PSD14, 31 August - 3 September, 2026, Queen Mary University of London, UK

SELF-QUENCHING OF 3D TRENCH DETECTORS: GEOMETRY DRIVEN GAIN & FAST TIMING

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

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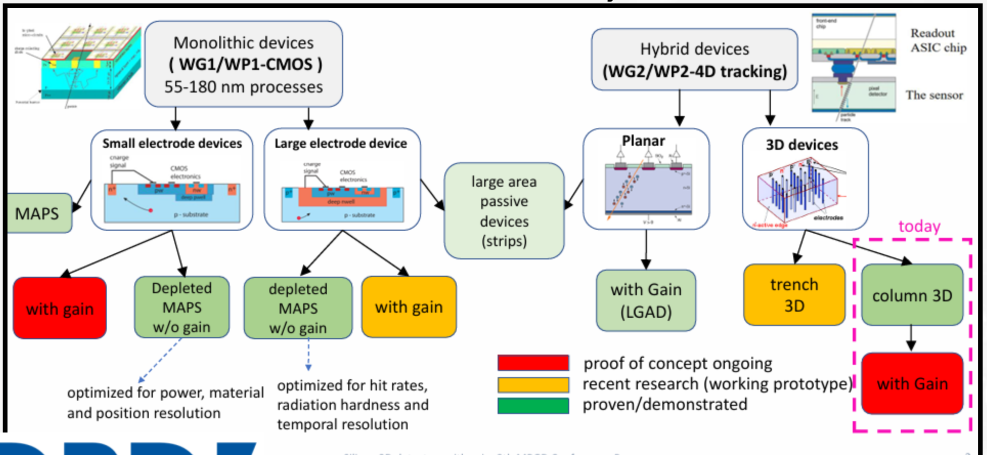
Outline

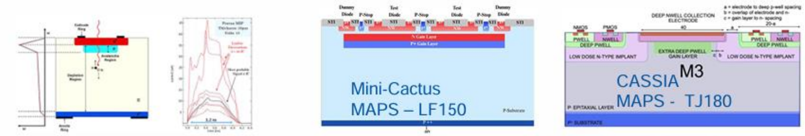
- Gain in silicon and motivation
- Overview of 3D IME-CAS devices produced in 8 INCH CMOS compatible technology
- Two Photon Absorption - Transient Current Technique studies
- Improvements of the design – future work
- Measurements of impact ionization in silicon using Straw (cylindrical) 3D IME-CAS
- Future work & Conclusions

Motivation:

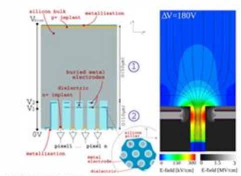
radiation hard, fast device with the intrinsic gain



- Utilizing the gain in **silicon (and recently SiC) detectors** has been the key advancement in **tracking detectors** opening possibility of real 4D tracking with planar devices over the last decade.
  - Low Gain Avalance Detectors - **the gain is achieved with fine tuning of gain layer doping**
  - Implementation of gain is now ongoing in several CMOS projects (CASSIA, CACTUS, ARCADIA, …)



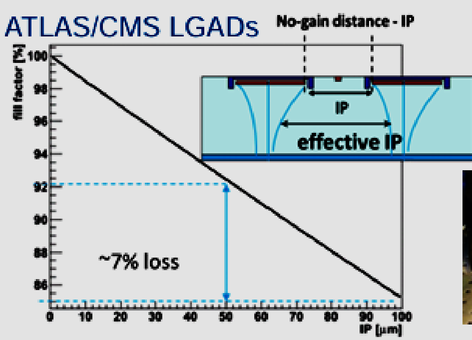
- Also recent developments in SiE multiplies – gain is achieved with special electrodes – field plates – creating a regions with high gain



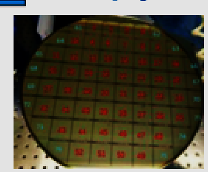
https://indico.cern.ch/event/1649276/attachments/3223769/5745318/20260213_DetectorSeminar_SiEM.pdf

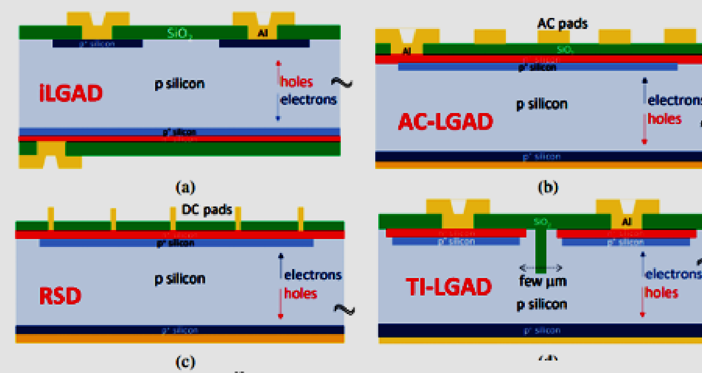
DRD3

Fill factor – largely solved (ongoing optimization studies)



ATLAS 2x2 cm2 (15X15, 1.3 mm2 pads) produced by IME Beijing

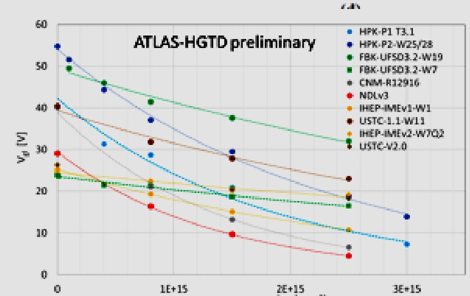




Radiation hardness – improved and not yet solved

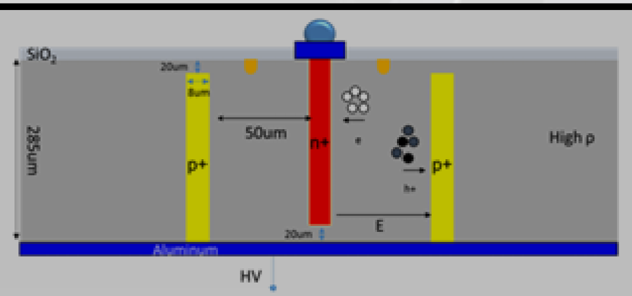
- Loss of gain layer doping with fluence
- Carbon co-implantation improves radiation hardness by 4-5x
- Ongoing studies to improve (compensated LGADs, Partially activated boron…)
- **Does impact ionization works at FCC-hh fluences?**

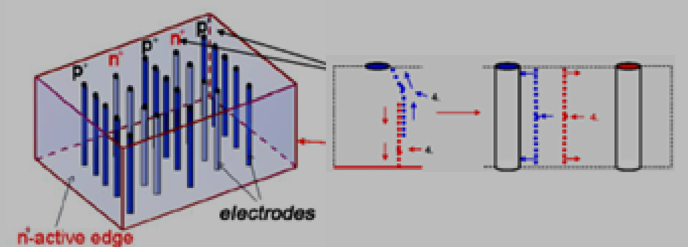
https://indico.cern.ch/event/1088953/attachments/2340254/3989714/GK-CERN-Seminar-Timing-HL-LHC.pdf

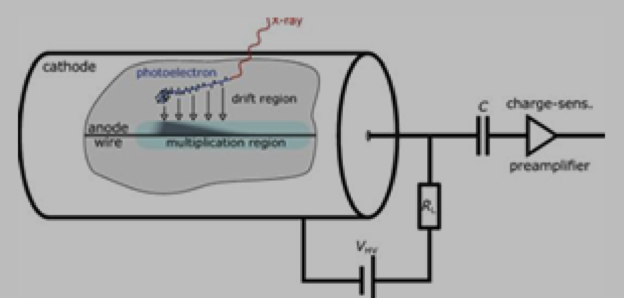


Motivation: radiation hard device with gain

- What about silicon 3D detectors?
  - The doping of columns of 3D detectors is almost impossible to control with the required precision – achieving high enough **electric field with doping is not possible**
  - The aspect ratio of HEP producers (FBK, CNM, Sintef) have been 25:1 so thick detector had column widths of ~10 μm which also limited cell sizes to ~50x50 (25x100).
  - Improvement of aspect ratio to 100:1 would lead to manufacturing of very narrow columns <1 μm with thicknesses of ~100 μm **which could lead to electric fields high enough (~30 V/μm) for multiplication** (goals established during the ECFA detector roadmap document preparation)
  - **We have observed gain multiplication in irradiated devices in the past** (ATLAS/CMS) at the tips of the – which actually limits the operation voltage for those detectors.
  - The CMOS processing line at **IME-CAS Beijing** has properties which are required for achieving the gain through geometry – studied before in simulations







IME-CAS devices overview

- Columns as narrow as 0.5 µm with aspect ratios of close to 100:1.
- The devices as thin as 30 µm
- Pixel detectors with cell sizes down to 15x15 μm^2.

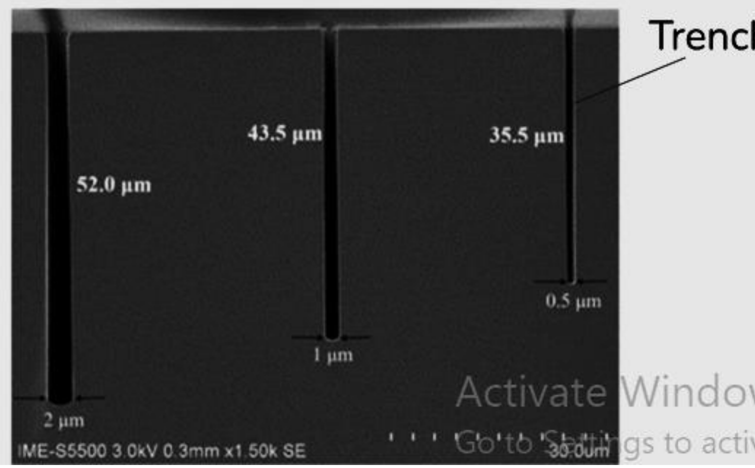
- Unlike in LGADs the gain is achieved simply by geometry and is much less affected by precise doping levels of columns.

- **As the gain is achieved by geometry and doesn't critically depend on doping levels they are much more radiation hard than LGAD detectors.**

Sensor devices manufactured by:

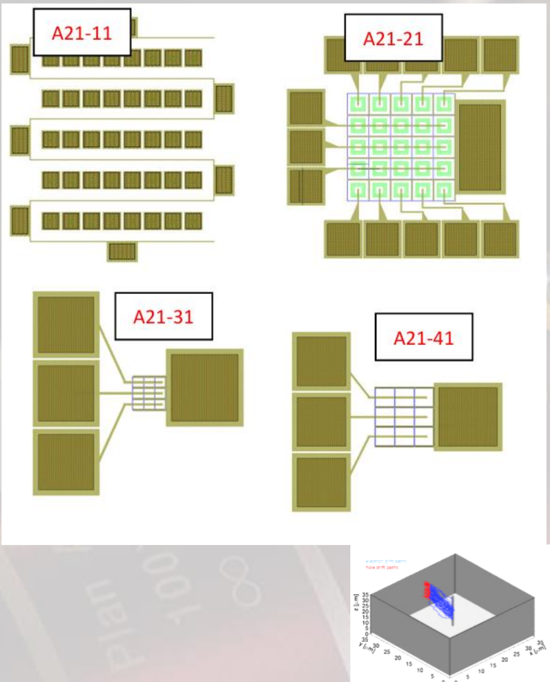
IMECAS

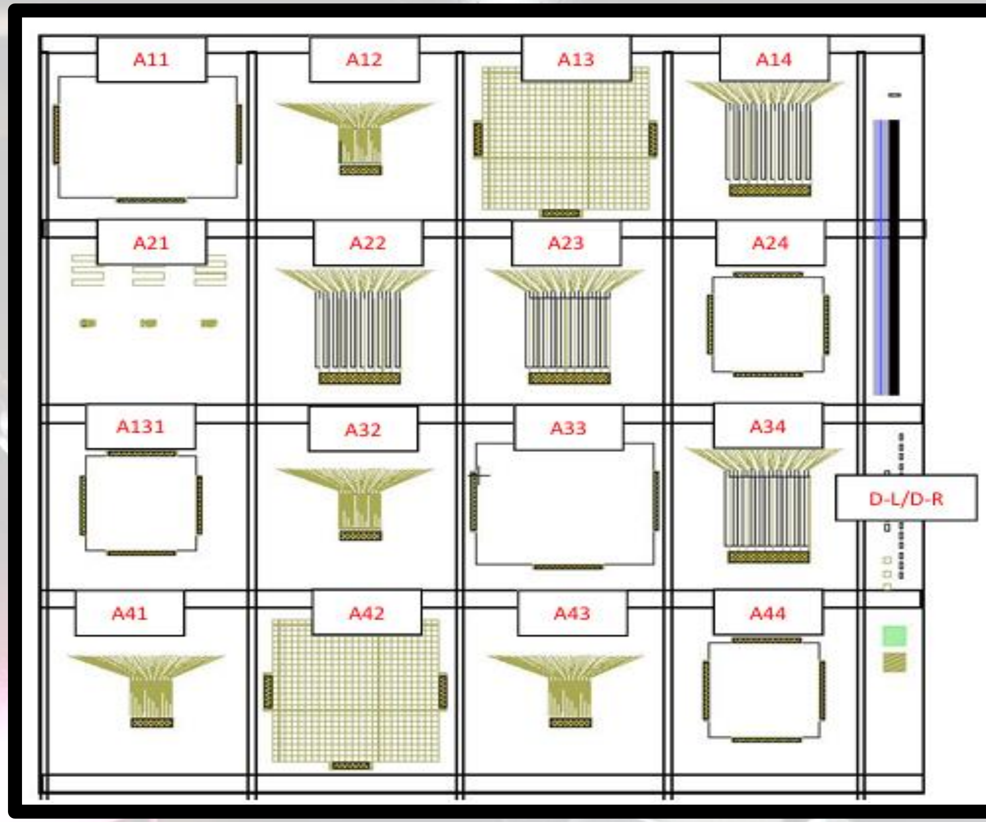
- 8-inch CMOS compatible process
- Columns manufactured using **DRIE** (Deep Reactive Ion Etching)
  - Aspect ratios up to 100:1
- Motivation: **geometric gain** (wire proportional chamber in Si)



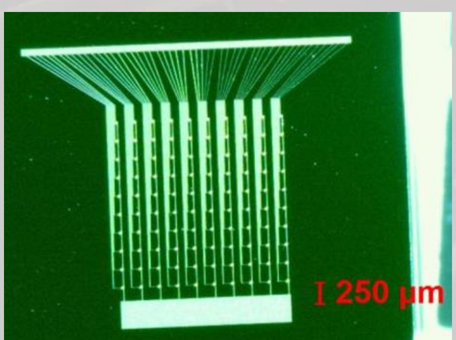
Different IME-CAS structures

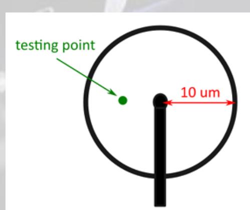
HEP structure – pixel detector



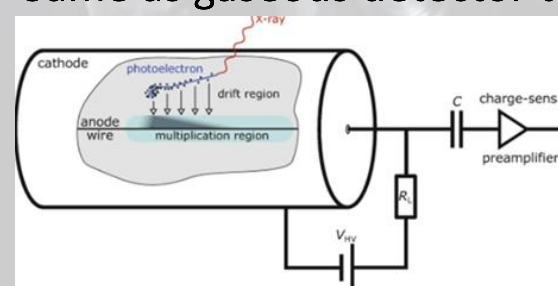


Non- HEP structures – array if tiny columns (straws





Same as gaseous detector tube



3D STRAW TUBES

Impact ionization studies

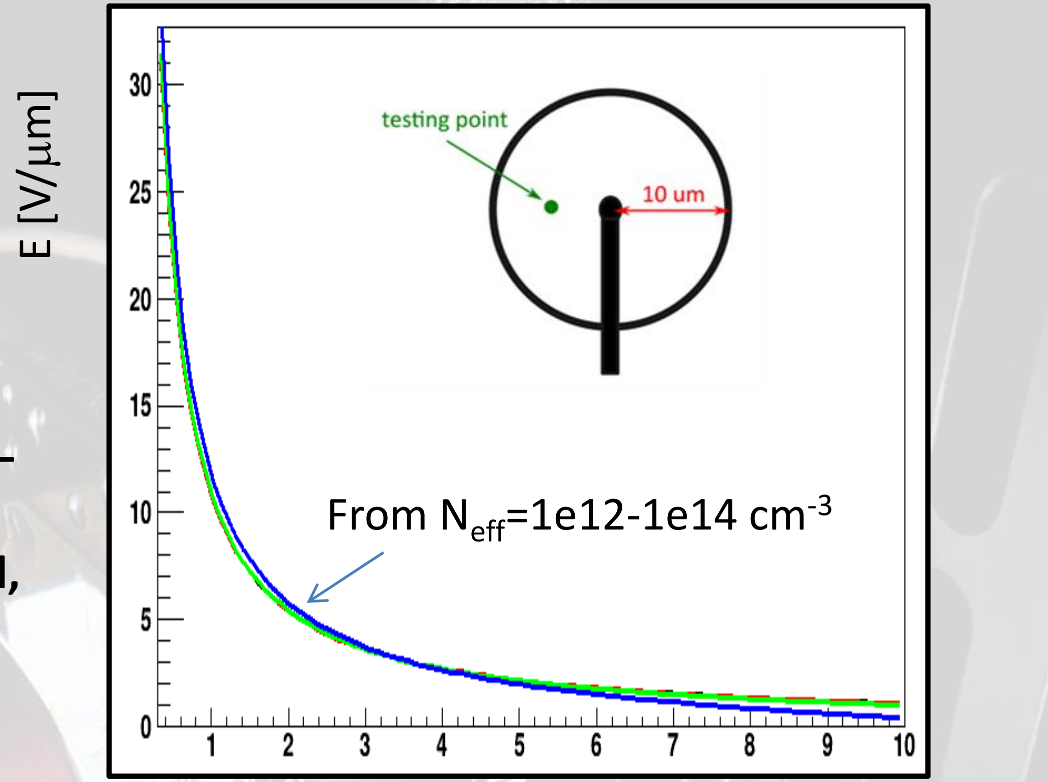
Ideal structures to study impact ionization – especially after irradiation – **as the field can be solved analytically**
Experimentally this is very complicated, but we managed to do it.

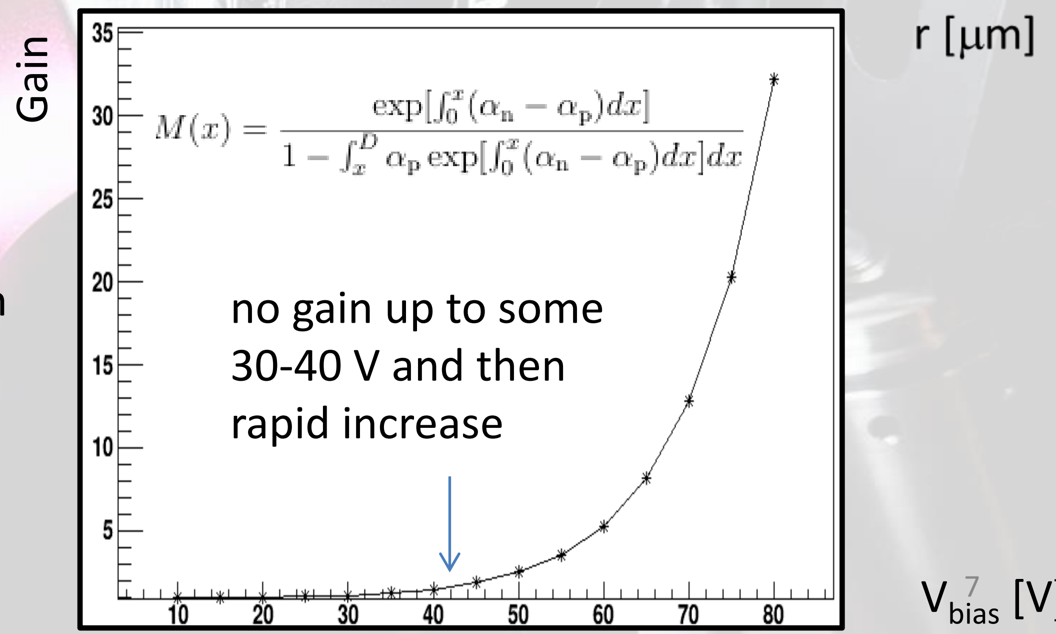
Therefore, we will be able to study impact ionization at severe fluences.

$$E_r(r) = \frac{V_0 - \frac{e_0 N_{\mathrm{eff}}}{4\varepsilon\varepsilon_0}(b^2 - a^2)}{r \ln(b/a)} + \frac{e_0 N_{\mathrm{eff}} r}{2\varepsilon\varepsilon_0}$$

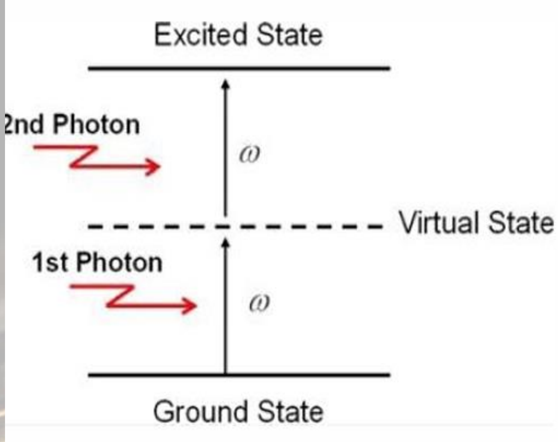
a=0.5 μm and b=10 μm

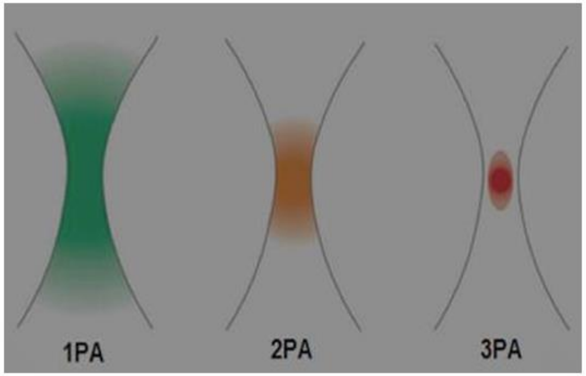
At the z=15 μm one can calculate analytically the gain – so fitting and extraction of impact ionization is straightforward

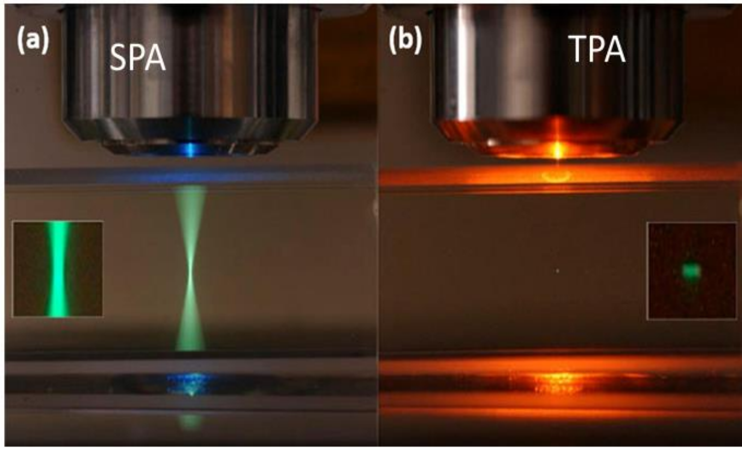




Characterization technique: Two Photon Absorption - TCT







Generation of free carriers by light and observing their drift – Transient Current Technique – has been a workhorse in many semiconductor detectors (lots of advantages):

➢ Two photon absorption is a step forward as it allows a very localized deposition in a voxel (~ 1-2 mm x 10 mm) . The key is to have very fast ~100 fs laser pulse focused to 1 mm with high enough energy

➢ 3D detectors are actually one of the best (if not the best) case studies for these techinque

➢ Large Laser facilities (such as ELI beams in Prague) allow even more photon absorption 3PA (longer wavelengths and more power) reaching very small voxel sizes

TCT set at at ELI

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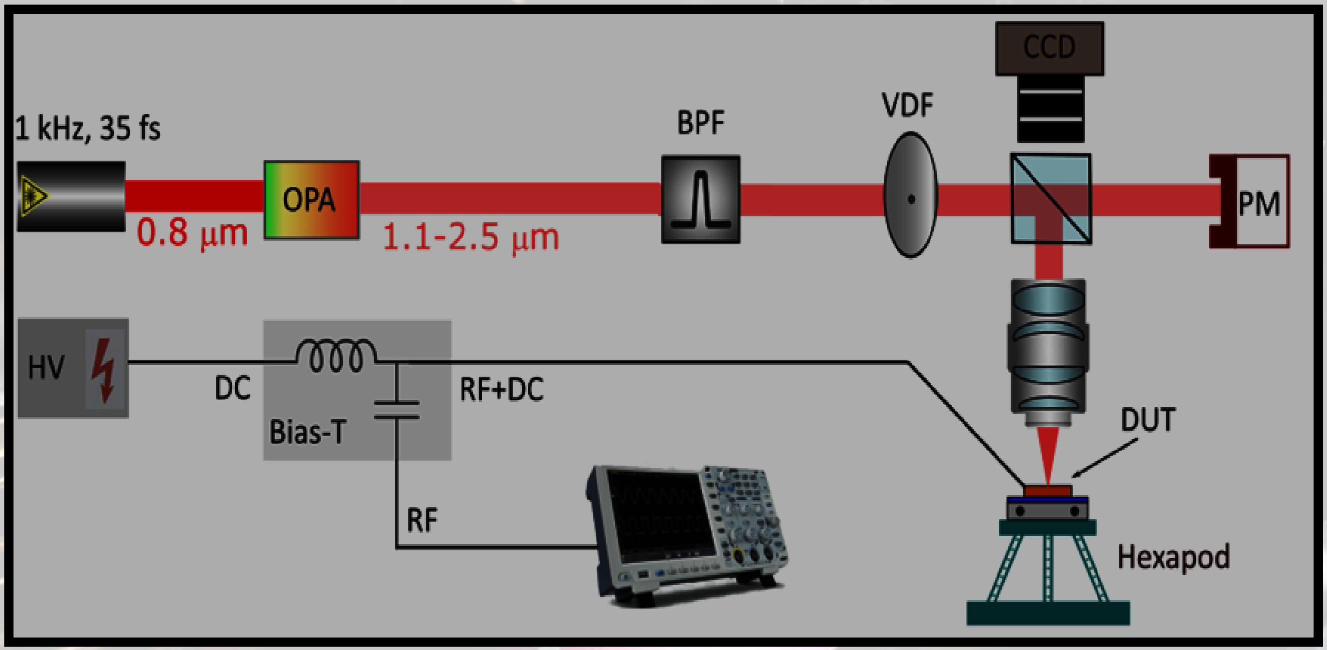


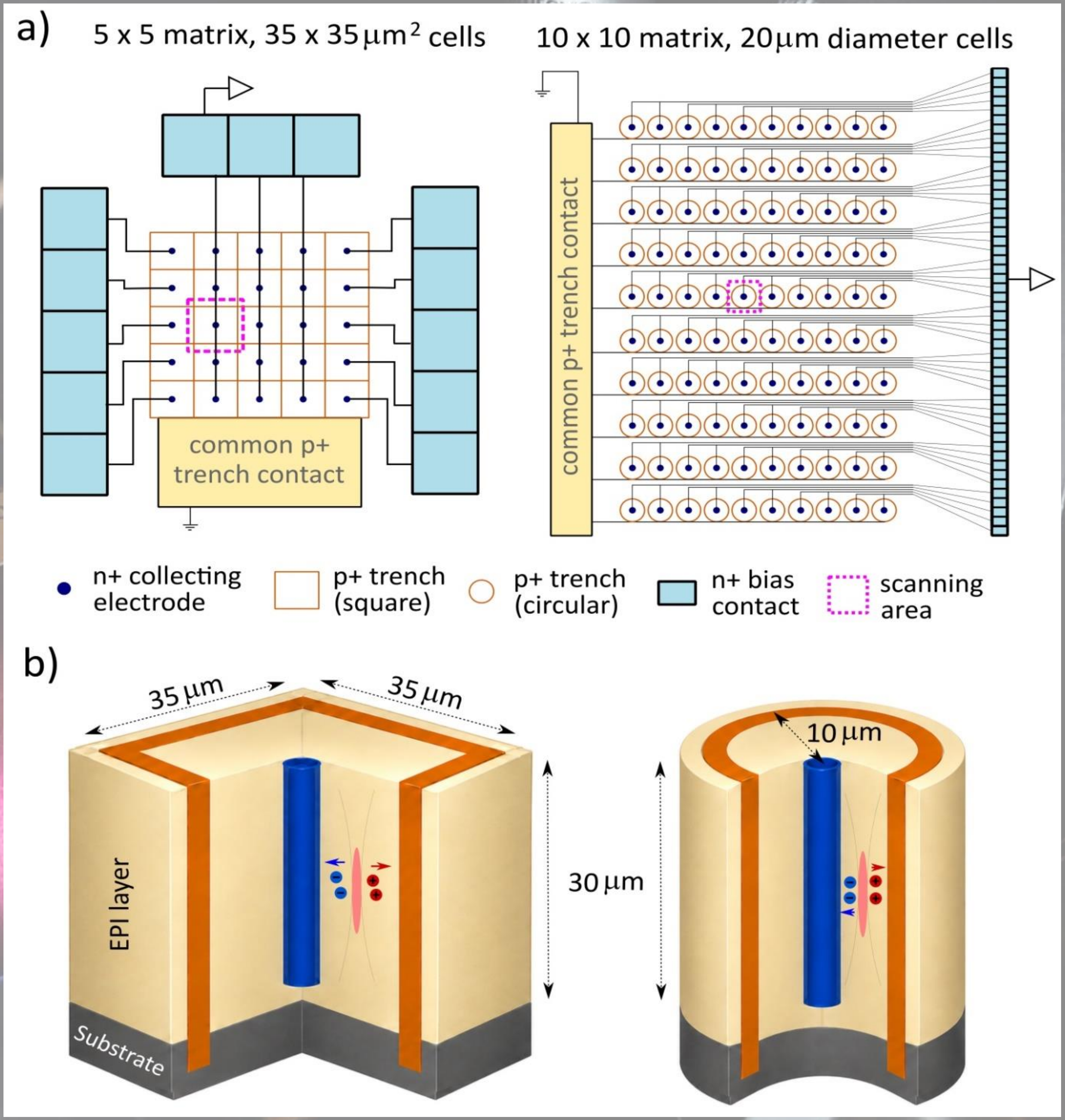
Place	ELI Beamlines
Operational modes	Single and two photon absorption (SPA and TPA)
Pulse energy on sample	Variable by ND filters (accuracy: 0.2 pJ) 800 nm (SPA), 1550 nm (TPA)
Wavelength	1550 nm, ~ 150 fs 800 nm, ~ 50 fs
Pulse width in sensor	
Focus waist radius	0.85 µm (SPA), 1.5 µm (TPA)
Rayleigh 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 a 2.5GHz, 20 GS/s oscilloscope.

Investigated Devices

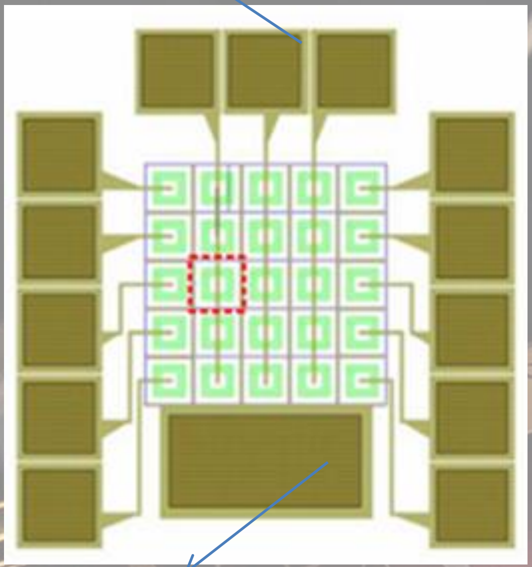
1

2

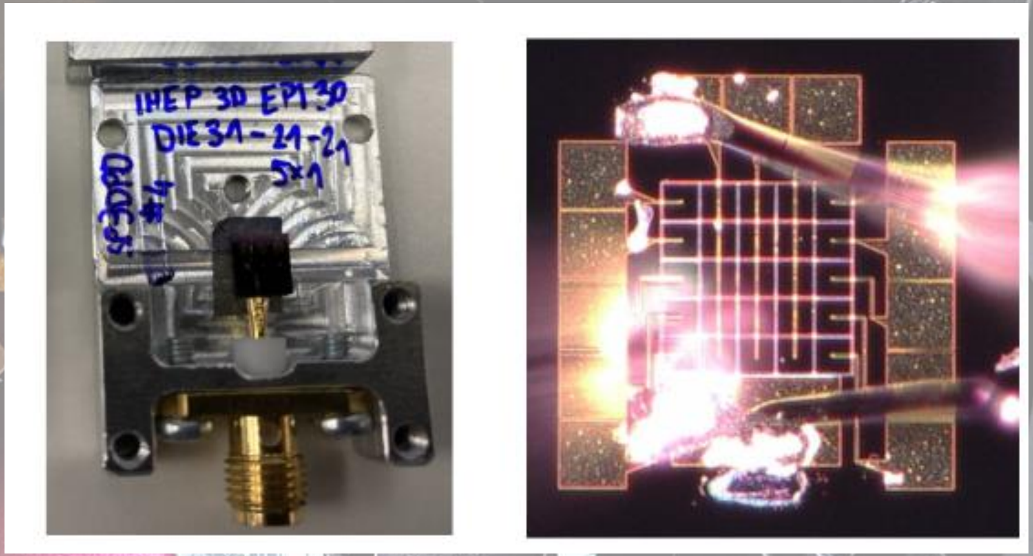


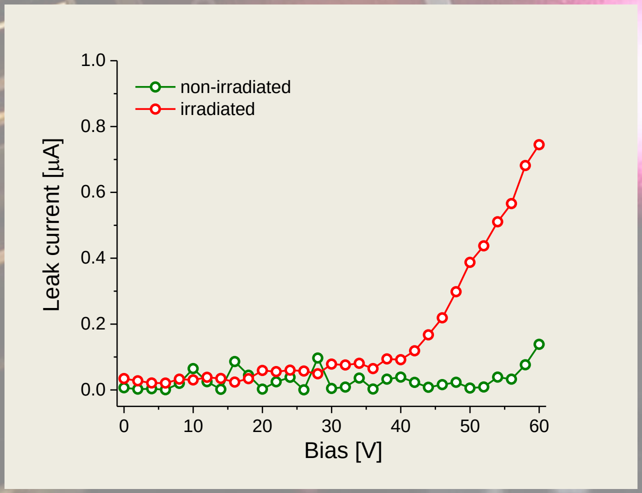
1 3D trench with square shape

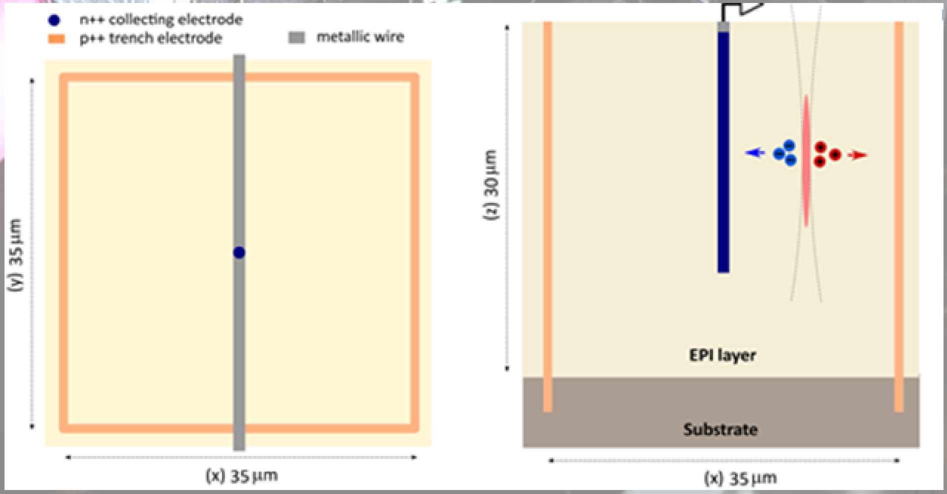
Column readout



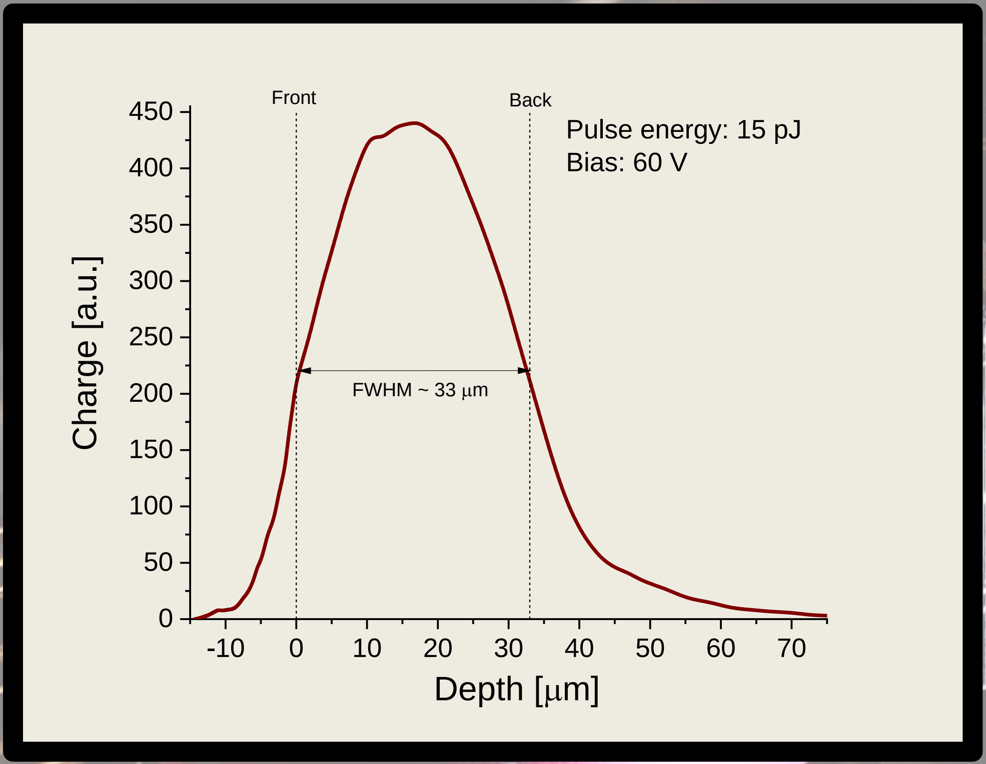
Trench electrode (V bias)

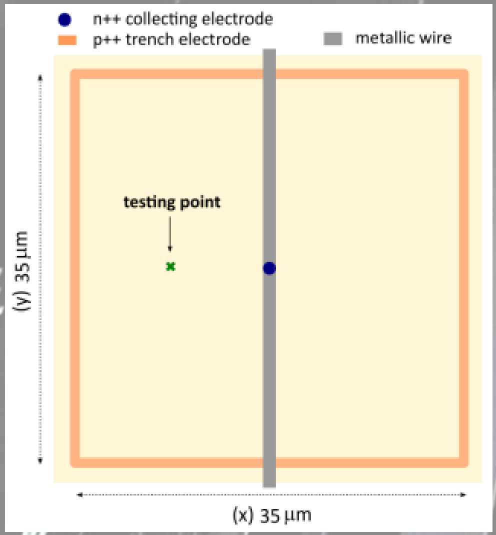






Z- Scan

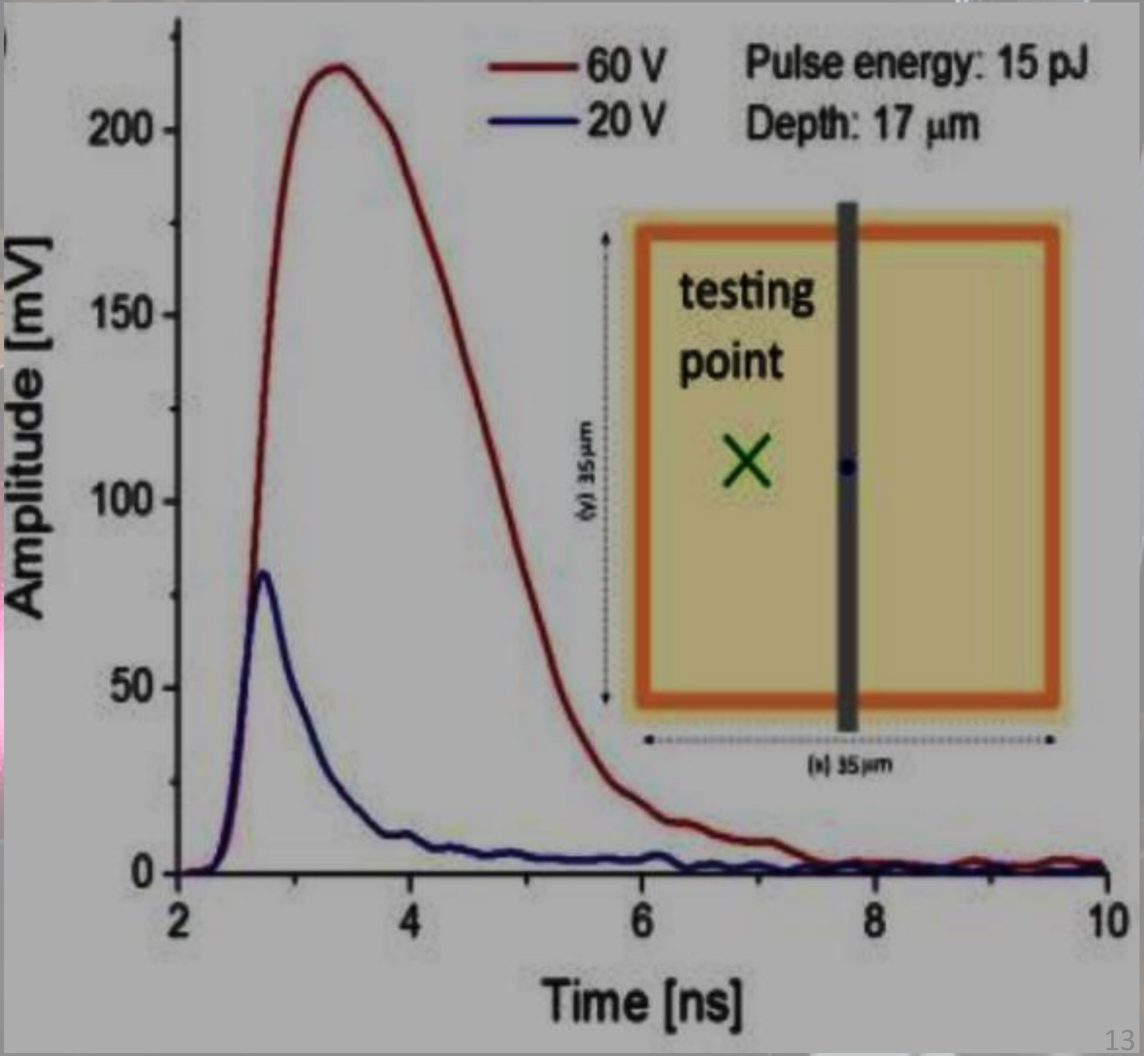




- ✓ FWHM of the profile is close to the nominal thickness which is 30 um.
- ✓ We checked profiles in a few different points with very similar results.

Waveforms at two biases: 20 V and 60 V

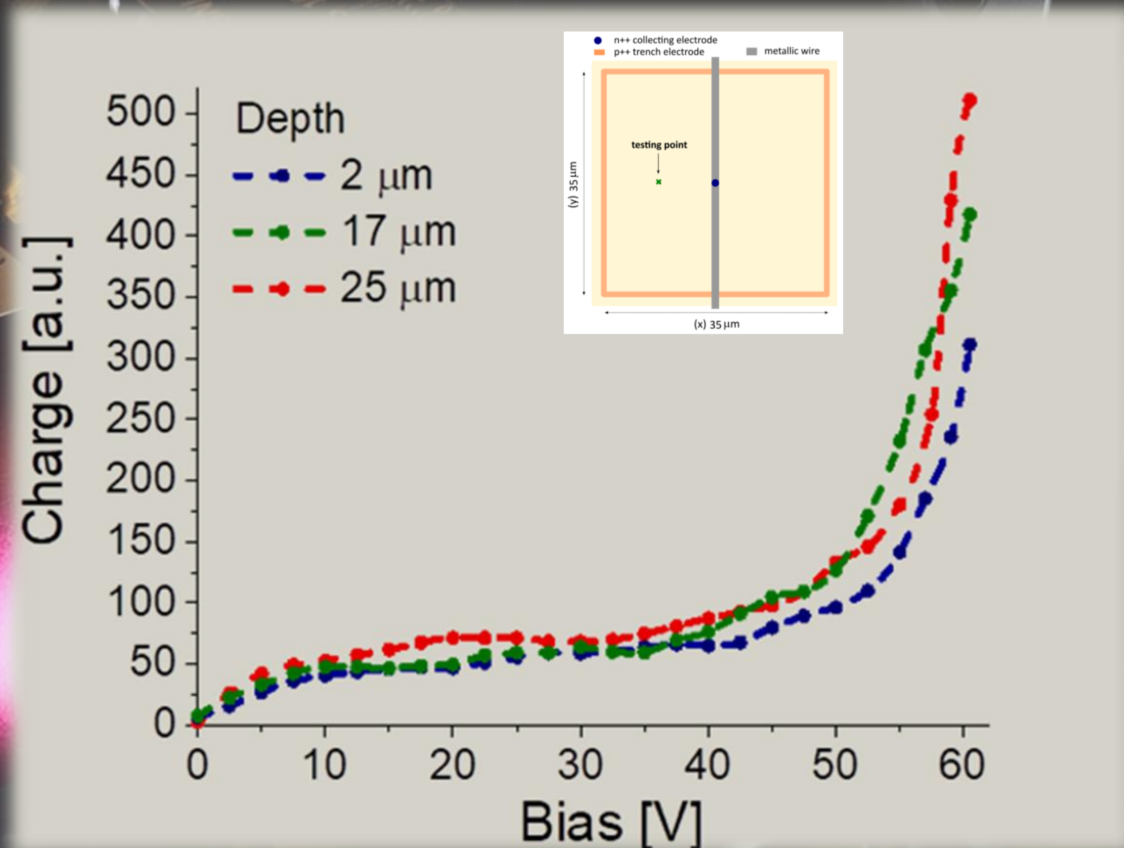
- ✓ **Another indicator of charge multiplication is the extended duration of the induced signals which results from the drift of the secondary holes to the ohmic contacts after the primary electrons undergo multiplication. Obviously enlarged amplitude can be seen.**



Charge collection and gain confirmation

- ✓ After the initial depletion phase the device becomes fully depleted at around 25V, where the collected charge reaches a plateau.

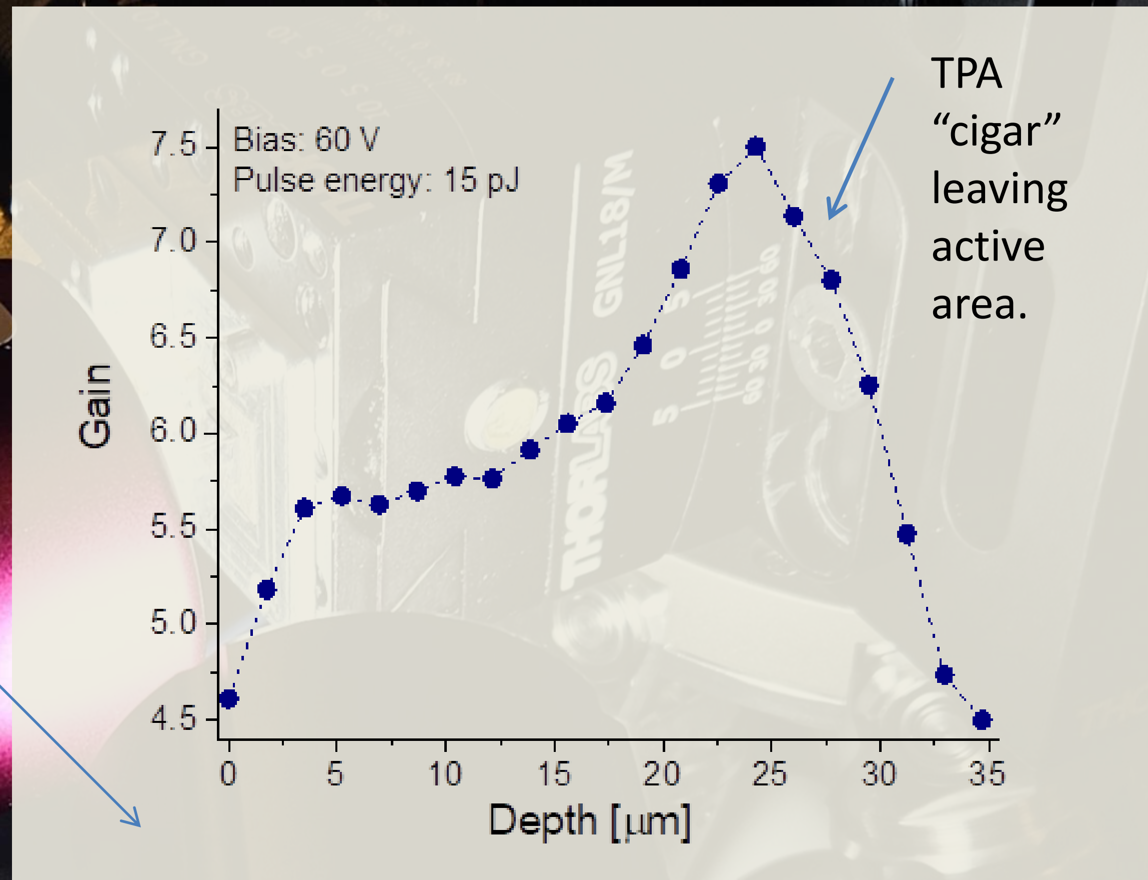
- ✓ Steep increase of the collected charge that coincides with the rise in the leakage current clearly shows the avalanche breakdown

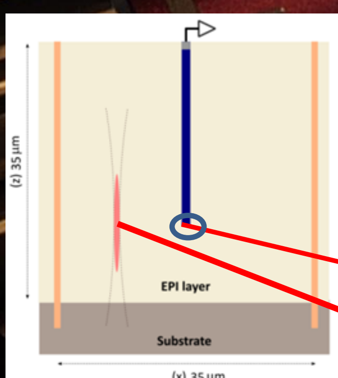


Gain Depth Dependence

At 60 V and at the depth of 25 µm the gain is around G=Q(V)/Q(Vfd)~7.5

“cigar” leaving active area



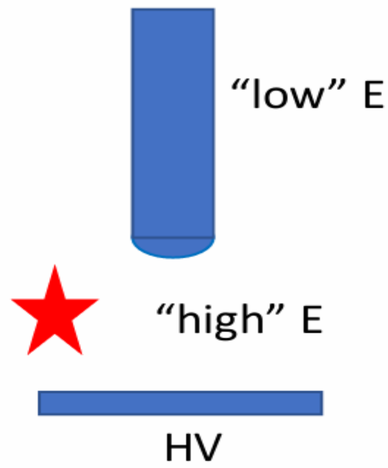


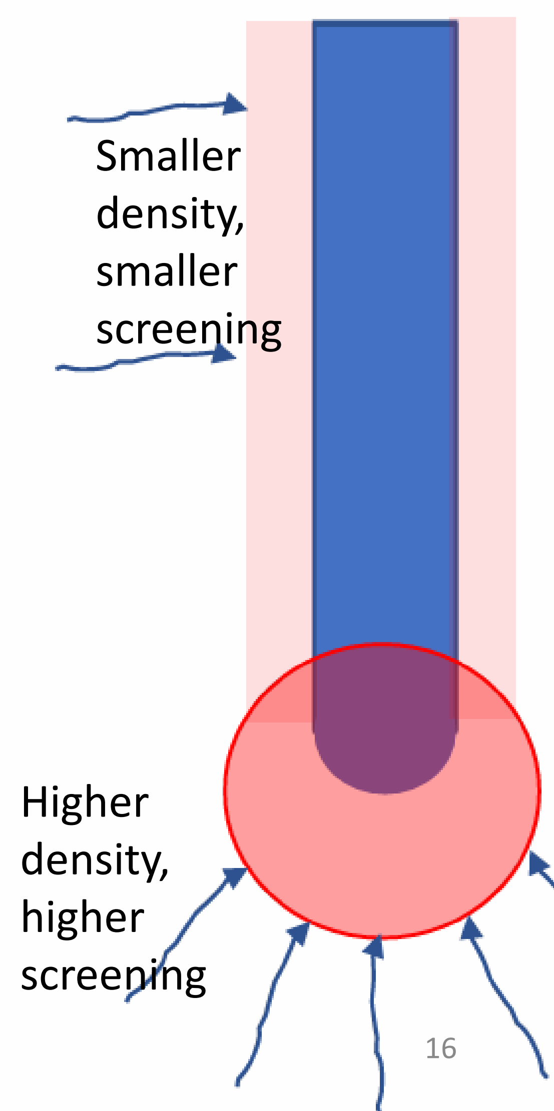
Tip of n+ electrode

Illustration of focal point at the tip positon and TPA ellipsoidal voxel

Why don't we see early breakdown?

Why don't we see early breakdowns or larger collected charge difference in the bottom – close to the tip (large gradients)?





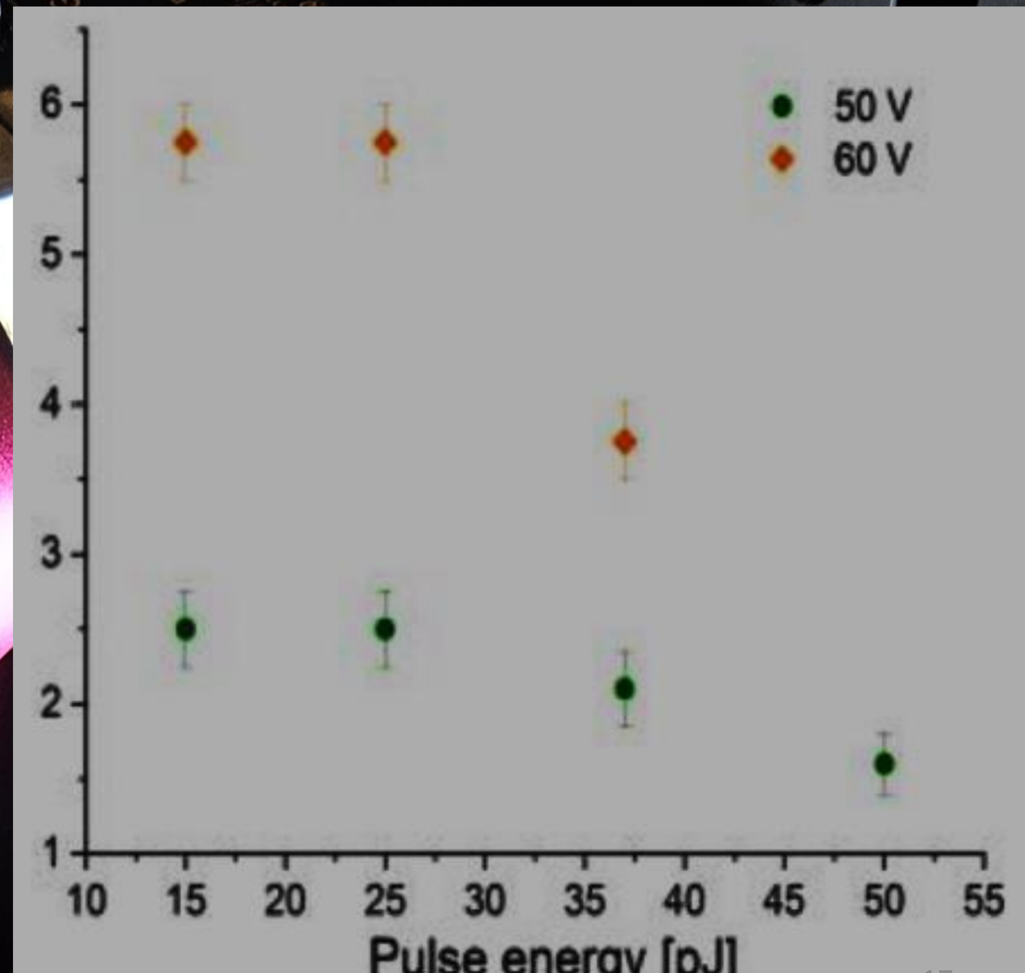
Tentative explanation:

- For vey narrow column the gain in a small volume creates enough charge even for mip to screen the field – self quenching
- For conventional 3D this is not the case – 10 µm column is too large
- Along the electrode the difference is very small – small density no large screening

Gain self-quenching demonstrated

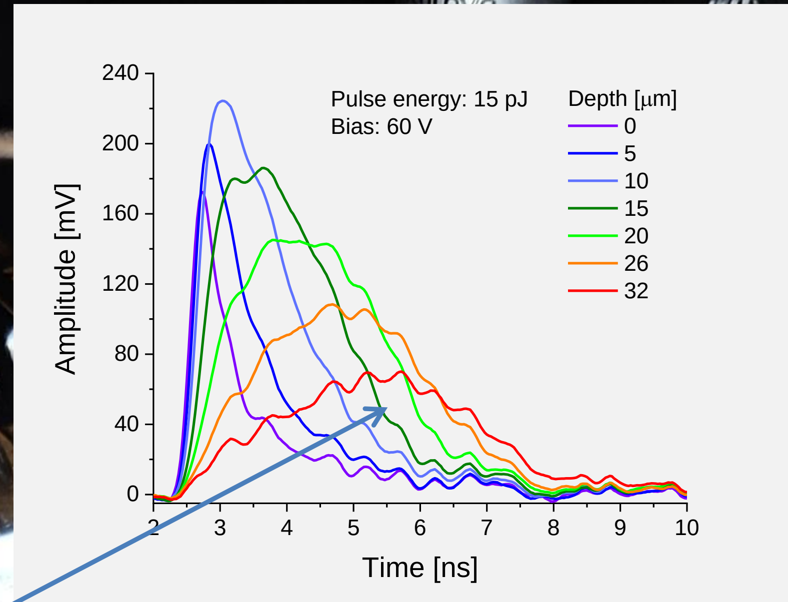
Screening observed- gain depends on carrier density

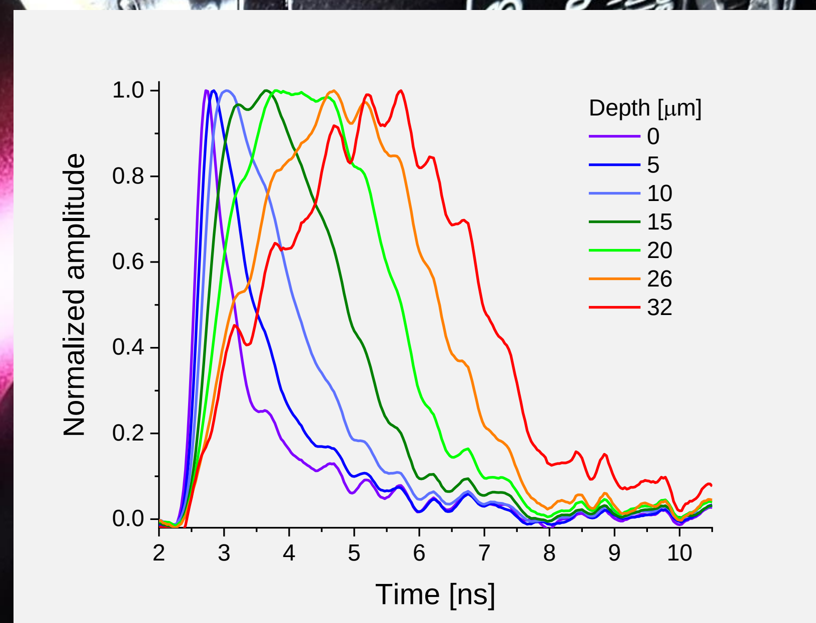
- ✓ Gain suprression is observed
- ✓ **The small column diameter – gain stabilizer**

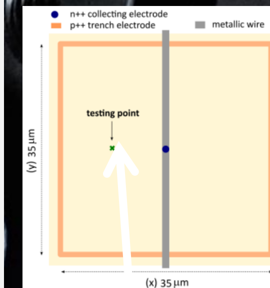


Slew Rate Depth profiling

Signal becomes slower and arrives later with increasing depth.





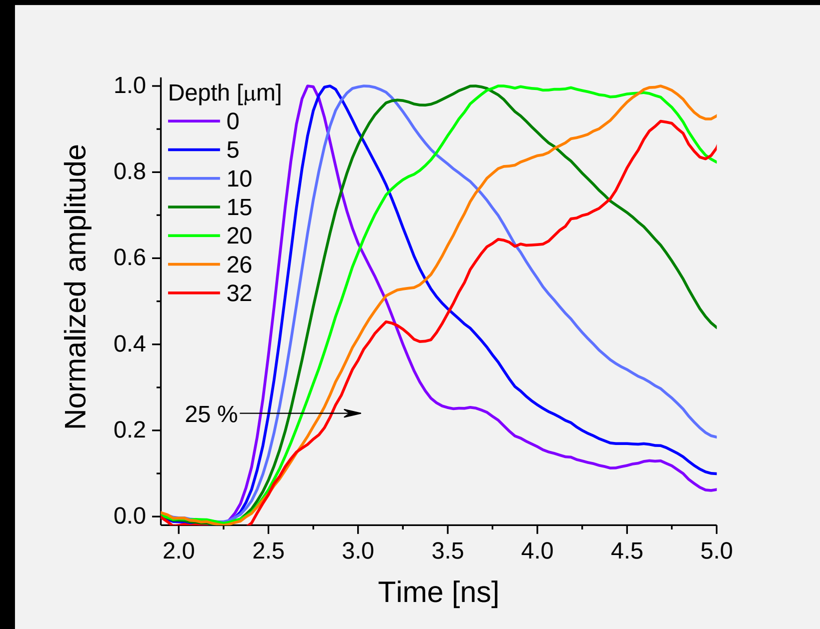


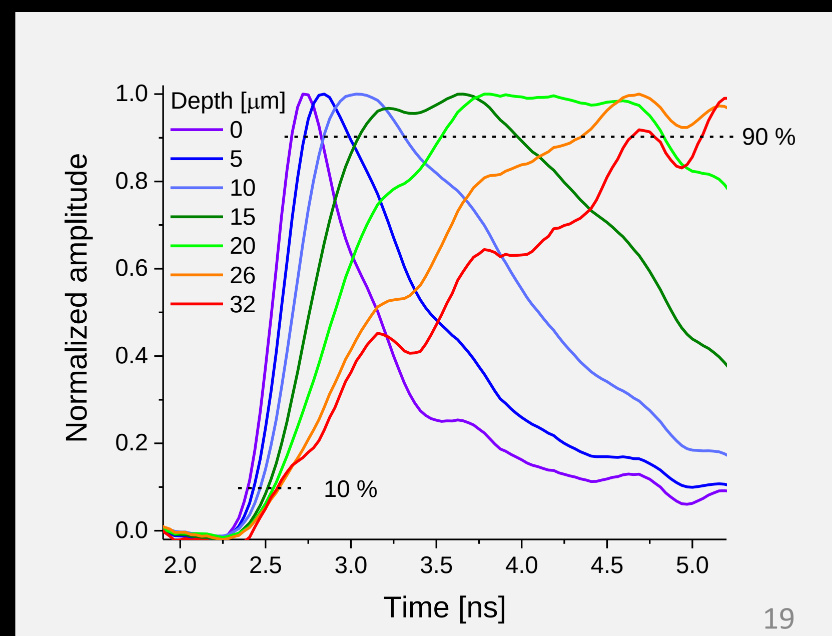
Position (x,y) where z-scan was performed.

When the “cigar” enters substrate the carriers need to diffuse to the active zone – longer signals

Large slew rate difference across the sensor results in hit position dependent jitter for MIPS:

- ➢ Timing distributions will be skewed – different to LGADs

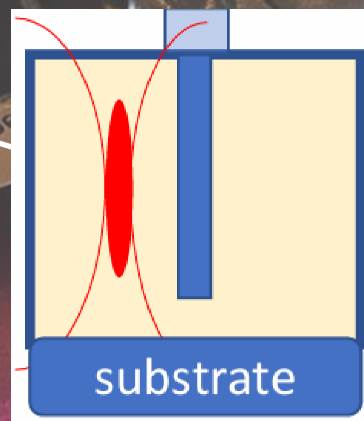


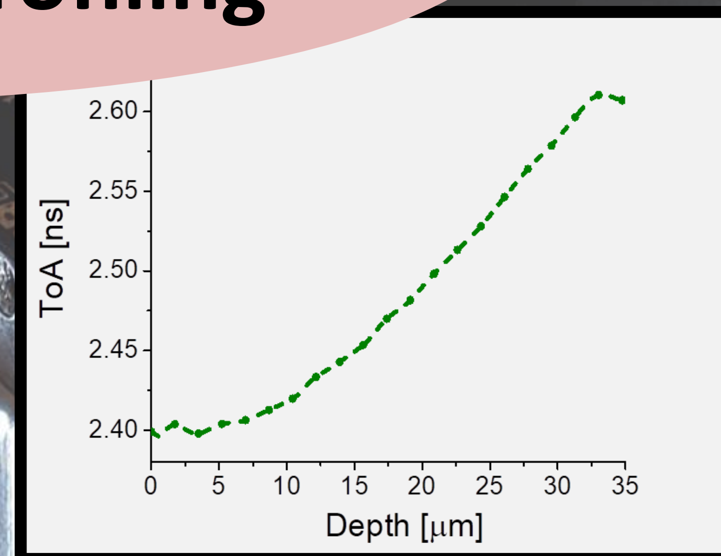


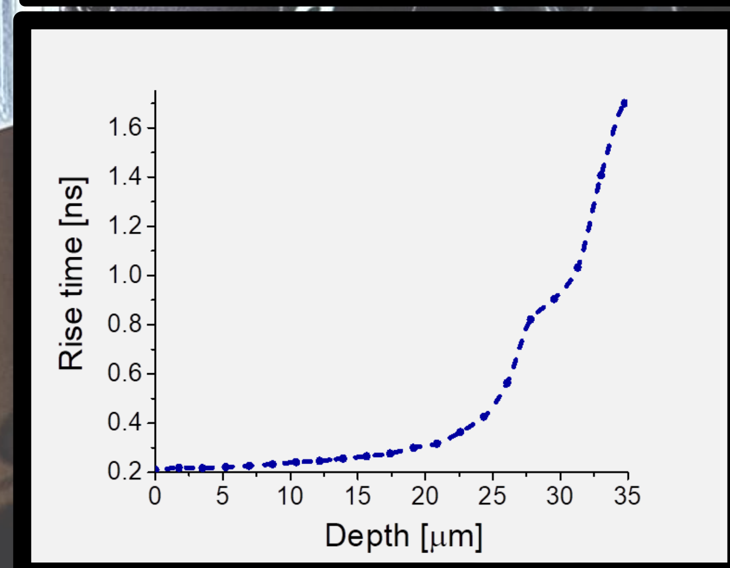
Already shown in previous slide but here magnified (selected time window reagion).

Rise Time & Time of Arrival Depth Profiling

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





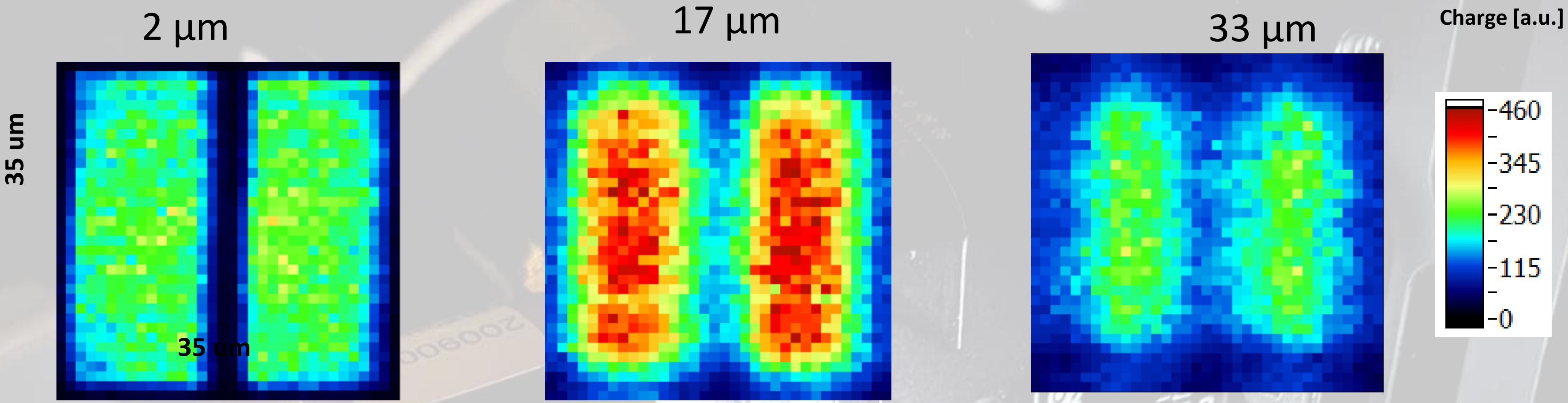


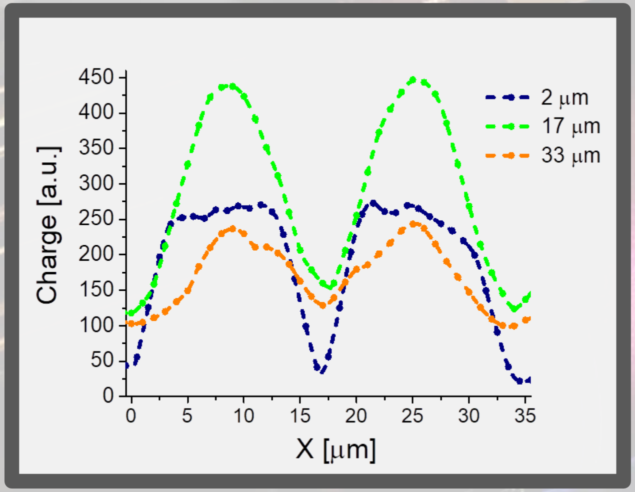
ToA and RT is increasing with increasing depth;

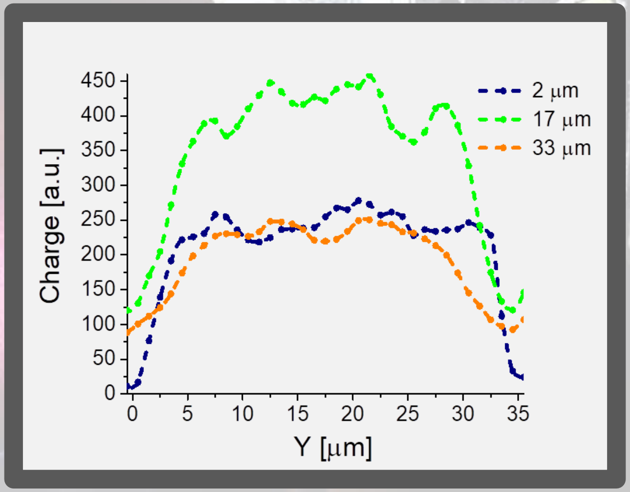
- gain increases but also screening effect (slower movement of clouds of holes).

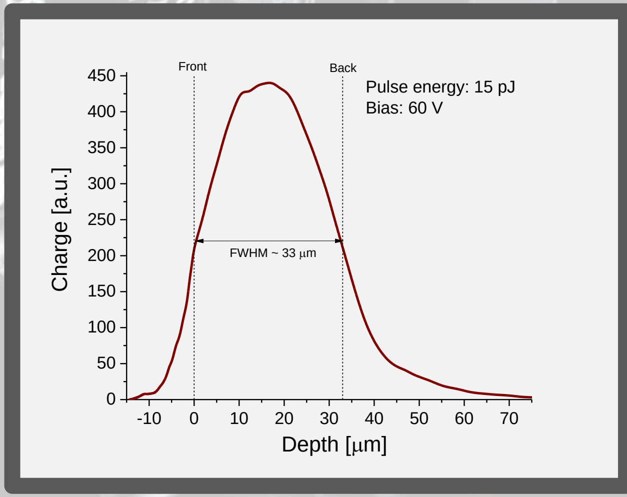
When the “cigar” enters substrate the carriers need to diffuse to the active zone – longer signals

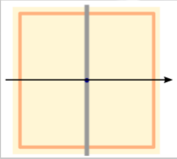
Charge vs. X
Charge vs. Y

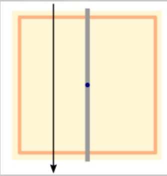


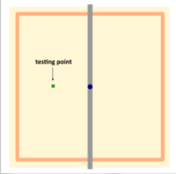






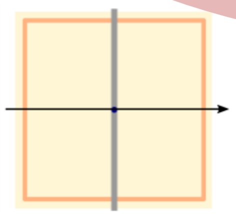


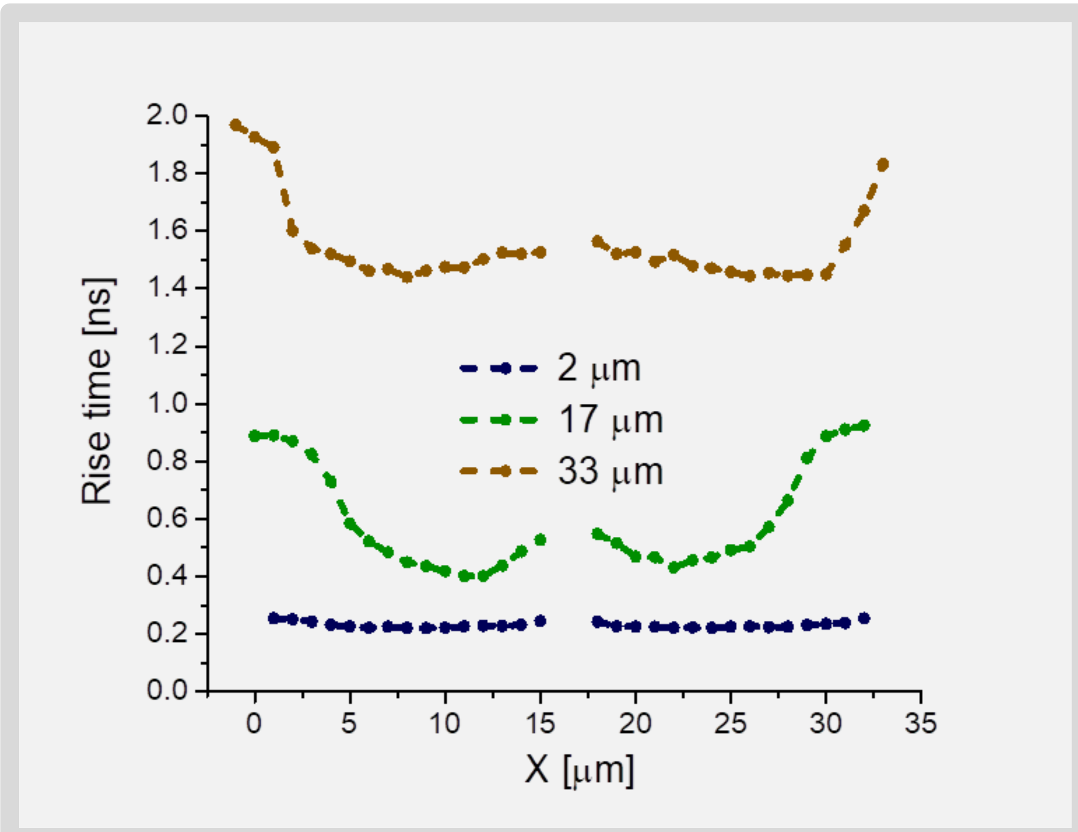


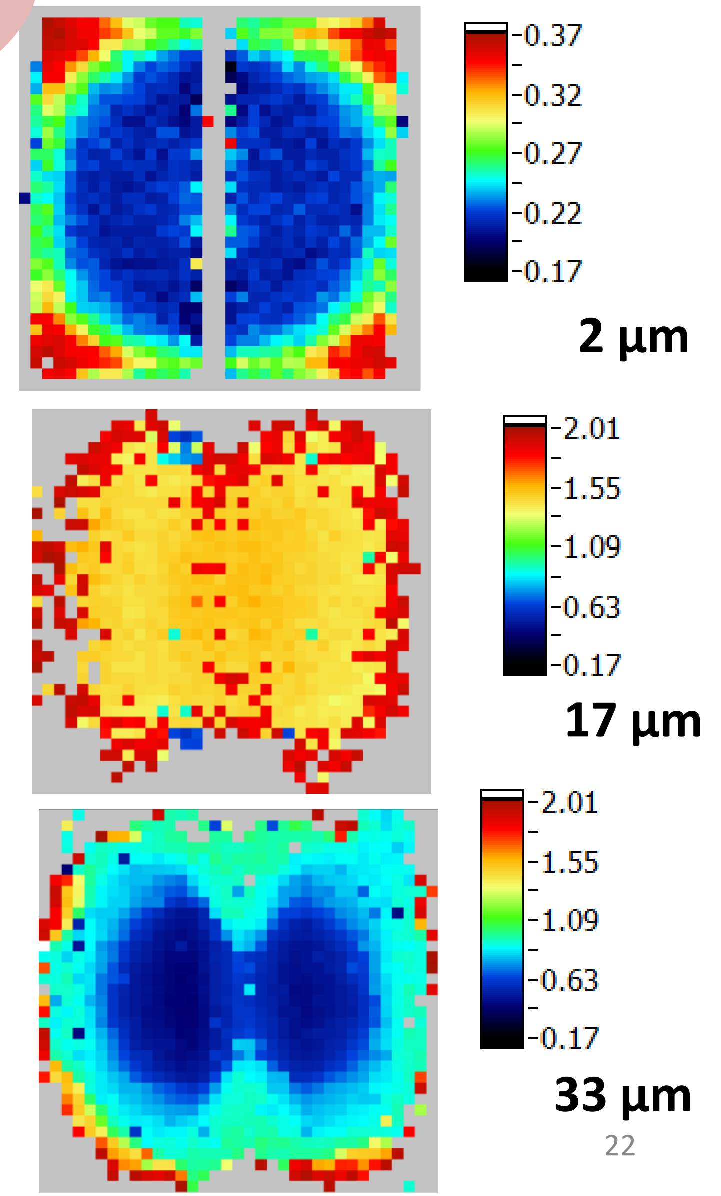


Lateral variation of Rise Time (RT):

In X direction







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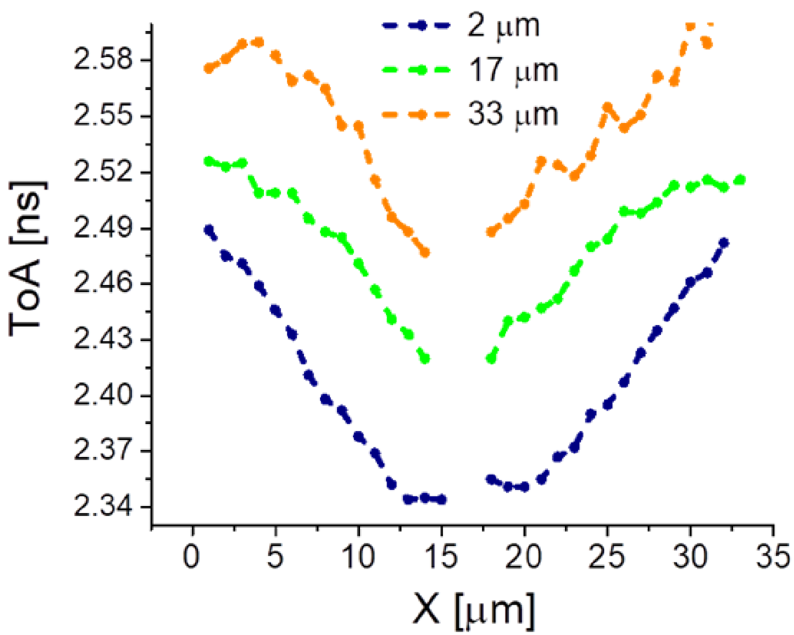
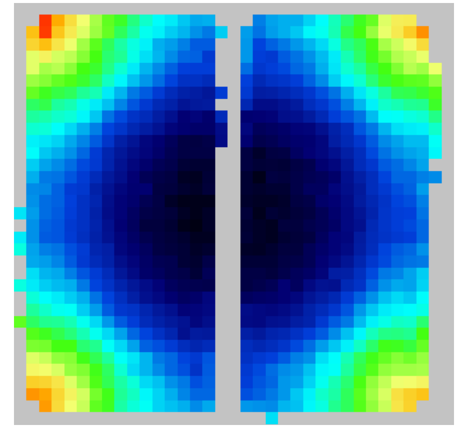
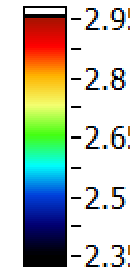
Lateral variation of ToA:

In X direction

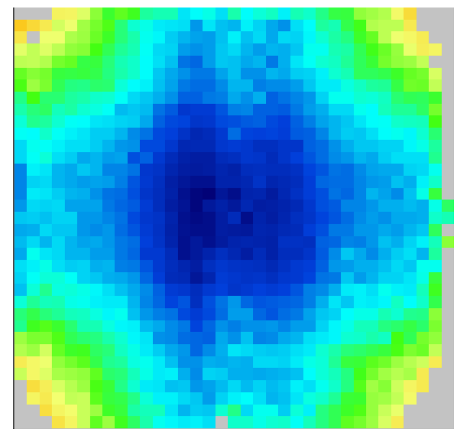
ToA



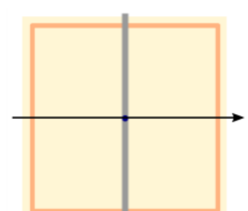


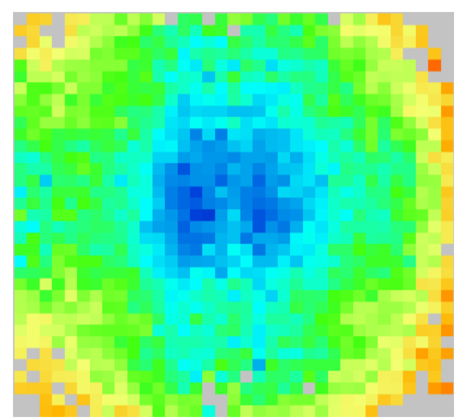


2 µm



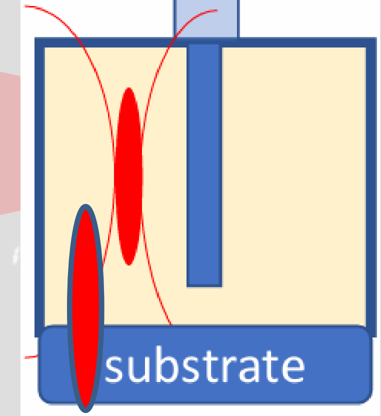
17 µm



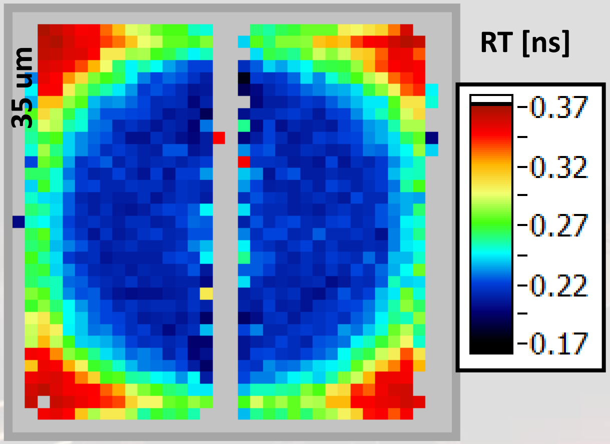


33 µm

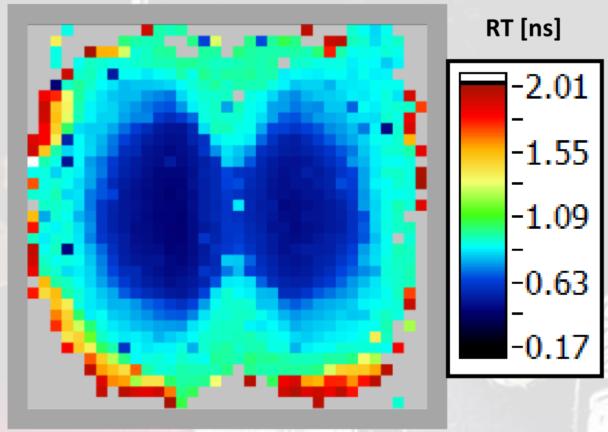
Rise Time spread



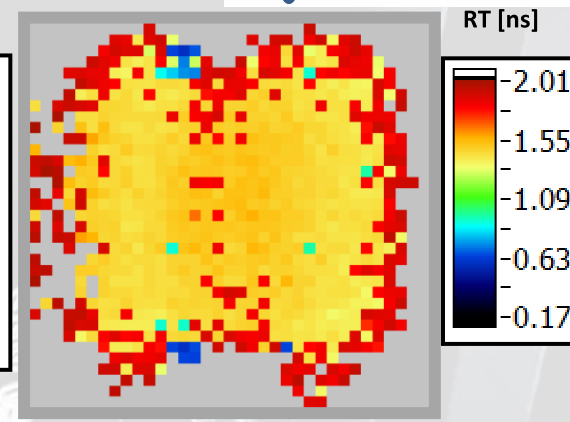
2 µm

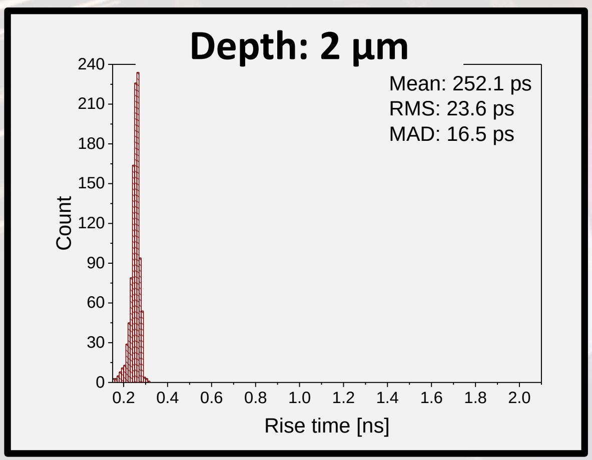


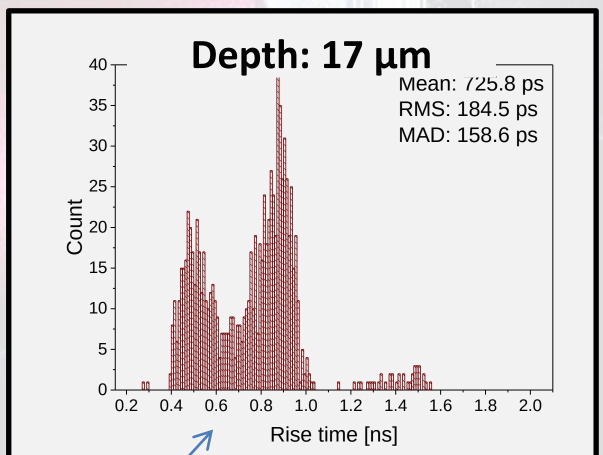
17 µm

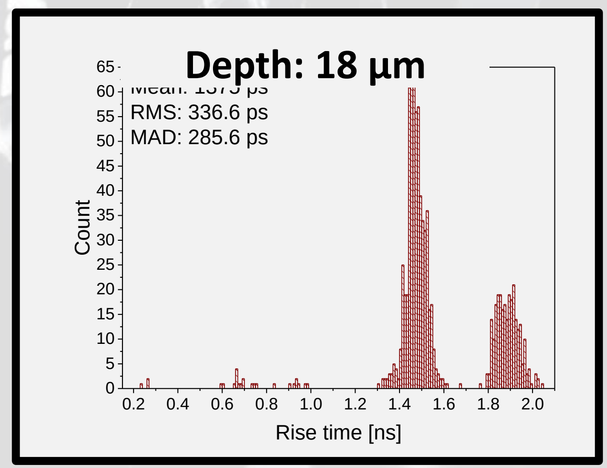


33 µm



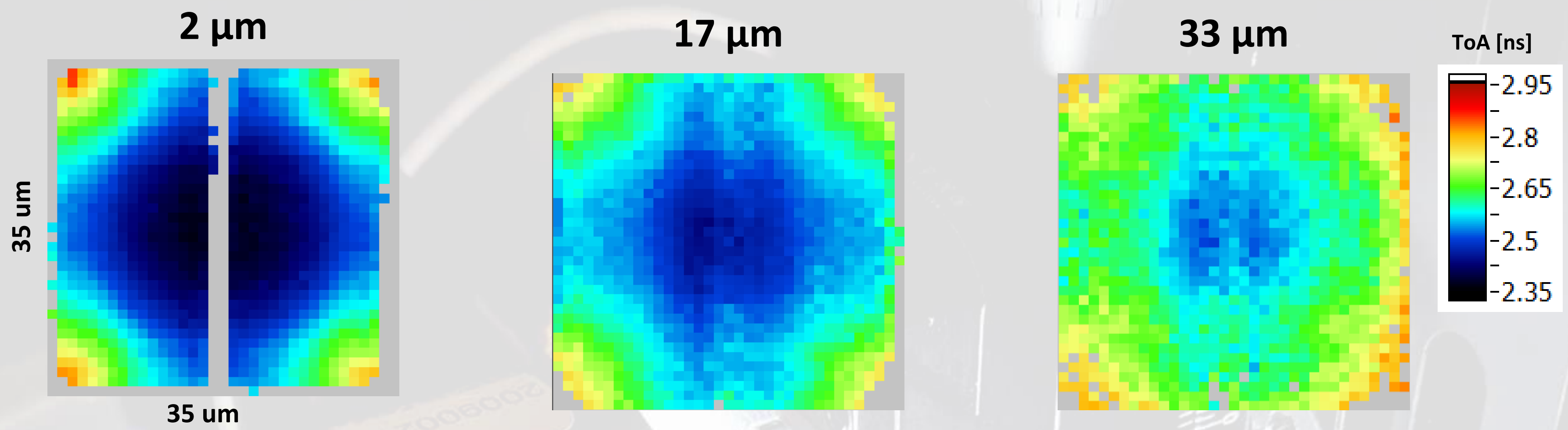


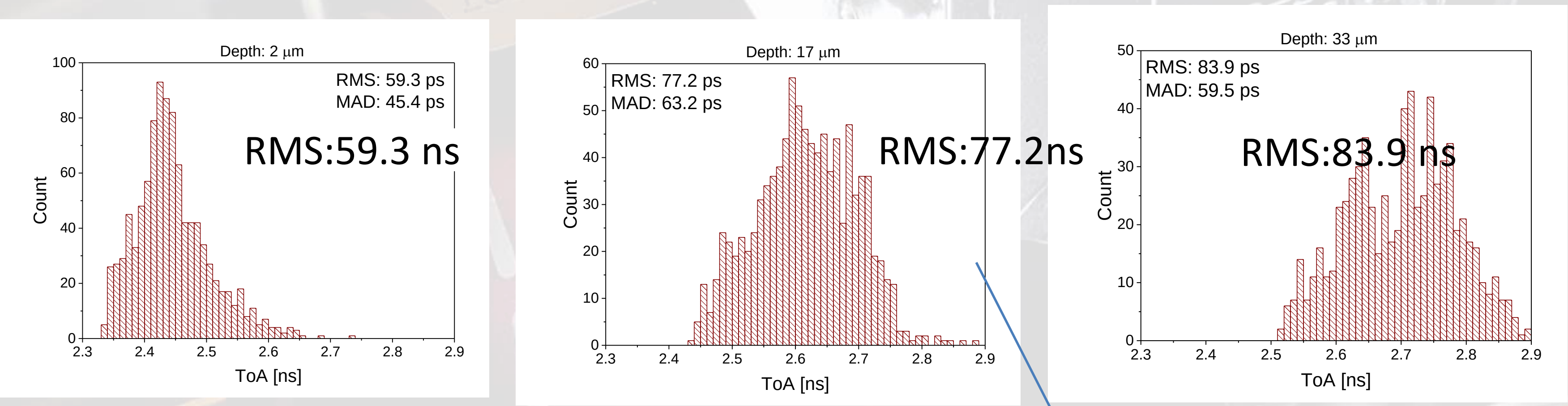




TPA vortex covers different el field regions

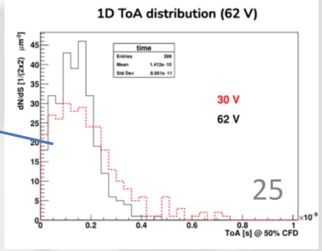
ToA spread





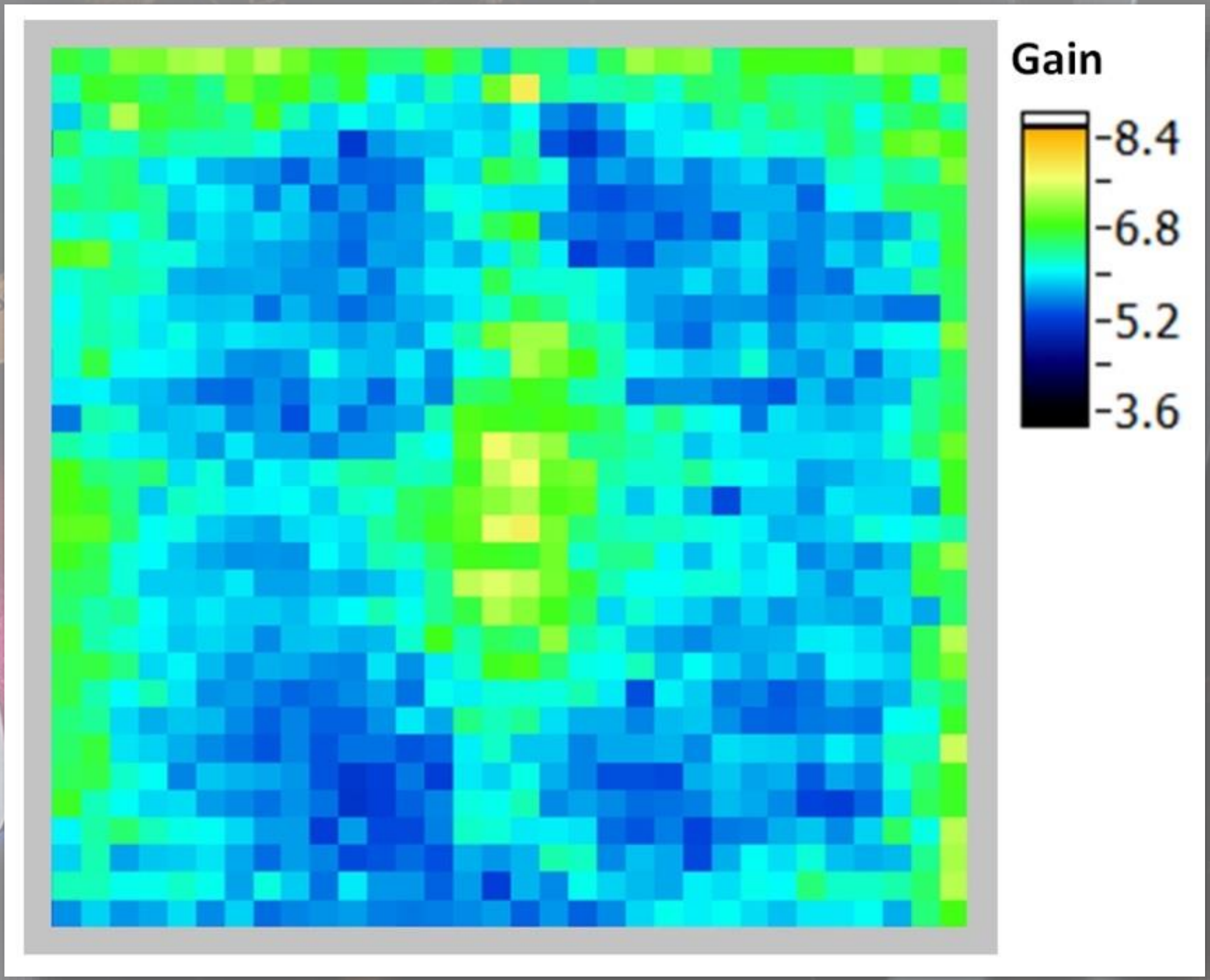
Distribution of ToA at different depths is much more homogenous than rise time. However shifts towards bigger values with depth is clear. Also RMS increases vs depth from 59.3 ps close to top surface to 83.9 ps close to the bottom.

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)



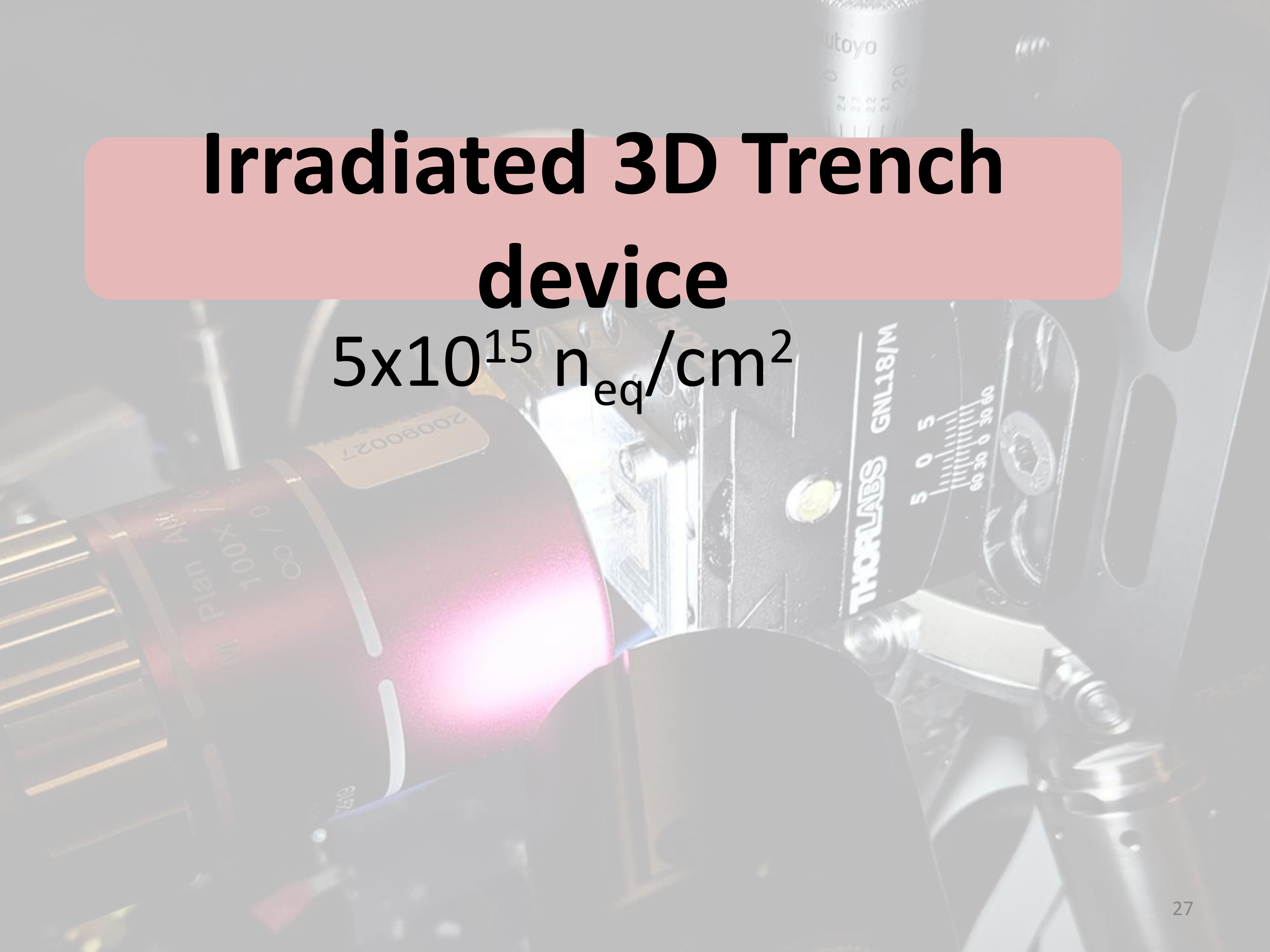
2D Gain Map

Pulse energy: 15 pJ
Depth: 17 um



Irradiated 3D Trench device

$5x10^{15}\ n_{eq}/cm^2$

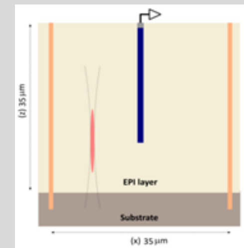


Gain after irradiation and other control plots

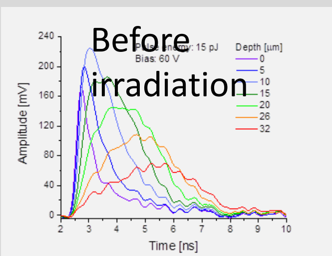
at +20^{0}C (RT)

We see changes in performance:

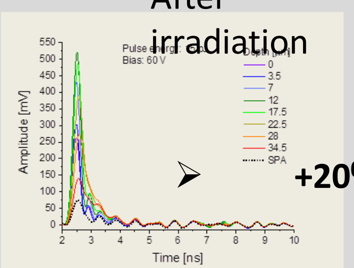
- ➢ no plateau at full depletion but continuous increase of charge (trapping – geometry related);
- ➢ onset of gain at about the same voltage;
- ➢ slightly less gain and larger depth dependence;



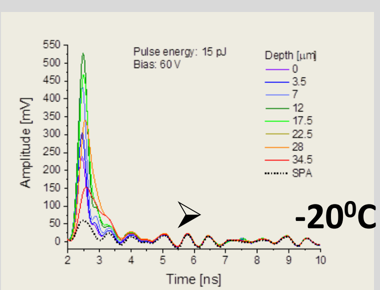
Before irradiation



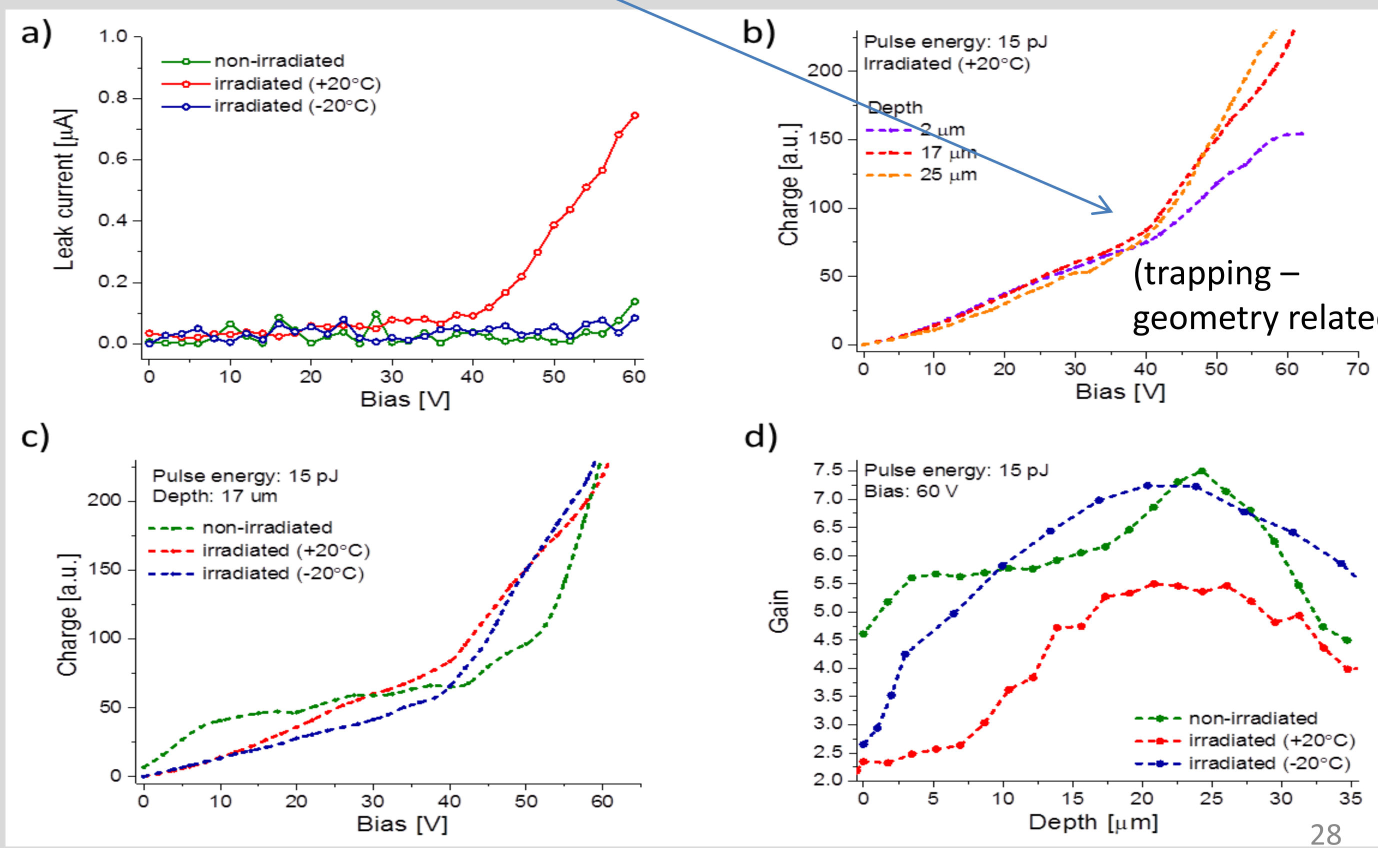
After irradiation



➢ +20^{0}C



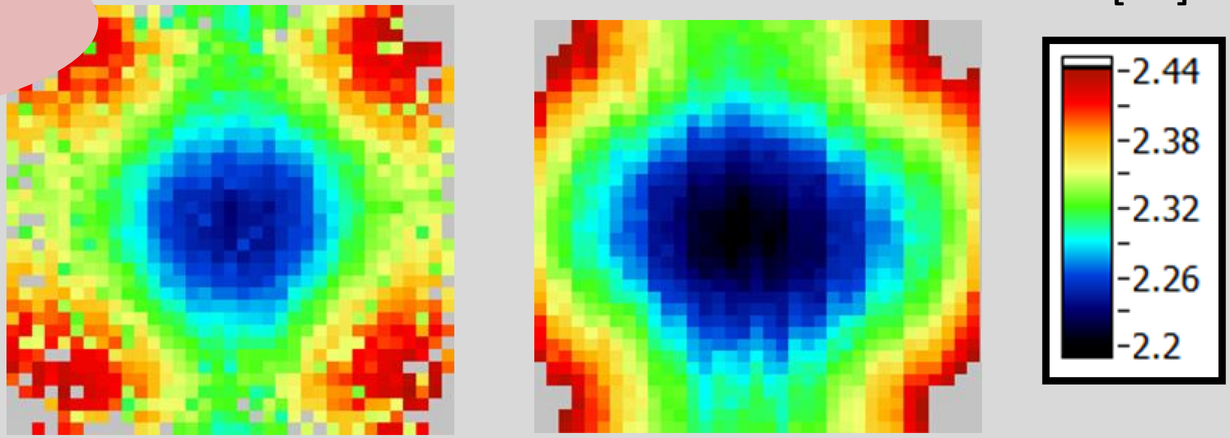
➢ -20^{0}C

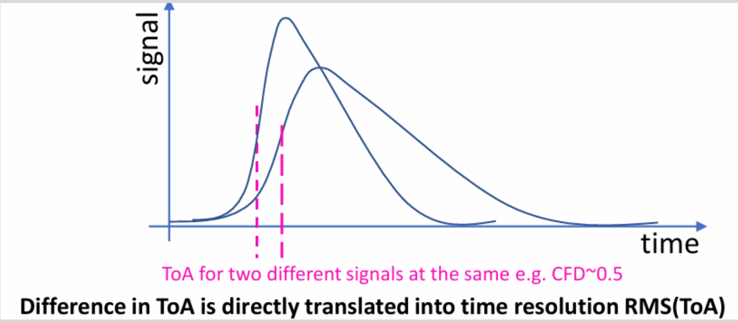


(trapping – geometry related

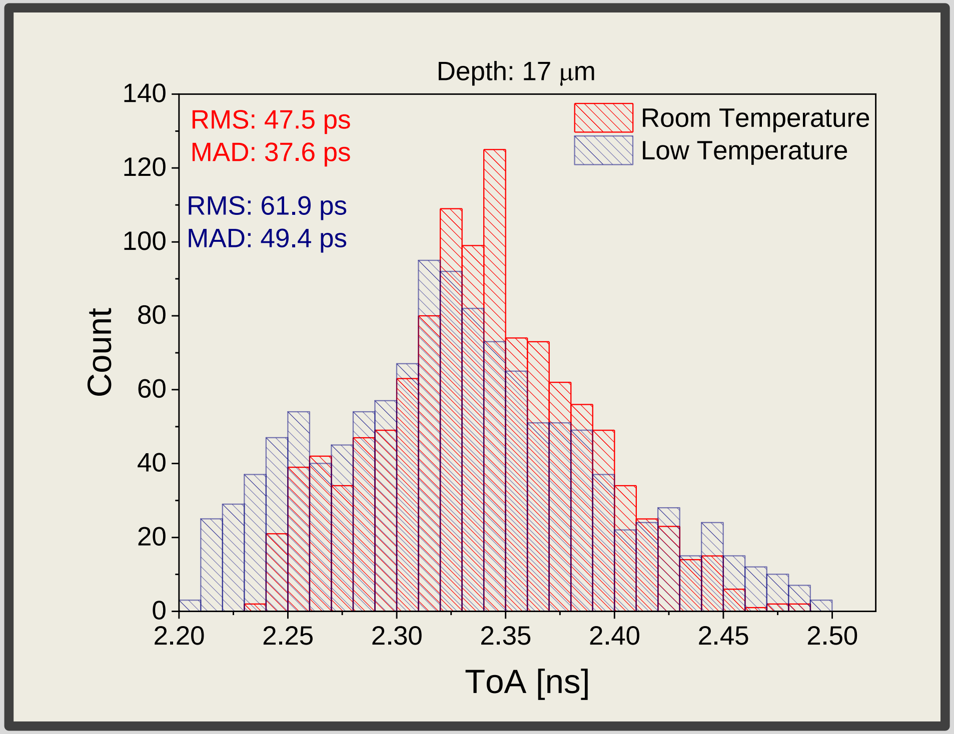
ToA after irradiation

2D image of ToA
- ✓ at RT (left)
- ✓ at -25^{0}C (right)



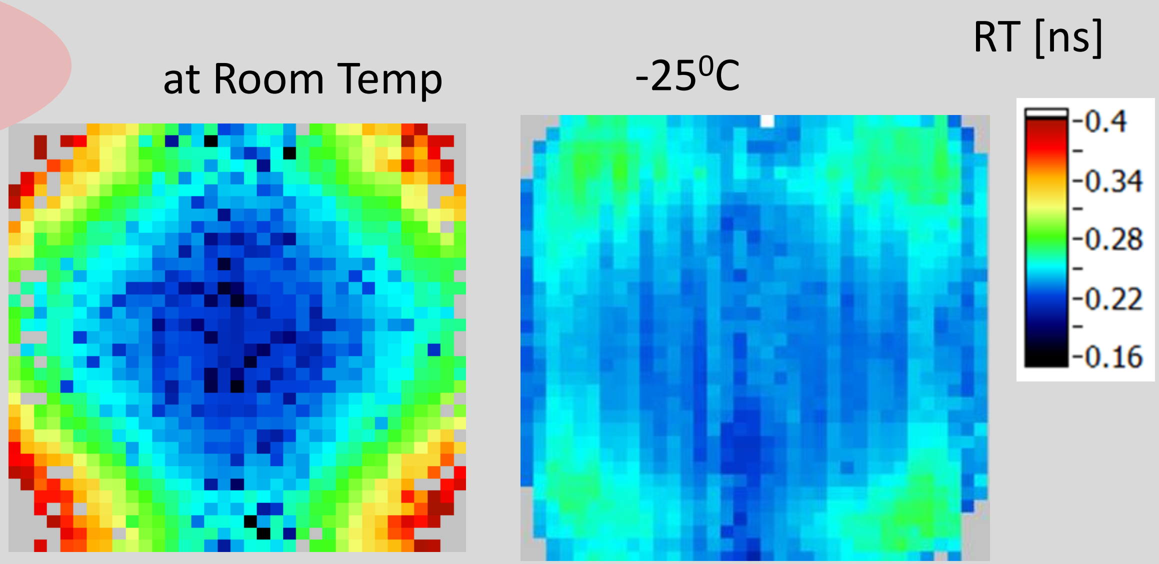


RMS, MAD (ToA)
- ✓ at RT (red)
- ✓ -25^{0}C (blue)



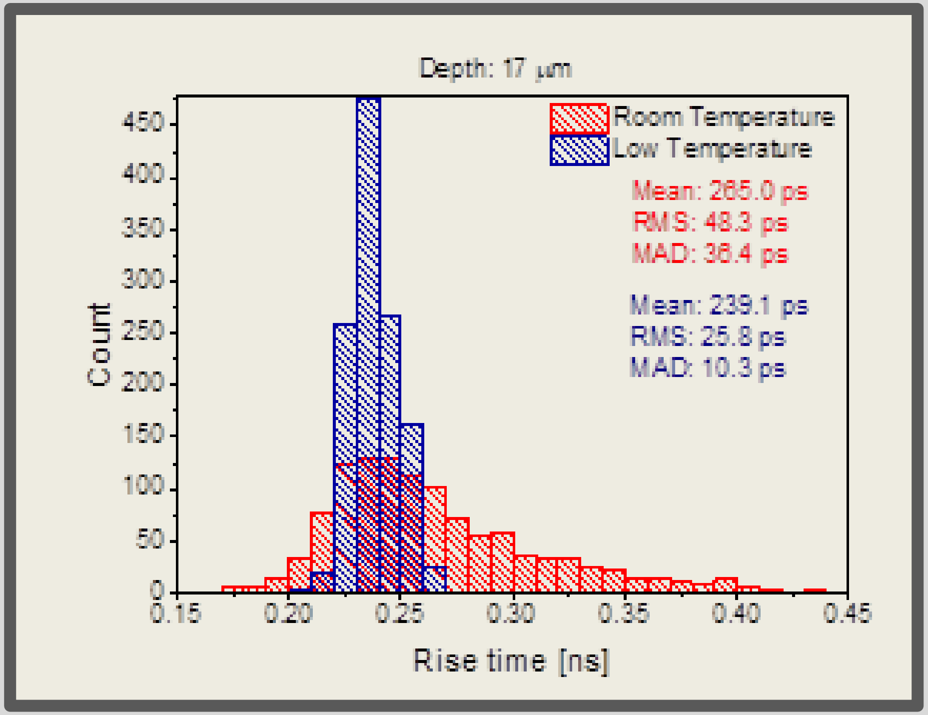
RT after irradiation

2D image of Rise Time

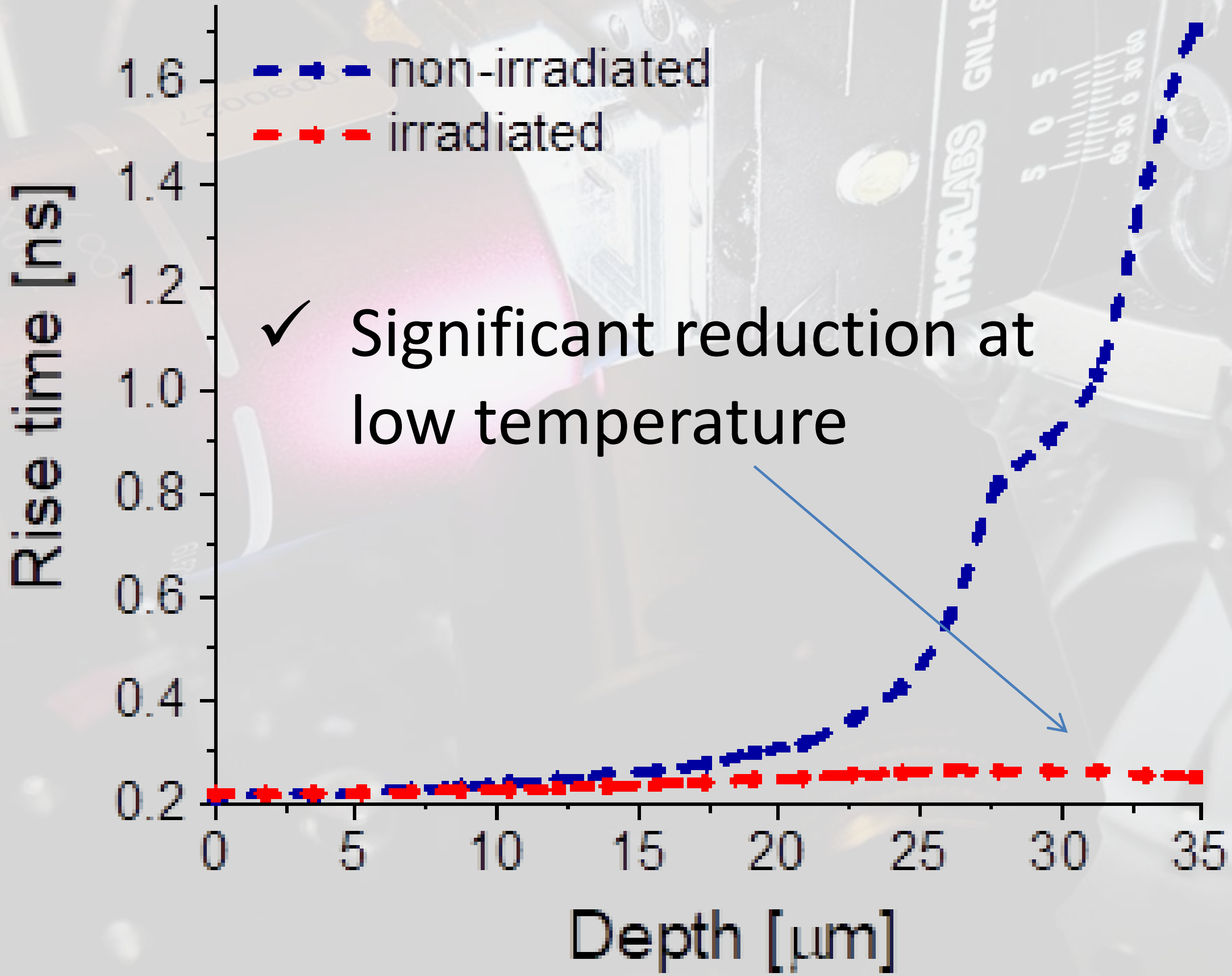


RMS, MAD (Rise Time)

- ✓ at RT (red)
- ✓ $-25^{0}C$ (blue)

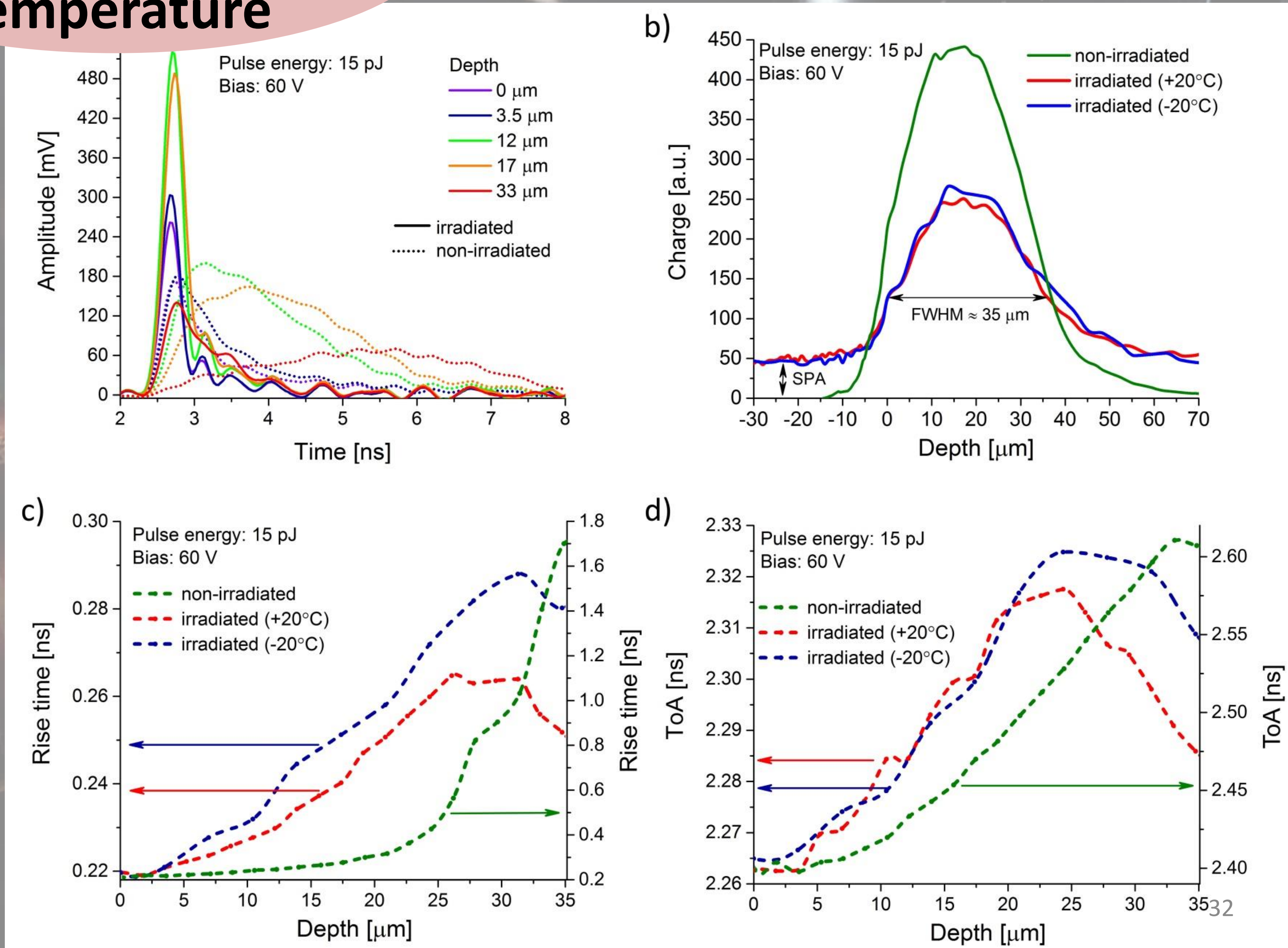


ToA, RT at low and room temperature

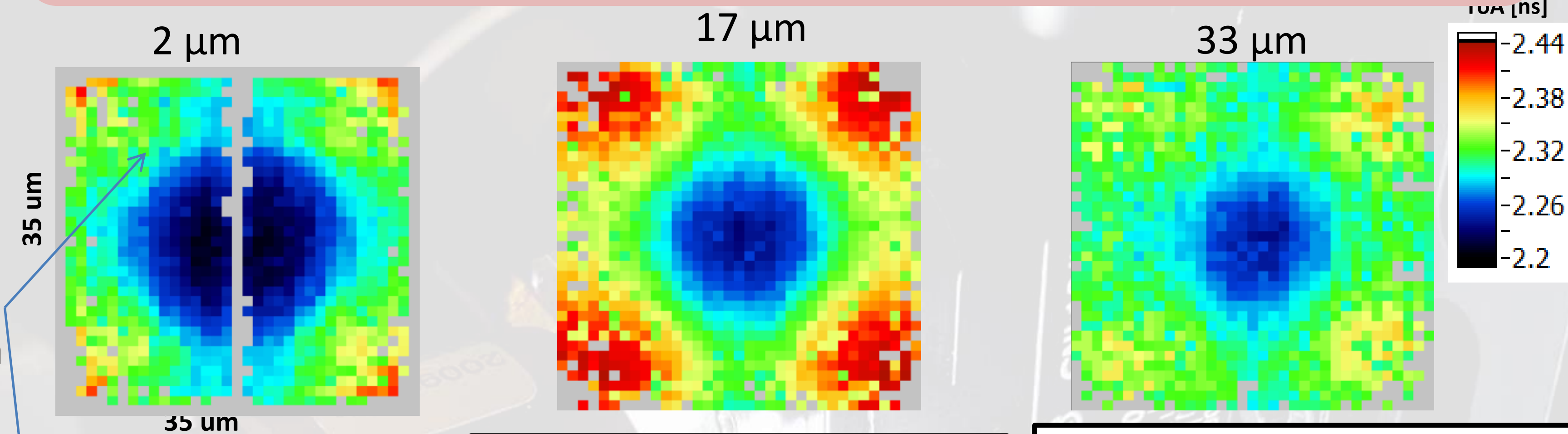


✓ Significant reduction at low temperature

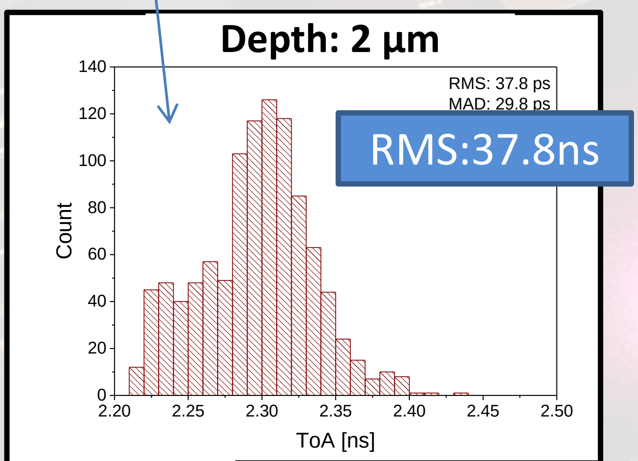
ToA, RT at low and room temperature

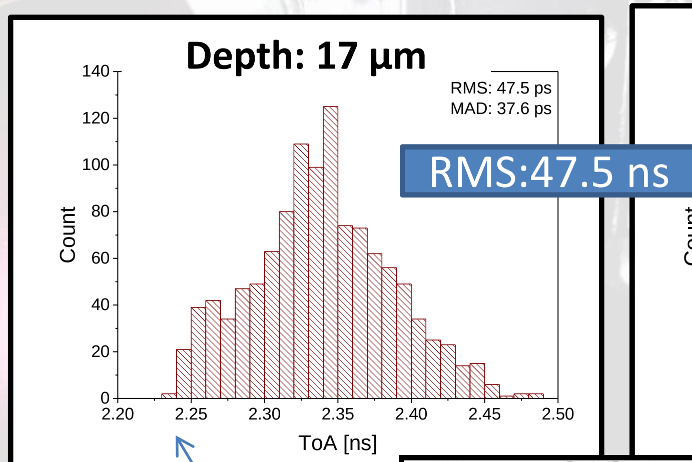


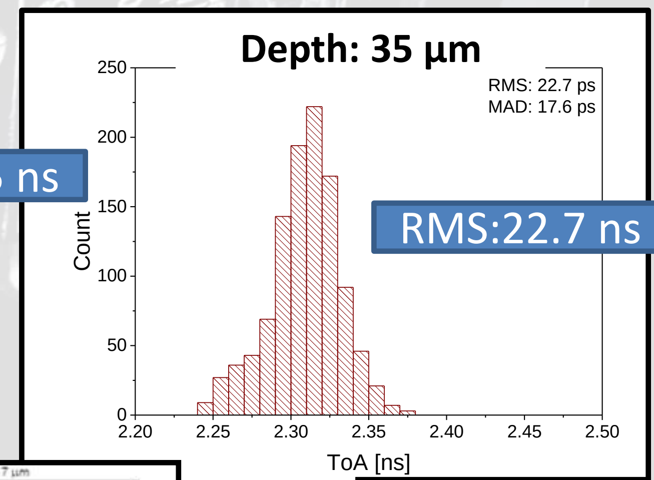
ToA vs. depth before and after irradiation



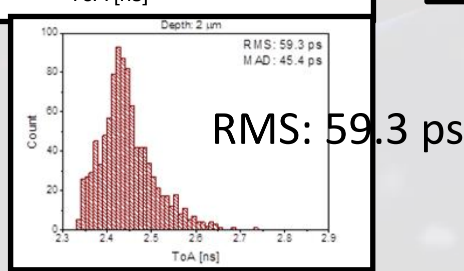
After irradiation





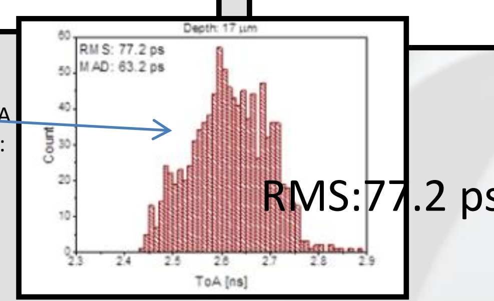


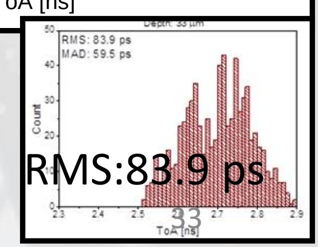
Before irradiation



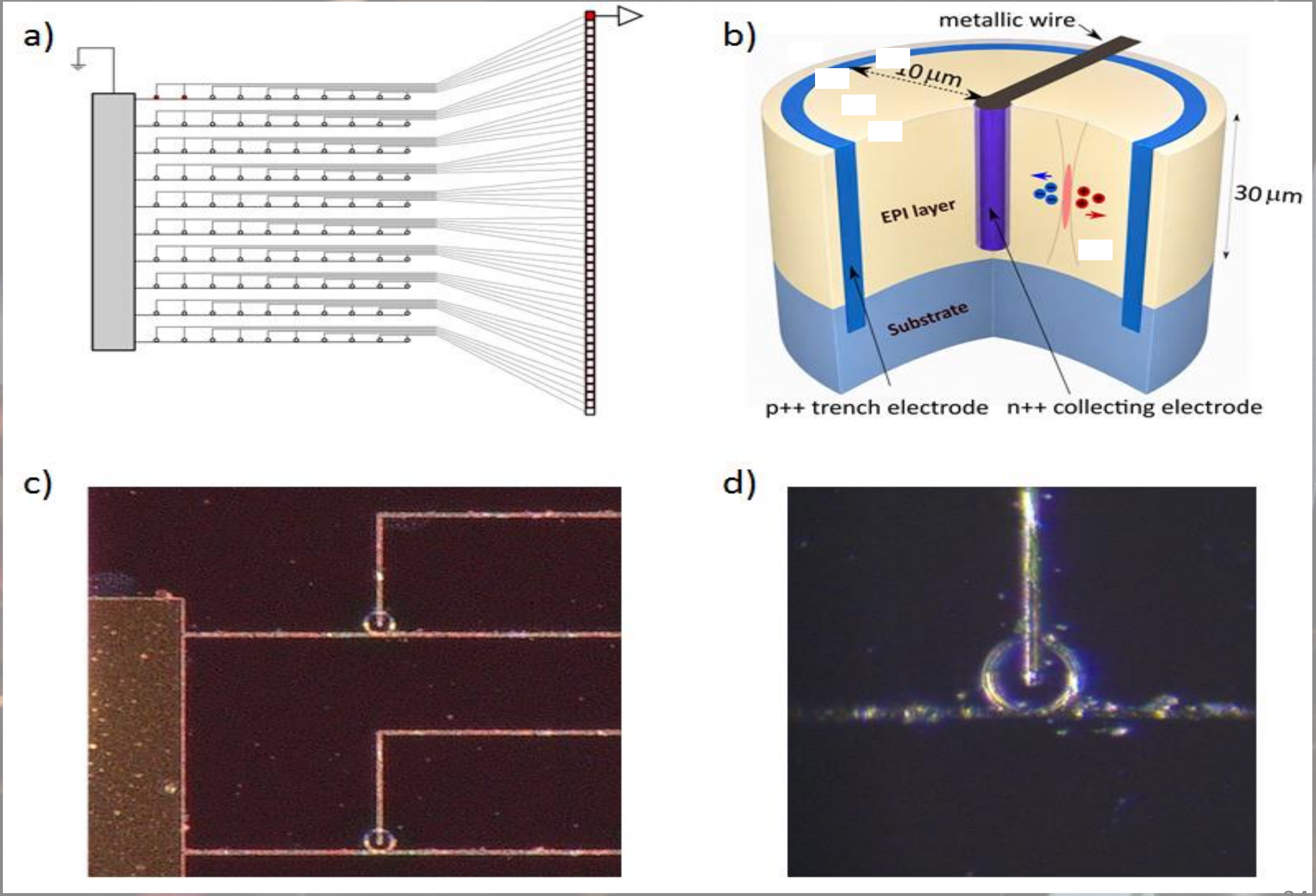
Quite significant improvement (not yet fully understood) in ToA (CFD@0.5 from ~80 ps to 50 ps:

- ➢ trapping reduces longer tails
- ➢ larger space charge leads to gradients in field – faster collection

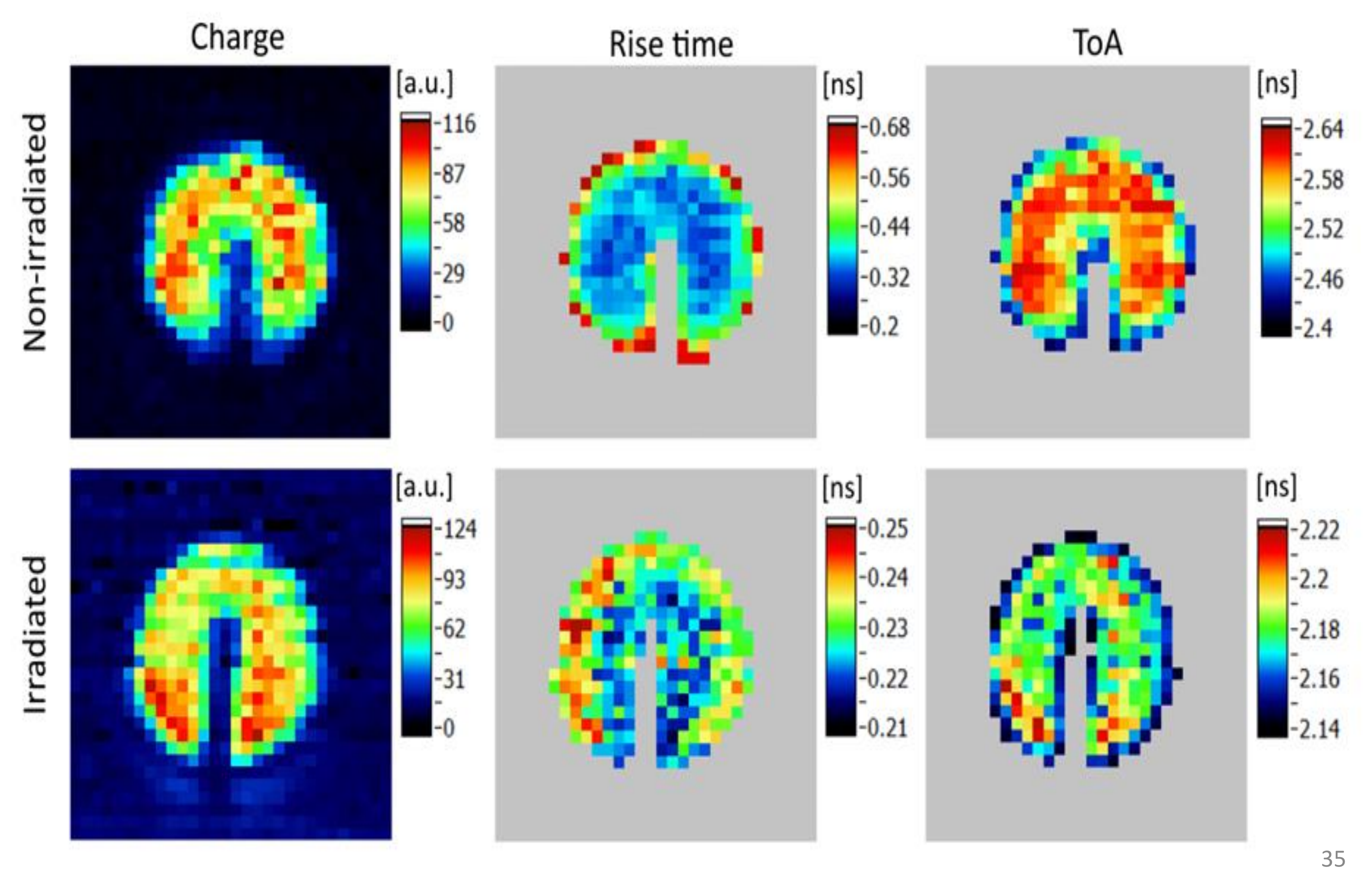




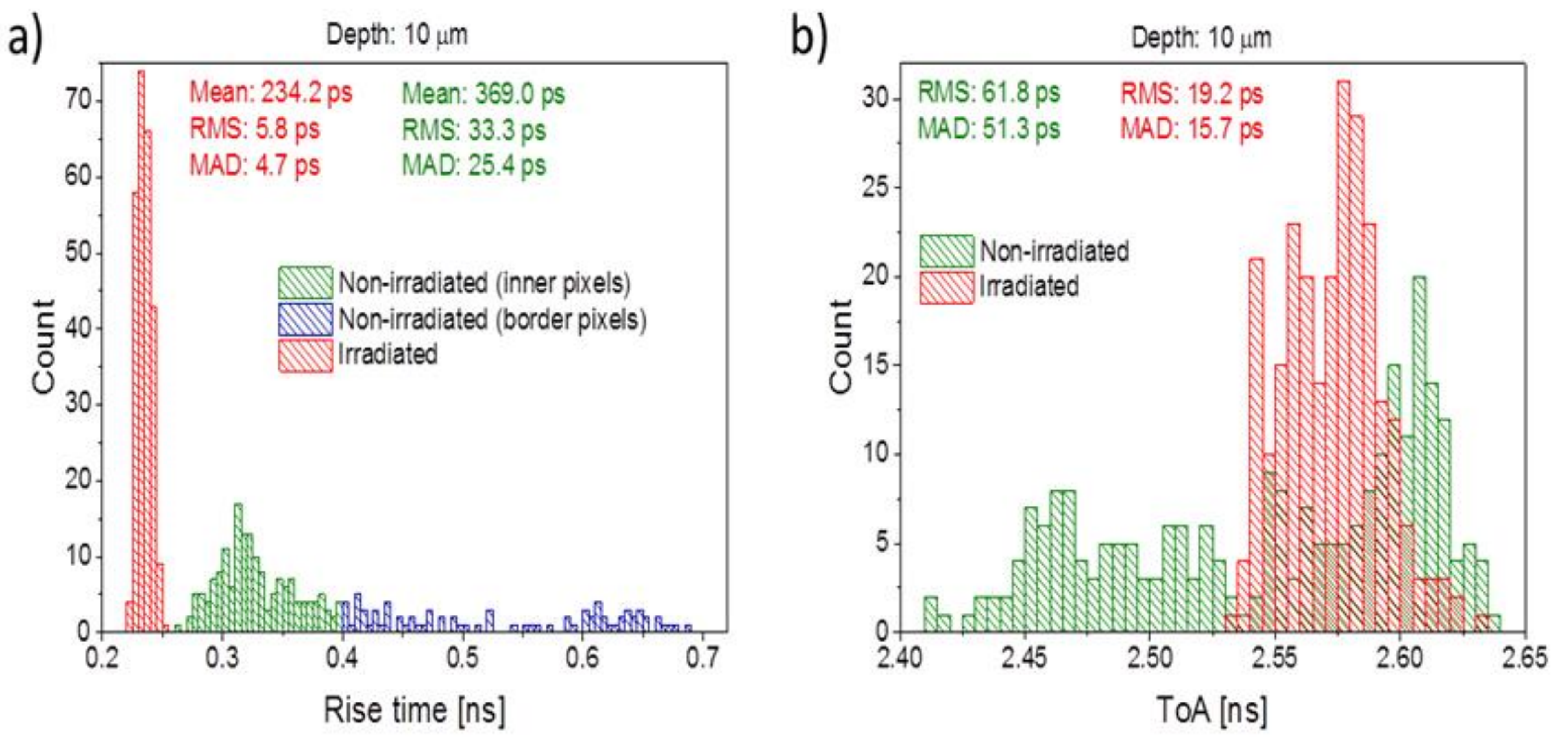
2 Straw Tube IME-CAS Detectors



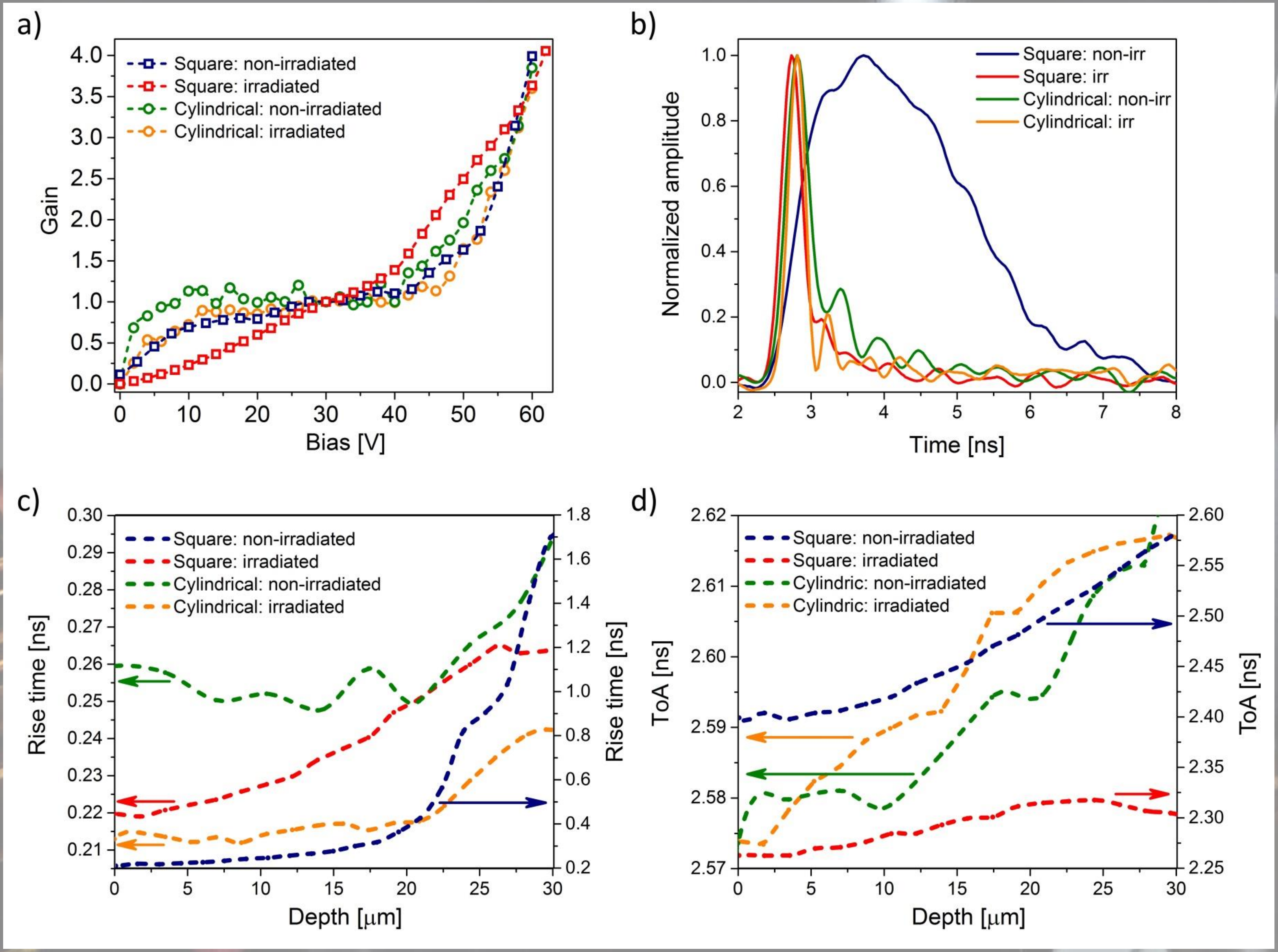
2D of Charge, Rise time and ToA distribution before and after irradiation



RMS of RT and ToA before and after irradiation



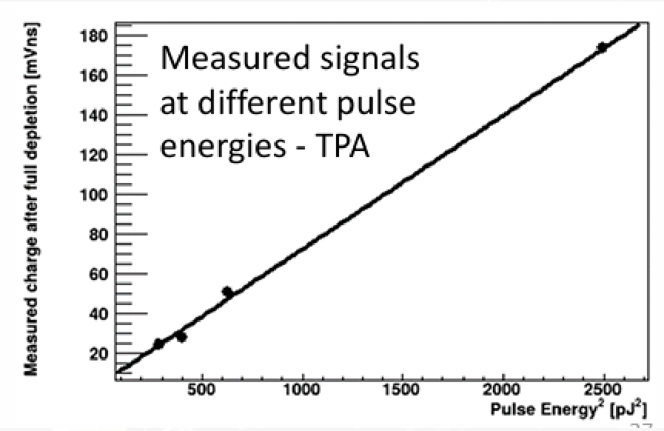
Other control plots



Impact Ionization Study

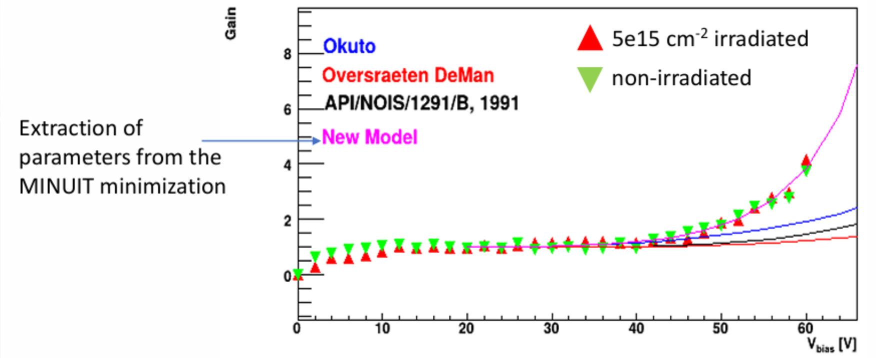
In the first approximation field can be calculated analytically and also the gain:

- ➢ up to 10^{16} cm^{-2} the changes to Neffcan be ignored
- ➢ short distances render trapping of the drifting charge negligible
- ➢ TPA allow injection away from the tip where analyti calculation is more reliable
- ➢ TPA allows also studies of charge screening effects



Extending the studies to very high fluences – above 10^{17} cm^{-2} will reveal the answer if silicon gain devices can be operated - **this is the key question for Silicon in FCC-hh. Without gain we know silicon will fail.**

- ➢ a clear underestimation of the charge by the literature models
- ➢ no impact of radiation up to 5e15 cm^{-2}
- ➢ extraction of parameters depends critically on "wire dimensions" (column width + doping layer) - we are now expanding the studies to more columns widths for more reliable extraction.

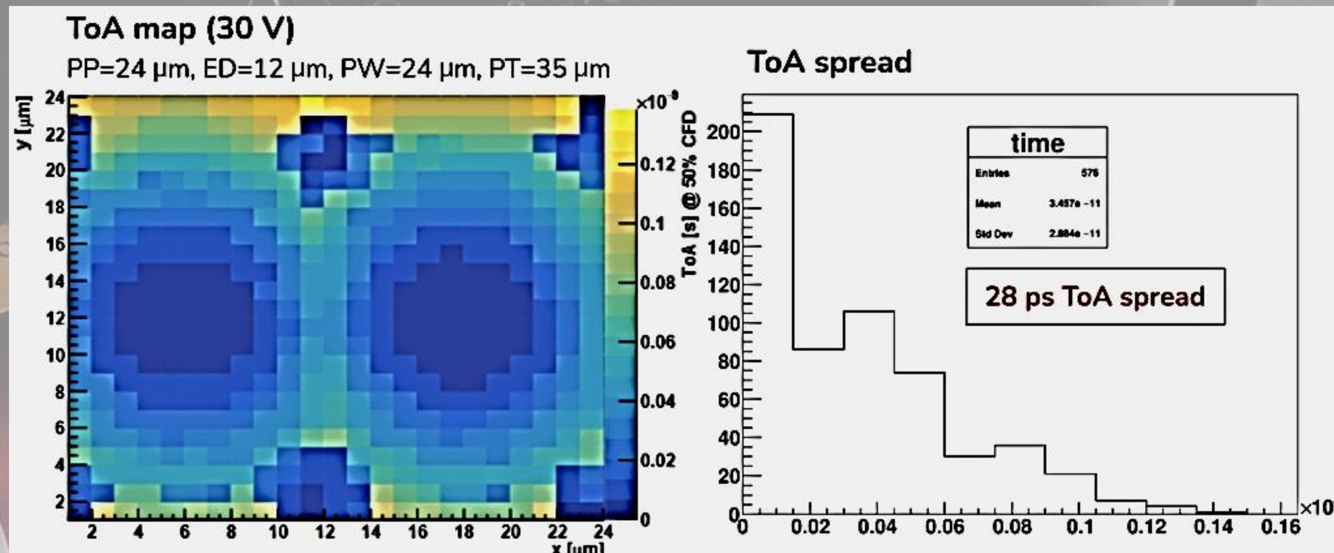


IDEAL 4D Tracking Device

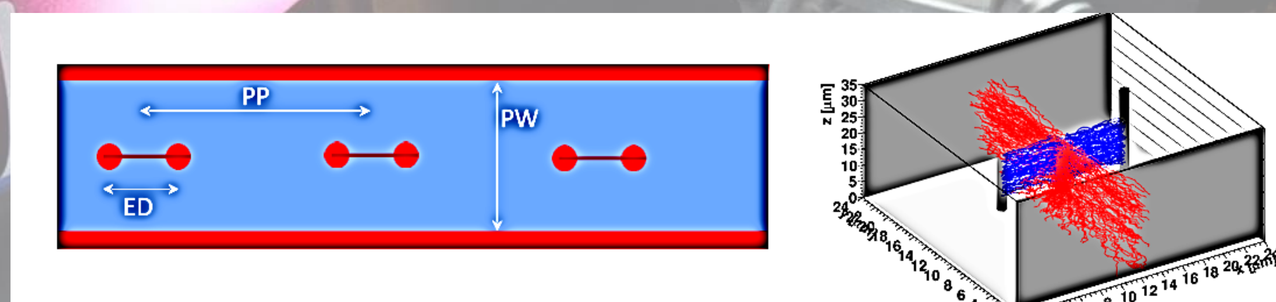
REF: M. Puklavec, Small cell 3D detectors with intrinsic gain, TREDI2026; https://indico.cern.ch/event/1586892/contributions/6846212

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

Conclusion

Silicon/Semiconductor gain devices are in the focus of R&D activities. LGADs still dominate – to be used for the first time in ATLAS/CMS, but others, SiEM and 3D detectors are also gaining momentum.

➢ Very small pitch and thickness 3D devices were produced with controllable gain (35x35x30 μm^3 cells) owing to 8” CMOS and DRIE processing at IME.

➢ Gains of up to around 10 were measured with devices fully functional at moderate voltages 62 V with only up to 20-30% gain variation across the cell was observed. Being thin these devices would have much better noise performance than standard 3D sensors.

➢ Devices were not optimized for timing and their timing performance is not excellent:

➢ Weighting field (distortion) contribution dominates the timing resolution

➢ rise time variation across the cell can lead to jitter variations - mapping for ToA and dV/dt of the device shows this

➢ Extremely small single cell cylindrical devices are ideal for impact ionization measurements at extreme fluences.

Future PLAN:

➢ 2 more runs with timing optimized devices will following until the end of 2027 devices optimized for timing applications will be included

➢ impact ionization measurements over the large fluence range

Thank you for your attention!

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RT vs depth after irradiation