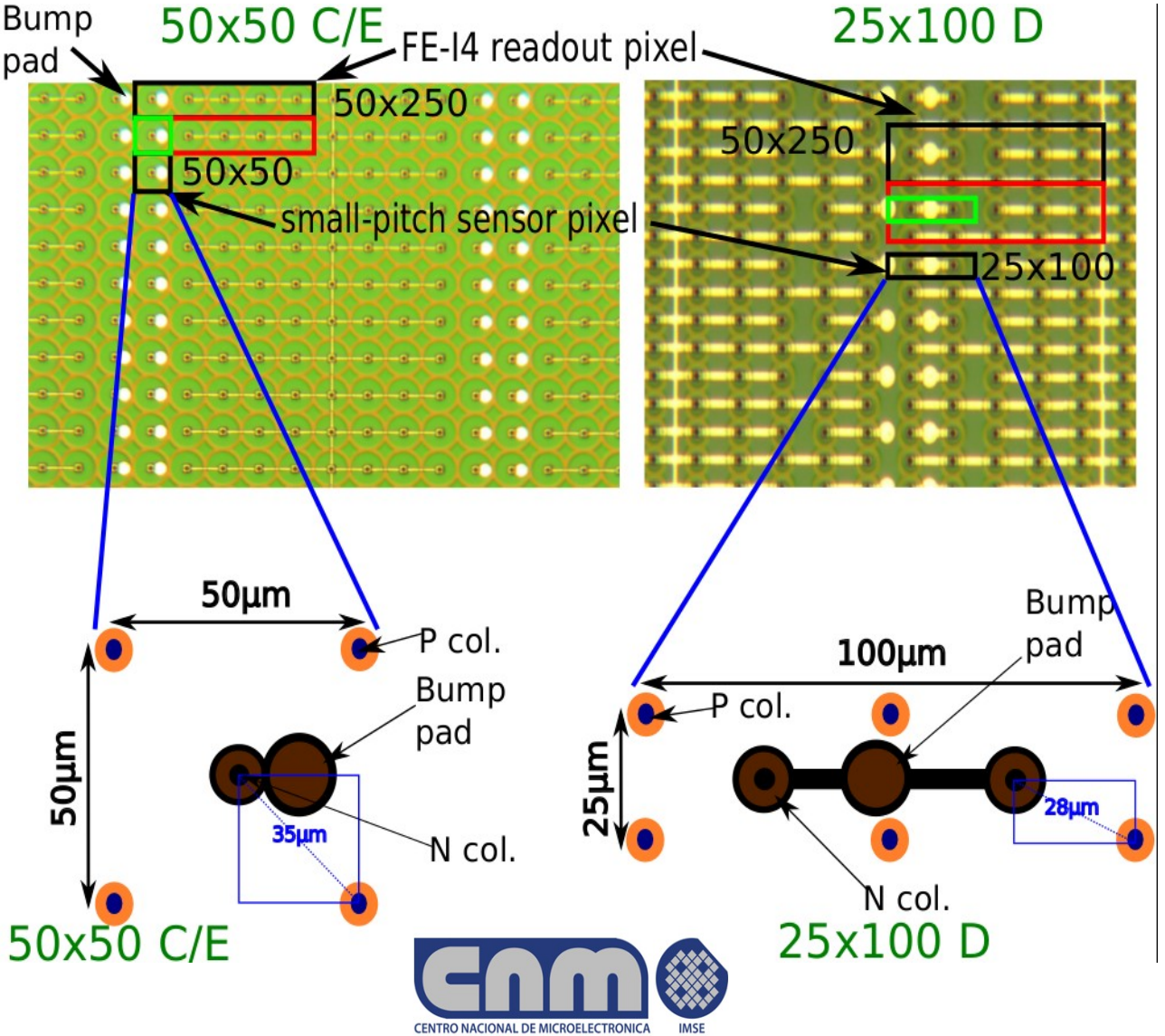






3D Small pixel structures

- Sensors produced by CNM-IMB
  - 230 µm thick
  - 8 µm 3D columns diameter
  - Characterization of this production in 2017 JINST 12 C01026
- **RD53** chip being developed for small pixel sensors
  - 50x50 µm² pixel size
  - Compatible with 50x50 and 25x100 µm² pixel size
  - Still not ready
- **FEI4** chip used to test first production of small pixel sensors
  - 50x50 and 25x100 µm² sensors need a **special structure** to use the FEI4 chip
  - One small size pixel (sensor pixel) connected to each FEI4 pixel (readout pixel)
    - The rest are connected to ground
    - **80% insensitive area** to take into account



Summary of Beam Tests

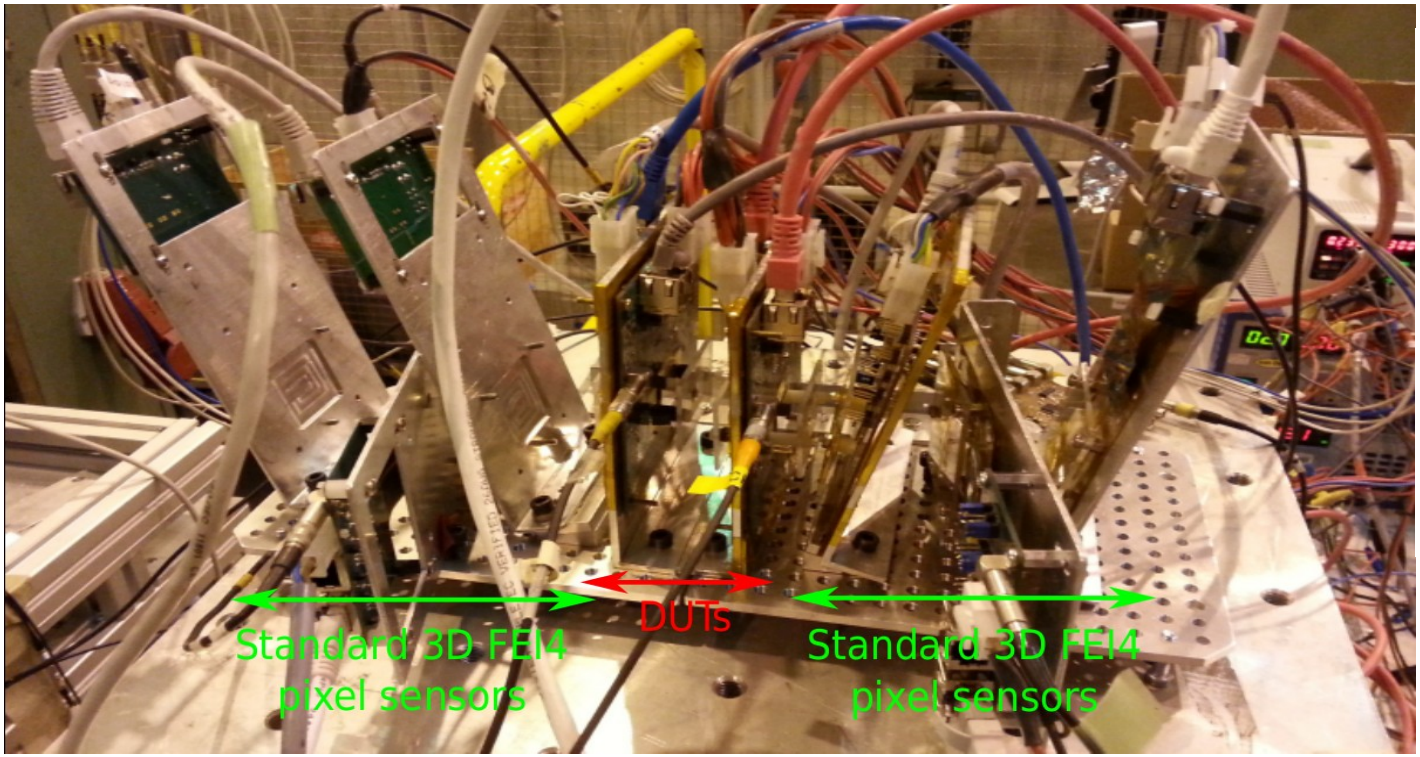
- Beam Tests with small pitch sensors (in CERN SPS)

Telescope	Reconstruction framework	Sensor geometry (μm²)	Irradiation (neq/cm²)	Reconstruction
Custom-made 3D FEI4	Judith	50x50 + 25x100	Not irradiated	Small sensor-pixel based
EUDET	EUTelescope + TBmon2	50x50 + 50x50	5e15 (KIT)	FEI4 readout pixel based

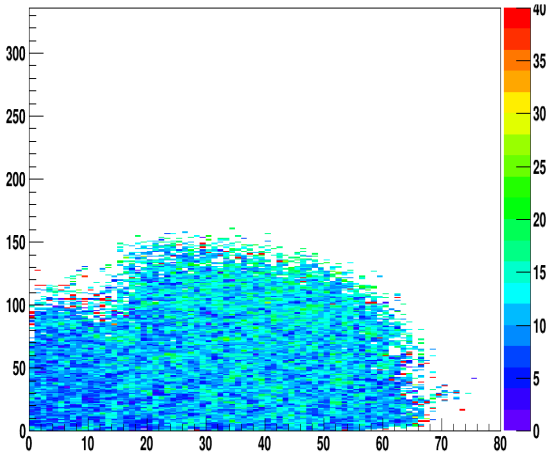
- First beam tests for small pixel sensors
  - No specific reconstruction software
- Two different approaches:
  - **3D FEI4 telescope + Judith** software: the structure of the sensor is implemented before the reconstruction and only the active sensor pixels are considered to calculate tracks
  - **EUDET telescope + EUTelescope** software: the calculation of the tracks is made over the full FEI4 pixel. In **TBmon2** analysis a region of interest (ROI) is chosen where the small pixel efficiency is calculated
- The results for FEI4 telescope/Judith are already published in 2016 JINST 11 C11024

The custom-made FEI4 telescope Judith reconstruction

The FEI4 telescope



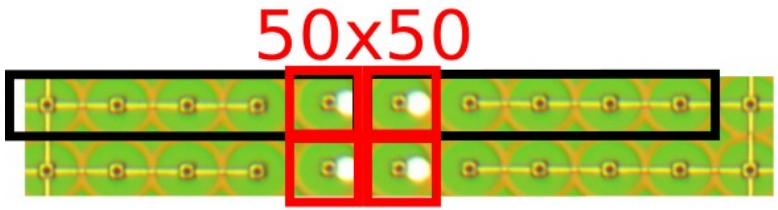
50x50 hitmap

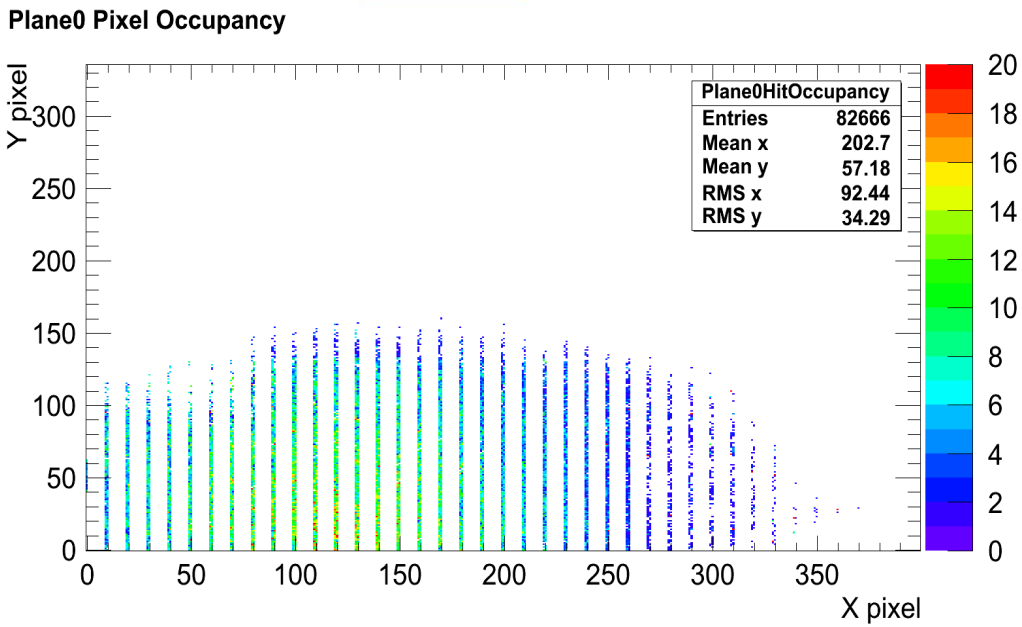


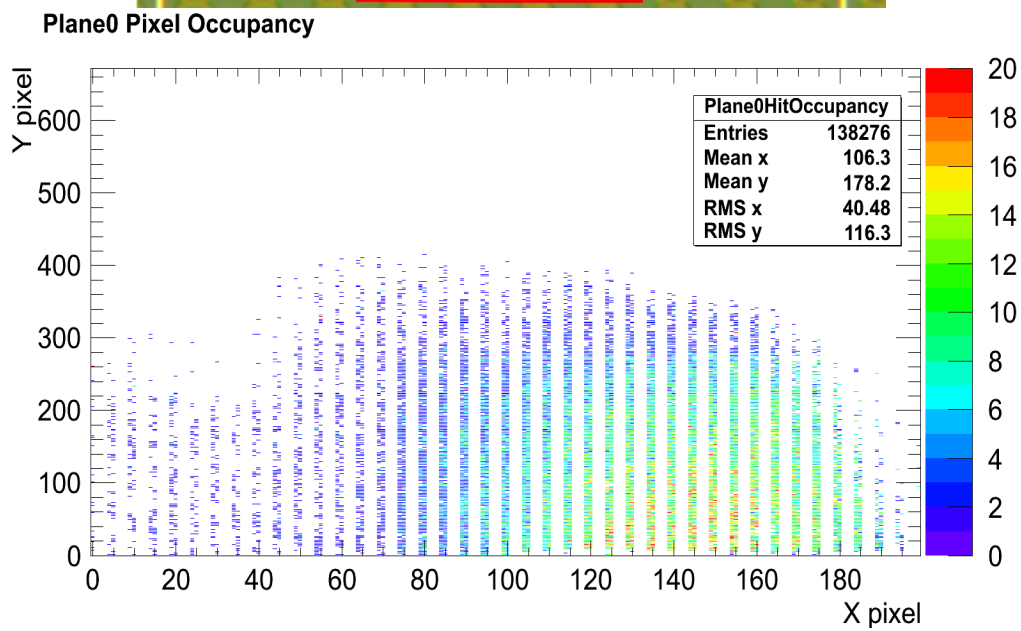
- Problems during the bonding to the FEI4 chip made that only part of the sensor is active

- Due to unexpected problems with EUTelescope reconstruction in past year beam tests, we created a custom 3D FEI4 telescope
- 3 + 3 telescope planes and DUTs between the arms
  - Telescope planes tilted (14º) in short pixel direction and two are rotated to increase the resolution
- Resolution 6 µm/plane in short pixel direction (2016 JINST 11 P09005) → ~4.2 µm in X and ~3 µm in Y expected
- Readout with RCE + analysis made in Judith framework (https://twiki.cern.ch/twiki/bin/viewauth/GeneveAtlas/GenevaJudith)

Judith reconstruction



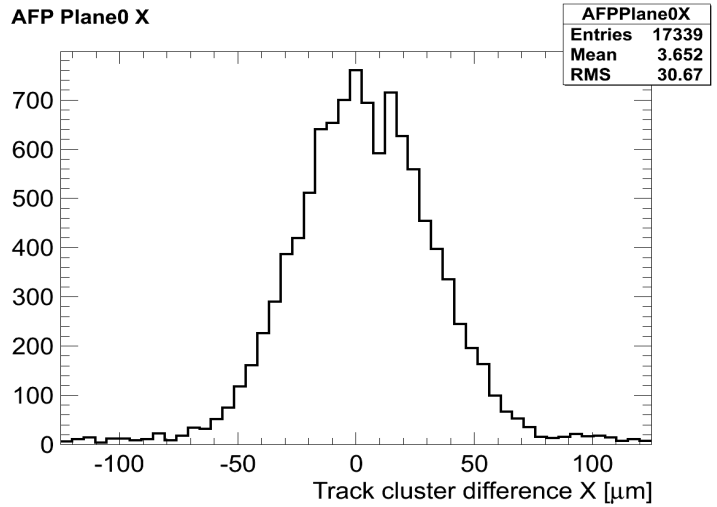


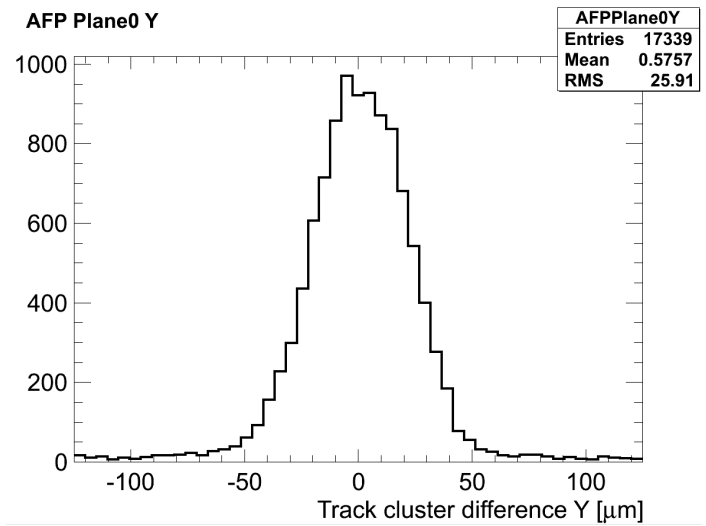


- The hits on the FEI4 pixel are assigned to the connected small pixel cell, to take into account only the sensitive area
  - The 50x50 µm² case presents a 100 µm width column pattern because of the 2 consecutive pixels in X
  - The 25x100 µm² case has active islands of 25x200 µm² because no neighbor exists in Y direction

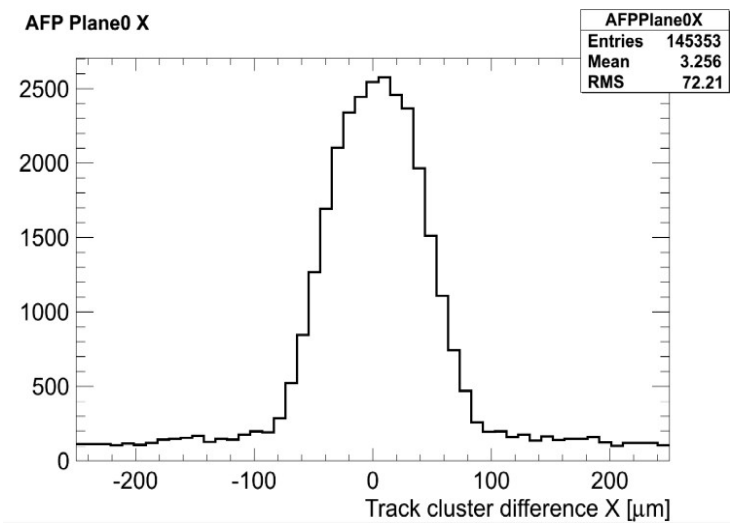
Judith reconstruction Residuals

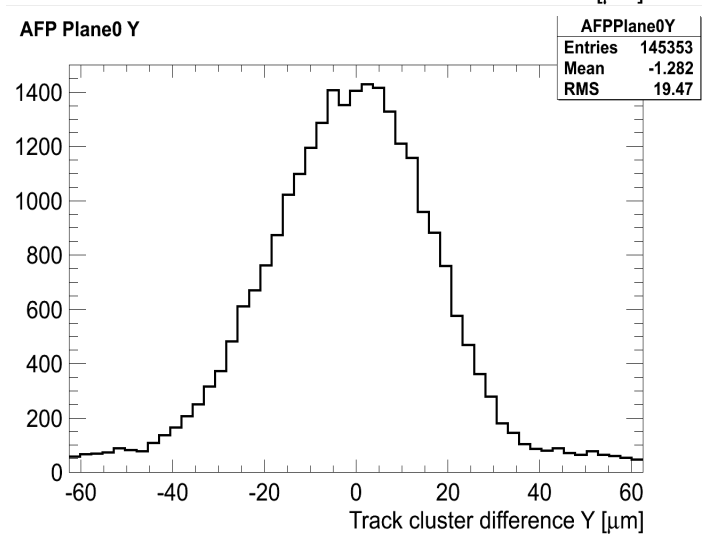
50x50 µm² residuals





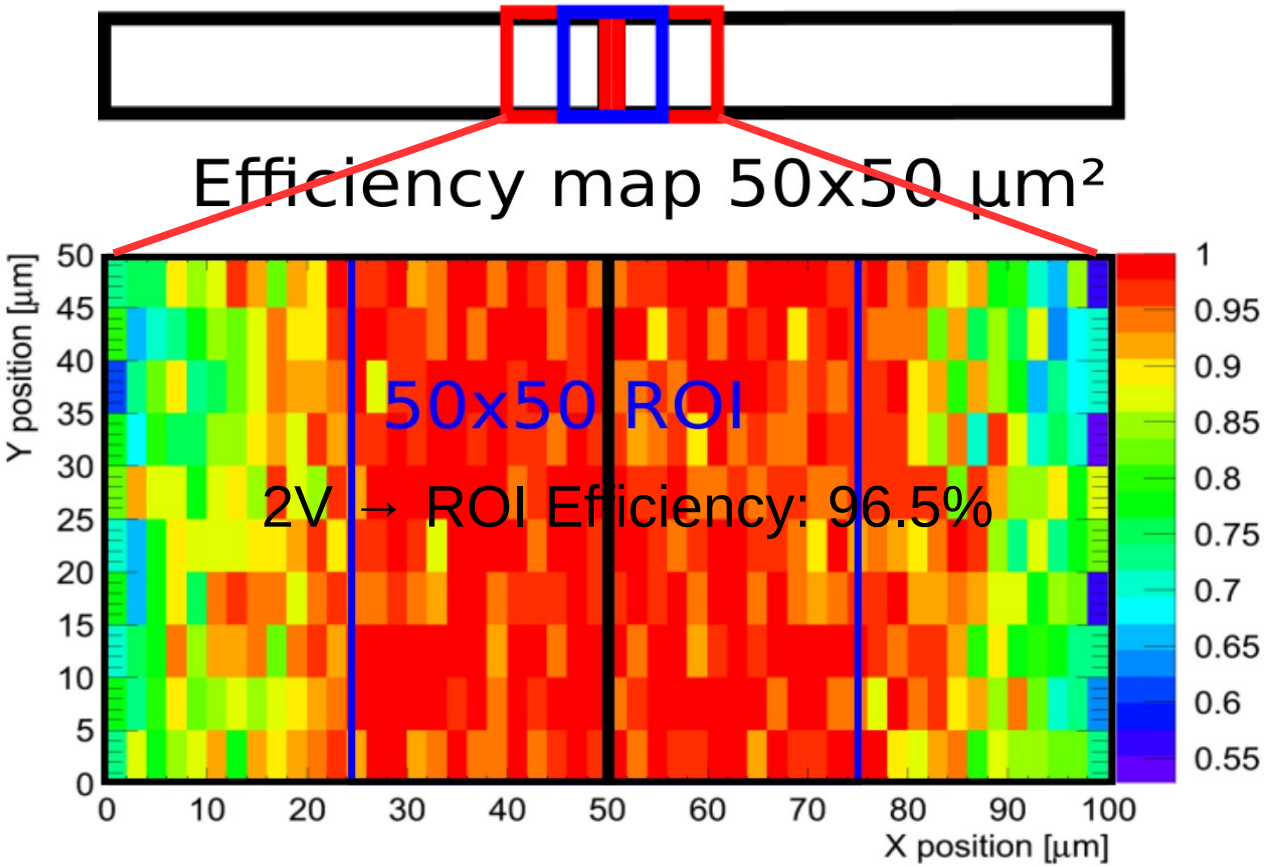
25x100 µm² residuals





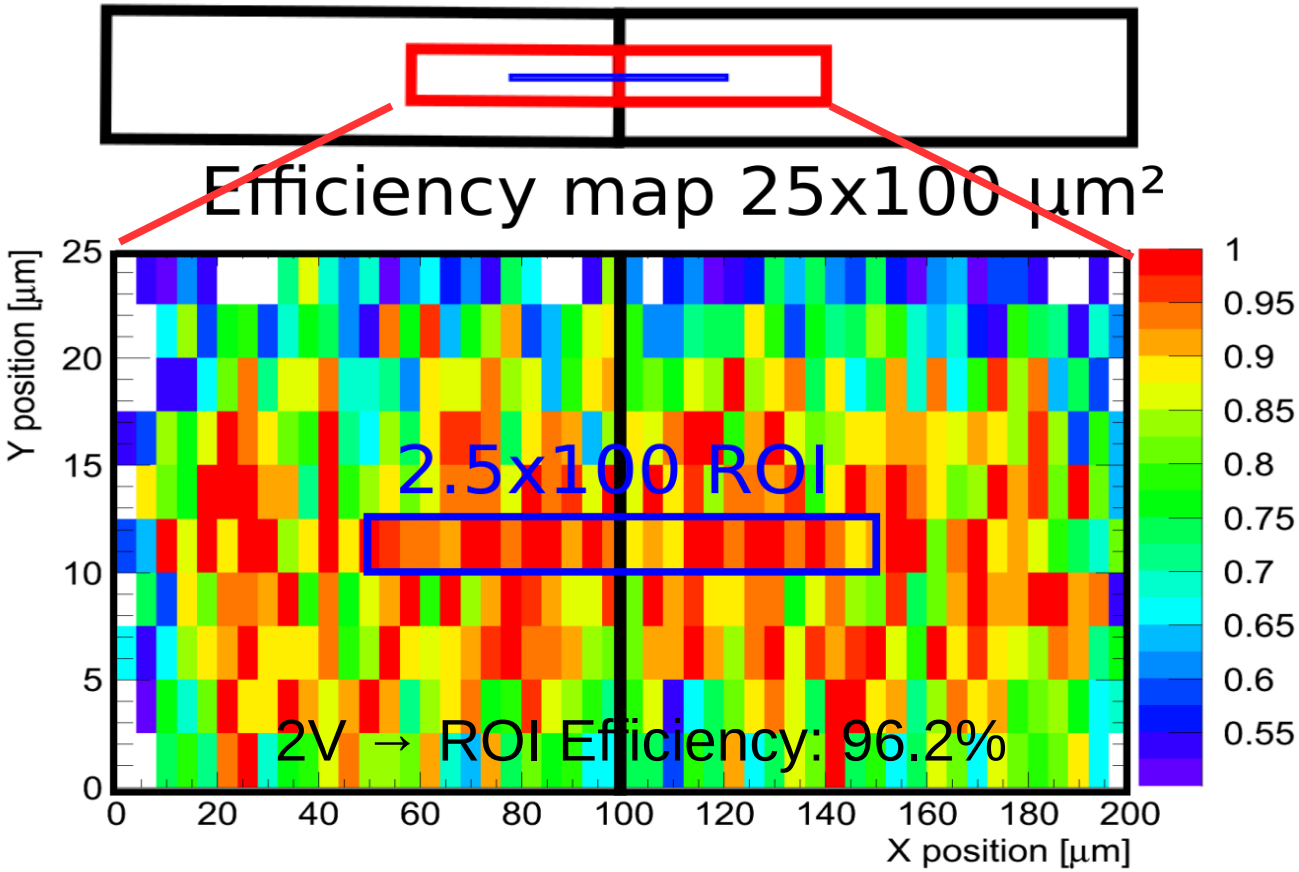
- The width of the residuals match with the pixel size

Judith reconstruction Efficiency (50x50 µm²)



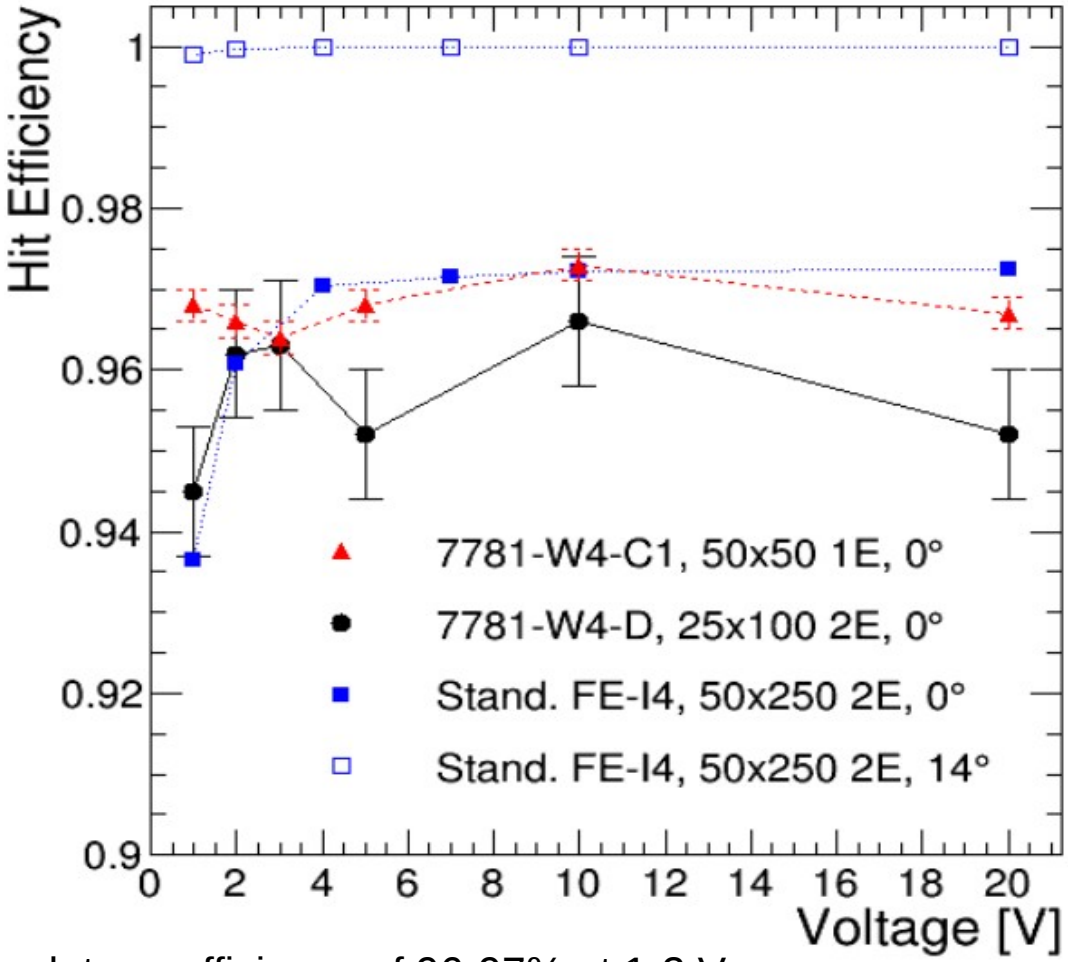
- The efficiency is calculated in two neighbor pixels (50x100 µm² area) in a central ROI of 50x50 µm² to avoid smearing in X

Judith reconstruction Efficiency (25x100 µm²)



- The efficiency is calculated in two neighbor pixels (25x200 µm² area) in a central ROI of 2.5x100 µm² to avoid smearing in X and Y

Judith reconstruction Efficiency



- Small pixels reach plateau efficiency of 96-97% at 1-2 V
- Similar efficiency to standard 3D FEI4 reference which needs 4V to reach the plateau
- Tilt can highly improve the efficiency up to 99.9% as demonstrated for FEI4 (small pitch tilted under analysis)

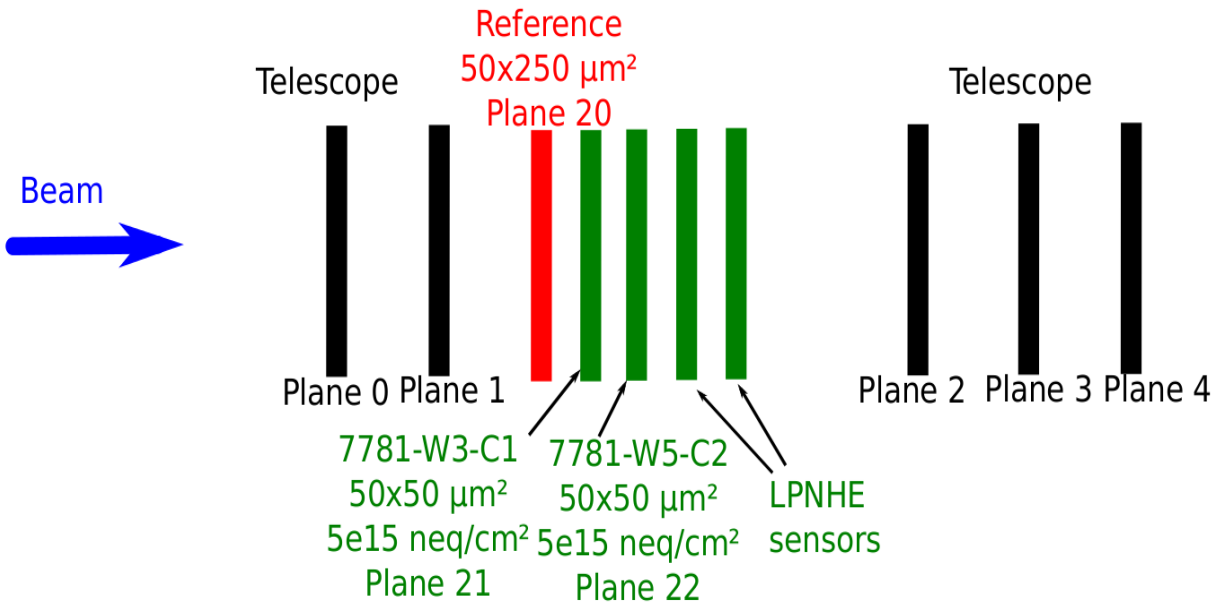
EUDET telescope
EUTelescope reconstruction

EUTelescope reconstruction Beam Test configuration

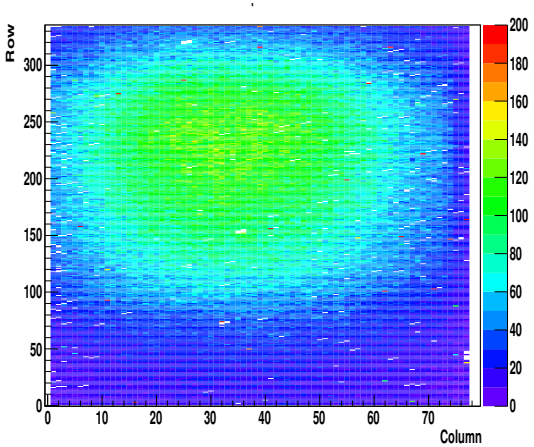
- EUDET-type Telescope in previous talks (https://telescopes.desy.de/)
- 1 Telescope plane missing due to malfunctioning
  - Reconstruction still worked
- 4 DUTs + 1 reference
- Reconstruction focused in planes 21 + 22 (only 50x50 µm² sensors irradiated uniformly to 5e15 n_{eq}/cm²)
  - Plots from plane 21
- Our approach:

  1) Make reconstruction from the point of view of the chip (50x250 µm²)

  2) Define region of interest (ROI) and calculate the efficiency on the active area

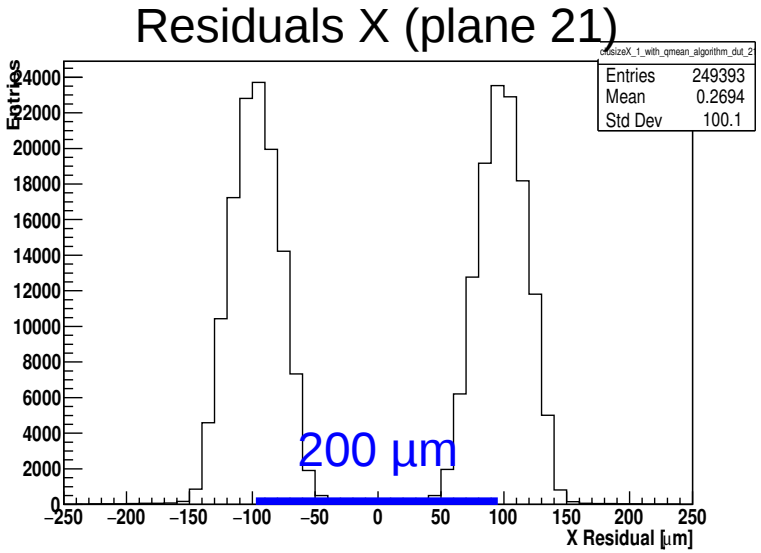


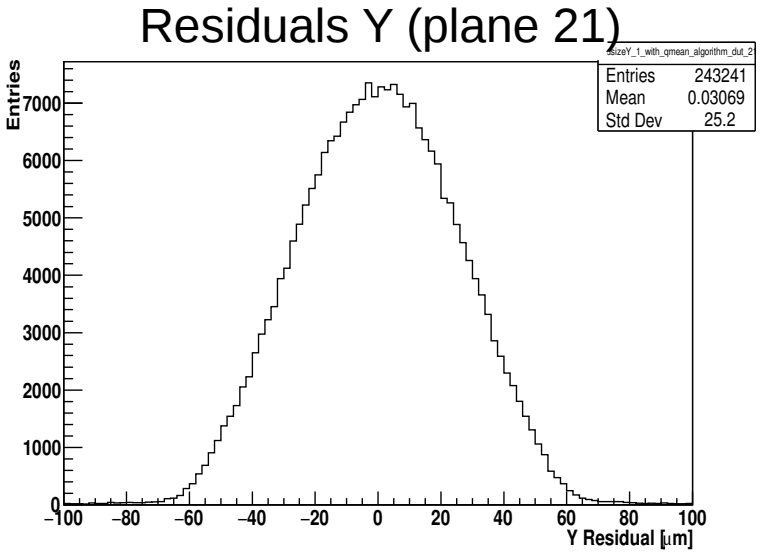
Hitmap plane 21

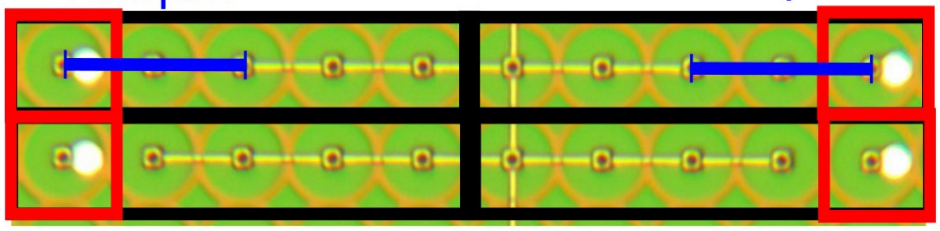


EUTelescope reconstruction & TBmon2 analysis - Align

- The main difference in small pixel reconstruction is the double peak in X
- Residuals in alignment are calculated assigning hits to the center of the FEI4 pixel
  - Half of the FEI4 pixels have the active small pixel in the leftmost part and half in the rightmost, meaning two distances are calculated





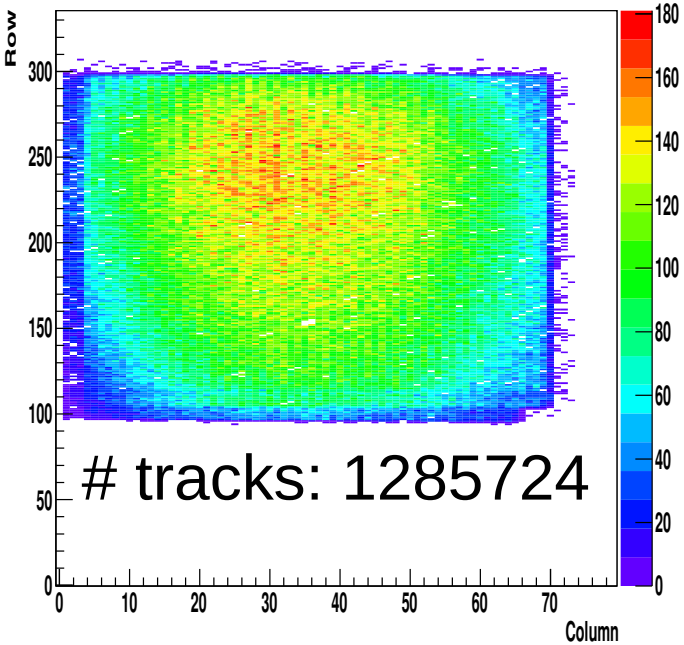


small pixel connected on leftmost side of FEI4 pixel

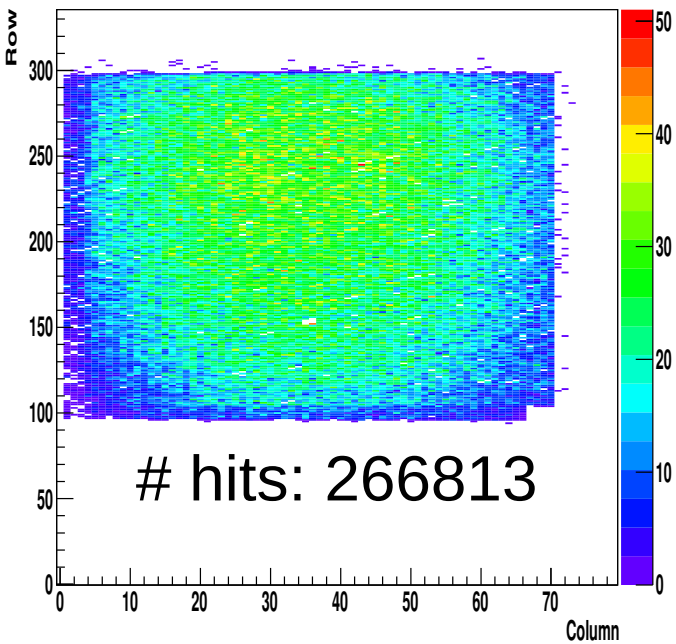
small pixel connected on rightmost side of FEI4 pixel

EUTelescope reconstruction & TBmon2 analysis - Efficiency

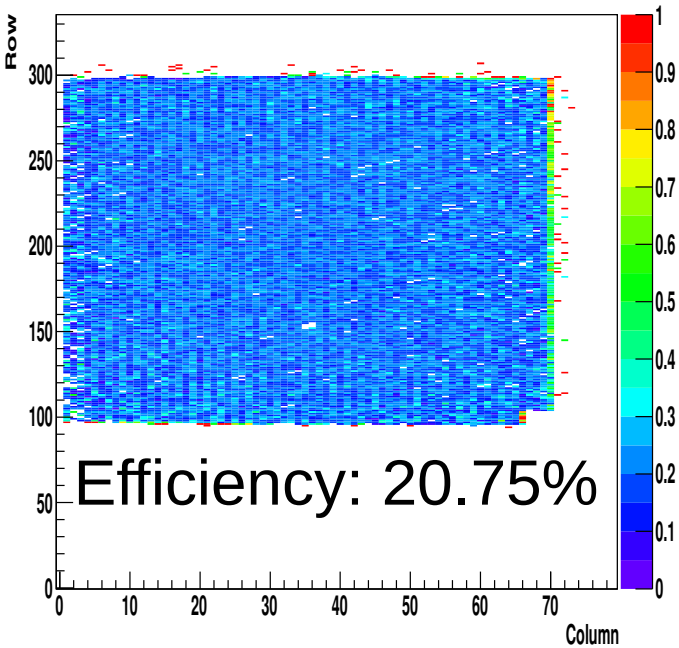
Reconstructed tracks (plane 21)



Hits on plane 21

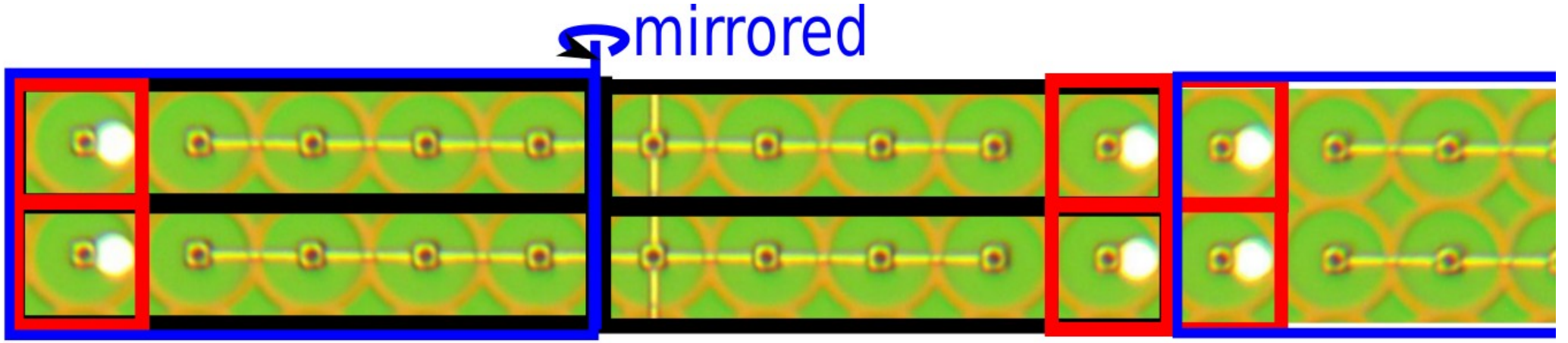


Efficiency on plane 21



- Global efficiency calculated dividing the hits observed on one plane by the tracks reconstructed by EUTelescope
  - Due to the special structure of the sensor (20% area active) the efficiency is only ~20% (already good indicative)
  - Efficiency >20% due to charge sharing from non active areas

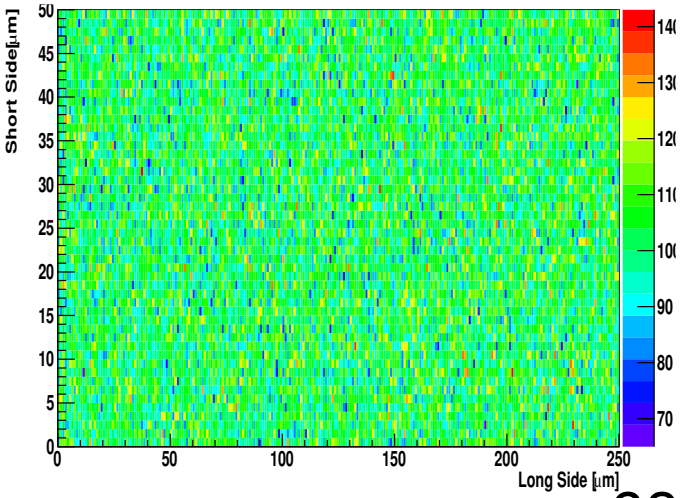
EUTelescope reconstruction
In-pixel efficiency detail



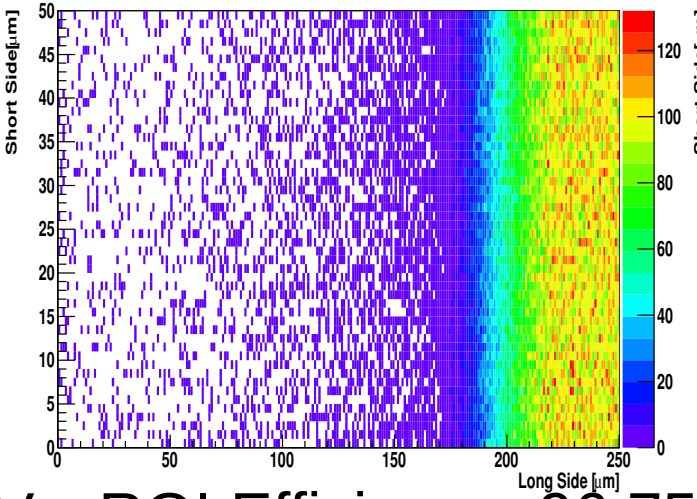
- To calculate the in-pixel efficiency it is needed to add up the efficiency in the same area
- The FEI4 pixels with the leftmost sensor pixel connected are mirrored

EUTelescope reconstruction & TBmon2 analysis – In-pixel effic.

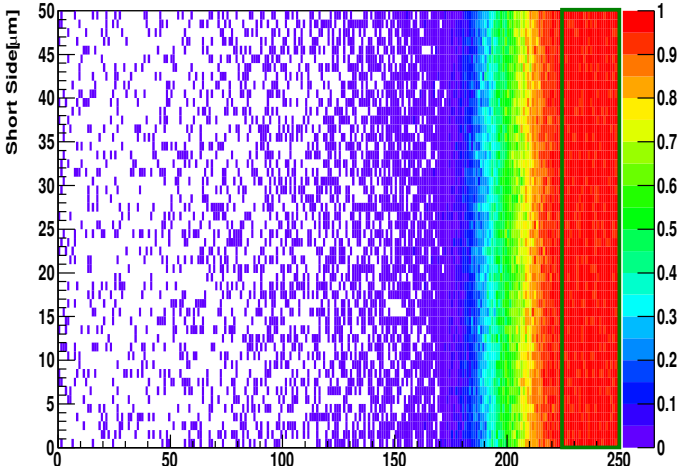
Reconstructed tracks (plane 21)



Hits on plane 21

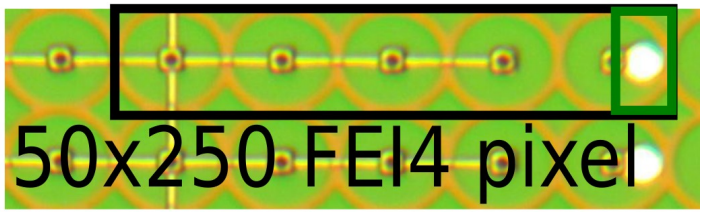


Efficiency on plane 21



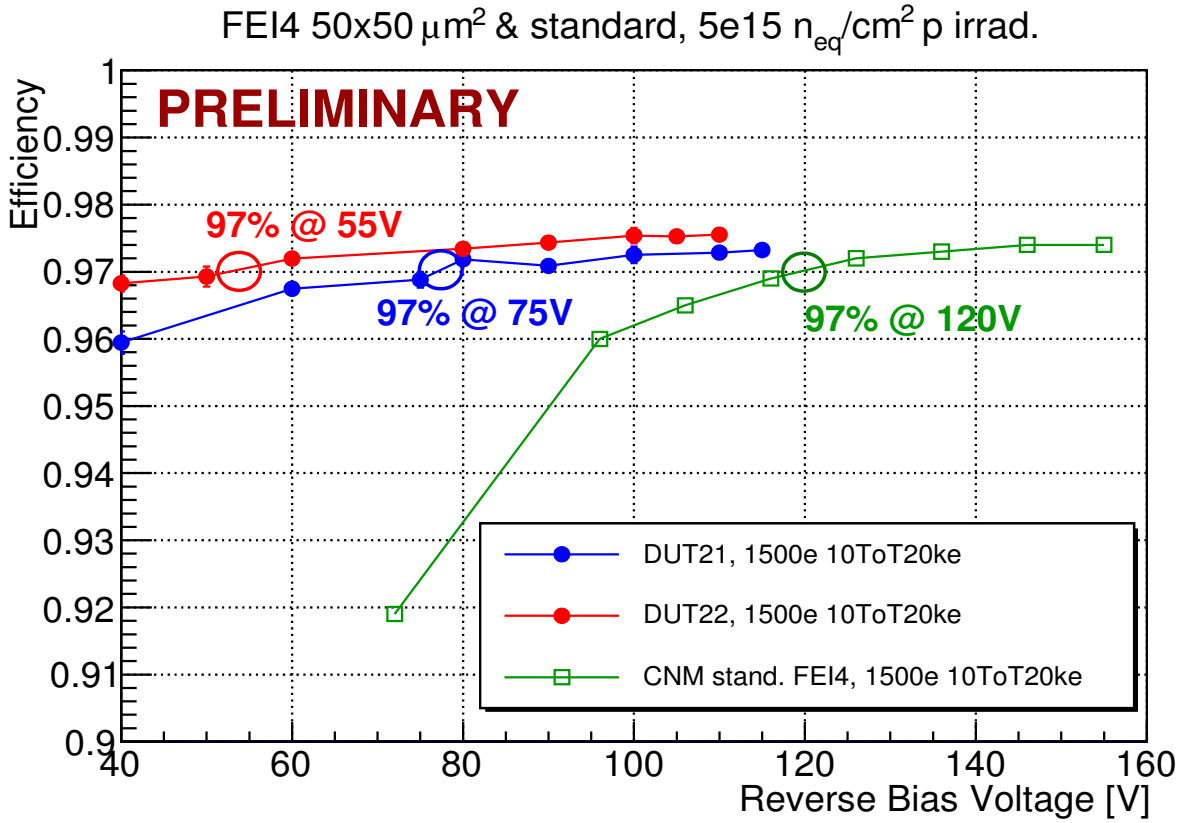
60V → ROI Efficiency: 96.75%

50x25 ROI



- To calculate the in-pixel efficiency, a region of interest is defined in the edge of the FEI4 pixel (from 0 to 50 µm in Y and from 225 to 250 µm in X)
  - Taking 50x25 instead 50x50 µm² to avoid telescope smearing
  - Neighbor pixel connected → no smearing in the right side
  - Excludes the effect in the insensitive area

EUTelescope reconstruction & TBmon2 analysis – Efficiency



- Efficiencies measured at 1ke and 1.5ke thresholds (10ToT @ 20ke) at -40ºC and -50ºC (temperature on chip -20ºC and -30ºC) for each DUT
  - Agreement within 0.2%
- At 5e15 n_{eq}/cm^2 irradiation the efficiency reaches 97% at much lower voltages than the IBL sensors
- Plateau efficiencies at 80 V

Conclusions

- First 3D production of small pixel structures
  - Need to use FEI4 chip due to RD53 chip unavailability
  - Small pixel sensors need a special structure to be readout with FEI4 chip
- Need to adapt the reconstruction and analysis tools to the special small pitch + FEI4 structures
  - 3D FEI4 Telescope + Judith reconstruction & analysis
  - EUDET Telescope + EUTelescope reconstruction & TBmon2 analysis
- Analysis of 50x50 and 25x100 µm² small pitch sensors not irradiated with Judith
  - Defined the internal structure of the small pixel structures before the reconstruction
  - Both small pixel devices show plateau efficiencies at 1-2 V with 96-97% efficiency
  - Lower voltage needed than standard FEI4 to reach the plateau
- Analysis of 50x50 µm² small pitch sensors irradiated to 5e15 n_{eq}/cm² with EUTelescope & TBmon2
  - Reconstruction is made over the full FEI4 pixel and the efficiency is calculated over a ROI
  - Operation voltage much lower than IBL generation irradiated to the same fluence
  - Plateau efficiencies at ~80V

Thanks for your attention