# Performance studies of Inverse Low Gain Avalanche Detectors (i-LGAD) coupled to the Timepix3 ASIC

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https://indico.cern.ch/event/829863/

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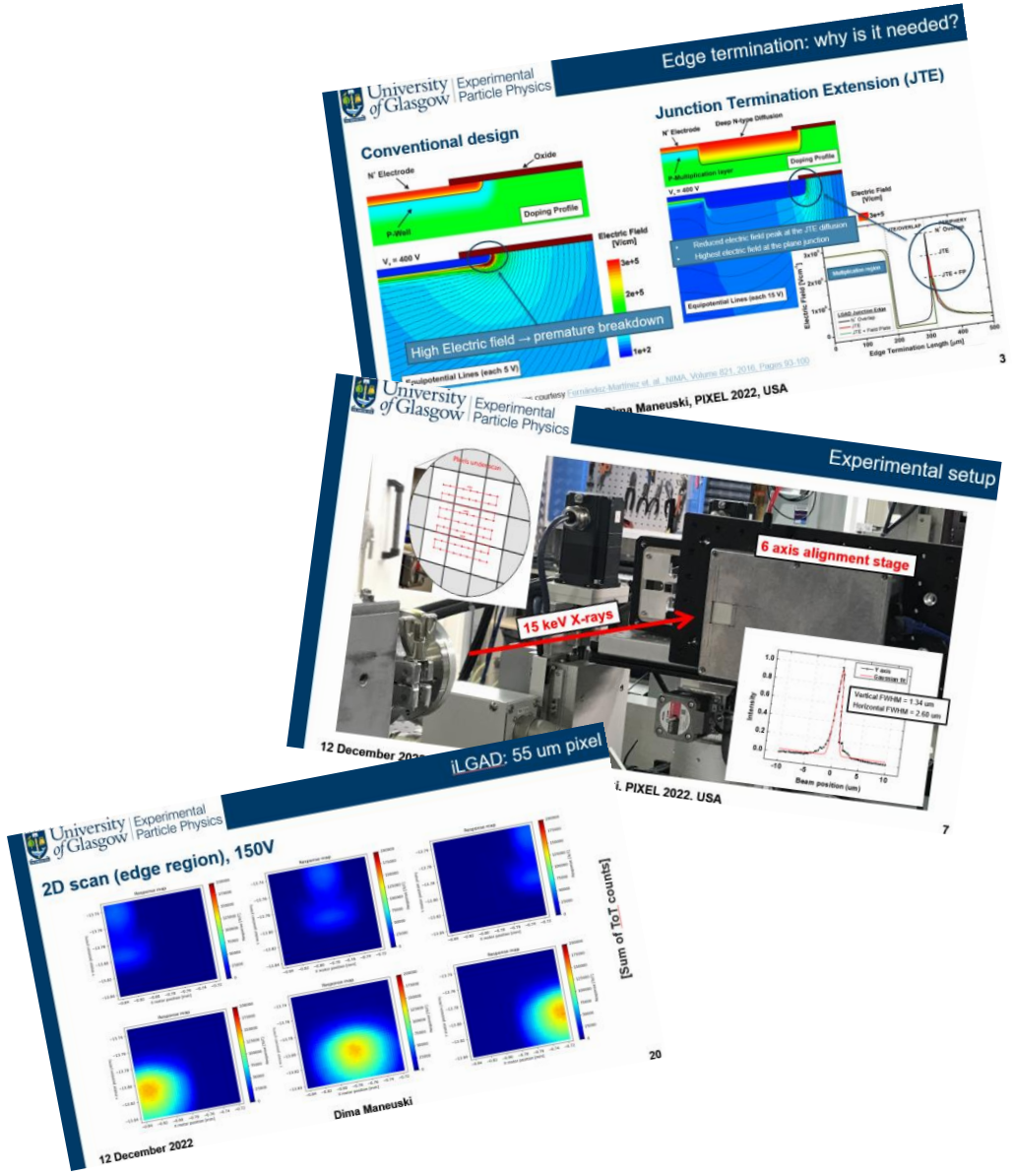


# LGAD sensors development program

## Research agenda and motivation

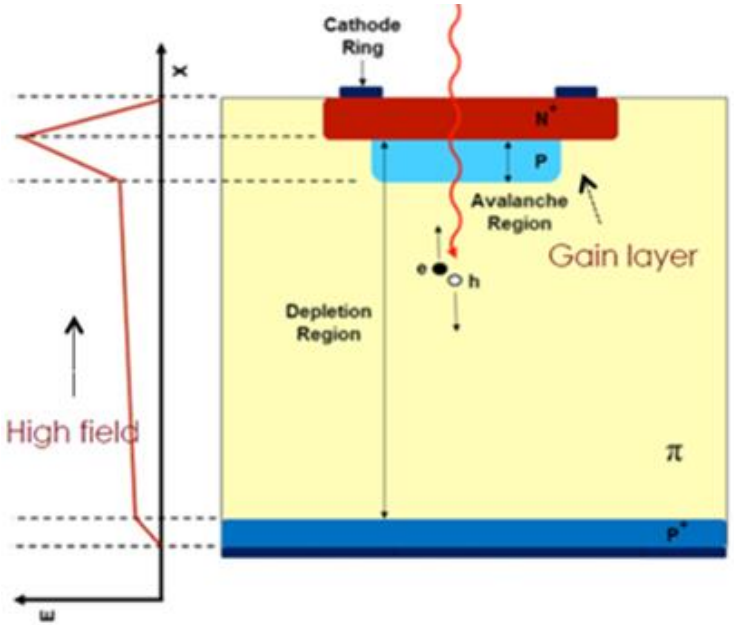
- Fast timing silicon pixel detectors (sub 100 ps)
- “Tender” (< 5 keV) energy x-rays detectors

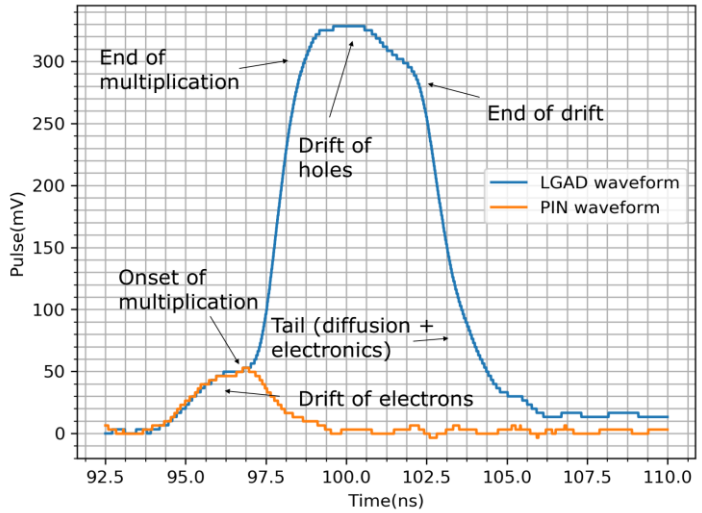
- Understand LGAD technology
- Create simulation models
- Develop fabrication process (at Micron Semiconductor)
- Build characterisation infrastructure
- Explore potential applications

- Synchrotron applications
- LHCb VELO II upgrade

MICRON SEMICONDUCTOR LIMITED

LGAD principle



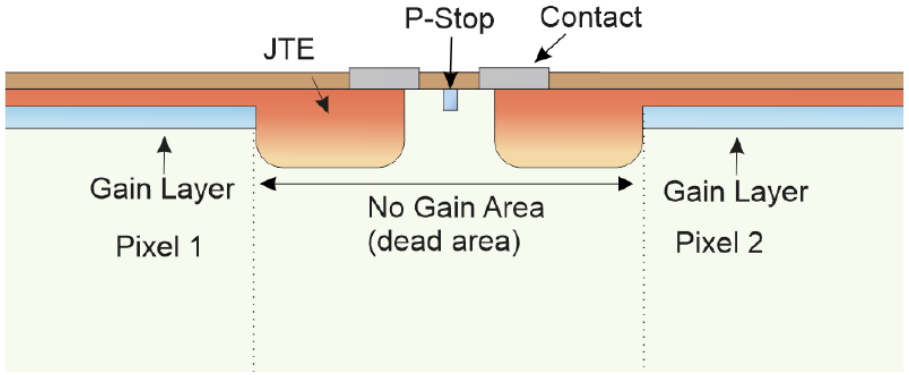

Figures courtesy Moffat, (2020), PhD thesis

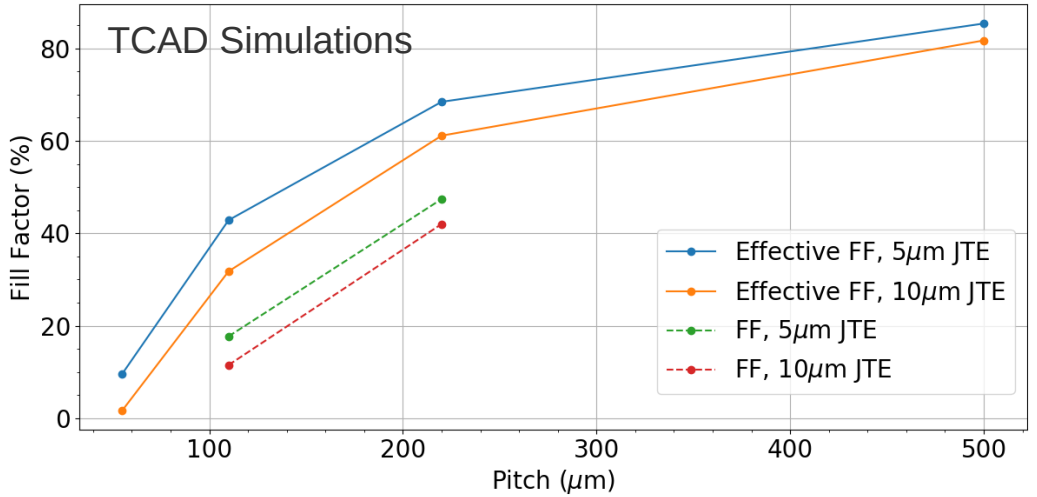
# Small pixels → poor fill factor

## Considerations for small pixels

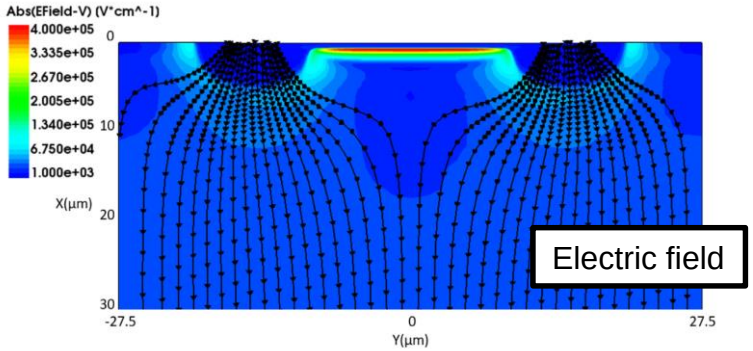
- Small pixels have poor geometric fill factor
- Geometric fill factor is affected by JTE

$$Geometrical\ Fill\ Factor = \frac{Gain\ Area}{Total\ Area}$$




- Need to account for drift to JTE




TCAD Simulations

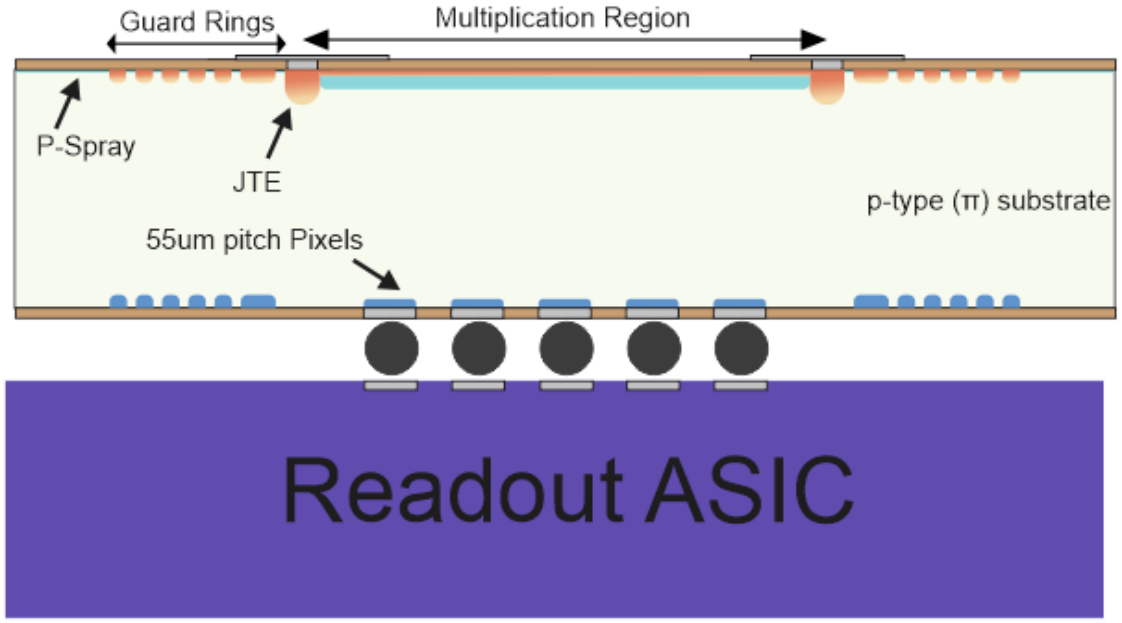
| Pixel Pitch | JTE Width | Geometrical Fill Factor | Simulated Fill Factor |
|---|---|---|---|
| 55 μm | 5 μm | 9.55% | 0% |
| 55 μm | 10 μm | 1.62% | 0% |
| 110 μm | 5 μm | 42.84% | 17.7% |
| 110 μm | 10 μm | 31.77% | 11.5% |
| 220 μm | 5 μm | 68.44% | 47.4% |
| 220 μm | 10 μm | 61.12% | 42% |

Figures and table courtesy Moffat and Bates, NIMA, Volume 1018, 2021, 165746

JTE - Junction Termination Extension

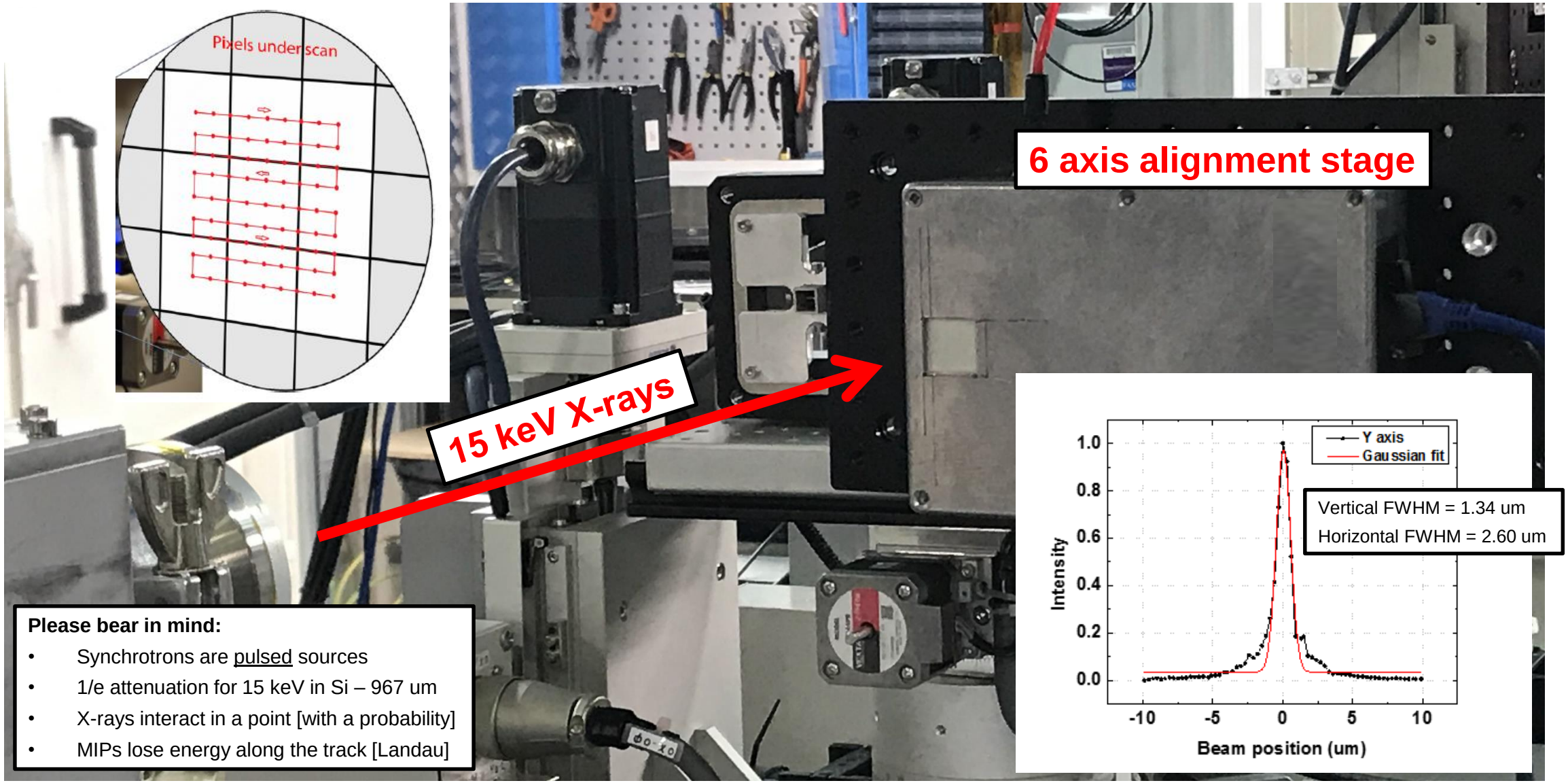
# Options for small pixels: Inverse LGAD

- Segmentation at the ohmic contact: strip and pixels
- Multiplication extended over all the device
- P-type collector ring at the ohmic side to extract leakage current
- JTE to protect the n+/p curvature and channel stopper to avoid the depletion reaches the end of the detector
- Readout is made by the strips/pixels: holes collection




Cons
- Double side processing
- Backside sensitive to scratches
- Needs to be fully depleted

# Diamond Light Source, B16




**Please bear in mind:**

- Synchrotrons are pulsed sources
- 1/e attenuation for 15 keV in Si – 967 um
- X-rays interact in a point [with a probability]
- MIPs lose energy along the track [Landau]

# DUTs and tests

## Devices produced and tested

- C10 – 55 um pixel, “standard” sensor for benchmarking
- LGAD devices
- C04 - 110 um pixel, 10 um JTE, expected gain ~5-7
- C06 - 110 um pixel, 20 um JTE, expected gain ~5-7
- D04 - 55 um pixel, 5 um JTE, expected gain ~5-7
- Devices have a control no-multiplication region of 9x9 pixels in the right bottom corner
- Inverse LGAD devices
- I11 - 55 um pixel, expected gain ~5-7
- F08 - 110 um pixel, expected gain ~2-5
- L07 - 220 um pixel, expected gain ~2-5
- Devices have a control no-multiplication rim of 3 pixels wide at each edge

N.B. Time-over-threshold (ToT) ~ Energy (keV)

### Tests performed

- Line scan over Pixel of Interest (PoI) @ V
  - In the middle of the device
  - At the edge over control and gain pixels
- Voltage scan in the middle of PoI
  - In the middle of the device
  - At the edge over control and gain pixels
- 2D scan @ Vmax

### TPX3 settings

- ToT+ToA mode, data-driven
- Only ToT data is analysed
- AdvaDAQ TPX3 USB3.0

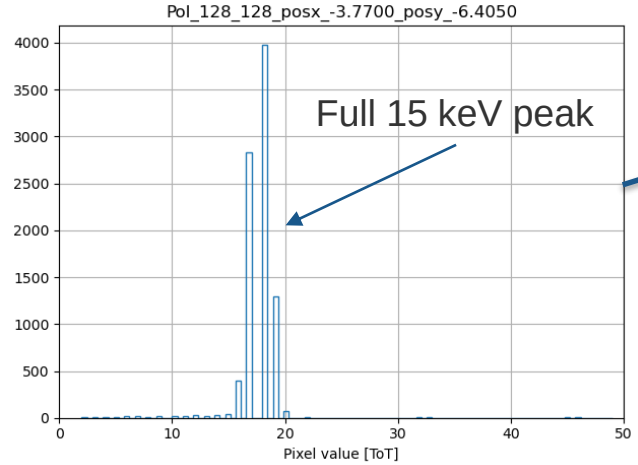
I will show results from:

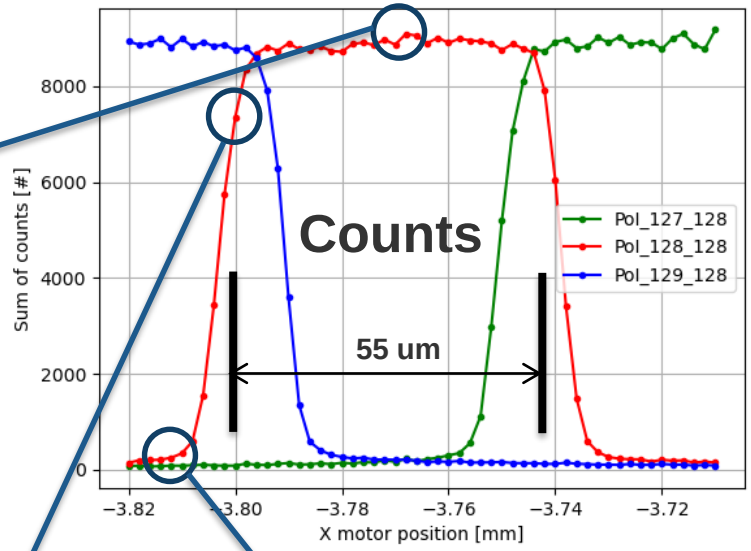
- 55 um “standard” pixel
- 110 um, 10 um JTE, LGAD
- 55 um, 5 um JTE, LGAD
- 55 um, iLGAD

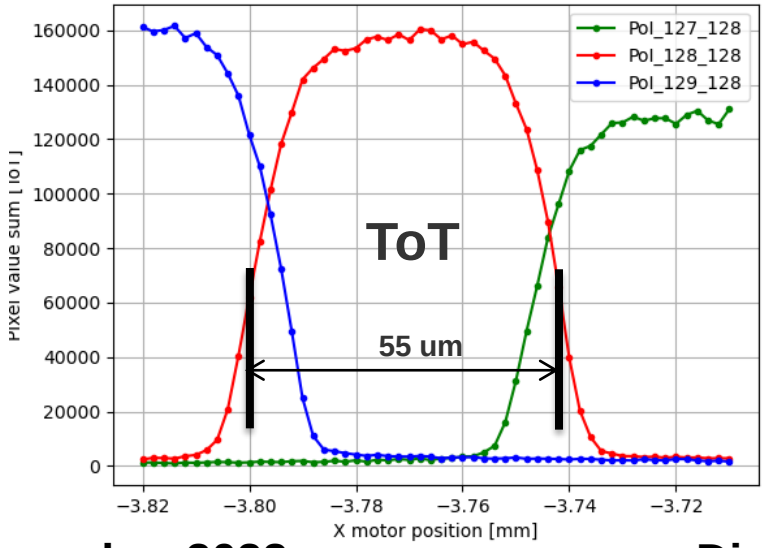
# C10 - 55 um pixel, standard PIN device

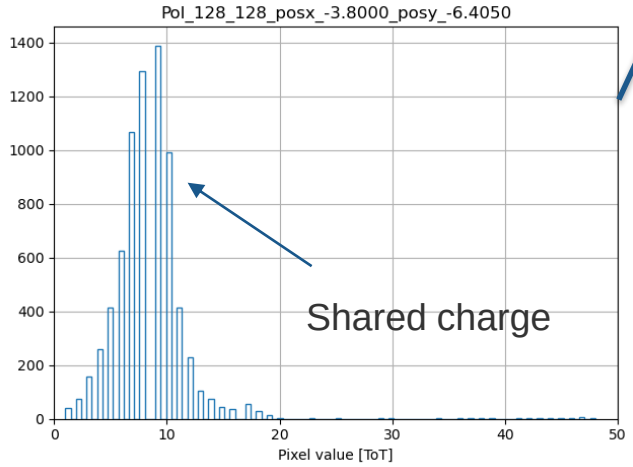
## Line scan

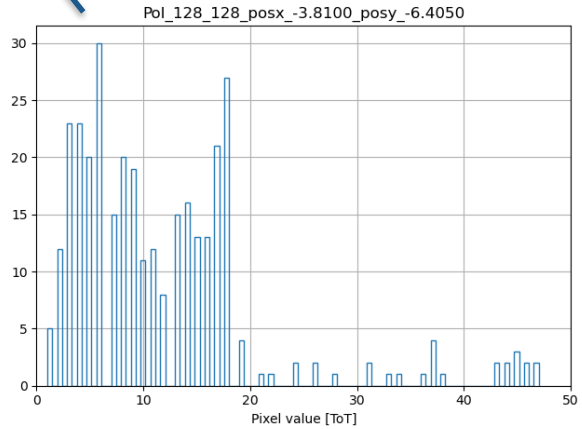
- Step function pixel response
- Convoluted with finite beam size
- Full 15 keV peak observed in the middle
- Shared charge observed in between pixels
- Charge outside pixel due to beam harmonics passing X-ray lens (Al attenuation hardening)



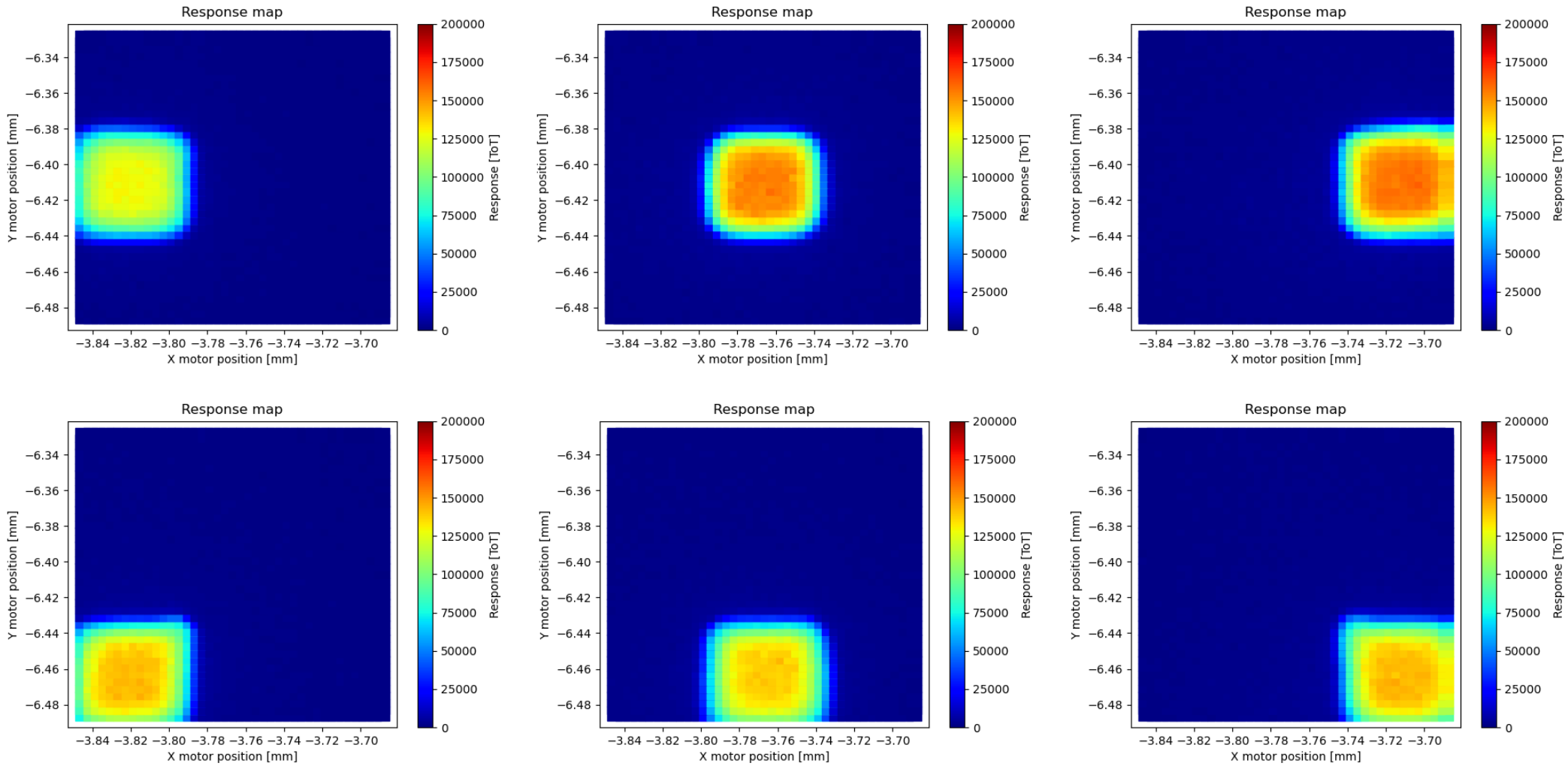



# Standard PIN device: 55 um pixel

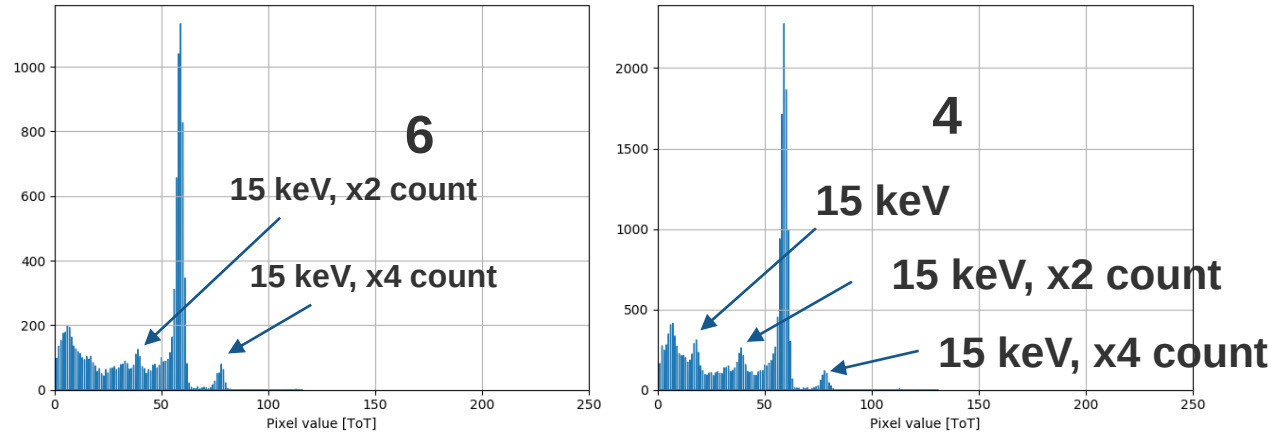
## 2D scan, 100V




[Sum of ToT counts]

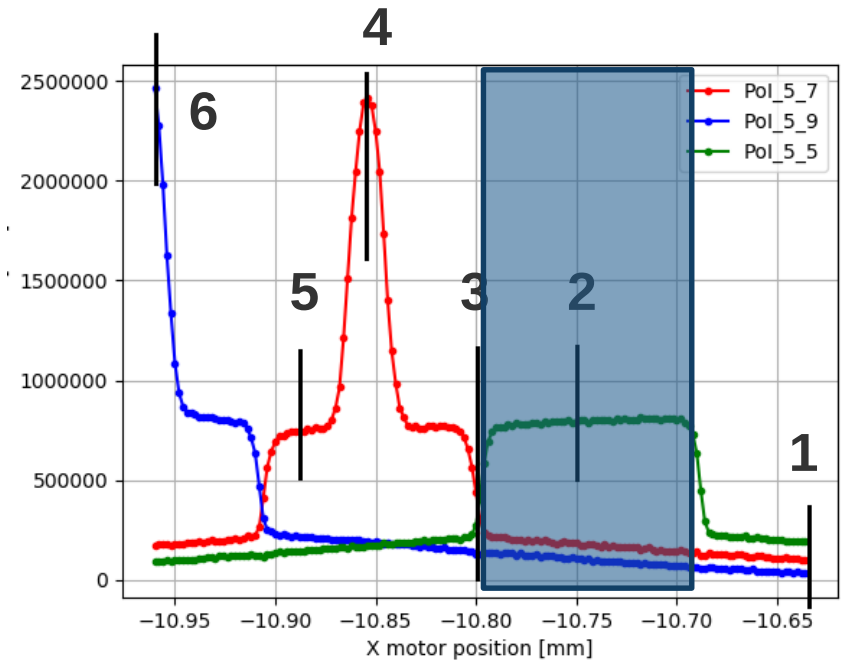
# LGAD: 110 um pixel, 10 um JTE

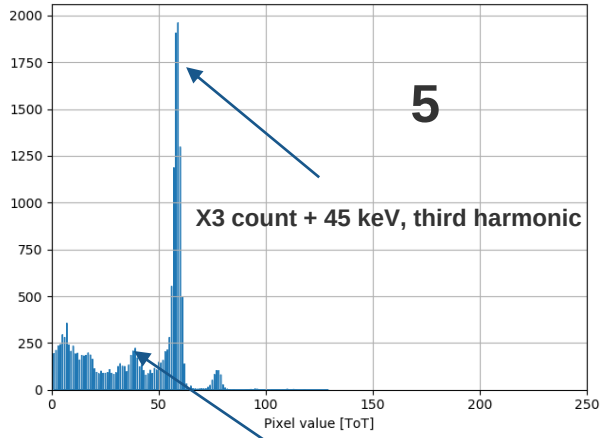
## 1D line scan, no gain pixel (5, 5), -350V

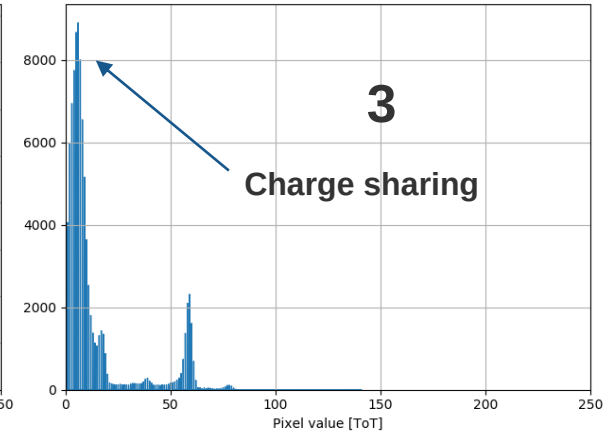


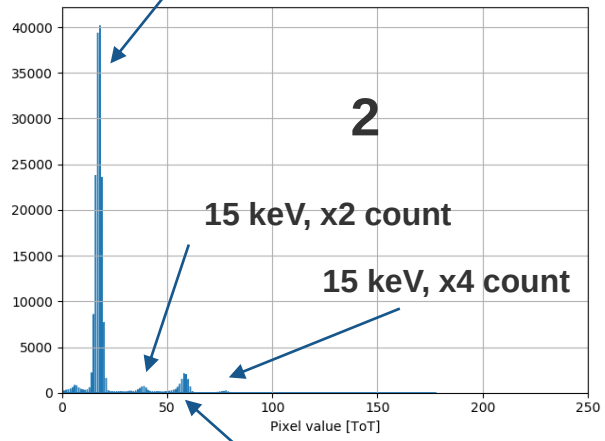


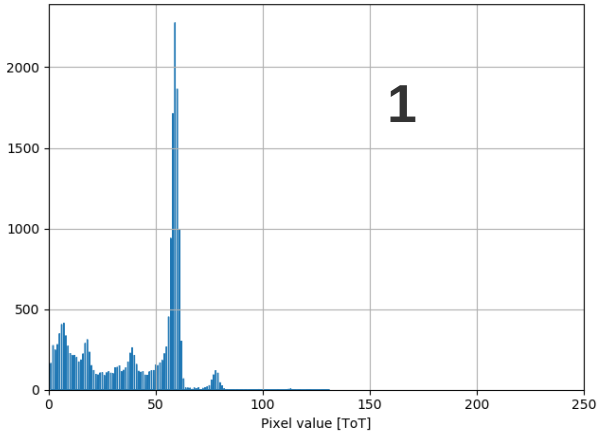




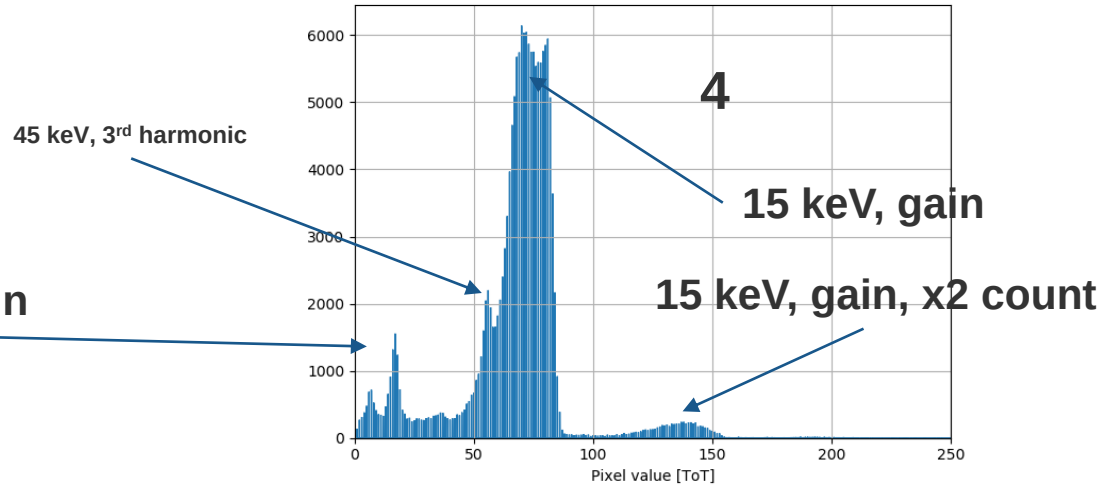



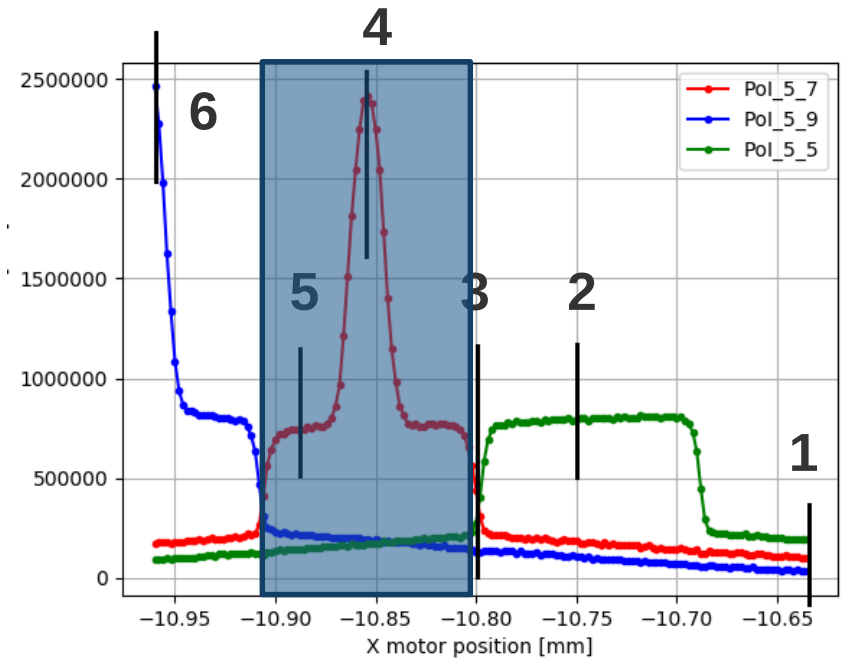



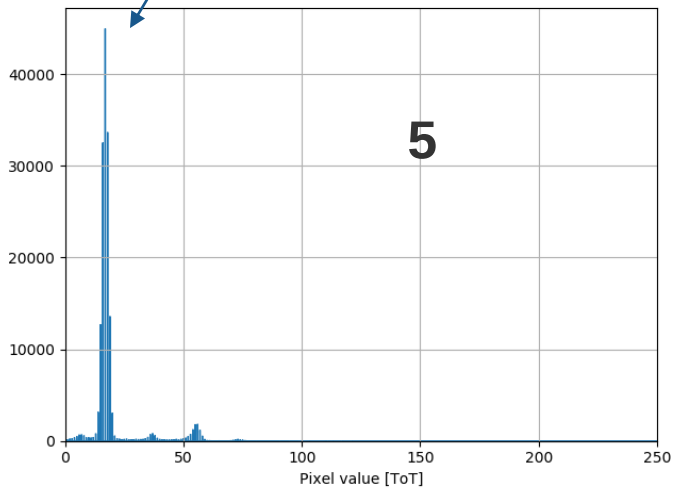



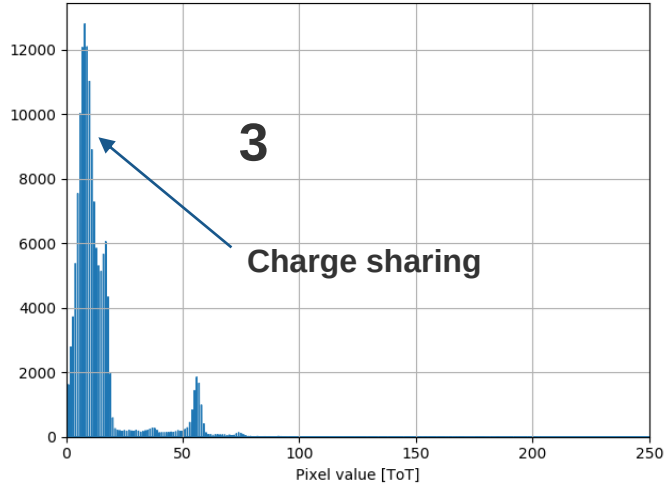
# LGAD: 110 um pixel, 10 um JTE

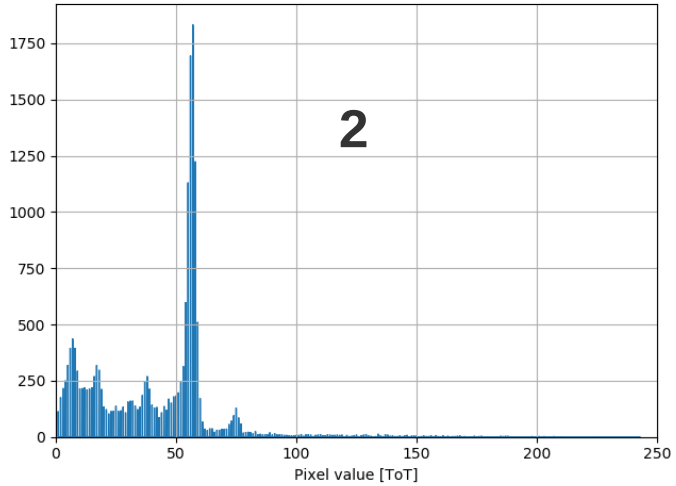
## 1D line scan, gain pixel (5, 7), -350V



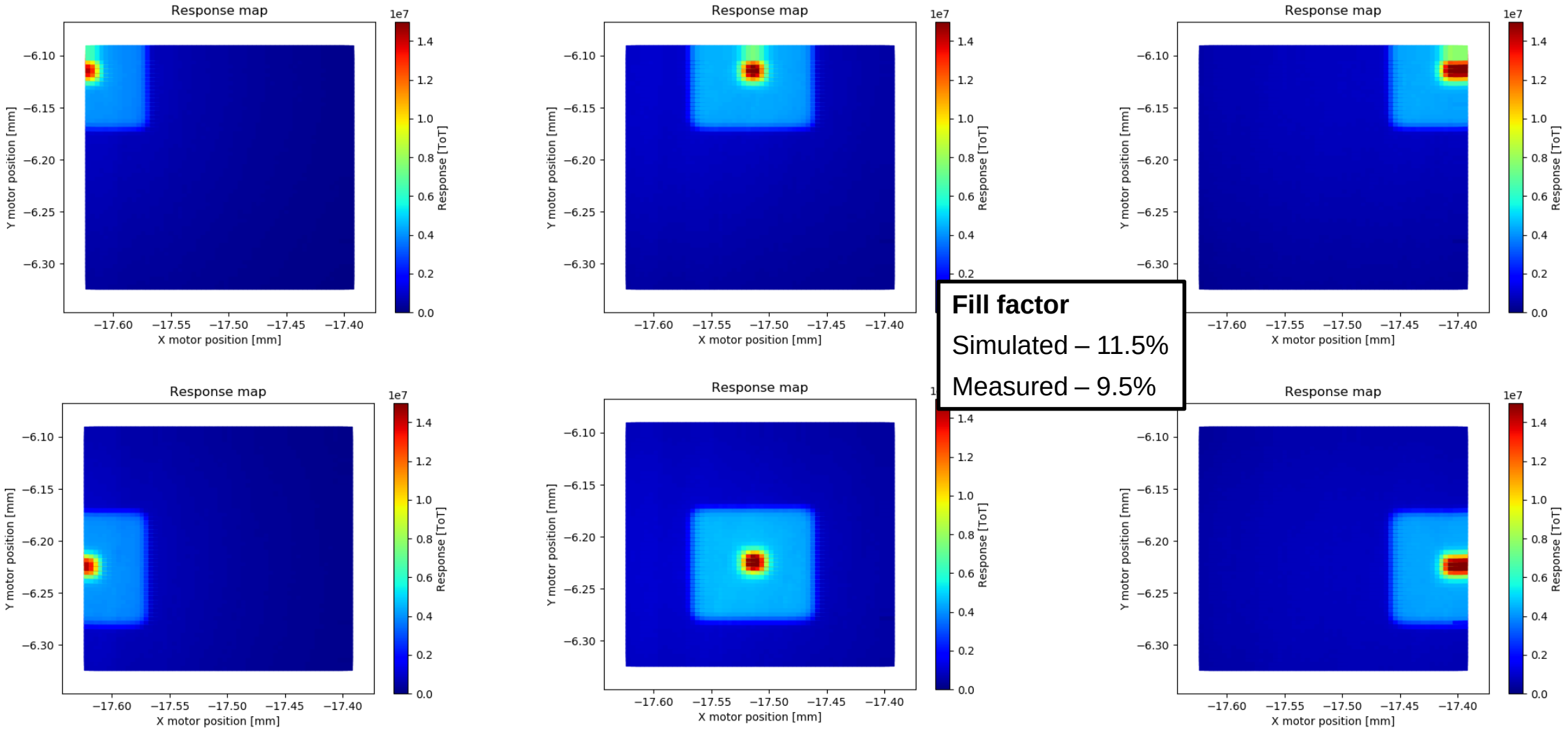



# LGAD: 110 um pixel, 10 um JTE

## 2D scan (-350V)




**Fill factor**

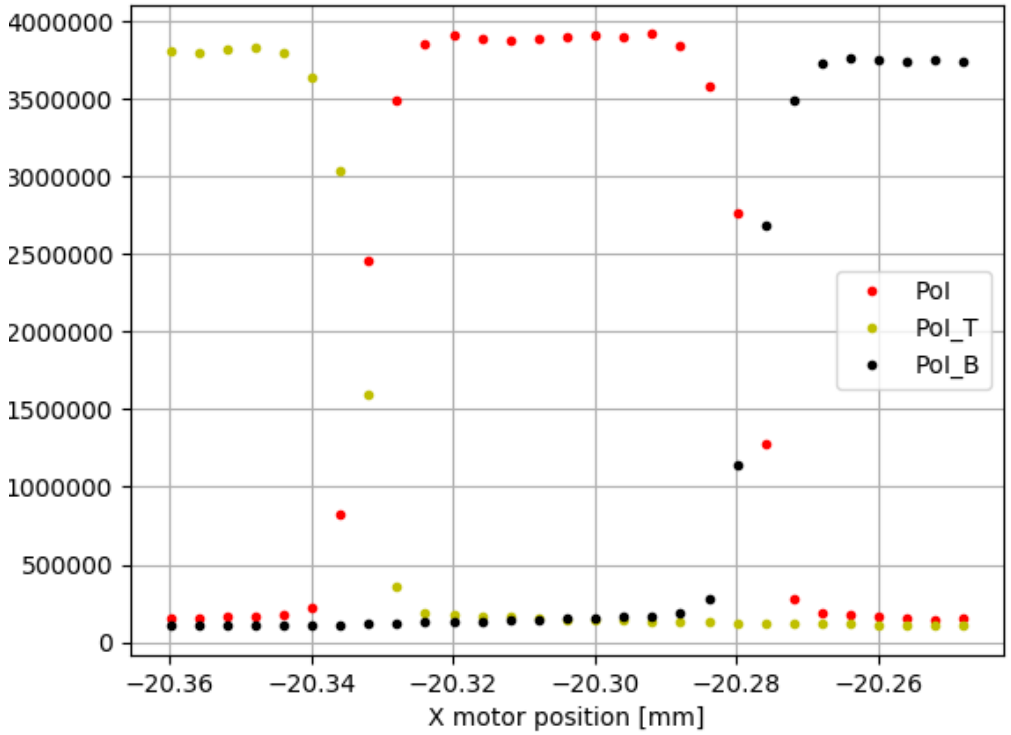
Simulated – 11.5%

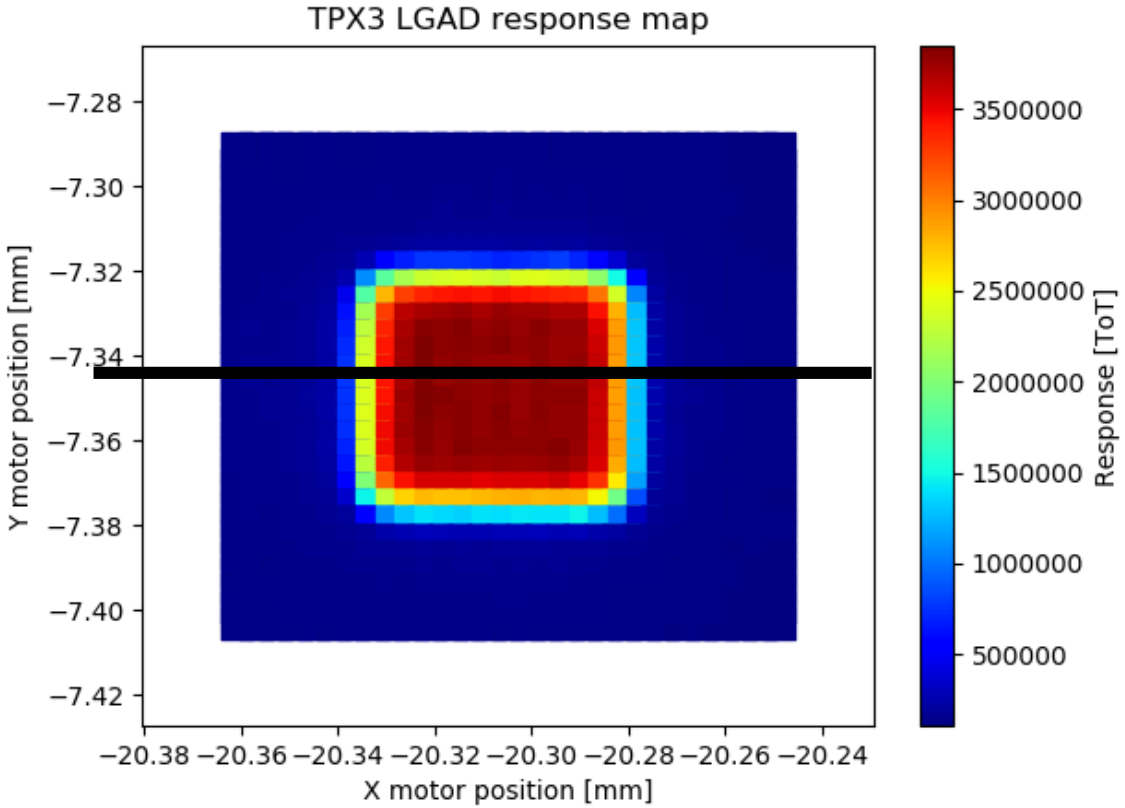
Measured – 9.5%

[Sum of ToT counts]

# LGAD: 55 um pixel, 5 um JTE

## 1D line scan, gain pixel (127, 127), -400V



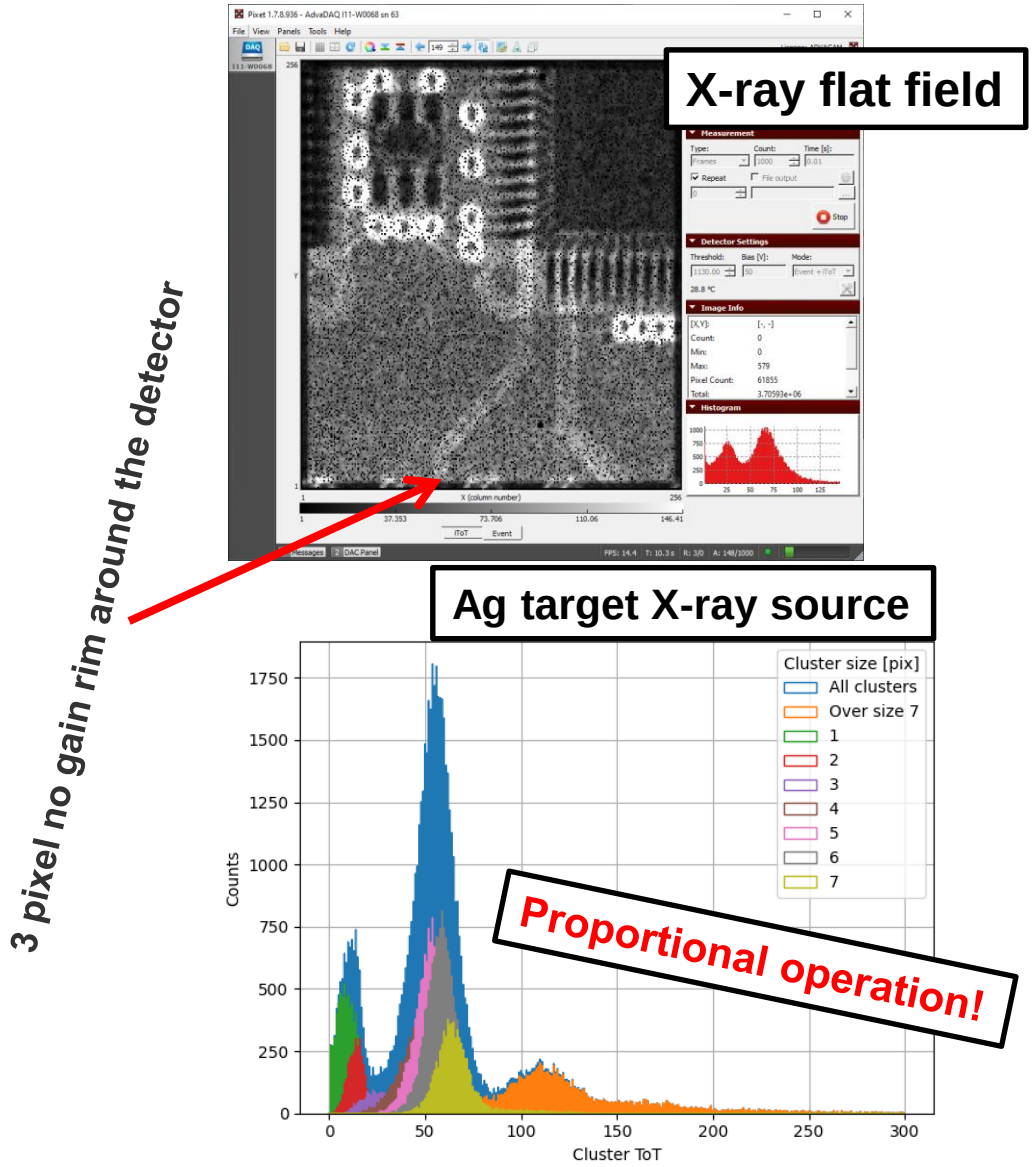




No gain observed as expected

# Inverse LGAD on Timepix3

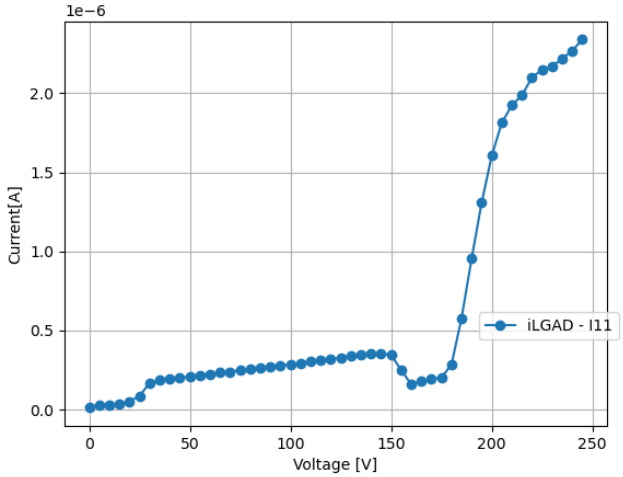
## Ongoing research program

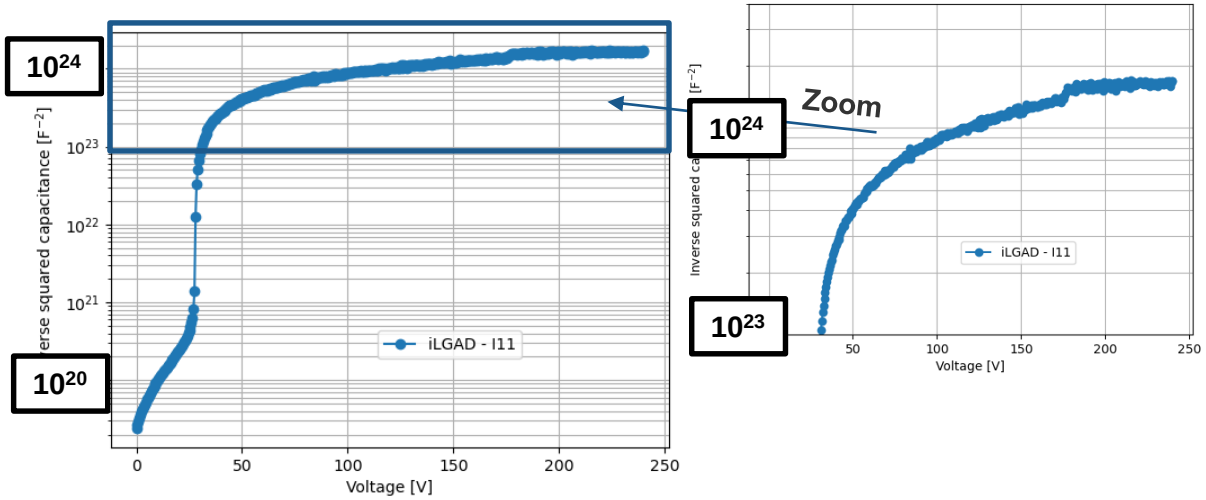
- Wafers with two gain implants
- Pixels 55, 110, 220 um
- Program to:
- Measure and understand spectra
- In-pixel gain uniformity:
- Test beam at Diamond (July 2022)
- Test beam at CERN SPS (September 2022)

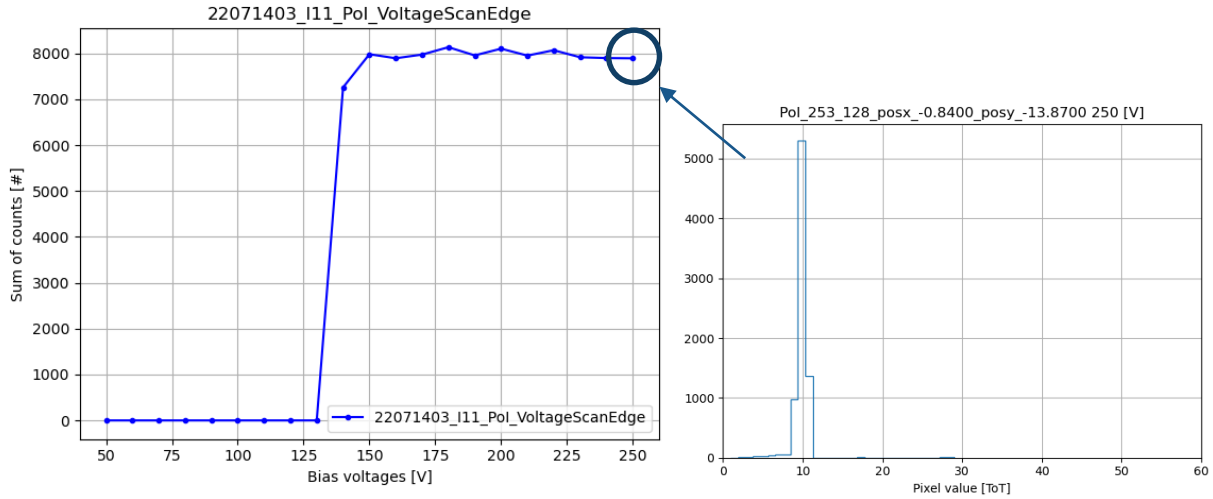


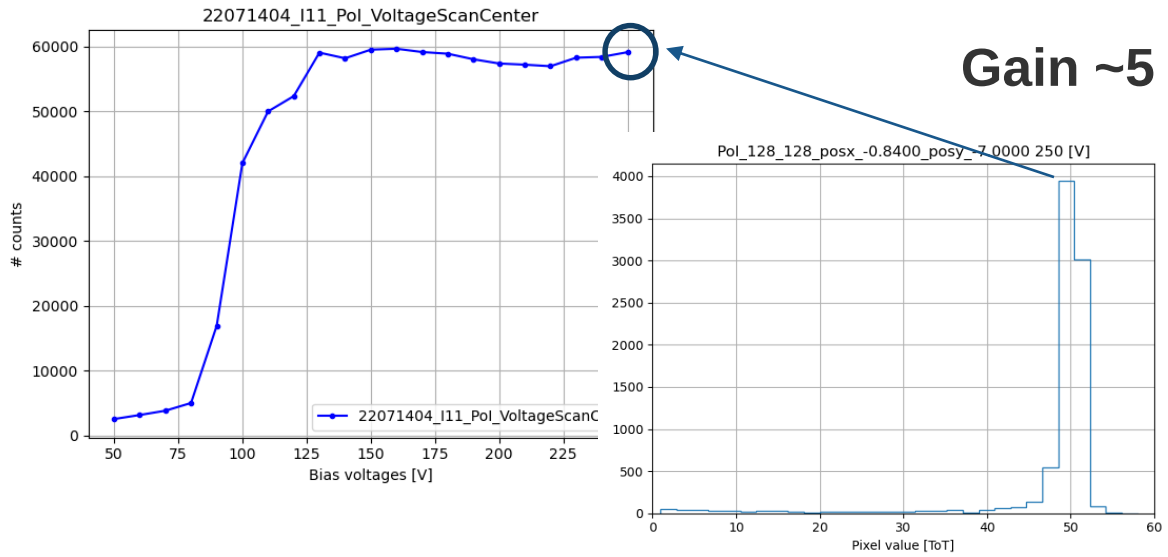
# iLGAD: 55 um pixel

## Voltage scan and IV / CV



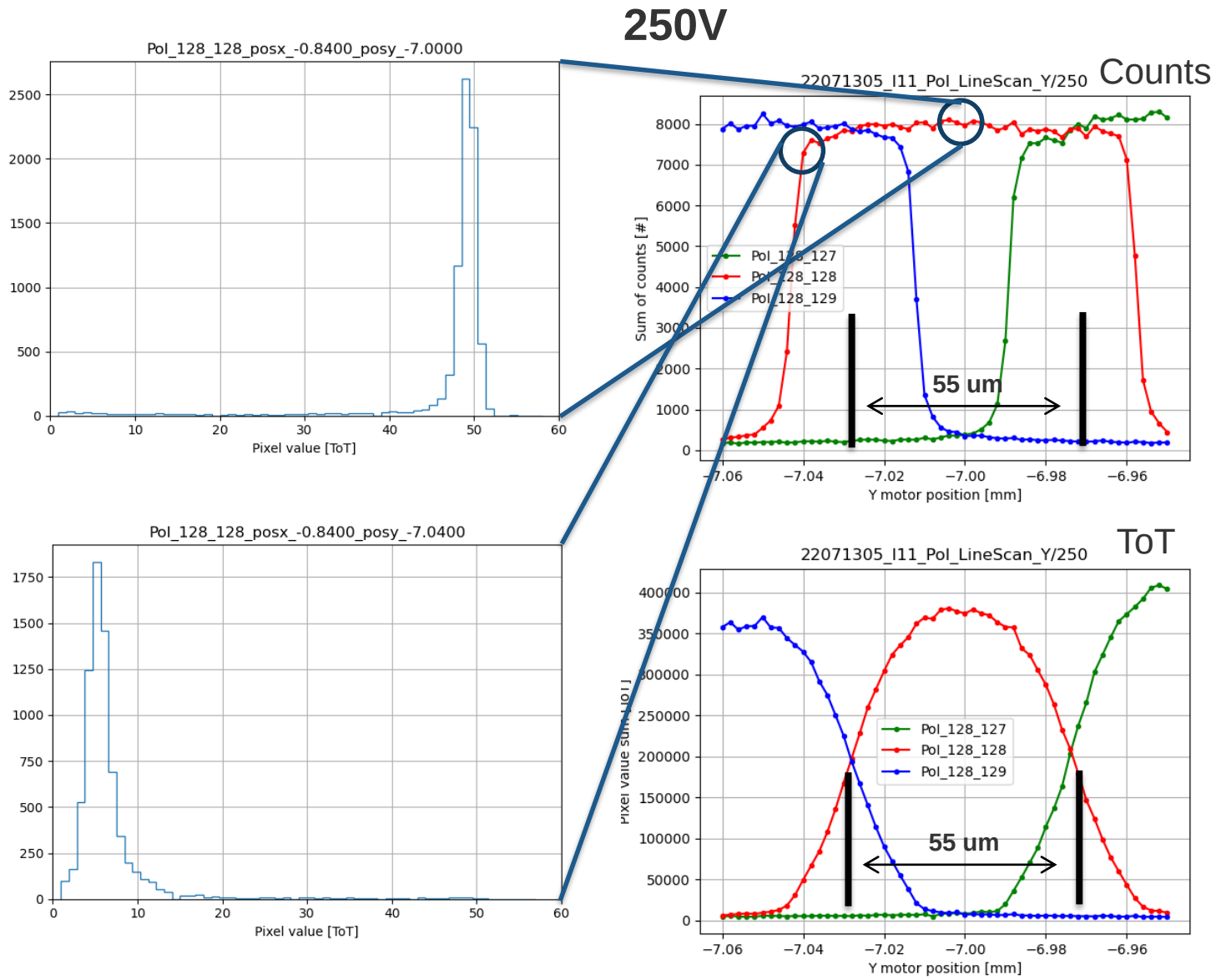




**Gain ~5**

# iLGAD: 55 um pixel

## Line scan (gain pixel)

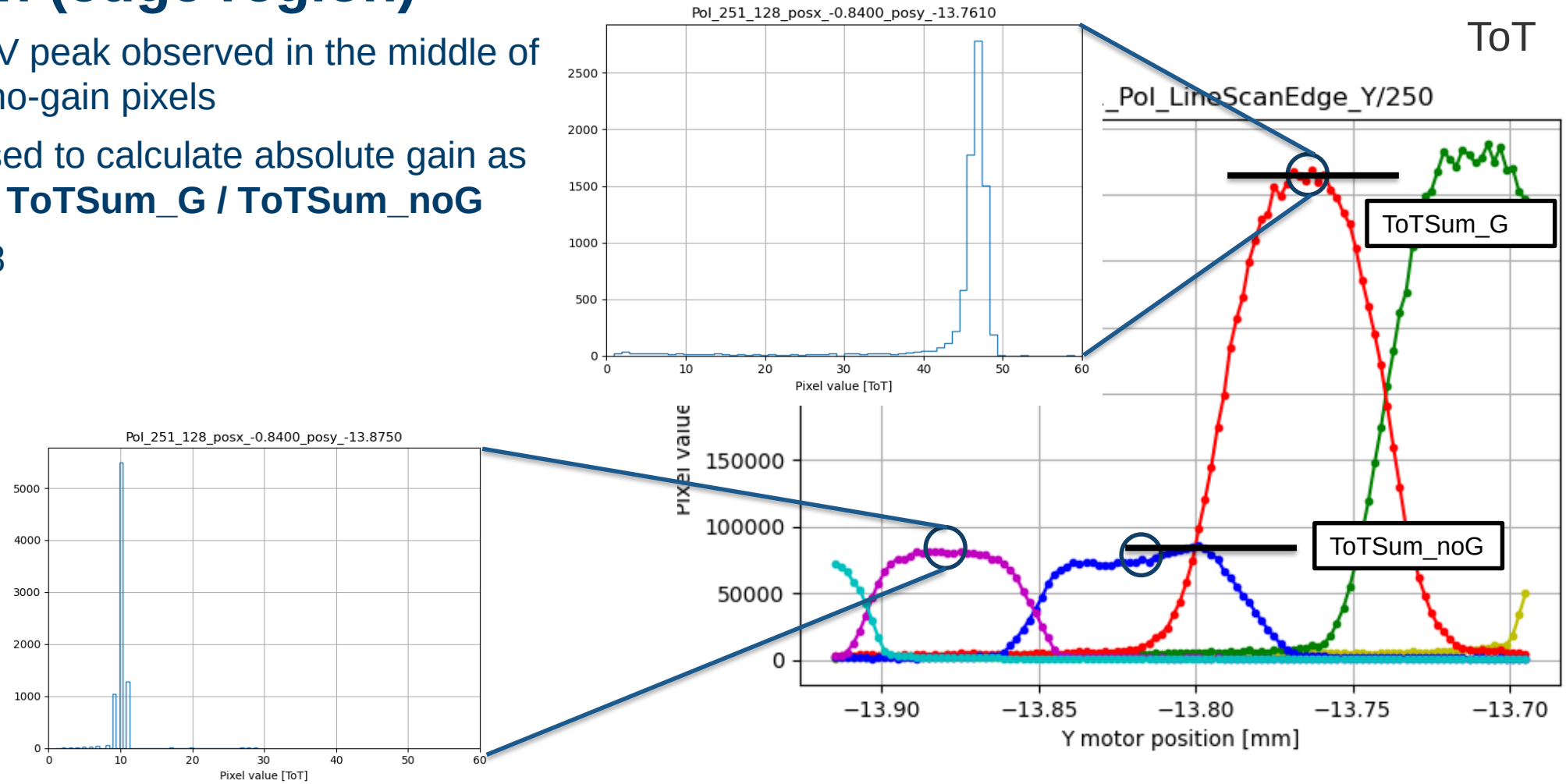
- Step function pixel response
- Convoluted with finite beam size
- Full 15 keV peak observed in the middle (with gain)
- Wider “effective” pixel due to higher signal / threshold ratio (compared to PIN device)
- **Uniform gain achieved**



# iLGAD: 55 um pixel

## Line scan (edge region)

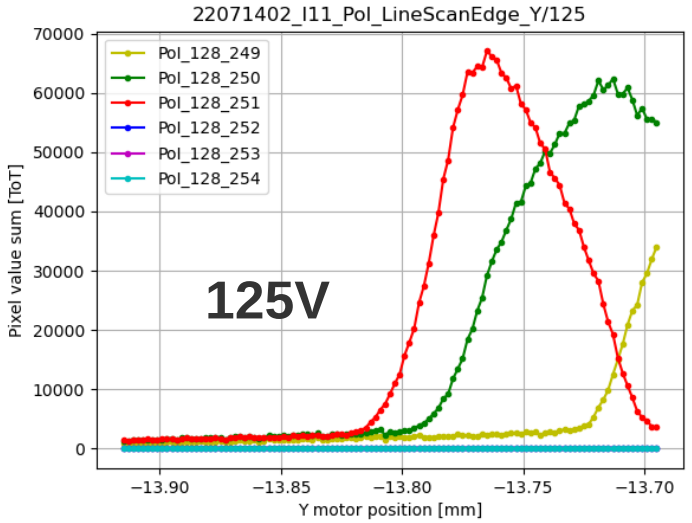
- Full 15 keV peak observed in the middle of gain and no-gain pixels
- Can be used to calculate absolute gain as ratio peak **ToTSum_G / ToTSum_noG**
- Gain ~ 4.8

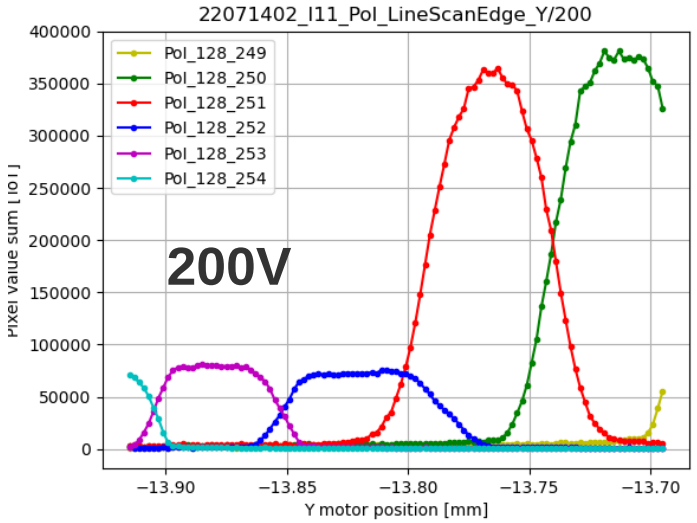


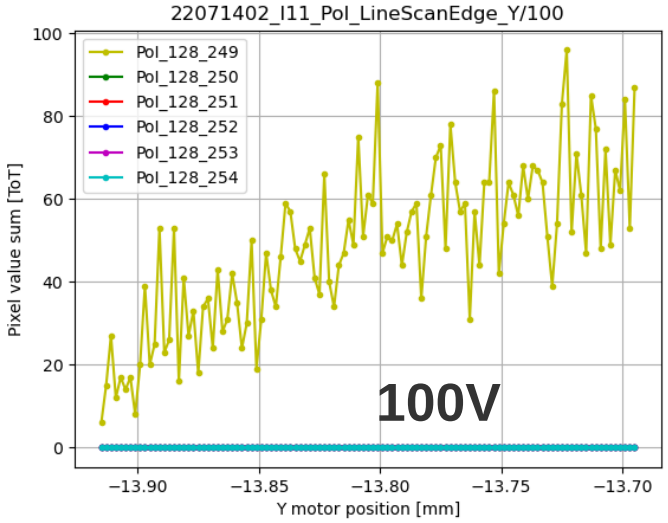
# iLGAD: 55 um pixel

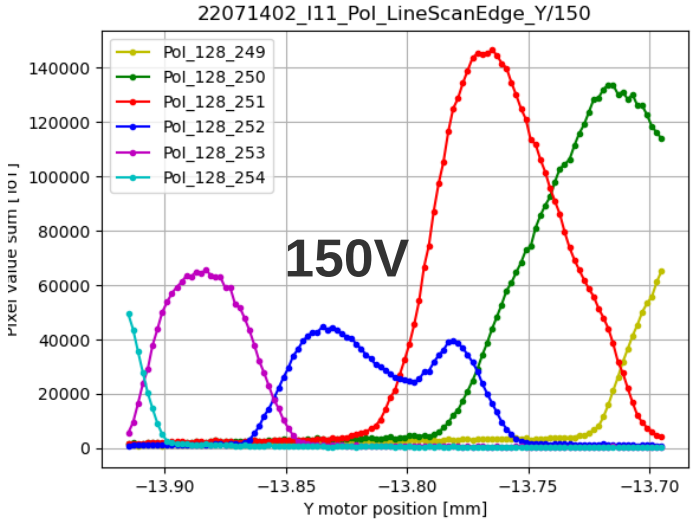
## Line scan (edge region)

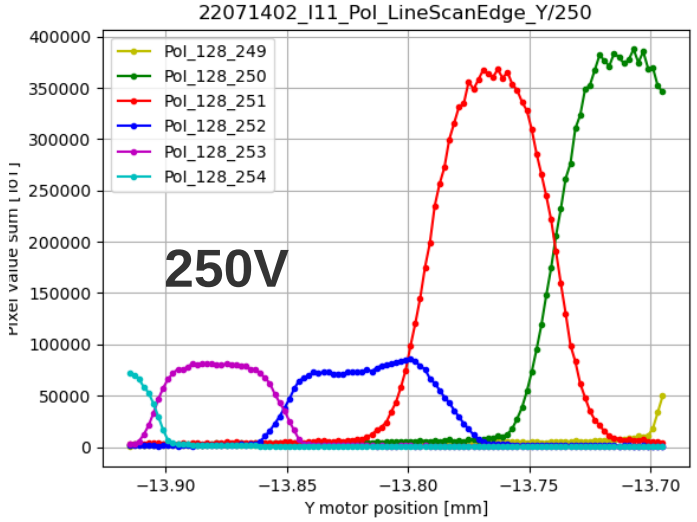
- Studied as function of bias voltage
- No counts observed at 50V
- Full charge collection appear after ~200V
- No gain pixels are more affected by low bias voltages (no charge collection below ~140V)



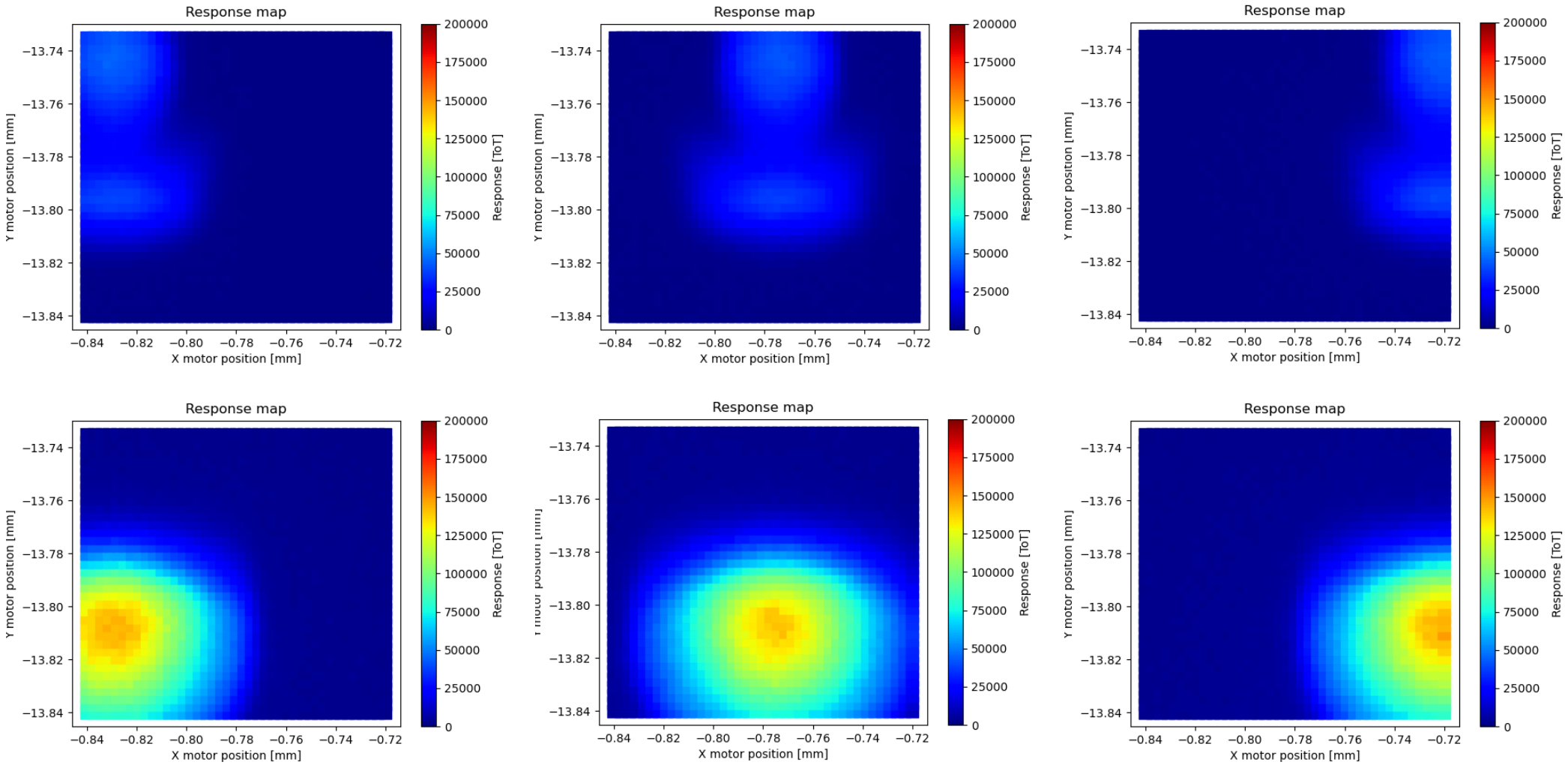



# iLGAD: 55 um pixel

## 2D scan (edge region), 150V

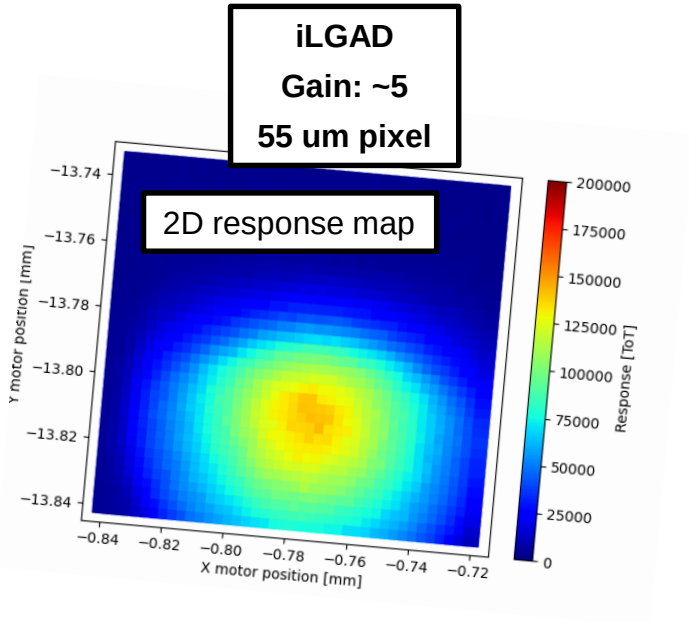


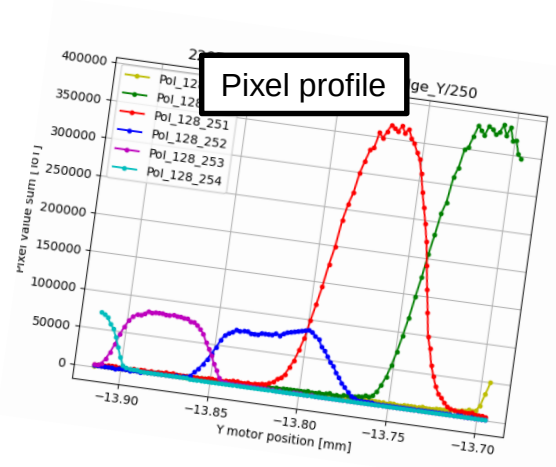

[Sum of ToT counts]

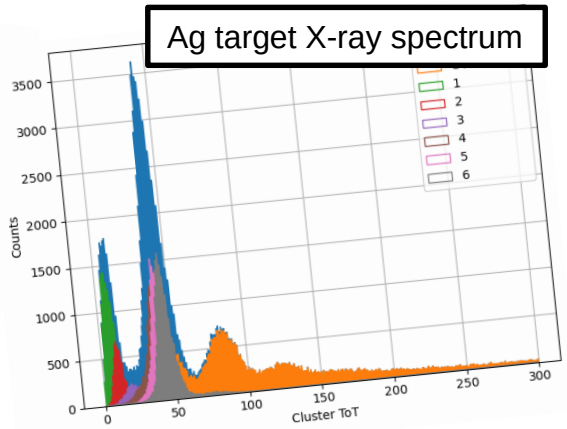
# Summary and future work

## Summary

- **Demonstrated 55 um pixel uniform i-LGAD device**
- Strong program to design, produce and test LGAD devices
  - TCAD simulations
  - Mask design, device fabrication
  - Device characterisation by means of IV, CV, TCT, TPA, X-rays
- Predicted and demonstrated gain in small pixel devices
  - Various pixel sizes
  - Various JTE sizes
- Resolved fill factor limitation in small pixel devices
- Inverse LGAD design
- Future work directions
  - Inverse LGADs: improve gain, improve breakdown voltage
  - Trench isolation design



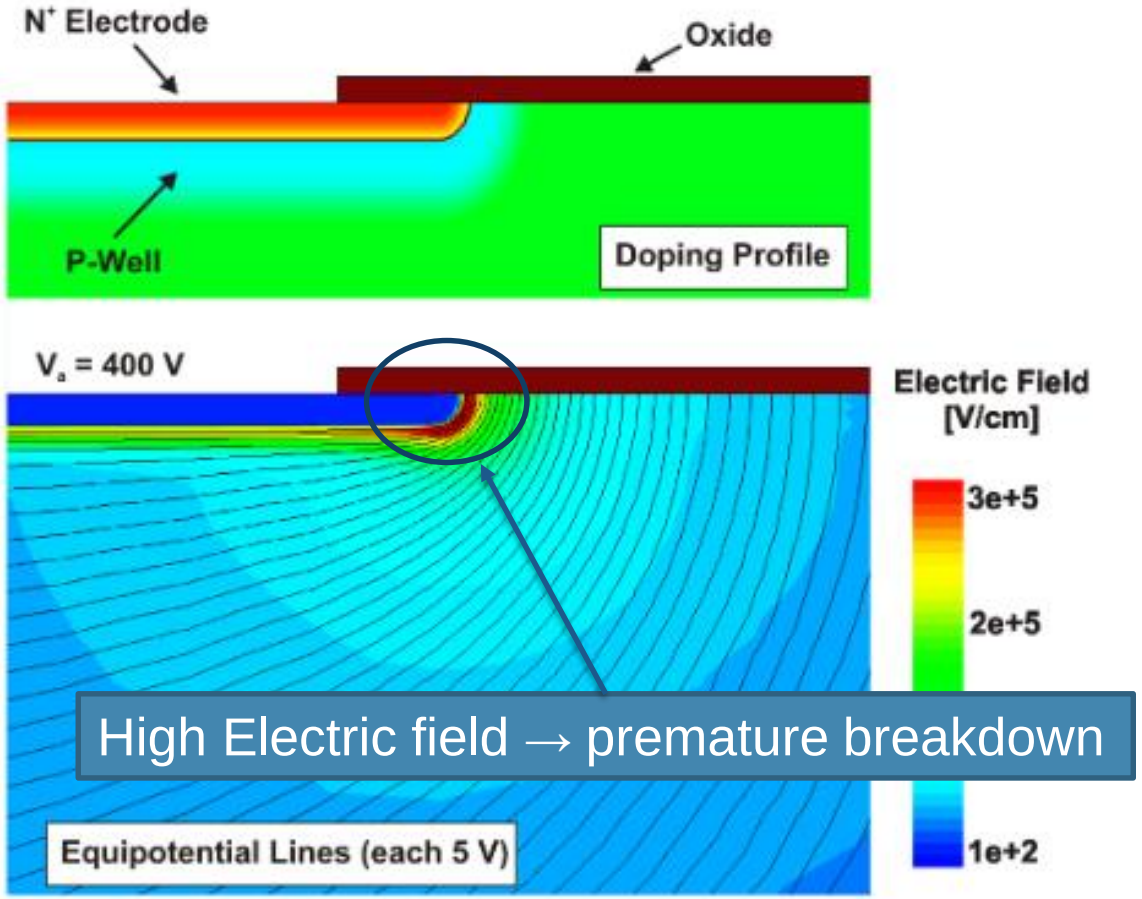




Email: dima.maneuski@glasgow.ac.uk

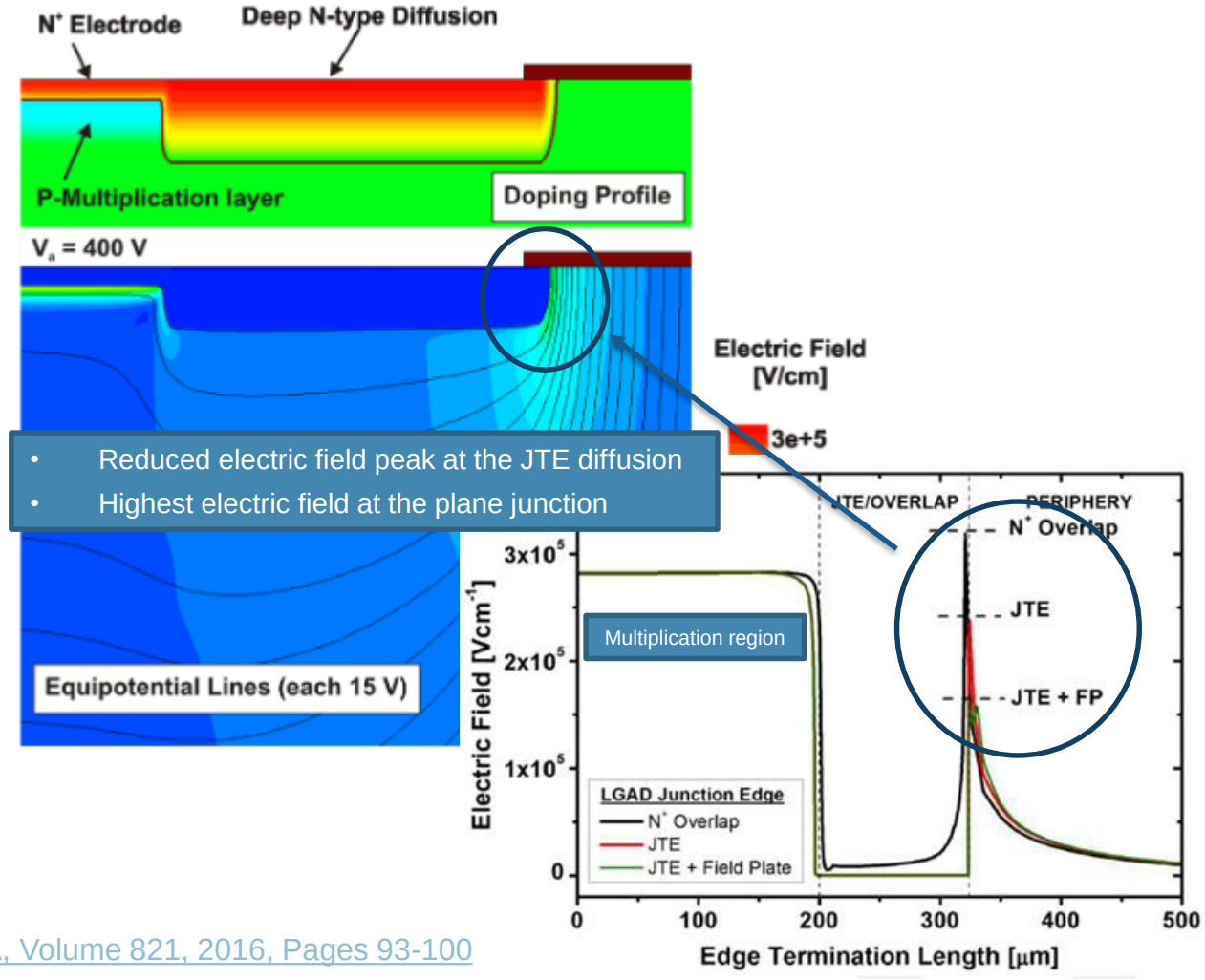
# BACKUP SLIDES

# Edge termination: why is it needed?

## Conventional design




## Junction Termination Extension (JTE)




Figures courtesy Fernández-Martínez et. al., NIMA, Volume 821, 2016, Pages 93-100

# B16: Test Beamline

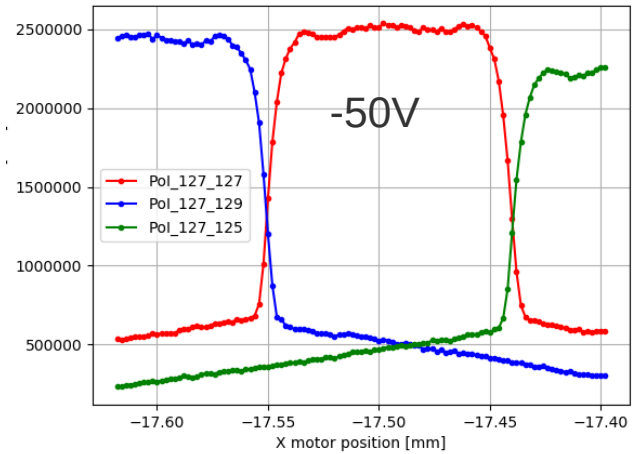
- Flexible and versatile beamline for testing new developments in optics and detector technology and for trialling new experimental techniques
- 4 – 45 keV photon energy range
- Operational modes:
- Focused, unfocused
- Monochromatic, white beam
- High flux

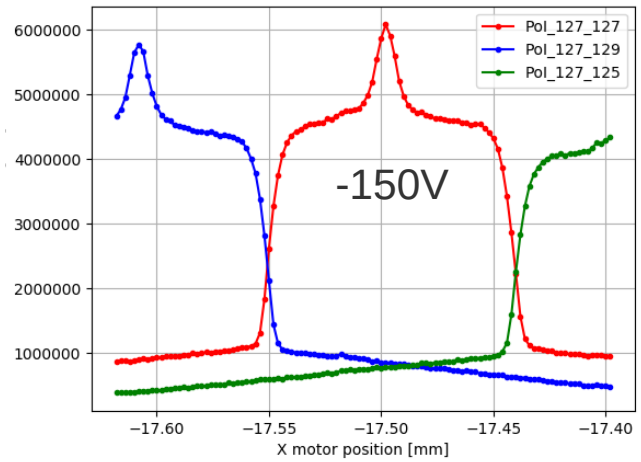
# What we use

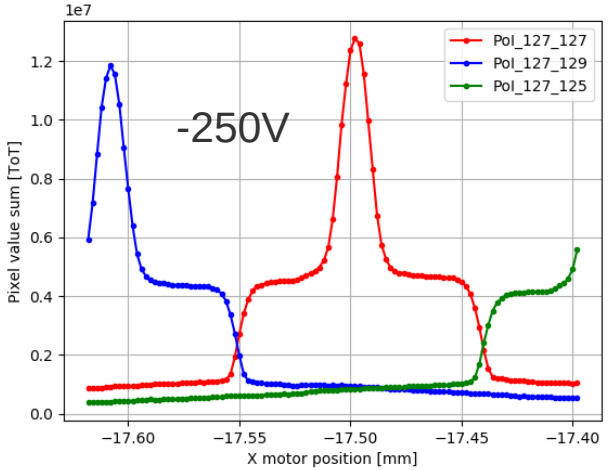
- 15 keV monochromatic beam
- Focused to about a micron FWHM

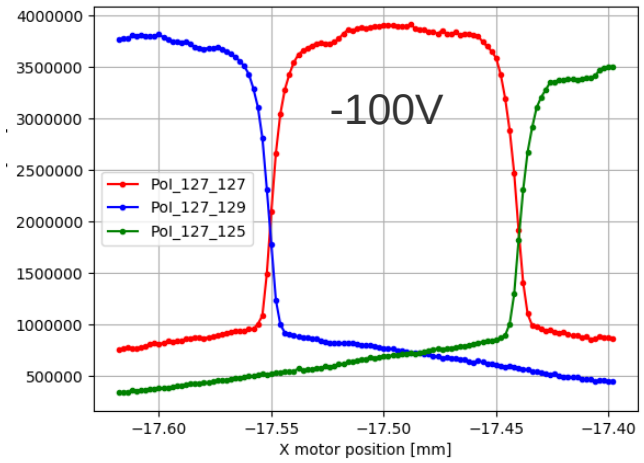
# LGAD: 110 um pixel, 10 um JTE

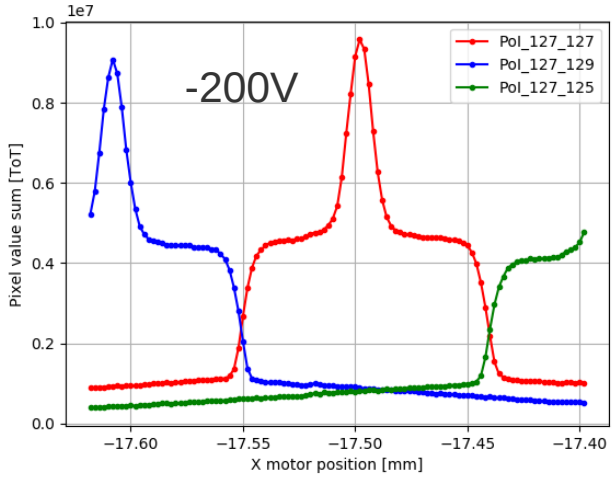
## 1D line scans @ voltages, gain pixel (127, 127)

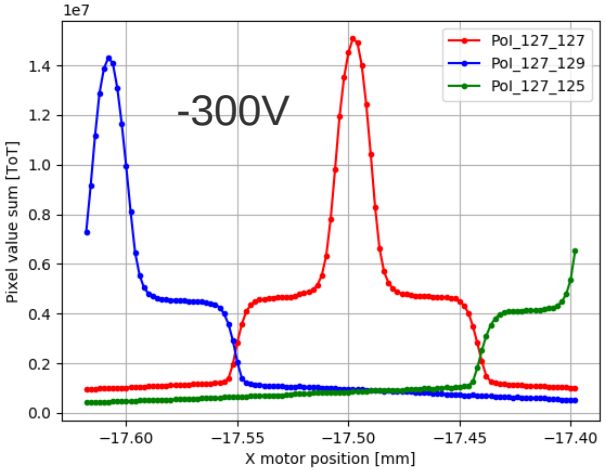


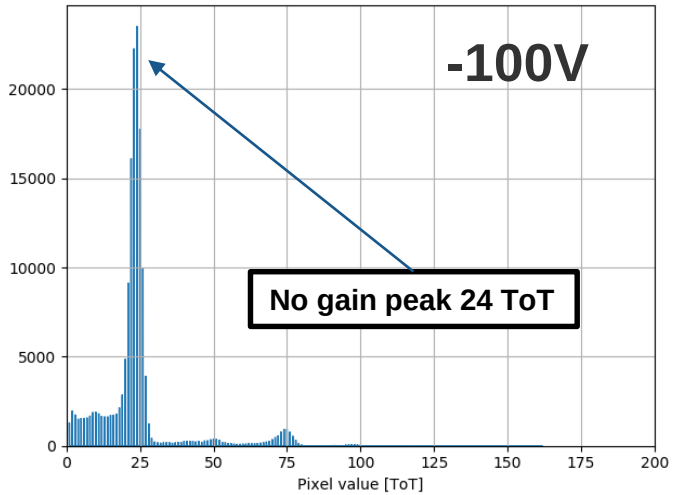



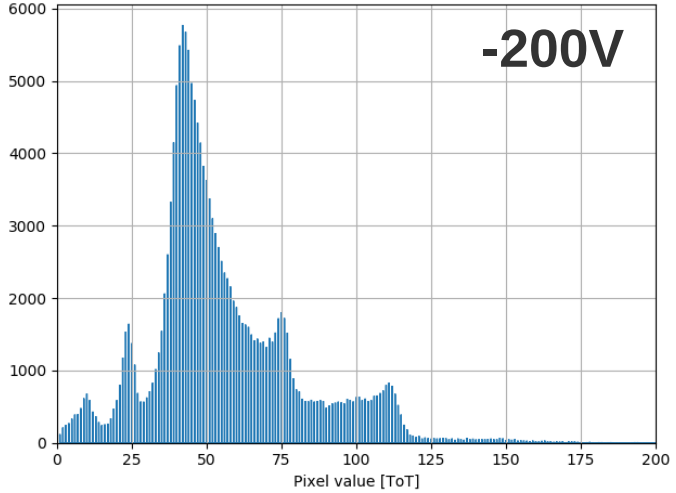



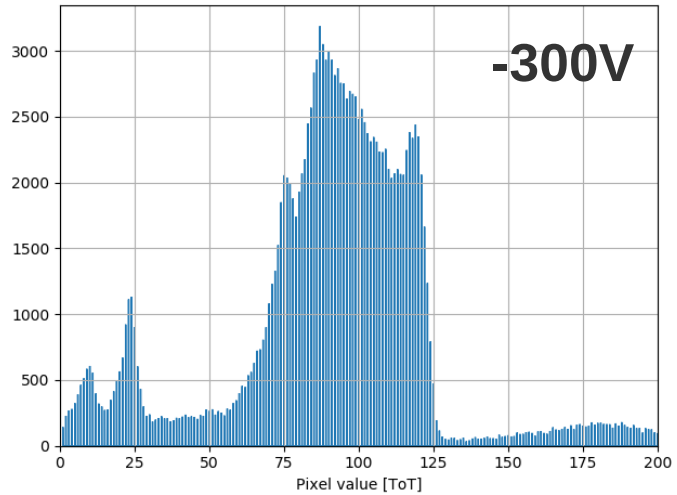



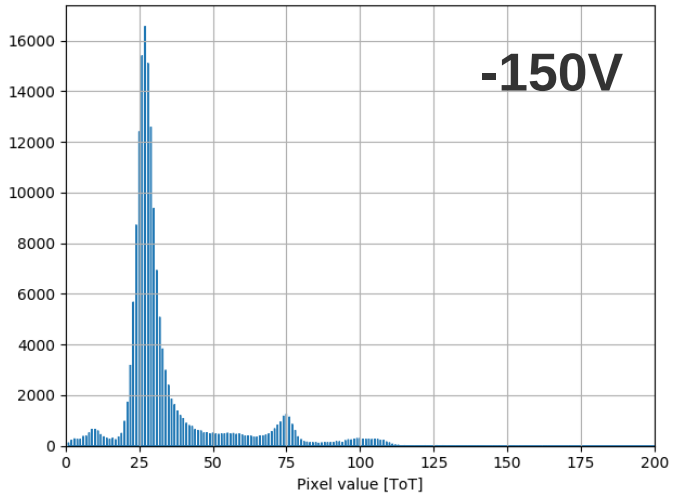
# LGAD: 110 um pixel, 10 um JTE

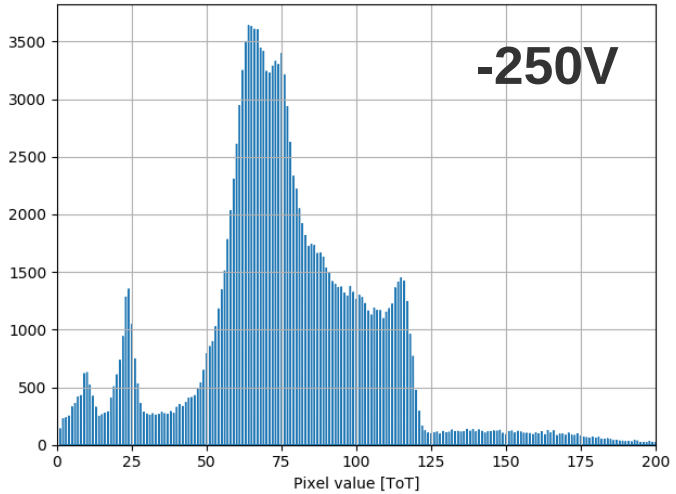
## Spectrum in the middle of gain pixel (127, 127)

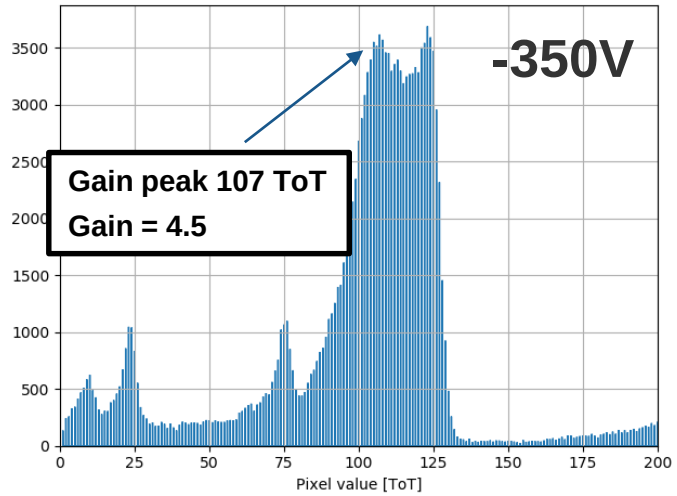


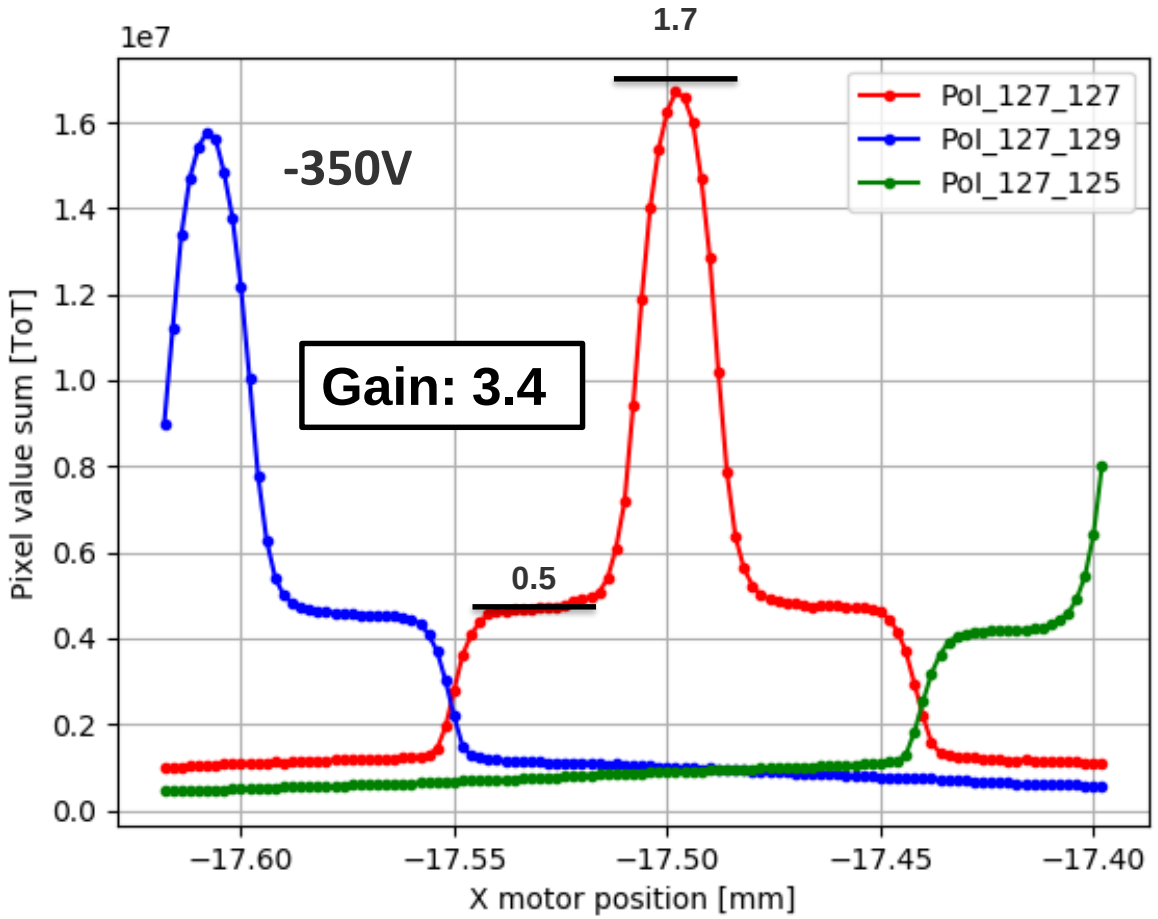



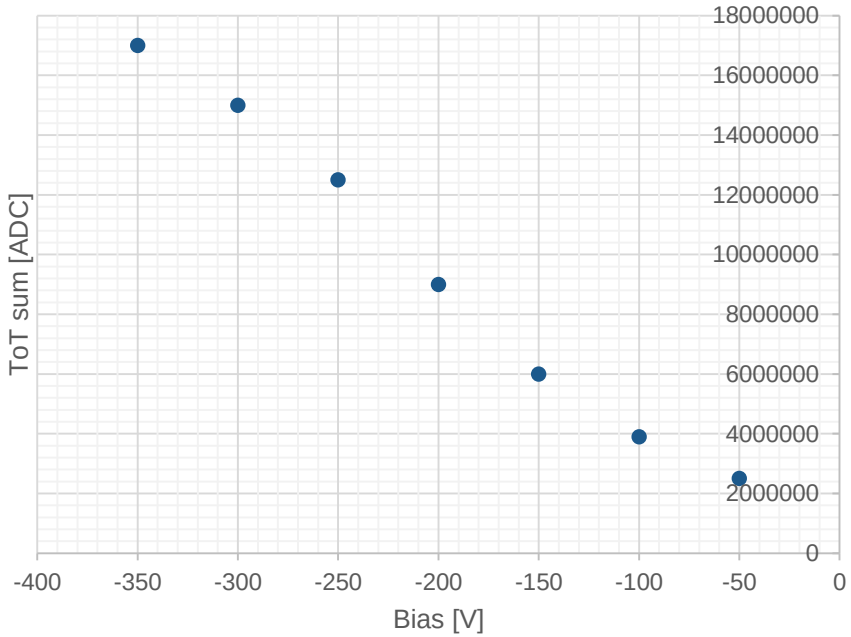



# LGAD: 110 um pixel, 10 um JTE

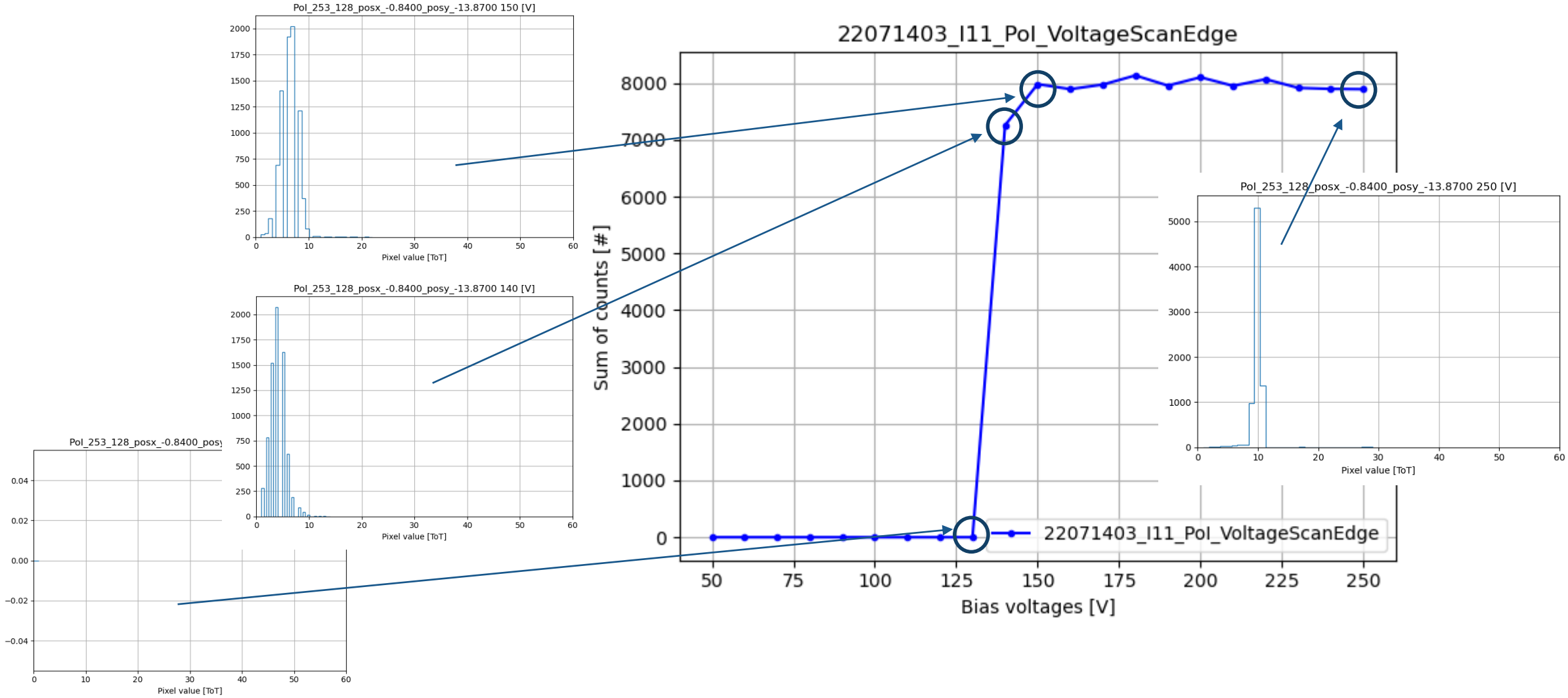
## Gain @ voltages, gain pixel (127, 127)



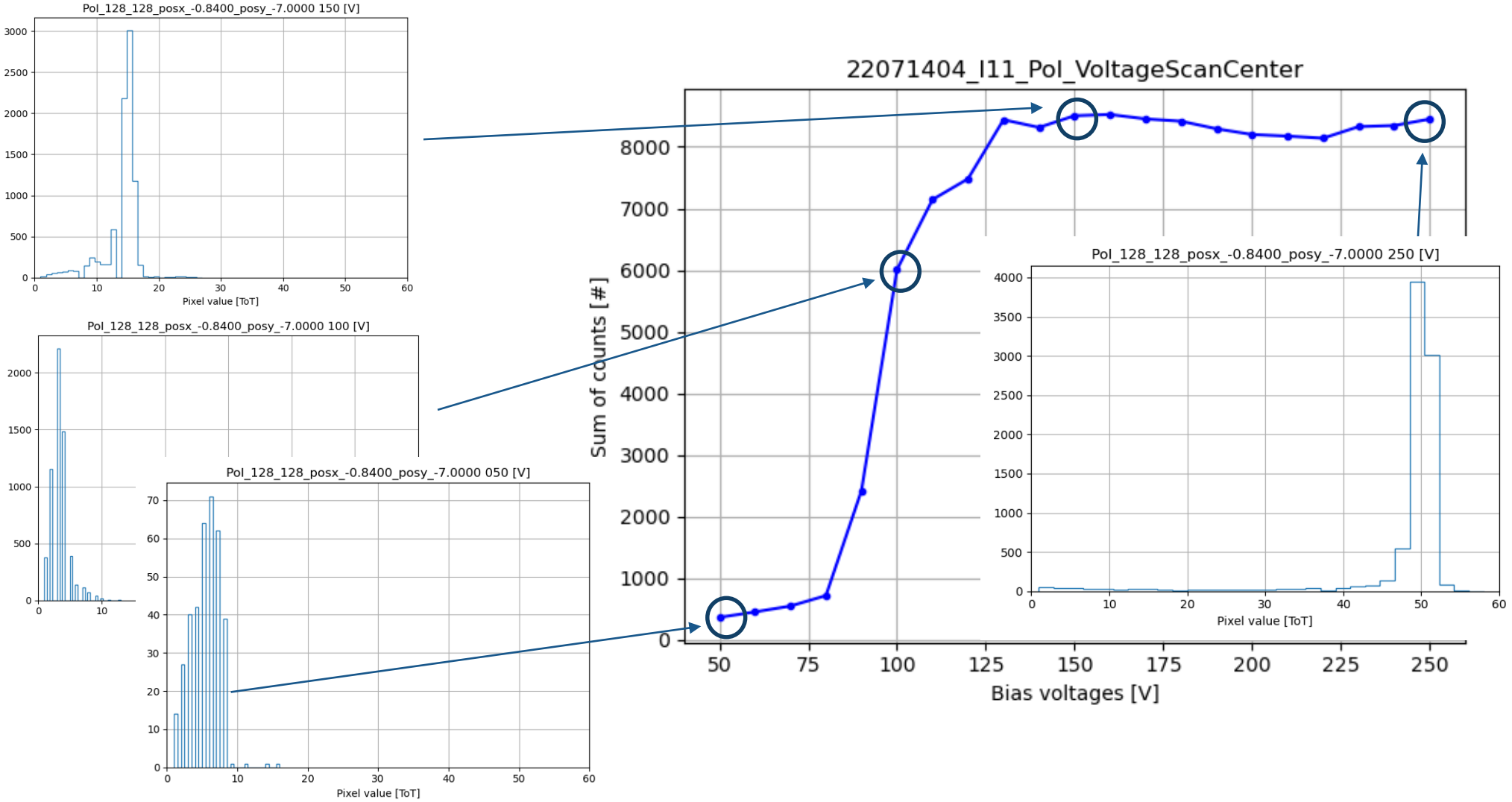
# iLGAD: 55 um pixel

## Voltage scan and spectra [EDGE, no gain pixel]



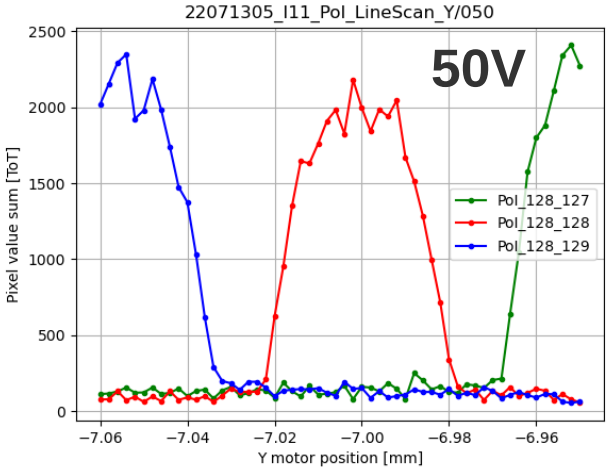
# iLGAD: 55 um pixel

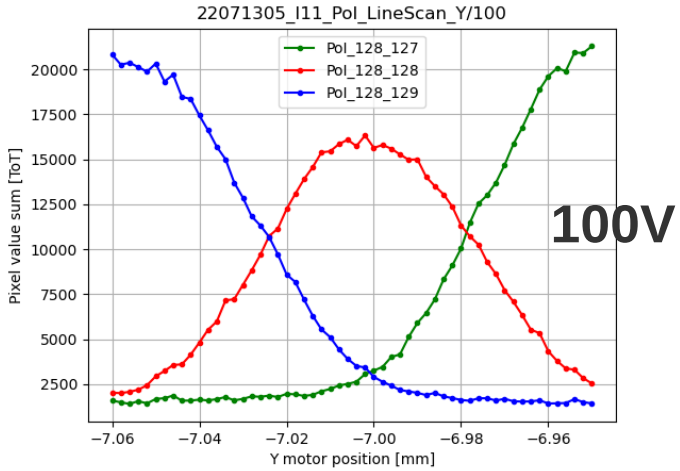
## Voltage scan and spectra [CENTRE, gain pixel]

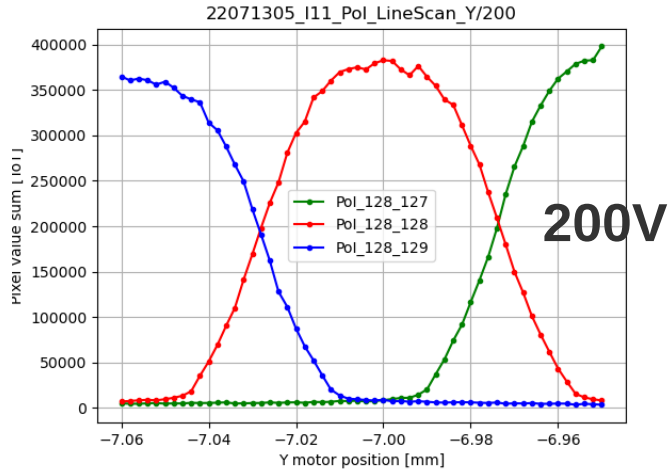


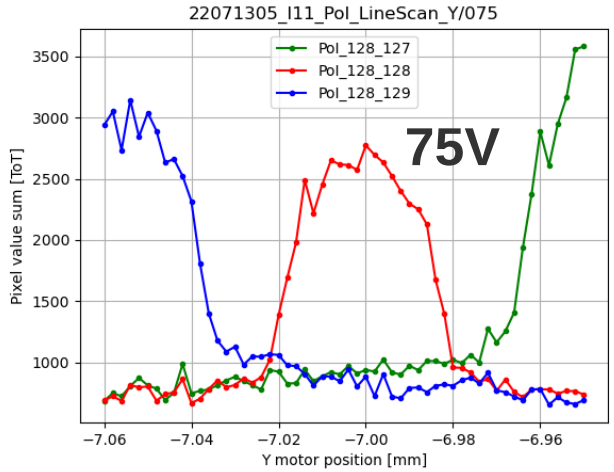
# iLGAD: 55 um pixel

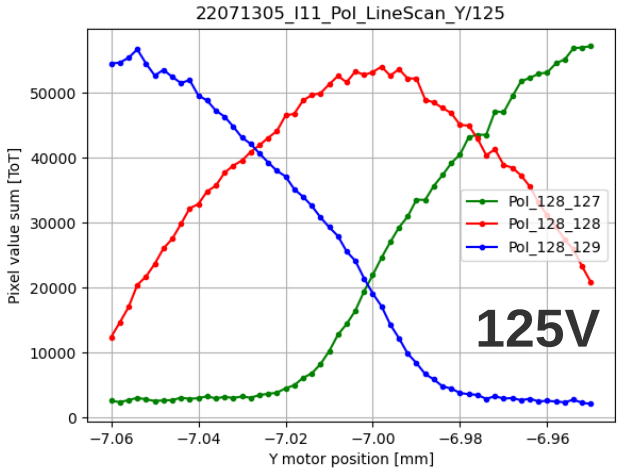
## Line scan CENTRE @ voltages

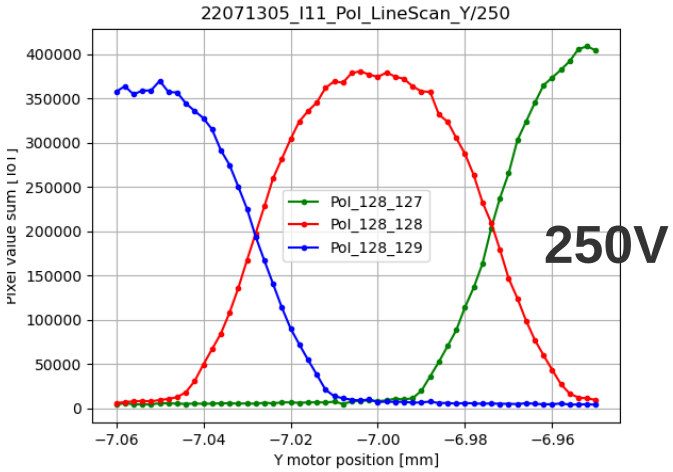


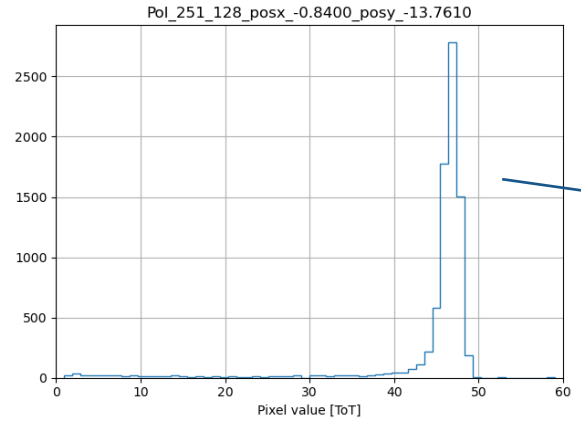
# iLGAD: 55 um pixel

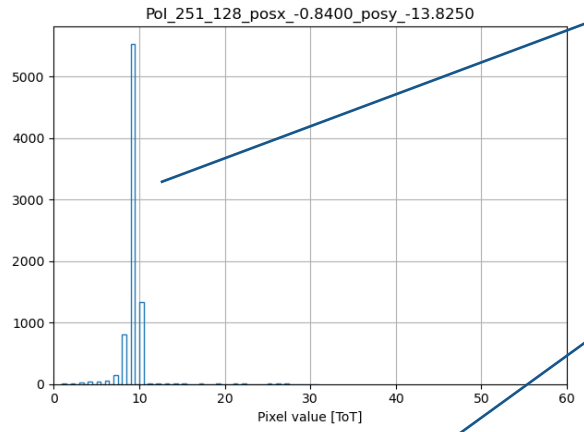
## Line scan EDGE

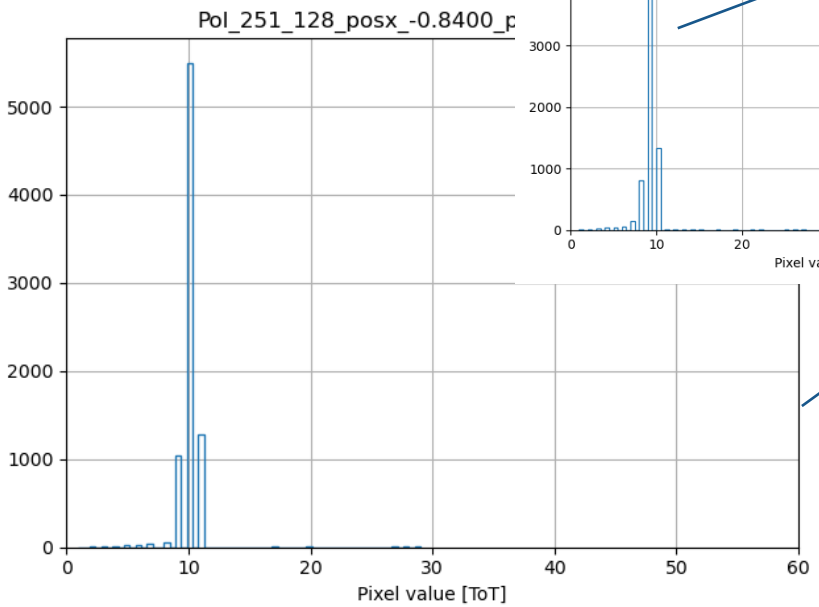
**COUNTS**

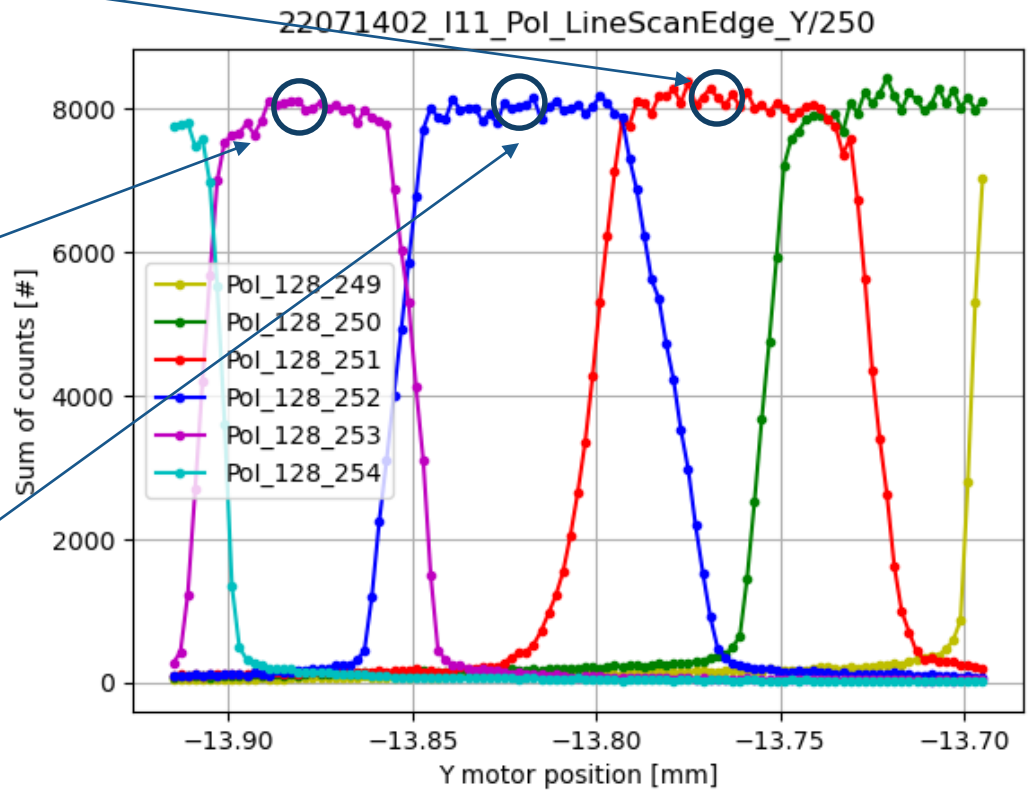
**Peak_G / Peak_nG**

**Gain ~4.6**



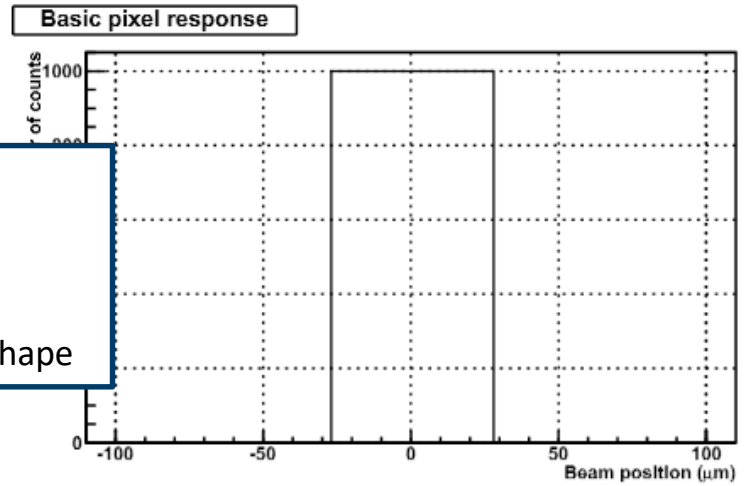



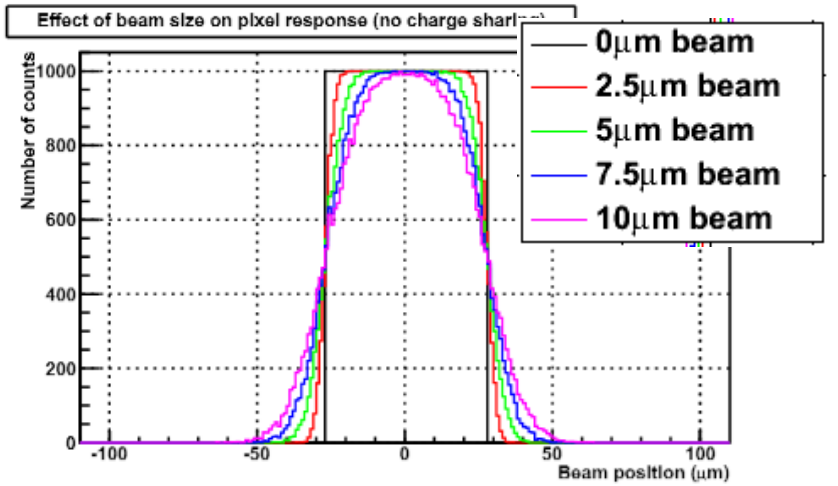
# Pixel response simulation

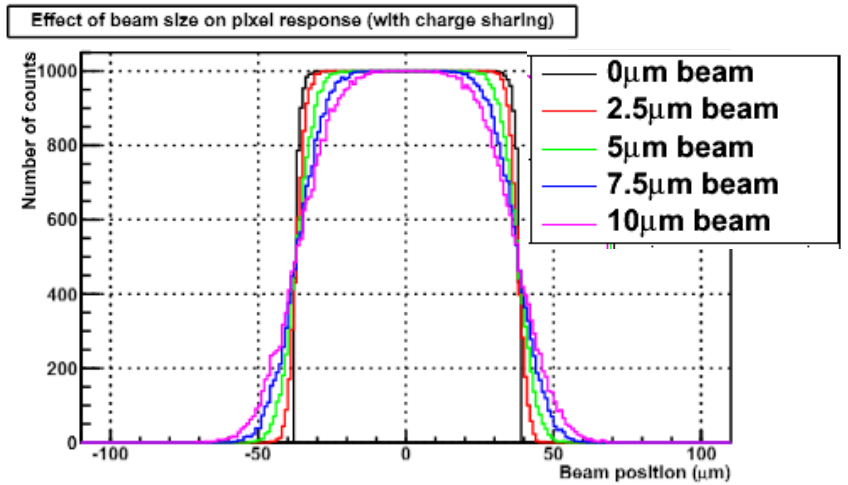
## Toy model

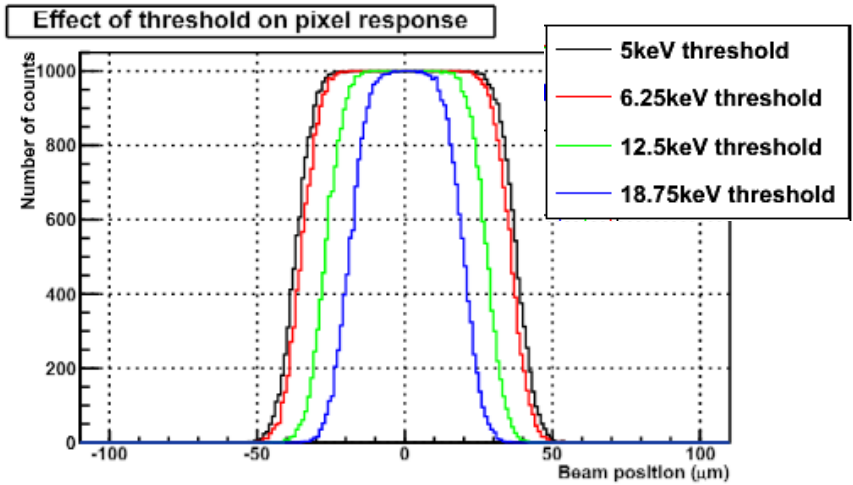
**Some basic conclusions**

- Beam size affect shape only
- Threshold affect width, but not shape
- Charge sharing affects width, but not shape



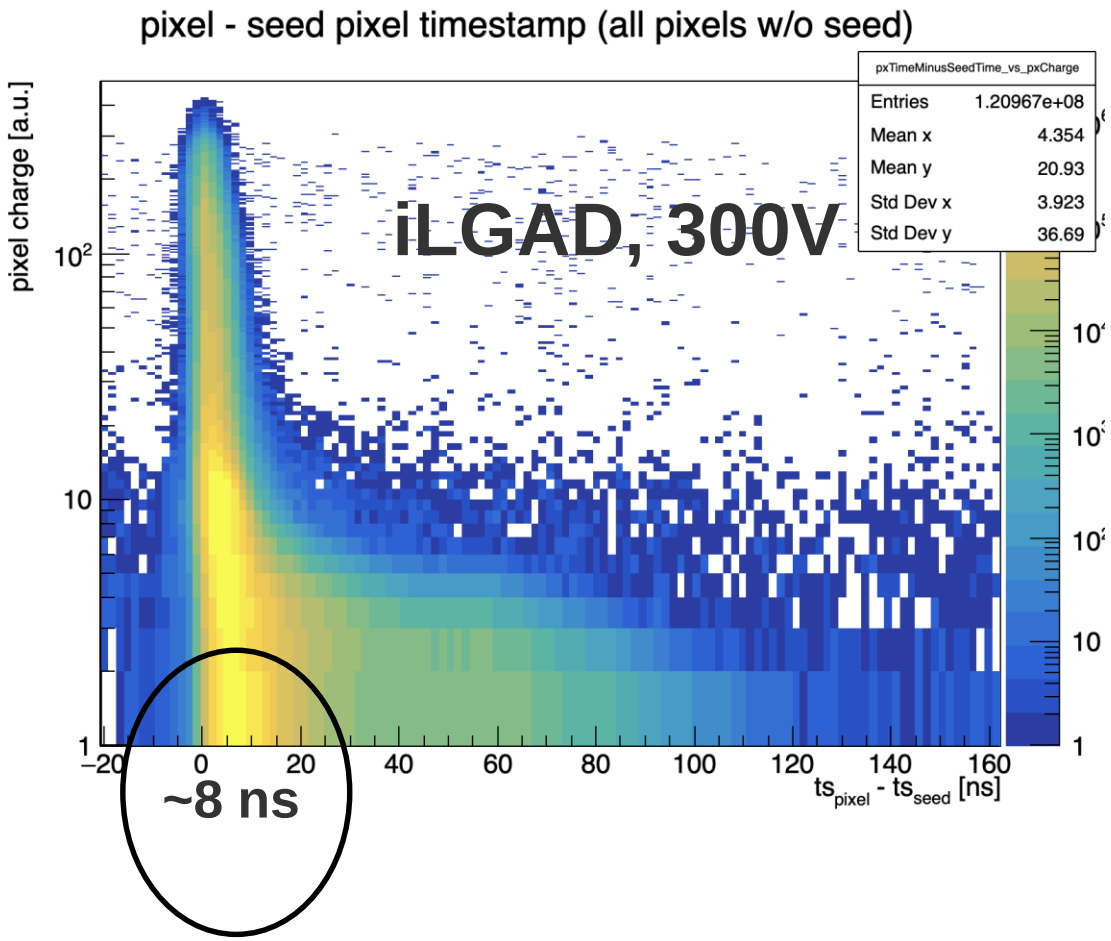



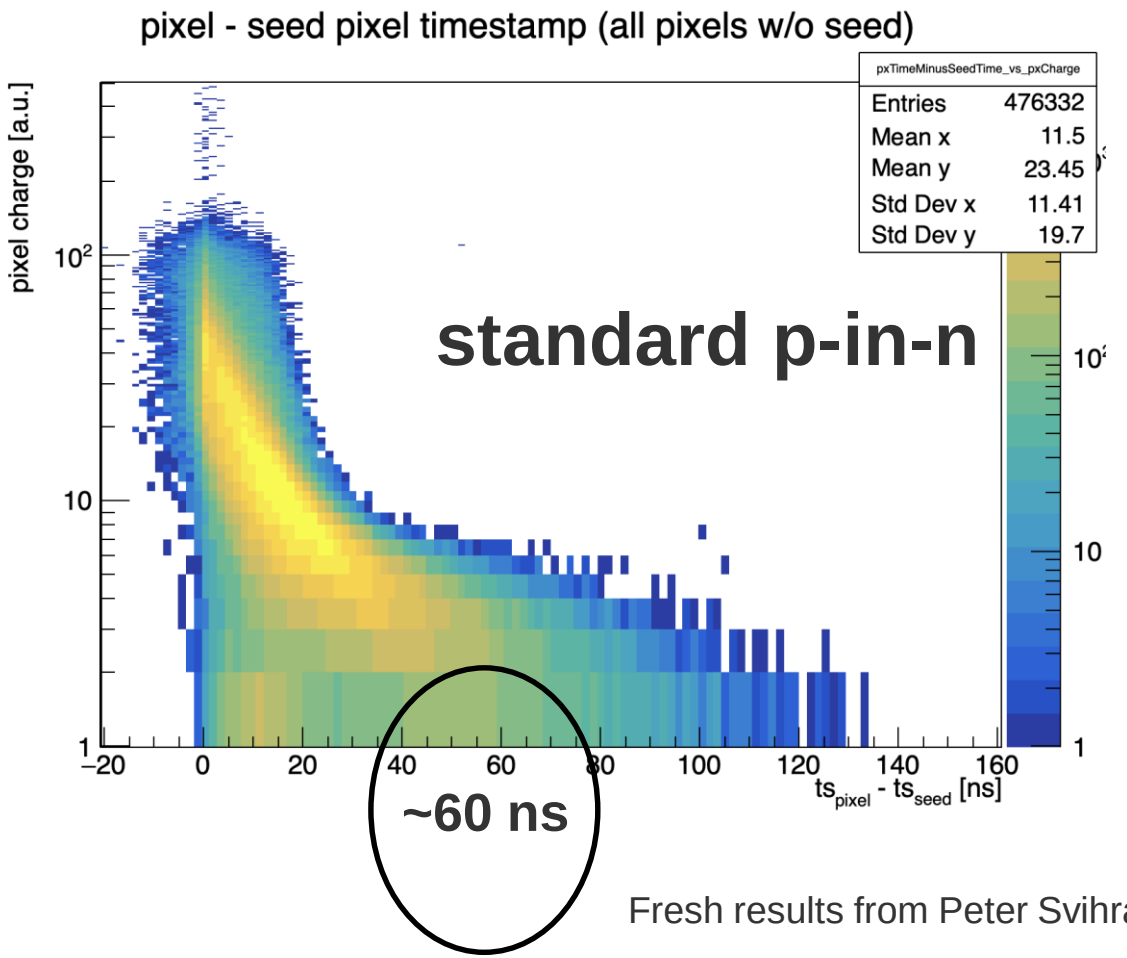



# Timing resolution

## SPS (120 GeV pions) test beam timing resolution comparison

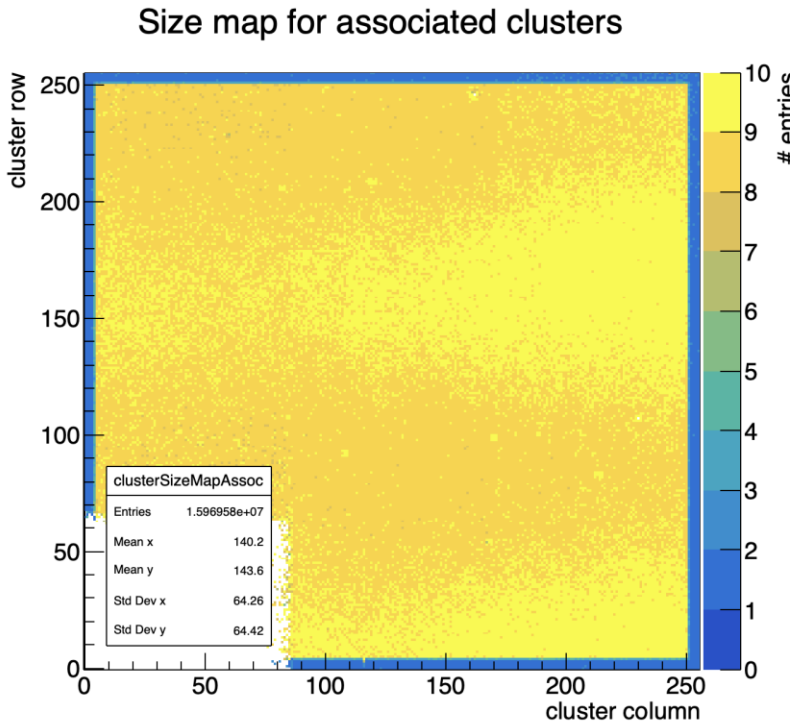


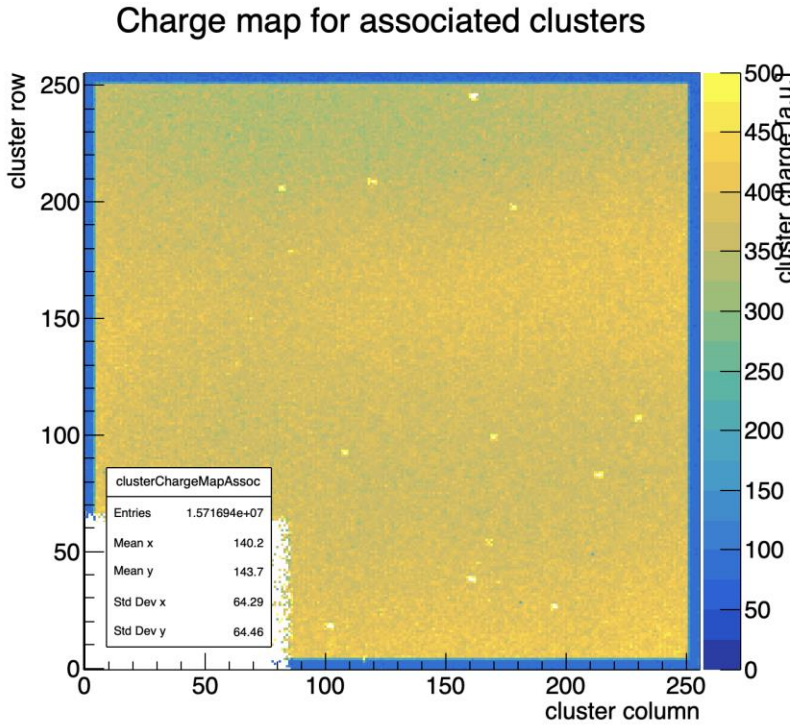



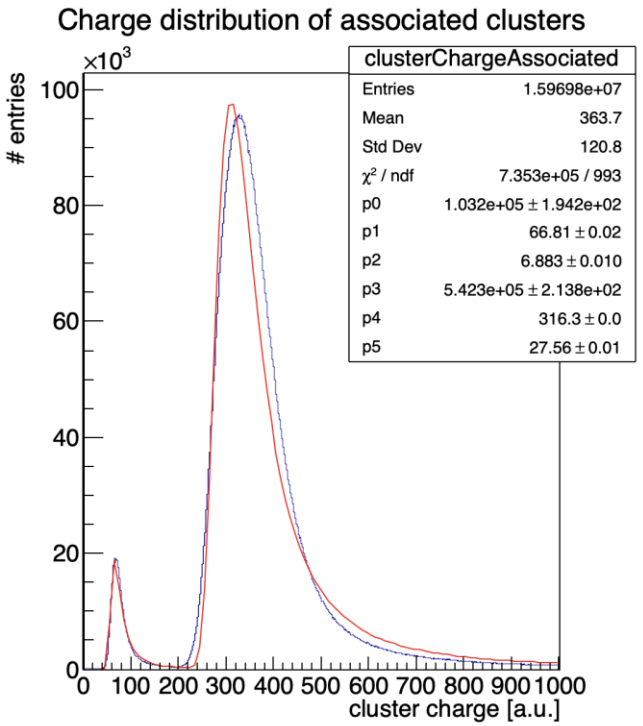

Fresh results from Peter Svihra

# Matrix gain uniformity

## SPS (120 GeV pions) test beam gain uniformity map




Gain about 4.75 at 300V

ToT not corrected!

Fresh results from Peter Svihra