TI-LGAD

beta, test beam and TCT characterization

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FONDAZIONE BRUNO KESSLER

RD50

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Presentation layout

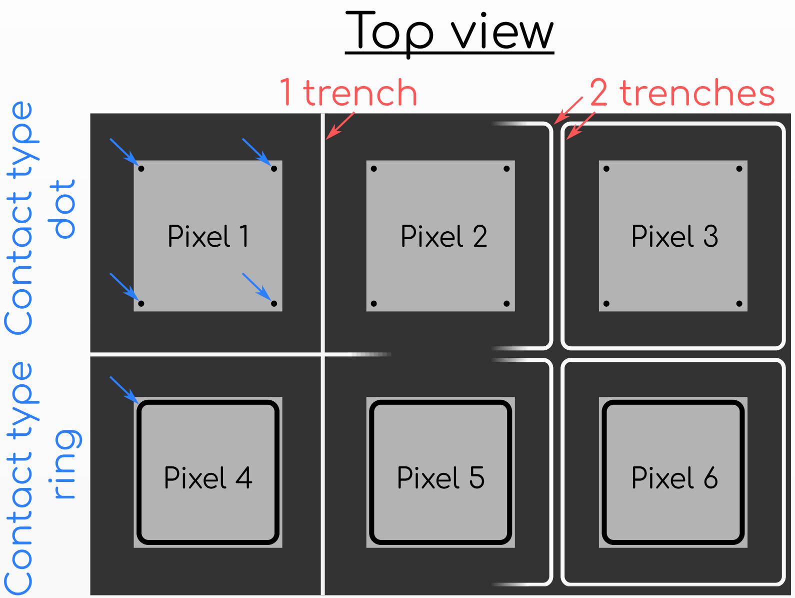
- Introduction
- TCT results
  - Inter-pixel distance
  - Time resolution uniformity
- Beta source results
  - Time resolution
  - Collected charge
- Test beam results
  - Time resolution
  - Collected charge

The “RD50 TI-LGAD Project”

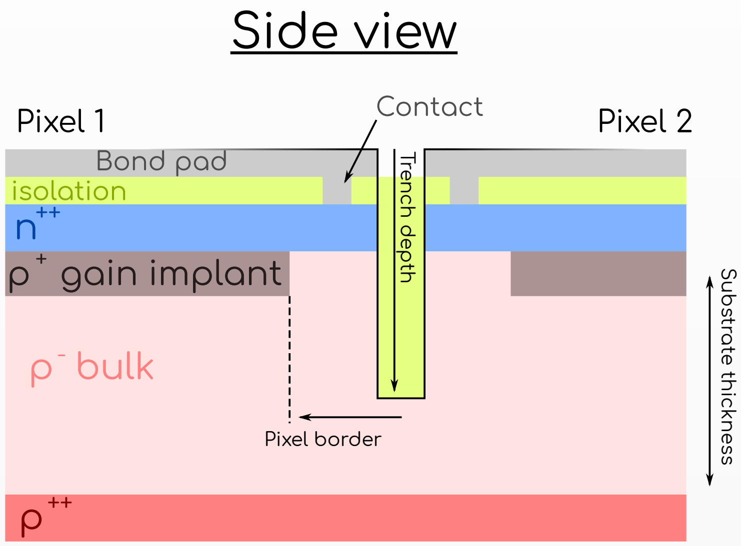
- Goal: “design and production of TI-LGAD with small pixels (<= 100 um) and high Fill Factor (> 80%)”[1].
- TI-LGAD: Pixels are separated by trenches.

Design patterns

1) Trenches:
   - 1 or 2
2) Contact type:
   - Ring
   - Dot
3) Pixel border:
   - V1 (smallest) , V2, V3, V4 (largest)
4) Trench depth
   - D1 (shallowest), D2, D3 (deepest)



*These design patterns are constant within each sample, here they are drawn all together as in a single sample just to illustrate.



**These cartoons show a simplified/idealized picture and are meant for visualization purposes.

[1] G. Paternoster. “Latest Developments on Trench-Isolated LGADs.” Presented at the 35th RD50 Workshop, CERN, November 19, 2019. https://indico.cern.ch/event/855994/contributions/3637012/.

Our irradiation campaign at UZH

- TI-LGADs aimed towards future trackers.
  - Possible replacement of pixel disks of the CMS experiment in Phase-3, with fluence range 3-5×10^{15} n_{eq} cm^{-2}.

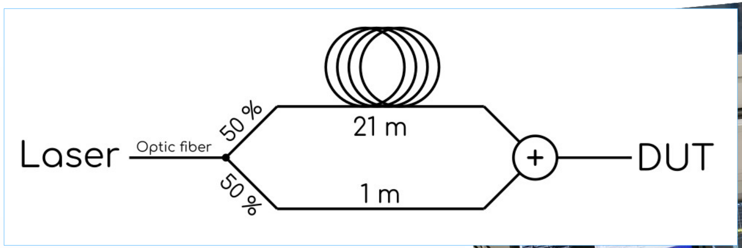
- We irradiated with reactor neutrons at JSI (Ljubljana) to 4 fluences:
  1) 1.5×10^{15} n_{eq}/cm^2
  2) 2.5×10^{15} n_{eq}/cm^2
  3) 3.5×10^{15} n_{eq}/cm^2
  4) 5.0×10^{15} n_{eq}/cm^2

  (3 and 4:) Gain is heavily affected, not shown in this presentation

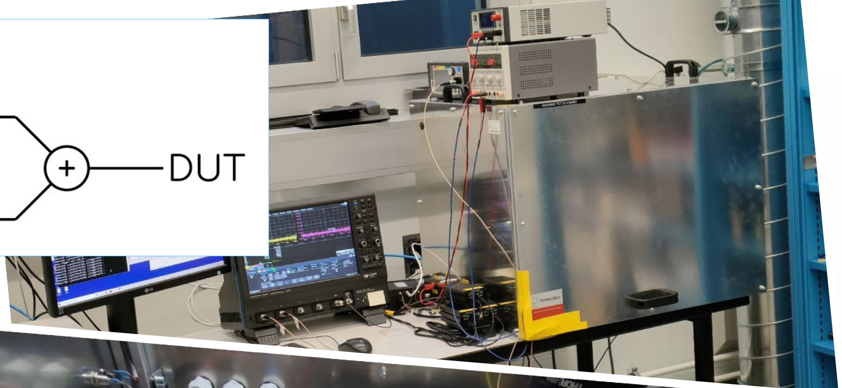
- Irradiated devices were kept all the time at -20 °C except for handling, to avoid annealing effects.

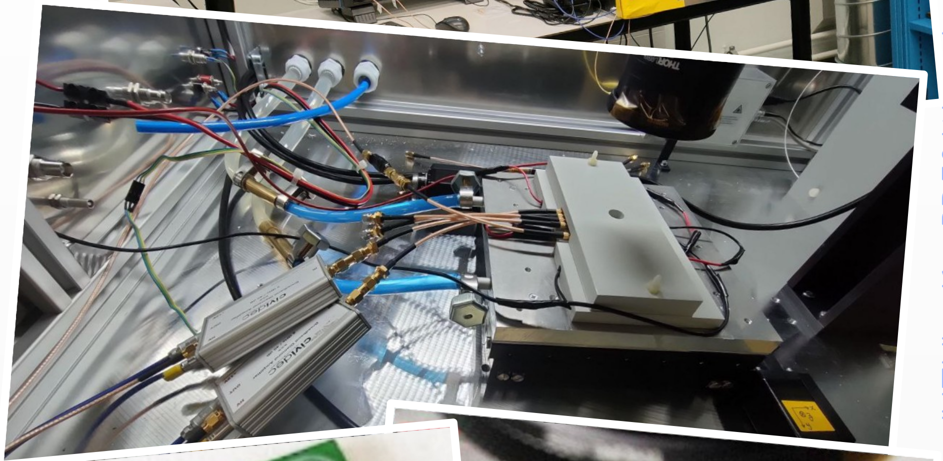
TCT measurements

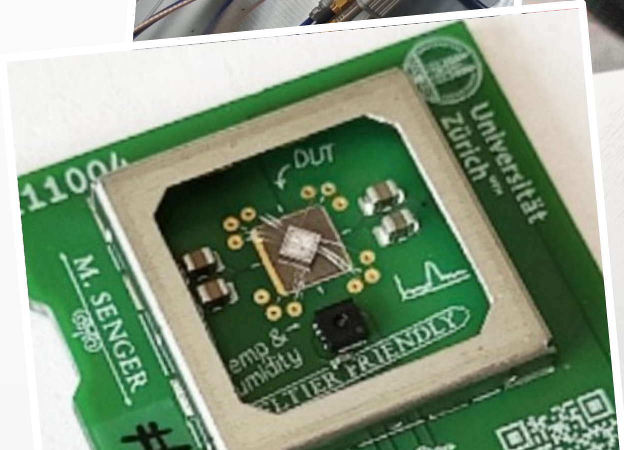
UZH TCT setup



- Particulars Scanning TCT:
  - Infrared laser (1064 nm).
  - Laser spot Gaussian with[1] σ ~ 9 μm.
  - Laser splitting+delay[2] with optic fiber for timing measurements provides two pulses separated by 100 ns.
- Custom made passive readout board.
  - Temperature + humidity sensed close to DUT.
- Cividec C2HV amplifier.
  - 2 GHz, 40 dB.
- Oscilloscope WaveRunner 640Zi or 9254M.
  - 4 GHz, 40 GS/s.
- Keithley 2470 bias voltage source.

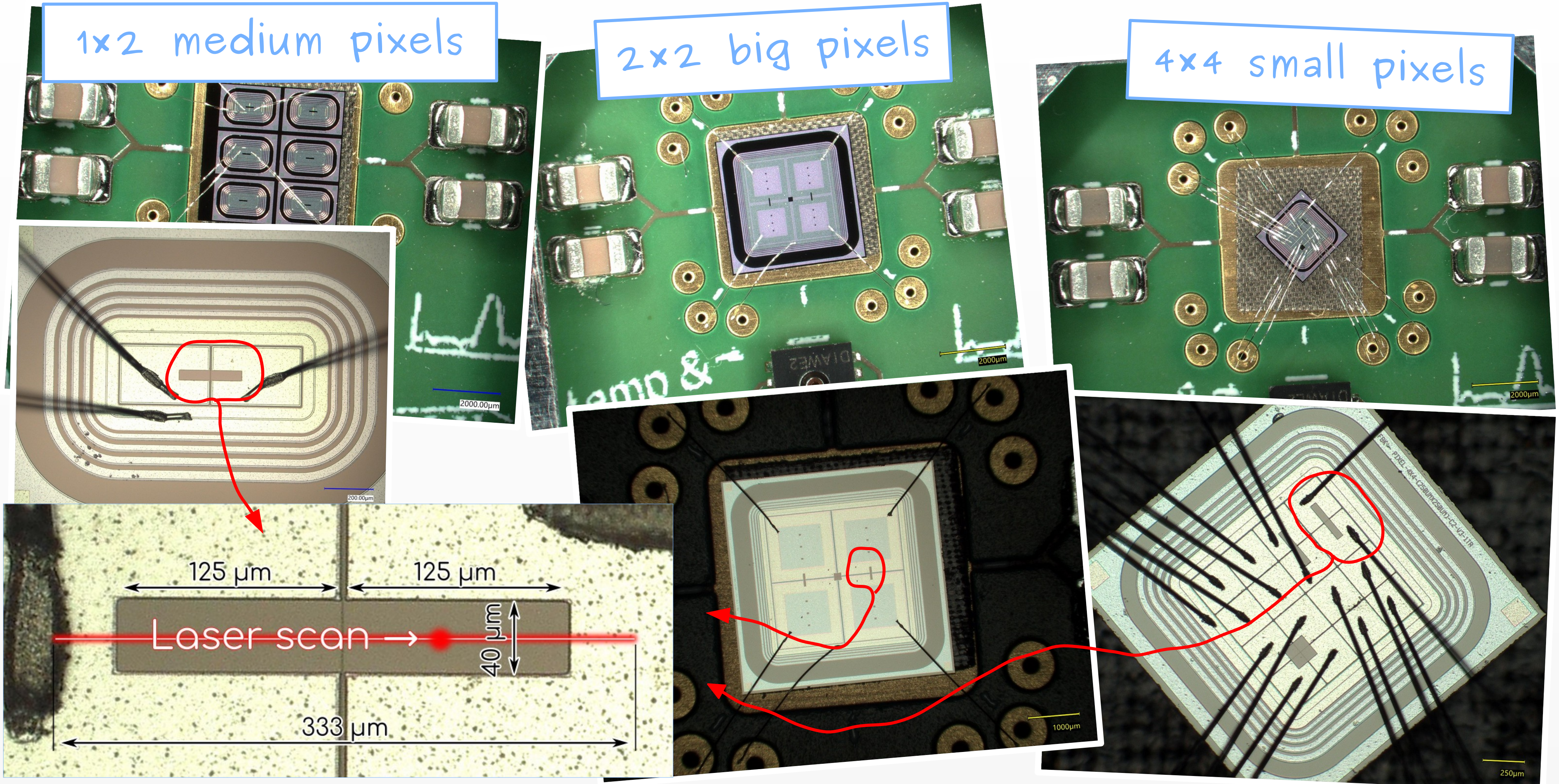






[1] https://msenger.web.cern.ch/a-spacial-characterization-of-the-tct/
[2] https://msenger.web.cern.ch/laser-delay-system-for-the-scanning-tct/

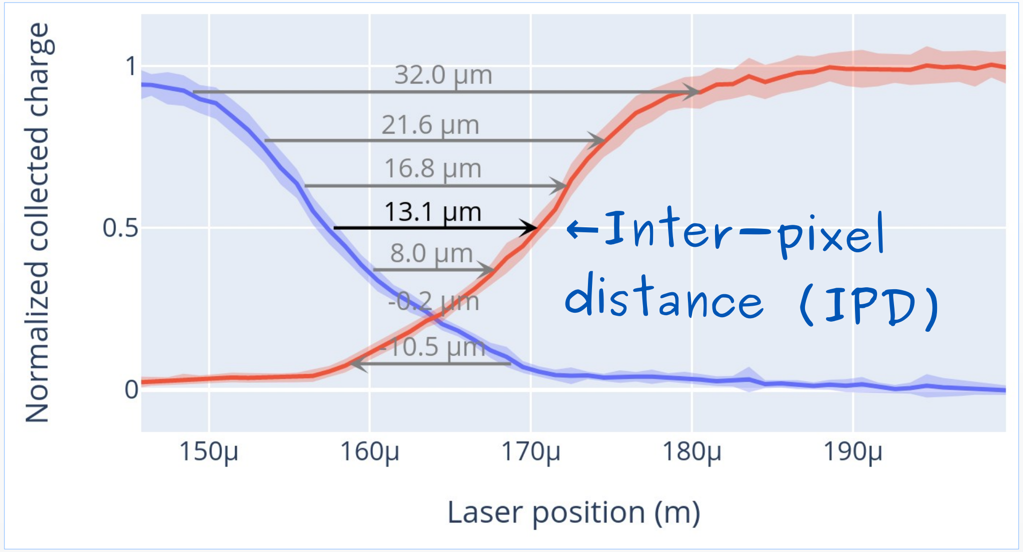
Samples geometry and laser scans

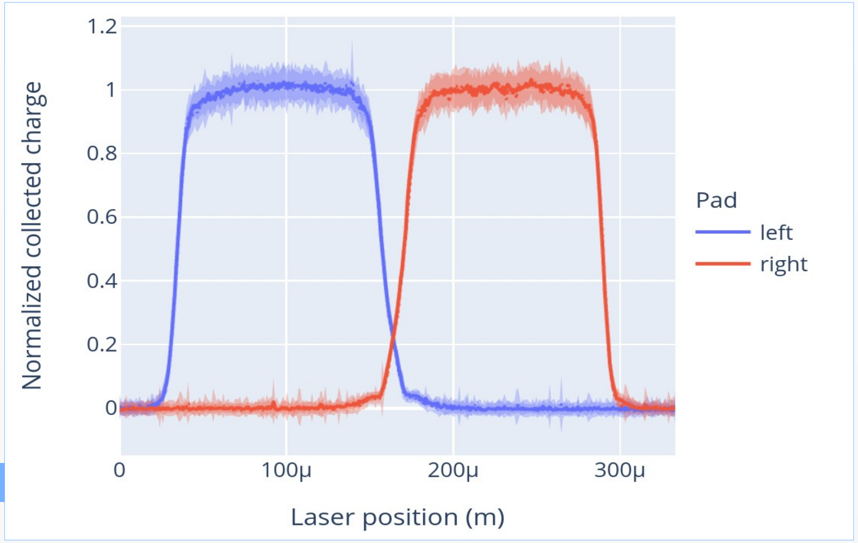


Inter-pixel distance

- Defined as distance between 50 % of normalized collected charge of each channel.
- Linear interpolation, not "S function".
  - Observed deviations from "S", different for each design pattern and dependent on the bias voltage, thus opted for interpolation.

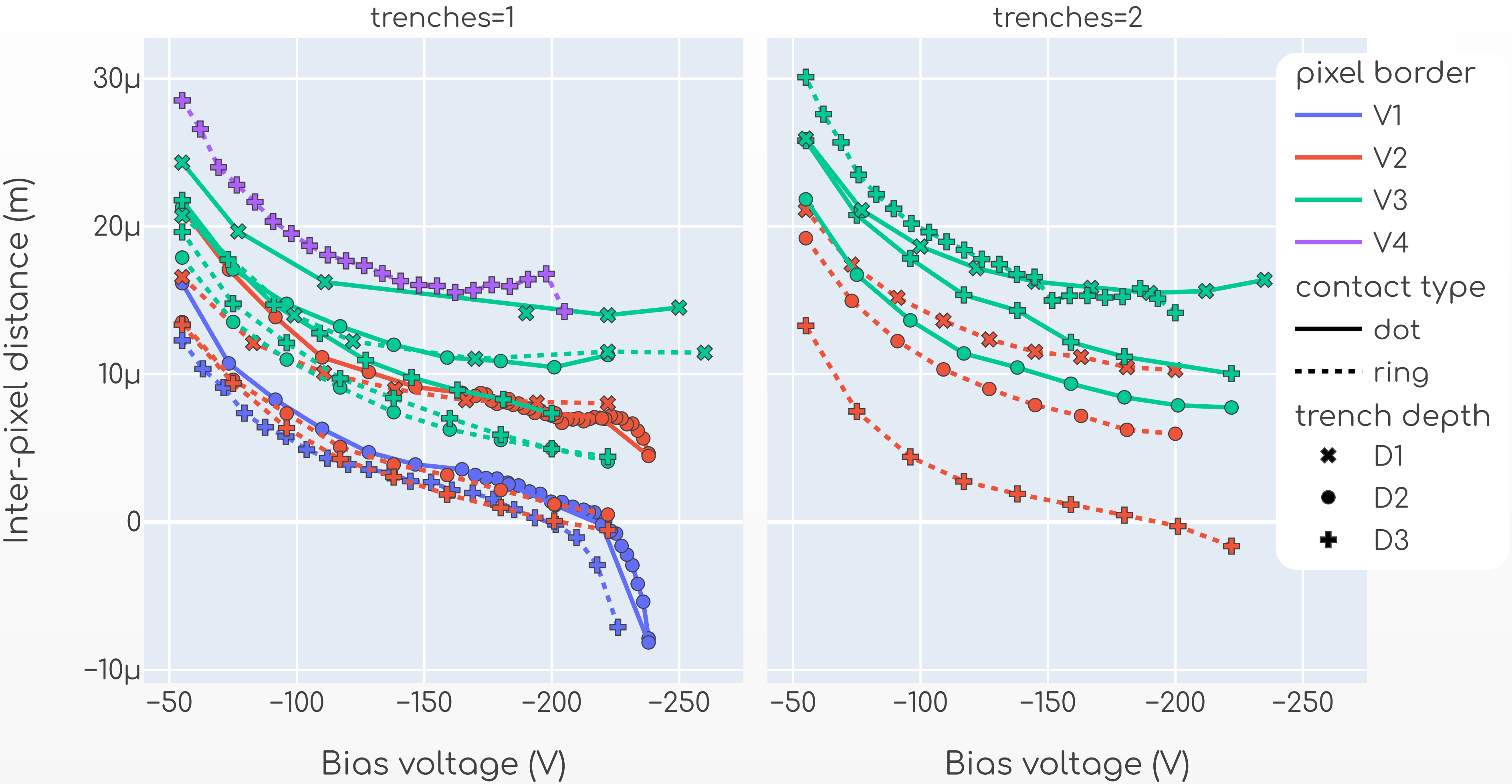
Example from a random scan (non irradiated device)





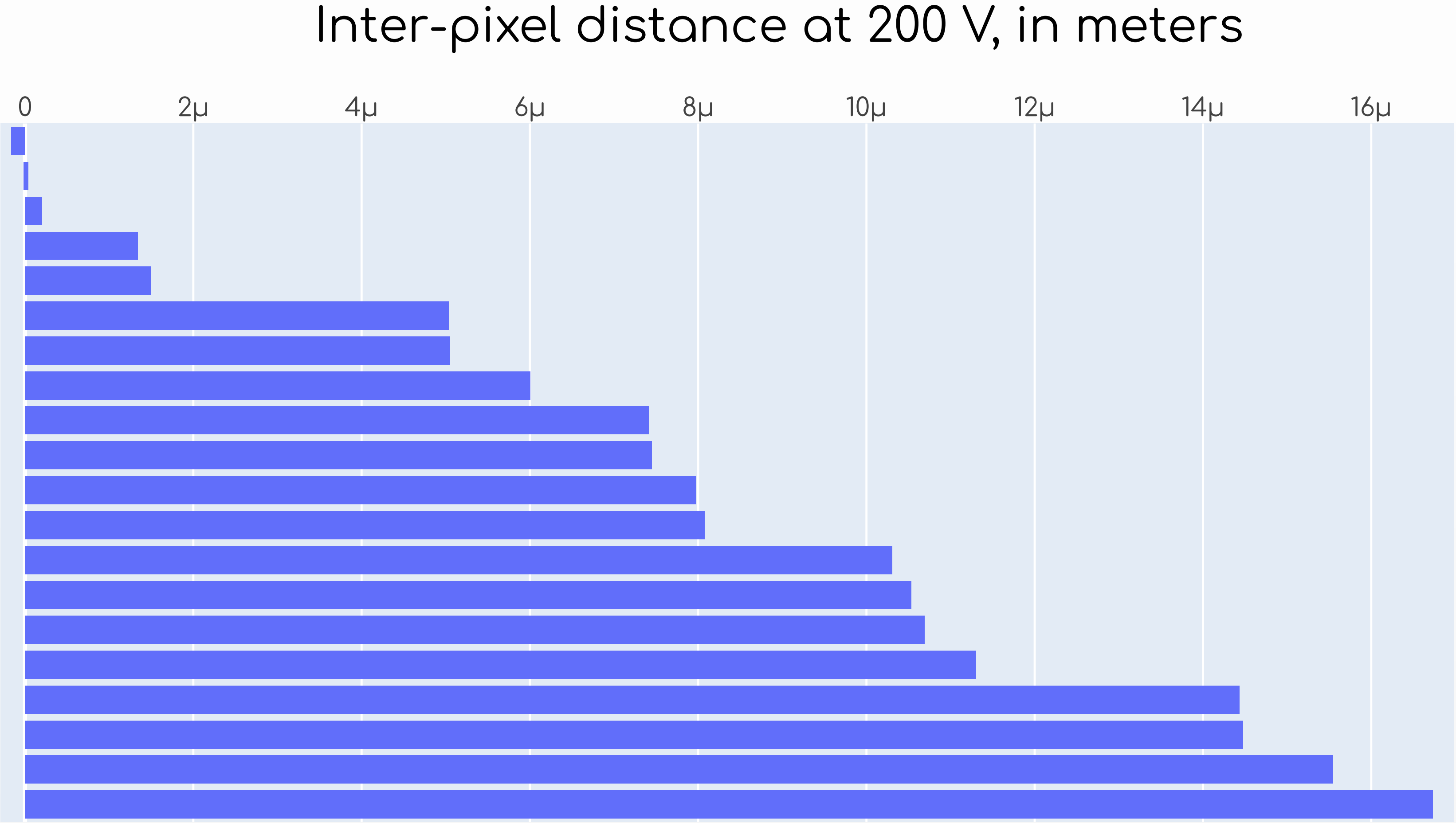
Inter-pixel distance vs bias voltage

- All non irradiated samples, all at -20 °C



Summary of inter-pixel distance

Wafer	Trench depth	Trenches	Pixel border	Contact type
16	D3	2	V2	ring
16	D3	1	V1	ring
16	D3	1	V2	ring
7	D2	1	V2	ring
7	D2	1	V1	dot
7	D2	1	V3	ring
16	D3	1	V3	ring
7	D2	2	V2	ring
7	D2	1	V2	dot
16	D3	1	V3	dot
7	D2	2	V3	dot
11	D1	1	V2	ring
11	D1	2	V2	ring
7	D2	1	V3	dot
16	D3	2	V3	dot
11	D1	1	V3	ring
16	D3	2	V3	ring
11	D1	1	V3	dot
11	D1	2	V3	dot
16	D3	1	V4	ring

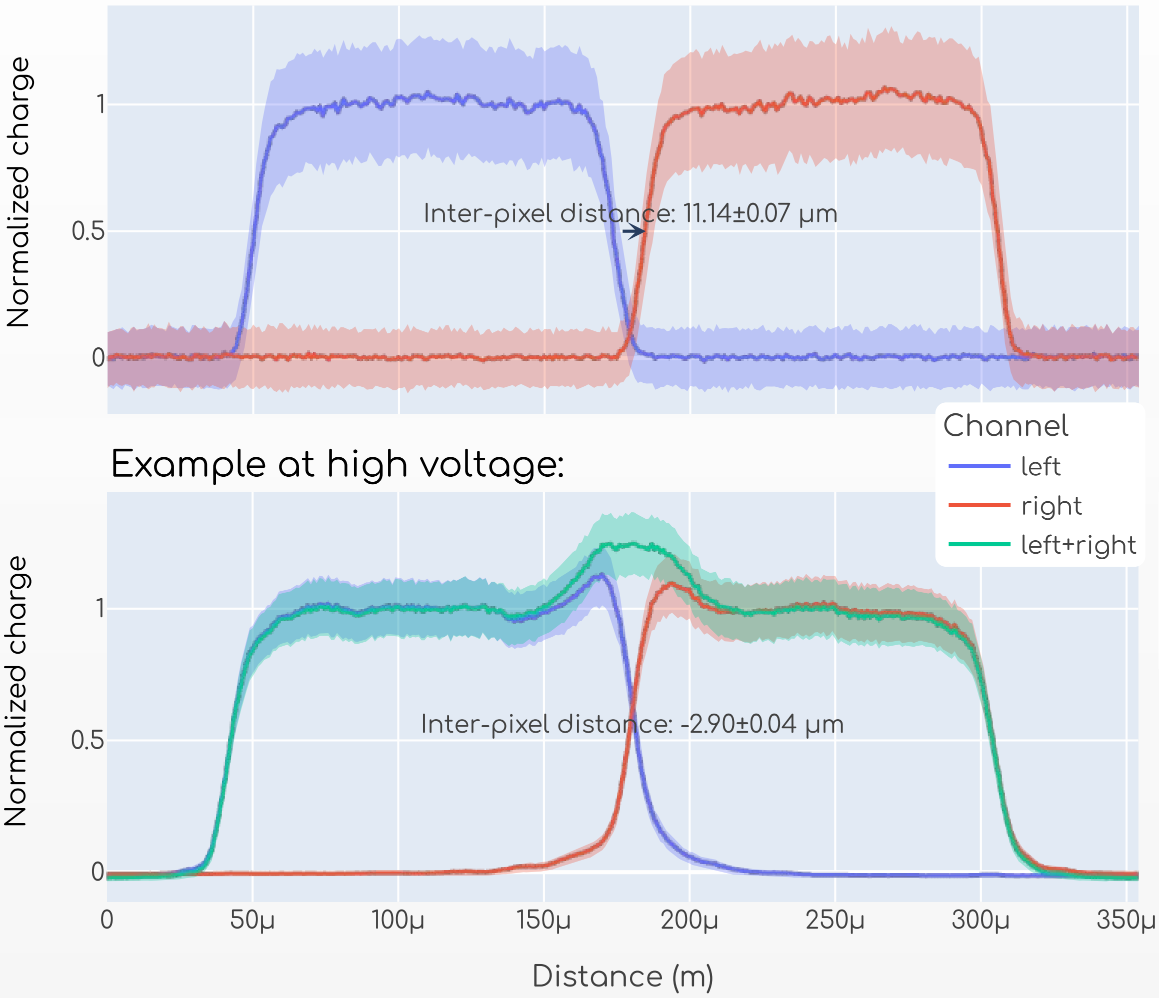


Negative inter-pixel distance

- Negative values arise at high voltages for some structures, due to additional multiplication in the inter-pixel region.
- Extra multiplication also reported by previous studies[1].
- In this regime the devices are probably not so useful because of auto triggering (studies pending).

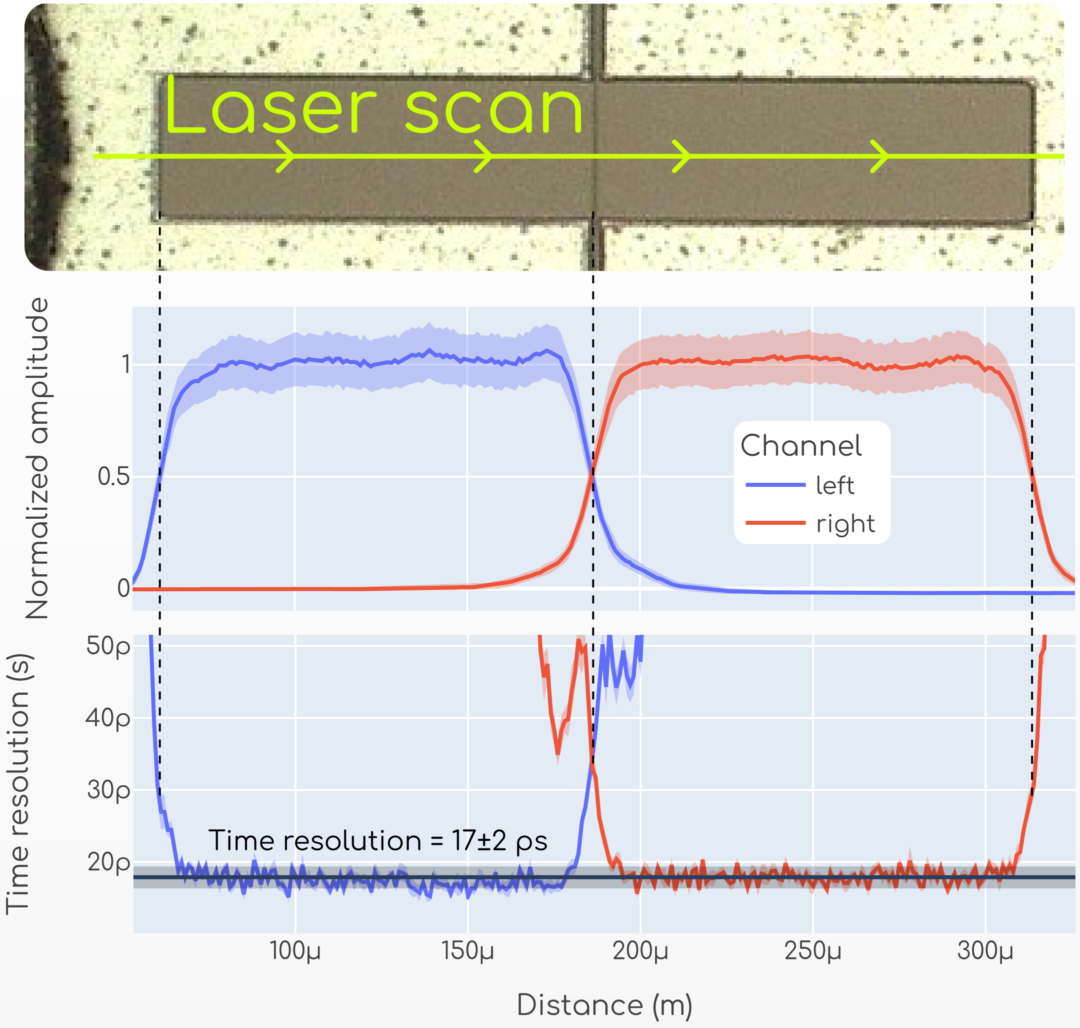
Example at low voltage:

Example at high voltage:



[1] Ashish Bisht. "Characterization of Novel Trench-Isolated LGADs for 4D Tracking." Presented at the WORKSHOP ON PICO-SECOND TIMING DETECTORS FOR PHYSICS, Zurich, September 9, 2021. https://indico.cern.ch/event/861104/contributions/4514658/.

Time resolution uniformity (TCT setup)



- Time resolution is very uniform until pixel edges.
- All tested devices show this behavior.
- Laser ⇒ missing Landau fluctuations ⇒ absolute value not very relevant.

Resilience of trenches to irradiation

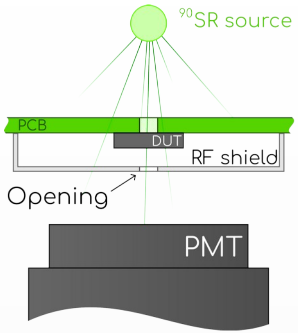
- Isolation provided by trenches does not seem to be affected by irradiation:
  - Inter-pixel distance does not get worse.
  - Isolation between neighboring pixels remains almost perfect.

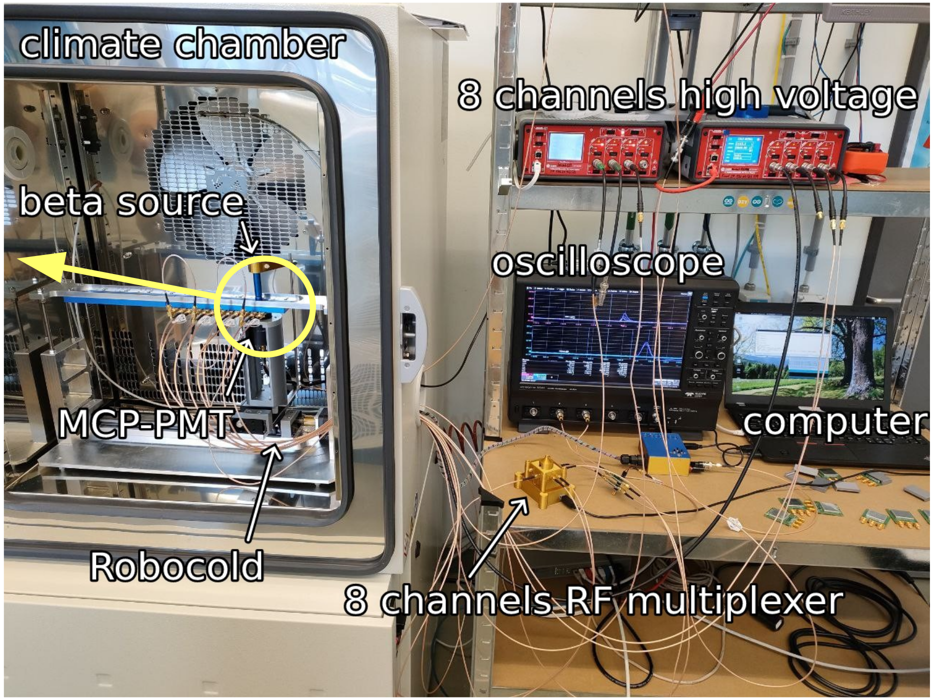
- See our previous results: https://doi.org/10.1016/j.nima.2022.167030.

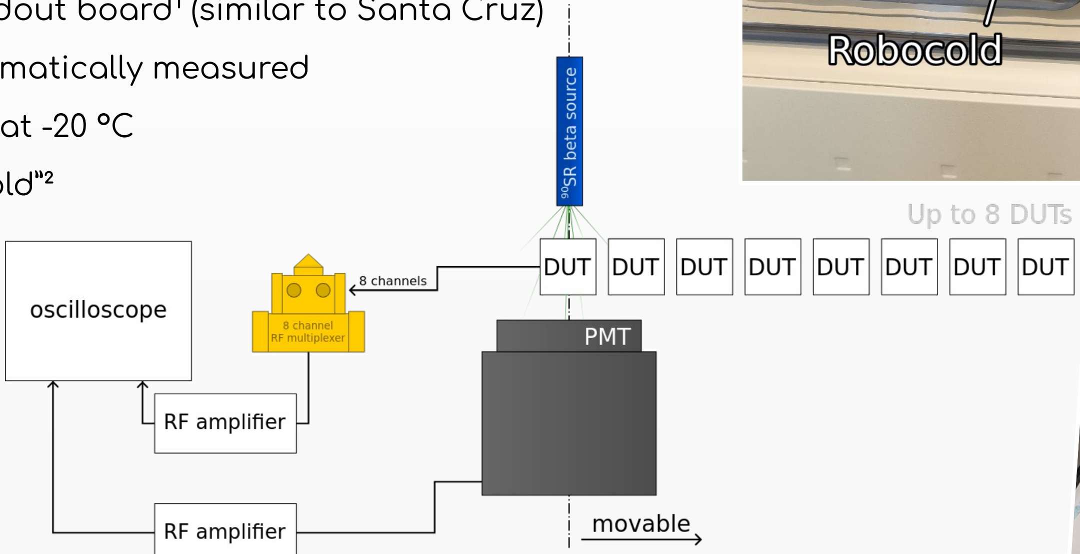
Beta source measurements

UZH beta setup

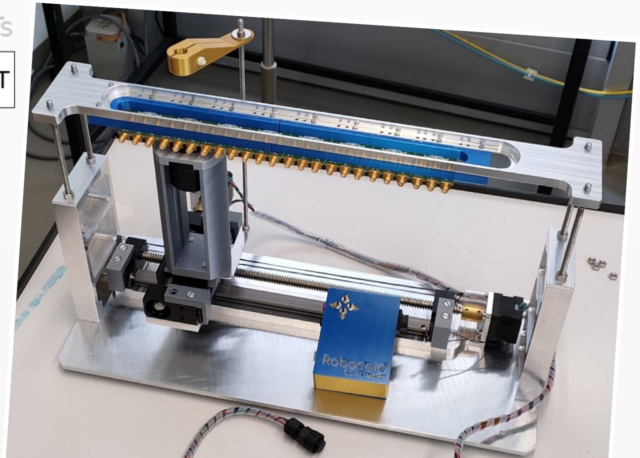
- Photonis MCP-PMT trigger & time reference
  - 17±2 ps time resolution
- ^{90}Sr beta source, 74 kBq
- Oscilloscope LeCroy WaveRunner 9254M
  - 4 GHz bandwidth
  - 40 GS/s
- CAEN high voltage power supply
- Custom made readout board[1] (similar to Santa Cruz)
- Up to 8 DUTs automatically measured
- All measurements at -20 °C
- Self made "Robocold"[2]







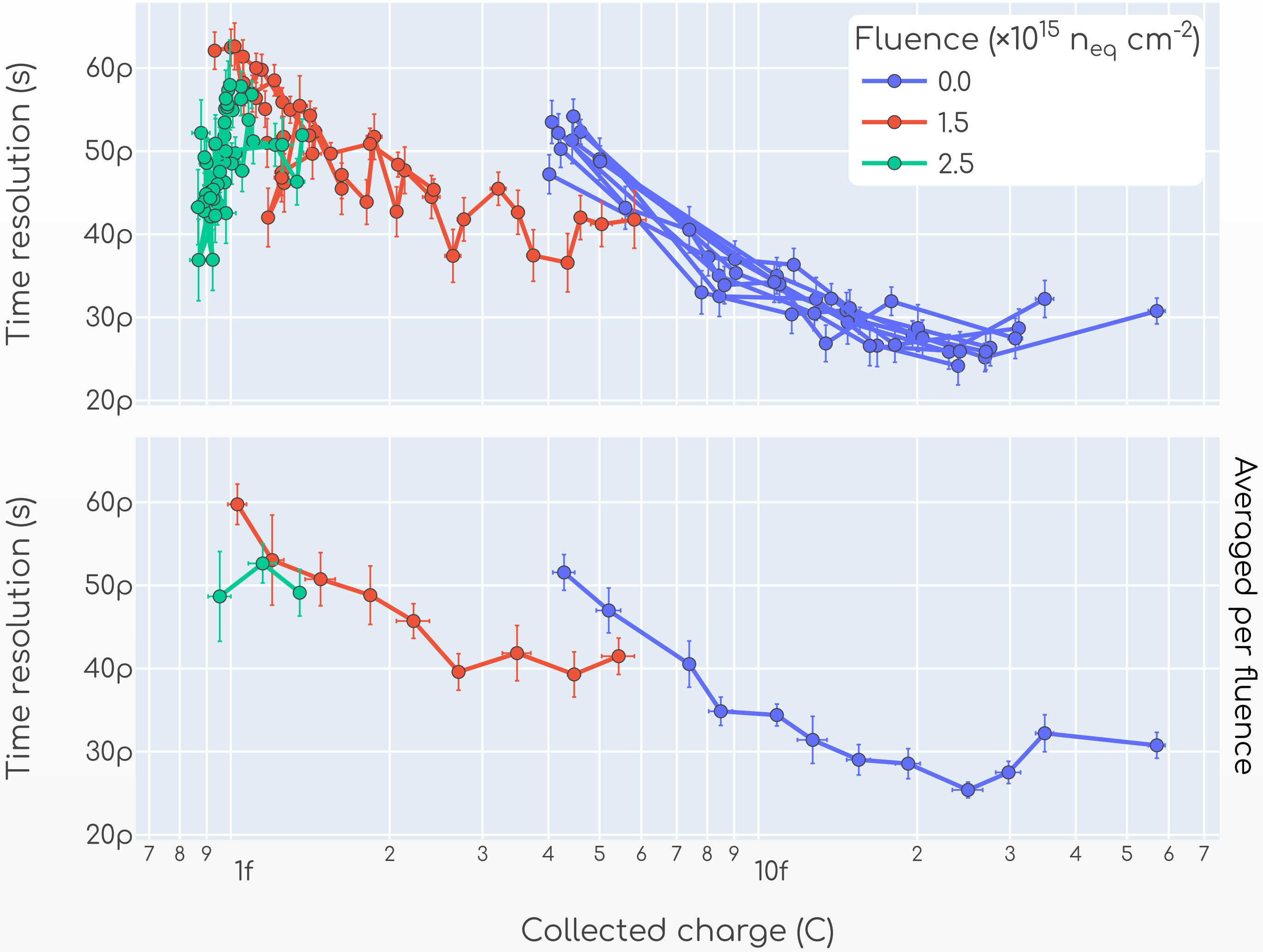
Robocold →



[1] https://github.com/SengerM/ChubutBoard
[2] https://msenger.web.cern.ch/the-robocold-beta-setup/

Time resolution vs charge (beta source)

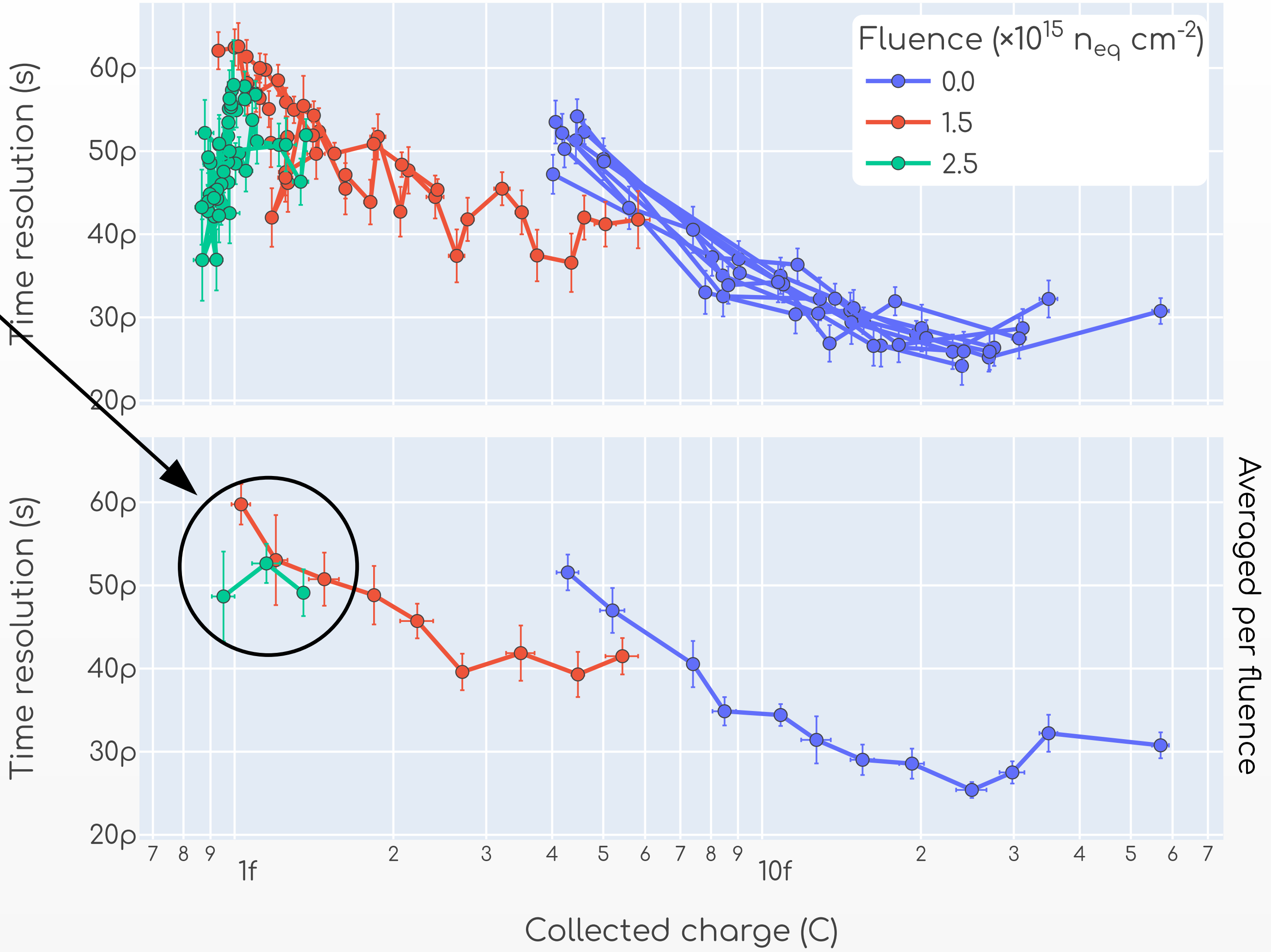
- Constant fraction discriminator different for each fluence:
  - 20 % for 0
  - 40 % for 1.5
  - 50 % for 2.5
- Top plot: Each line is a different device.
- Bottom plot: Average per fluence.
- We don’t observe systematic dependence with trenches design.



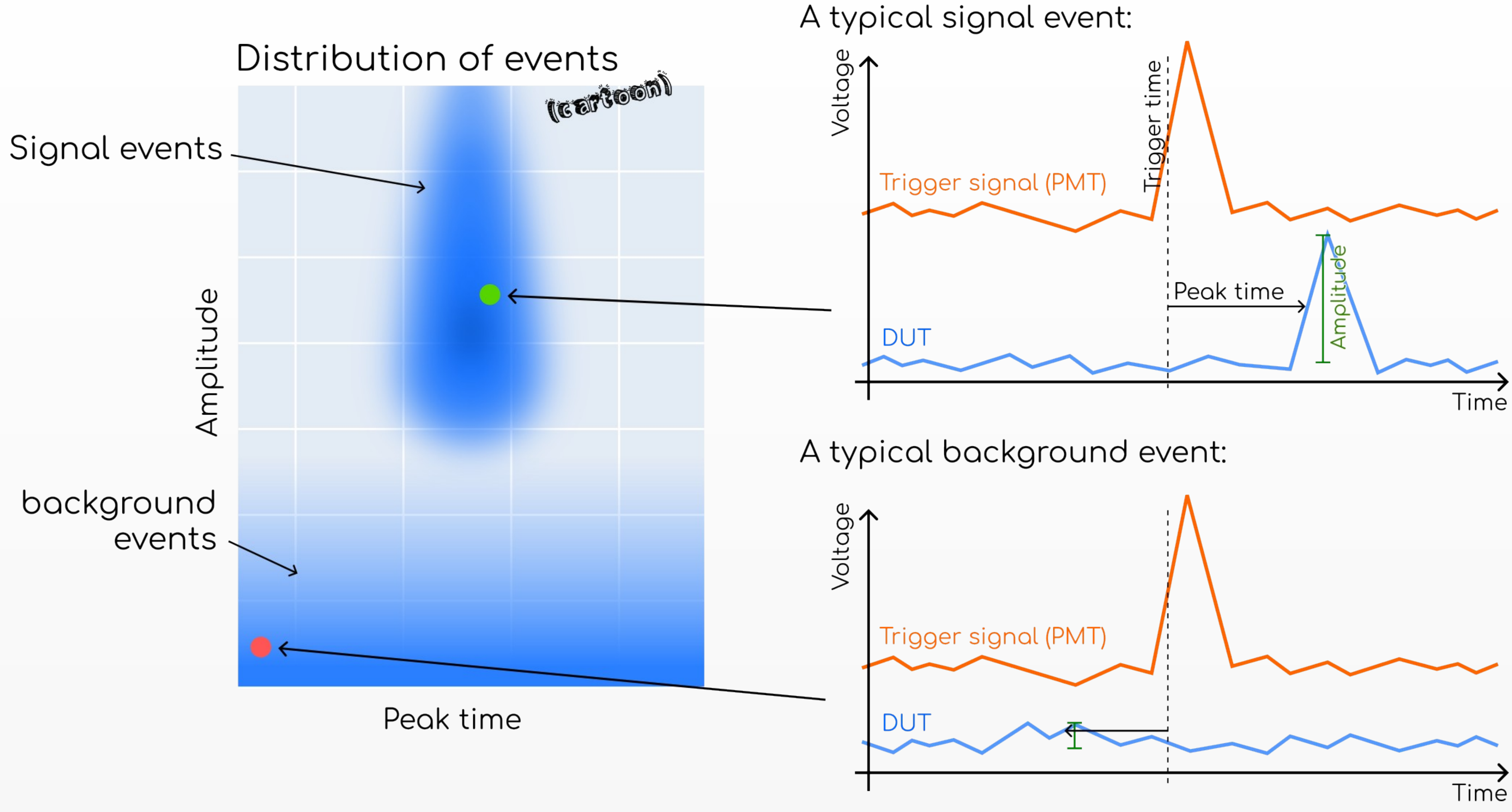
Time resolution vs charge (beta source)

- How is it that green is better than red?

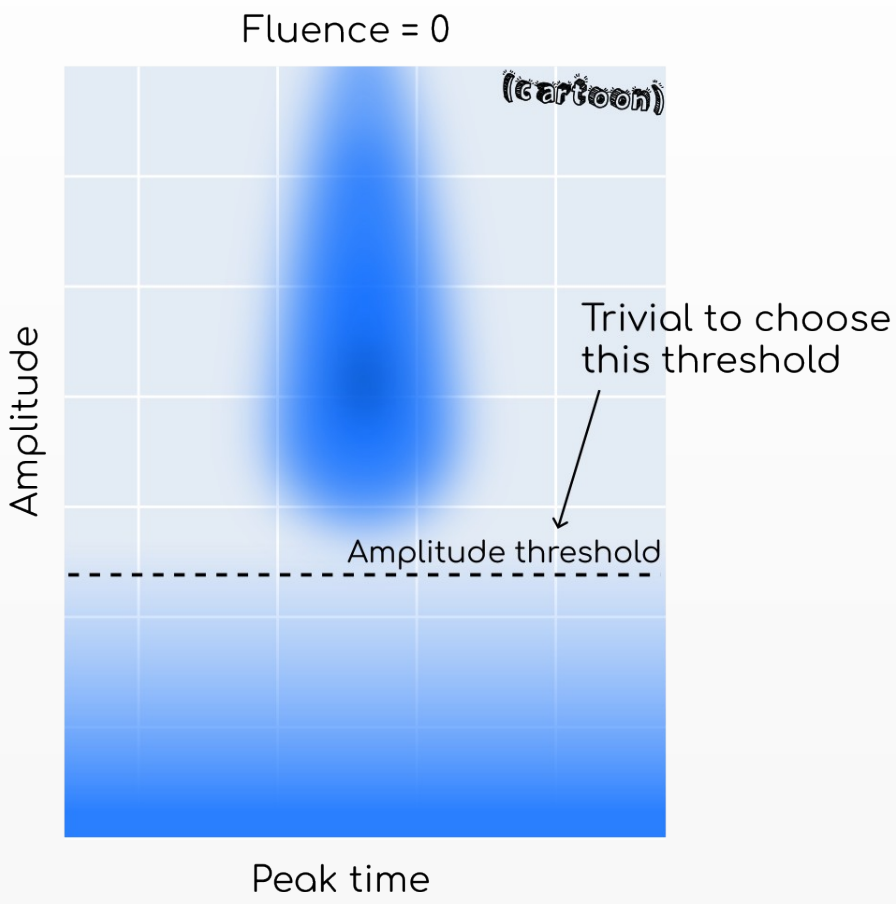
TL;DR: Lower efficiency because lower gain so only looking at tail of Landau

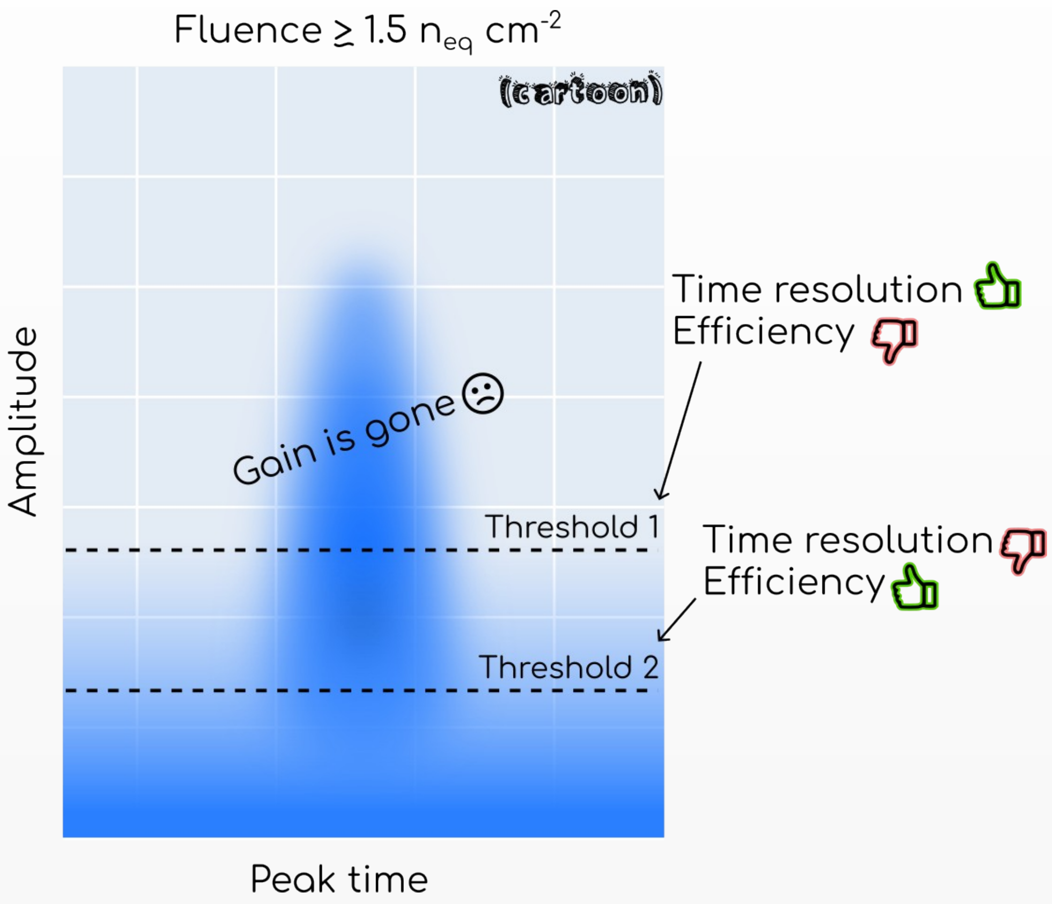


Signal vs background events (in our beta setup)

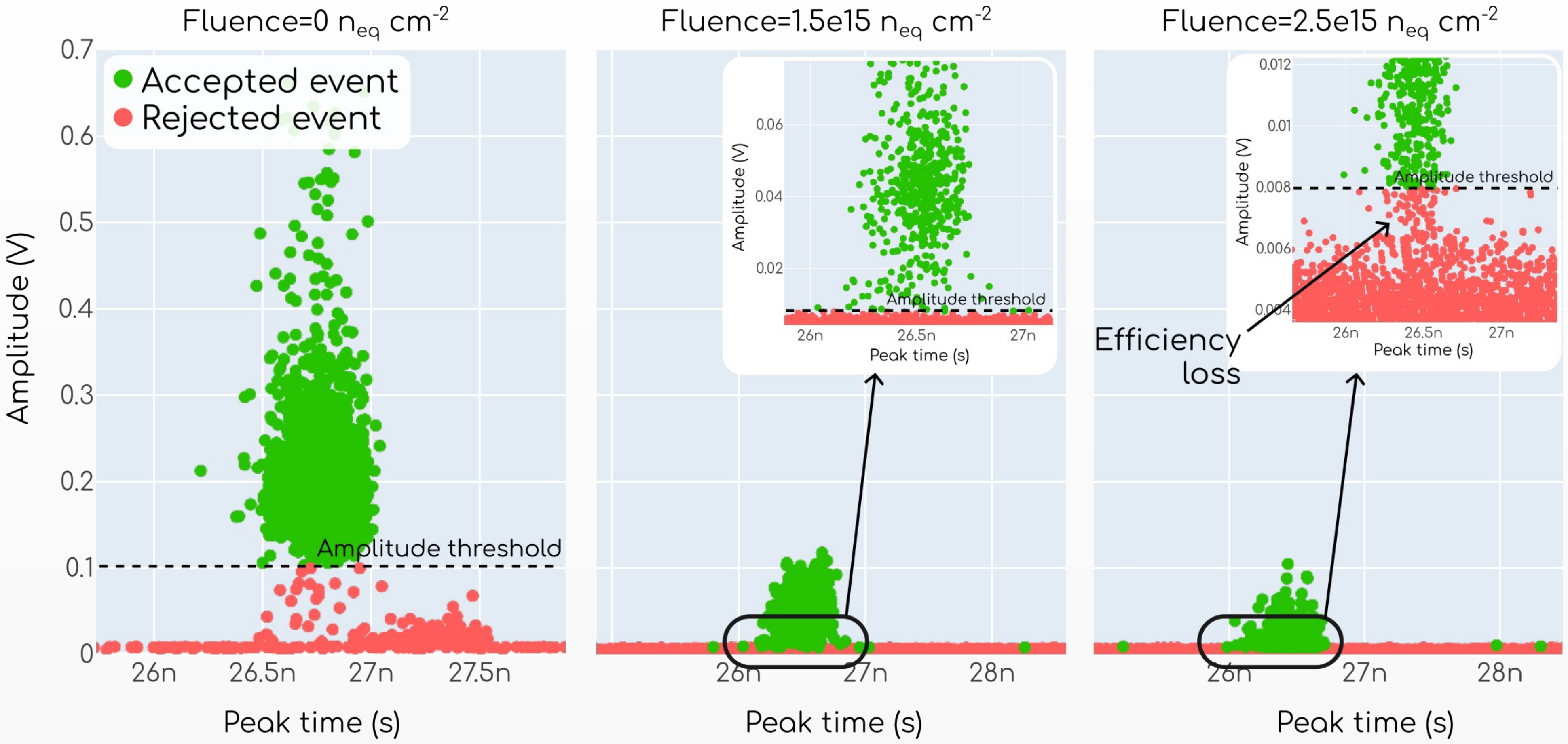


Compromise between time resolution and efficiency after irradiation





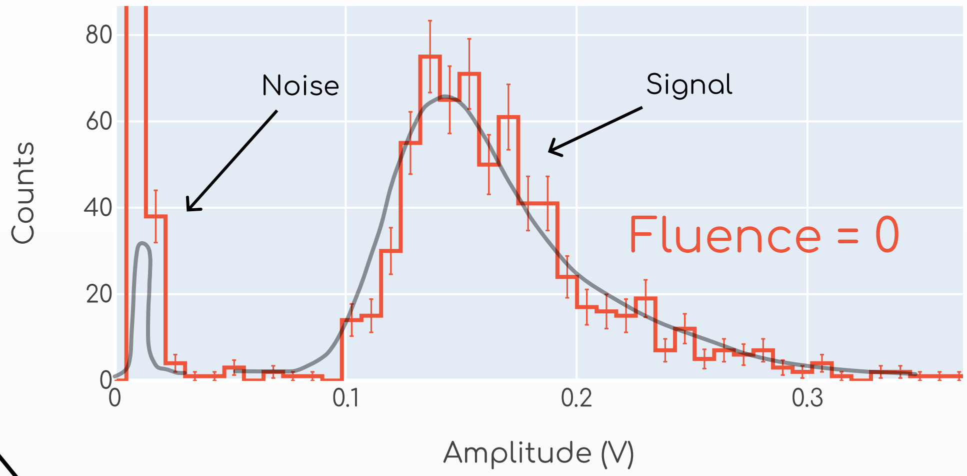
There is a loss of efficiency hidden

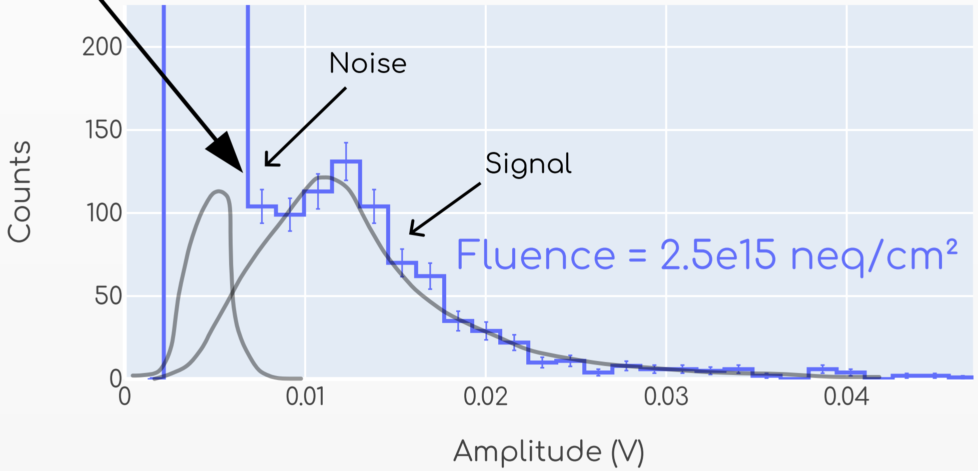


This explains why 2.5e15 n_{eq} cm^{-2} seems to have better time resolution than 1.5e15 n_{eq} cm^{-2}. The price is a severe loss of efficiency (not precisely quantifiable with our setup).

Amplitude/charge distributions

This issue can also be spotted in the amplitude (and charge) distributions.

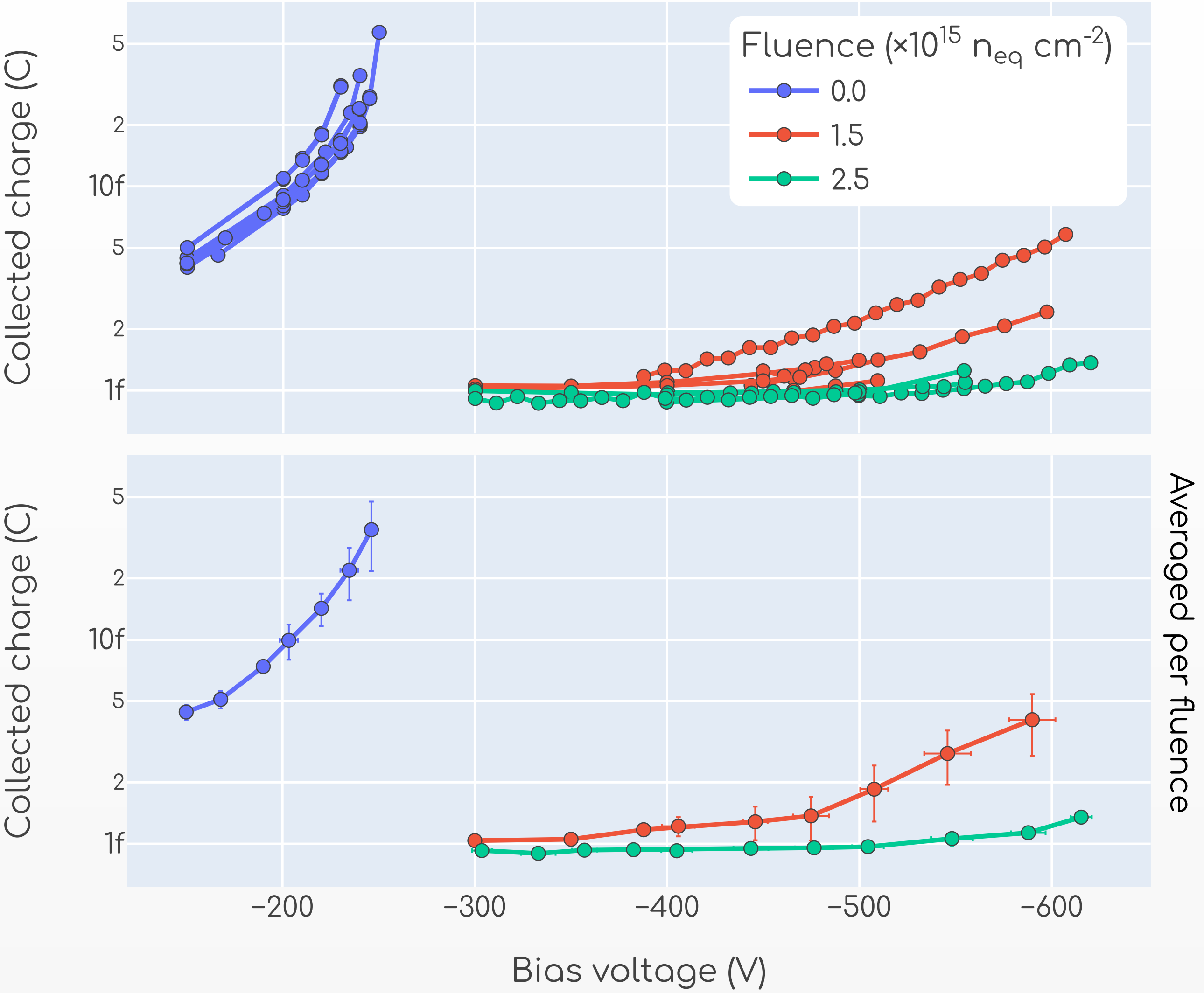




Collected charge with beta source (beta source)

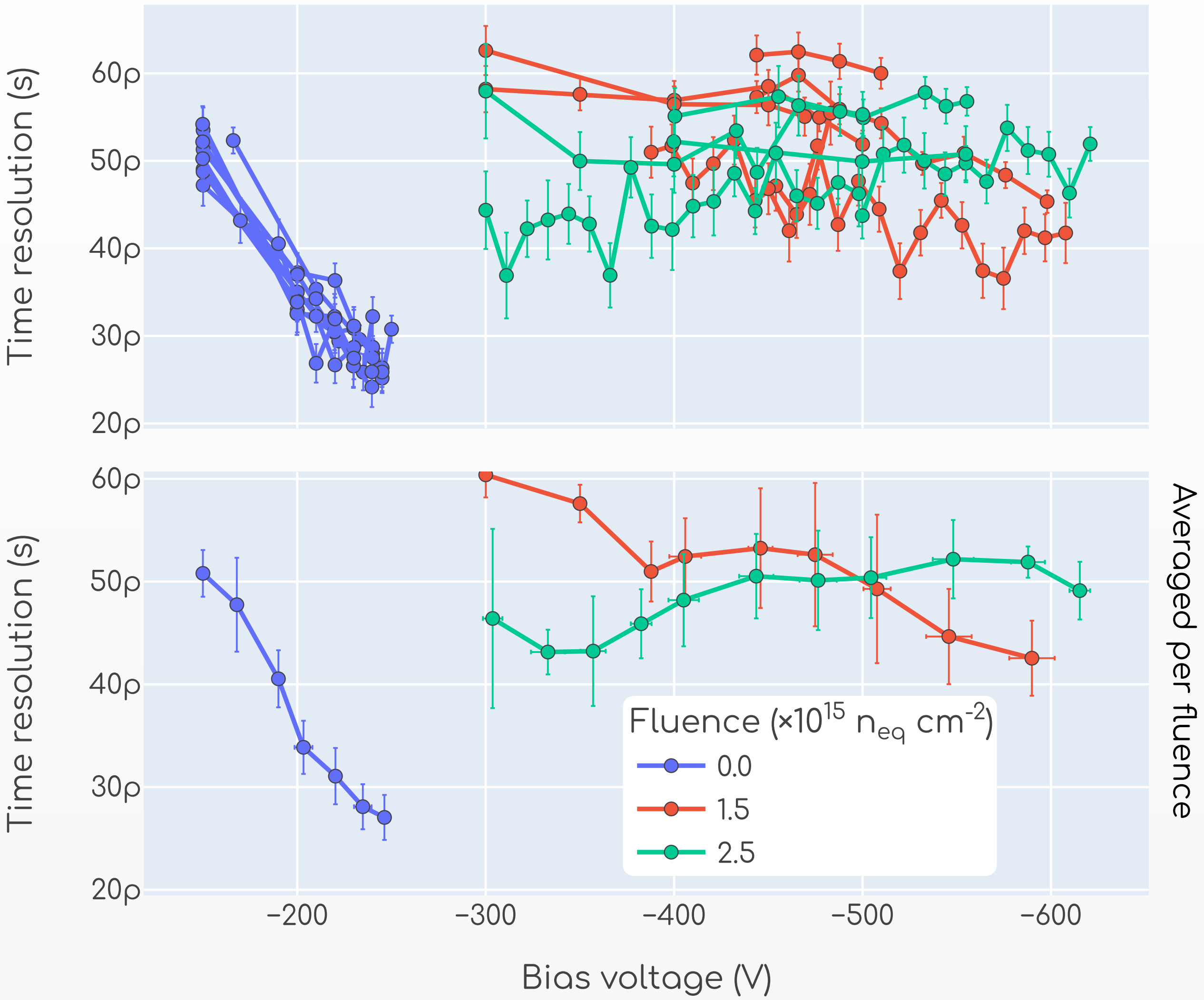
- Charge severely affected by fluence.
- For 0 fluence: No systematic dependence on trenches.
- For higher fluences: Need more testing.
- At 2.5×10^{15} n_{eq} cm^{-2} signal is almost within the noise.
- After 600-700 V all TI-LGAD suffer unrecoverable breakdown.

- Top plot: Each line is a different device.
- Bottom plot: Average per fluence.



Time resolution vs voltage (beta source)

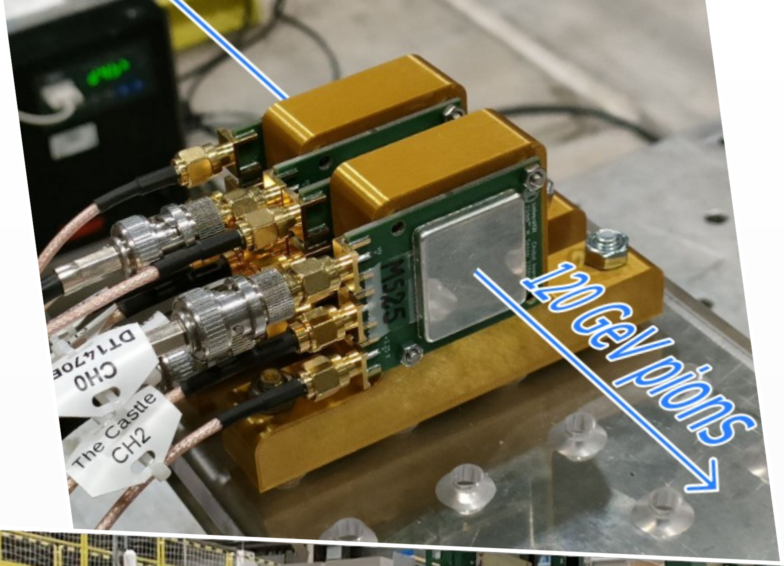
- For 0 fluence: No systematic dependence on trenches.
- For higher fluences: Need more testing.
- Top plot: Each line is a different device.
- Bottom plot: Average per fluence.
- After 600-700 V they all die.



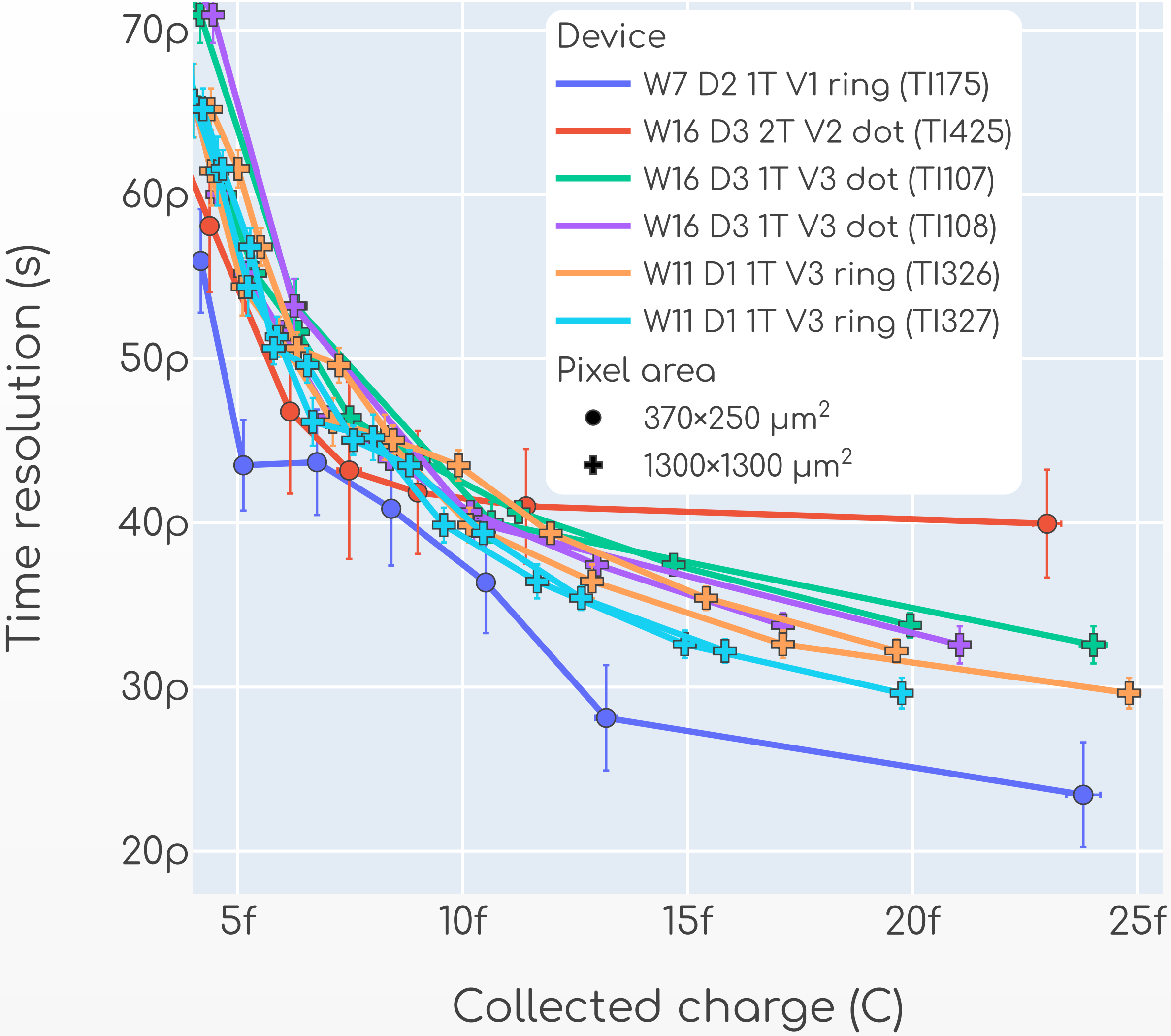
Test beam measurements

Setup at the test beam

- No tracking.
- Same instruments and boards from our beta setup.
- Time resolution measured in pairs:
  - Identical devices → √2
  - Calibrated reference → subtraction in quadrature
- Room temperature.
- Only tested non-irradiated devices.



Test beam results



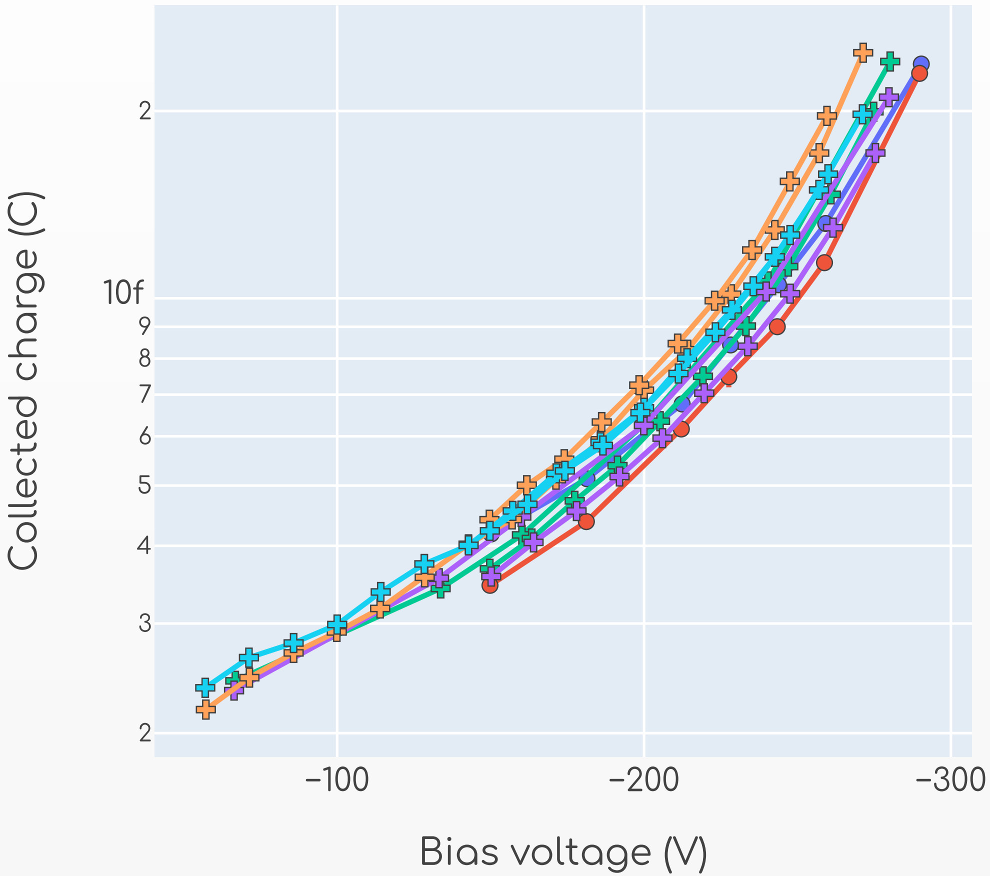
- Time resolution ~30 ps achieved at ~20 fC.
- No systematic influence of trenches design.

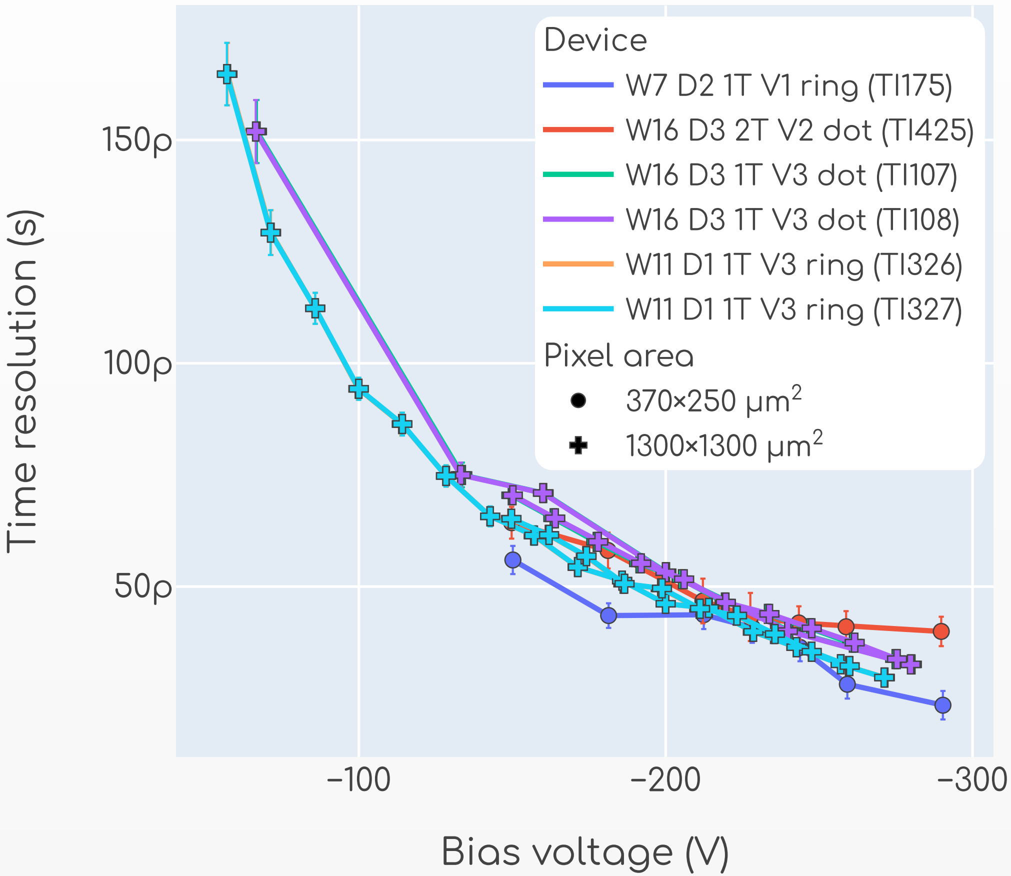
T = Room T (September)

Test beam results

T = Room T (September)

Same data from previous slide but as function of bias voltage.





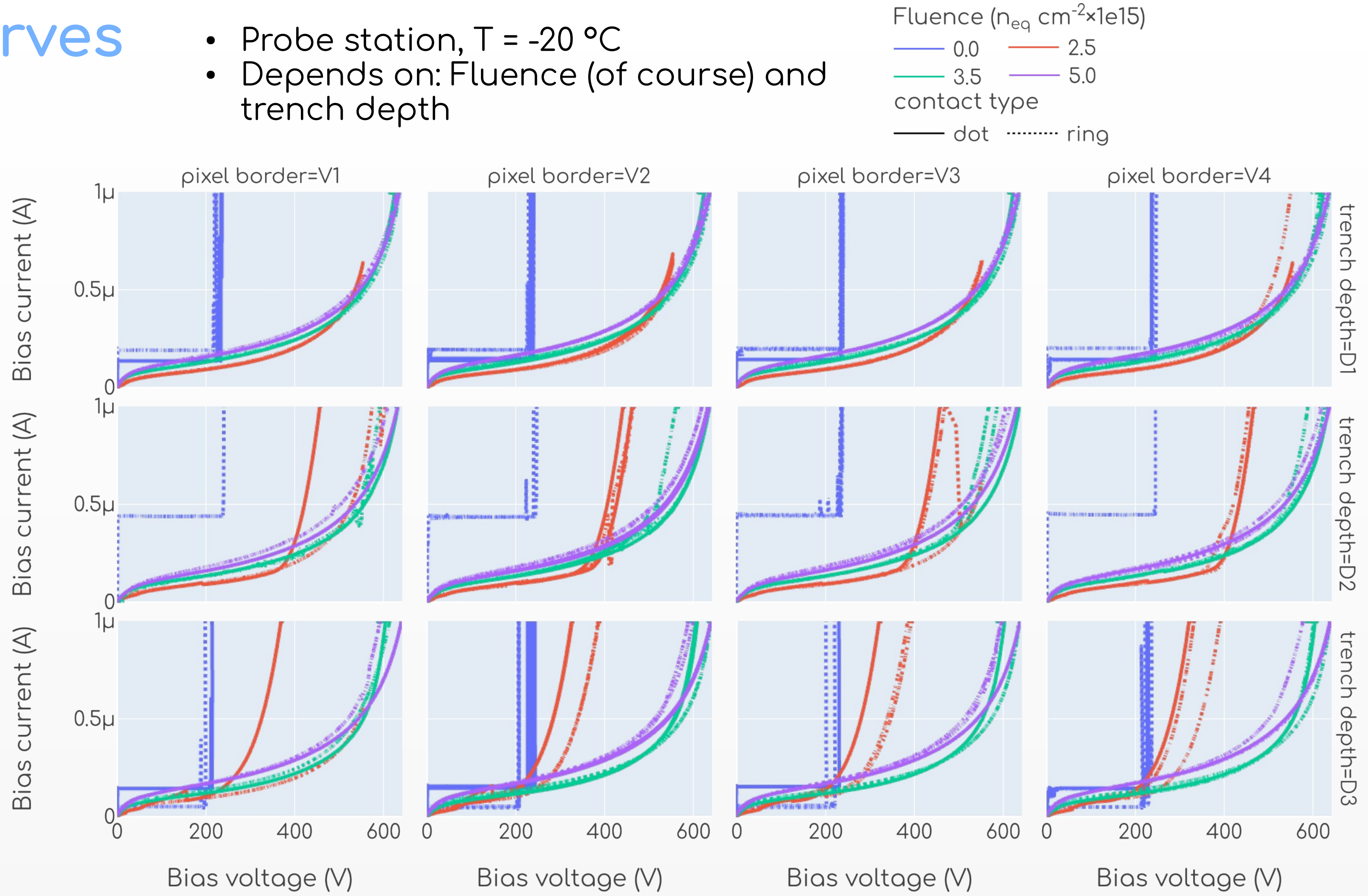
Test beam results

- Devices were kept at “high voltage” for several hours exposed to the beam.
- Not any adverse effect/degradation was observed (e.g. sudden death).

IV curves in the probe station

IV curves

- Probe station, T = -20 °C
- Depends on: Fluence (of course) and trench depth



Conclusions and outlook

Conclusions and outlook

- An extensive characterization of the first production of TI-LGADs was performed.
- All in all it is a promising technology for 4D-tracking:
  - Time resolution is good.
    - Beta source & 120 GeV pions.
  - Inter-pixel distance is good for high granularity.
  - Radiation hardness needs to be improved.
- Trenches design has strong influence in inter-pixel distance and doesn't seem to affect much the other variables like time resolution (still to be studied a bit further).
- The most promising design splits were identified.
- We plan to do test beam studies of irradiated structures within the AIDAinnova WP6 program.

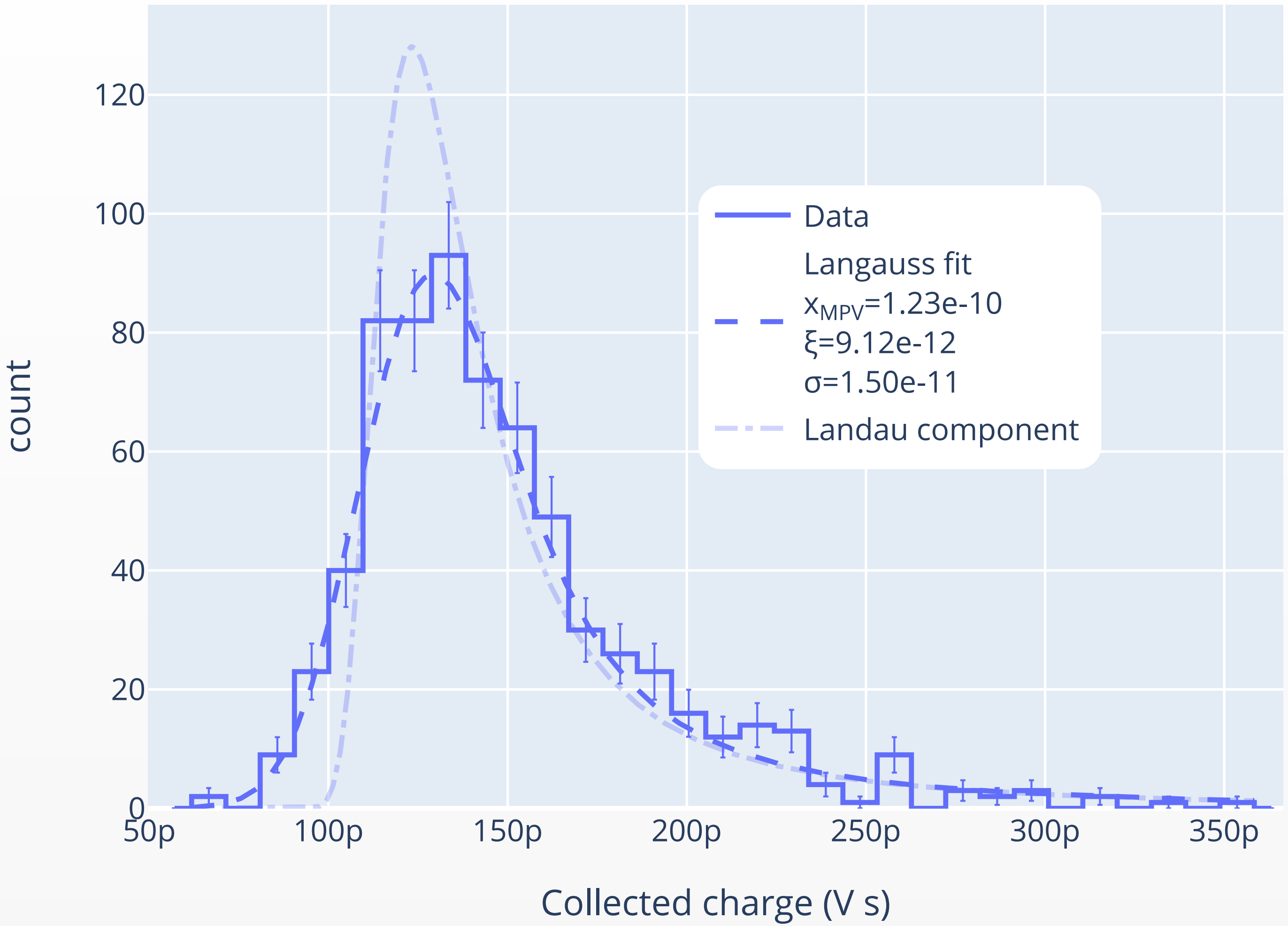

The End

Backup slides

Collected charge

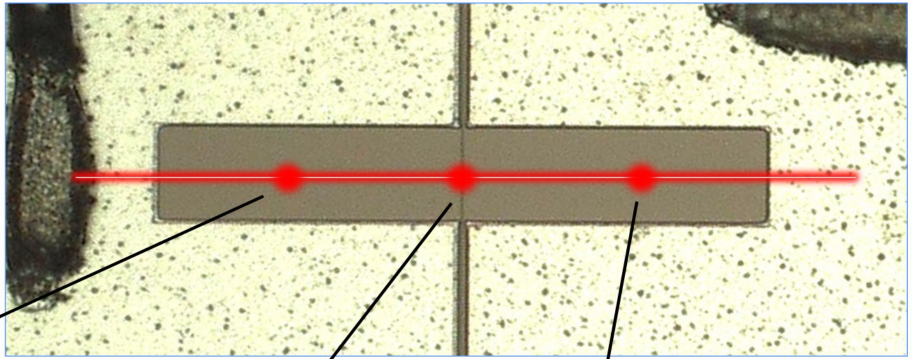
Langauss fit to integral of signal. An example is shown.

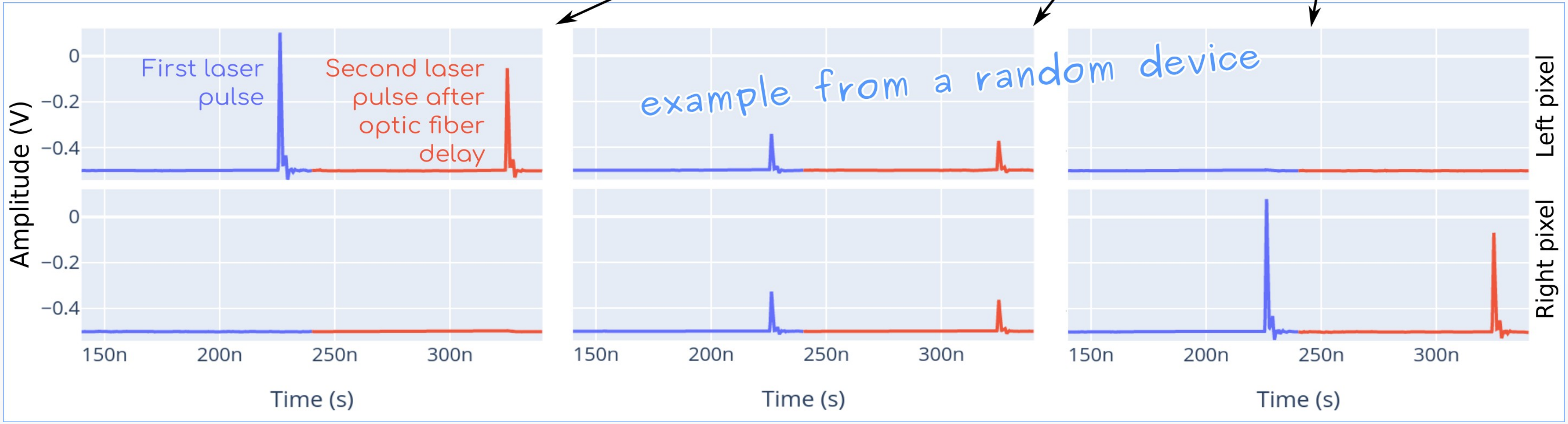
Landau (and Langauss) distribution in Python: https://github.com/SengerM/landaupy



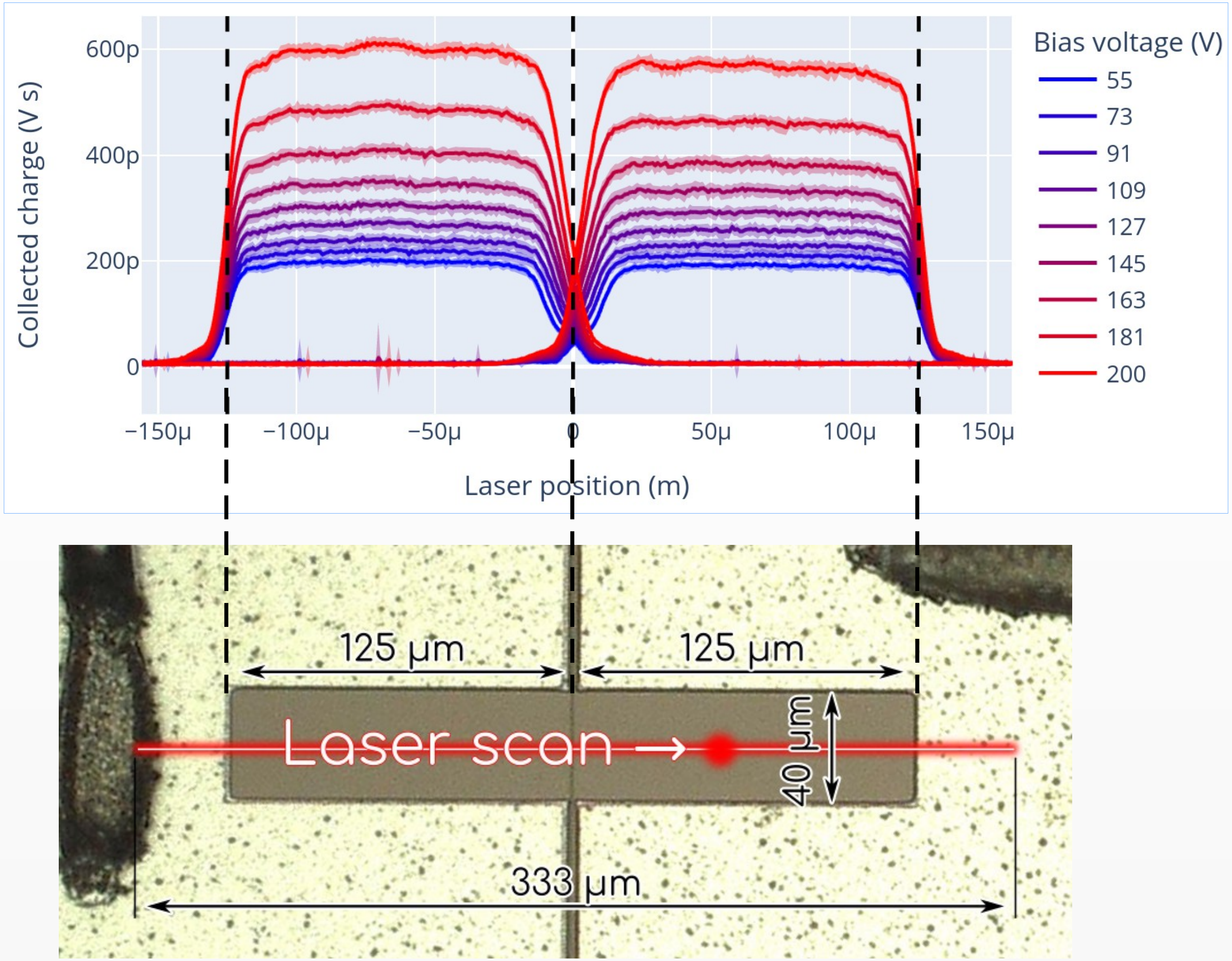
Laser scans

- Trenches provide good isolation.
- The signal is shared in the middle due to the size of the laser spot (~18 μm diameter).
- Similar behavior for all devices.





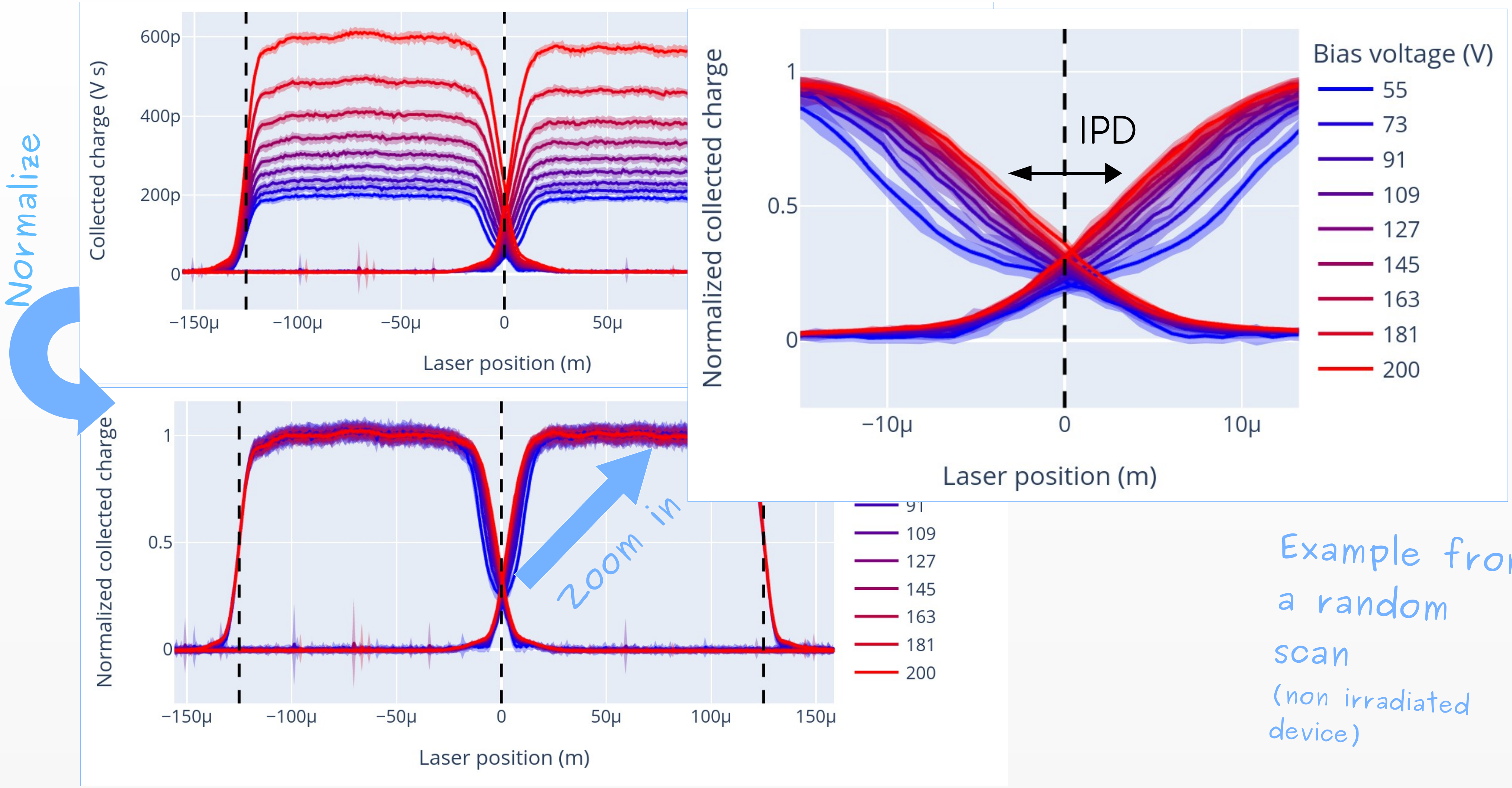
Scanning at different bias voltages



Example from a random scan

(non irradiated device)

Inter-pixel distance depends on bias voltage



Example from a random scan (non irradiated device)

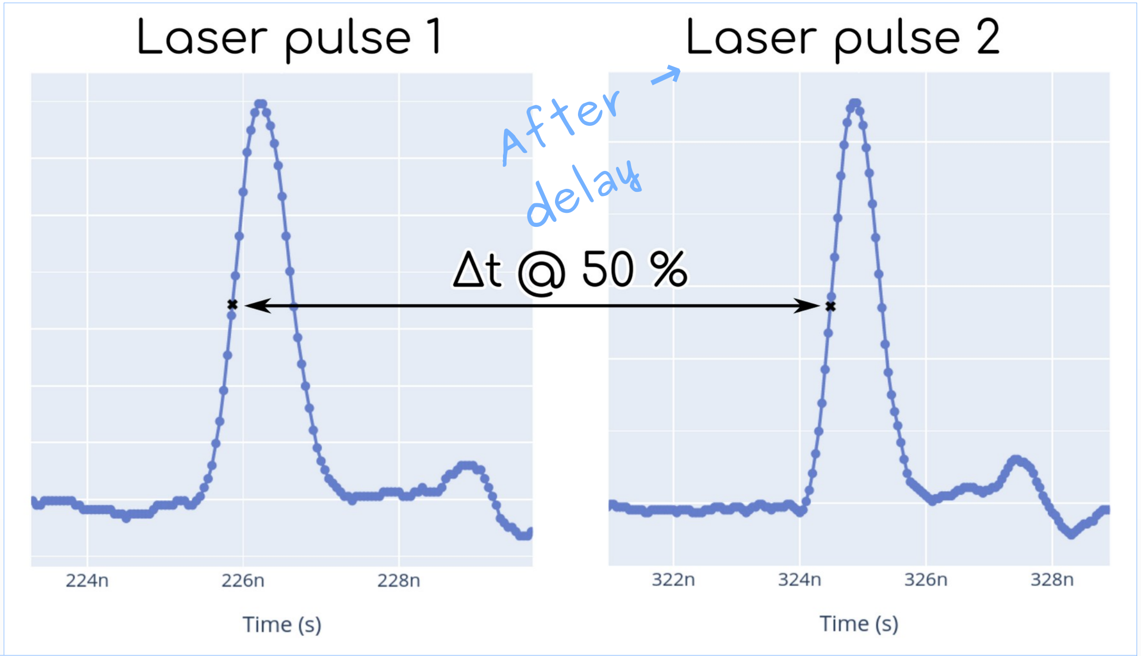
Time resolution

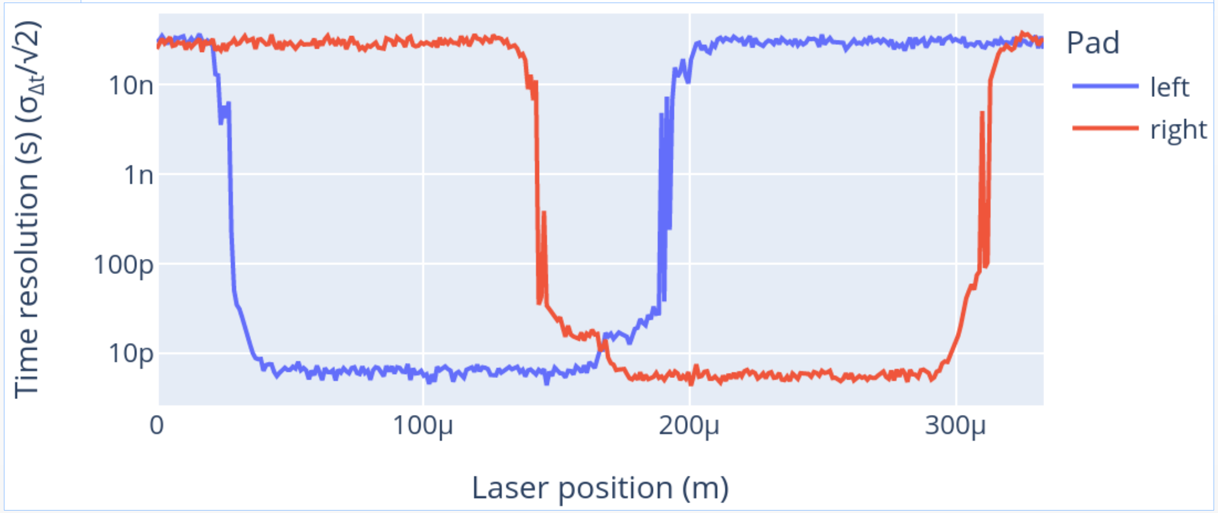
- Constant fraction discriminator.
- Time resolution vs laser position.

$$Time\,resolution = \frac{\sigma_{\Delta t}}{\sqrt{2}}$$

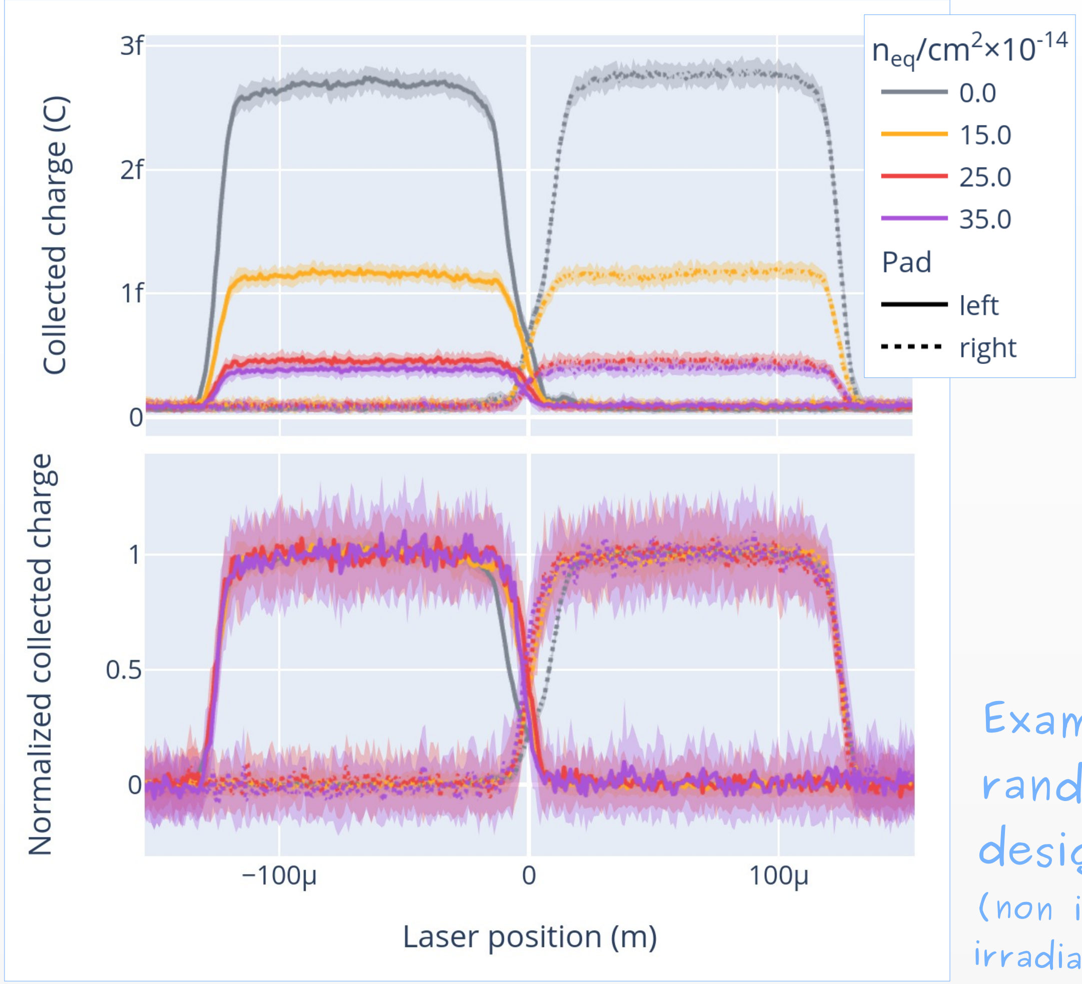
- Within window (laser in silicon):
  - ~ 10 ps ✔

  Outside window (laser in metal):
  - > 10 ns because the software is measuring noise ✔





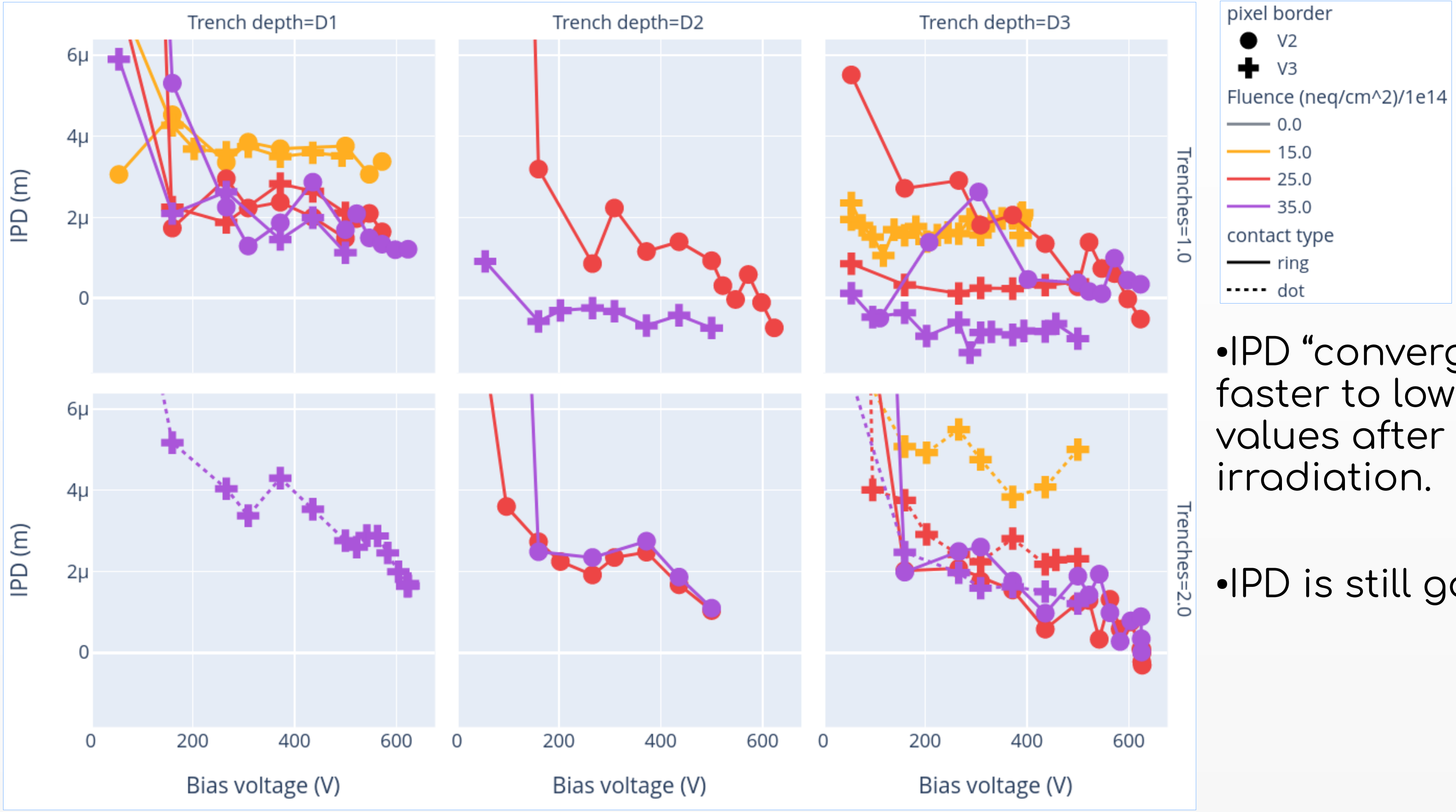
Scanning along irradiated devices



- Same procedure and analysis as for non irradiated devices.
- Gain is significantly reduced.
  → SNR worse, still can measure.
- Behavior in inter-pixel area is "washed away", all designs look similar now.
- Pixel isolation is still perfect.

Example from one random family of design patterns
(non irrad @ 200 V, irradiateds @ 500 V)

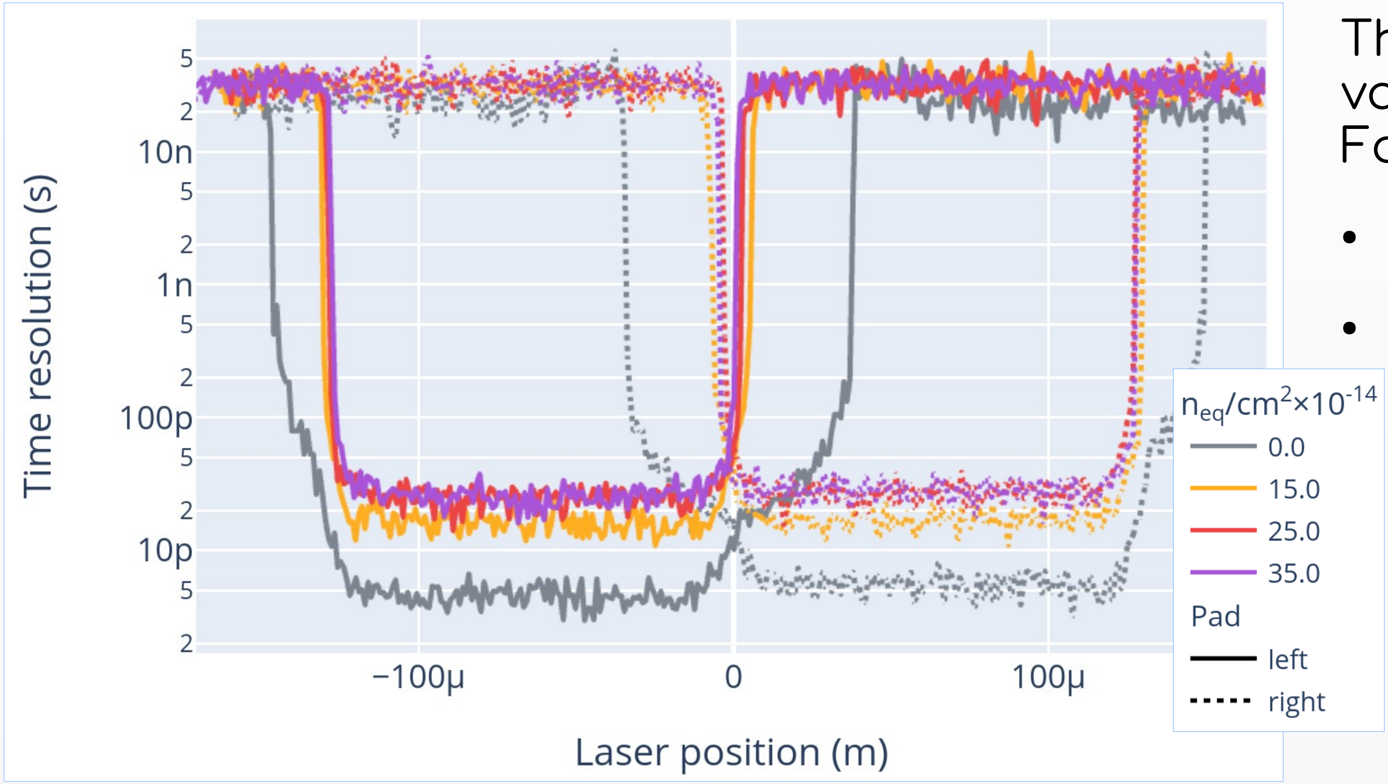
Inter-pixel distance after irradiation



- IPD "converges" faster to lower values after irradiation.
- IPD is still good.

Time resolution (TCT) vs position

- Time resolution degraded by radiation (yes, that was expected...)
- Still uniform until the edges (the plateaus are not deformed)

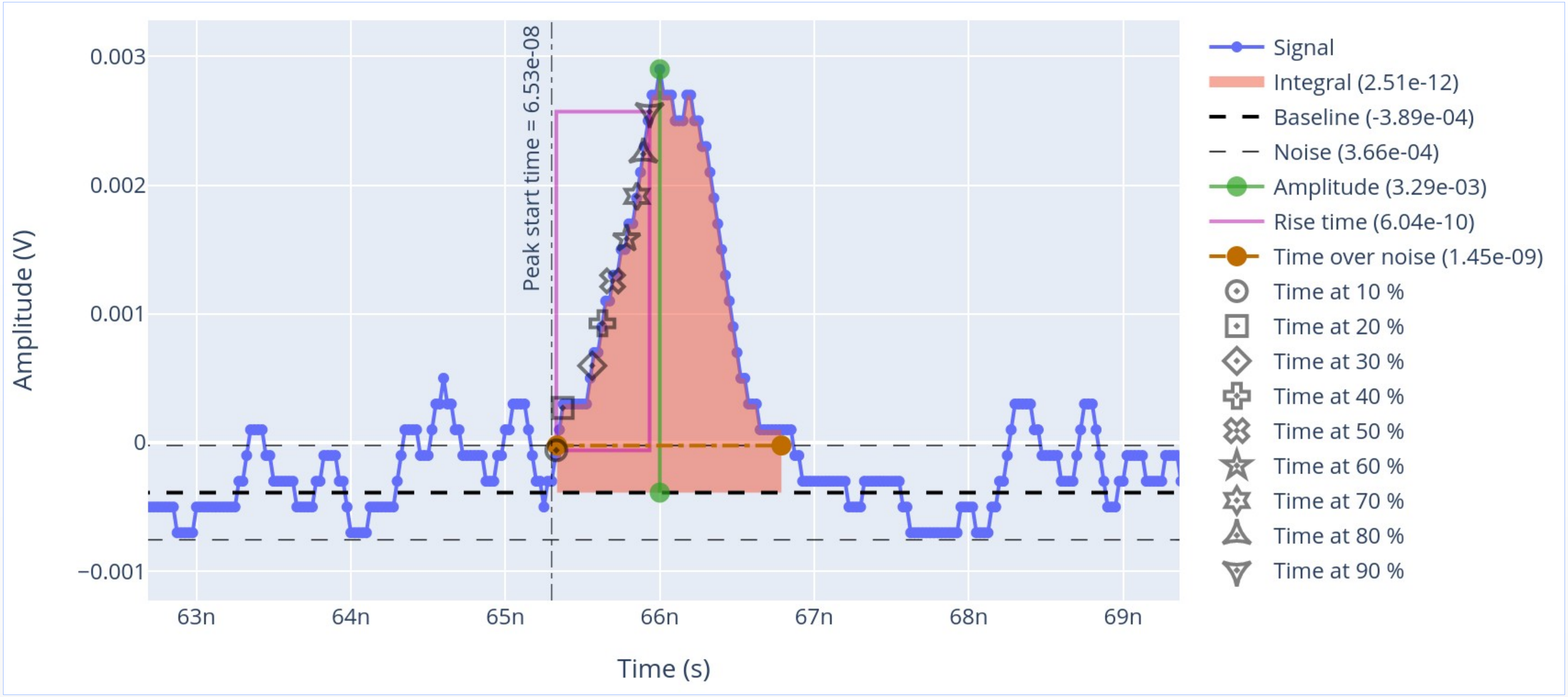


The time resolution is the value within the plateau. For this example:

- Non irrad: ~ 5 ps
- Irrads: ~ 15-30 ps

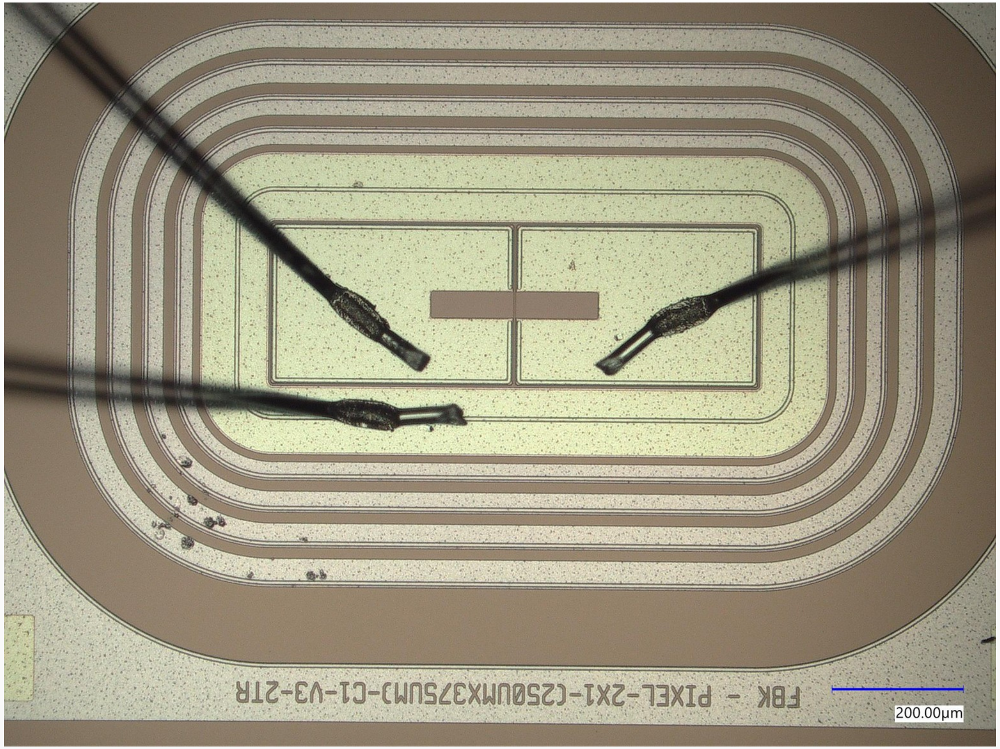
Example from one random family of design patterns (non irrad @ 200 V, irradiateds @ 500 V)

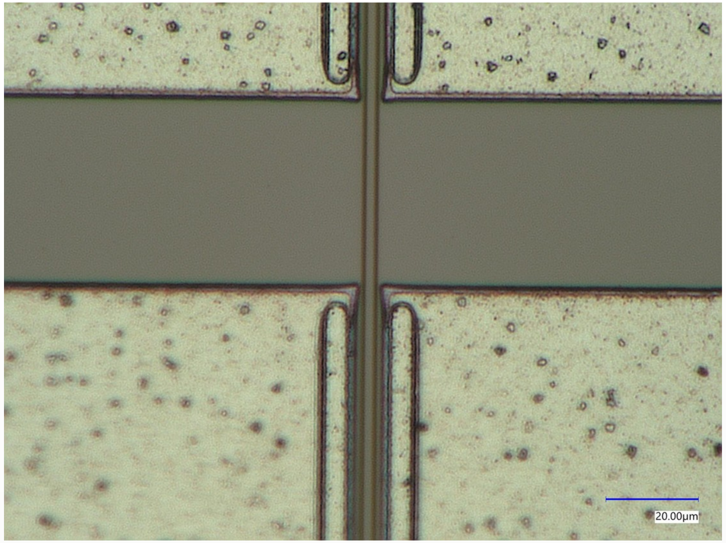
Signals processing



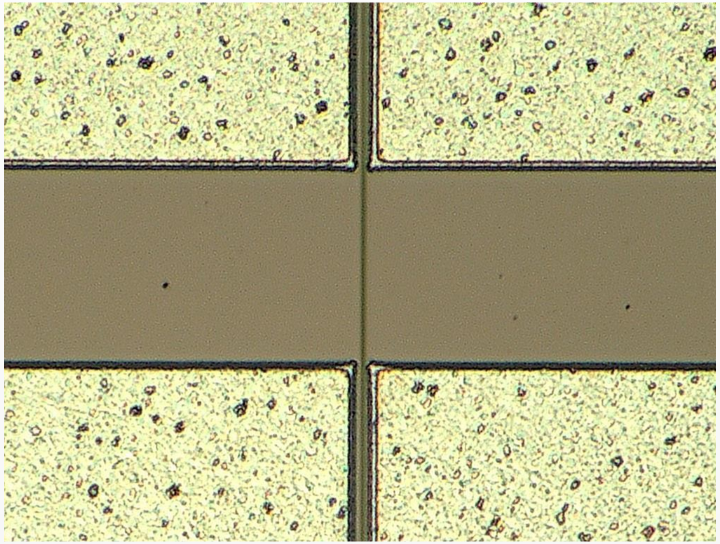
- Processing in Python using this https://github.com/SengerM/signals.
- Signal is linearly interpolated.

The trenches in the microscope





2 trenches



1 trench