Analysis of FBK sensor performance with data from DESY Test Beams

Simone Gennai

on behalf of the CMS Phase-2 Inner Tracker Group

Acknowledgements

- ☐ Due to COVID-19 pandemic the access to TB facilities has been quite problematic.

  - ☐ We would like to thank DESY, Hamburg and Zurich University teams for having made the data taking possible

- ☐ For their invaluable contribution in design and production of both planar and 3D pixel sensors, we would also like to thank:

  - ☐ M. Boscardin, F. Ficorella, S. Ronchin (FBK)

  - ☐ G.F. Dalla Betta (UniTN)

Design implications for the sensors of the pixel detector

HL-LHC operation conditions	Sensor design contraints
Luminosity $7.5 \times 10^{34}/(cm^2 s)$ Up to **200 events/25 ns** bunch crossing	Maintain occupancy at ‰ level and increase spatial resolution ➜ pixel cell size ~ 25x100 μm² or 50x50 μm²
Fluence **~2.3×10^{16} n_{eq}/cm²** for first pixel layer at 3000 fb⁻¹ (~10 years) ➜ carriers lifetime ~0.3 ns, **mean free path ~30 μm** for electrons at saturation velocity	Reduce electrodes distance (**L**) to increase electric field and the signal ➜ thin planar or 3D columnar technologies

Joint ATLAS-CMS INFN collaboration, partnership with Fondazione Bruno Kessler-**FBK** (Trento, Italy), for the development of **thin planar** and **3D columnar n-in-p** sensors on **6"** **FZ wafers** with **Direct Wafer Bond**[1]
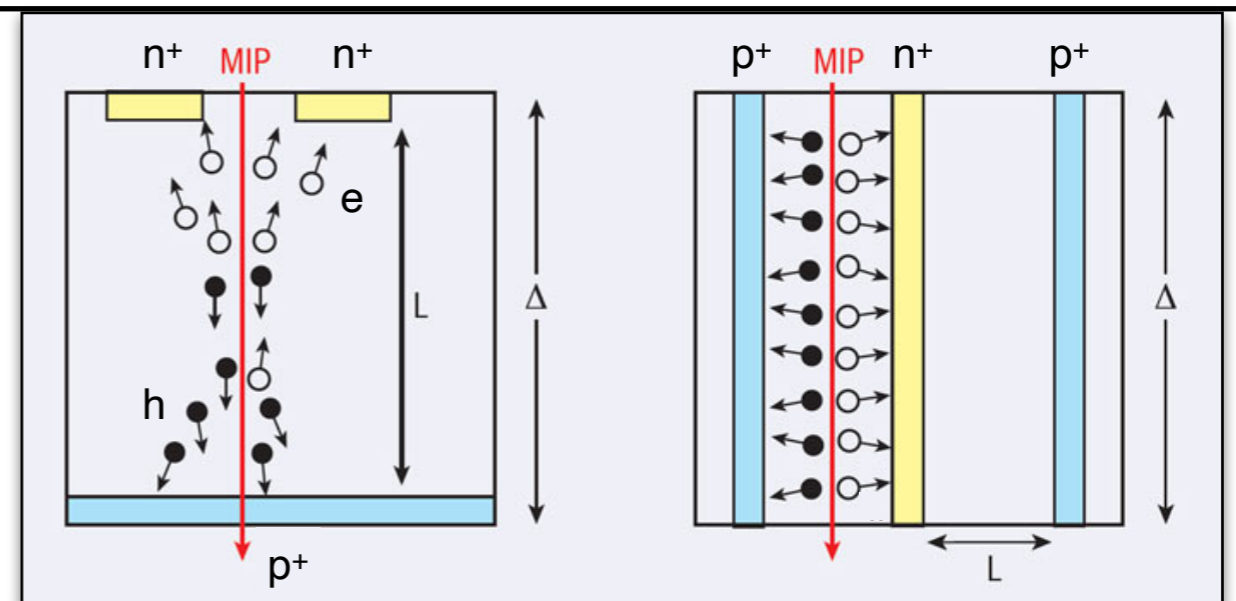
[C. Da Vià et al, NIMA (2012)]
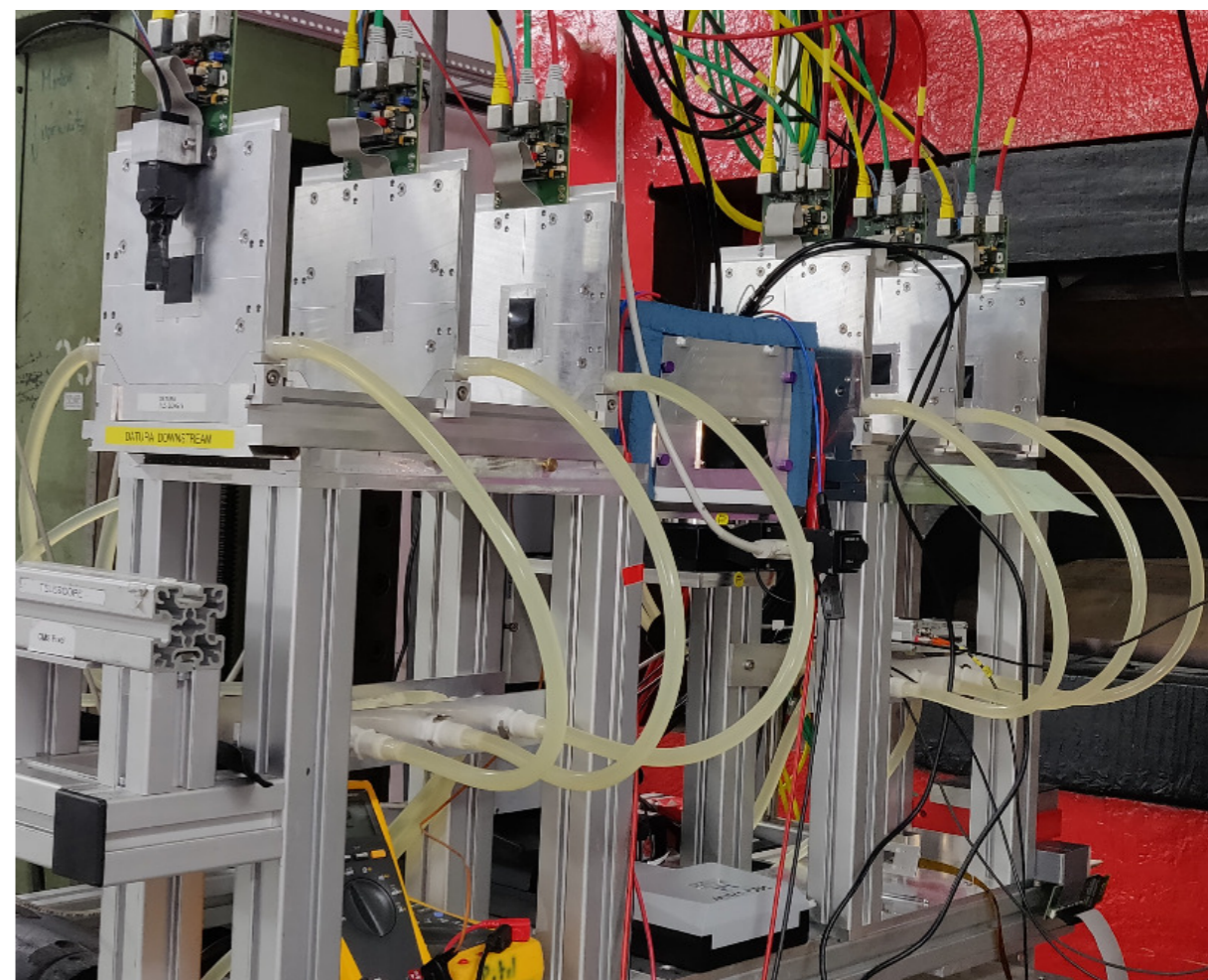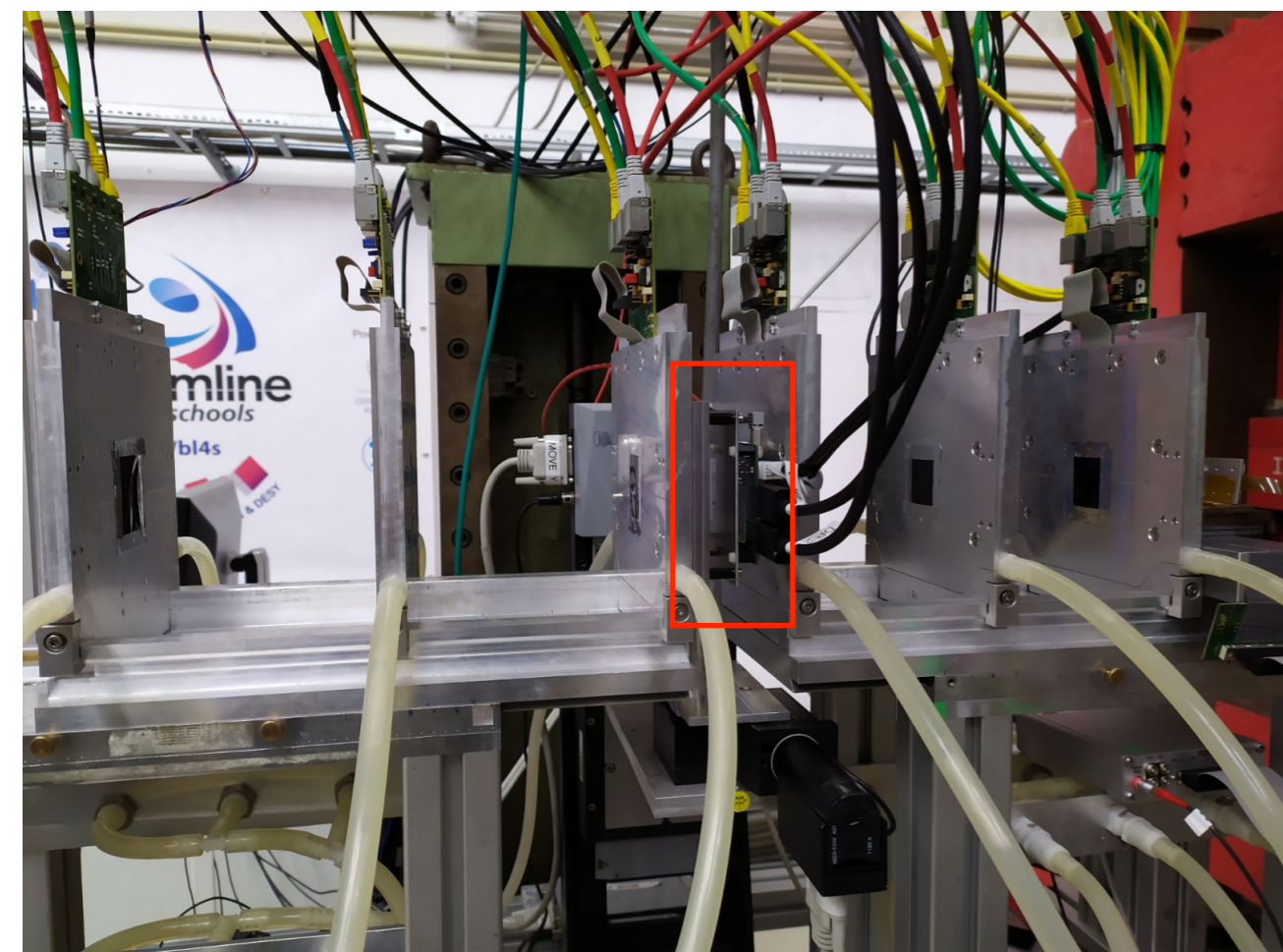
[1] IceMos Technology, Belfast

Test Beam set up

- **Mimosa Telescope**

    - 3 planes before the Device Under Test (DUT)

    - 3 planes after the DUT

    - Spatial resolution up to ~3.8 um

        - When the cold box is not installed!

- **Data collected in several TB**

    - November 2019

    - June 2020

    - July 2020

    - December 2020

FBK Sensors equipped with RD53A chip

☐ All sensors were produced by FBK

  ☐ 25×100 um^2 and 50×50 um^2

  ☐ Active thickness 130/150 um

  ☐ Wafer thinned down to a total of 200 um thickness and bonded to a RD53A chip

☐ Performance measured before and after irradiation

  ☐ Not on the same sensor, though

  ☐ Max radiation fluence of 1.2E16 n_{eq}/cm^2

    ☐ Sensor irradiated at KIT facility

Data from November 2019

- ☐ 3D sensors tuned with a threshold around 900 e-

    - ☐ **25x100**: (130 um) 3D Mask Aligner

        - ☐ both VB = -6 and -30 V, around 0.13 uA

        - ☐ Bump Bonded at IZM Germany

    - ☐ **50x50**: (150 um) 3D Stepper

        - ☐ VB = -6 around 6.5 uA, and -30 V around 16 uA

        - ☐ Bump Bonded at Leonardo Italy

- ☐ Data analyzed for efficiency, Signal collection and cluster size distributions

    - ☐ All plots shown are based on data with incident angle at 0 degrees

    - ☐ Sensors were **NOT** irradiated

3D - 25×100 µm²
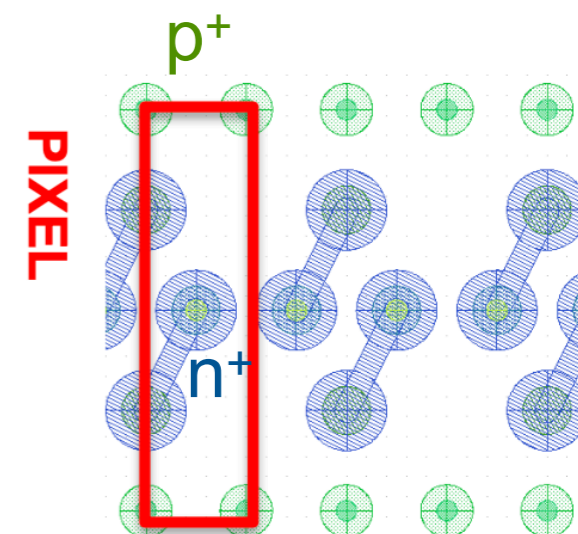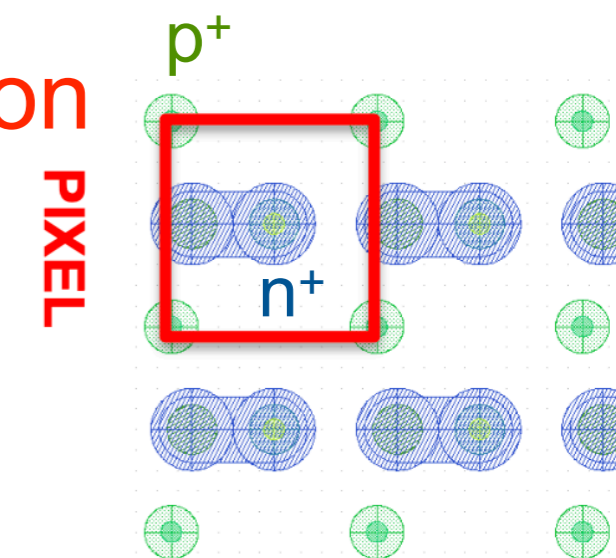
3D - 50×50 µm²

25x100 3D sensor

□ **Efficiency and signal distribution per cell**

  □ small residual misalignment ~2 um

  □ Average efficiency > 99%

  □ **No pixel by pixel calibration has been applied**

□ **Plots made with Vbias = -30 V**

  □ Perpendicular tracks only

PIXEL

3D - 25×100 µm²

Efficiency per cell

n⁺ column

30V

p⁺ column

x track mod 100 [µm]

y track mod 100 [µm]

Signal per cell

n⁺ column

30V

p⁺ column

x track mod 100 [µm]

y track mod 100 [µm]

LIN <cluster signal> [ToT]
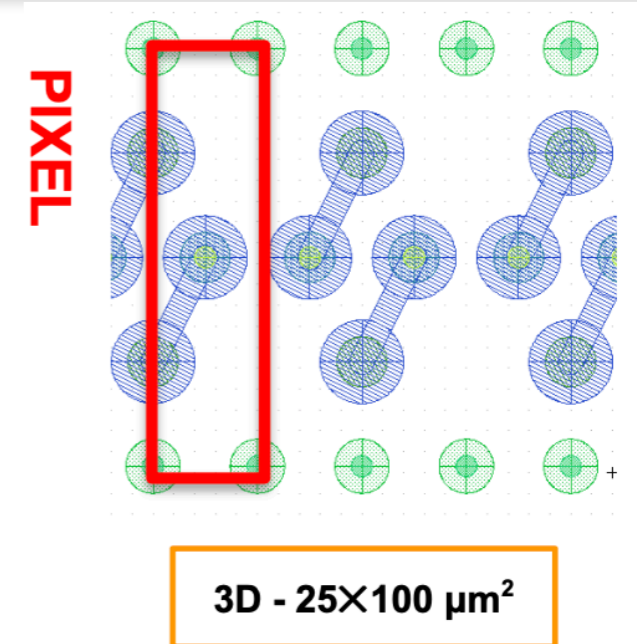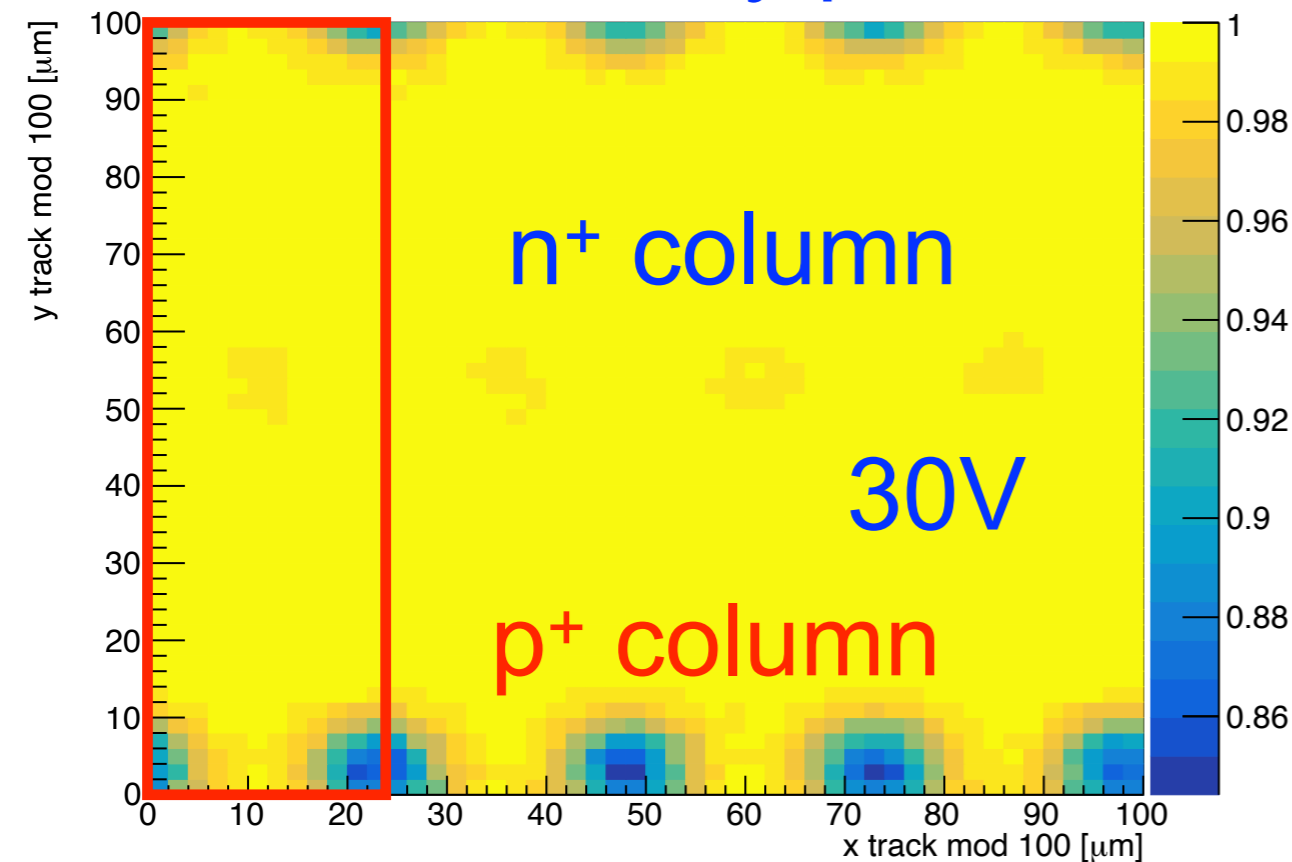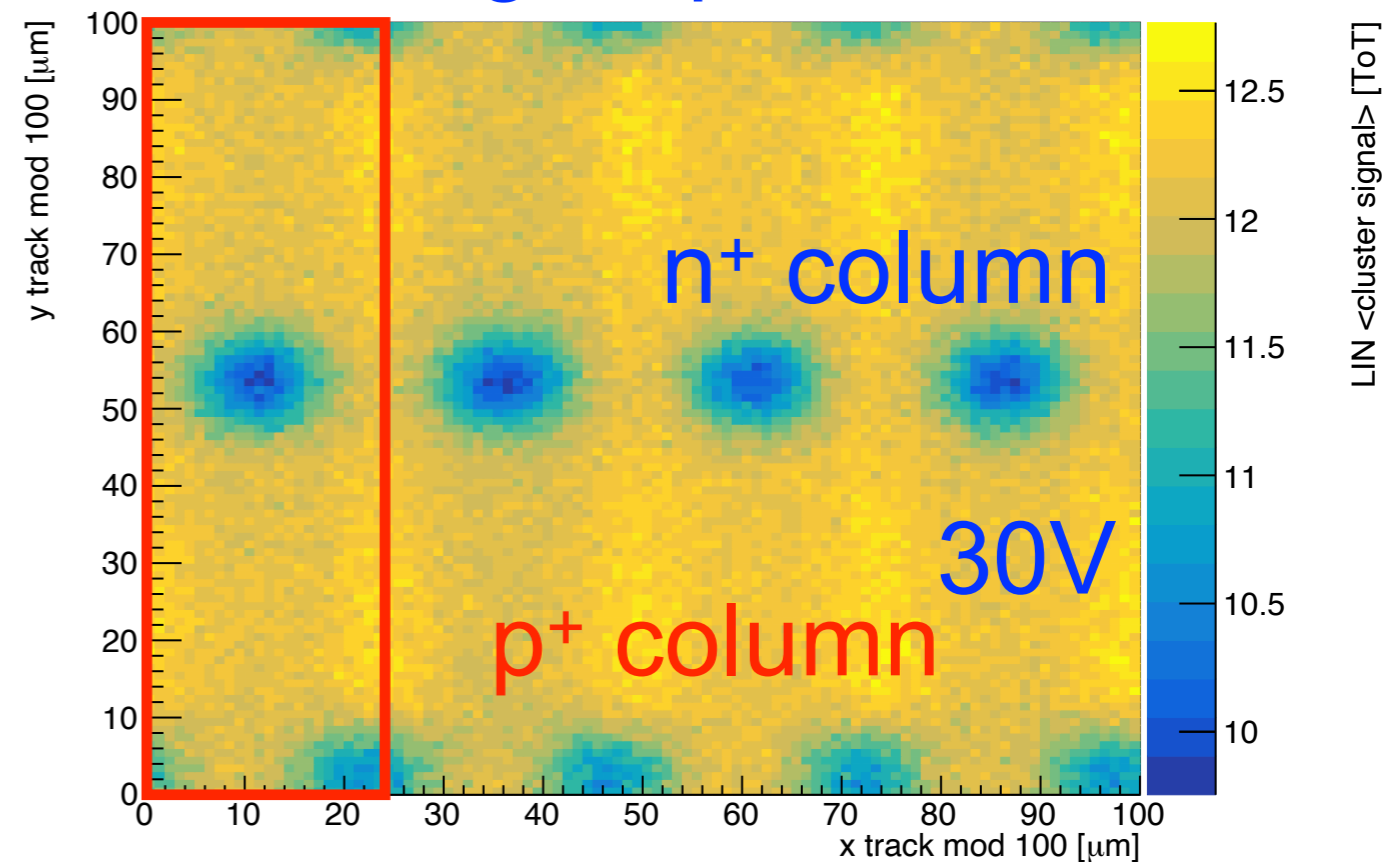
25x100 3D sensor

- **Cluster size per cell**

  - Left for -30 V, right for -6 V

  - **Please mind the different Z axis scale**

  - 130 um thickness

    - The number of tracks is different in the two cases

  - Perpendicular tracks only

PIXEL

3D - 25×100 µm²

Clustersize per cell

<Nclus>
~1.3

30V

Clustersize per cell

<Nclus>
~1.5

6V
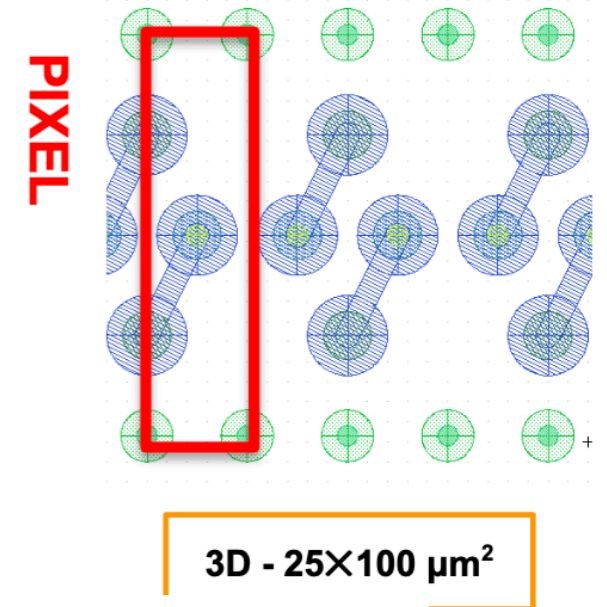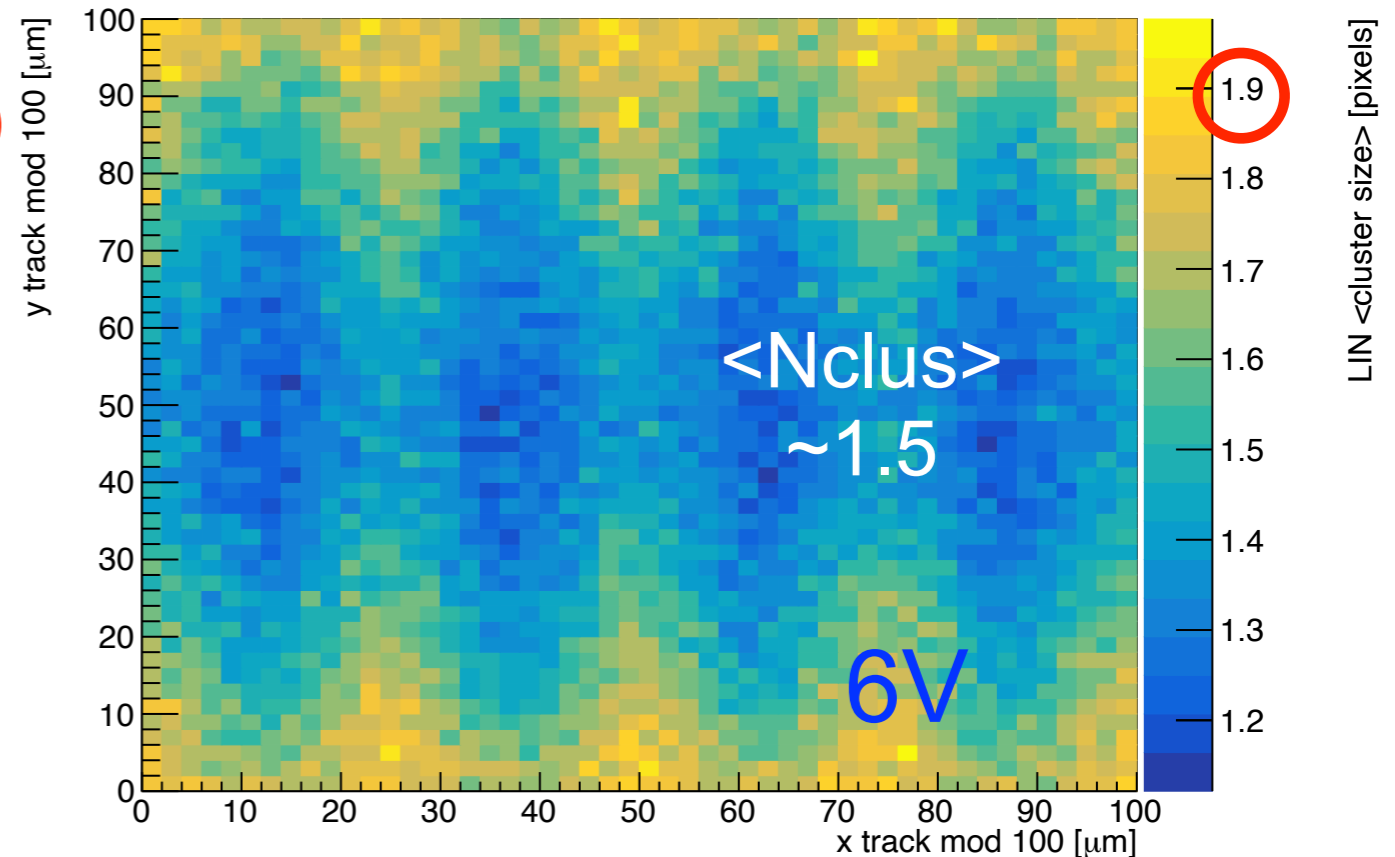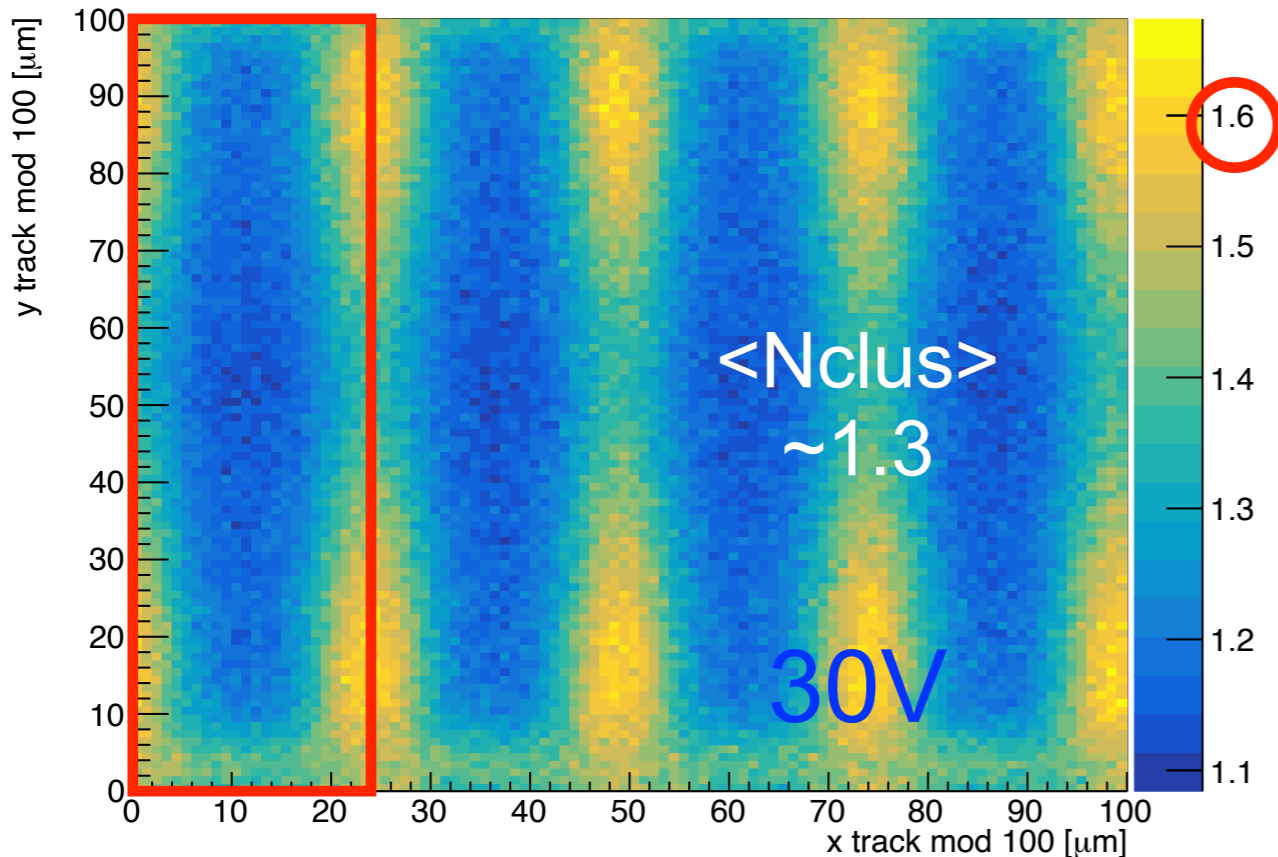
50x50 3D sensor

- **Efficiency and Signal distribution per cell**
  - Average efficiency > 99%
  - n+ columns visible in the efficiency map
  - **No pixel by pixel calibration has been applied**
- **Vbias = -30 V, thickness = 150 um**
  - Perpendicular tracks only

PIXEL

3D - 50×50 μm²

Efficiency per cell

p⁺ column

30V

Signal per cell

30V
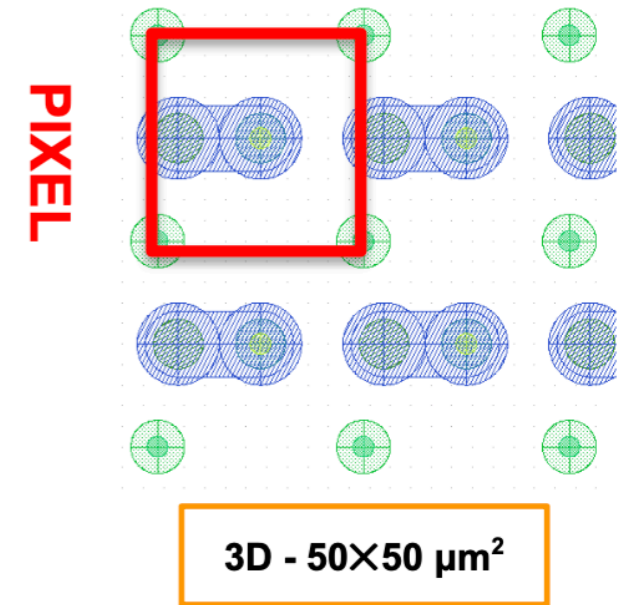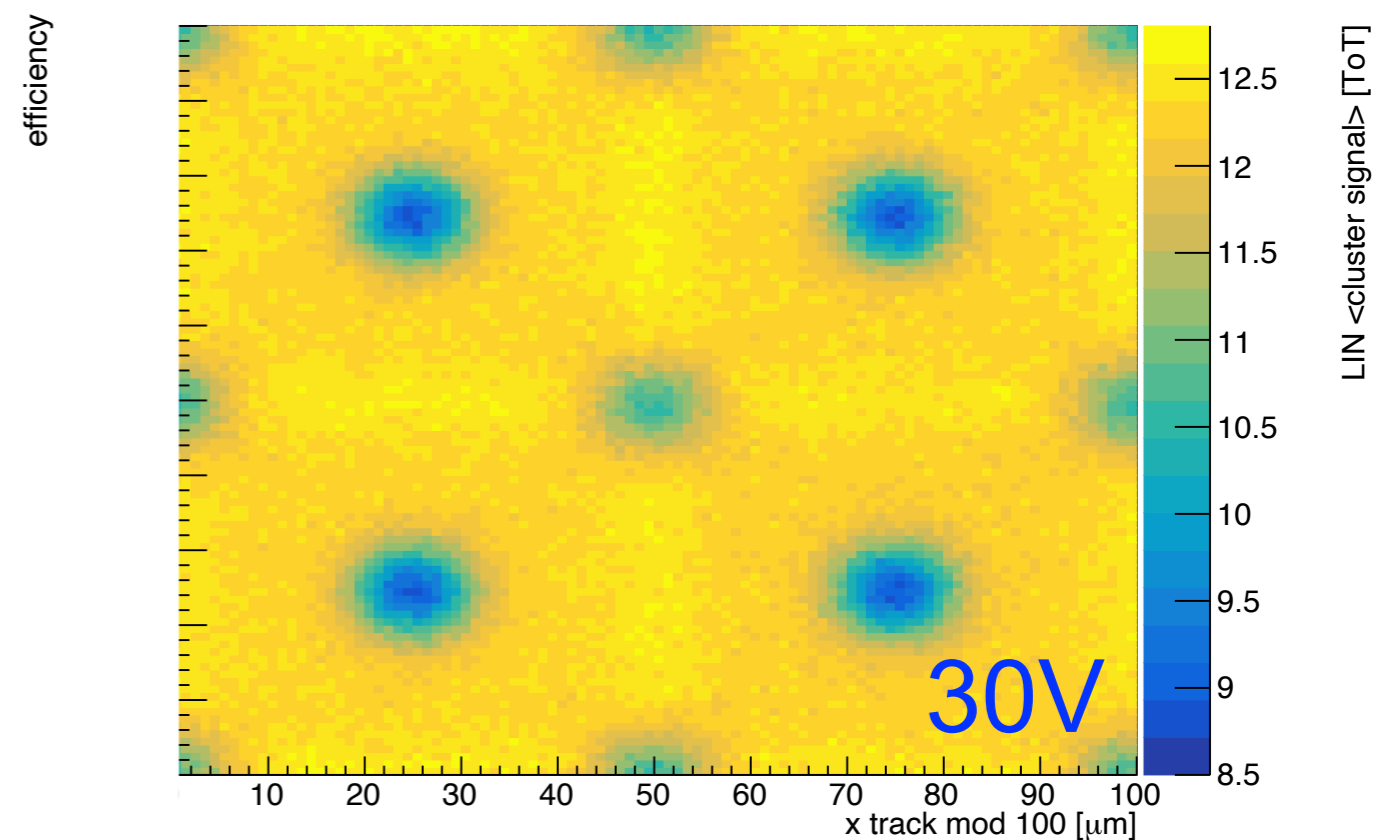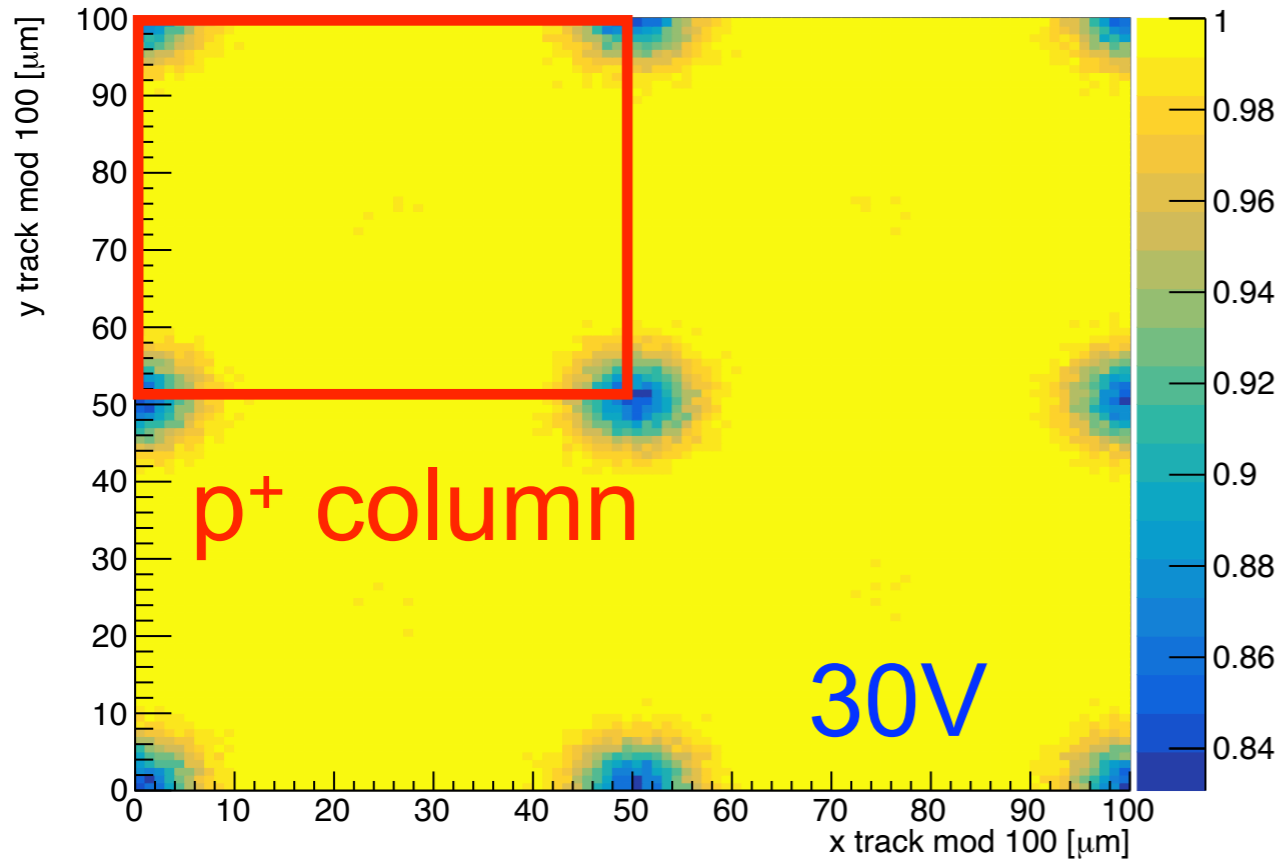
50x50 3D sensor

- **Cluster size per cell**
  - Left for -30 V, right for -6 V
  - **Please mind the different Z axis scale**
  - 150 um thickness
    - The number of tracks is different in the two cases
  - Perpendicular tracks only

PIXEL

3D - 50×50 μm²

Clustersize per cell

<Nclus> ~1.2

30V

Clustersize per cell

<Nclus> ~1.3

6V
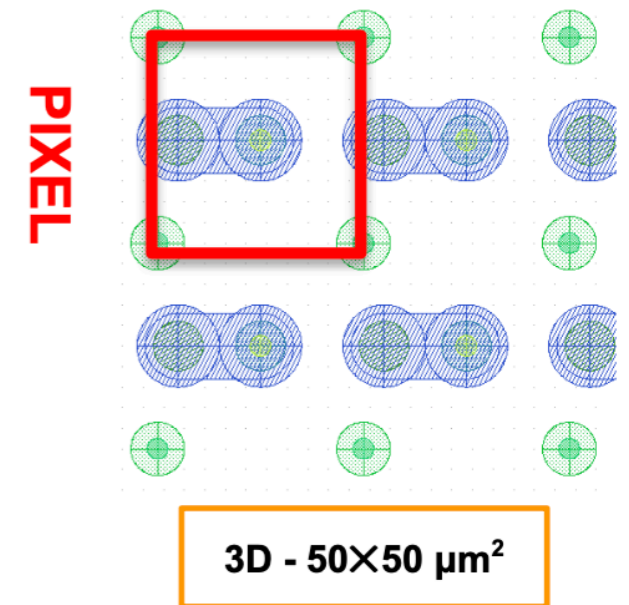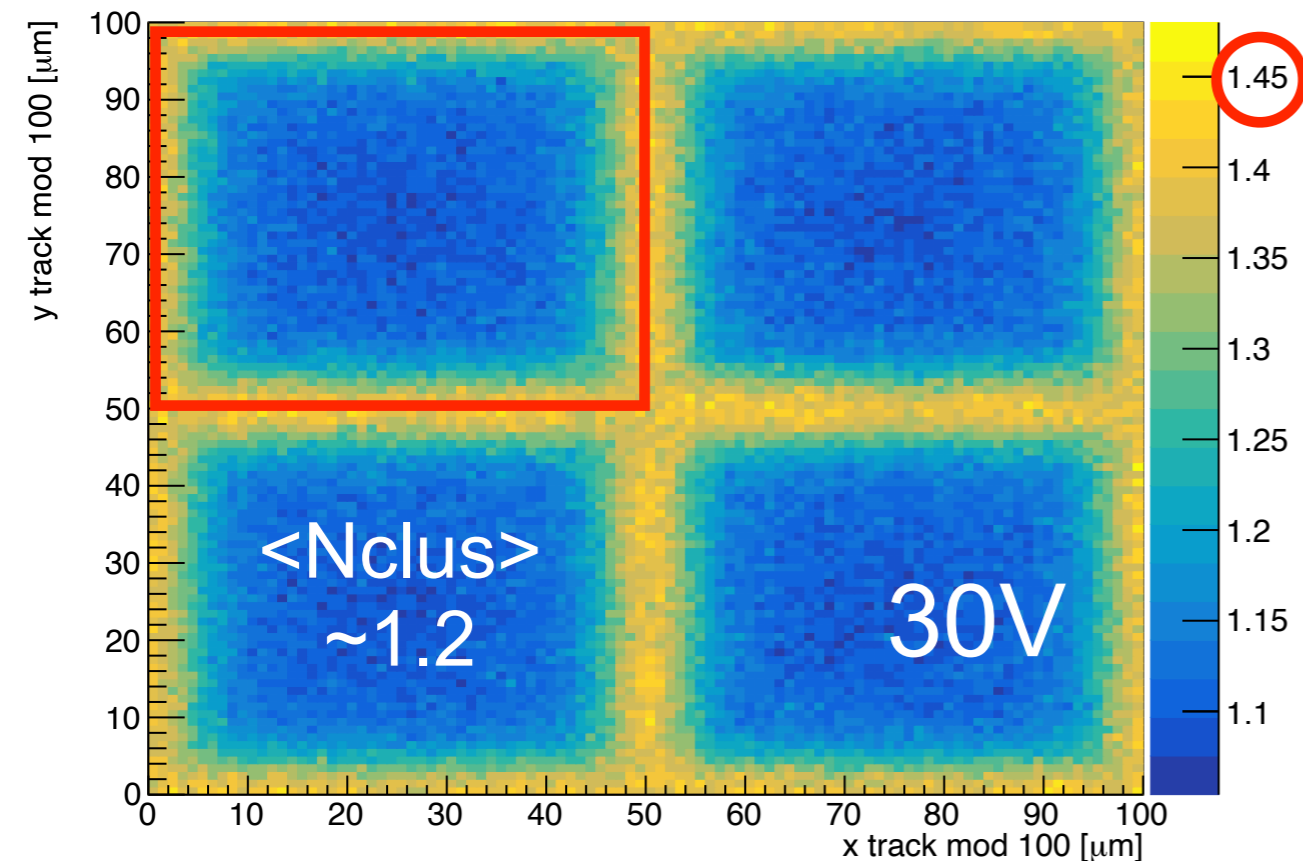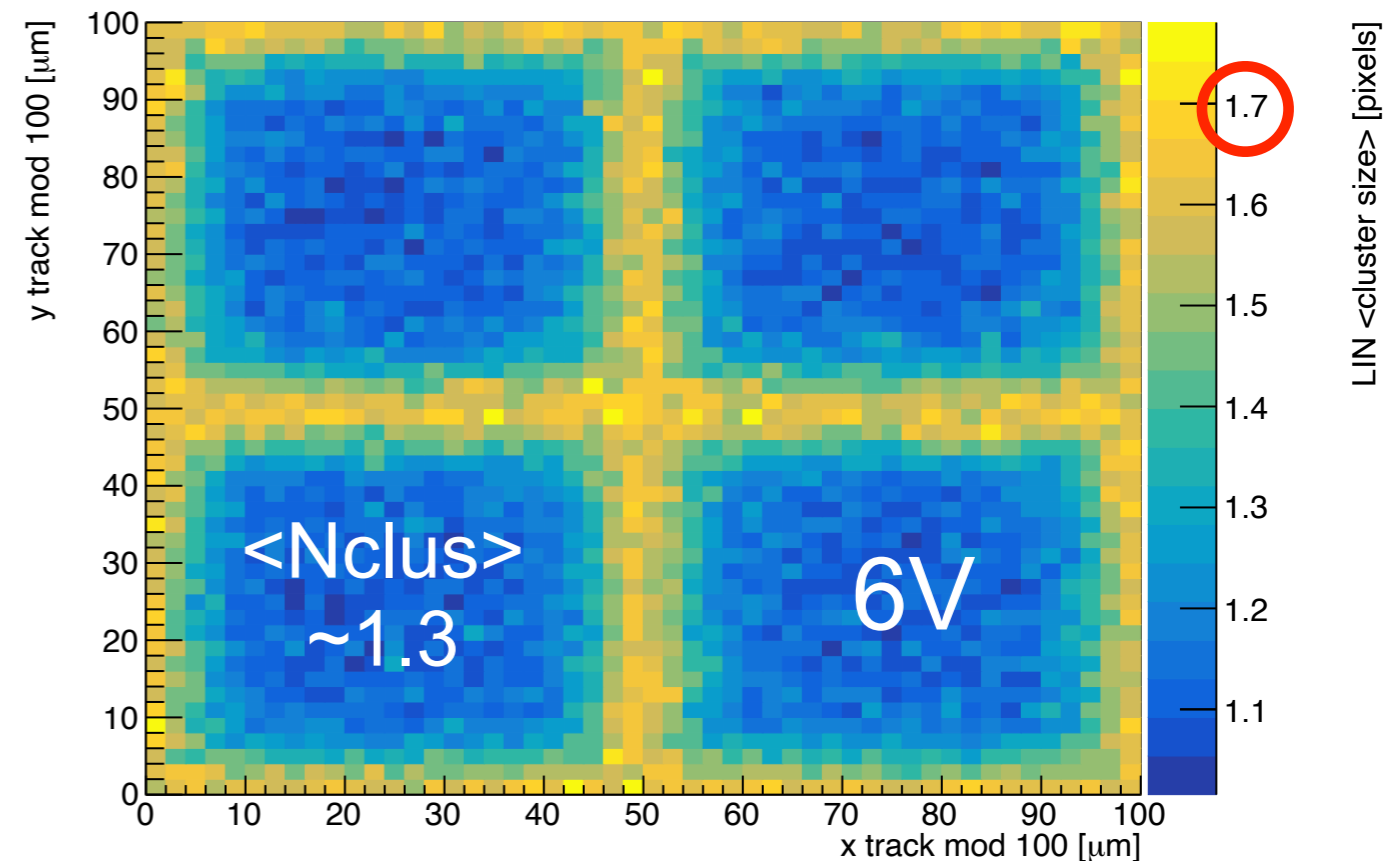
Data from June 2020

☐ **3 sensors tested (all FBK 25x100, 150 um thickness)**

  ☐ Planar with bitten implant

  ☐ Planar with bitten field plate

  ☐ 3D
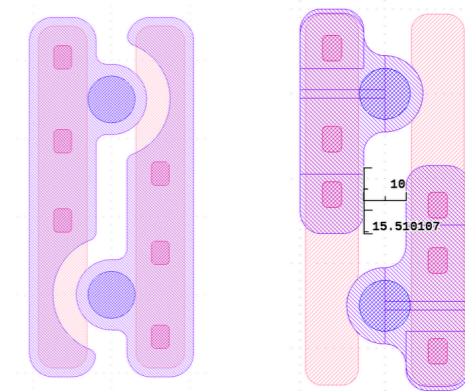
Planars
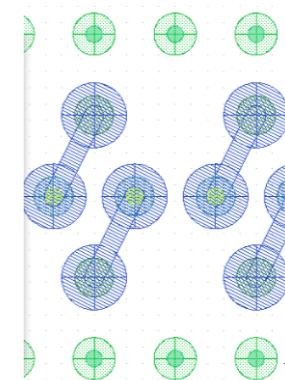
3D

☐ **Data analyzed for X-talk studies and position resolution vs track angle**

  ☐ Sensors were **NOT** irradiated

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Hit efficiency (0 degrees)
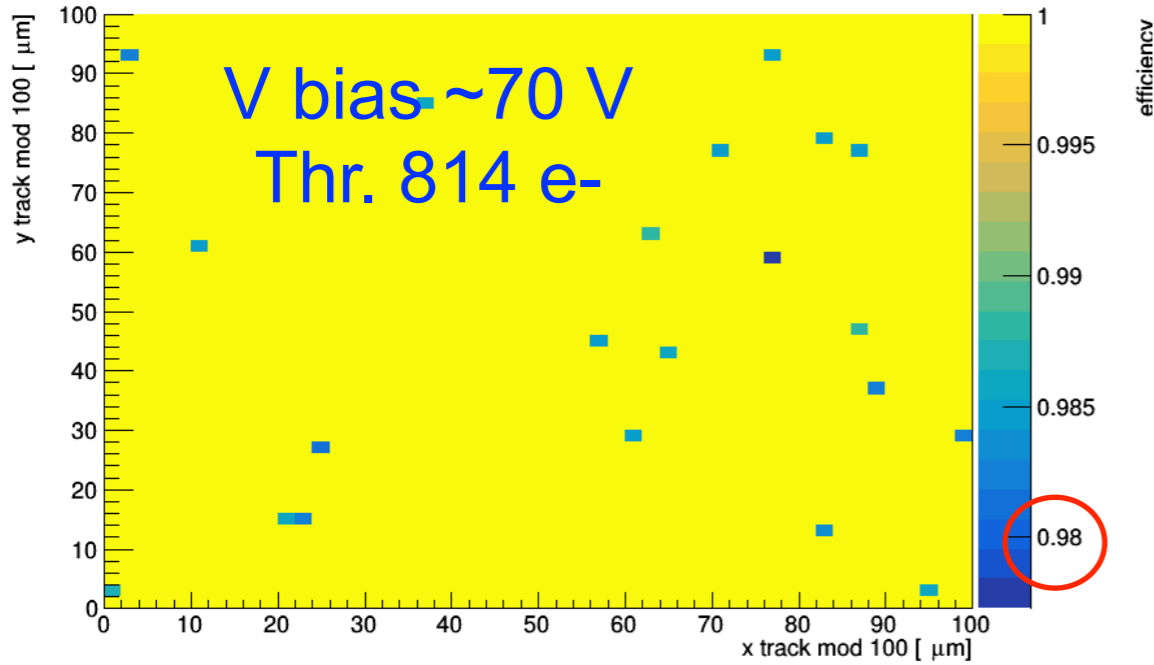
V bias ~70 V
Thr. 814 e-

Bitten

V bias ~70 V-
Thr. 793 e-
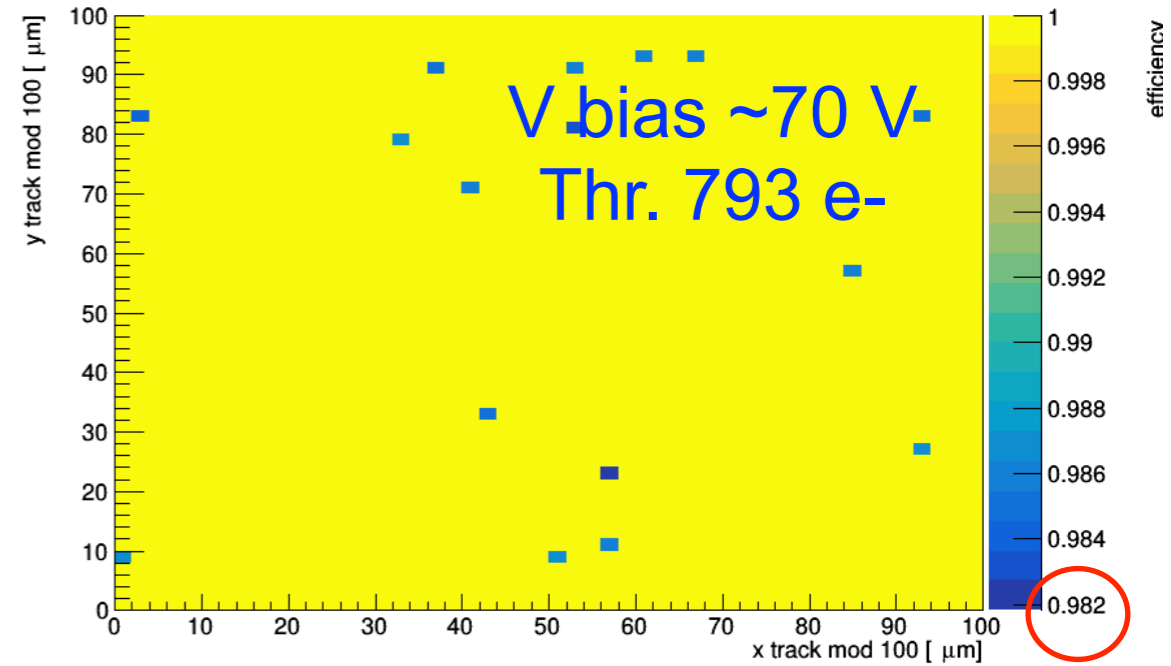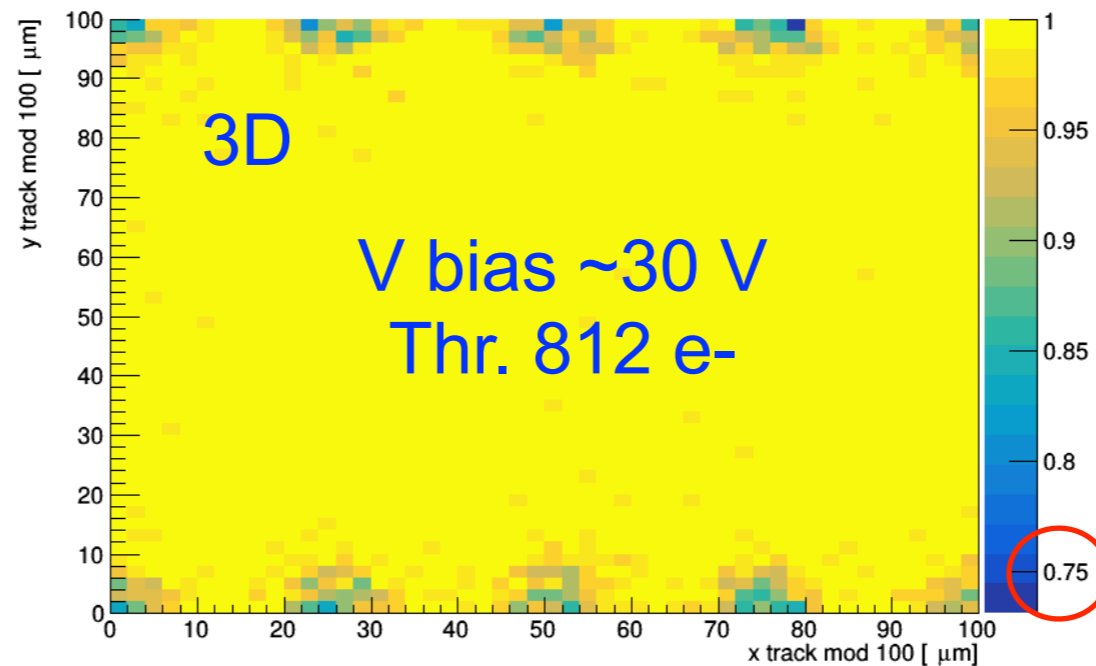
Bitten FP

Eff for planars =
0.9997 +/- 0.0001
Eff for the 3D =
0.9944 +/- 0.0002

3D

V bias ~30 V
Thr. 812 e-

Please note
the different Z axis

3D

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Cluster size (0 degrees)

LIN cluster size vs xmod ymod
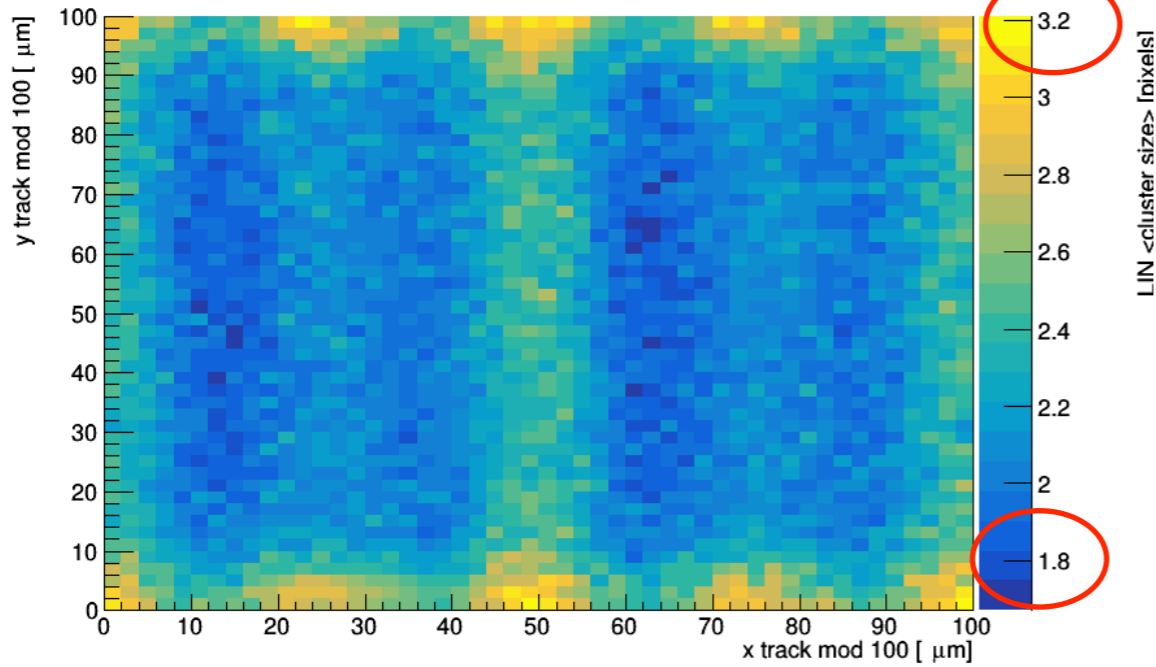
Planar Bitten Thr. 814 e-

LIN cluster size vs xmod ymod
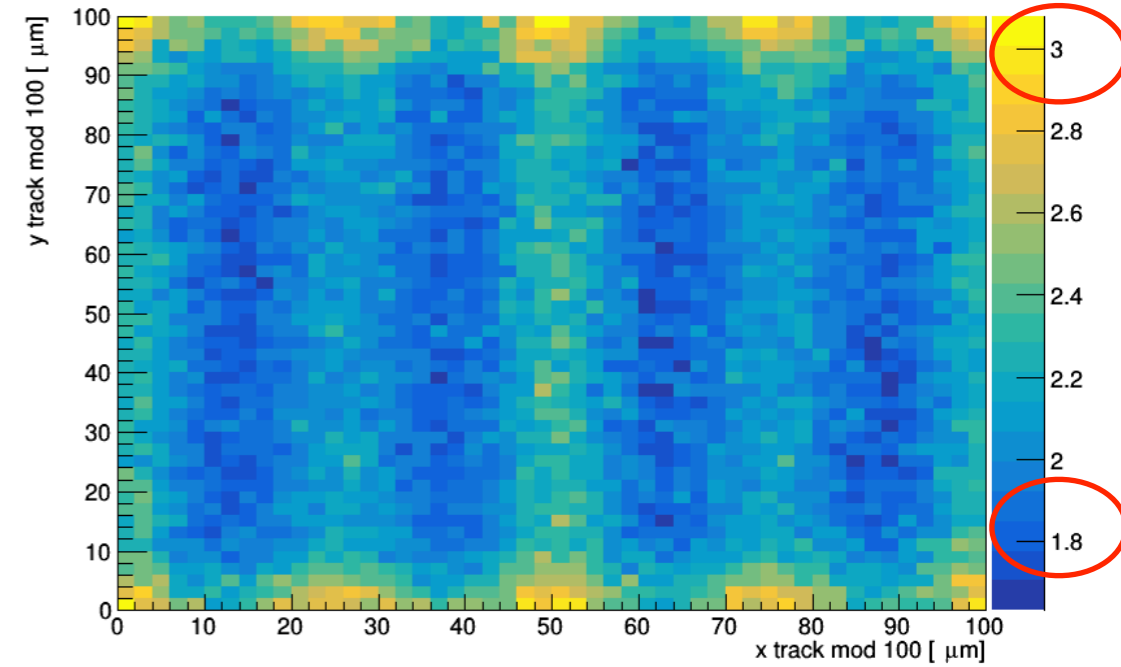
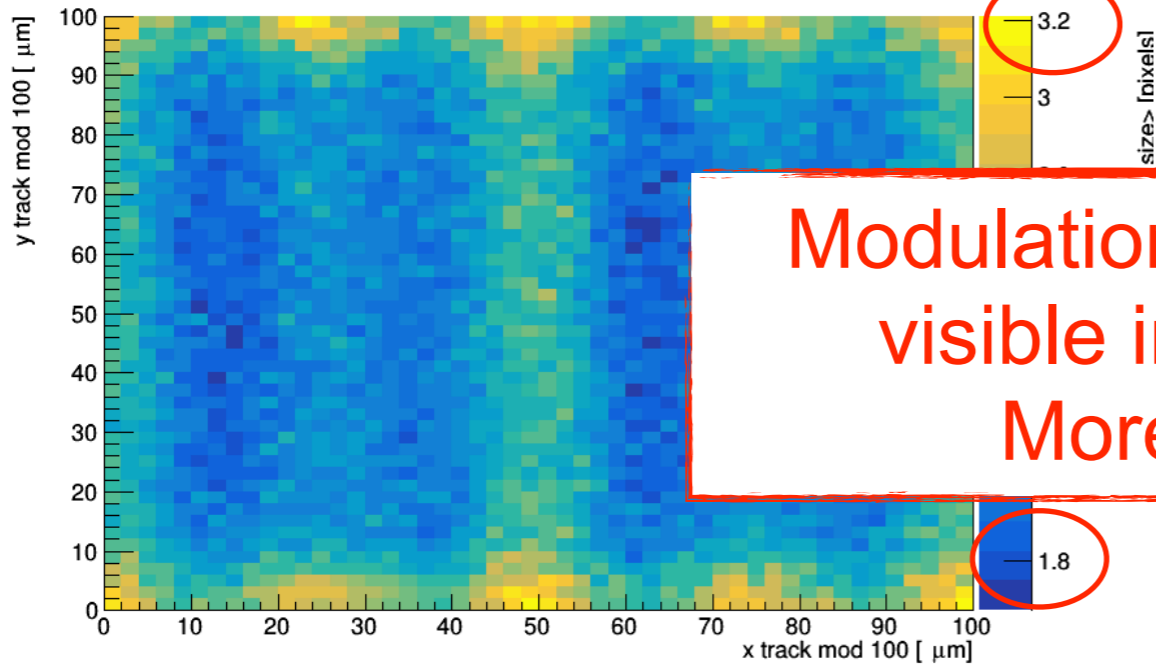Planar Bitten FP Thr. 793 e-
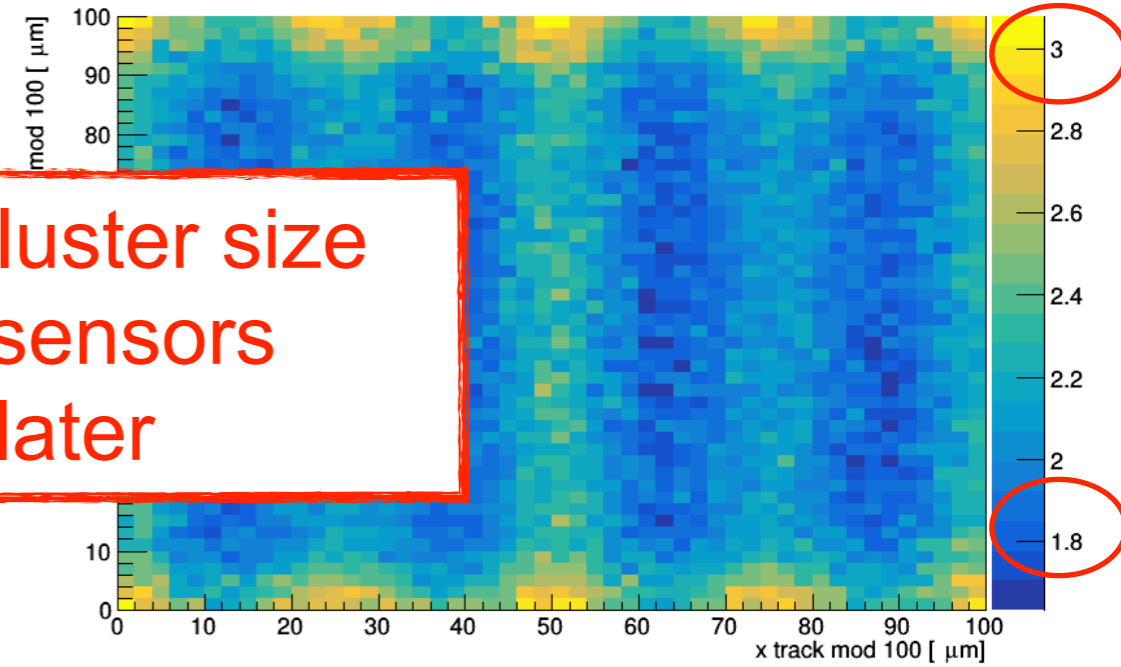
LIN cluster size vs xmod ymod

3D Thr. 812 e-

Mind the different Z-scales!

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Cluster size (0 degrees)

Modulation in the cluster size
visible in planar sensors
More on this later

Planar Bitten Thr. 814 e-

Planar Bitten FP Thr. 793 e-

3D Thr. 812 e-

Mind the different
Z-scales!

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☐ Larger cluster size when track falls between unpaired pixels This can be explained by the combination of two effects:

☐   charge sharing (always present)

☐   For a fraction of events there is also charge induced in a nearby pixel due to the pairing through bump bonding (x-talk)

paired
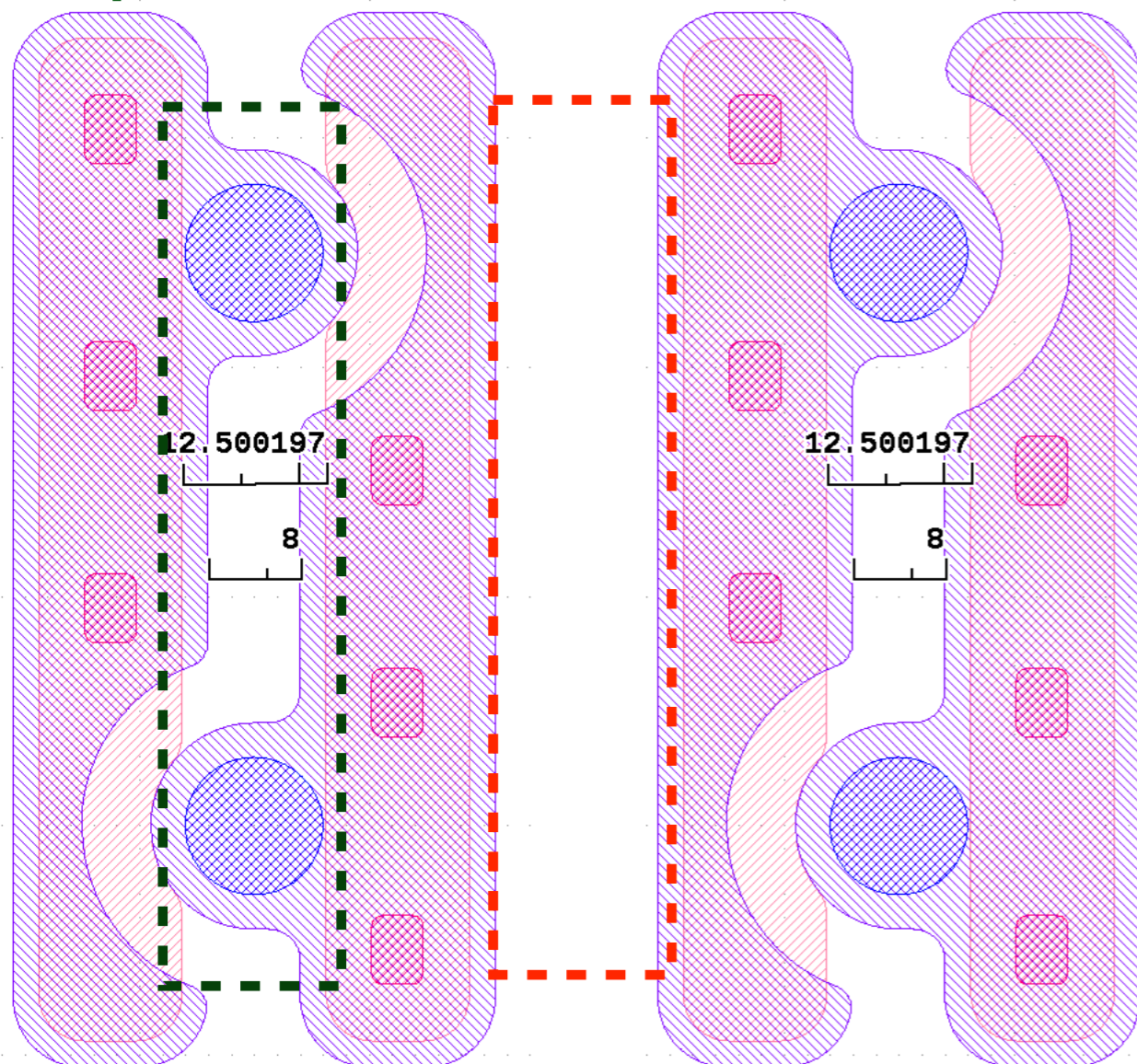
unpaired

LIN cluster size vs xmod ymod

10 um

x track mod 100 [μm]
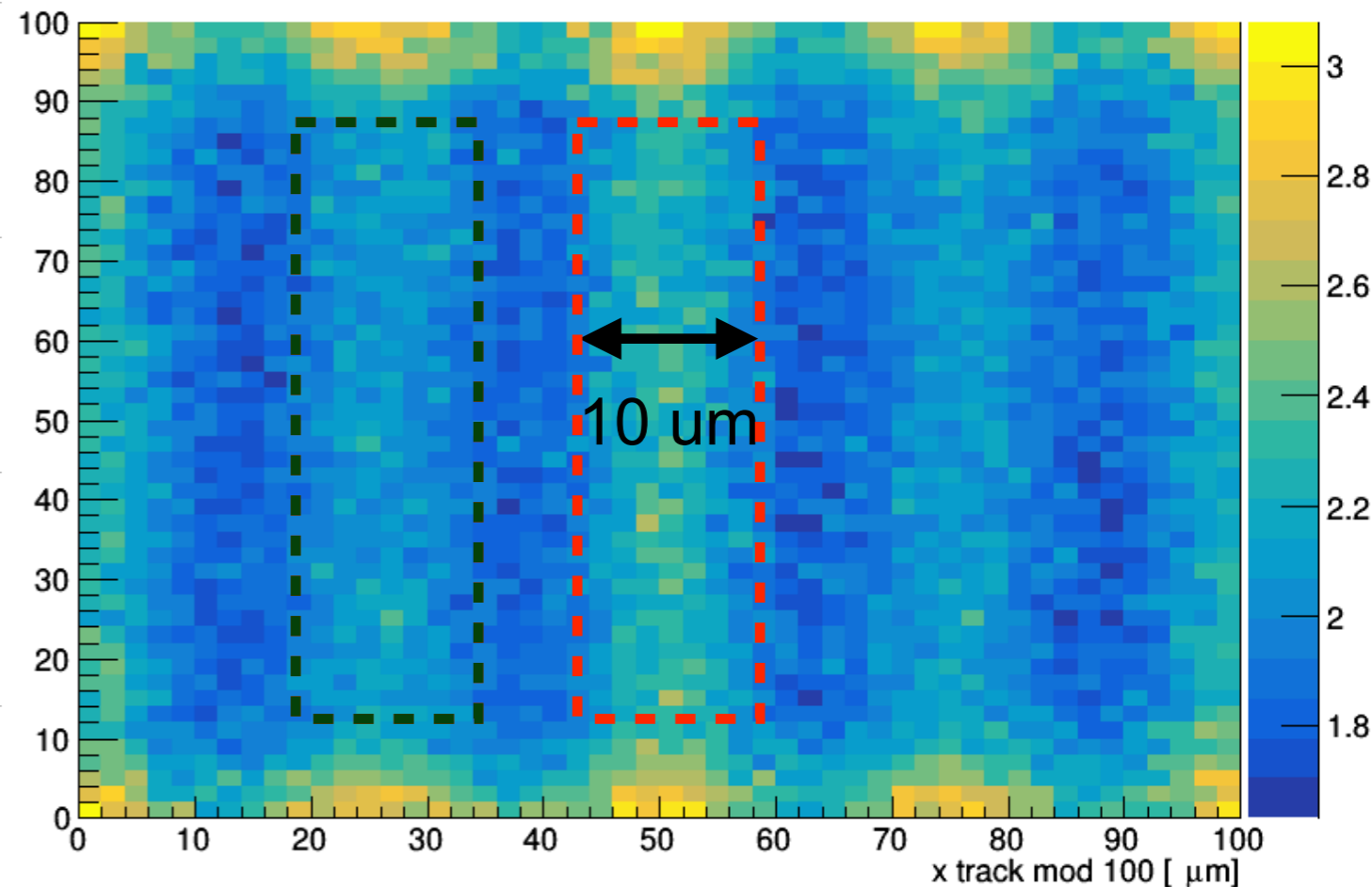
X-Talk (lab measurement)

- Tested FBK modules:
  - Planar 25x100 Bitten Implant
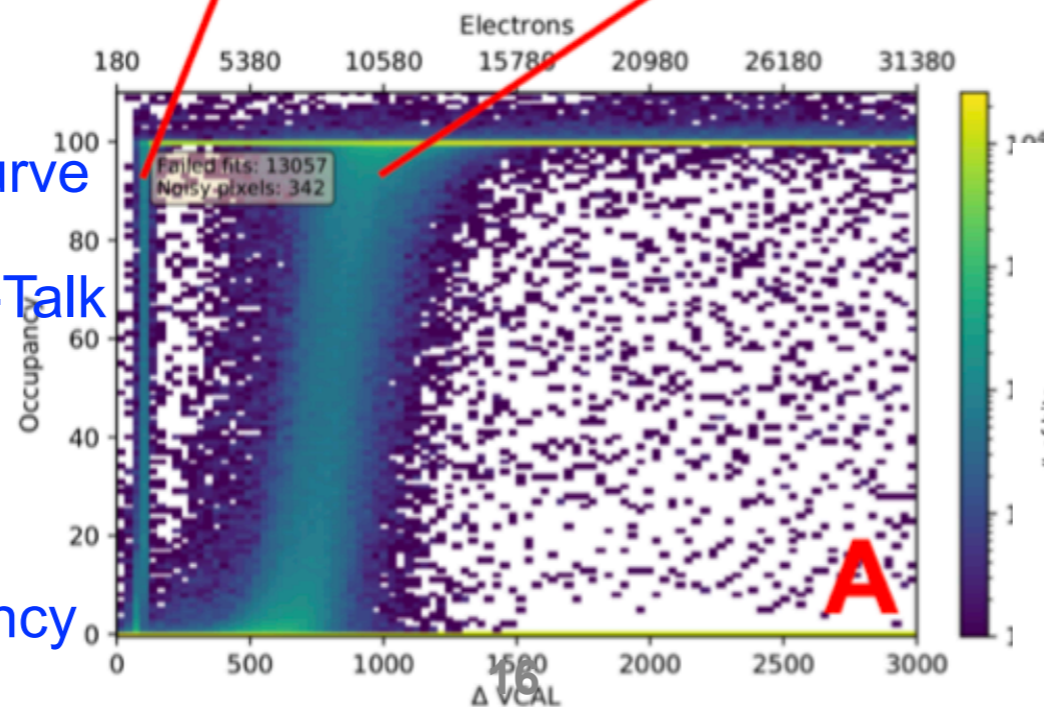 - Planar 25x100 Standard

- Injection in (0,0)

- Read only (0,0) and (0,1)

- Two S-Curves
  - First one is the true SCurve
  - Second one is due to X-Talk
  - X-Talk $= Q1/(Q1+Q2)$
  - Q1 (Q2) = charge at 50% (150%) occupancy
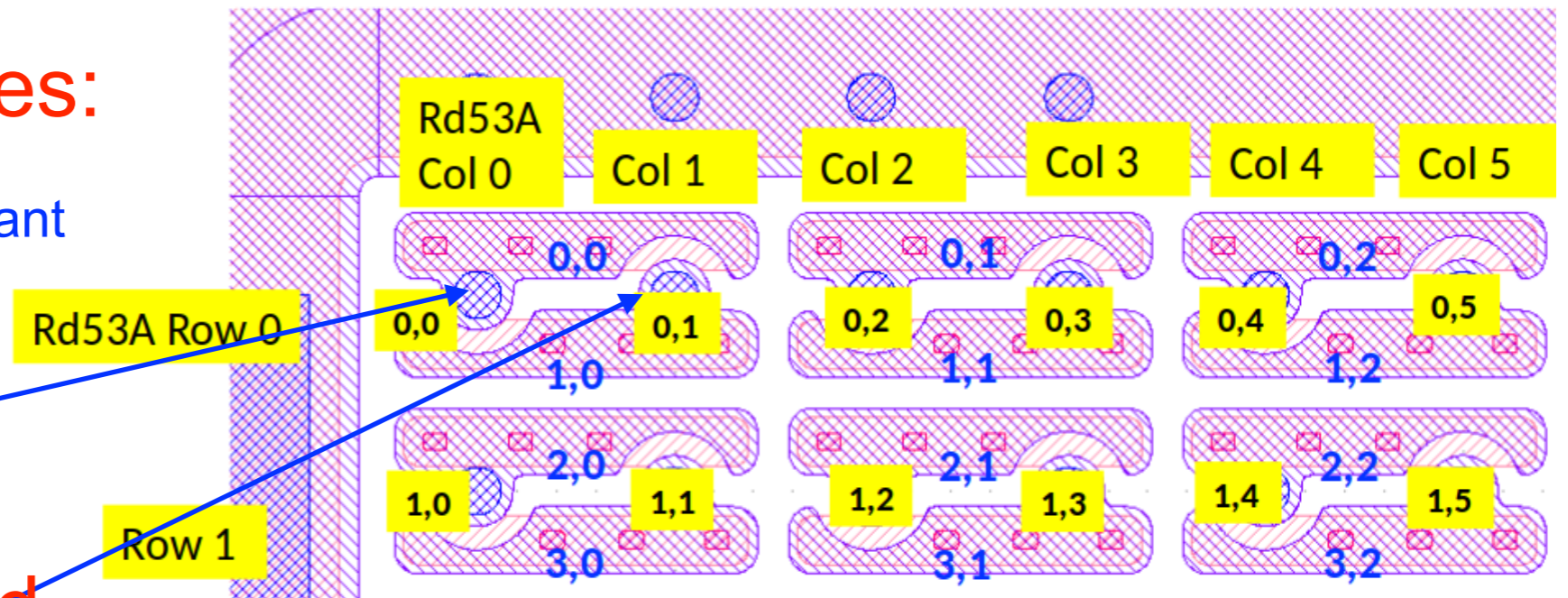
First S-Curve   Second S-Curve
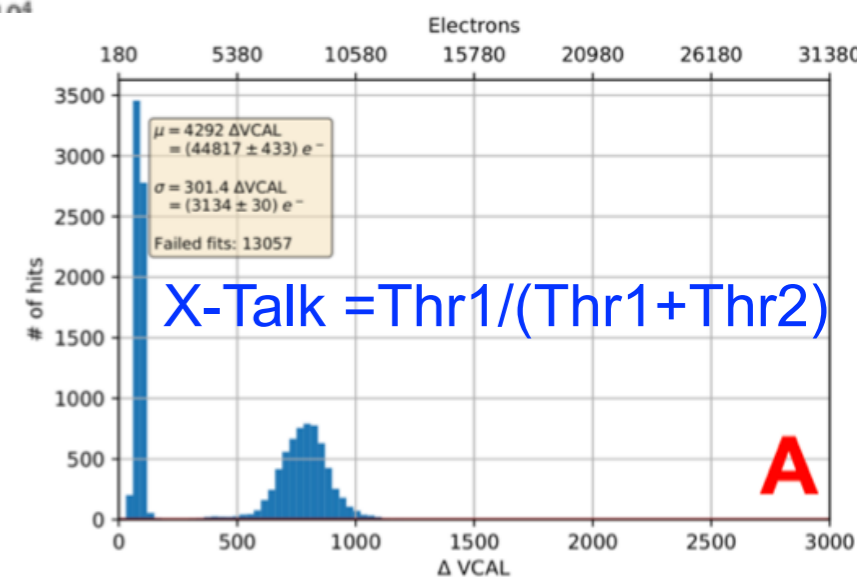
X-Talk $=Thr1/(Thr1+Thr2)$

X-talk results

Bias Voltage	Main Threshold	Second Threshold	X-Talk
Planar 25x100 Standard (SOI)			
40 V	1140 e	8140 e	**12.3%**
20 V	2050 e	15294 e	**11.8%**
Planar 25x100 Bitten Implant			
40 V	1114 e	11388 e	**8.9%**
20 V	2303 e	22530 e	**9.3%**

Bitten implant reduces the x-talk by few %

Planar Bitten

V bias ~70 V
Thr. 814 e-

Planar Bitten FP

V bias ~70 V
Thr. 793 e-

3D

V bias ~30 V
Thr. 812 e-
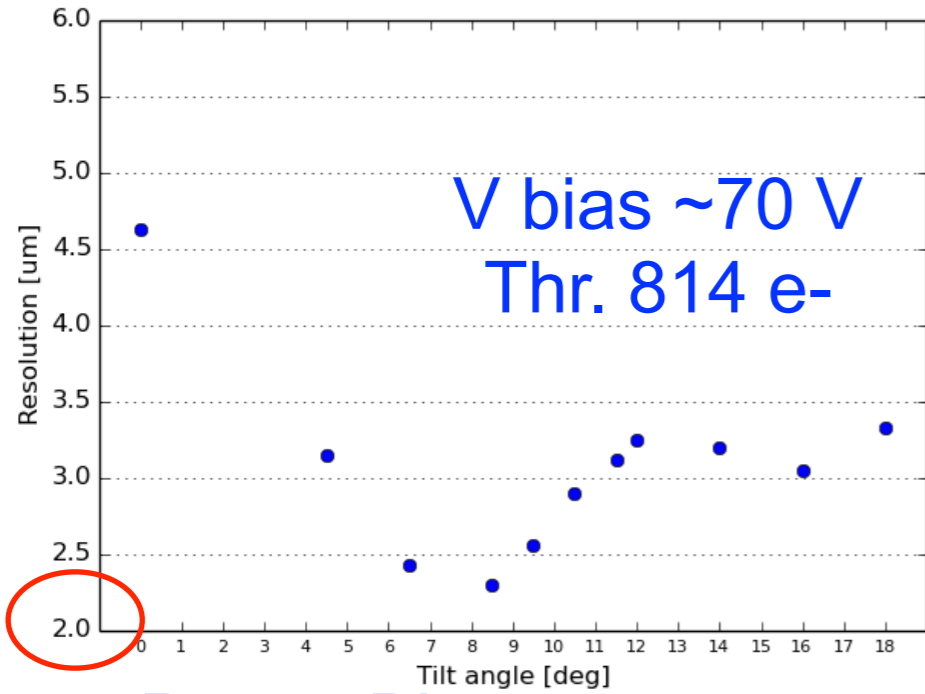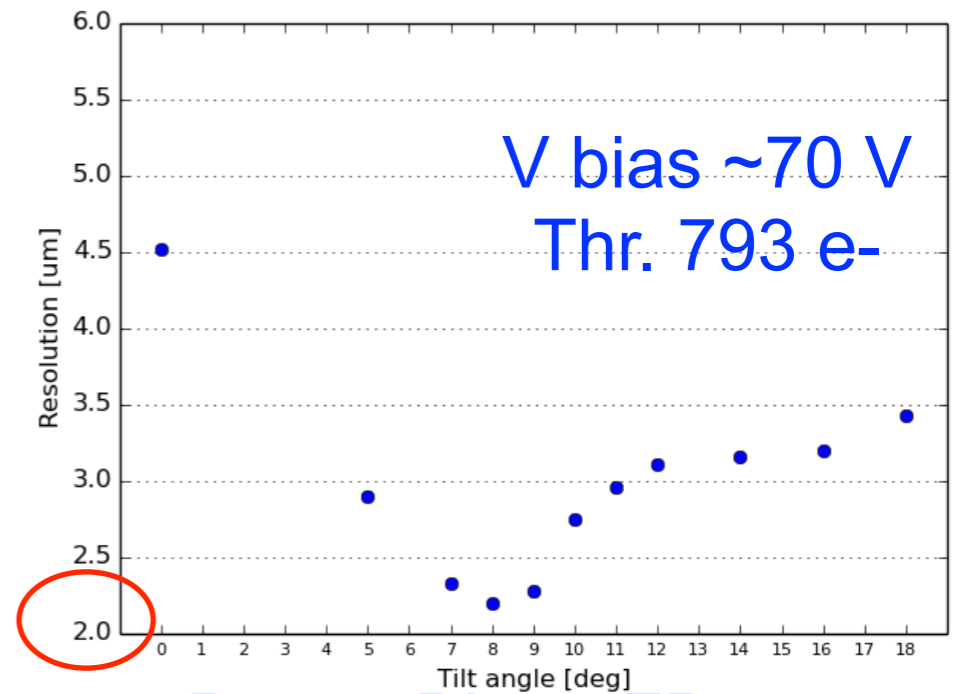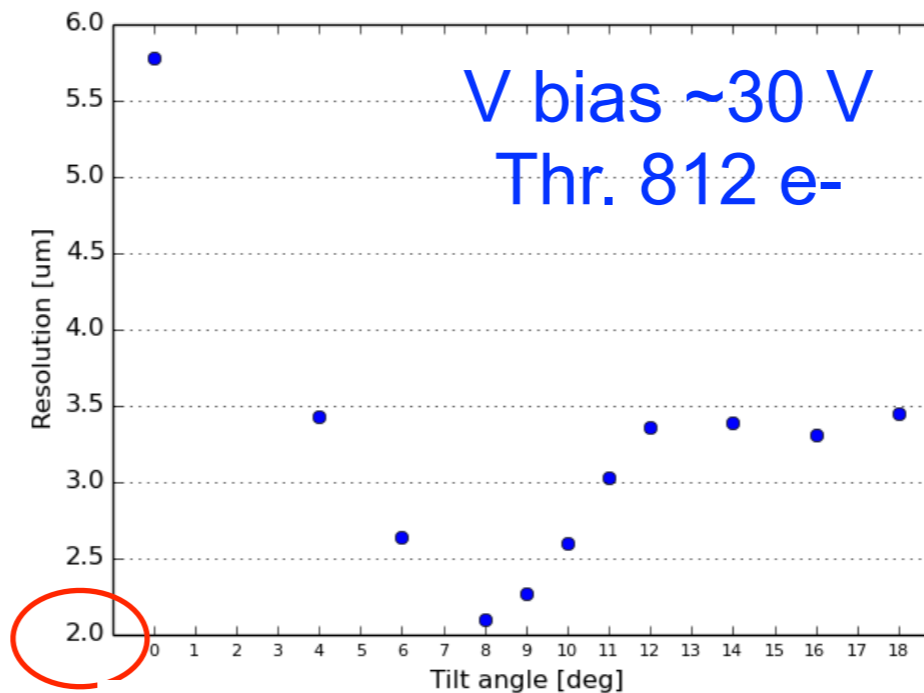
Position resolution well below the digital resolution of 7.2 um
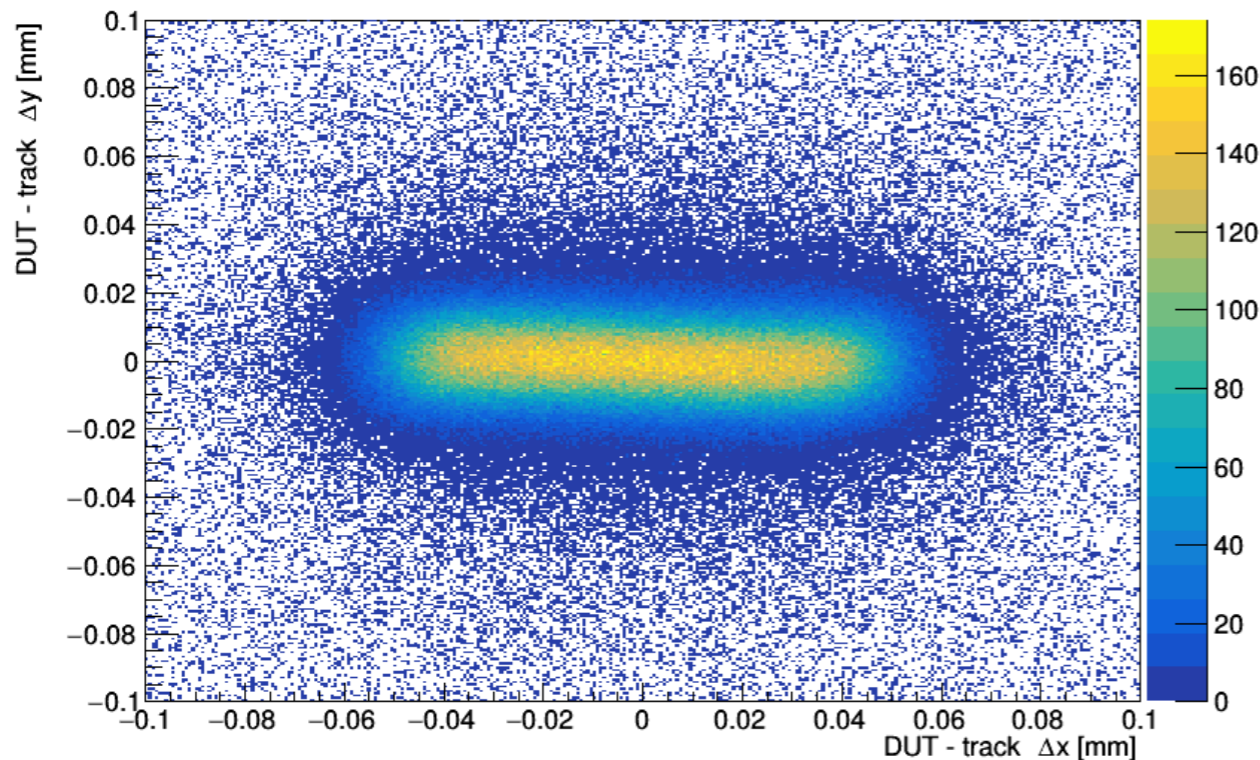
Sensor thickness = 150 um
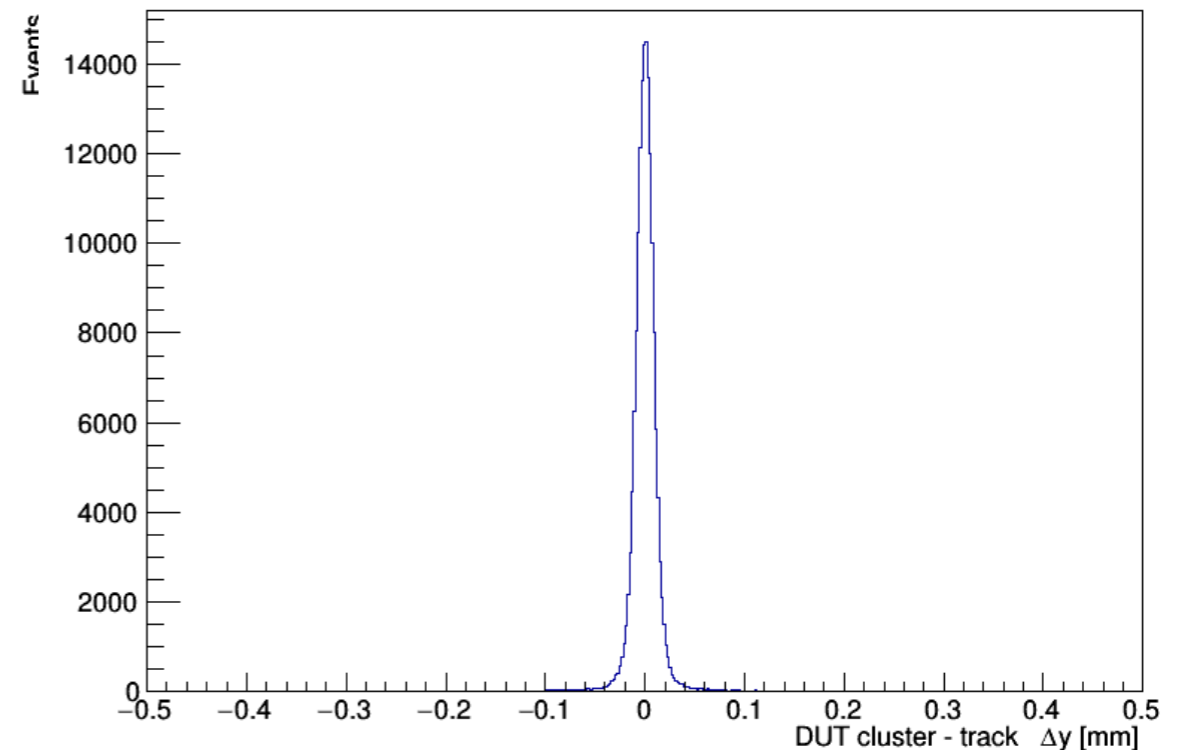
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Data from July 2020

- Planar 25x100 sensor irradiated at ~7.5E15 neq/cm^2

  - Active 100 um

- Data analyzed for studies on 25 um residuals
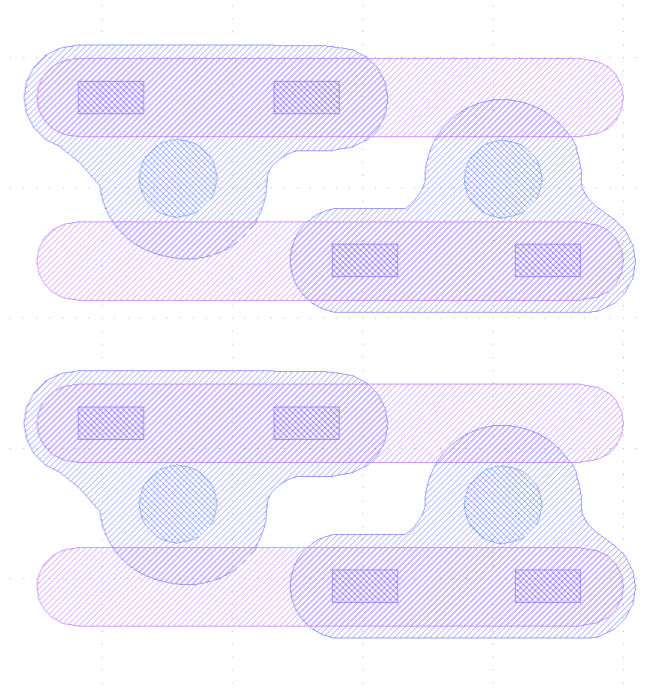
DUT cluster - track

DUT - track dy

Residual of the Y coordinate

☐ Residuals show a change of sign within a cell in the presence of the bonding-pad

  ☐ This is a different effect wrt x-talk, it is present also for cluster size = 1

  ☐ The same effect have been seen also on irradiated planar sensors from other companies

25x100 Planar   500 V Thr. 1400
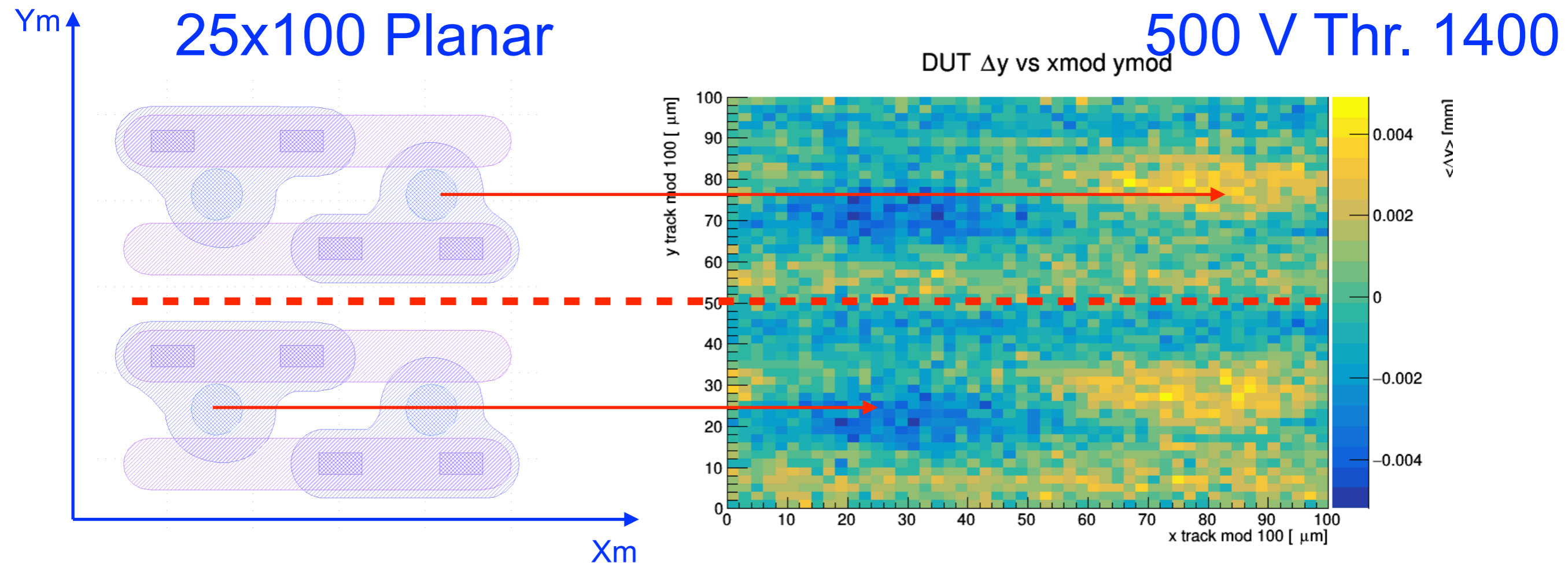
Residual is computed as DUT_position - Track_position

Let's zoom in

☐ Clear effect due to the presence of the bonding-pad

  ☐ Restricting to cluster size = 1 reduces the effect, but it still visible

Cluster size ==1

DUT Δy vs xmod ymod

500 V Thr. 1400

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□ **Residuals show a change of sign within a cell in the presence of the bonding-pad**

□ <u>The effect is anyway small</u>, localized, and the analysis of the December 2020 data has shown that its impact on the overall resolution is marginal
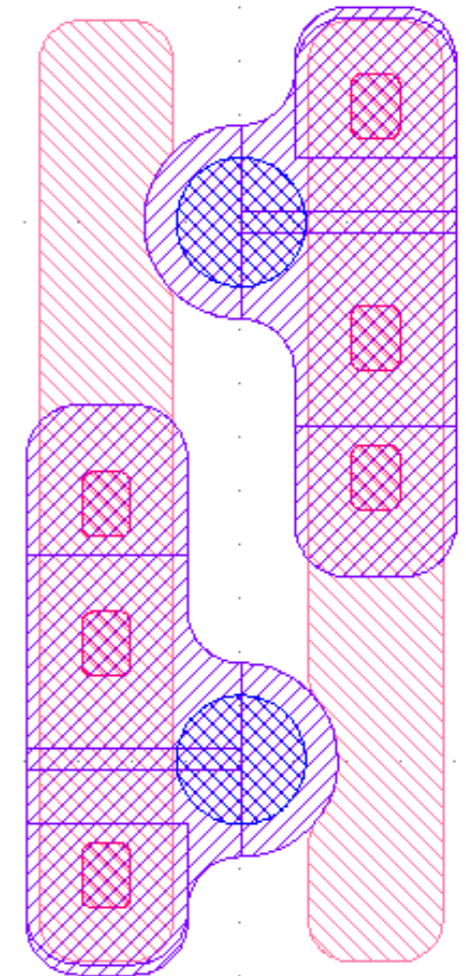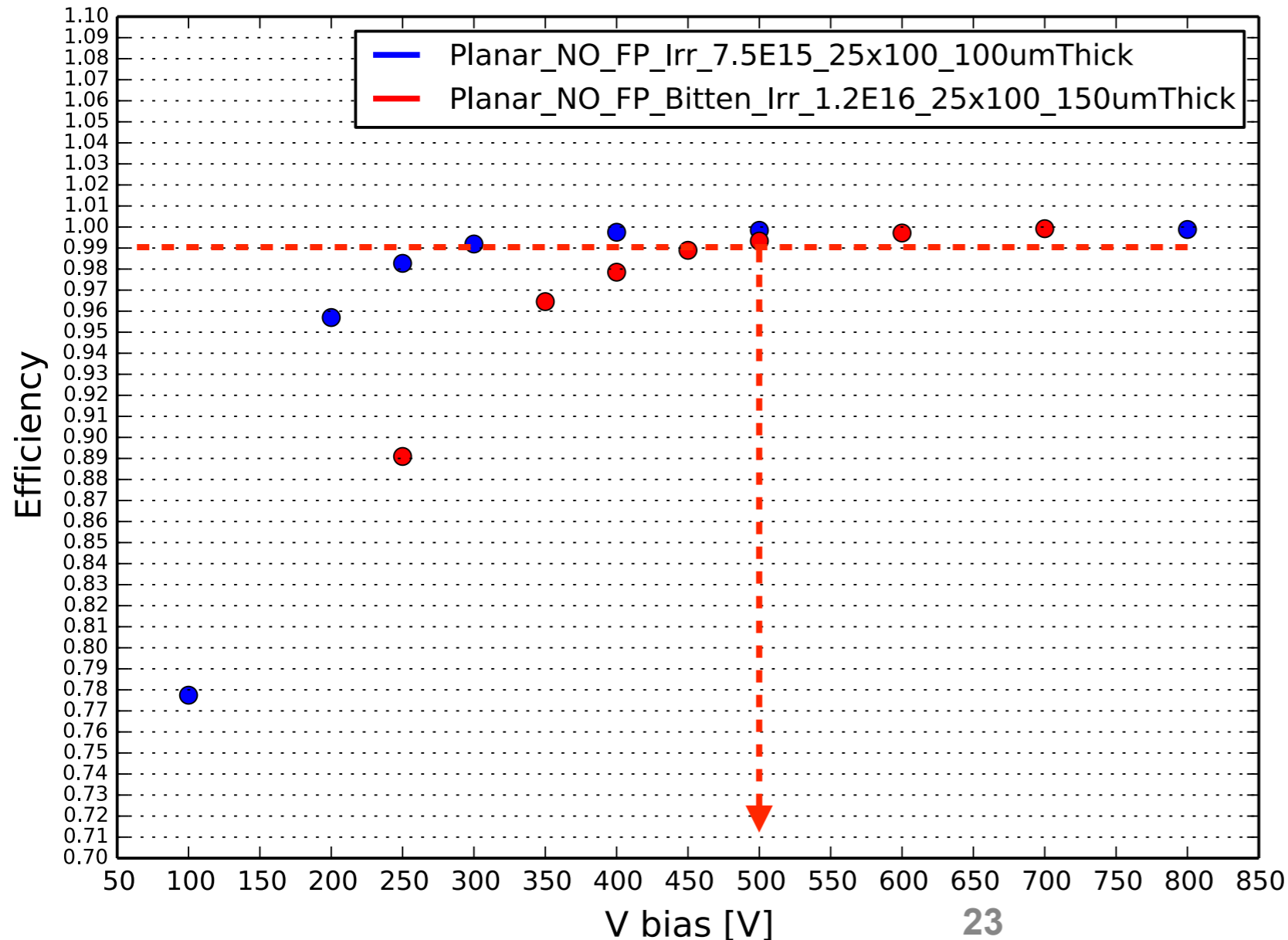

25x100 Planar

Y scale is in mm!
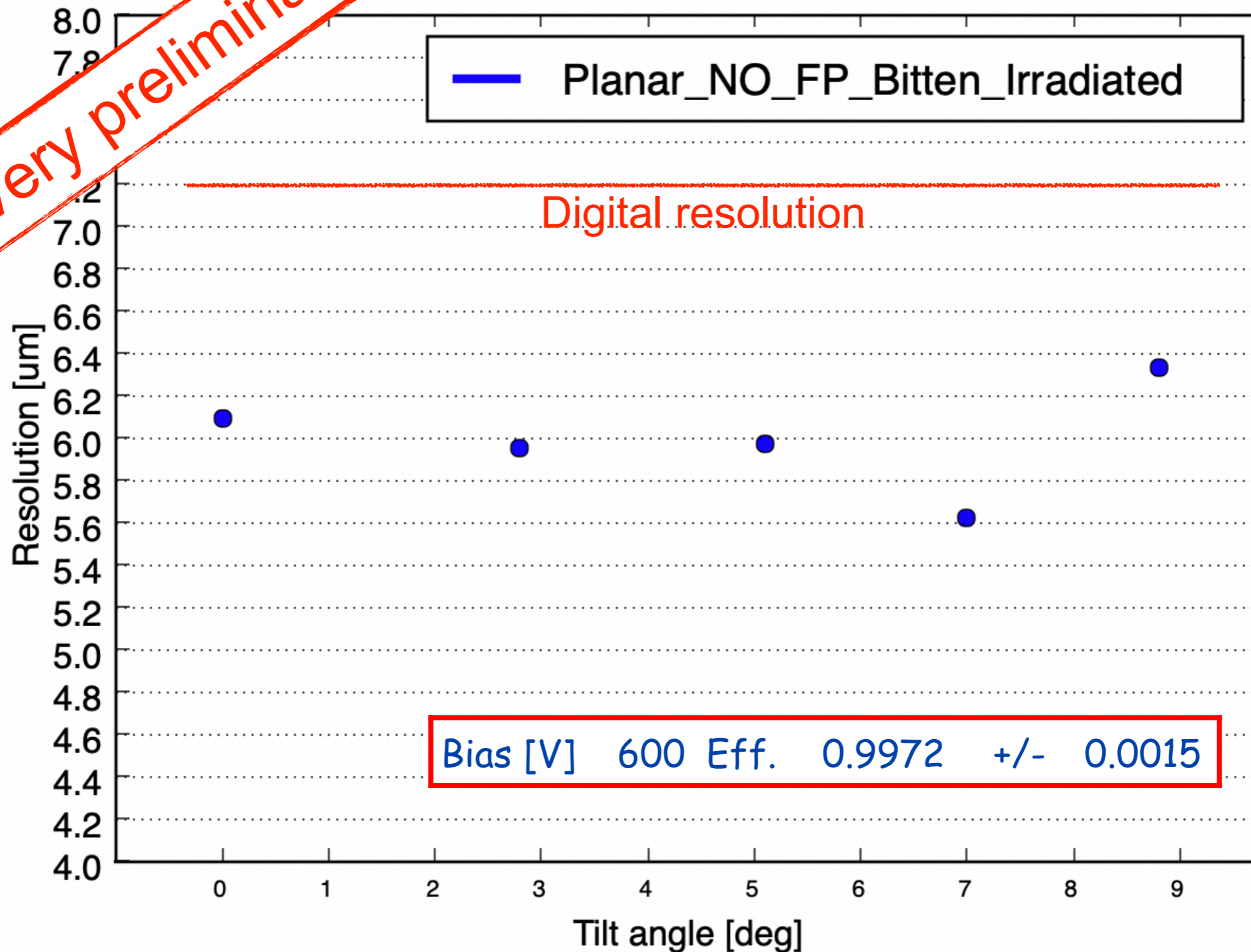
DUT Δy vs xmod
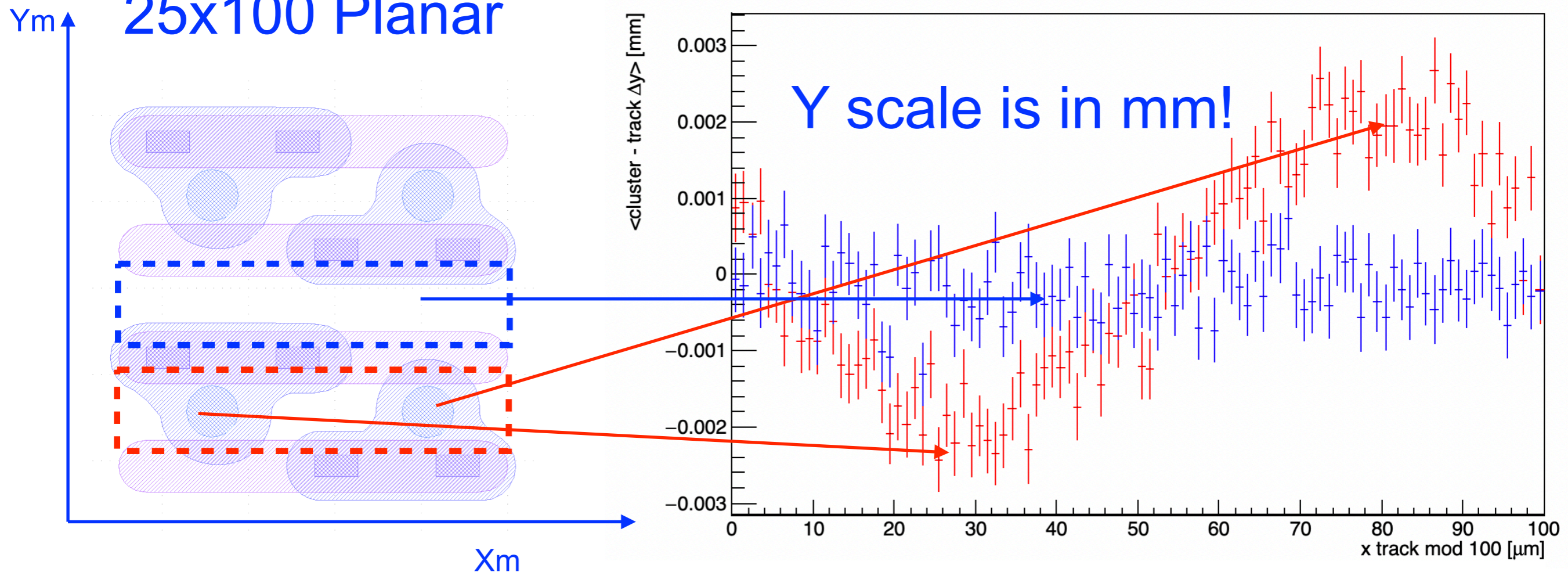
Residual is computed as DUT_position - Track_position

Data from December 2020

- Planar Sensor 25x100 um²

  - Vthreshold_LIN: 361 ~ 1249 e-, noise is around 125 e-

- Data analyzed for efficiency and position resolution studies

  - Sensor were irradiated up to 1.2E16 neq/cm²

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Resolution vs angle

Conclusions

- **FBK sensor performance has been studied with several test beams data**

    - Planar and 3D sensors

    - 25x100 and 50x50 um^2 layout

    - Fresh and irradiated sensors at different fluences

- **For both 3D and Planar sensors**

    - Efficiency remains larger than 99.5% even after irradiation

    - Preliminary estimation of position resolution is about 6 um for irradiated sensors at 1.2E16neq/cm^2

Back-up

DUT Δy vs xmod ymod
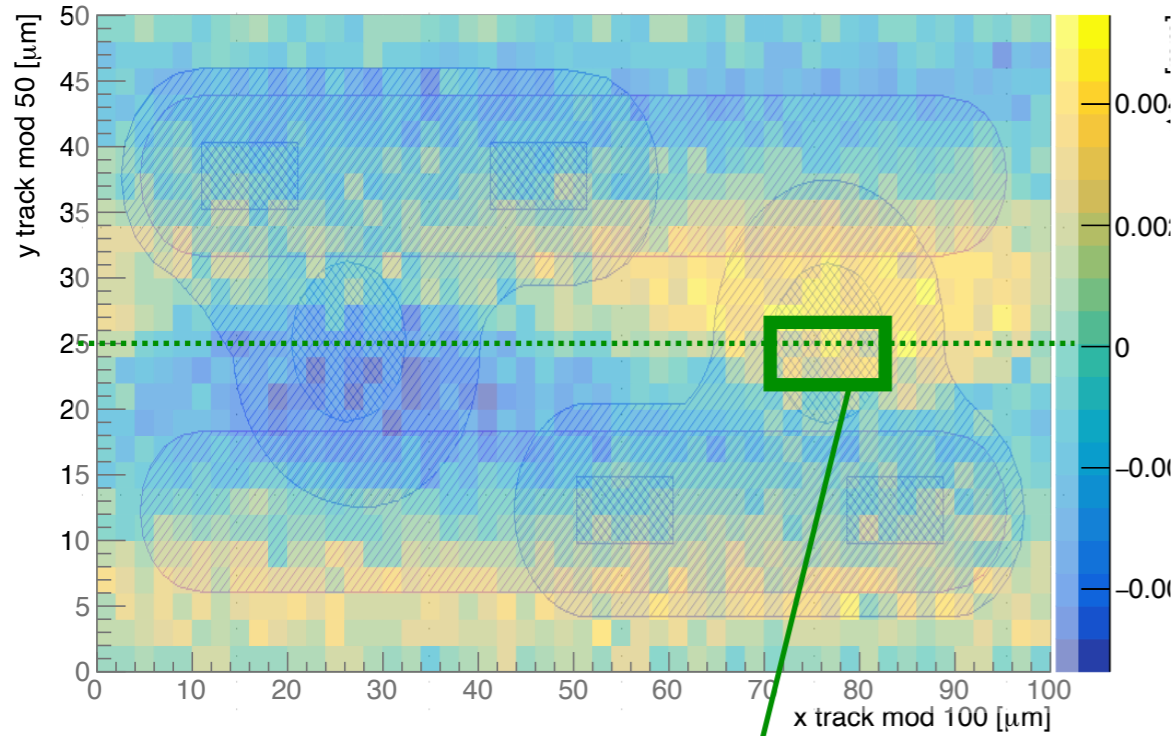
DUT Δy around the bonding pad

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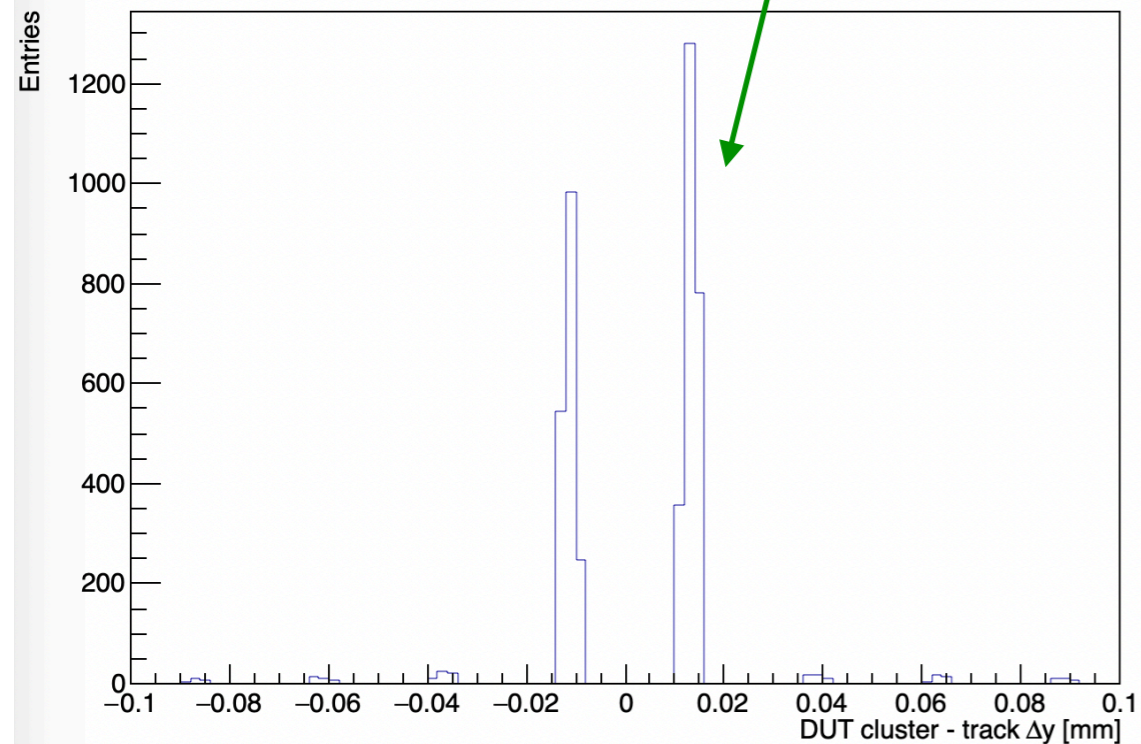
Sensor layout

□ I used the cluster size and the residual distribution to make sure we understand the sensor layout in the test beam and the position of the bump bondings
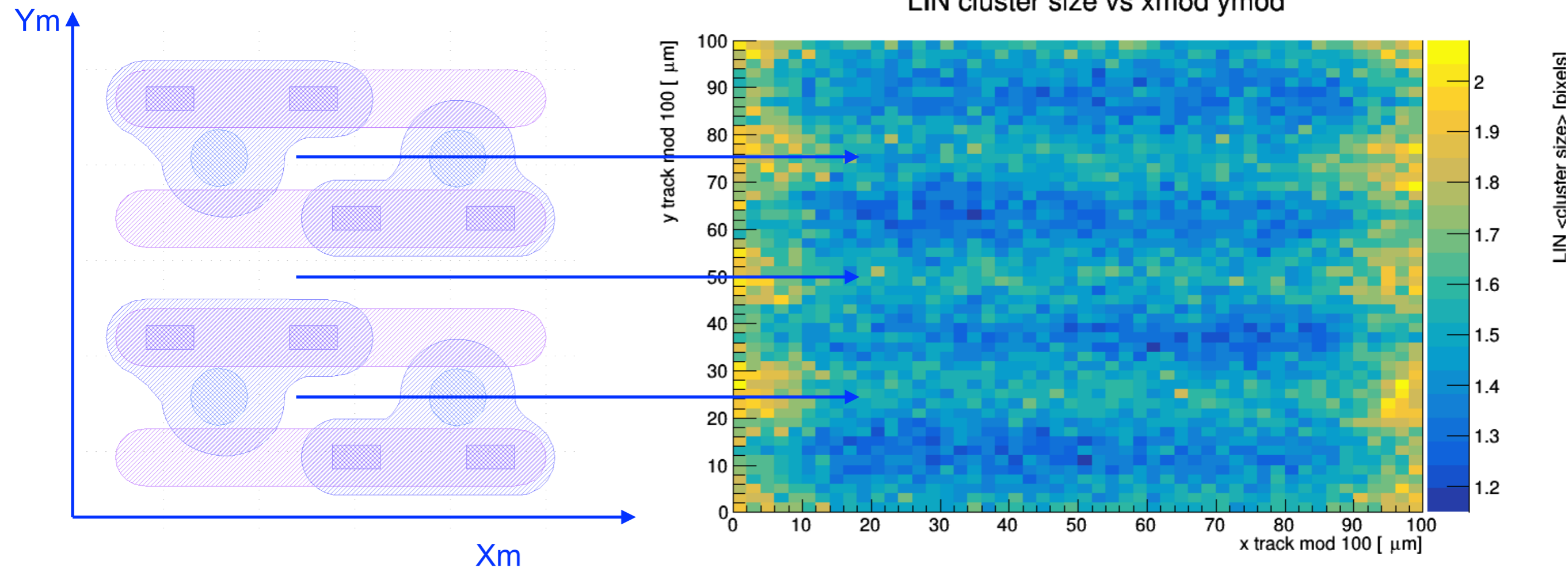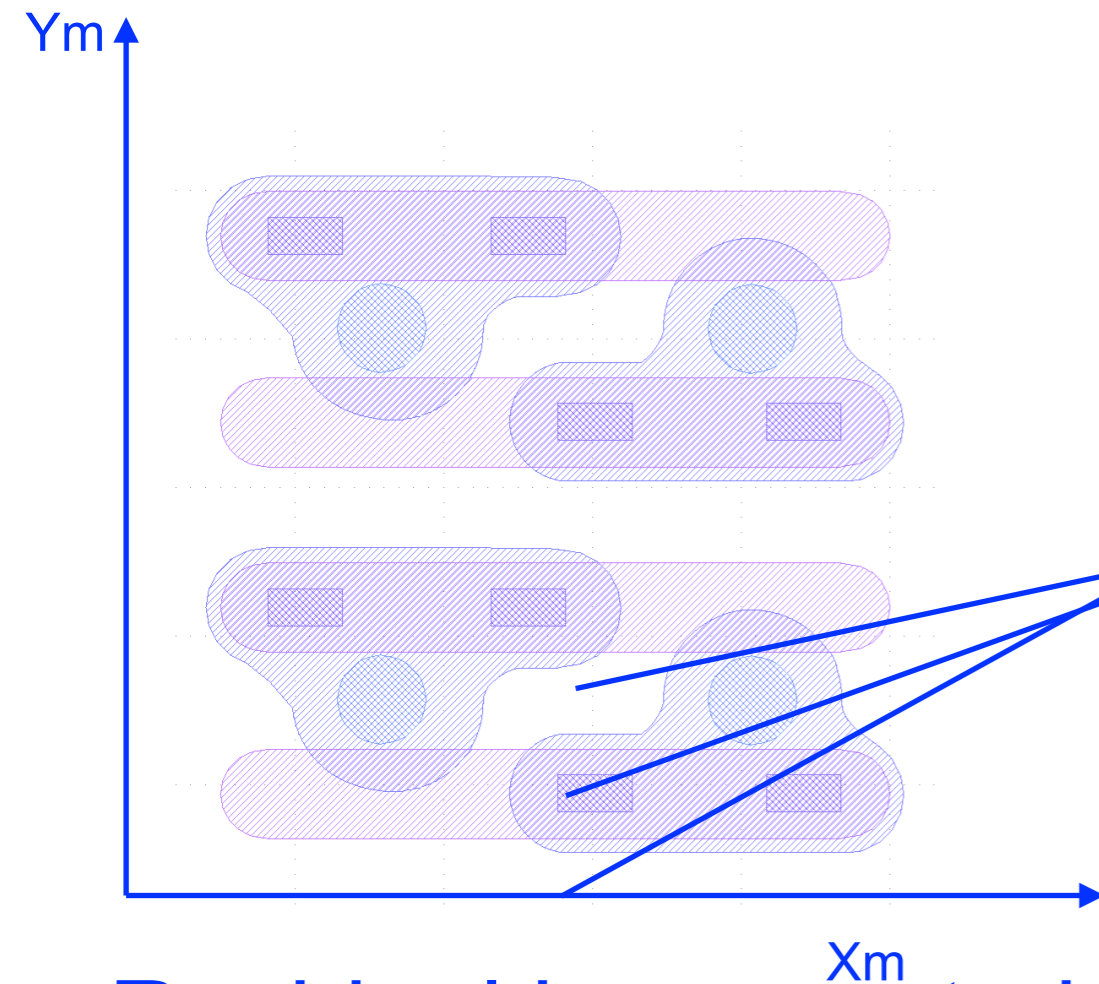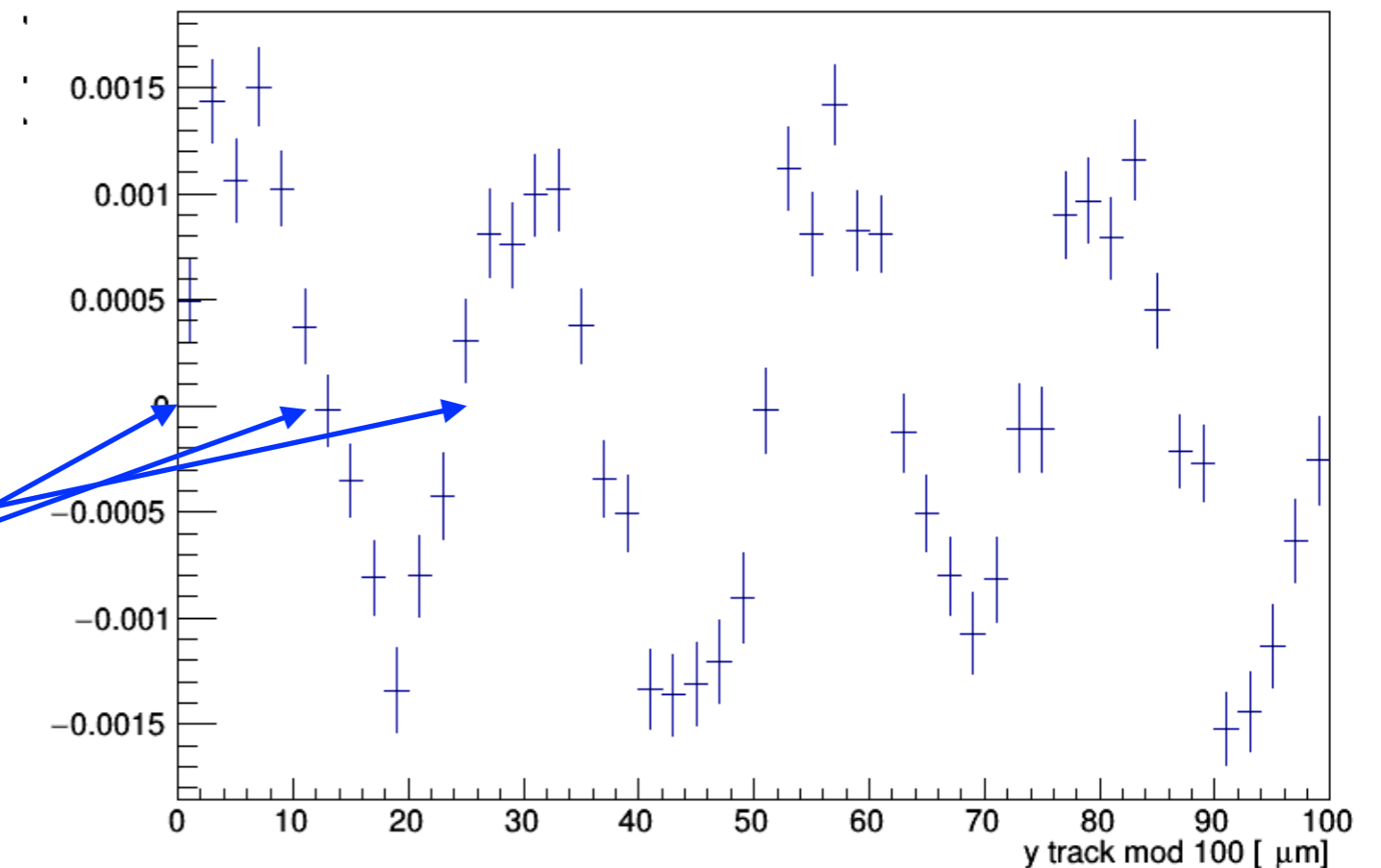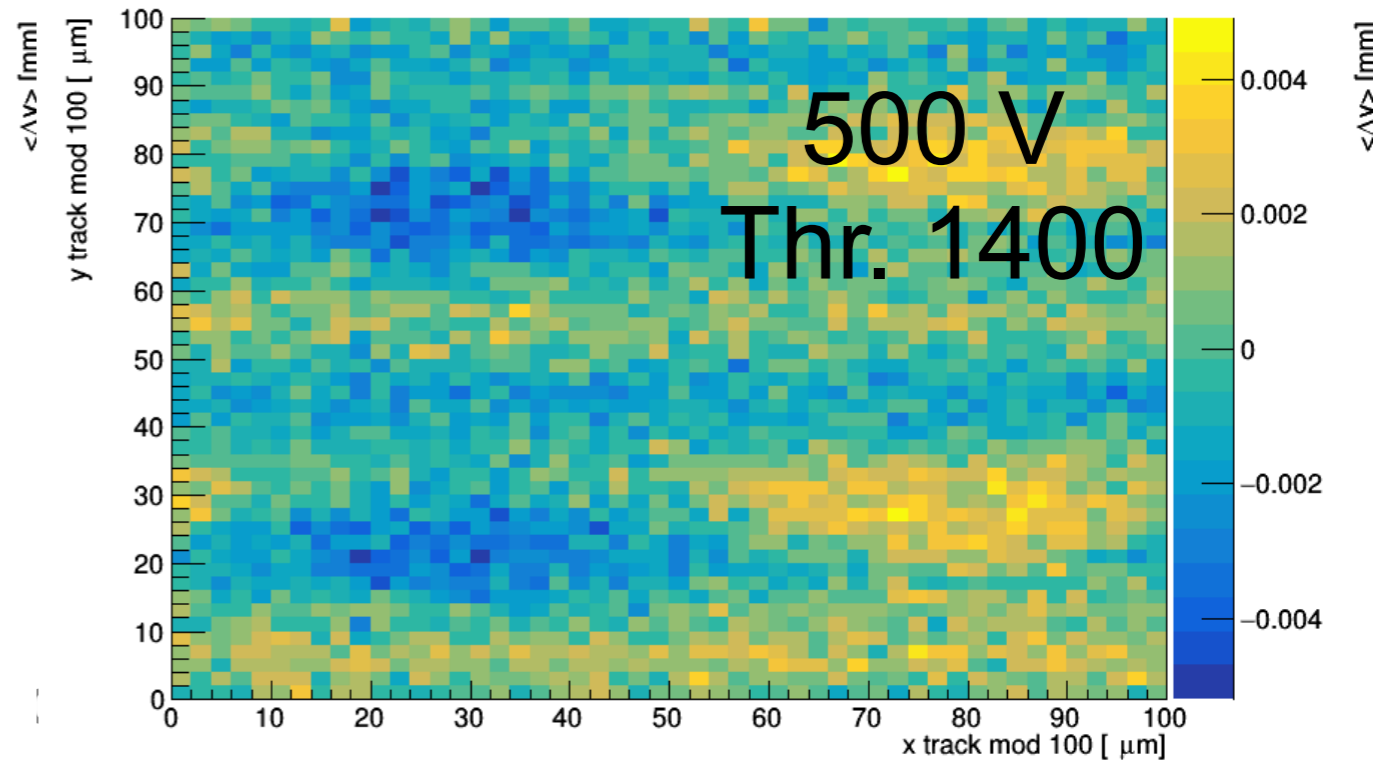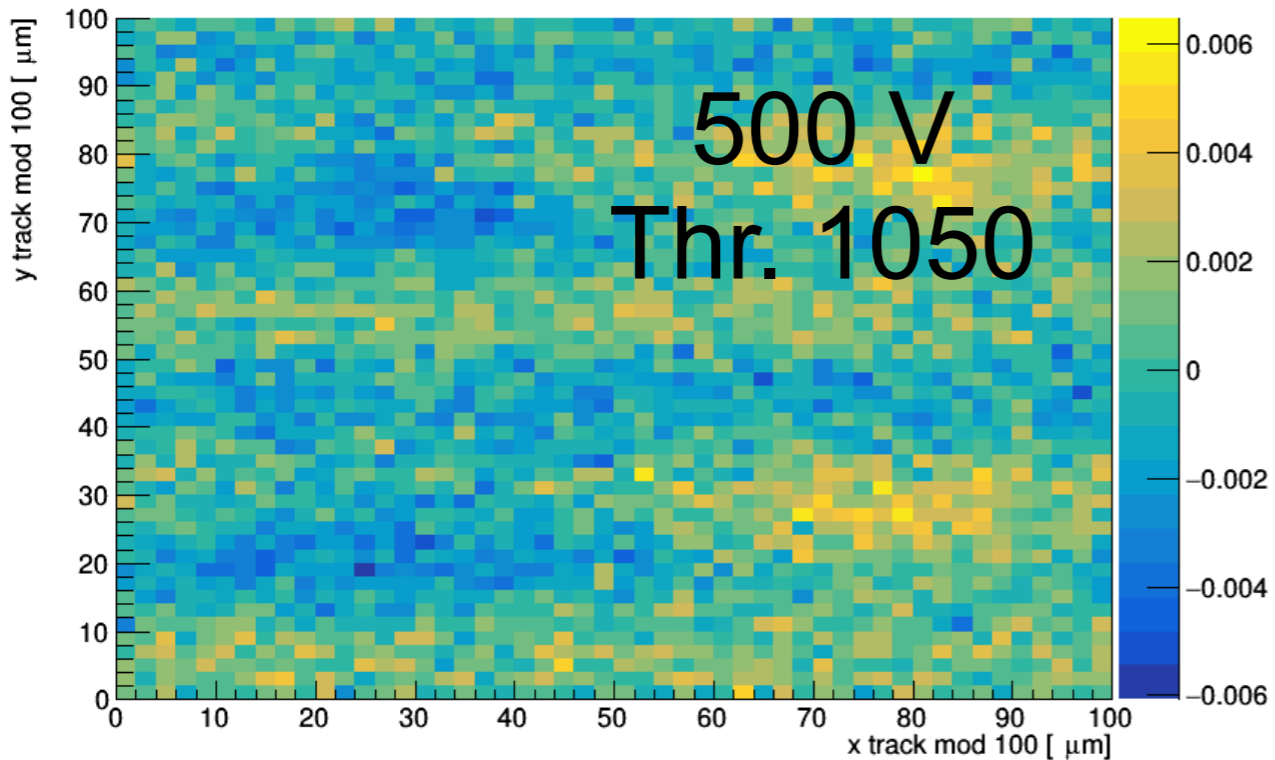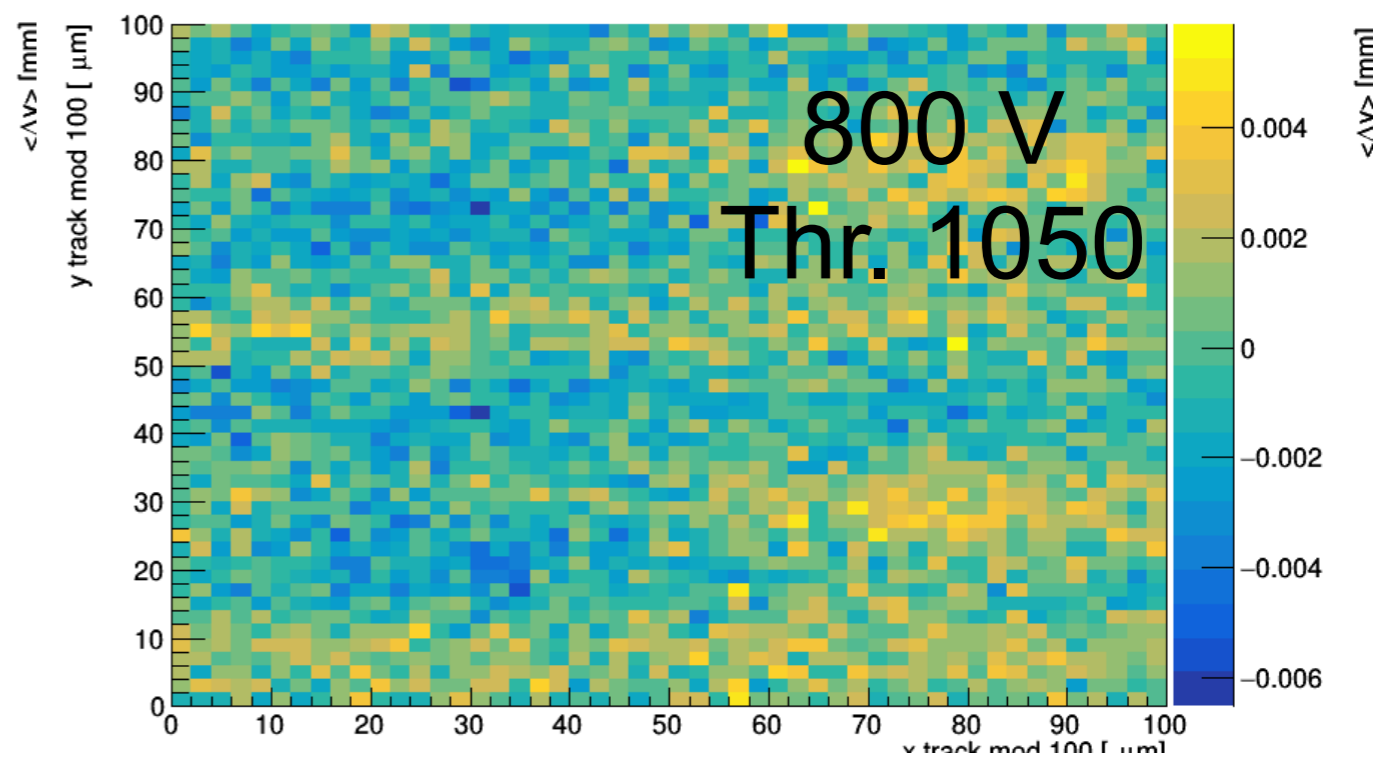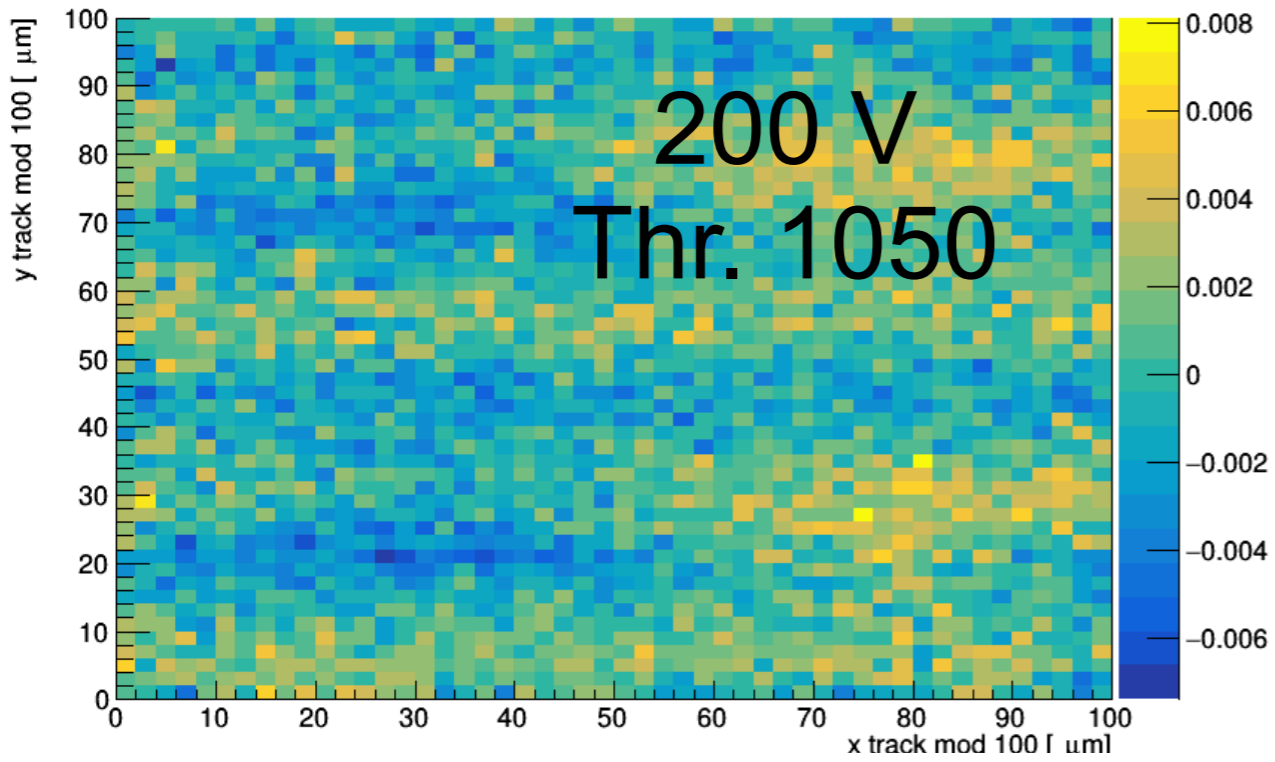
25x100 Planar FBK

Sensor layout

☐ I used the cluster size and the residual distribution to make sure we understand the sensor layout in the test beam and the position of the bump bondings

25x100 Planar FBK

Residual is computed as DUT_position - Track_position

Residuals at different V bias and Thresholds

25x100 Planar FBK

Possible x-talk effect

- Correlation between even and odd row clearly present

  - apparently we do see a pattern in the cluster size

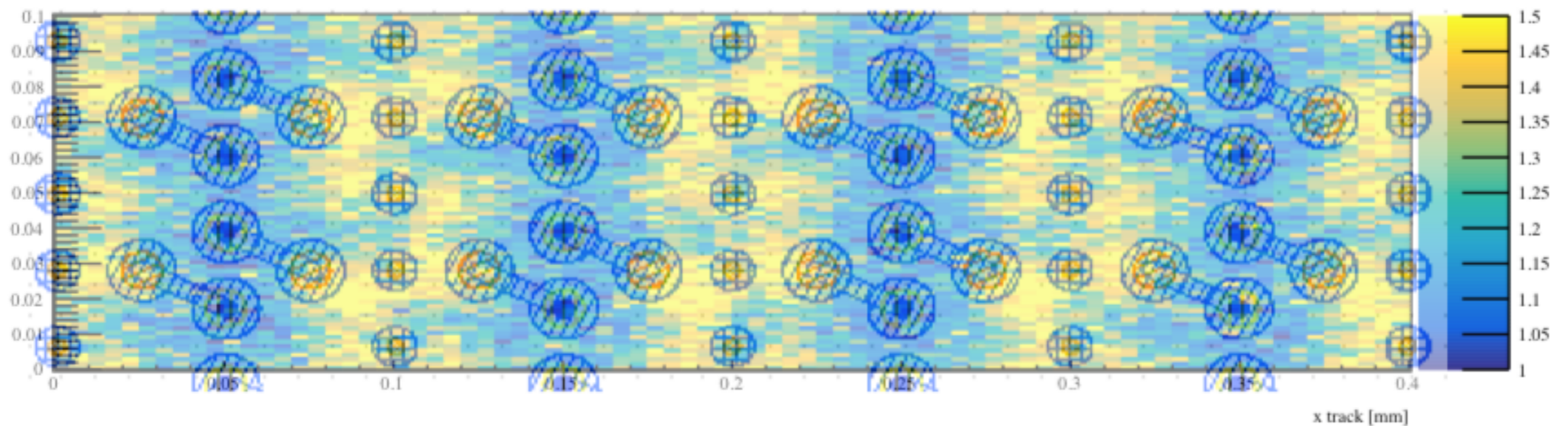 - whether it is significant or not still has to be quantified.

3D

Planar
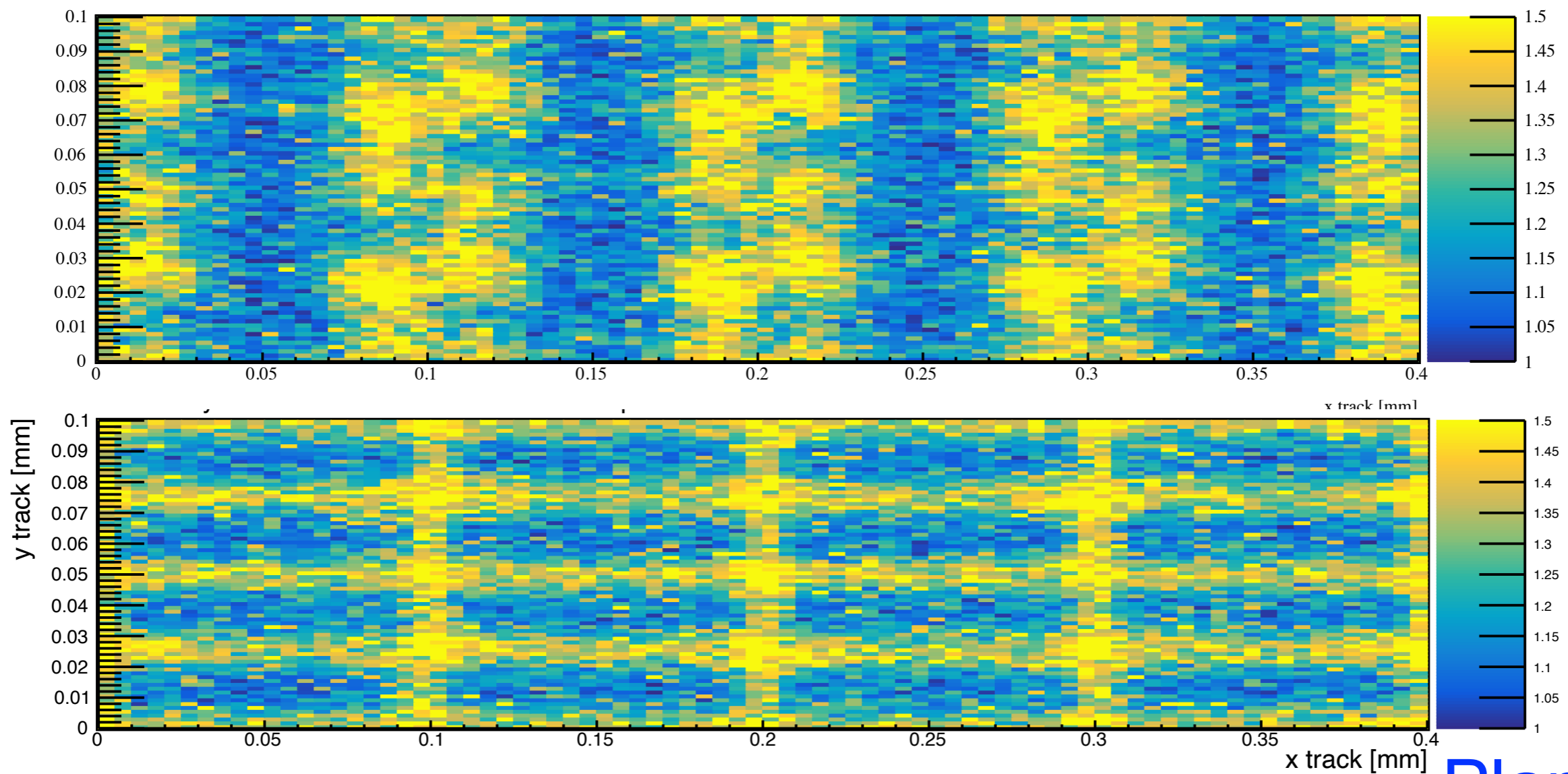
Possible x-talk effect

☐ Correlation between even and odd row clearly present

  ☐ apparently we do see a pattern in the cluster size

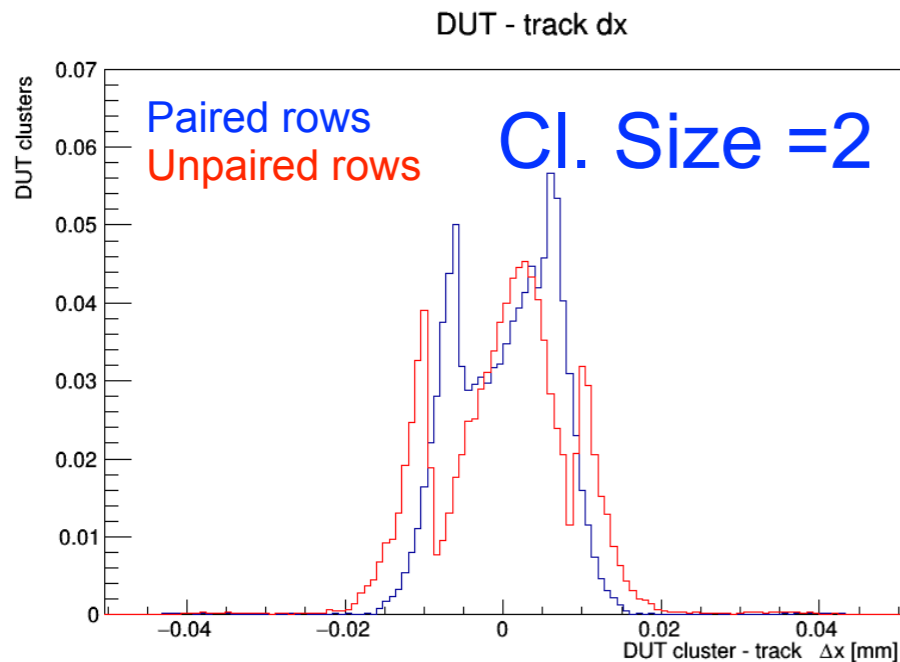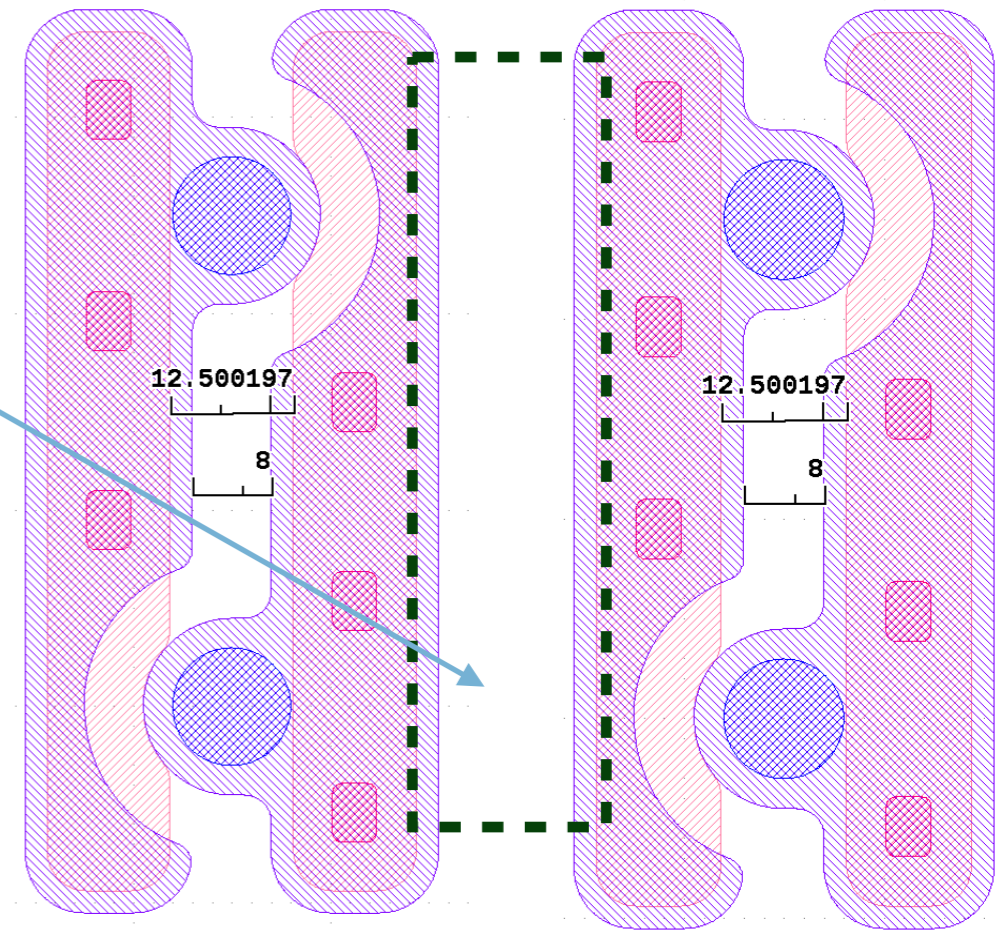 ☐ whether it is significant or not still has to be quantified.

M. Meschini

Bitten (Vbias = 70 V)

Tracks arrives in this area, but far enough from the divide so that charge sharing for diffusion is suppressed

Still these are cluster 2 events! the second cluster is the one induced by the x-talk on the farer row

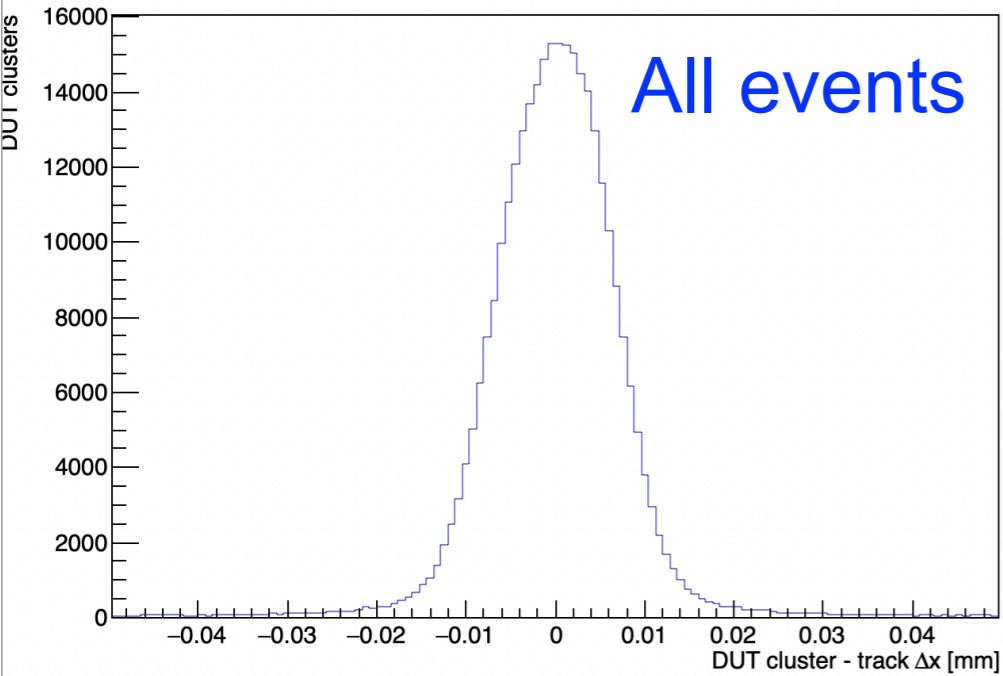One of the cases in which x-talk can spoil the resolution

12.500197
8

12.500197
8

DUT - track dx

Paired rows
Unpaired rows

Cl. Size =2

DUT clusters

DUT cluster - track Δx [mm]

Horns for Unpaired rows are coming from events where the second hit is induced by x-talk

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Resolution plots vs Clsize
bitten (Vbias = 70 V)

All events

N.B. events are selected +/- 5 um around the divide!

Cl. Size 1

Paired rows
Unpaired rows

Cl. Size 2
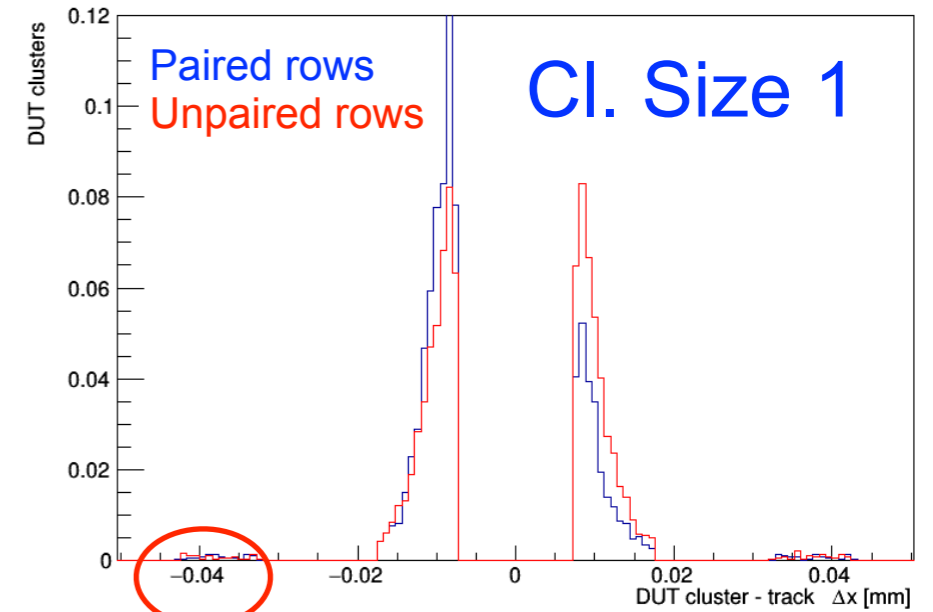
Paired rows
Unpaired rows
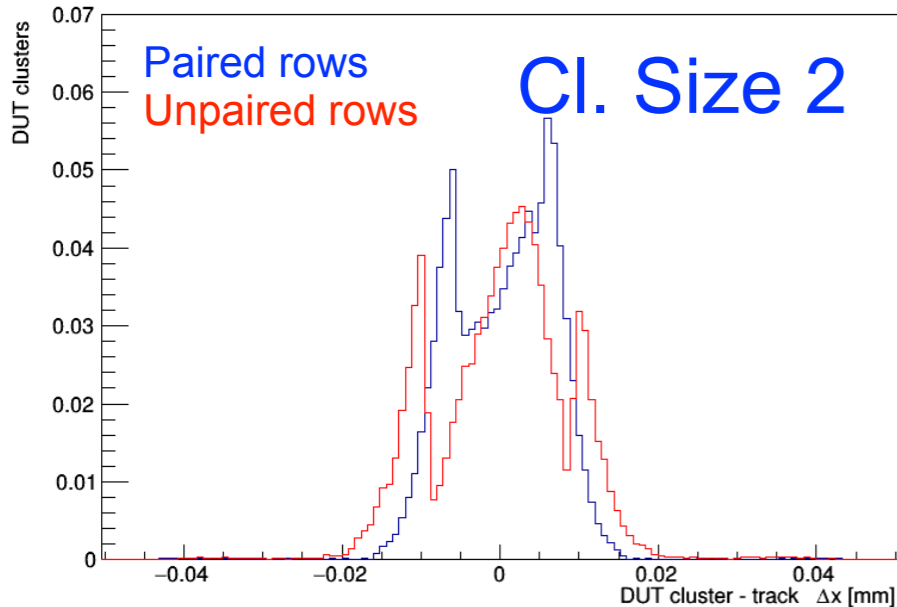
Asymmetry for Paired rows to be understood

Cl. Size 1 || 2

Paired rows
Unpaired rows
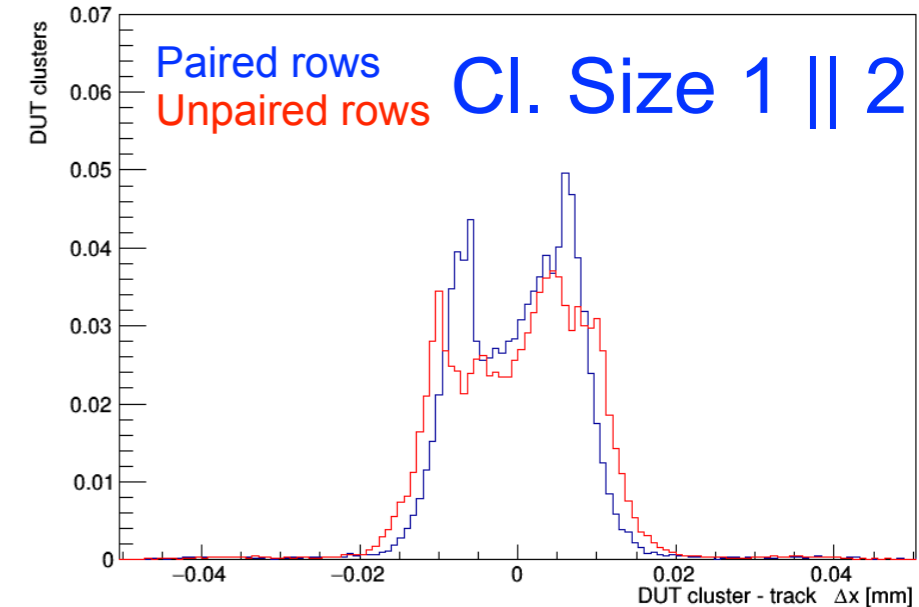
Cluster size

3D pixel sketch

[G.F. Dalla Betta et al., NIMA 824 (2016) 386]
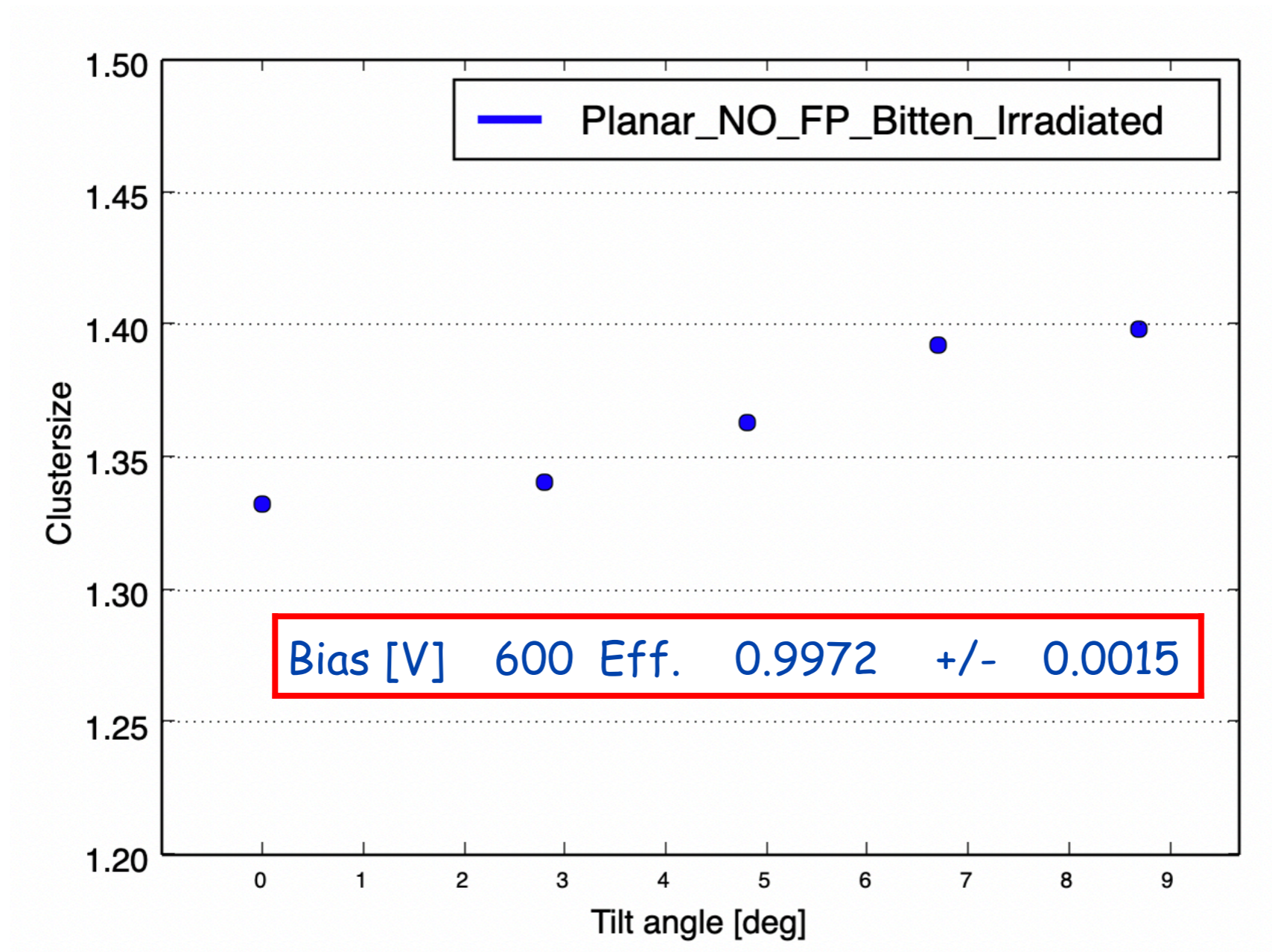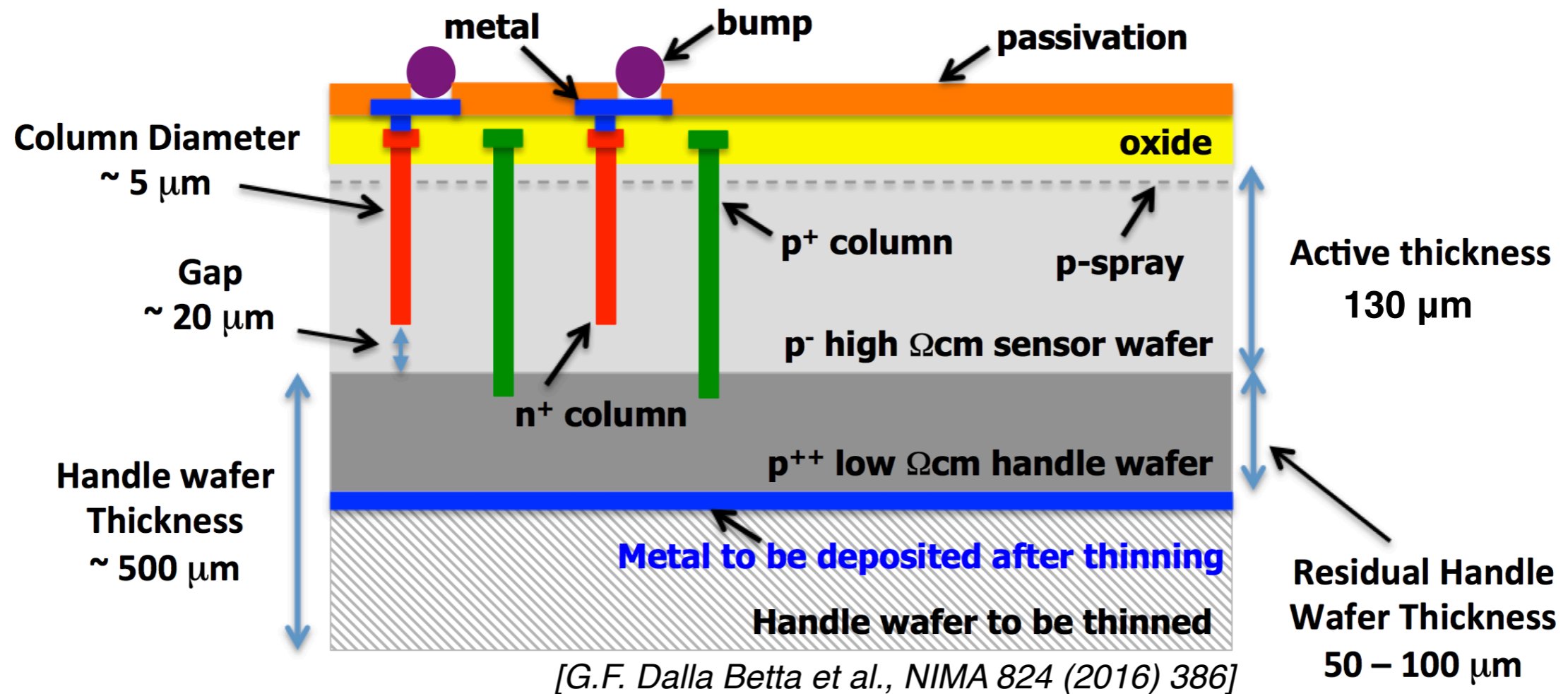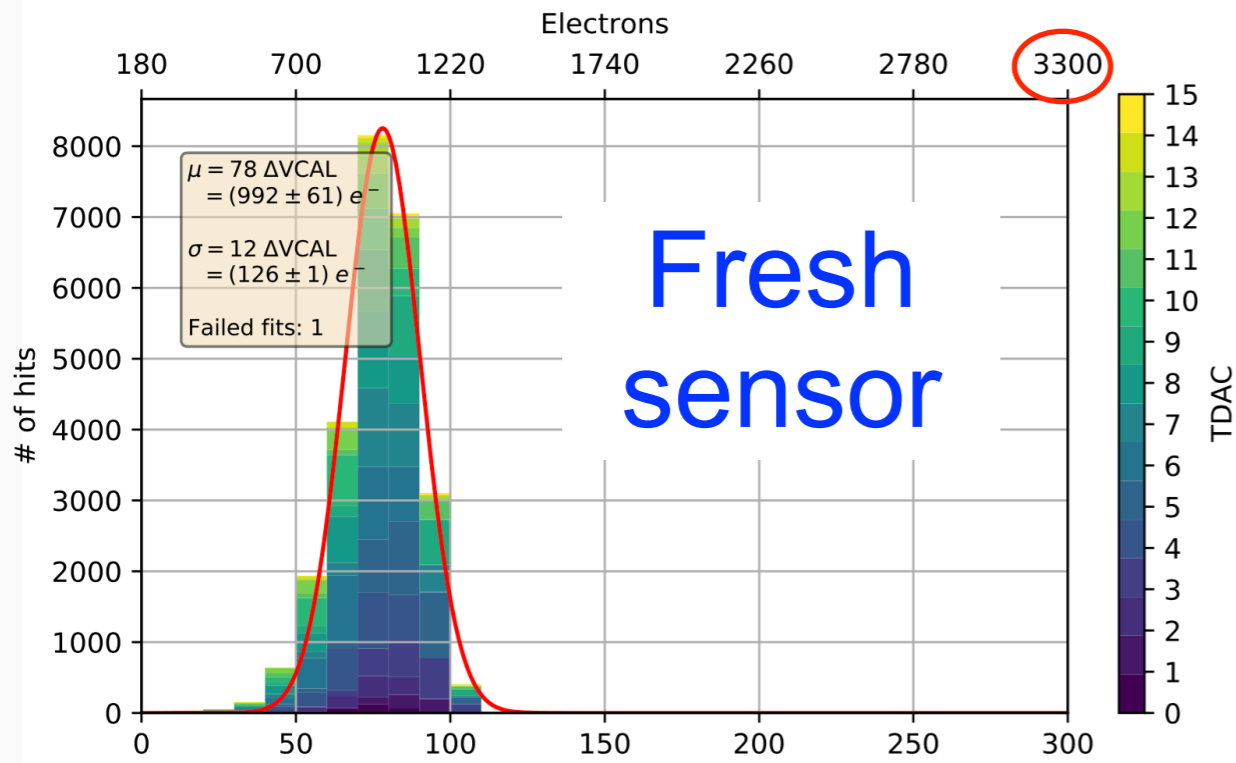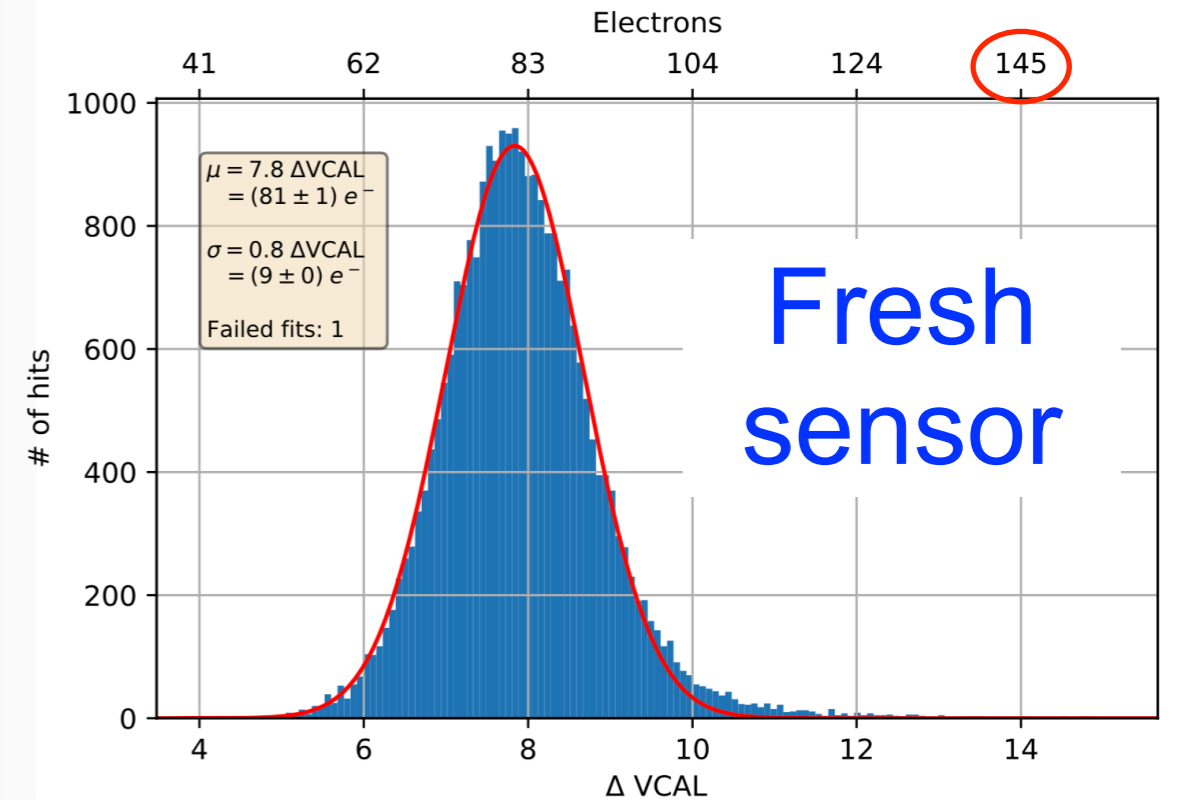
- ☐ 3D single sided process, optimised by FBK
- ☐ Ohmic columns/trenches depth > active layer depth (for bias)
- ☐ Junction columns depth < active layer depth (for higher Vbreakdown)
- ☐ Reduction of columns diameter to ~5 µm
- ☐ Holes (at least partially) filled with poly-Si
  - ☐ Two wafers, high and low resistivity, bonded together
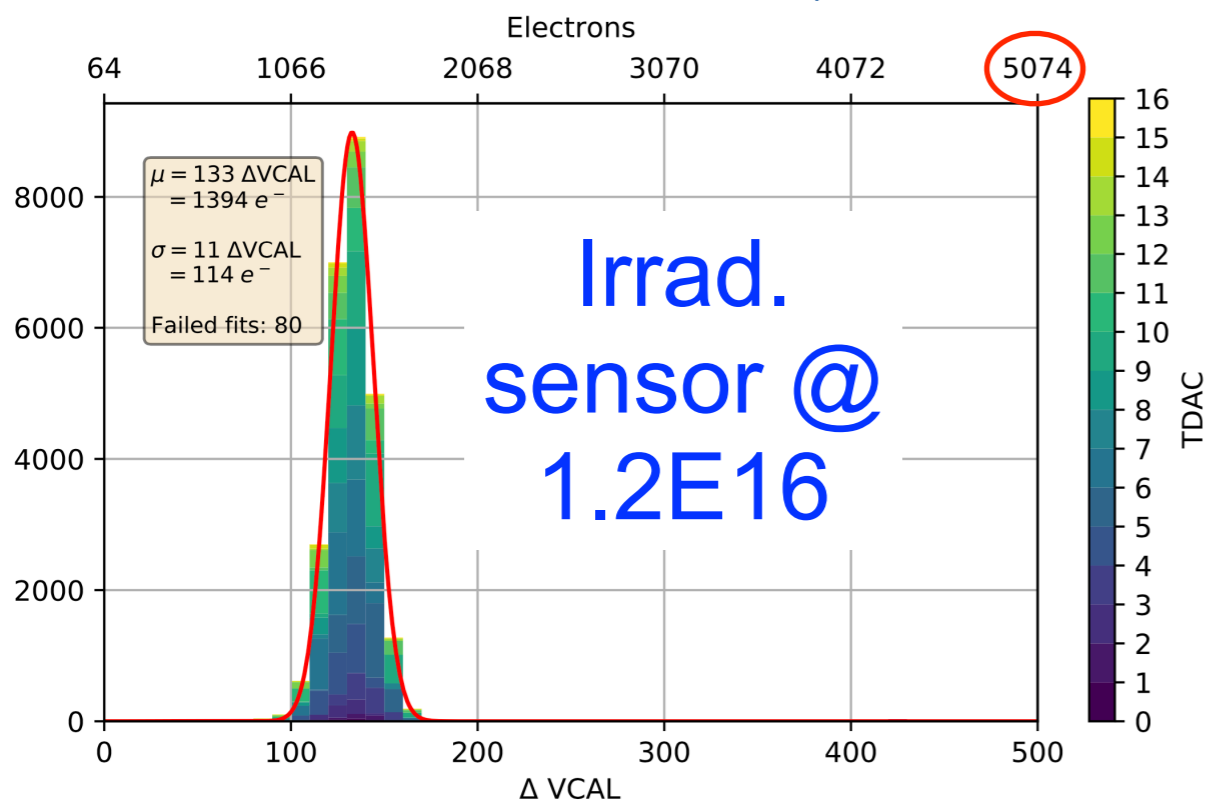
Planar sensors tuning