Update on AIDAInnova device characterization at test beam

AIDAinnova 3rd annual meeting

19 Mar 2024

Matías Senger on behalf of the

AIDAinnova WP6
test-beam team

AIDAinnova WP6 test-beam team

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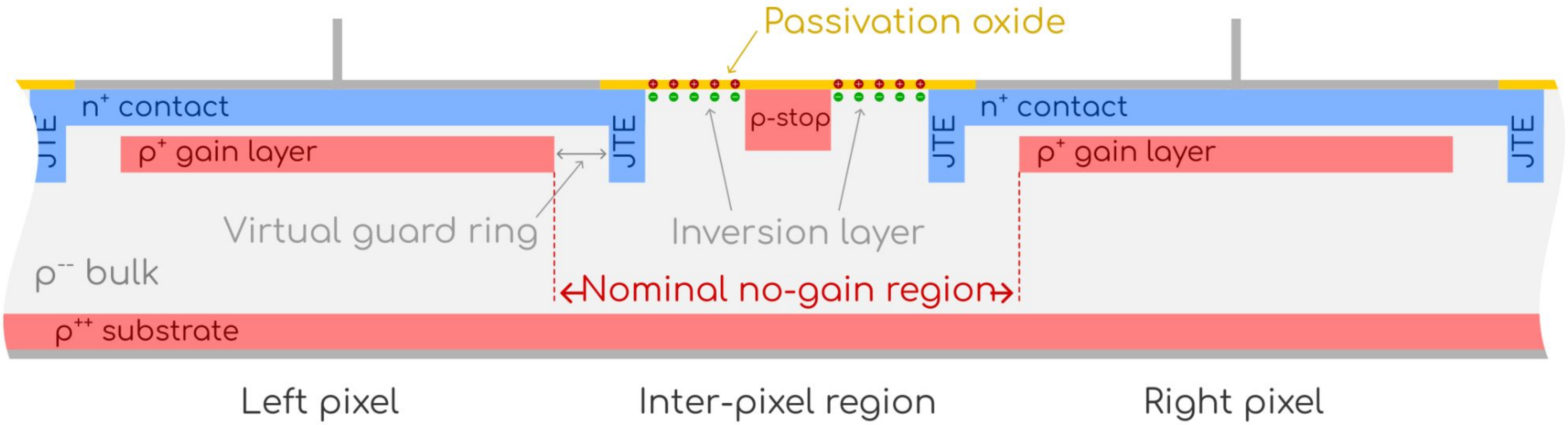
Acknowledgements

- DESY test beam coordinators for being super helpful
- LHCb-Velo group for lending us the equipment
- Uni-HH group for Chiller and cold finger

LGAD technology

Low Gain Avalanche Detector (LGAD):

- Thin planar silicon sensor (~50 μm thickness)
- Large electric field in gain layer
- Impact ionization linear gain ~10-80



Applications of LGAD technology in HEP

LGADs provide ~30 ps time resolution for high energy charged particles, and will be used in the high-luminosity LHC:

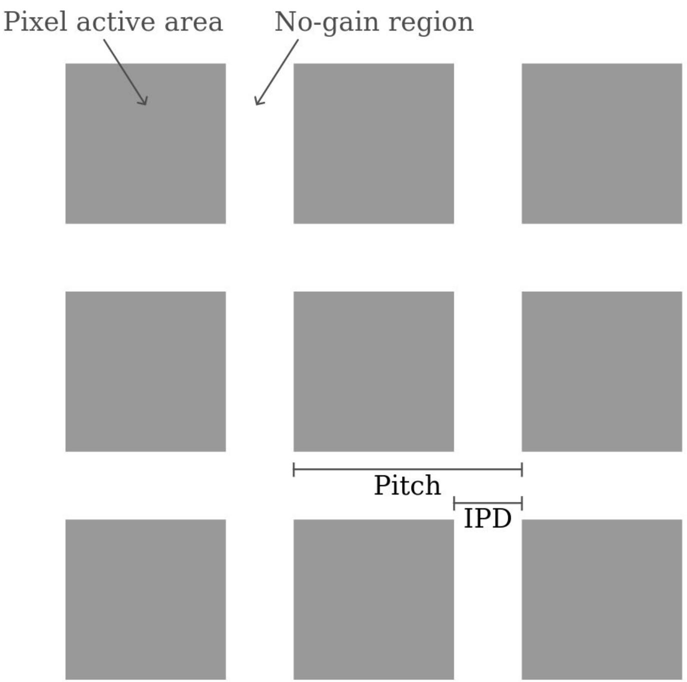
- CMS ETL[1]
- ATLAS HGTD[2]

[1] CMS collaboration. "A MIP Timing Detector for the CMS Phase-2 Upgrade." Technical Design Report. CMS, March 15, 2019. https://cds.cern.ch/record/2667167.

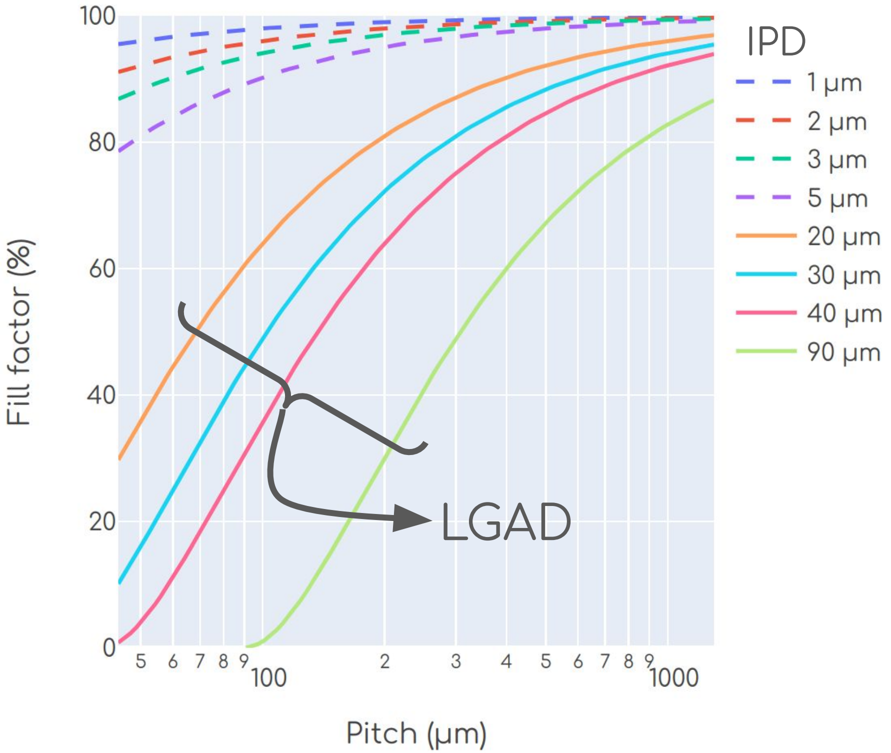
[2] ATLAS colaboration. "Technical Design Report: A High-Granularity Timing Detector for the ATLAS Phase-II Upgrade." Technical Design Report. ATLAS. CERN, June 5, 2020. https://cds.cern.ch/record/2719855.

Limitations of LGAD technology

- Not suitable for pixels smaller than ~1000×1000 μm²



$$\text{Fill factor} \stackrel{\text{def}}{=} \frac{\text{Sensor active area}}{\text{Total sensor area}}$$

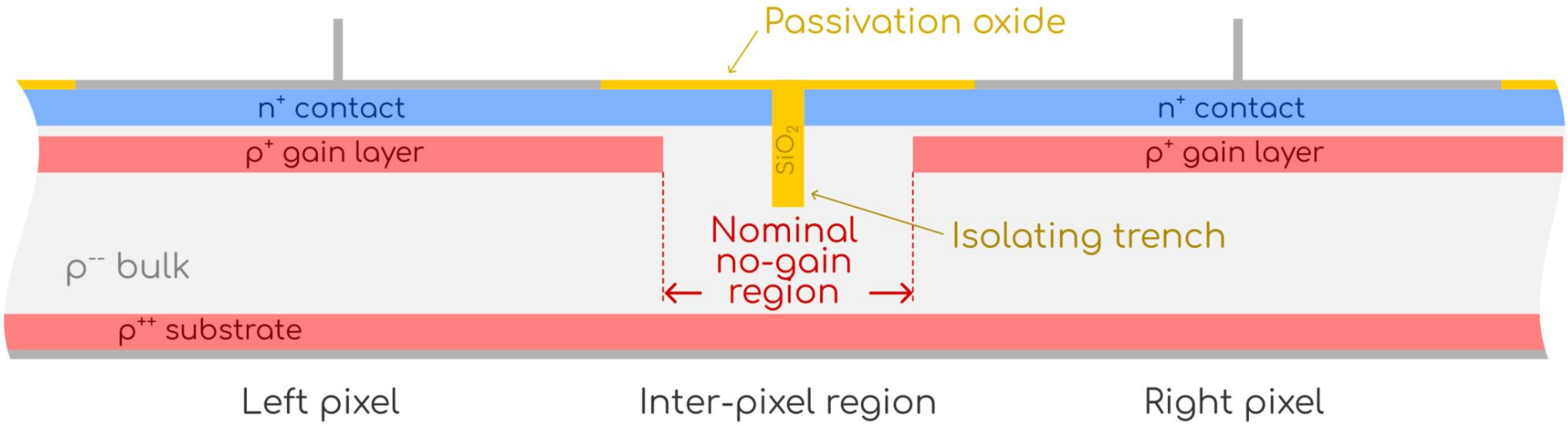


TI-LGAD technology

The TI-LGAD technology

Goal: Sensor with small pixels (~100×100 µm or smaller) and high fill factor (95 % or higher).

LGAD pixels isolated with trenches, smaller no-gain region:



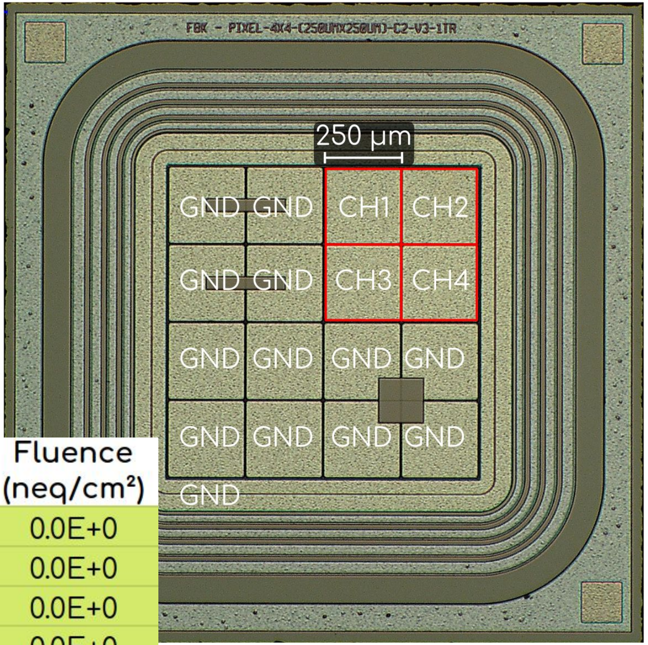
TI-LGAD productions

- TI-LGAD RD50 FBK
  - First production of this technology
  - Completed in 2021
  - Goal: To explore the effect of different design parameters related to the trenches
  - Carried out in the framework of the RD50 collaboration
- TI-LGAD AIDAinnova FBK
  - Second production
  - Incorporates inputs from studies from previous production
  - Goal: Make the TI-LGADs more radiation hard by adding carbon co-implantation in the gain layer
  - Production completed, wafer 1 diced, wafers 6 and 10 will be diced soon
  - Carried out in the framework of the AIDAinnova project

Test beam characterization at CERN SPS

Tested devices

- All from FBK RD50 TI-LGAD production
- Same physical layout and connection →
- 8 DUTs, details in table below ↓

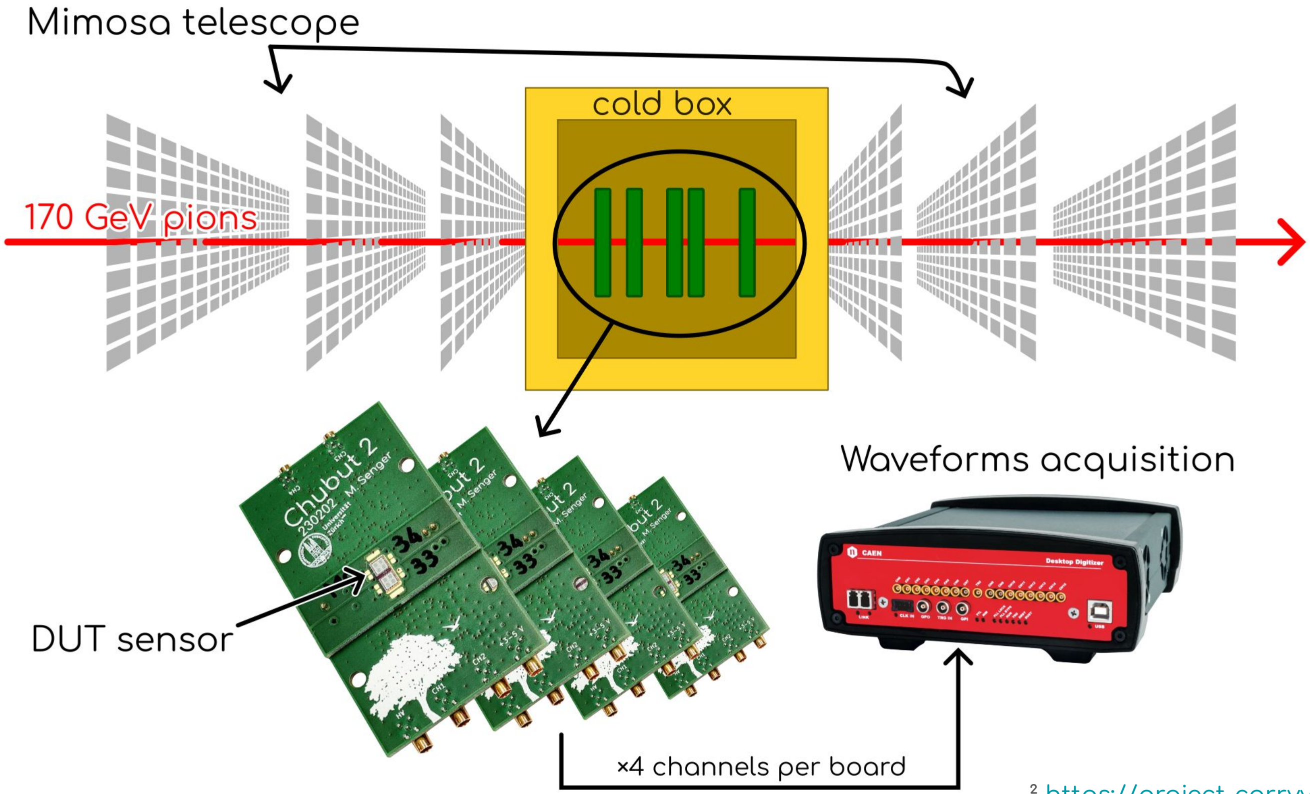


device_name	wafer	trench process	trench depth	trenches	pixel border	contact type	Fluence (neq/cm²)
TI116	16	P2	D3	1	V3	dot	0.0E+0
TI122	16	P2	D3	1	V3	ring	0.0E+0
TI123	16	P2	D3	1	V3	ring	0.0E+0
TI143	16	P2	D3	1	V2	ring	0.0E+0
TI145	16	P2	D3	1	V2	ring	1.0E+15
TI146	16	P2	D3	1	V2	ring	1.0E+15
TI229	7	P2	D2	1	V3	ring	1.0E+15
TI230	7	P2	D2	1	V3	ring	1.0E+15

* Devices were irradiated with reactor neutrons at JSI, Ljubljana.
** "device_name" can be ignored, it is shown here for curious readers who may want to see details from the examples.

Test beam setup at CERN

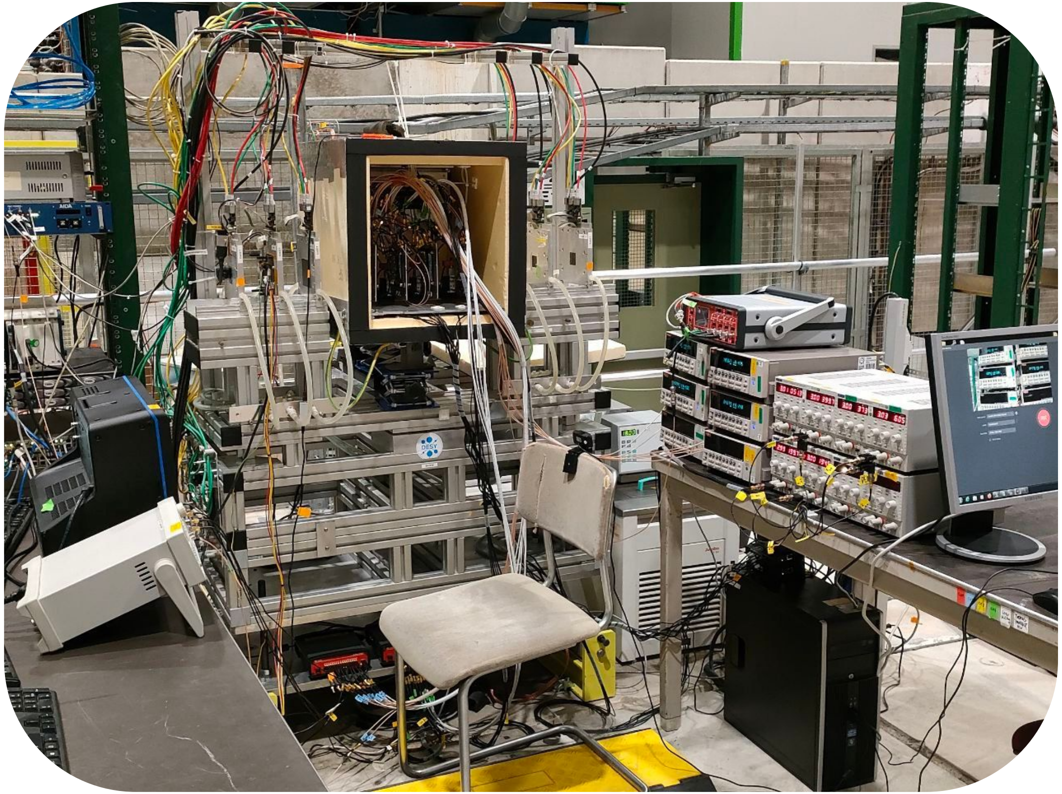
Simplified diagram:

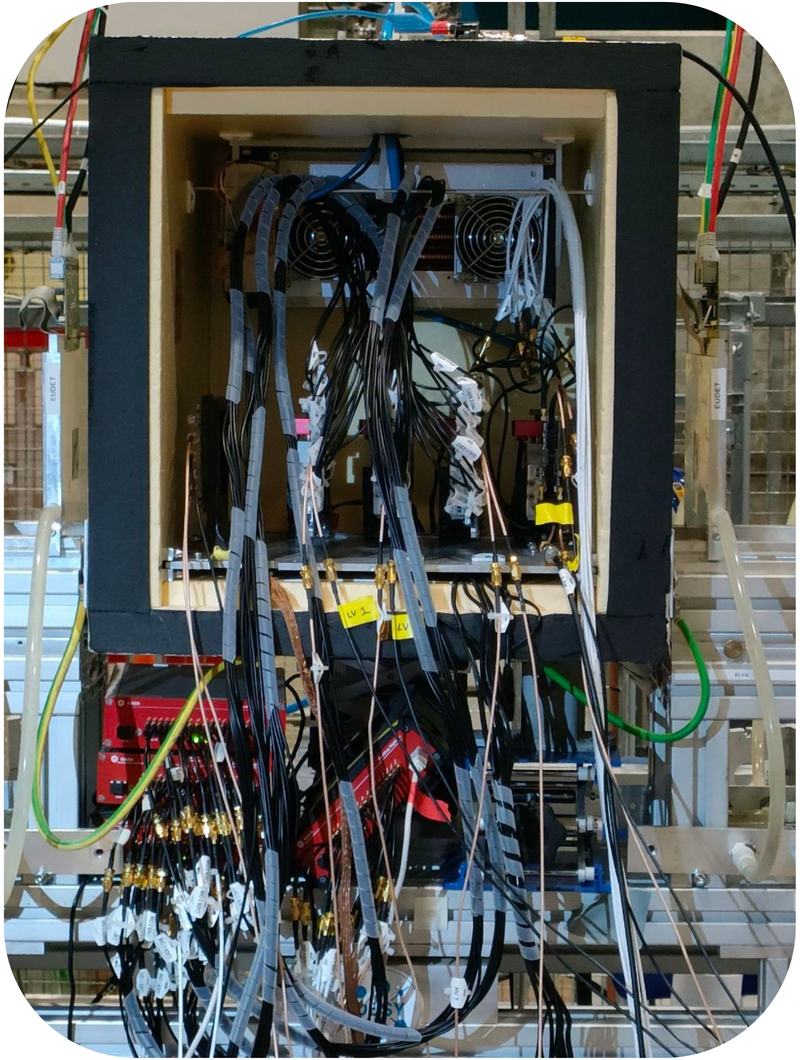


- CERN H6 beamline (120 GeV pions)
- Mimosa telescope
- Chubut 2, 4 channels readout board[1]
- CAEN DT5742 digitizer, 500 MHz @ 5 GS/s
- Cold box for irradiated DUTs, down to -12 °C
- Tracks reconstruction using Corryvreckan[2]

[1] https://github.com/SengerM/Chubut_2
[2] https://project-corryvreckan.web.cern.ch/project-corryvreckan/

Test beam setup at CERN

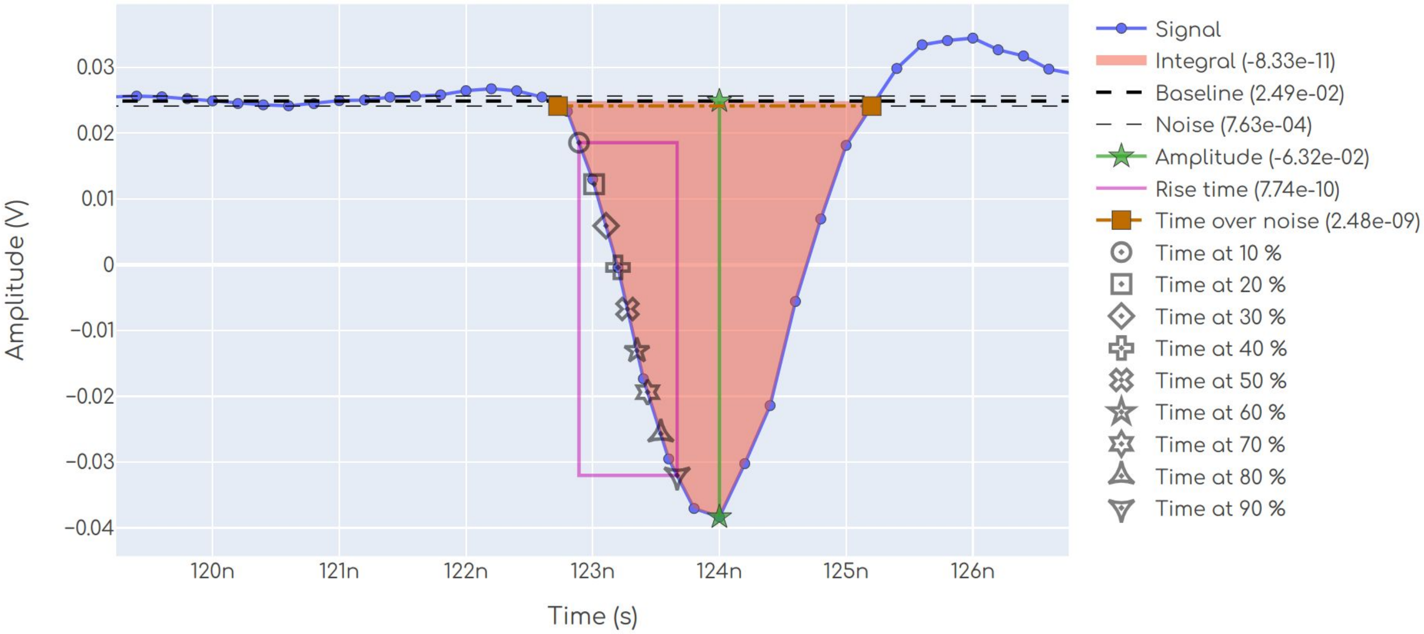




Offline analysis and results

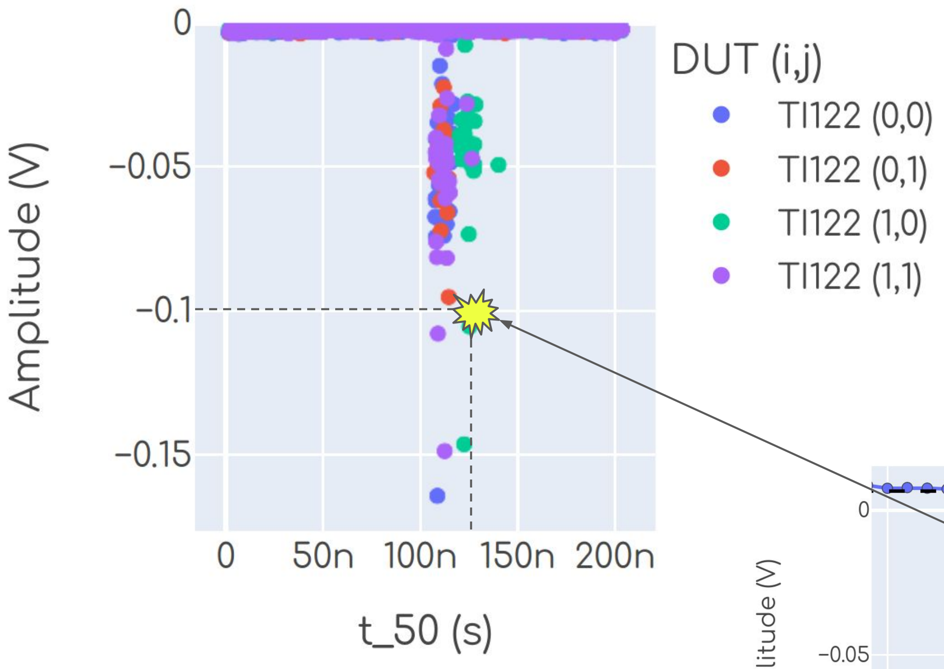
Waveforms analysis

We record the waveforms, then process them offline*. Example:

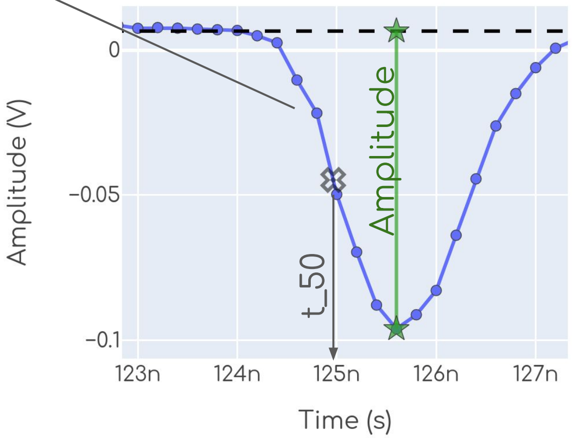


* https://github.com/SengerM/signals

Waveforms distribution and events selection



- Each dot is one waveform
- Color denotes channel

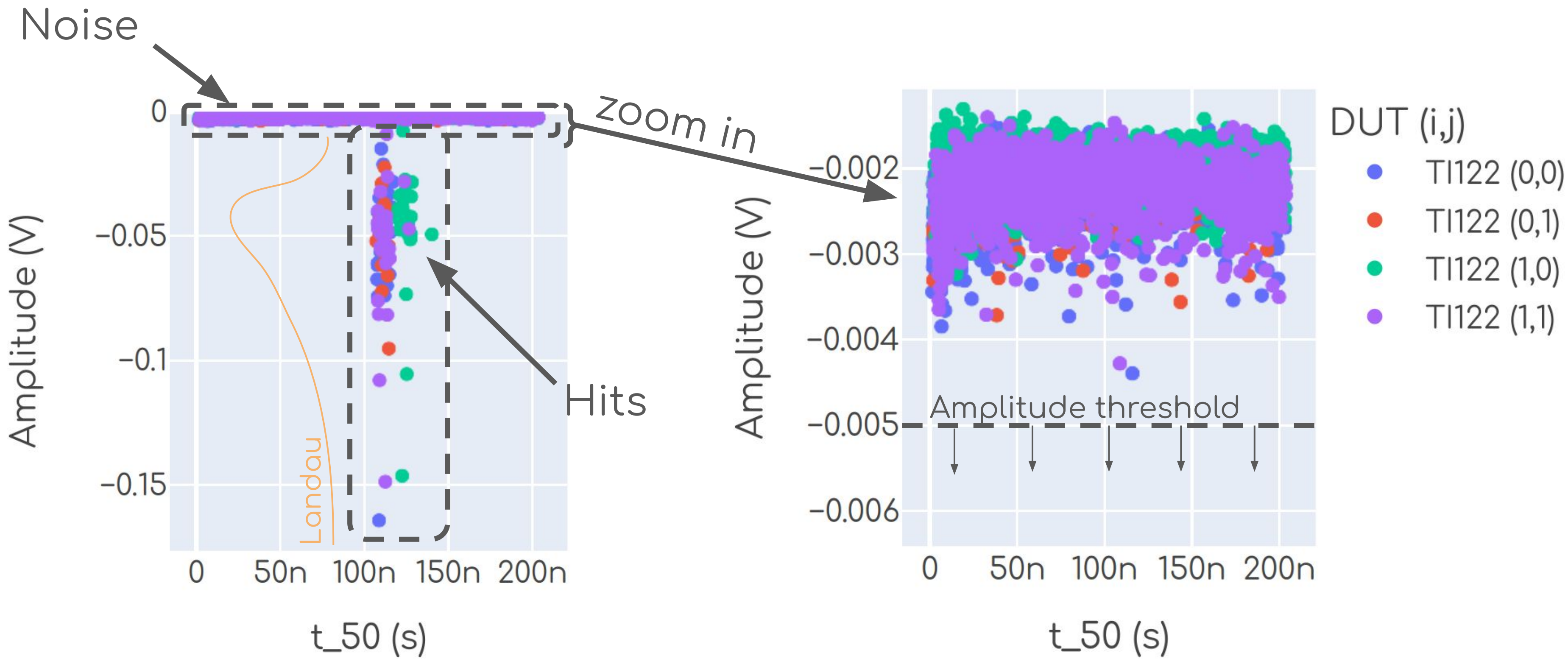


Example: This waveform has amplitude = 100 mV and t_50 = 125 ns

* This example is for one DUT, they all look similar.

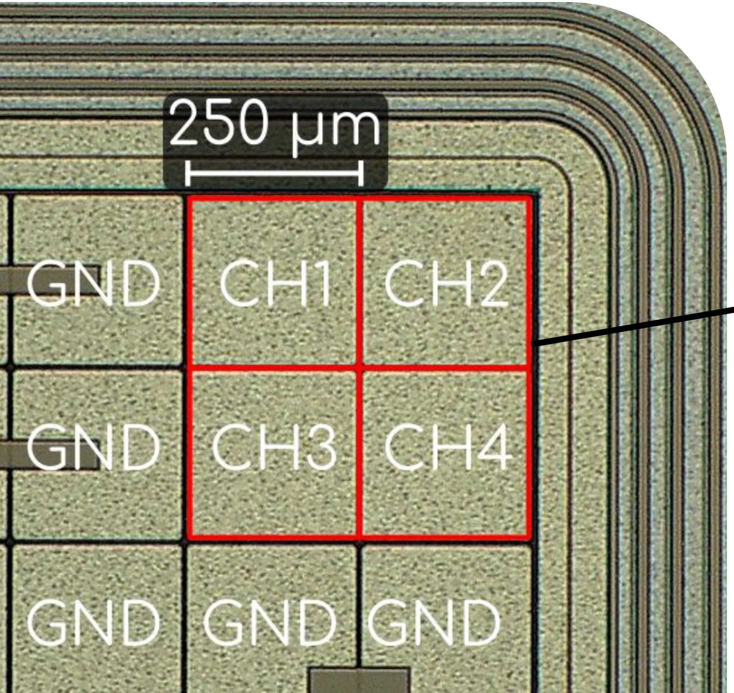
Waveforms distribution and events selection

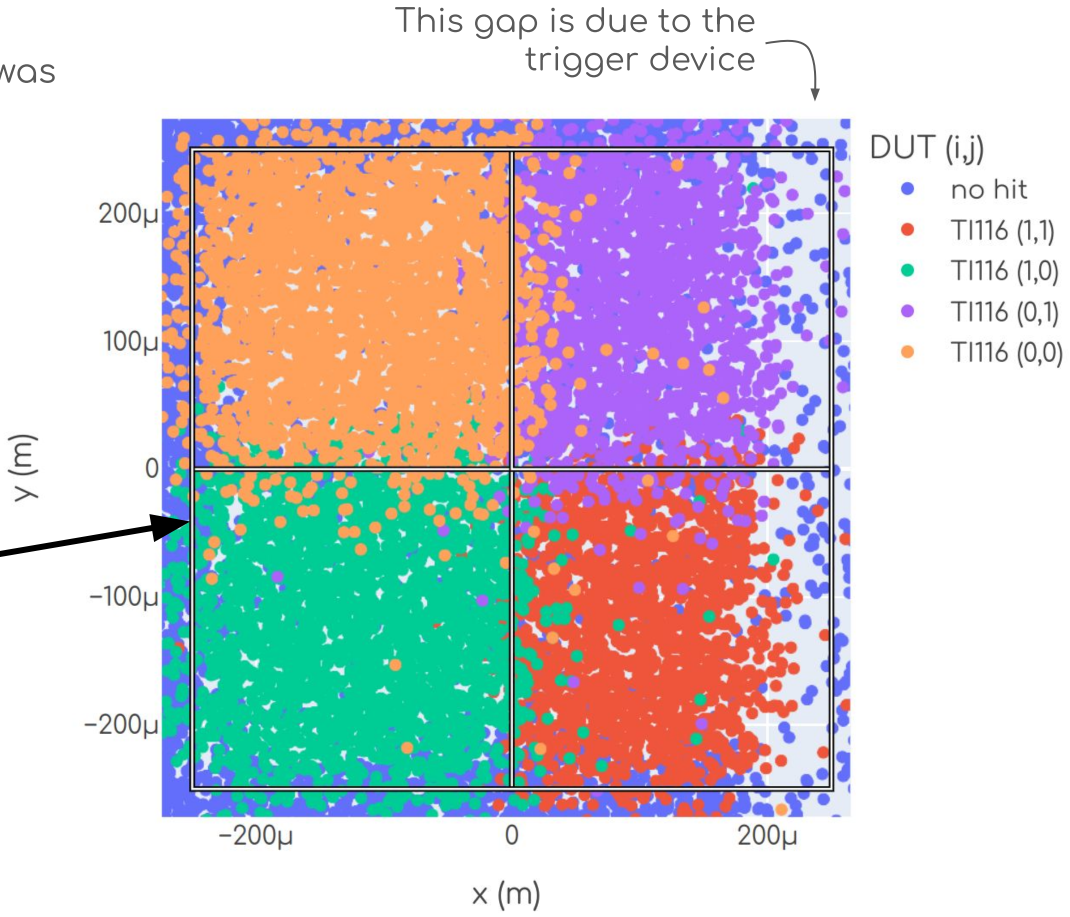
A threshold in amplitude defines what we consider a hit in a pixel:



Tracks and hits on DUTs

- Each dot is a track
- Colored according to which channel was hit
- Tracks reconstruction using Corryvreckan[1]



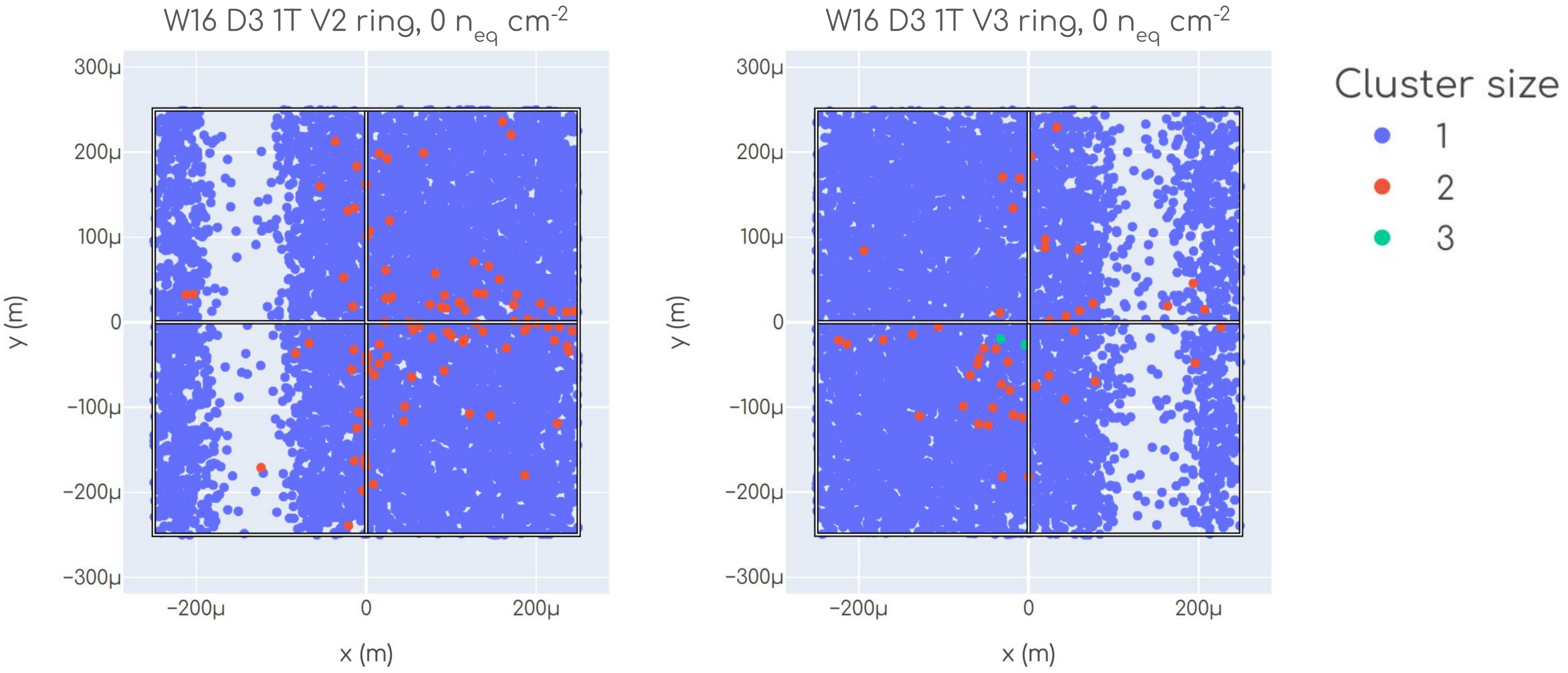


Charge sharing in TI-LGADs

* This example is for two DUTs, they all look similar.

We look at the cluster size, i.e. number of active pixels per hit.

Example for two DUTs:

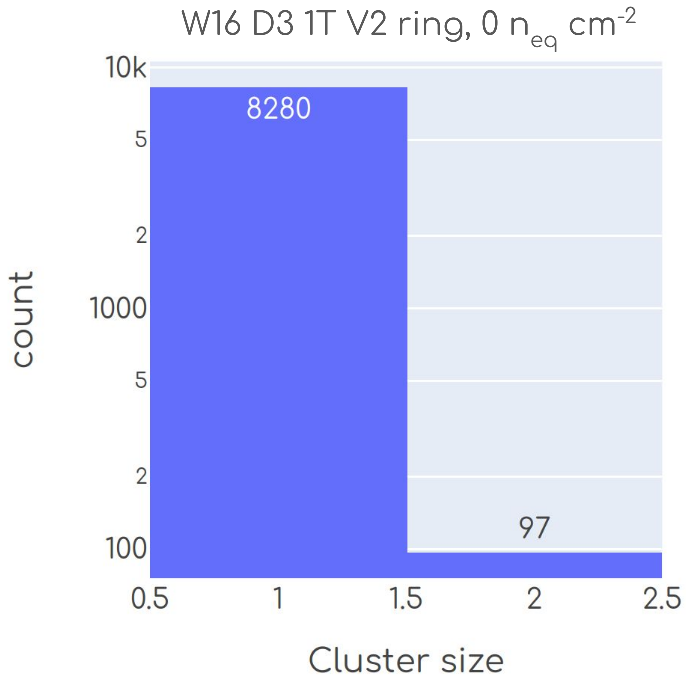


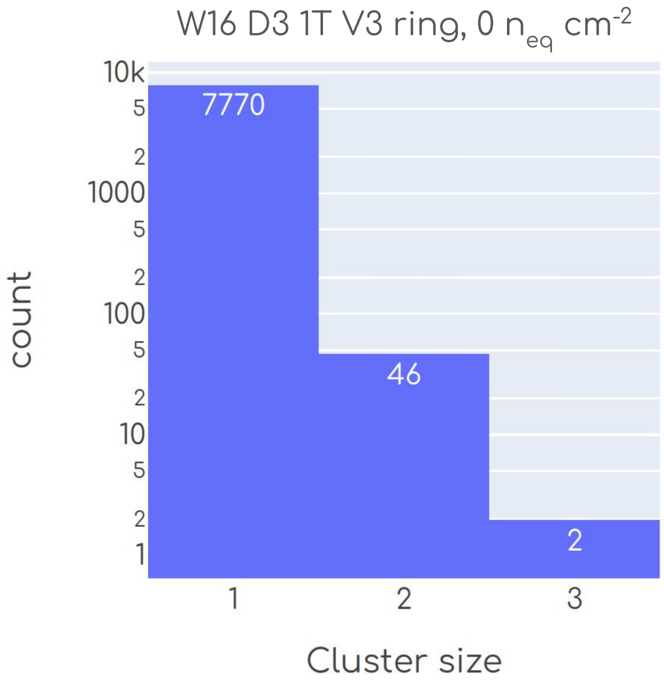
Charge sharing in TI-LGADs

* This example is for two DUTs, they all look similar.

Only ~1 % of events share charge, low value consistent with expectation ✅

Example for two DUTs (similar for all of them):

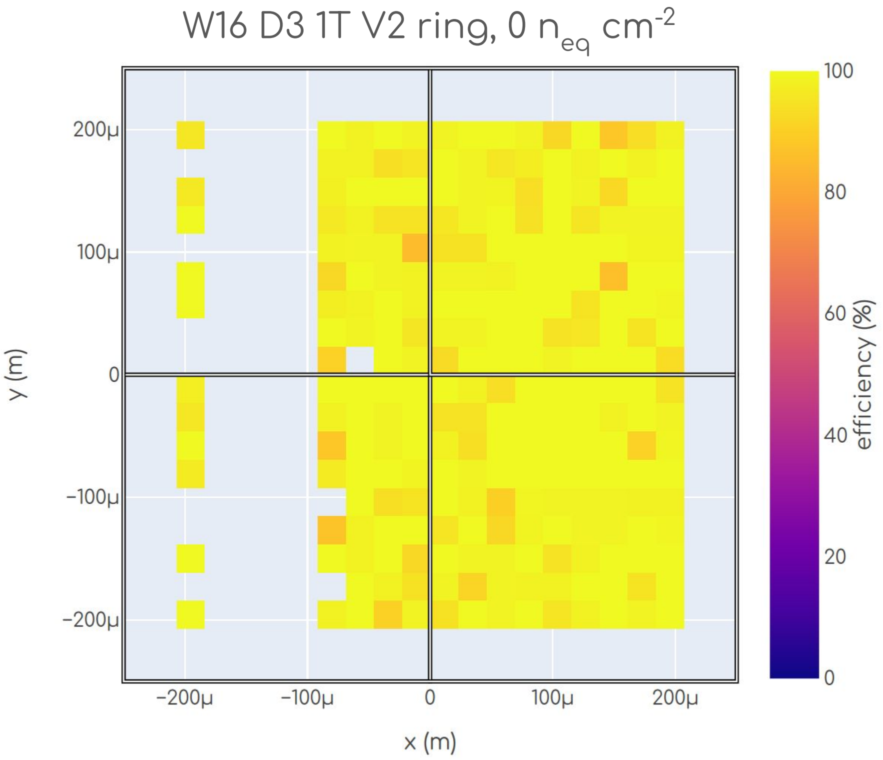


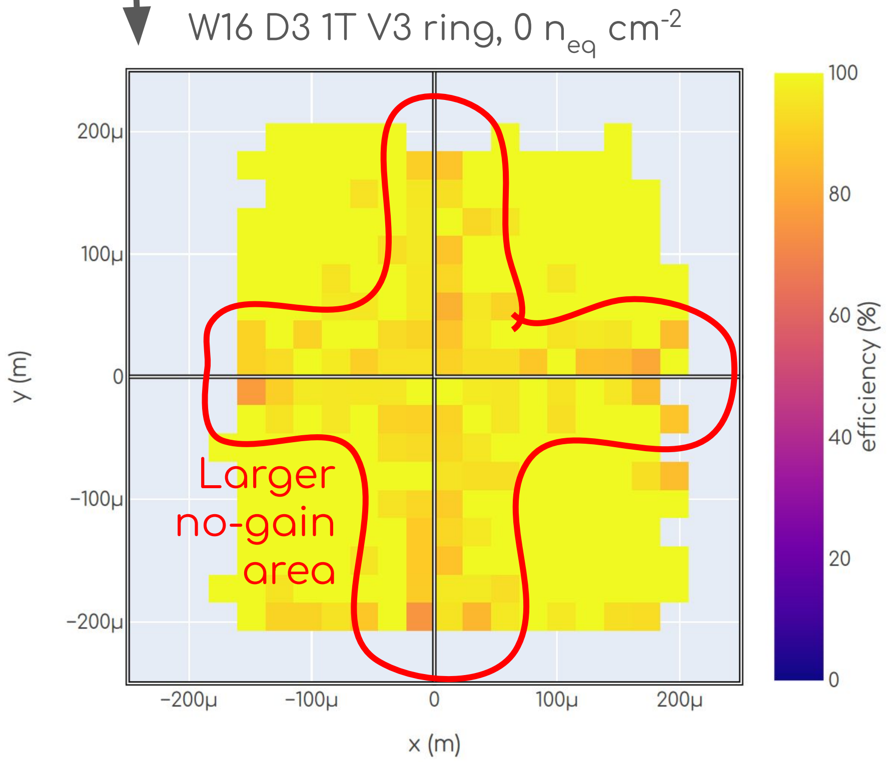


Efficiency vs position

$$\text{Efficiency} = \frac{\text{Number of detected particles}}{\text{Number of particles that went through}}$$

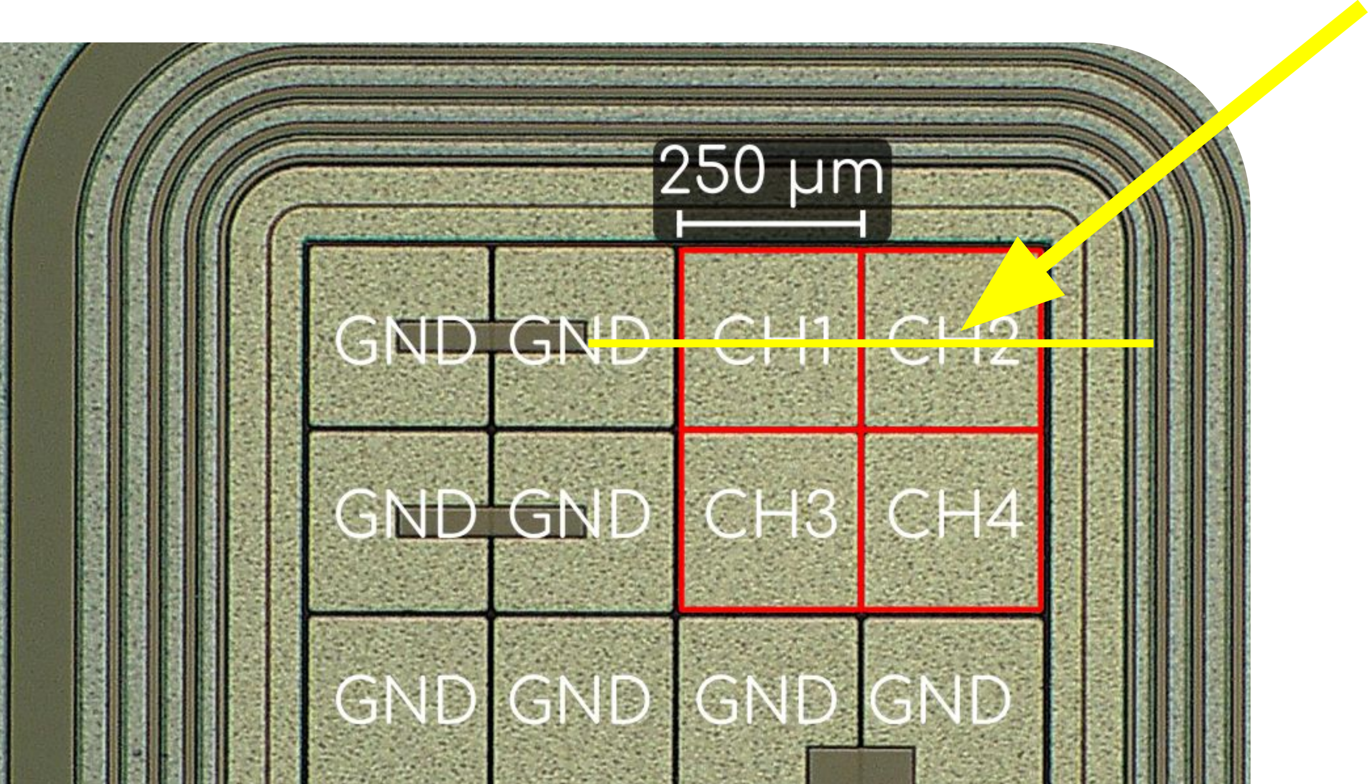
This DUT was measured as a control DUT, knowing it has a larger inter-pixel distance. Here we can see it ✅





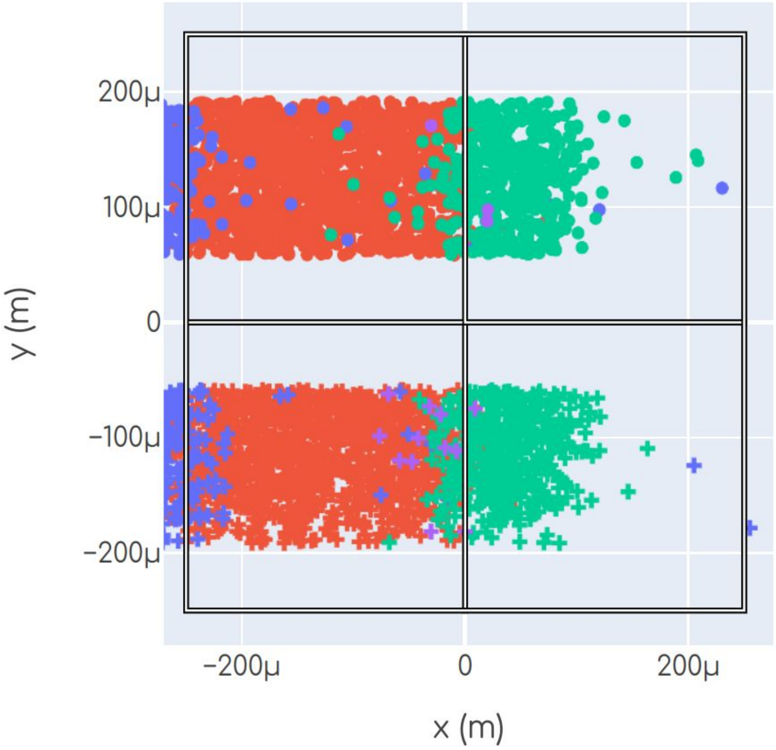
Efficiency profile

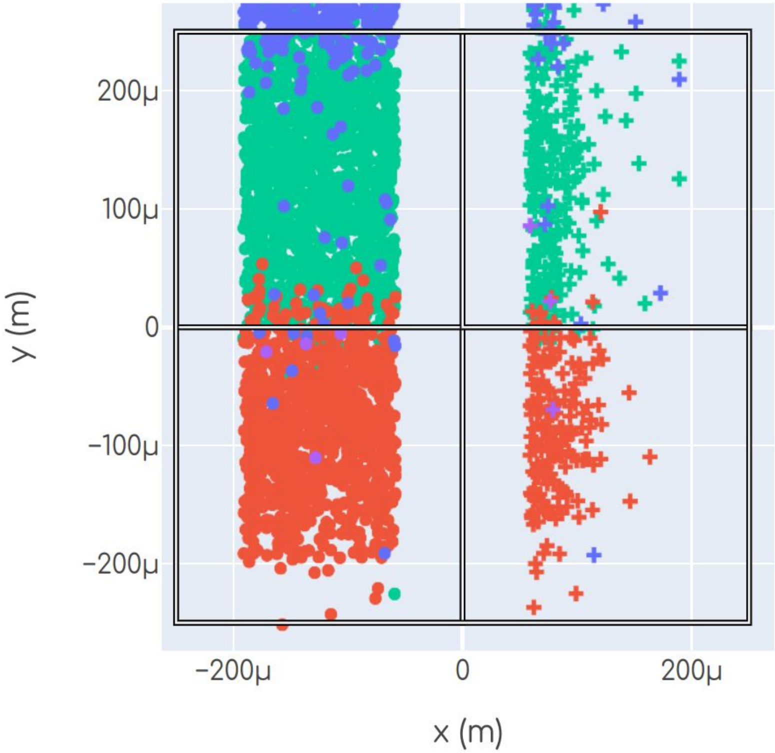
What's the efficiency profile along two pixels?



Efficiency profile

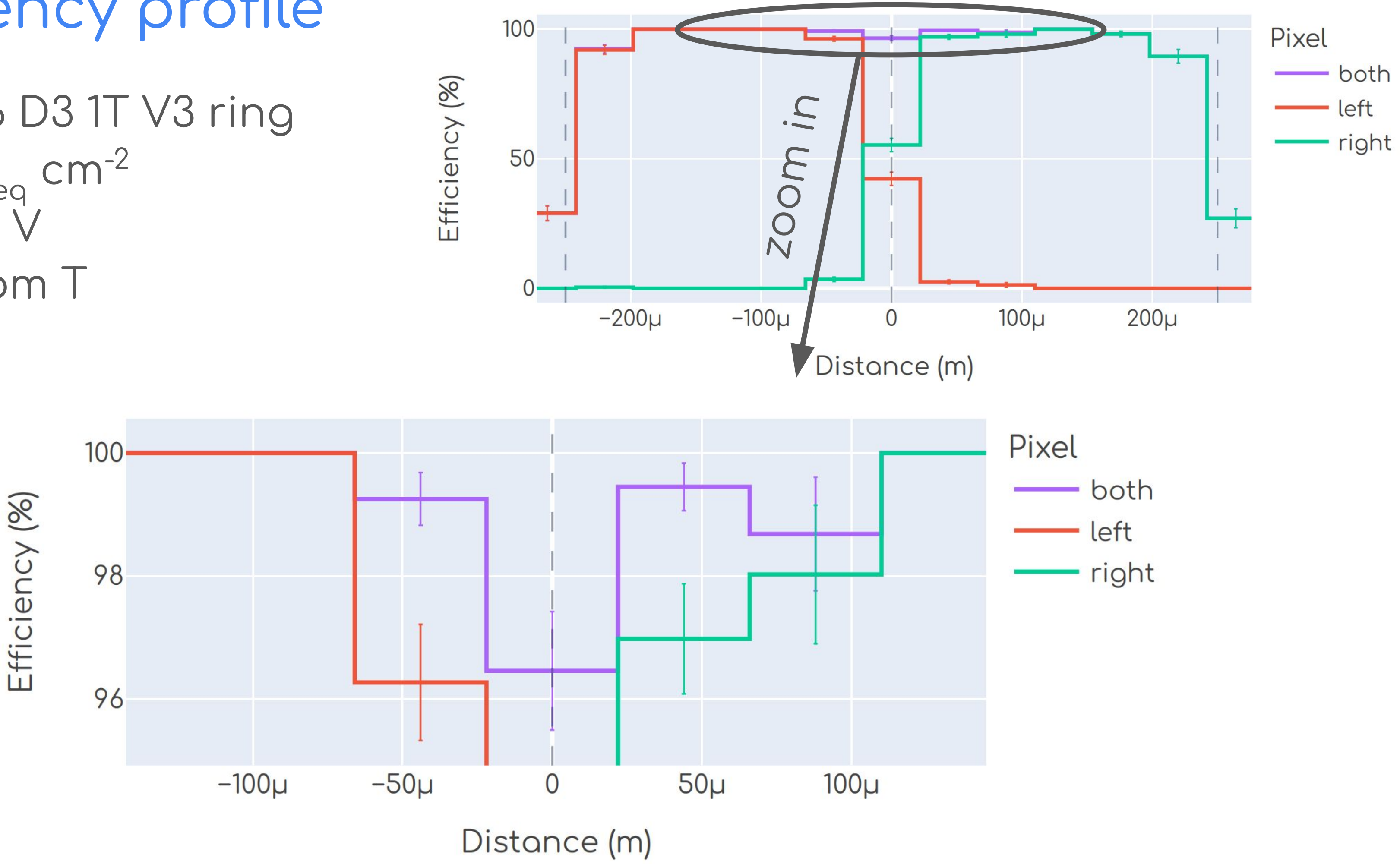
Select tracks within these strips and project along x and y





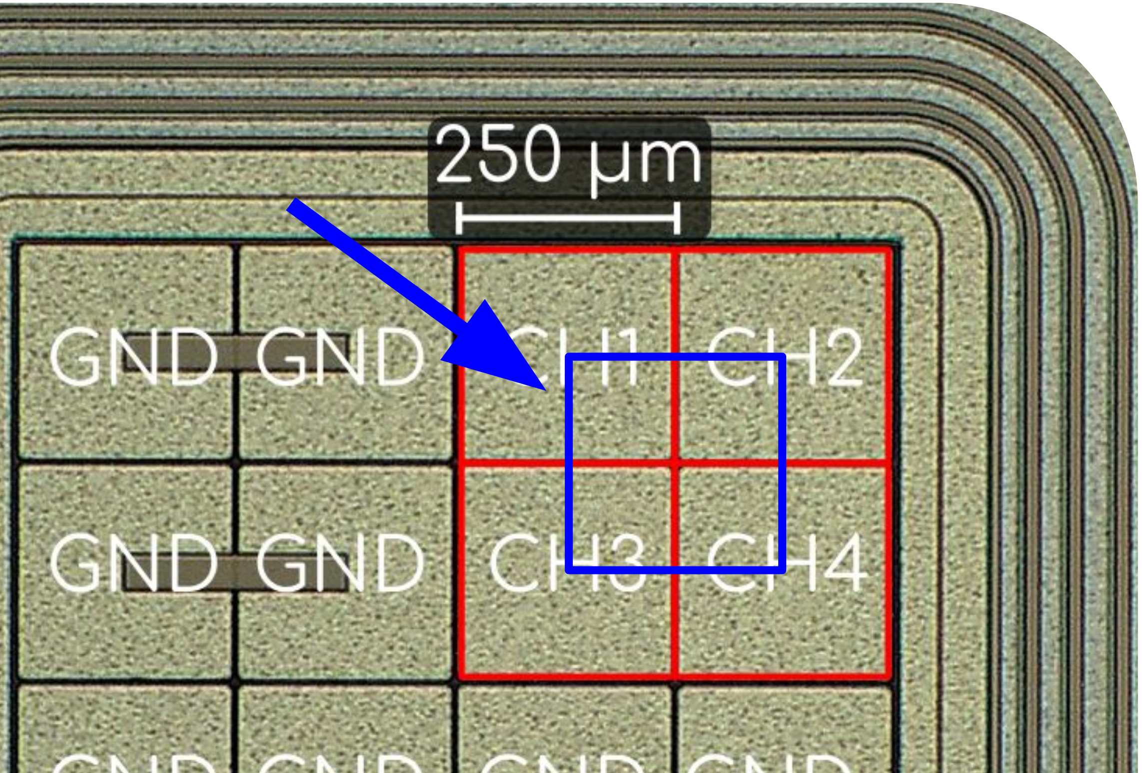
Efficiency profile

- W16 D3 1T V3 ring
- 0 n_{eq} cm^{-2}
- 230 V
- Room T



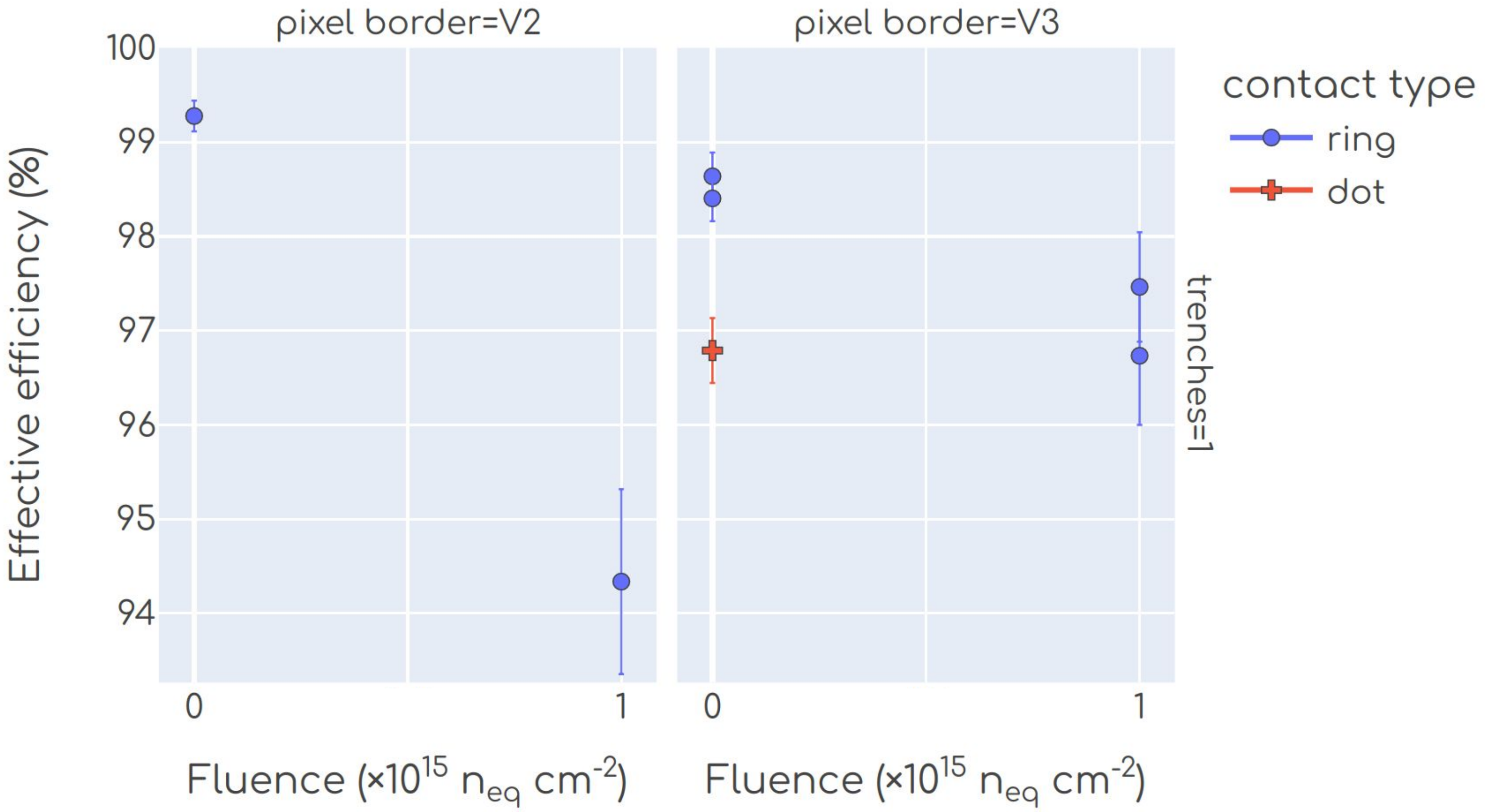
Effective efficiency

Efficiency measured in an area of the same size as a pixel. To avoid edge effects, take it close to the center:



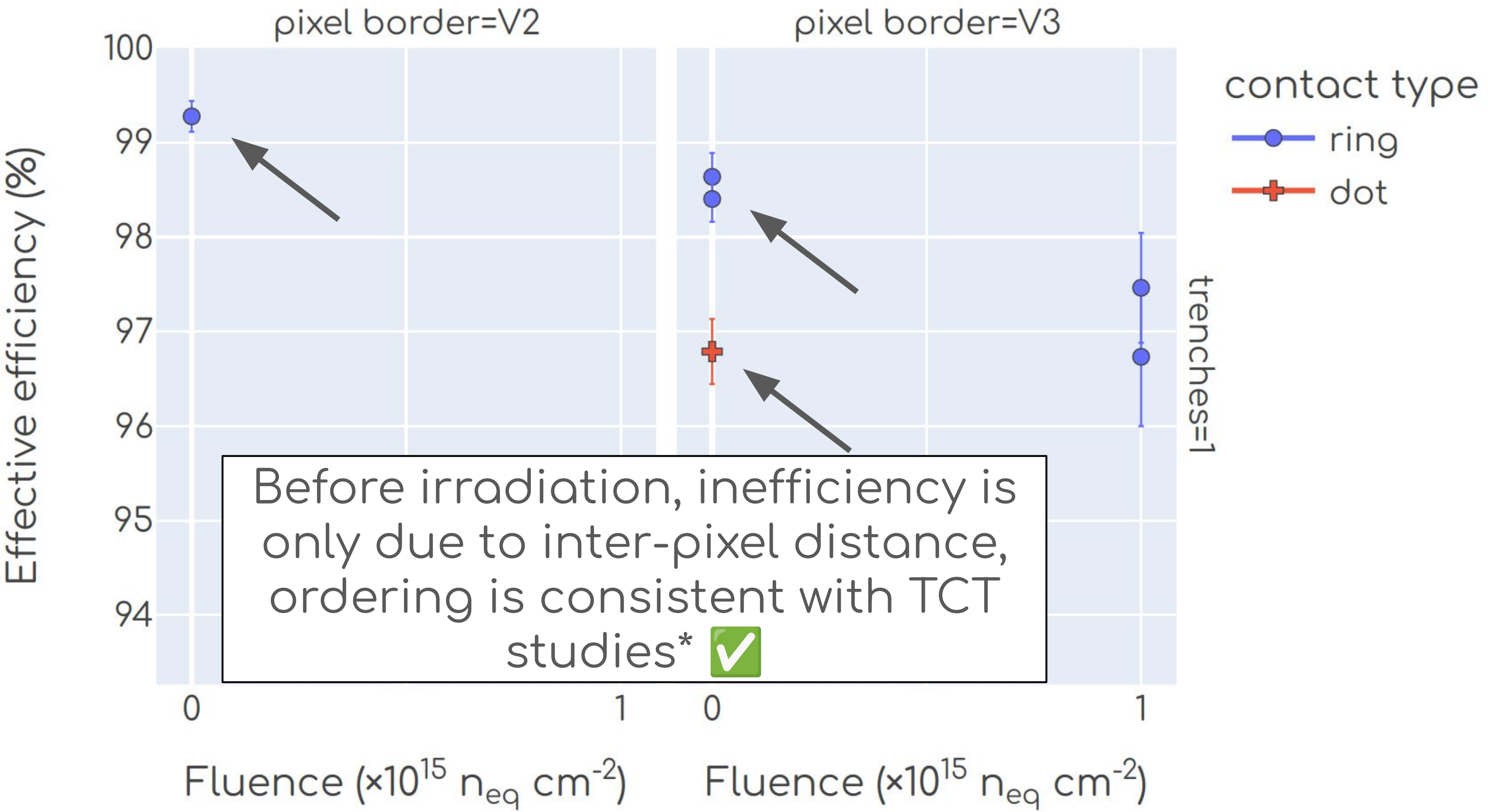
- Global efficiency that a large area sensor would have
- Thanks to DUT symmetry, it is translation invariant
- Higher statistics

Effective efficiency



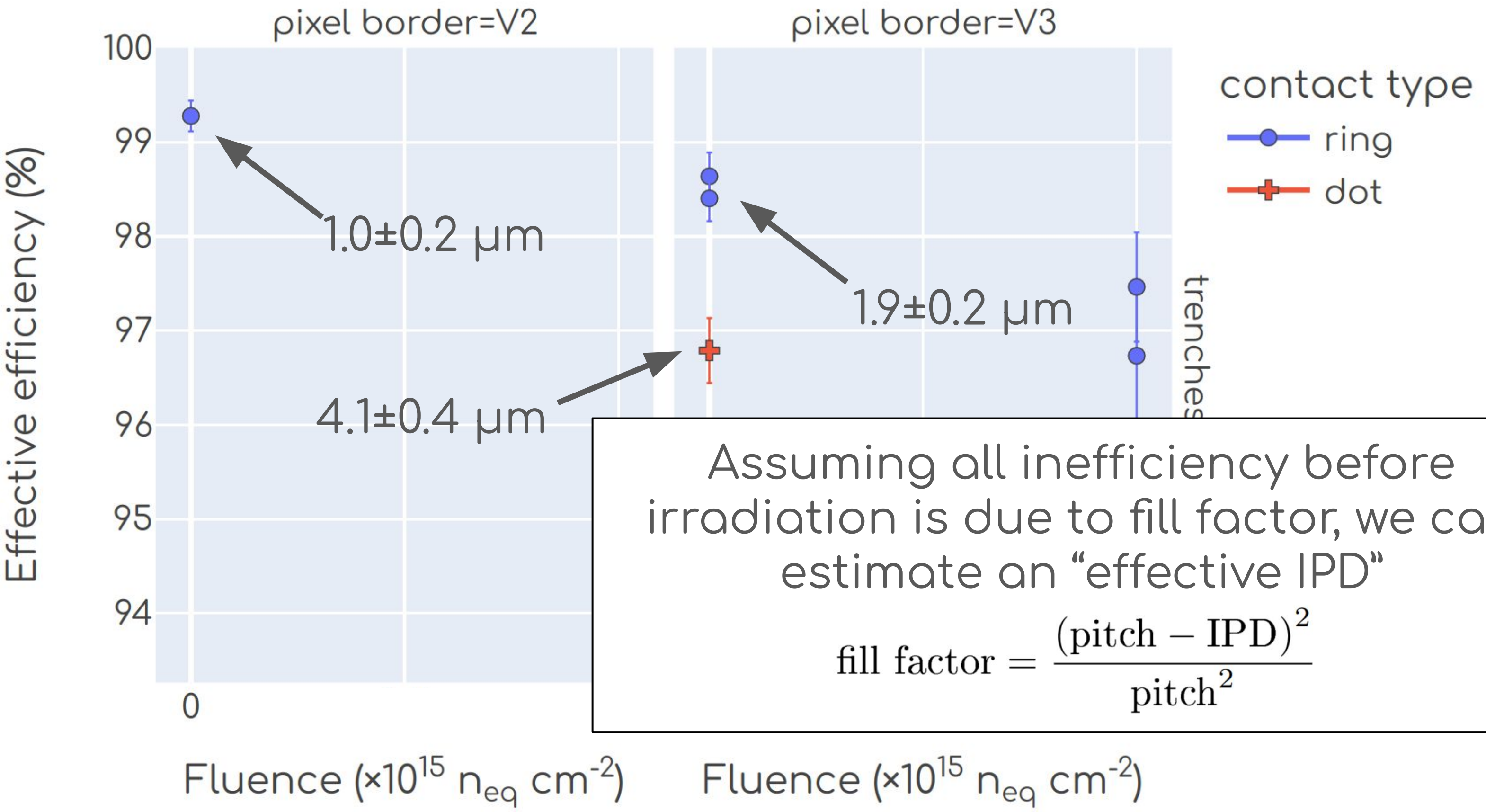
Effective efficiency

* Senger, M.; Macchiolo, A.; Kilminster, B.; Paternoster, G.; Centis Vignali, M.; Borghi, G. A Comprehensive Characterization of the TI-LGAD Technology. Sensors 2023, 23, 6225. https://doi.org/10.3390/s23136225



Before irradiation, inefficiency is only due to inter-pixel distance, ordering is consistent with TCT studies* ✅

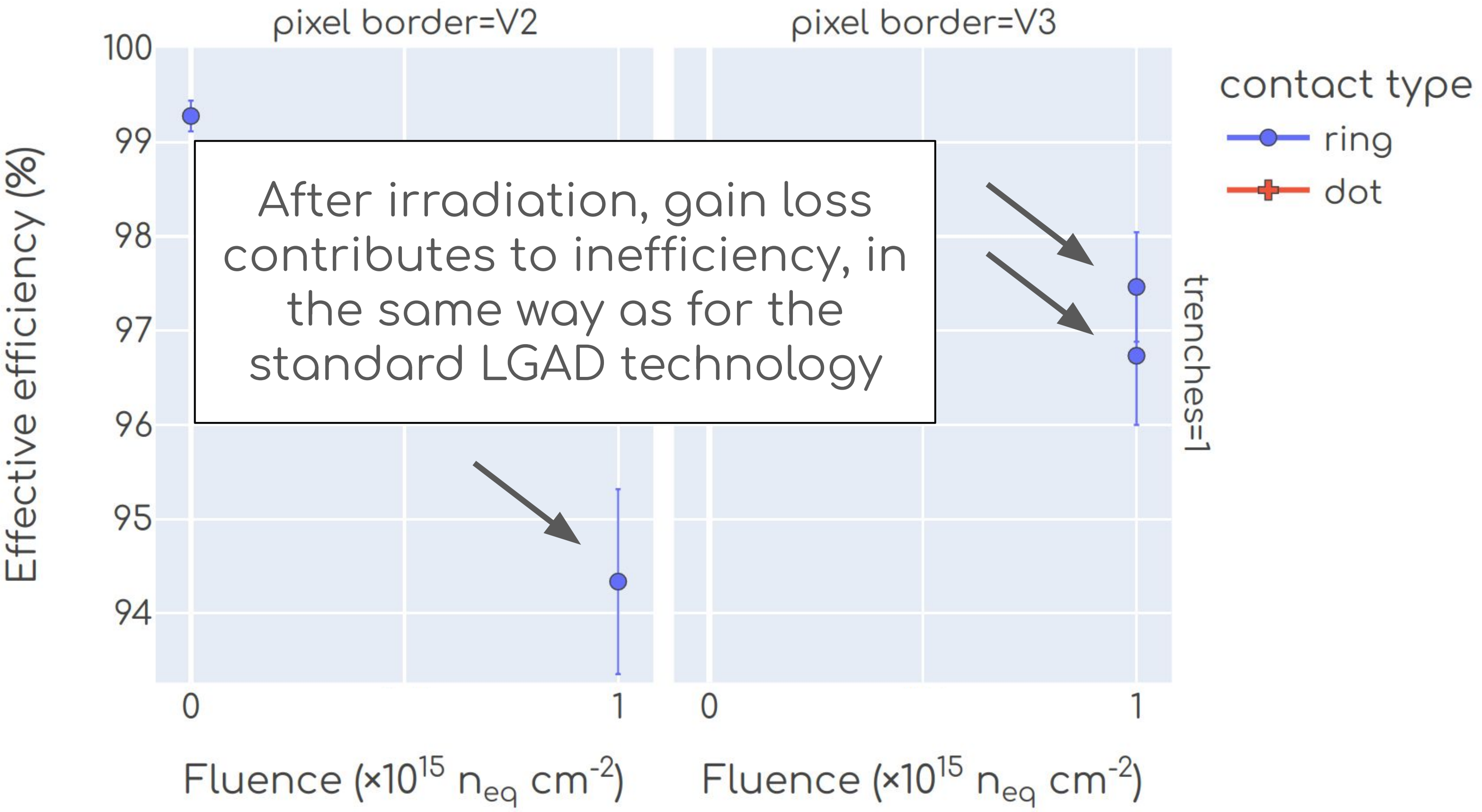
Inter-pixel distance (IPD)



Assuming all inefficiency before irradiation is due to fill factor, we can estimate an "effective IPD"

$$\text{fill factor} = \frac{(\text{pitch} - \text{IPD})^2}{\text{pitch}^2}$$

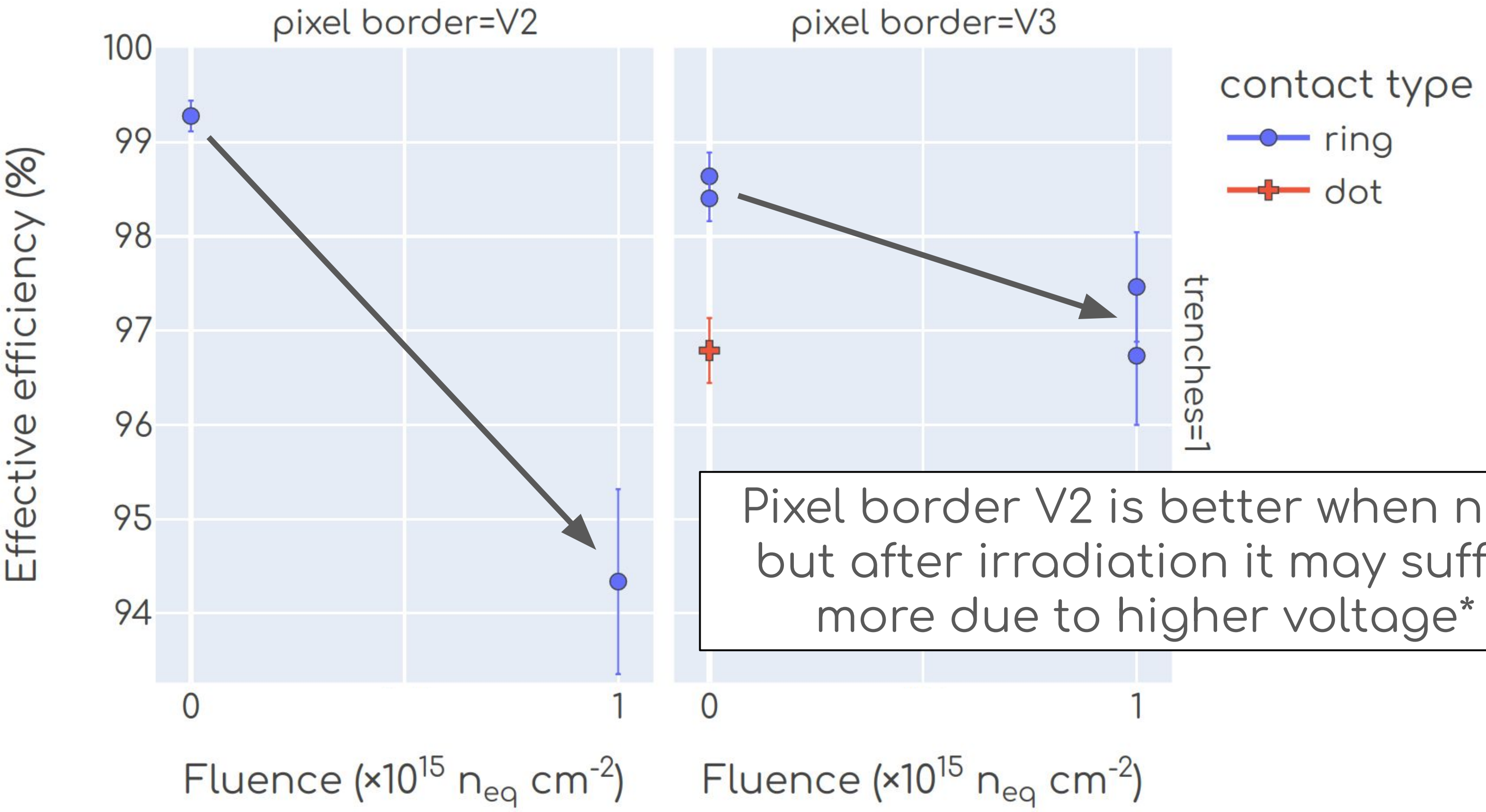
Effective efficiency



After irradiation, gain loss contributes to inefficiency, in the same way as for the standard LGAD technology

Effective efficiency

* Unfortunately only one voltage point was taken for V2, it may happen that reducing the voltage a bit fixes this issue and efficiency goes up again



Pixel border V2 is better when new, but after irradiation it may suffer more due to higher voltage*

Test beam characterization at DESY

Studied devices

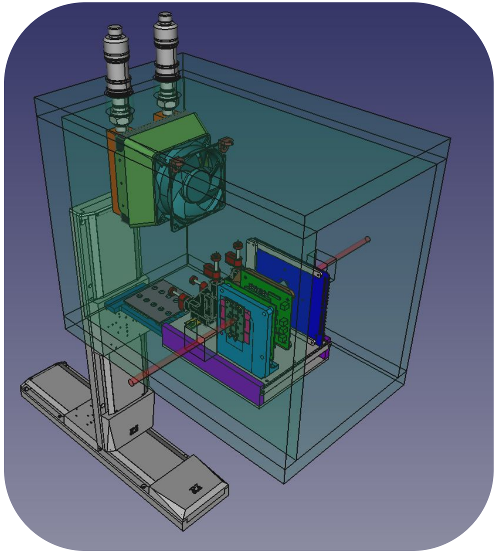
TI-LGADs from AIDAinnova FBK production with carbon co-implantation for enhanced radiation hardness.

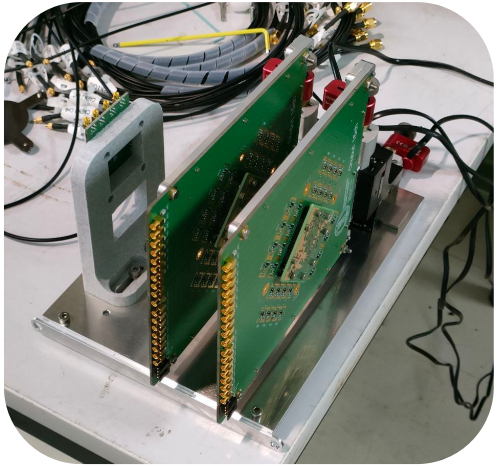
Four irradiation fluences are being studied:

1. $0\ n_{eq}\ cm^{-2}$
2. $8\times10^{14}\ n_{eq}\ cm^{-2}$
3. $15\times10^{14}\ n_{eq}\ cm^{-2}$
4. $25\times10^{14}\ n_{eq}\ cm^{-2}$

Test beam setup at DESY

Setup similar to CERN



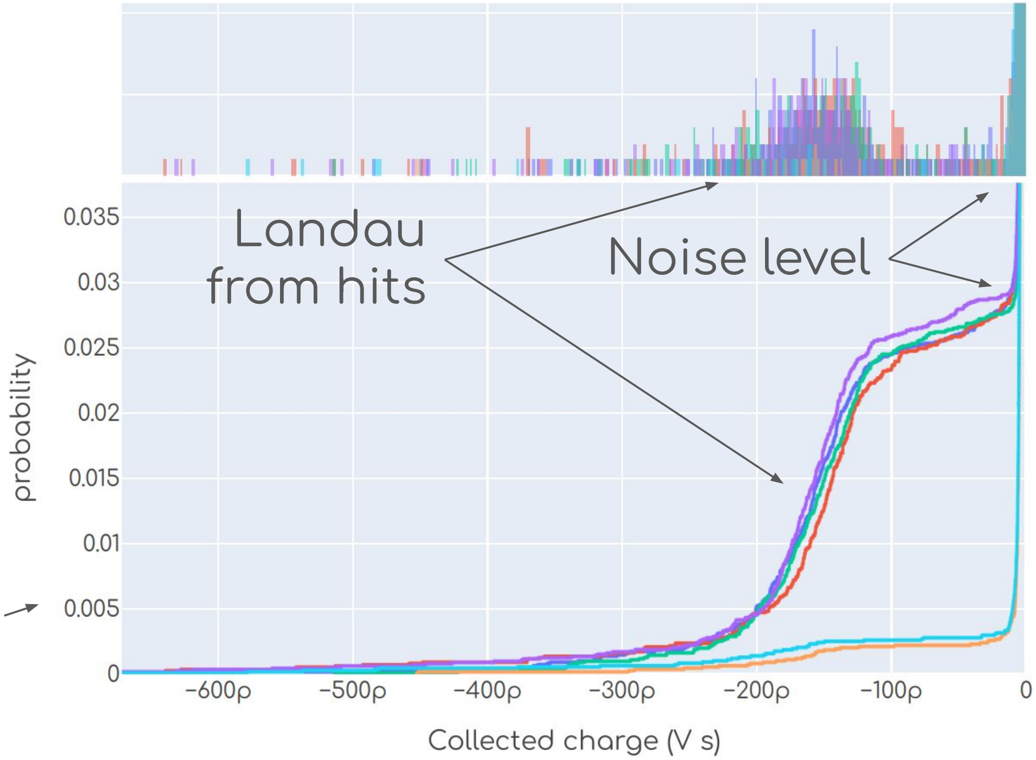


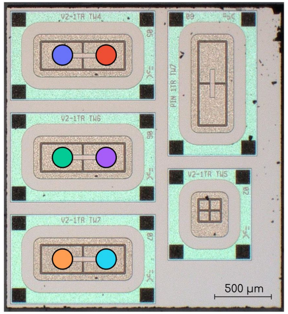
Preliminary results

Non-irrad TI-LGAD with carbon co-implantation

Bias voltage = 205 V, T = -25 °C

ECDF plot →

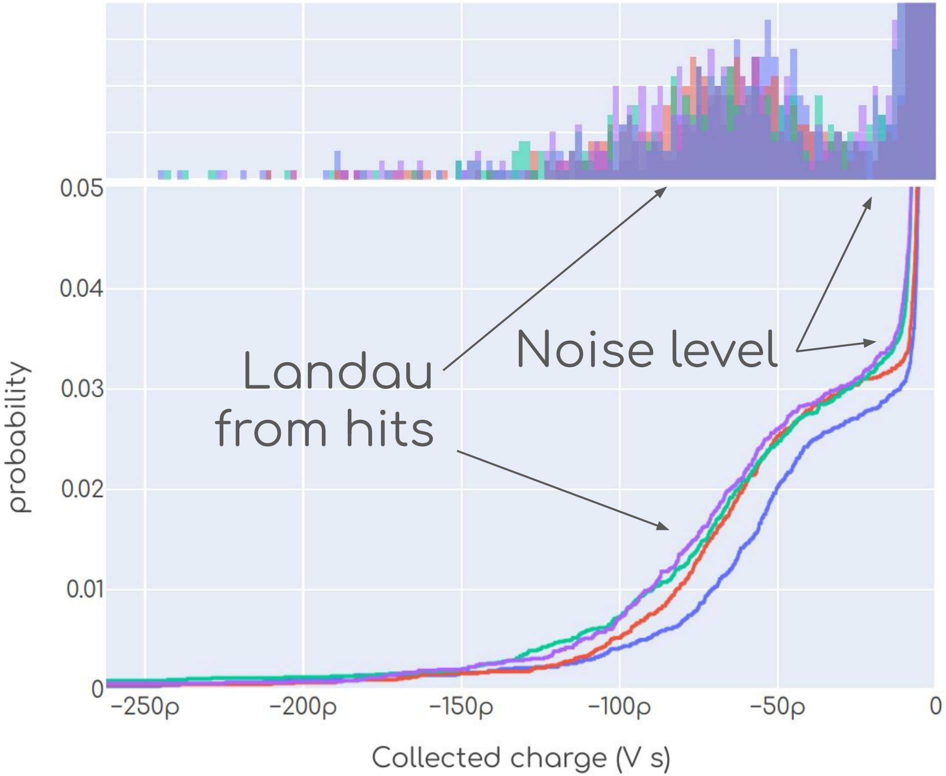


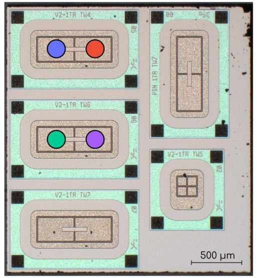


The sensors work 👍

TI-LGAD w/carbon, irradiated to 25e14 n_{eq} cm^{-2}

Bias voltage = 650 V, T = -25 °C





Clear separation between Landau and noise ✅

Sensor still works at the highest fluence 👏

Conclusions

Conclusions

- TI-LGAD samples were characterized in a test beam setup at CERN
- Before irradiation, 99.2±0.2 % efficiency measured
- After 1e15 n_{eq} cm^2 with reactor neutrons, 97.4±0.6 % efficiency measured
- TI-LGADs with carbon co-implantation were tested in a test beam setup at DESY

Future work

- Complete the analysis of data gathered at DESY
  - Efficiency
  - Inter-pixel distance
  - Radiation hardness
  - Time resolution

Thank you for your attention!

Acknowledgements

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