27th International Workshop on Radiation Imaging Detectors
28 June to 2 July 2026
Ghent, Belgium

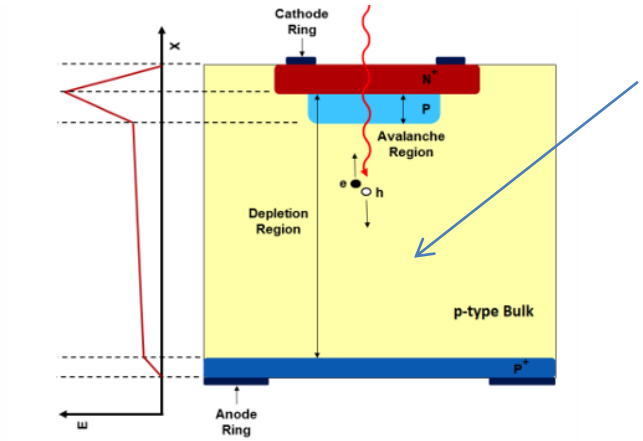
STABILITY AND SELF-QUENCHING OF THE FIELD-FOCUSED GAIN IN 3D-TRENCH IMECAS

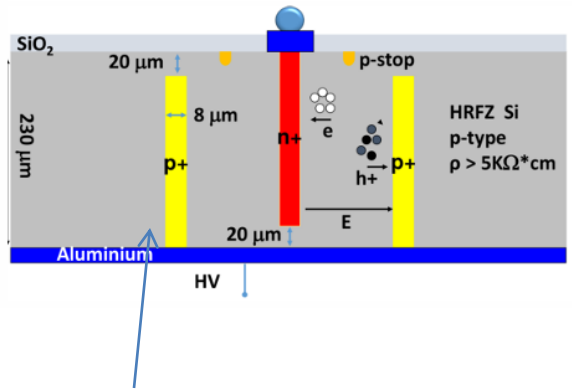
CERN-DRD3 collaboration - WP2 project:
Novel silicon 3D-trench pixel detectors based on 8-inch CMOS process (IME)

G. Laštovička-Medin,[a] G. Kramberger,[b] , I. Mandić, [b] J. Kroll,[c]
H.Ji,[d] M. Liu,[d] Z. Li,[d] J. Lu,[d] Z.Li,[e] and M. Rebarz[f]

[a]Faculty of Natural Sciences and Mathematics, University of Montenegro, Dzordza Vashingtona bb,, 81000, Podgorica, Montenegro,
[b] Jozef Stefan Institute, Jamova cesta 39, 10 000 Ljubljana, Slovenia
[C] Institute of Physics of the Czech Academy of Science, Prague
[D] Institute of Microelectronics of the Chinese Academy of Sciences ,3 Beitucheng West Road, Chaoyang District, Beijing, China
[E] *The School of Integrated Circuits, Ludong University, Yantai 264025, China*
[F] *ELI Beamlines Facility, The Extreme Light Infrastructure ERIC, Za Radnicí 835, 25241 Dolní Břežany, Czech Republic*

Why 3D ?

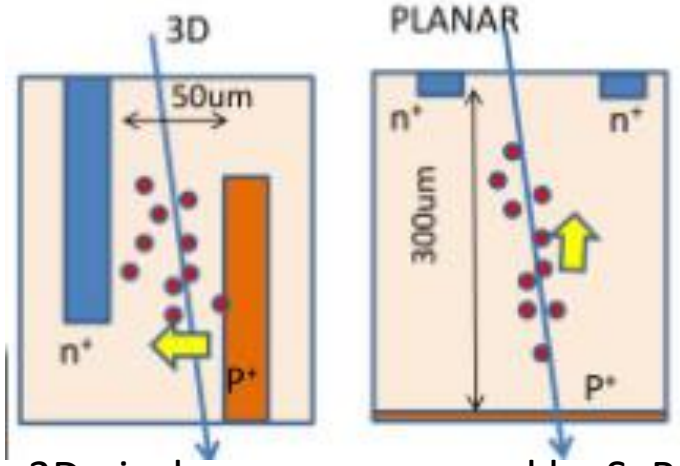




3D Devices: radiation hardness much higher (enabled by geometry): shorter druft distance preventing (reducing) trapping

LGAD – Planar device, mature timing technology (baseline timing technology for ATLAS and CMS at LHC in CERN), well understood

Problem: gain lost at high fluencies (acceptor removal mechanism), gain supression when high density of charge is created (screening of the el field), Single Event Burnout that lmits the applied bias (needed for recovery of lost gain)



The 3D pixel sensors proposed by S. Parker et al. in 1997

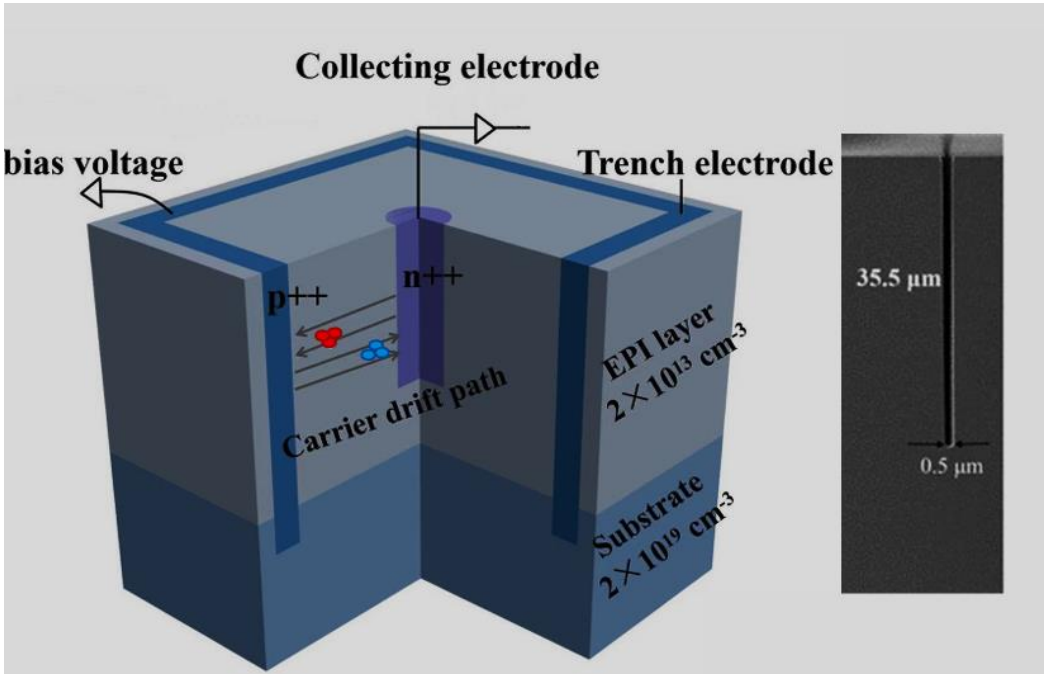
Problems: aspect ratio/scalability, breakdown at the tip of electrode

3D with Geometric Gain

Utilizing the gain in silicon (and possibly SiC) detectors has been the key advancement in tracking detectors opening possibility of real 4D tracking with planar devices.

- The gain is achieved with fine tuning of gain layer Implementation of gain is now ongoing in several CMOS projects (CASSIA, ARCADIA, …).
- What about 3D detectors? The doping of columns of 3D detectors is almost impossible to control with the required precision. Marriage of 3D and LGAD of therefore almost impossible .
- Improvement of aspect ratio to 100:1 allows manufacturing of very narrow columns . Can this be solution? **Can we progress from "solid state ionization chamber" to semiconductor "wire proportional chamber"?**

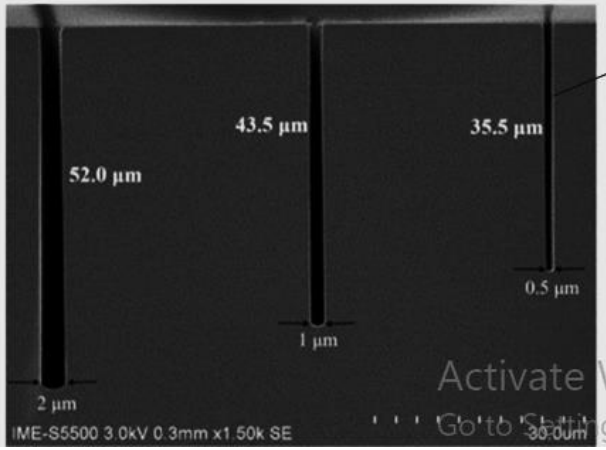
Investigated device



Sensor devices manufactured by:

IMECAS

- 8-inch CMOS compatible process
- Columns manufactured using **DRIE** (Deep Reactive Ion Etching)
  - Aspect ratios up to 100:1
- Motivation: **geometric gain** (wire proportional chamber in Si)



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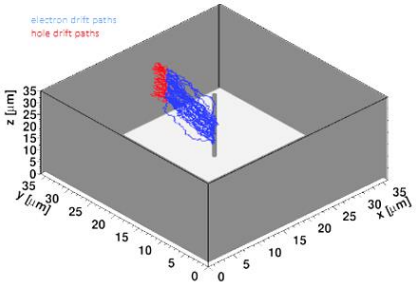
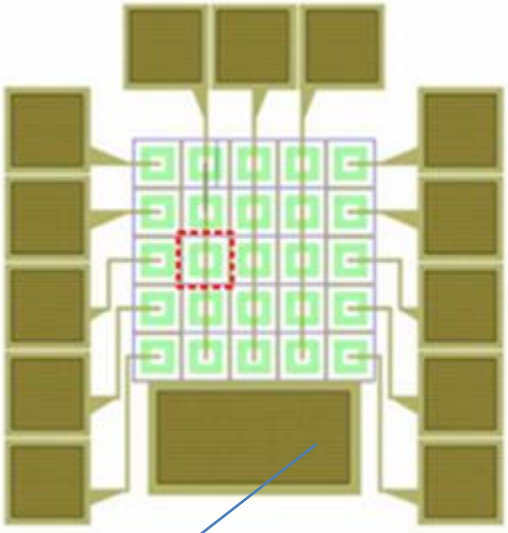
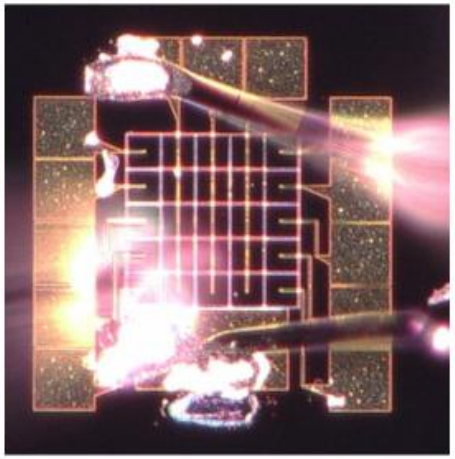
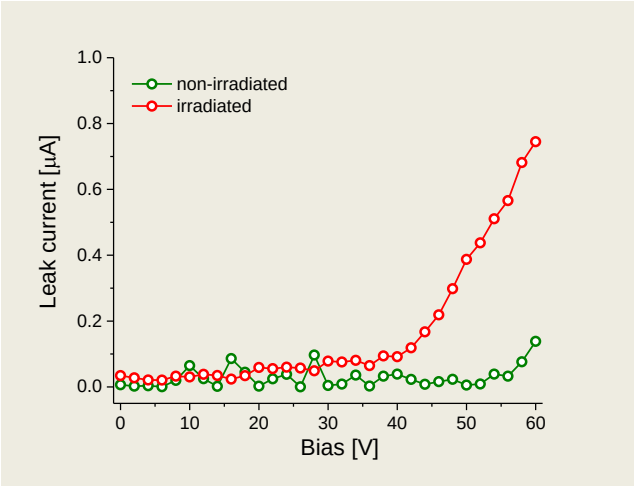
References:
H. Ji et al., "Development of 3D Pixel Sensors via an 8-inch CMOS-Compatible Process." arXiv preprint arXiv:2510.10031 (2025).

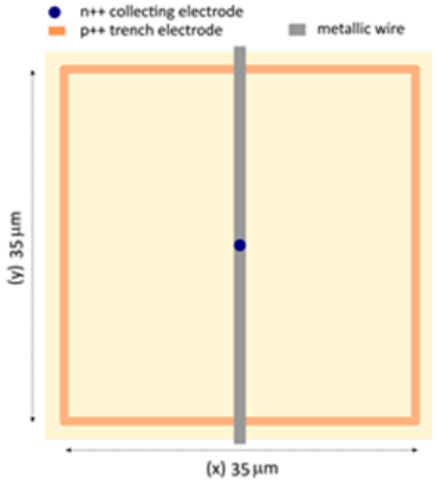


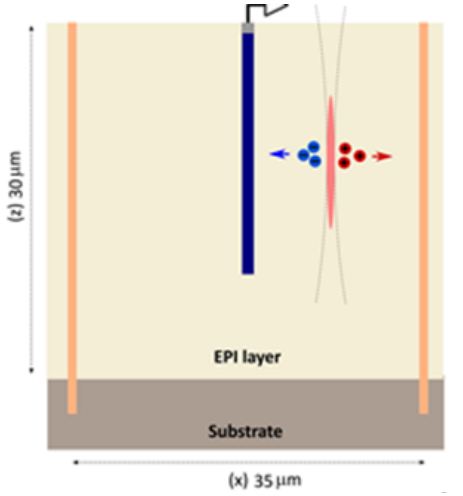


Trench electrode (V bias)



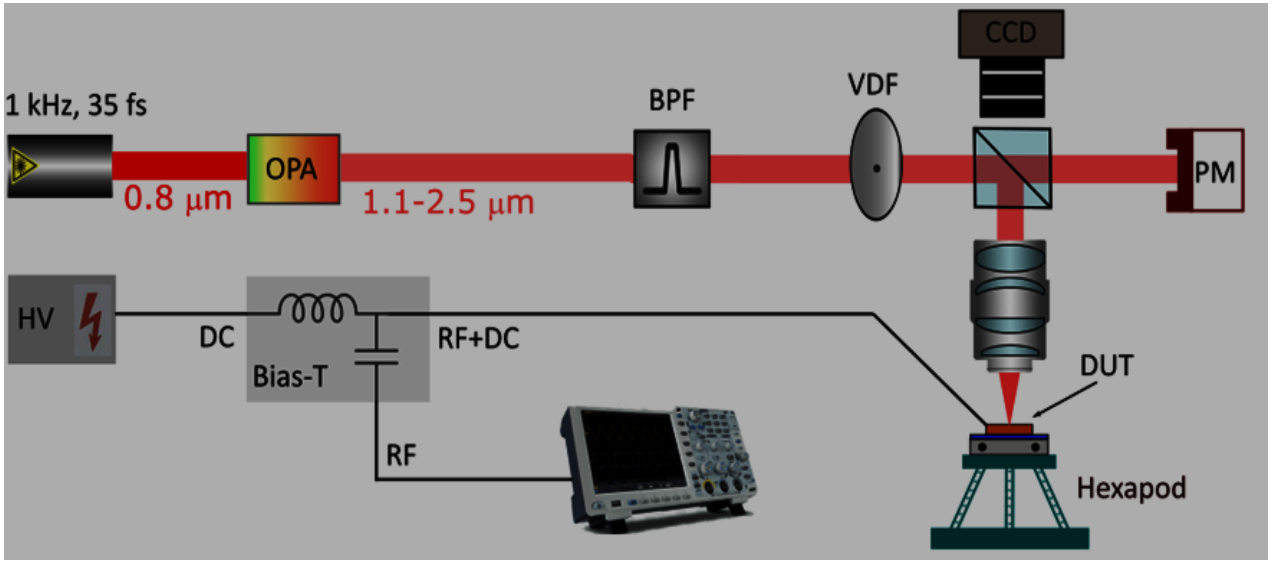




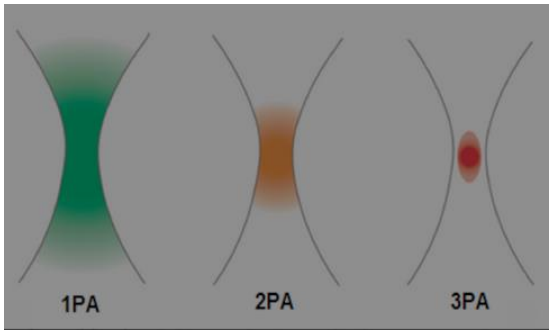


Characterization technique: TPA - TCT

Laser pulse energy: 15 pJ

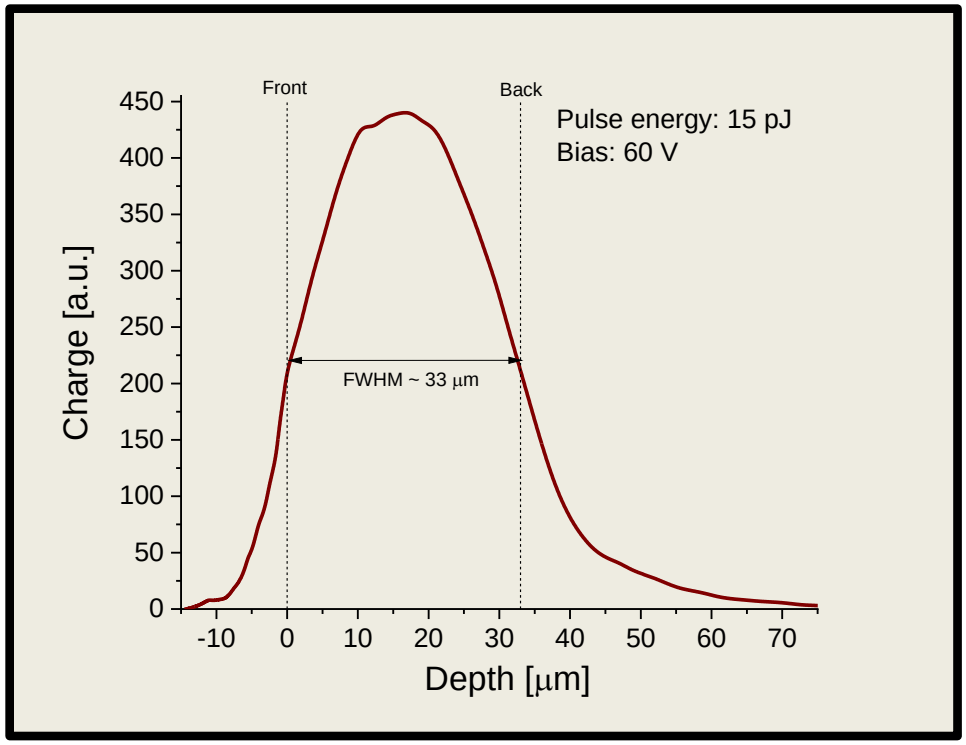


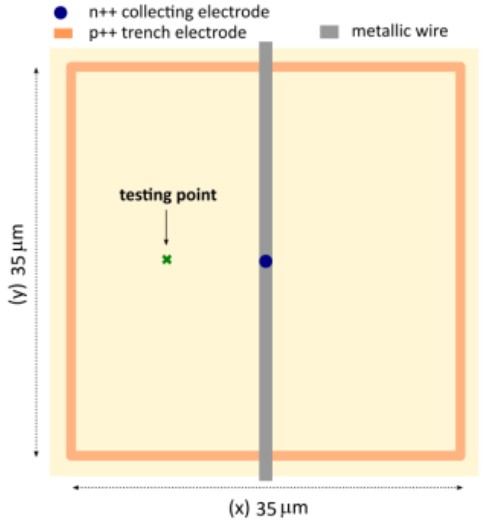
Place	ELI Beamlines
Operational modes	Single and two photon absorption (SPA and TPA)
Pulse energy on sample	Variable by ND filters (accuracy: 0.2 pJ) 800 nm (SPA), 1550 nm (TPA)
Wavelength	1550 nm, ~ 150 fs 800 nm, ~ 50 fs
Pulse width in sensor	
Focus waist radius	0.85 µm (SPA), 1.5 µm (TPA)
Rayleigh length	3.31 µm (SPA), 7.74 µm (TPA)
Sample cooling	Down to -25 deg. C
Sample movement	X, Y, Z
Bias voltage	up to or > 720 V
Detection	6 GHz (20 GSa) oscilloscope and leakage current measurement (accuracy: 0.1 µA)



The sample is electrically connected by wire bonds: the junction electrode is connected to high voltage (HV) via the Bias T circuit (Particulars BT-01), while the trench electrodes are grounded. The transient (RF) signals, decoupled from the HV by the Bias-T, are amplified by a wideband amplifier (Particulars AM-02 A, 3GHz, 53dB) and digitized by oscilloscope.

Z- Scan

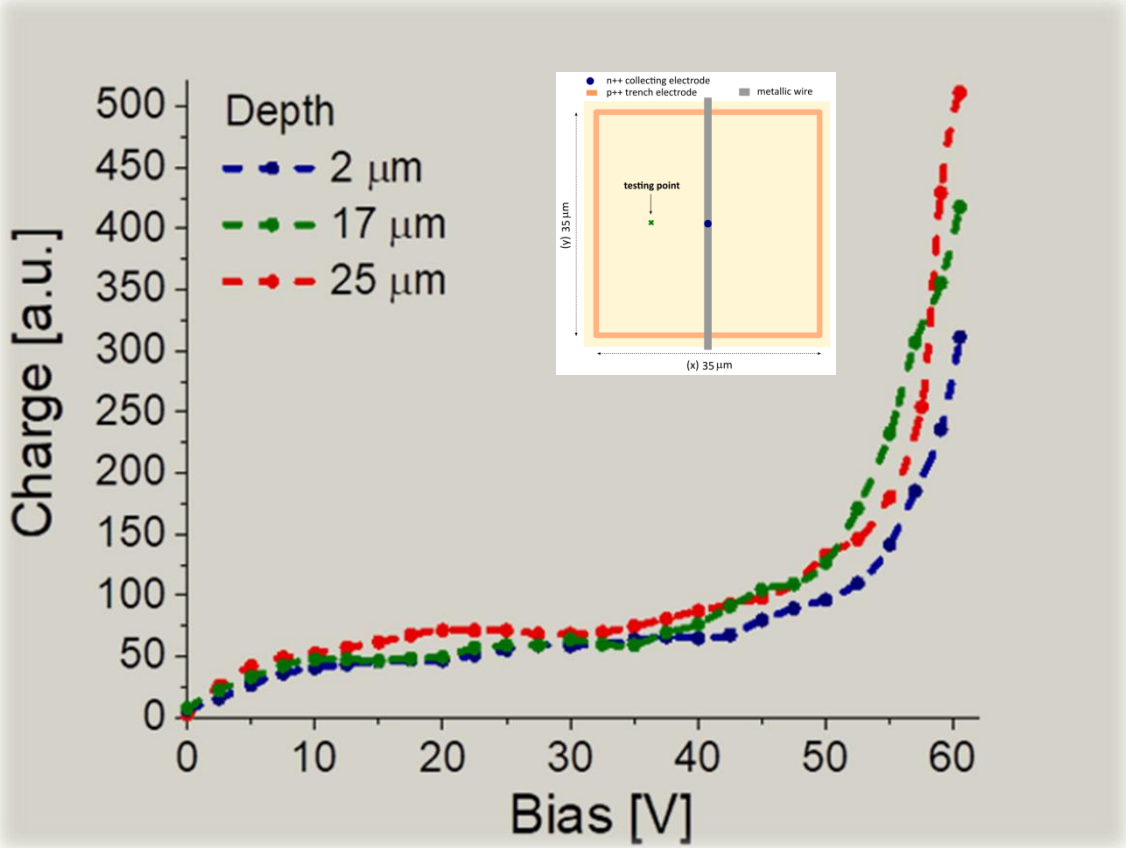




- ✓ FWHM of the profile is close to the nominal thickness which is 35 um.
- ✓ We checked profiles in a few different points with very similar results.

Charge collection and observation of the gain

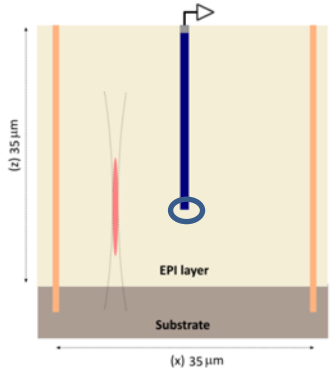
- ✓ TPA-TCT collected charge in the representative point at three different TPA depths.
- ✓ Device becomes fully depleted around 25V, where the collected charge stabilizes.
- ✓ The following exponential increase occurs in the gain regime.

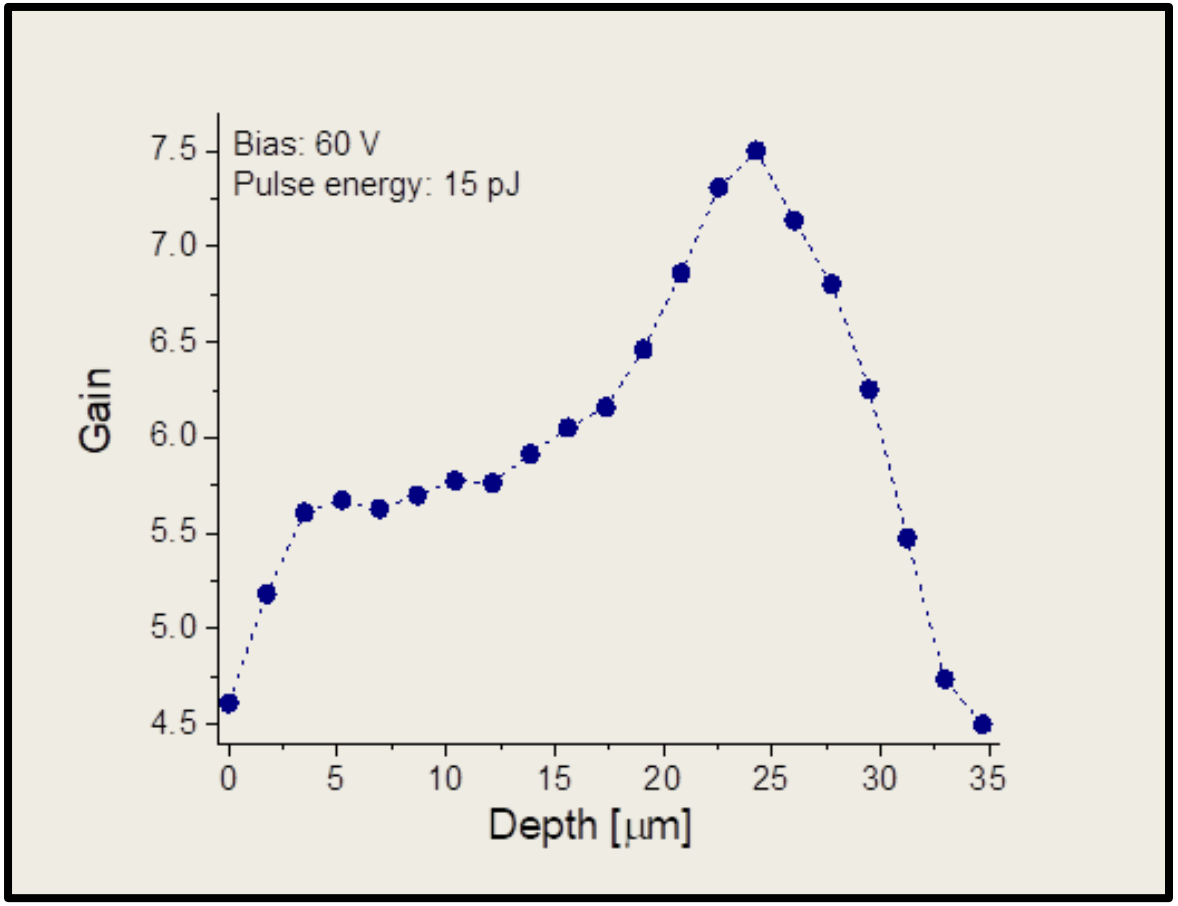


The device becomes fully depleted at around 25V, where the collected charge reaches a plateau

Gain vs. Depth

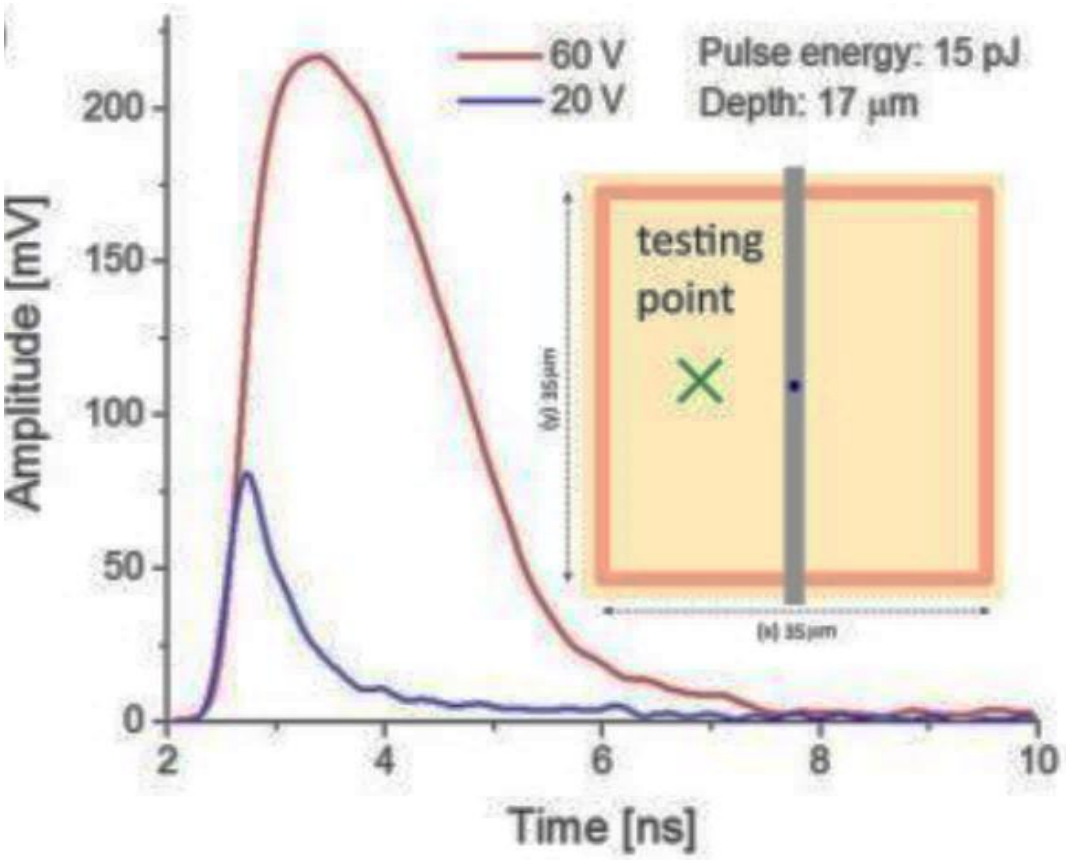
At 60 V and at the depth of 25 µm the gain is around $G=Q(V)/Q(V_{fd})\sim7.5$





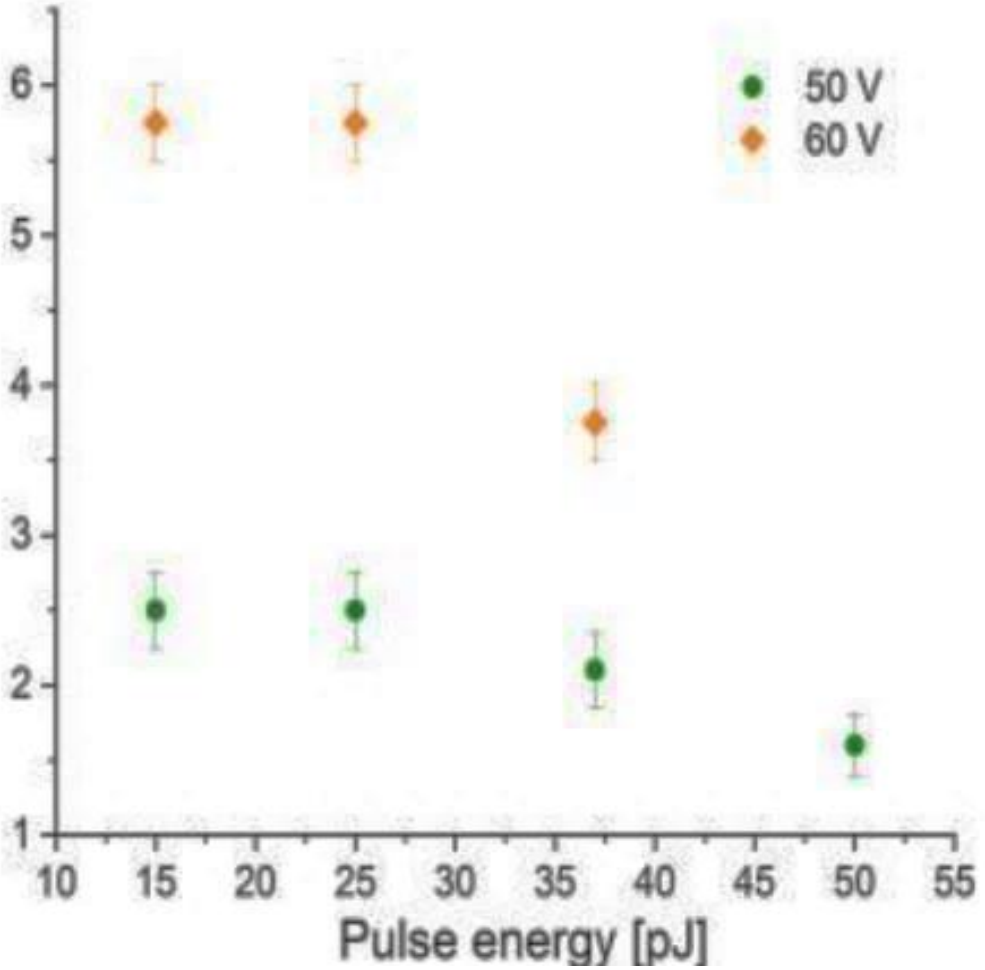
Waveforms at 20 V and 60 V

- ✓ Another indicator of charge multiplication is the extended duration of the induced signals which results from the drift of the secondary holes to the ohmic contacts after the primary electrons undergo multiplication. Obviously enlarged amplitude can be seen.



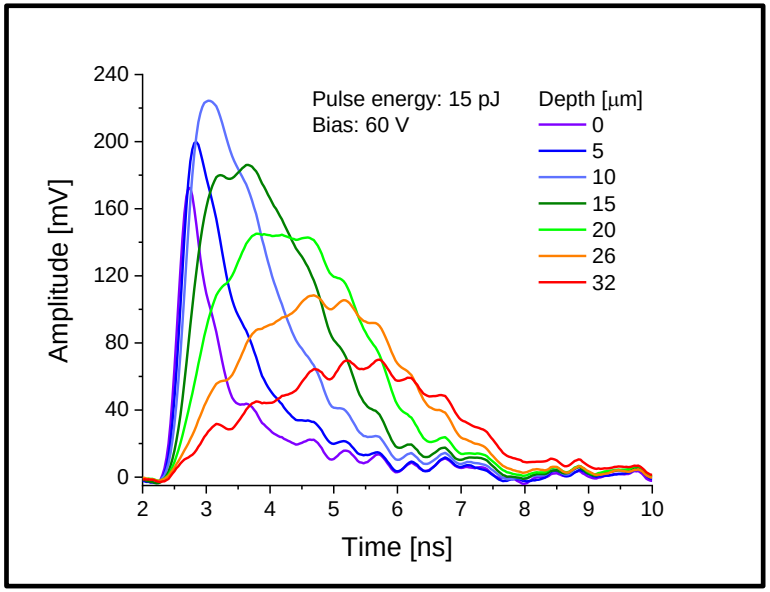
Laser power variation

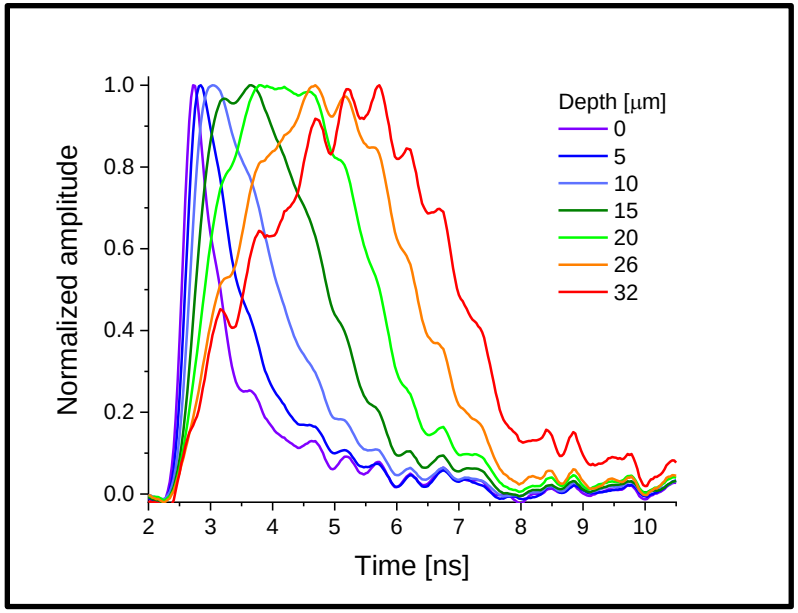
- ✓ Gain suppression is observed



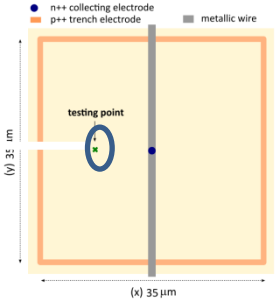
Focal –depth charge dependence

- ✓ Signal becomes slower and arrives later with increasing depth.





Position (x,y) where z-scan was performed and the RT and ToA are extracted (from corresponding waveforms



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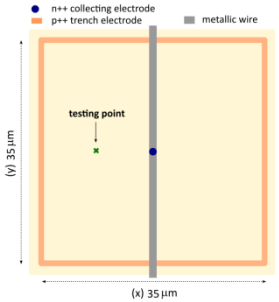
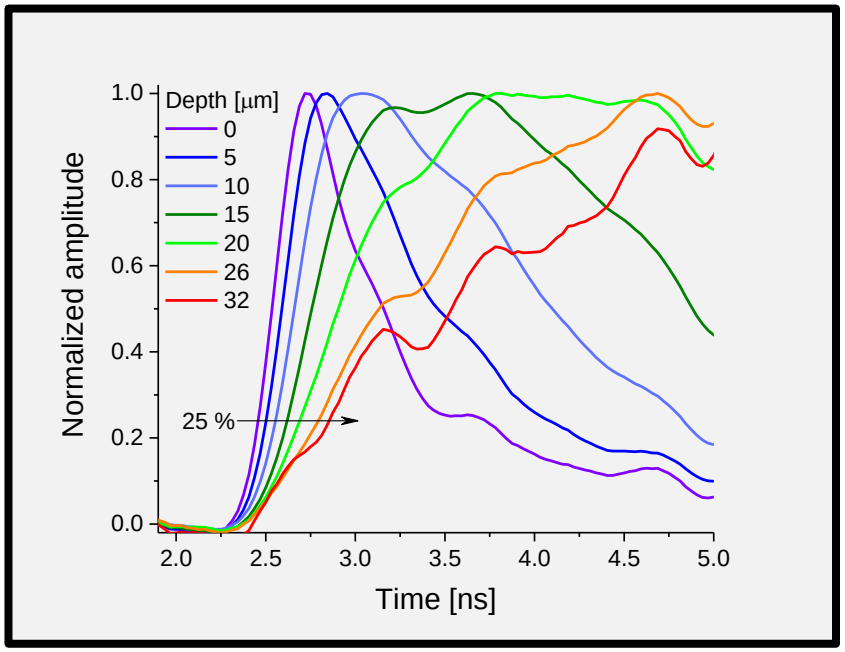
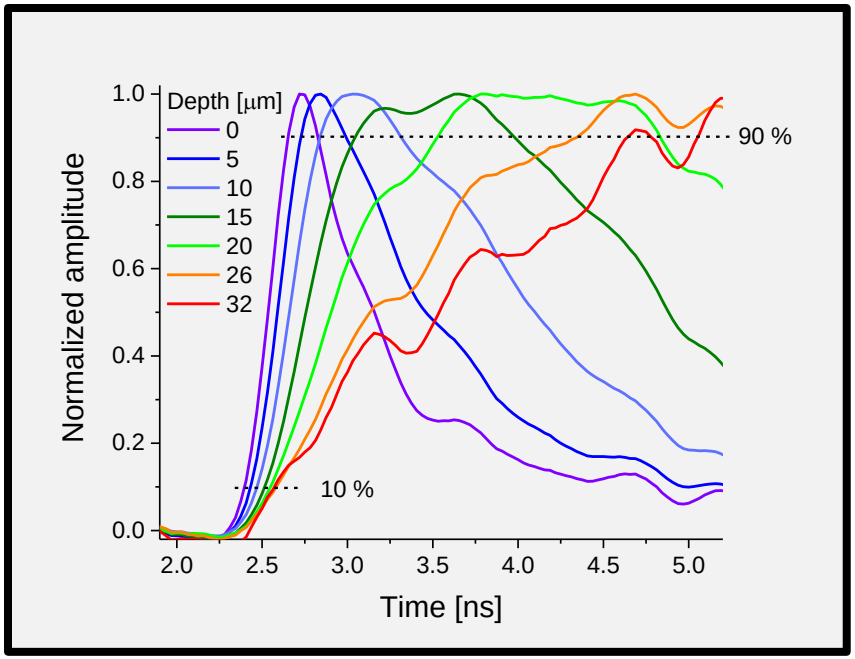
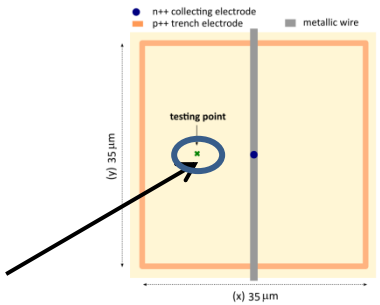


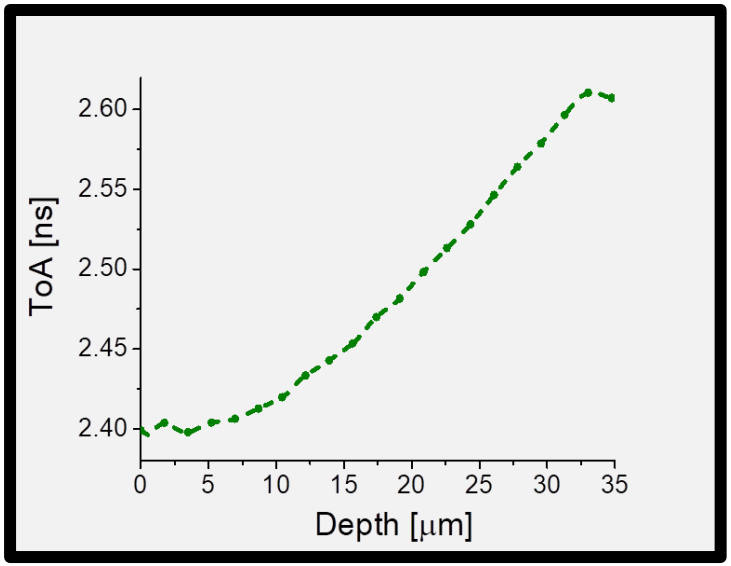


Already shown in previous slide but here magnified (selected time window region).

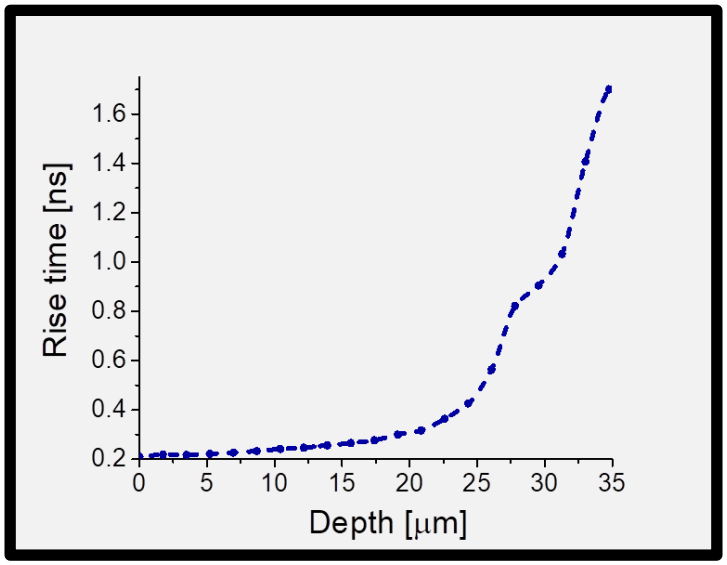


Focal–depth timing dependence



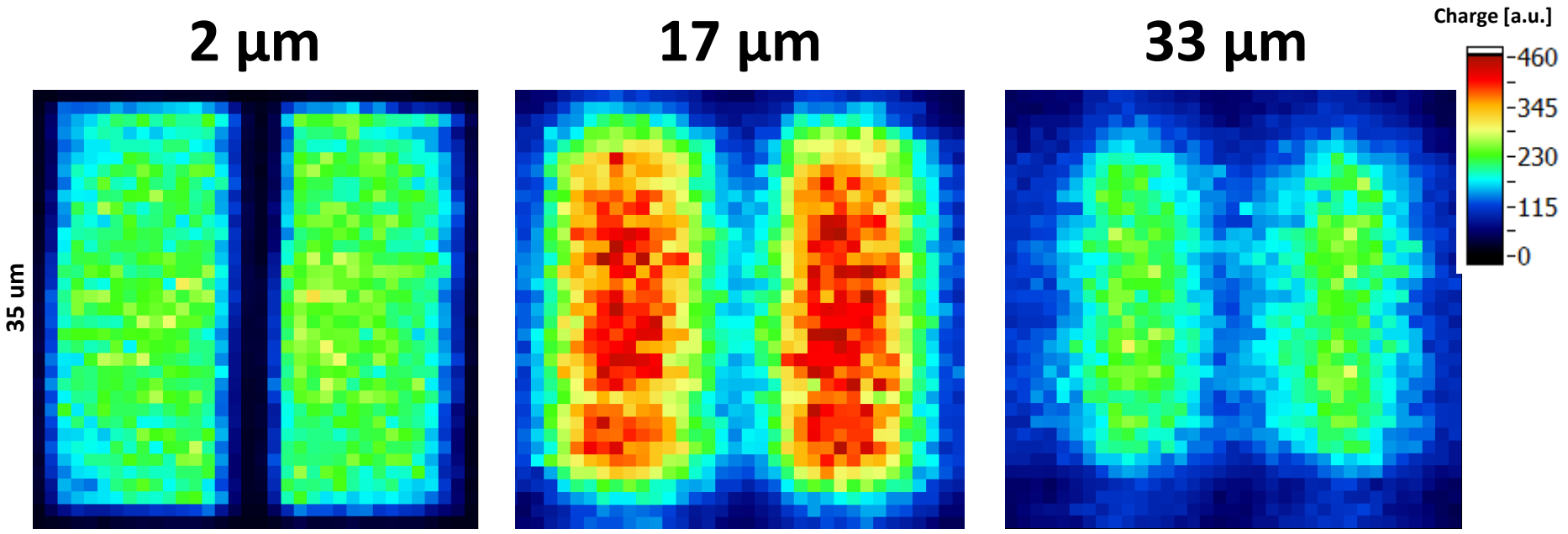


Position (x,y) where z-scan was performed and the RT and ToA are extracted (from corresponding waveforms)



ToA and RT is increasing with increasing depth; gain is increase but also screening effect (slower movement of clouds of holes).

Charge Map versus depth

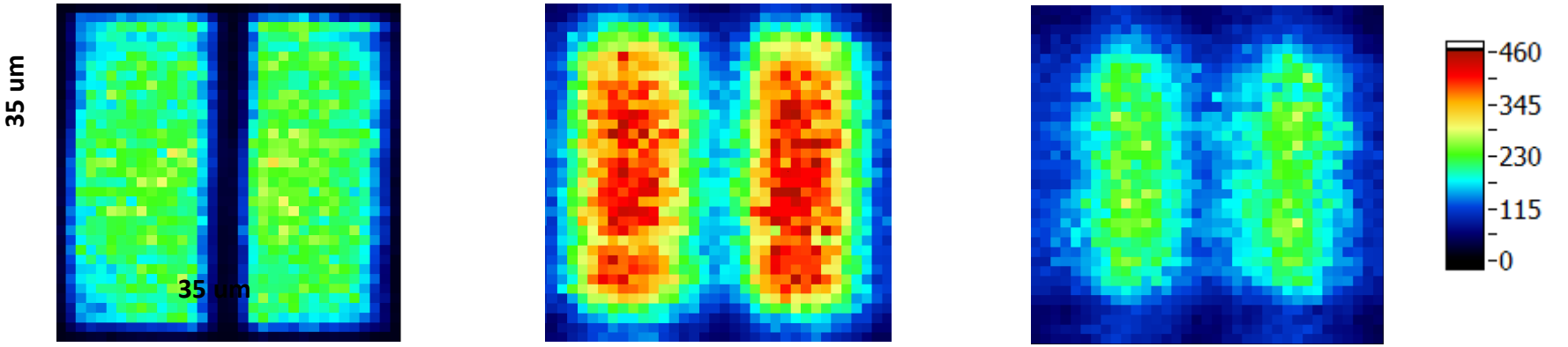


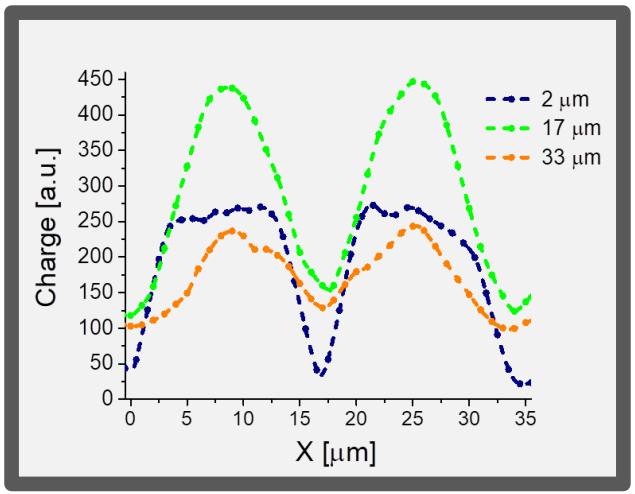
Remark: Less charge at 2 µm and at 33 µm is not only consequence of lower gain but also the result of incomplete TPA vortex.

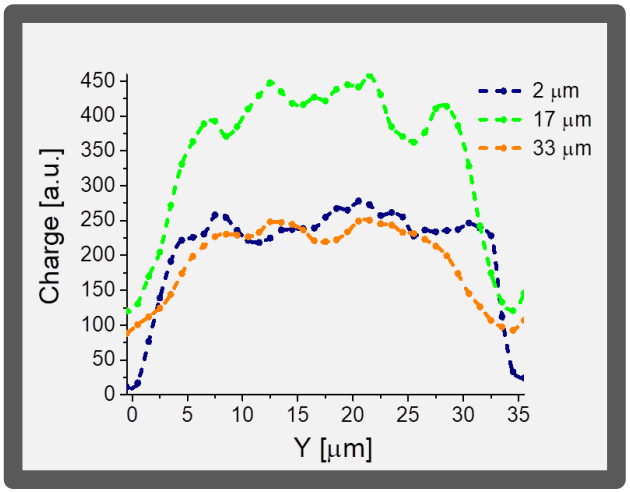
X- and Y- Charge Profile

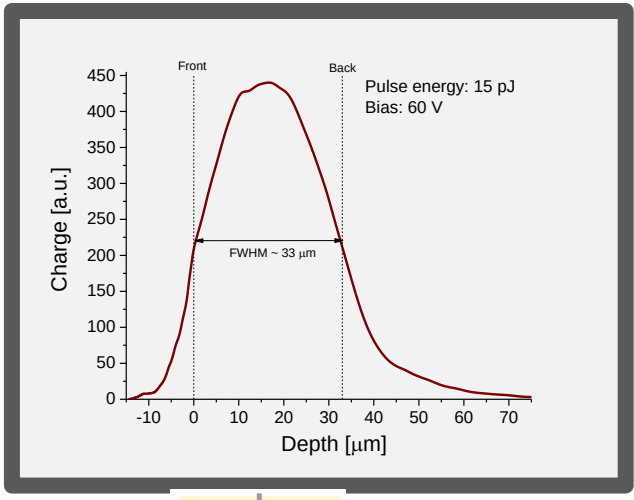
2 µm

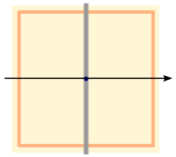
33 µm

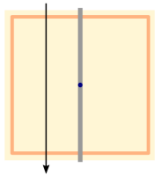


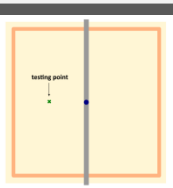








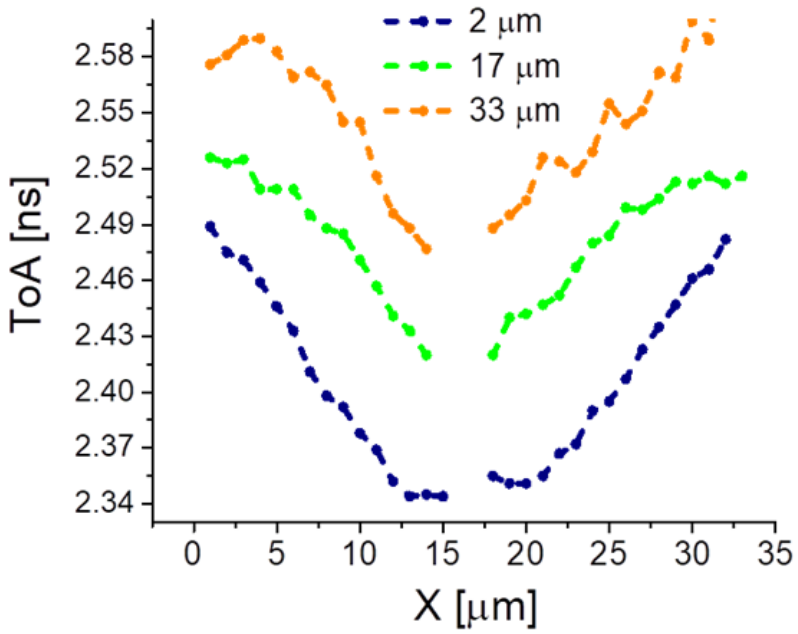


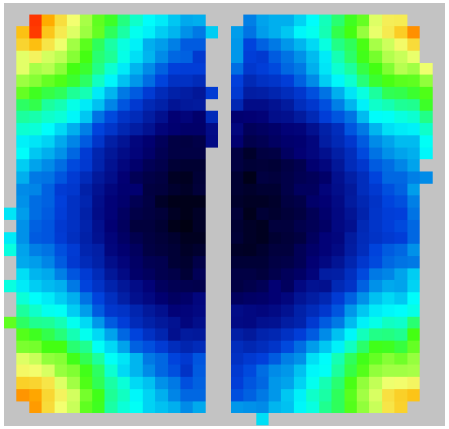


Lateral variation of ToA:

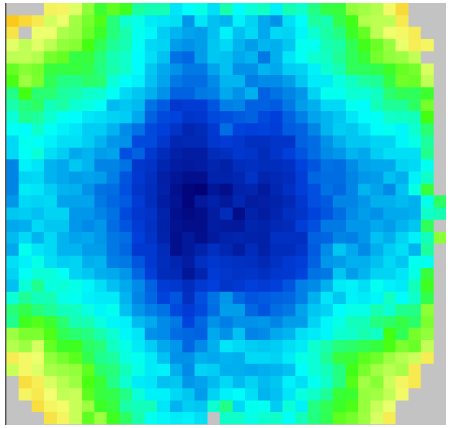
In X direction

ToA

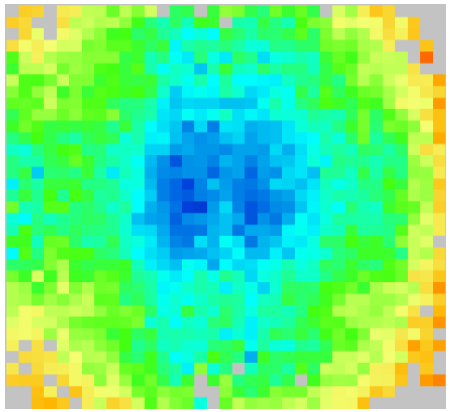




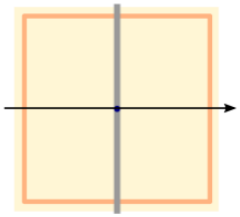
2 µm



17 µm



33 µm



Lateral variation of Rise Time (RT):
In X direction

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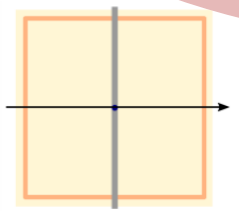
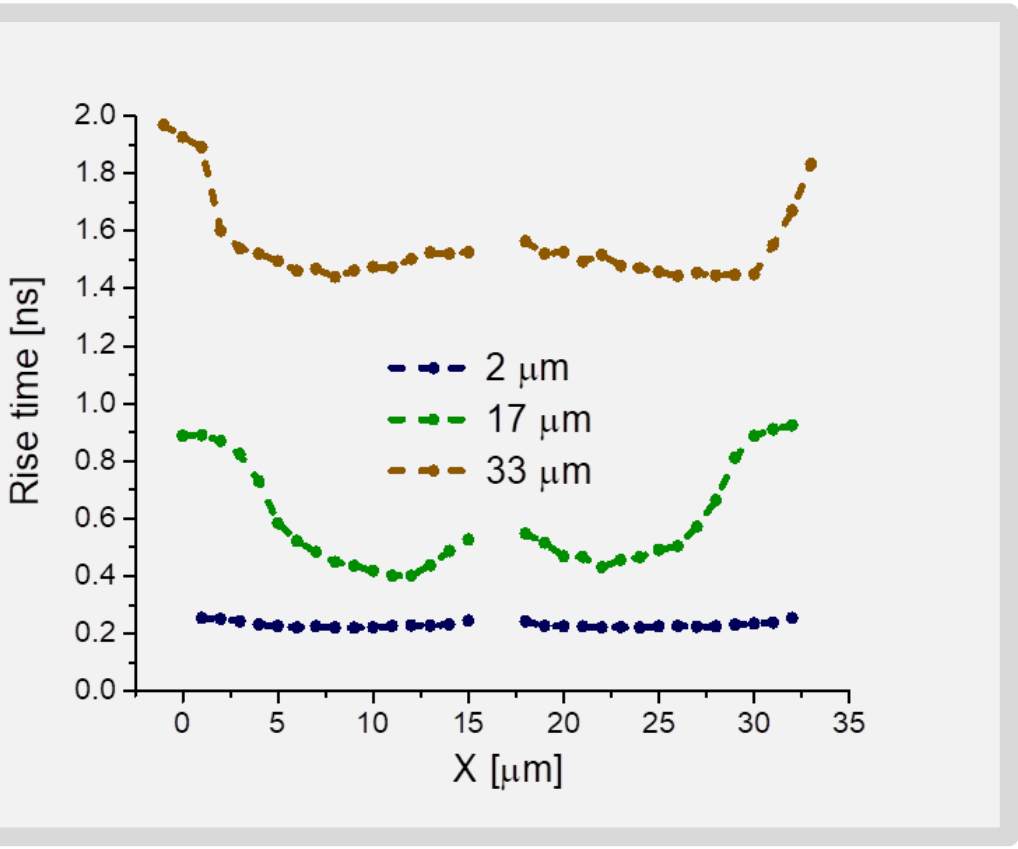
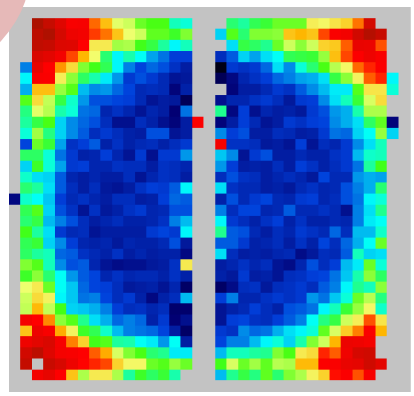
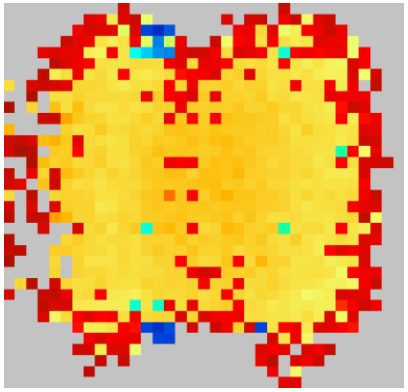


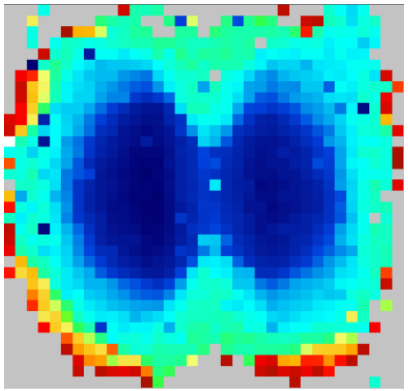




2 μm



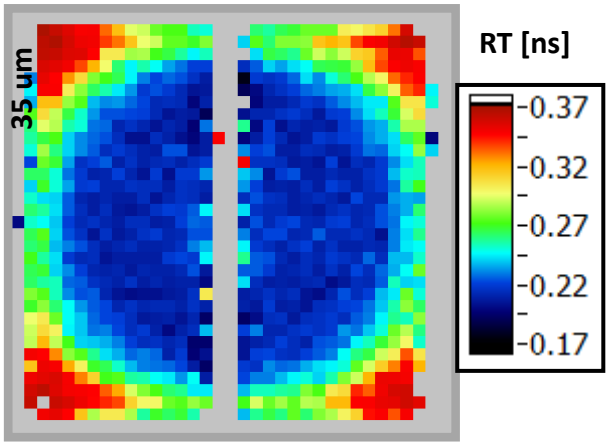
17 μm



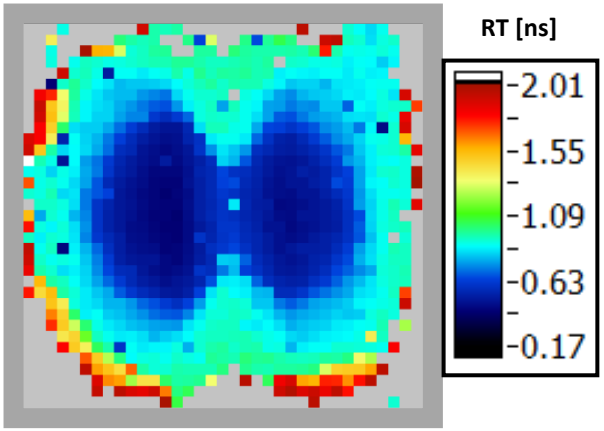
33 μm

RT spread

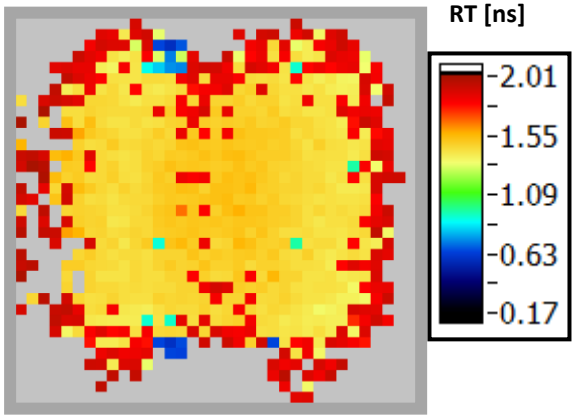
2 µm

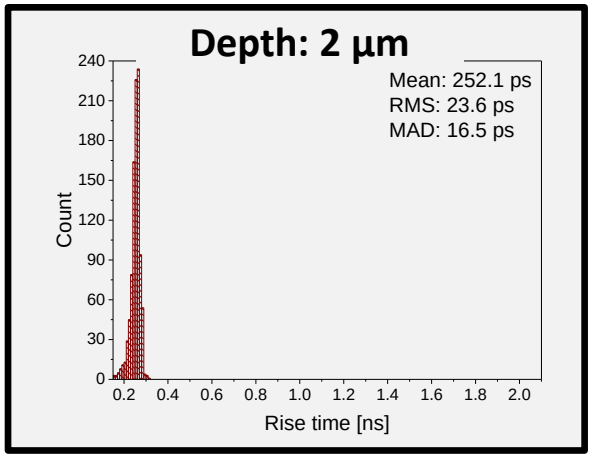


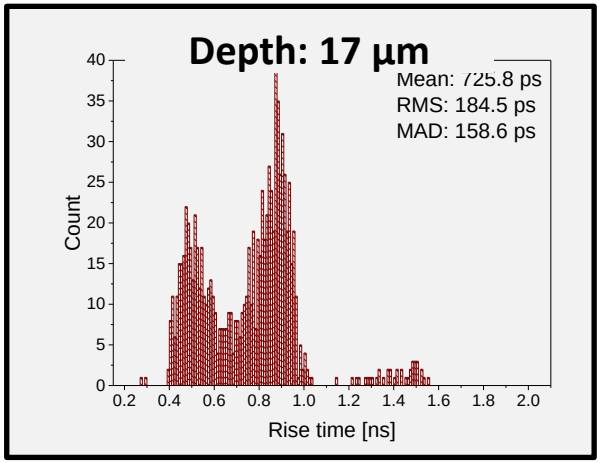
17 µm

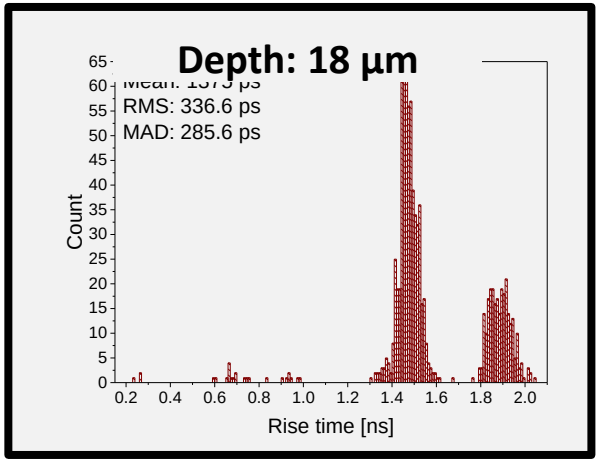


33 µm

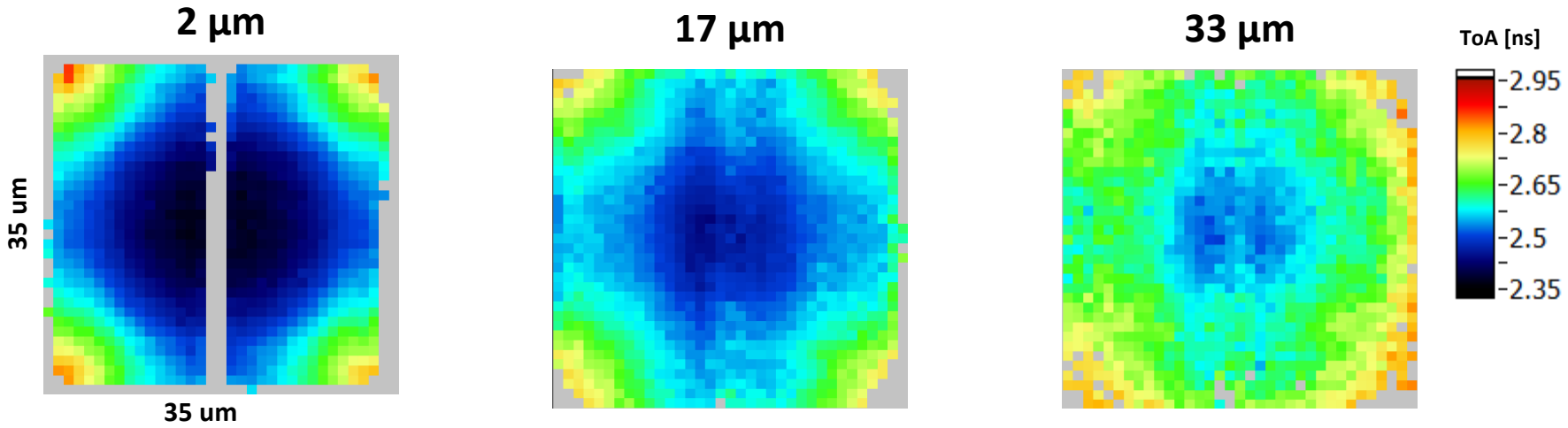


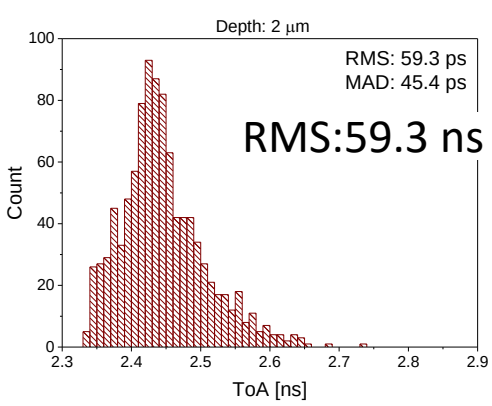


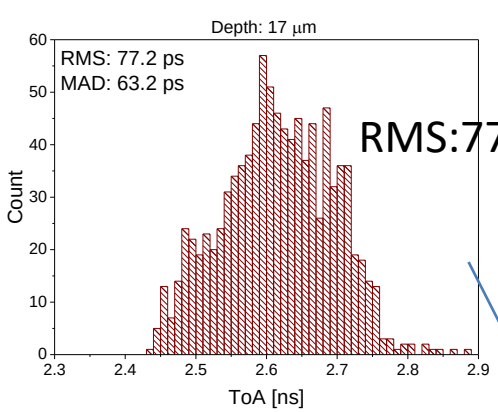


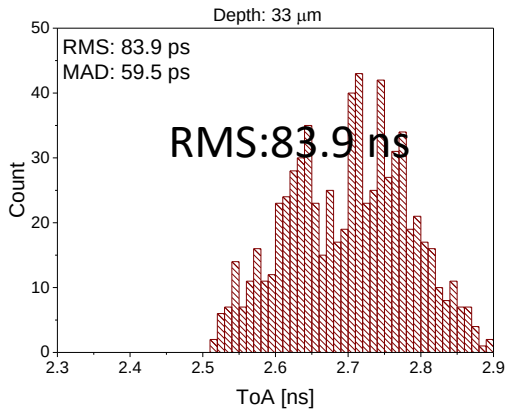


ToA spread



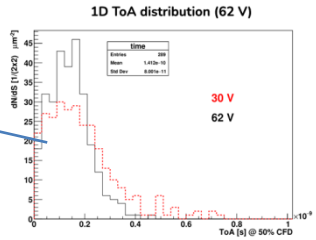






Distribution of ToA at different depths is much more homogenous than rise time. However shifts towards bigger values with depth is clear. Also RMS increases vs depth from 59.3 ps close to top surface to 83.9 ps close to the bottom.

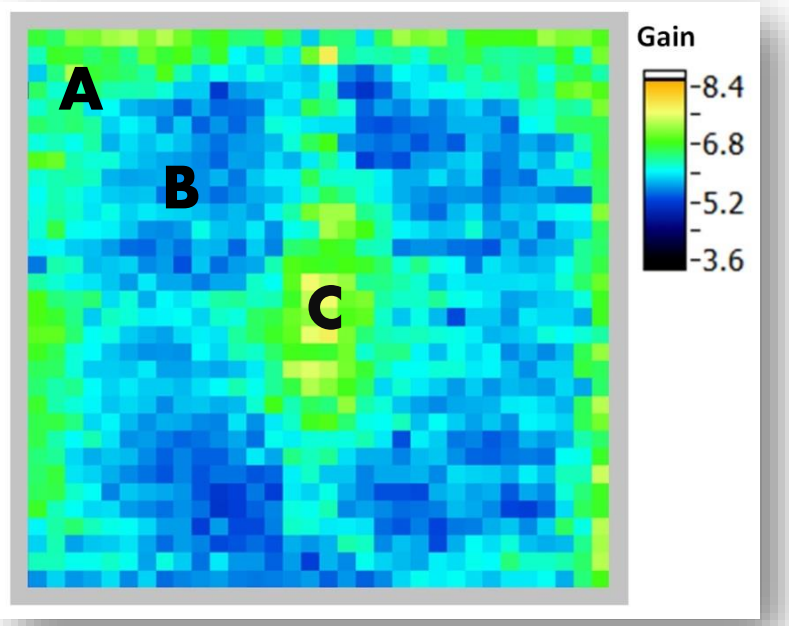
Simulated ToA spread of 80 ps at 62 V is in excellent agreement with TPA-TCT measurements (77.2 ps). (S9mulation performed by G. Kramberger (TREDI2026)



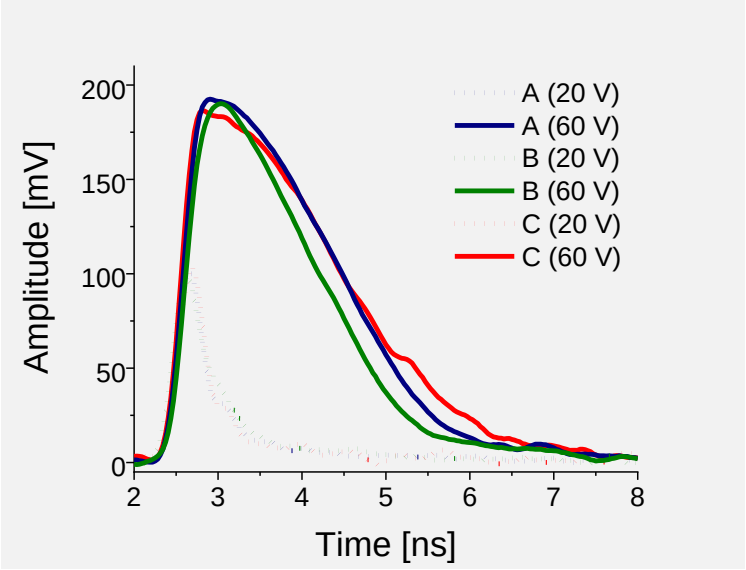
2D Gain Map

Pulse energy: 15 pJ
Depth: 17 um

Waveforms at different gain areas (A,B,C marked on gain map)



Waveforms at 20 V are very similar. Waveforms at 60 V differs each other. The one in central area (B) is narrower what gives smaller charge (integral) and in consequence lower gain



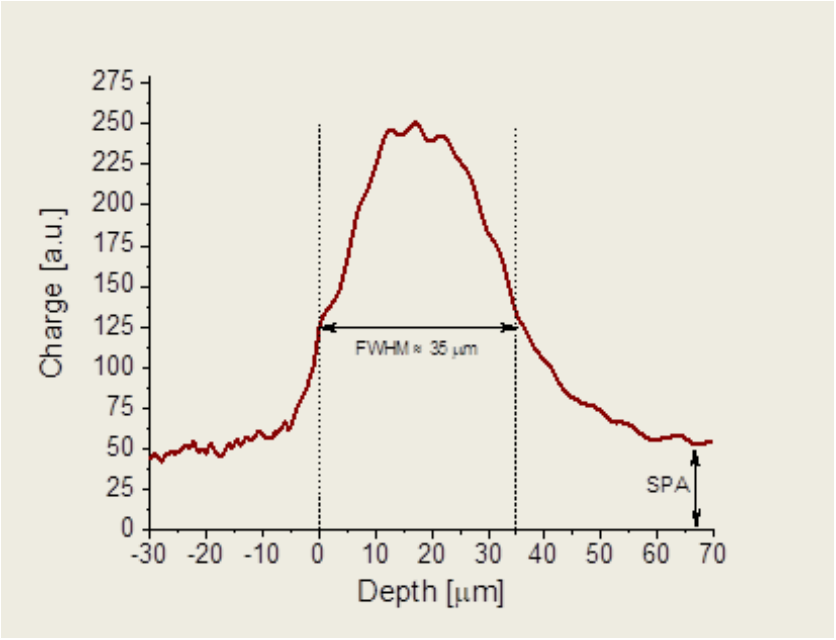
Irradiated device

Irradiated at fluency:

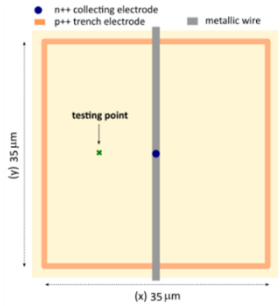
$5.5 \times 10^{15}\ n_{eq}/cm^2$

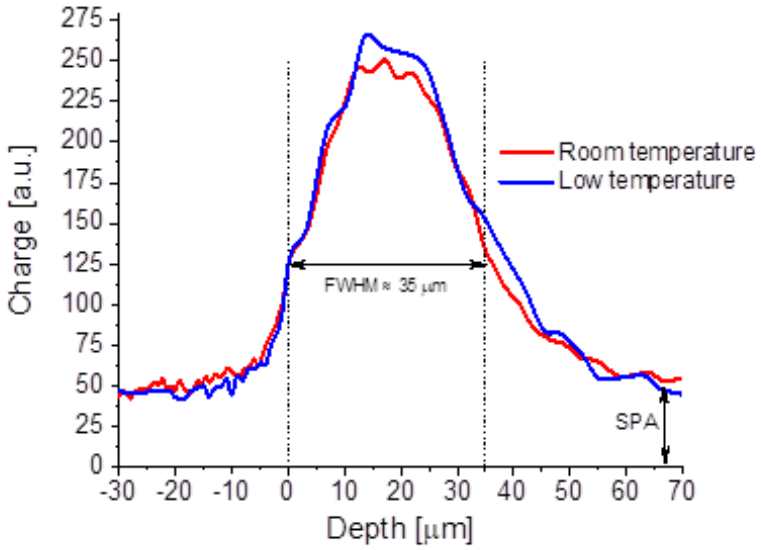
Z-Scan

✓ Room Temperature

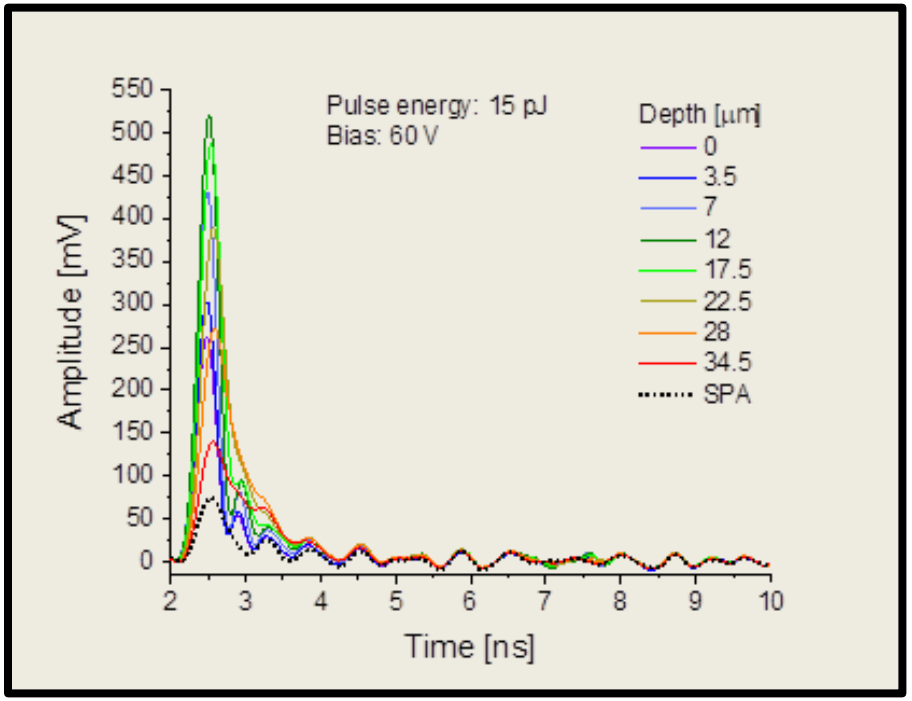


✓ -25^{0}C

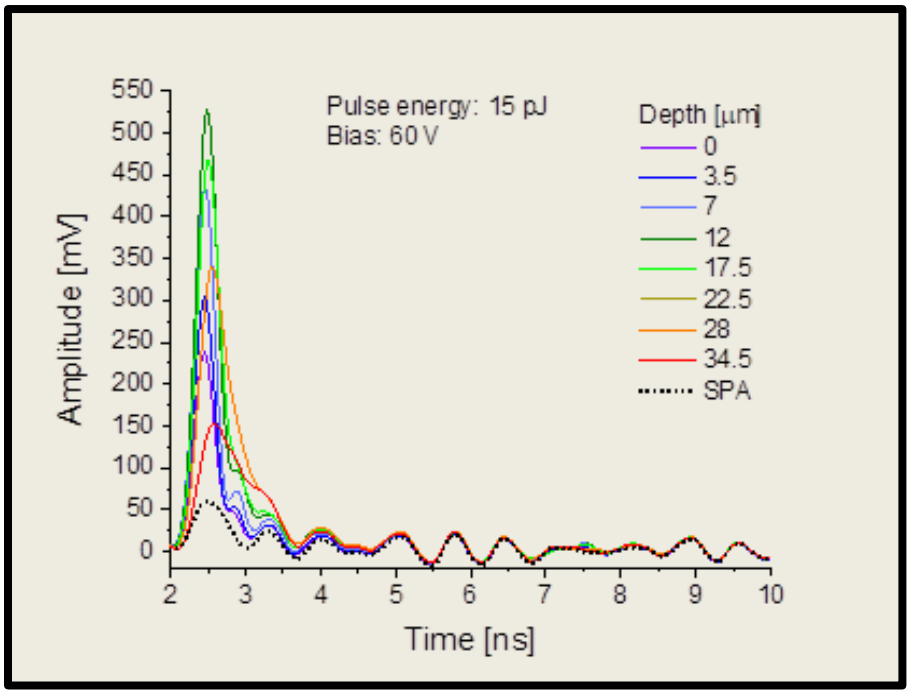




✓ Room Temperature

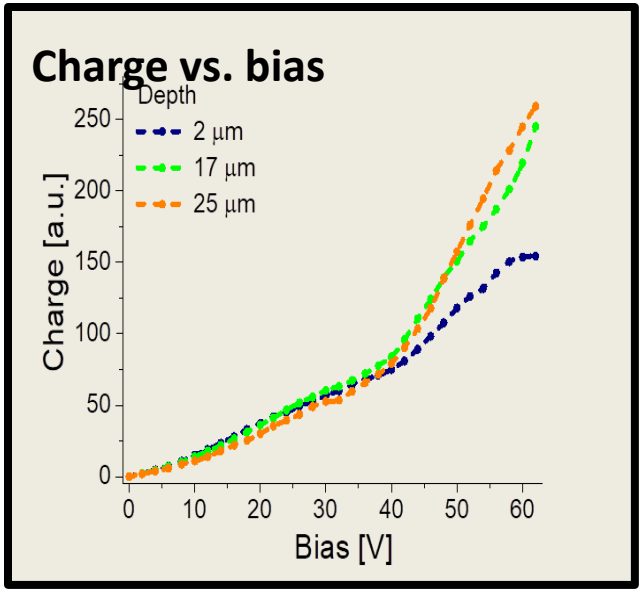


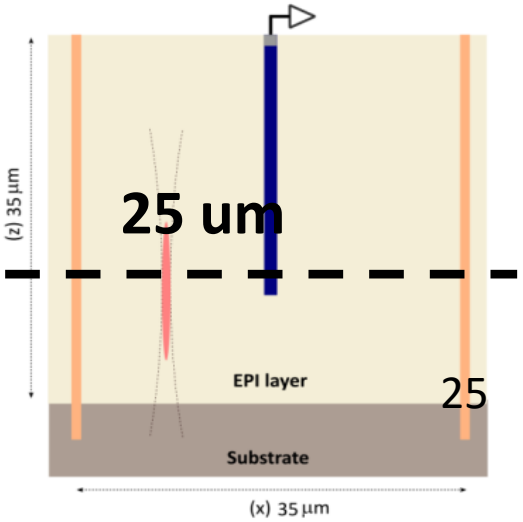
➢ -25^{0}C

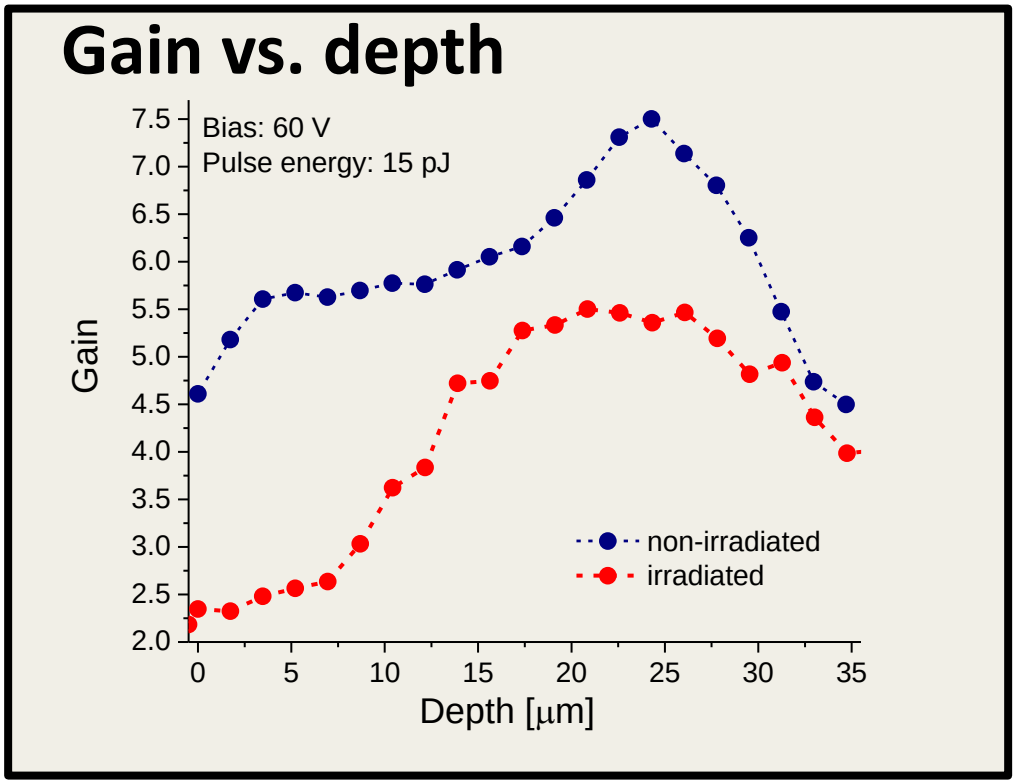


Gain after irradiation

➢ at +20^{0}C (RT)
in irradiated device



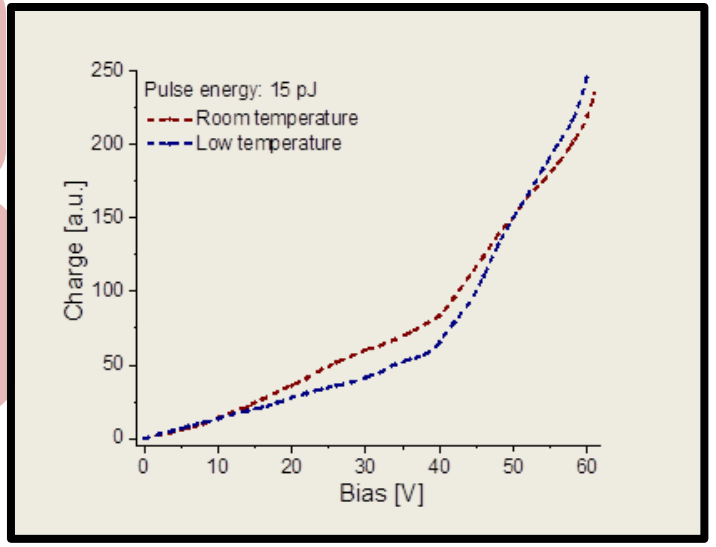




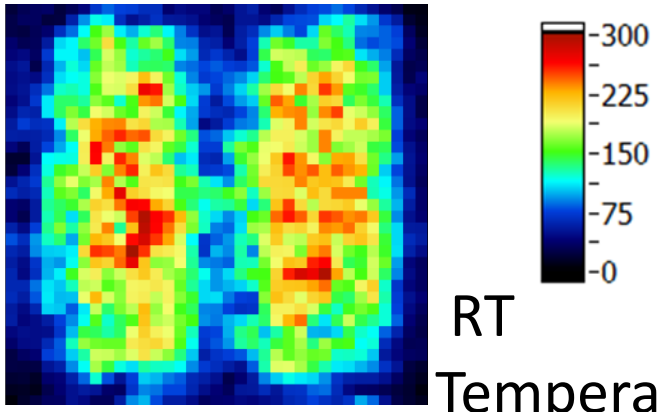
- The speed is faster due to trapping and reduced carrier life time from the substrate.
- The irradiated signal is much better for timing, but why it is factor of two lower at the same bias is an interesting question.
- Next time we will narrow region for signals only at 7-12 um depth as there the situation with creation is clearer.
- We would have expected that irradiation would not decrease the gain at the same bias voltage. Question: it should be possible to increase the bias to recover it ? We will investigate this next time.

Gain after irradiation

at -25^{0}C
in irradiated device



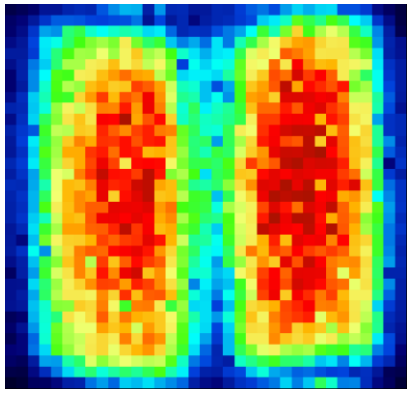
Charge [a.u.]



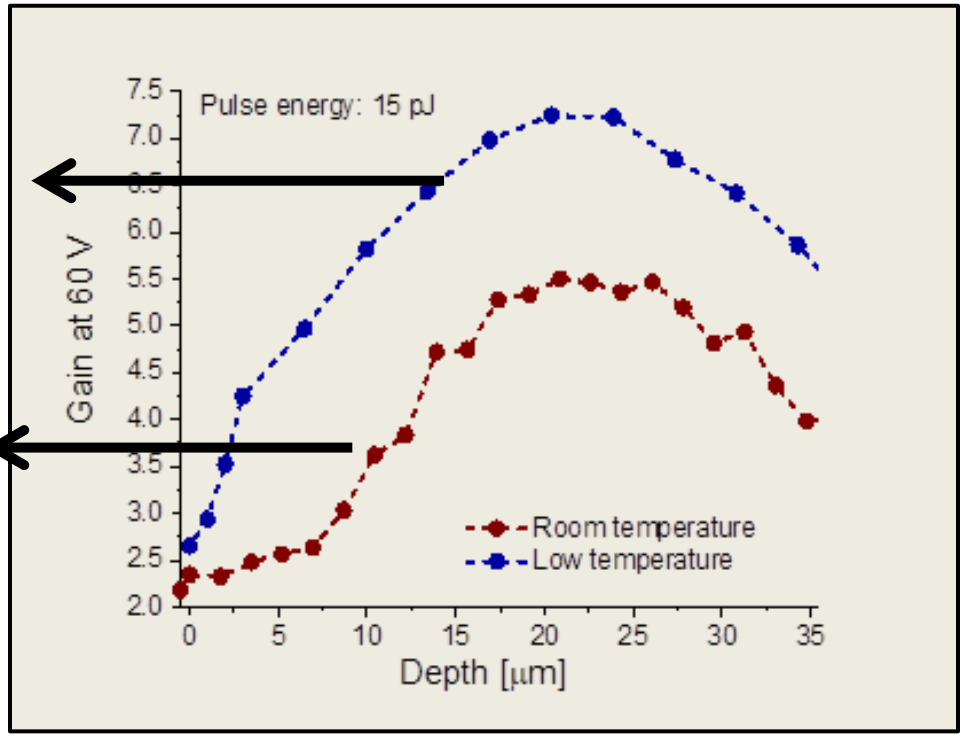
RT Temperature

-25^{0}C

25^{0}C



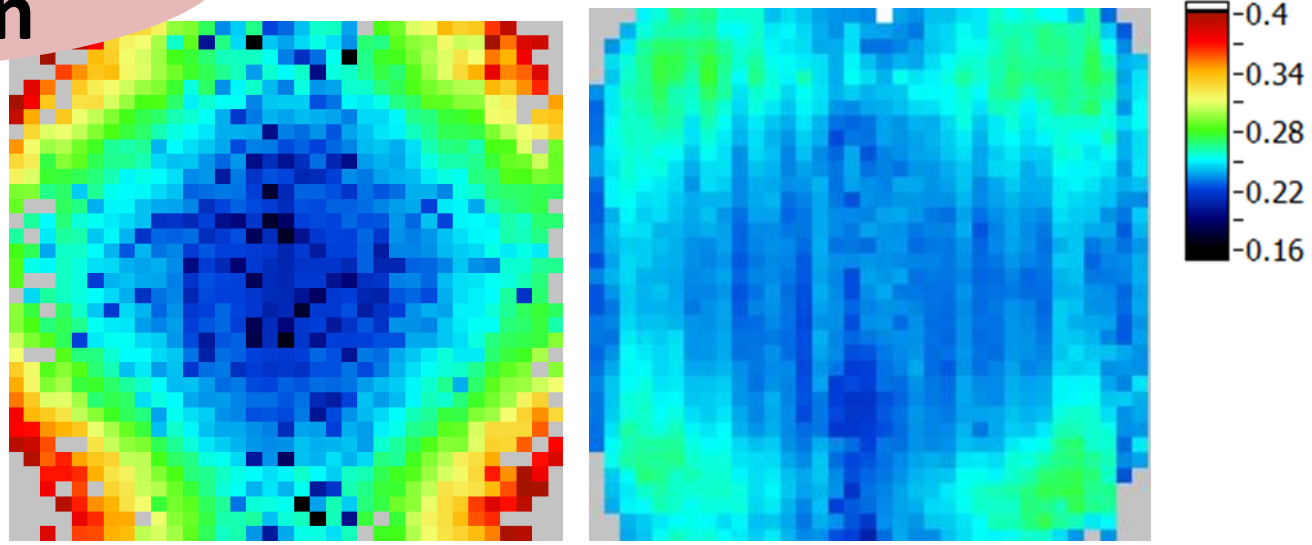
Low Temperature



RT after irradiation

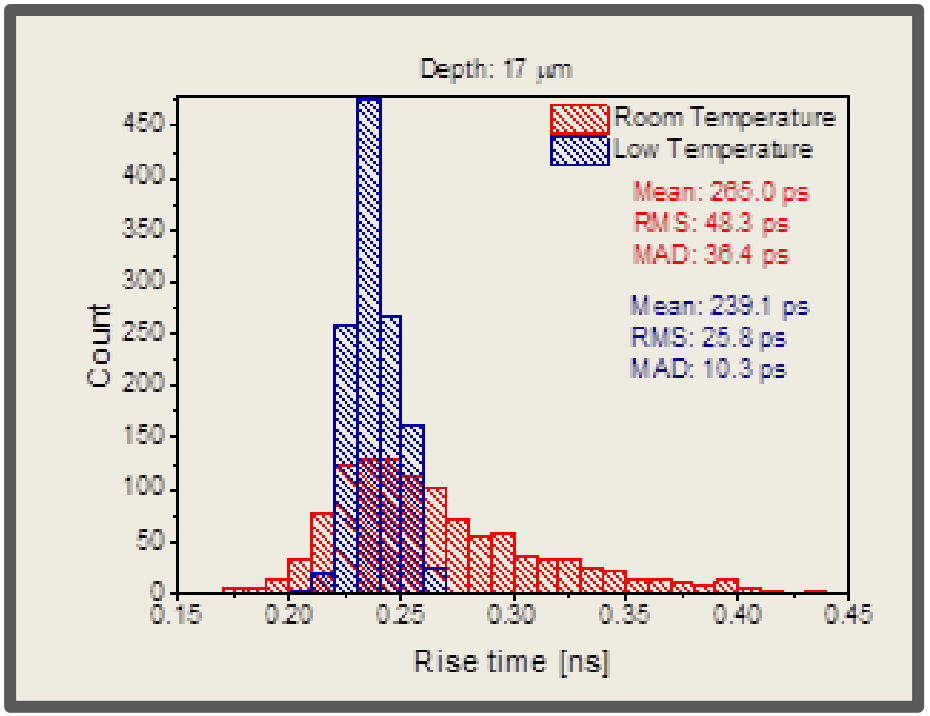
2D image of Rise Time

- ✓ at RT
- ✓ -25^{0}C



RMS, MAD (Rise Time)

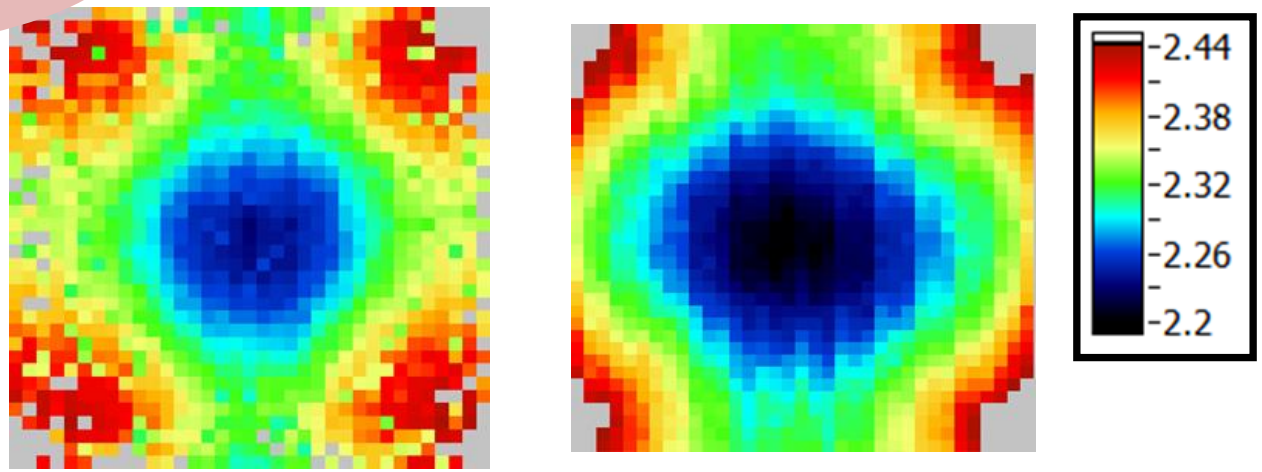
- ✓ at RT (red)
- ✓ -25^{0}C (blue)



ToA after irradiation

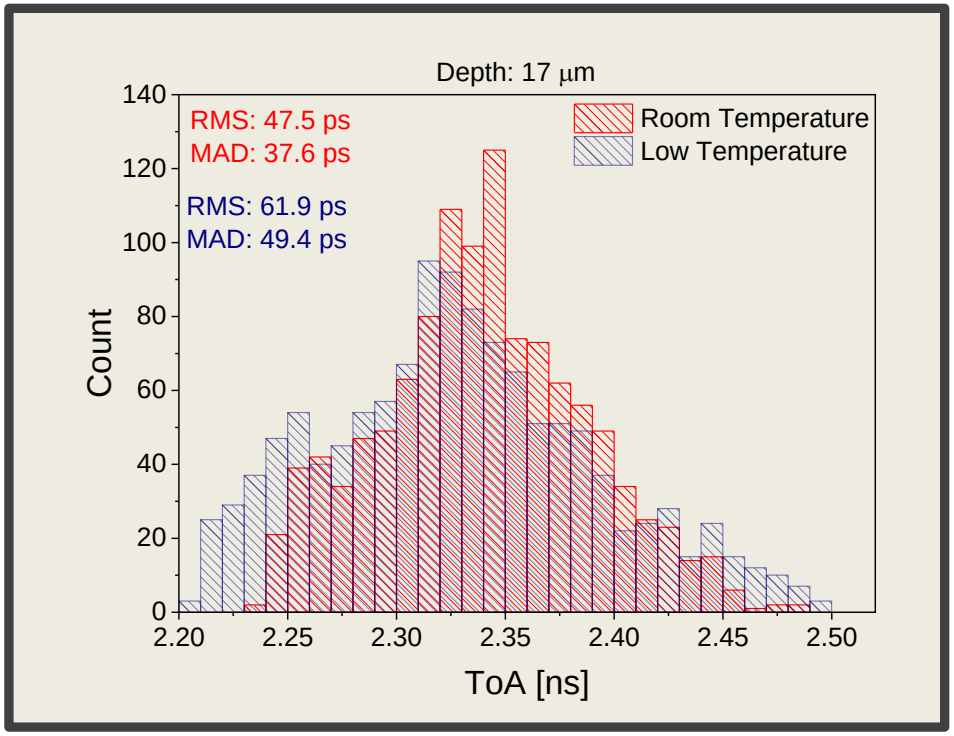
2D image of ToA

- ✓ at RT (left)
- ✓ at -25^{0}C (right)

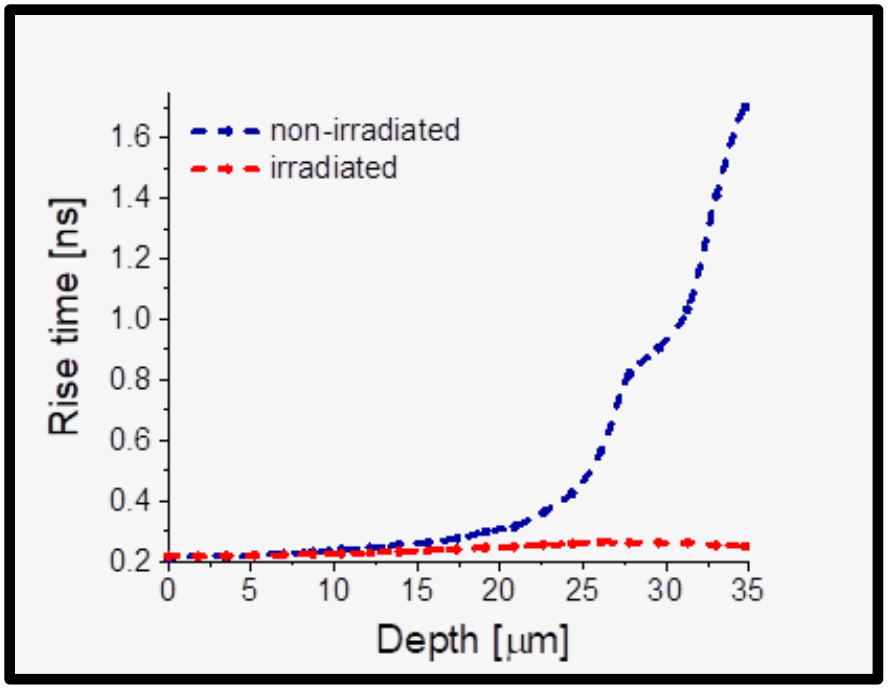


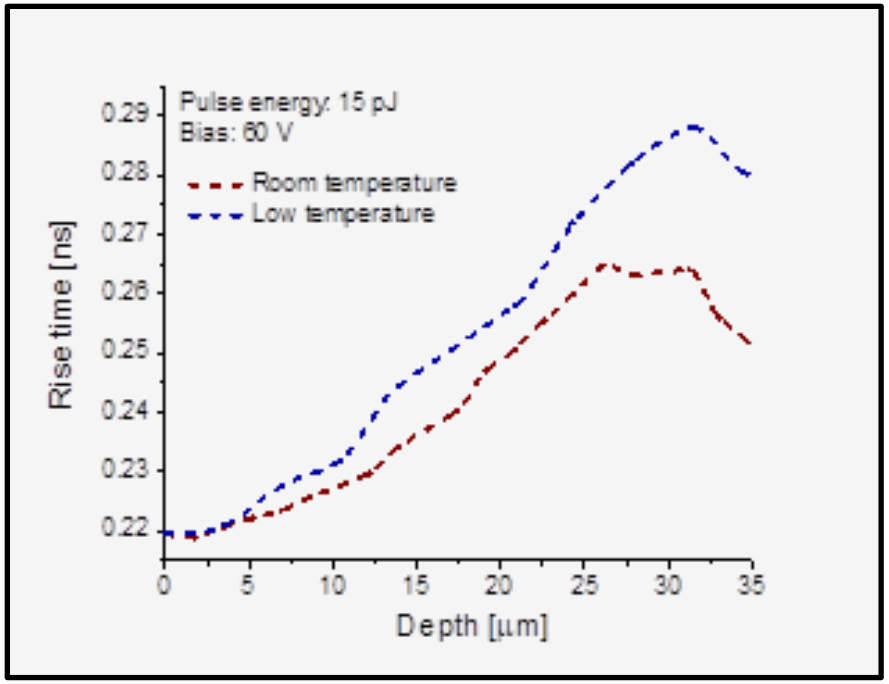
RMS, MAD (ToA)

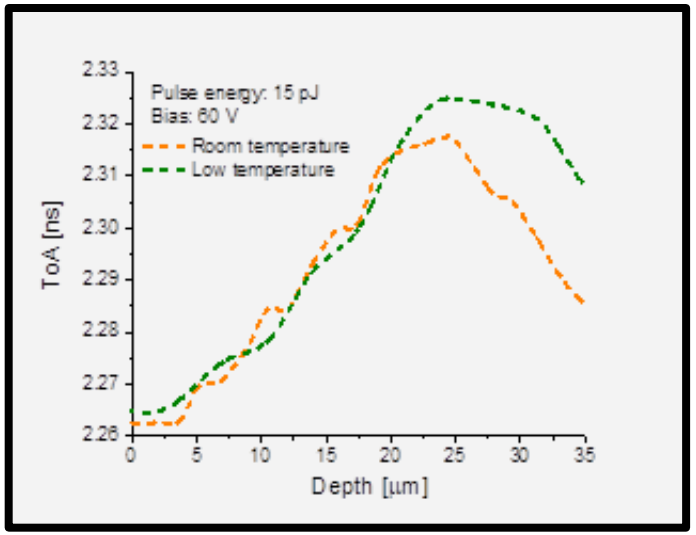
- ✓ at RT (red)
- ✓ -25^{0}C (blue)



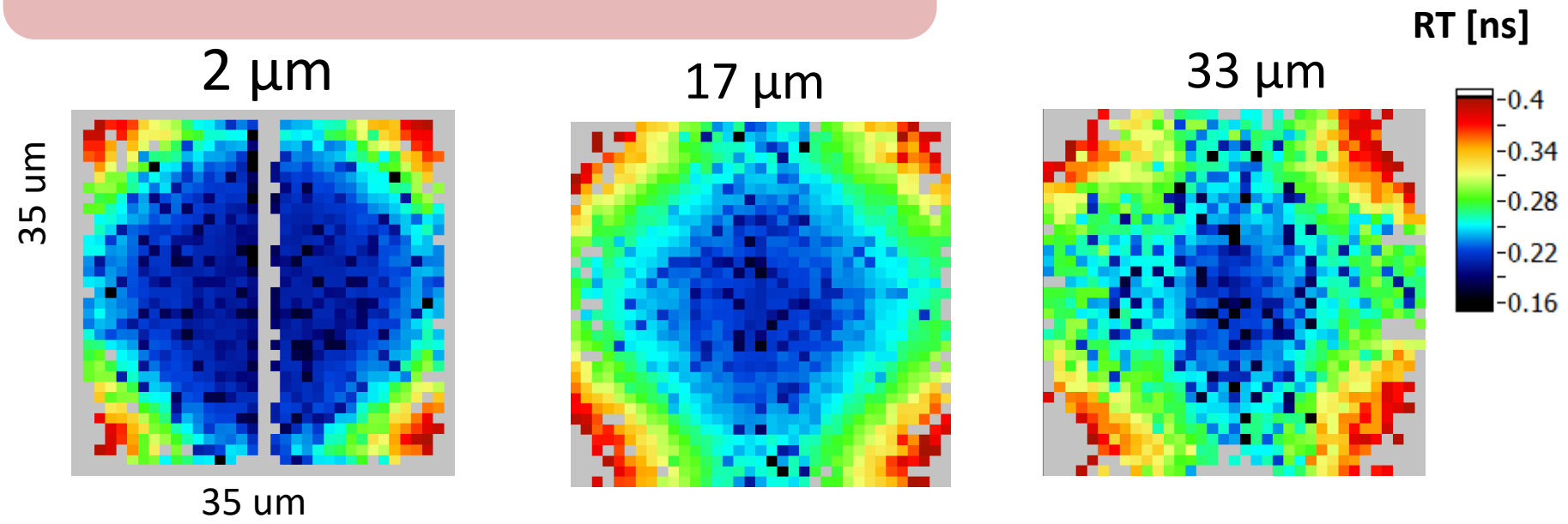
ToA, Rise Time at low and RT temperature

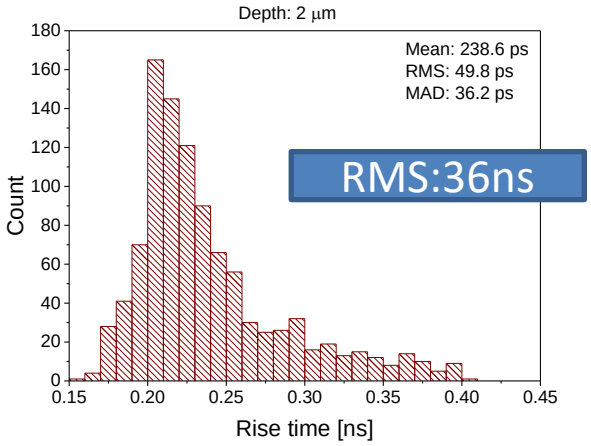


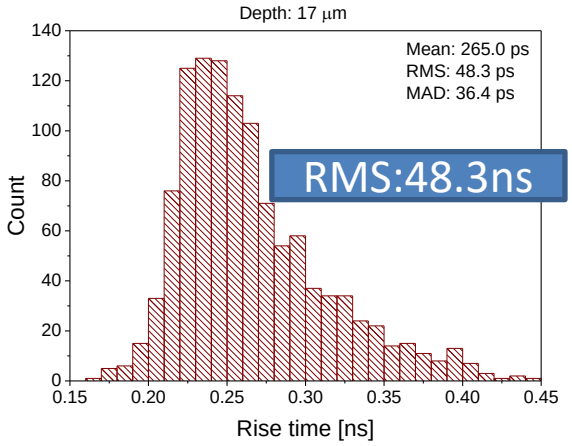


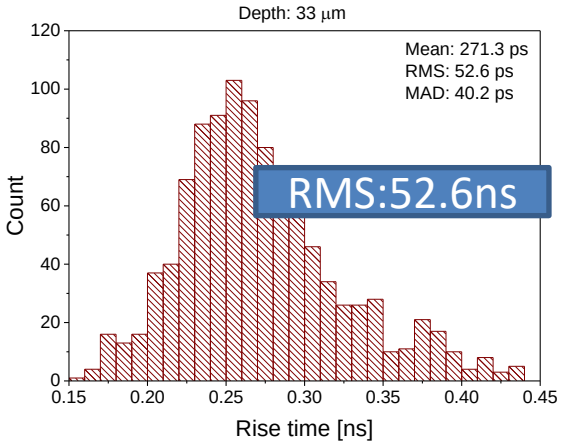


Rise Time vs Depth

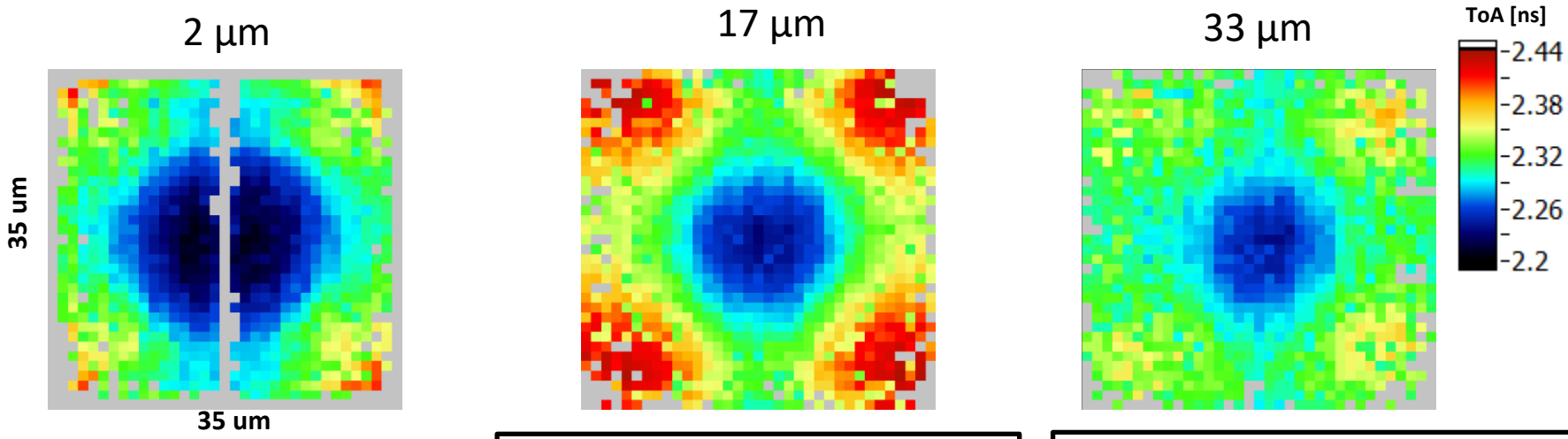


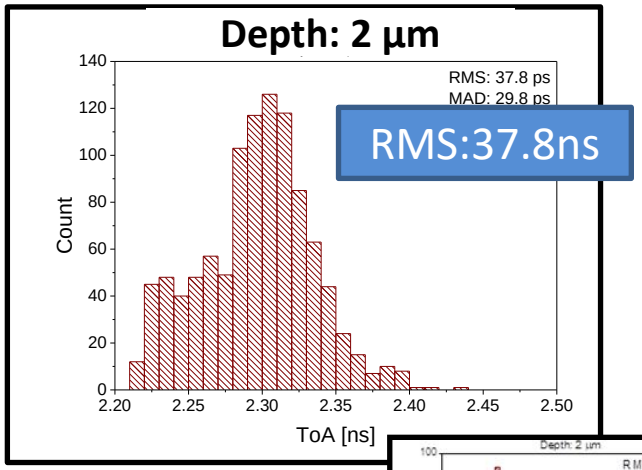


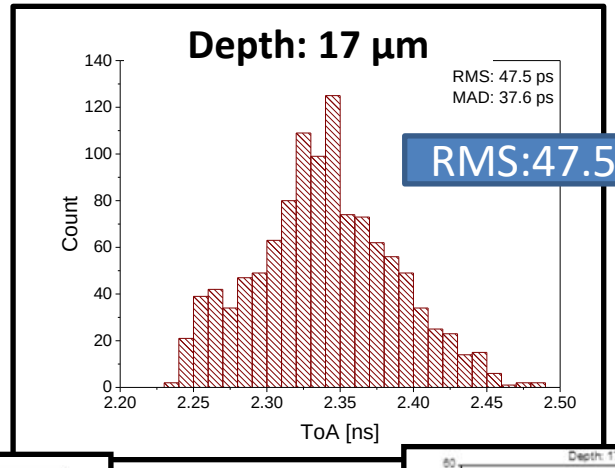


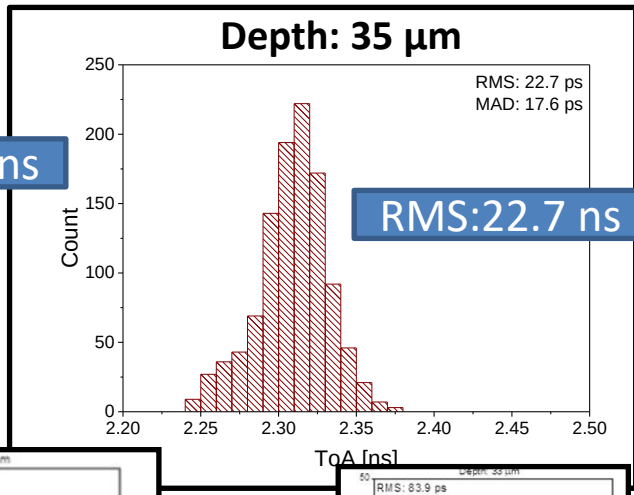


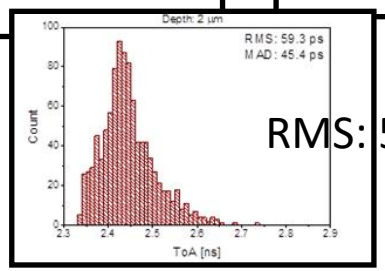
ToA vs. Depth



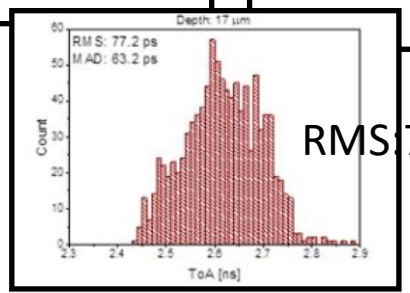




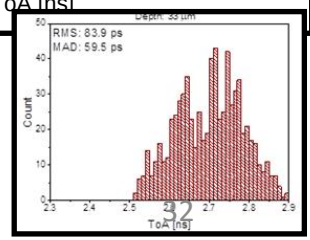




RMS: 59.3 ps

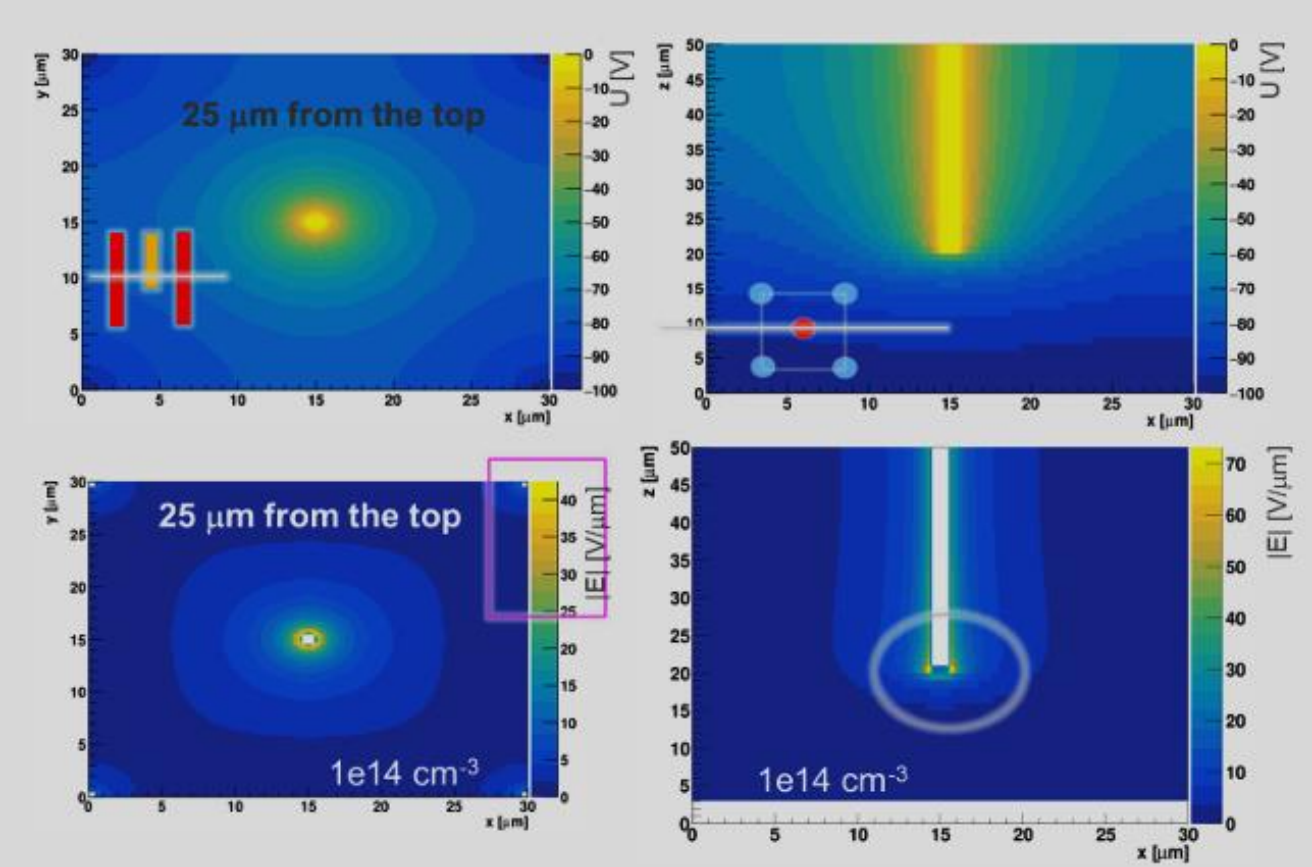


RMS: 77.2 ps



Discussion on “Tip Problem”

REF:
G. Kramberger et al., Explanation of tip performance (WP2 project : Novel silicon 3D-trench pixel detectors based on 8-inch CMOS process (IME)



We have learnt from previous 3D productions that electric field at the tip can be a big problem:

➢ simulations are clear

➢ we have observed increase of noisy pixels in ATLAS and CMS 3D pixel detectors at higher bias voltages what was clearly linked to distance of the tip to the substrate

We assumed that would be even larger problem for small column 3D detector as field focusing will be even larger:

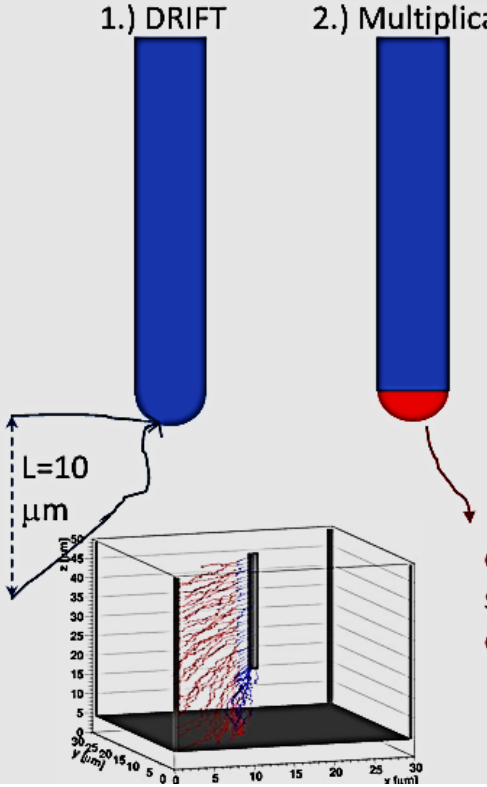
- larger increase of the field wrt to the rest of the column – earlier breakdown
- Lots of variation of the breakdown performance as the tip is hard to control

This turned out not to be the case and sensors perform with controllable gain and I-V/Gain-V performance is similar for all.

The small column – gain stabilizer

REF:
G. Kramberger et al., Explanation of tip performance (WP2 project : Novel silicon 3D-trench pixel detectors based on 8-inch CMOS process (IME)

Uniform performance (within 20%) across the cell. Given that there is a large fraction of carriers ending their drift at the tip one would expect larger difference?



cloud of holes screens the external field

If we assume charges are generated at the tip of the column with the gain=10 The tip is a (half) sphere so in the first approximation an elementary charge at the distance of the tip radia (r=0.5 μm) creates the field of

$$E_0 = \frac{e_0}{4\pi\varepsilon\varepsilon_0 r^2} \sim 5 \cdot 10^{-4}\ \mathrm{V/\mu m}$$

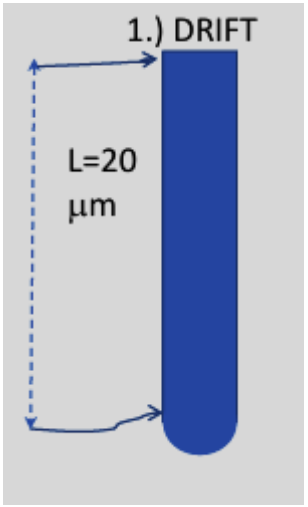
For G=10 and that taking charges from depth of around L=10 μm and all come to the tip at the same time this means multiplied holes

$$E \sim E_0\ 100\ \frac{\mathrm{e-h}}{\mu m}\ \mathrm{G} * \mathrm{L} \sim 5\ \mathrm{V/\mu m} \qquad (v_e >> v_h)$$

Since the impact ionization is strong function of electric field reduction of ~5V/μm significantly reduces the gain!

What about the rest of columns?

REF:
G. Kramberger et al., Explanation of tip performance (WP2 project : Novel silicon 3D-trench pixel detectors based on 8-inch CMOS process (IME)



For the rest of the column we can assume it is a wire (2D problem – approximation only)

$$E_0 = \frac{e_0}{2\pi\varepsilon\varepsilon_0 L\, r} \sim 5 \cdot 10^{-10} \frac{1}{L}\ \mathrm{V}$$

or G=10 and that taking charges from the length of the column of around L=20 μm nd assuming diffusion smears the collection to 0.5 μm (half of the column η=0.5)

$$E \sim E_0\ 100\ \frac{\mathrm{e-h}}{\mu m}\ \frac{G}{\eta} * \mathrm{L} \sim\ 10^{-6}\ \mathrm{V/\mu m}$$

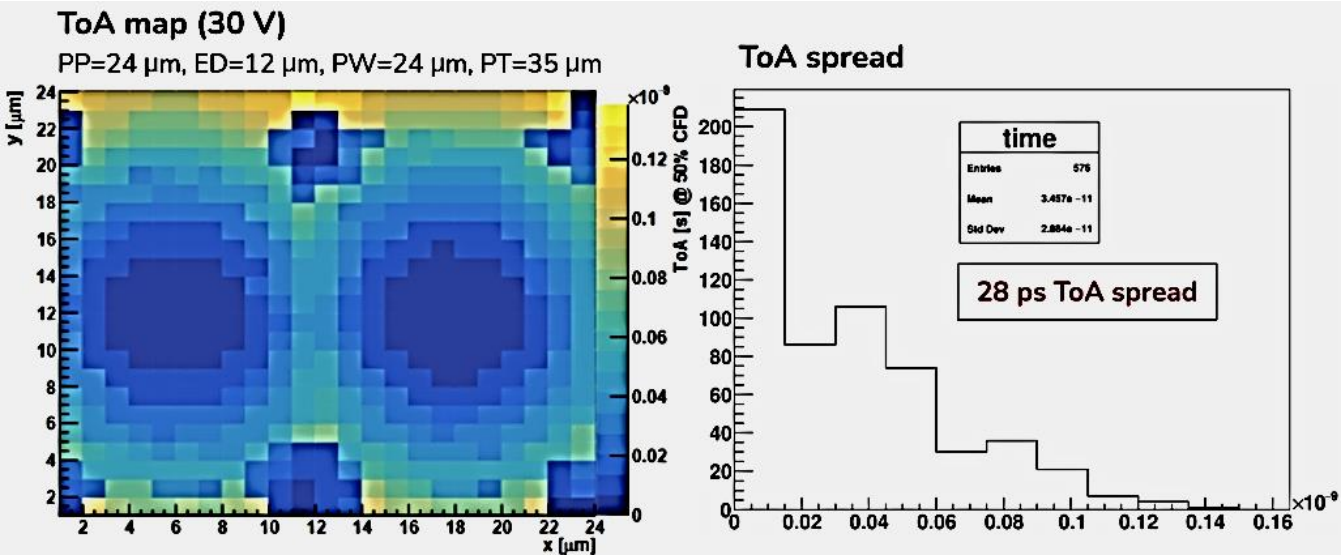
This value here is far from screening – minimal impact of screening to performance along the length of the column!

IDEAL 4D Tracking Device

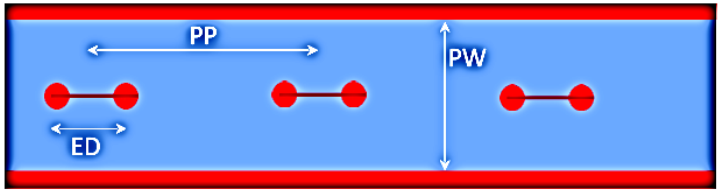
REF: M. Puklavec, Small cell 3D detectors with intrinsic gain, TREDI2026; https://indico.cern.ch/event/1586892/contributions/6846212

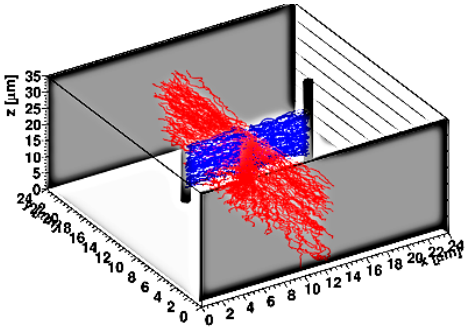
Optimization of geometry to achieve better timing performance is underway

Trench-column 2E/nE devices Timing resolution of 20 ps Improvement of simulation tools



Optimization parameters:
PP – pixel pitch
PW – pixel width
ED – electrode distance
PT - Thickness





Small cell 3D detectors with intrinsic gain

Conclusions

- 8-INCH CMOS TECHNLOGY was successfully applied in 3D Si Trench-Column Device at the IME-CAS in Beijing
- Gain up to 7.5 at a depth of 25 um and a bias of 60 V (near breakdown) and 10 at 62 V is measured using 2PA-TCT set up at the ELI ERIC, ELI Beamlines in Prague.
- REMARK: This is geometrical gain (opposite to gain due to highly doped "gain" layer in LGAD that is planar device).
- ToA and RT increases by increasing the TPA depth as consequence of both gain and screening of el. field by slow moving cloud of holes.
- Device stabilized Itself through self-suppression of gain at the tip of electrode where the focused el field is highest.
- TPA – TCT was successfully applied, limitations understood.
- Gained knowledge will be applied in second Ime-CAS bach production.

- The tip of the column which may be seen as the weakest point regarding the breakdown is actually self stabilized due to field focusing and screening of external field .
- The sample-sample performance variation is so small, and “self-stabilized tip” may explain why the charge collection performance across the cell is so homogenous.
- The same calculation show that this stabilization is not possible for thick columns – observed in ATLAS/CMS noisy pixels.
- The very simple calculation also explains why for the rest of the column screening is not significant.

Thank you for your attention!

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