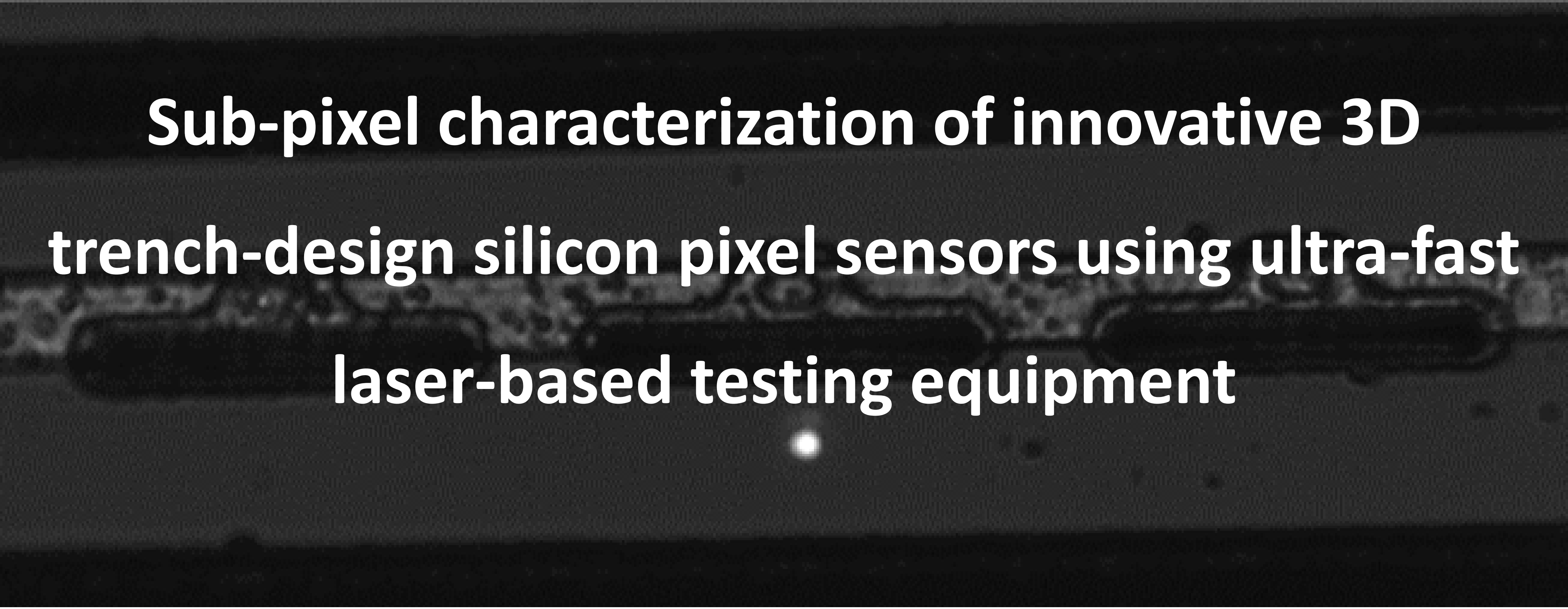


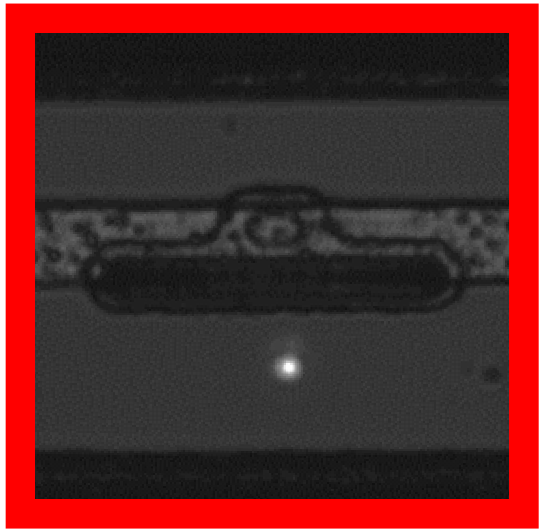
Sub-pixel characterization of innovative 3D trench-design silicon pixel sensors using ultra-fast laser-based testing equipment

16th (Virtual) "Trento" Workshop on Advanced
Silicon Radiation Detectors

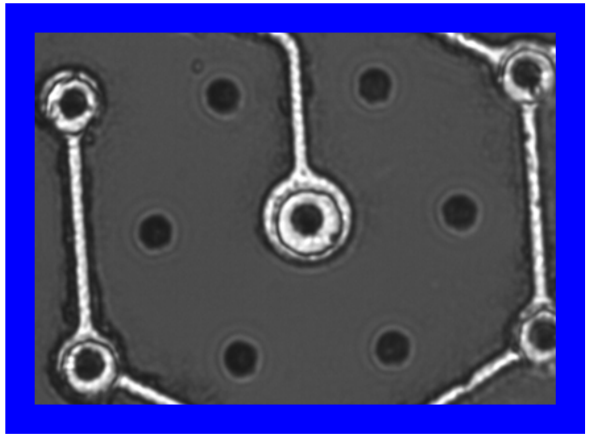
A. Lampis on behalf of the TimeSPOT team

Outline

- Sensor non uniformity contribution to a charged particle detector time resolution



- Laser based setup
- Sensor characterization:
    - Amplitude maps
    - Time of Arrival maps



- Comparison between trench sensor and column sensor

Sensor non-uniformity σ_{un}

The sensor signal is produced by the drift of the charge carriers created along the path of the (charged) particle across the pixel volume, this charge motion induces an instantaneous current at the readout electrode defined as

$$i = q\,\vec{E}_w \cdot \vec{v}_d$$

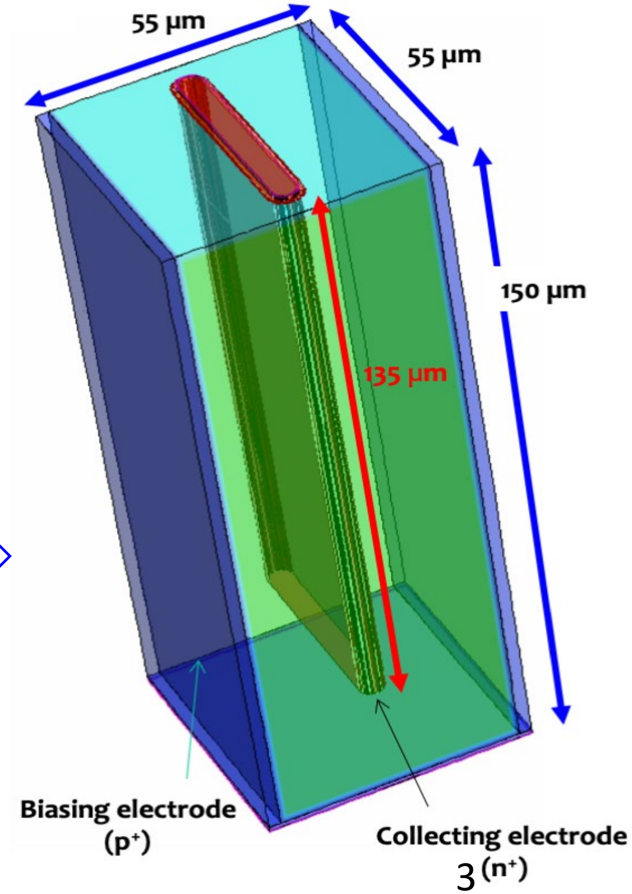
weighting field

carrier's drift velocity

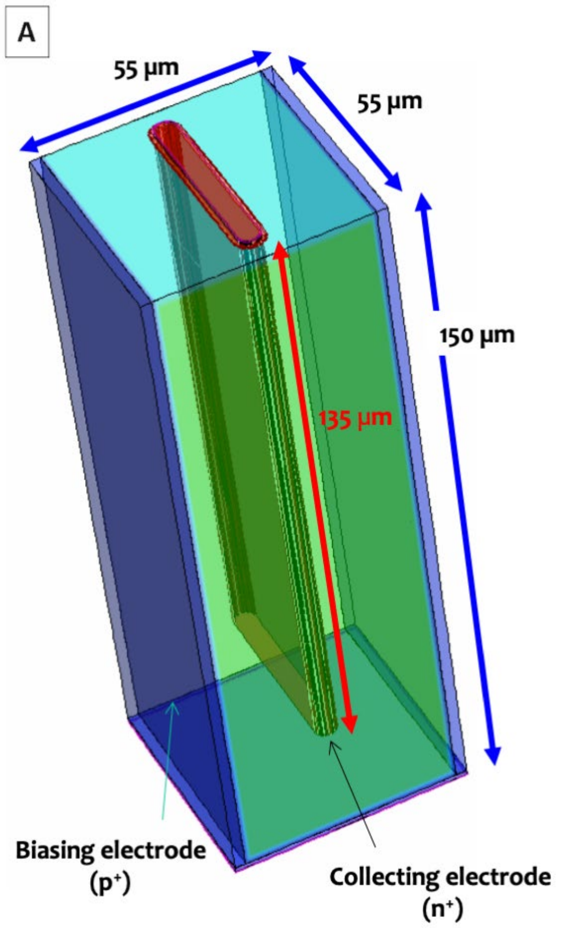
If $\vec{E}_w \cdot \vec{v}_d$ **is as uniform as possible** inside the active volume the **signals do not depend on where the charged particle has crossed the detector**:

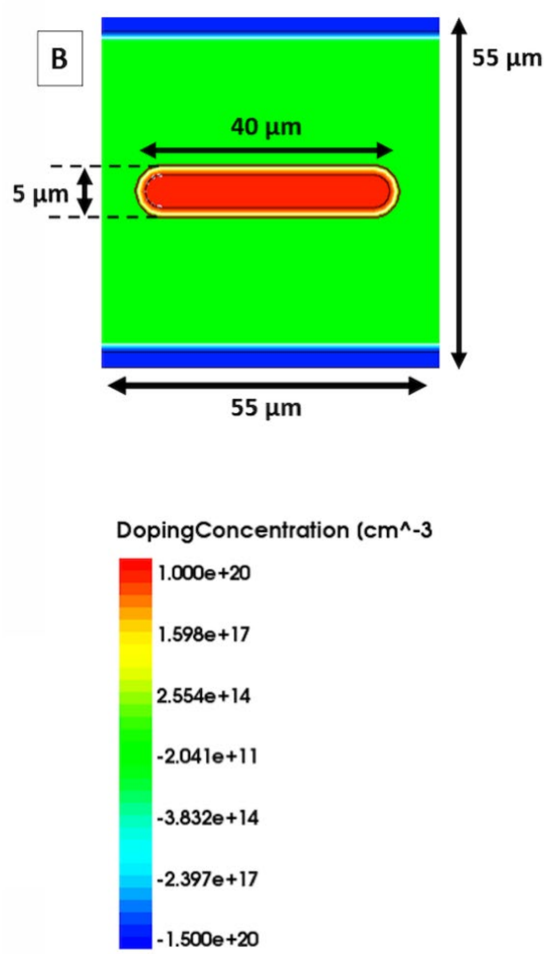
- $\vec{E}_w$ uniform by design
- work in a velocity saturation regime

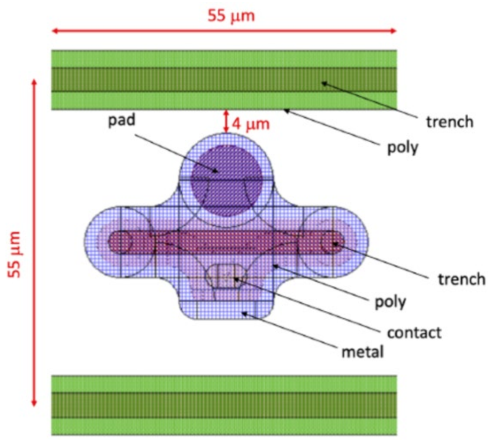
Trench geometry

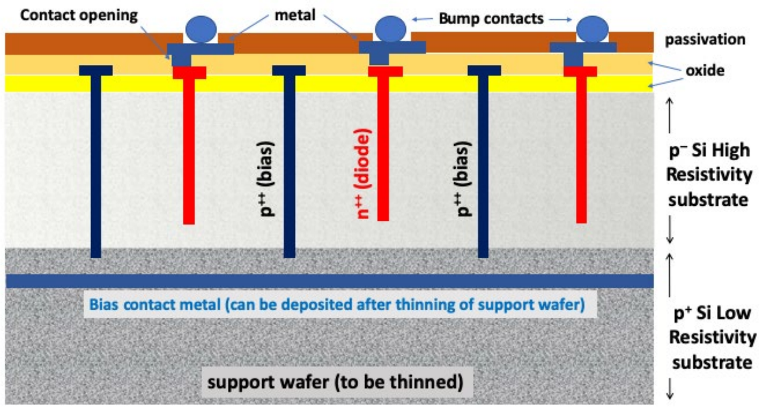


The trench-type TimeSPOT 3D pixels







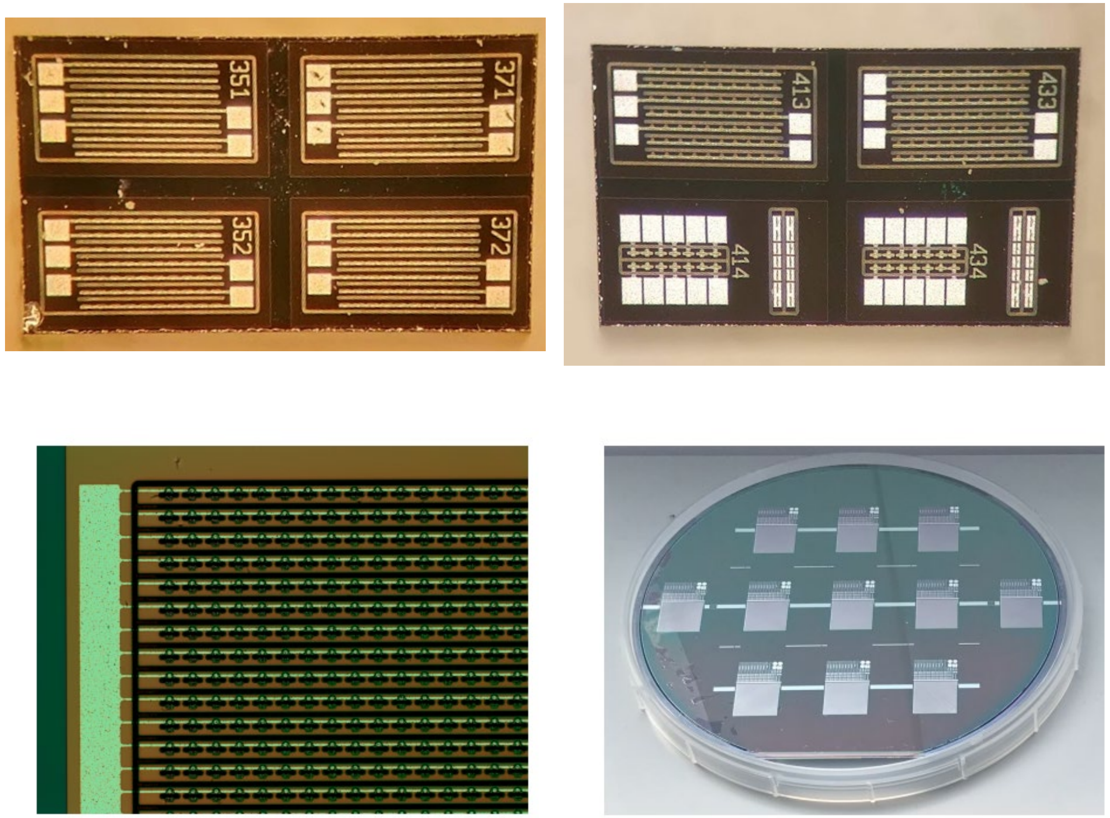


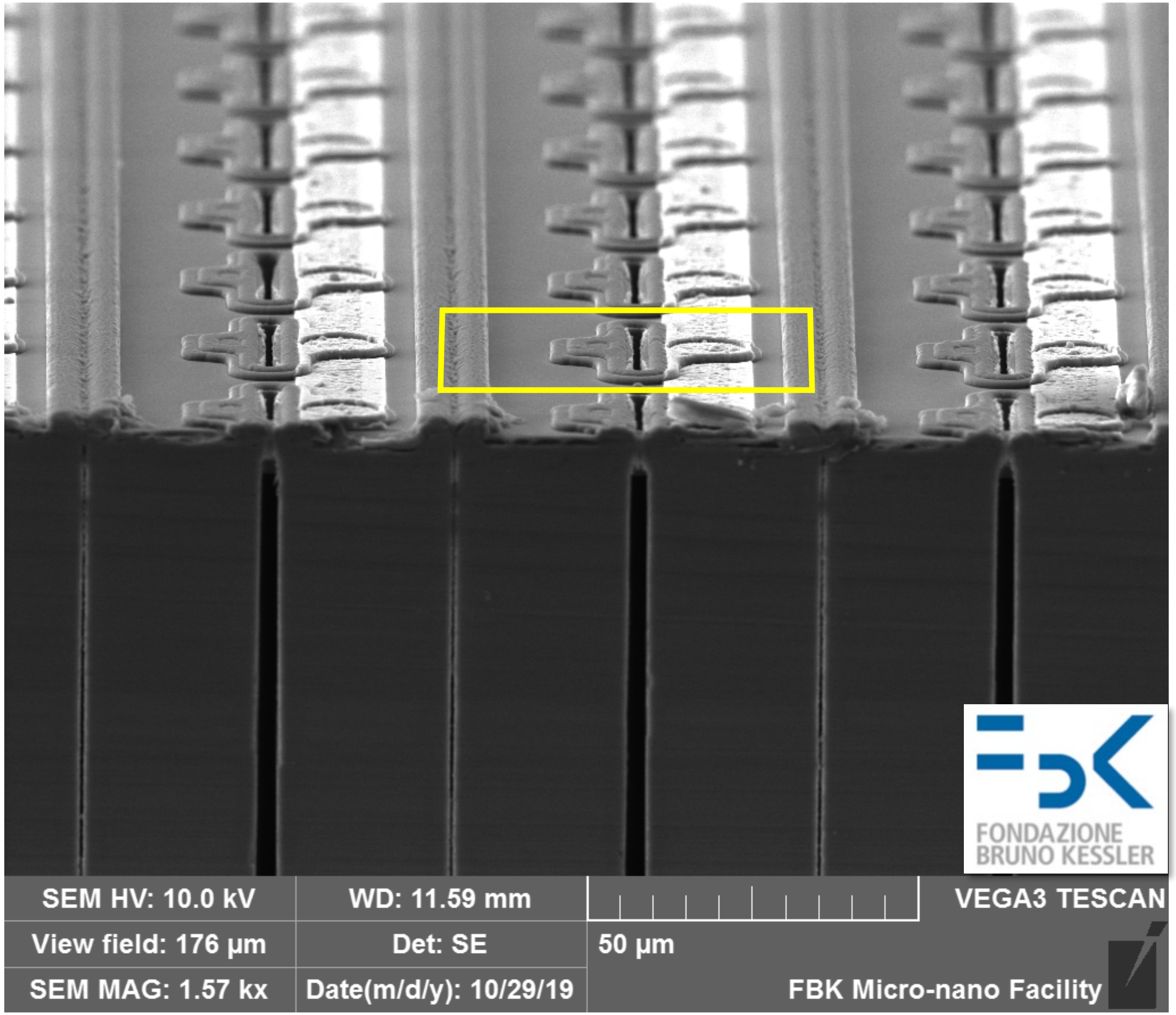
- 55µm x 55µm pixels (to be compatible with existing FEE, for example the Timepix family)
- In each pixel a 40µm long n++ trench is placed between continuous p++ trenches used for the bias
- 150µm-thick active thickness, on a 350µm-thick support wafer
- The collection electrode is 135µm deep

TimeSPOT silicon sensor

First batch produced in 2019 at Fondazione Bruno Kessler (FBK, Trento, Italy)

Many devices fabricated (single, double pixels, pixel-strips, 256x256 pixel matrices)

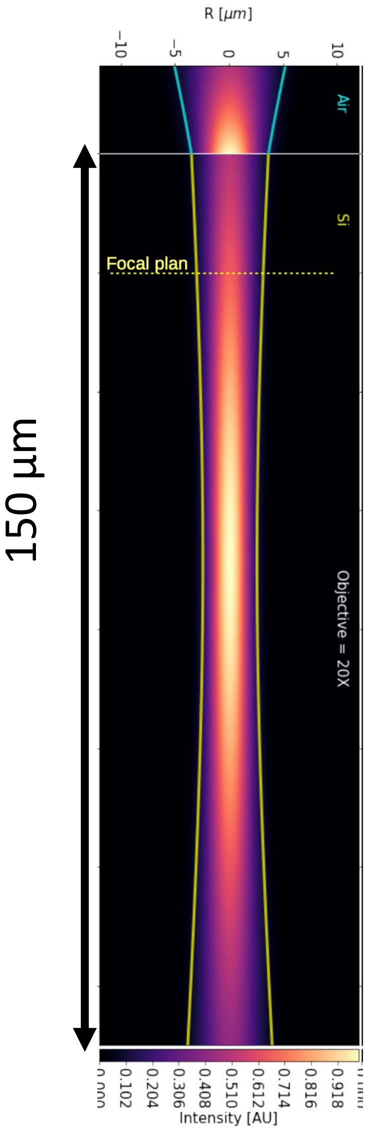


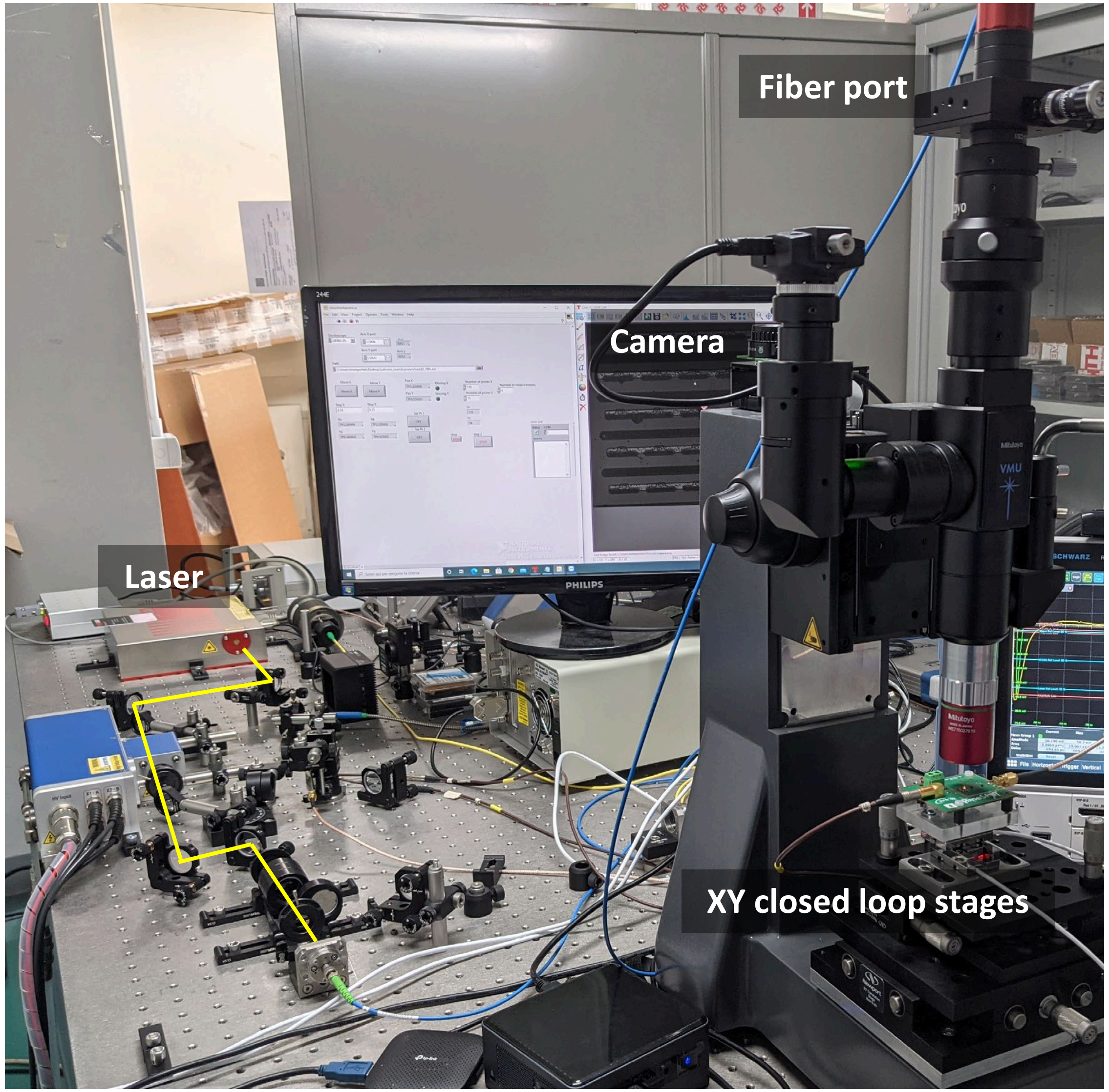


Laser-based setup

Laser setup allows to emulate the energy deposit of a MIP passing through the sensor

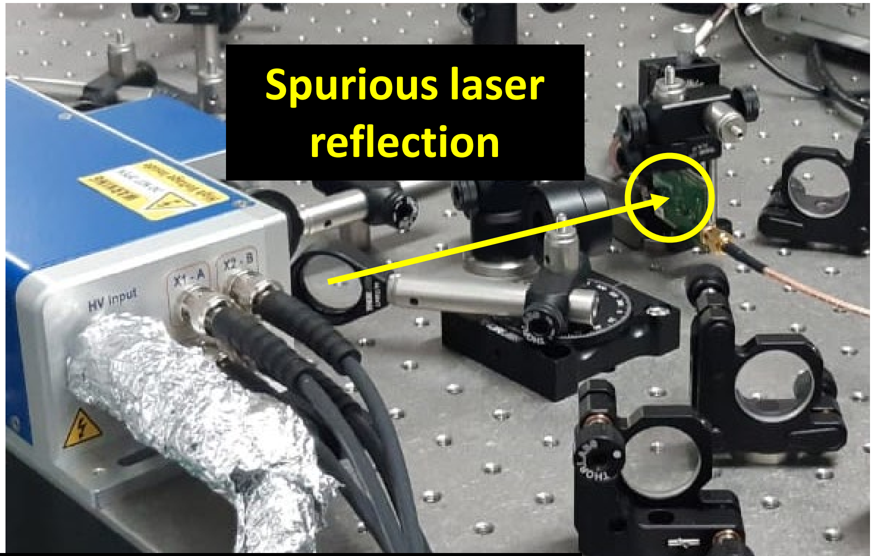
- Pulsed laser:
  - IR Laser (1030 nm), FWHM < 200 fs
- Optical fiber from laser to **microscope**.
- **Focused spot** of $\sim 5\ \mu m$
- Observation **camera**
- **XY closed loop stages**
- **Optical laser time reference**: accuracy **<1ps**



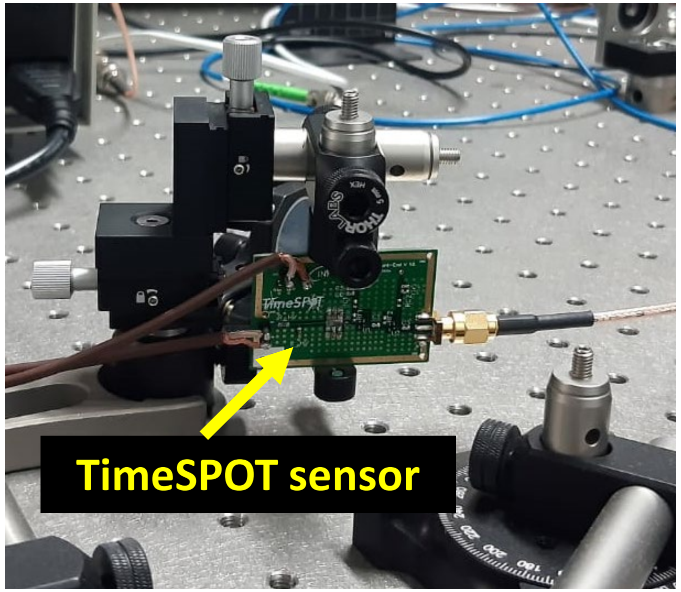


Optical laser time reference

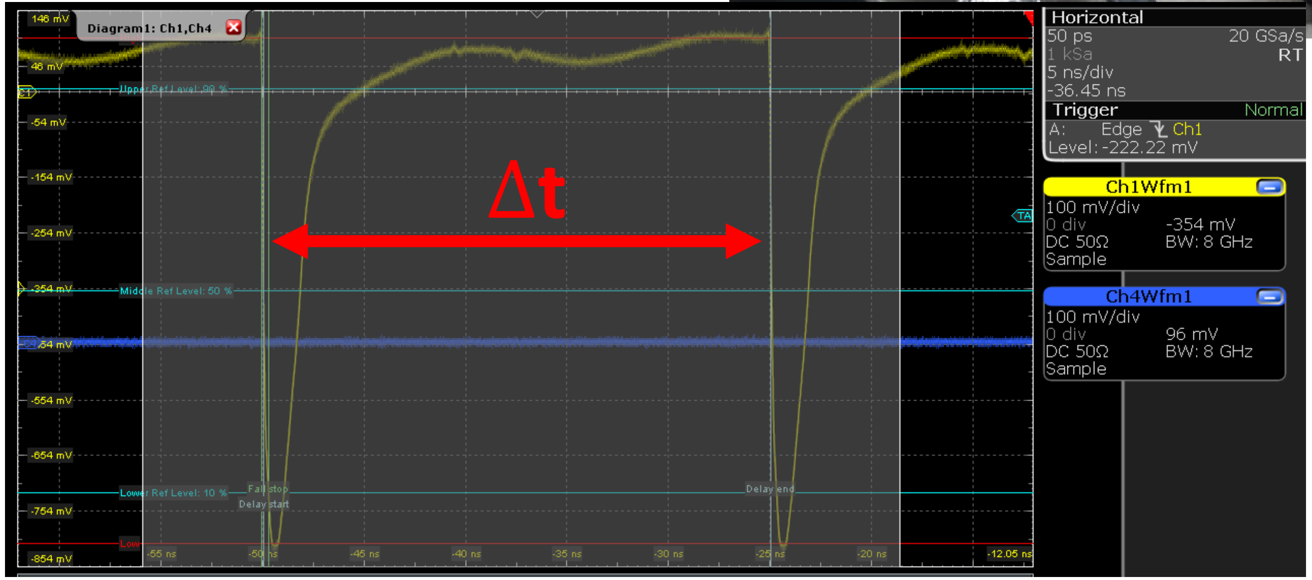
The time reference is itself a TimeSPOT 3D sensor but stimulated with high intensity (~10 MIP)



Spurious laser reflection



TimeSPOT sensor

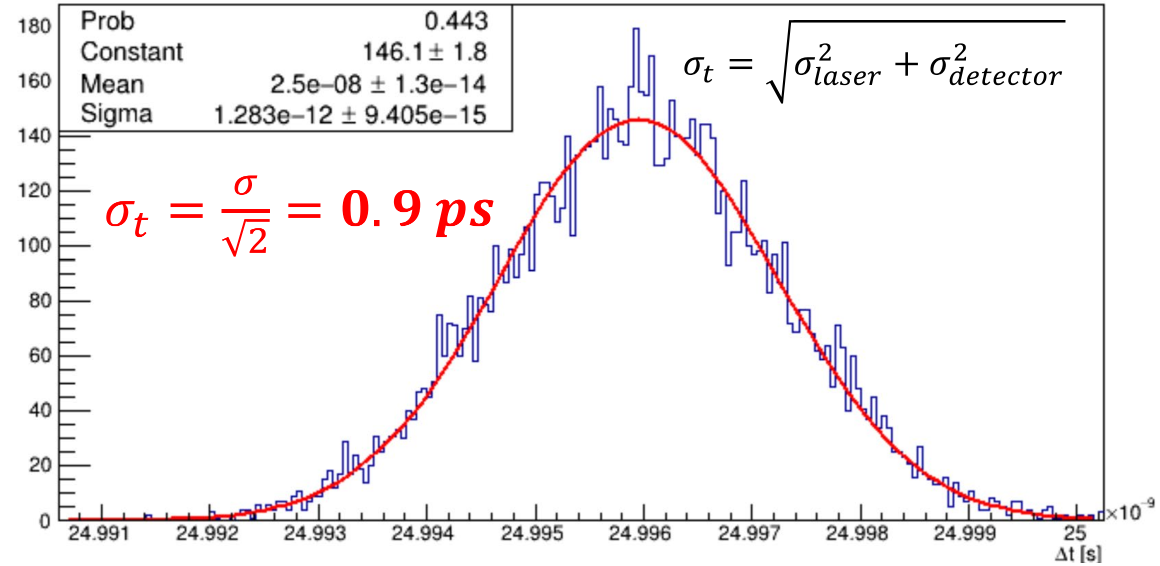


Horizontal
50 ps 20 GSa/s
1 kSa RT
5 ns/div
-36.45 ns

Trigger Normal
A: Edge Ch1
Level: -222.22 mV

Ch1Wfm1
100 mV/div
0 div -354 mV
DC 50Ω BW: 8 GHz
Sample

Ch4Wfm1
100 mV/div
0 div 96 mV
DC 50Ω BW: 8 GHz
Sample



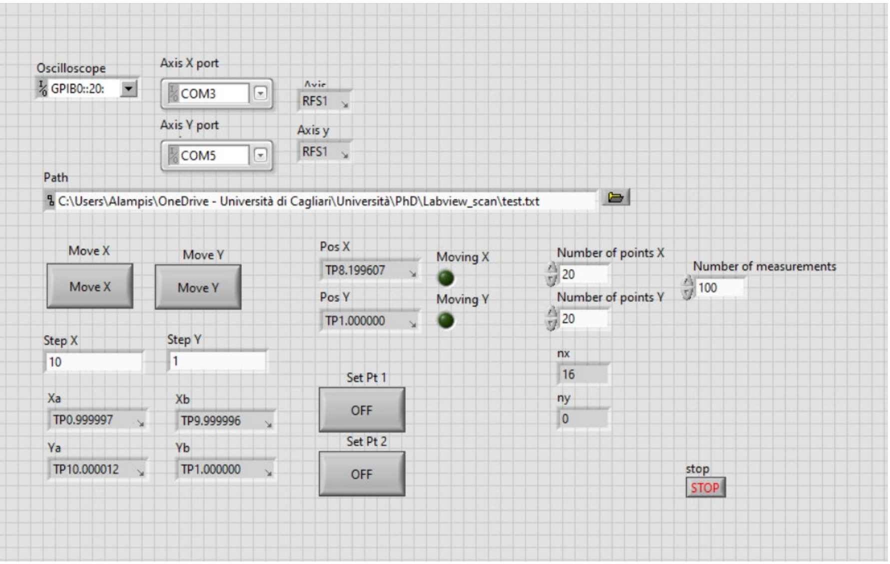
Prob 0.443
Constant 146.1 ± 1.8
Mean 2.5e−08 ± 1.3e−14
Sigma 1.283e−12 ± 9.405e−15

$$\sigma_t = \sqrt{\sigma_{laser}^2 + \sigma_{detector}^2}$$

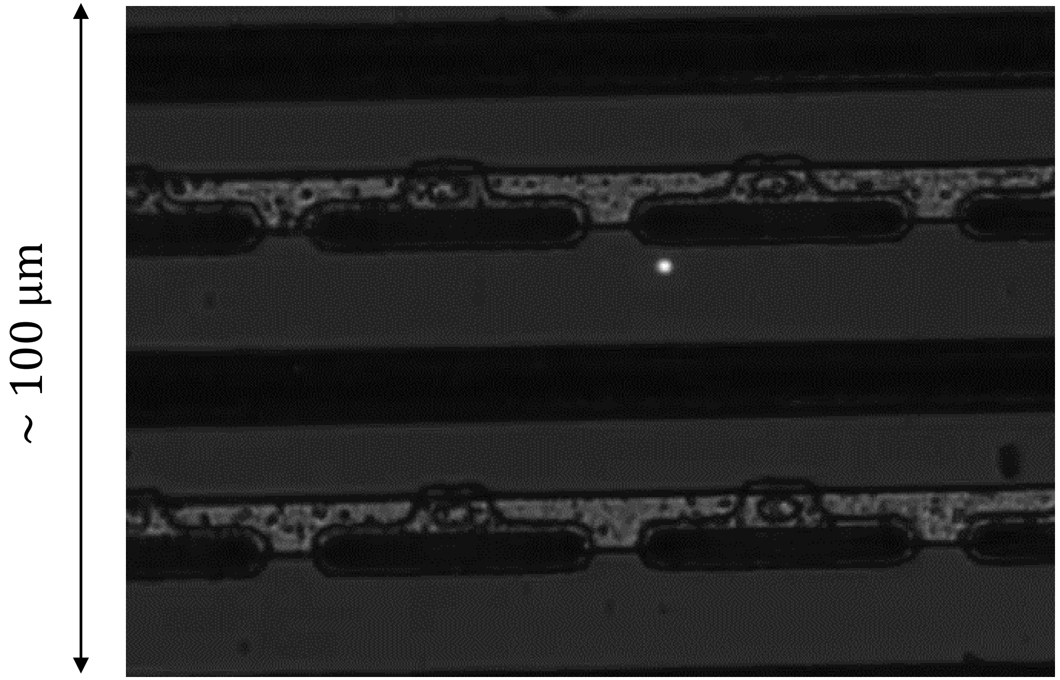
$$\sigma_t = \frac{\sigma}{\sqrt{2}} = \mathbf{0.9}\ ps$$

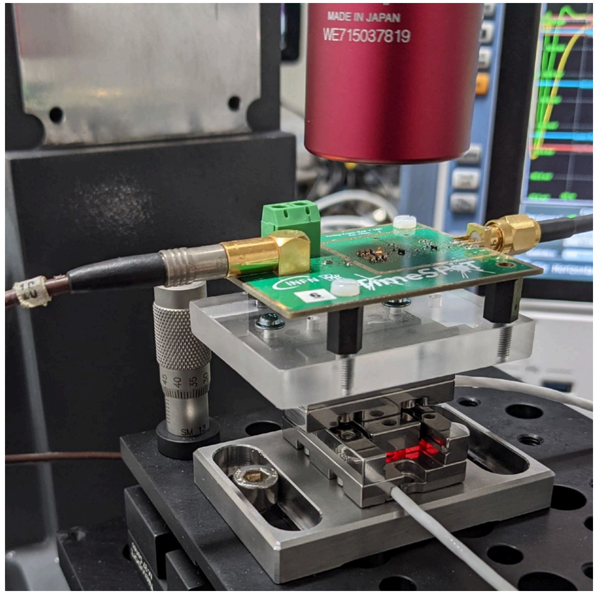
The sensor scan

- Labview software to perform the sensor scan:
    - XY closed loop stages move the sensor with respect to the laser beam ⟶ **scanning step 1 μm**
    - Oscilloscope acquires sensor’s waveforms and perform the measurements



Oscilloscope: GPIB0::20:
Axis X port: COM3
Axis: RFS1
Axis Y port: COM5
Axis y: RFS1
Path: C:\Users\Alampis\OneDrive - Università di Cagliari\Università\PhD\Labview_scan\test.txt
Pos X: TP8.199607
Pos Y: TP1.000000
Number of points X: 20
Number of points Y: 20
Number of measurements: 100
Step X: 10
Step Y: 1
nx: 16
ny: 0
Xa: TP0.999997
Xb: TP9.999996
Ya: TP10.000012
Yb: TP1.000000
Set Pt 1: OFF
Set Pt 2: OFF



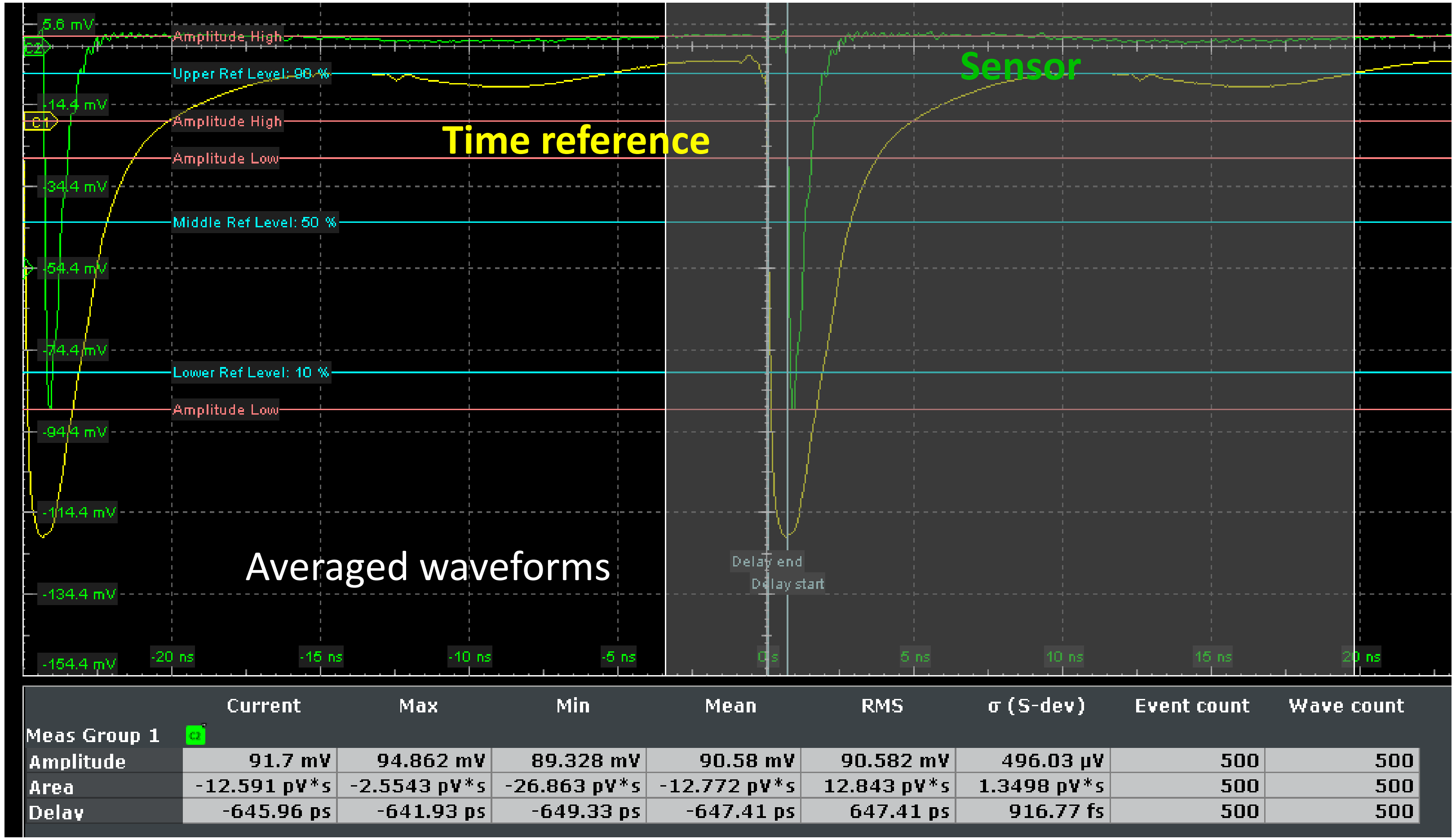


Measurements

- Measurements performed via 8 GHz oscilloscope 20 GSa/s
- Averaged waveform to reduce electronic noise contribution: ⟶ $\sigma = \sqrt{\sigma_{un}^2 + \sigma_{ej}^2}$
- **For each position** we measured:
  - Sensor signal **amplitude**
  - **Time of Arrival** (ToA) of laser pulses

$$\boxed{\mathbf{ToA} = t_{sensor} - t_{ref}}$$

t_{sensor} and t_{ref} by CFD @ 50% of amp

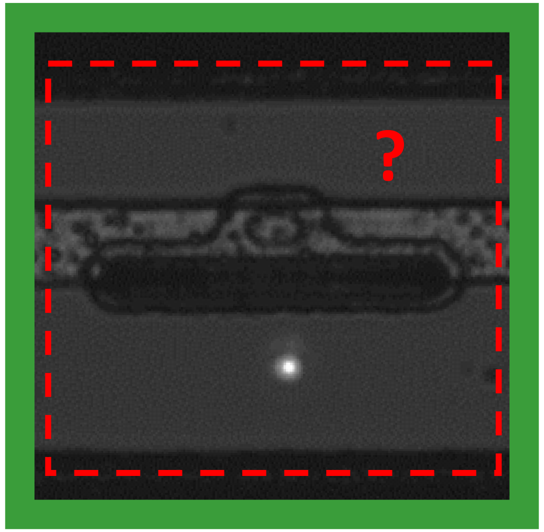


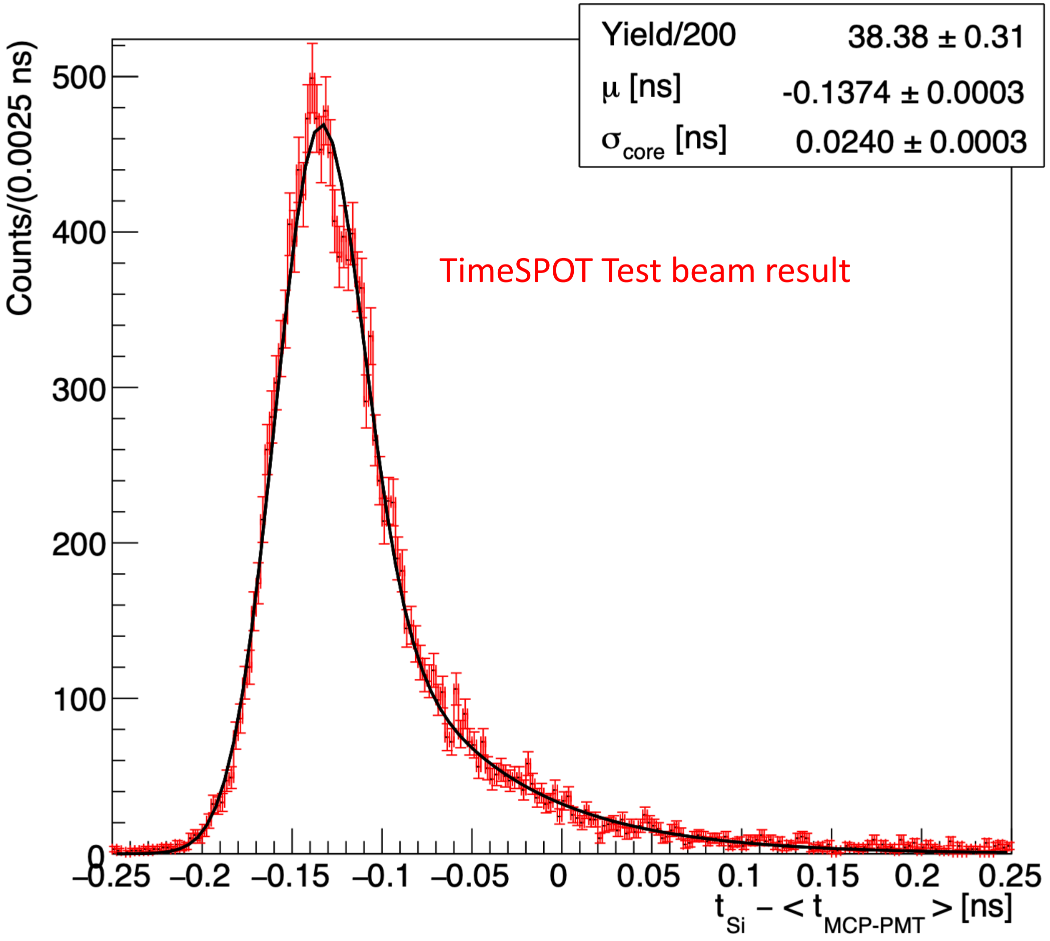
Meas Group 1	Current	Max	Min	Mean	RMS	σ (S-dev)	Event count	Wave count
Amplitude	91.7 mV	94.862 mV	89.328 mV	90.58 mV	90.582 mV	496.03 µV	500	500
Area	-12.591 pV*s	-2.5543 pV*s	-26.863 pV*s	-12.772 pV*s	12.843 pV*s	1.3498 pV*s	500	500
Delay	-645.96 ps	-641.93 ps	-649.33 ps	-647.41 ps	647.41 ps	916.77 fs	500	500

Why a sensor scan?

In a test beam characterization you only look to the signals that fulfil a trigger condition (in general a threshold in the DUT signal amplitude)

- How do you ensure you are looking at all the sensor active region?



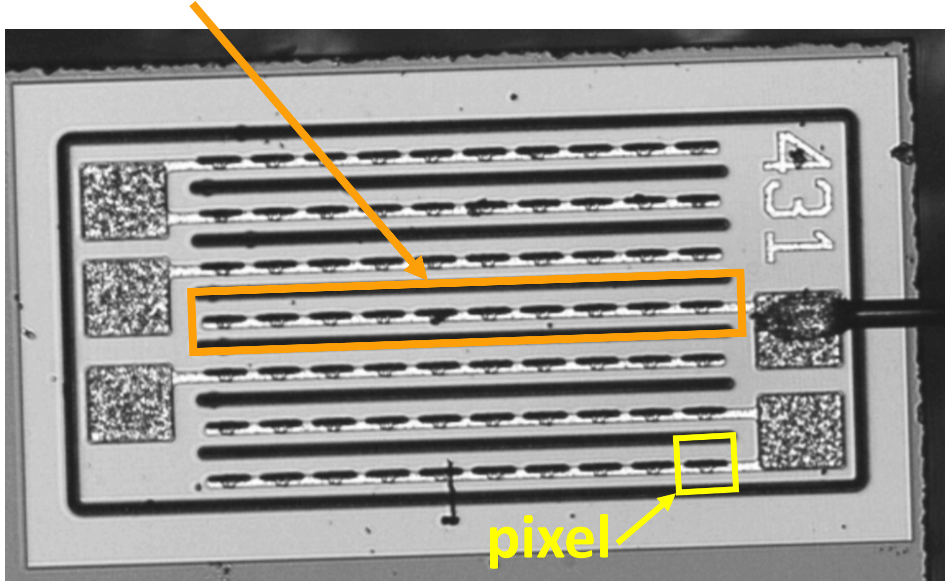


- For trench design we don't expect high disuniformity but is it true also for a more classic 3D geometry?

The laser scan allows to measure the **detailed response of the full sensor active area**

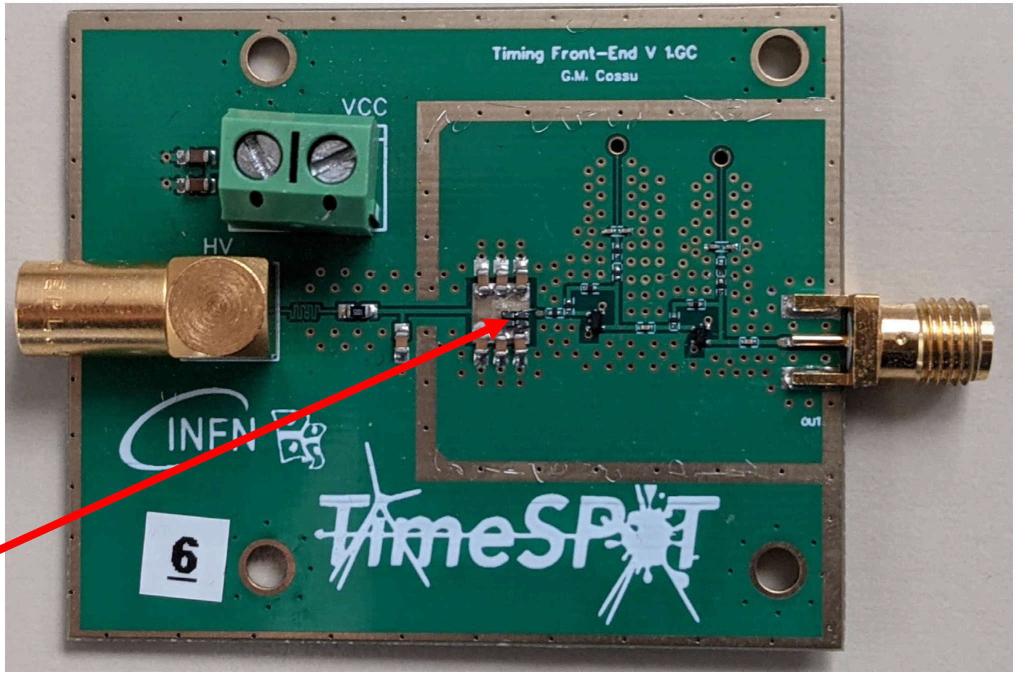
Device Under Test

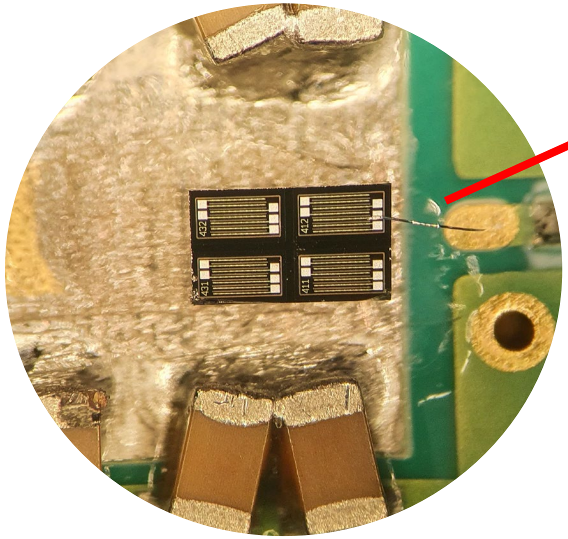
PIXEL STRIP: 10 pixels with readout electrodes shorted together



Wire bonding

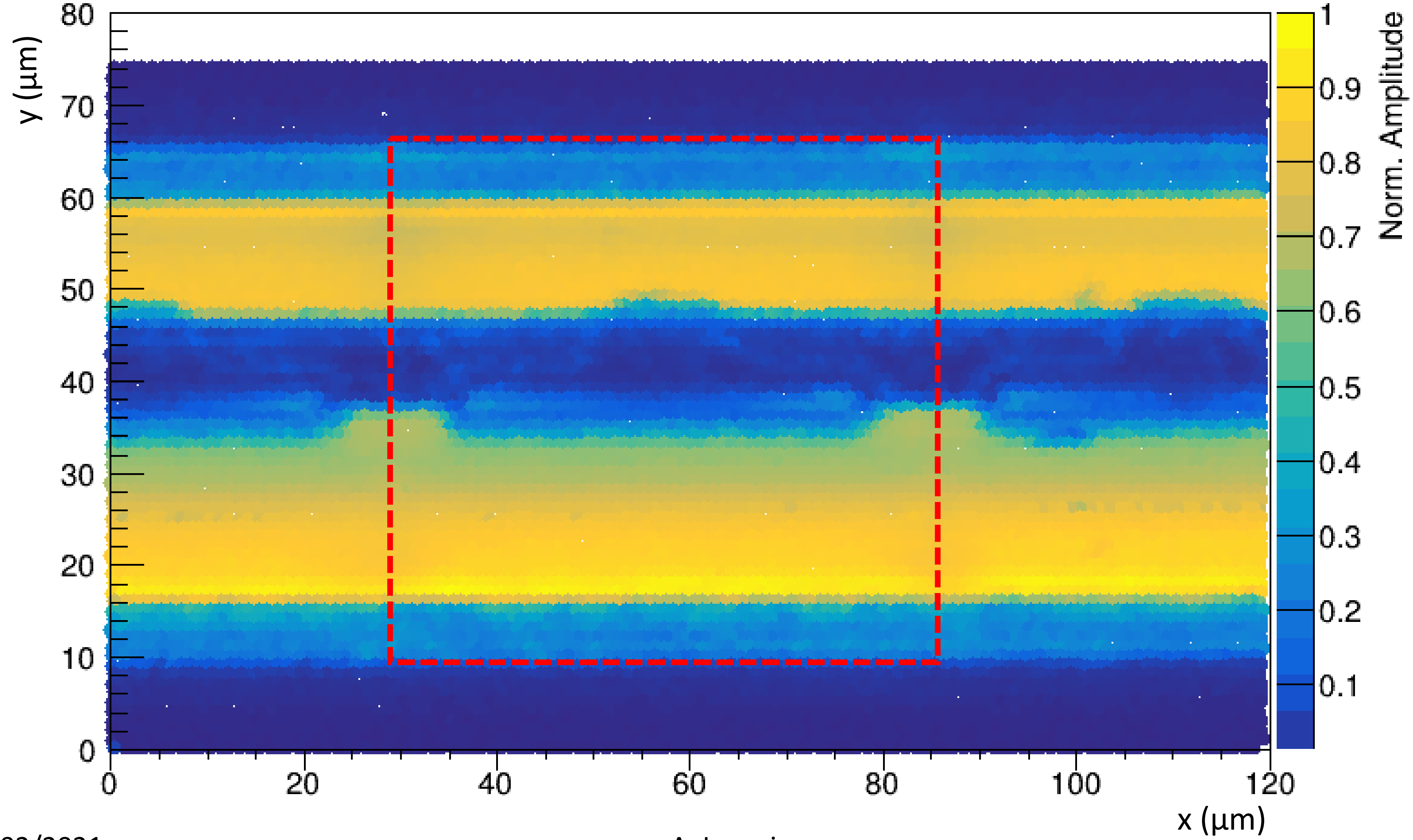
Front End Electronic board



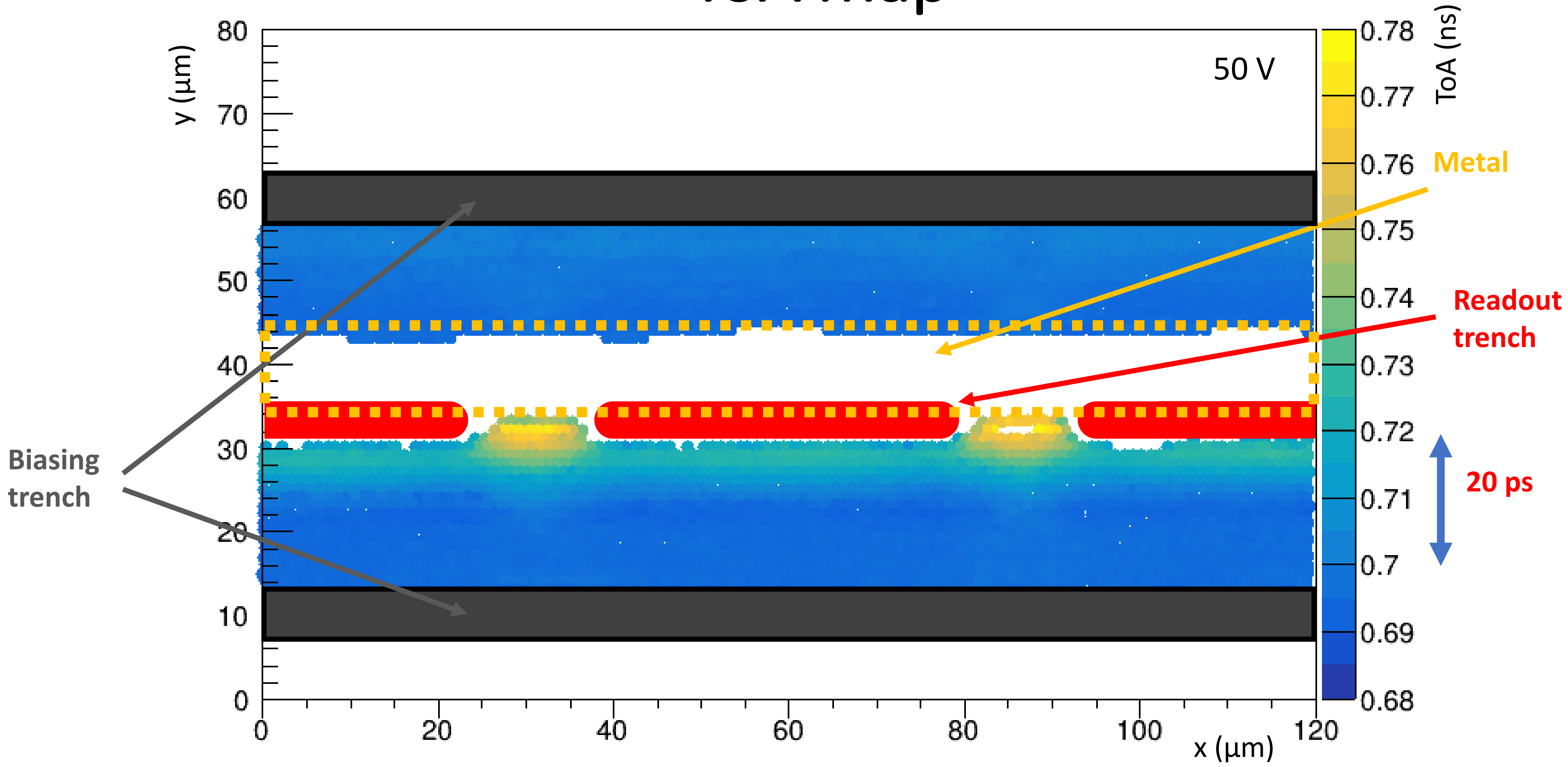


- Electronic **optimized for the TimeSPOT sensors**
- Two stages of **transimpedance amplifier** with ultra low noise SiGe Bjt allows to read very fast sensor's current

Amplitude Map

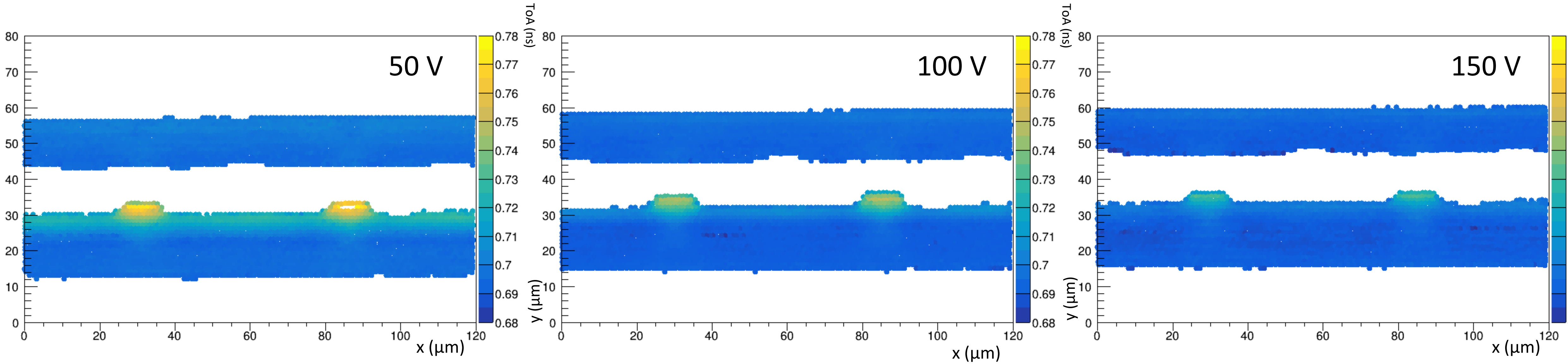


ToA map



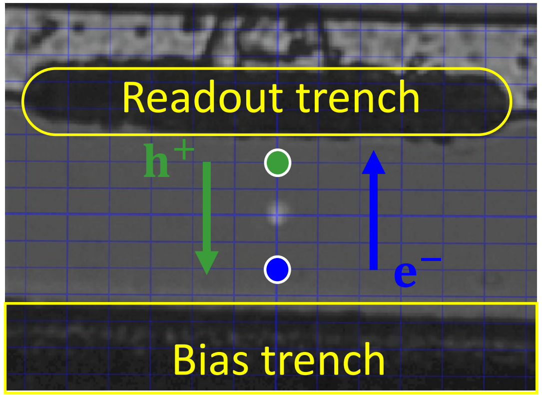
ToA extremely uniform

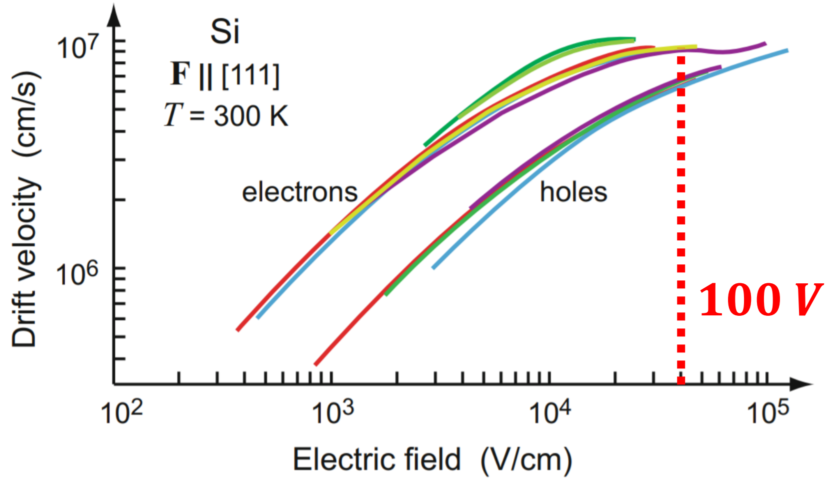
ToA vs Bias



- Slower regions near the readout trench due to holes drift velocity

- Trend confirmed: as the sensor bias increases the slower zones become faster (the holes drift velocity get closer to saturation)



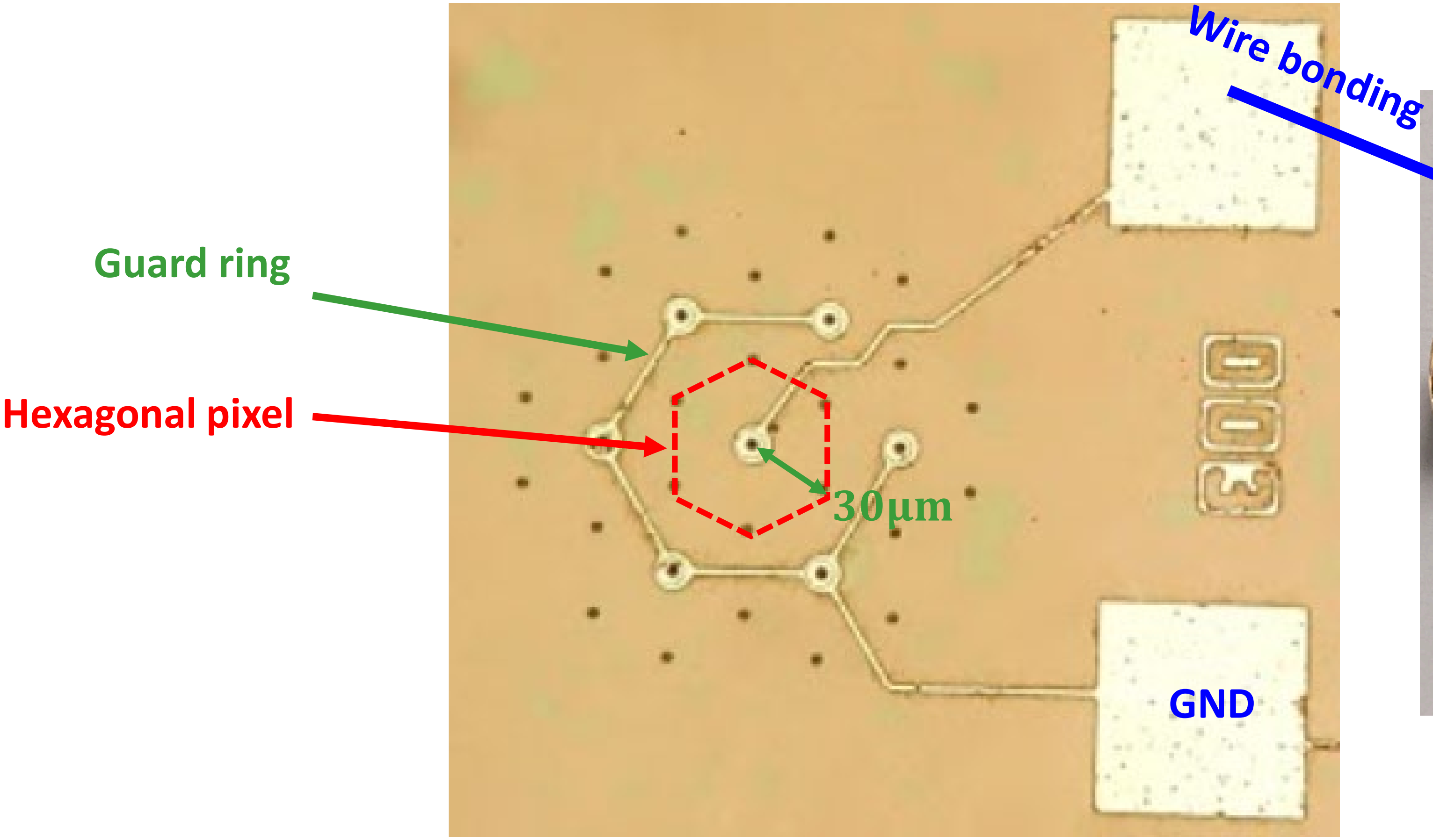


Böer K.W., Pohl U.W. (2018) Carrier Scattering at High Electric Fields. In: Semiconductor Physics. Springer, Cham. https://doi.org/10.1007/978-3-319-69150-3_24

Trench pixels produce extremely uniform ToA but increasing the bias voltage they become even more uniform

Device Under Test: Hexagonal pixel

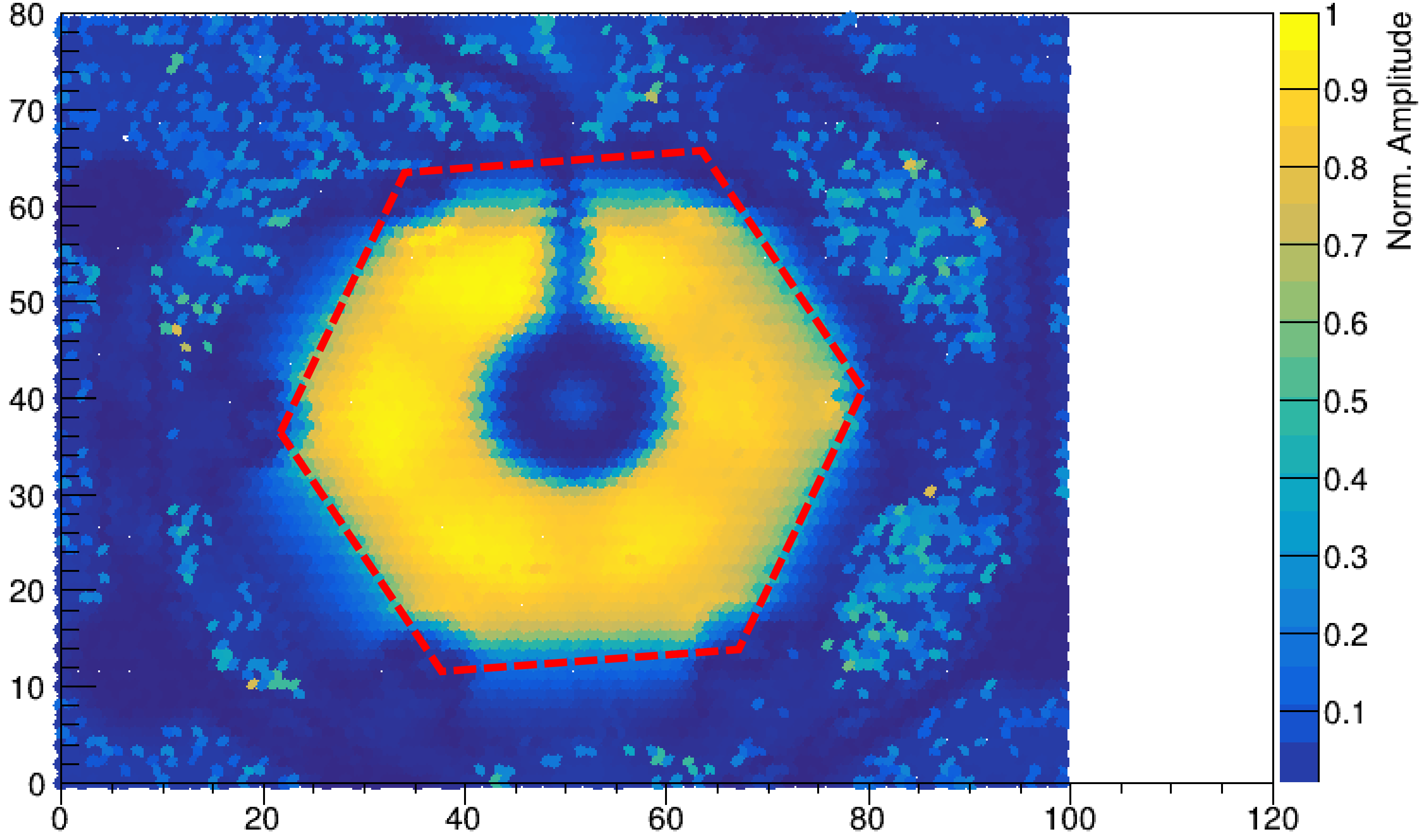
3D column electrodes



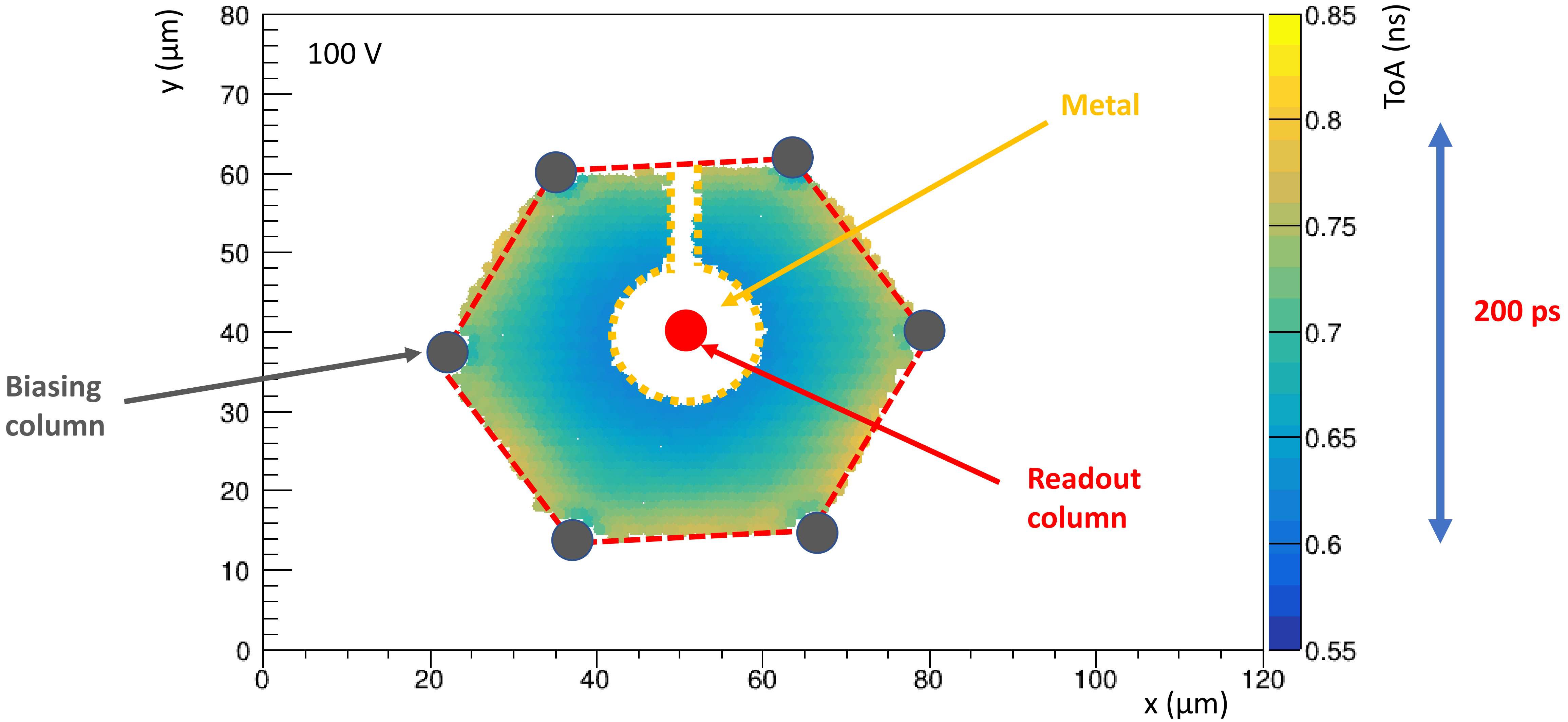
- Same front end electronic board

[Sultan, D M S. (2017). Development of Small-Pitch, Thin 3D Sensors for Pixel Detector Upgrades at HL-LHC. DOI: 10.13140/RG.2.2.36253.82403/1]

Amplitude Map: 3D Hexagonal

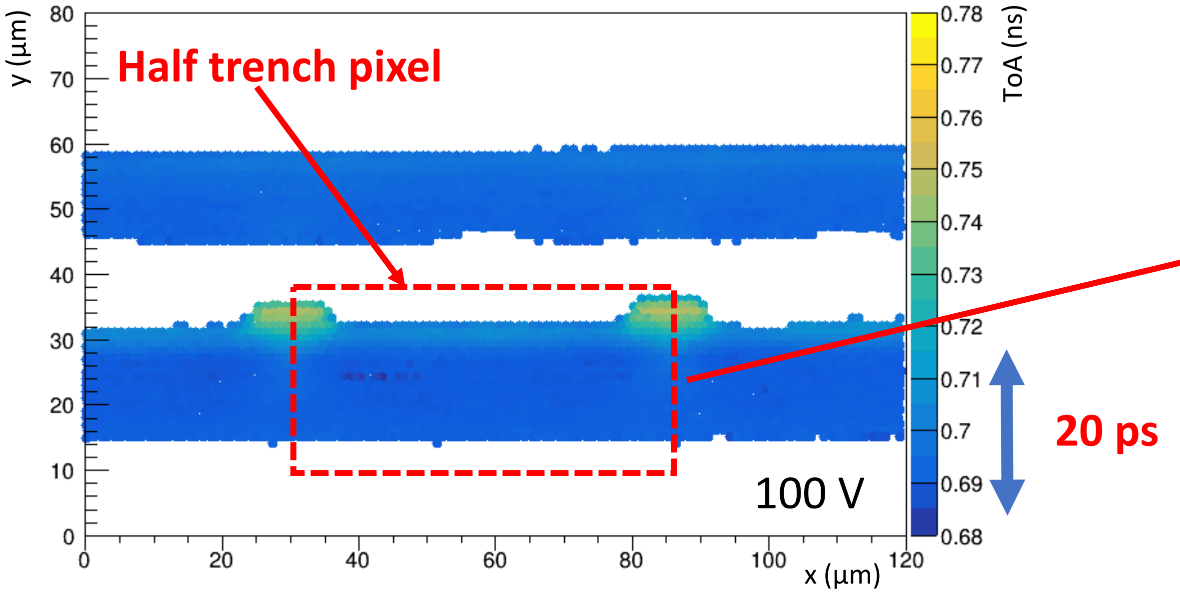


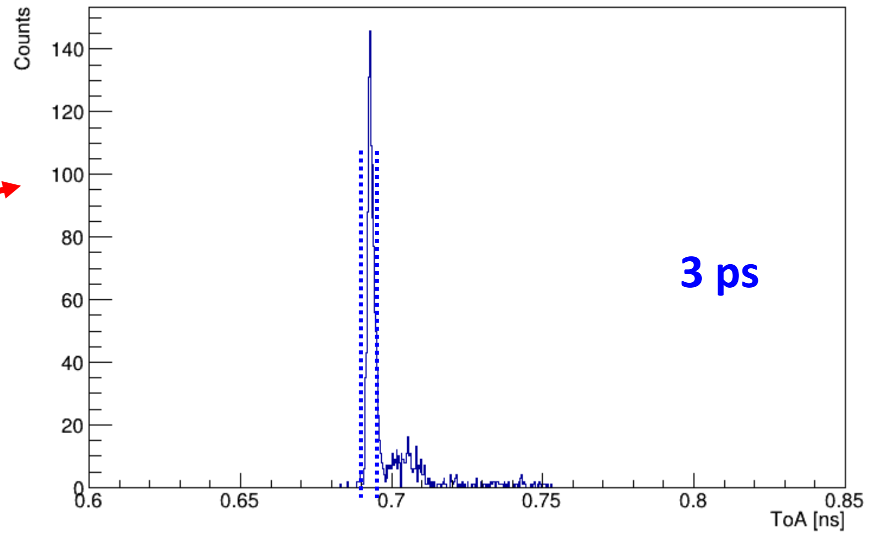
ToA map: 3D Hexagonal



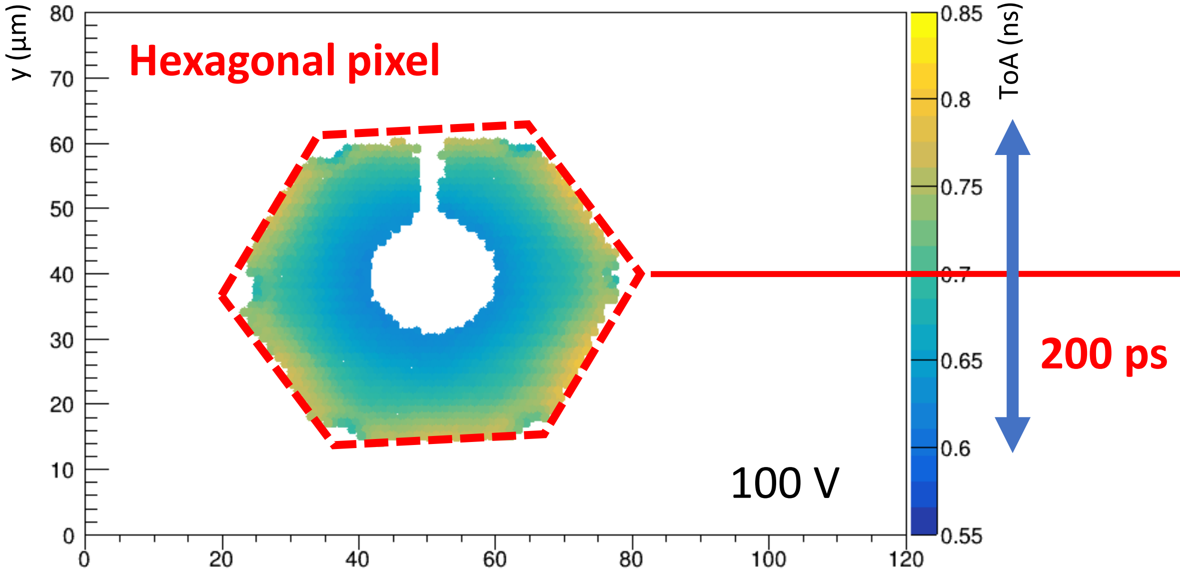
Standard 3D geometry has a very **high spread in ToA**

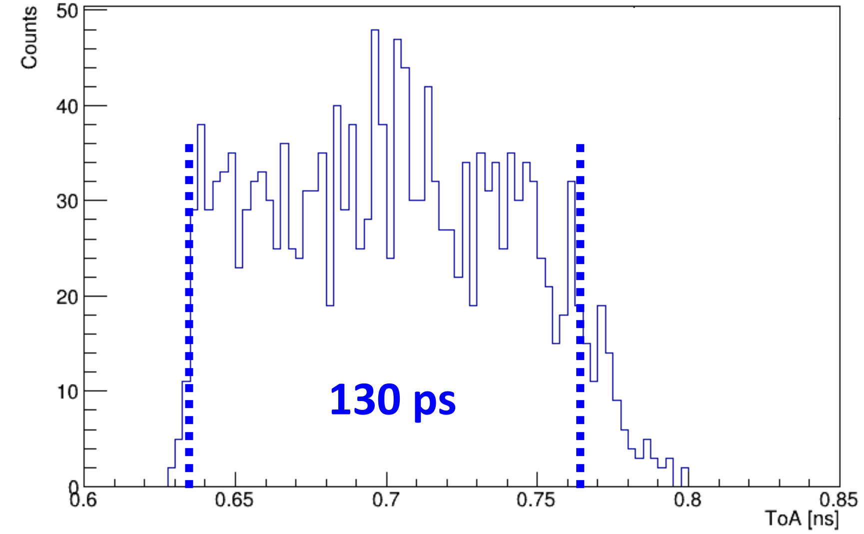
Trench vs Hexagonal





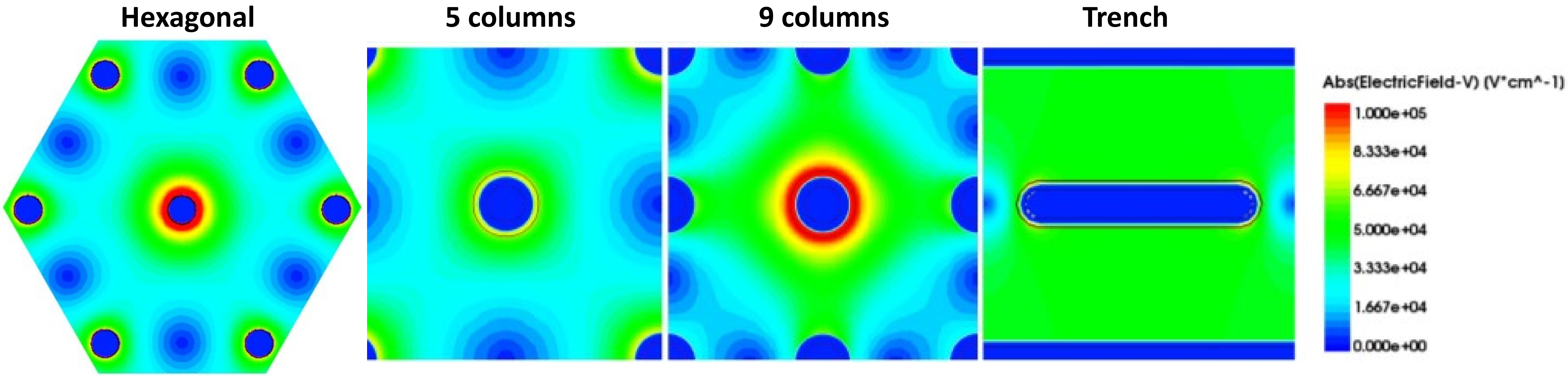
For good timing, it's not important to be fast but to be uniform!





Trench vs column

- Electrid field maps for several 3D sensors geometries



TCAD simulations, Bias 100 V

Electric field maps are **less uniform for all column geometries** with respect to trench design

Conclusion

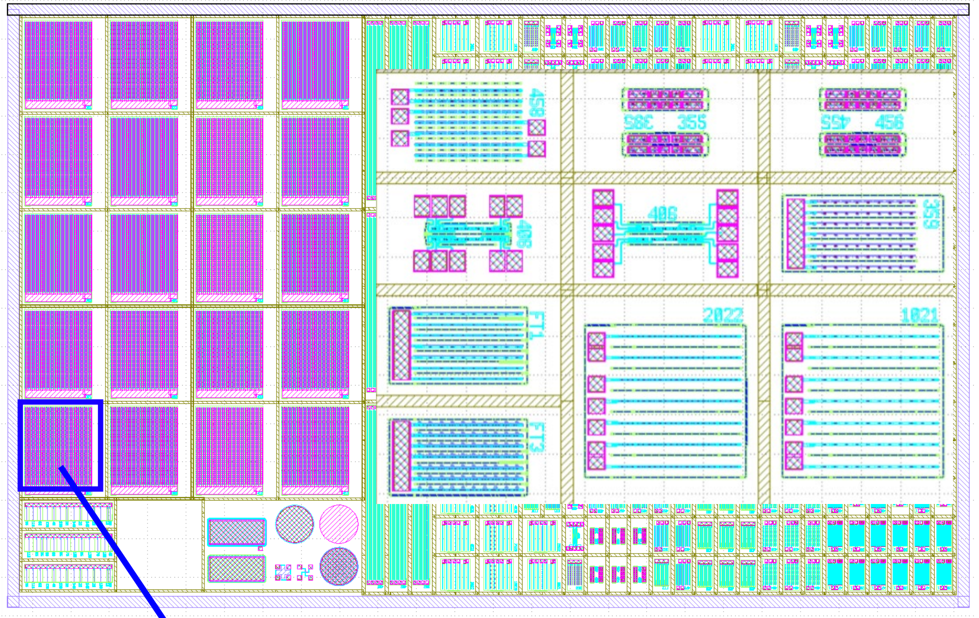
- We built a setup that allows to accurate study the timing performances of different sensors geometries

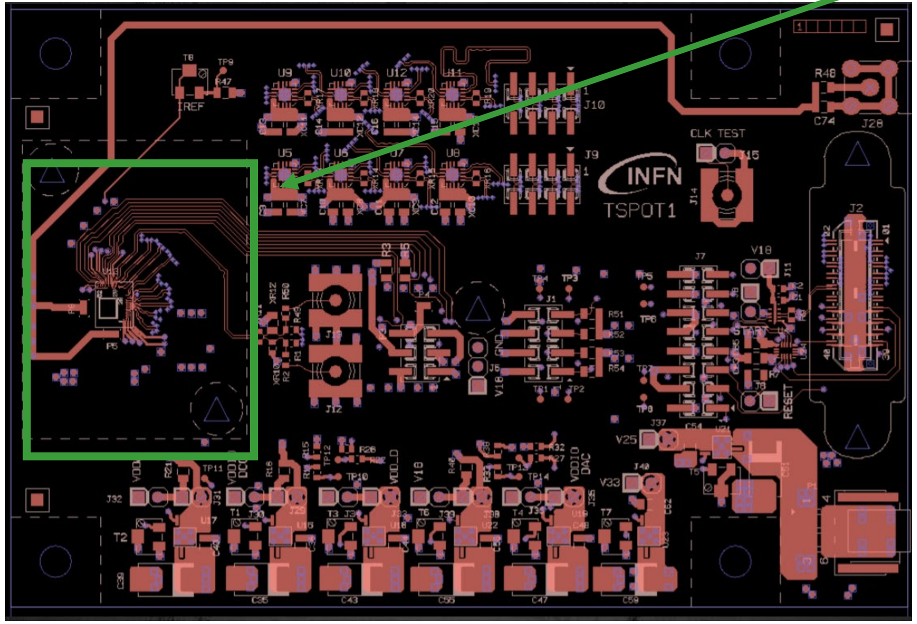
- Unlike test beam and radioactive source characterizations we measured a **detailed response** of the **full sensor active area**

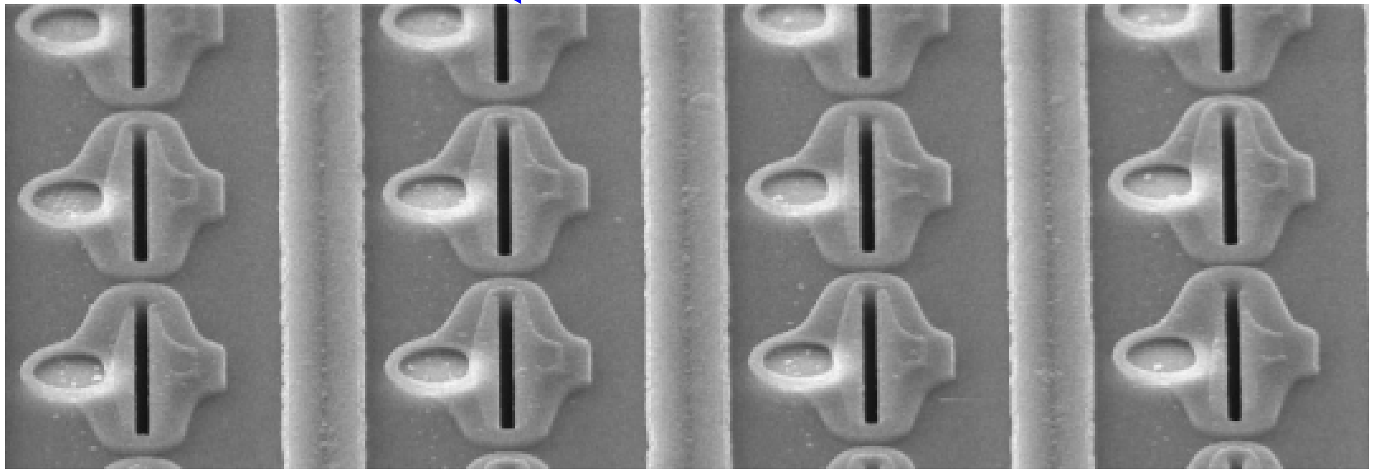
- The **3D trench TimeSPOT sensors** have shown an **excellent timing performance** with respect to more classic 3D geometry

Outlook

- New sensor production at FBK is completed:
  - New test structures, to continue the characterization of these innovative 3D pixels
  - Matrix of pixels for **bump bonding**
- Characterization of pixels matrix read with optimized VLSI electronics (CMOS 28nm)







S. Cadeddu's talk