Balkan Physical Union
BPU12 Congress
National University of Science and Technology POLITEHNICA Bucharest
July 8 to July 12, 2025

3D SI DEVICES & 3D TIMING STUDY USING 2PA-TCT AND 3PA-TCT

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DRD3

Content

- Timing detectors and 4D tracking in HEP (Quick introduction)
- 3D Si devices (motivation/challinge)
- Two-Photon and Three – Photon Absorption Transient Current Technique as the state–of-the art 3D characterization tools

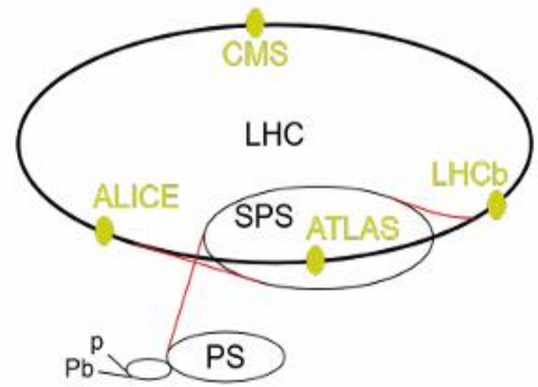
This research was funded by Montenegro Ministry of Education, Science and Innovation through the project ''TAIDA: Advancement and Innovation for Detectors at Accelerators'' (Contract No. 0402-082/23- 1740/5).

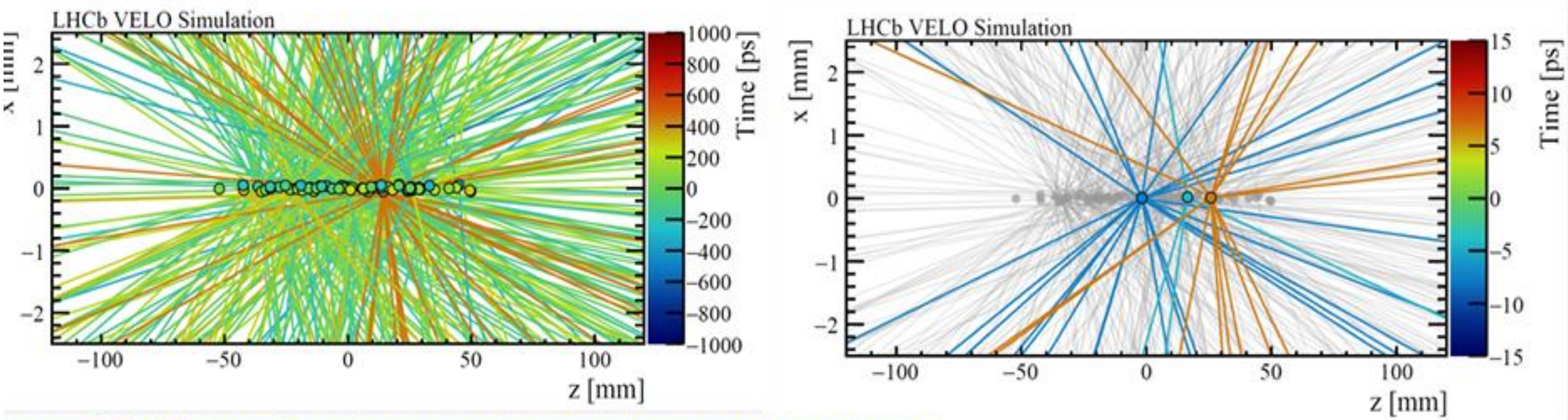
The authors acknowledge the use of the ELI Beamlines Facility, Extreme Light Infrastructure ERIC.

Requirements for NEW DETECTORS

Requirement for new detectors

- Upgrade Large Hadron Collider 2026-2030
- Increase in number of events per bunch crossing
- To distinguish quasi simultaneous collisions time information needed
- Study fast sensors! (3D, LGAD, **iLGAD**)
- Focus on sensors in combination with Timepix4





Geertsema, R. E. (2024). Chasing time: Characterisation and application of precision temporal measurements with silicon pixel detectors.

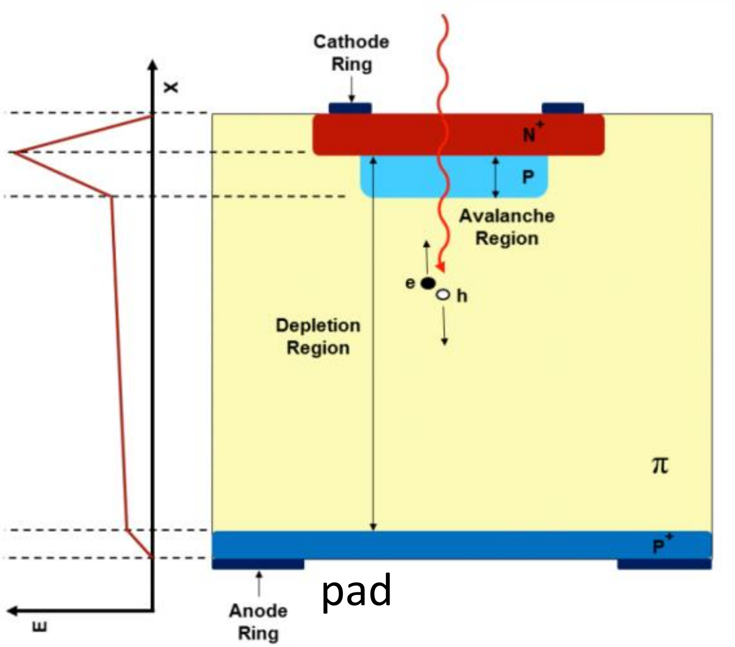
LOW GAIN AVALANCHE DETECTOR – LGAD (silicon based)

- ✓ Baseline sensor technology for timing detectors at ATLAS and CMS\
- ✓ Excellent timing (30 ps)

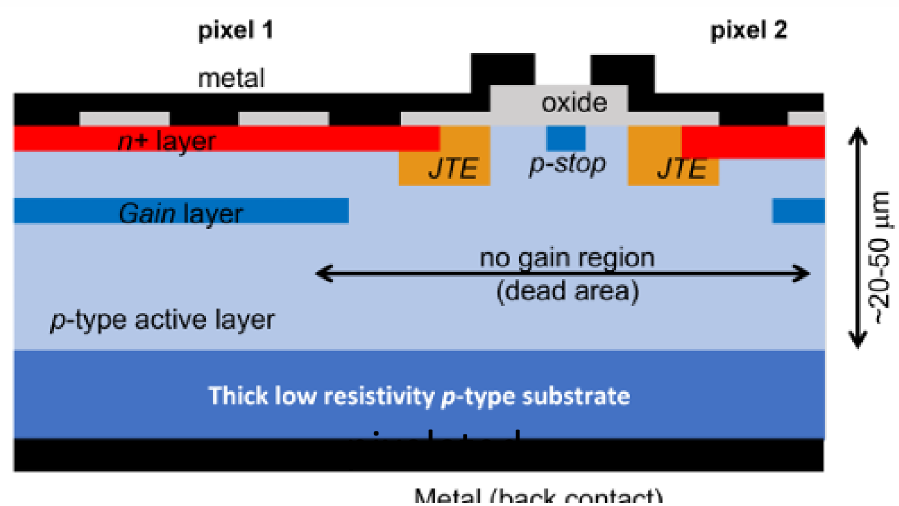
Problems:

- Fill factor (not sufficient for 3D tracking
- Lost of gain at high fluencies > 2.6 neq/cm^2

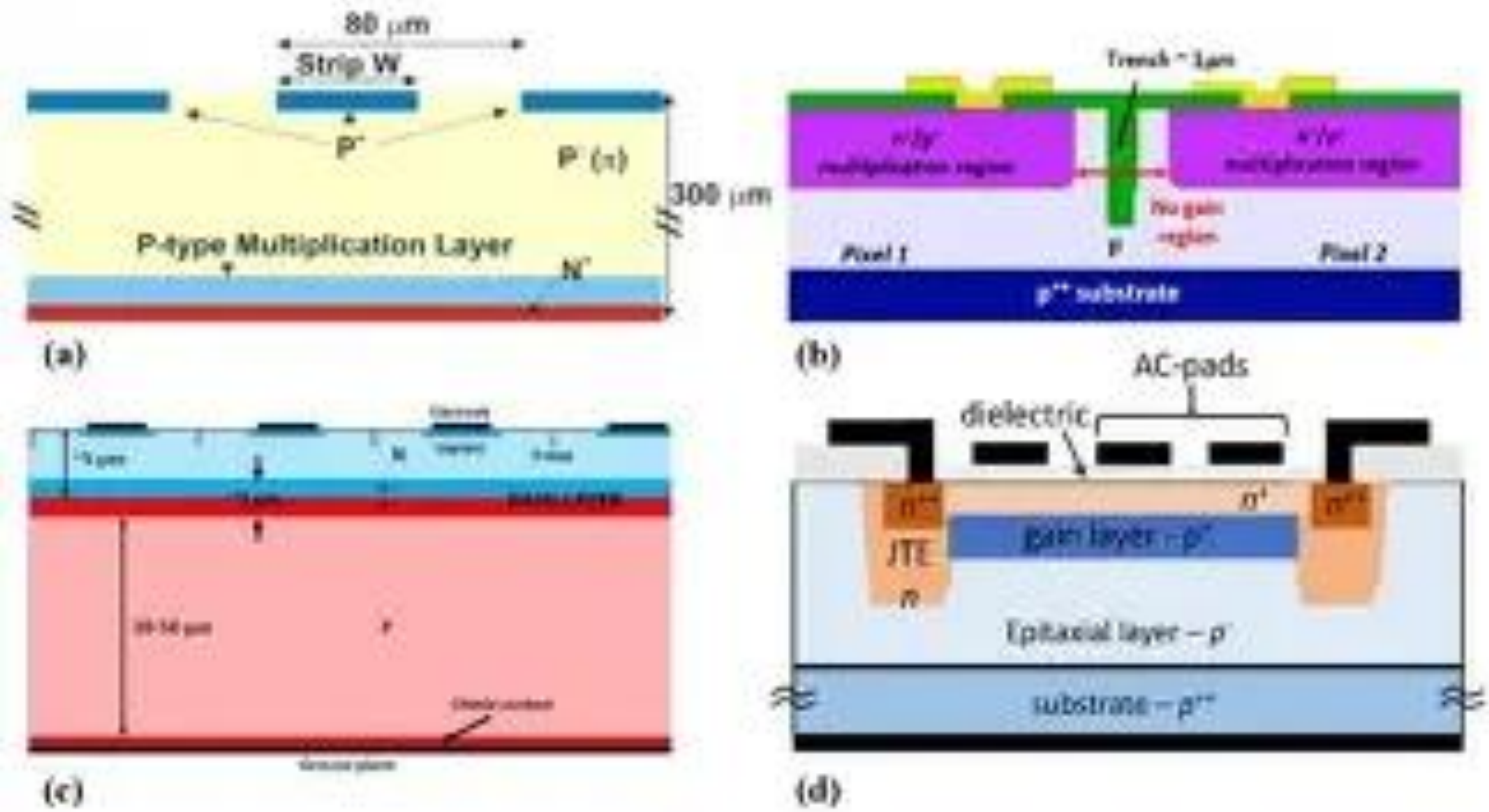
Cross section LGAD

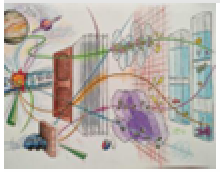


Breakdown bias limited by SEB (single event burnout



Family of LGADs

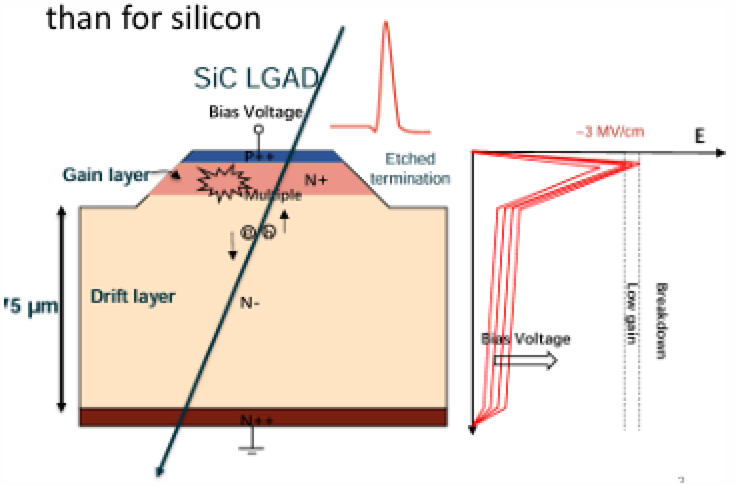


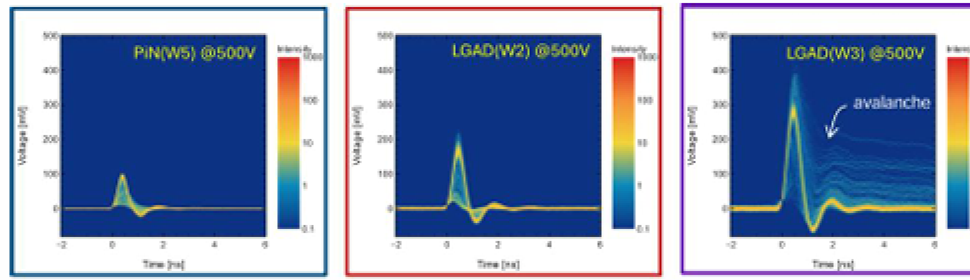


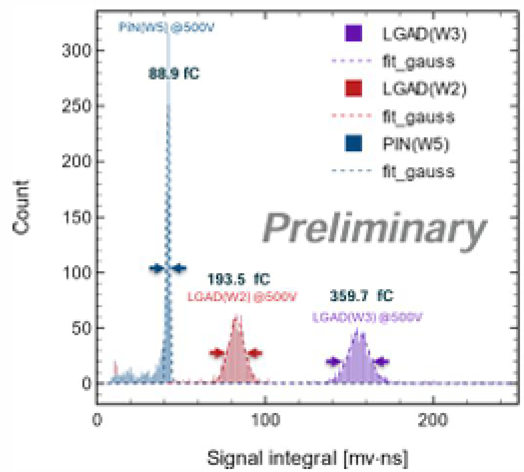
Silicon Carbide LGADs

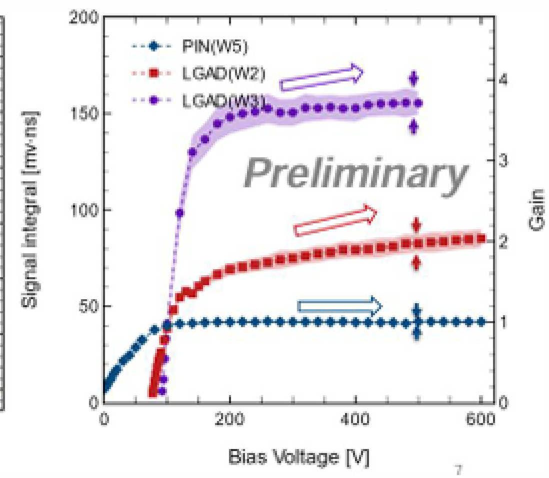
LBNL & NCSU

Quite different processing – but wafers are available
- not the same implant depth as for Si)
- Apart from JTE and **bevel-ed** edge termination
- Doping levels of gain layer an order of magnitude higher than for silicon







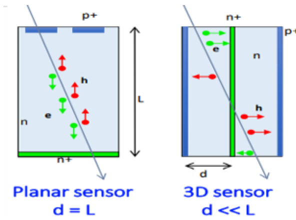


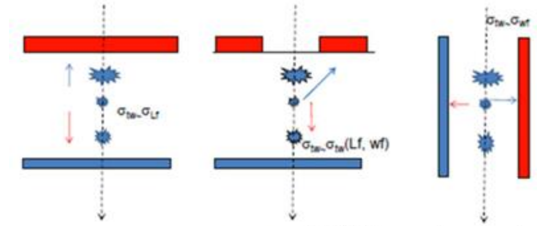
Note – impact ionization is larger for holes than for electrons in SiC (p^{++}-n^{+}-n device)

Why to study 3D Si?

Using 3D sensors is a way to mitigate two main obstacles of present day LGADs:

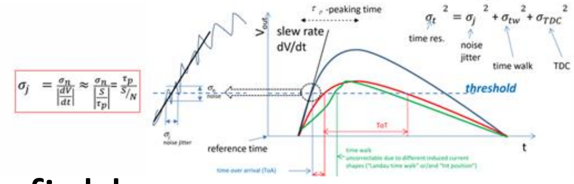
- ➢ radiation hardness and
- ➢ fill factor.





Constraints in timing?

- ➢ Geometry (configuration of 3D electrodes)
- ➢ EwE (weighting field/distortion component)
- ➢ Variation in ToA is due to the variation in weighting field



$$\boxed{\sigma_{tw}^2=\sigma_{wf}^2+\sigma_{lf}^2}$$

How to study timing properties resolved in space (spatially resolved ToA)?

- ➢ we can study timing properties as function of position of charge injection

TPA

- ➢ allows localized charge injection not only in x,y , but also in z

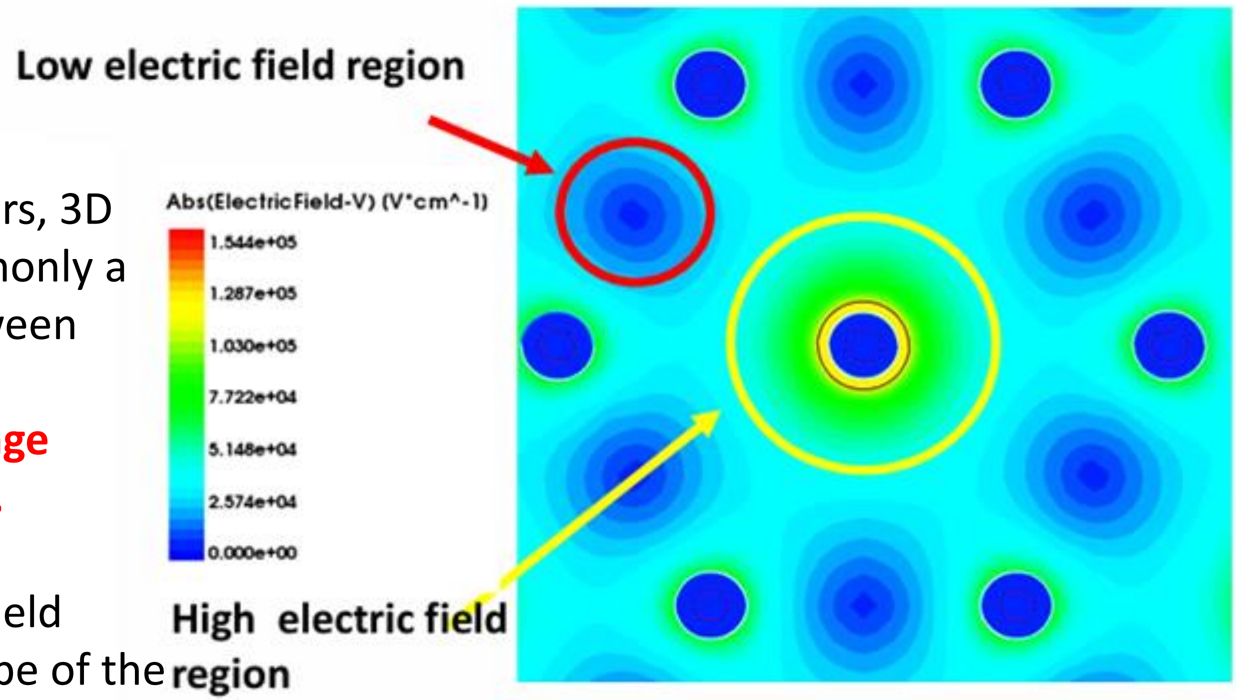
Better way to study irradiated 3D Si?

- ➢ 3PA (by increasing fluency → SPA contribution increases in 2PA→ 3PA could be better tool)

Non-uniformity of weighting field

- Unlike planar silicon sensors, 3D sensors do not have commonly a uniform electric field between their electrodes
- **The electric field can change much from point to point.**

- Effects of a non uniform field influence strongly the shape of the output current signal, following Ramo theorem, which also is a crucial factor for a fast timing sensor.



↑ Electric field map for a hexagonal pixel with a electrode geometry of 5 corner electrodes for electric field bias and a central diode electrode for signal output. Between same kind electrodes the field goes down to 0 V/cm which is a critical factor for timing

$$\boxed{i_1 = q_m \nabla\left(\frac{V_m}{V_1}\right) \cdot \mathbf{v} = -q_m \mathbf{E}_w \cdot \mathbf{v}}$$

What are the major research topics in this presentation?

2PA

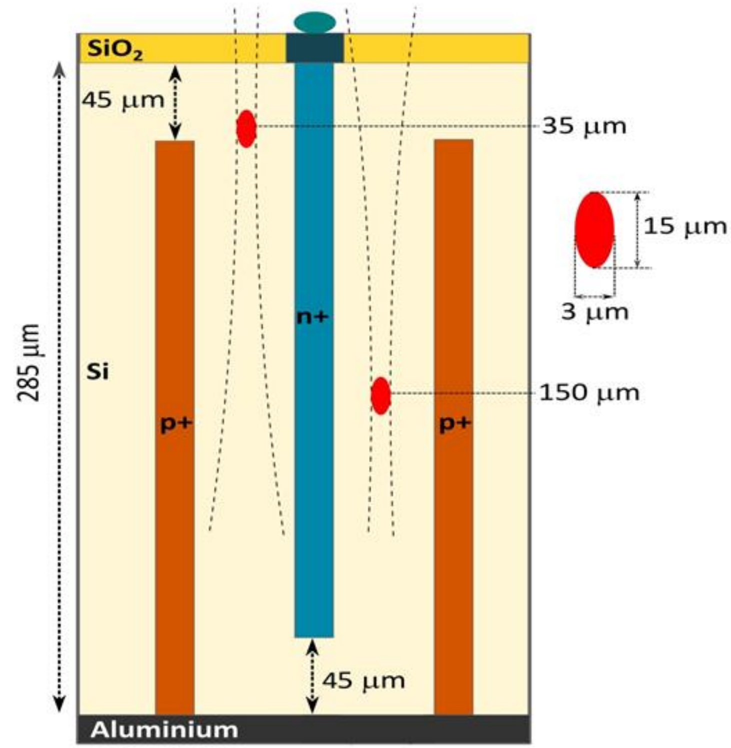
1

- Large 3D Si structures
  - 10x10 Square 3D cells
  - 5x5 Hex 3D cells

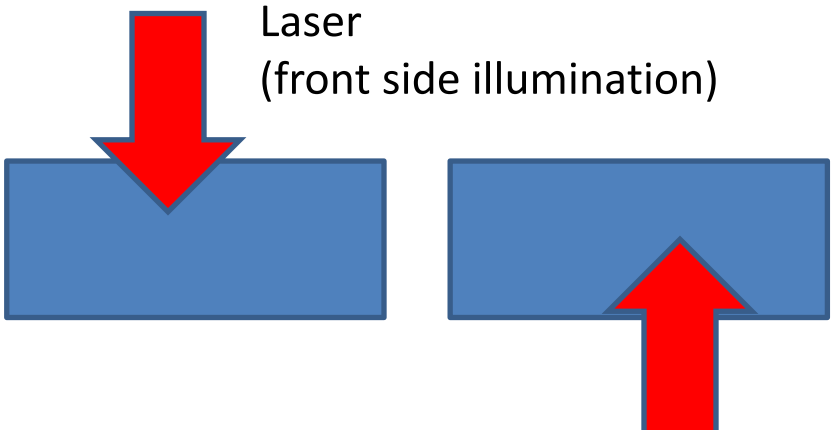
2

- Single cells
  - 1x cell
  - 2x-cells

2PA



Laser
(front side illumination)

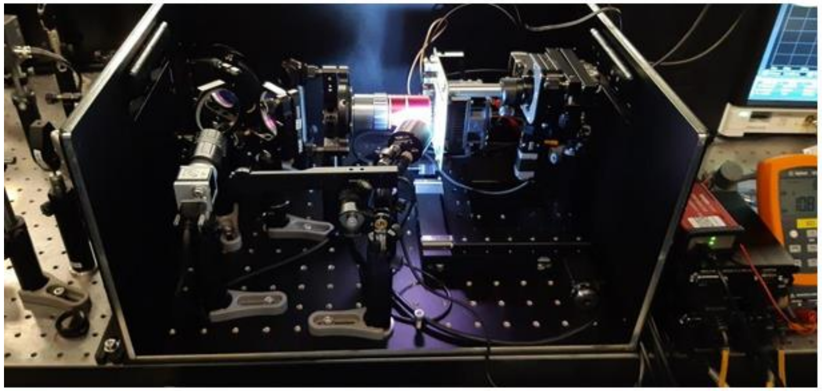


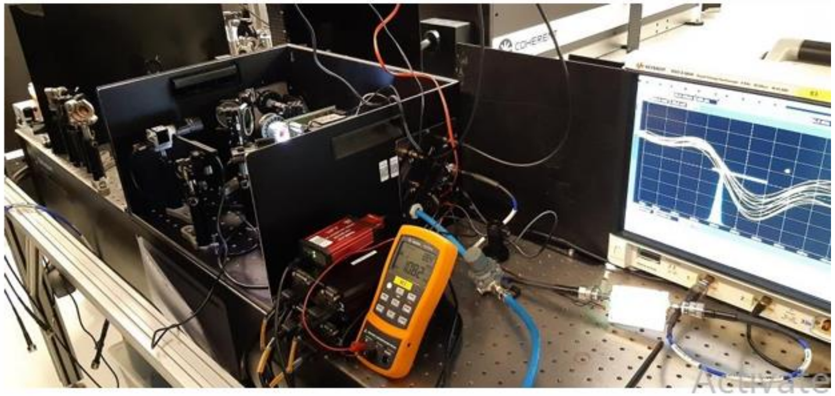
Laser
(back side illumination)

3

3PA

EXPERIMENT: Campaign at ELI

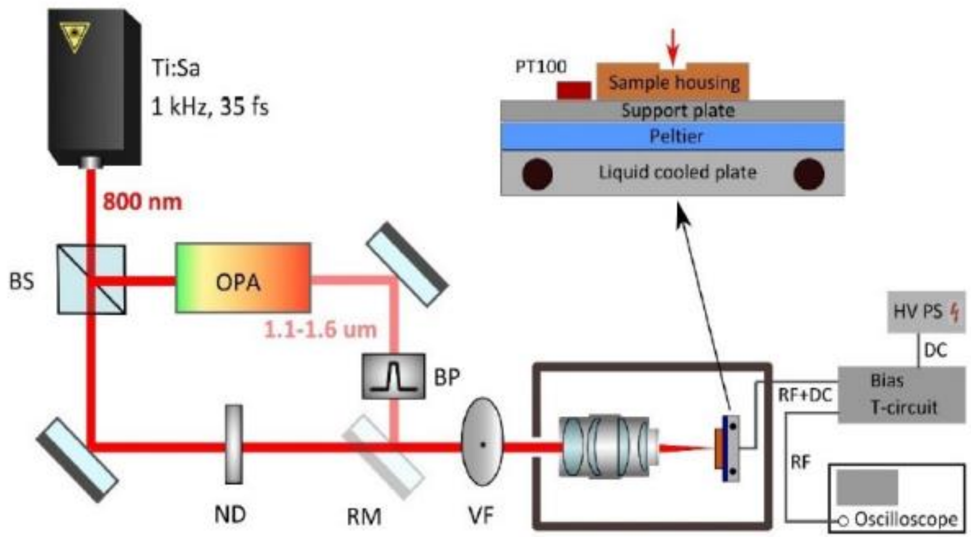




TCT set up at ELI ERIC, ELI Beamlines

TCT at ELI

Originally designed and built during COVID for LGAD SEB study!
Very successful campaign lasted 2 years (building the exp station , verification, measurements).



G. Laštovička-Medin et al. "Femtosecond laser studies of the single event effects in low gain avalanche detectors and PINs at ELI beamlines." *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 1041 (2022): 167321.

Transient Current Technique (TCT)

- Operational modes: Single and Two photon absorption (SPA and TPA)
- Wavelength: 800 nm (SPA), 1550 nm (TPA)
- Pulse energy on sample: Variable by ND filters (accuracy: 0.2 pJ)
- Focus waist radius: 0.85 um (SPA), 1.5 um (TPA)
- Rayleigh length: 3.31 um (SPA), 7.74 um (TPA)
- Sample cooling: Down to -25 deg. C
- Sample movement: X, Y, Z
- Bias voltage: variable, up to >720 V
- Detection: 6 GHz (20 GSa) oscilloscope and leakage current measurement (accuracy: 0.1 uA)

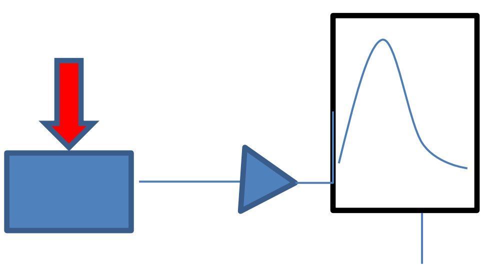
Jitter on Triggering Signal

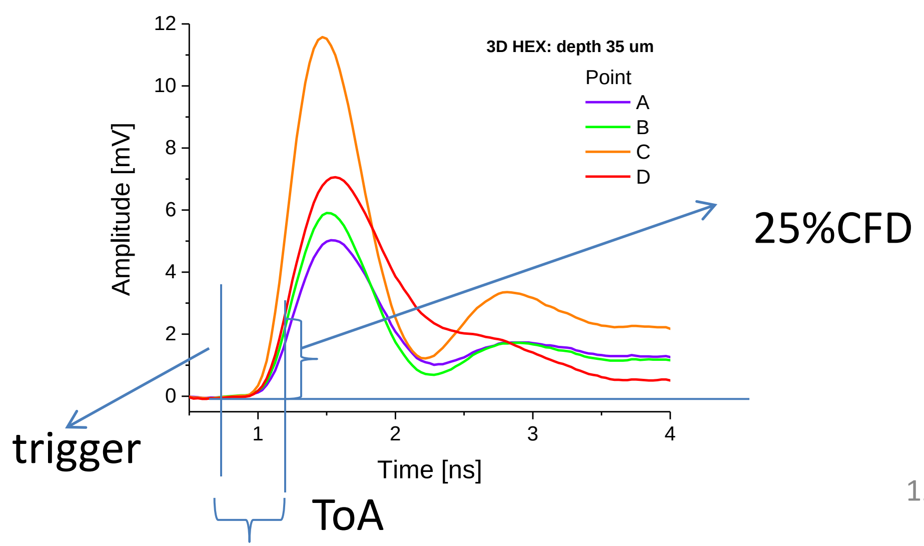
In our measurements performed at ELI we split the laser pulse:

- one part to fast InGaAs photodiode (as trigger), second part to investigated detector.
- Then, only one source of jitter is. It comes from the InGaAs photodiode and it is it's internal jitter which is much better than laser SDG signal.

We used fast InGaAs photodiode (ET-3000 from Eotech) as trigger. Manufacturer (Eotech) doesn't provide information on the jitter **but the rising edge we use for triggering has rise time < 17 ps so the jitter should be significantly better than this value.**

A very accurate oscilloscope is used so signals of few mV were recorded





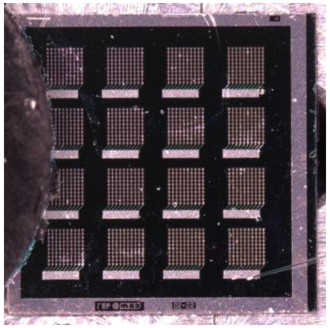
1ST PART: MULTI-CELL 3D SI STRUCTURES

100 3D SQUARE CELLS, 25 HEX 3D CELLS

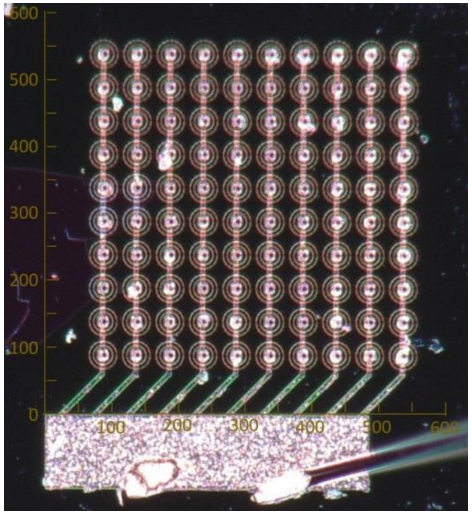
ALL CELLS ARE BIASED

Single dice =
6x4 array of devices

6-x SQUARE



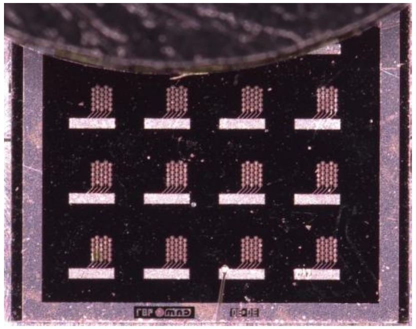
Zoom of wirebonded sensor (with scale in µm)



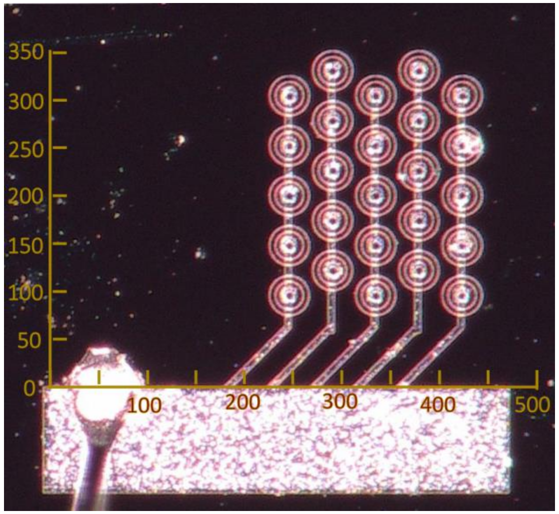
Each device has an array of 10x10 cells.

Single dice =
4x3 array of devices

4-x HEX



Zoom of wirebonded sensor (with scale in µm)

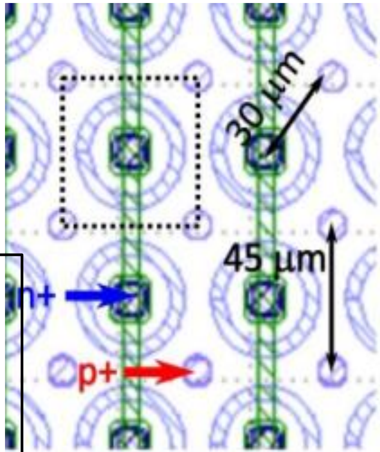


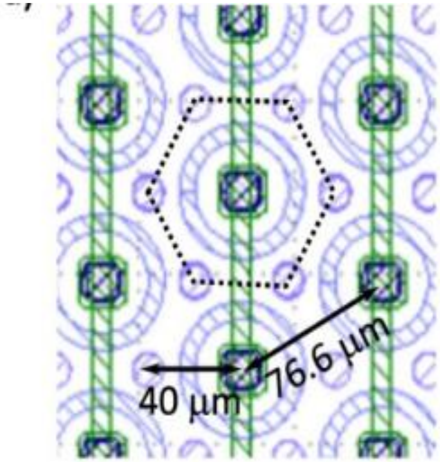
Each device has an array of 5x5 cells.

Main goal: to investigate differences in signal parameters in different areas in the sensor

- Charge collection
- Rise time (10-90%)
- Time of arrival (25%)

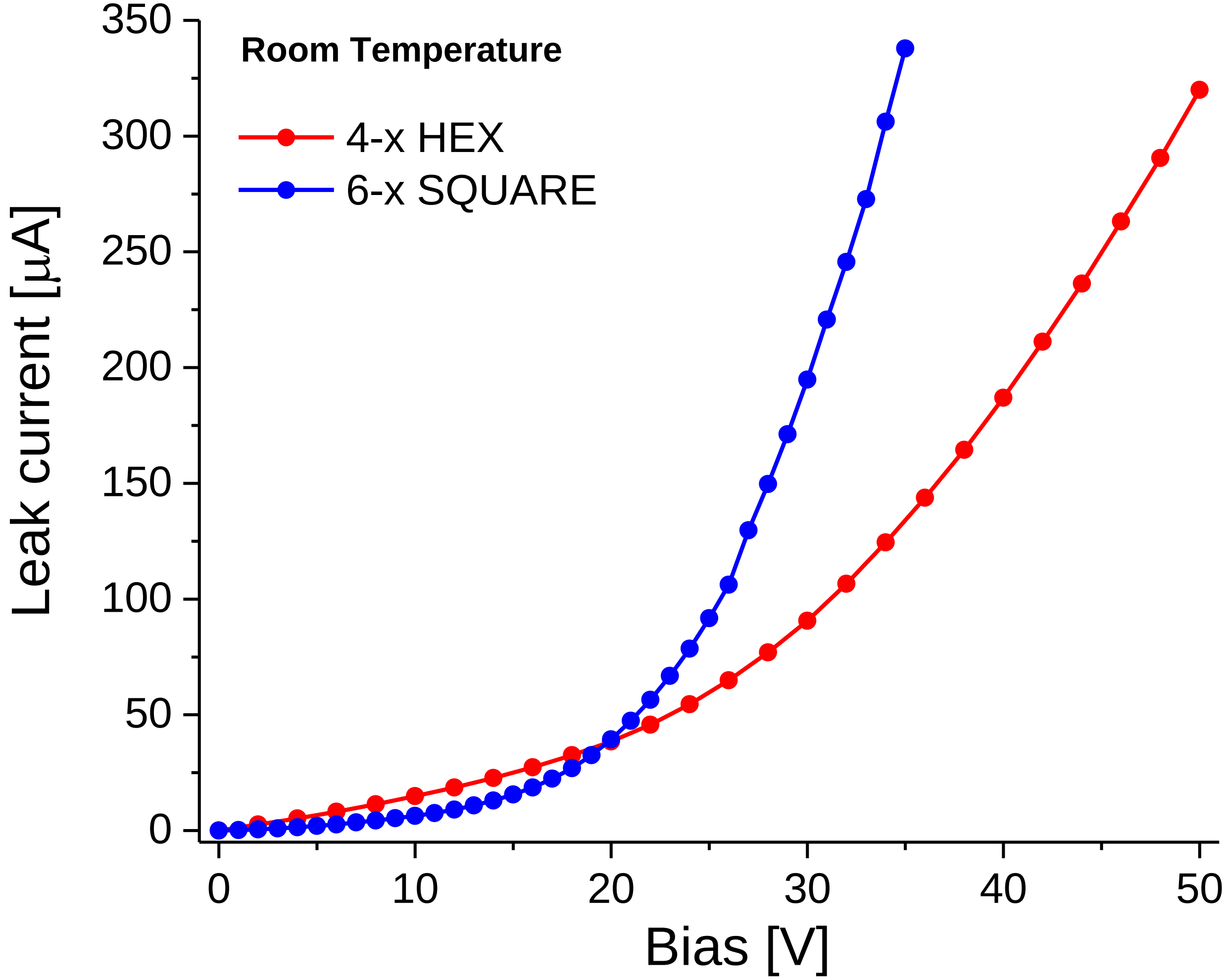
✓ sensor pitch: 55 µm
✓ sensor thickness: 285 µm
✓ column diameter: 10 µm
✓ column gap: 45 µm





Leakage current and bias limit

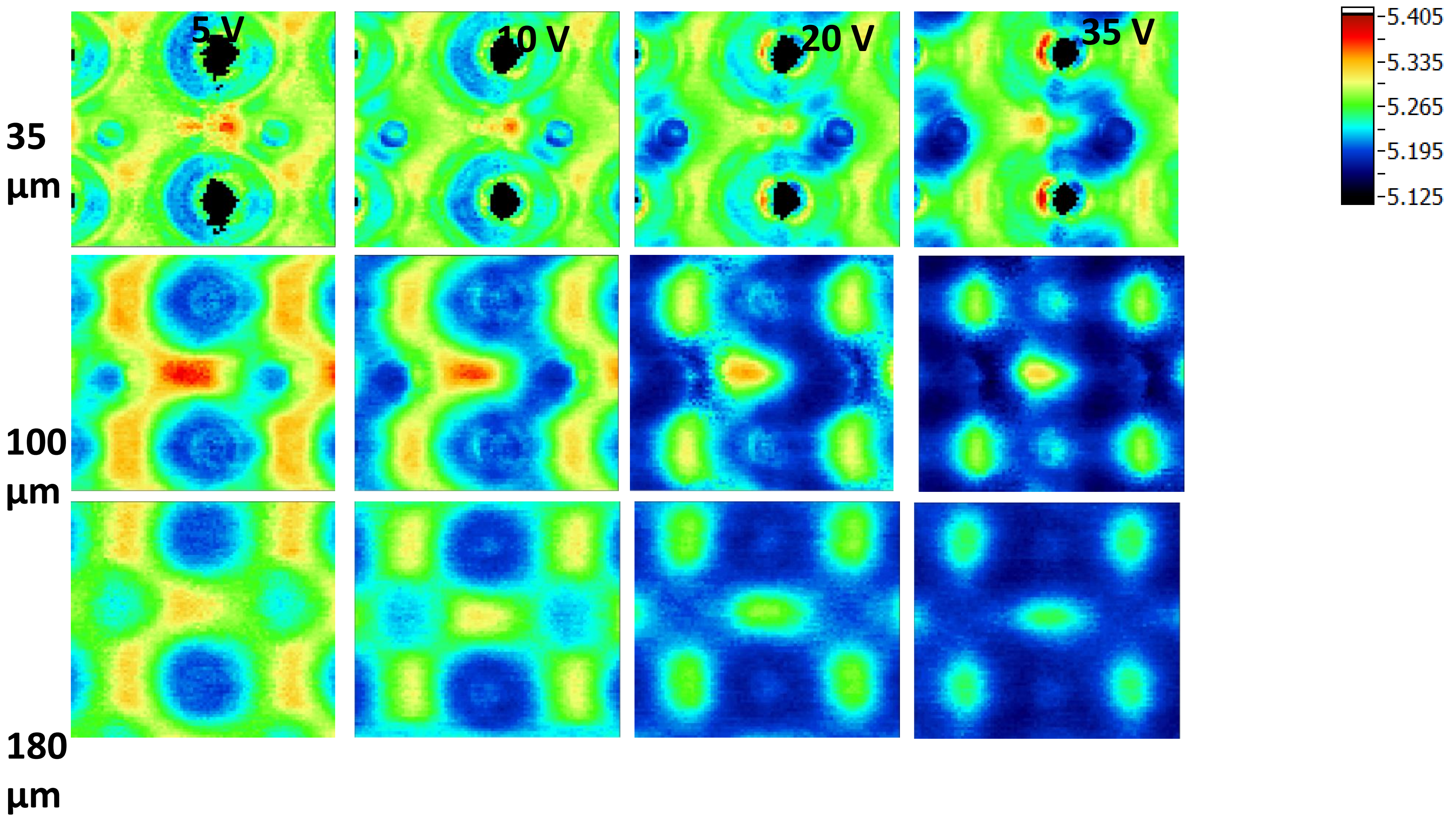
Maximal bias limited by IV curves



SQUARE ToA

ToA vs bias

Pulse energy: 200 pJ

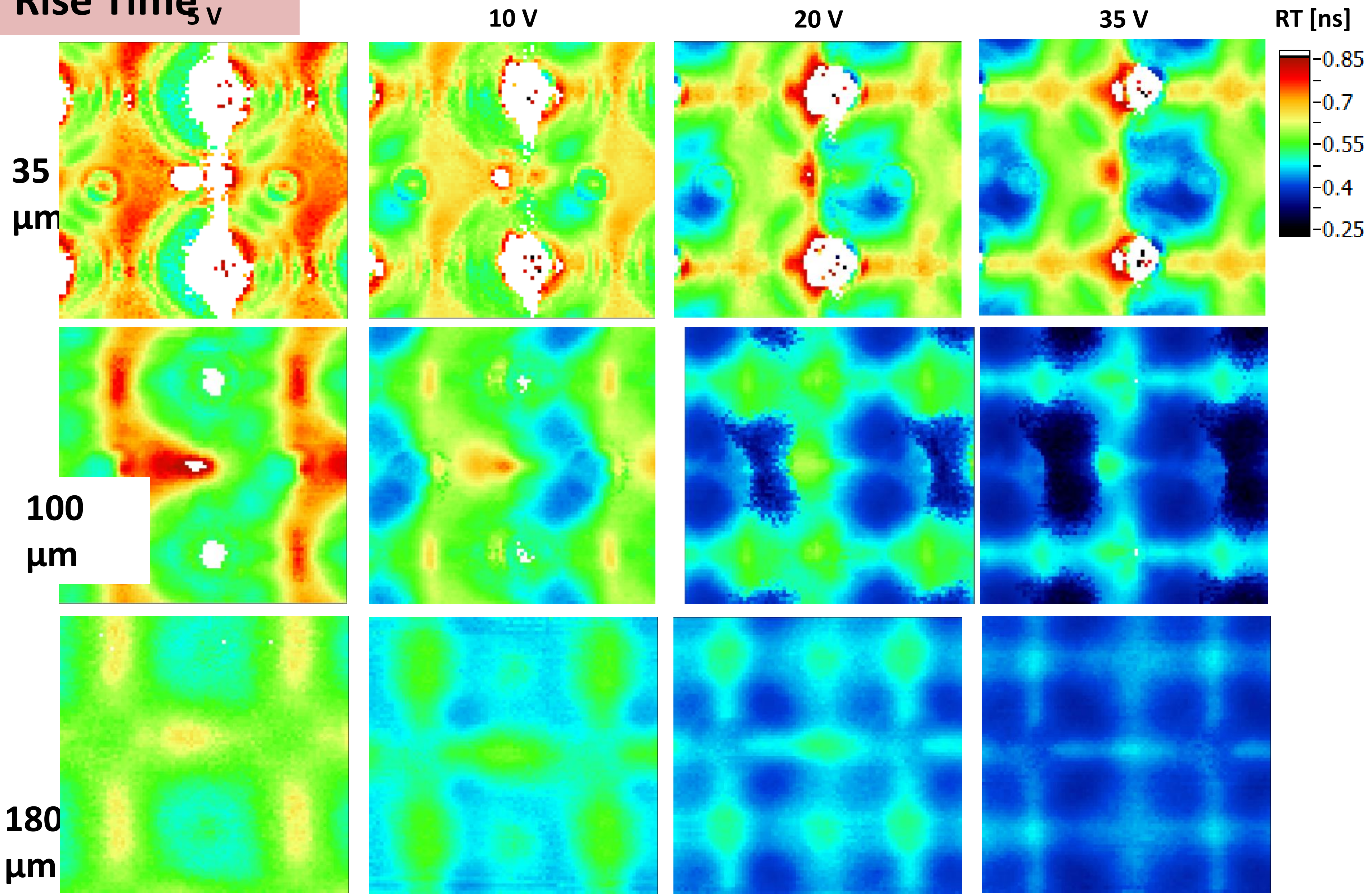


At 36 um we are just above p+ (by increasing the bias, holes are more faster colelcted by p+!

SQUARE
Rise Time

Rise Time vs bias

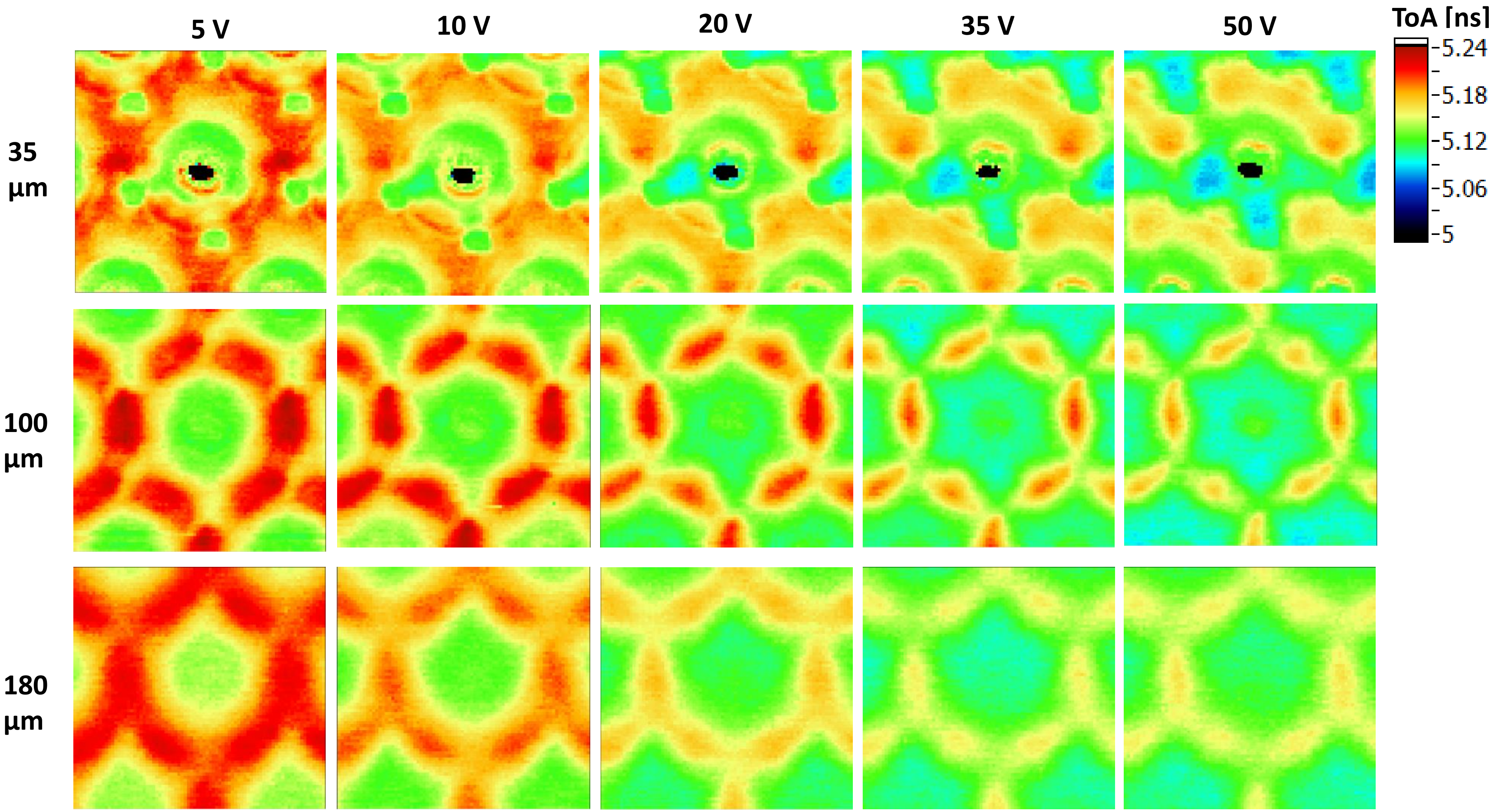
Pulse energy: 200 pJ



HEX ToA

ToA vs bias

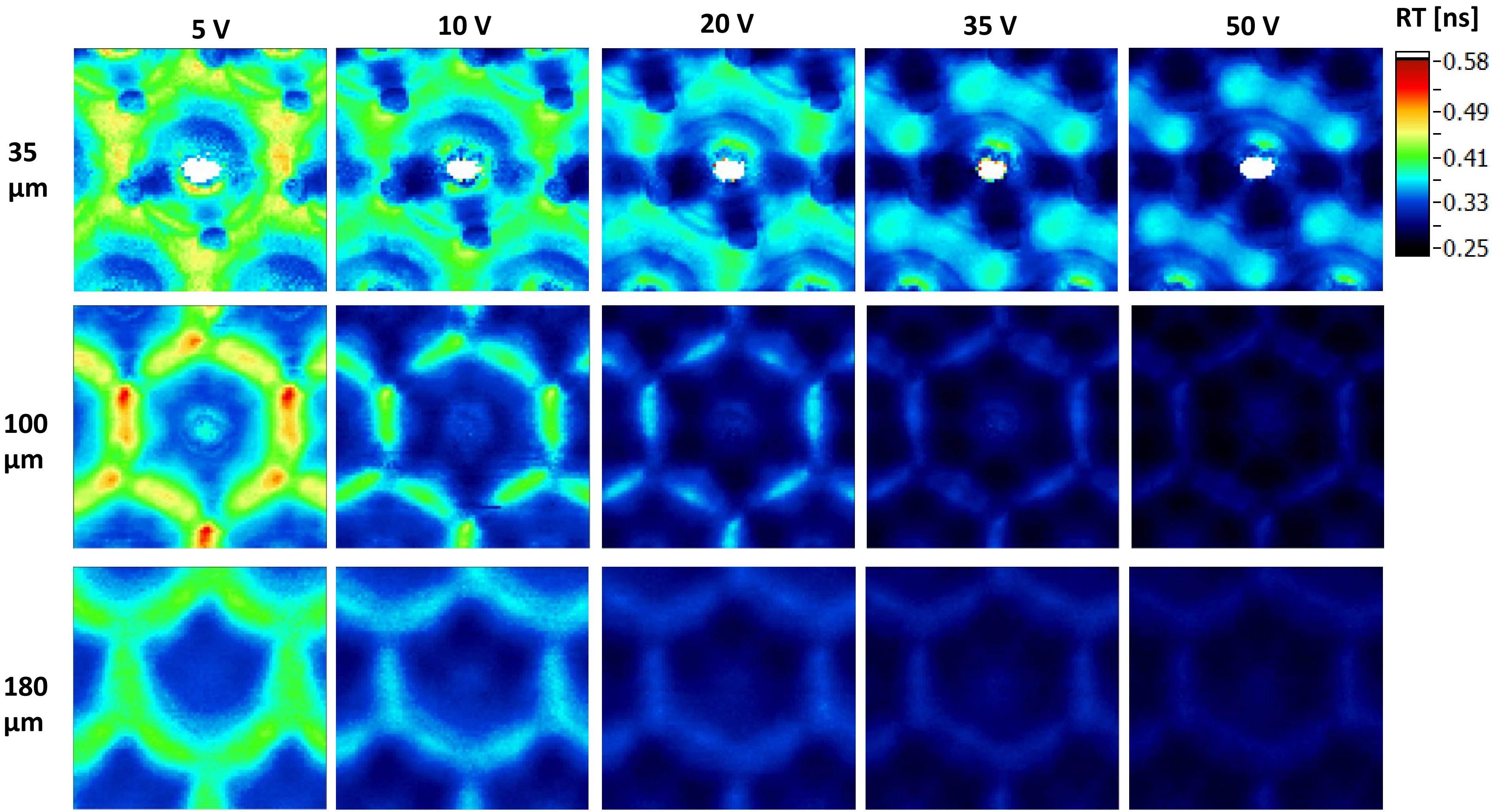
Pulse energy: 200 pJ



HEX Rise Time

Rise Time vs bias

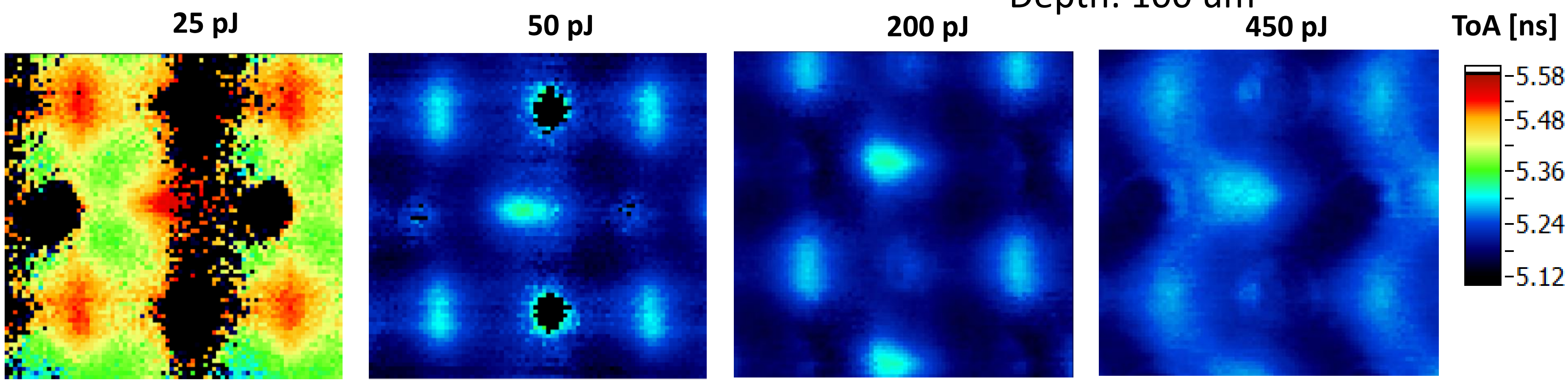
Pulse energy: 200 pJ



SQUARE ToA

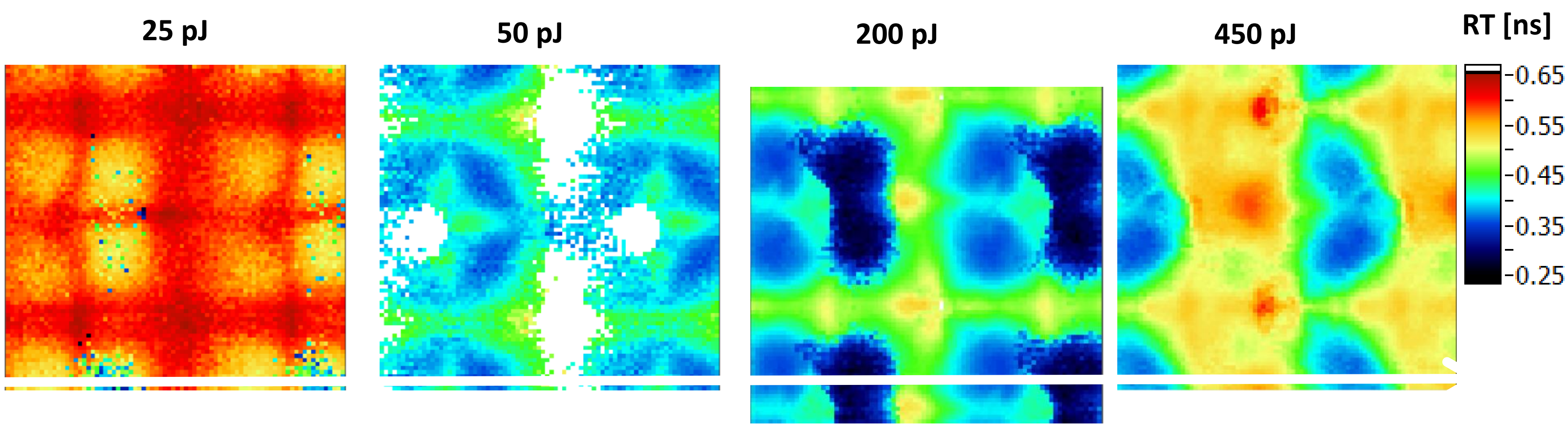
ToA vs power

Bias: 35 V
Depth: 100 um



SQUARE Rise Time

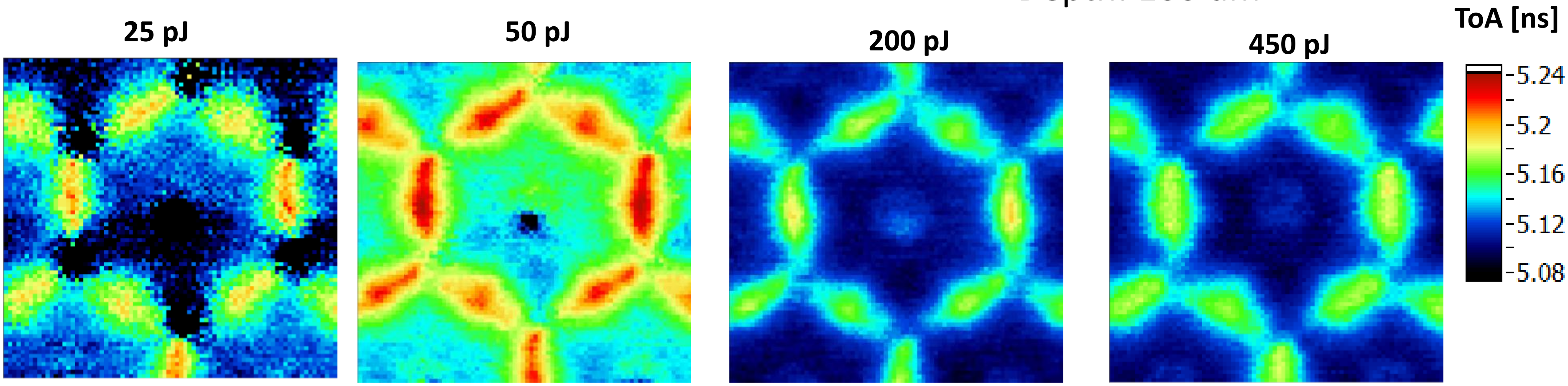
Rise Time vs power



HEX ToA

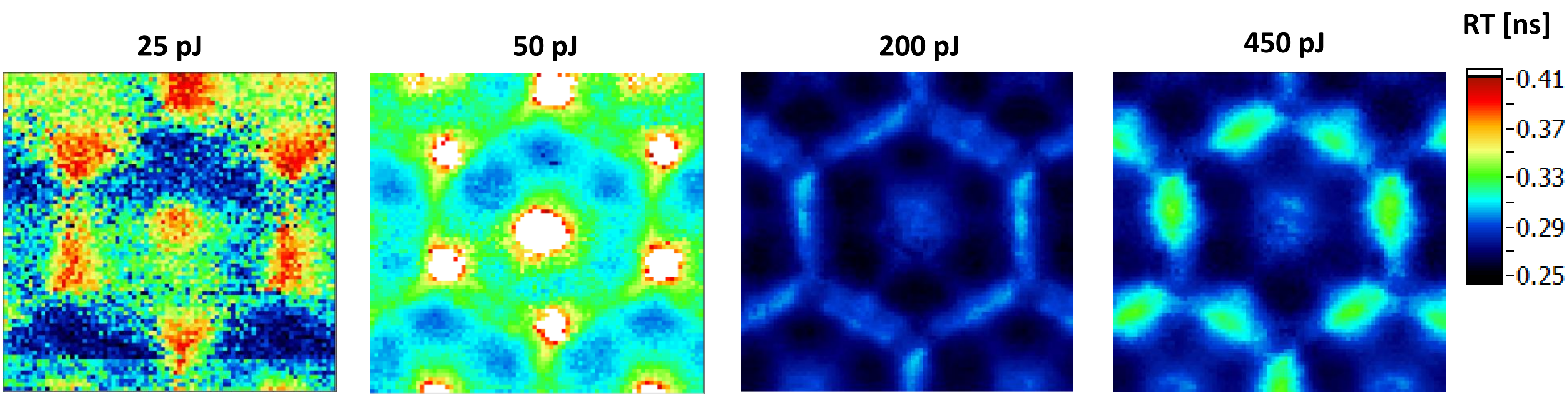
ToA vs power

Bias: 35 V
Depth: 100 um



HEX Rise Time

Rise Time vs power

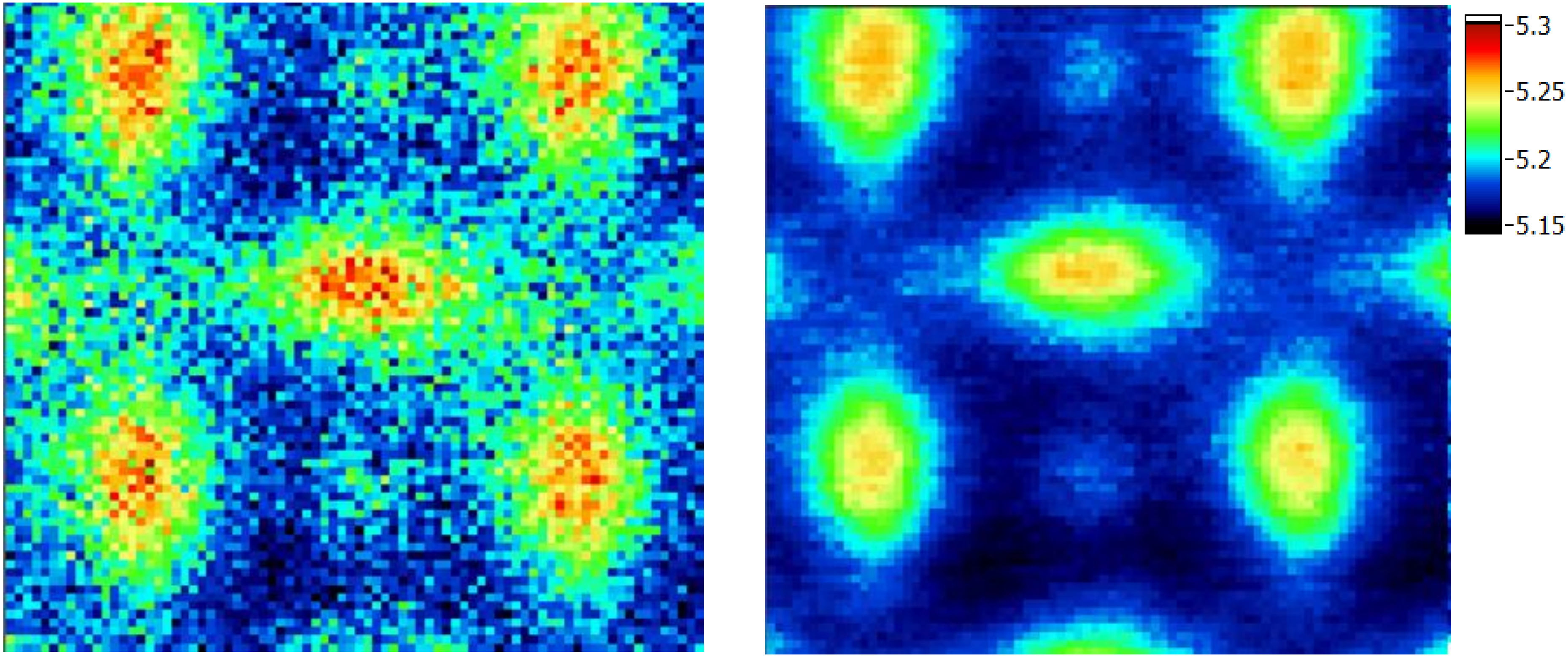


SQUARE ToA

Averaging effect

1 shot

256 shot

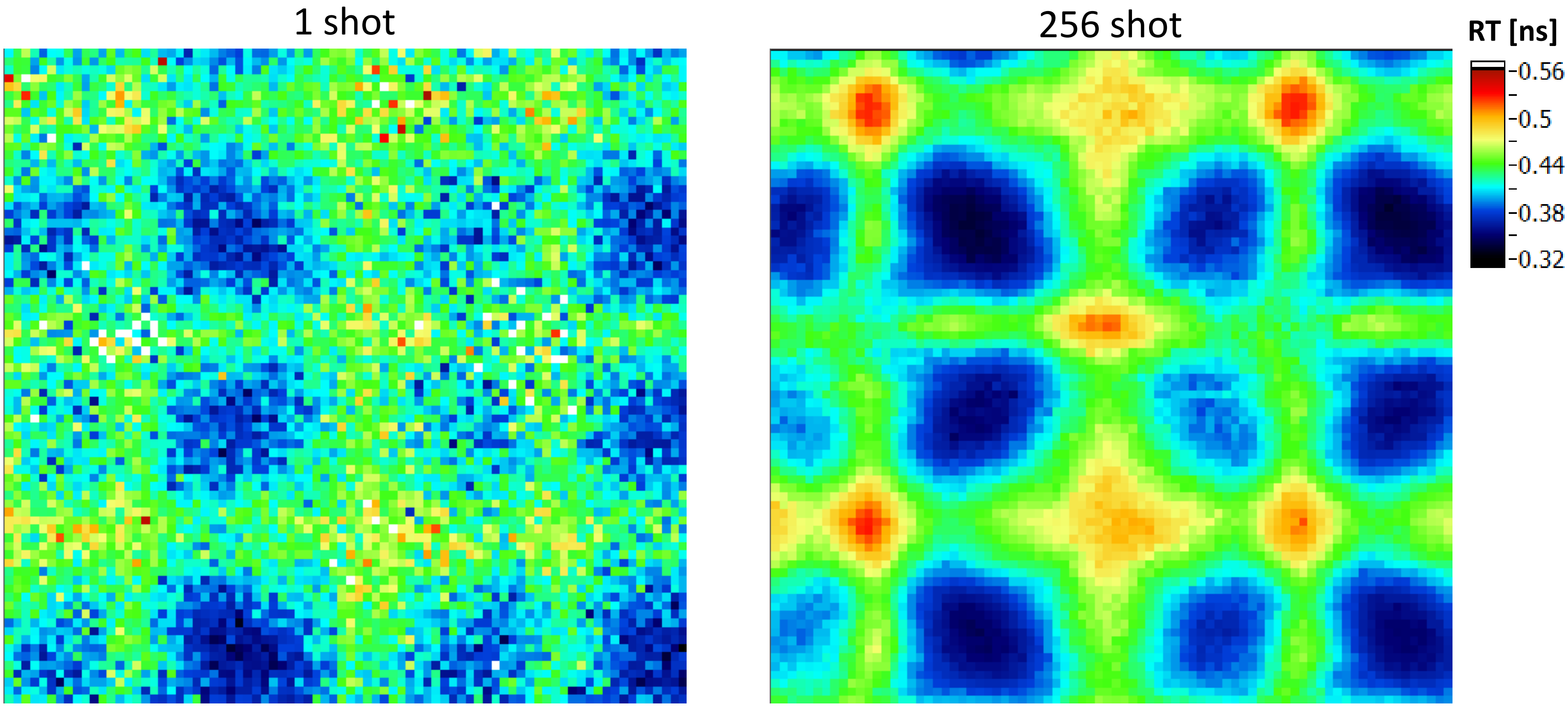


RMS: 26.0 ps

RMS: 21.4 ps

Depth: 180 um
Bias: 35 V
Pulse energy: 200 pJ

Averaging effect



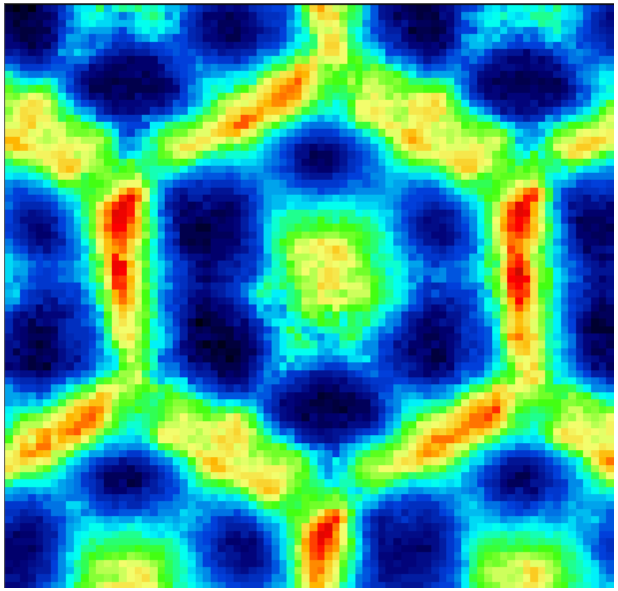
RMS: 29.4 ps

RMS: 22.9 ps

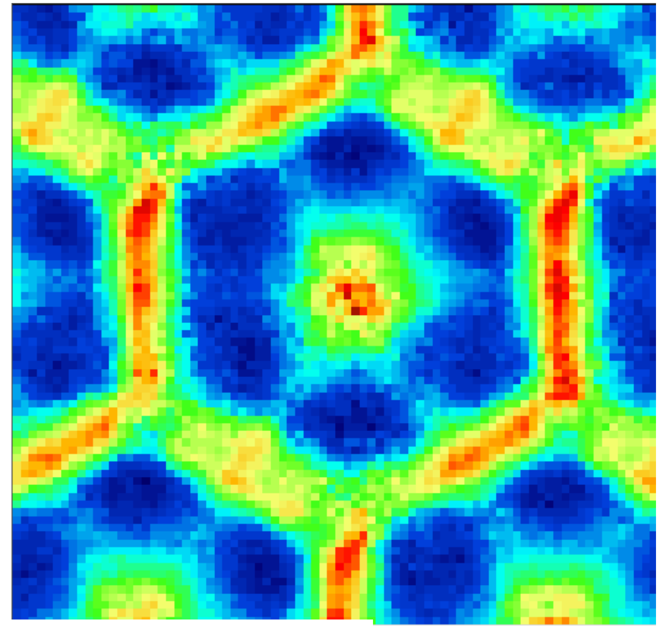
Depth: 180 um
Bias: 35 V
Pulse energy: 200 pJ

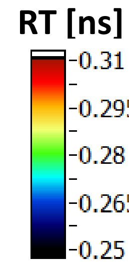
Amplifier effect

No amplifier

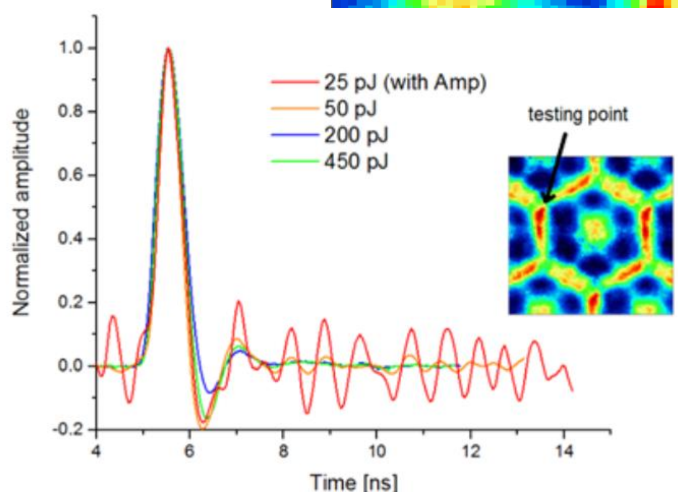


Amplifier 35 dB

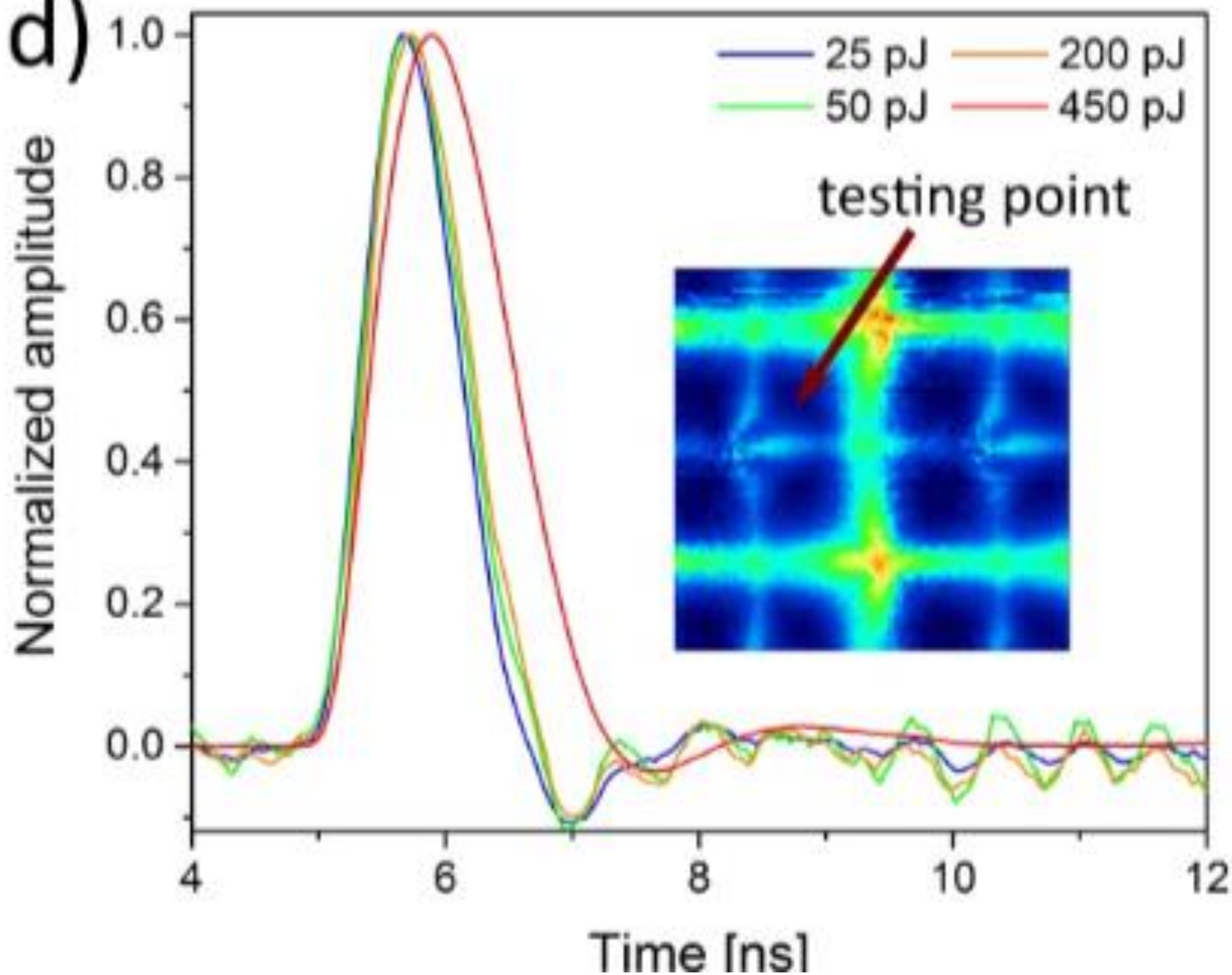




RMS: 11.4 ps



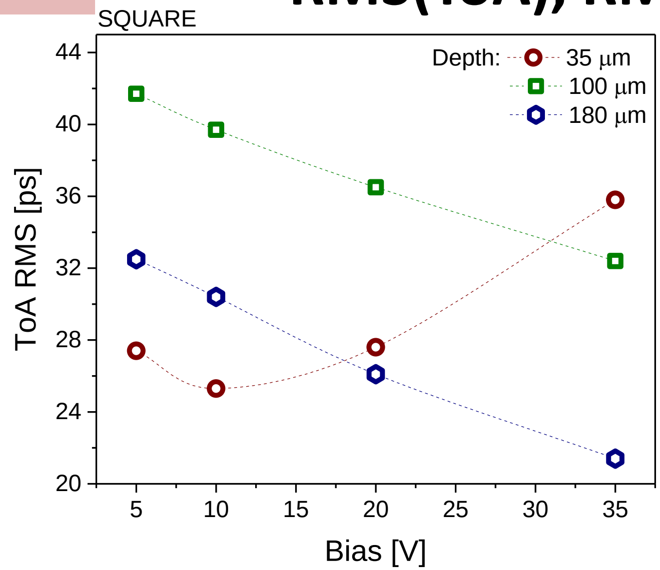
Depth: 100 um
Bias: 50 V
Pulse energy: 200 pJ

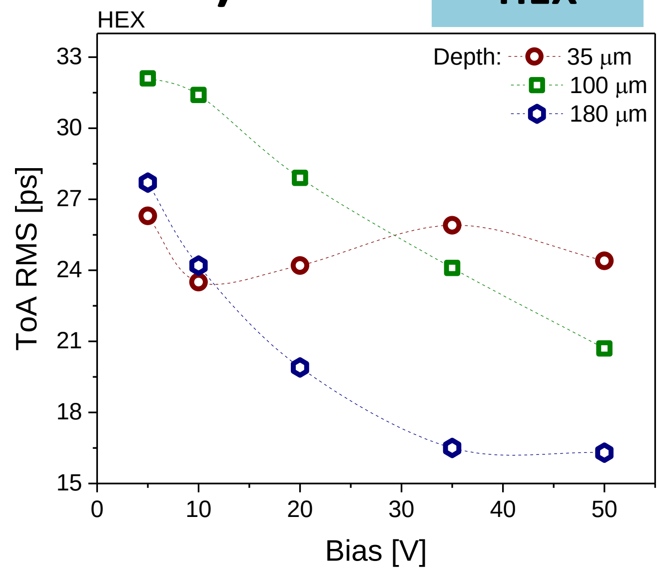

d)
1.0
0.8
0.6
0.4
0.2
0.0
Normalized amplitude
4
6
8
10
12
Time [ns]
25 pJ
200 pJ
50 pJ
450 pJ
testing point

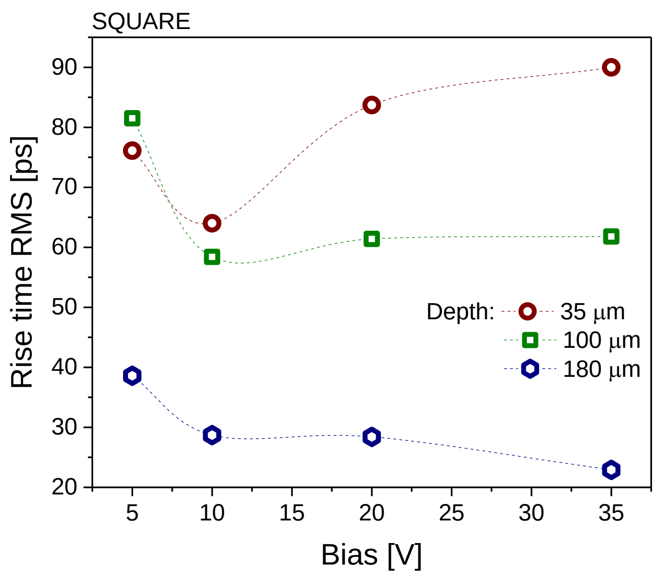
Bias dependence at different depths: RMS(ToA), RMS(Rise Time)

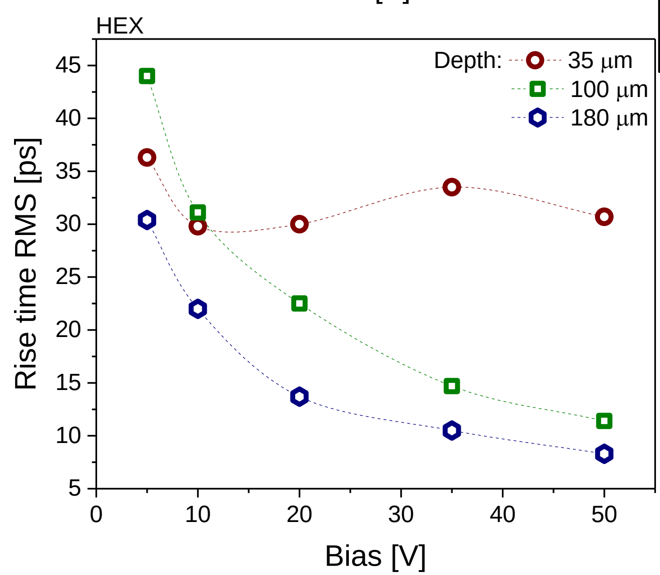
SQUARE

HEX









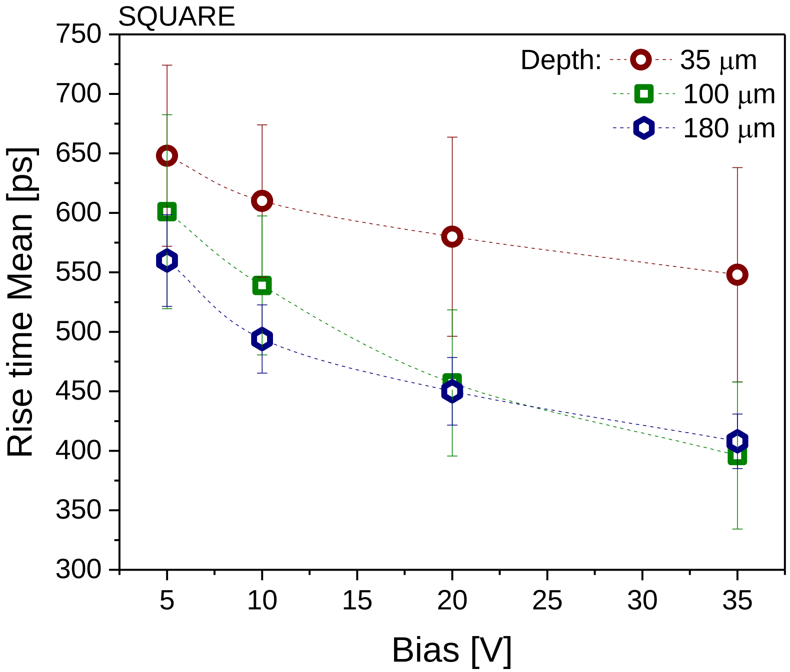
Observations

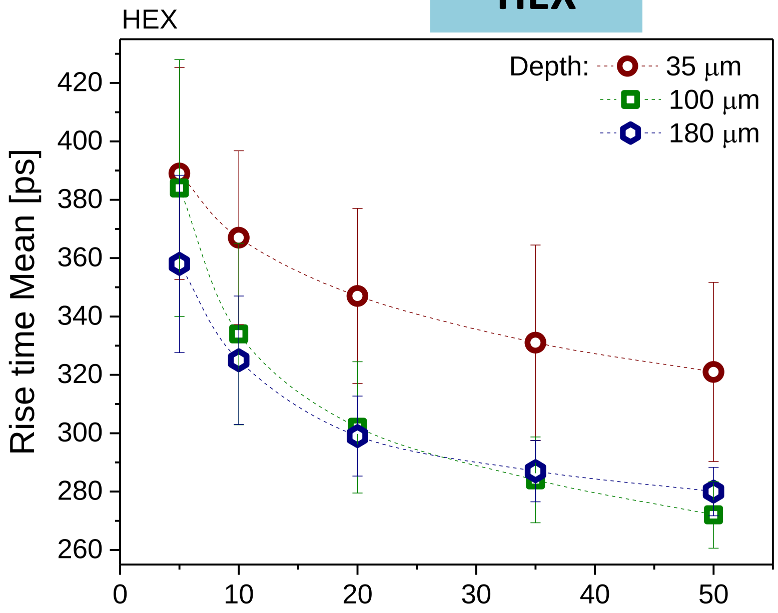
- Spread of ToA decreases with increasing bias. At all studied depths
- 35 um shows more complex tendency
- Spread of ToA increases with increasing depth at each studied bias.

Bias dependence at different depths:
Rise Time Mean

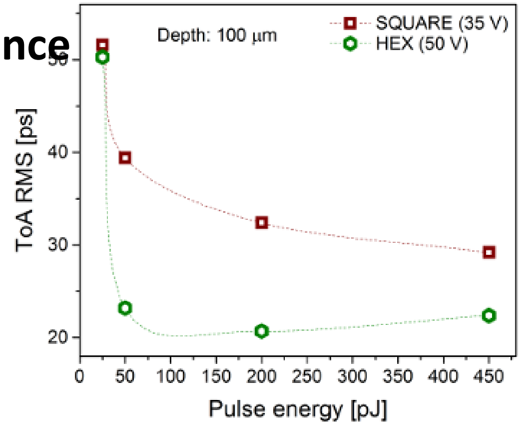
HEX

SQUARE

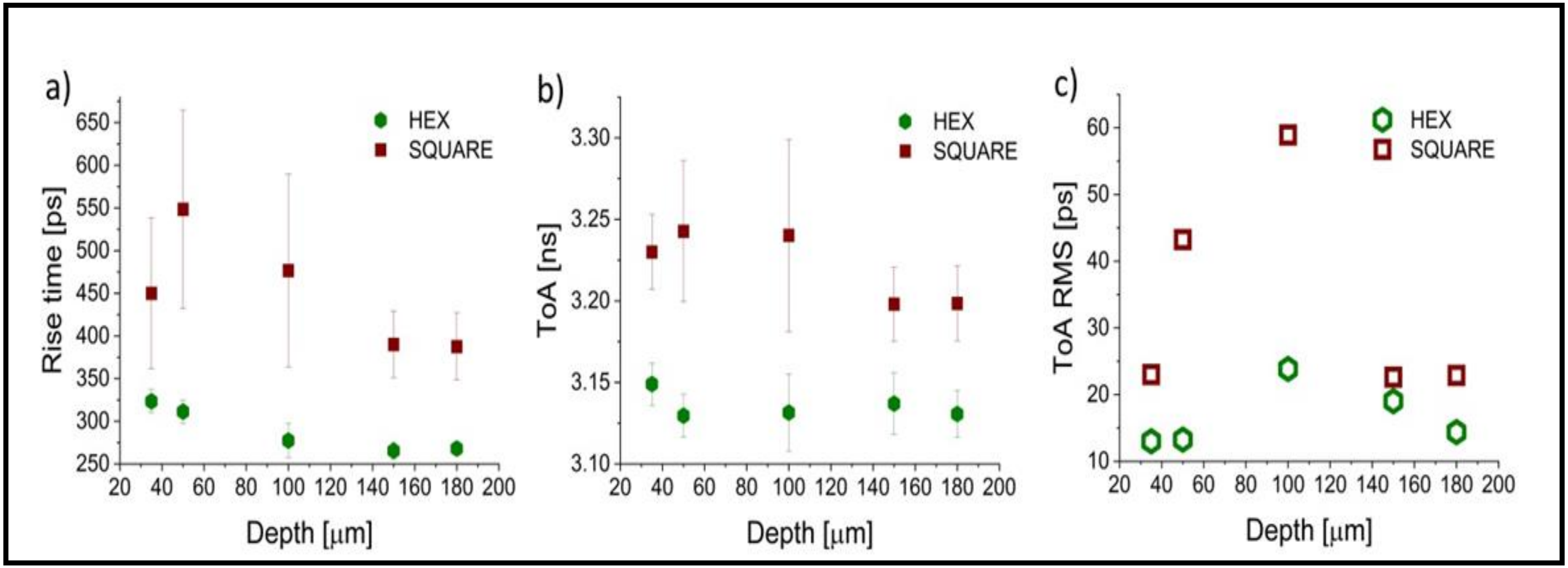




Lasr dependence



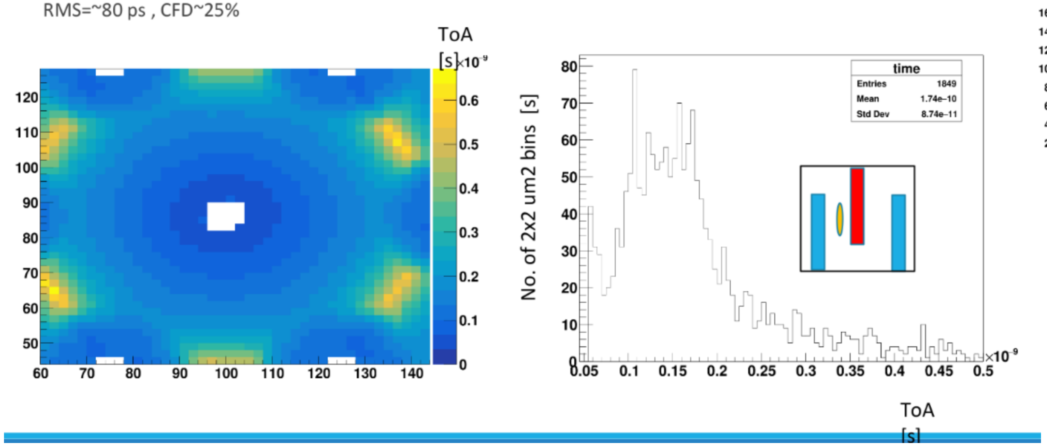
SUMMERY: Hex vs Square



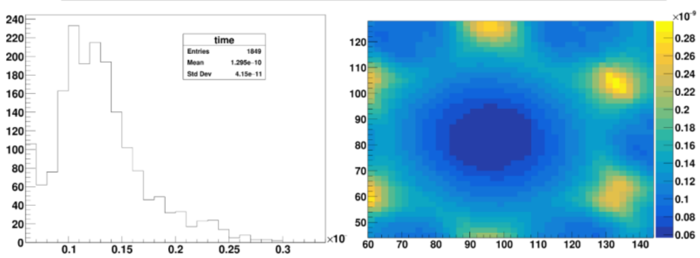
Simulation

Distribution at 150 µm depth

RMS=~80 ps , CFD~25%



Wider "cigar simulation" – 20 um



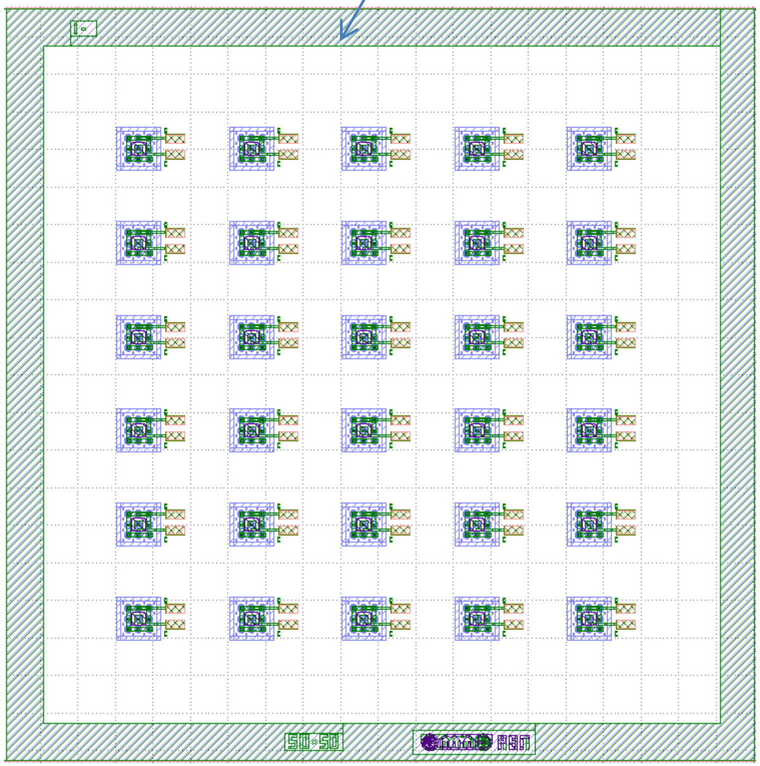
Backside illumination is needed to verify hypotheses why RMS (ToA) is lower than simulation shows.

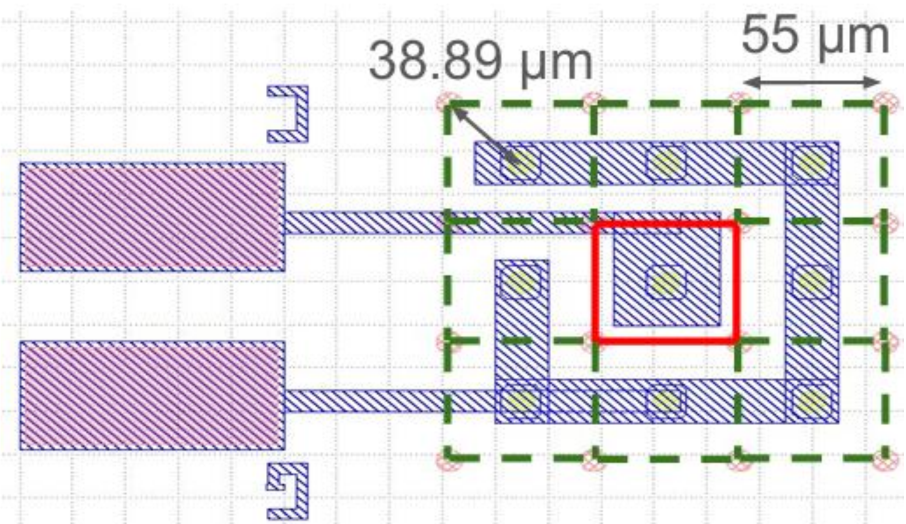
II PART

ONLY ONE CELL IS BIASED

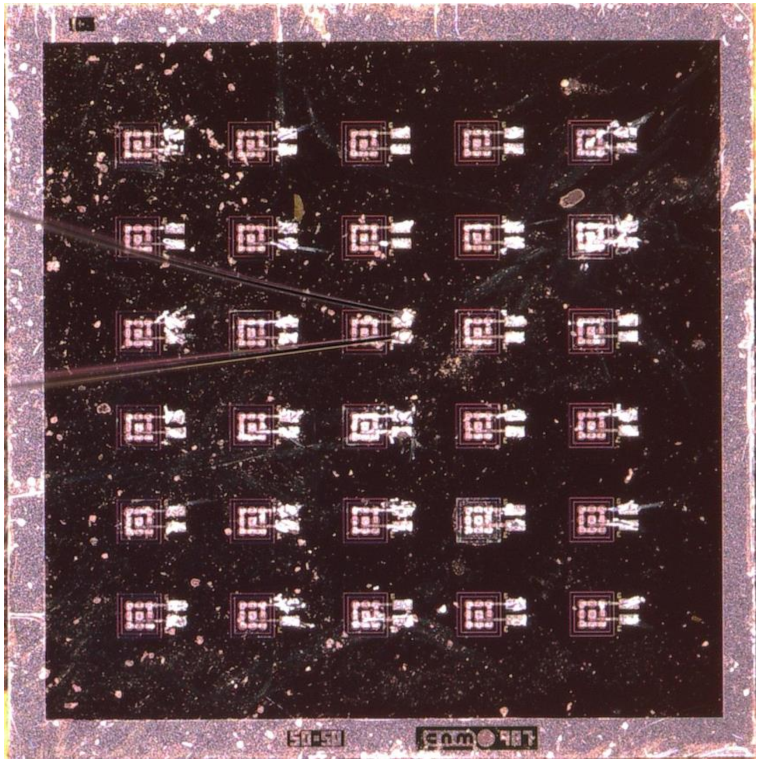
SQUARE 1-X

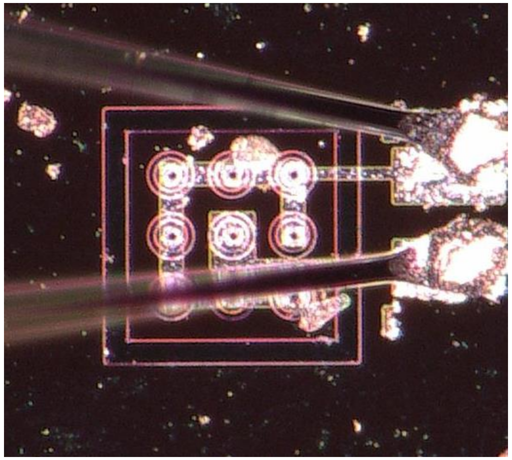
- Single dice = 5x6 array of devices;
- 23 per wafer → total of 46 already diced.
- Devices of 3x3 pixels of orthogonal geometry, single central channel, 55µm pixel pitch





SQUARE 1-X

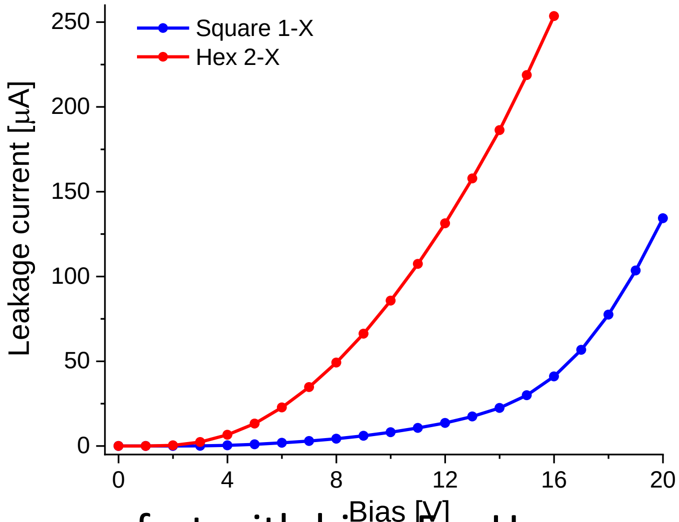




Problem of front illumination are

- metal parts and unfortunate bonding (covered part of region of interest).
- Back side illumination does not suffer that but for some reasons much higher laser power (about 5-6 times) is needed to generate comparable signal (not perfectly removed metal part can be the reason)

Leakage current



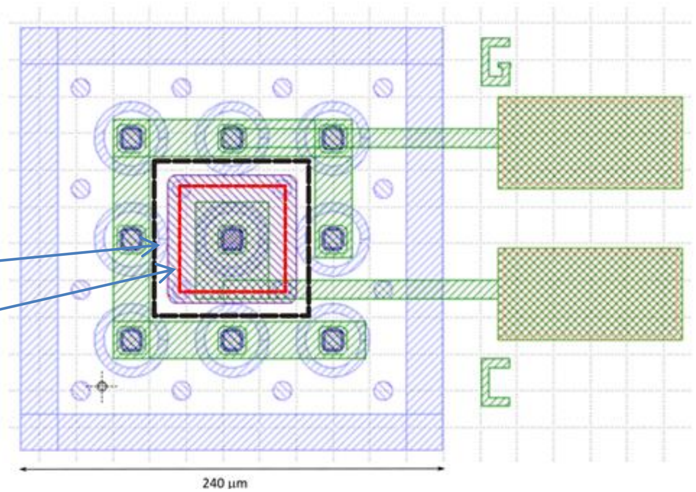
- V_{BD} much lower than what we see in large multi-cell biased structures.

Leak current grows fast with bias. For Hex sensor maximal used bias was 16 V (to stay safely below current limit). For Square sensor slightly higher bias can be used but maximal used bias was the same as for Hex sensor (16 V).

Two scanning areas:
-one corresponding to cell
- another one with extended area

Size: 90x90 μm^2

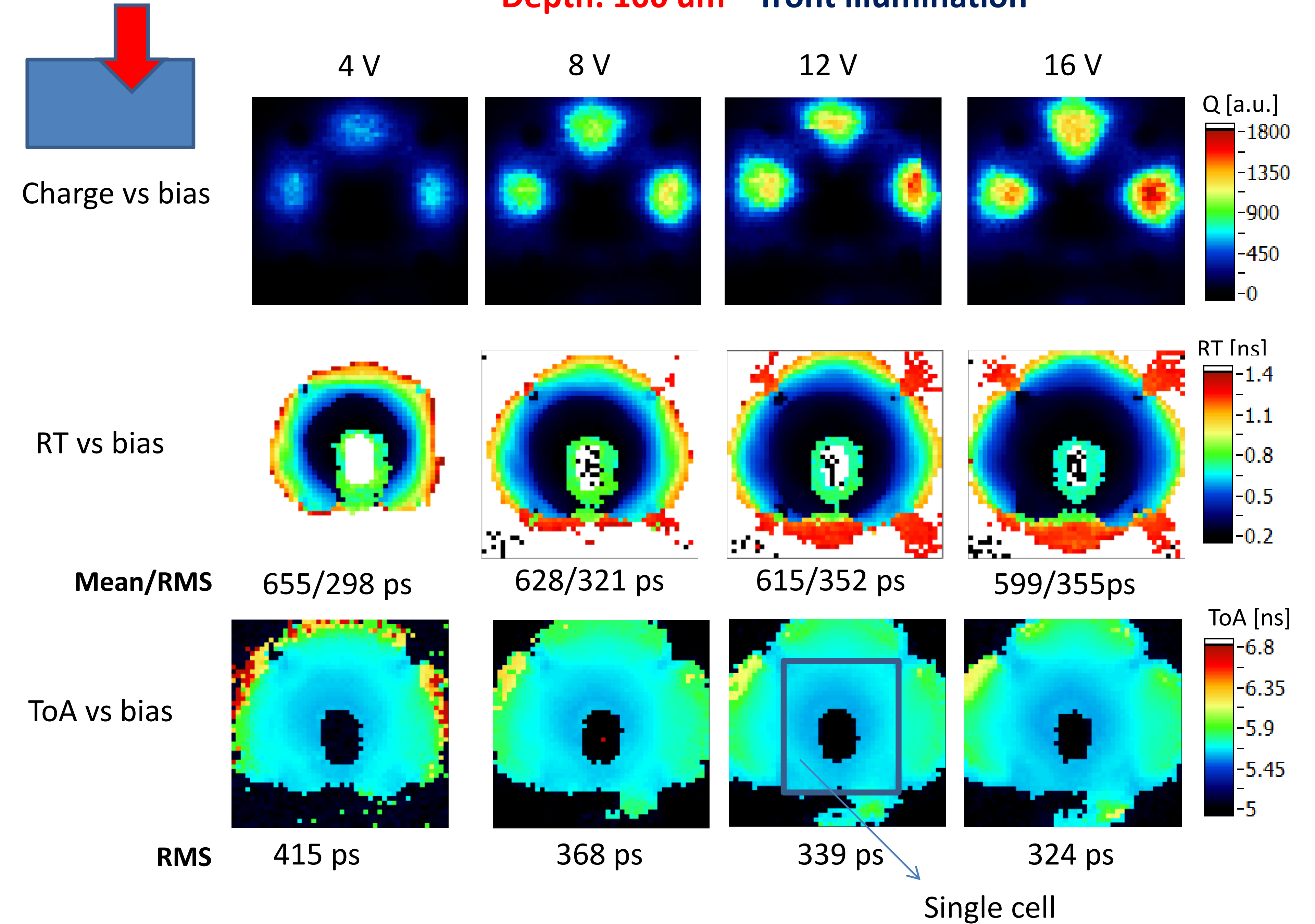
Size: 60x60 μm^2



SQUARE 1-X

90 x 90 um

Depth: 100 um – front illumination



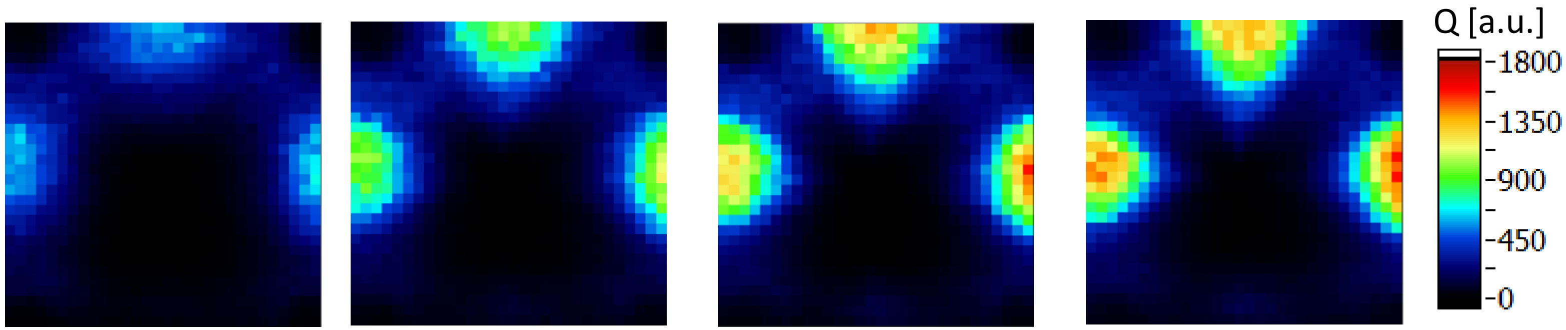
SQUARE 1-X

60 x 60 um

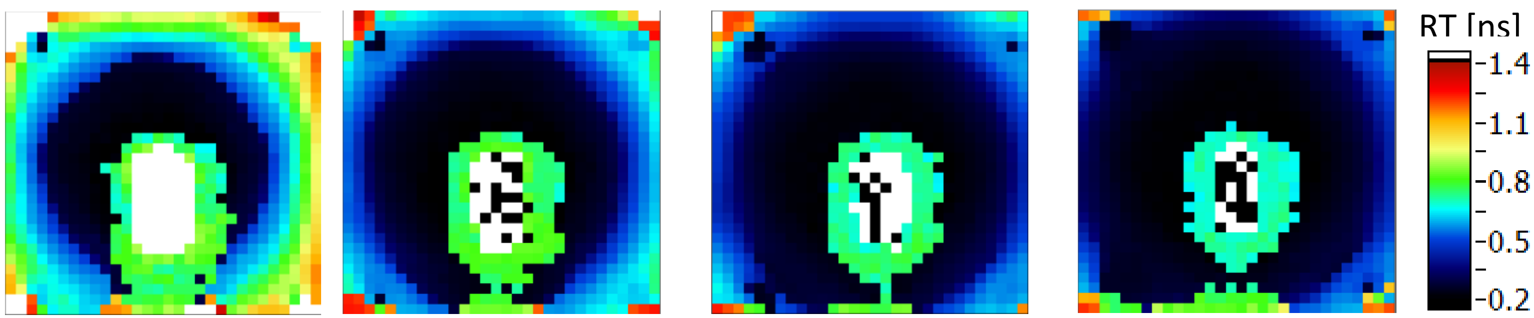
Depth: 100 um – front illumination

	4 V	8 V	12 V	16 V

Charge vs bias

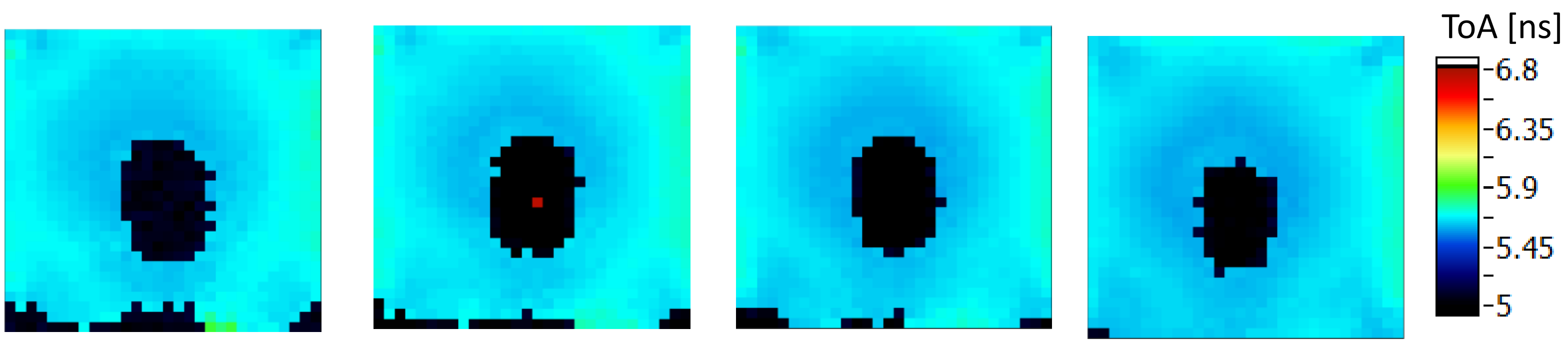


RT vs bias



Mean/RMS	595/266 ps	444/221 ps	396/218 ps	364/217 ps

ToA vs bias



RMS	49 ps	51 ps	34 ps	36 ps

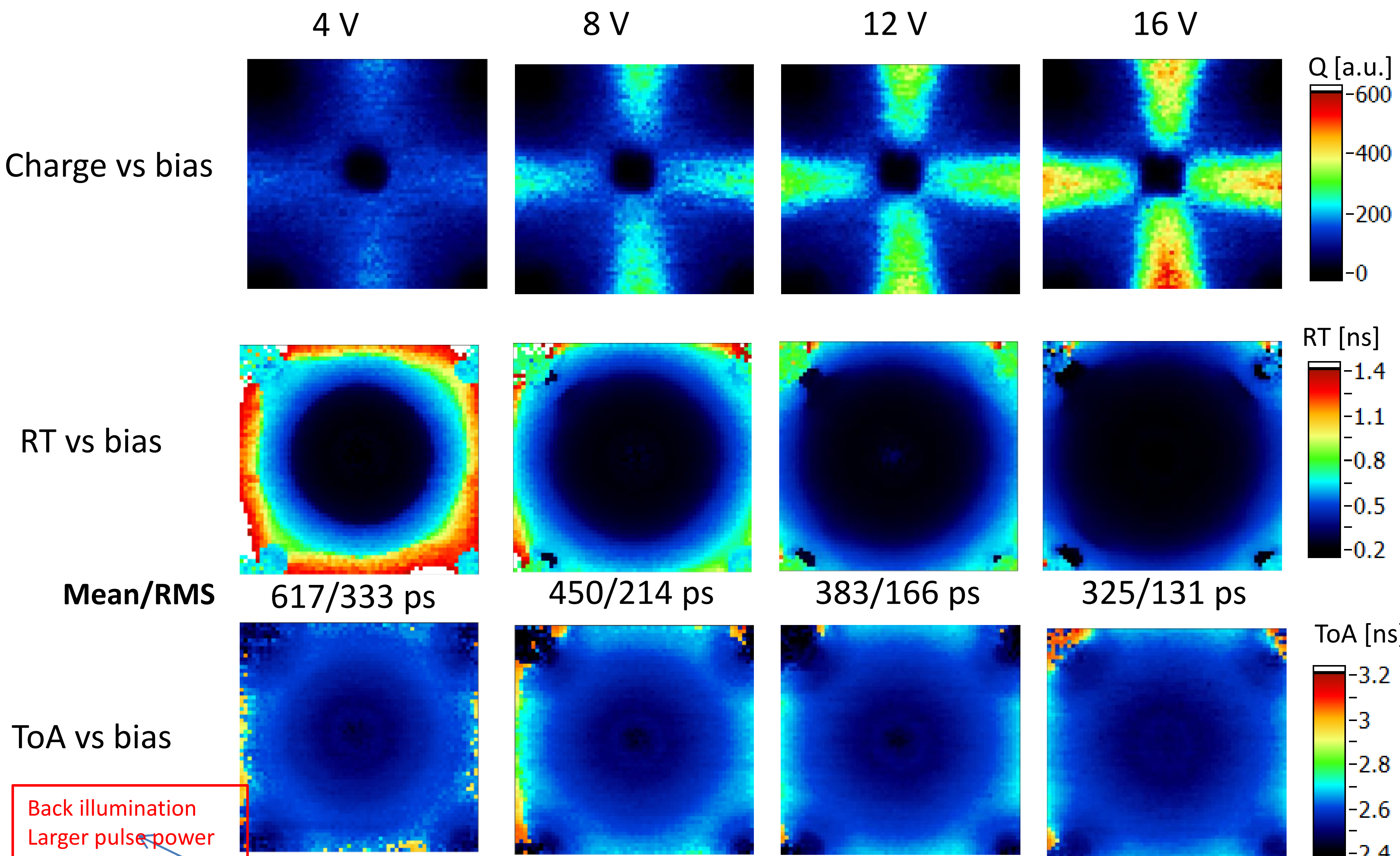
90x90

RMS	415 ps	368 ps	339 ps	324 ps

SQUARE 1-X

60 x 60 um

Depth: 185 um – back illumination

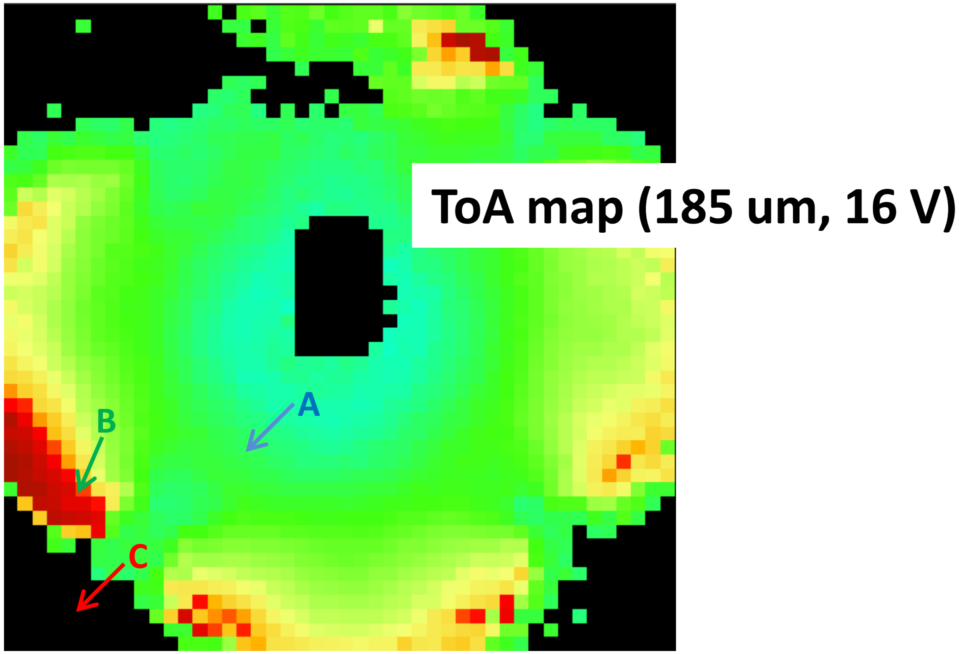


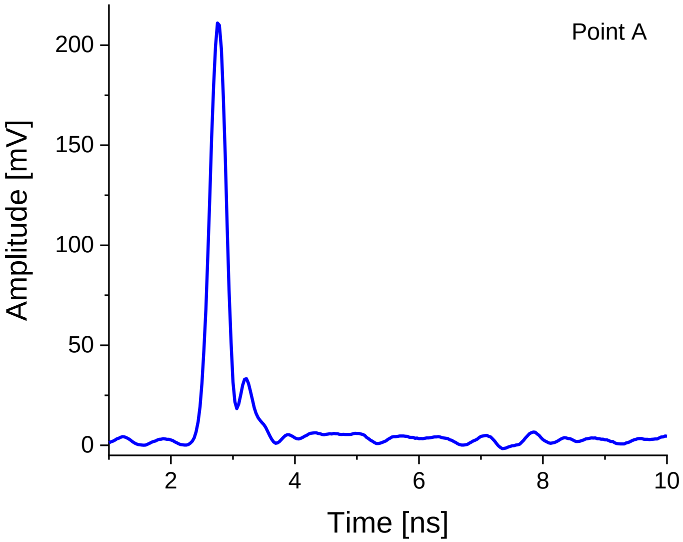
	4 V	8 V	12 V	16 V
RMS	79 ps	89 ps	65 ps	50 ps
RMS	49 ps	51 ps	34 ps	36 ps

Front illumination

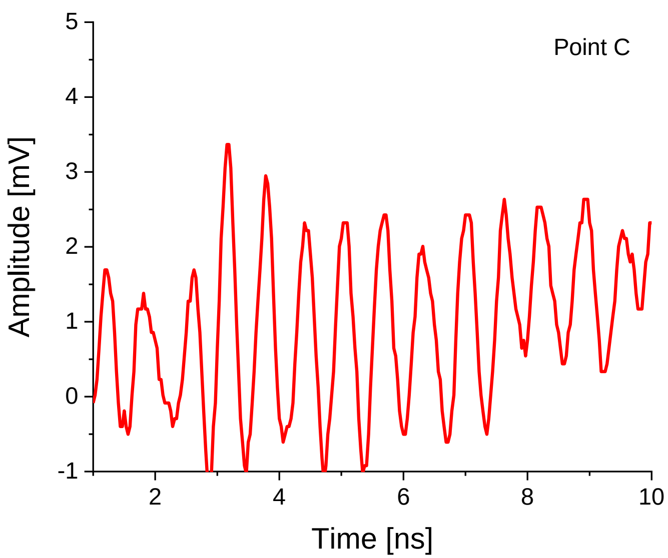
SQUARE 1-X

Example of waveforms

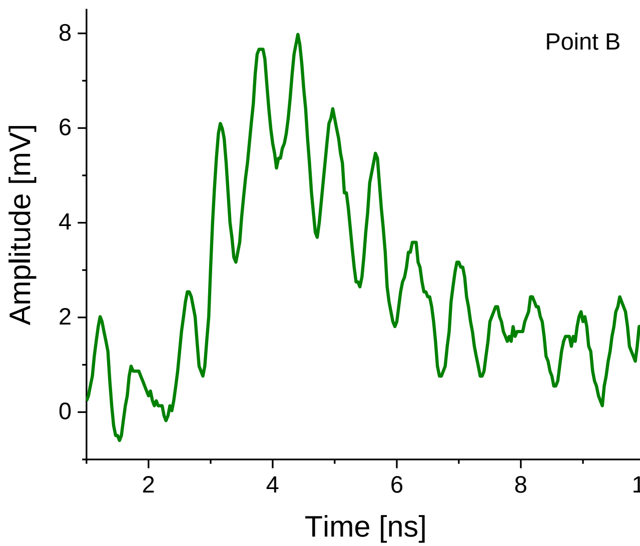




nice signal: timing parameters clearly determined



meaningless signal, timing parameters cannot be extracted (fake parameters can be generated by algorithm), such point should be excluded

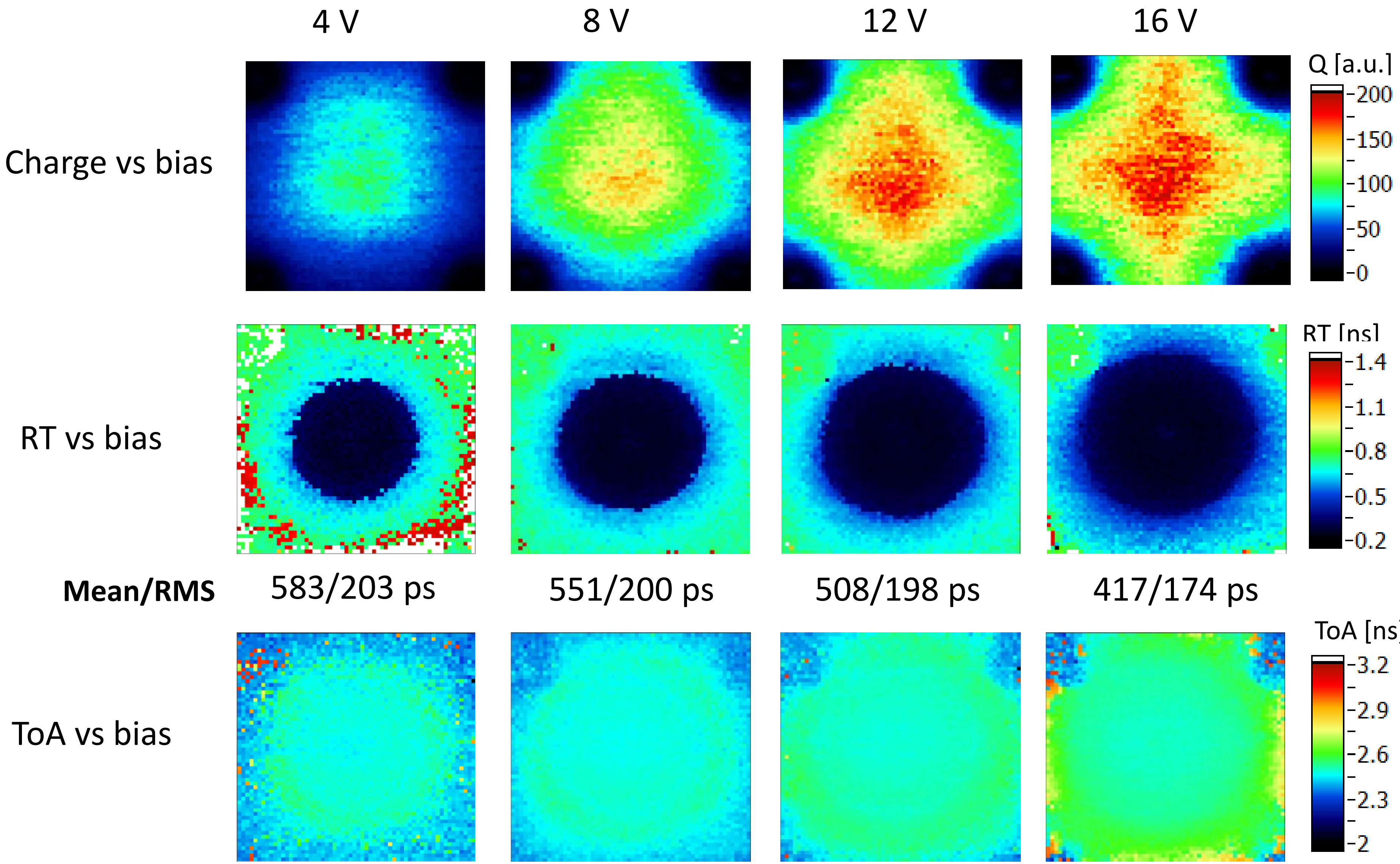


not nice but doable: timing parameters can be extracted with compromised uncertainty (fitting can be used to improve the quality)

SQUARE 1-X

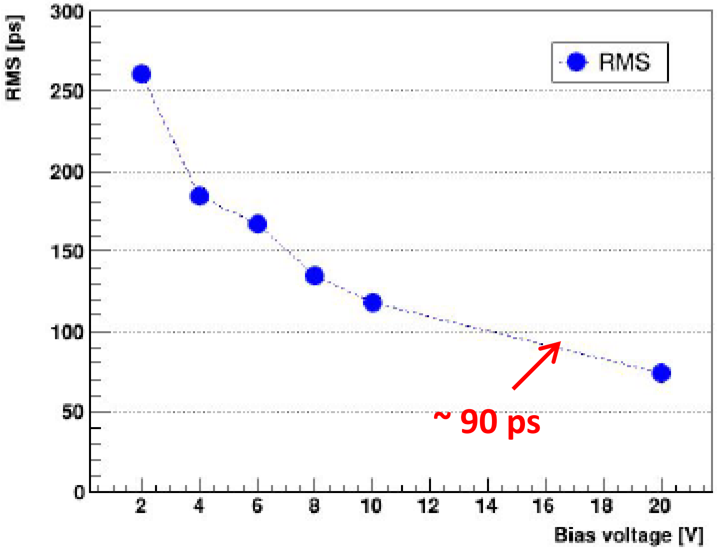
60 x 60 um

Depth: 250 um – back illumination



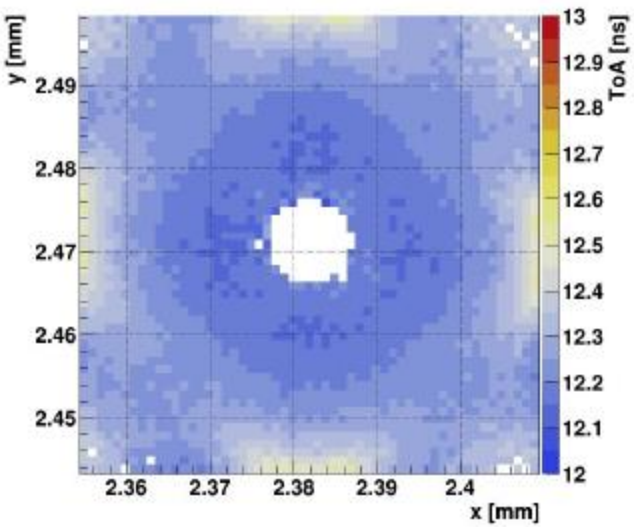
	4 V	8 V	12 V	16 V
Mean/RMS	583/203 ps	551/200 ps	508/198 ps	417/174 ps
RMS	79 ps	36 ps	42 ps	91 ps

Comparison with IFCA results

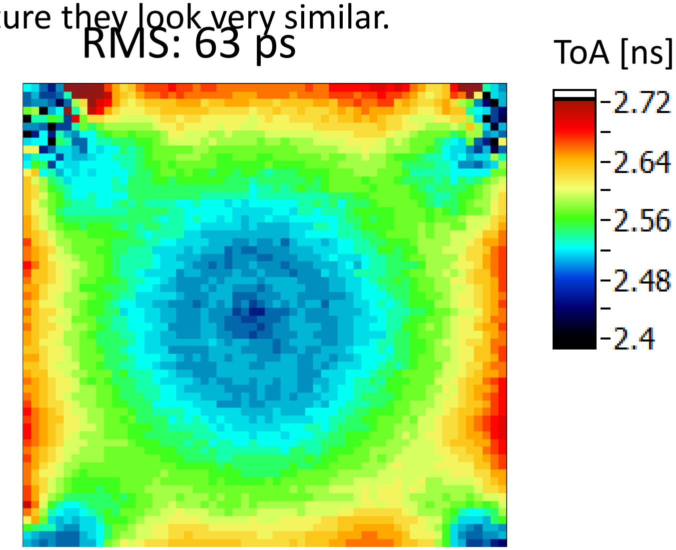


- TPA depth: 185 um;
- Backside illumination by laser.
- ICFA group didn't measure ToA at 16 V (our max bias); however, RMS (ToA) can be estimated from their plot vs bias. It is about 90 ps.
- In our case it's 63 ps.
- Difference in laser power is not known.
- In general, results can be very sensitive to the quality of back surface (removal of metal cover) .

Both maps have different colour coding but in terms of structure they look very similar.

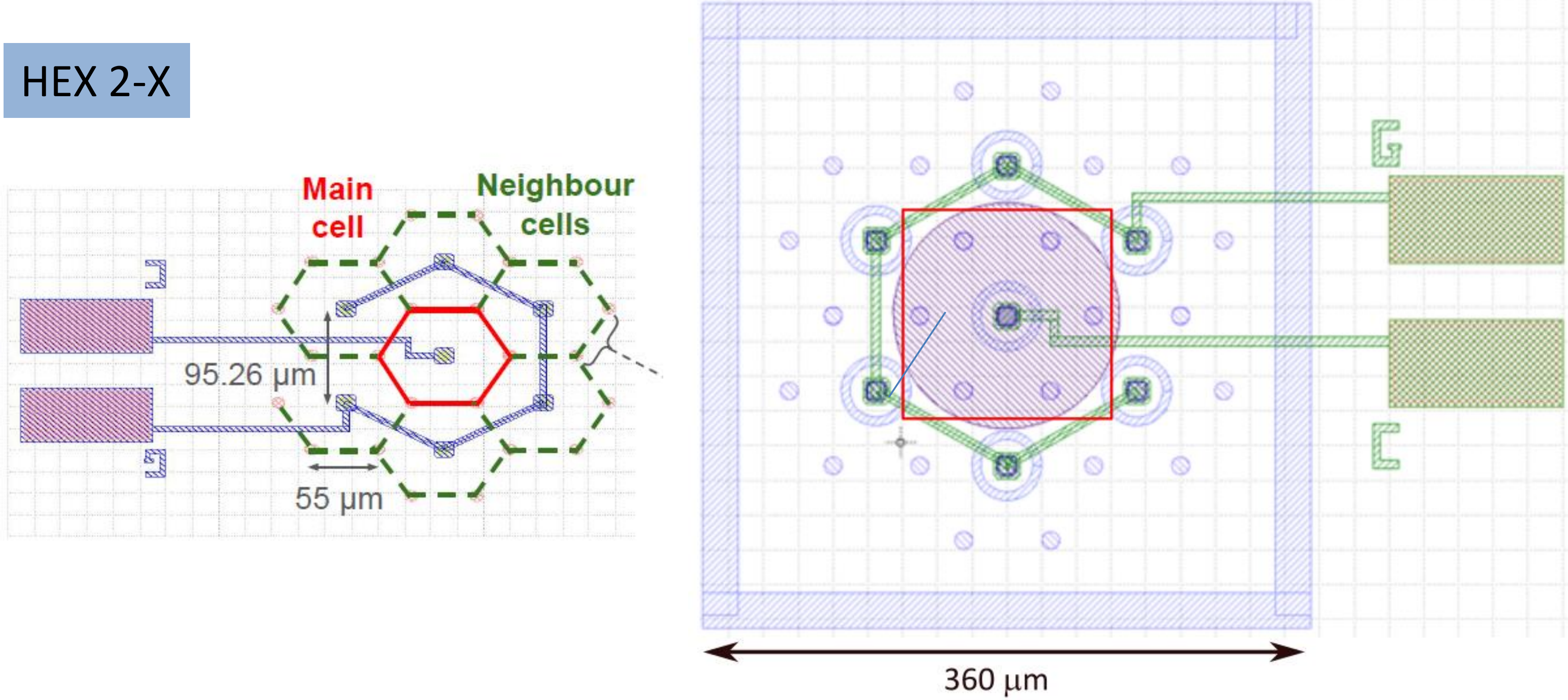


CERN

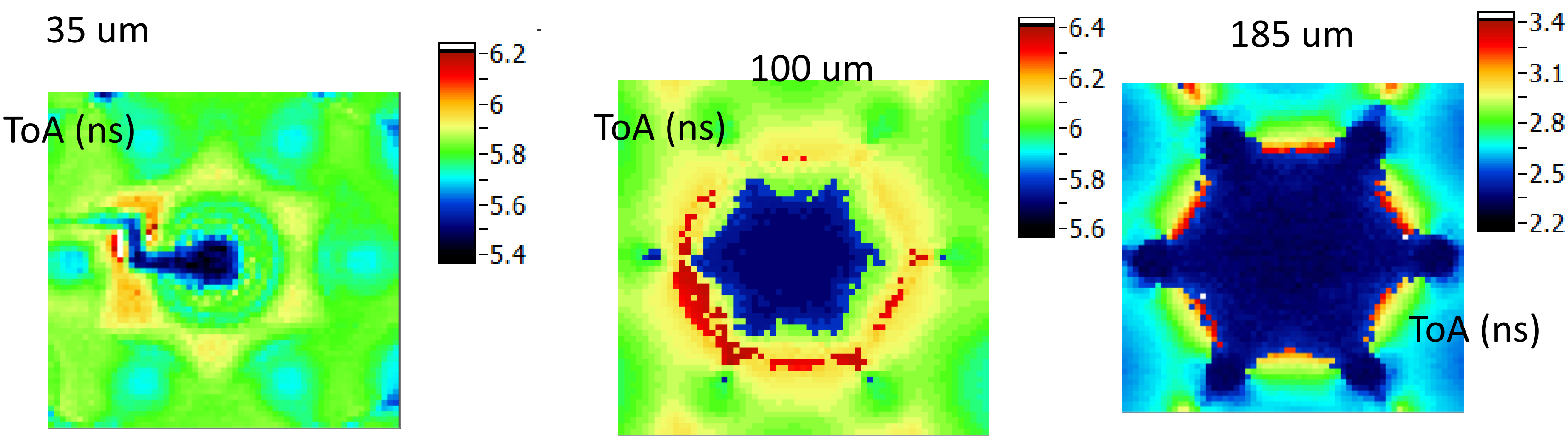


ELI

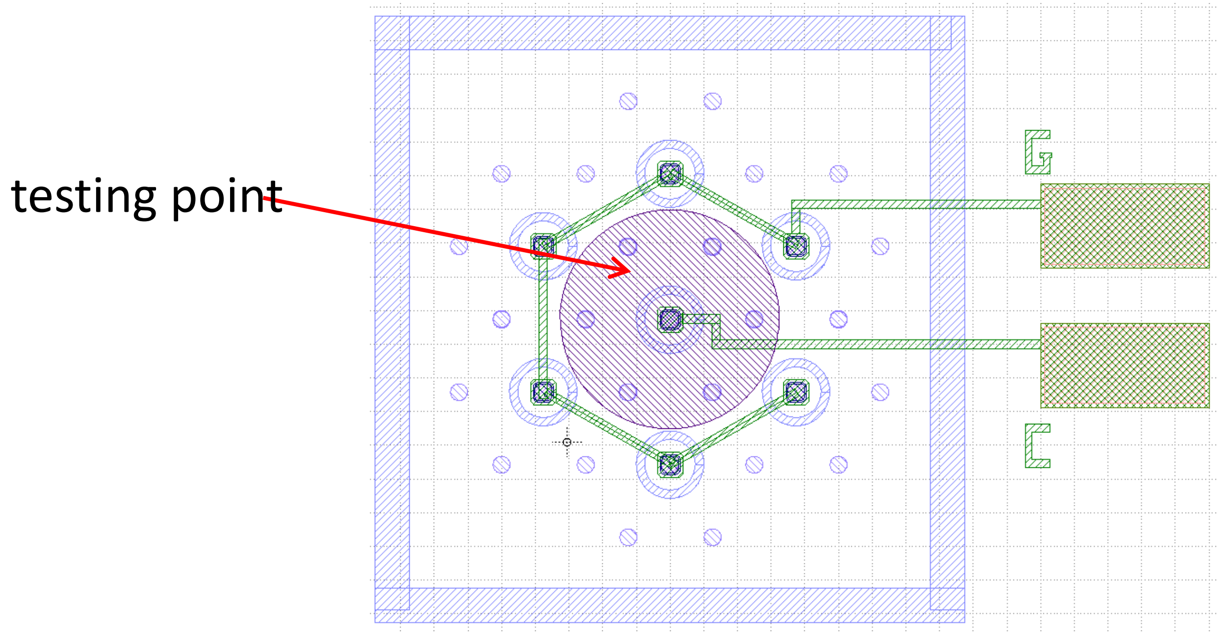
HEX 2-X



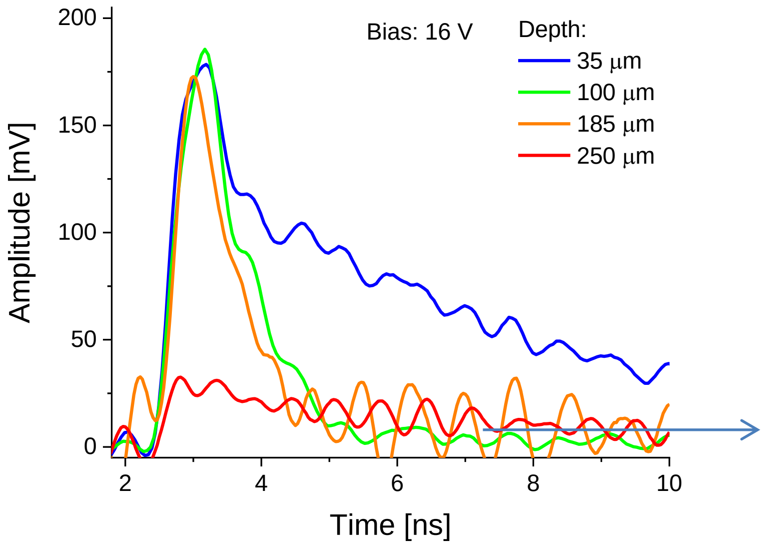
Scanning area: 120 x 120 um around central electrode (red square) I t fully covers central cell with some reserve



HEX 2-X



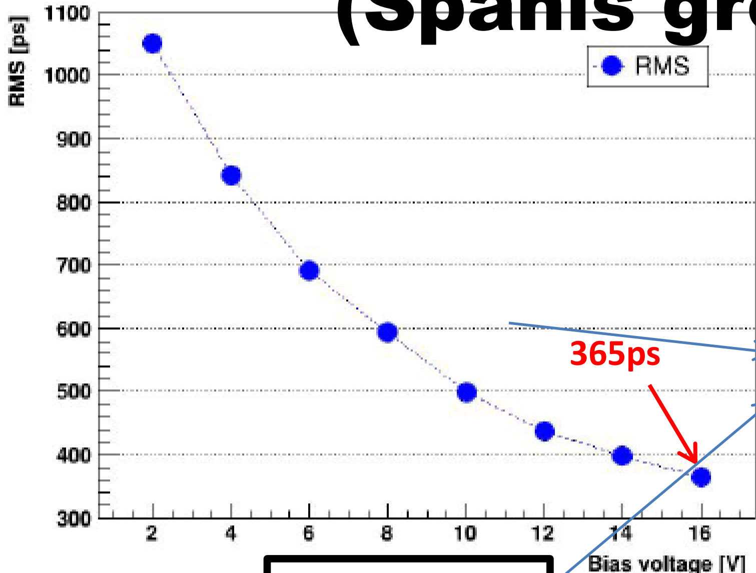
Waveforms taken in testing point at different depth



- 35 and 100 um recorded at 100 pJ (front)
- 185 and 250 um recorded at 650 pJ (back)(much higher power needed for backside illumination to get comparable signal, it was adjusted to get similar amplitude for 100 and 185 um depth at the same points)

Noisy, data at 285 um are not reliable

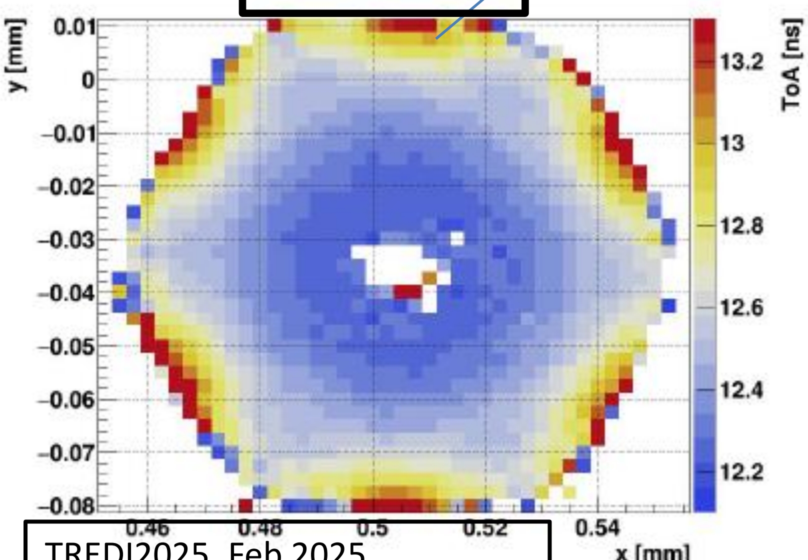
Comparison with IFCA (Spanis groupp) results



- IFCA result: 365 ps measured for RMS (ToA) at 16V
- We measured 149 ps for RMS (ToA) at the same bias and laser power 100 pJ.
- For lower power 50 pJ we measured slightly bigger value: 178 ps.

C. García et al., [The influence of pixel cell layout on the timing performance of 3D sensors]() ***TREDI2025***

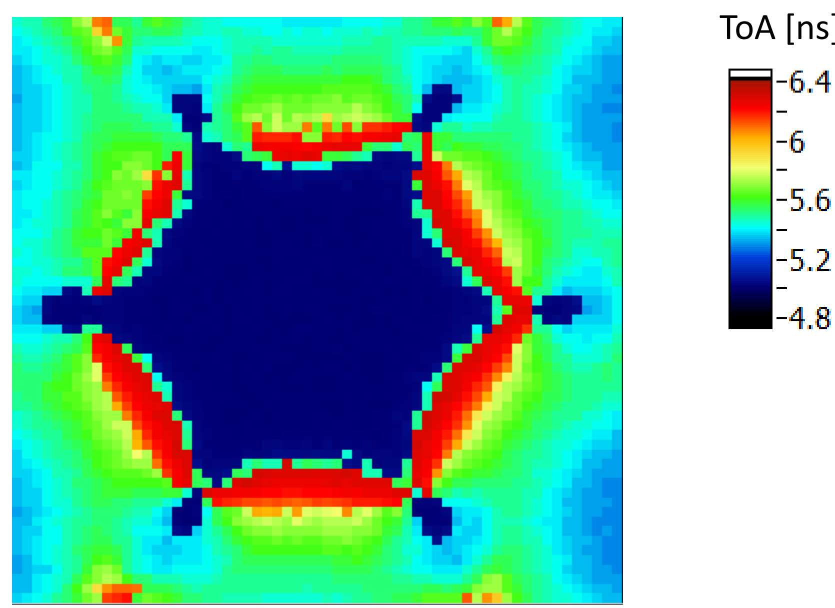
RMS: 365 ps



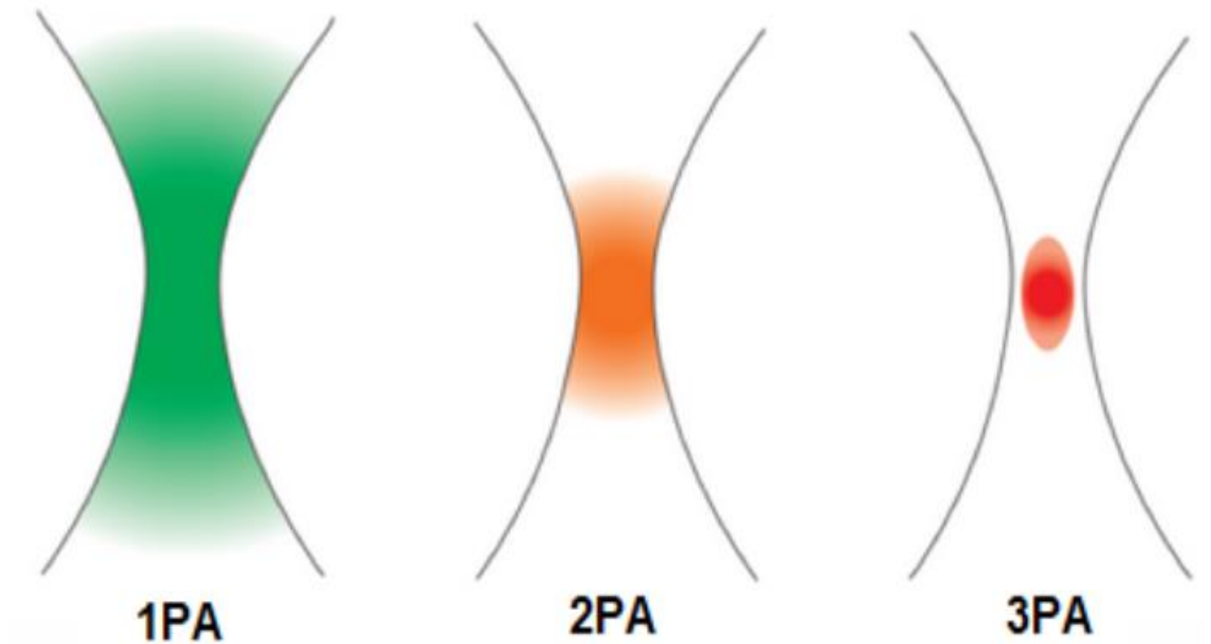
TREDI2025, Feb 2025

Measured using 2PA –TCT at CERN

Our result
RMS: 178 ps



Measured using 2PA-TCT at ELI



3^{RD} PART

2250 nm was used; at this wavelength the 3 photons are needed to excite electrons to conduction band (to have absorption).

- Band gap in Si is 1.12 eV (1107 nm) so for 1PA the wavelength has to be < 1107 nm. For 2PA we need at least two photons with 0.56 nm (2214 nm) so the wavelength has to be in range 1107-2214 nm. Above 2214 nm 2PA can not happened; we need at least 3 photons to jump to conduction band and generate the charge.
- we have only 2250 nm wavelength (the output is optically filtered very well); therefore, only 3PA is possible.

$$\frac{dI}{dz'} = -\alpha I - \beta I^2 - \gamma I^3$$

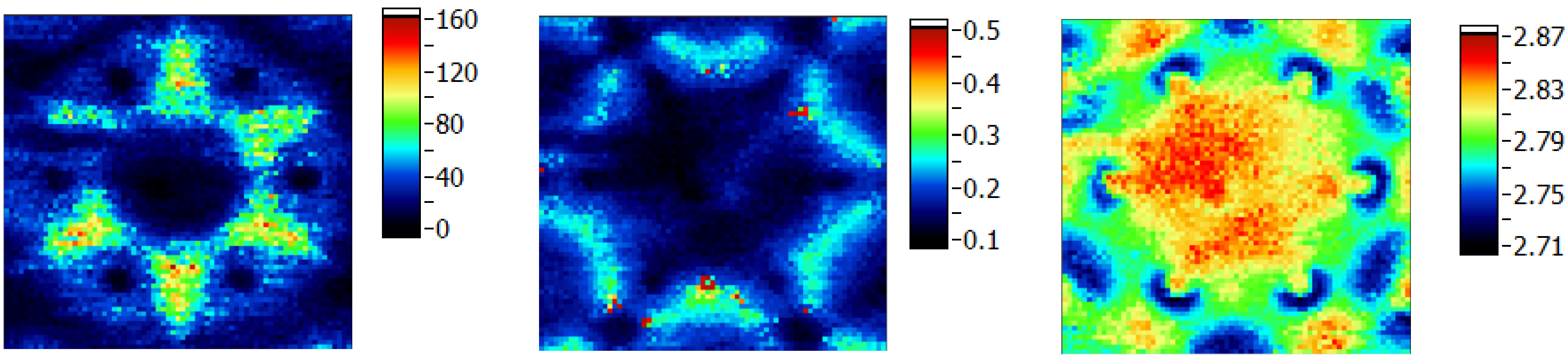
HEX 2-X

3PA vs 2PA

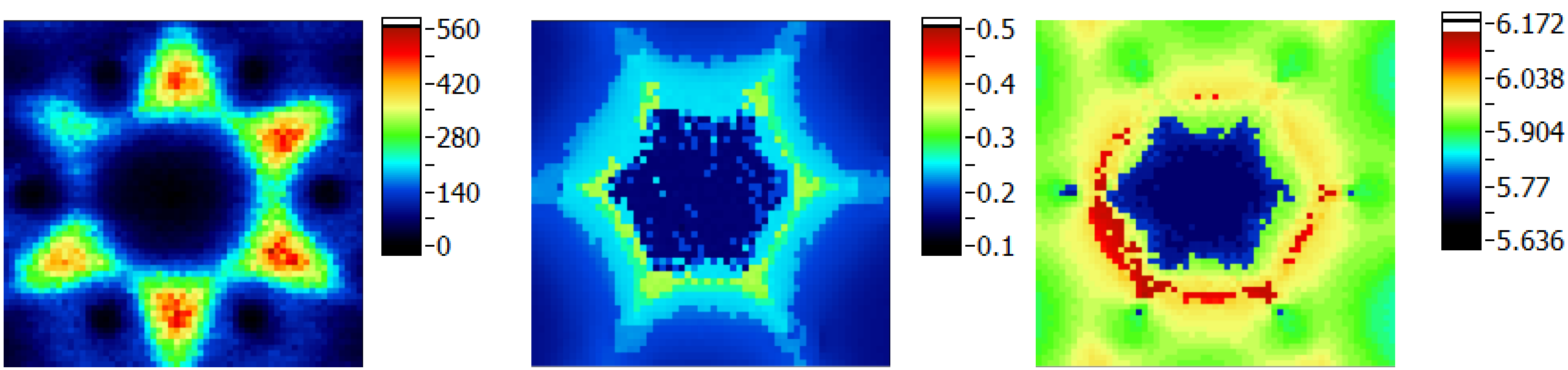
3PA: 2250 nm, 16 V, depth 100 um, power not known

RMS: 178 ps

Charge Q [a.u.]   Rise time RT [ns]   ToA ToA [ns]

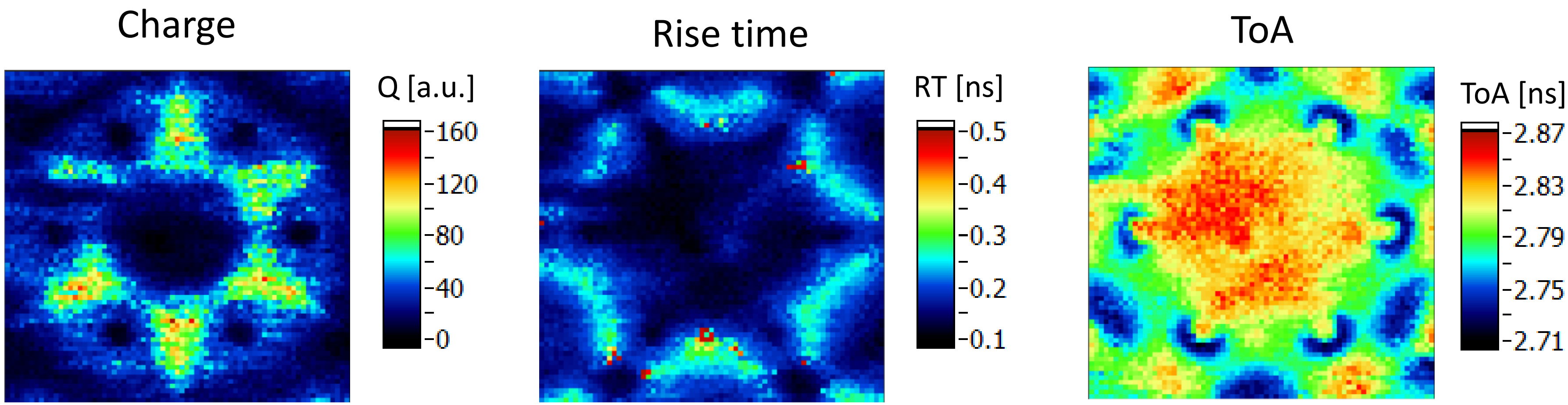


2PA: 1550 nm, 16 V, depth 100 um, power 100 pJ



RMS: 149 ps

3PA : preliminary results



Example data obtained by three photon absorption on HEX 2-X sensor.
Wavelength: 2250 nm
Depth: about 100 um (front illumination)
Power: < 1 nJ (not known exactly, dedicated powermeter is needed)

Method dedicated mostly to irradiated sensors (to decrease SPA contribution) but first feasibility tests performed on non-irradiated sensor.
Necessary improvements:
- dedicated optics (especially beamsplitters) to avoid power losses
- dedicated powermeter (sensitive enough for very low power and compact to fit in the measurement box). Devices are ordered and existing 3PA set-up will upgraded in next campaign in August/September

Conclusons

- We successfully develop an advanced, high resolution 3D characterization technique based on 2PA -TCT and implemented on 3D Double Sided Double Type Si devices.

- The aim is to calibrate and further develop simulation. For that more experimental studies are planned (next campaign).

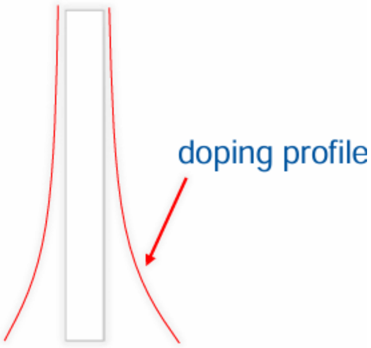
- The final aim is to have full prediction of ToA for any track inside 3D.

- Also well calibrate and understood simulation will help us to design the most optimal 3D double sided double column device.

- We were successful in getting the first scan with 3PA (on non-irradiated 3D samples). The aim is to have advanced tool for irradiated 3D devices (to reduce 1PA contribution as its contribution to 2PA significantly increases with increasing fluency).
- 3D large Hex stricture shows better ToA (less spread) than in large structute Square 3D cell. Opposite trend is seen In a singke 3D structur

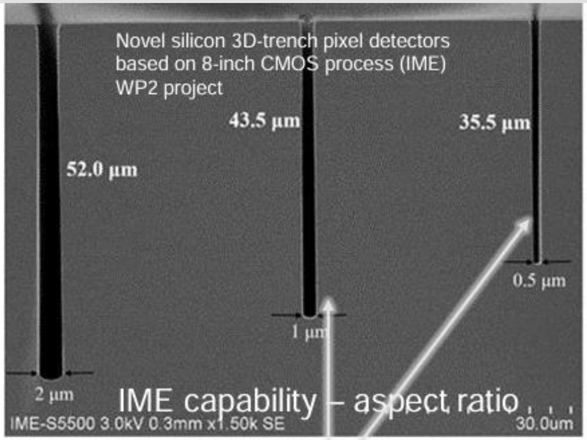
Food for thought

- 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 <1 μm which can be seen as proportional wire counter. The questions are:
  - Can electric field high enough be achieved by "field focusing" rather than gradient of doping?
  - Is it possible to dope the columns with profile that is narrow enough to assure that field focusing allows gain?
  - How can such device be realized and what would be the consequences of the standard single sided "not full through columns processing" on device performance?



How to dope as narrowly as possible to minimize the effective width of the column, The field depends as E~1/r

Can we progress from "solid state ionization chamber" to semiconductor "wire proportional chamber"?

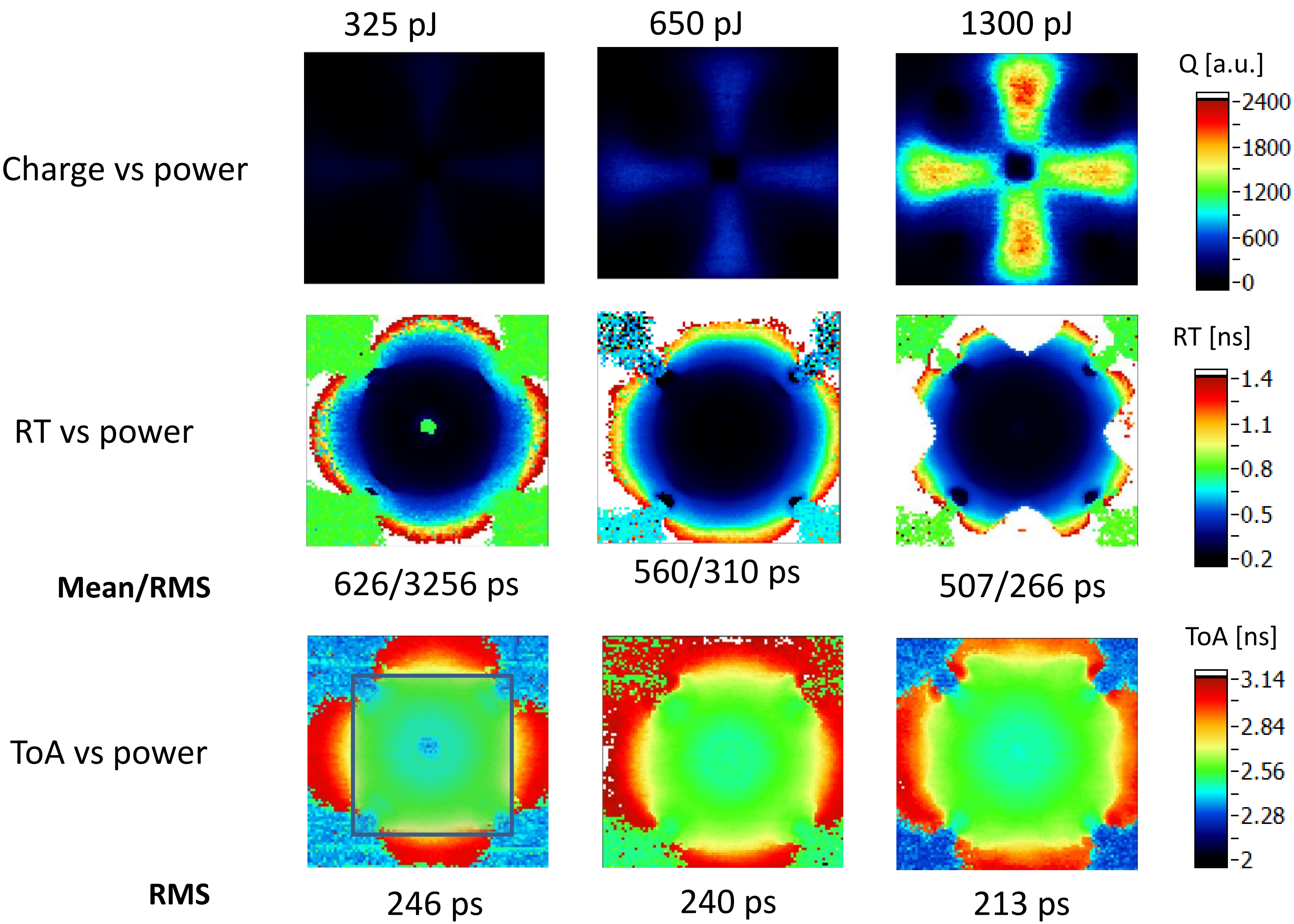


BACKUP

SQUARE 1-X

90 x 90 um

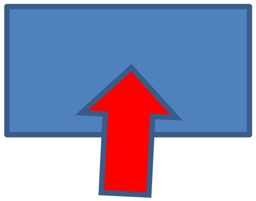
Power dependence at 16V at 185 um (back side)



SQUARE 1-X

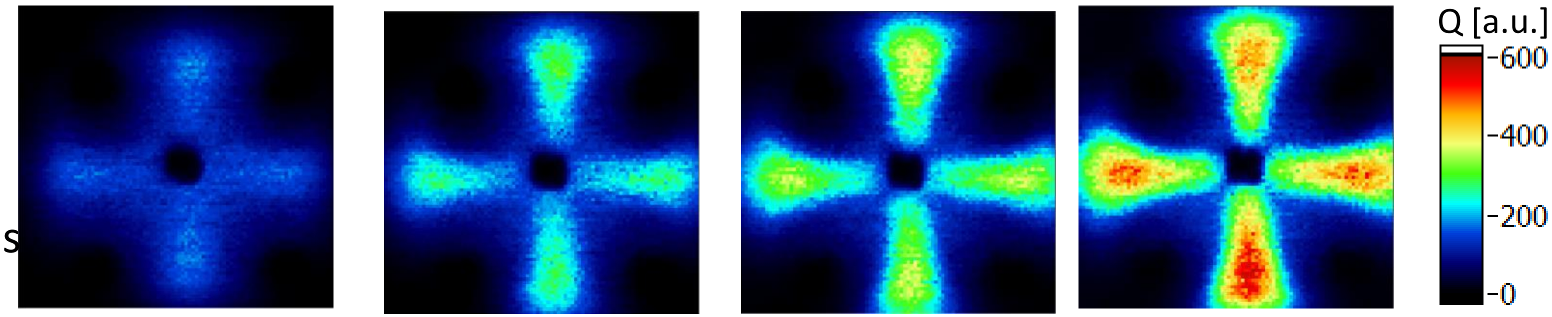
90 x 90 um

Depth: 185 um – back illumination

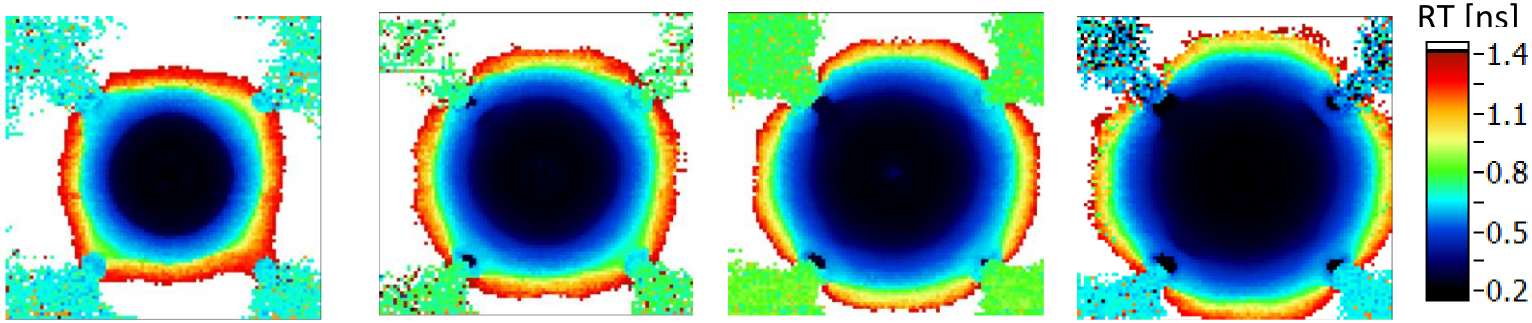


	4 V	8 V	12 V	16 V

Charge vs bias

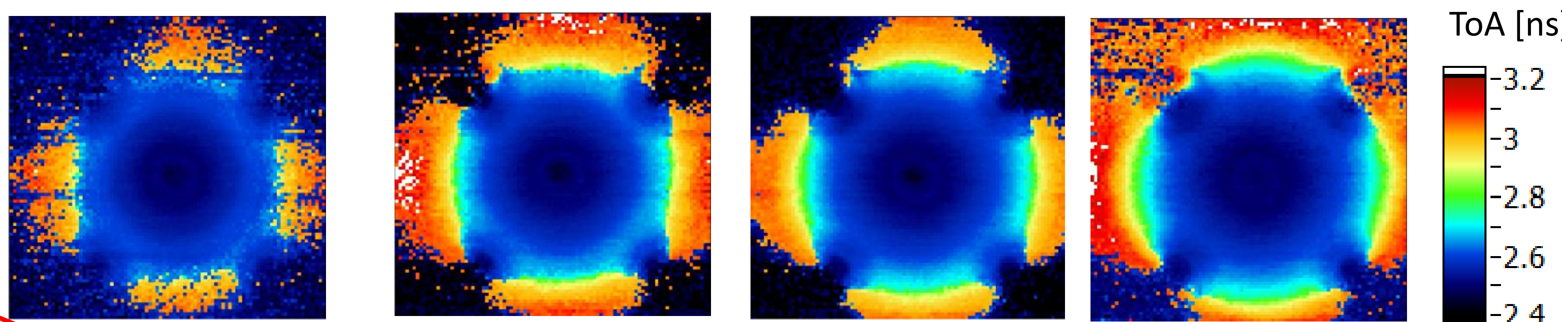


RT vs bias



Mean/RMS	676/314 ps	657/349 ps	614/297 ps	560/310 ps

ToA vs bias



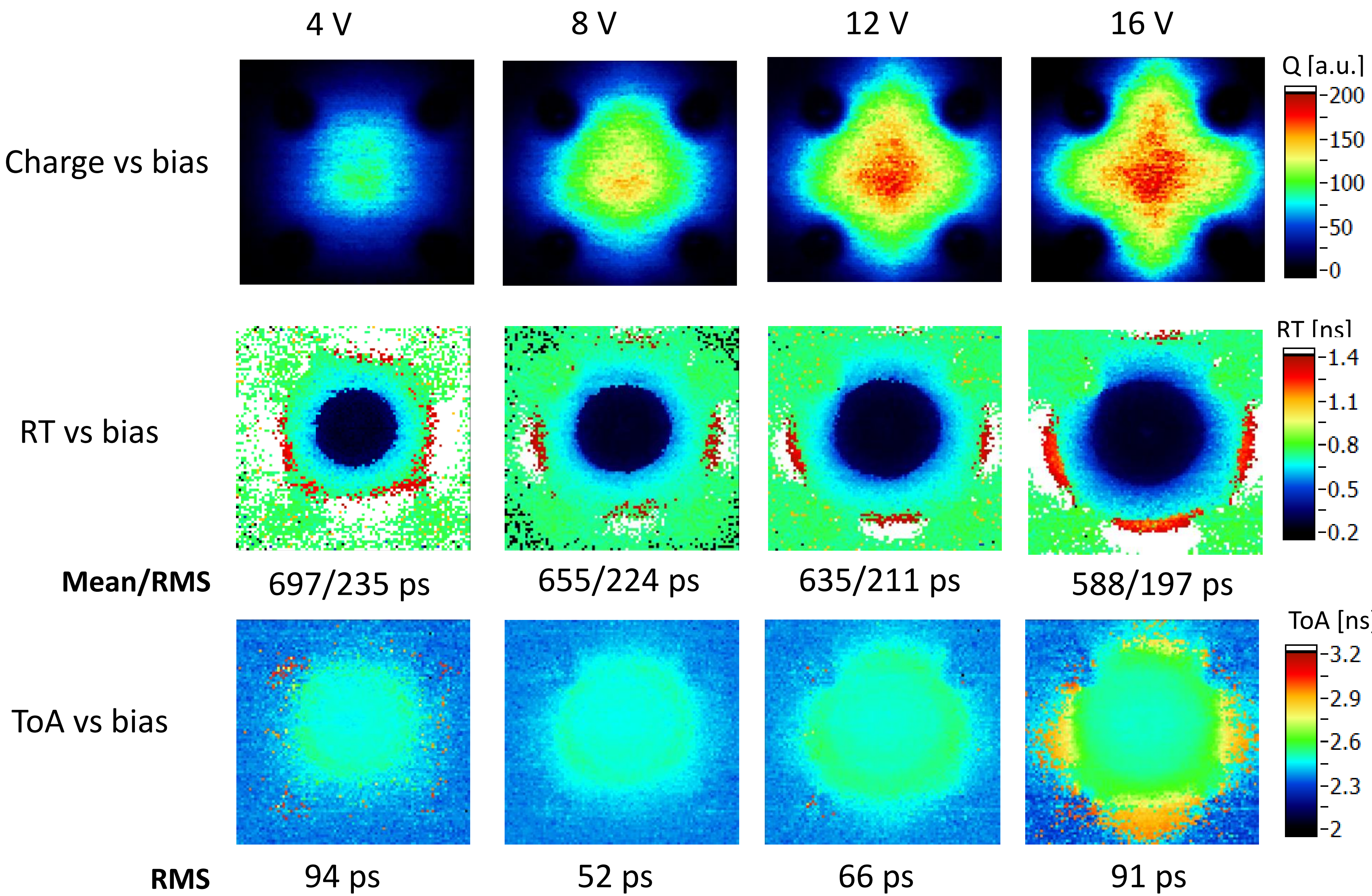
Large laser power was used!

		4 V	8 V	12 V	16 V
	RMS	257 ps	252 ps	219 ps	240 ps
Front TPA	**RMS**	415 ps	368 ps	339 ps	324 ps

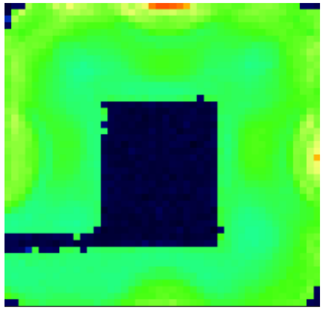
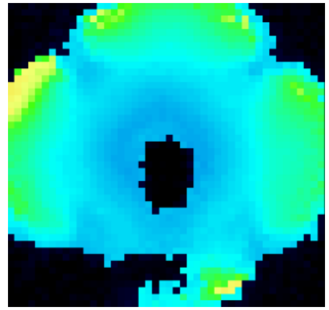
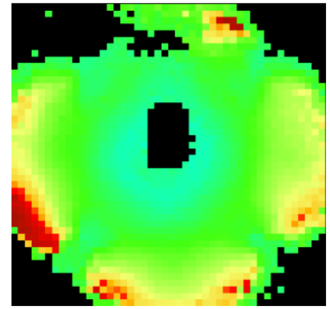
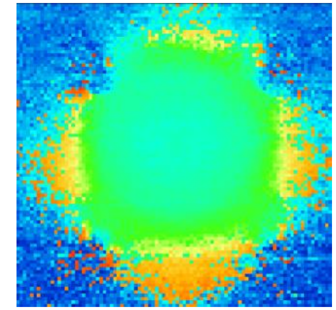
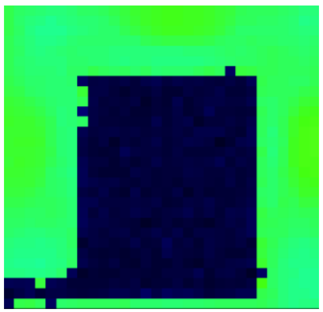
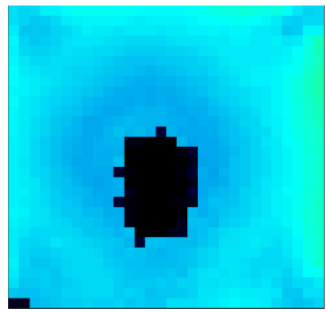
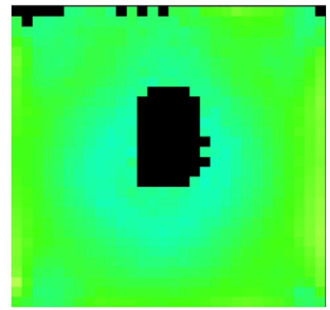
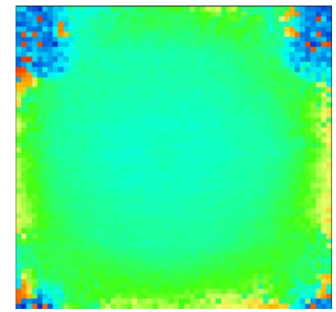
SQUARE 1-X

90 x 90 um

Depth: 250 um – back illumination

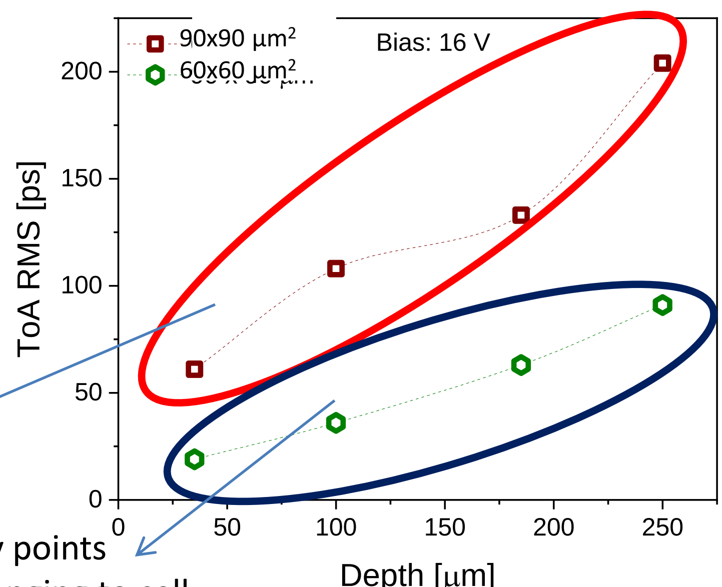


SQUARE 1-X

	Depth 35 um	100 um	185 um	250 um
ToA 90x90				
RMS	61ps	108 ps	133 ps	204 ps
ToA 60x60				
RMS	19 ps	36 ps	63 ps	91 ps

Colour coding was set to show clearly which areas are meaningless and excluded from analysis (black areas).

RMS ToA vs depth for two different areas of analysis



Included points outside the cell

only points belonging to cell

In both cases dependence is similar: RMS increases vs depth

However, the precise RMS(ToA) depends on how well the cell size is defined.