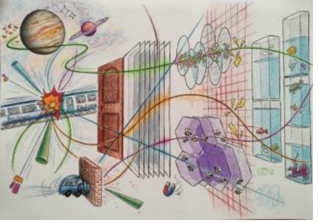

DRD3

3D detectors with gain for 4D tracking

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Work performed in the framework of the DRD3 WP2 project : Novel silicon 3D-trench pixel detectors based on 8-inch CMOS process

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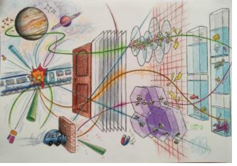
Nikhef 50

JSI Ljubljana Slovenia

University of Sheffield

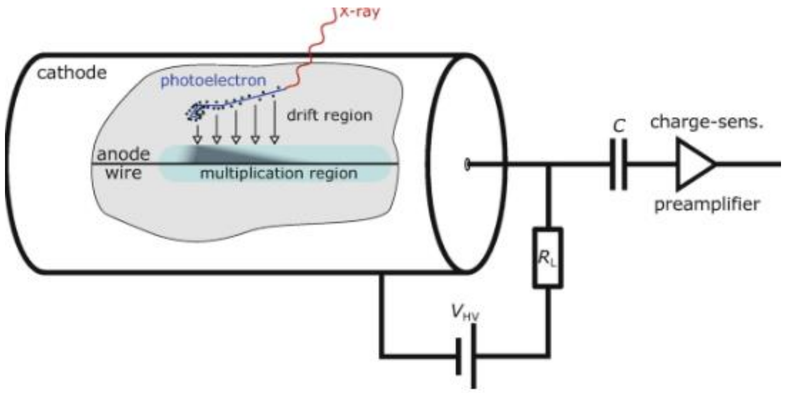
Institute of High Energy Physics Chinese Academy of Sciences

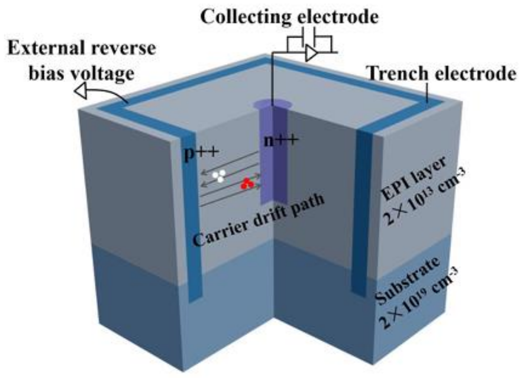


Motivation

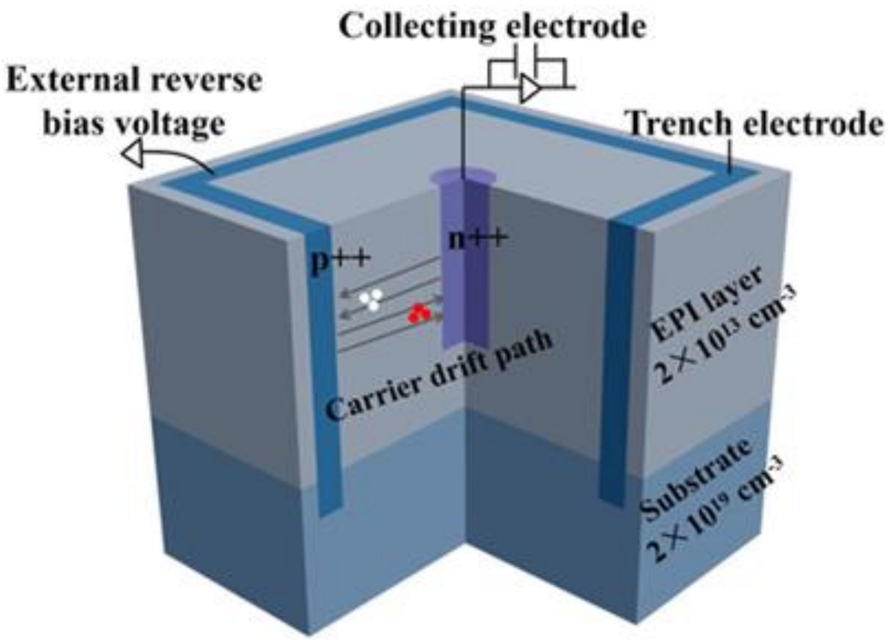
- Utilizing the gain in silicon (and possibly SiC) detectors has been the key advancement in tracking detectors opening possibility of real 4D tracking with planar devices.
  - the gain is achieved with fine tuning of gain layer
  - implementation of gain is now ongoing in several CMOS projects (CASSIA, CACTUS, ARCADIA, …)
- What about 3D detectors? The doping of columns of 3D detectors is almost impossible to control with the required precision.
  - Improvement of aspect ratio to 100:1 allows manufacturing of very narrow columns <1 μm which can be seen as proportional wire counter.

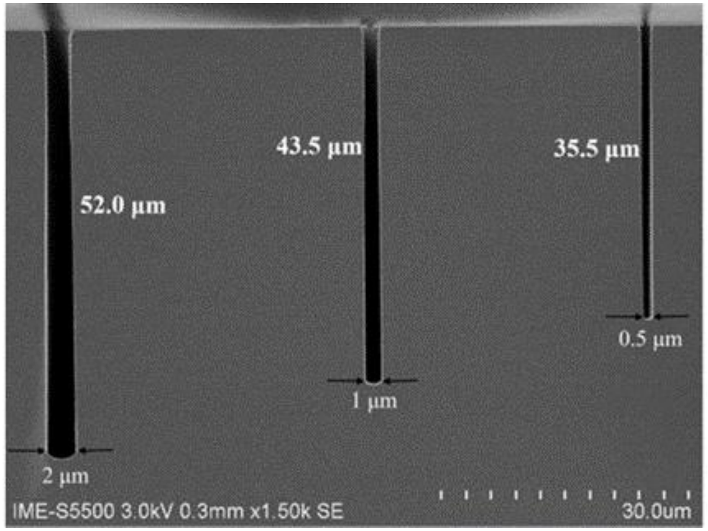
Can we progress from "solid state ionization chamber" to semiconductor "wire proportional chamber"?

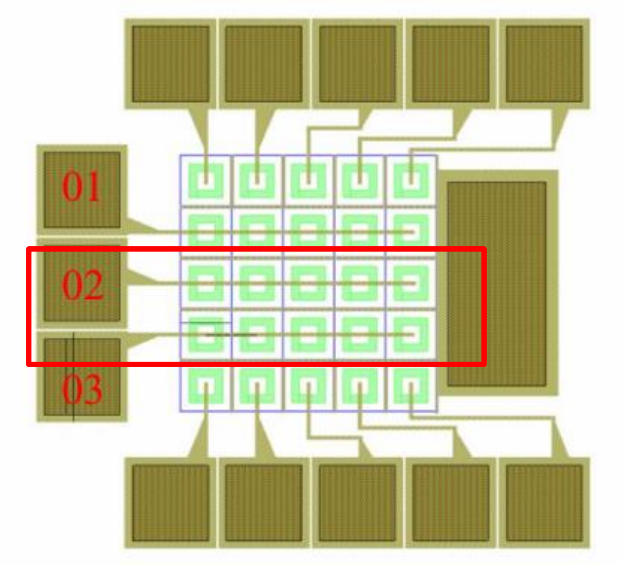


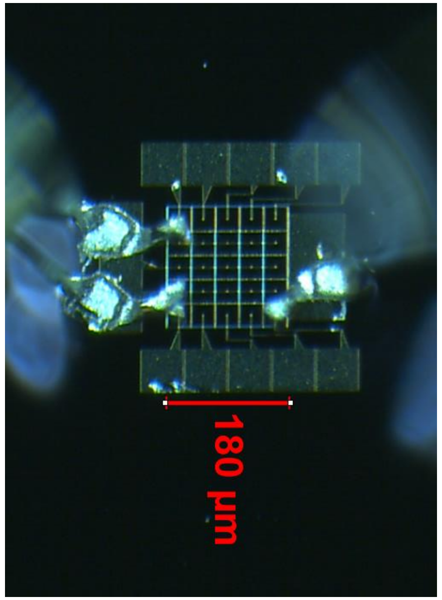


Small pitch narrow – column/trench sensors





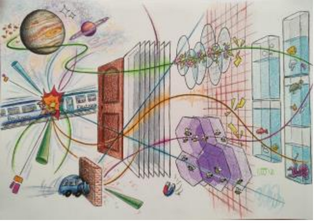




Samples studied

- 0.5 μm column width detector – highest fields possible (1/r dependence of the field) – choice guided also by simulations (see 3rd DRD3 week).
- 35x35 μm^2 cell size detector due to easier investigation of detectors by TPA-TCT technique (less metallization)
- Concentrated on ganged cells – due to the bias distribution the weighting field is "contained" to each cell

The project has also studied other samples (by USTC, IHEP) – see WP2 project indico pages



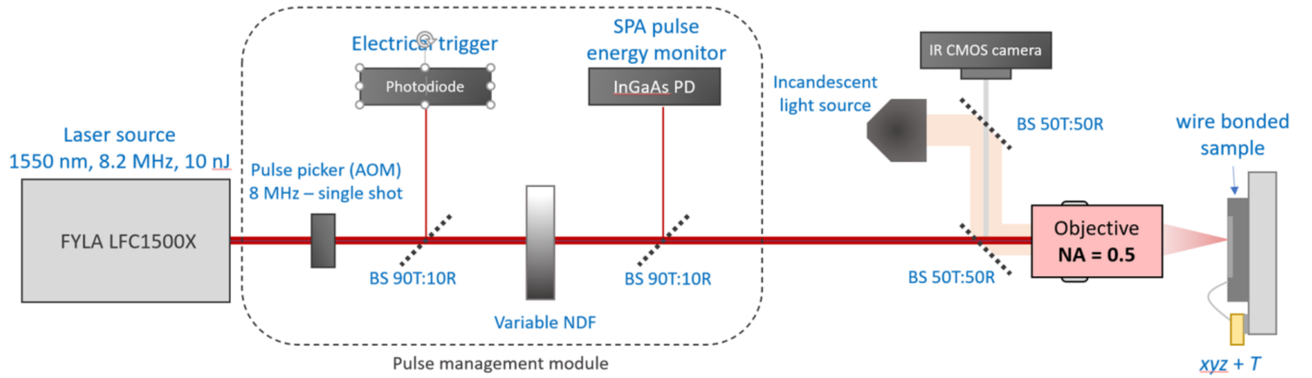
Techniques used for studies

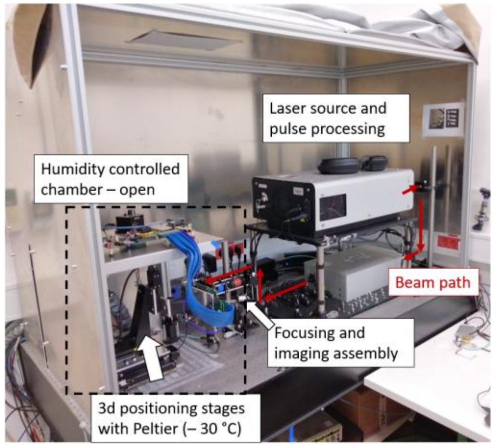
Two Photon Absorption TCT setup at JSI

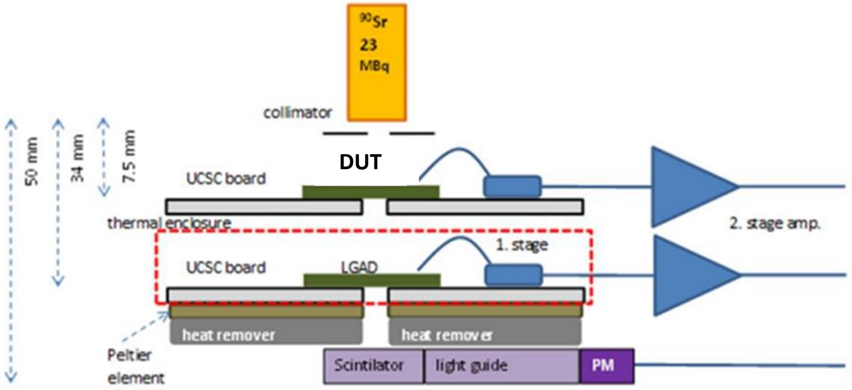
- Standard FYLA laser (1520 nm) with custom made optical system
- Samples wire bonded in JSI housing and connected to AM-02A through bias-T
- Waveforms readout by an oscilloscope (2.5 GHz, 20 GS/s)

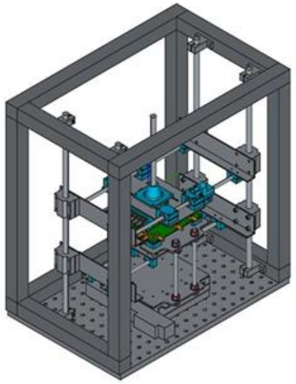
New scanning ^{90}Sr setup at JSI for climate chamber

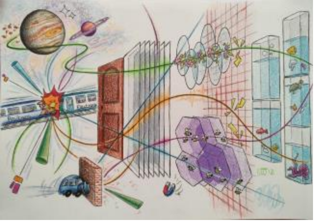
- Samples wire-bonded on UCSC boards
- Waveforms readout by CAEN digitizer (500 MHz) and oscilloscope (2.5 GHz, 20 GS/s)
- DAQ rate limited –> 2 plane trigger used DUT-REF







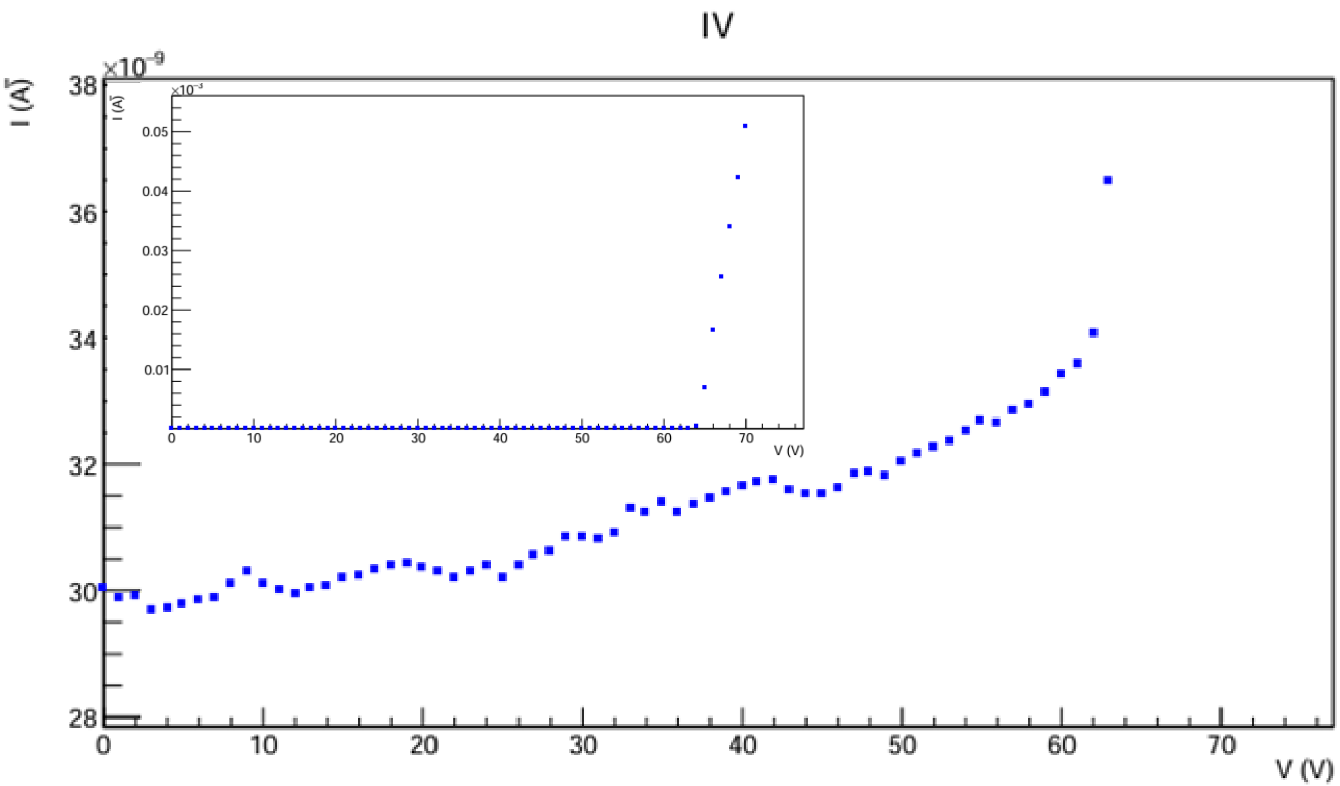


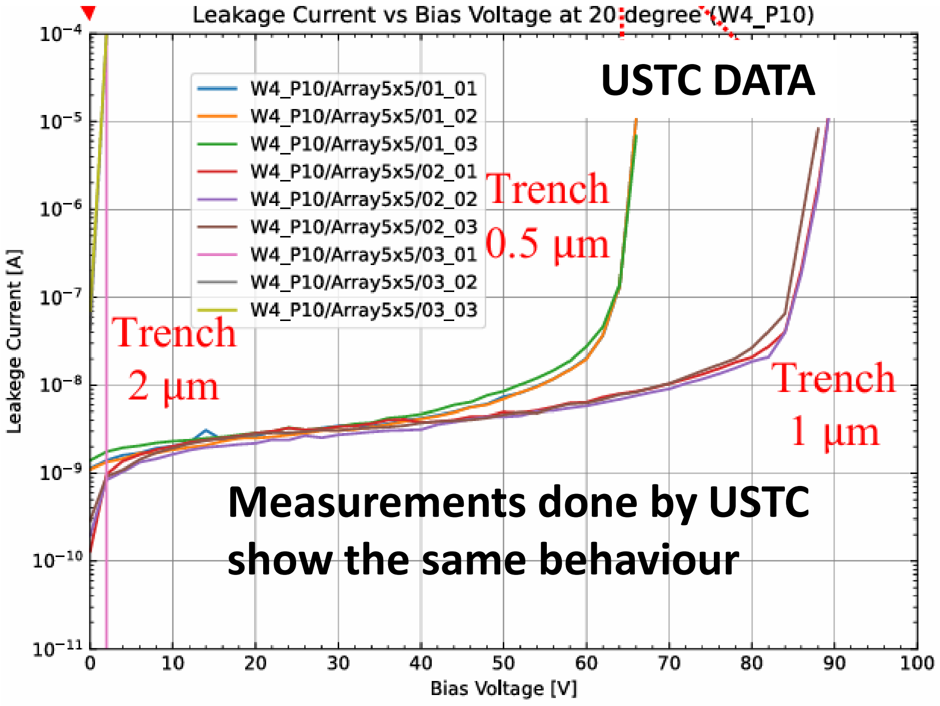


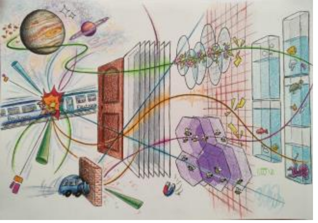
IV of the devices

DRD3

- The device has small leakage current up to the point of the breakdown
- There seems to be an offset of the current (slight light leak is possible at JSI)
- In general the IV-s of all devices is very reproducible – **seems a very good control of the process**

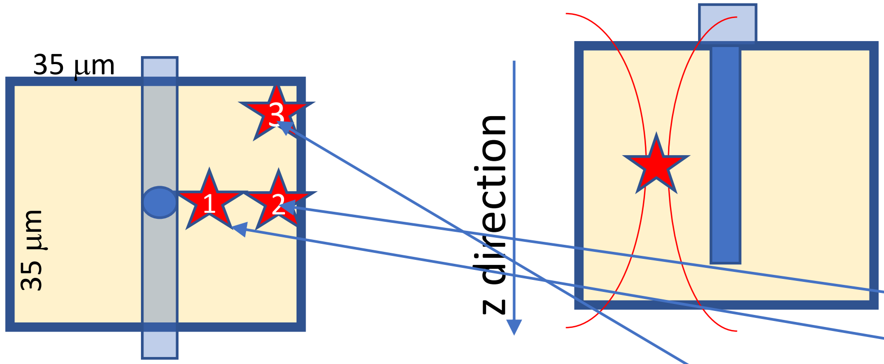


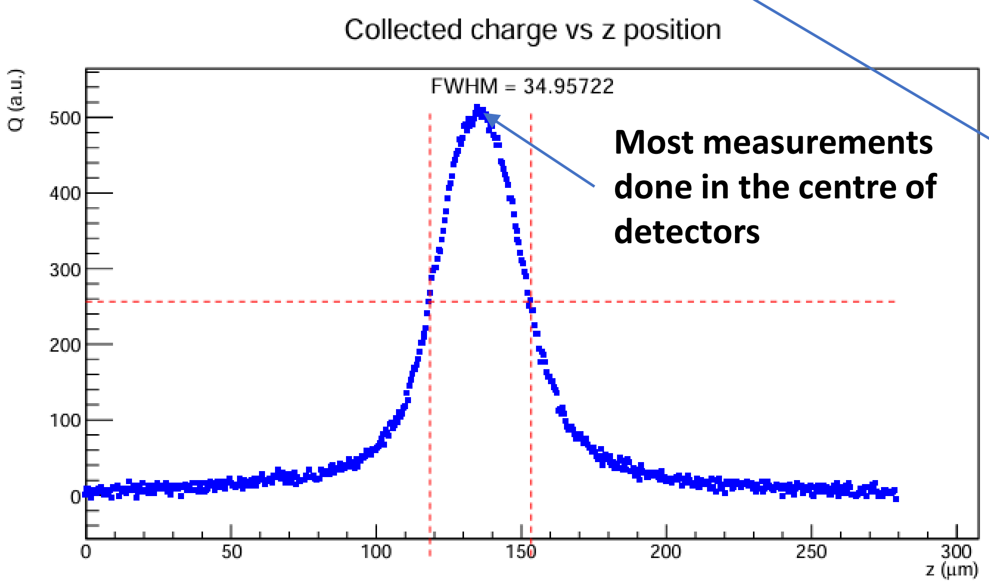




TPA measurements

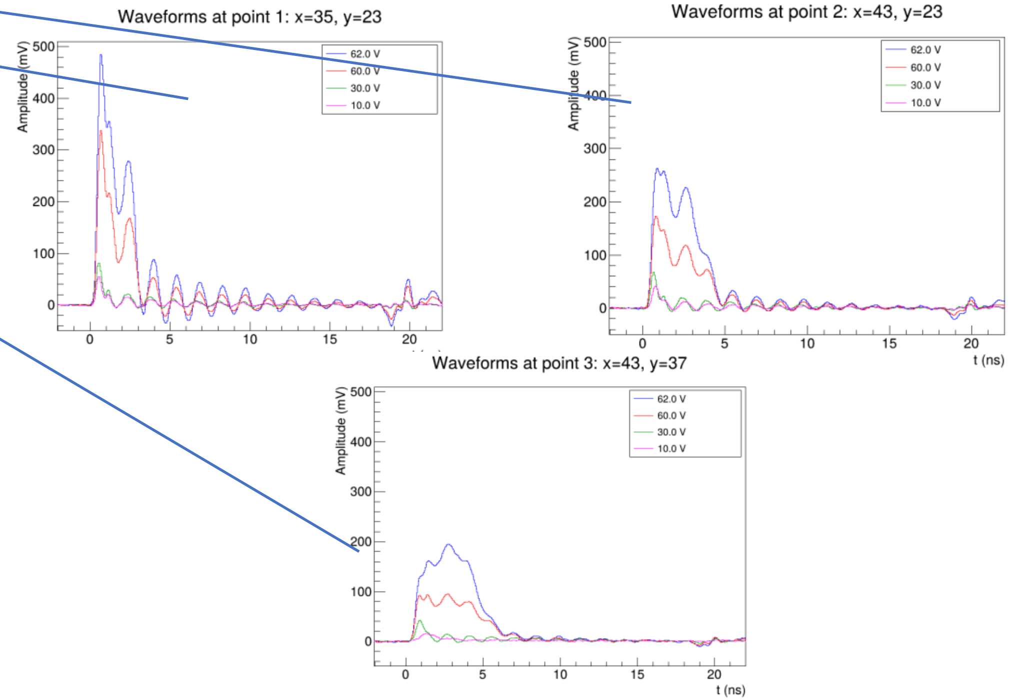
z scan across the cell size

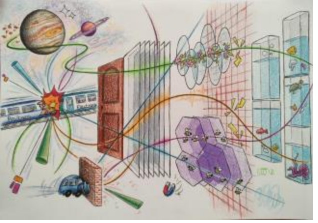




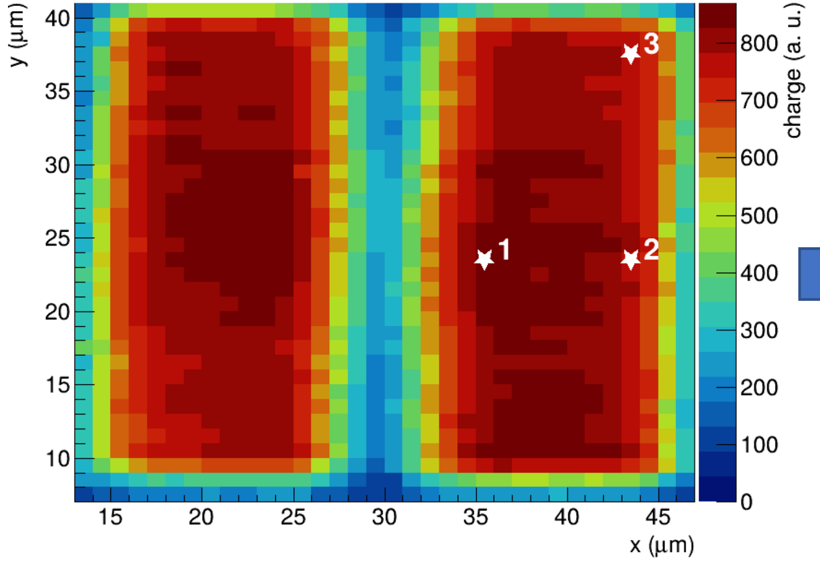
Pulse before multiplication very fast and short < 2ns

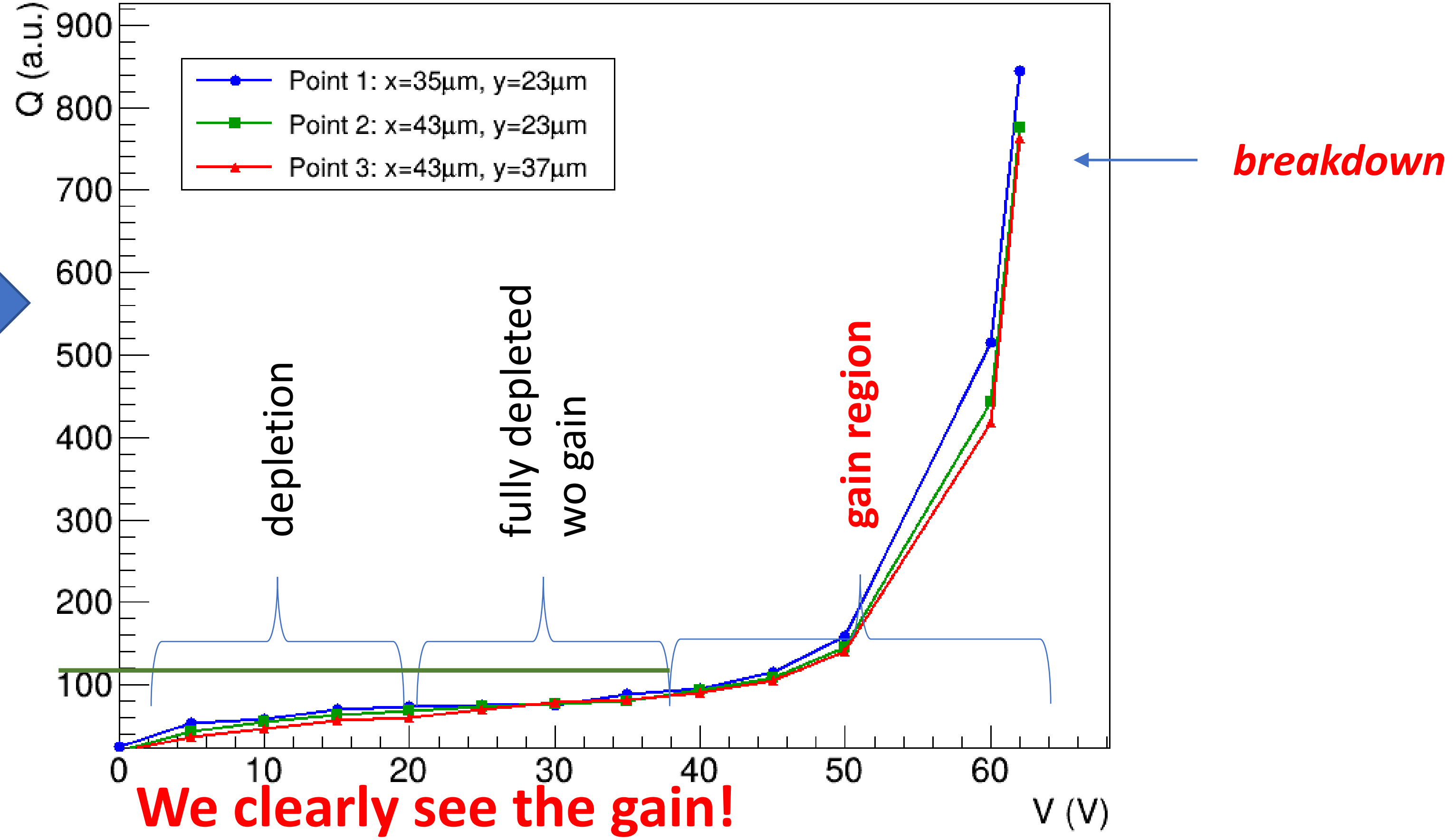
- the oscillations are due to improper impedance match
  - no effect on rise time
  - no effect on the charge integral
- Attention paid that we are far away from saturation of the amplifier and that we have maximum bandwidth





Hunting for gain



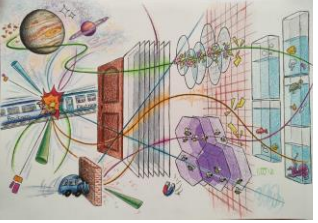


Operation at 62 V:

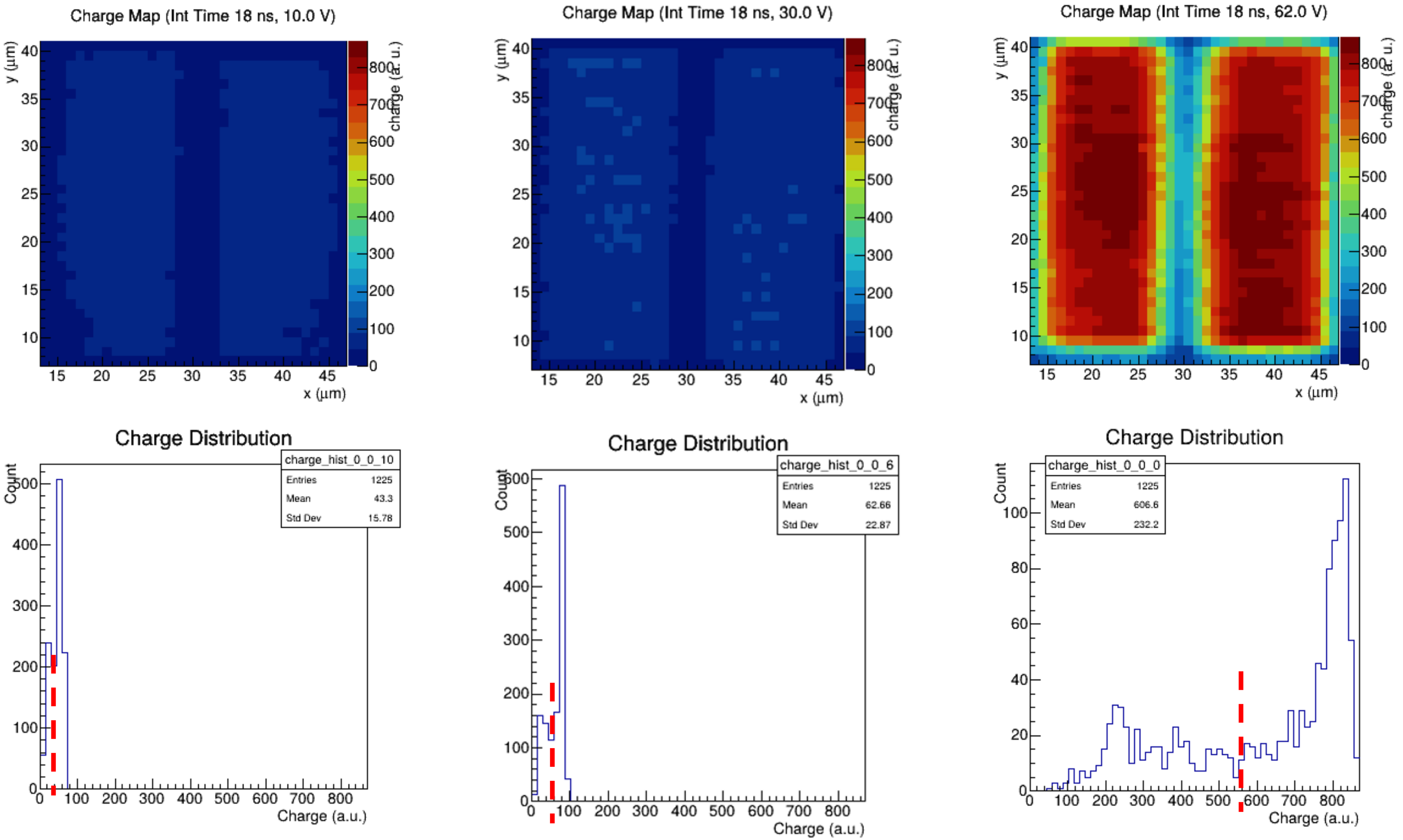
- Variation of the gain across the cell is only on the level of 20% !
- metal line prevents probing of the gain close to the column – limitation of the TCT
- No appearance of "ghost" like events. Very stable operation at very close to breakdown!

We clearly see the gain!

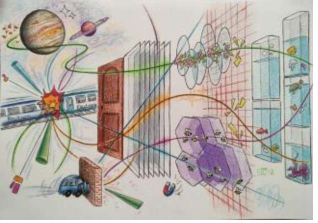
- Gain appears at ~40V
- reaches G~3-4 at 50V
- Reaches G~8-10 at 60 V



Bias Voltage Scans

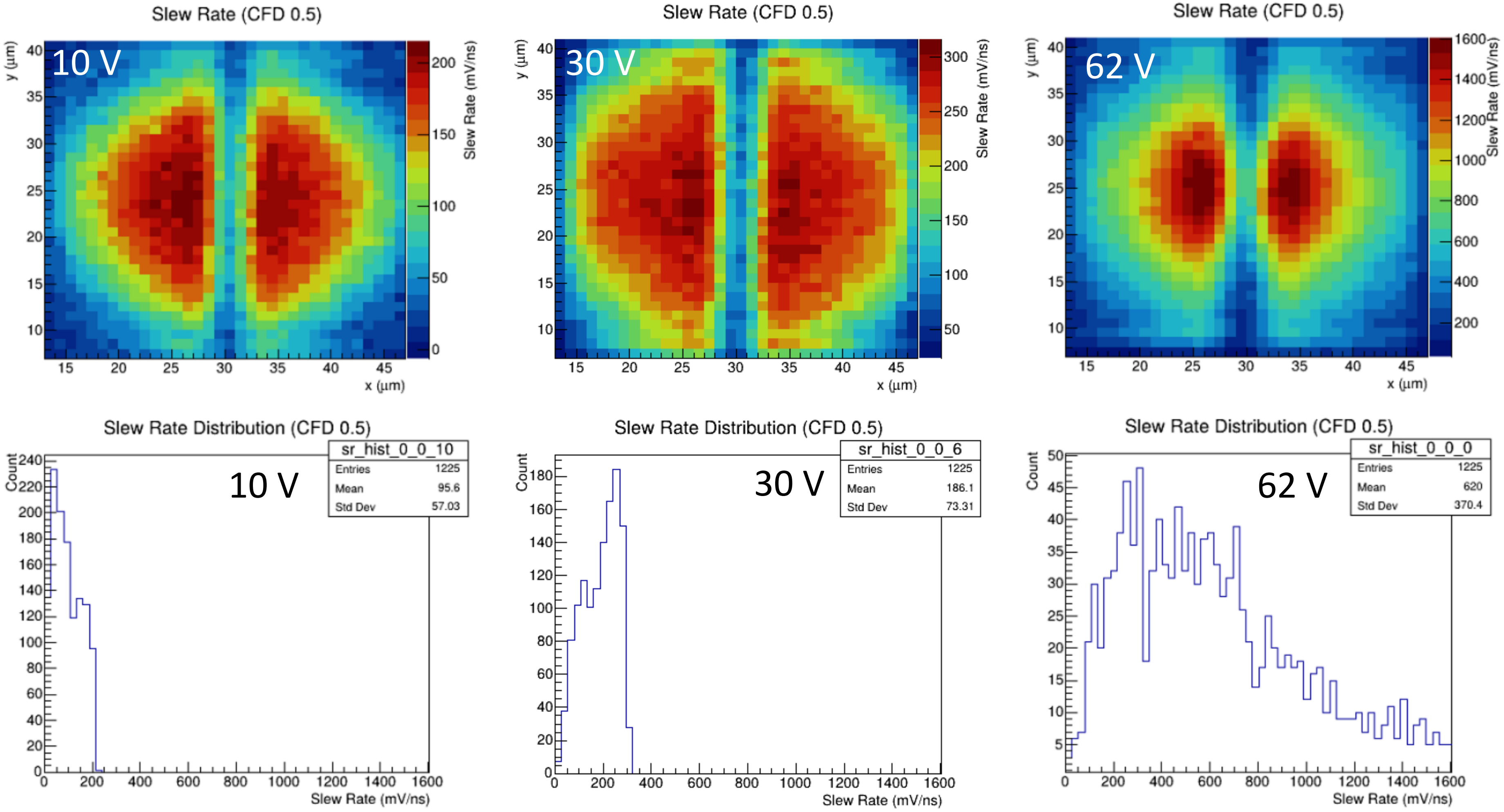


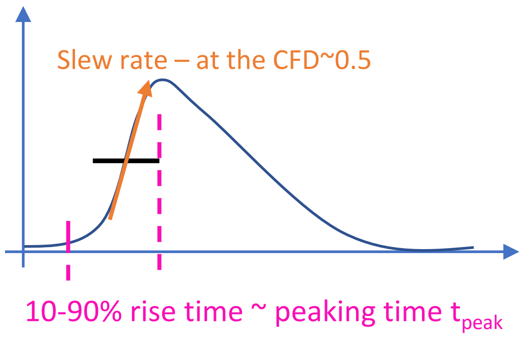
- The homogeneity of response improves after the sensor becomes fully depleted 30 V.
- Gain variation at the highest operation bias voltage is only around 20%, but area very close to the column could not be probed due to the metallization over the column



Rise time – dV/dt

Speed of the response drives the jitter contribution to the time resolution – the faster the rise time the smaller is the jitter. The following measurements show dV/dt at the threshold level (CFD~0.5)



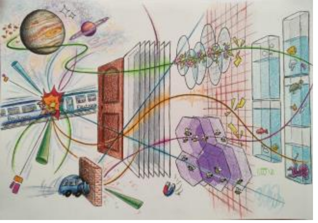


Two different definitions of the rise time:

- **Slew rate at the CFD level (jitter)**

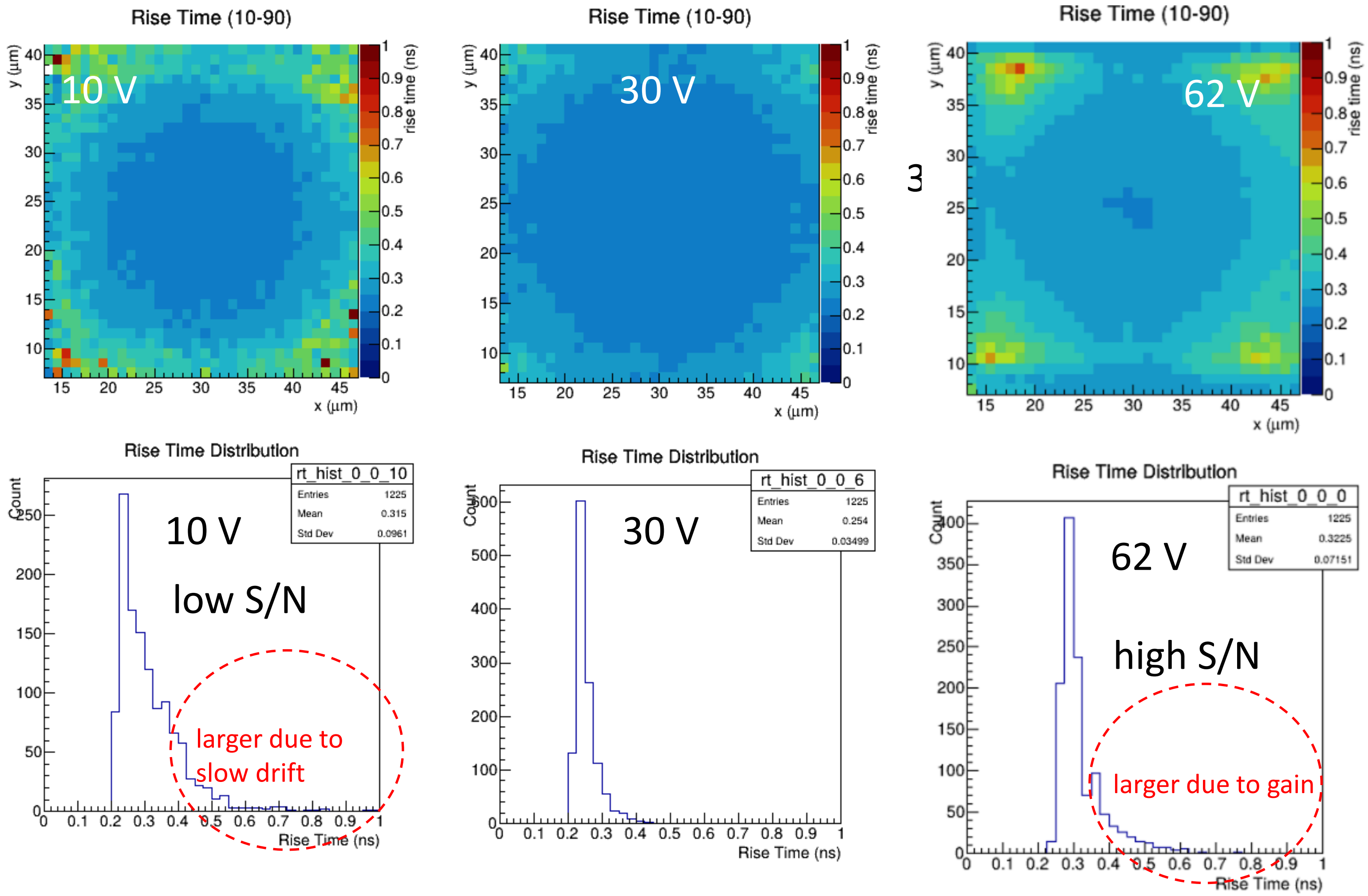
$$\sigma_{jitter}=\sigma_N/(dV/dt)$$

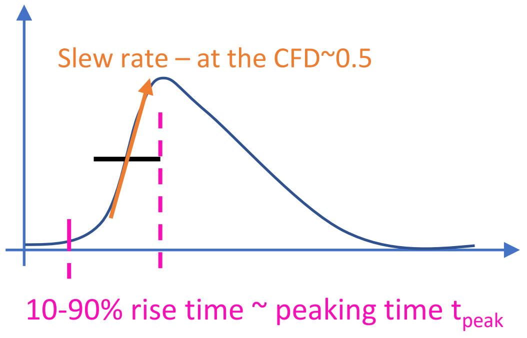
- ➢ G~15 at 62 V is reflected only in 8 times larger slew rate.
- ➢ Large difference across the sensor will result in hit position dependent jitter.



Rise time (10-90%)

These devices are not optimized for timing performance – **unfavourable weighting field contribution (called also distortion component)** – large variation of ToA which can be even worse when gain kicks in (see following slides on simulations)



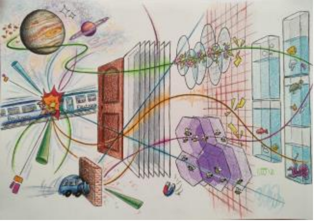


Two different definitions of the rise time:

- **Time from 10-90% of the peak**

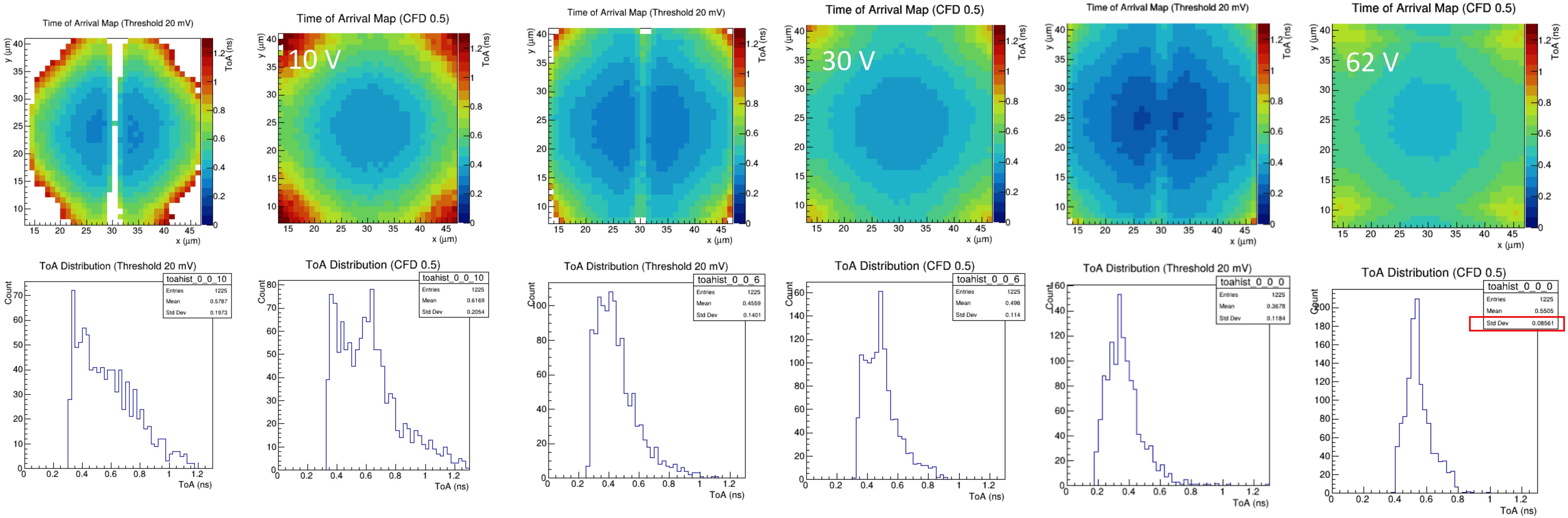
- **Large difference across the sensor will result in hit position dependent jitter.**
- Optimization of electronics is required - slower rise time and longer integration – rise of S/N should offset longer integration time

$$\sigma_{jitter}=t_{peak}/(S/N)$$

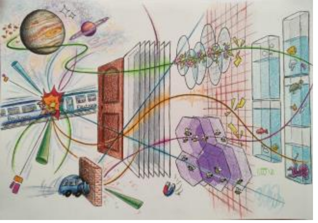


ToA of the devices weighing field/distortion component

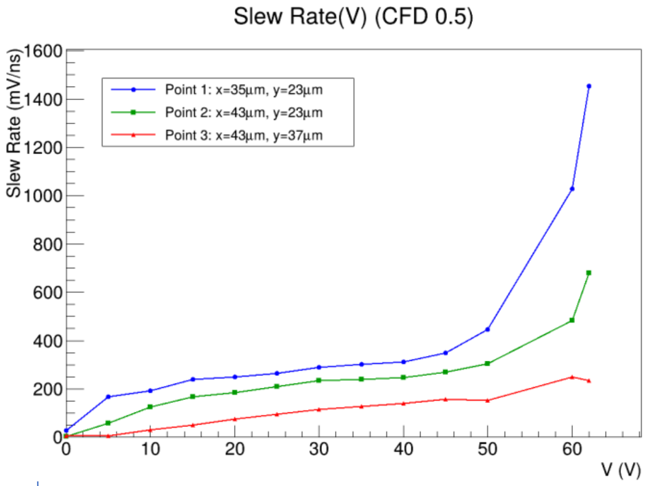
These devices are not optimized for timing performance – **unfavourable weighting field contribution (called also distortion component)** – large variation of ToA which can be even worse when gain kicks in (see following slides on simulations)

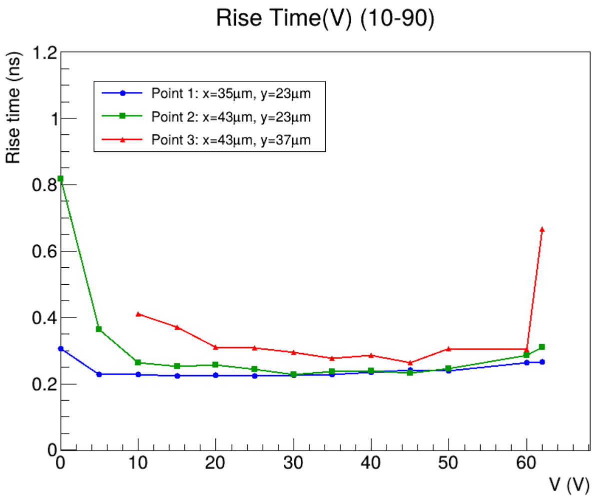


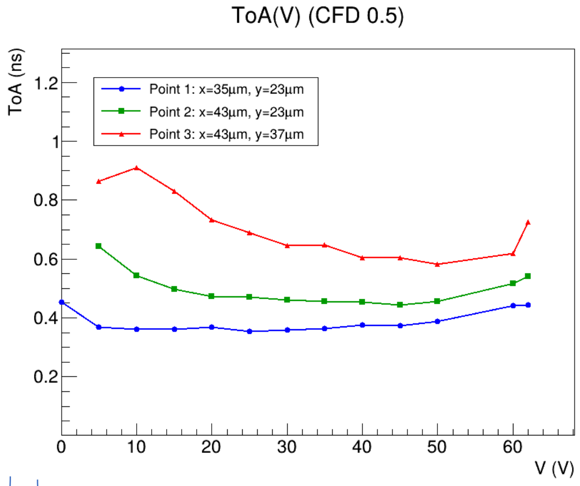
The time of arrival (wrt. to laser trigger) is getting reduced at this bias voltages, but the ToA spread is ~90 ps at 62 V.

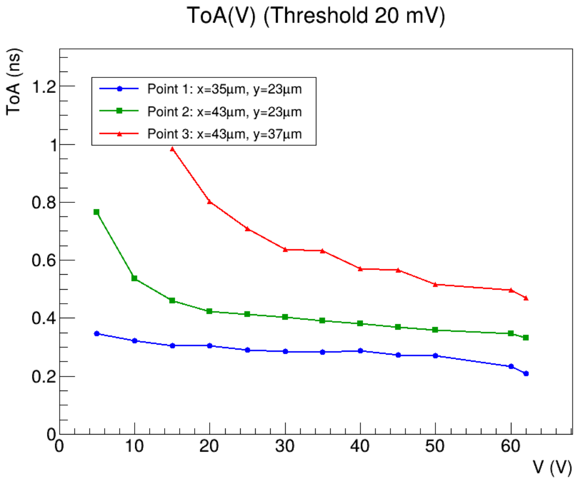


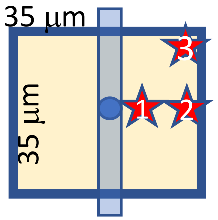
ToA vs. V_{bias}, Rise Time vs V_{bias}

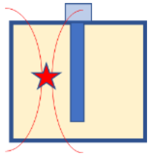






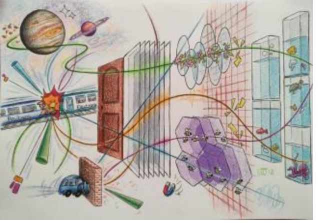




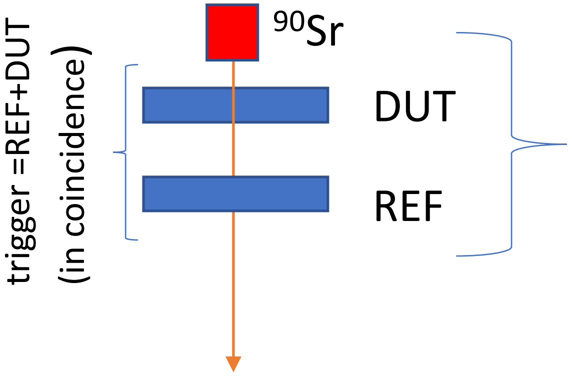


- optimization of the **electronics is needed** – integration time of around 1 ns to maximize S/N that offsets somewhat larger t_{peak}
- Due to large variation of the drift times the jitter will be position dependent – would be even without the gain as shown by points below the onset of multiplication

- **optimization of electrode geometry** is needed to minimize the ToA difference between different hit position.
- Inclination of detectors to large degree solves this issue – minimization of the ToA spread
- Apart from smaller capacitance (reduction of the noise) the inclined tracks become less of a problem – much easier clustering.

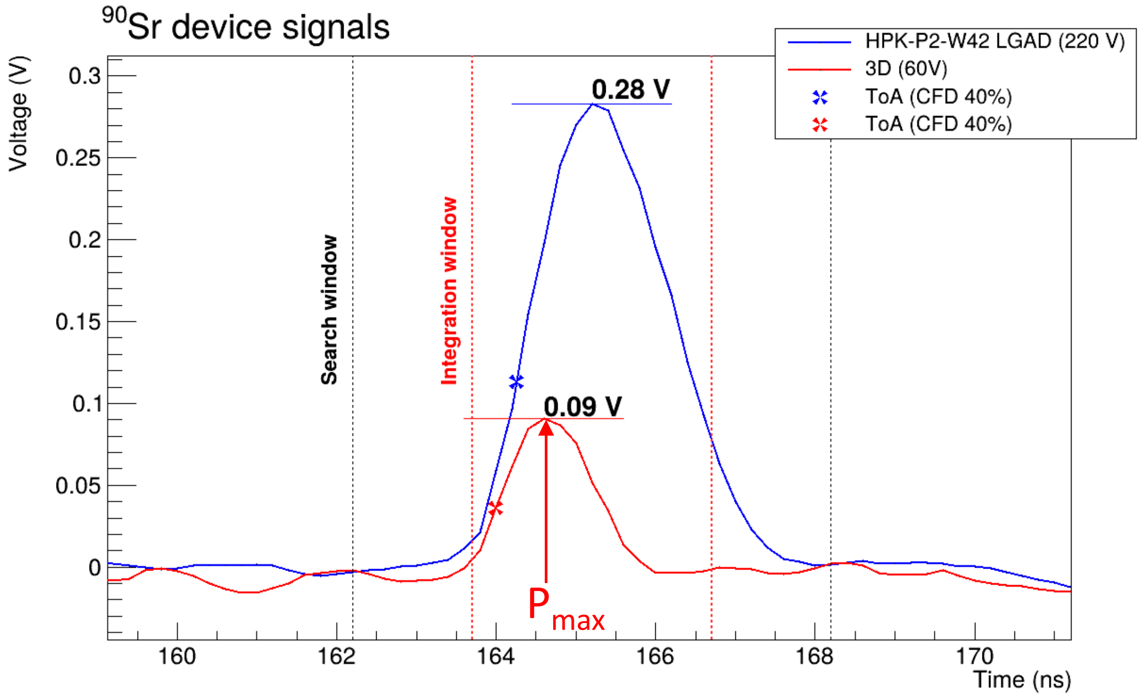


Signal measurements with ^{90}Sr

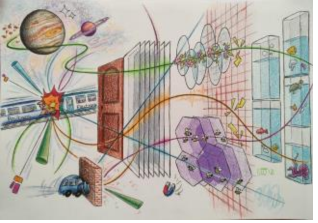


Operating conditions:

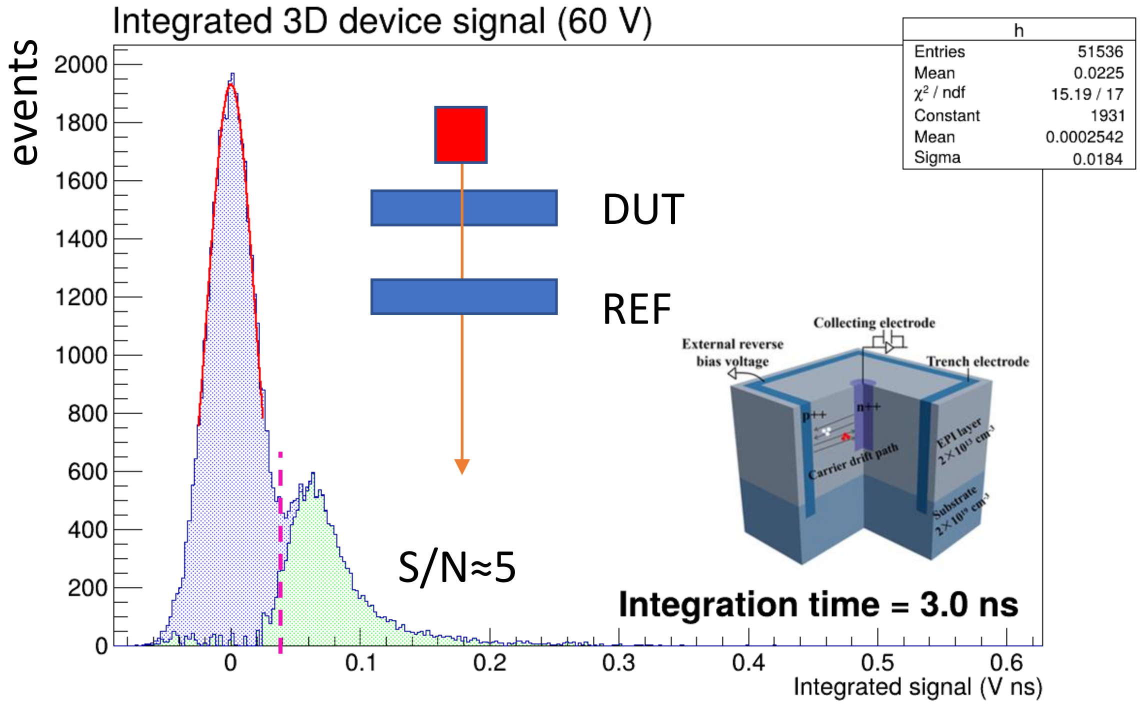
- REF detector is 2x2 HPK-P2-W42 LGAD at 220V at room temperature (larger capacitance than standard single pixel one – slower rise time/more noise)
- DUT is the same type of device as tested in the TPA
- Difficulties in operation
  - Small devices of 100x100 μm^2 – small DAQ rate (22 MBq Sr90 source)
  - noise of the UCSC timing boards high (fast and broadband) so detection of events in devices with small signal/moderate gain is demanding.

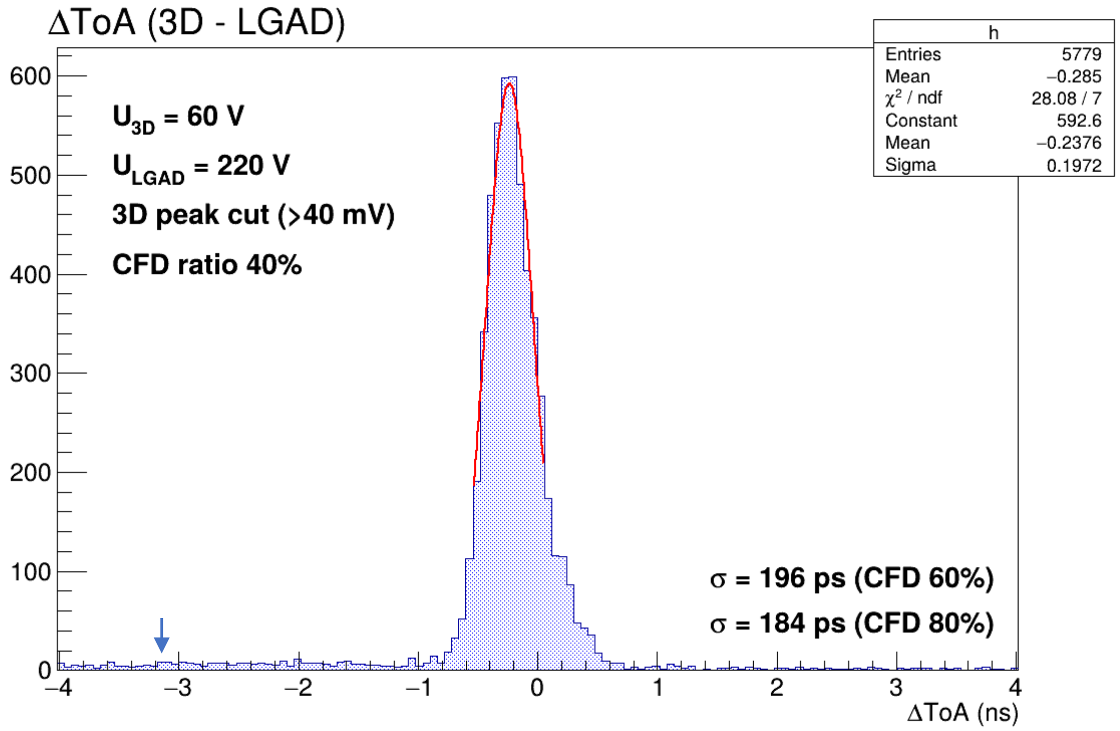


- Unlike REF triggering the signal in 3D is very small therefore we recorded huge number of event as very small threshold (few mV) – mostly noise in order not to bias the analysis with too high thresholds.
- Expected signal for 35 μm device is around 2400 e MPV which is lower than noise – **the fact that we see signal from close to minimum ionizing electrons with UCSB boards is a proof of gain.**



Charge and time resolution





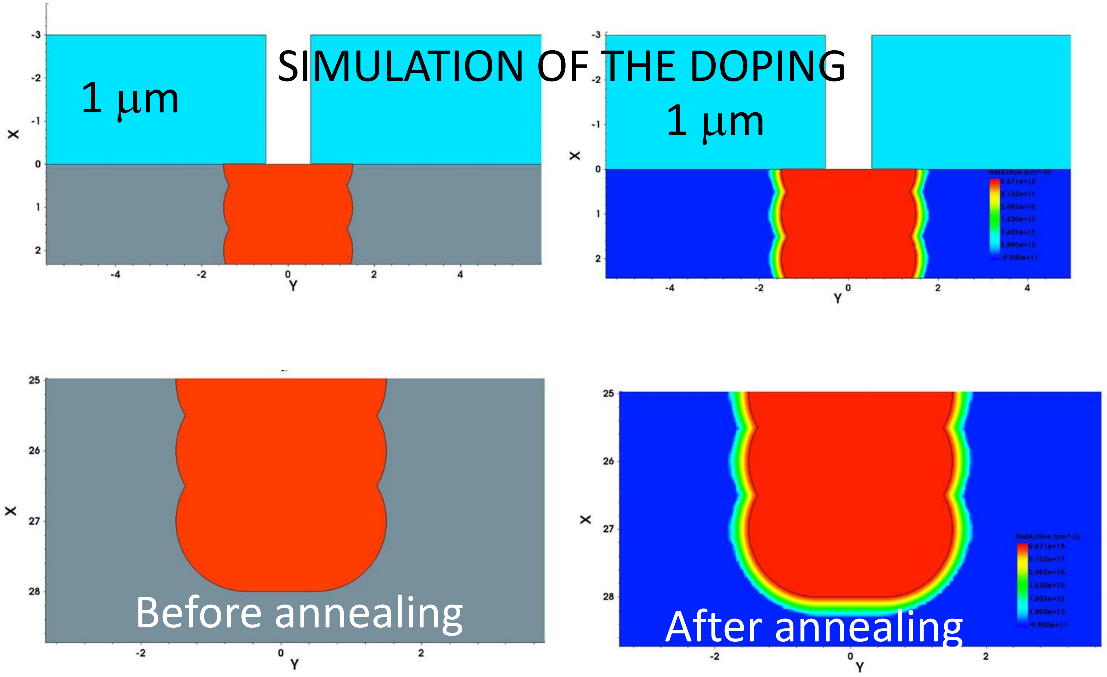
- Unlike for LGADs where P_{max} and integral of charge give the same results for 3D simply using Pmax doesn't produce a clearly visible most probable signal peak in the spectrum – indication of larger variation of signal shapes
- Noise~0.5 fC and SN~4-5 means MPV signals of ~2-2.5fC (Gain~6-8)

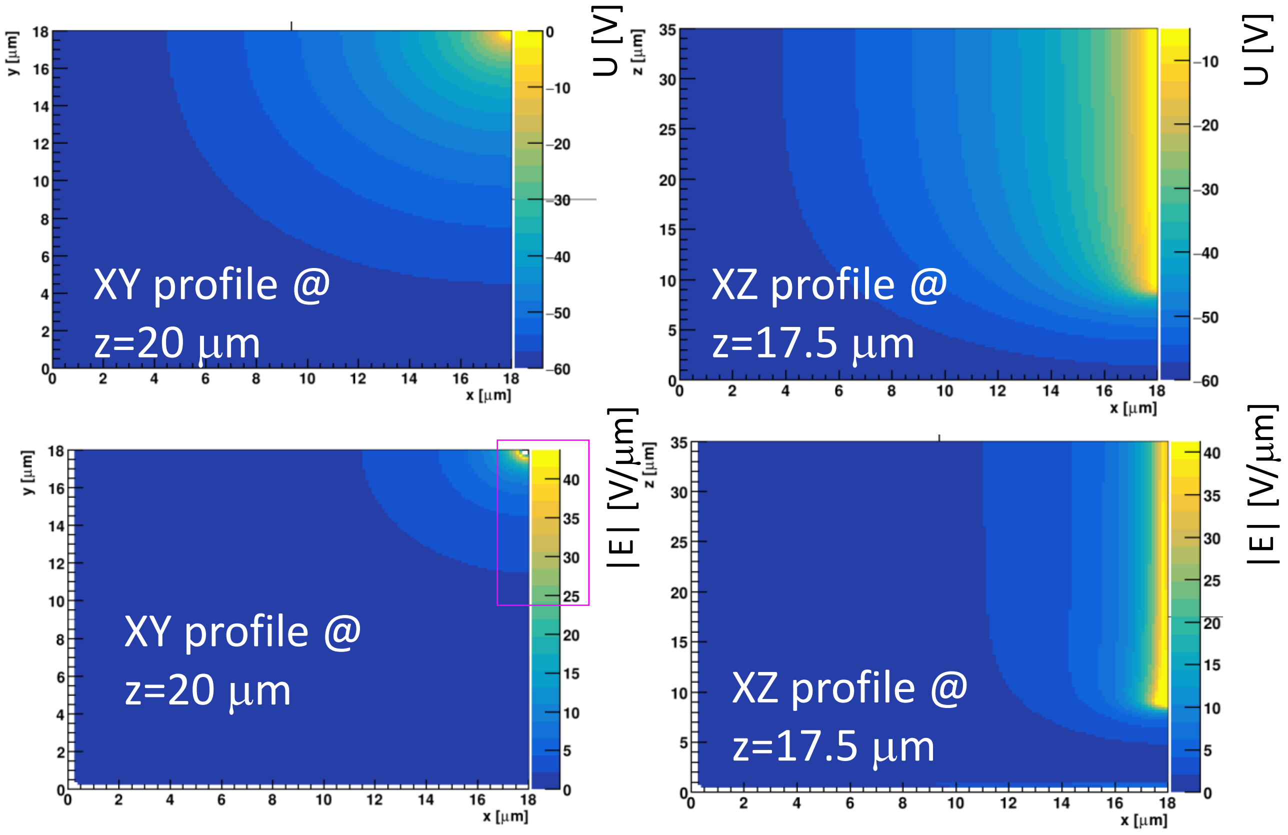
- Time resolution is order of 170 ps (subtracted contribution from the reference detector)
  - ToA from TPA-TCT ~ 100 ps
  - the jitter contribution is ~100 ps which (rise time of 600 ps, S/N~5)
  - "Landau fluctuations"?

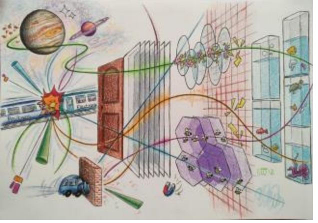
Simulations and understanding

- The concept of the simulations studies was presented at the last DRD3 week (https://indico.cern.ch/event/1507215/contributions/6537314/attachments/3081100/5454328/3D-timing-simualtion.pdf)
- We constructed the simulation of quarter of cell with parameters provided by IME – what is not yet fully implemented in simulation is the doping profile of the columns – we use effectively 2R=0.75 μm wide column with abrupt doping profile
- TPA "cigar spot shape" is also taken as linear distribution of carriers in cylinder of L=20, R=2 μm.
- resistivity of the p$^+$

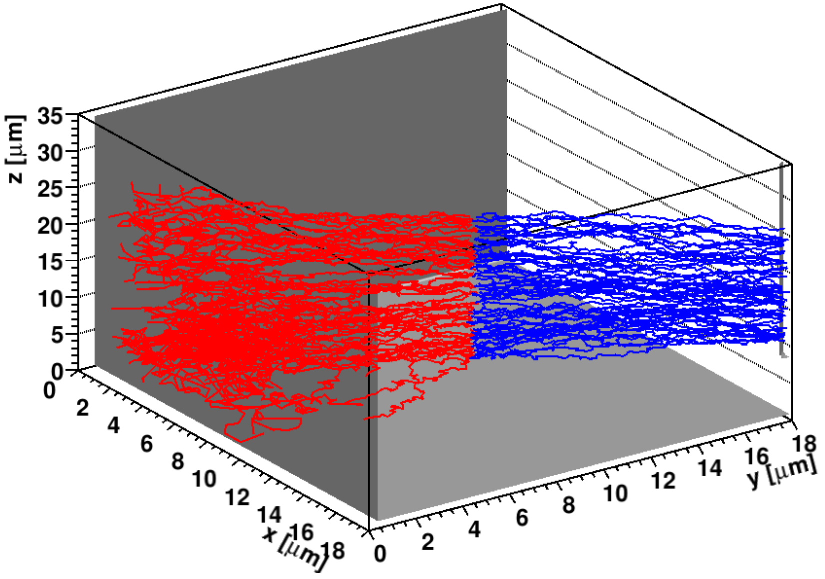
Still early days of understanding these devices!

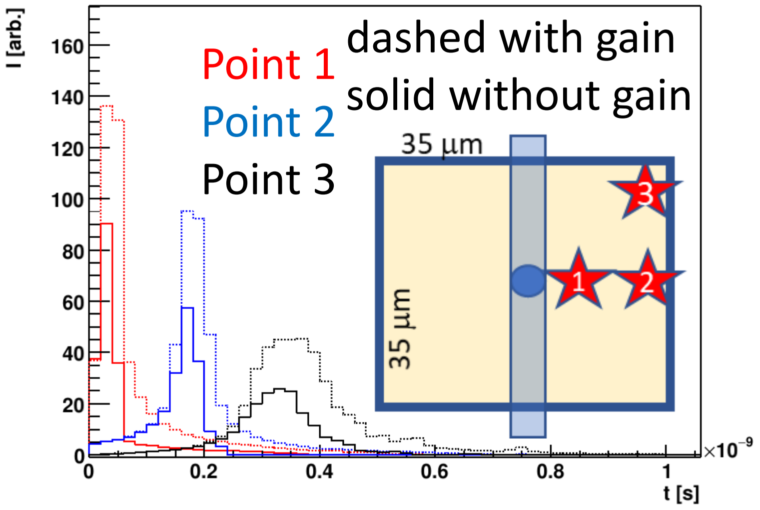




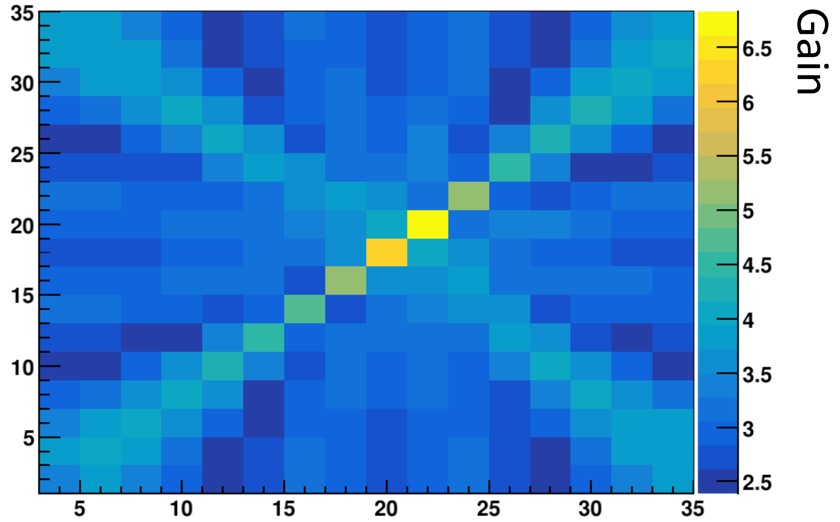


Gain uniformity across the sensor



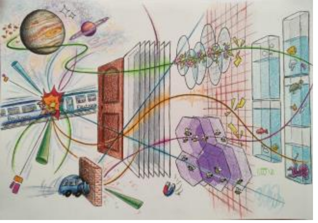


Gain distribution across the sensors for TPA (around **~2x lower gain than** measured)



The induced currents at 60V are of order of 0.5-1 ns . Notably longer signals are measured with TPA – slide 6 (partly this can be attributed to amplifier, still looking for reasons why?)

Finding the right doping profile of the column and right impact ionization parameters will be the challenge. Once these parameters are found they will serve as an anchor for fast simulations (calibrated).



Conclusions and plans

Conclusions:

- First very small pitch and thickness 3D devices were produced with controllable gain (35x35x35 μm^3 cells)
- **gains of up to around 15 were measured with devices fully functional at moderate voltages 62 V**
- **only a small gain variation across the cell was observed**
- 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 clearly shows this
- Sr 90 measurements confirmed the performance with time resolution compatible with expectations

Plans:

- more studies with other structures
- irradiation of the samples – radiation damage studies
- test beam also for inclined tracks
- Design of sensor optimized for timing.