VCI 2022 — VIENNA CONFERENCE ON INSTRUMENTATION

University of Zurich[UZH]

FONDAZIONE BRUNO KESSLER

RD50

Time and space characterization of novel TI-LGAD structures

before and after irradiation

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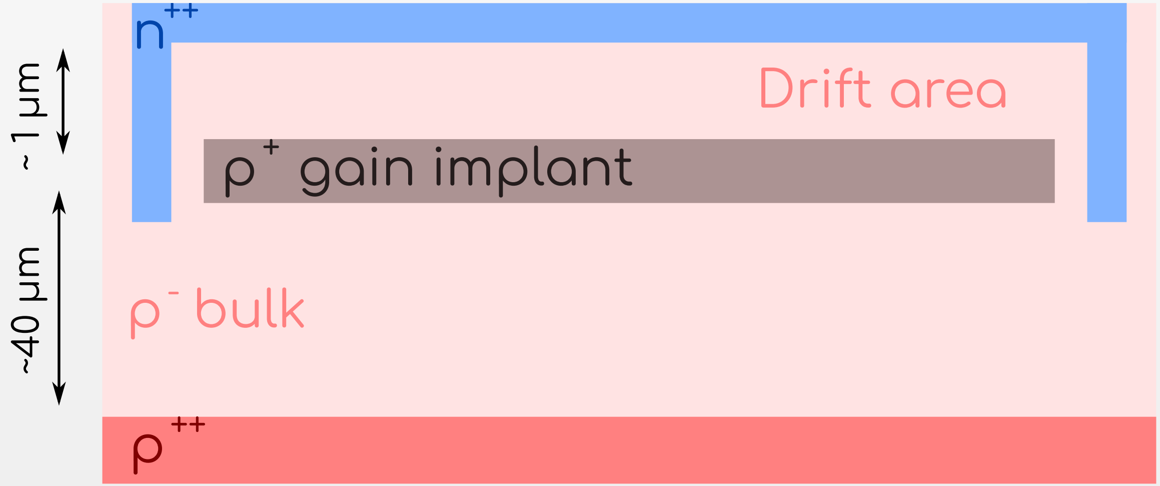
25 Feb 2022

Previous talk on this project: 39th RD50 Workshop @ Valencia (link)

LGAD

- Low Gain Avalanche Detector (LGAD)
- Solid state diode:
  - Very thin active thickness ~40 μm.
  - Gain layer provides gain ~10.
  - Time resolution for 1 MIP ~10-30 ps.

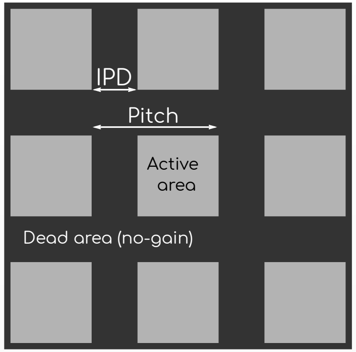


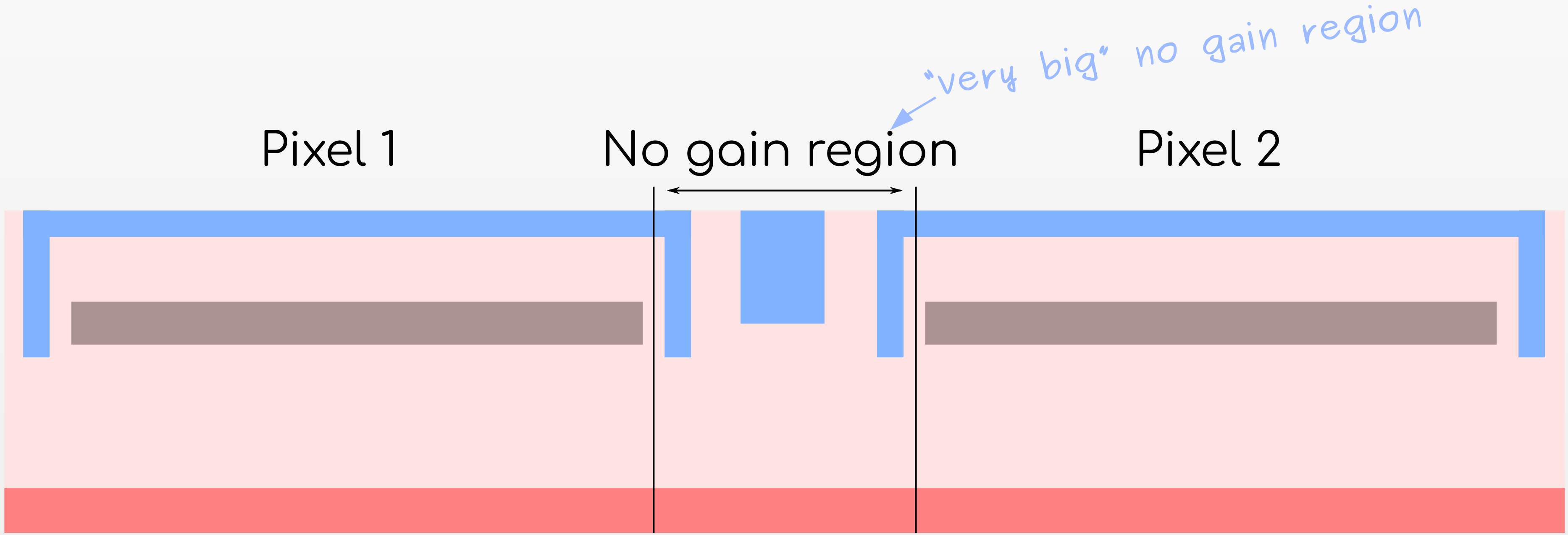
*Cartoon adapted from Ferrero, M., Arcidiacono, R., Mandurrino, M., Sola, V., Cartiglia, N., 2021. An Introduction to Ultra-Fast Silicon Detectors: Design, Tests, and Performances. CRC Press. https://doi.org/10.1201/9781003131946

LGAD technology and (x,y,z,t) tracking

- “Plain LGAD”: mature technology.
  - CMS ETL
  - Atlas HGTD
- Outstanding time resolution.

- Issue: Fill factor
  - Inter-pixel distance (IPD) is on the order of 20-50 μm.[1]





[1]Ferrero, M., Arcidiacono, R., Mandurrino, M., Sola, V., Cartiglia, N., 2021. An Introduction to Ultra-Fast Silicon Detectors: Design, Tests, and Performances. CRC Press. https://doi.org/10.1201/9781003131946

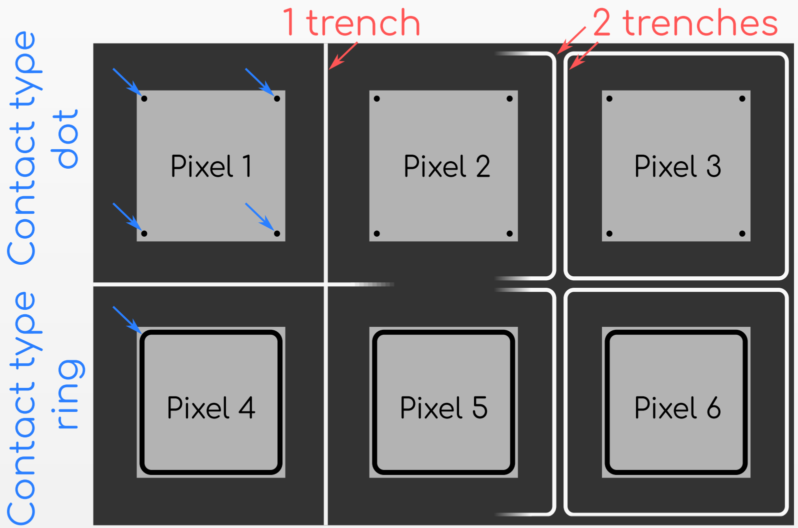
The “RD50 TI-LGAD Project”

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

Design patterns

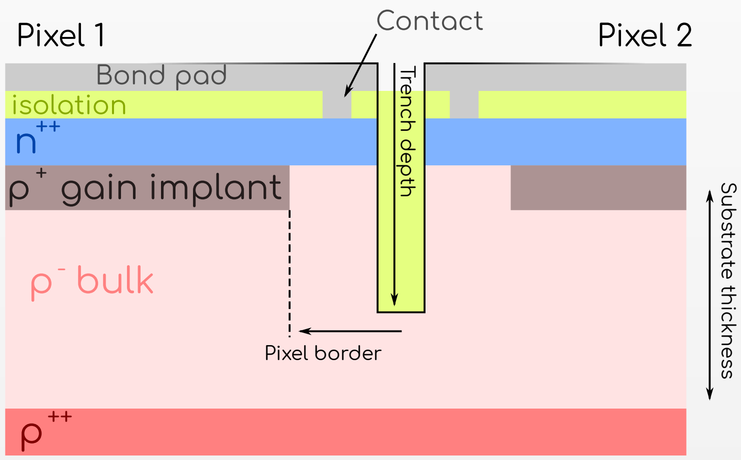
1) Trenches:
   - 1.
   - 2.
2) Contact type:
   - Ring.
   - Dot.
3) Pixel border:
   - trench-gain layer distance.
4) Trench depth.

Top view



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

Side view



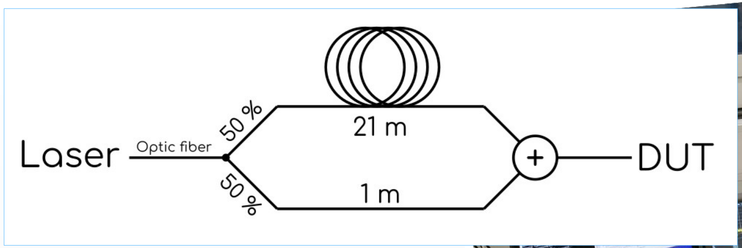
**These cartoons show a simplified/idealized picture and are meant for visualization purposes.

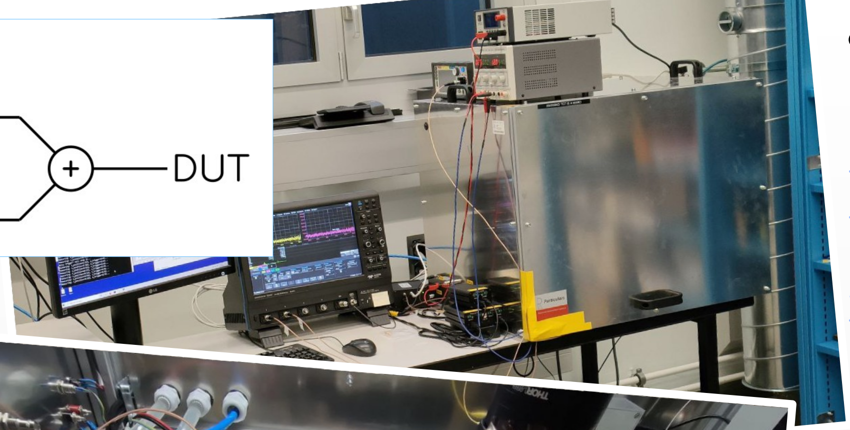
[1] G. Paternoster. “Latest Developments on Trench-Isolated LGADs.” Presented at the 35th RD50 Workshop, CERN, November 19, 2019. https://indico.cern.ch/event/855994/contributions/3637012/.

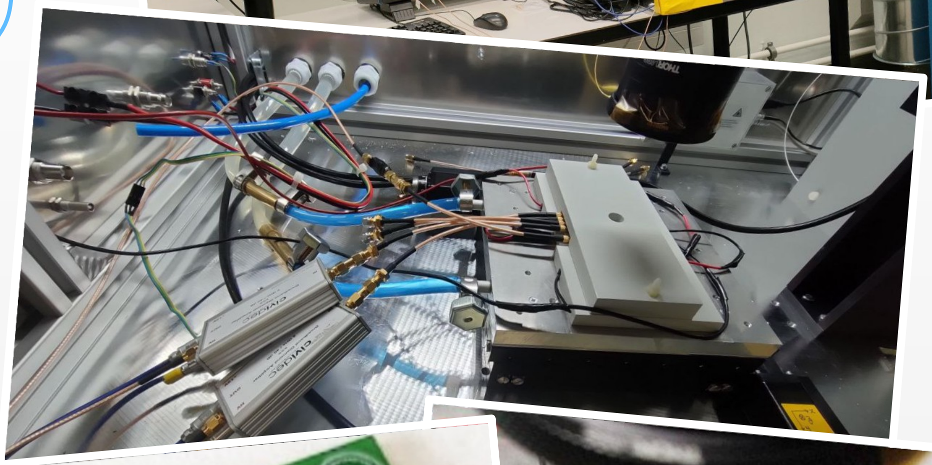
Experimental setup and procedures

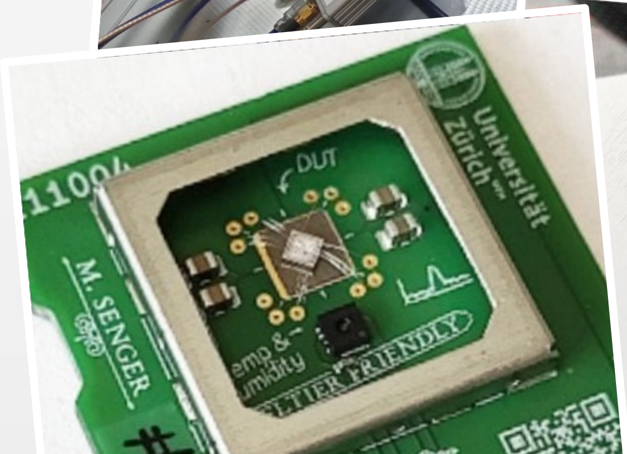
TCT setup @ UZH

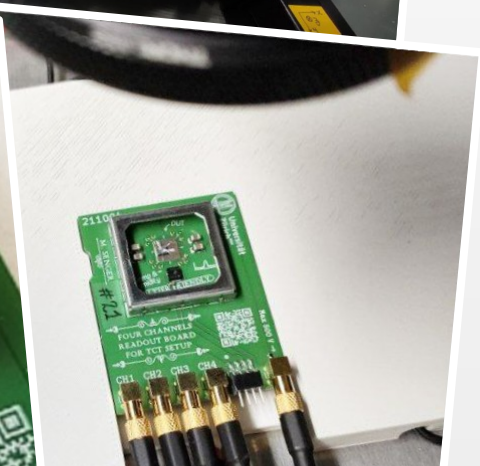
- Particulars Scanning TCT:
  - Infrared laser (1064 nm).
  - Laser spot Gaussian with[1] σ ~ 9 μm.
  - Laser splitting+delay[2] with optic fiber for timing measurements provides two pulses separated by 100 ns.
- Custom made passive readout board.
  - Temperature + humidity close to DUT.
- Cividec C2HV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







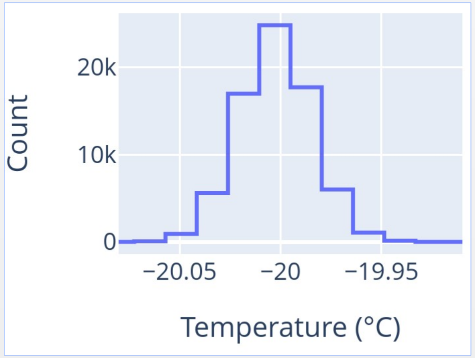




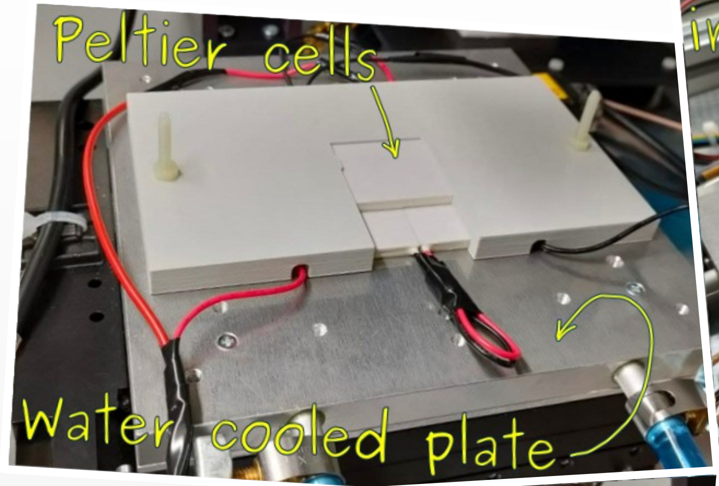
[1] https://msenger.web.cern.ch/a-spacial-characterization-of-the-tct/
[2] https://msenger.web.cern.ch/laser-delay-system-for-the-scanning-tct/

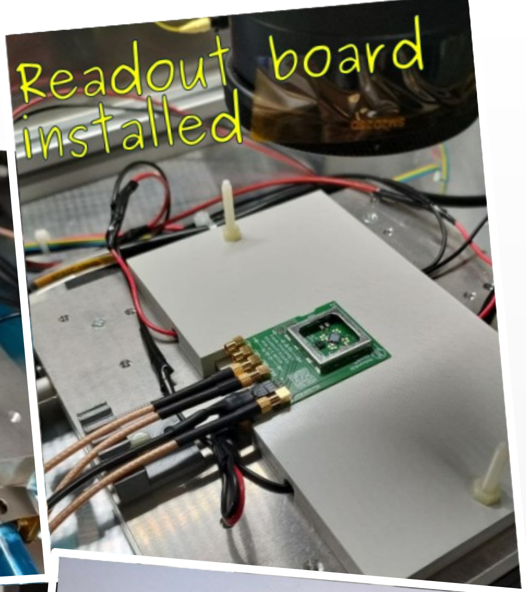
Low temperature system

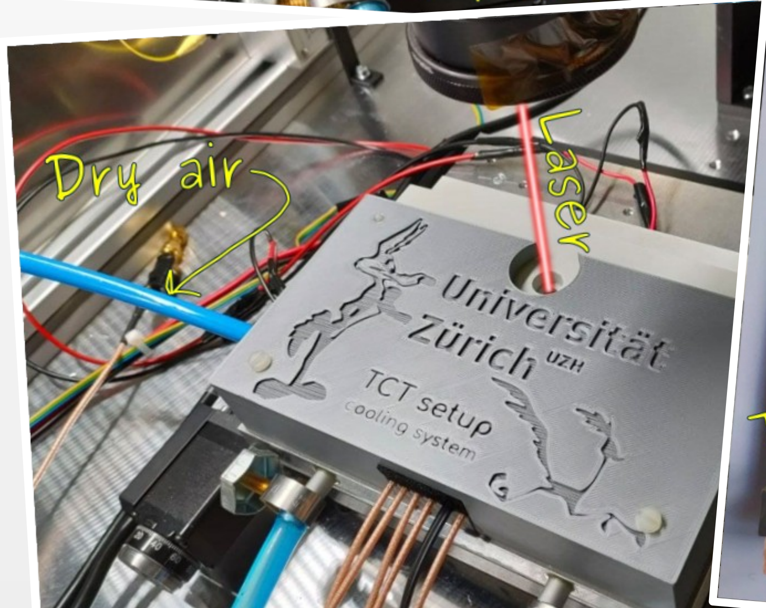
- Used for irradiated devices.
- Chiller + peltier cells.
- Temperature and humidity measured on board, 5 mm away from DUT.
- PID control implemented in the computer.
- Measurements conditions:
  - T = -20.00 ± 0.02 °C
  - H < 1 %RH at all times

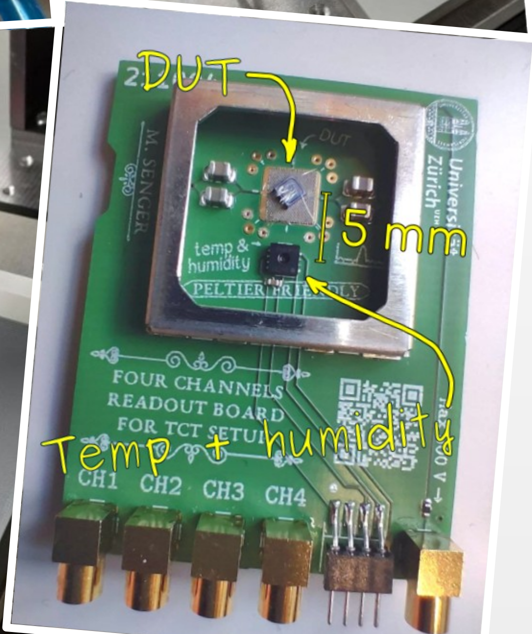


Example from one of the scans



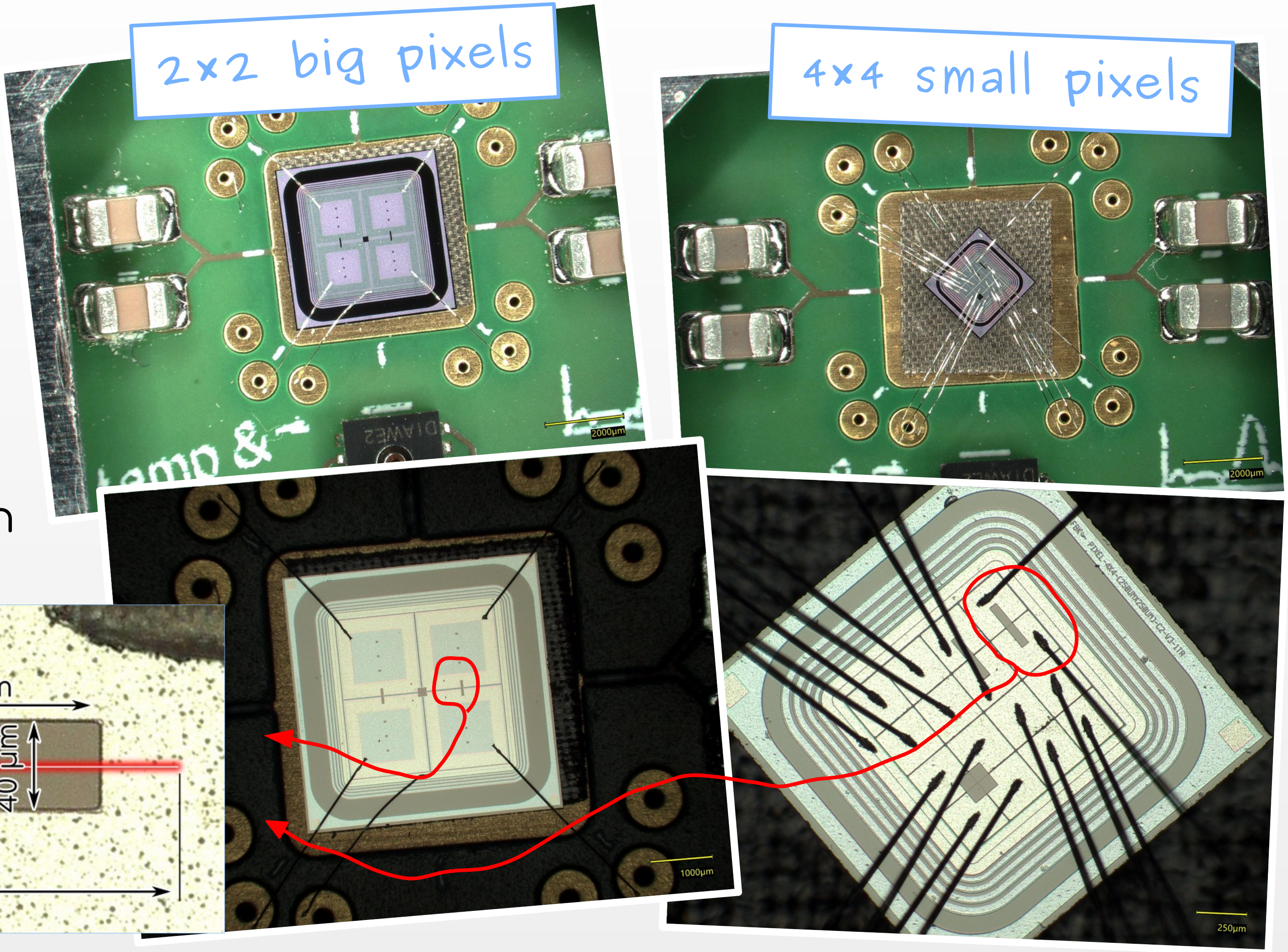


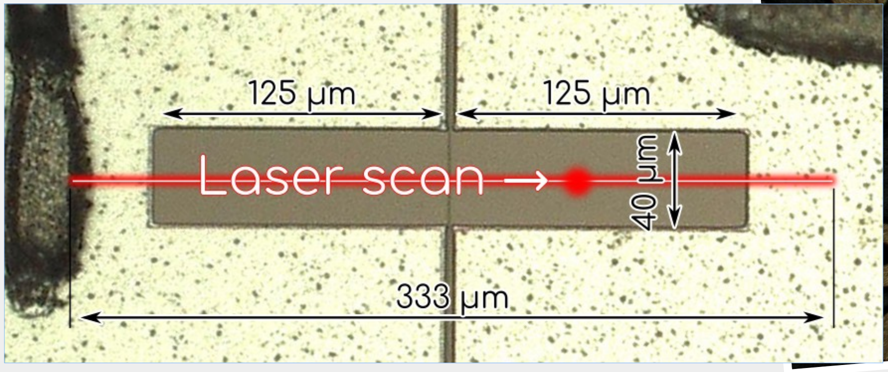




Samples geometry and laser scans

- 1D linear scan.
- From metal to metal crossing through the window.
- Two geometries:
  1) 2×2 big pixels.
  2) 4×4 small pixels.
  - Window is identical in both.

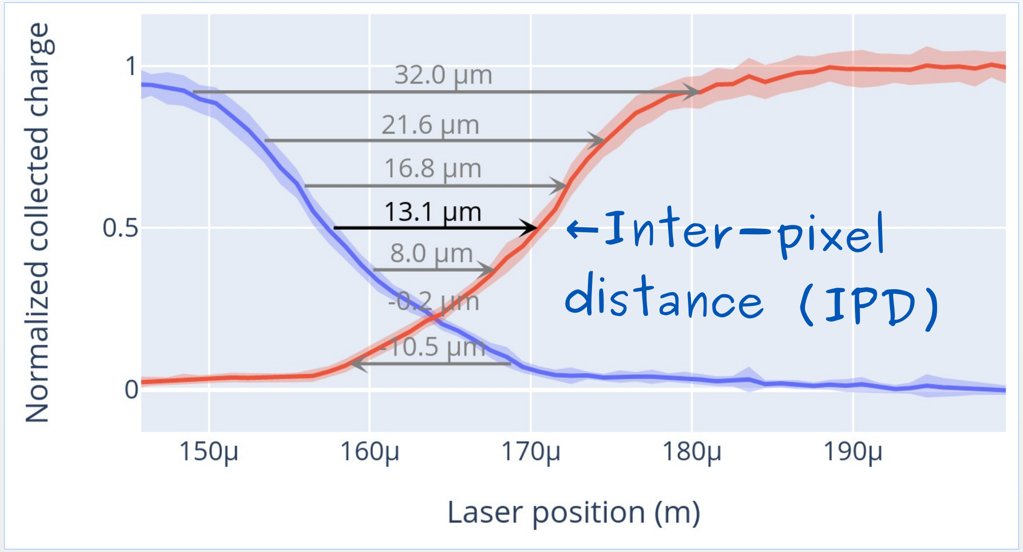


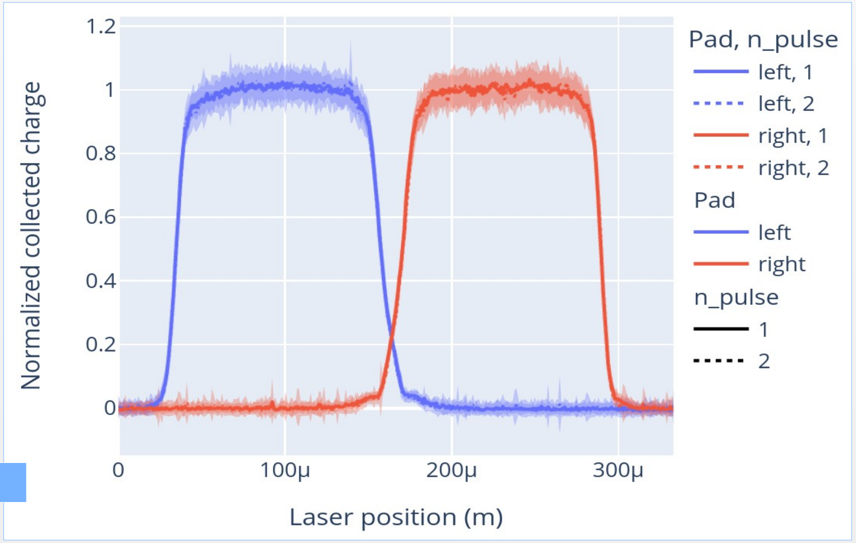


Inter-pixel distance (IPD)

- IPD: 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.

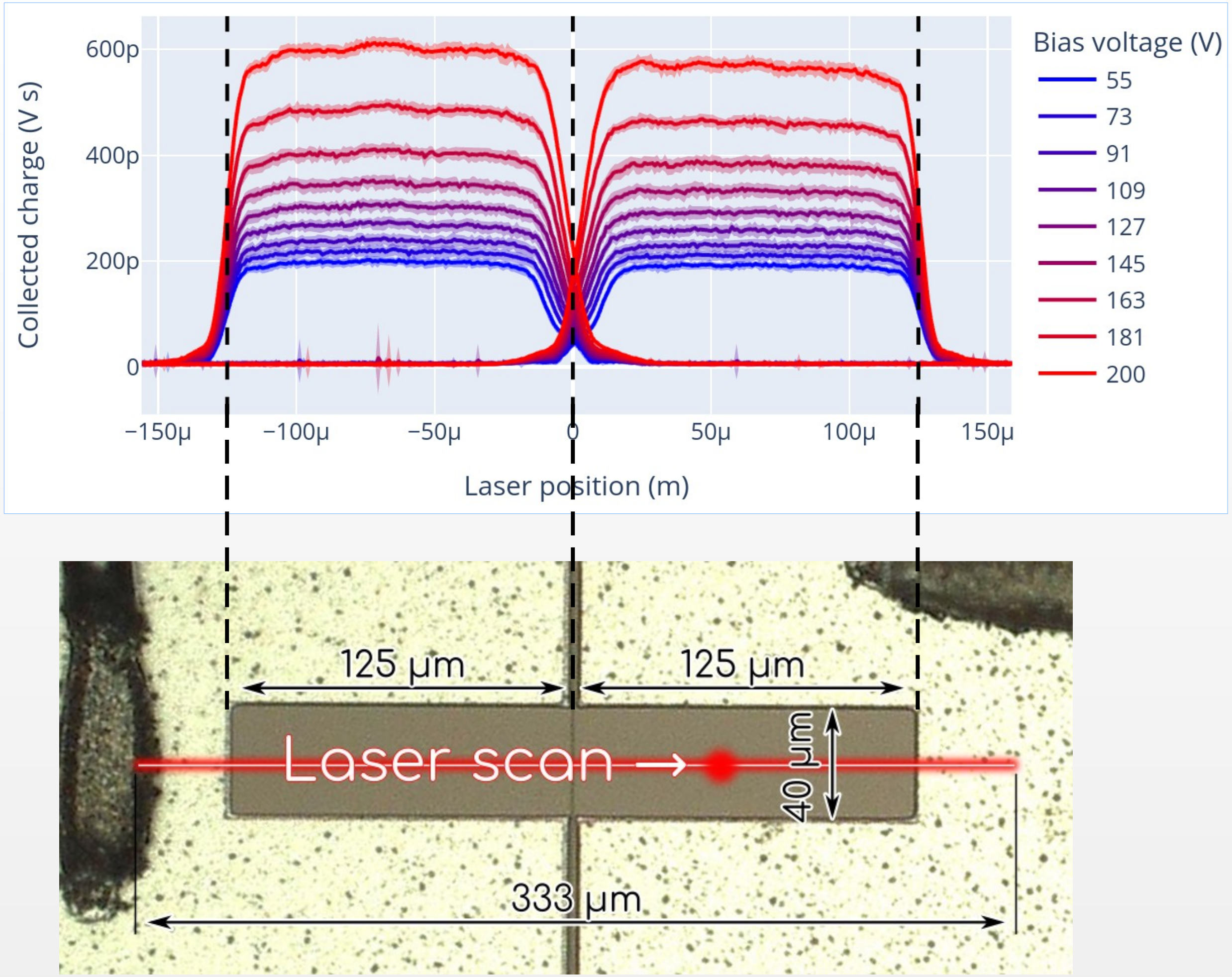
Example from a random scan (non irradiated device)





Scanning at different bias voltages

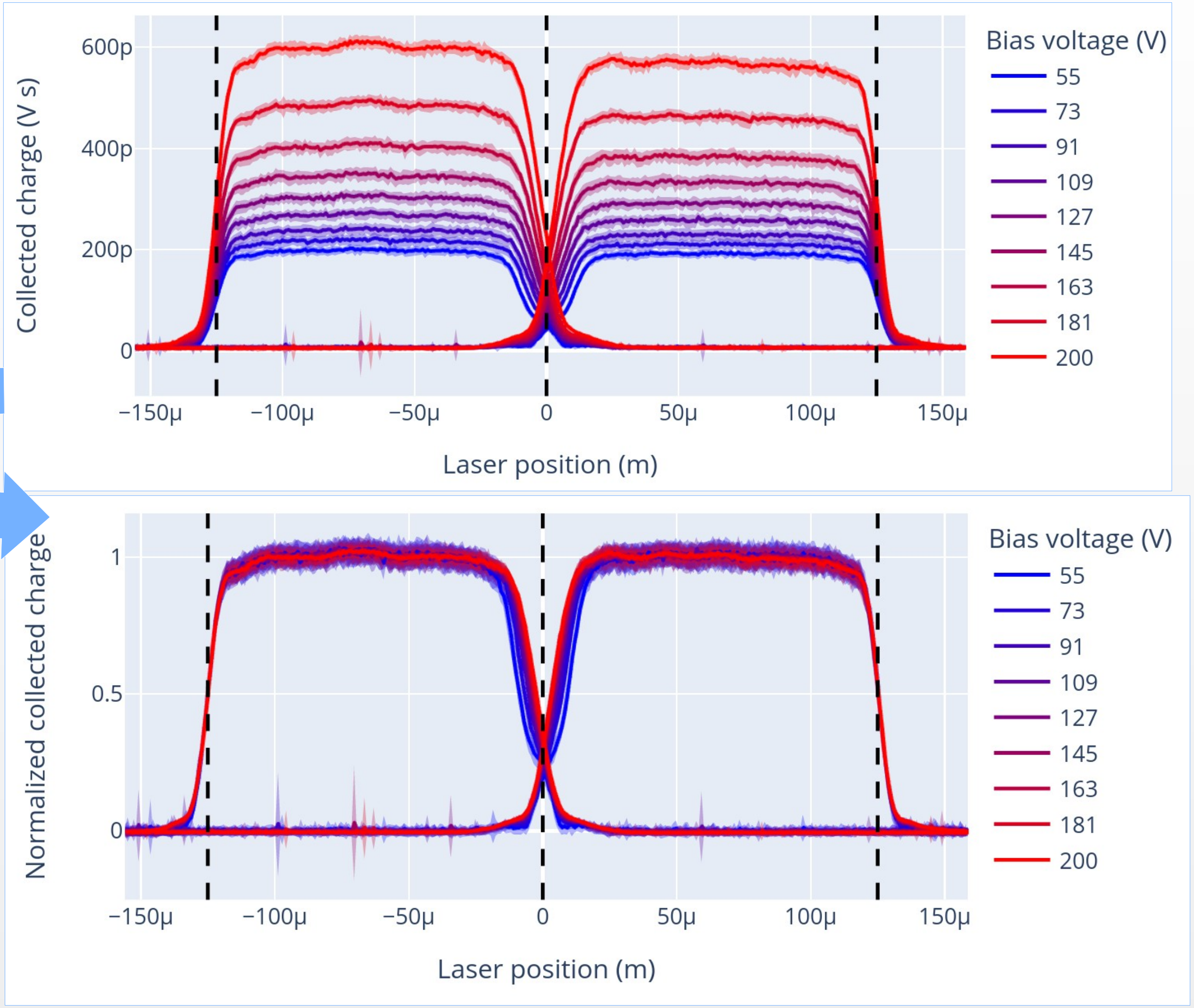
Example from a random scan (non irradiated device)



Scanning at different bias voltages

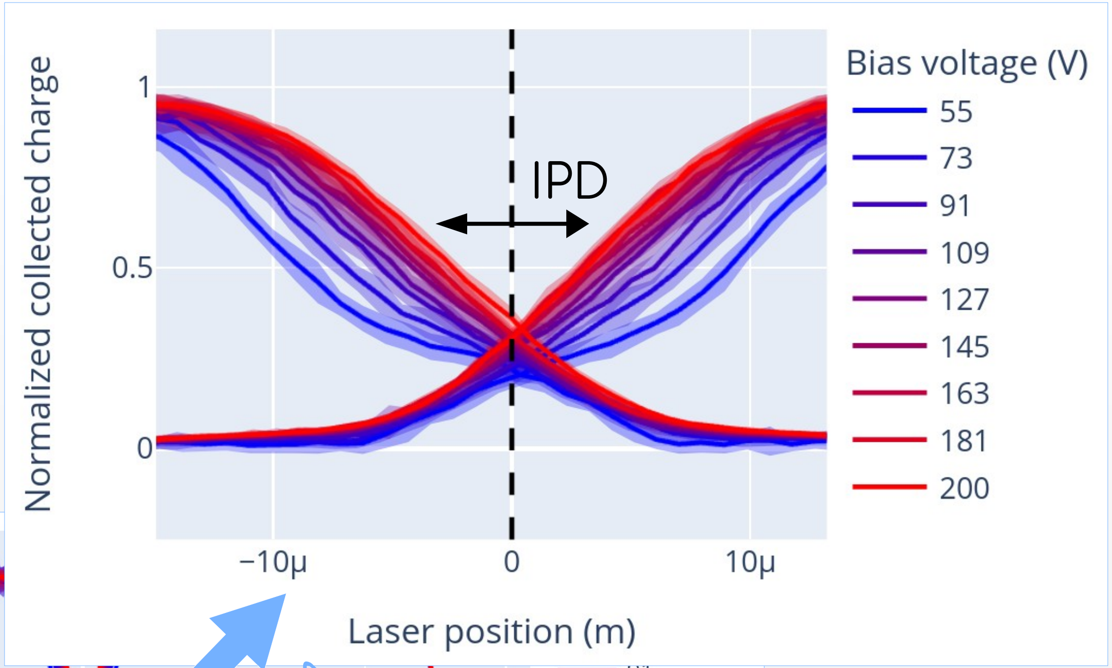
Example from a random scan (non irradiated device)

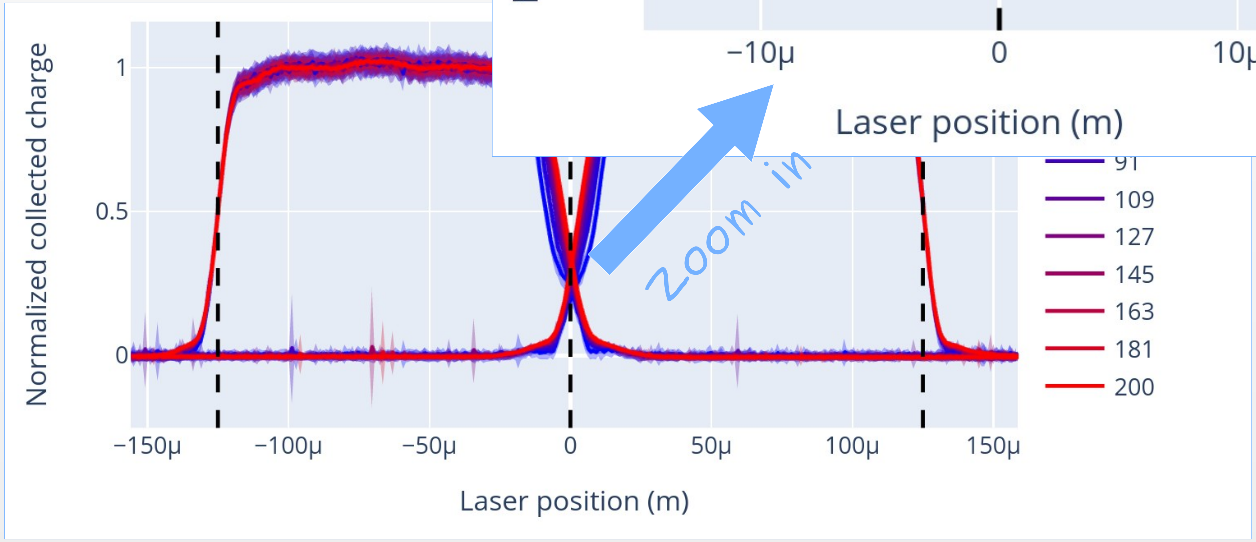
Normalize



Scanning at different bias voltages

Inter-pixel distance (IPD) depends on bias voltage[1].





Example from a random scan (non irradiated device)

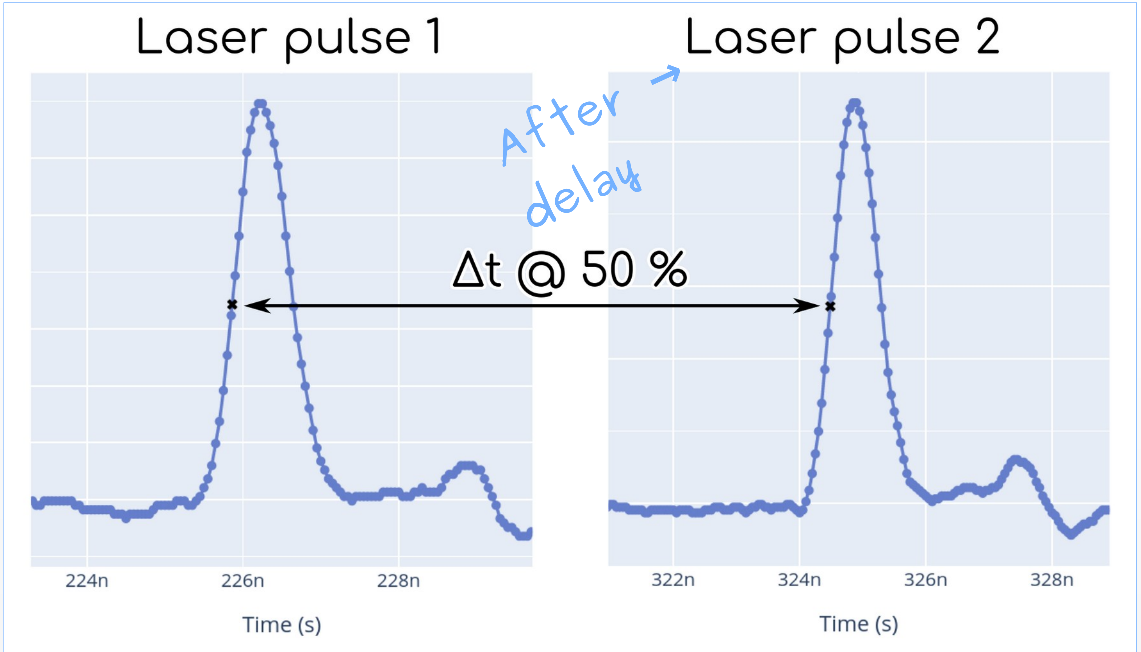
[1]Also reported by Ashish Bisht. 2021. "Characterization of Novel Trench-Isolated LGADs for 4D Tracking." Presented at the WORKSHOP ON PICO-SECOND TIMING DETECTORS FOR PHYSICS, Zurich, September 9. https://indico.cern.ch/event/861104/contributions/4514658/

Time resolution

Example from a random scan (non irradiated device)

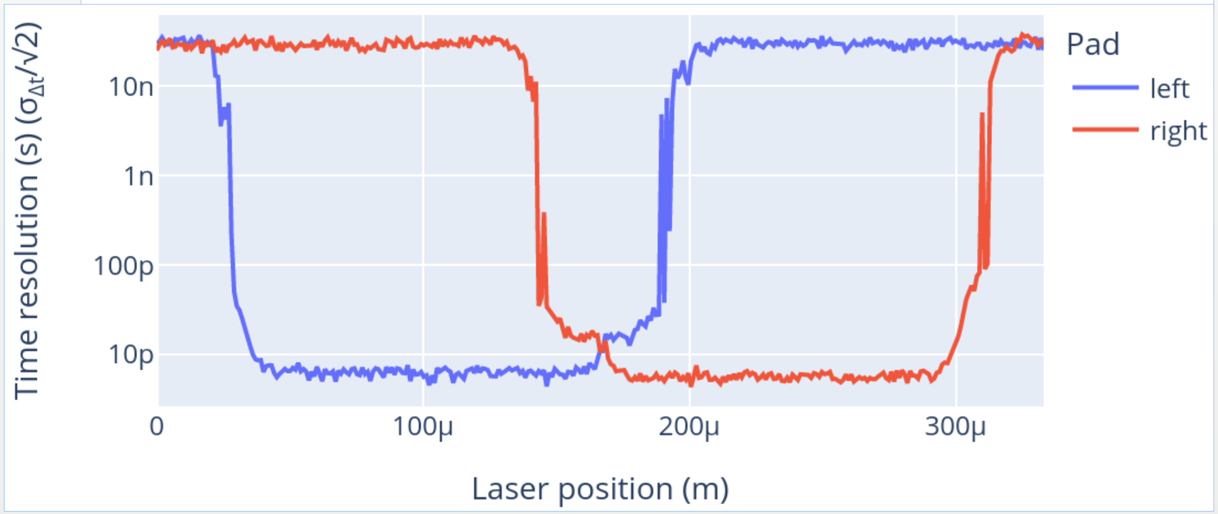
- Constant fraction discriminator.
- Time resolution vs laser position.

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



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

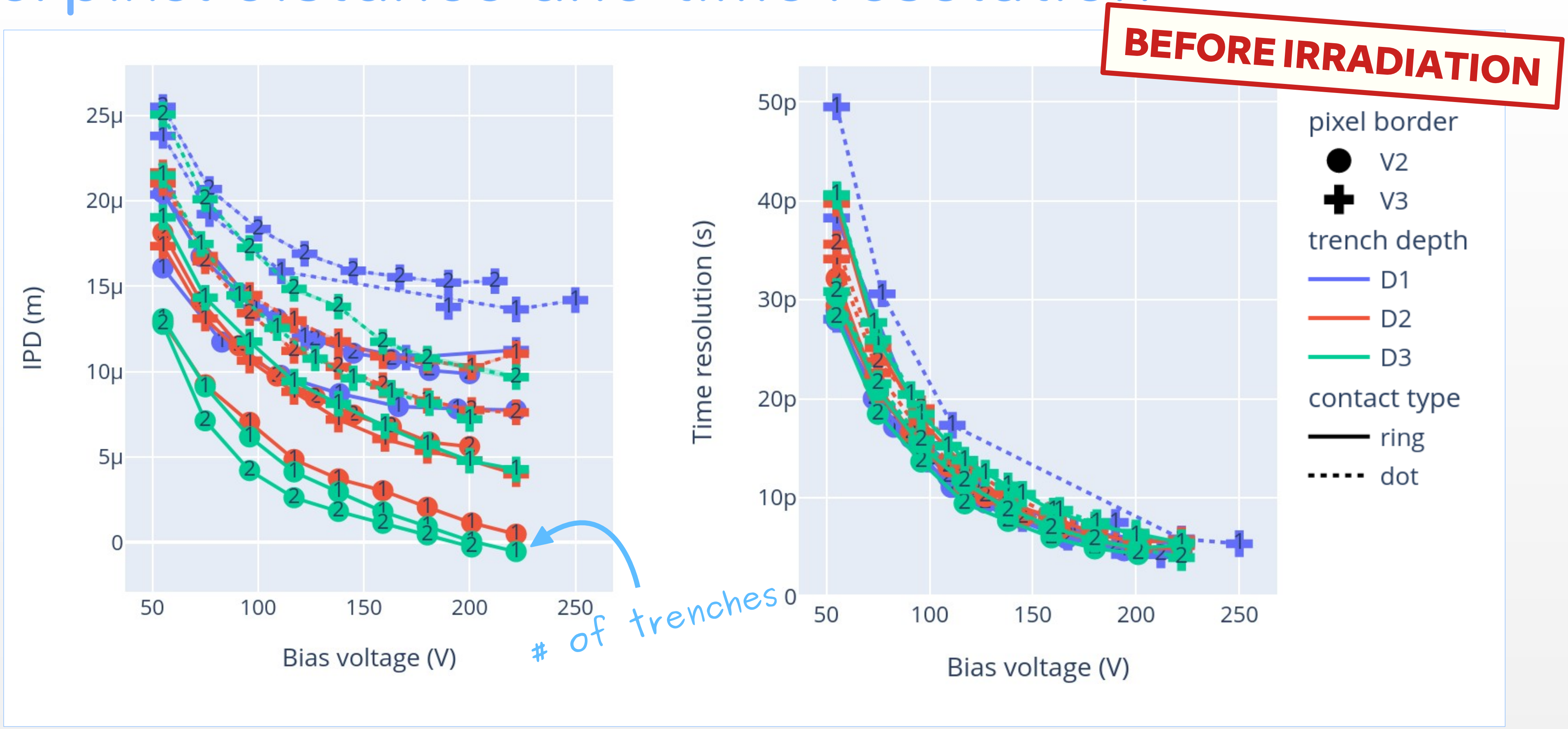
  Outside window (laser in metal):
  - > 10 ns because the software is measuring noise ✔



Results for non irradiated TI-LGAD

More details on the results of non-irradiated TI-LGADs in previous presentation @ 39th RD50 Workshop (click me!)

Interpixel distance and time resolution

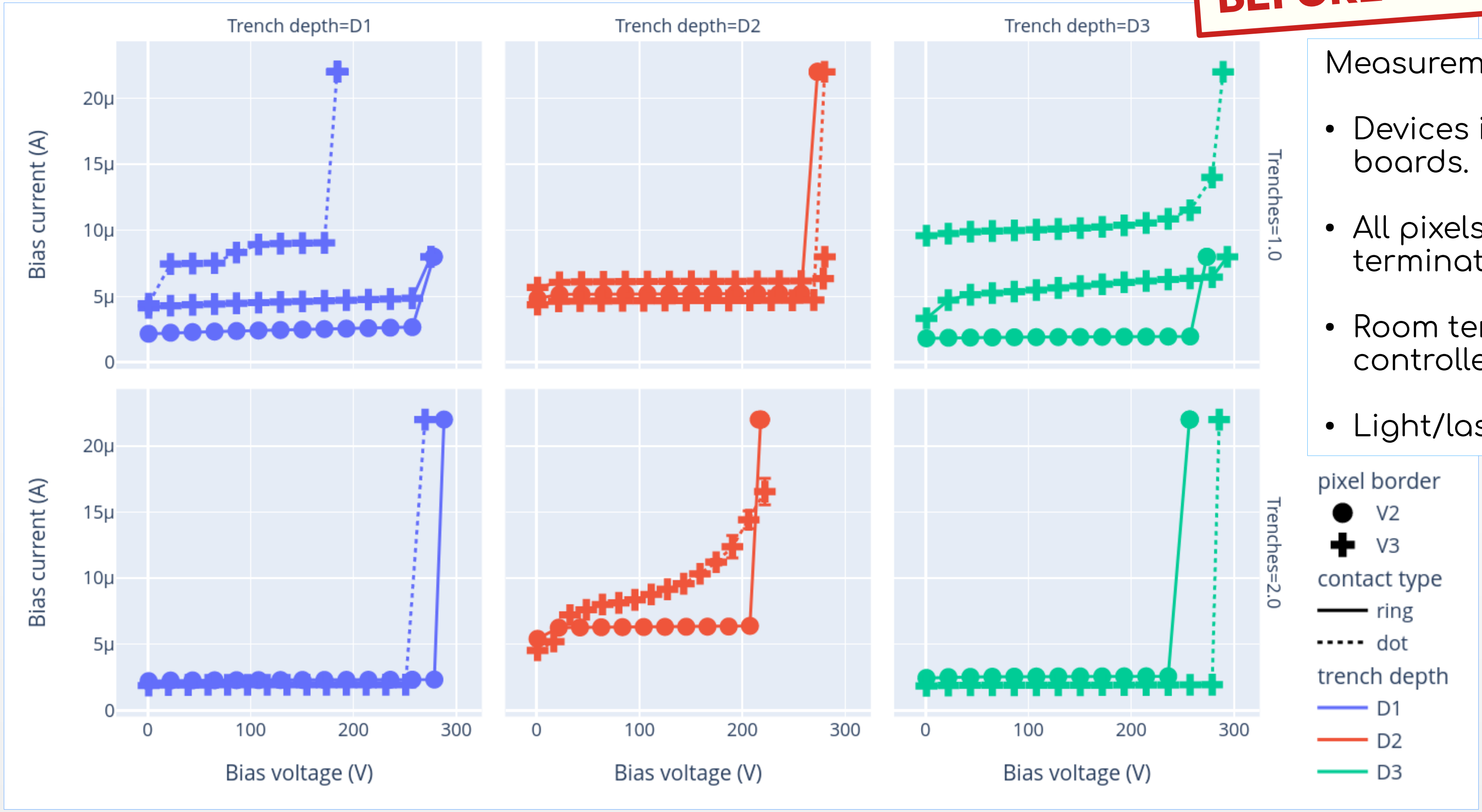


- Border V2 is always better.
- Deeper trenches are better.
- Contact type "ring" is better.

- Time resolution does not seem to depend systematically on these design parameters.

IV curves

BEFORE IRRADIATION



Measurement conditions:

- Devices installed in readout boards.
- All pixels grounded or 50Ω terminated.
- Room temperature (not controlled).
- Light/laser off.

⇒ All devices with "2 trenches" & "pixel border V3" & "contact type ring" went into breakdown at very low voltages (<10 V).

Irradiation campaign

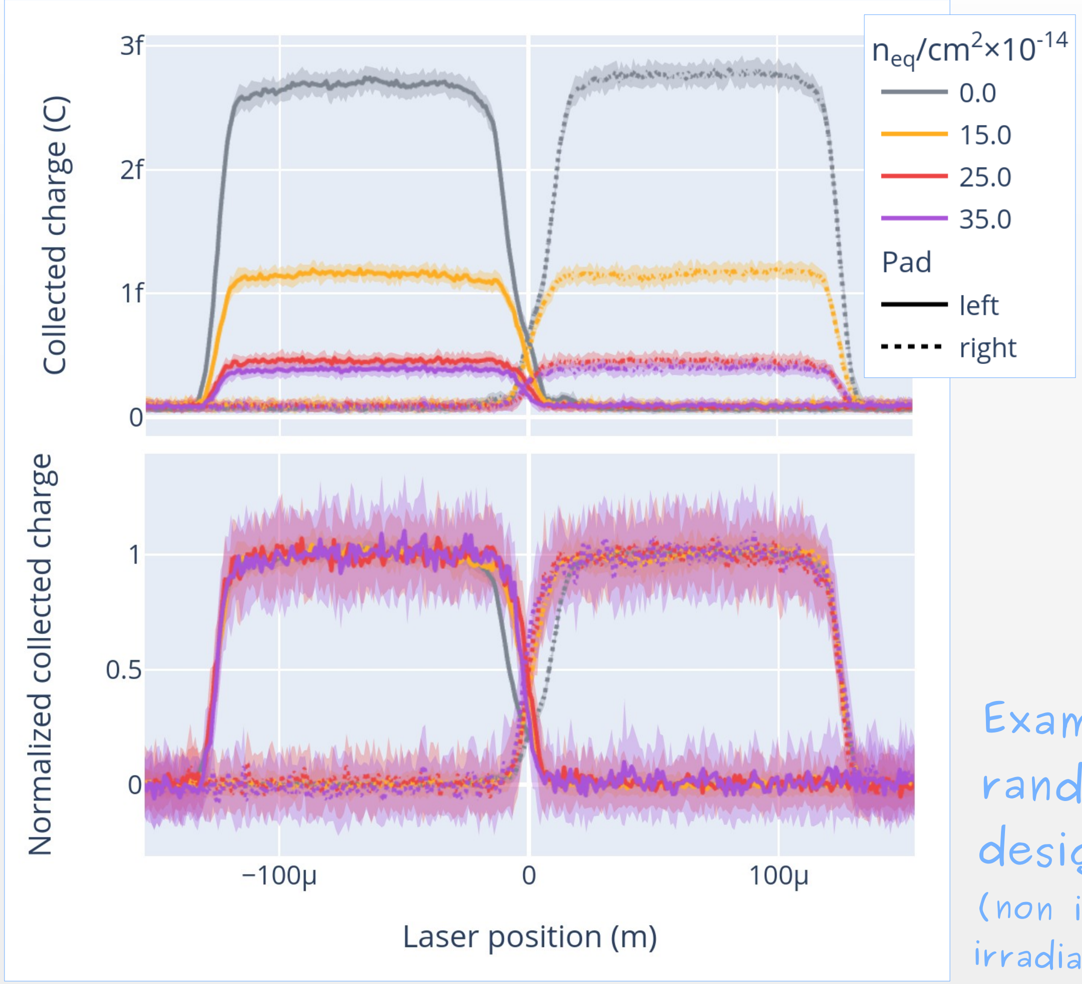
Our irradiation campaign at UZH

- 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.

- We irradiated with reactor neutrons at JSI to 3 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

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

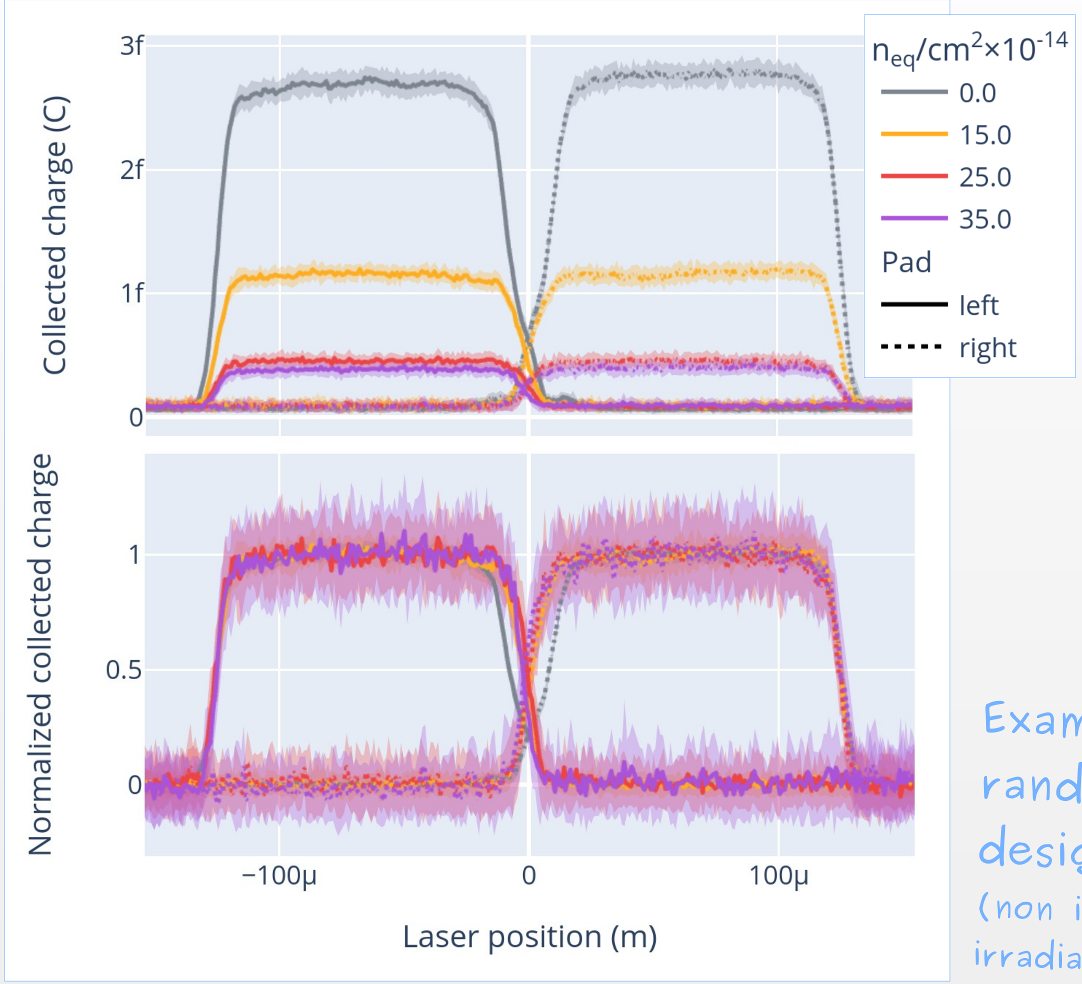
Scanning along irradiated devices



- 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 out", all look similar now.

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

Scanning along irradiated devices: Pixel isolation

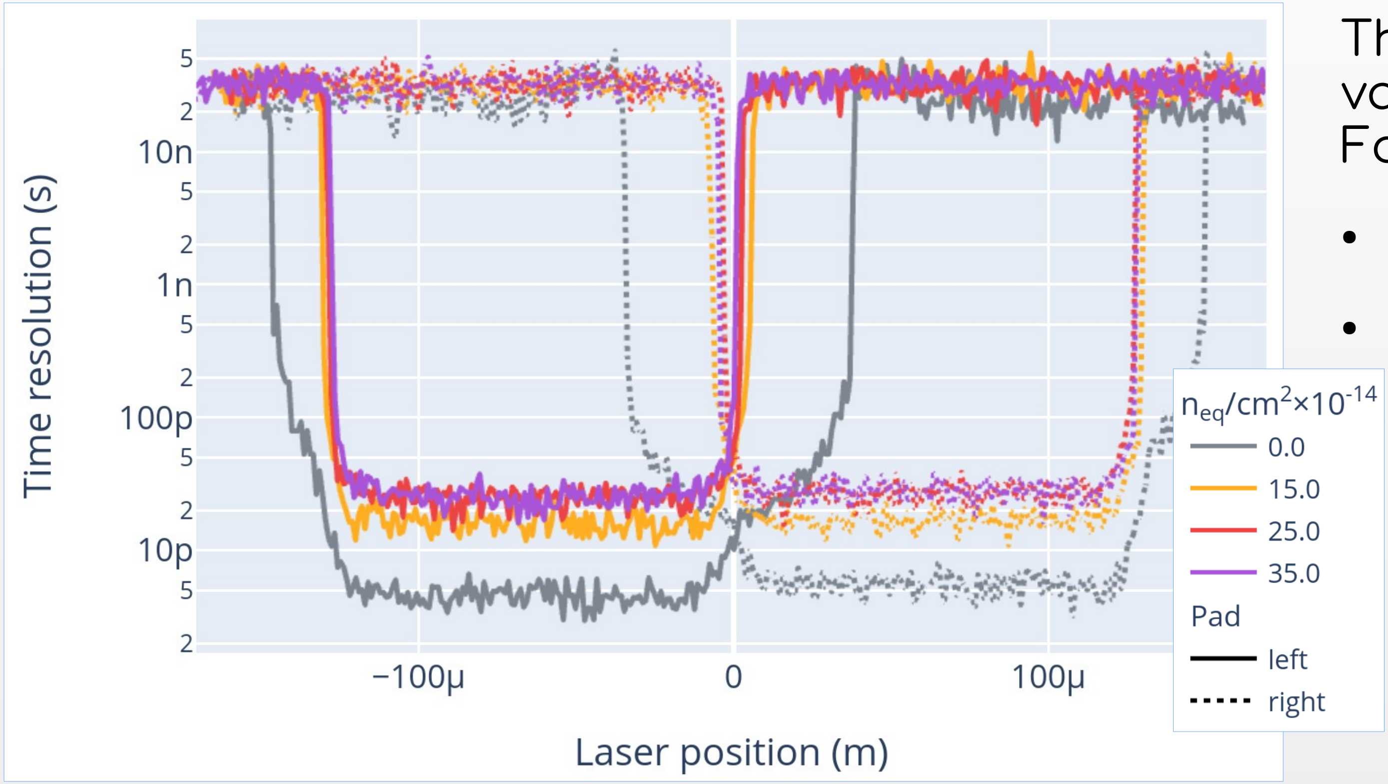


Pixel isolation is not affected by radiation.

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

Time resolution (TCT) vs position

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



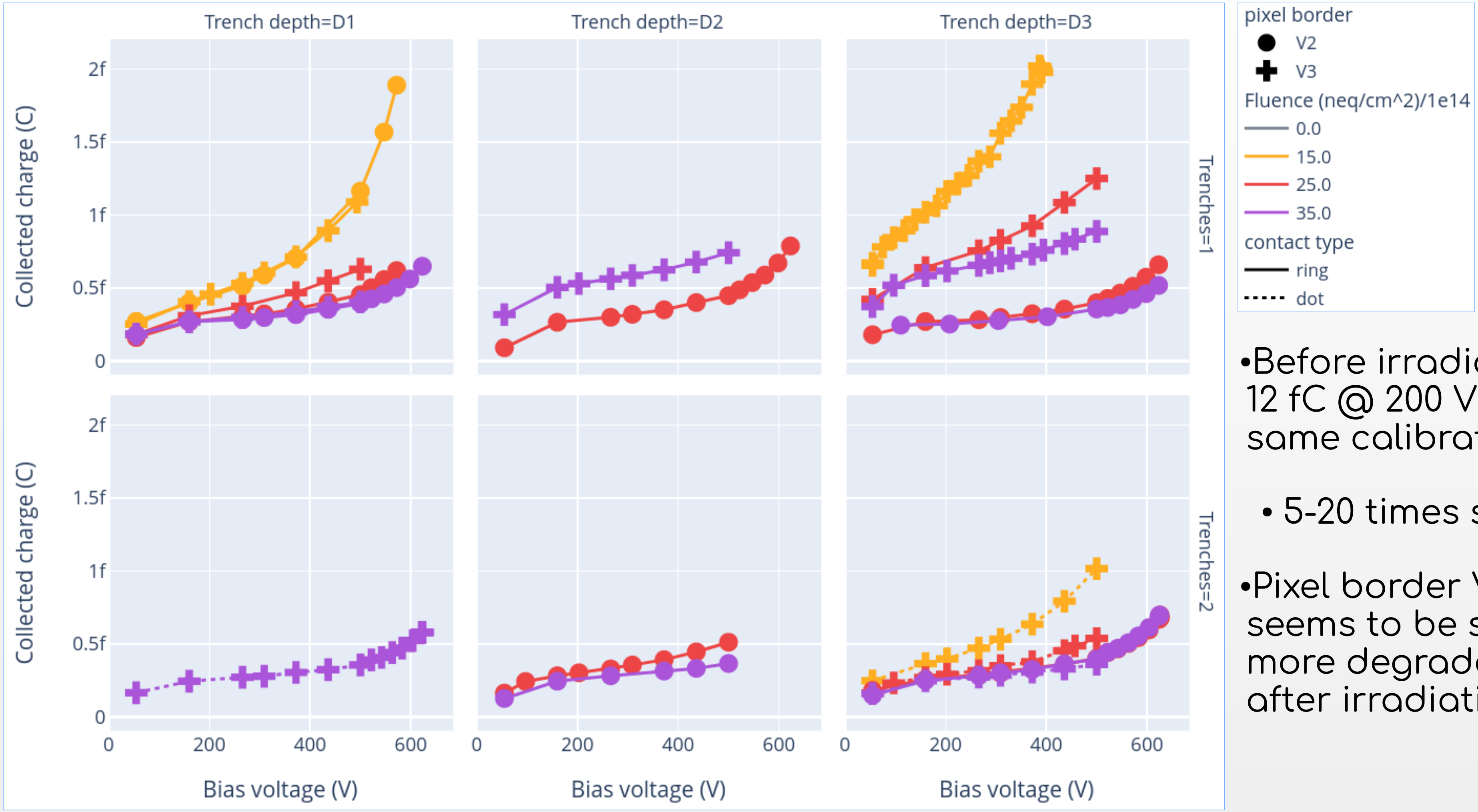
The time resolution is the value within the plateau. For this example:

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

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

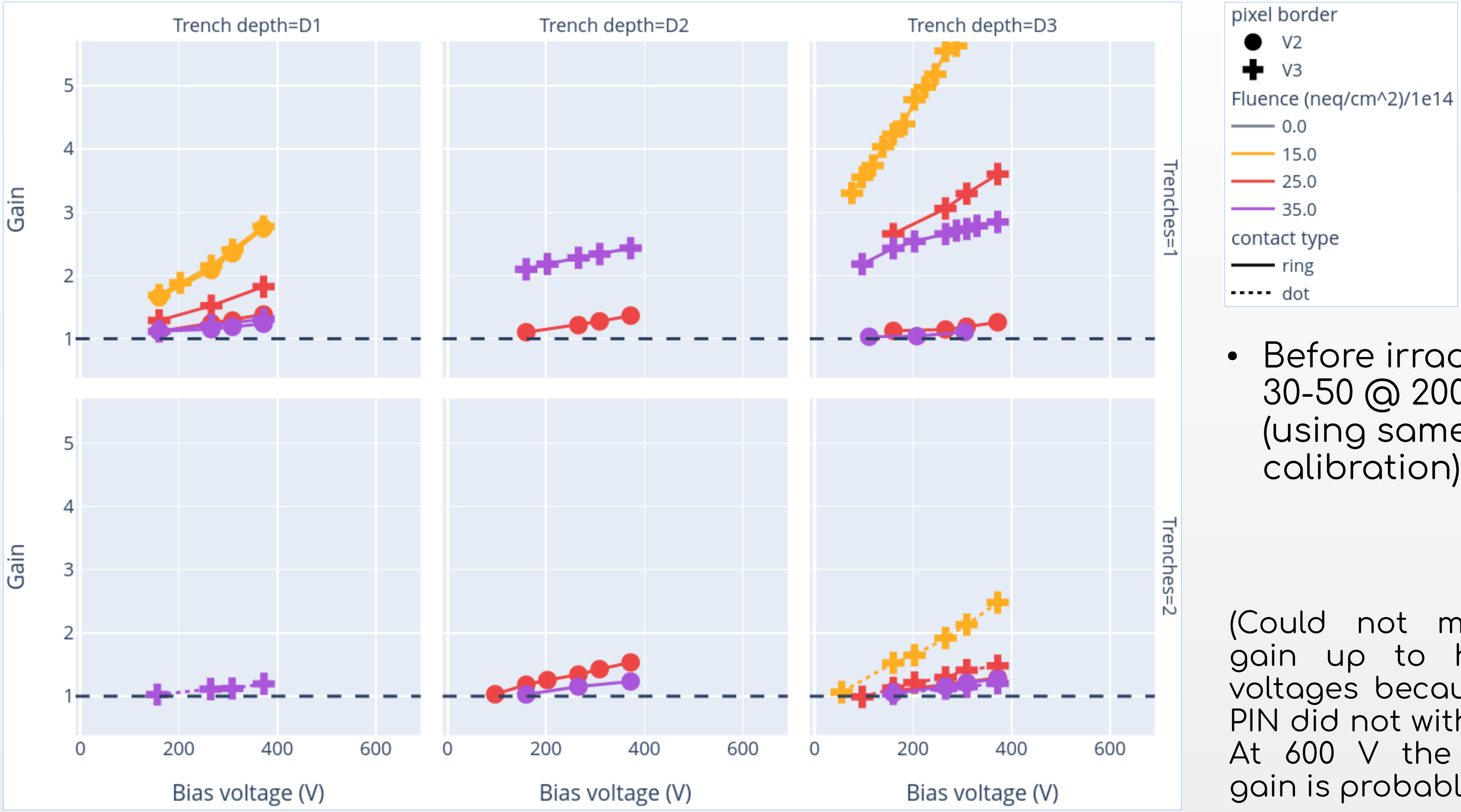
Results after irradiation

Collected charge after irradiation



- Before irradiation 8-12 fC @ 200 V (using same calibration).
  - 5-20 times smaller.
- Pixel border V2 seems to be slightly more degraded after irradiation.

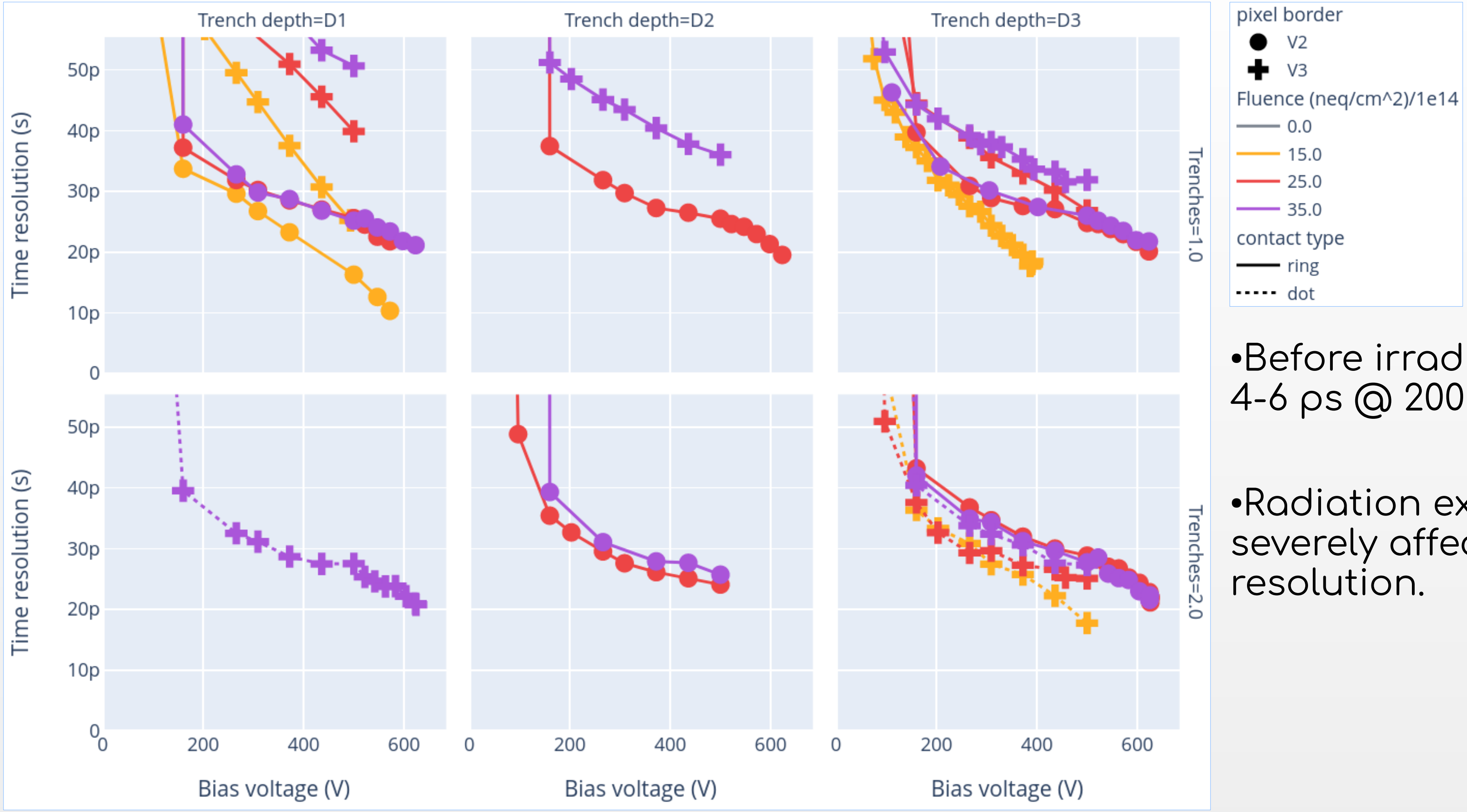
Gain after irradiation



- Before irradiation 30-50 @ 200 V (using same calibration).

(Could not measure gain up to highest voltages because the PIN did not withstand. At 600 V the lowest gain is probably ~ 2.)

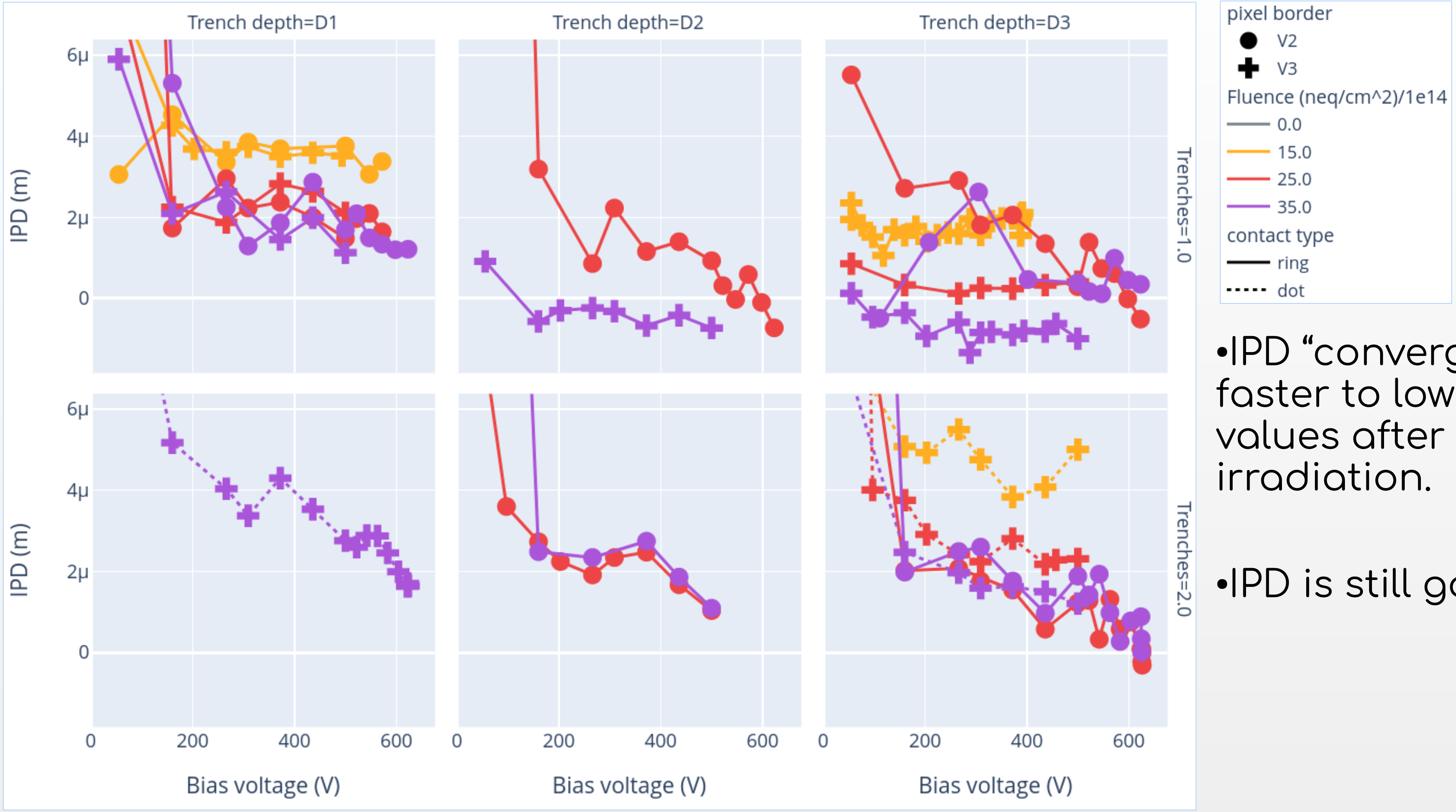
Time resolution (TCT) after irradiation



- Before irradiation 4-6 ps @ 200 V.

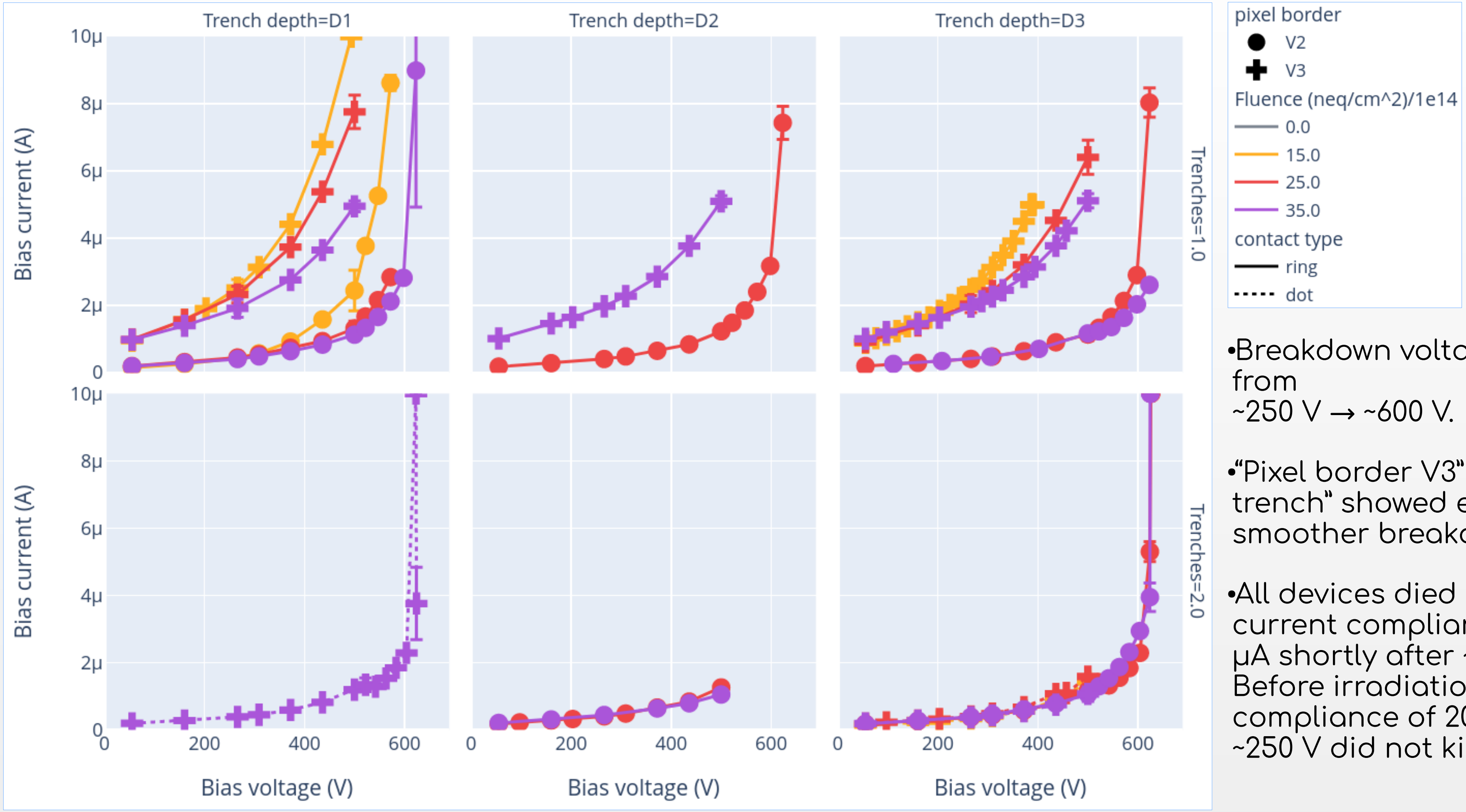
- Radiation exposure severely affects time resolution.

Inter-pixel distance after irradiation



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

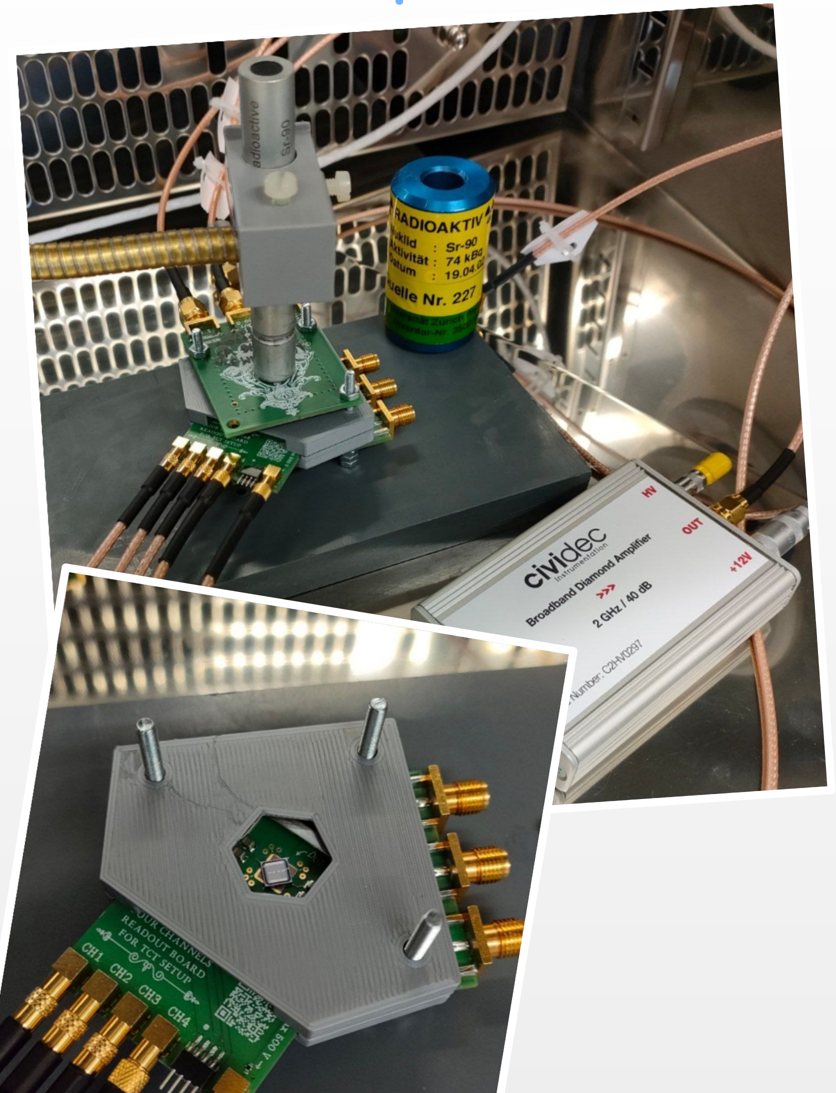
IV curve after irradiation



- Breakdown voltage moved from ~250 V → ~600 V.
- "Pixel border V3" & "1 trench" showed earlier and smoother breakdown.
- All devices died with current compliance of 10 µA shortly after ~620 V. Before irradiation compliance of 20 µA @ ~250 V did not killed them.

Beta source measurements

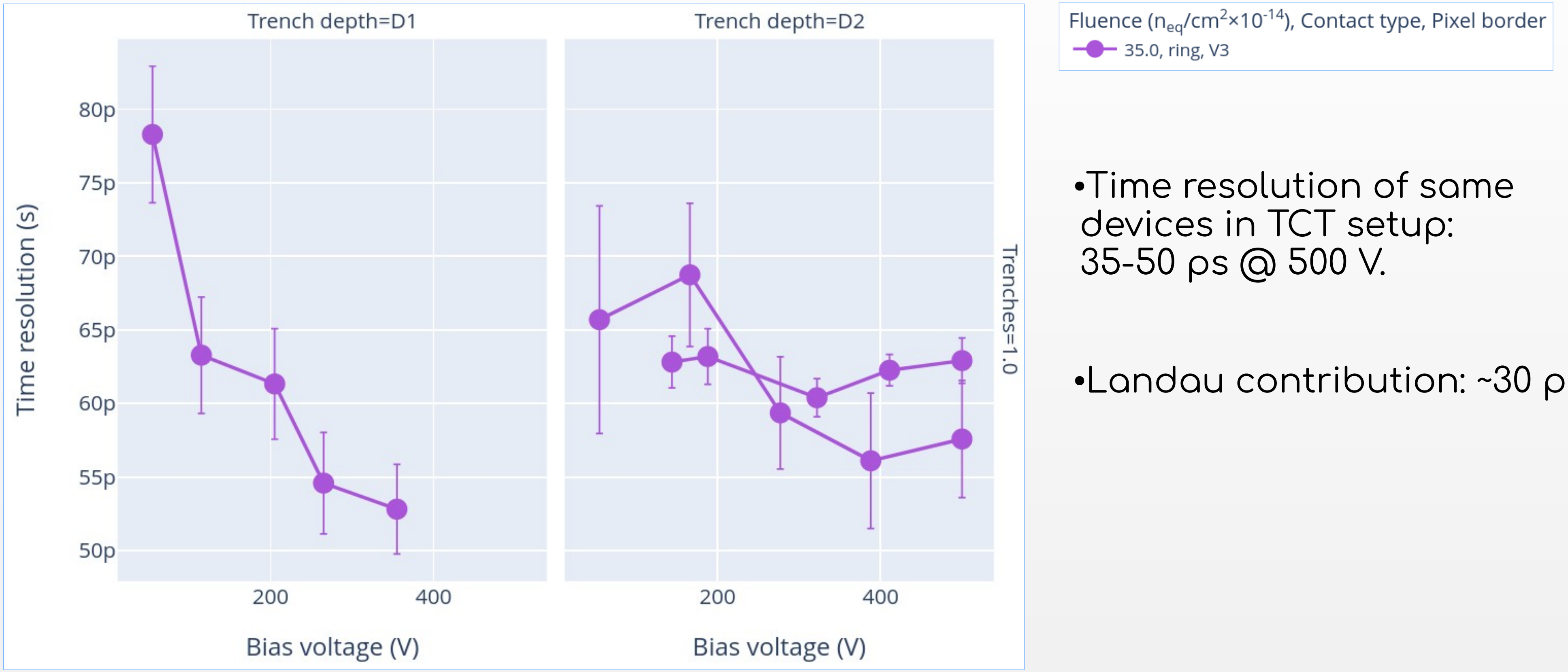
Beta setup



- Assembled inside climate chamber at -20 °C.
- DUT mounted in same readout board and with same amplifier as in TCT.
- Reference detector: Calibrated single pad LGAD mounted in “Chubut board”*.
- 74 kBq Sr-90 beta source.
- Oscilloscope triggering in coincidence of DUT and reference.

* Almost a clone of the Santa Cruz board in a smaller layout, the same performance was observed https://github.com/SengerM/ChubutBoard.

Time resolution with beta source



- Time resolution of same devices in TCT setup: 35-50 ps @ 500 V.
- Landau contribution: ~30 ps.

Conclusions

- A comprehensive characterization of novel TI-LGAD devices was performed using a scanning TCT setup.
  - Pixel isolation by trenches is good before and after irradiation.
  - Inter-pixel distance < 4 μm was observed both before and after irradiation, which allows for fine segmentation.
  - Gain performance severely affected by radiation levels studied.
  - Time resolution after irradiation also degraded.

- In samples tested with beta source setup:
  - Time resolution ~50-65 ps values observed using beta setup on most irradiated samples.

- **TI-LGAD is still, after 35×10^{34} n_{eq}/cm^2 of neutrons, a promising candidate towards 4D-pixels.**

Acknowledgments

Part of this work has been performed in the framework of RD50 CERN collaboration and the AIDAinnova project.

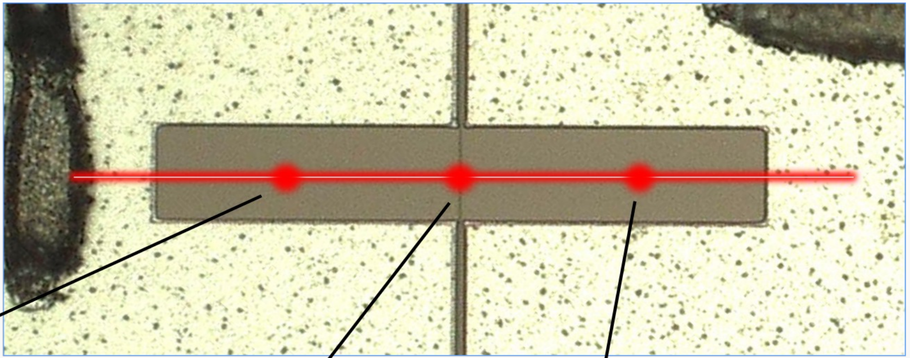
That's all,

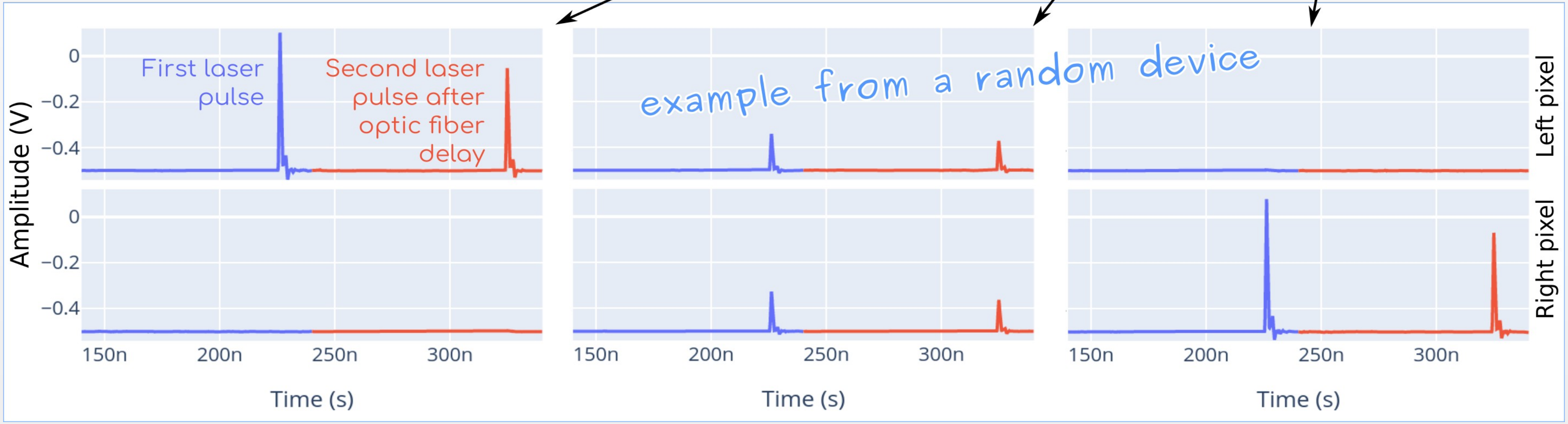
thank you for your attention

Extra slides

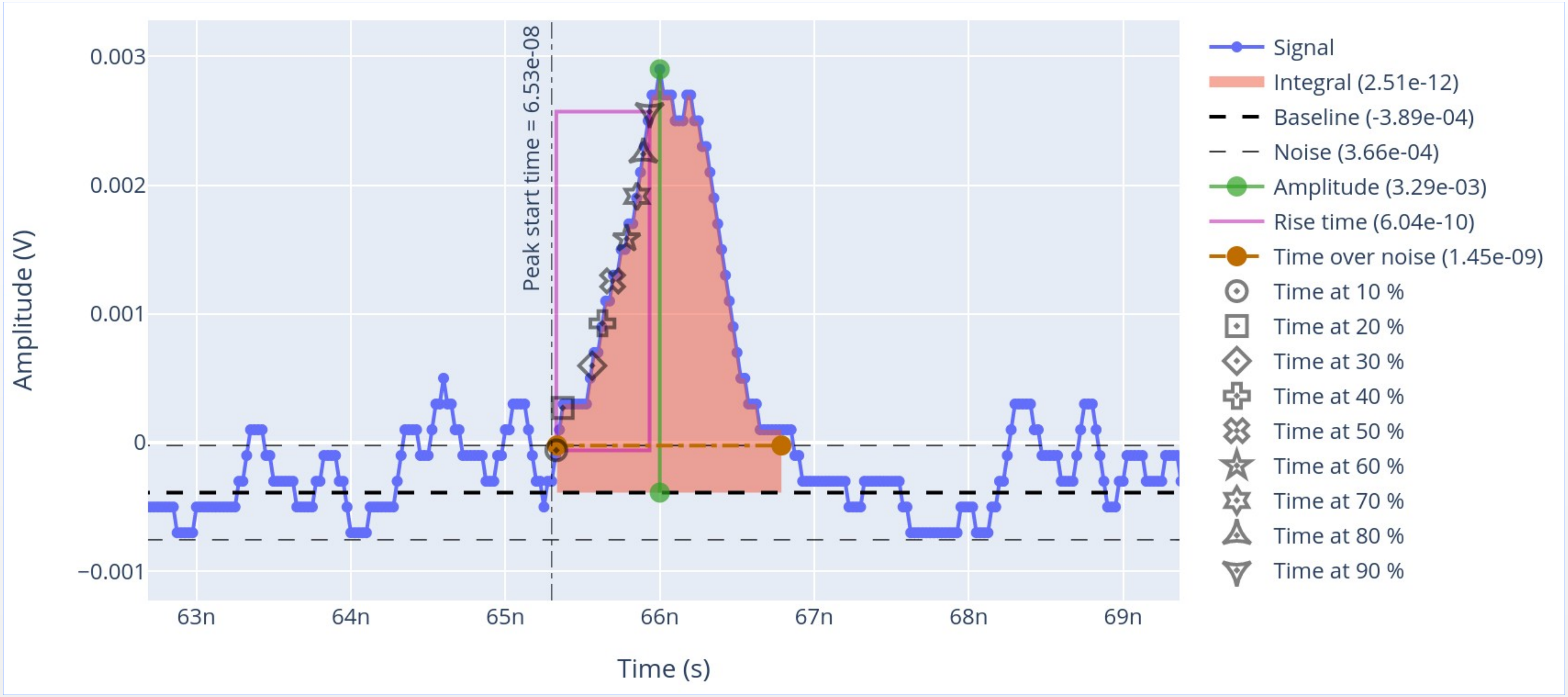
Laser scans

- Trenches provide good isolation.
- Shared signal in the middle is shared due to the size of the laser spot.
- Qualitative similar behavior for all devices.





Signals processing

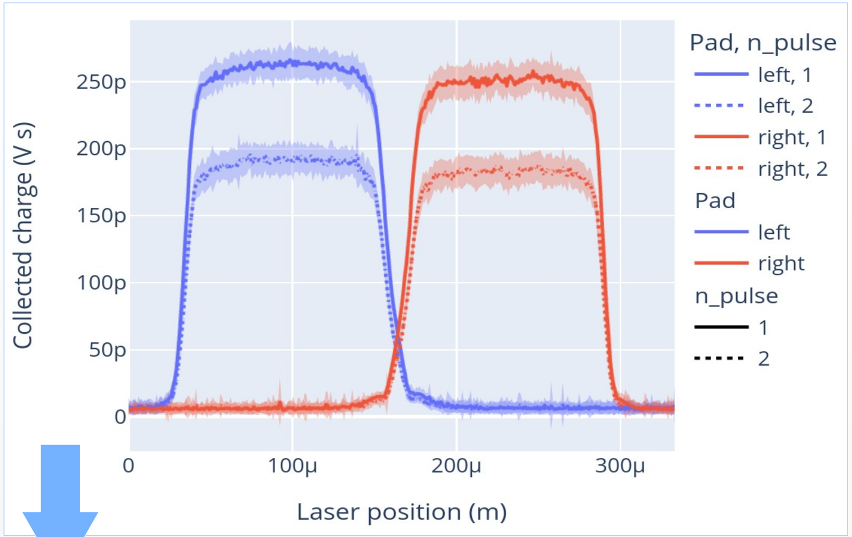


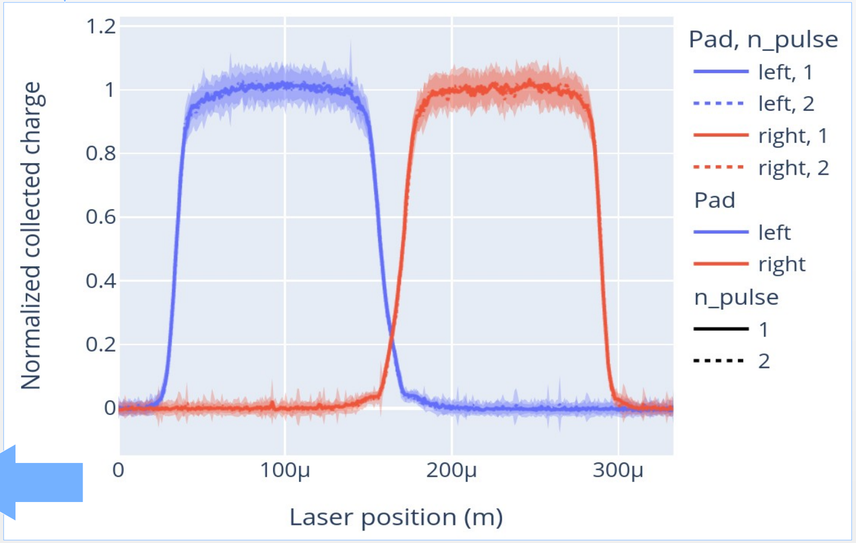
- Processing in Python using this https://github.com/SengerM/signals.
- Signal is linearly interpolated.

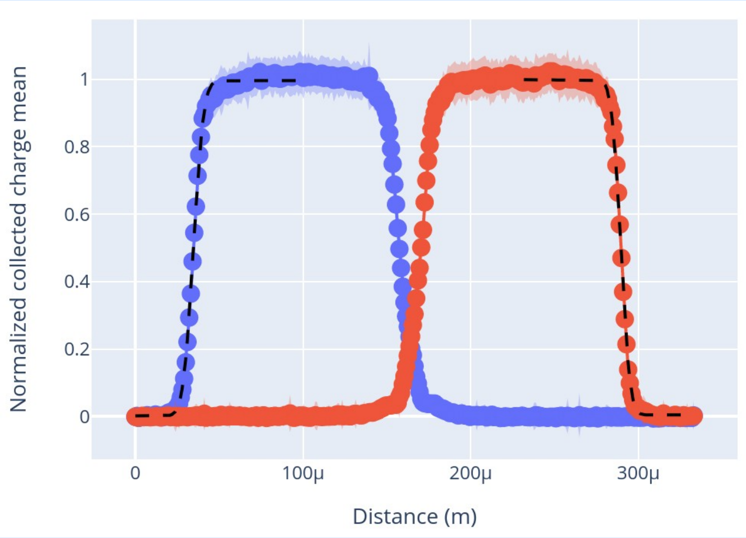
Laser scans

- Steps of 1 μm.
- ~ 50 events at each position.
- Metal-silicon interface as reference:
  - Check laser shape/size.
  - Distance scale correction (2-5 %).

Example from a random scan (non irradiated device)





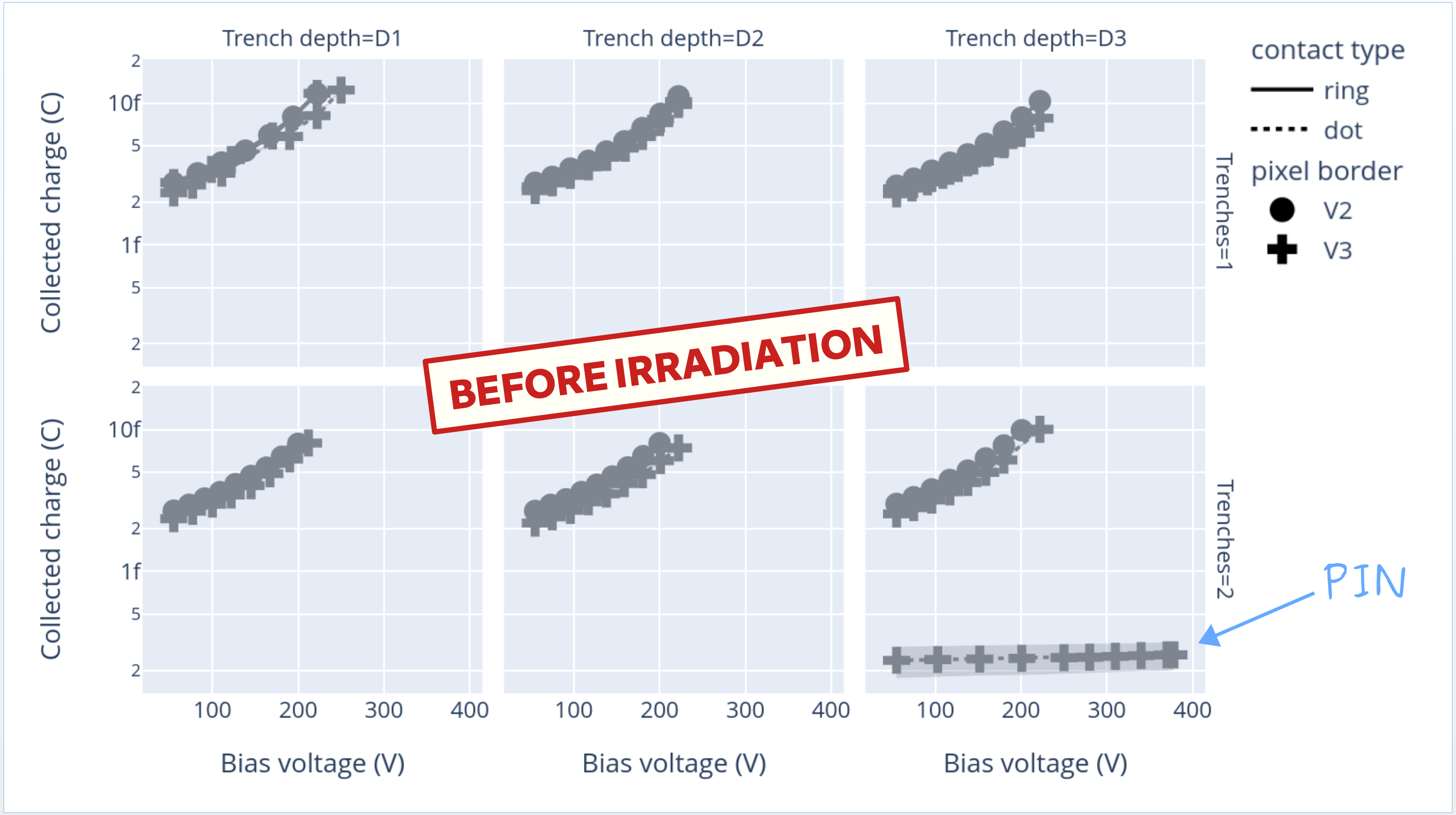


Check laser profile ✔

Provide scale reference ✔

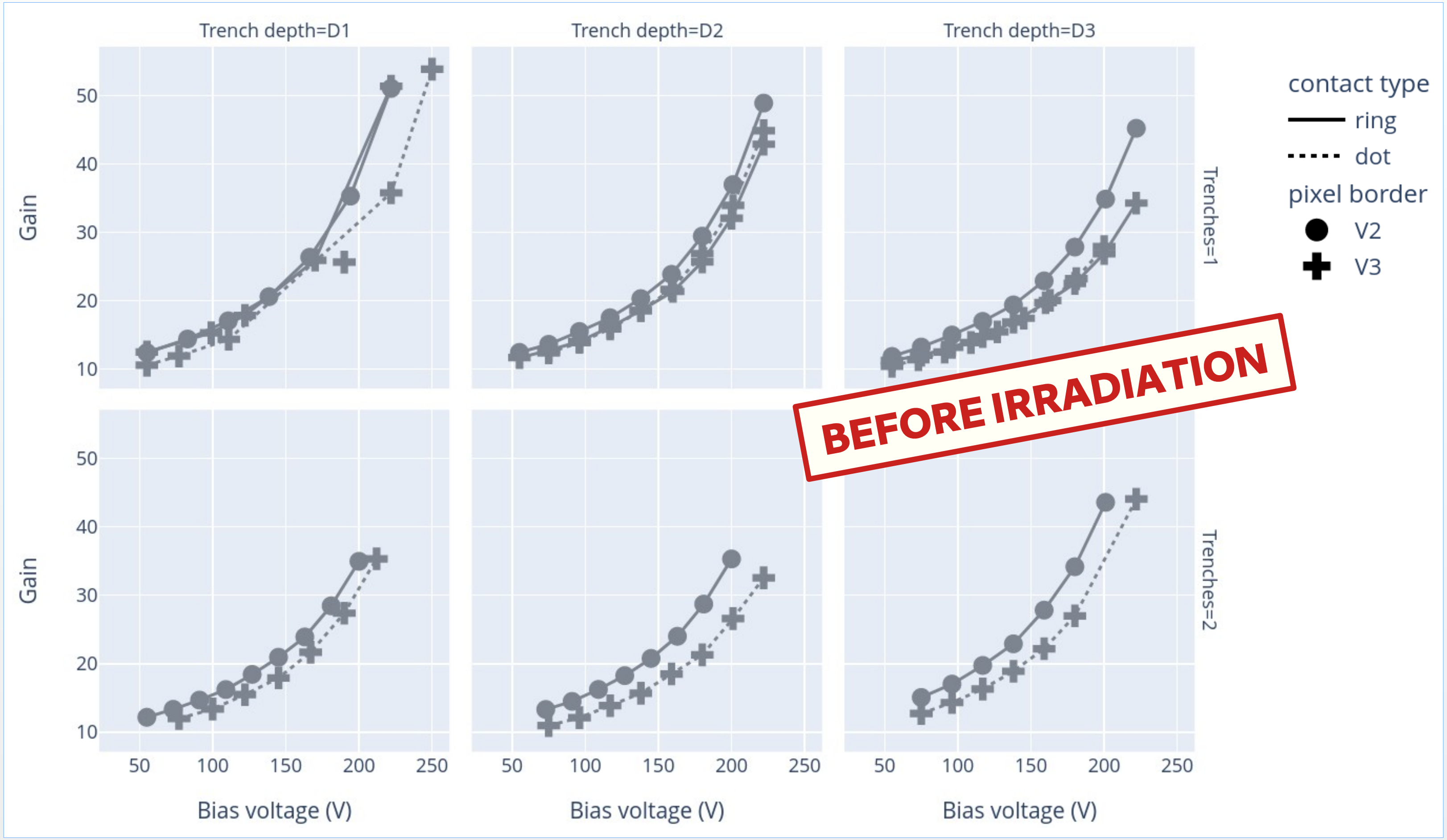
Collected charge

The value is the average of each scan within the plateau.



Gain

$$\text{Gain} = \frac{Q^{[\text{Vs}]}_{\text{LGAD}}(V_{\text{bias}}, \text{laser intensity})}{Q^{[\text{Vs}]}_{\text{PIN}}(V_{\text{bias}}, \text{laser intensity})}$$



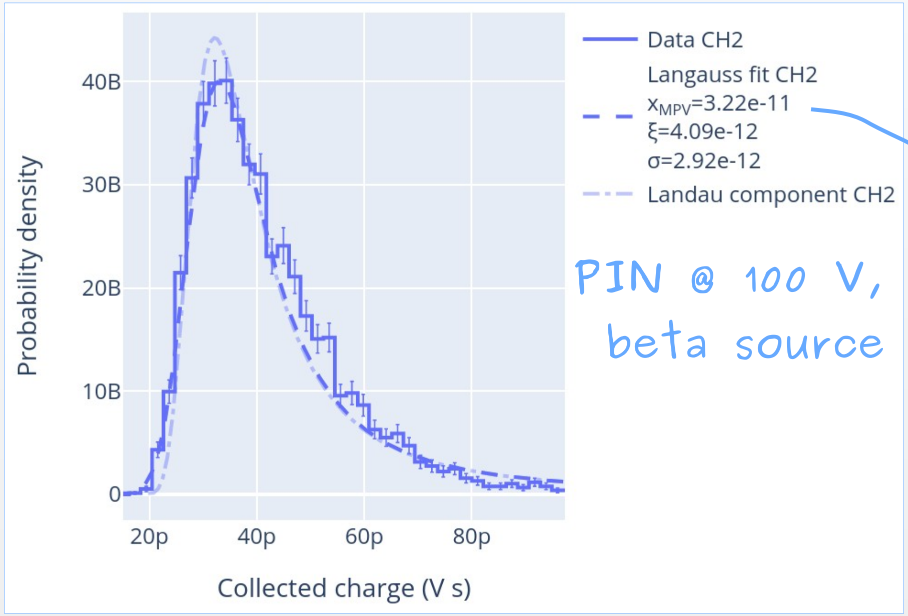
- "Border V2" & "contact ring" show ~ 20 % more gain.

Charge calibration

Deposited MPV charge by e⁻ in silicon[1]:

d=45 μm (for all devices of this production)

$$Q_{\text{MPV}} = e\frac{\left(31 \ln\left(\frac{d}{1\ \mu\text{m}}\right) + 128\right)\frac{d}{1\ \mu\text{m}}}{3.65} \Rightarrow 1\text{MIP} \approx 0.49\ \text{fC}$$

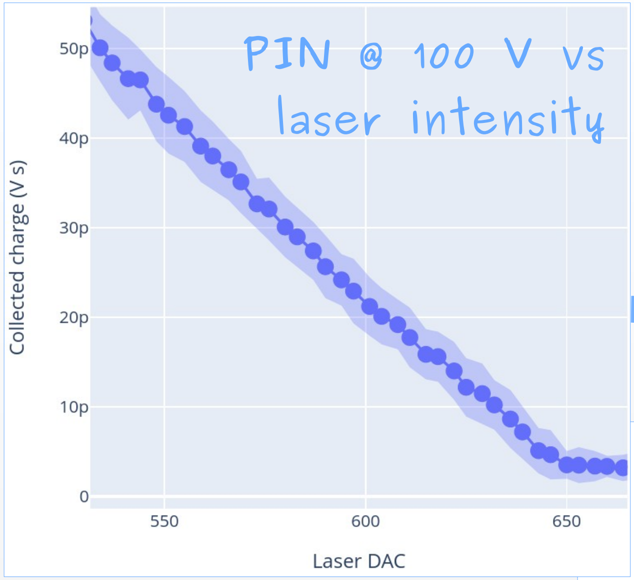


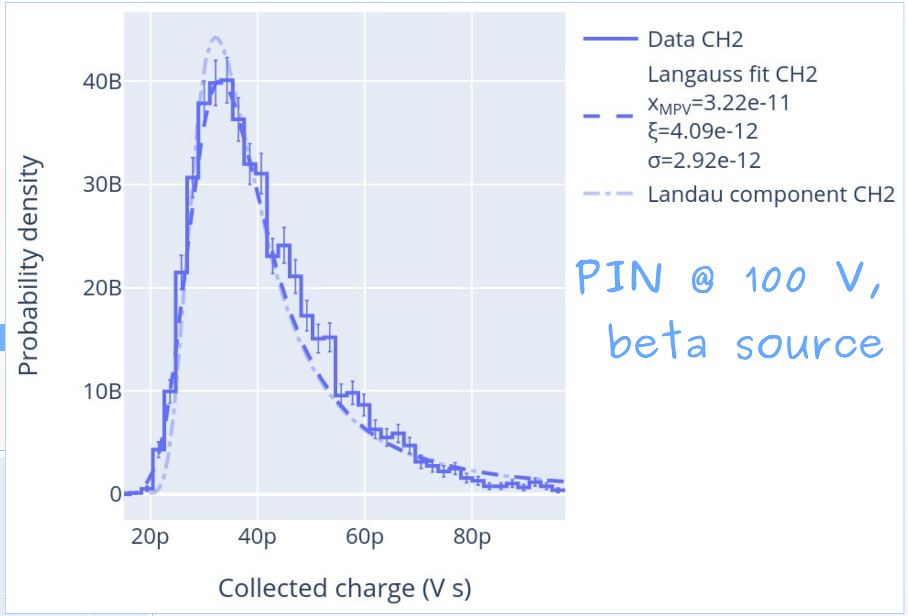
PIN @ 100 V, beta source

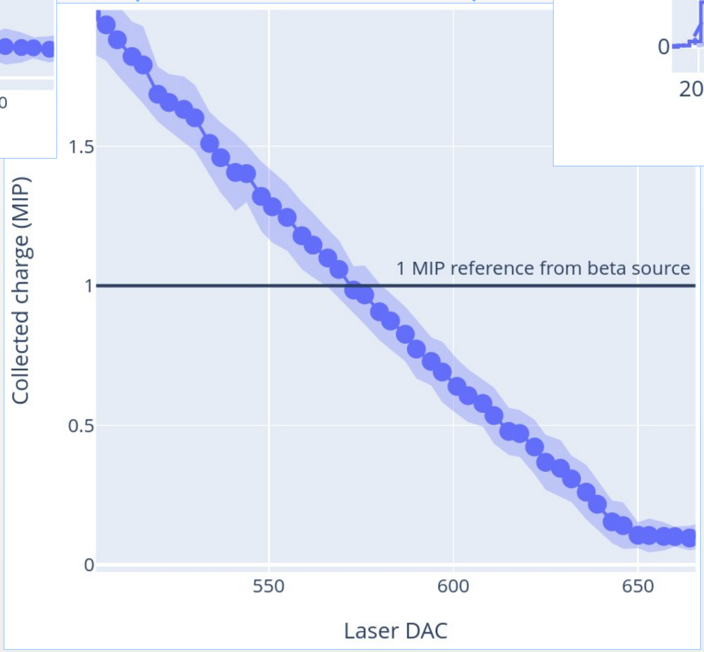
$$[\text{Coulomb}] \approx [\text{Vs}]\frac{0.49\ \text{fC}}{32\ \text{pVs}}$$

[1]Ferrero, M., Arcidiacono, R., Mandurrino, M., Sola, V., Cartiglia, N., 2021. An Introduction to Ultra-Fast Silicon Detectors: Design, Tests, and Performances. CRC Press. https://doi.org/10.1201/9781003131946

Laser intensity calibration







From the fit:

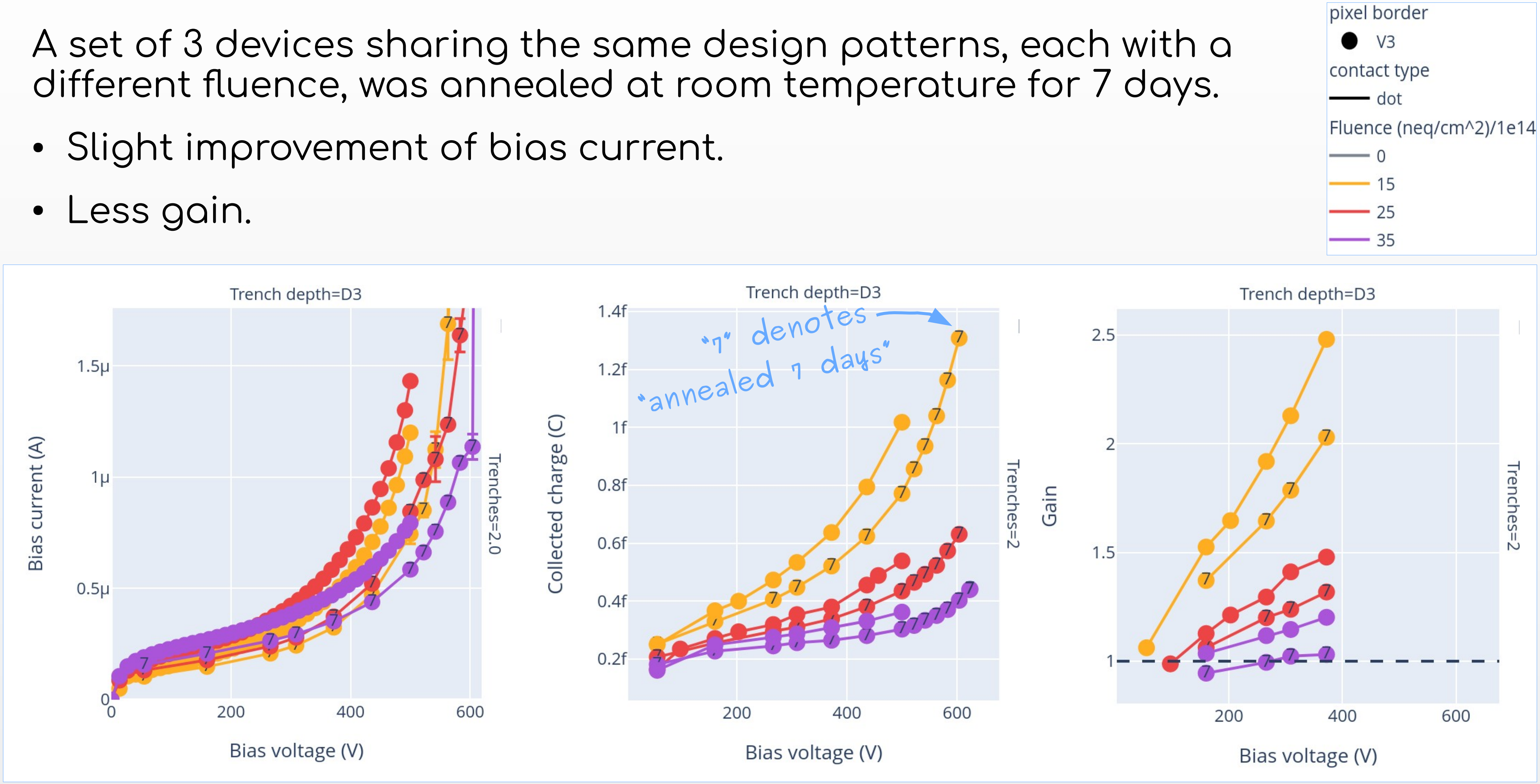
$$x_{\mathrm{MPV}} = 32\ \mathrm{pVs} \equiv 1\ \mathrm{MIP}$$

PIN used: Wafer 7, P250_4×4_1,
45 μm, D2, 1 trench, V3, dot

Annealing

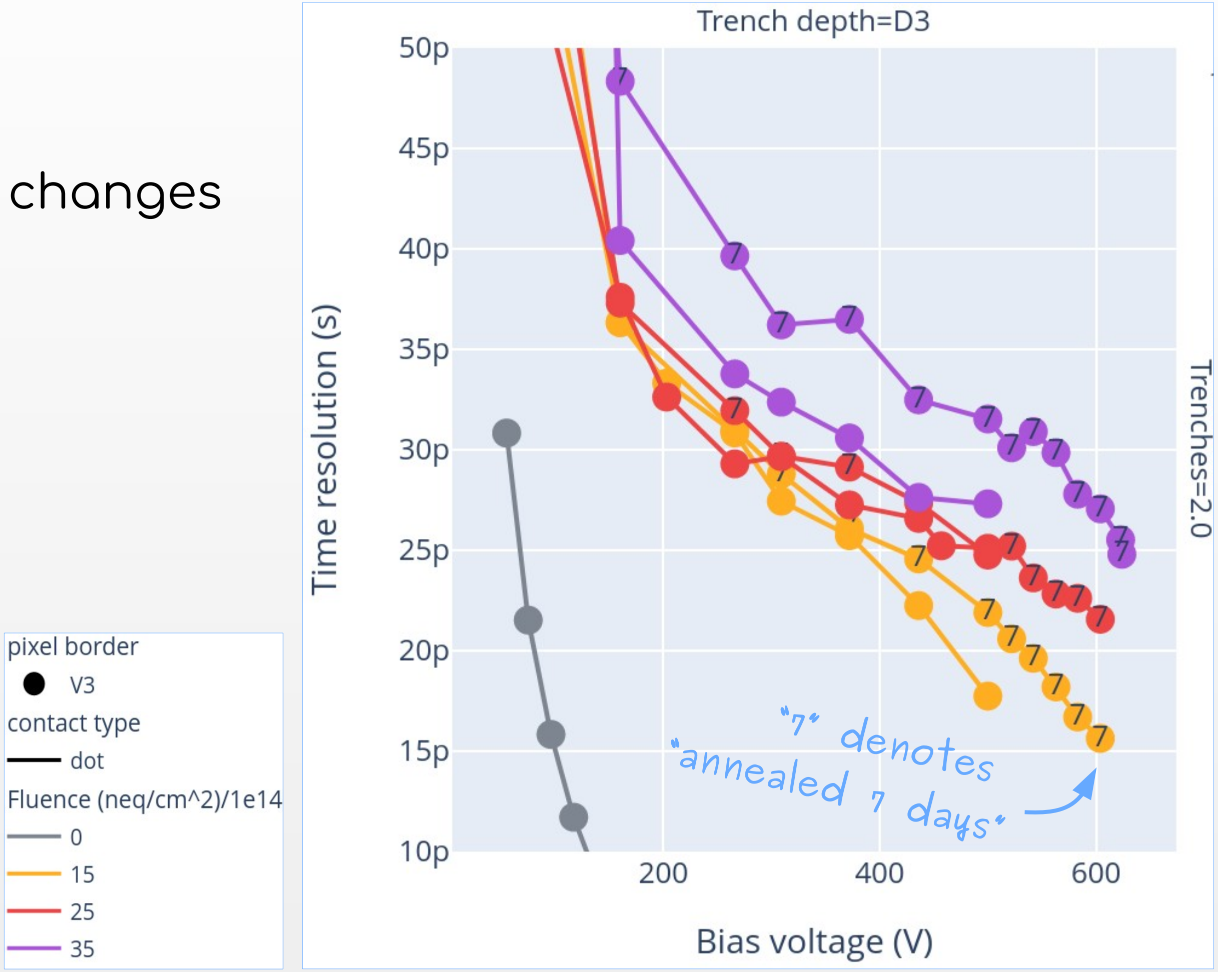
A set of 3 devices sharing the same design patterns, each with a different fluence, was annealed at room temperature for 7 days.

- Slight improvement of bias current.
- Less gain.

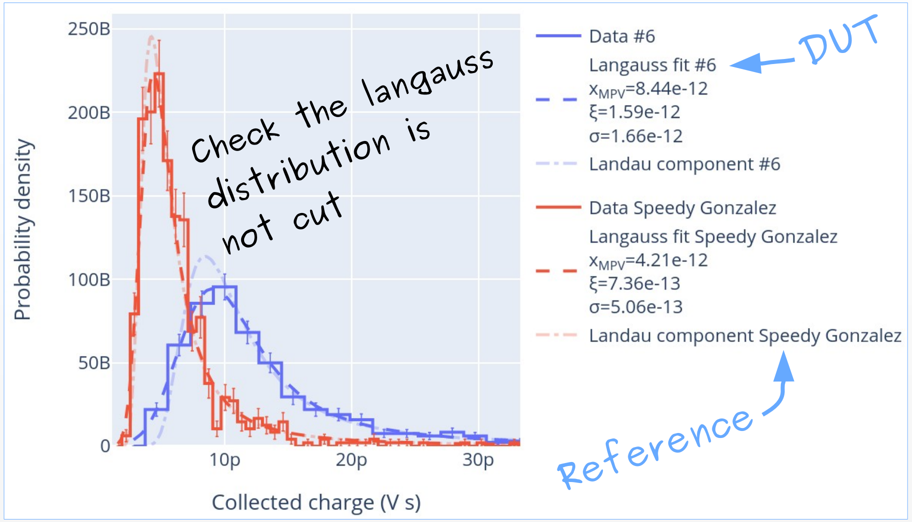


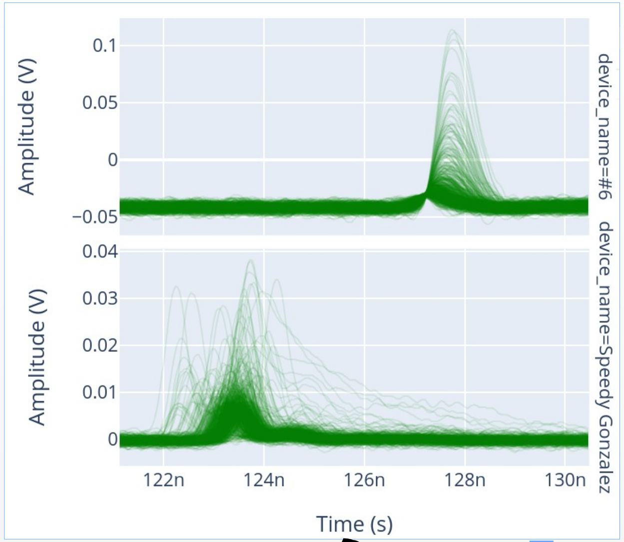
Annealing: Time resolution and IPD

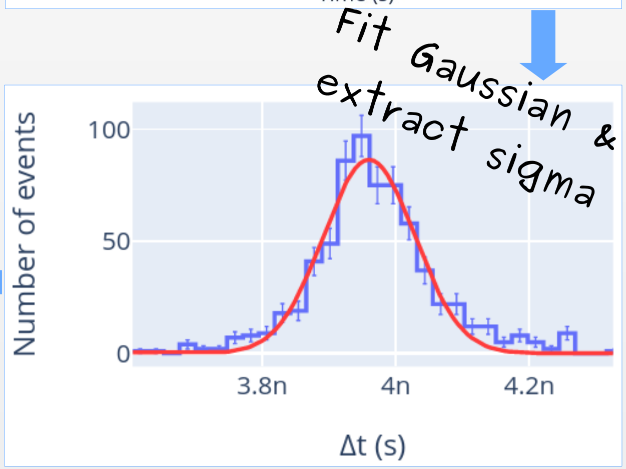
- Time resolution is worse after annealing (see plot).
- Inter-pixel distance shows no changes after annealing.

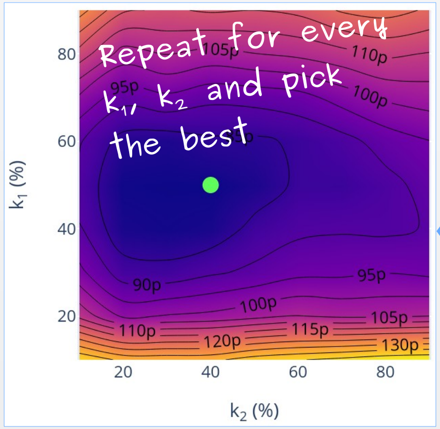


Data example from one beta scan









- Same constant fraction discriminator algorithm applied to TCT data was used here.
- This time “pulse 1” and “pulse 2” were “pulse DUT” and “pulse reference”.