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 pandemia the access to TB facilities has been quite problematic:

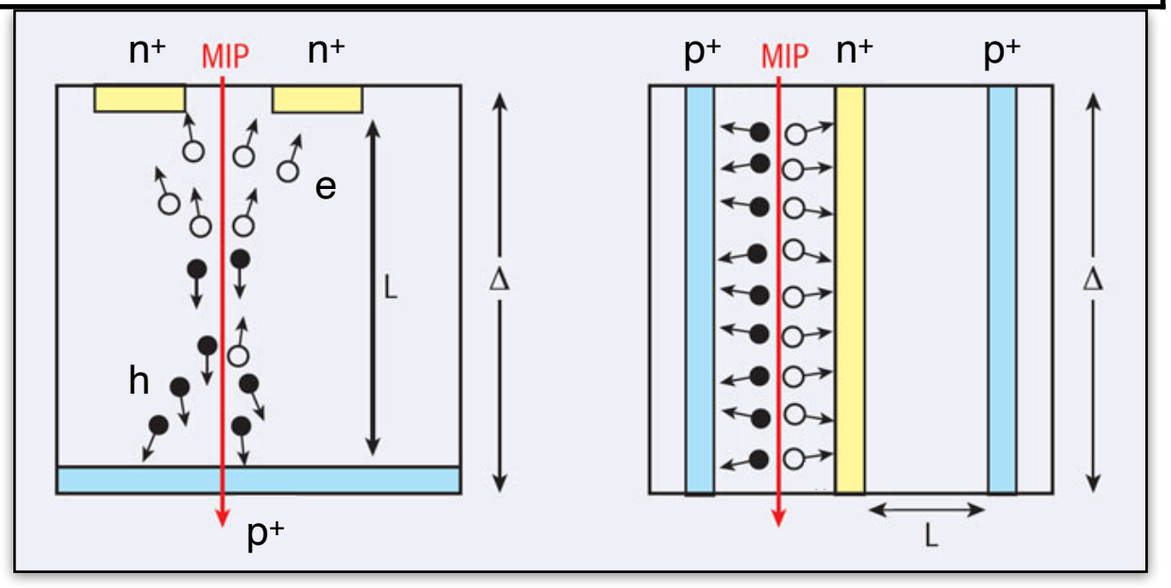
DESY, Hamburg and Zurich University teams made the data taking possible

I would like to help all the people involved, without them these analyses could not be performed.

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 μm^2 or 50x50 μm^2
Fluence **~2.3x10^{16} n_{eq}/cm^2** 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)

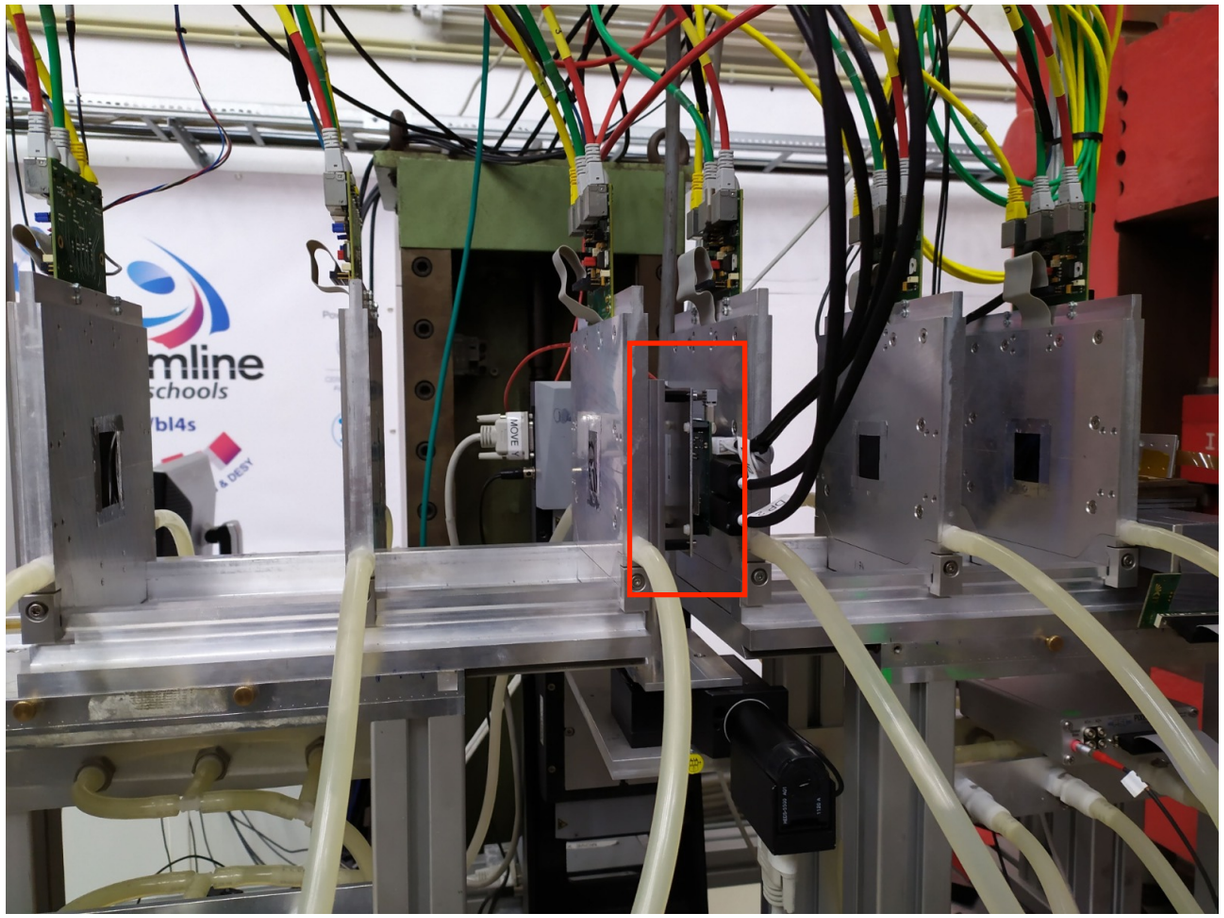


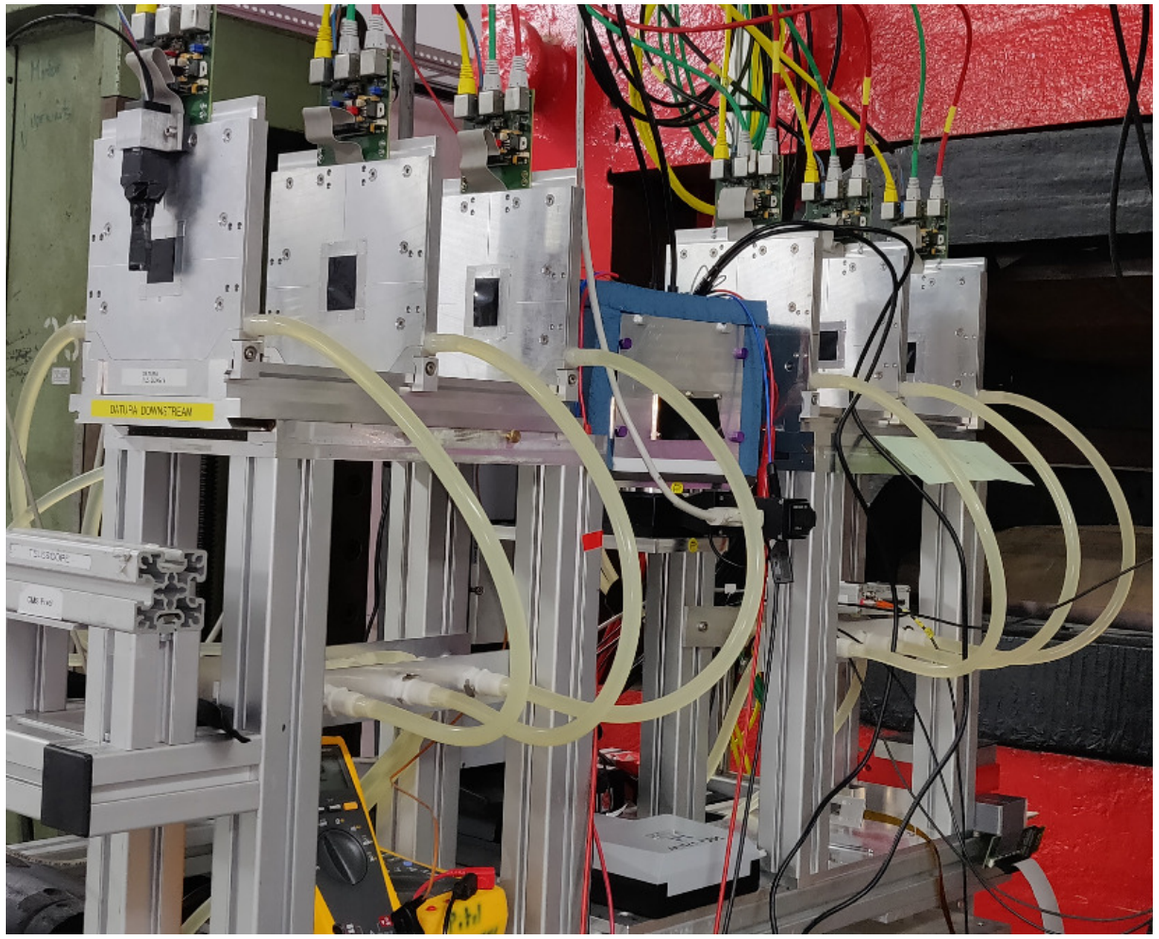
[C. Da Via et al, NIMA (2012)]

(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

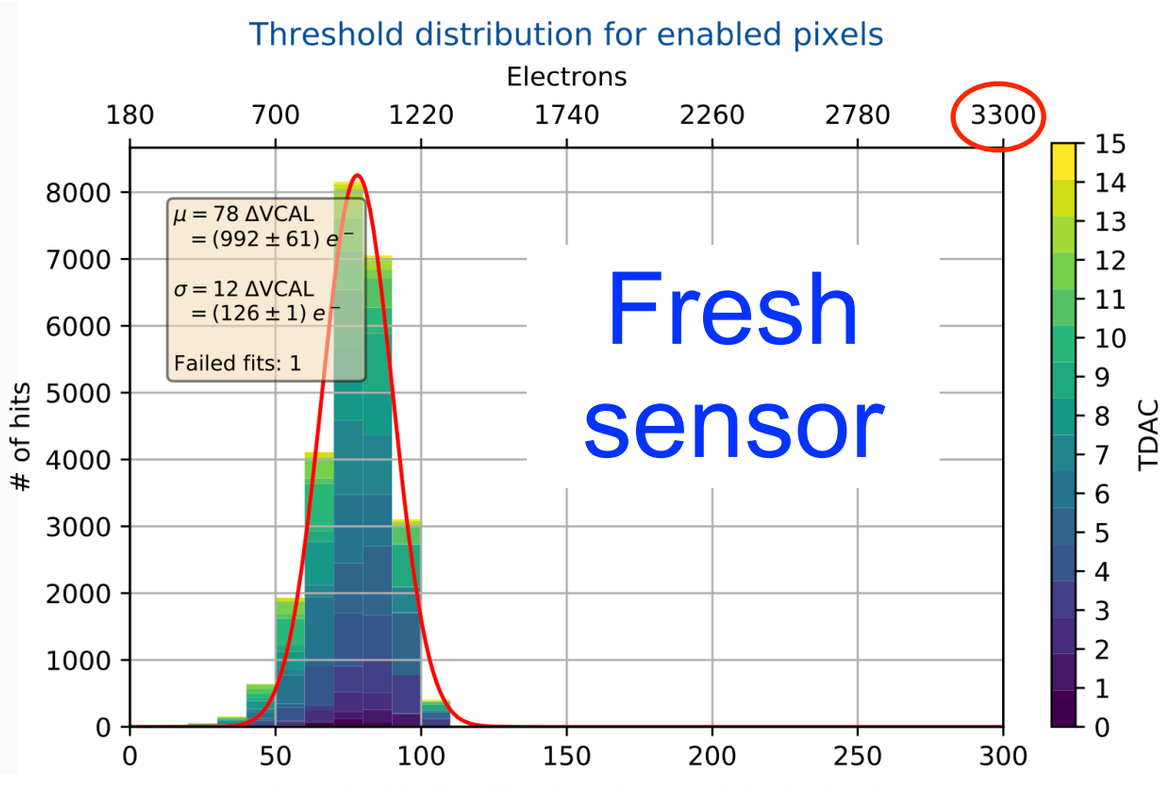


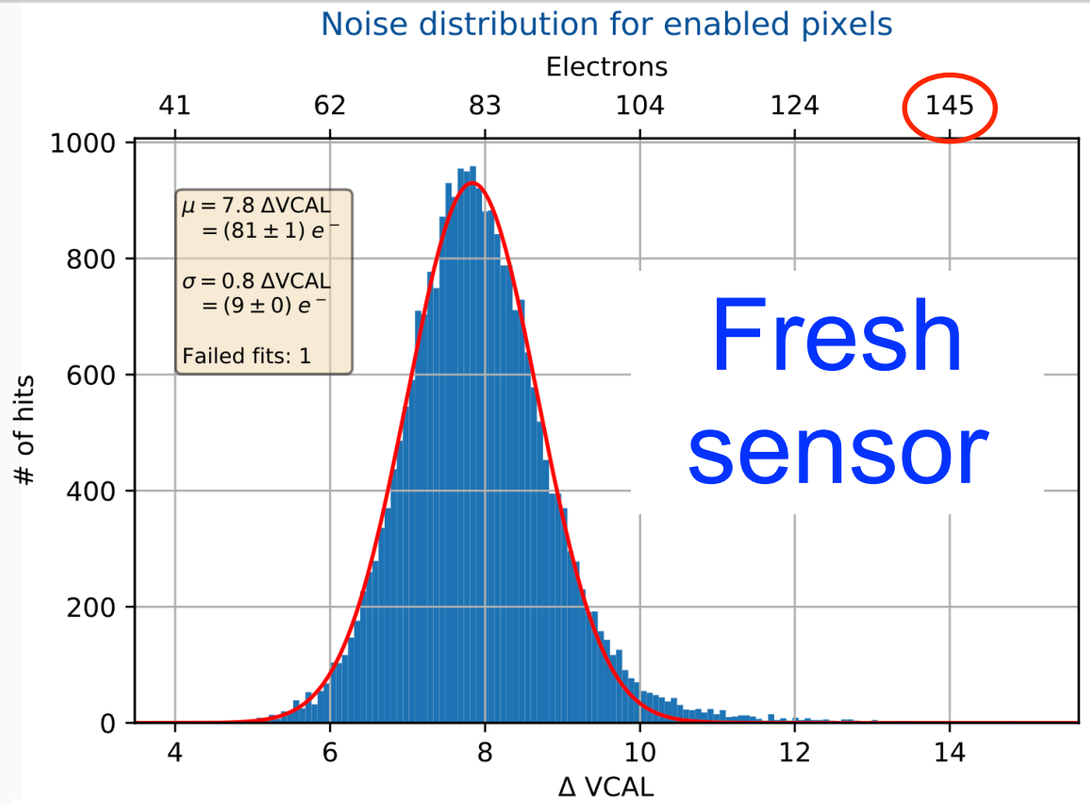


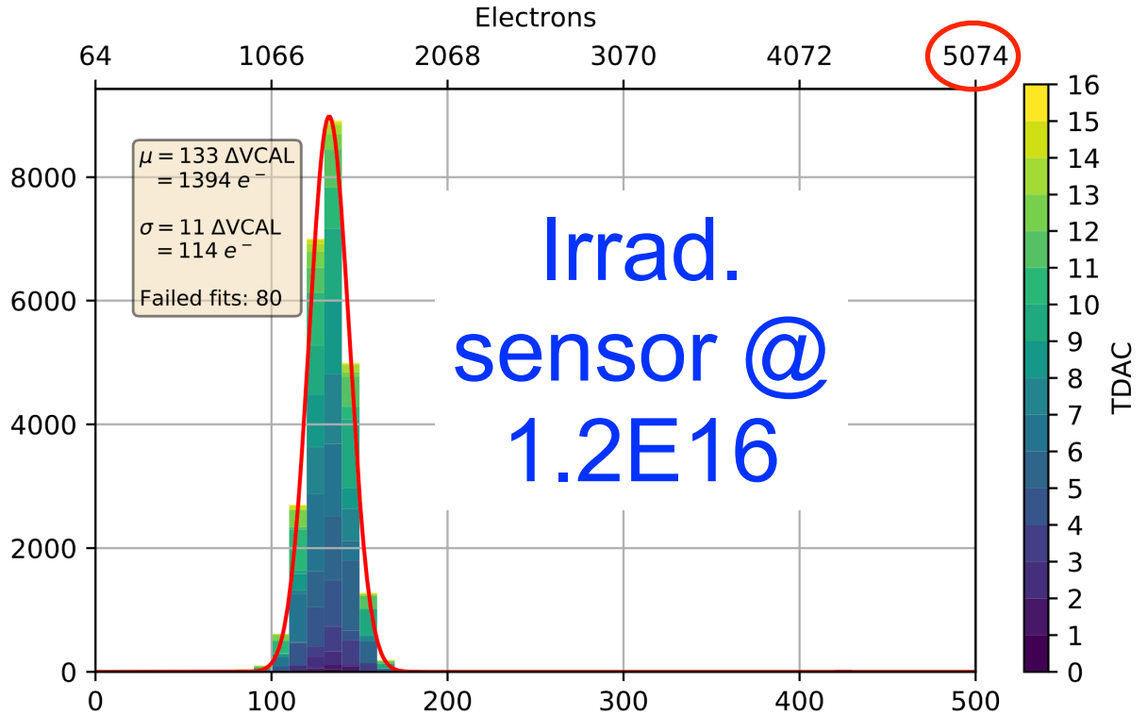
FBK Sensors equipped with RD53A chip

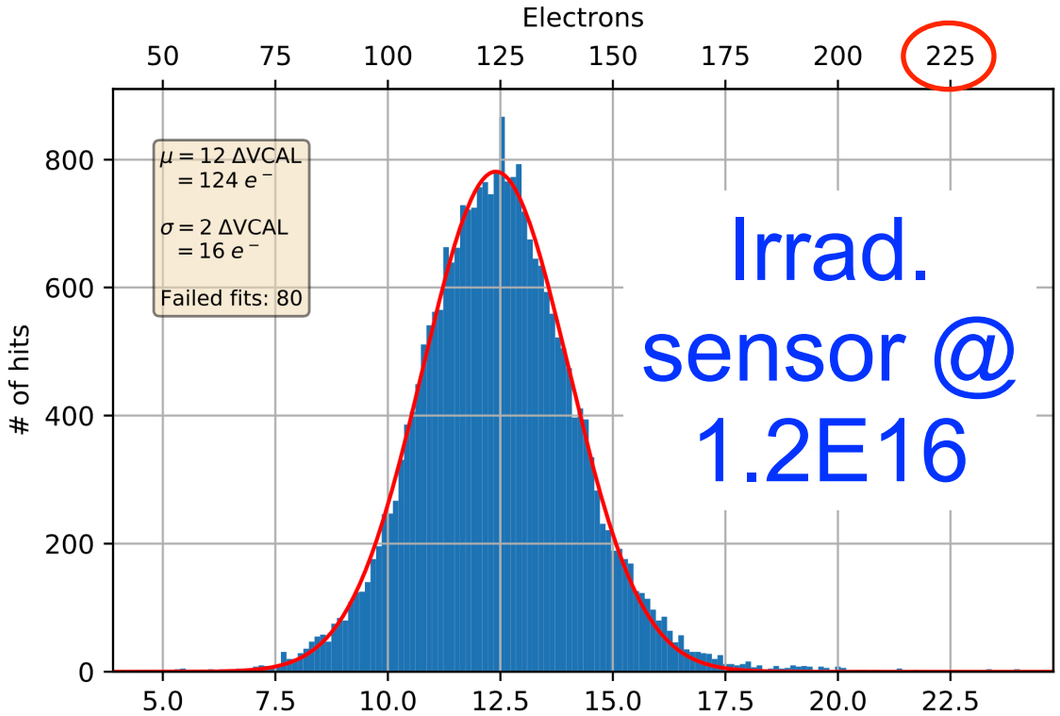
- All sensors were produced by FBK
  - 25x100 um^2 and 50x50 um^2
  - 130/150 um, Wafer thinned down to a total of 200 um thickness and bonded to a RD53A chip
- Performance measured before and after irradiation
  - Not on the same sensor, though
  - Max radiation fluence of 1.2E16 n_{eq}/cm^2

Planar sensors tuning



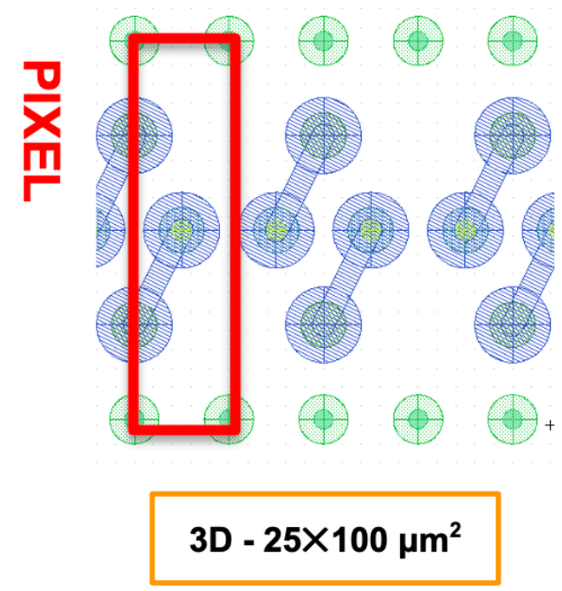




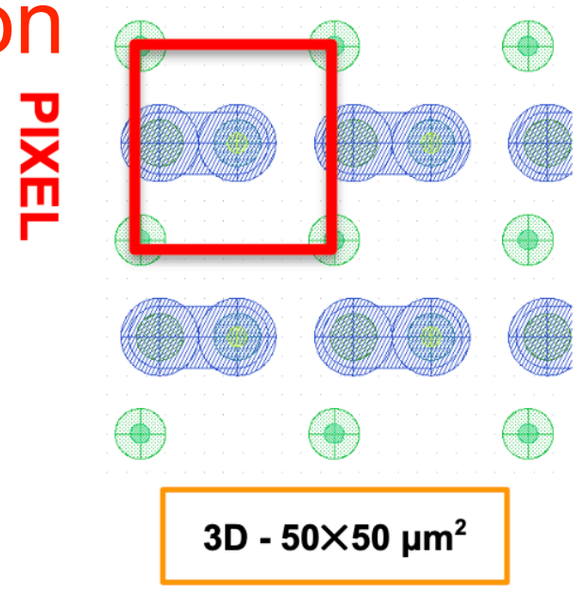


Data from November 2019

- 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

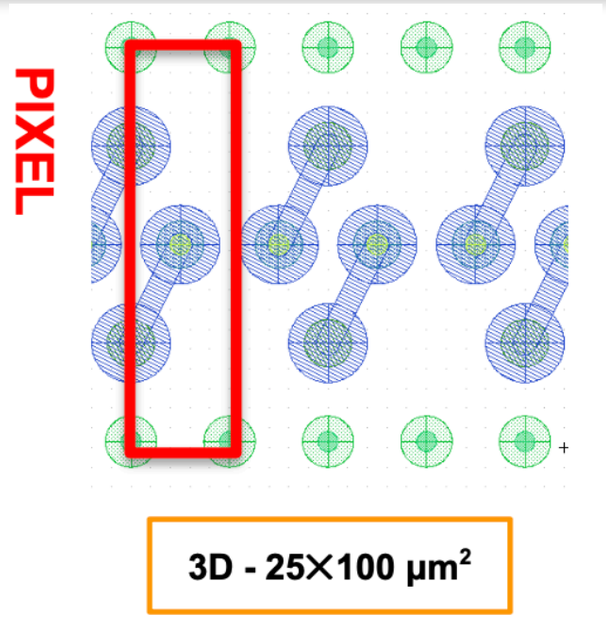


- Data analyzed for efficiency, Signal collection and cluster size distributions
  - All plots shown are based on data with incident angle at 0 degrees
  - Sensors were **NOT** irradiated

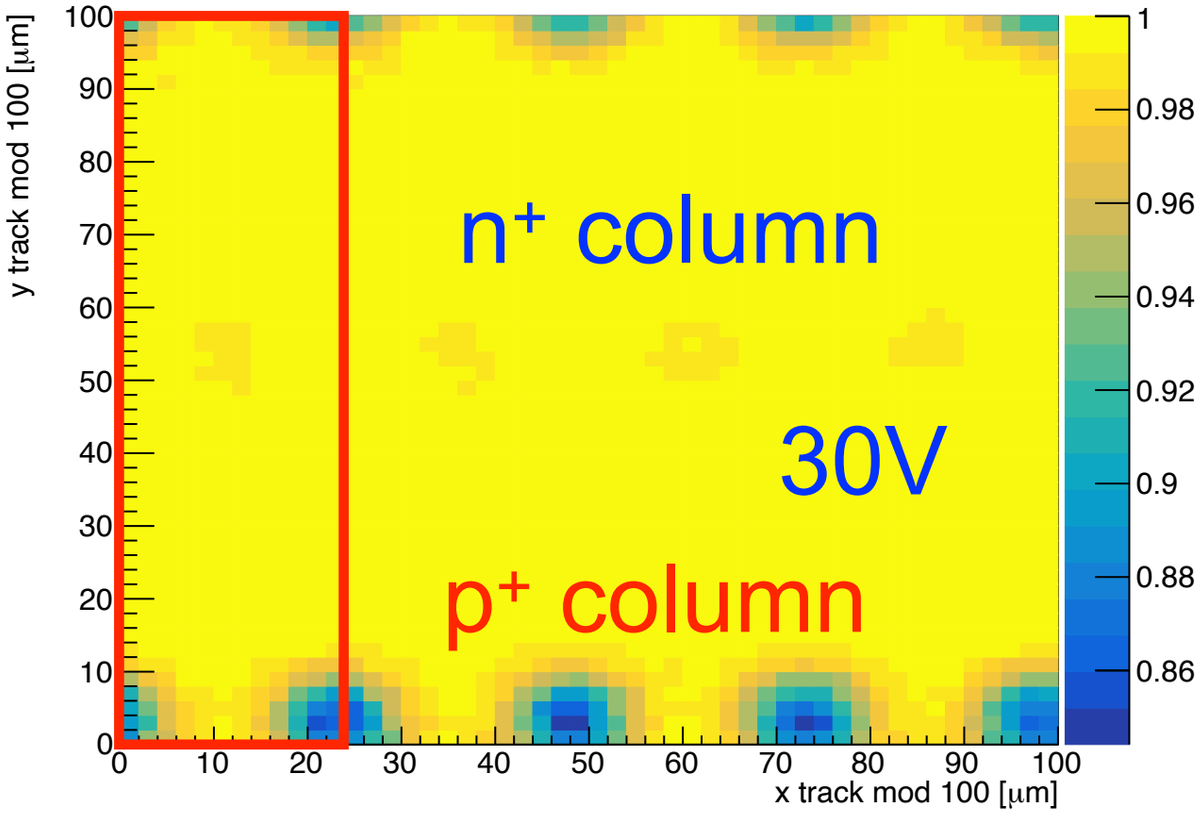


25x100 3D sensor

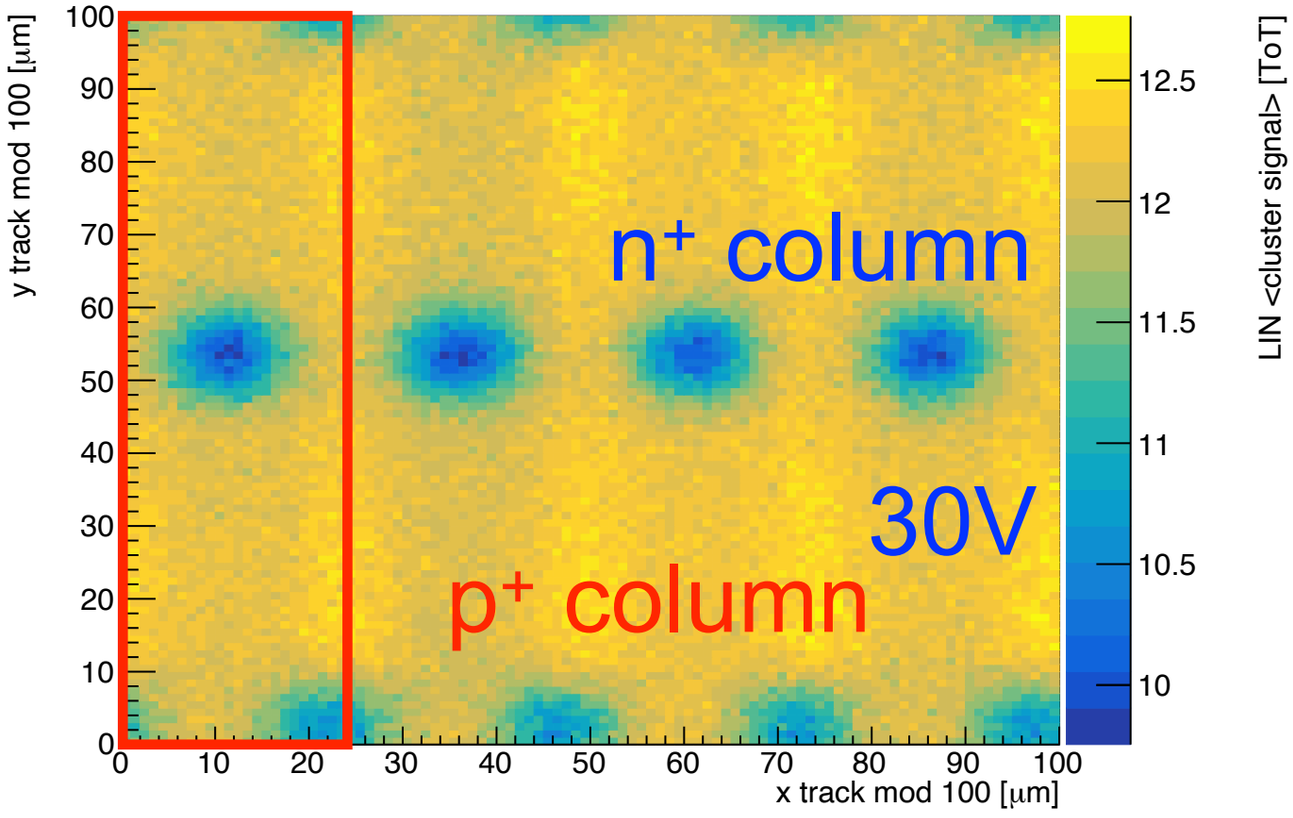
- Efficiency and signal distribution per cell
  - small residual misalignment ~2 um
  - Average efficiency > 99%
  - **No pixel by pixel calibration has been applied**
- Plots made with Vbias = -30 V
  - Perpendicular tracks only



Efficiency per cell

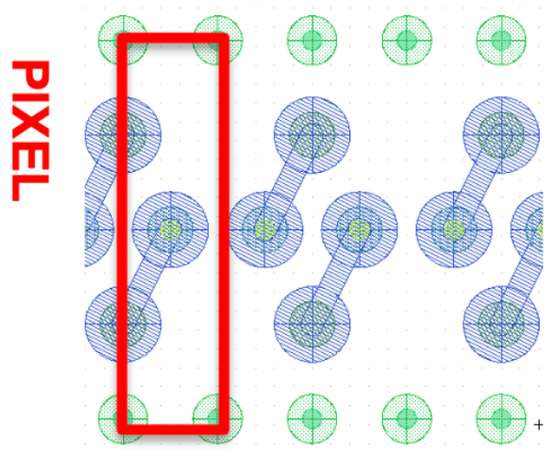


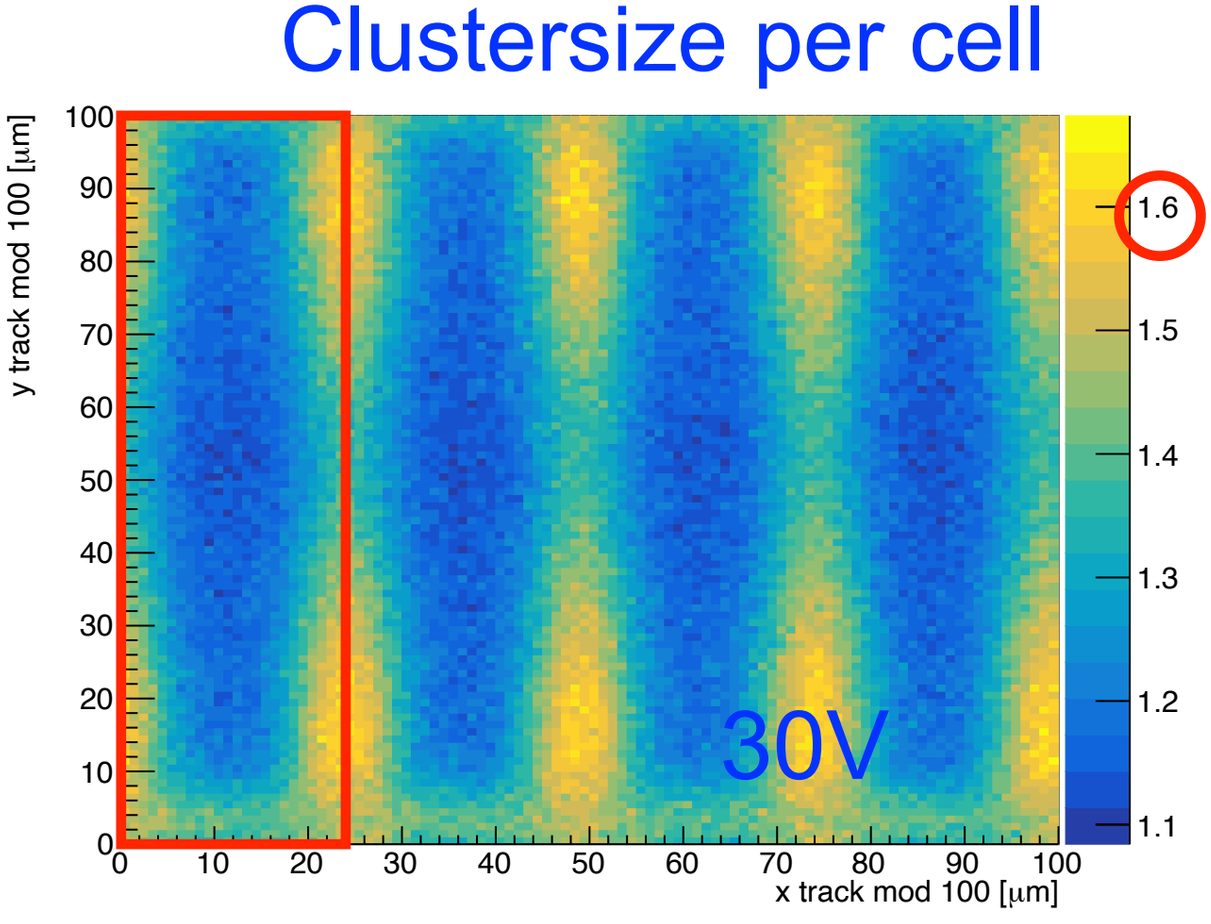
Signal per cell

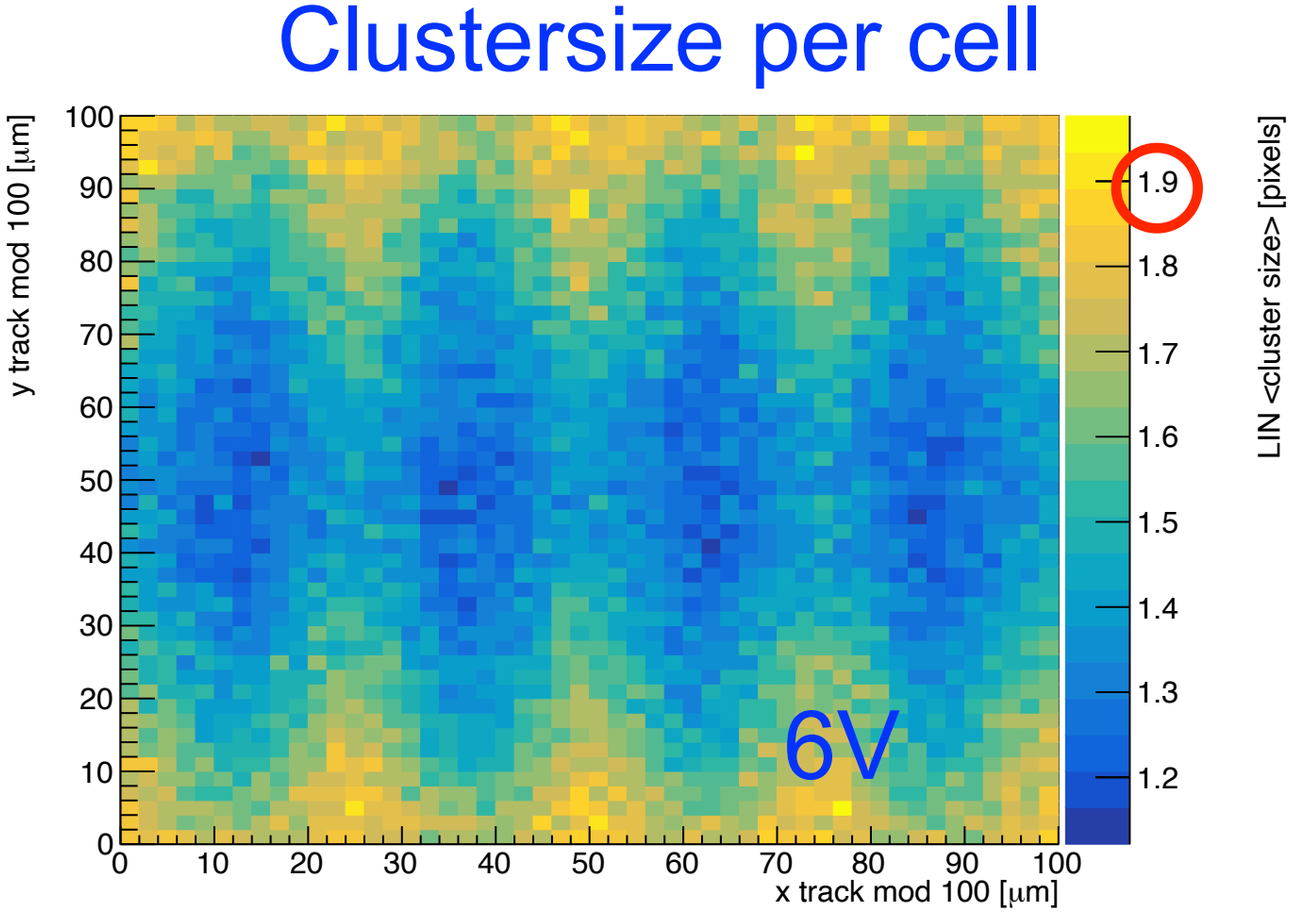


25x100 3D sensor

- 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

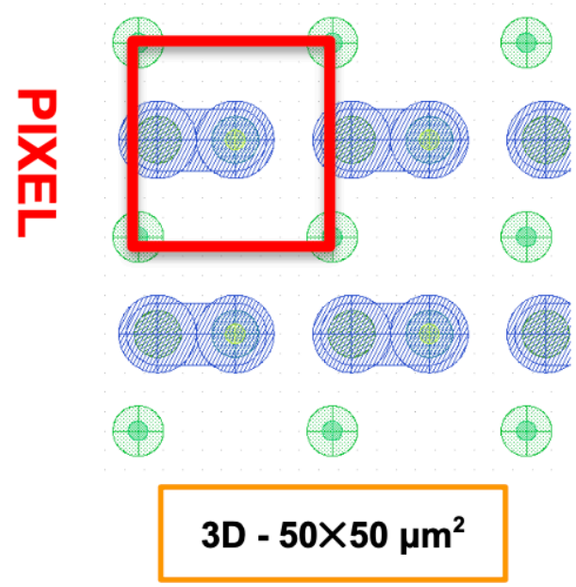




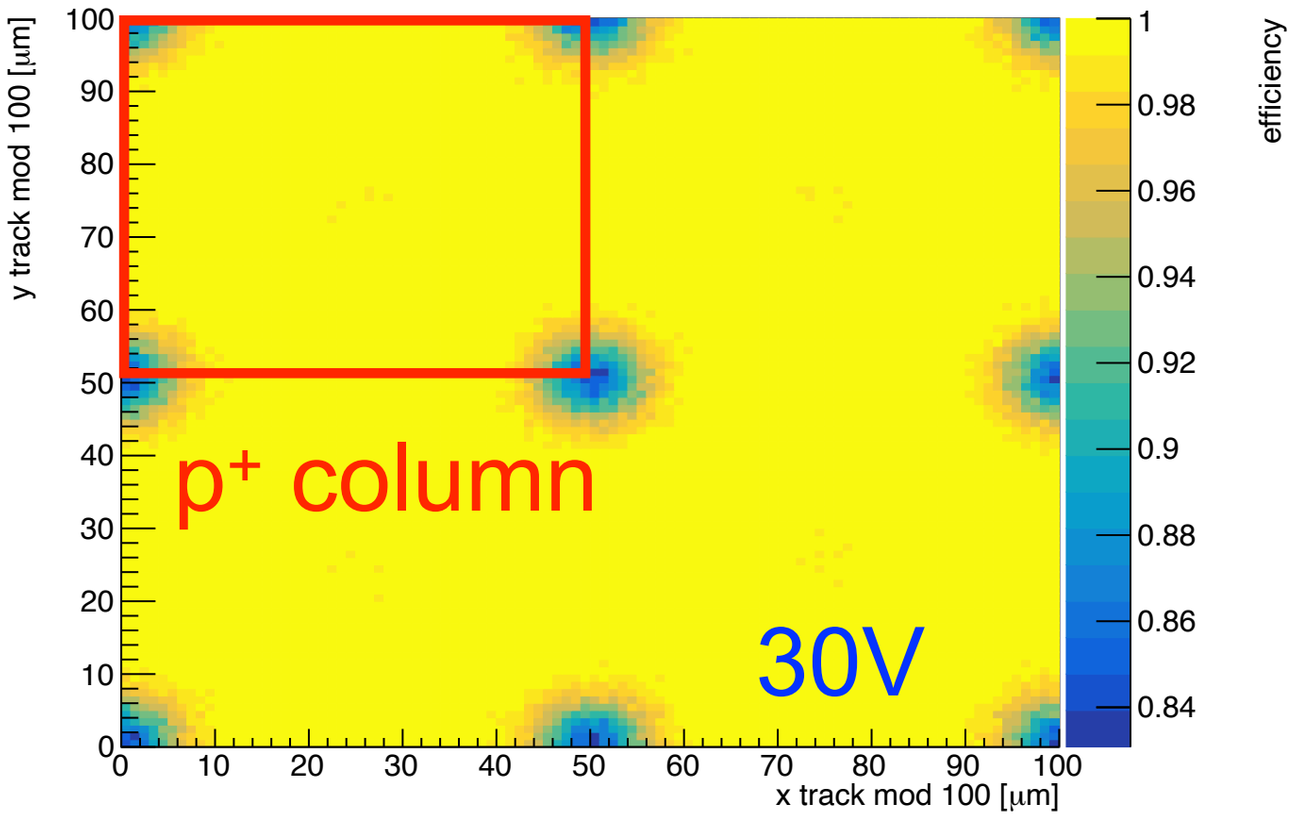


50x50 3D sensor

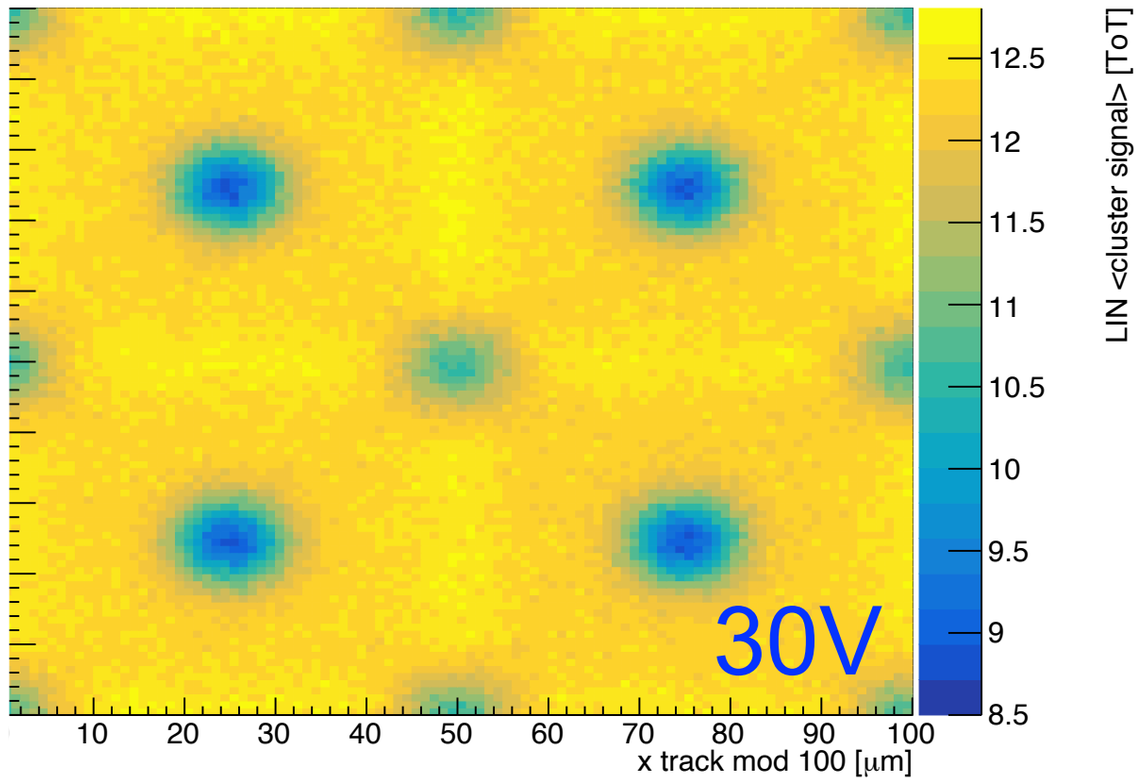
- Efficiency and Signal distribution per cell
  - Average efficiency > 99%
  - n+ columns visible in the efficiency map
  - **No pixel by pixel calibration has been applied**
- Vbias = -30 V, thickness = 150 um
  - Perpendicular tracks only



Efficiency per cell

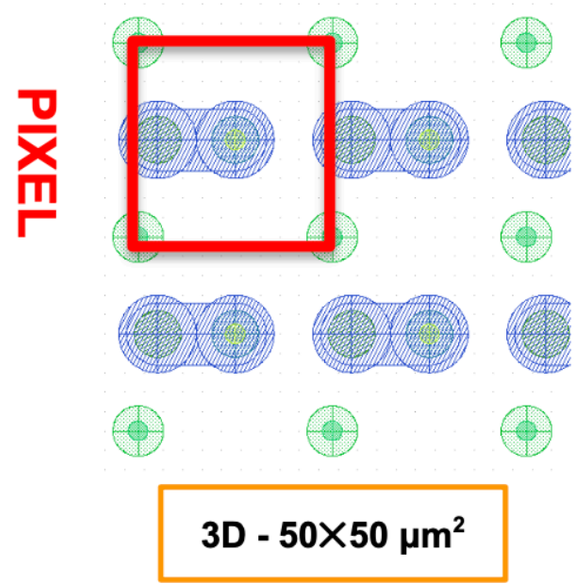


Signal per cell

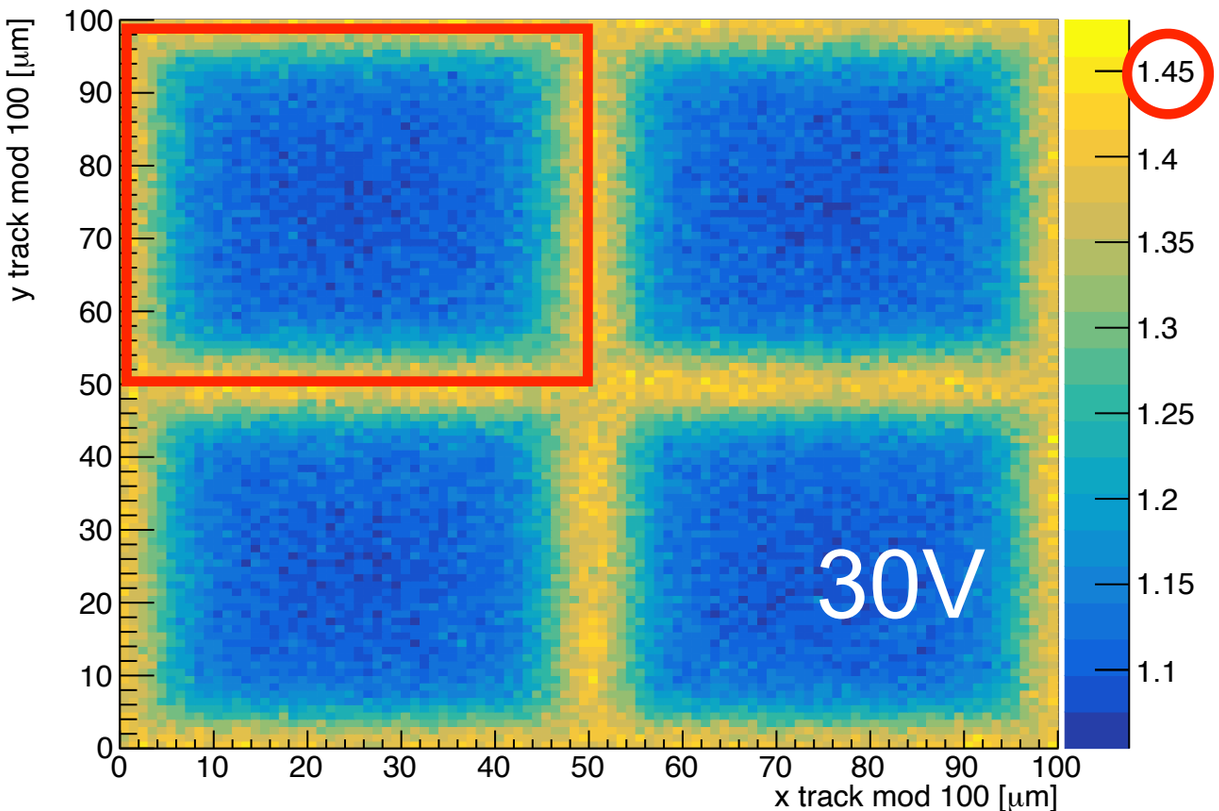


50x50 3D sensor

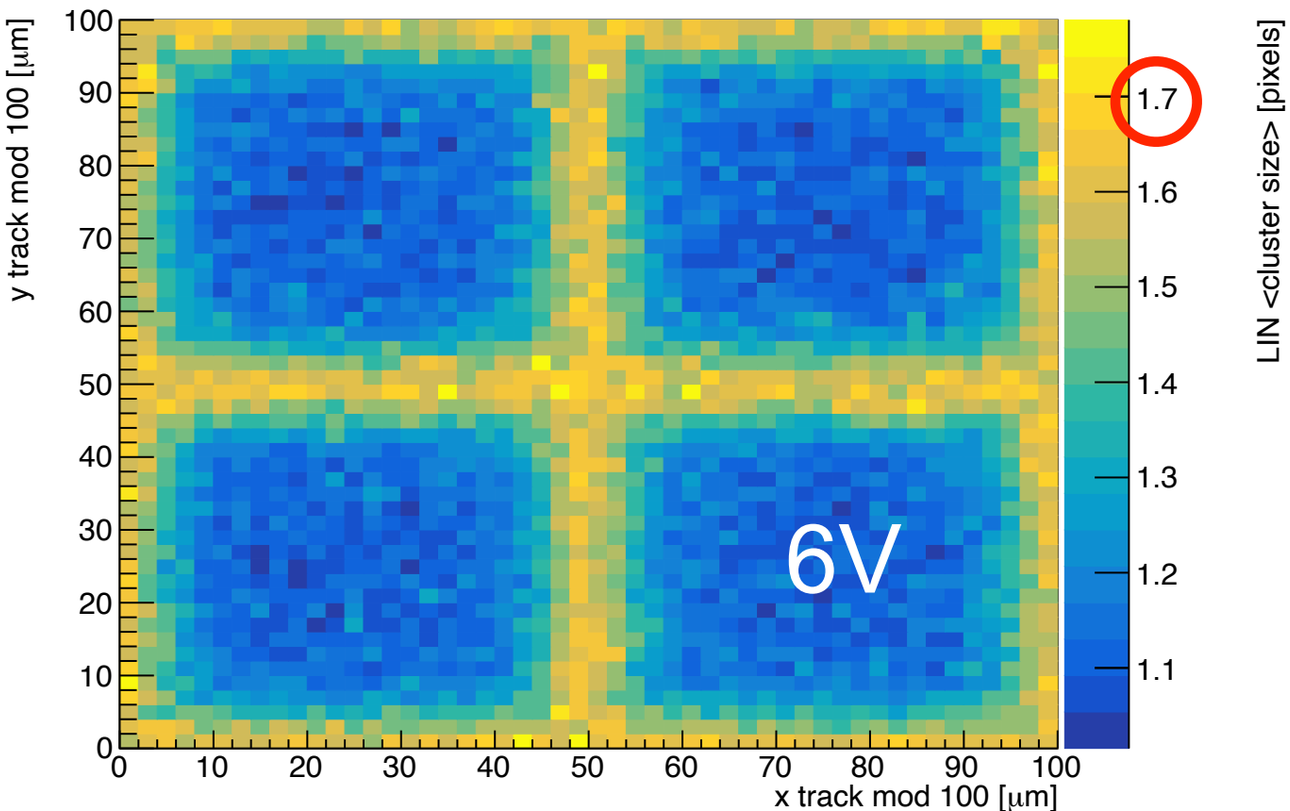
- Cluster size per cell
  - Left for -30 V, right for -6 V
  - **Please mind the different Z axis scale**
  - 150 um thickness
    - The number of tracks is different in the two cases
  - Perpendicular tracks only



Clustersize per cell

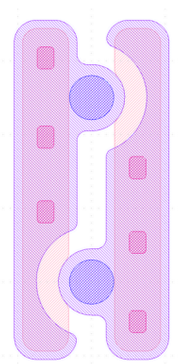


Clustersize per cell

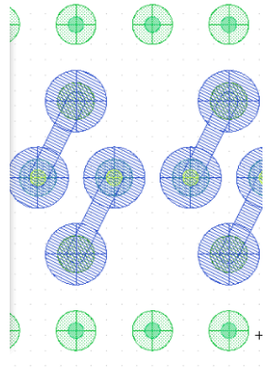


Data from June 2020

- 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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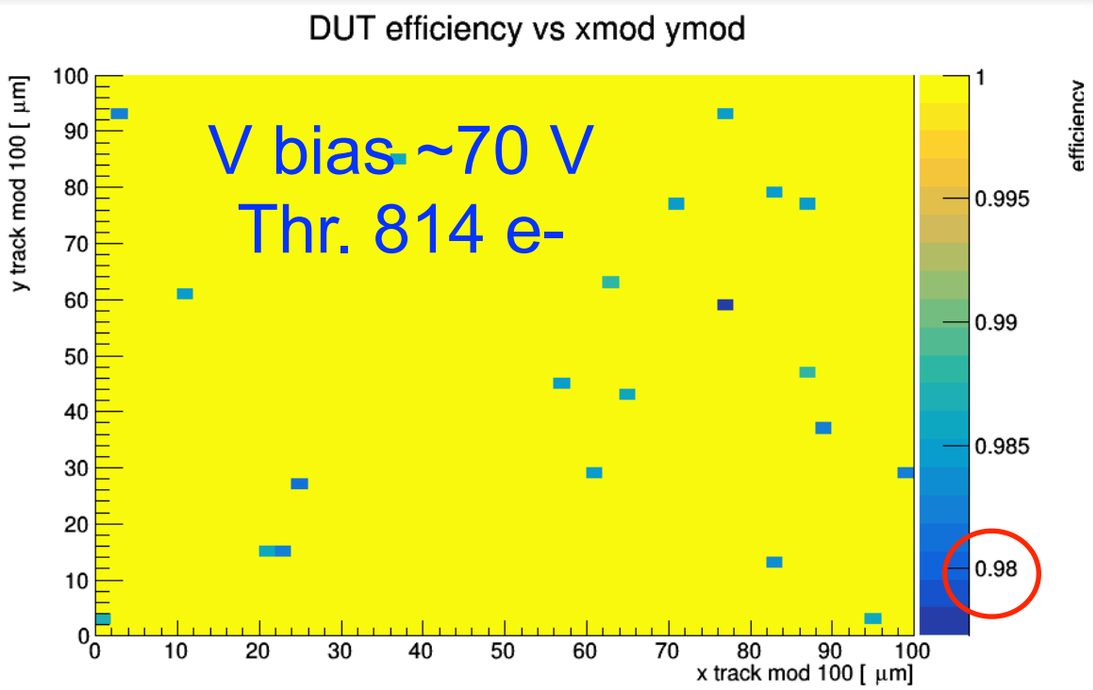
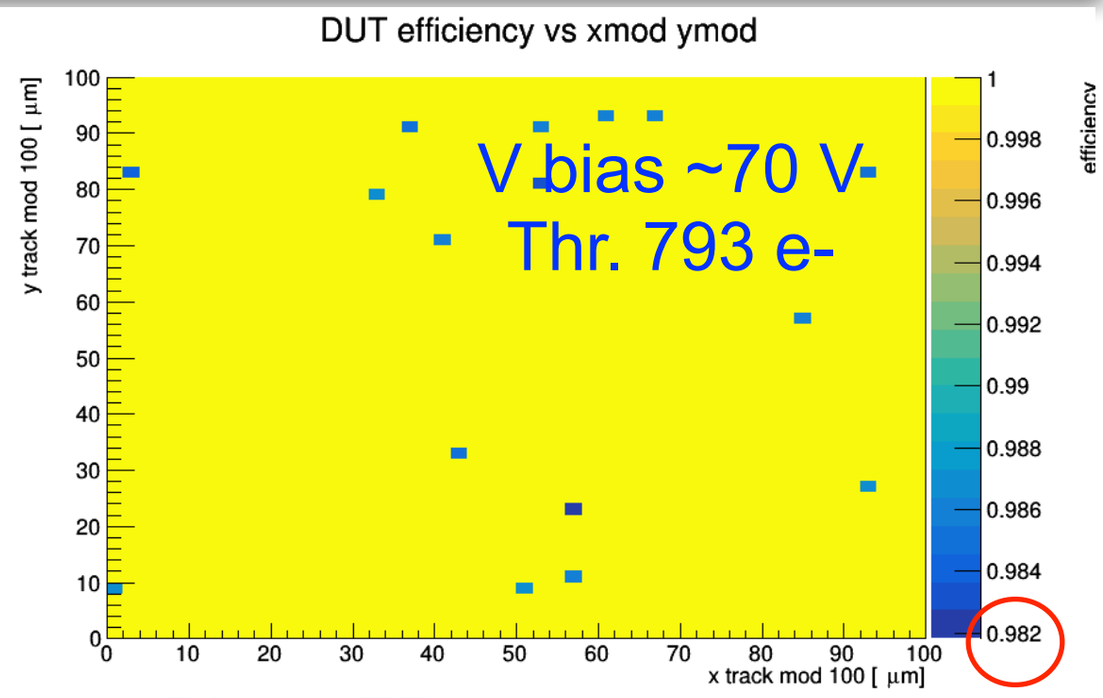
Hit efficiency (0 degrees)

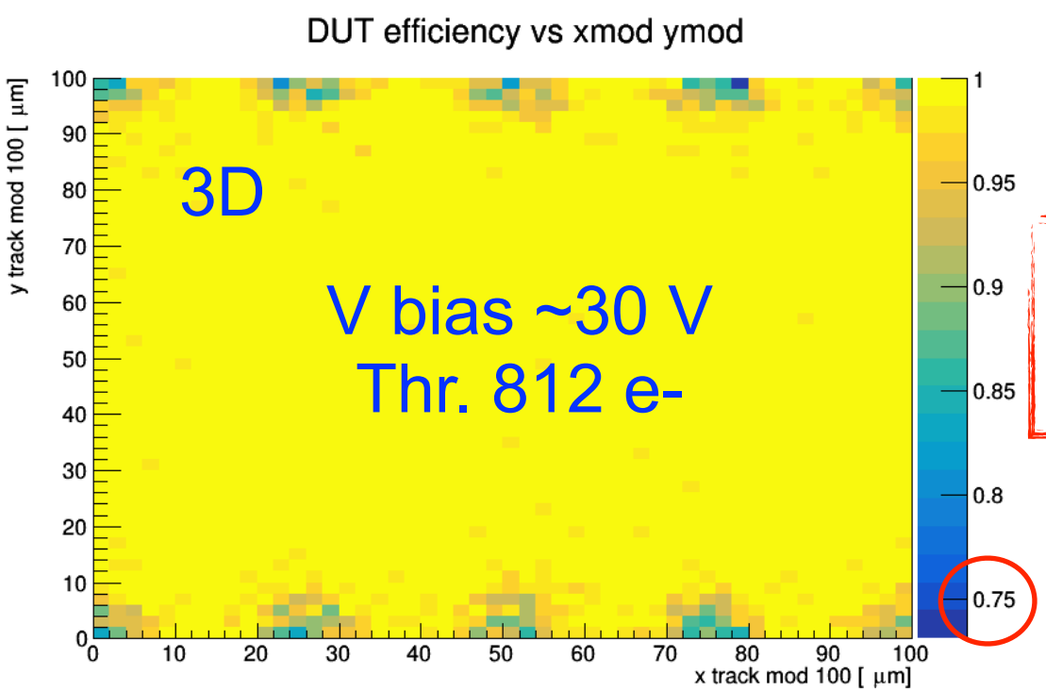


Bitten



Bitten FP

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



3D

Please note
the different Z axis

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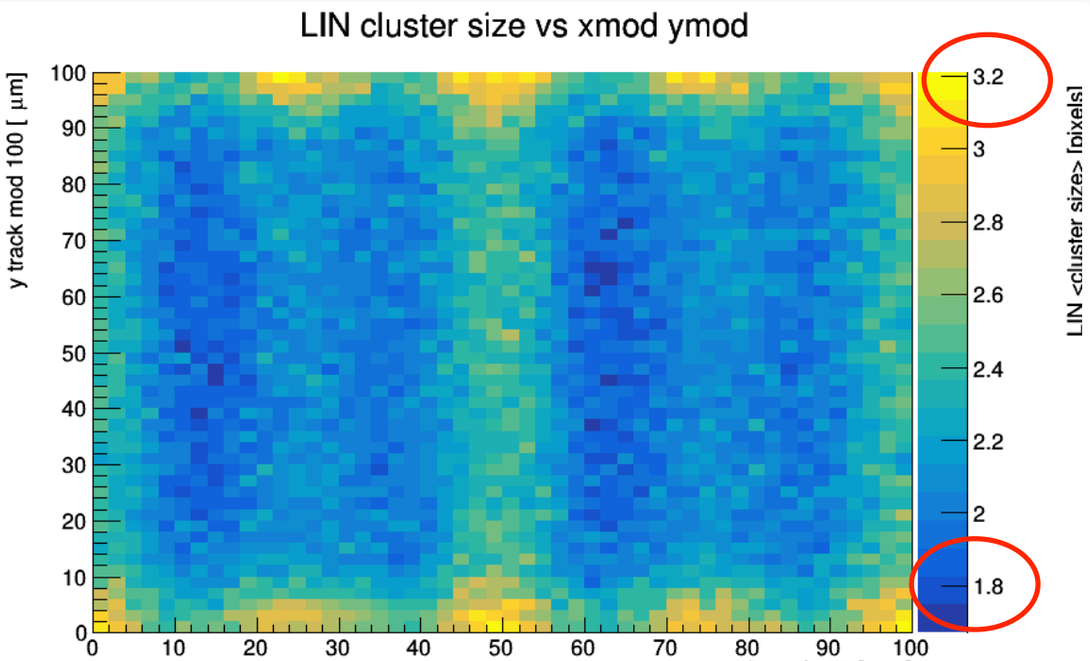
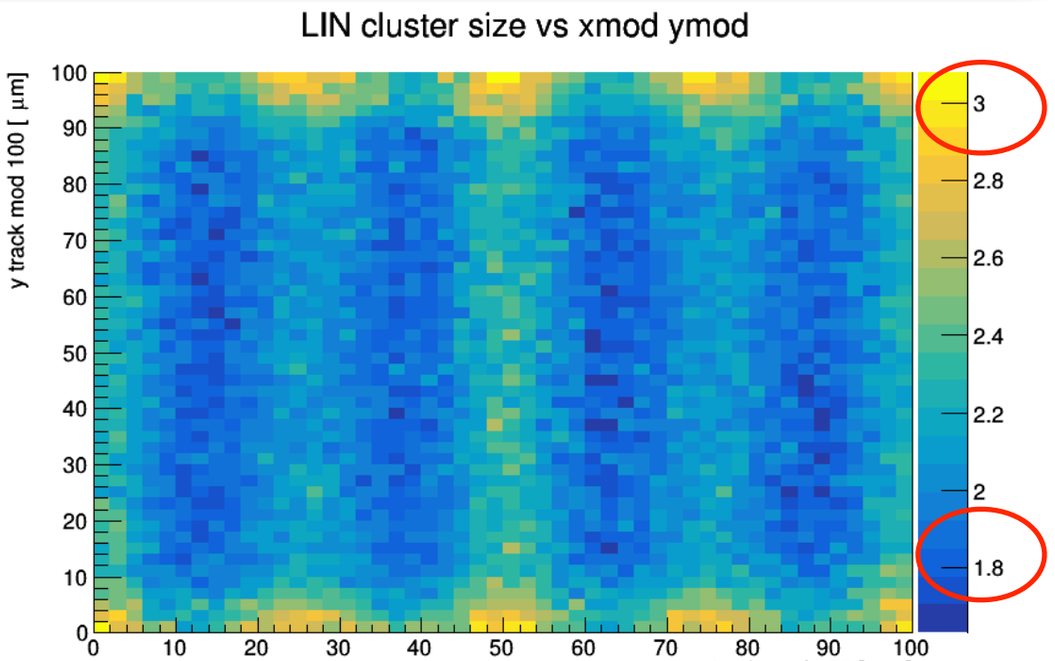
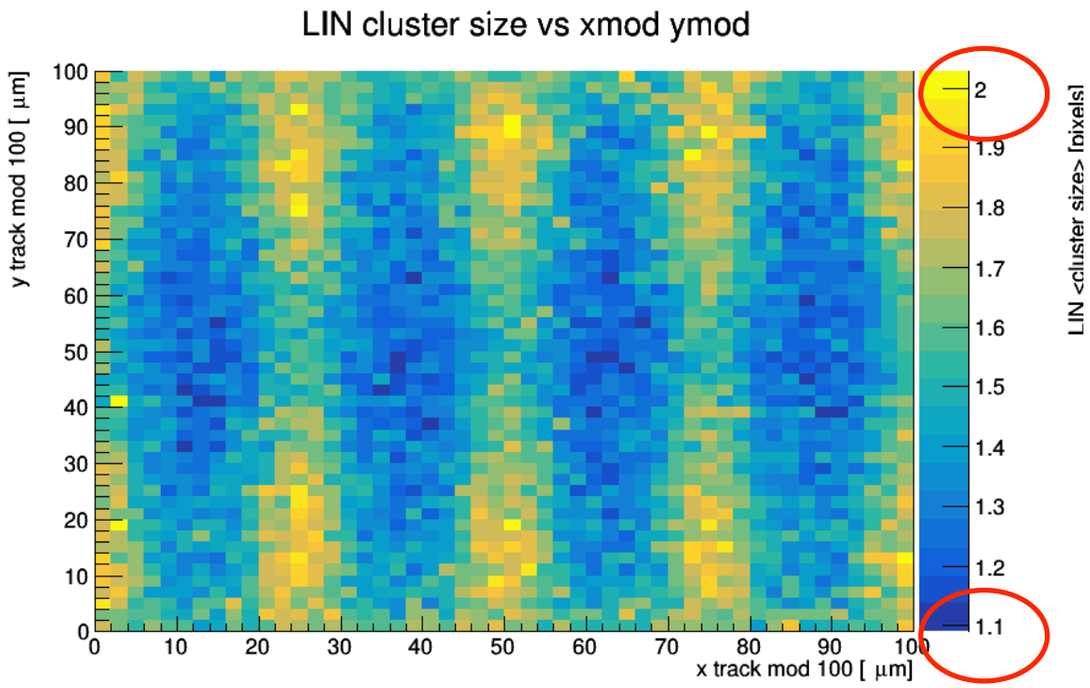
Cluster size (0 degrees)



Planar Bitten Thr. 814 e-



Planar Bitten FP Thr. 793 e-



3D Thr. 812 e-

Mind the different Z-scales!

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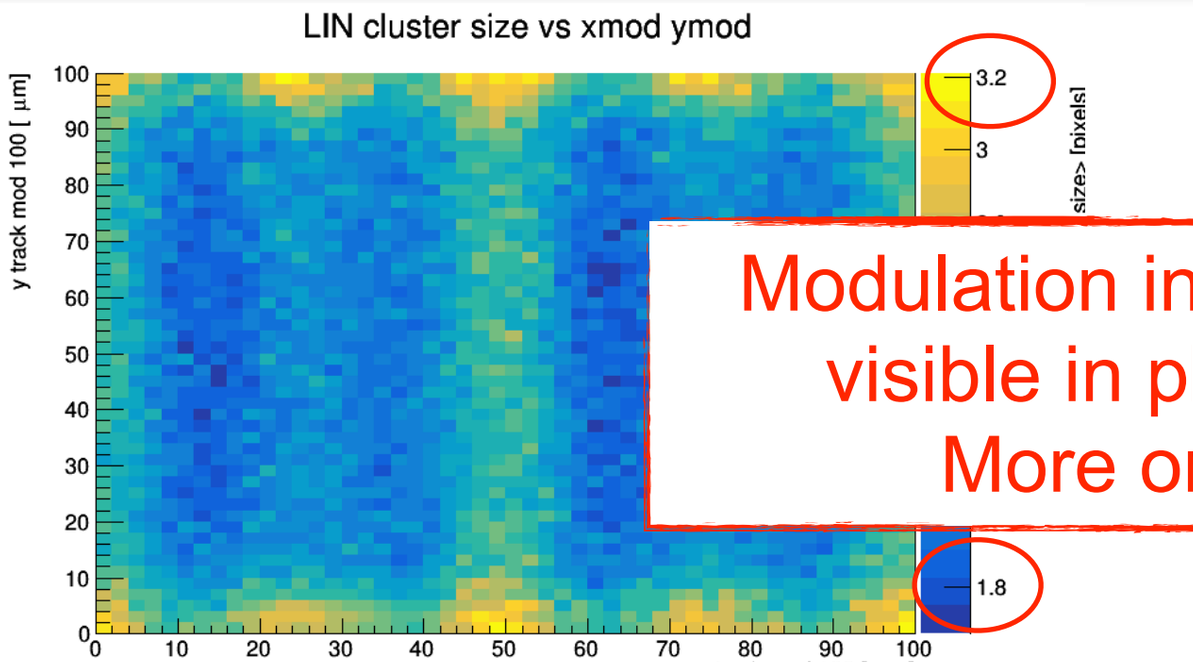
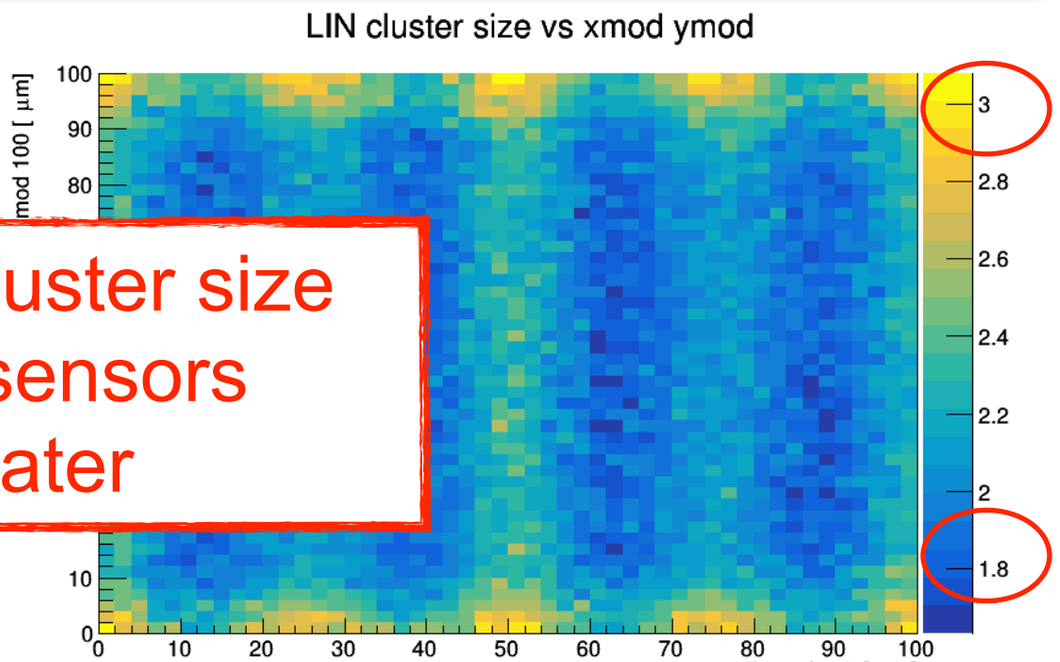
Cluster size (0 degrees)

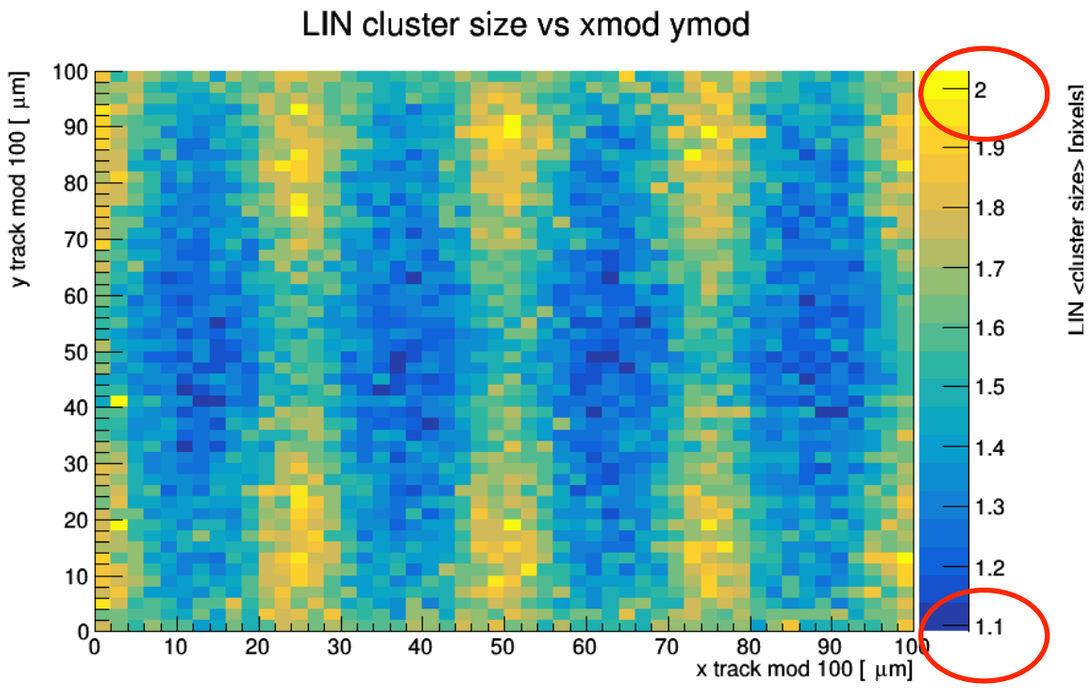




Modulation in the cluster size visible in planar sensors
More on this later

Planar Bitten Thr. 814 e-

Planar Bitten FP Thr. 793 e-



3D Thr. 812 e-

Mind the different Z-scales!

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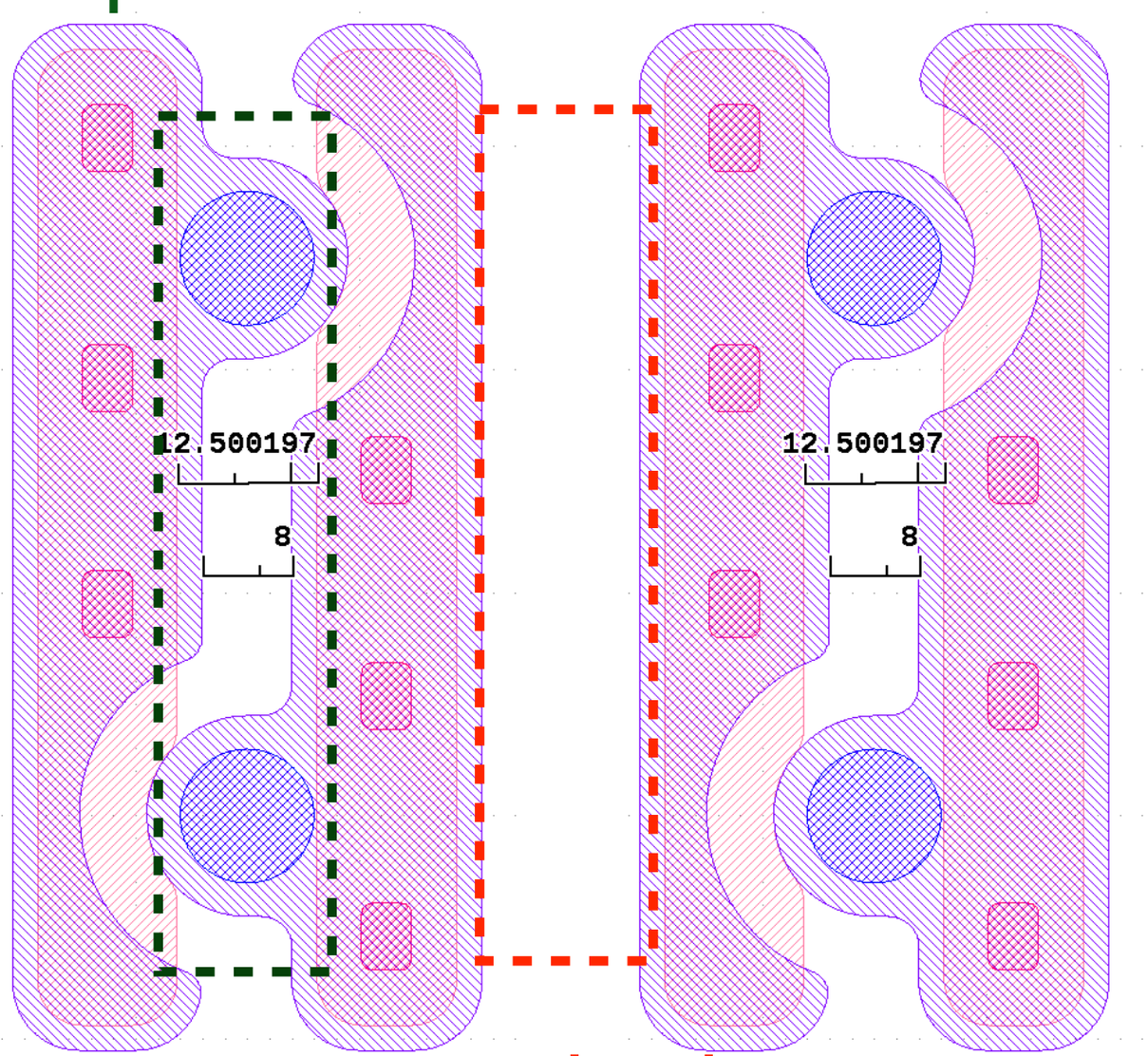
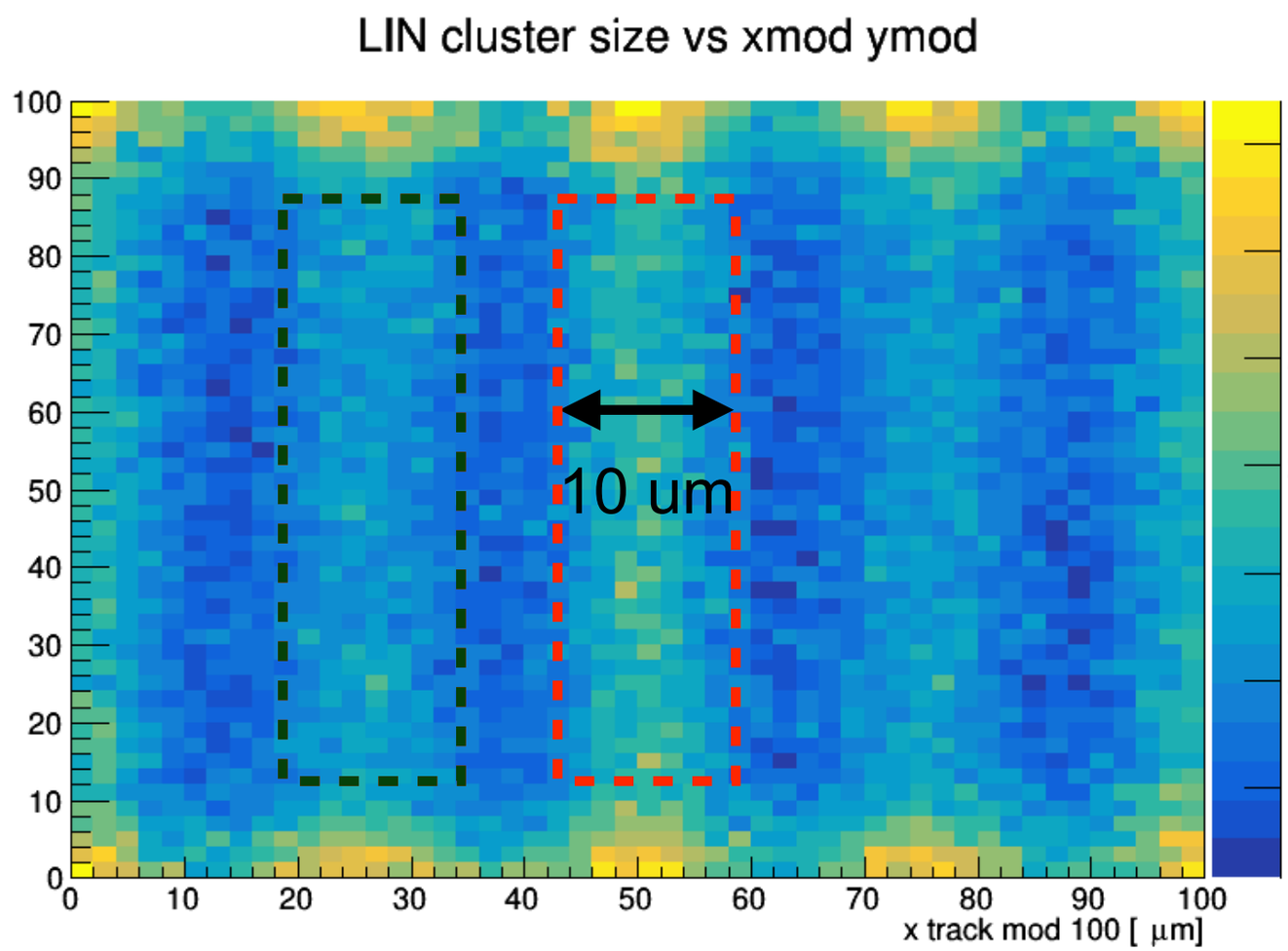
A deeper look at the effect of x-talk

- 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



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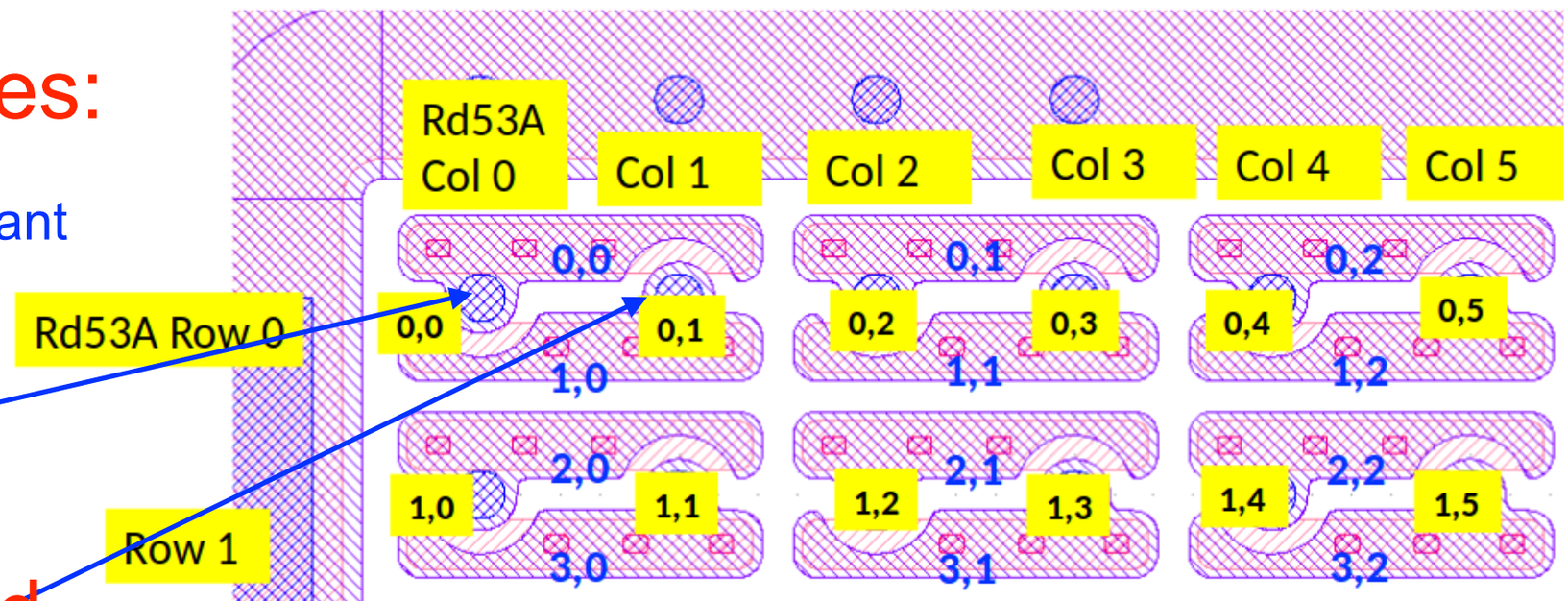
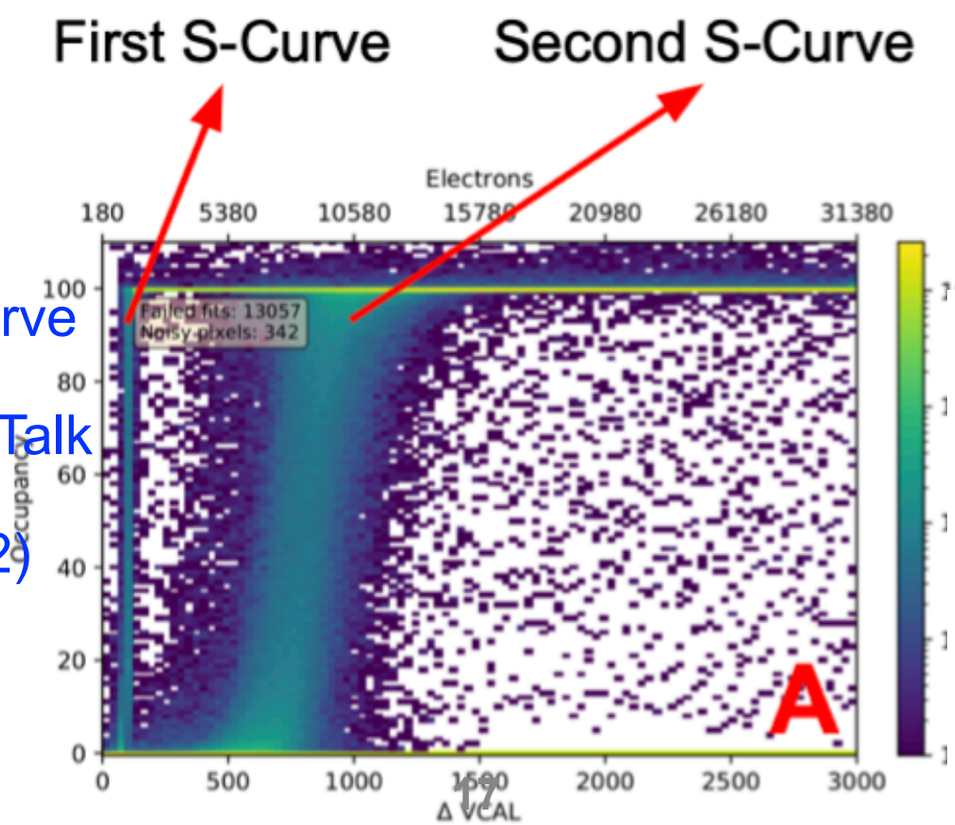
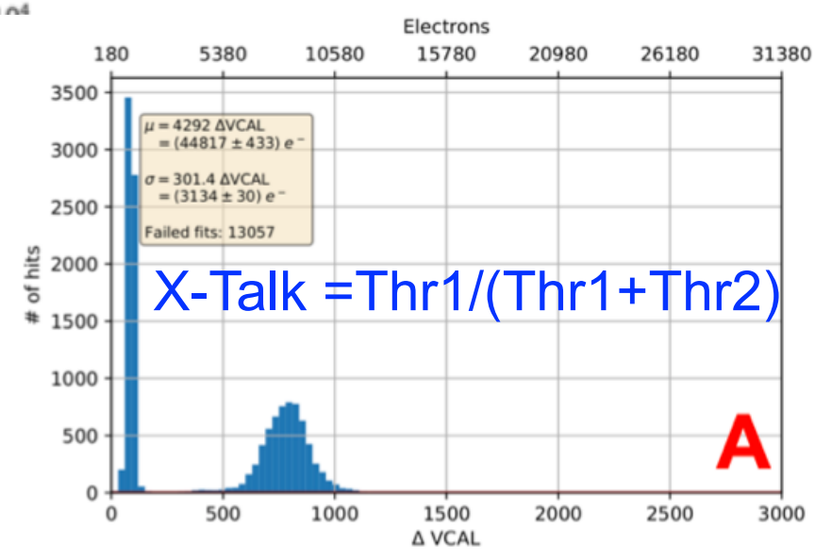
X-Talk (lab measurement)

- 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 =Thr1/(Thr1+Thr2)





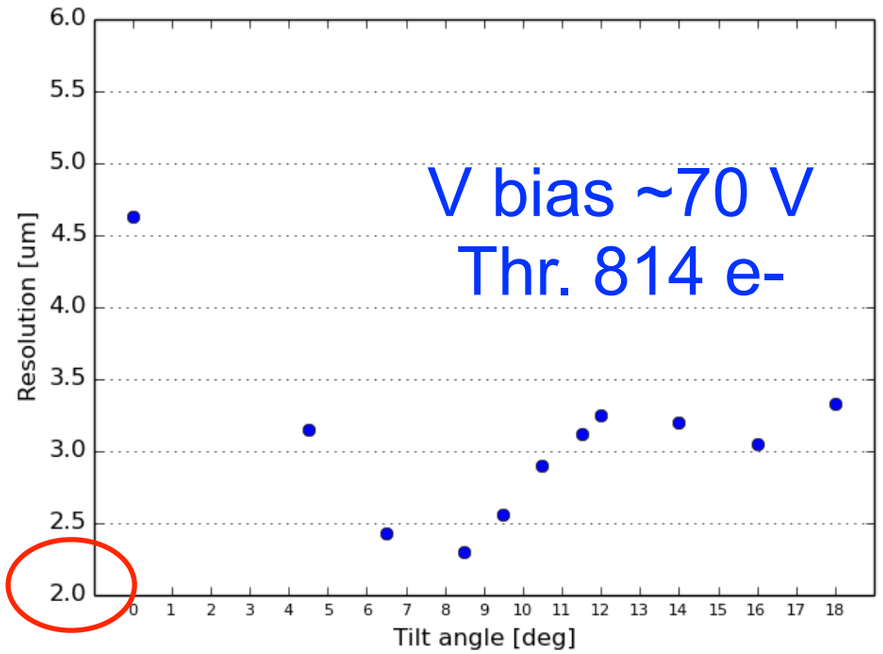


X-talk results

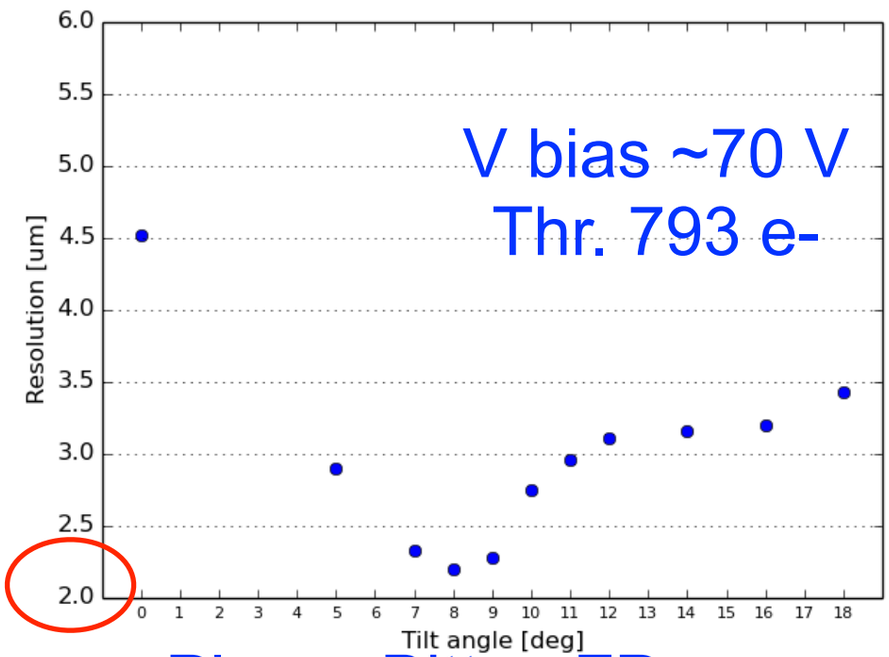
Bias Voltage	Main Threshold	Second Threshold	X-Talk
Planar 25x100 Standard (SOI)			
40 V	1140 e	8140 e	**12.3%**
20 V	2050 e	15294 e	**11.8%**
Planar 25x100 Bitten Implant			
40 V	1114 e	11388 e	**8.9%**
20 V	2303 e	22530 e	**9.3%**

Bitten implant reduces the x-talk by few %

Position resolution (25 um pitch)

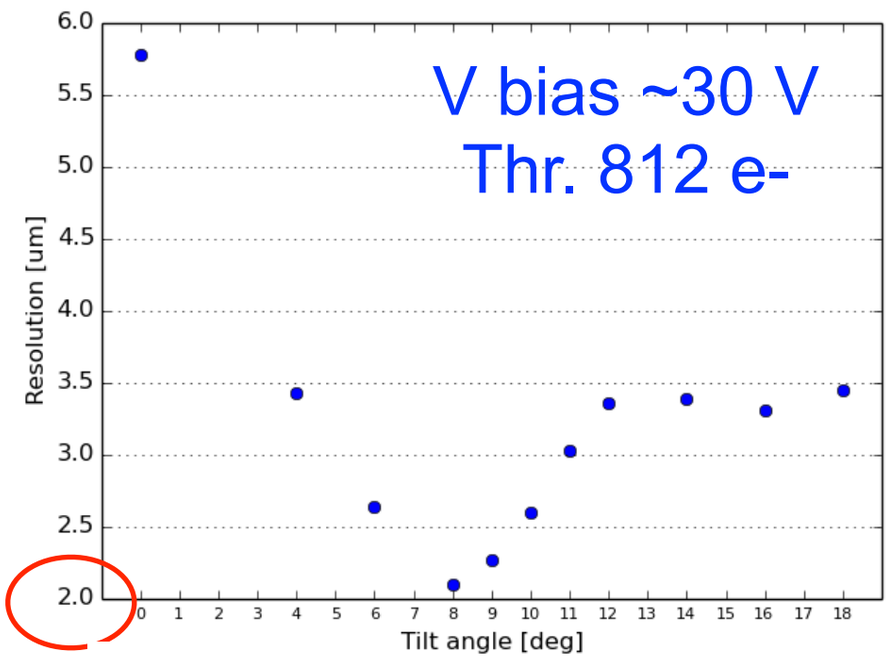


Planar Bitten



Planar Bitten FP

Position resolution well below the digital value



3D

Sensor thickness = 150 um

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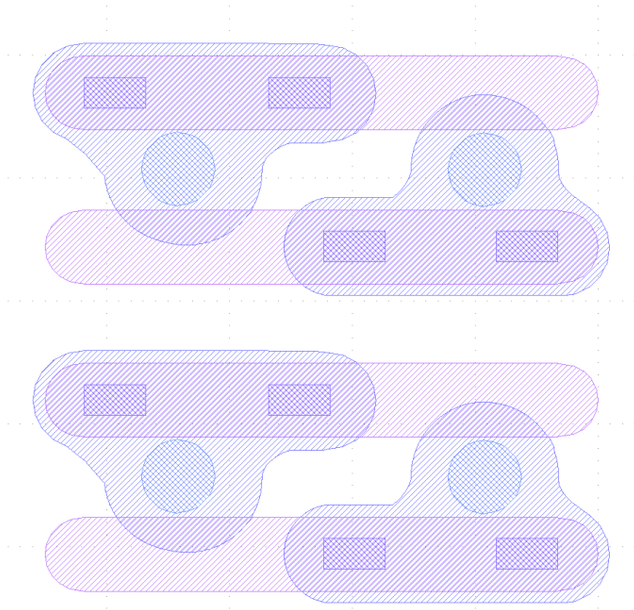
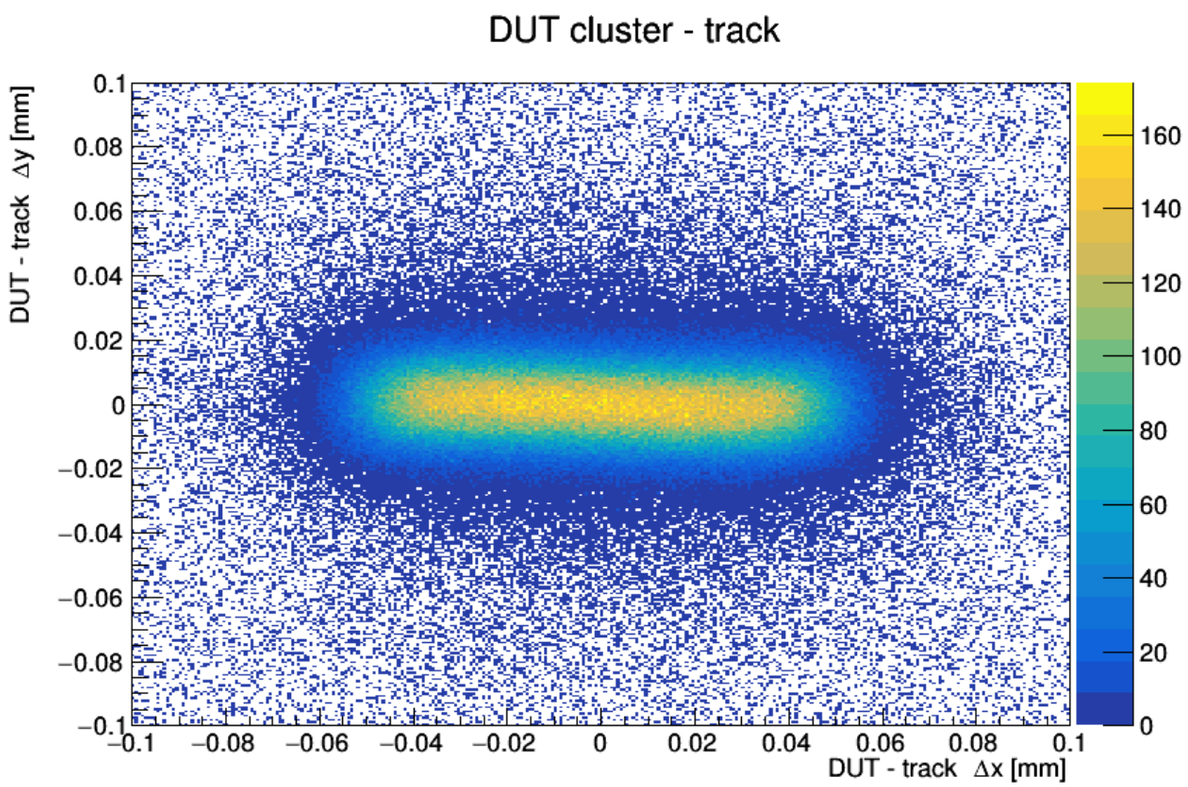
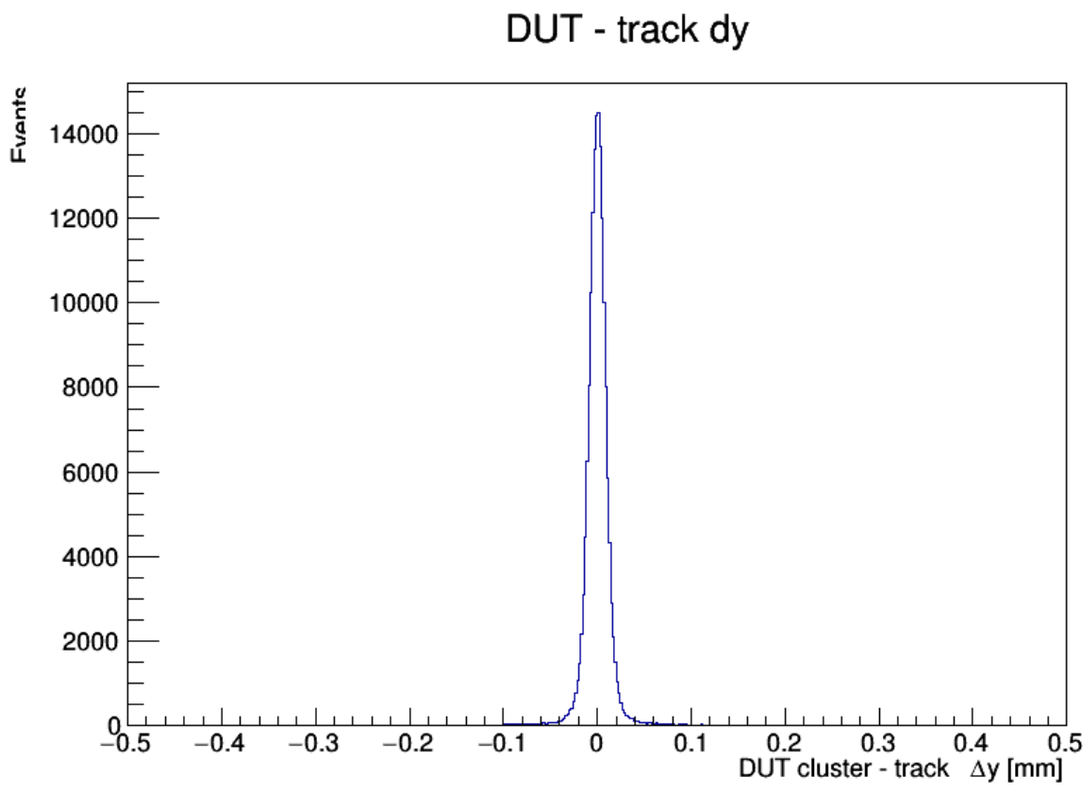
Data from July 2020

- Planar 25x100 sensor irradiated at ~7.5E15
  - Active 100 um
- Data analyzed for studies on 25 um residuals

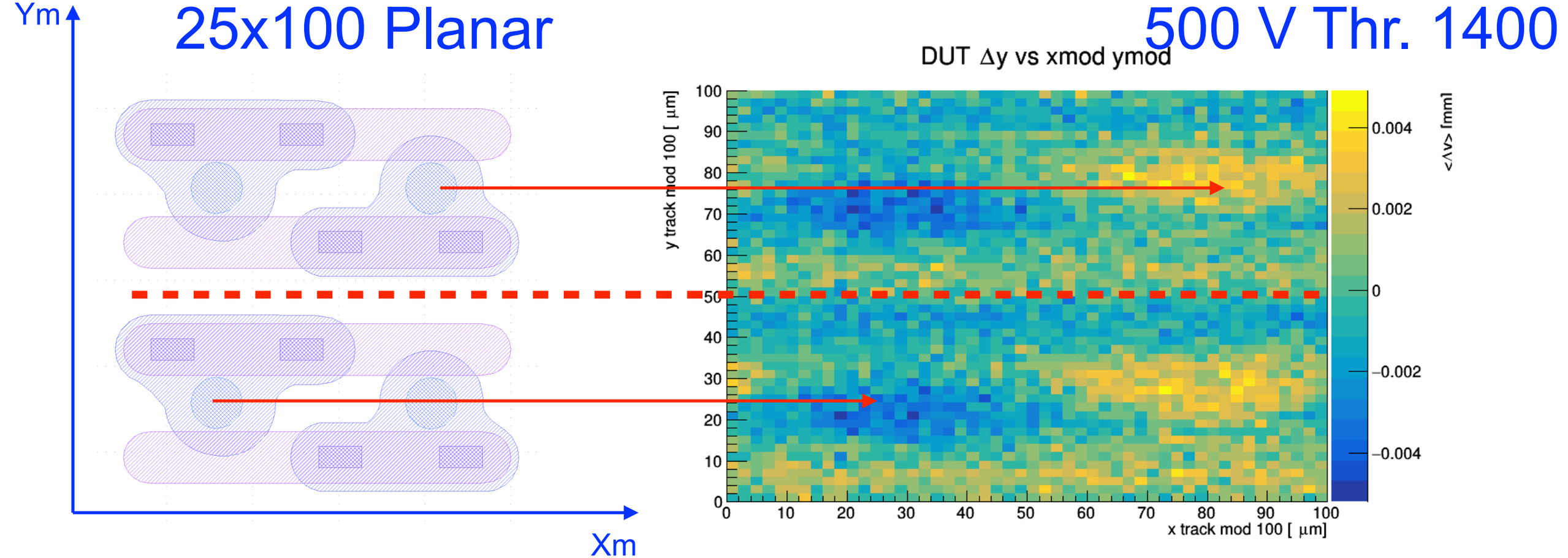






Residual of the Y coordinate

- 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



Residual is computed as DUT_position - Track_position

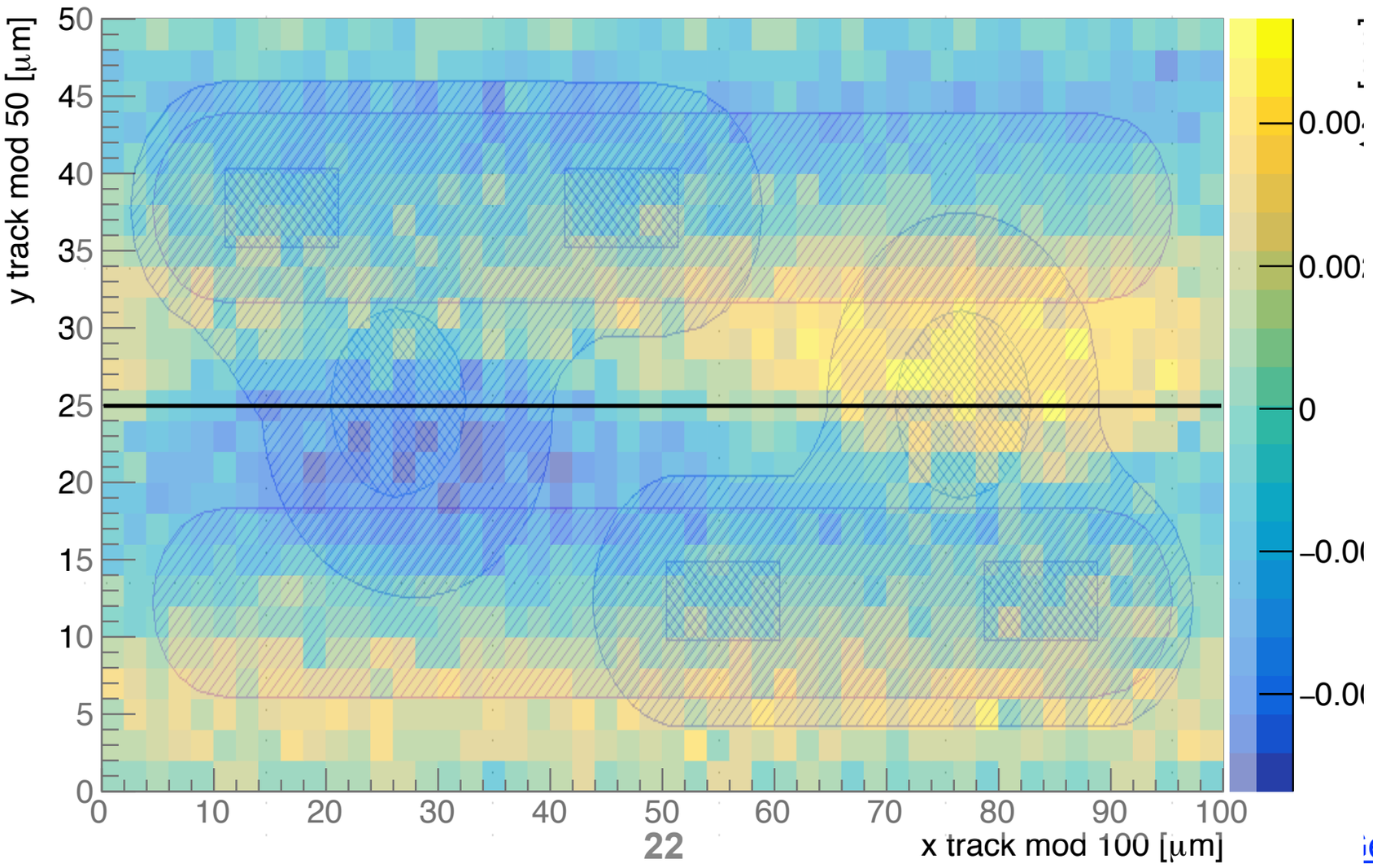
Let's zoom in

- 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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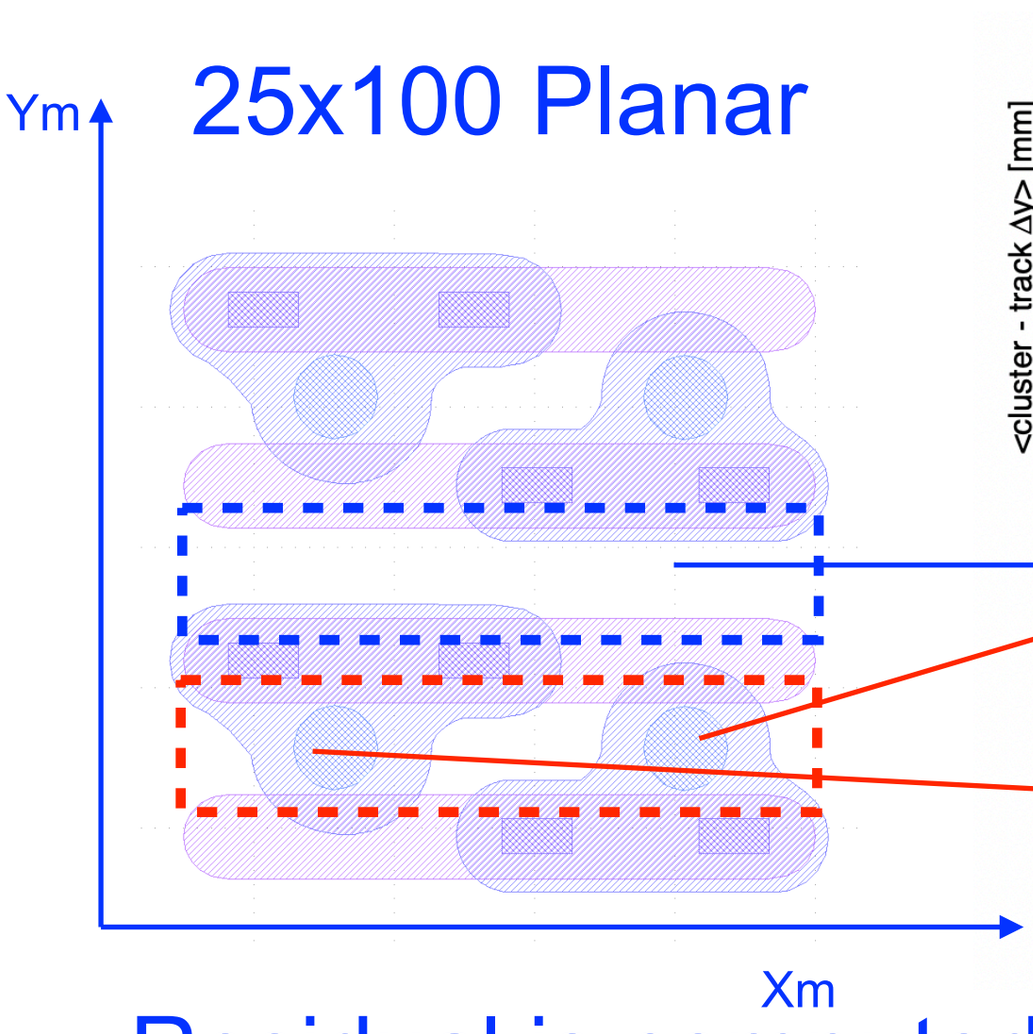
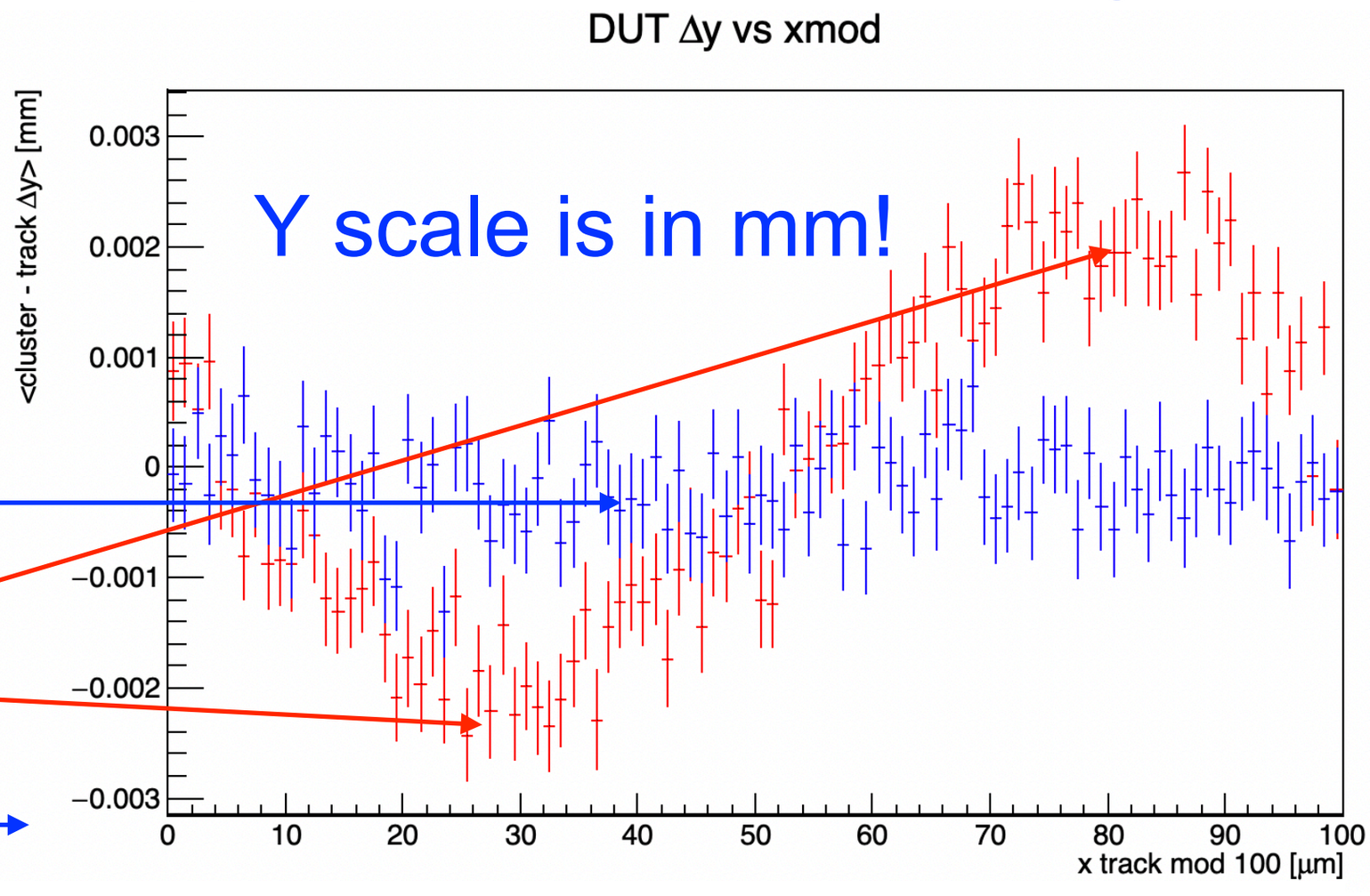
Profiling the residuals along X coordinate

- Residuals show a change of sign within a cell in the presence of the bonding-pad
  - The effect is anyway small, localized, and the analysis of the December 2020 data has shown that its impact on the overall resolution is marginal

25x100 Planar

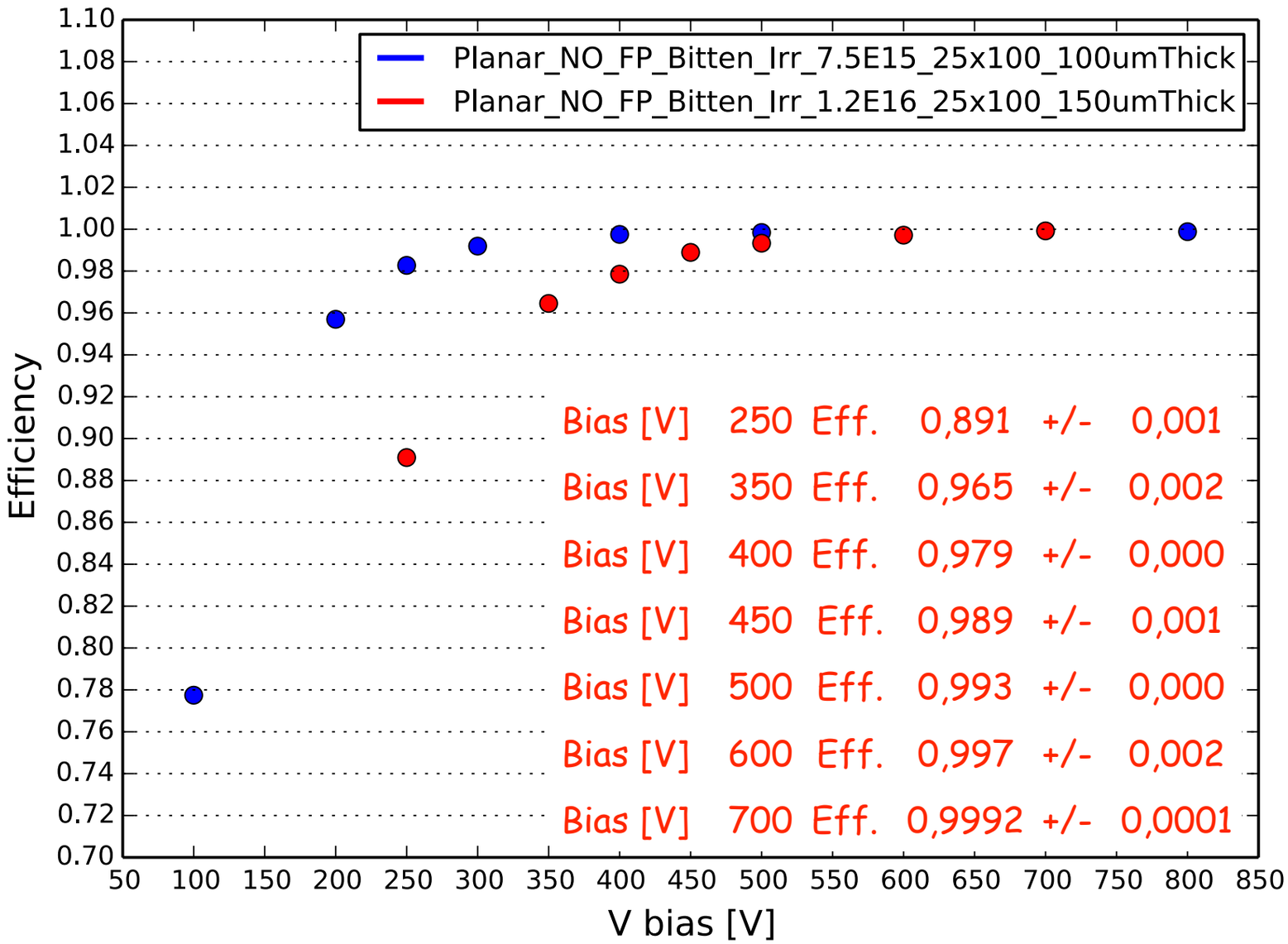


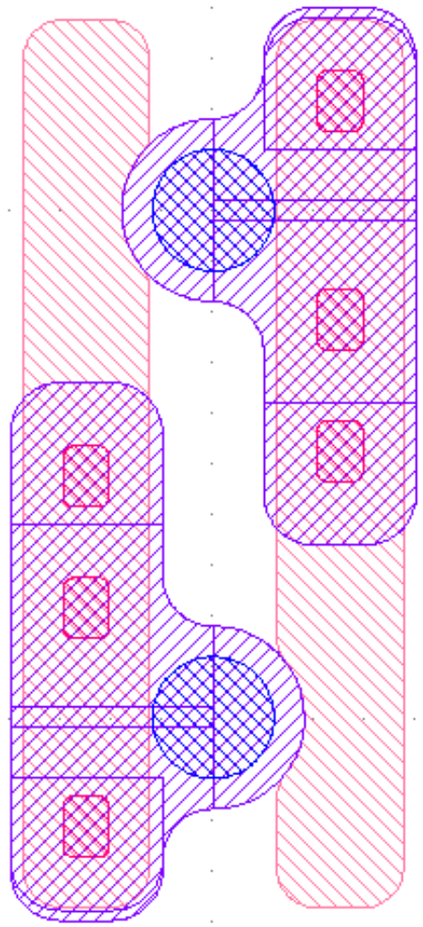


Residual is computed as DUT_position - Track_position

Data from December 2020

- Planar Sensor 25x100 um²
  - Vthreshold_LIN: 361 ~ 1249 e-
- Data analyzed for efficiency and position resolution studies
  - Sensor were irradiated up to 1.2E16 neq/cm²





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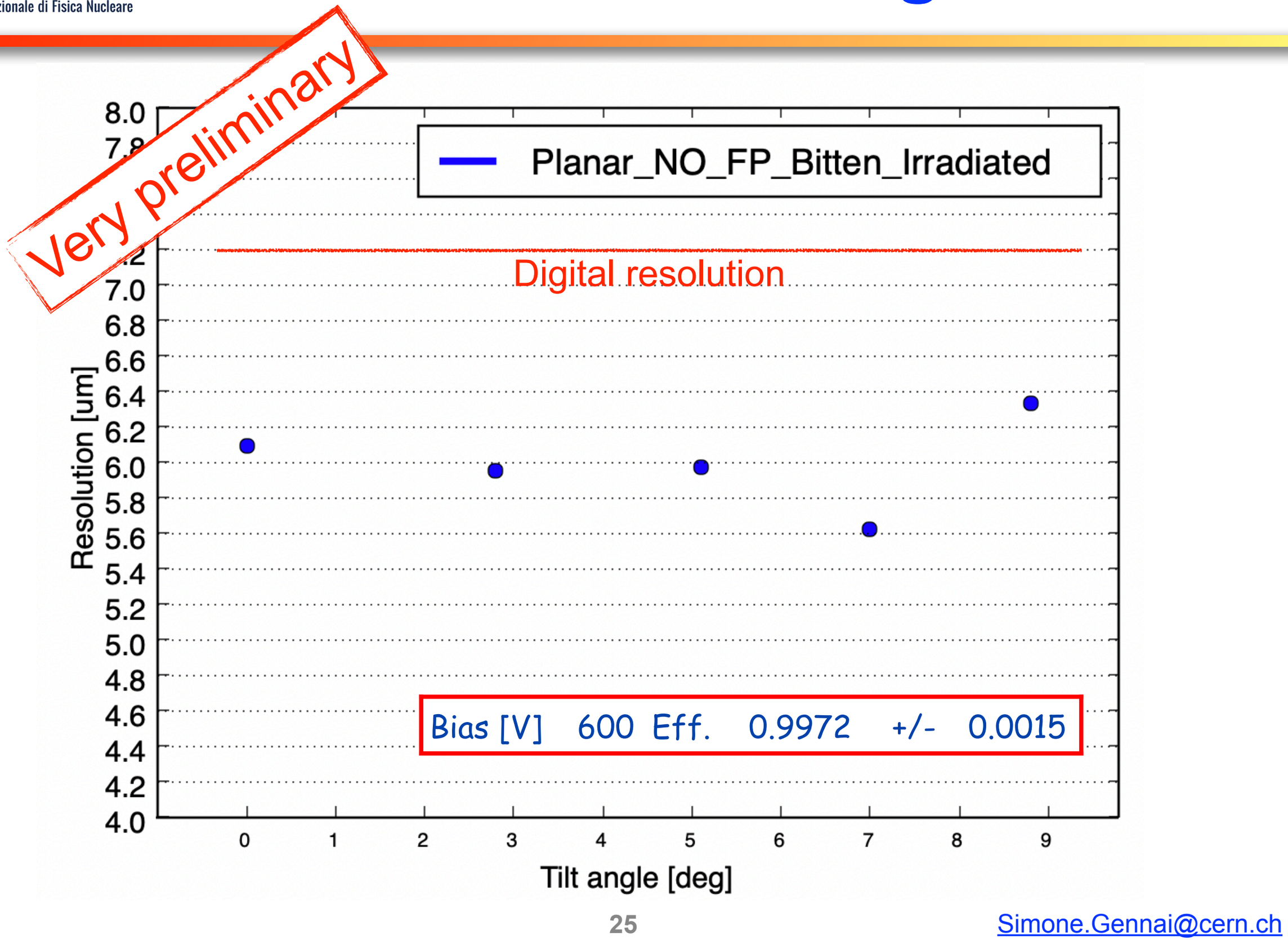
Resolution vs angle



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Conclusions

- FBK sensor perforamance 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

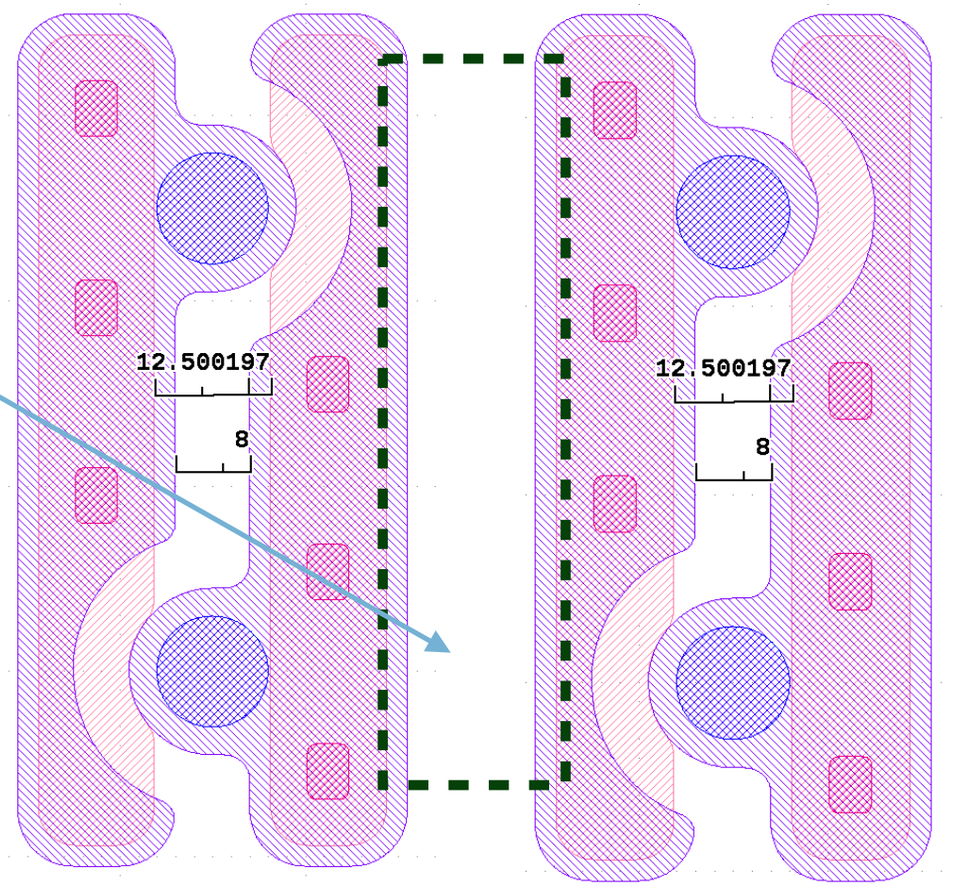
Back-up

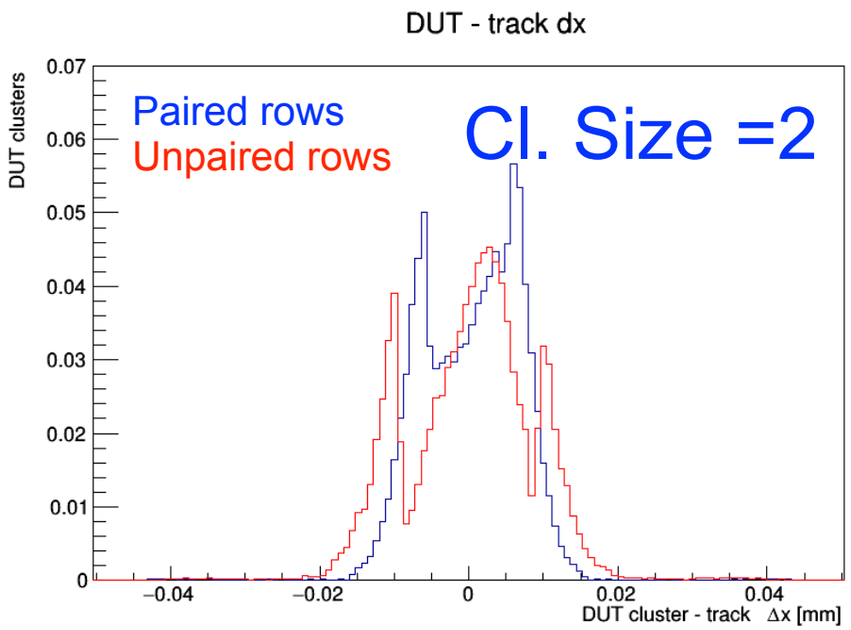
Resolution plots vs Clsize

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





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

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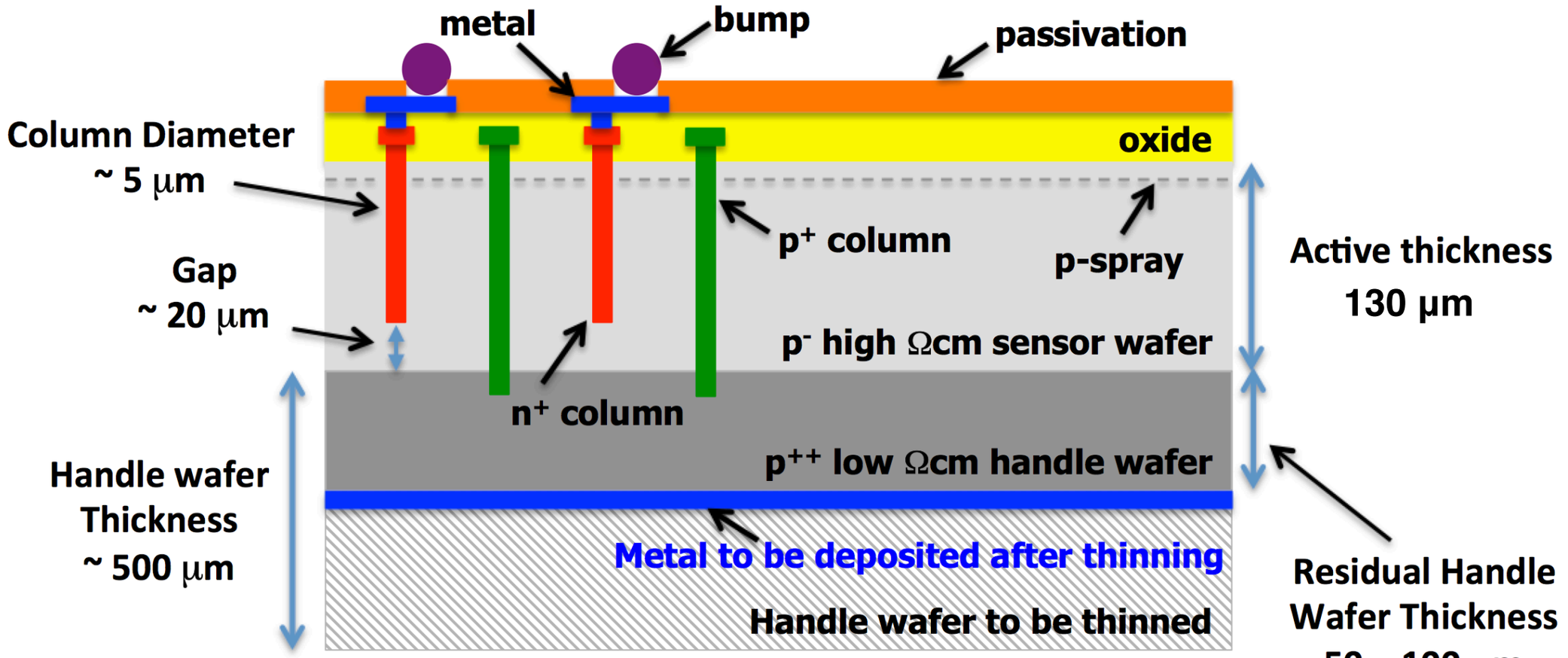
3D pixel @ FBK

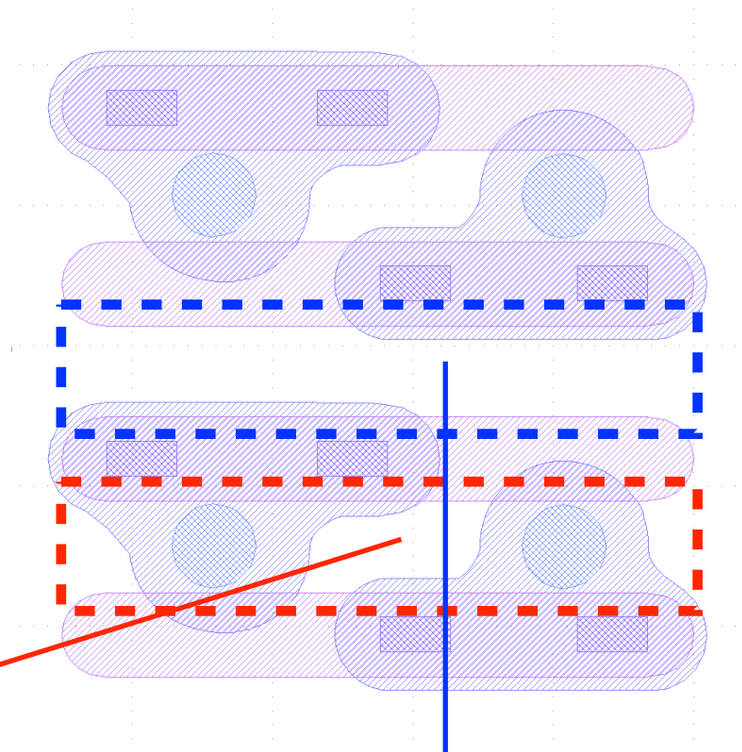


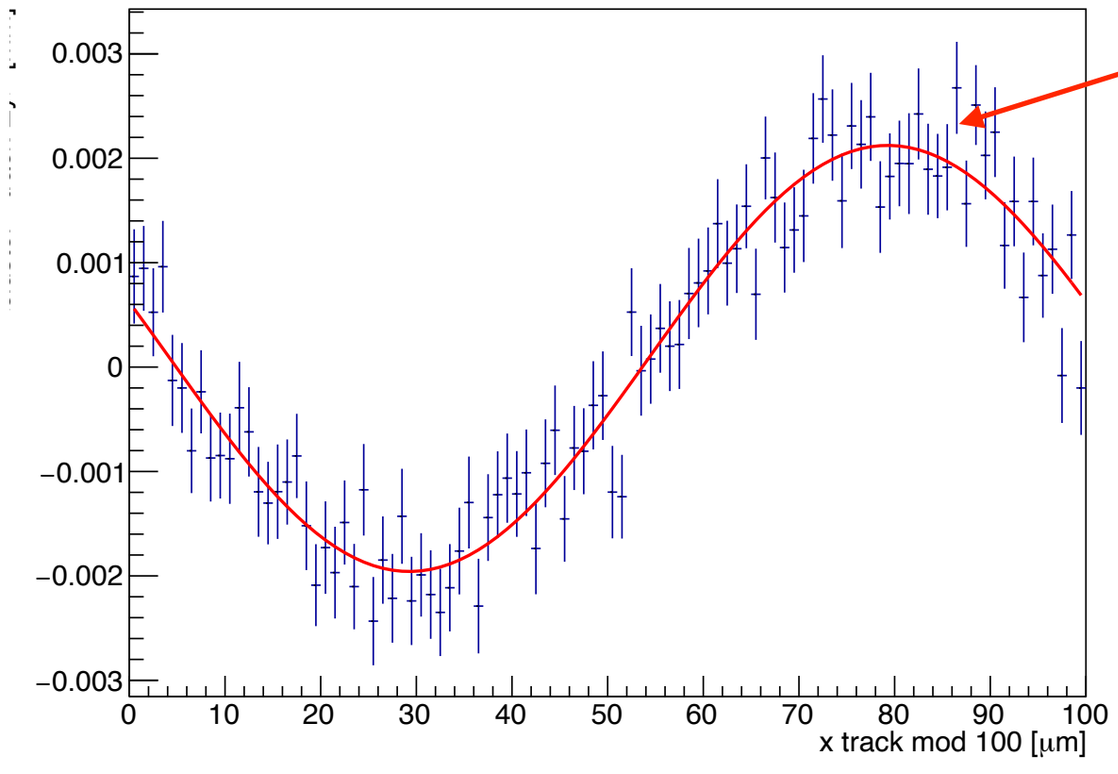
[G.F. Dalla Betta et al., NIMA 824 (2016) 386]

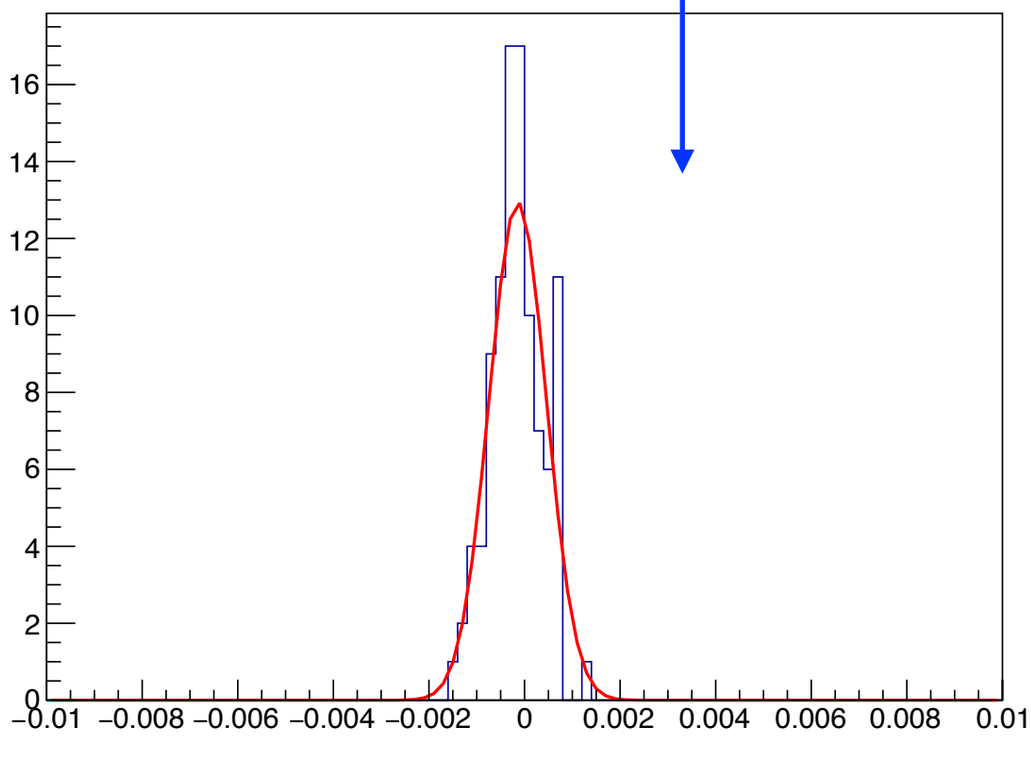
- 3D single sided process, optimised by FBK
- Ohmic columns/trenches depth > active layer depth (for bias)
- Junction columns depth < active layer depth (for higher Vbreakdown)
- Reduction of columns diameter to ~5 μm
- Holes (at least partially) filled with poly-Si
  - Two wafers, high and low resistivity, bonded together

Trying a simple fit

- We can fit the bonding residuals with a sinusoid function
  - But what to do for the no bonding residuals?
    - Fill an histogram with all the values and just take the RMS from gaussian fit
- And then we make the ratio between amplitude and rms



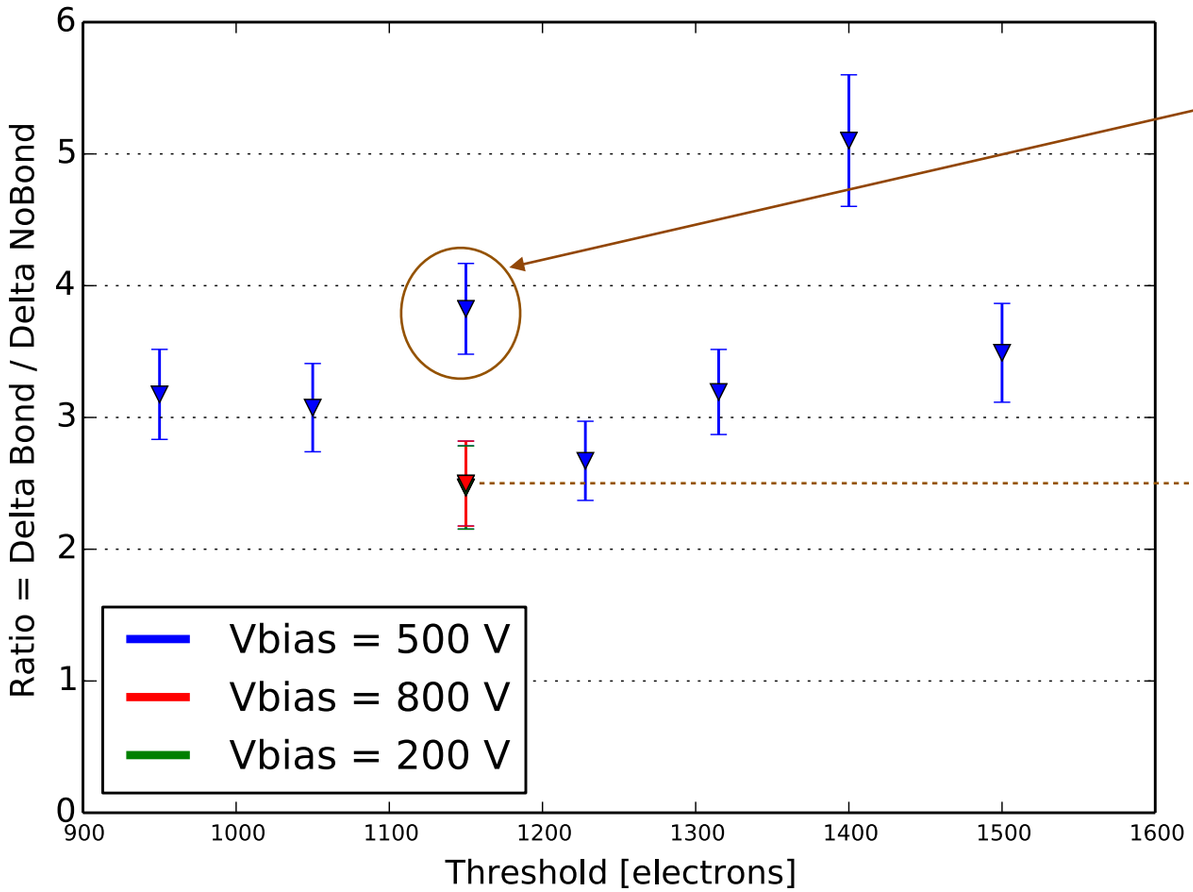


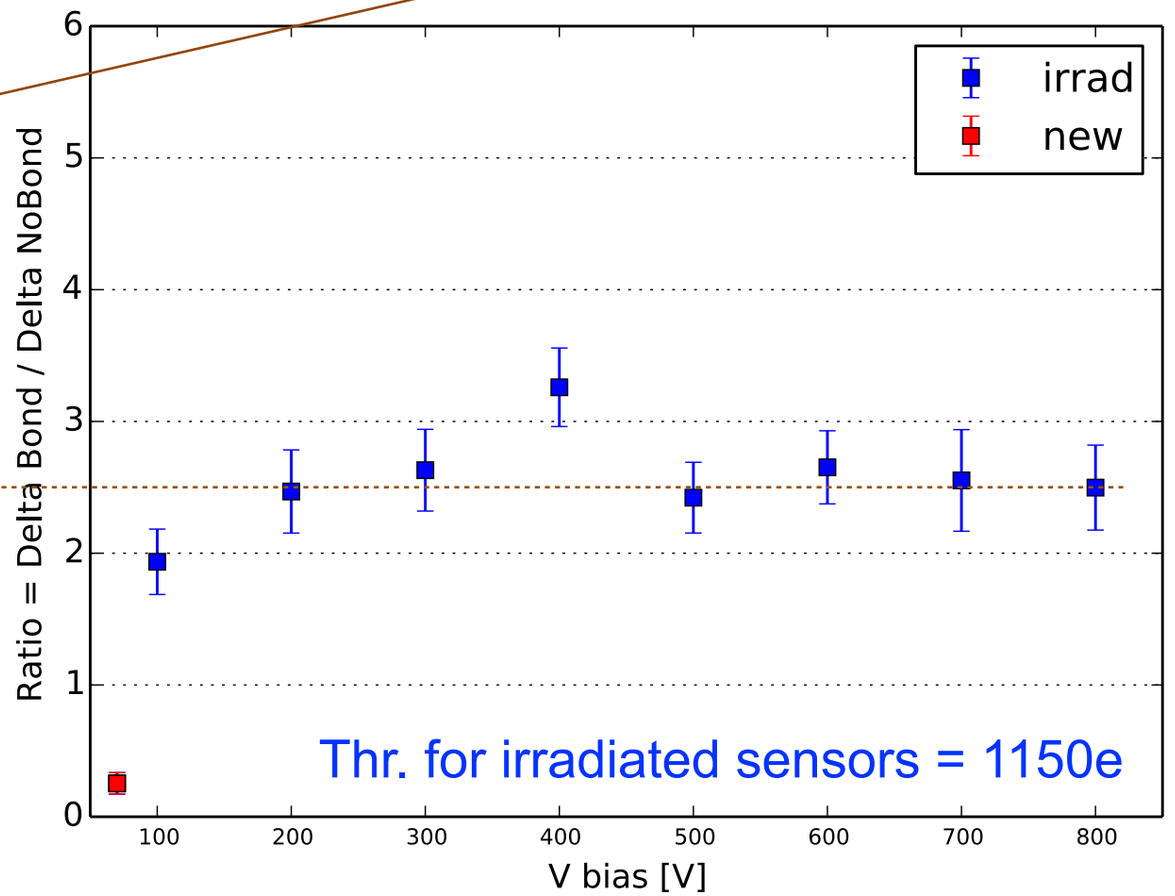


Results of the fit

- Does not seem to be a tendency vs threshold or bias

Not clear what is the real threshold for the this one





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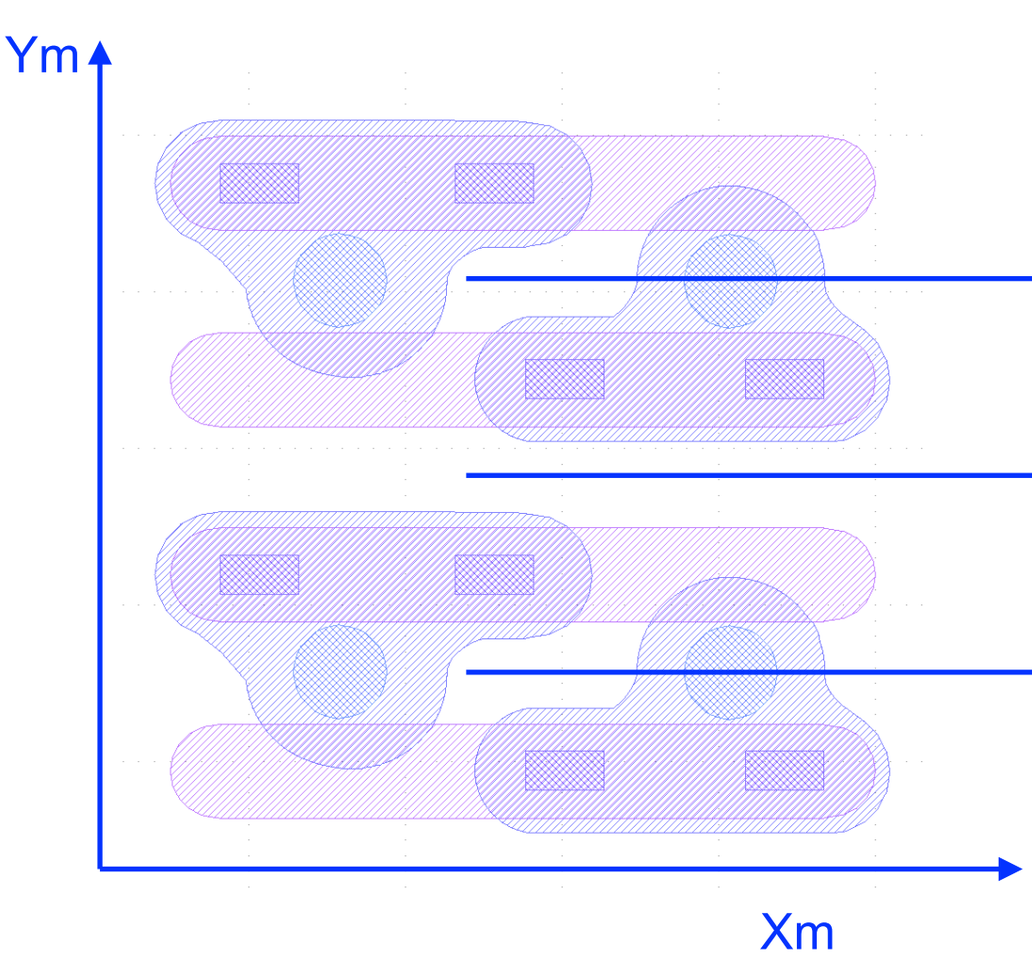
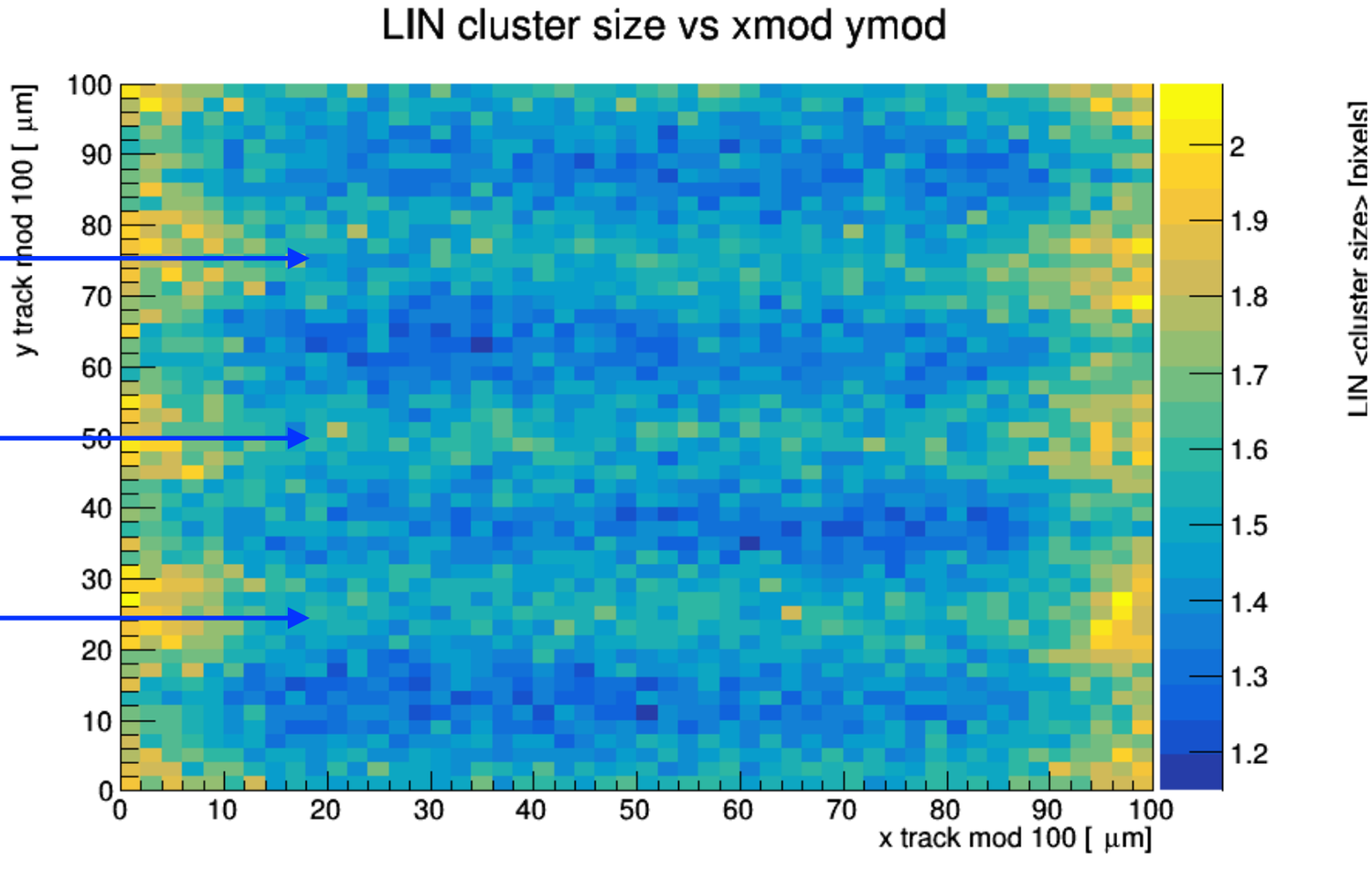
Sensor layout

- 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





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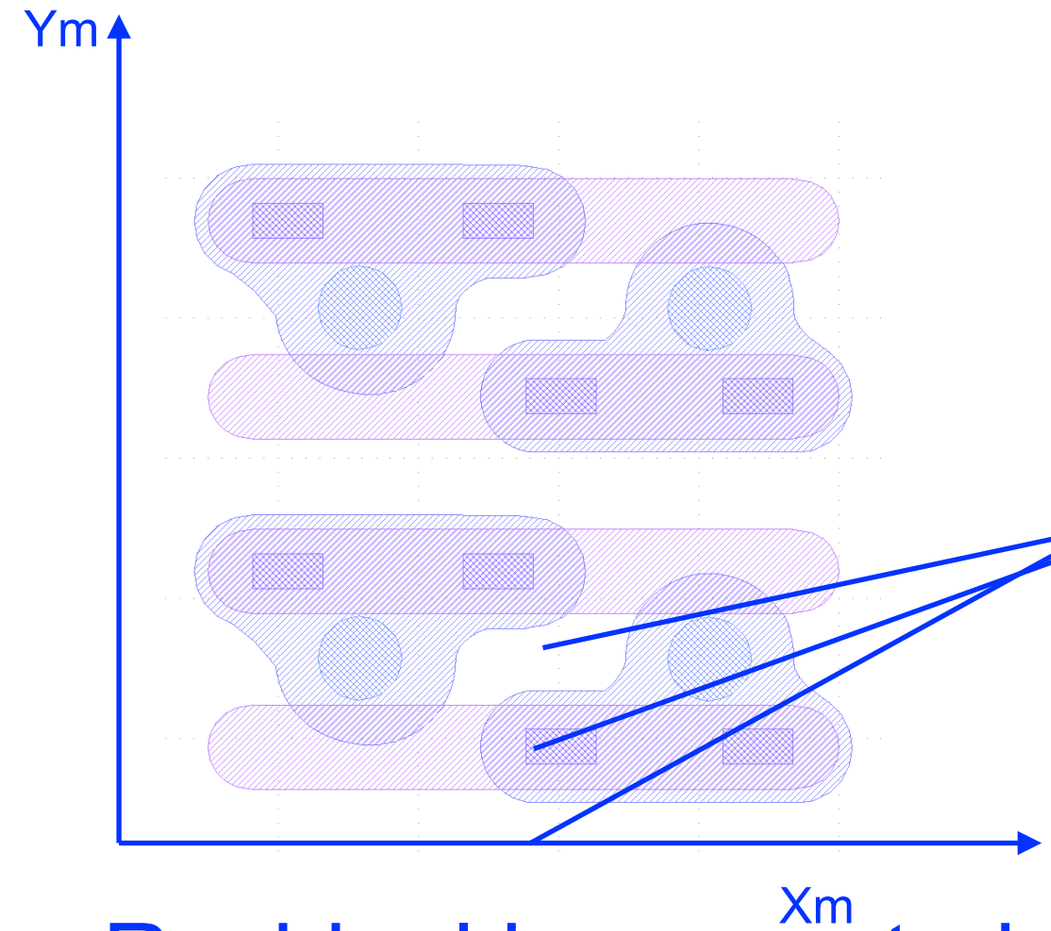
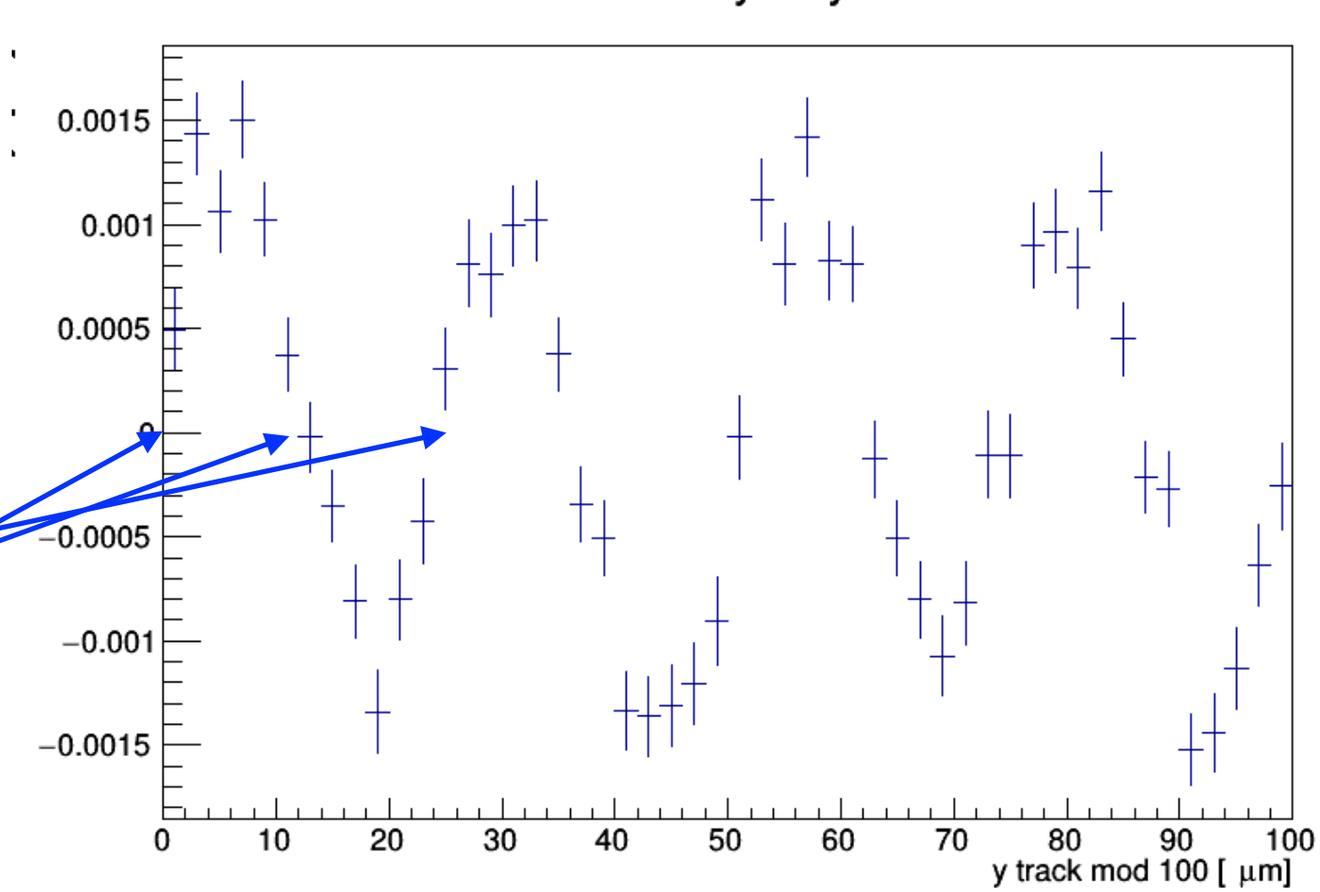
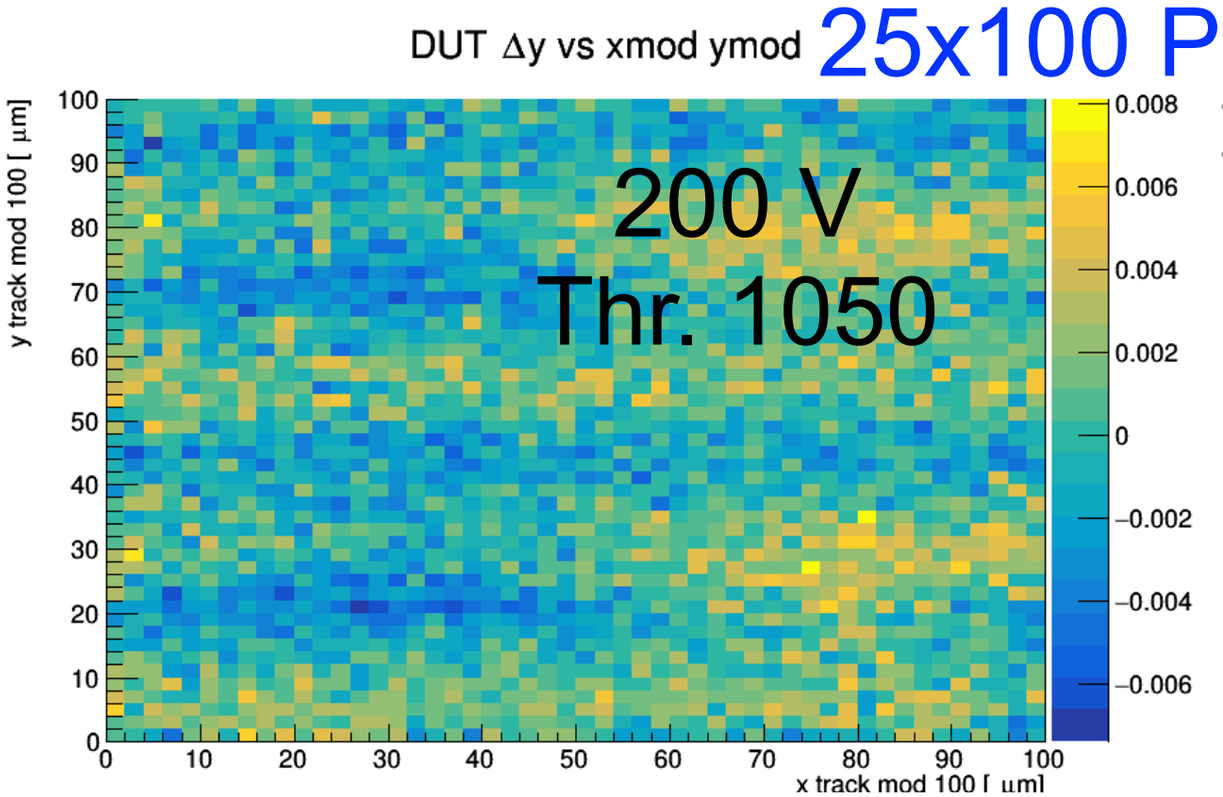
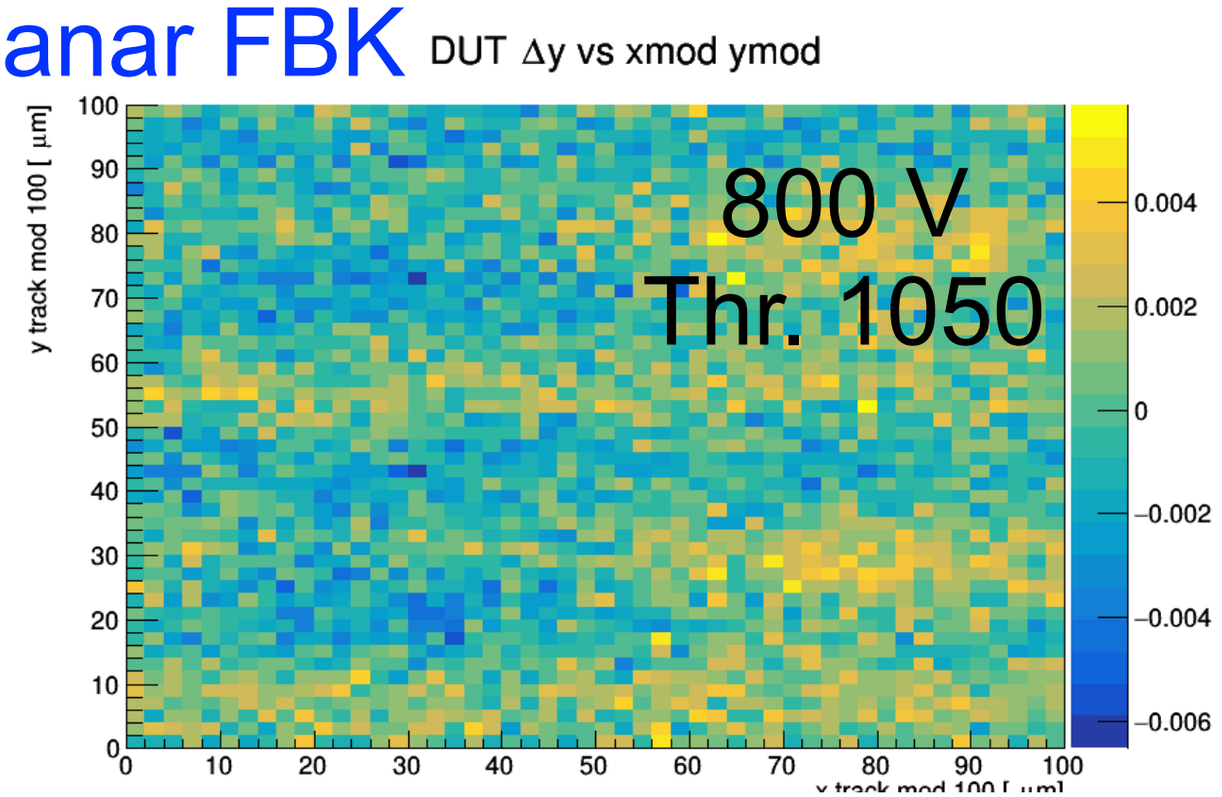




Residual is computed as DUT_position - Track_position

Residuals at different V bias and Thresholds

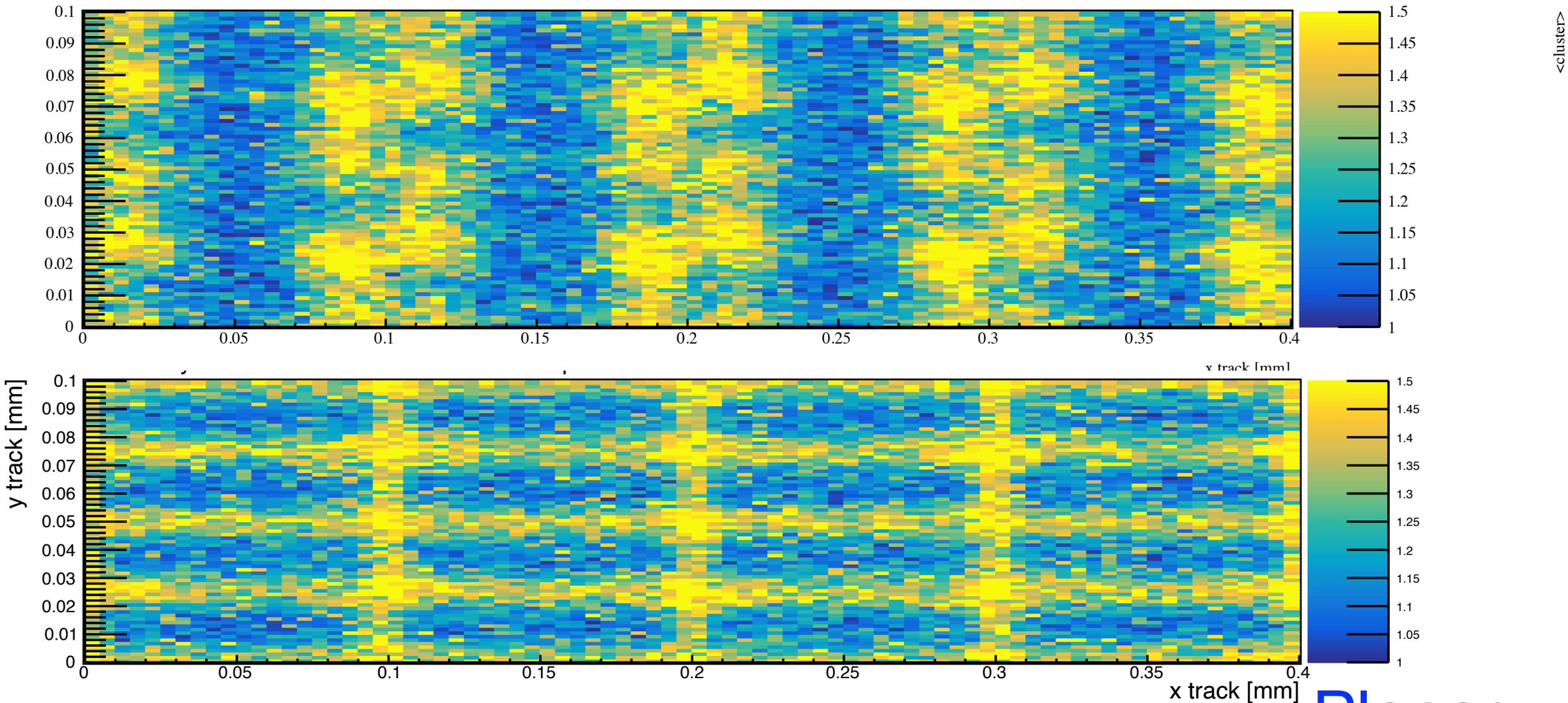




Possible x-talk effect

- 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.

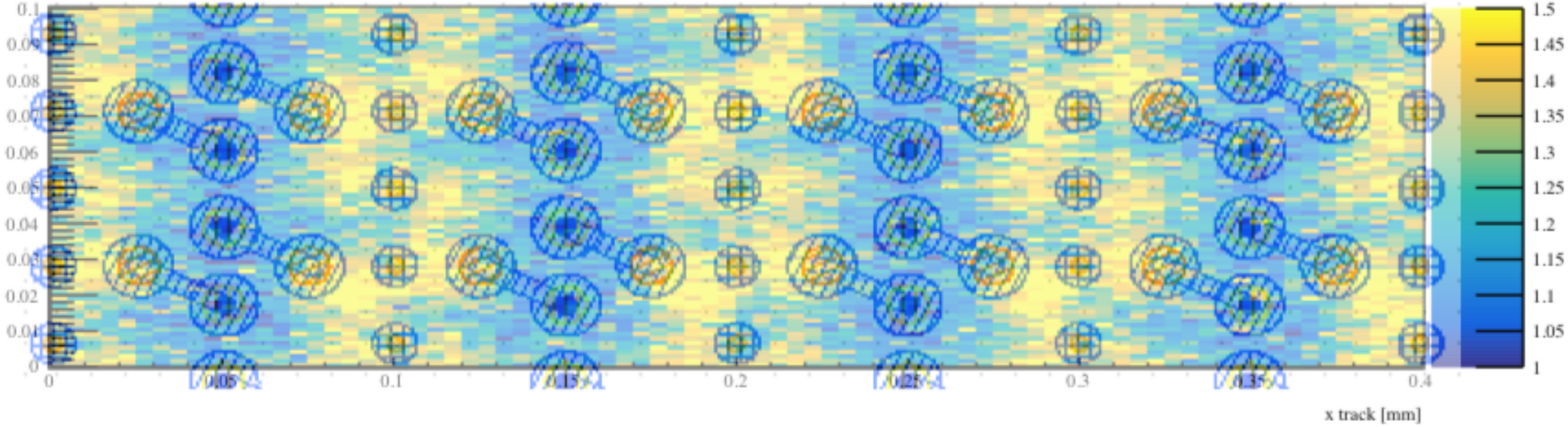
3D



Planar

Possible x-talk effect

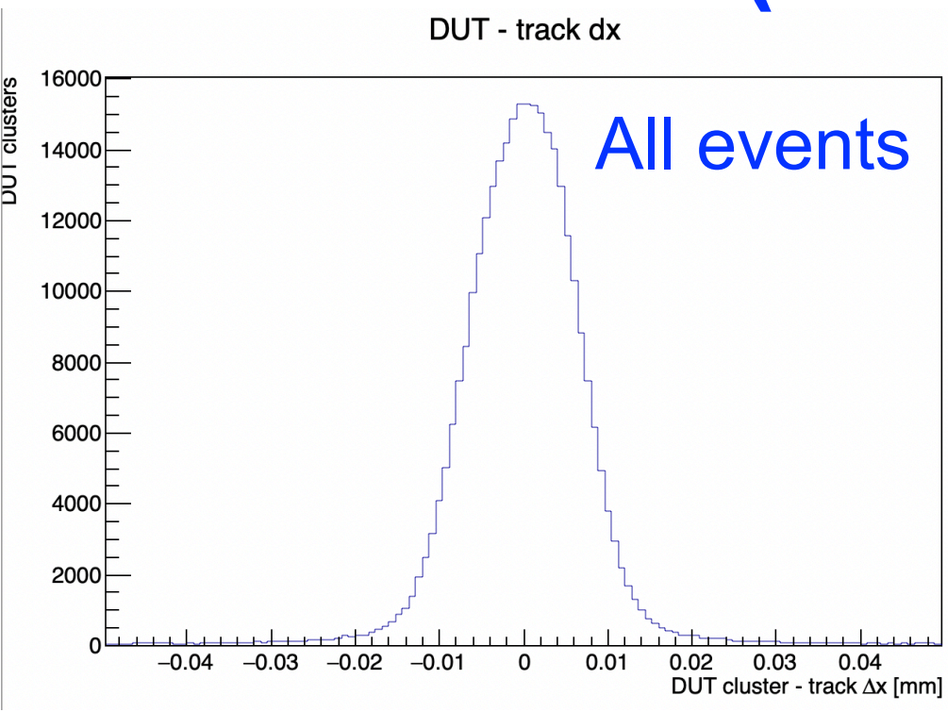
- Correlation between even and odd row clearly present
  - apparently we do see a pattern in the cluster size
  - whether it is significant or not still has to be quantified.



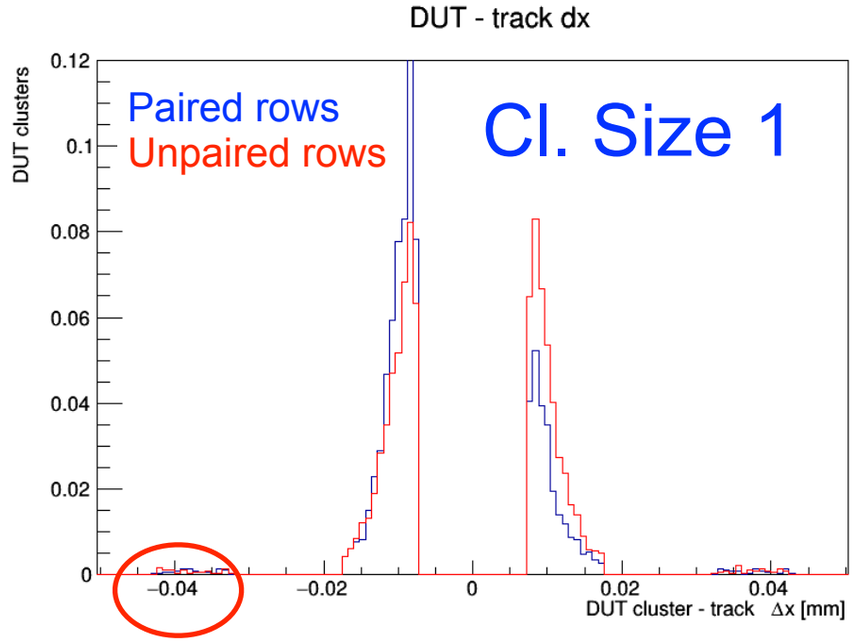
M. Meschini

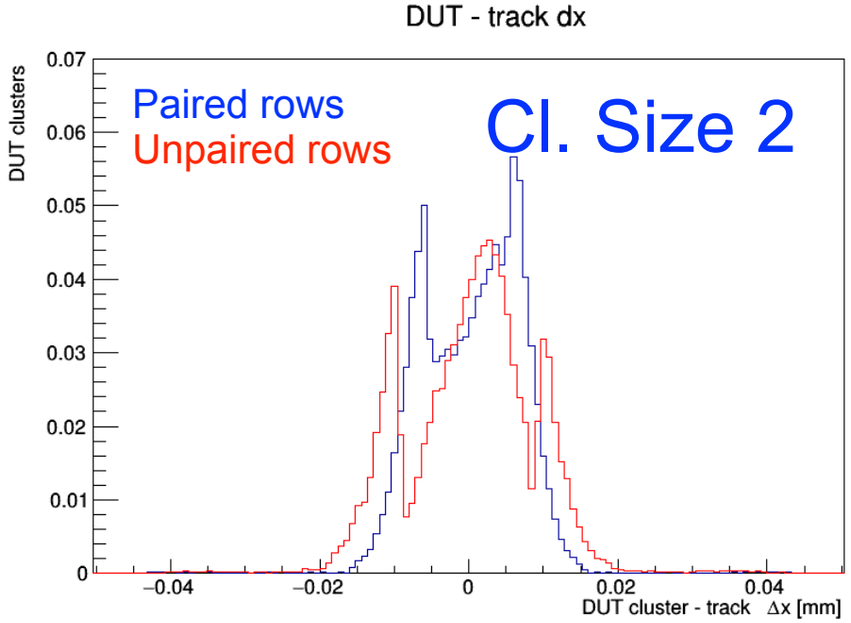
Resolution plots vs Clsize

bitten (Vbias = 70 V)

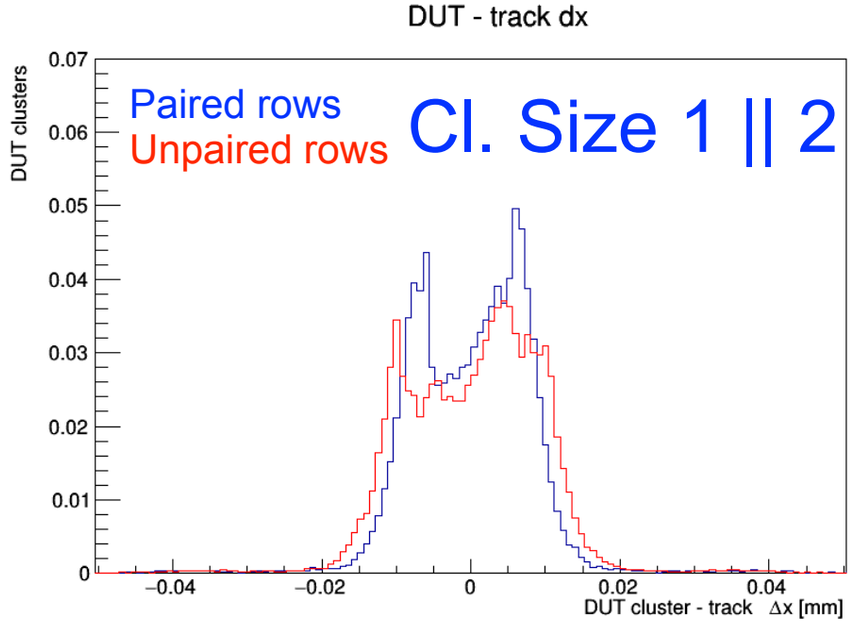


N.B. events are selected +/- 5 um around the divide!



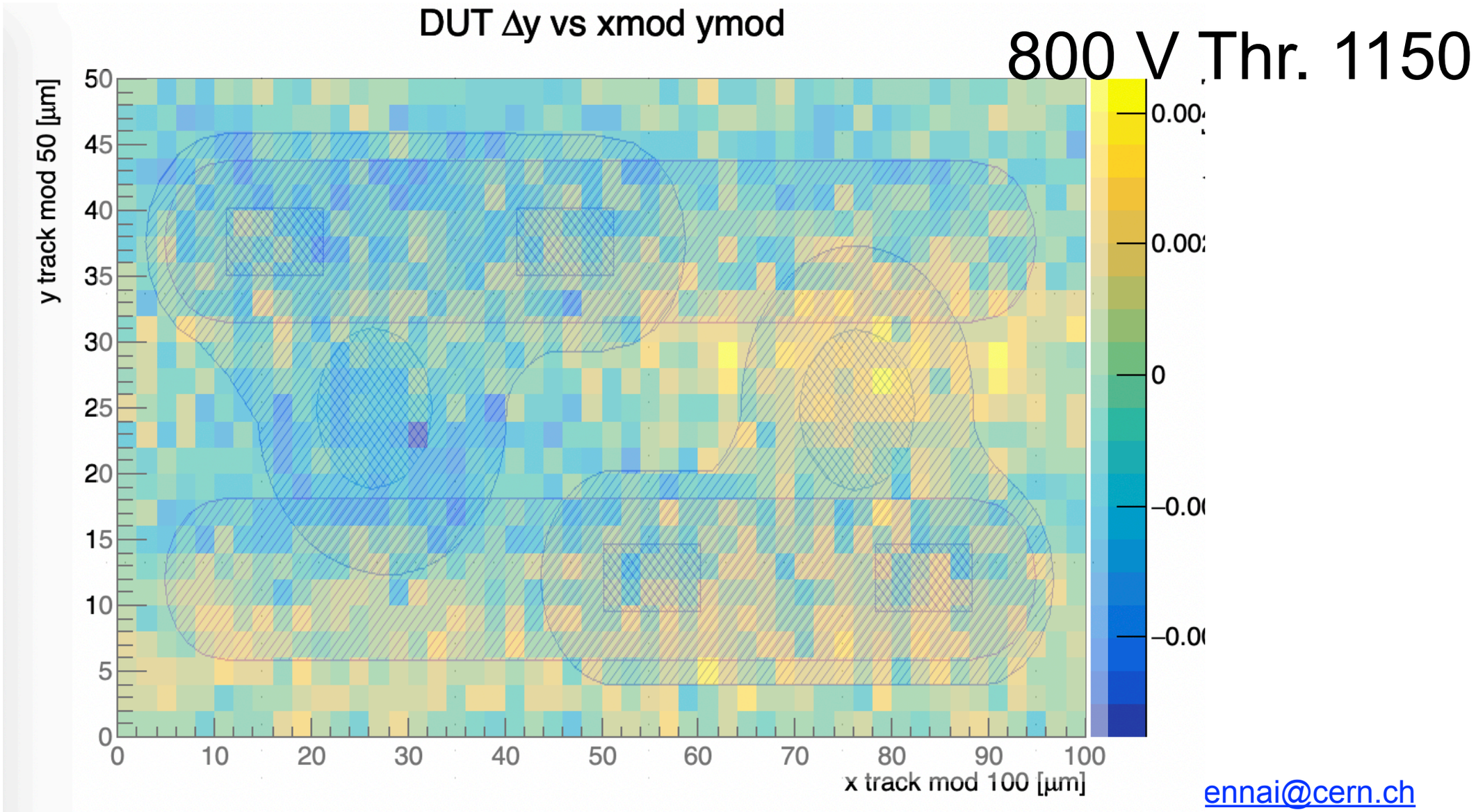


Asymmetry for Paired rows to be understood



Let's zoom in

- Clear effect due to the presence of the bump bonding
  - The difference wrt the past studies on x-talk is that on irradiated sensors the charge sharing is concentrated on the metallization
  - Mild effects can be seen also on the border of the pixel implant below the metallization



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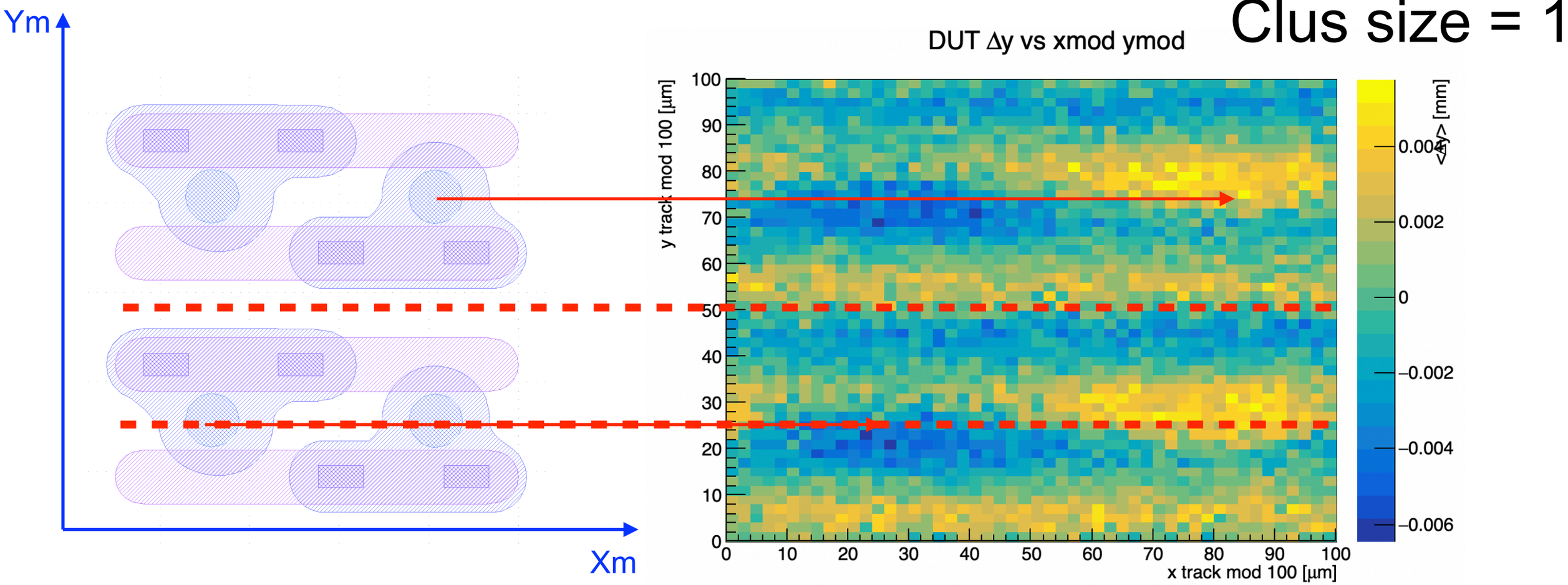
Study of residuals

- Residuals shows strange change of sign within a cell in the presence of the bump bonding
  - is this a sign that the signal reconstruction is affected by signal induced by the ?

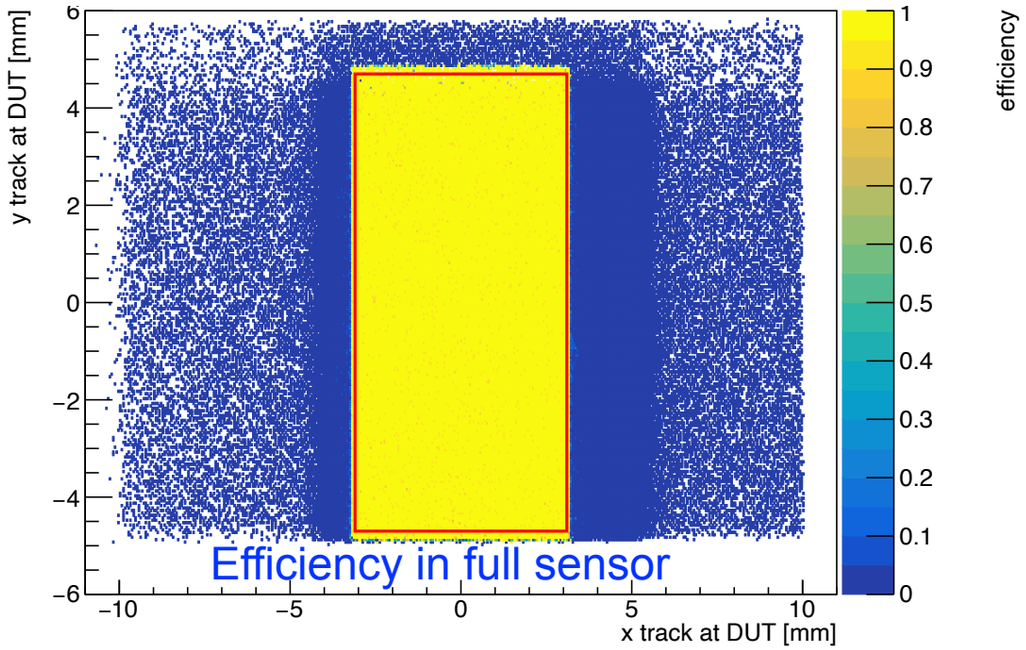
25x100 Planar FBK

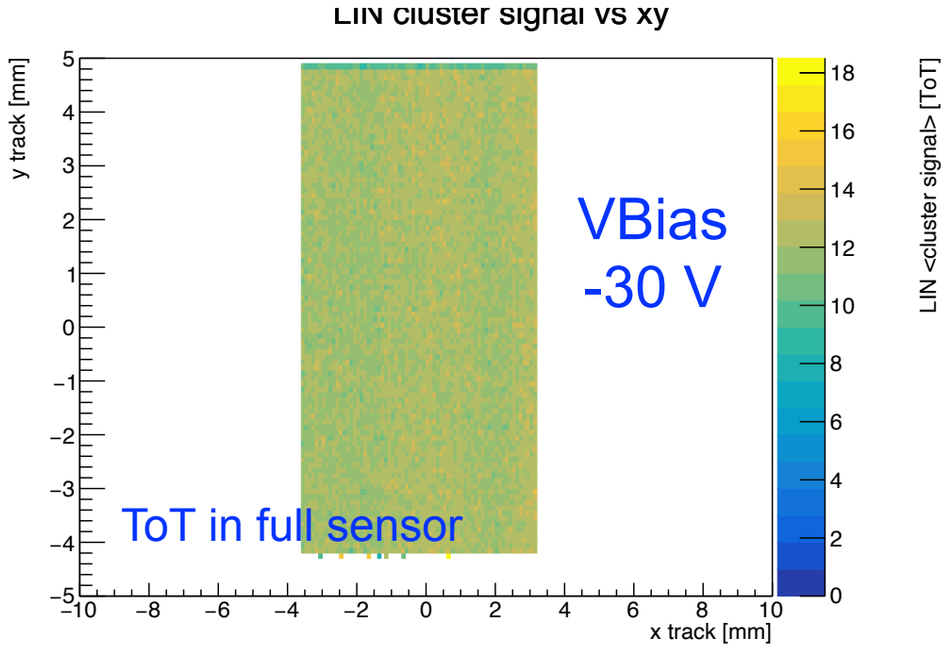


Residual is computed as DUT_position - Track_position

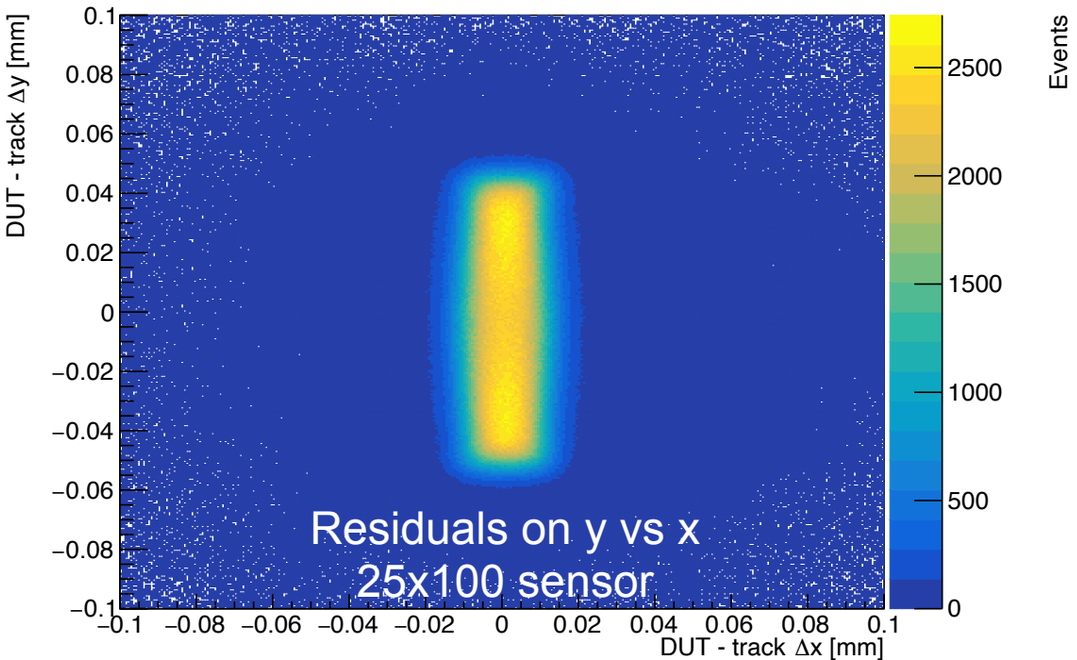
Preliminary checks

- Fiducial regions is defined as 1.5 mm from the edge
- Residuals show good level of alignment

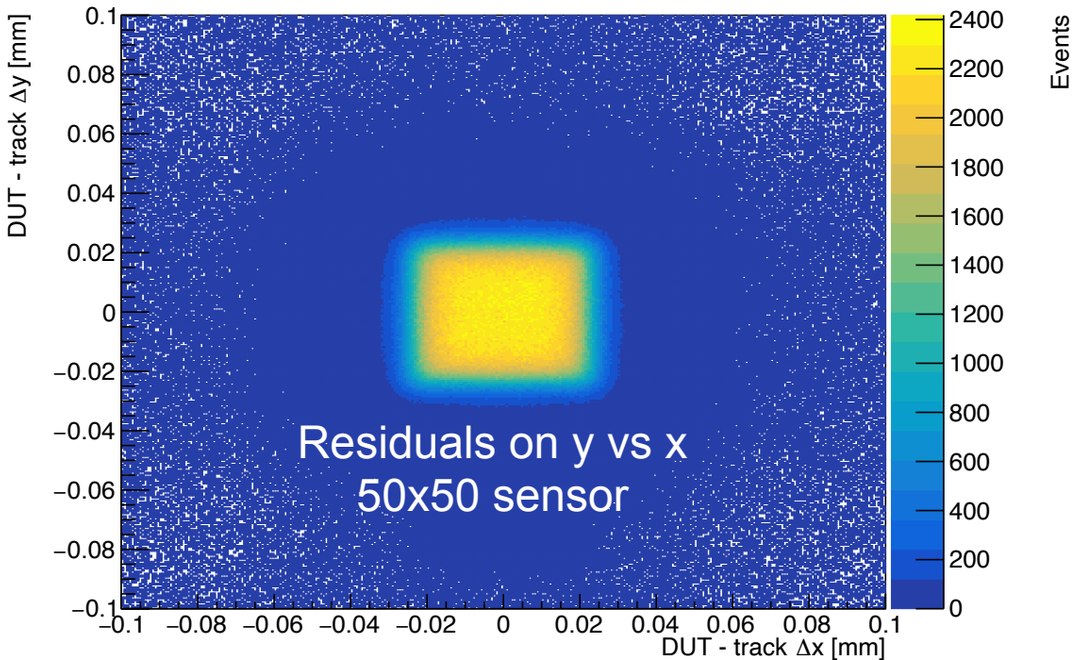




DUT cluster - track



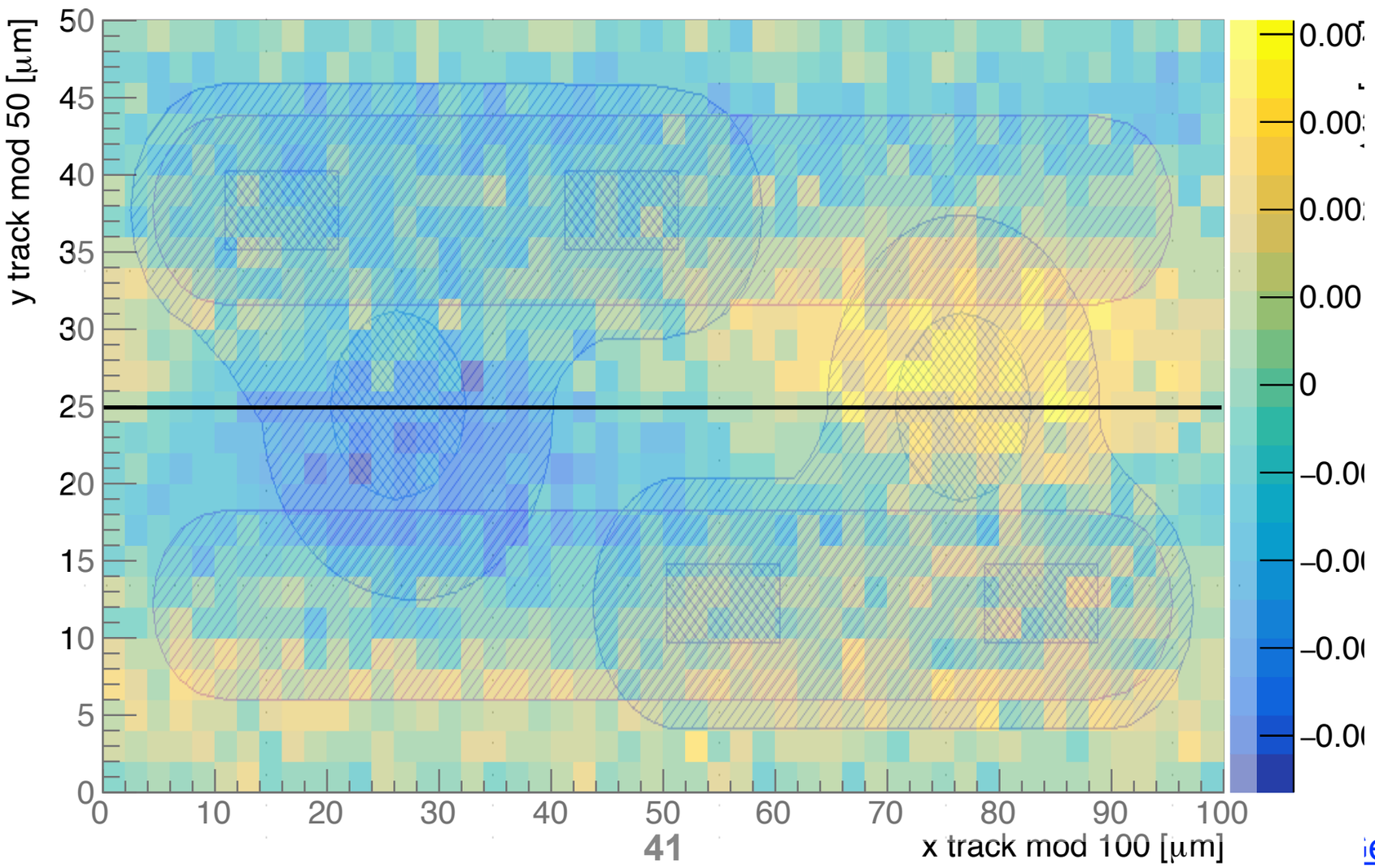
DUT cluster - track



Let's zoom in

- Clear effect due to the presence of the bonding-pad
  - The difference wrt the past studies on x-talk is that on irradiated sensors the charge sharing is concentrated on the metallization
- All clusters used

500 V Thr. 1400



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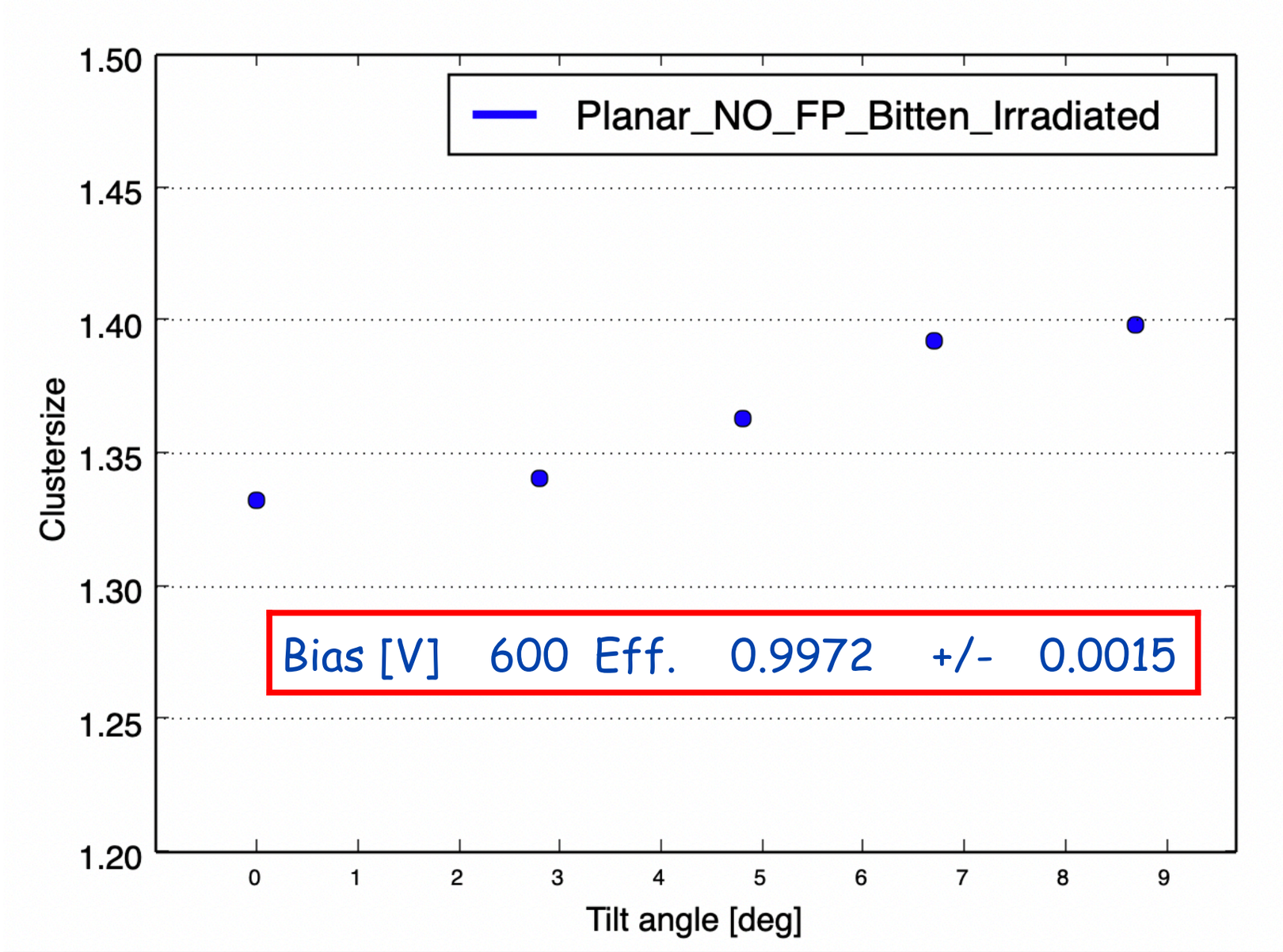
Cluster size



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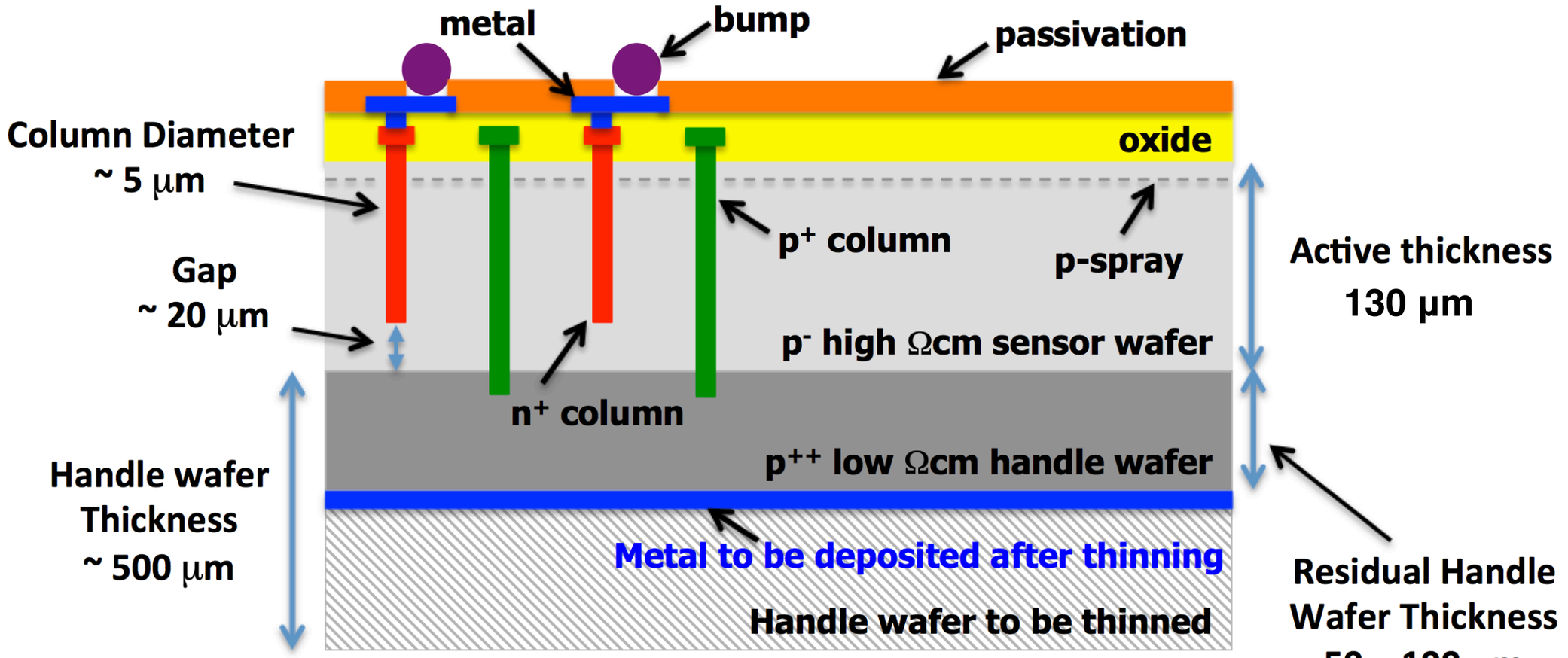
3D pixel sketch



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