Pixel Detector for LHCb VELO Upgrade

INFIERI 7th Workshop

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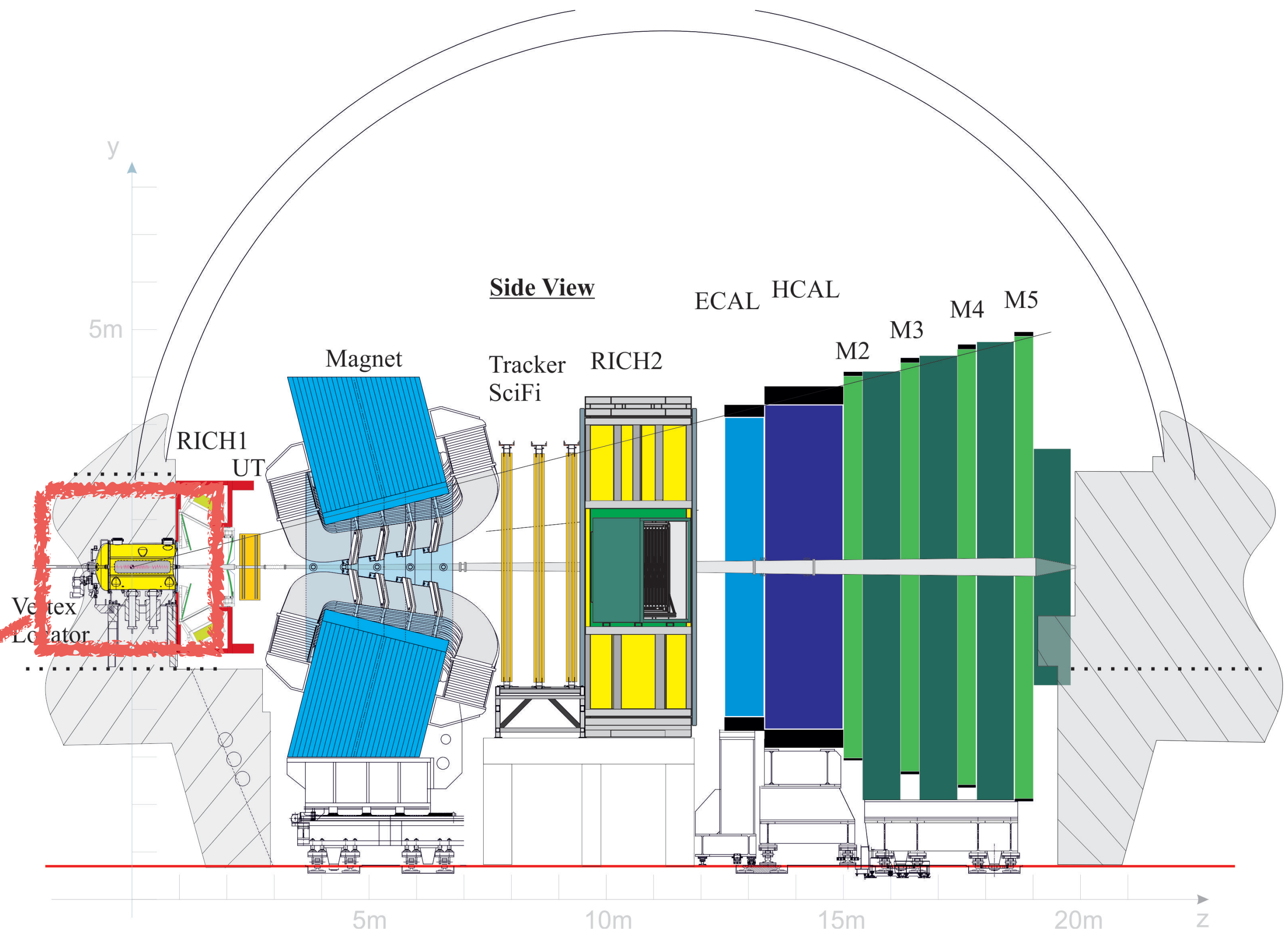
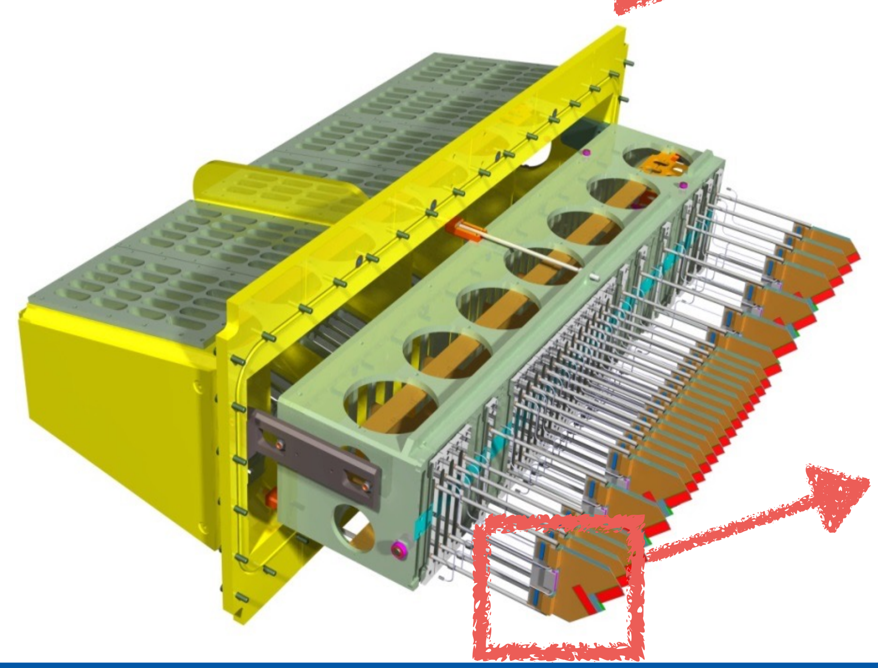
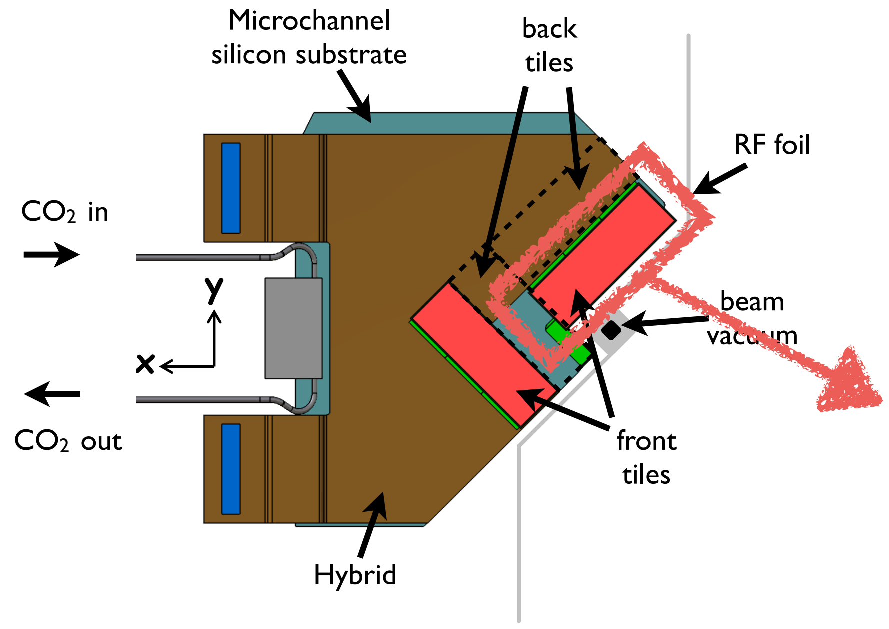
LHCb VELO Upgrade

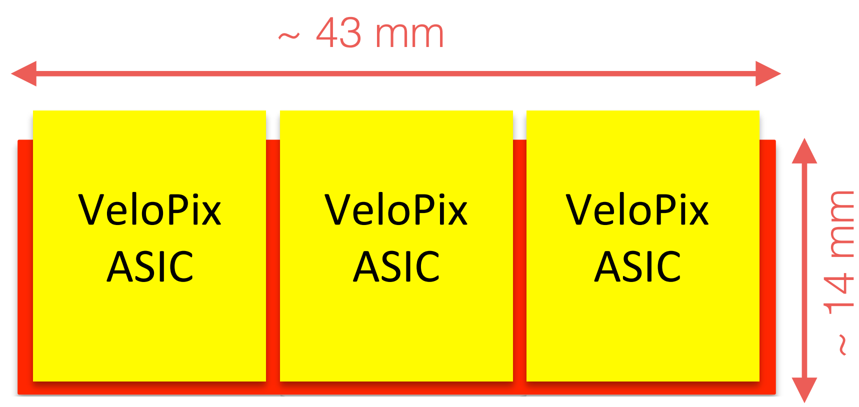
LHCb Detector
(Upgrade 2019/2020)

Luminosity: 2×10^{33} cm^{-2} s^{-1}









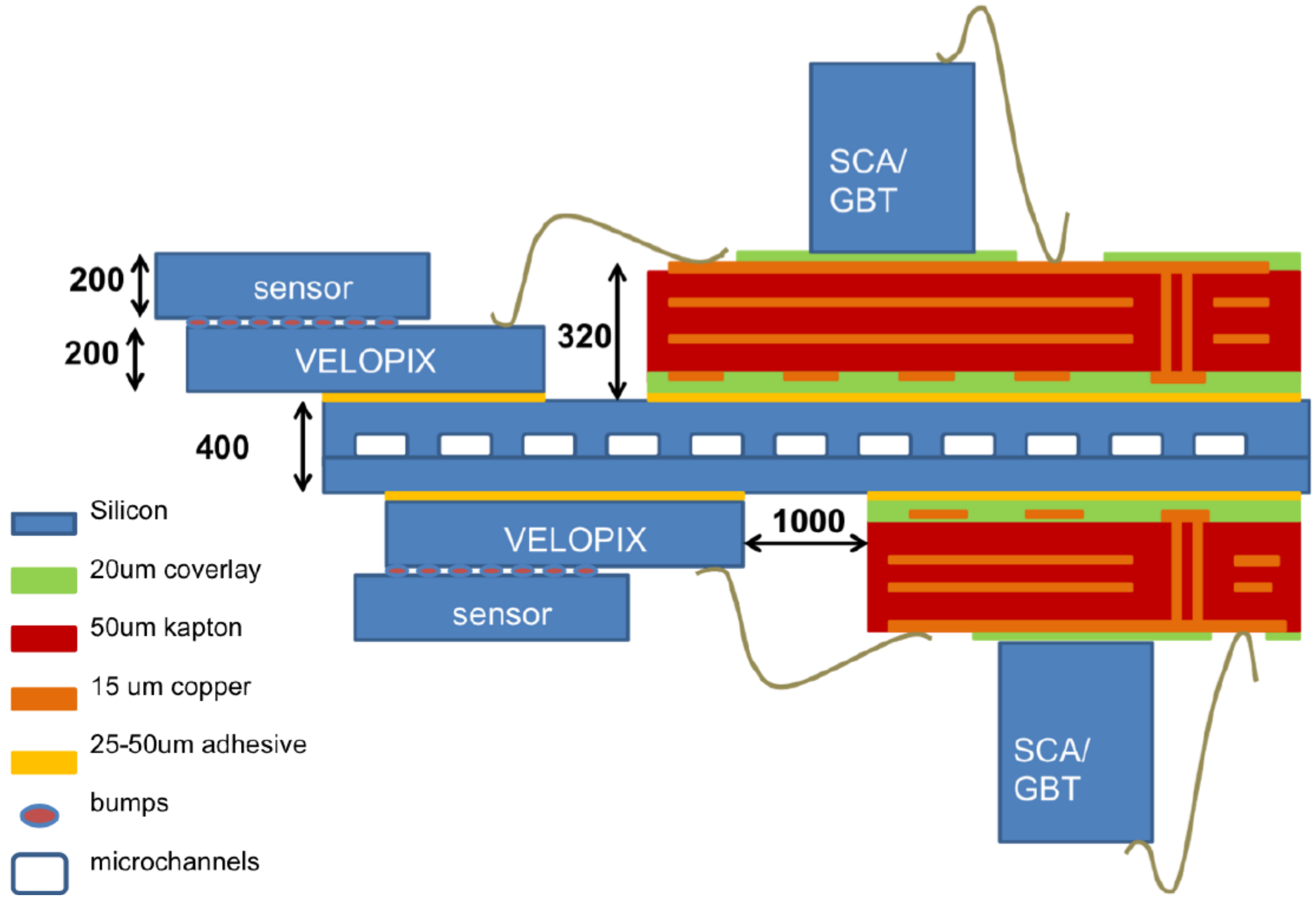
Nikhef in the VELO upgrade

Sensor

Test and characterisation of prototype sensors in combination with Timepix3 ASIC

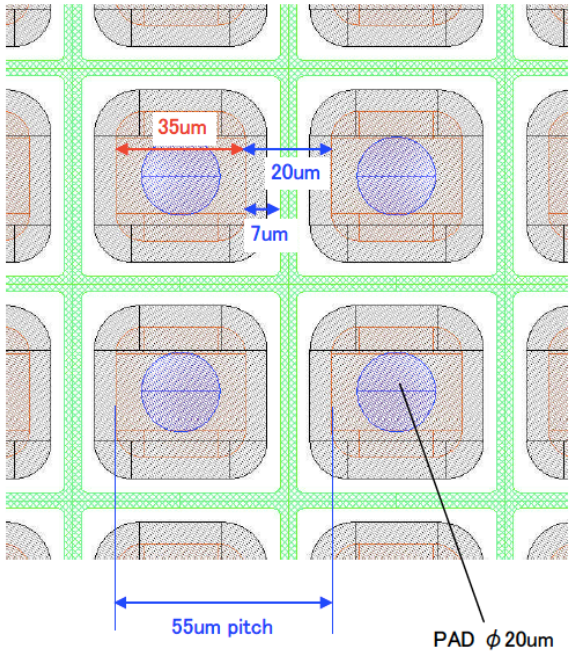
VeloPix

Development of the VeloPix ASIC. In particular: design of a new serialiser block

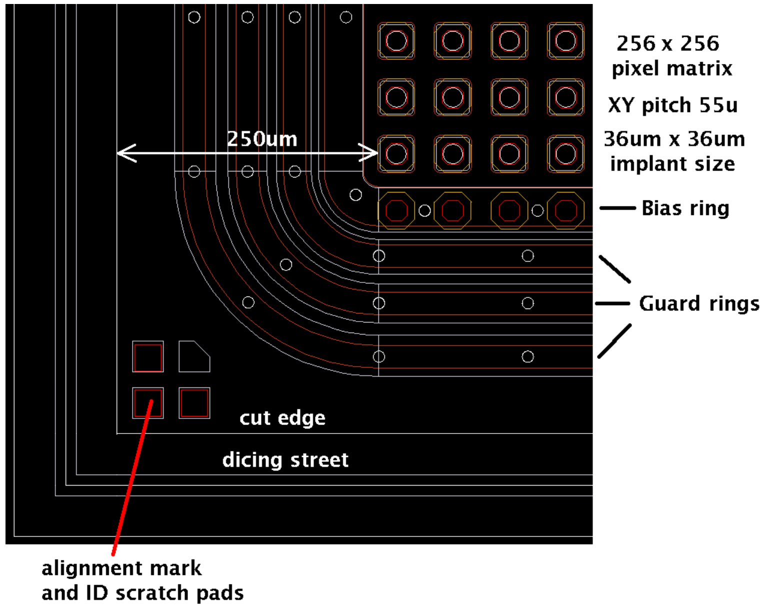


Sensors

Baseline: n-on-p, 200 μm thick, 450 μm guard ring size



Hamamatsu
- n-on-p (200 μm thick)
- implant width: 35 μm, 39 μm
- guard ring size: 450 μm, 600 μm



Micron
- n-on-p (200 μm thick)
- n-on-n (150 μm thick)
- implant width: 36 μm
- guard ring size: 450 μm, 250 μm, 150 μm

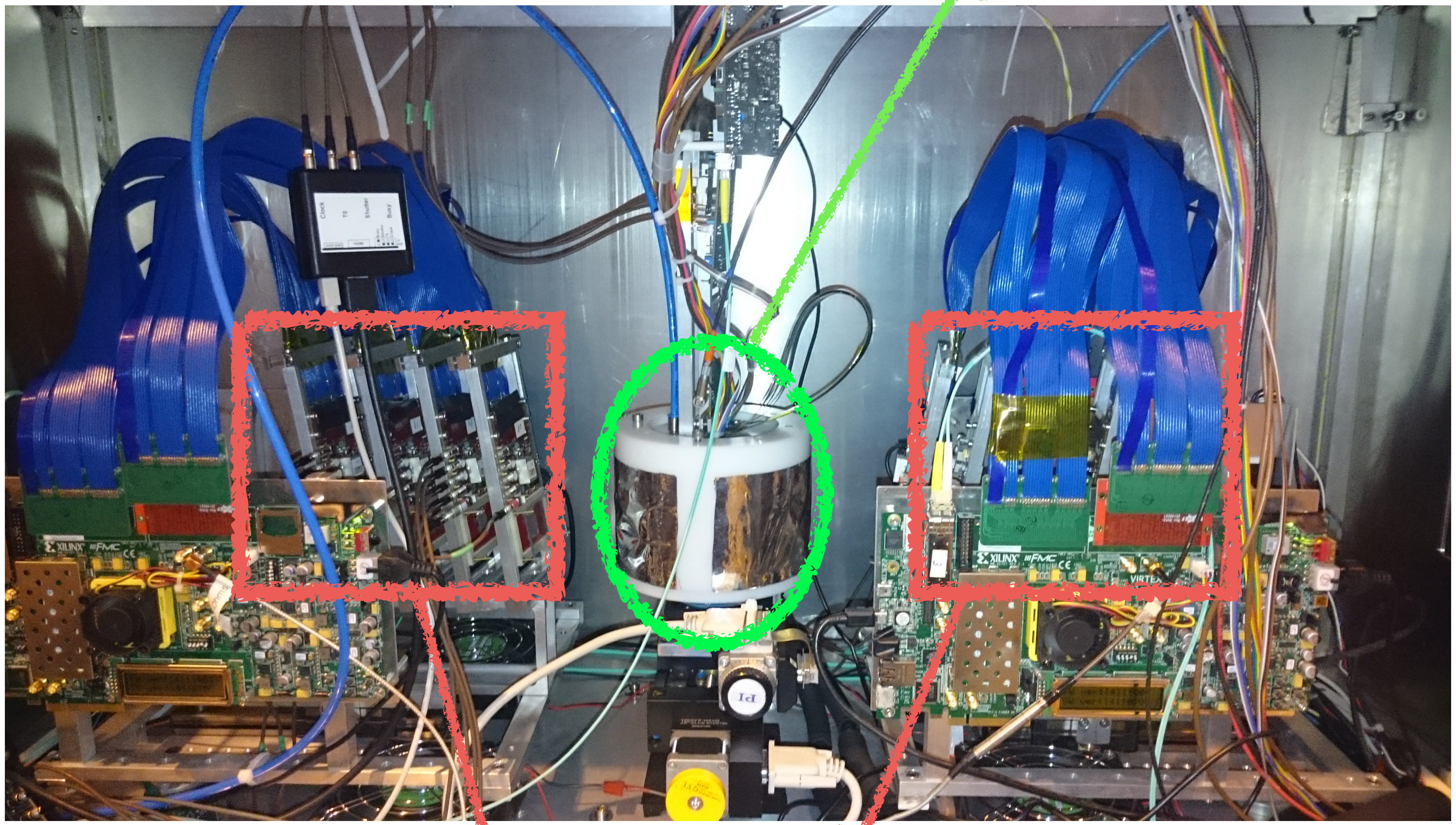
Sensors irradiated both uniformly and non-uniformly at KIT, IRRAD, JSI and Birmingham at different fluence (4 and 8 x 10^{15} n_{eq}/cm^2)

Timepix3 Telescope

Dedicated telescope to provide particle track position and time at high rate

- pointing resolution ~2 μm for a 180 GeV beam
- up to 5 million tracks/s reconstructed

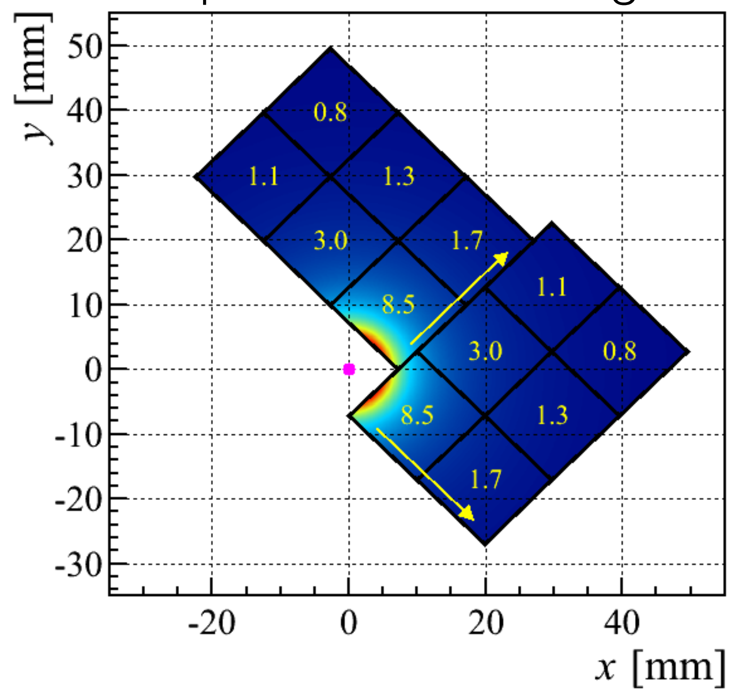
Device Under Test



4 + 4 Timepix3 planes

Sensor Characterisation

we want to maintain the high performance of the current VELO despite the higher rate and non uniform irradiation (8×10^{15} n_{eq}/cm^2 at the closest edge after 50 fb^{-1})



Results from the whole testbeam crew

	Requirement	HPK	Micron n-on-p	Micron n-on-n
HV tolerance	>1000 V			
Charge Collection	> 6000 e-			
Efficiency	> 99% uniform			
Spatial Resolution	excellent			
Edge Effect	none			

Tested before and after irradiation!

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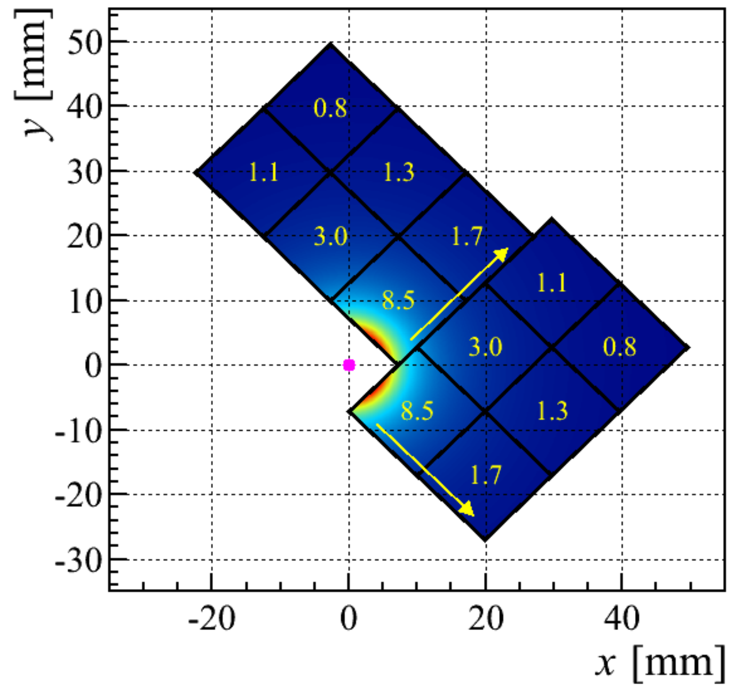
mean number of particles per event



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HV tolerance	>1000 V	✔	✔	✔
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in vacuum,
even after non-uniform irradiation!

Tested before and after irradiation!

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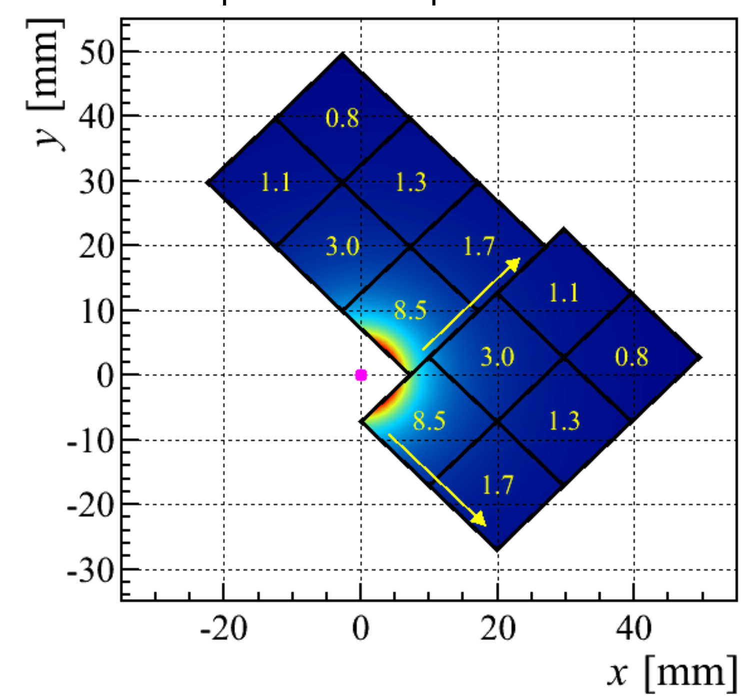

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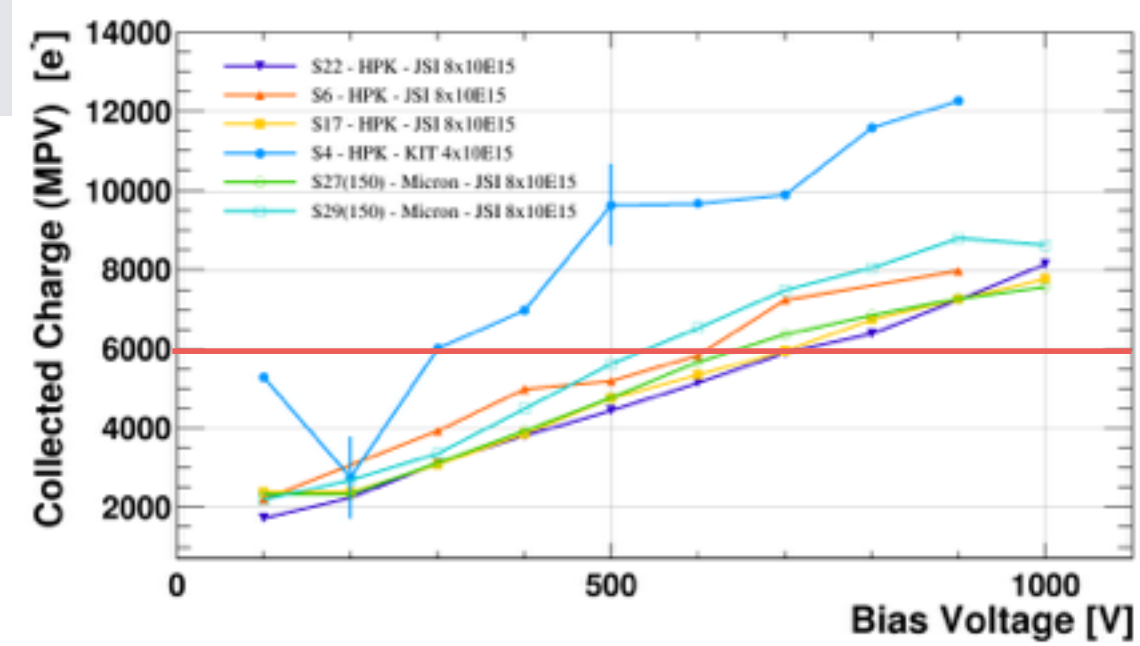

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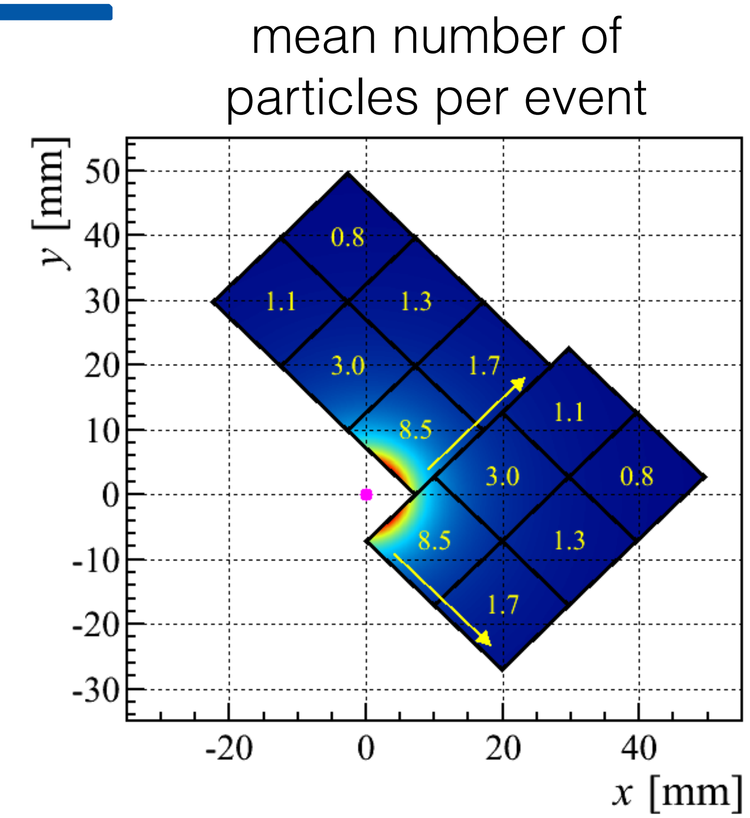

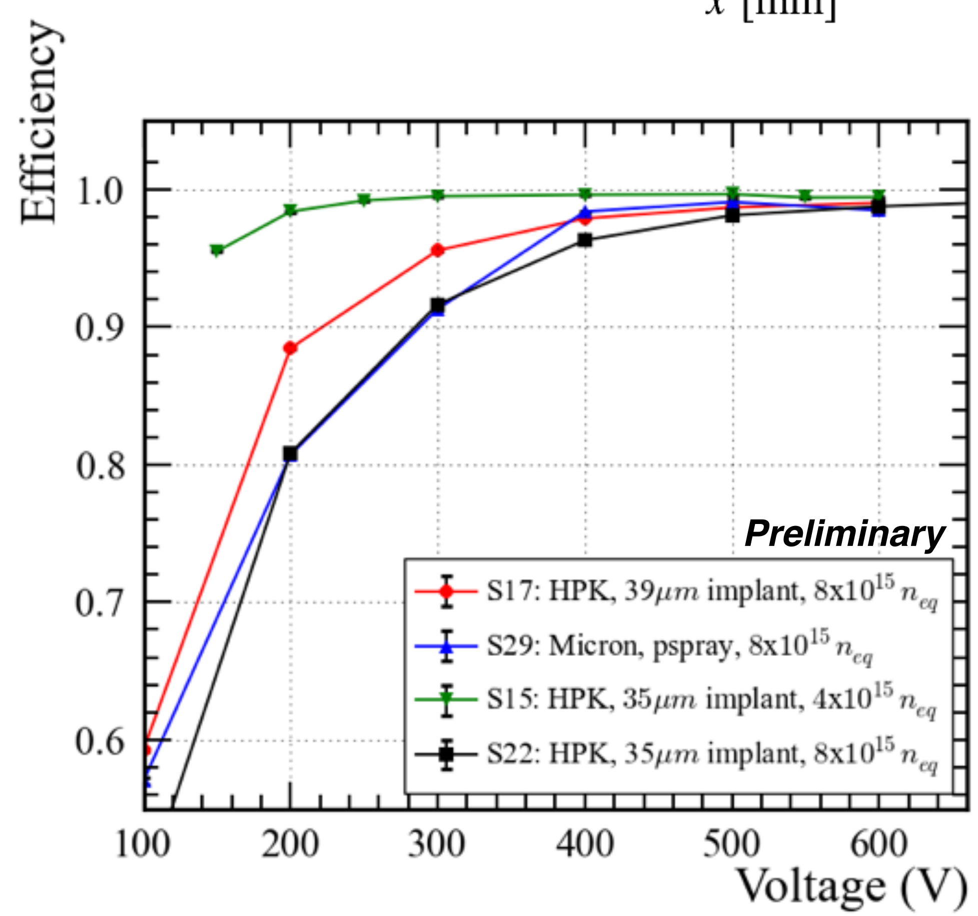

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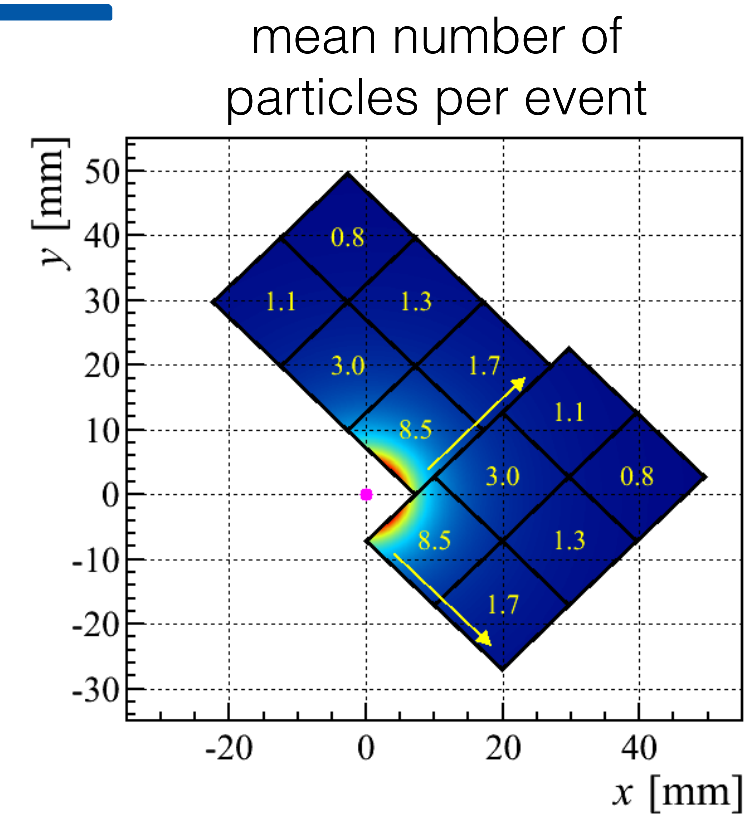

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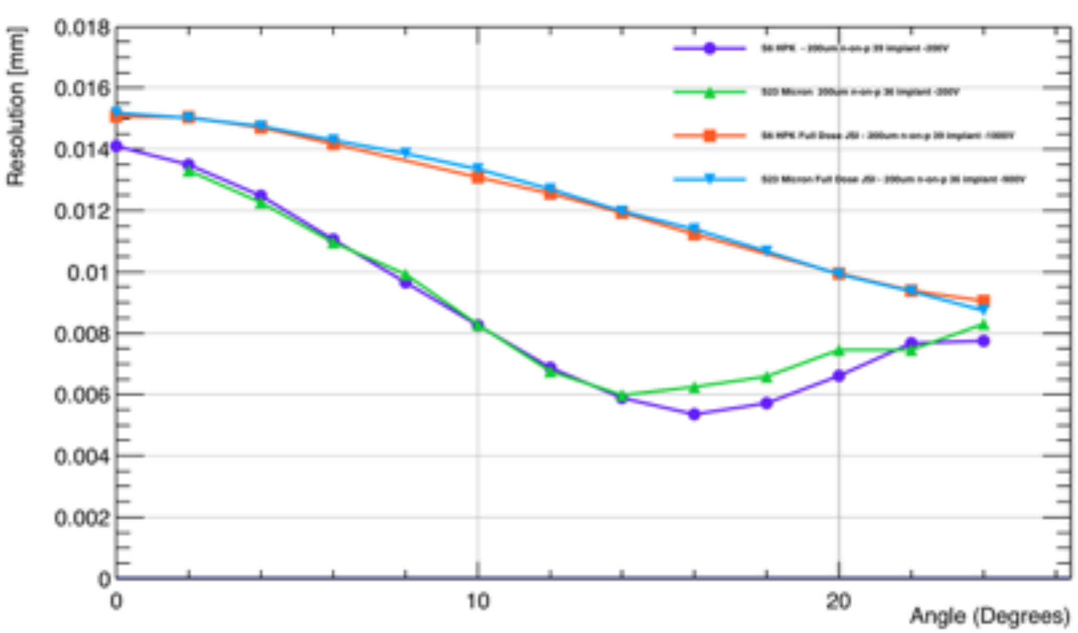

Tested before and after irradiation!

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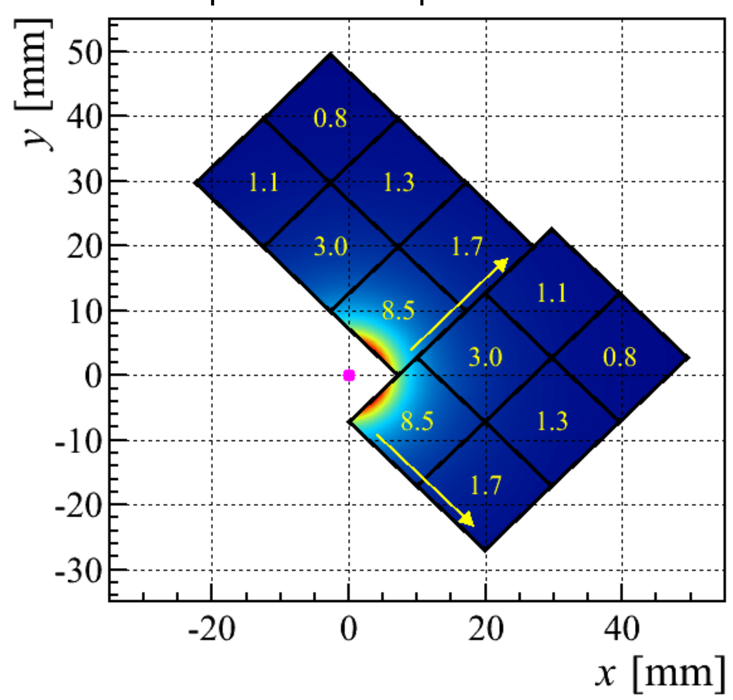
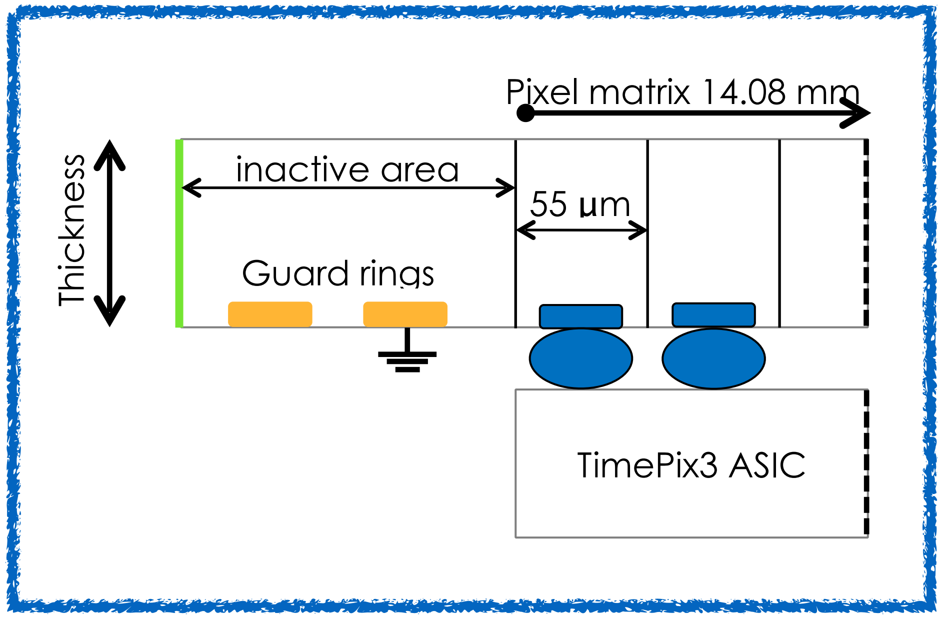
Efficiency	> 99% uniform	✔	✔	✔
Spatial Resolution	excellent	✔	✔	✔
Edge Effect	none	?	?	?

mean number of particles per event

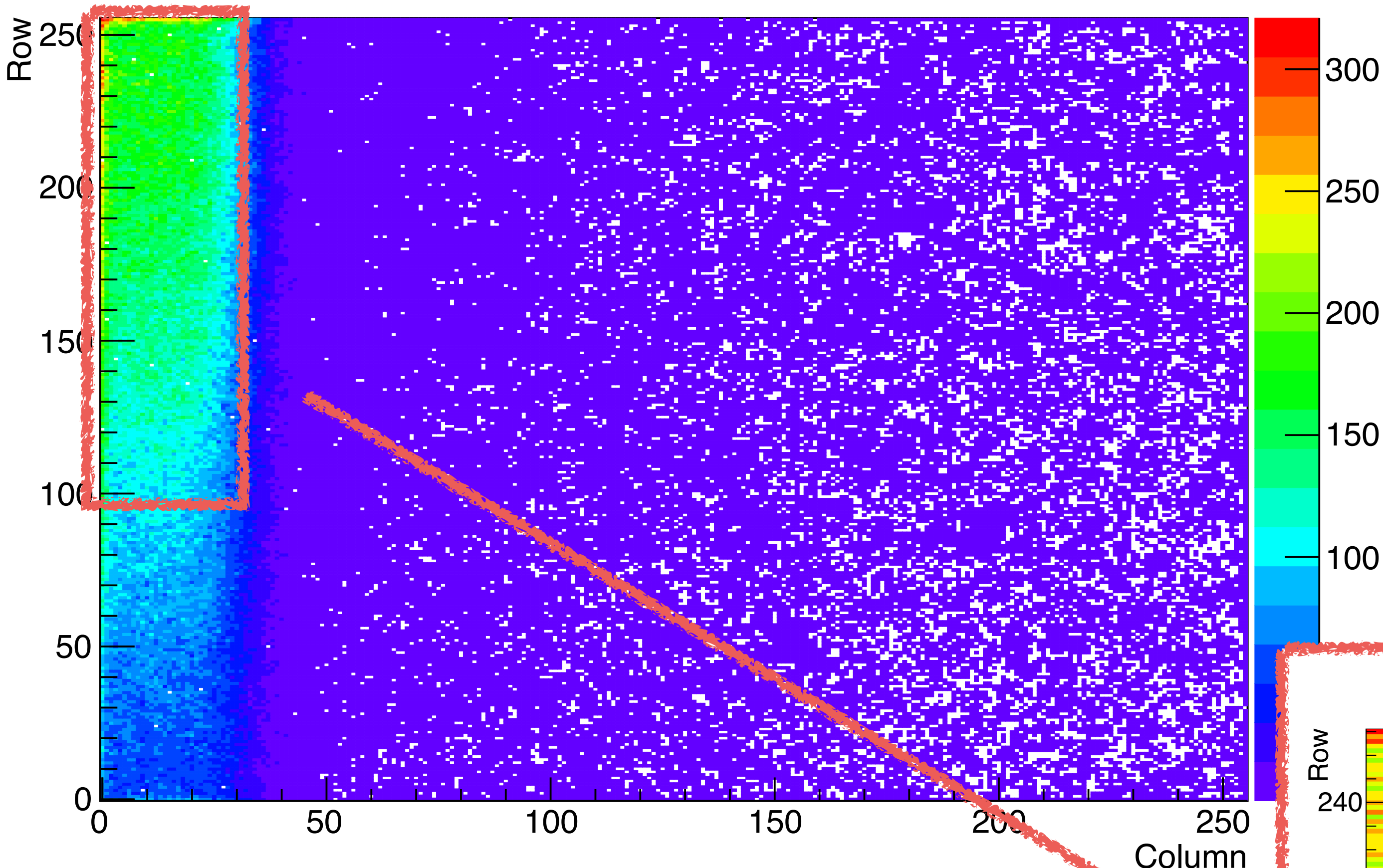




Tested before and after irradiation!

Edge

Micron 200V n-on-p

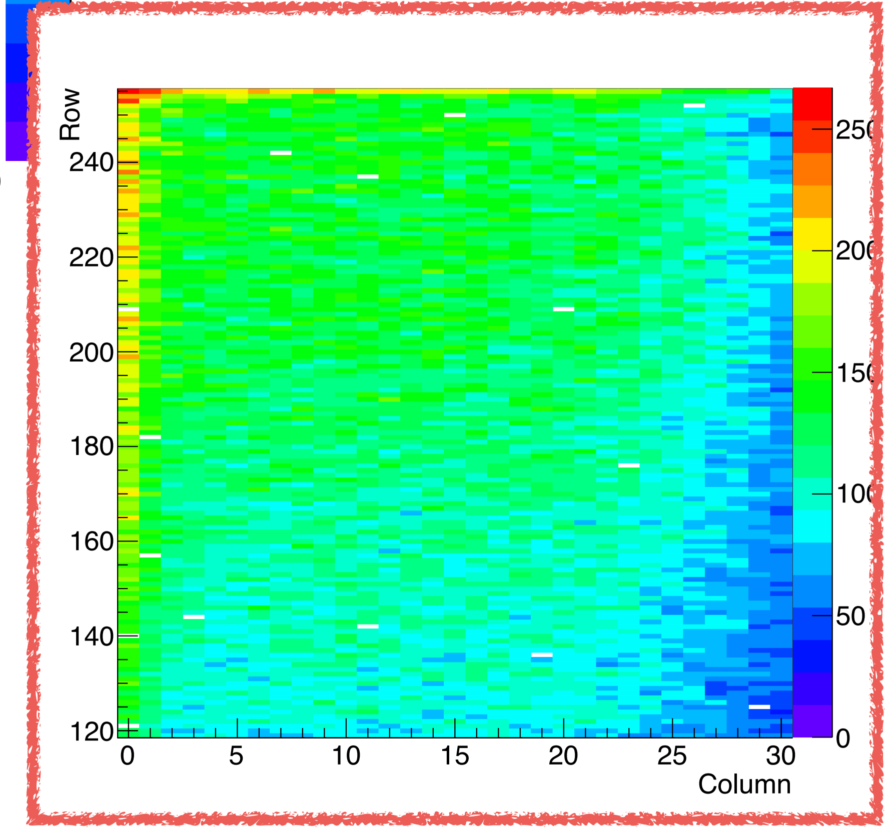


Excess in the first column!

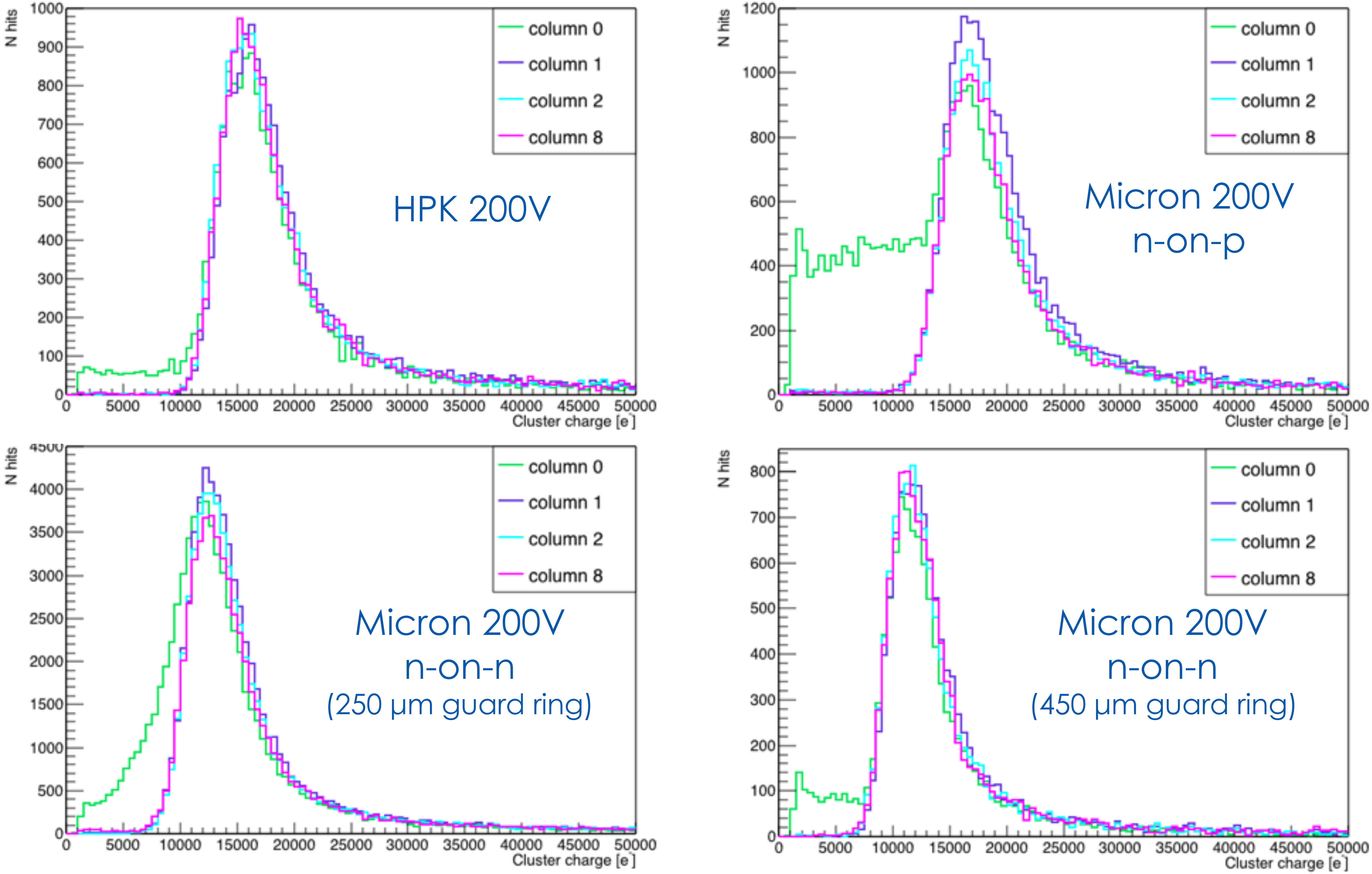
this represents a problem because it leads to

higher occupancy and data rate issue

worse resolution for first measured point

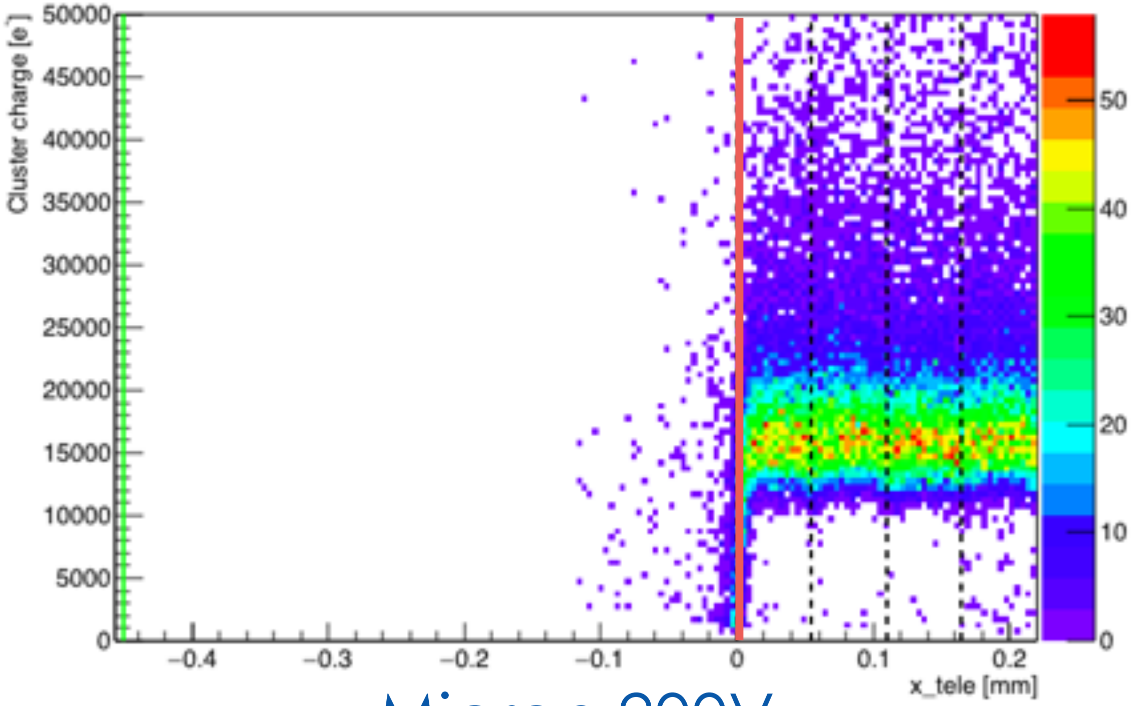


Charge Distribution Edge Columns for Different Sensors

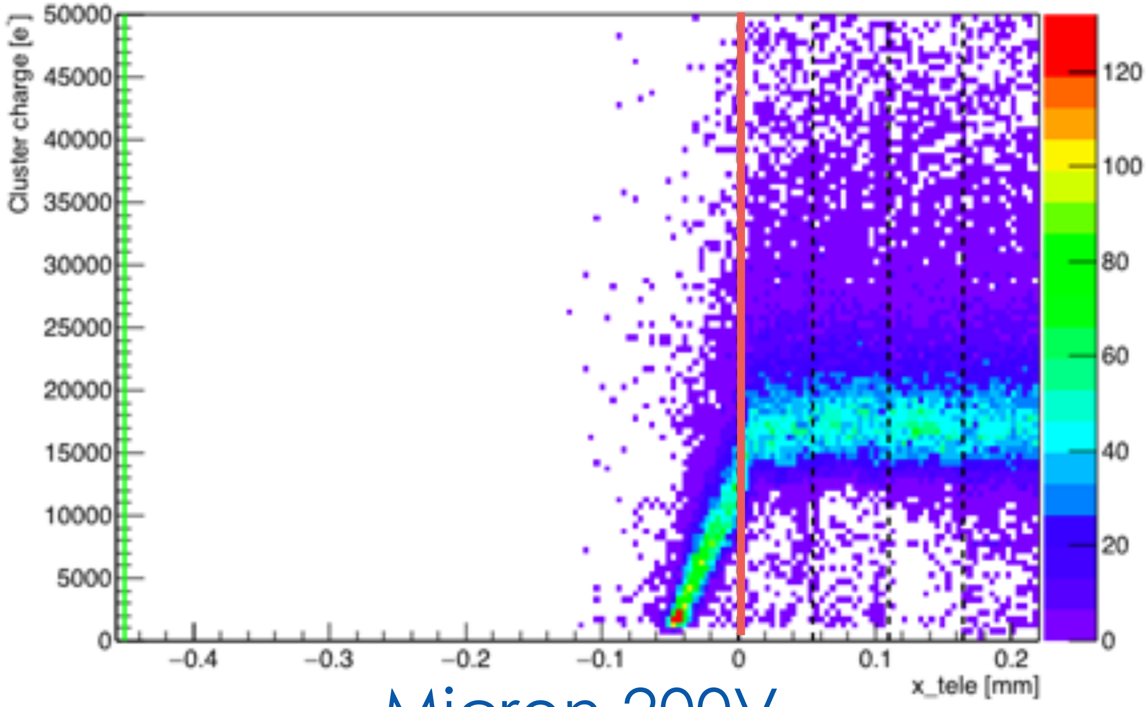


Edge

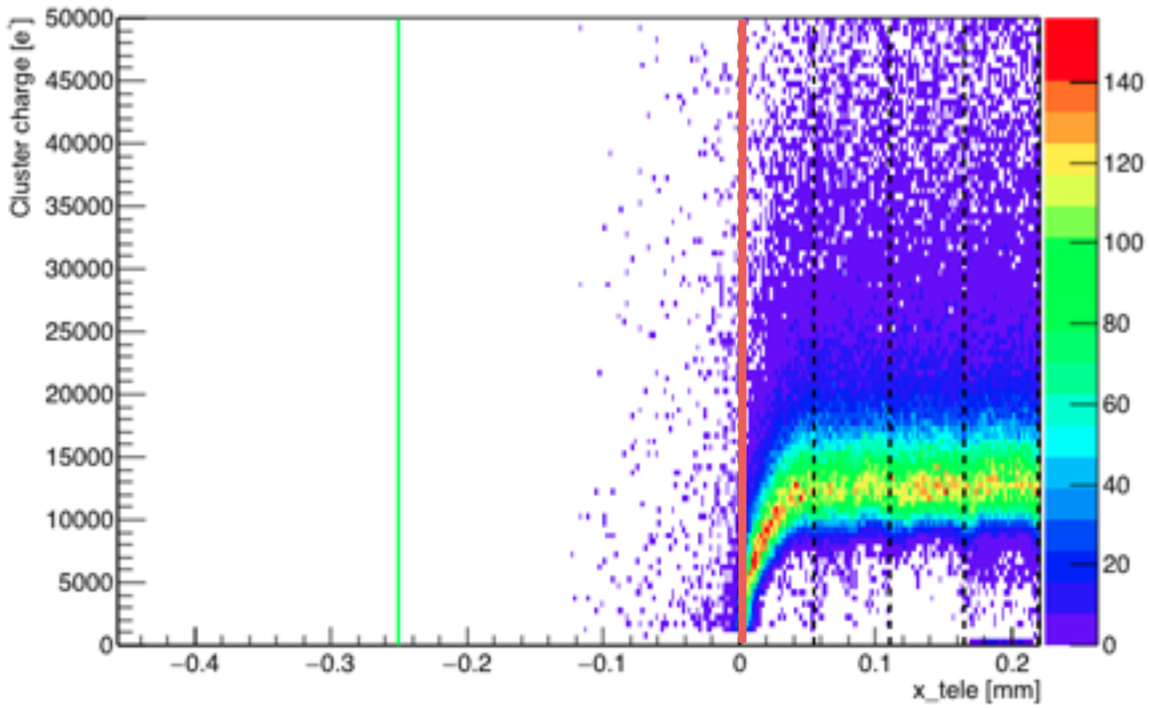
HPK 200V



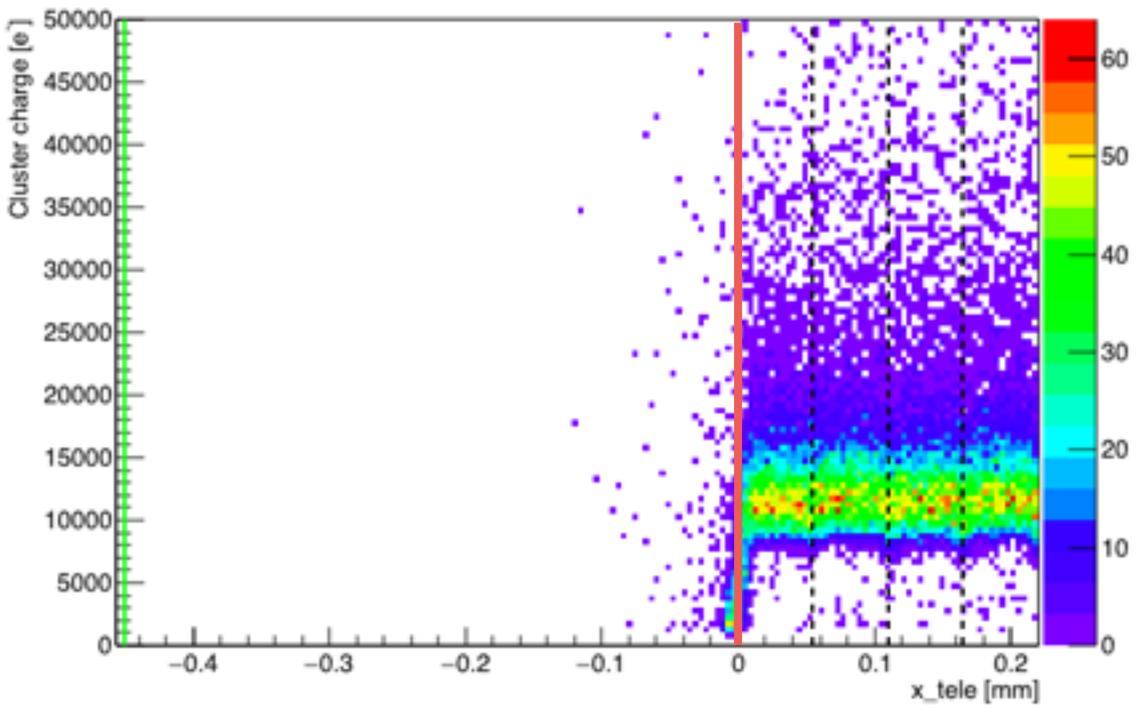
Micron 200V (n-on-p)



Micron 200V (n-on-n)

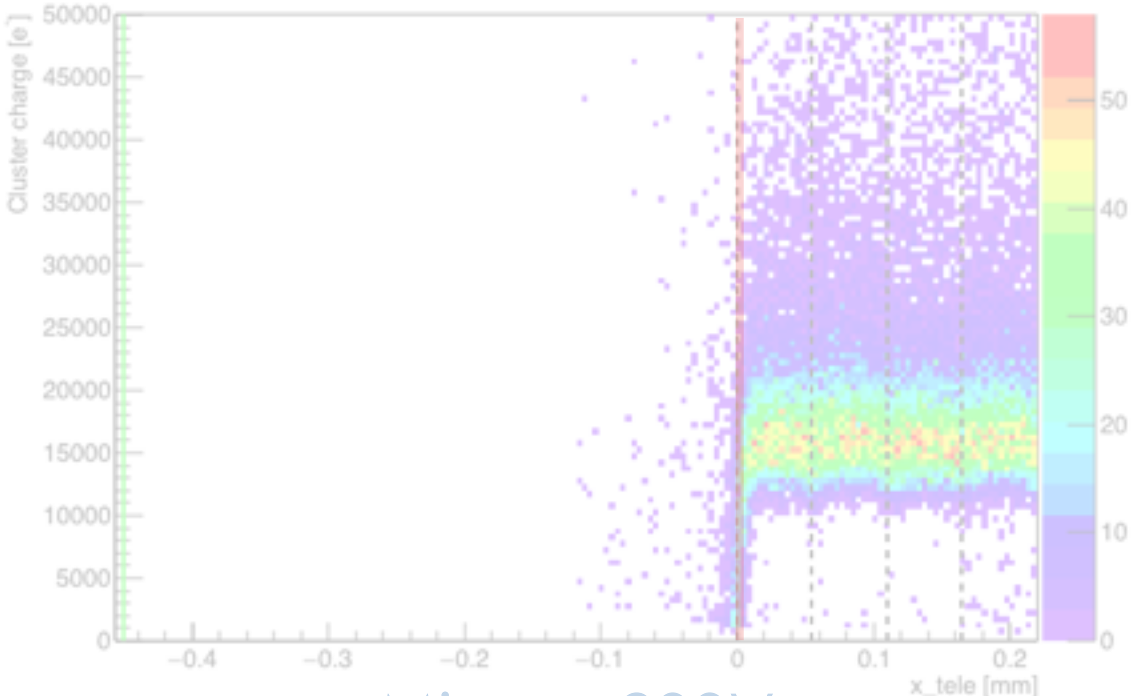


Micron 200V (n-on-n)

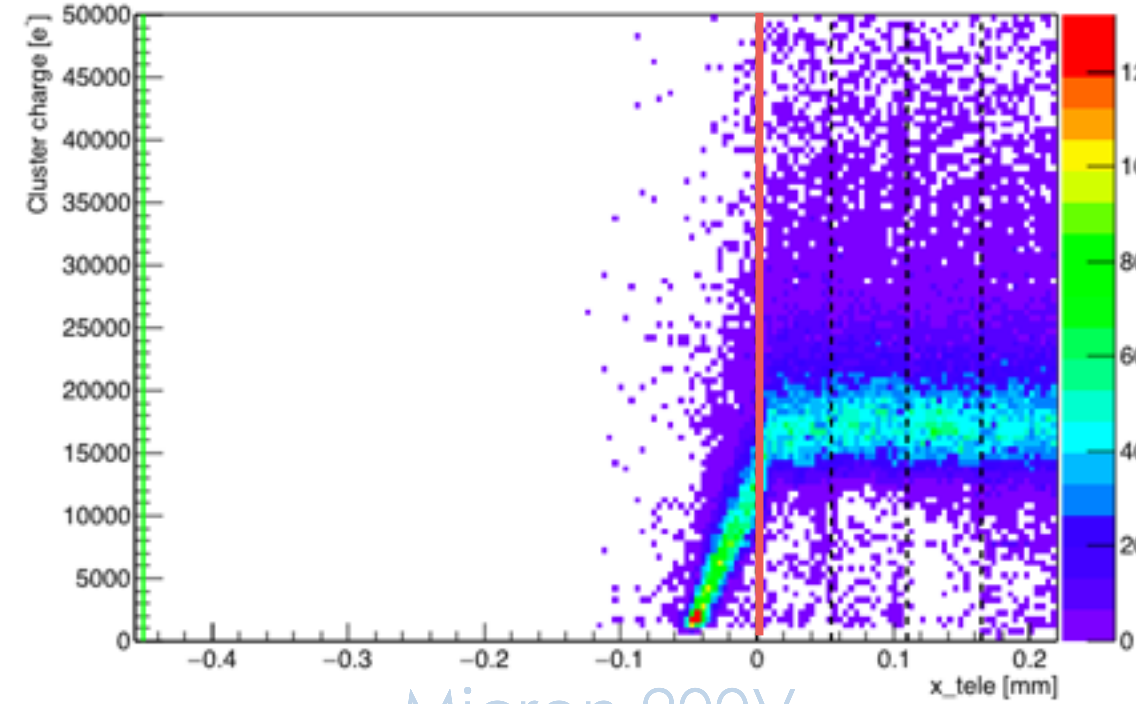


Charge Distributions

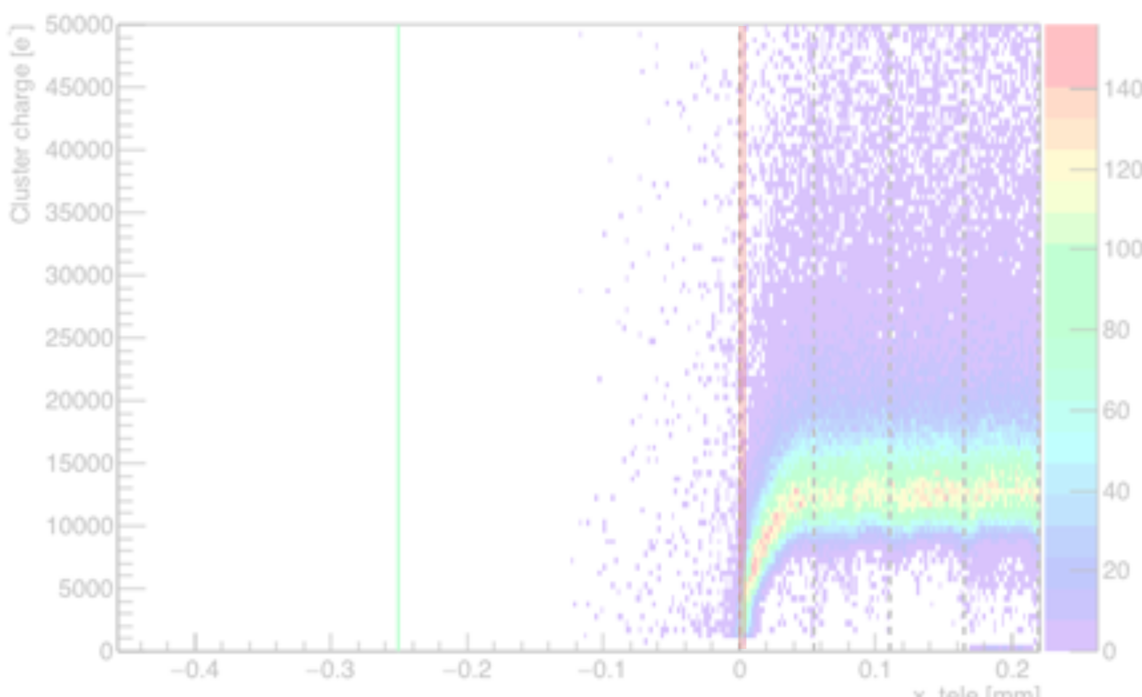
HPK



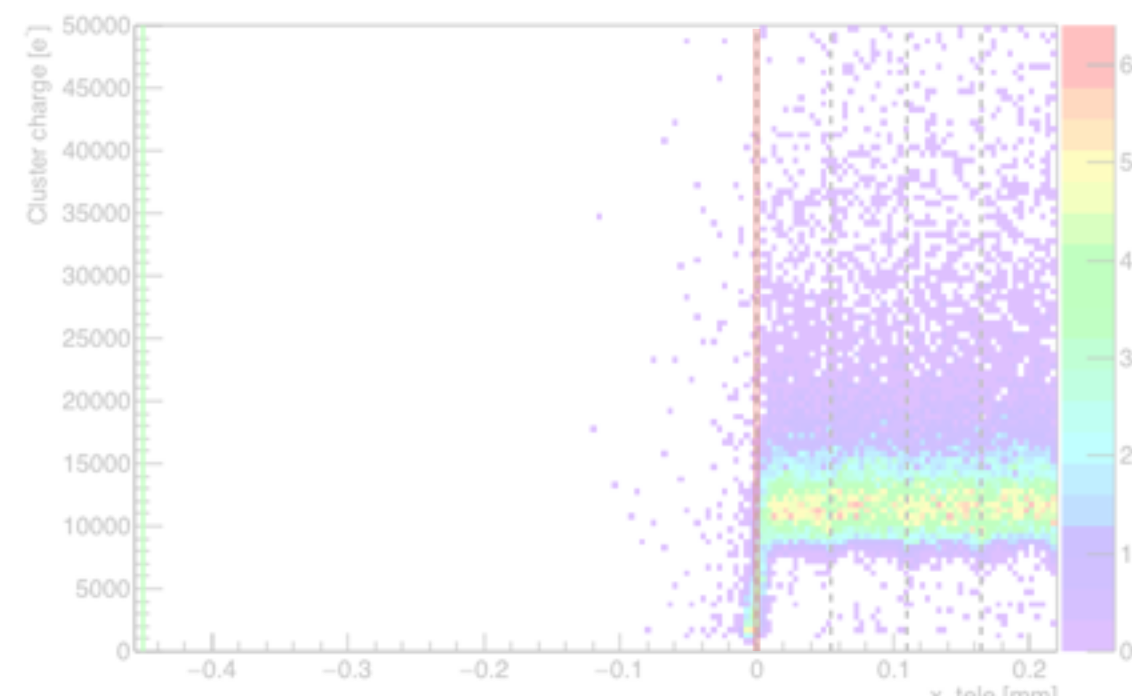
Micron 200V (n-on-p)



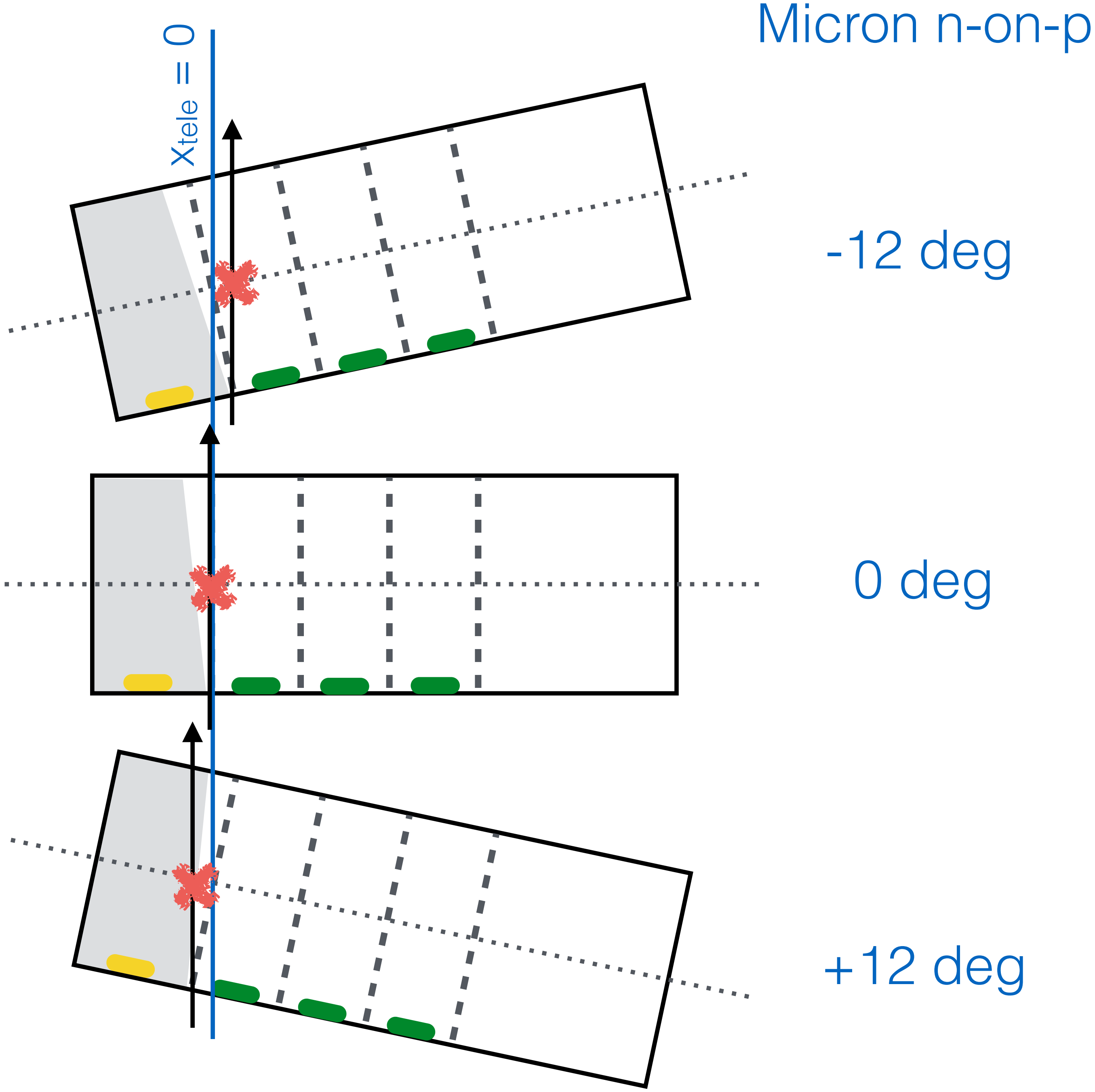
Micron 200V (n-on-n)

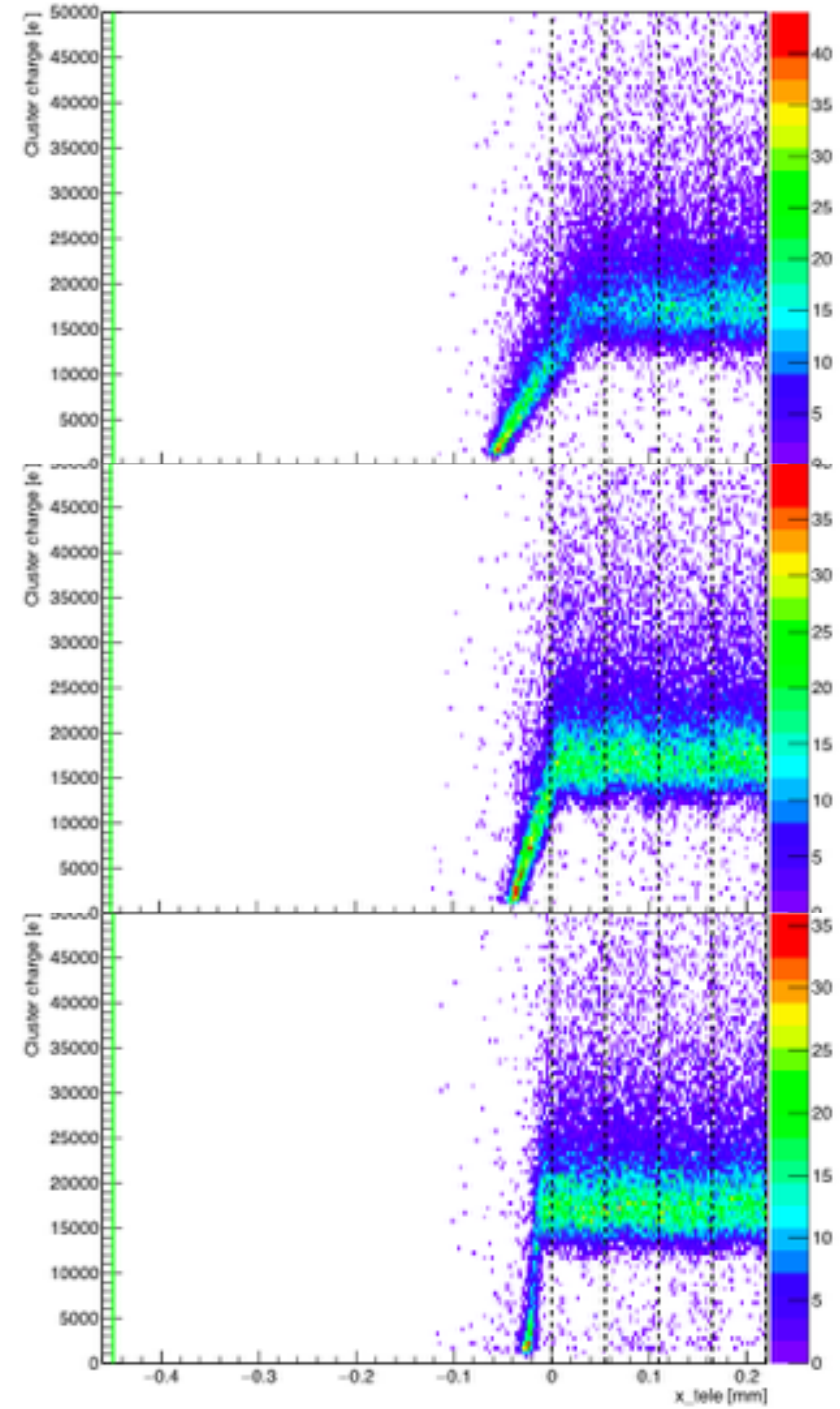


Micron 200V (n-on-n)



Charge Collection Region

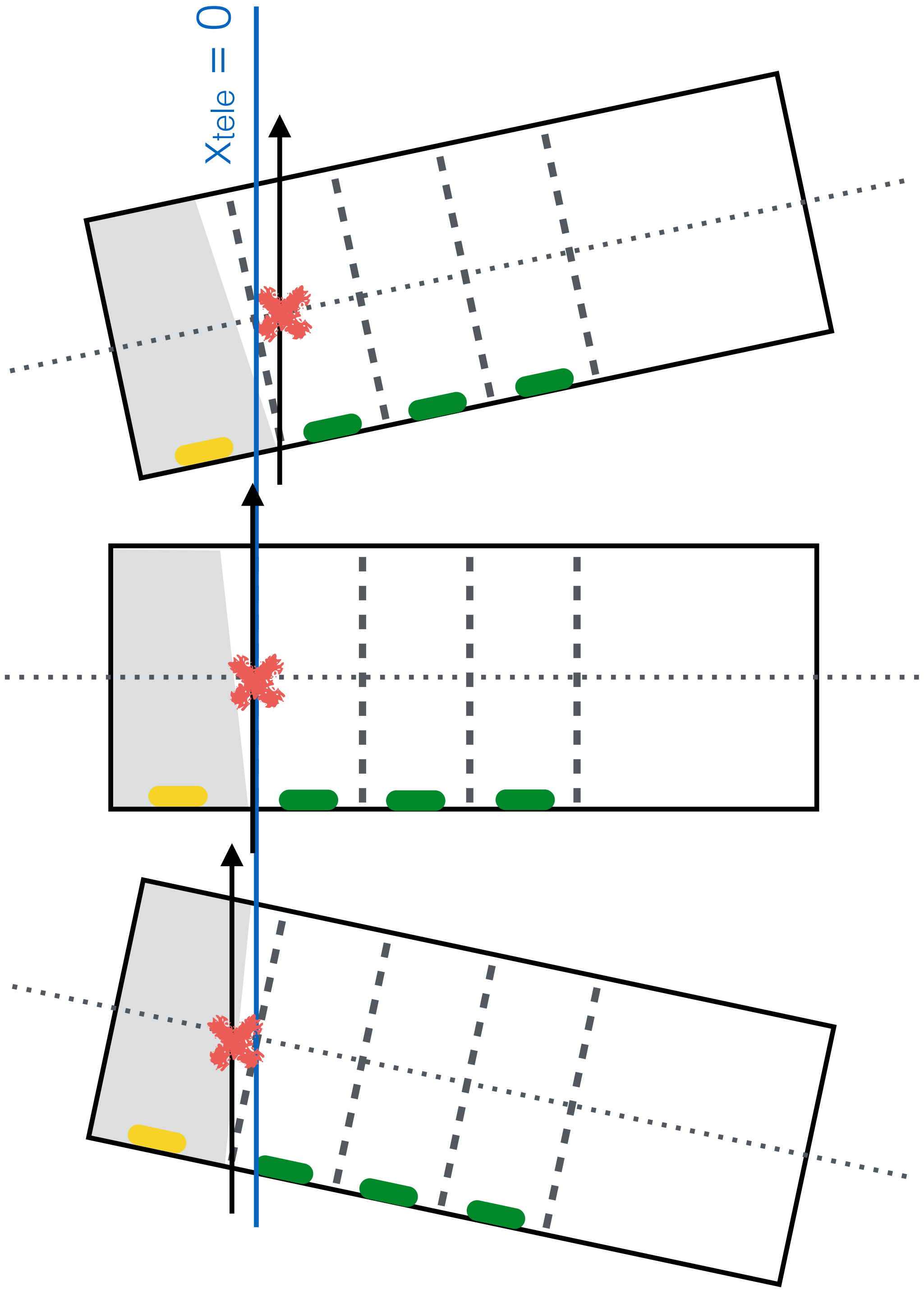


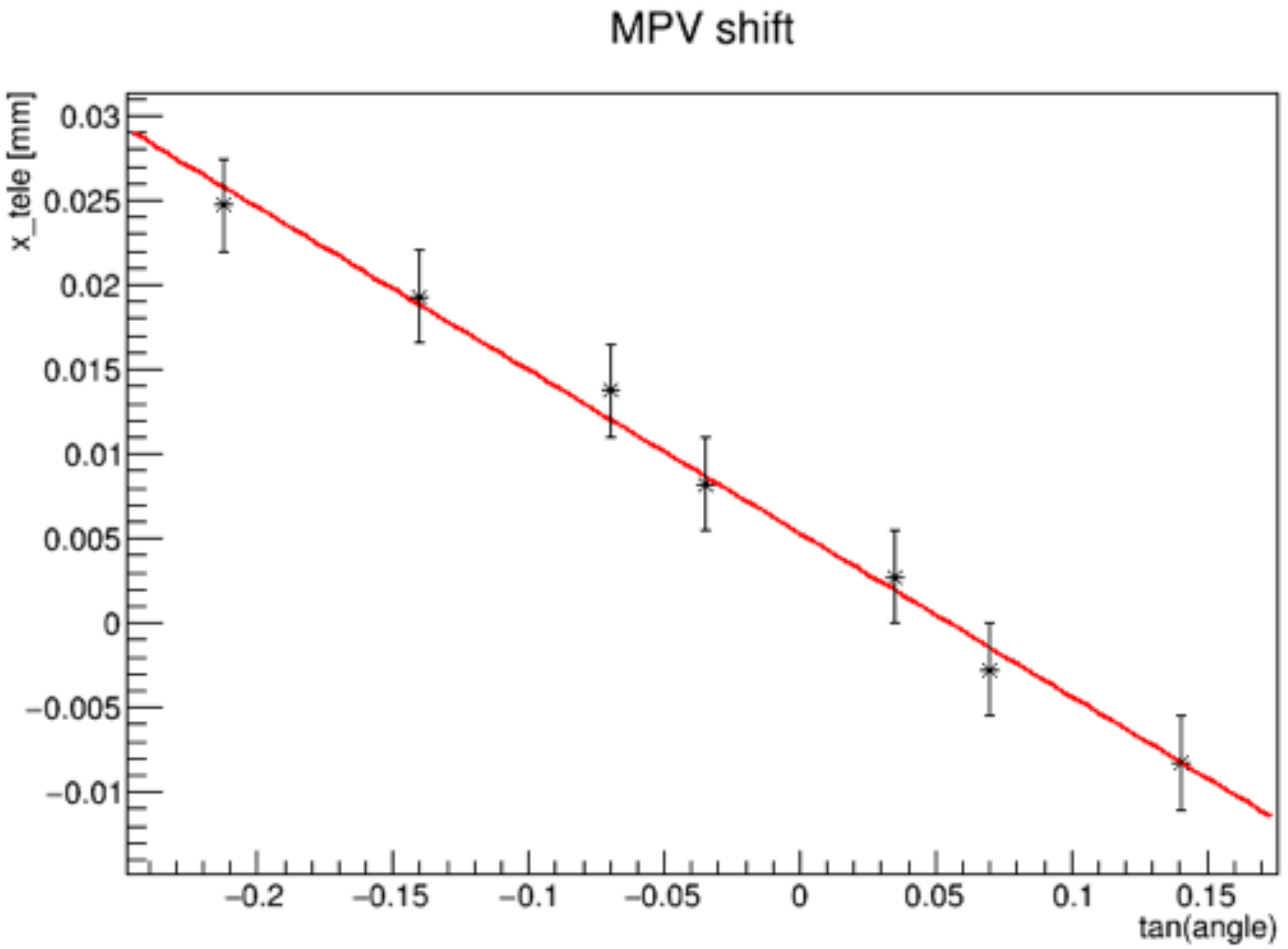


The angle runs allow to understand that the charge distribution is due to a tilted collection region

Charge Collection Region

Micron n-on-p

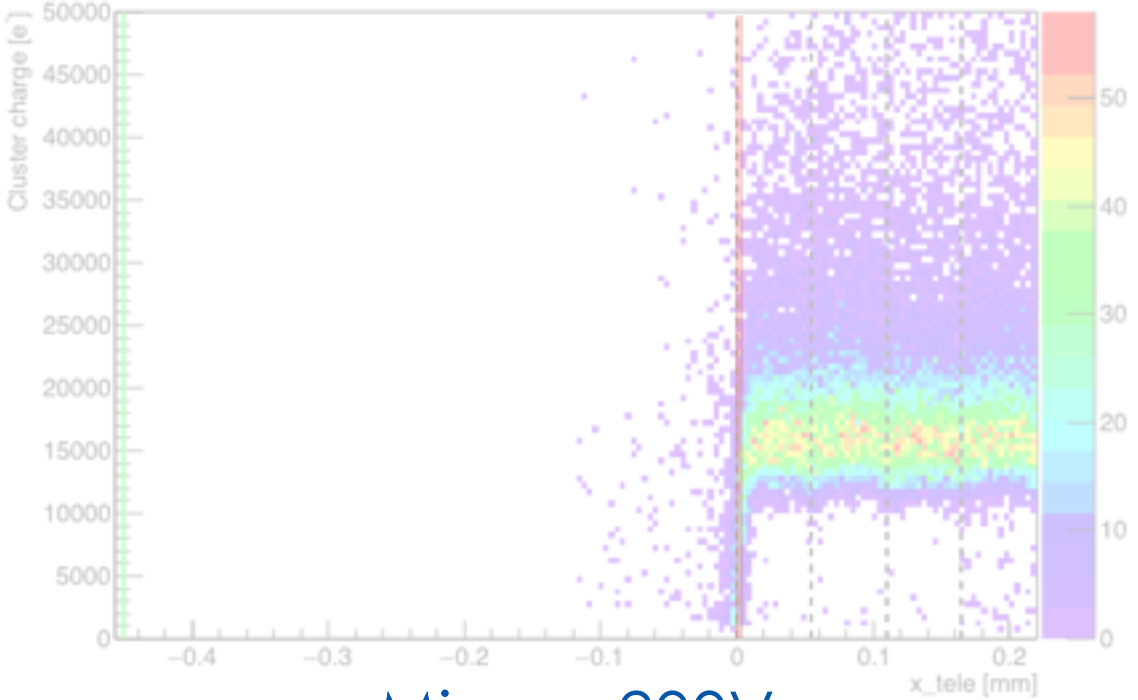




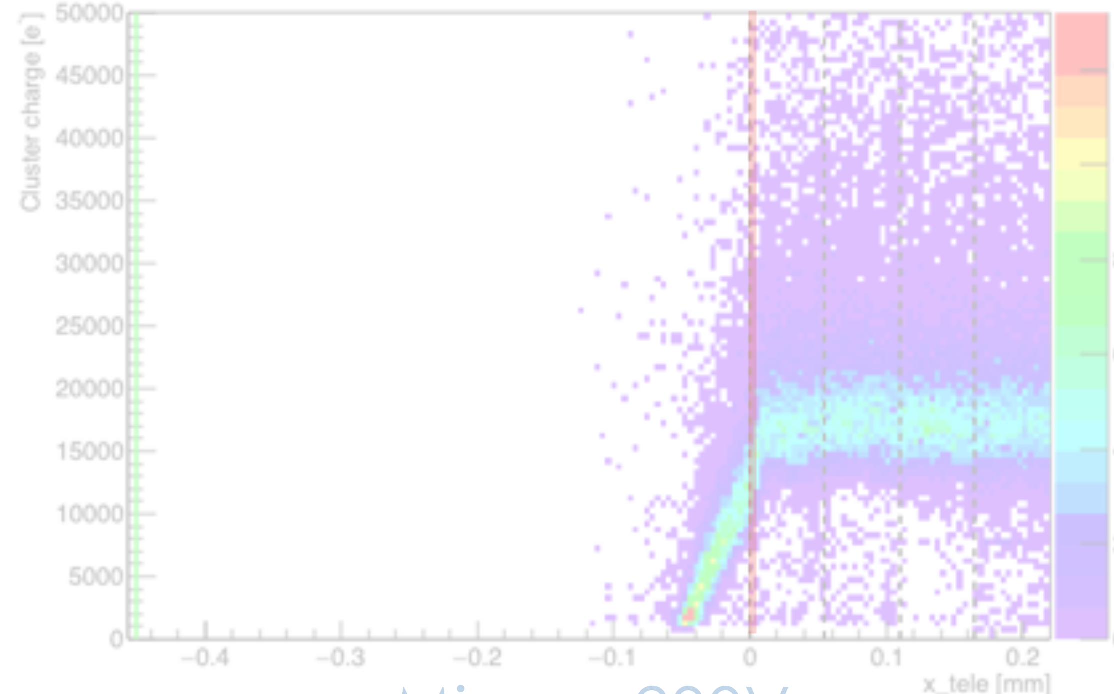
The slope indicates that an excess of charge occurs at the backplane side

Charge Distributions

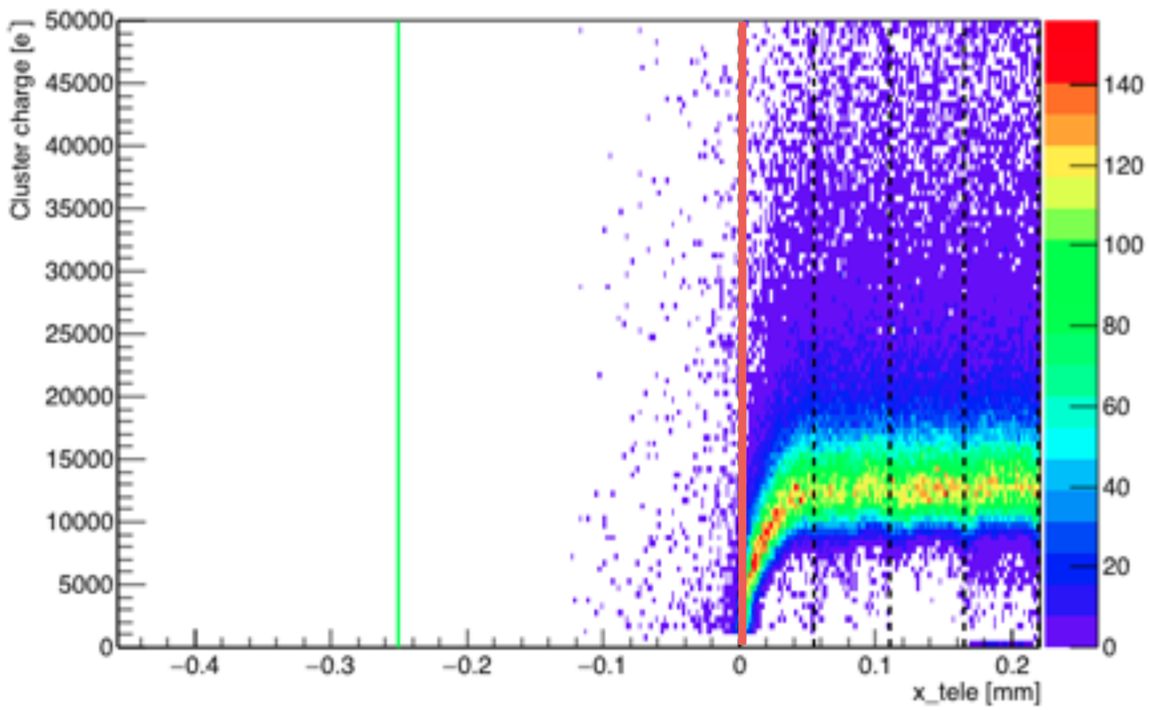
HPK



Micron 200V



Micron 200V
(n-on-n)



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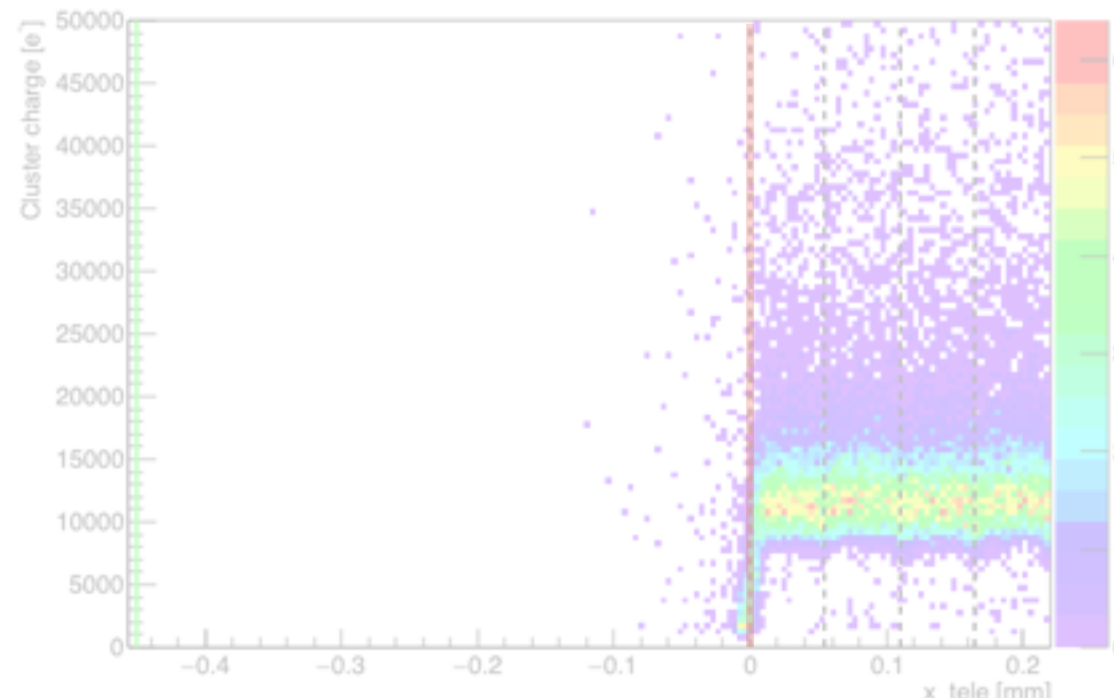
(n-on-n)



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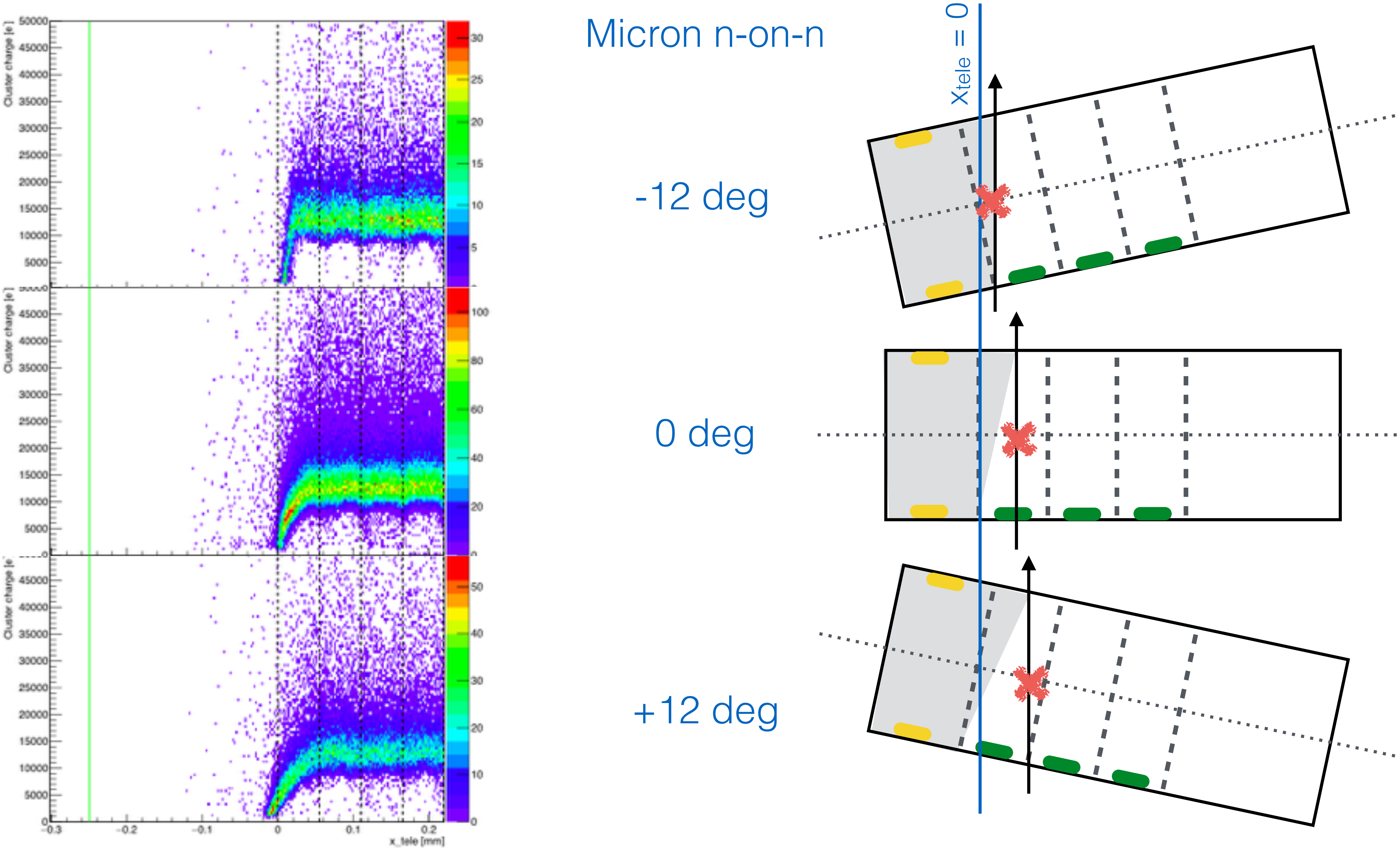

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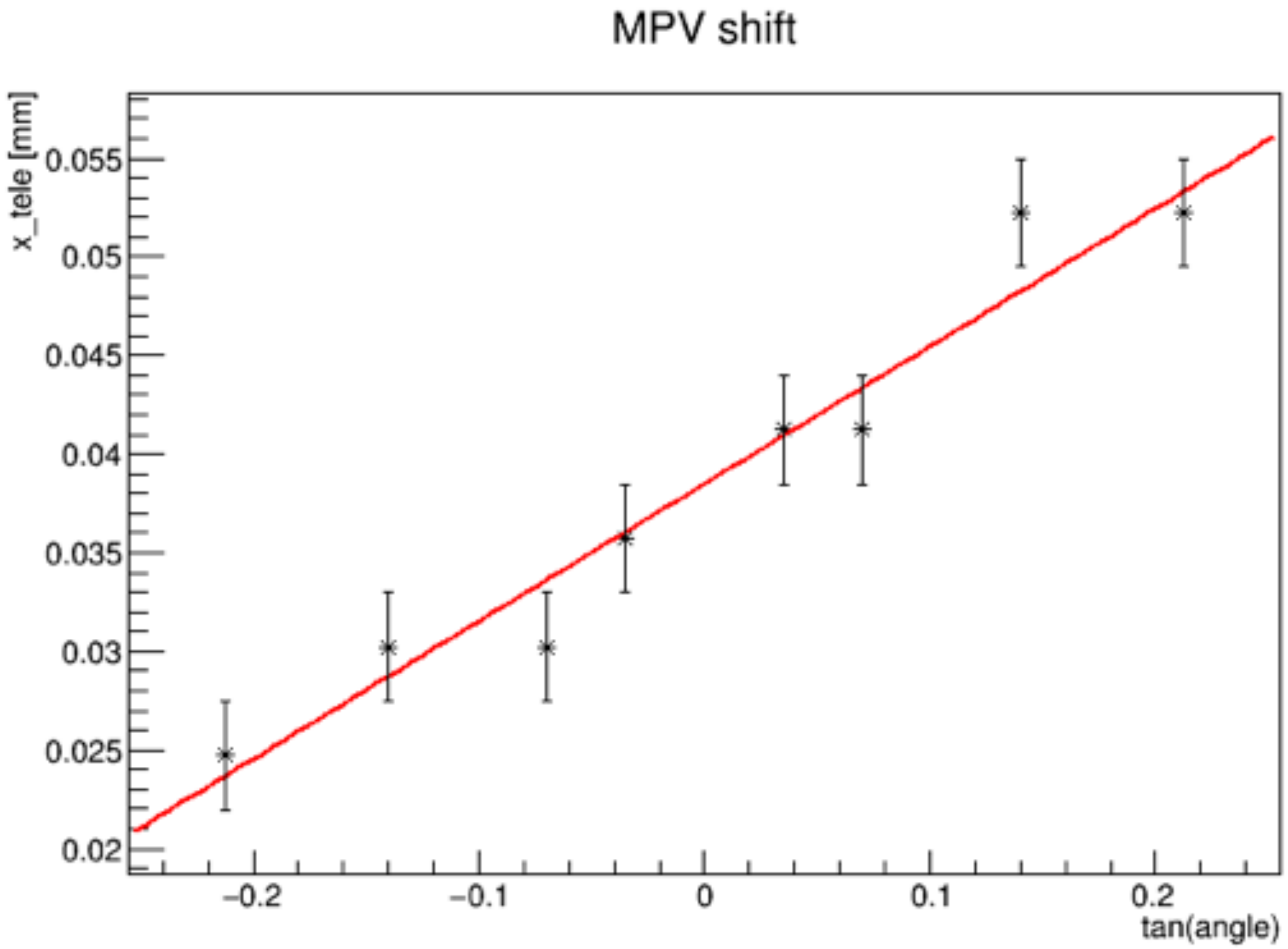
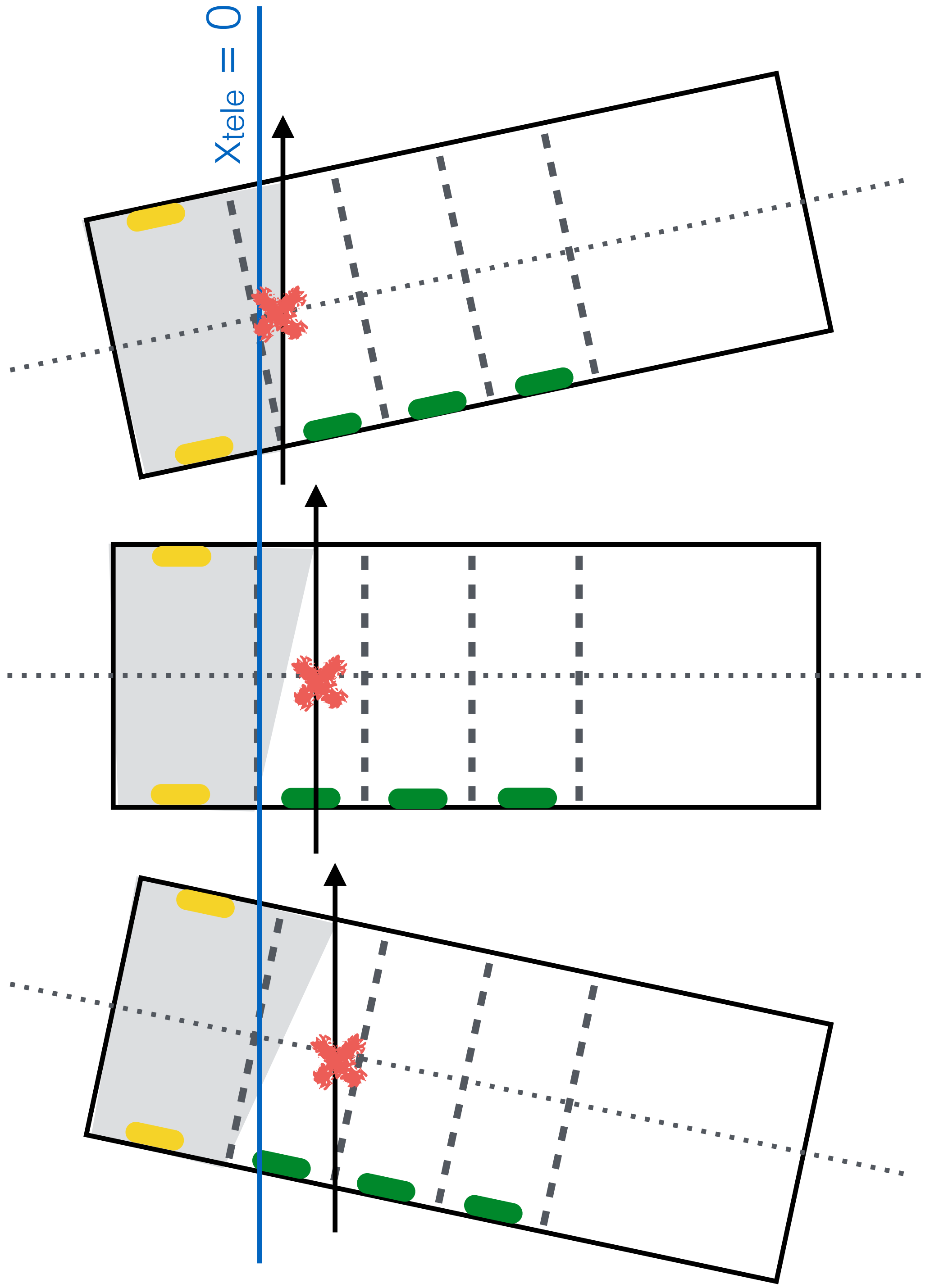
Charge Collection Region

Micron n-on-n



The slope indicates that a loss of charge occurs at the backplane side



Future Plans

- Challenging requirements on sensor: high fluence and non homogeneous irradiation
- The Timepix3 Telescope allowed to test beautifully all the sensor designs we have, before and after irradiation (of different type and dose)
- We investigated many different aspects of the sensors: some designs show already good results
- New prototypes requested with small change in sensor dimensions: expected in August
- In Summer we will test the prototype of final design!

VeloPix vs Timepix3

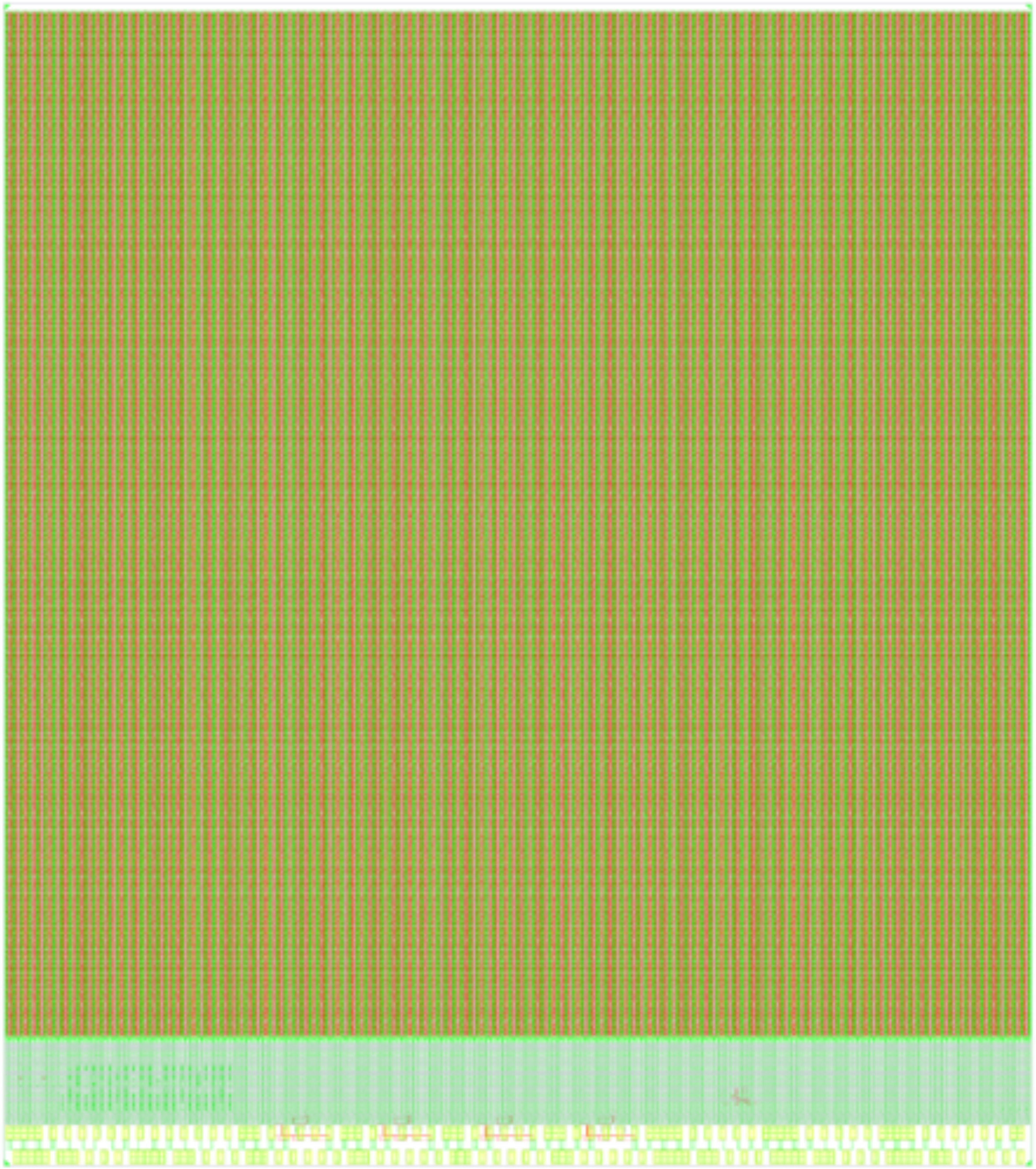
	Timepix3	VeloPix
Readout Type	continuous, triggerless, ToT	continuous, triggerless, binary
Timing Resolution	1.6 ns	25 ns
Power Consumption	< 1.0 W cm^{-2}	< 1.5 W cm^{-2}
Pixel Matrix, Pixel Size	256 x 256, 55 x 55 μm^2	256 x 256, 55 x 55 μm^2
Radiation Hardness	not specified	400 Mrad, SEU tolerant
Peak Hit Rate	80 Mhits/s/ASIC	900 Mhits/s/ASIC
Sensor Type	various, e- and h+ collection	planar silicon, e- collection
Max Data Rate	5.12 Gbps	20.48 Gbps
Technology	130 nm CMOS	130 nm CMOS

→ radiation hardness

→ increased data rate!

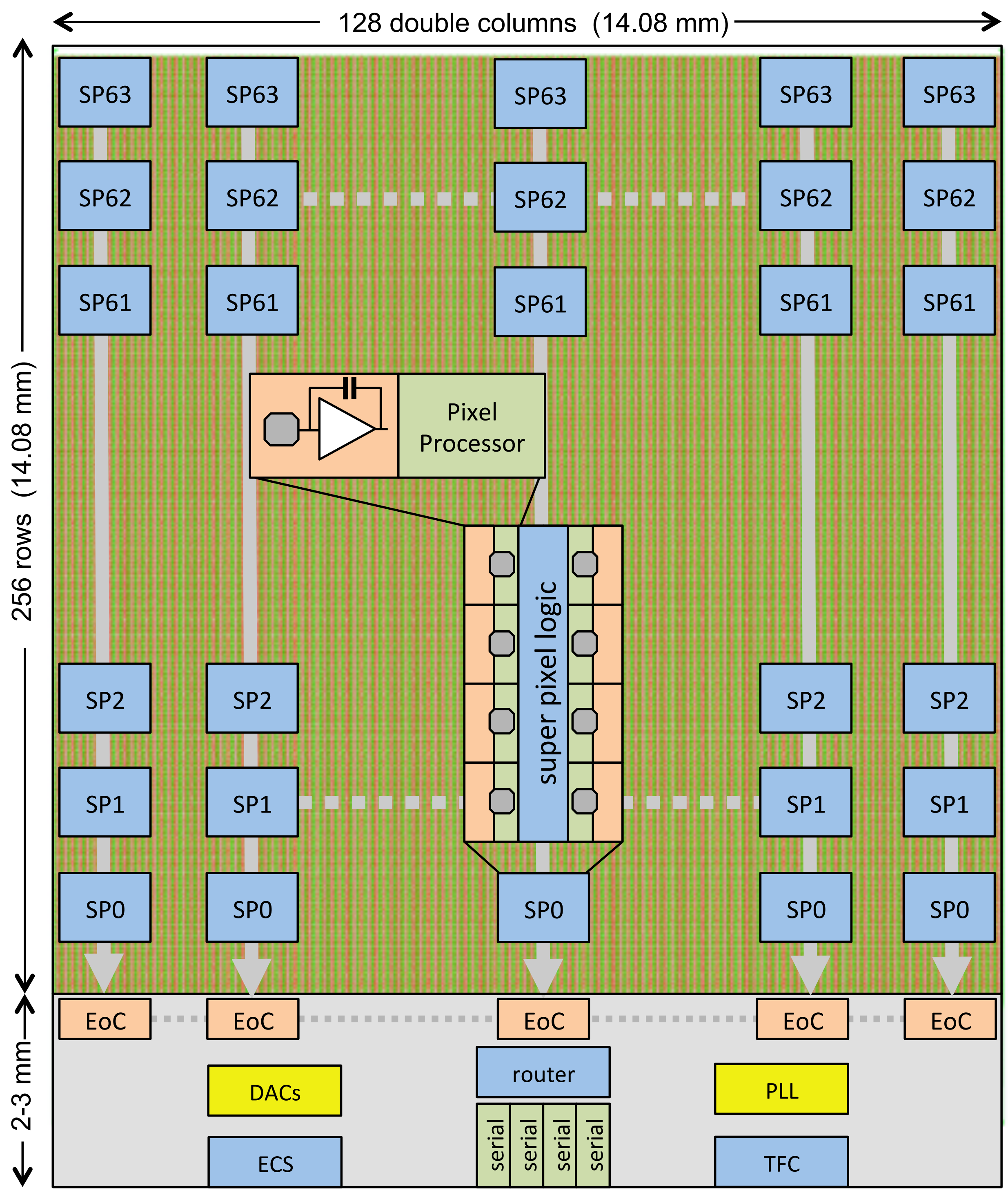
VeloPix Architecture

VeloPix Matrix Layout



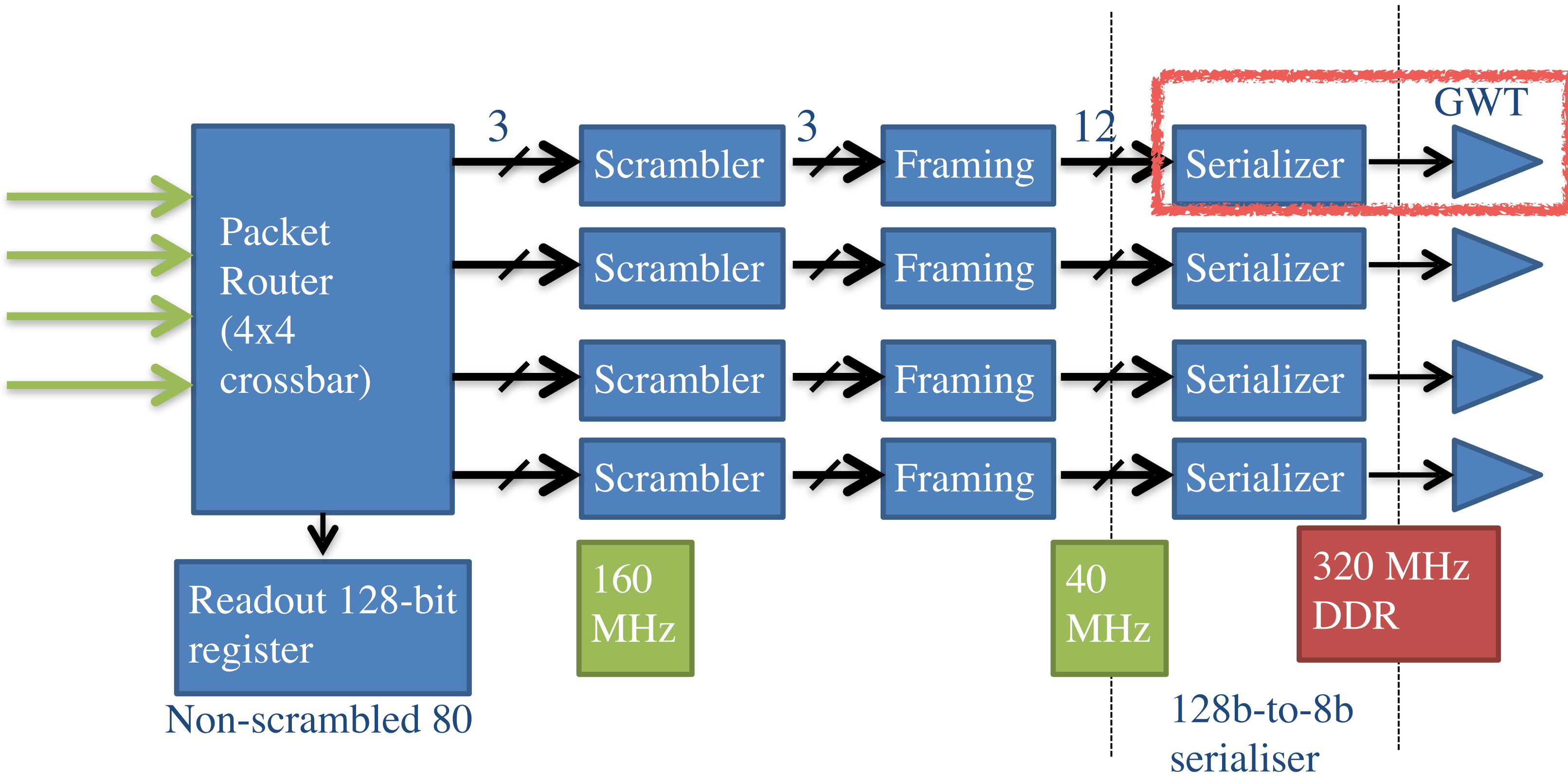
VeloPix Architecture

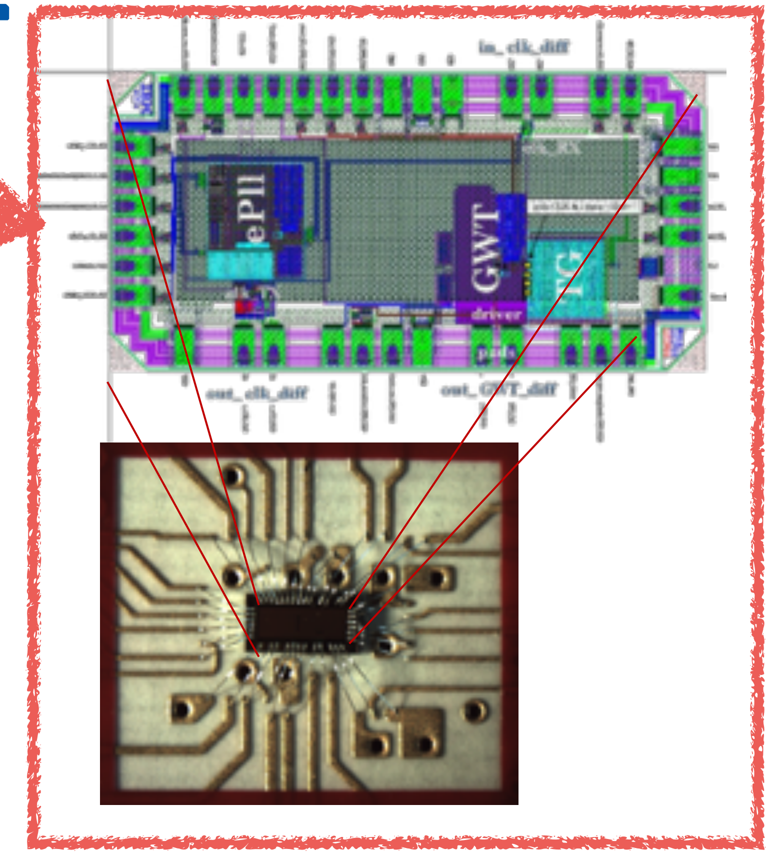
VeloPix Matrix Layout



- Super-pixel packet (2x4 pixels): 30% reduction of the data rate vs single-pixel
- Analog front-end sets 2 thresholds (chip-wide and trim DAC) + digital threshold on hit charge
- Data gathered column wise in the EoC logic
- Data from EoC routed to 4 output serialisers

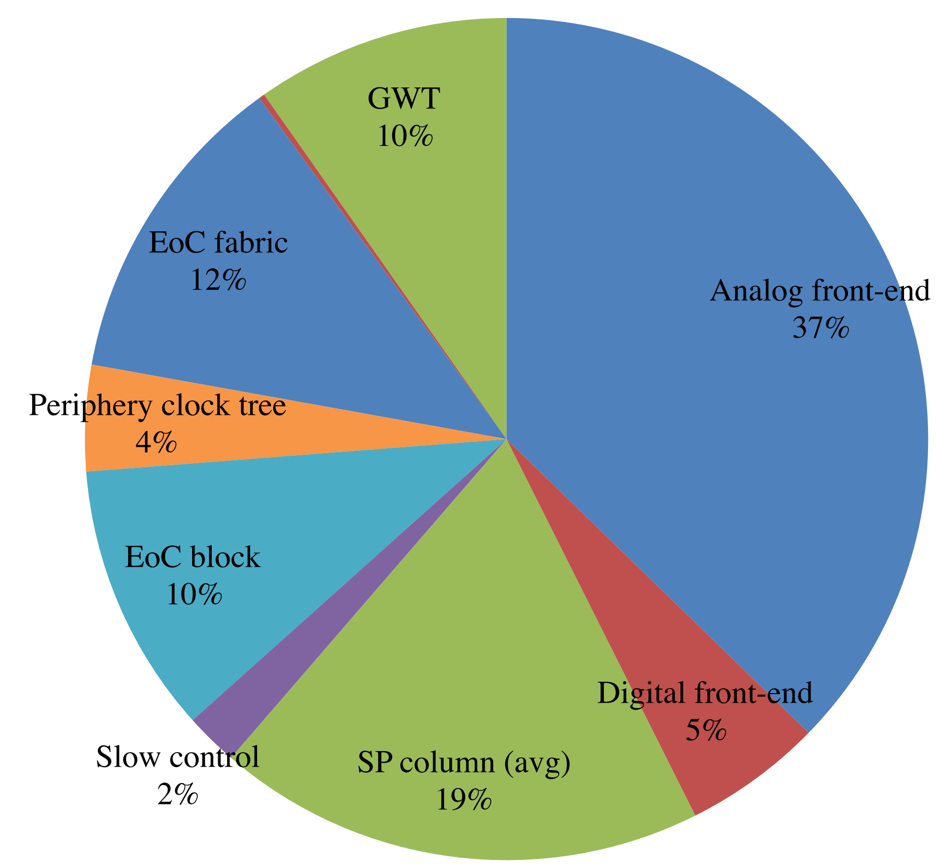
Output Logic





GWT: Gbps data serialiser and Wireline Transmitter

- 5.12 Gbps serialiser in 130 nm technology
- low power consumption: serialiser 15 mW, wireline driver 45 mW
- 4 GWT units on each VeloPix contributing only 10% to the chip power budget



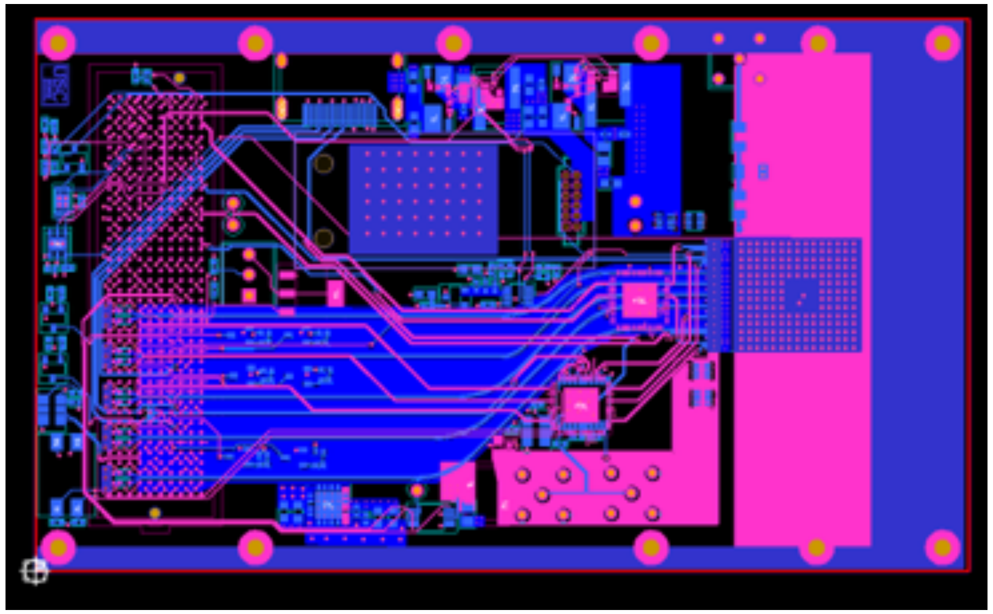
VeloPix Status

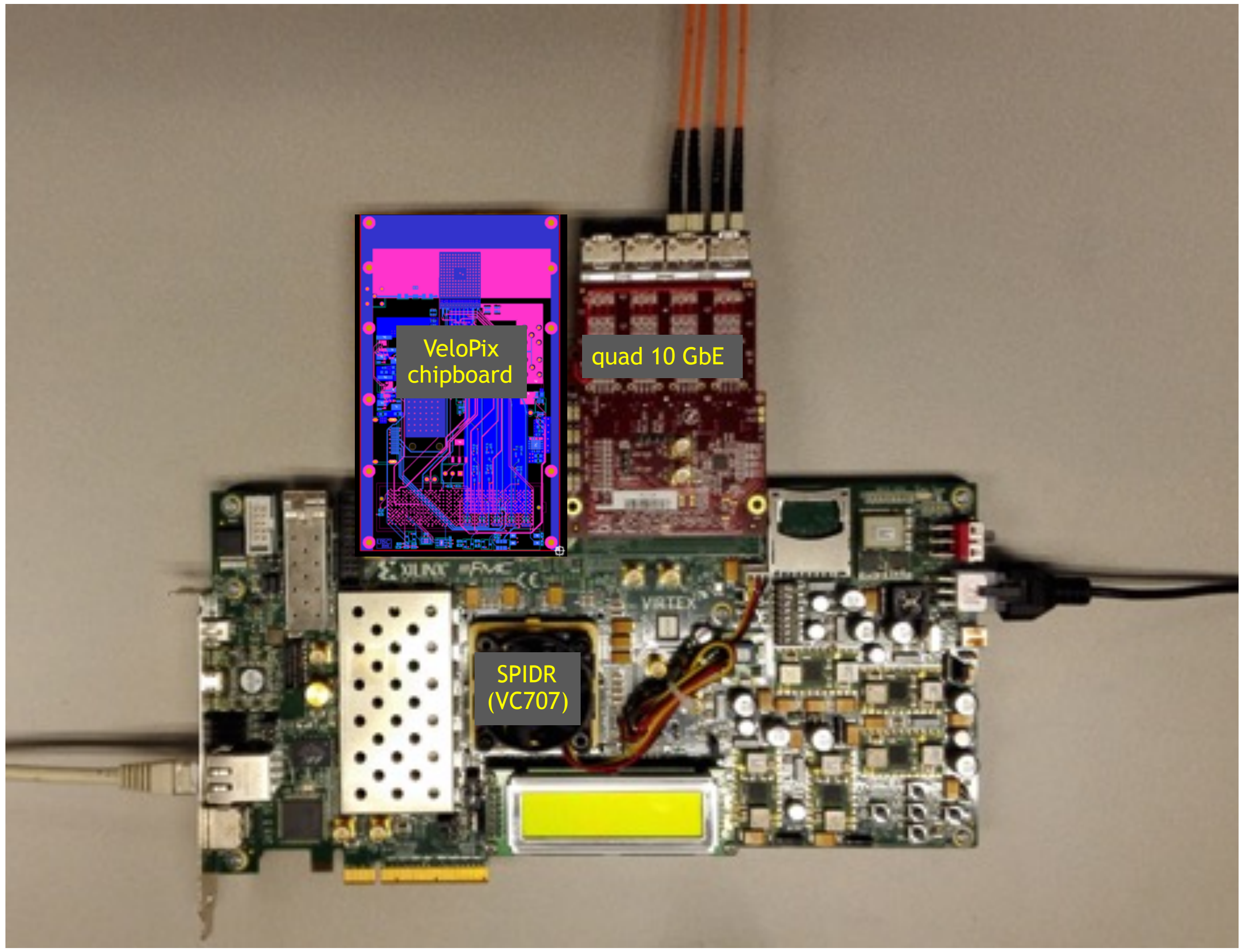
- All basic building blocks are ready and where possible already in execution design rule checks: submission at the end of April (the goal is one submission only!)
- The engineering run will take 6 weeks
- 6 wafers back mid-June
- Next tests done in parallel: bench tests will require a couple of months
- When ready from Advacam (VeloPix bump bonded to the sensor), the assemblies will be tested in the testbeam: aiming at August
- At the end of the year will start the production

VeloPix Test Setup

- SPIDR based system dedicated for VeloPix testing
- worked very well for Timepix3 testing
- chipboard already sent for production → expected soon!

VeloPix Chipboard





Summary

Sensor:

- very good results so far!
- new prototype sensors expected for the August testbeam

VeloPix:

- submission at the end of the month
- preparation of setup to test the VeloPix in progress
- planned parallel bench tests to save time

Sensor + VeloPix:

- testbeam in August, or at the latest in November

Back Up

Why closer to the beam?

Tracks originating from secondary vertices with large impact parameters are the principal signature of beauty and charm hadrons in LHCb

↓

performance of the detector evaluated in terms of impact parameter resolution

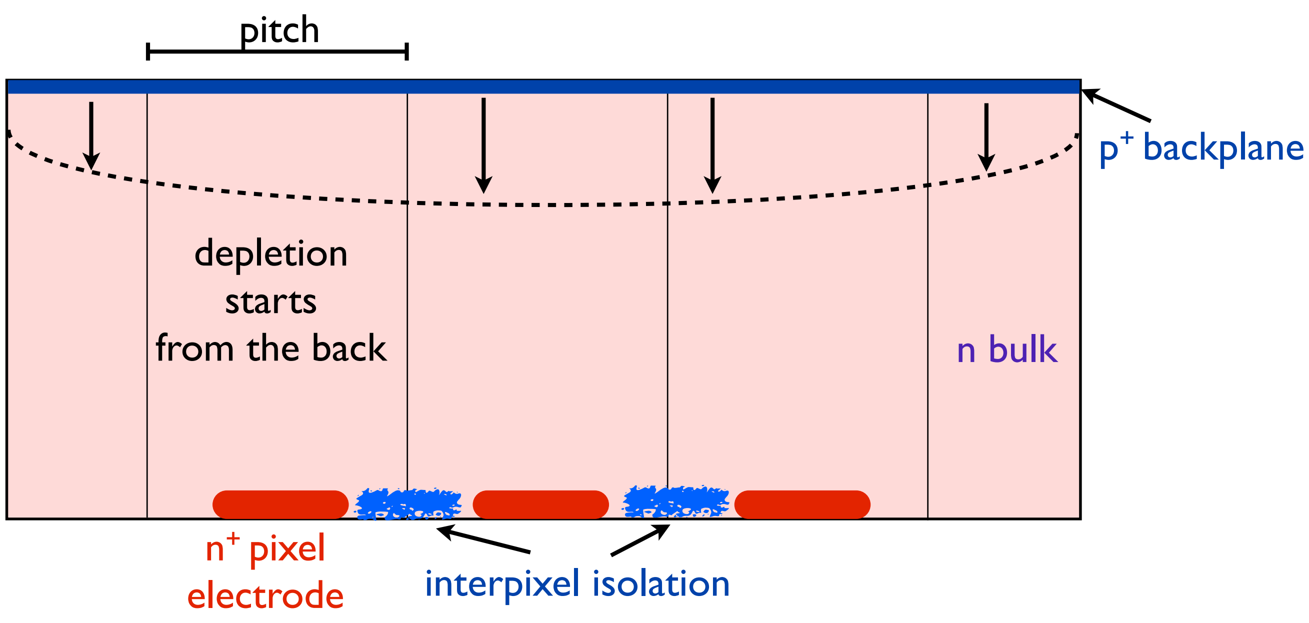
$$\sigma_{\mathrm{IP}}^2 = \frac{r_1^2}{{p_{\mathrm{T}}}^2}\left(0.0136\ \mathrm{GeV}/c\ \sqrt{\frac{x}{X_0}}\left(1 + 0.038\ \ln\left(\frac{x}{X_0}\right)\right)\right)^2 + \frac{\Delta_{02}^2\sigma_1^2 + \Delta_{01}^2\sigma_2^2}{\Delta_{12}^2}$$

it scales with the radius r_1 of the first measured point on the track

Sensor Types

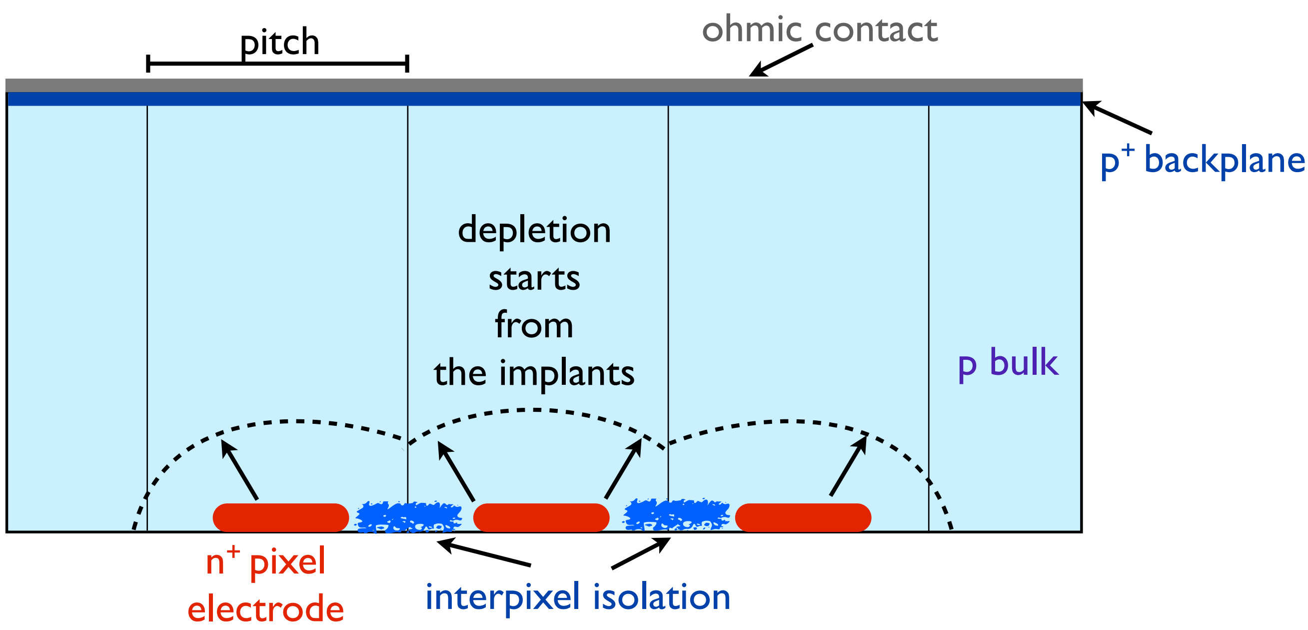
n-on-n

- n^+ pixel electrodes collect e^-
- depletion starts from backplane
- under irradiation: type inversion
  → the sensor turns to n-on-p
- double sided process, but preferred when high irradiation



n-on-p

- n^+ pixel electrodes collect e^-
- depletion starts from pixel side
- under irradiation: increase of the p-type effective doping concentration
- single sided process, therefore easier to realise



Doping Concentration

Non Irradiated

- HPK: 4.5×10^{12} cm^{-3}
- Micron n-on-p: $< 1.2 \times 10^{12}$ cm^{-3}
- Micron n-on-n: $< 1.4 \times 10^{12}$ cm^{-3}

After Irradiation

- effective doping: $N_{eff} \sim 10^{13}$ cm^{-3}

In the LHC Upgrade…

VELO

CMS phase I pixel upgrade

NA62 GTK

SIZE

VELO surface area:
1243 cm^2 , 41M pixels

COOLING

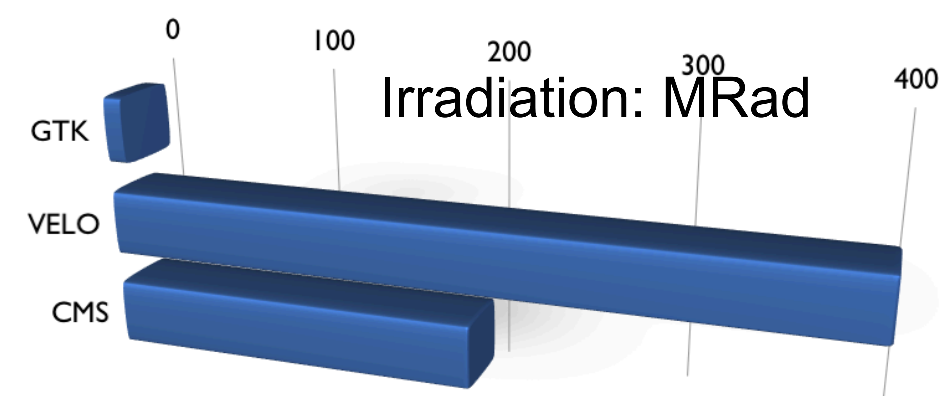
CO_2 for CMS

microchannels
for NA62

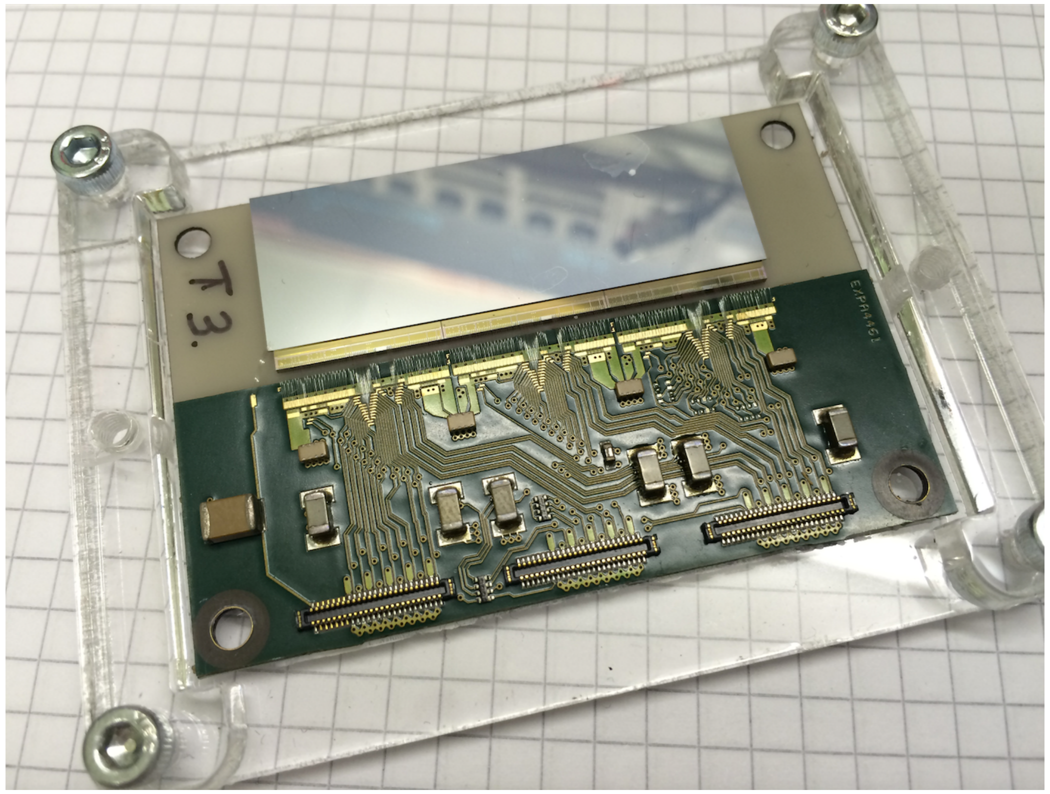
both
for LHCb

IRRADIATION

8×10^{15} n_{eq} cm^{-2} after 50 fb^{-1}



Timepix3



Sensors are tested in combination with Timepix3 ASIC

VeloPix (based on Timepix3) is still under development

Timepix3

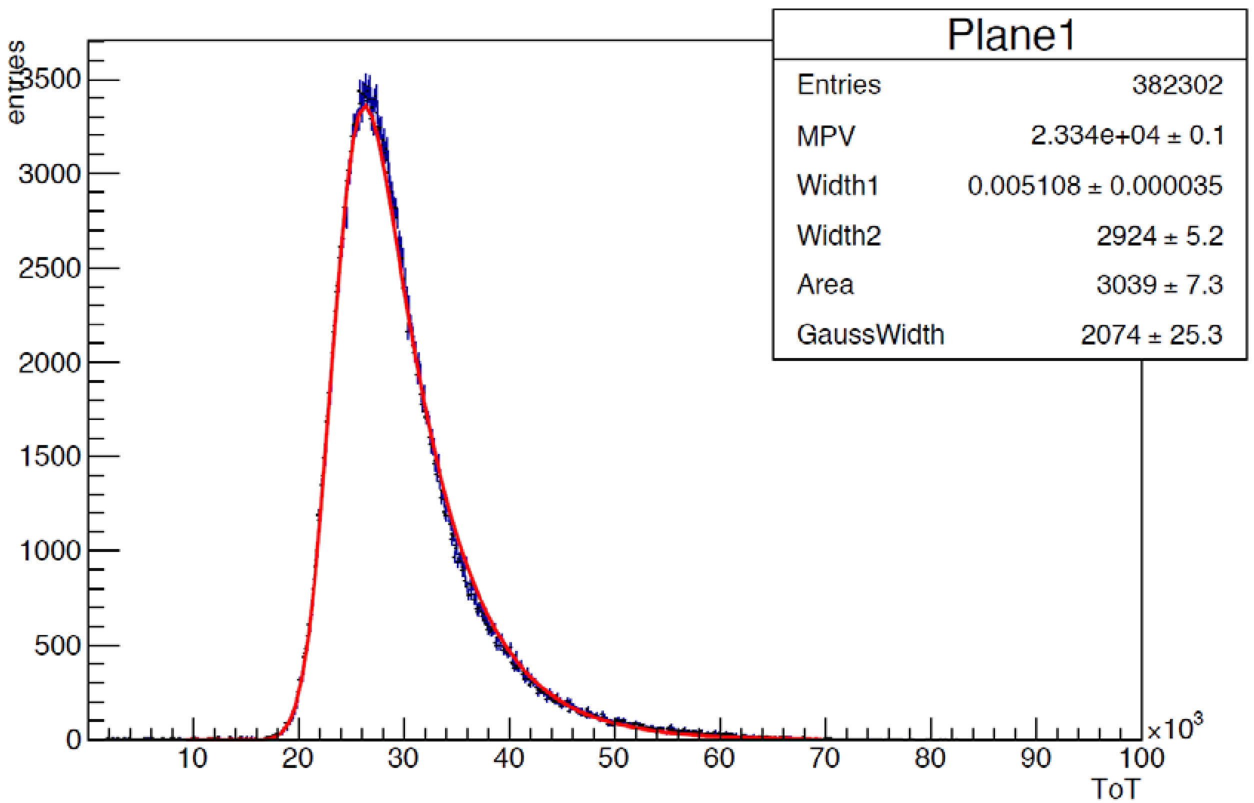
- matrix 256x256 square pixels
- pixel size 55x55 μm^2
- can measure simultaneously ToA and ToT (can be converted to charge)
- gives a timestamp with 1.6 ns accuracy
- calibration with test pulse, crossed checked with radioactive sources

→ this makes Timepix3 ideal for sensor testing!

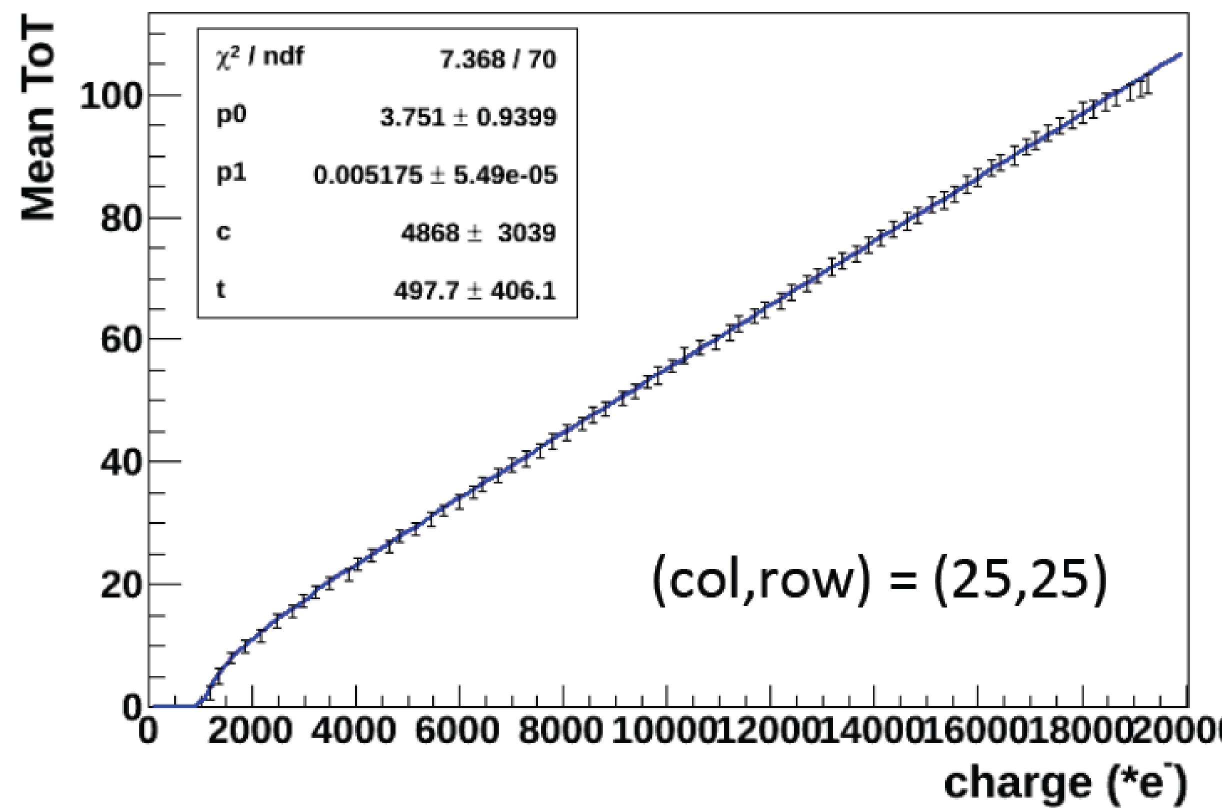
Charge Collection

Timepix3 allows to measure the ToT → we can convert ToT counts in number of electrons via test pulses

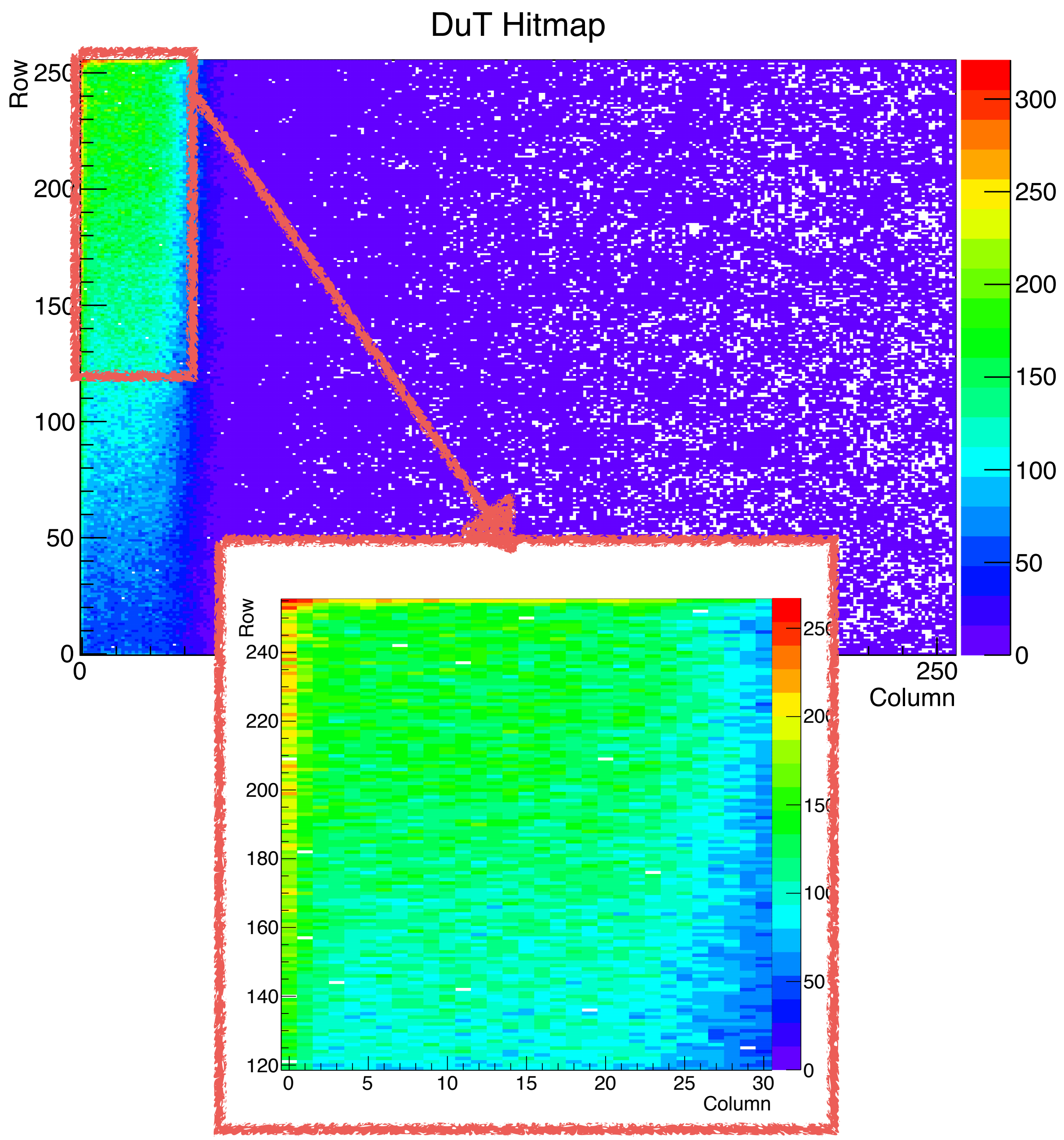
Example of charge collected before calibration

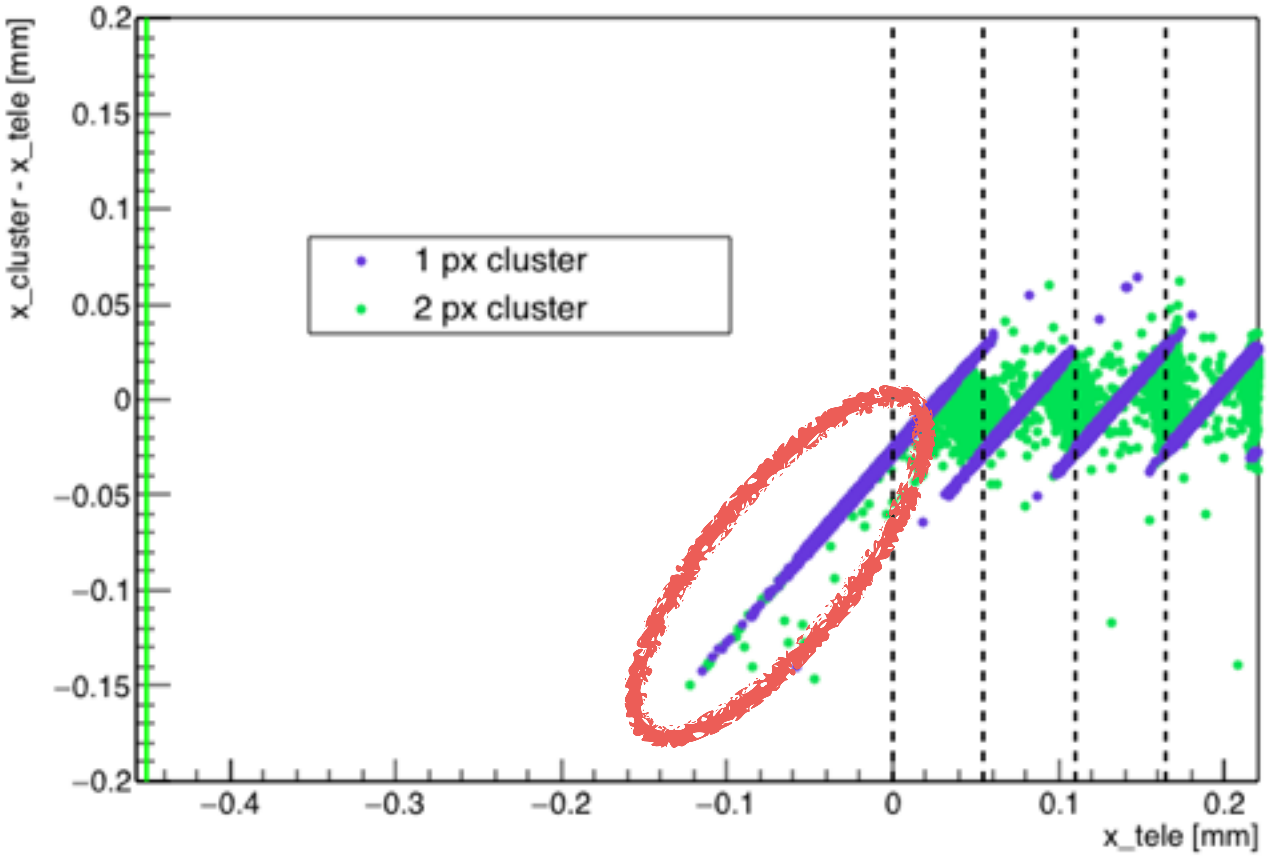


Calibration curve for a single pixel



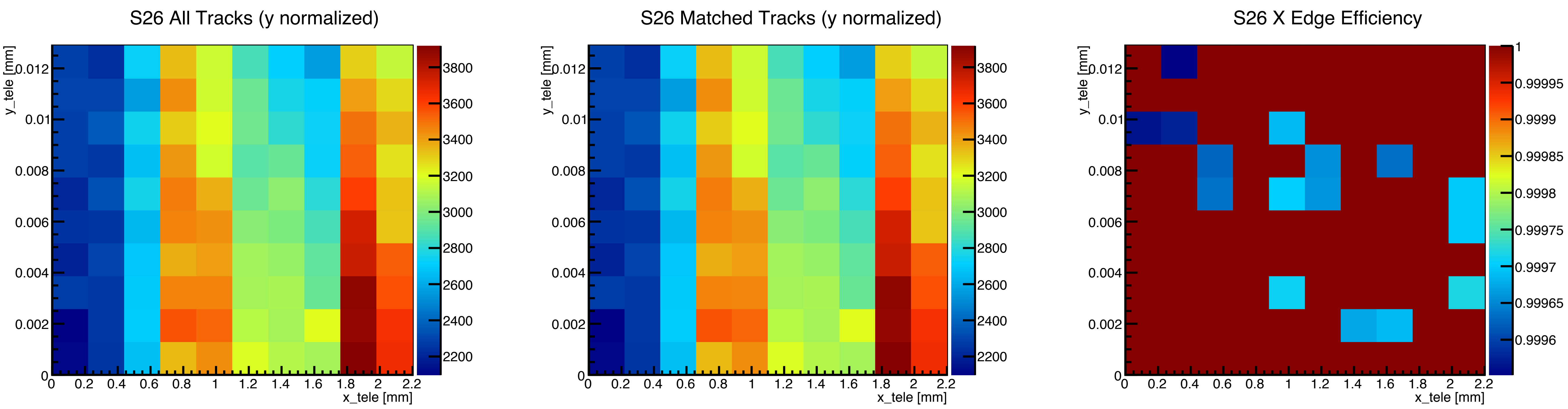
Edge



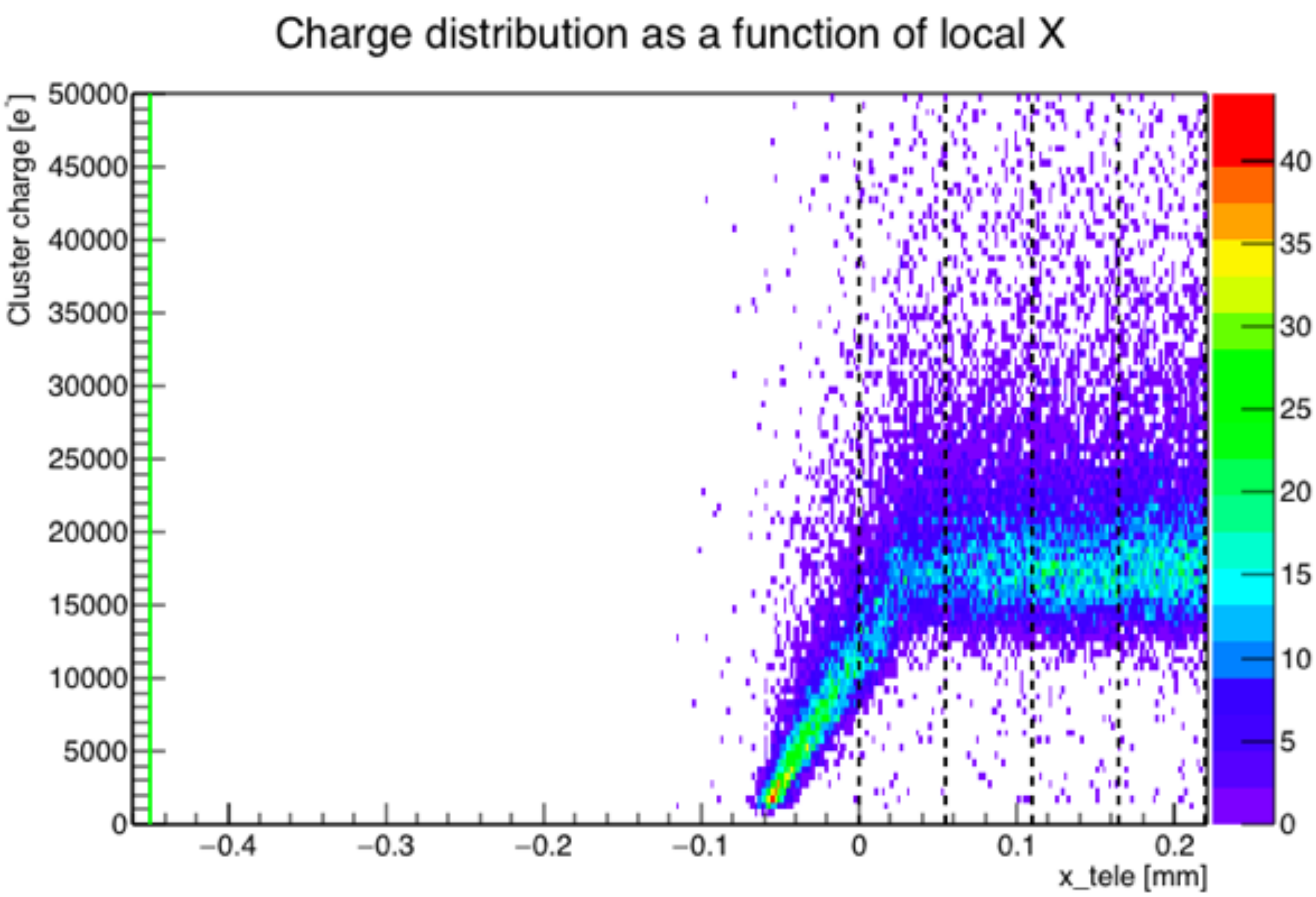


Excess in the first row and column!

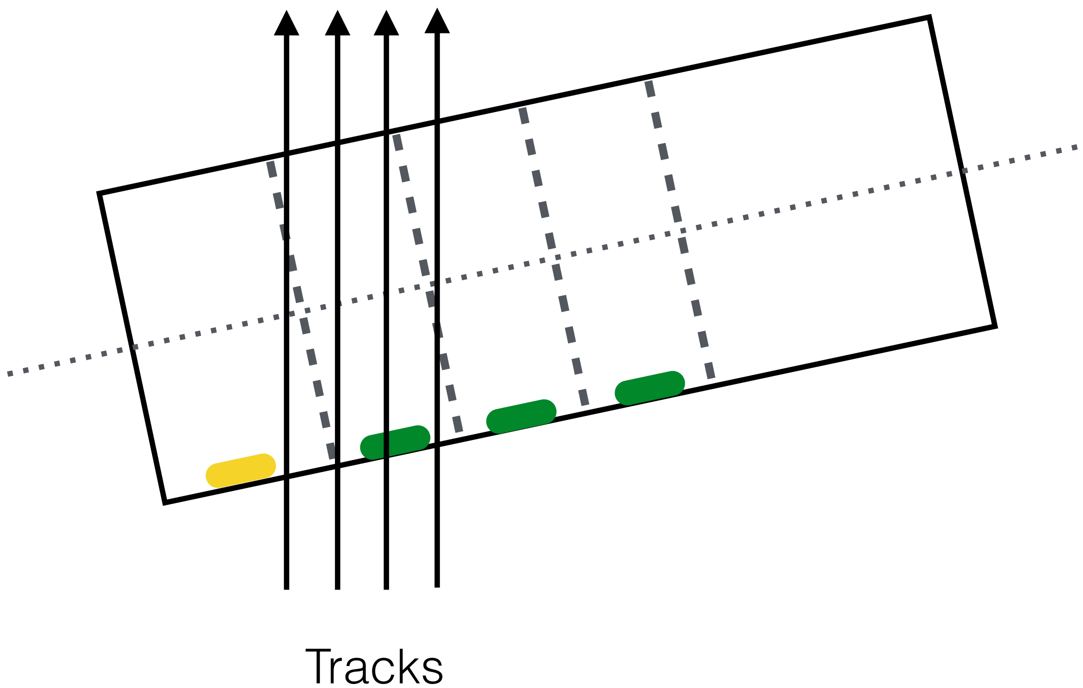
Efficiency at the Edge



Angled runs: S26 (n-on-p)



bias -380 V
angle -12 deg

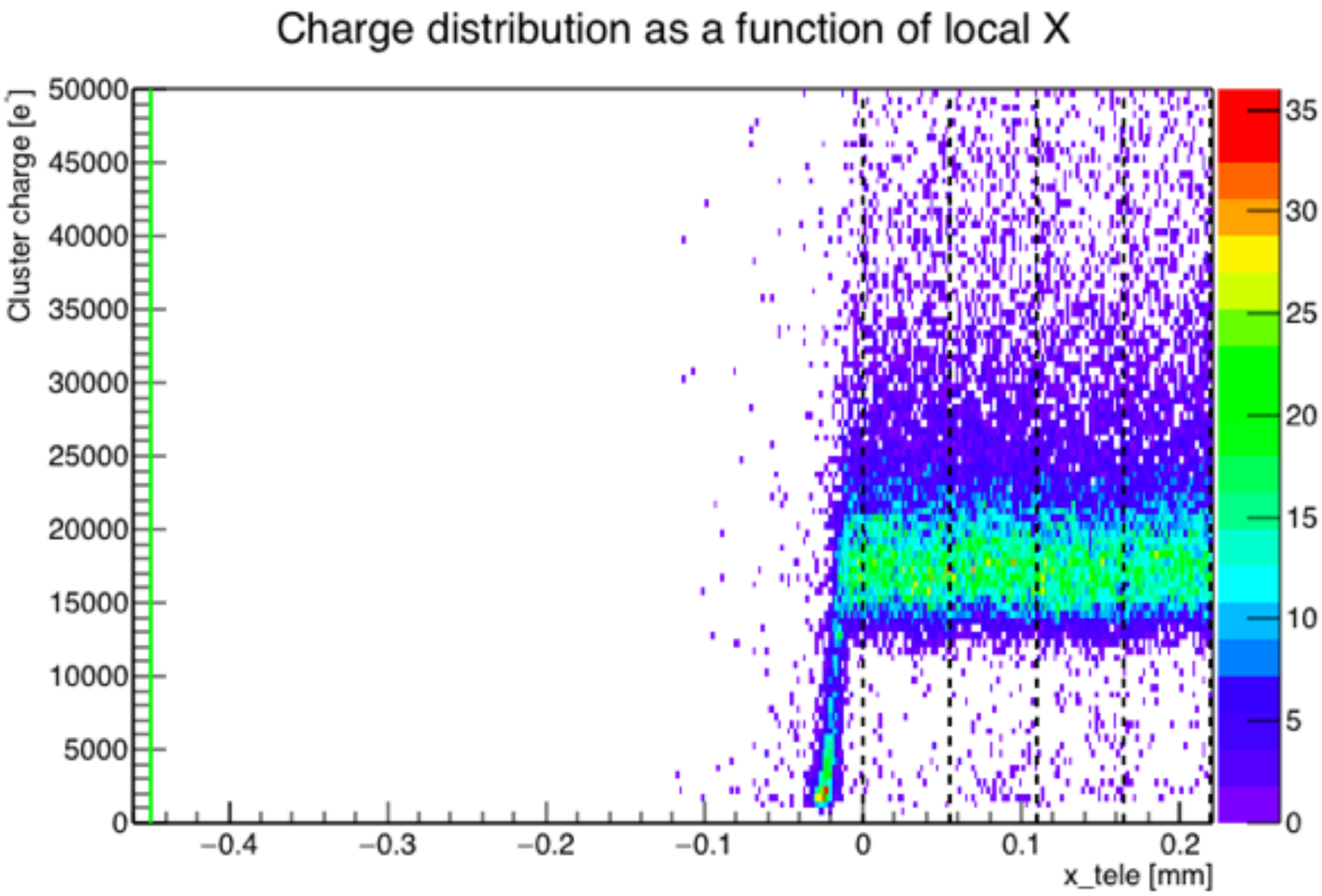


- The point of maximum charge collection moved
- Linear charge deposit still present

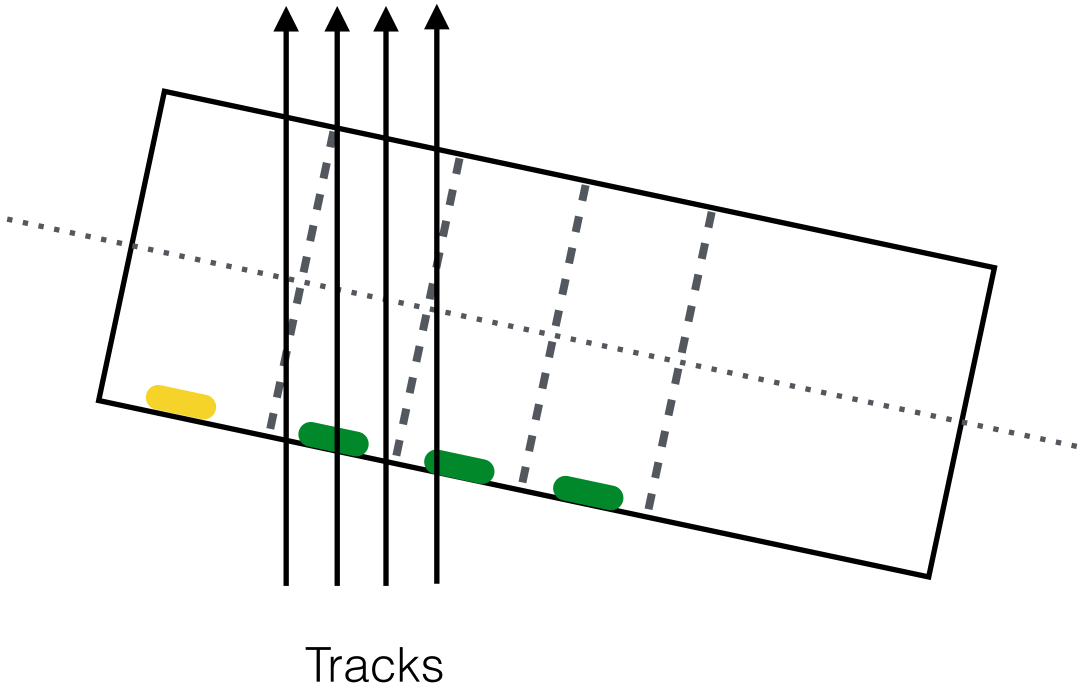
↓

- We gain charge from the front part of the sensor

Angled runs: S26 (n-on-p)



bias -380 V
angle +12 deg

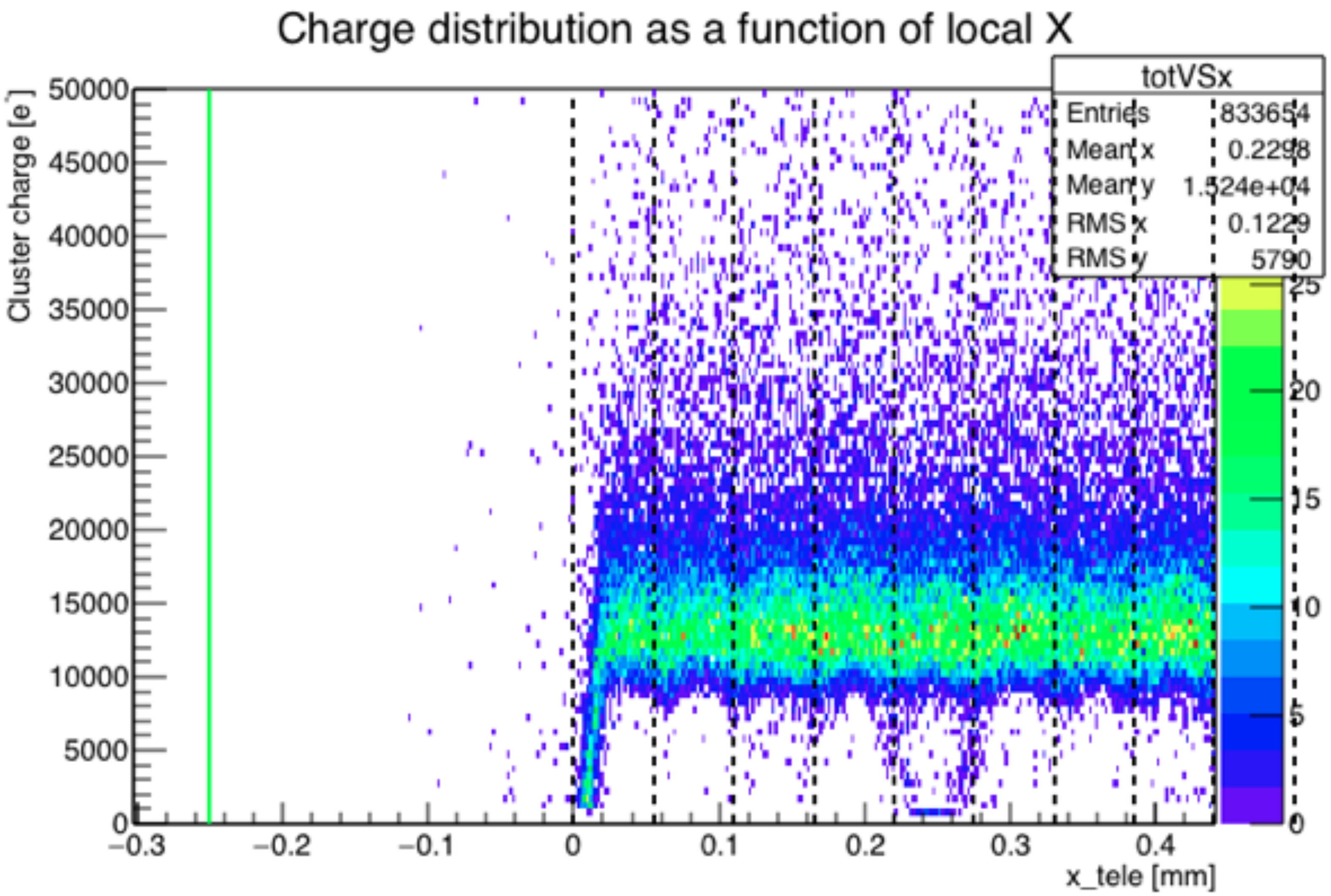


- The point of maximum charge collection moved, in the opposite direction this time
- Linear charge deposit disappears

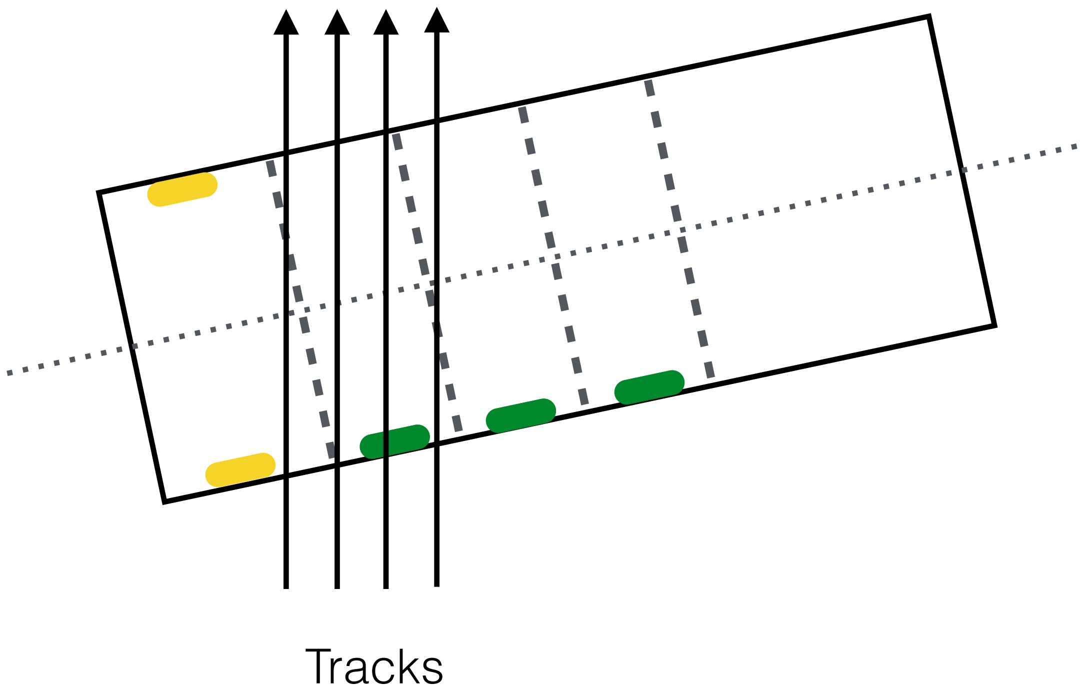
↓

- We gain charge from the front part of the sensor

Angled runs: S33 (n-on-n)



bias -500 V
angle -12 deg

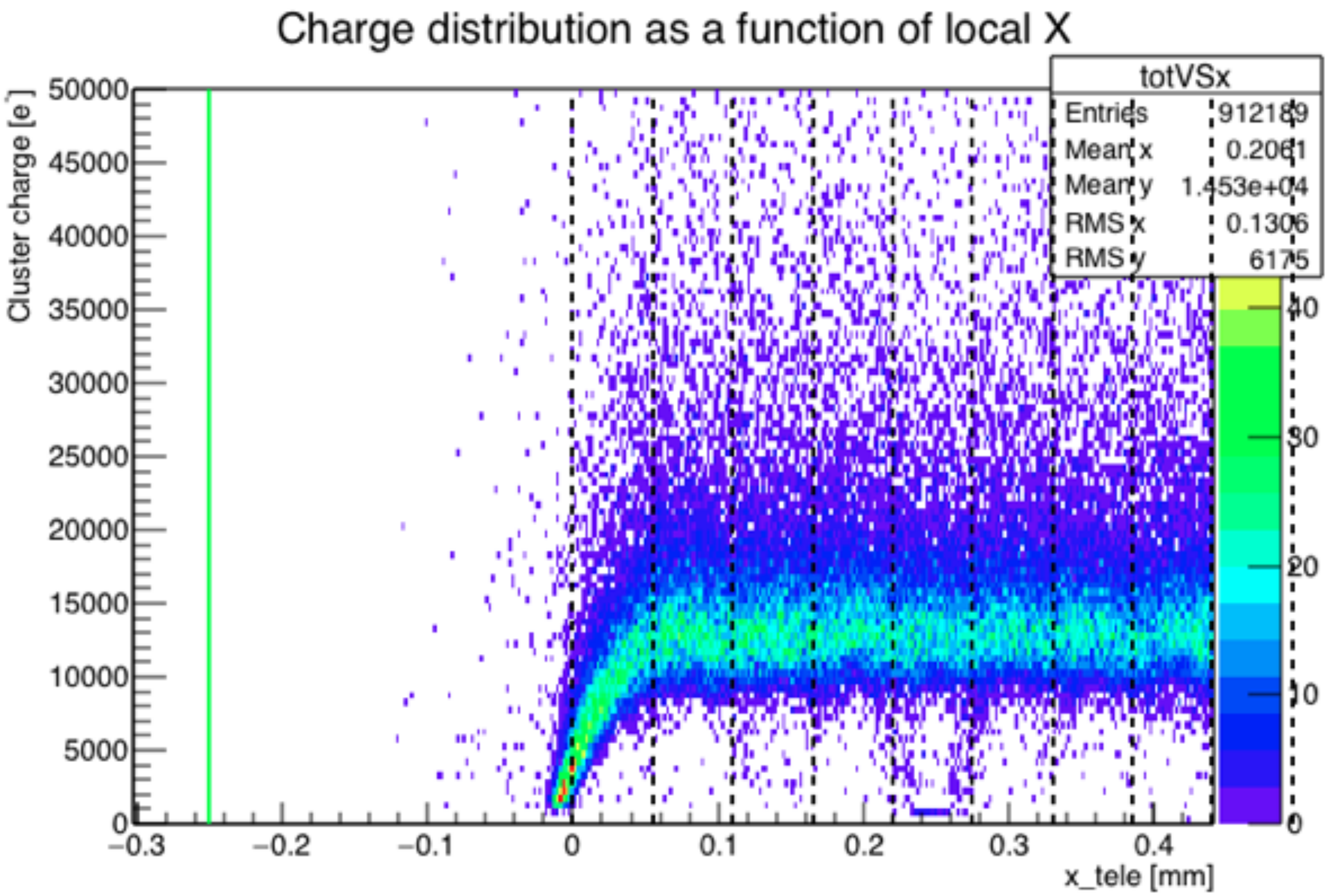


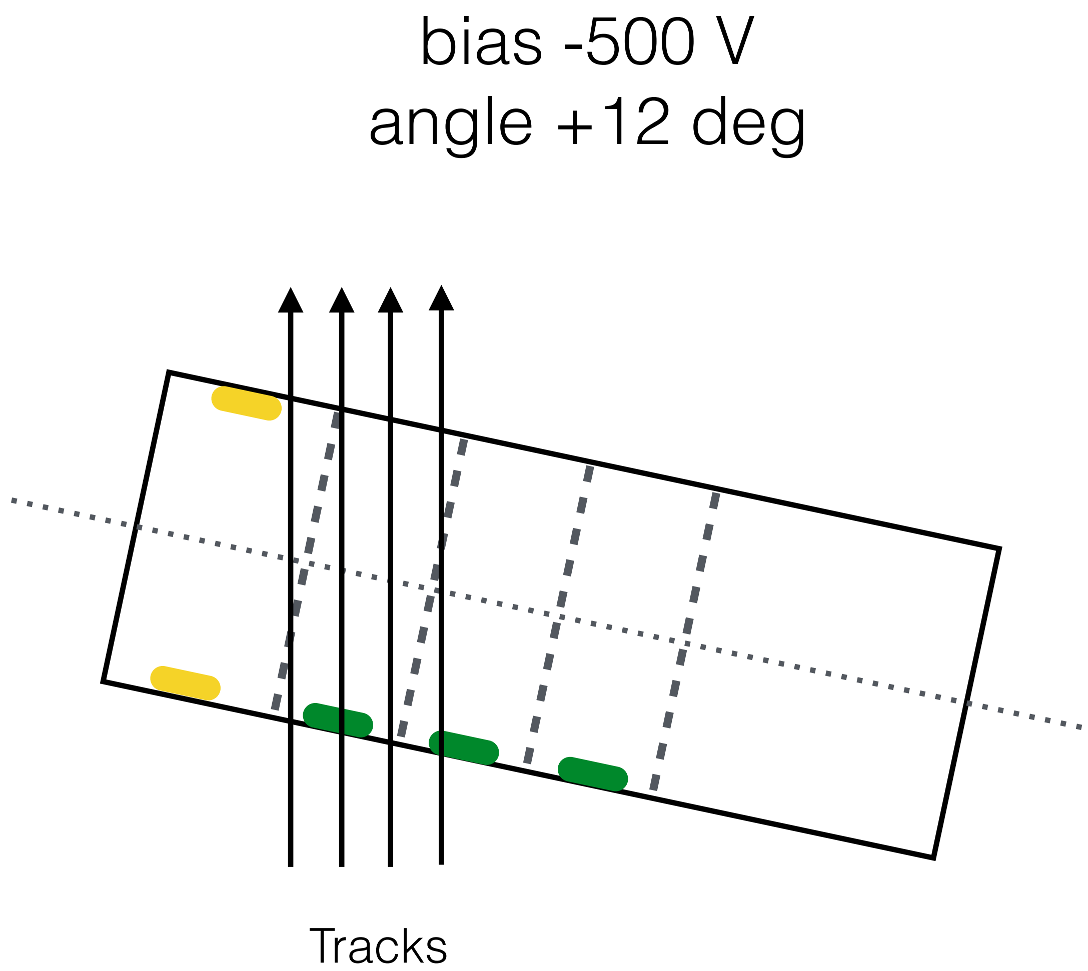
- The point of maximum charge collection moved
- Still some loss in the last pixel, but there is a steep transition within the boundary of the last pixel

↓

- The loss of charge is due to the back part of the sensor

Angled runs: S33 (n-on-n)





- The point of maximum charge collection moved
- The charge loss extends a bit more

↓

- The loss of charge is due to the back part of the sensor