GORDANA
LASTOVICKA-MEDIN

UCG
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COST ACTION CA24131
European Network for radiation-detection based Research and Innovation addressing increasing societal CHallenges (ENRICH)

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3D IME-CAS Si Radiation Detectors with Gain Driven by Geometry

Gordana Lastovicka-Medin, 1st ENRICH Cost Annual Meeting,
14-16 July 2026, Krakow

cost
EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

Funded by
the European Union

Overview

- ❑ Introduction
- ❑ Timing detectors
- ❑ 3D IME-CAS with gain (proof of concept)
- ❑ Future direction

Introduction/ CERN DRD3

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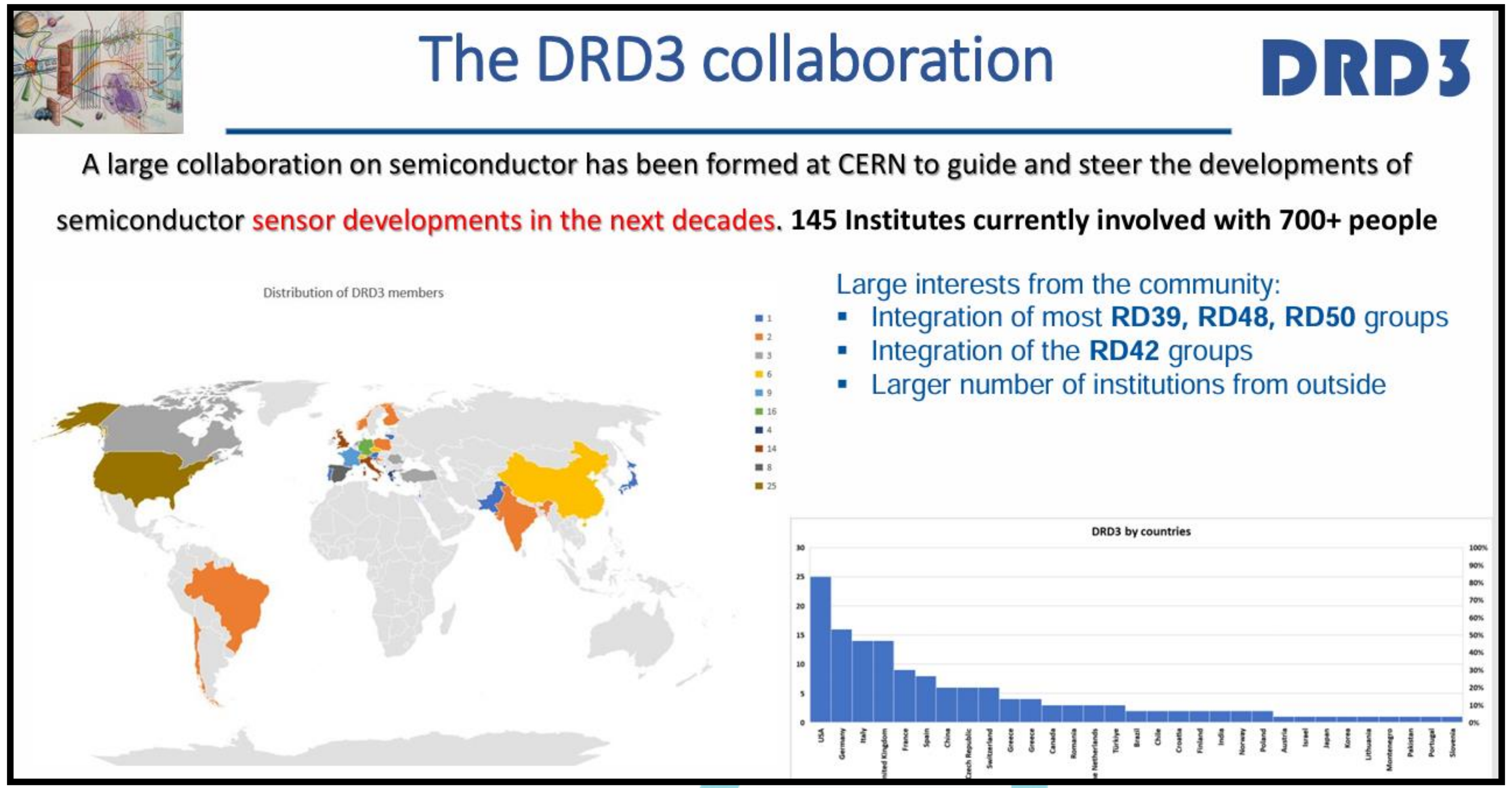
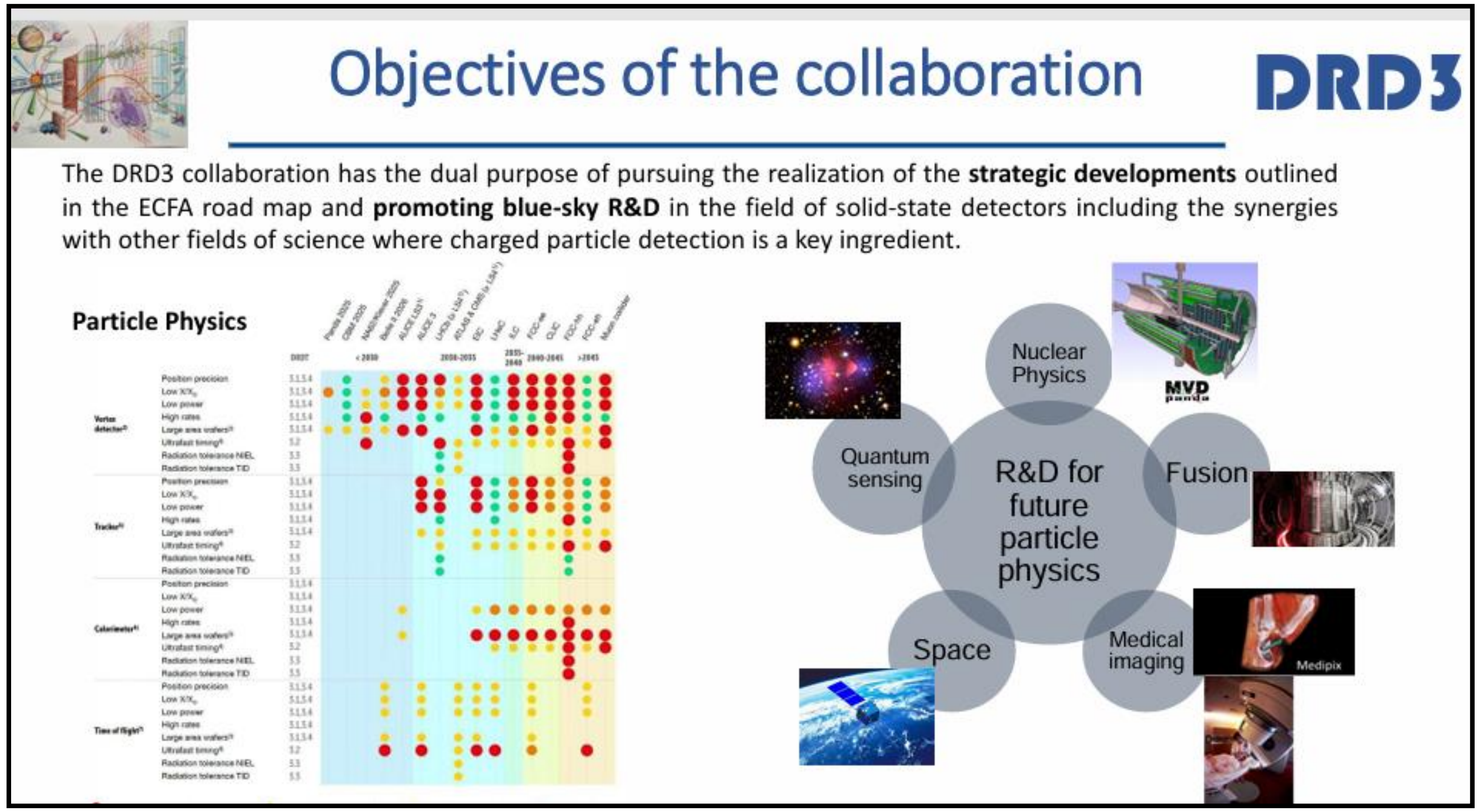
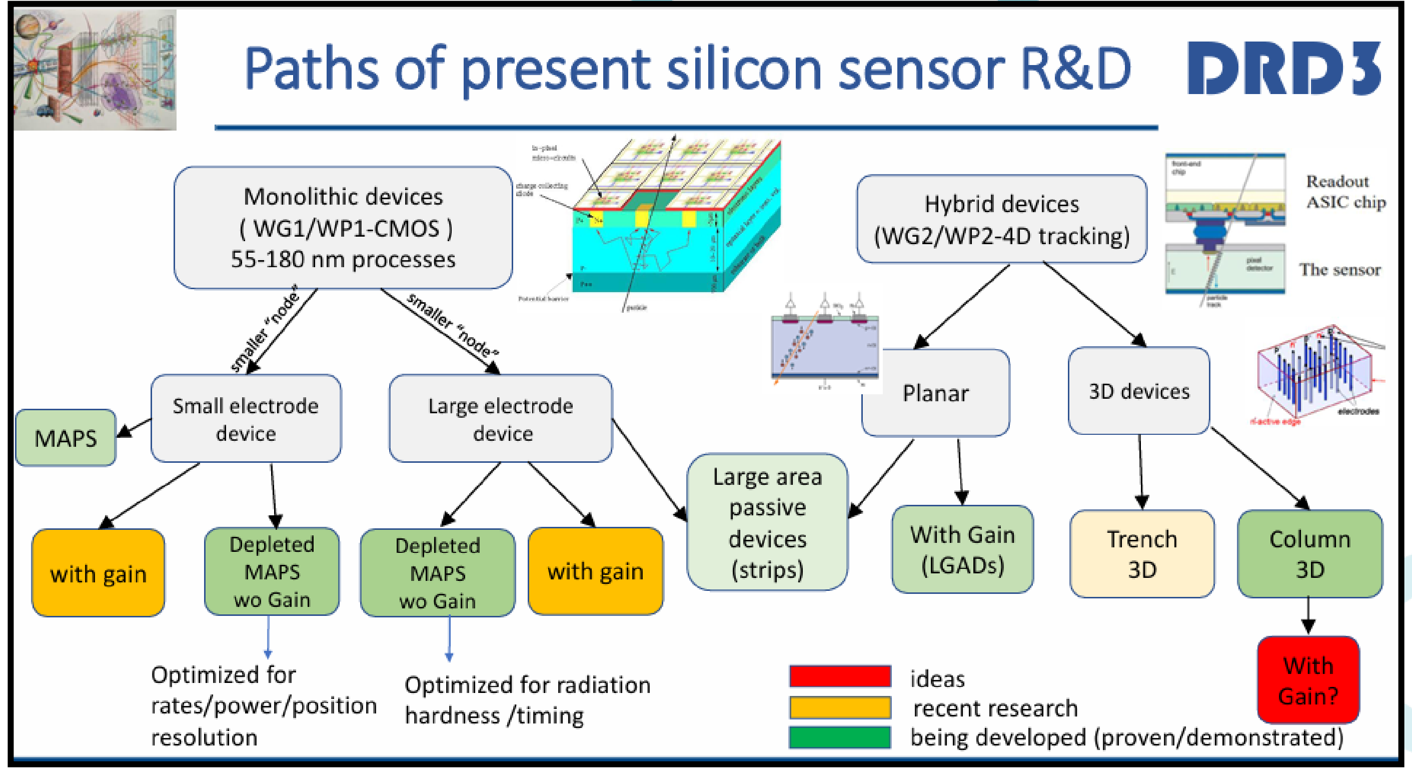
DRD3

(R&D on Solid-state Detector Technologies)

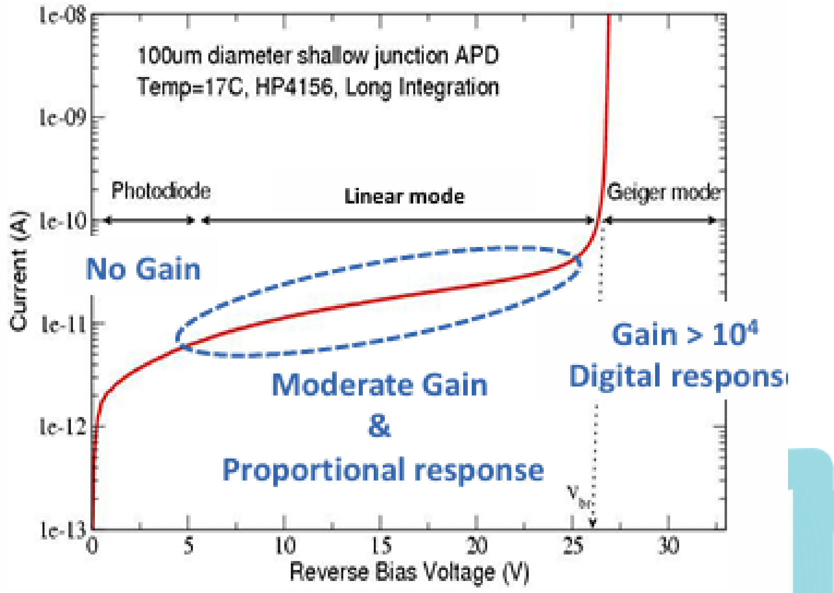




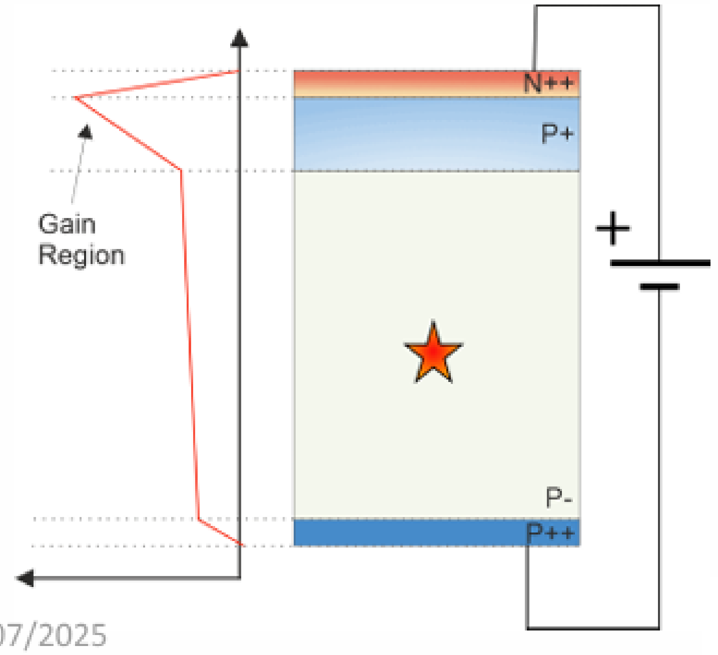


Low Gain Avalanche Detector

- Proposed by **IMB-CNM in 2014**
- Proportional response (linear mode operation)
- Better sensitivity (Gain)
  - S/N ratio increased
  - Excellent timing resolution (~ 30 ps)
  - **MIP** detection for **HEP**
- Thin detector integration with the same signal and higher collection efficiency

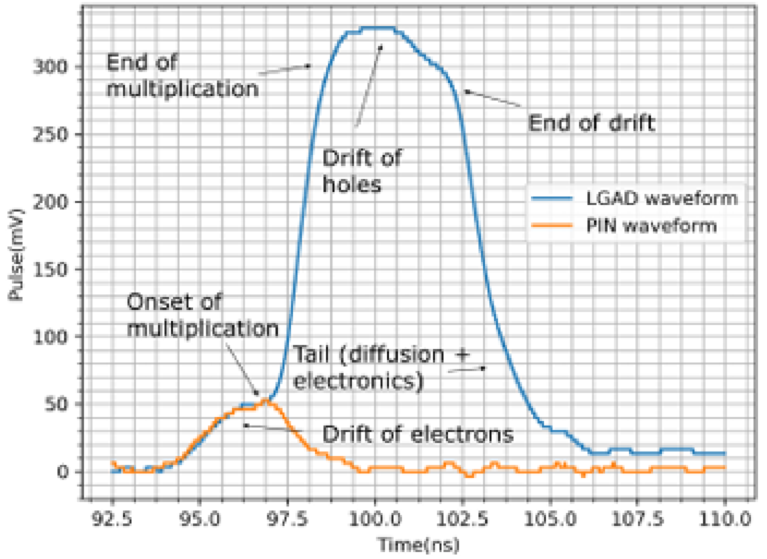


[1] A.G. Stewart et al. in Proc. of SPIE, Vol. 6119, 2006



Original paper

G. Pellegrini, et al., Technology developments and first measurements of Low Gain Avalanche Detectors (LGAD) for high energy physics applications, Nucl. Instrum. Methods A 765 (2014) 12.



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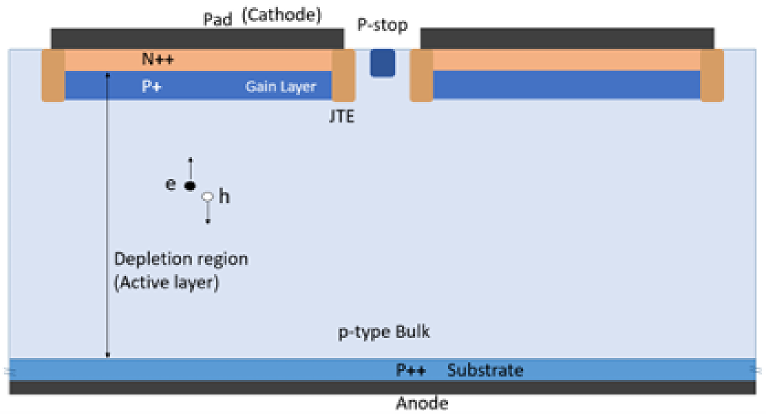
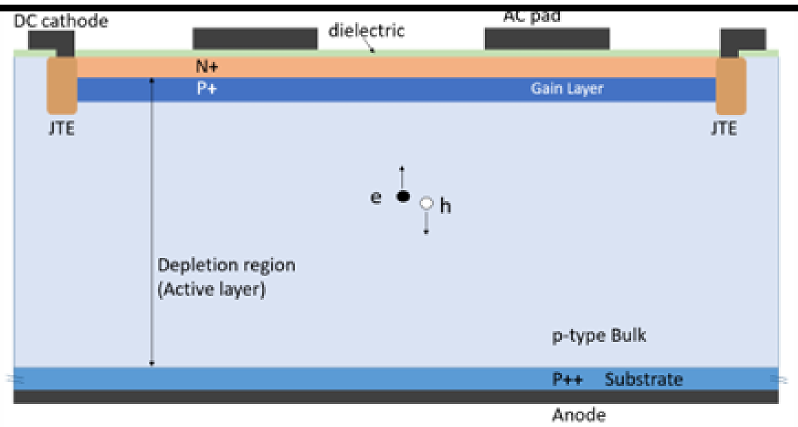
AC-LGAD - 4D detector fir future colliders





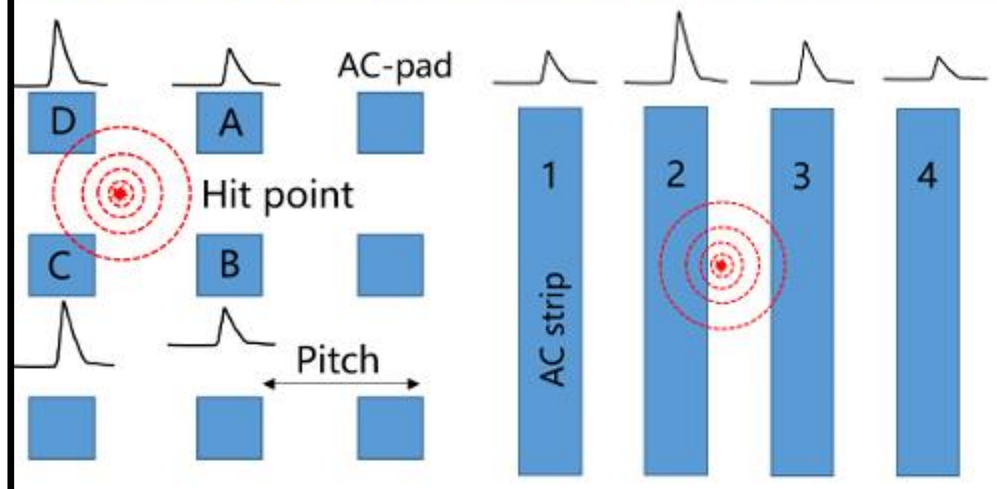
LGAD (Low-Gain Avalanche Diode)

- The read-out electronics is connected to n++ layer
- Time resolution ~ 30ps
- Position resolution: pixel size/$\sqrt{12}$
- Radiation hardness: $10^{15} \sim 10^{16} n_{eq}/cm^2$

AC-LGAD (AC-coupled LGAD)

- Metal AC-pads separated from the n+ layer by a thin dielectric (Si_3N_4, SiO_2)
- no dead zone (100% fill factor)
- Time resolution ~ 30ps
- Position resolution: 5~10 um
- Radiation hardness: $10^{15} \sim 10^{16} n_{eq}/cm^2$

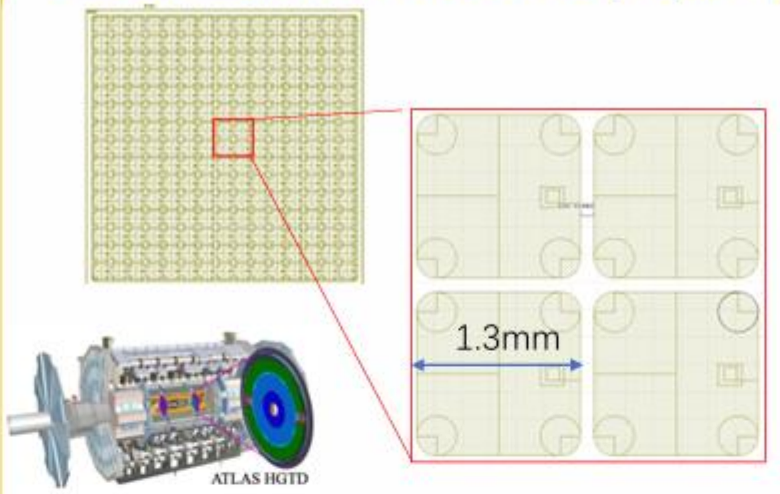
AC-LGAD: two layout schemes for AC-pads



Pixels AC-LGAD:
- Position information: 1 layer (x,y)
- Bump bonding

Strips AC-LGAD:
- Lower readout electronics, no bump bonding
- Position information: 2 layers for (x,y)

DC-LGAD:
15×15 LGAD for ATLAS HGTD project

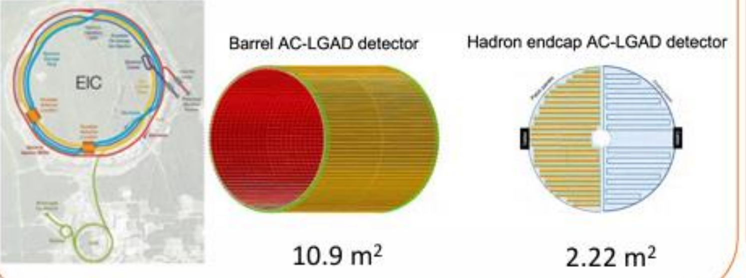


- **Dead zone : ~0.1mm**
- **Pixel size: 1.3mm**

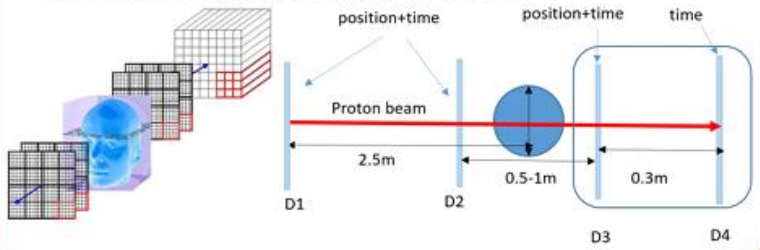
Smaller Pixel LGADs -> Lower fill factor

3

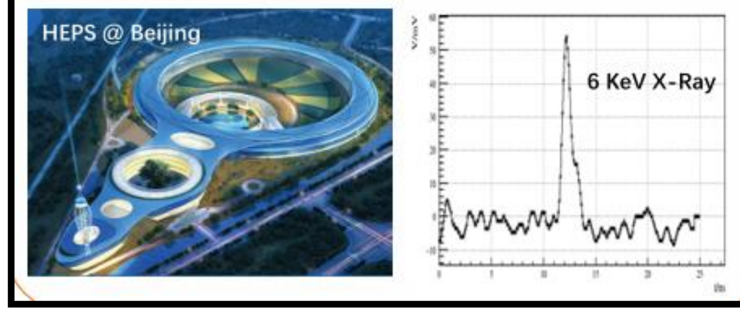
Electron-Ion Collider (EIC): Timing-tracker



Nuclear Medicine Instruments:
Such as proton therapy and proton CT



X-ray detectors @ advanced light sources



other applications
- Beam Telescope for Beam Test Platform
- LiDAR: Positioning and Navigation
- Track and time detectors in other particle physics and nuclear physics experiments
- …

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AC-LGAD - 4D detector (position + time
16 µm-patial resolution, 10-20 ps of timing resolution

LGAD based Timing Tracker Development for Future Electron Collider

MEI ZHAO(IHEP)

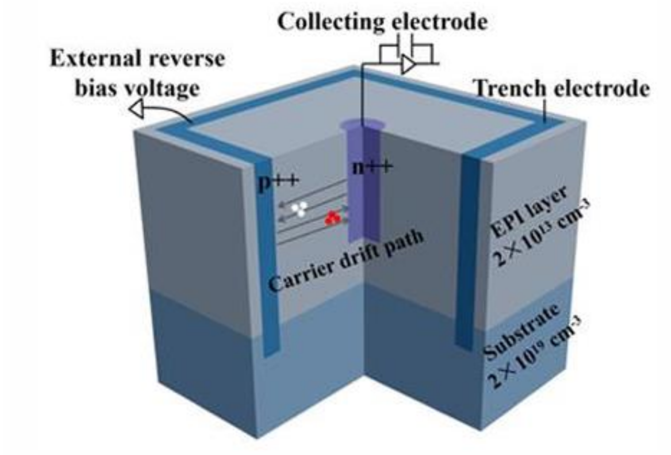
ON BEHALF OF GROUPS IN THE PROJECT

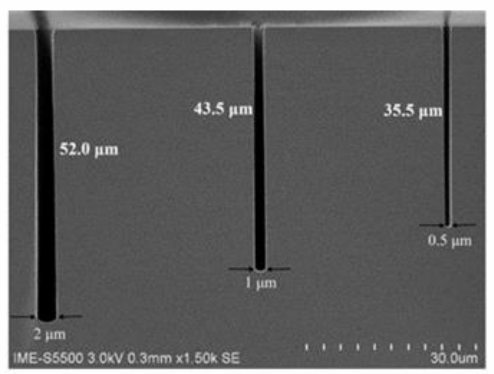
Jožef Stefan Institute Ljubljana, Slovenia
Universidade de São Paulo
UCG University of Montenegro

2025/6/4 3RD DRD3 WEEK ON SOLID STATE DETECTORS R&D, 2-6 JUN 2025, NIKHEF, AMSTERDAM 1

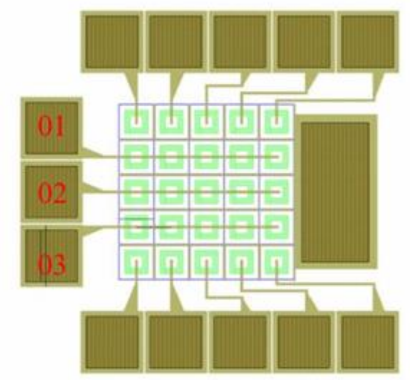
➤ **DRD3 WG2 Project:** LGAD based timing tracker development for future electron collider https://cds.cern.ch/record/2918306

Motivation of the project





Workhorse (5x5 matrix)



The IME-3D process can reach **aspect ratio of >70:1** which allows **columns of as narrow as 0.5 mm** penetrating 30-35 mm in the silicon – thin means much less capacitance (noise/power consumption at the same speed)

- The runs in the proposal include also structures for other uses – not particle physics only (X-ray detectors, Micro-dosimetry, Particle detectors)
- It is clear that improvement of aspect ratio to >70:1 allows manufacturing of very narrow columns <0.5 mm which can **be seen as proportional wire counter** – most of the work in the project done with this structure by different groups in the project (**IME, IHEP, LDU, USTC, NIKHEF, UCG-ELI, JSI, Sheffield**)

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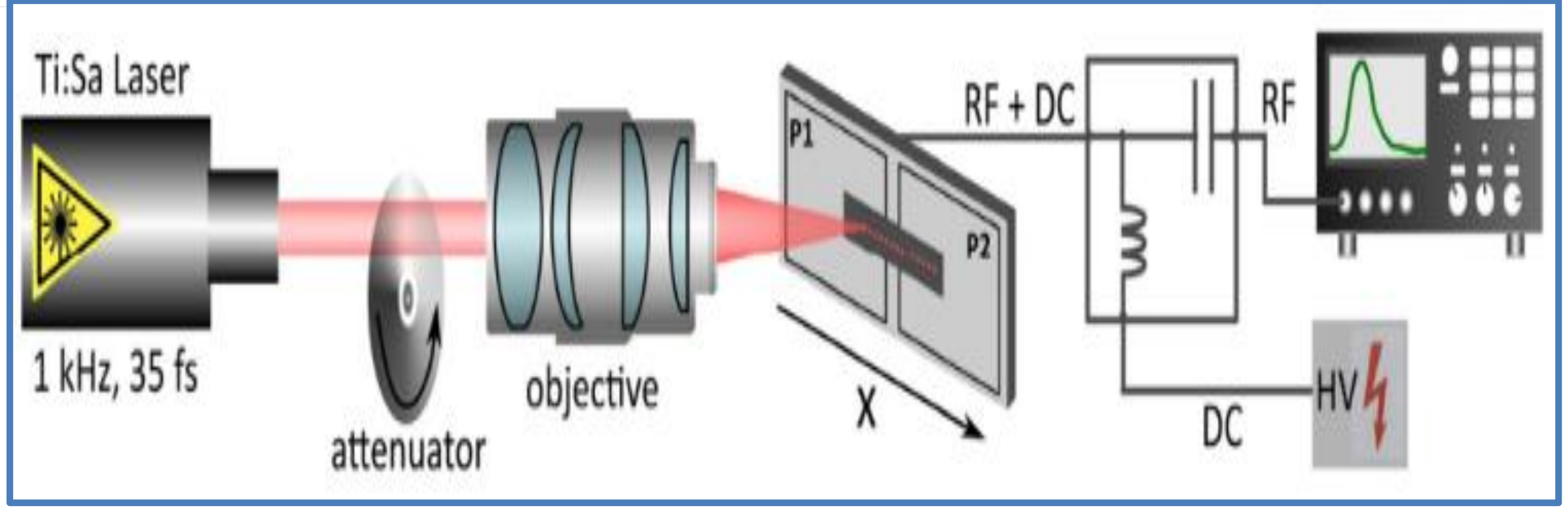
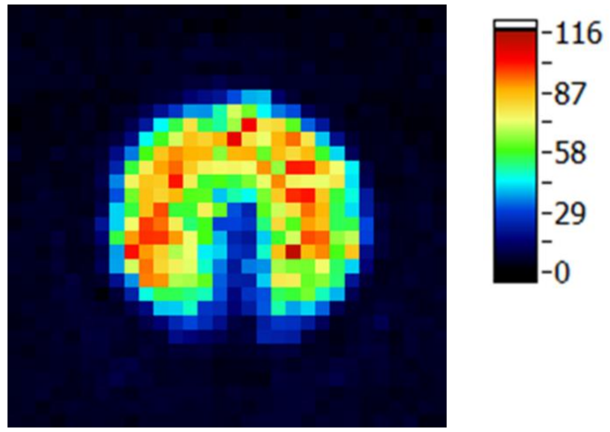
TPA-TCT / Characterisation technique



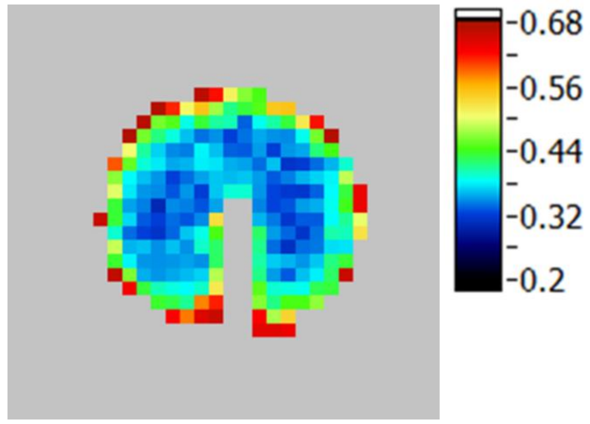
Place	ELI Beamlines
Operational modes	Single and two photon absorption (SPA and TPA)
Pulse energy on sample	Variable by ND filters (accuracy: 0.2 pJ)
Wavelength	800 nm (SPA), 1550 nm (TPA)
Pulse width in sensor	1550 nm, ~ 150 fs 800 nm, ~ 50 fs
Focus waist radius	0.85 µm (SPA), 1.5 µm (TPA)
Rayleigh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

TPA focal point at 10 um, 20 pJ, 60 V

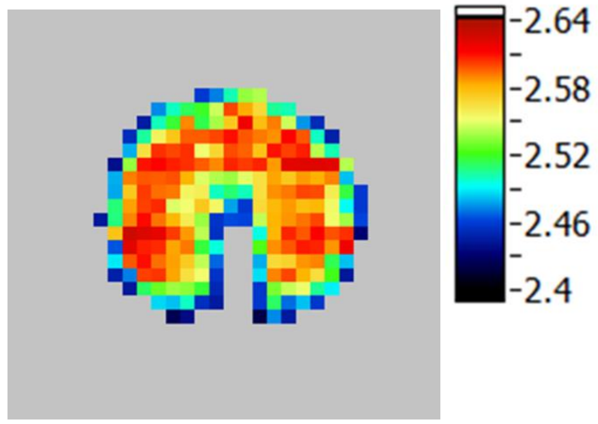
2D of charge distribution



2D of Rise Time [ns]

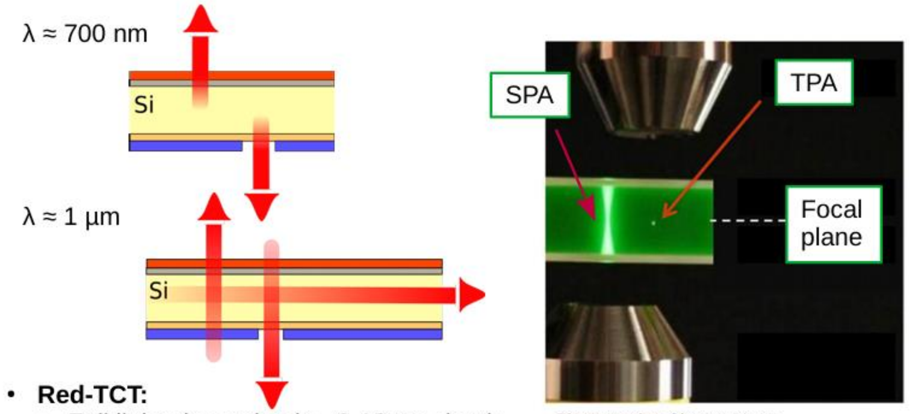


2D of Time of Arrival [ns]



CERN

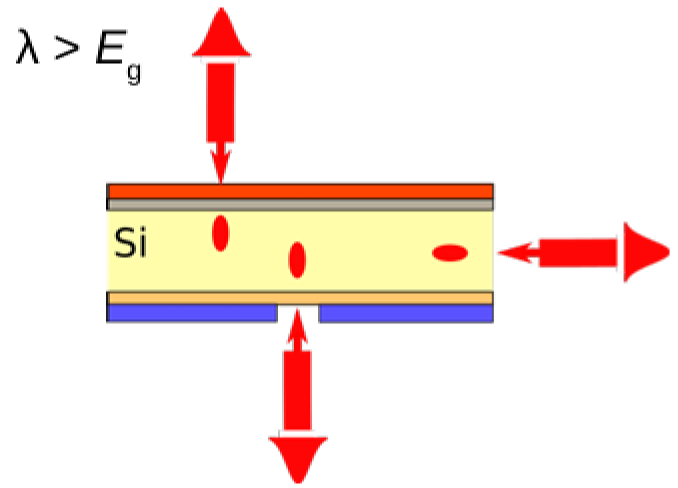
Single Photon Absorption-TCT



Photography: Ciceron Yanez, University of Central Florida

- **Red-TCT:**
  - Full light absorption in ~3-10 µm depth
  - optimal for e/h separation
  - Laser can be microfocused to < 5 µm: **2D resolution**
- **IR-TCT:**
  - Mimics MiP (continuous laser absorption)
  - Normally 6-10 µm **resolution 2D**
  - Edge injection in thick devices allows a depth study

Two Photon Absorption-TCT



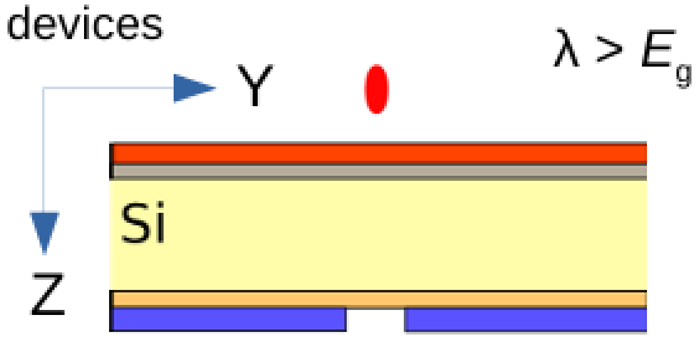
- **TPA** excites charge carriers into the CB
- Non-linear effect, strongly depends on intensity
- Coincidence in time and space needed

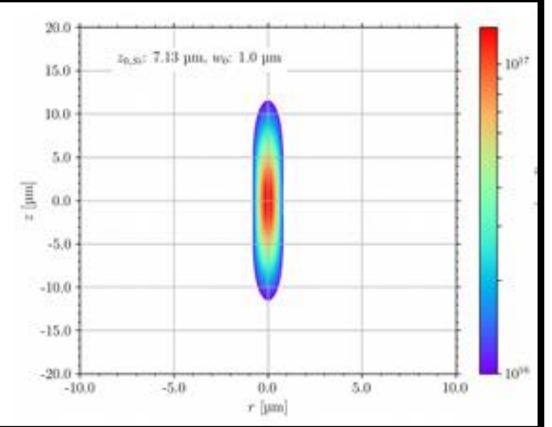
→ only excitation around focal point

- **3D resolution** tool to scan silicon devices

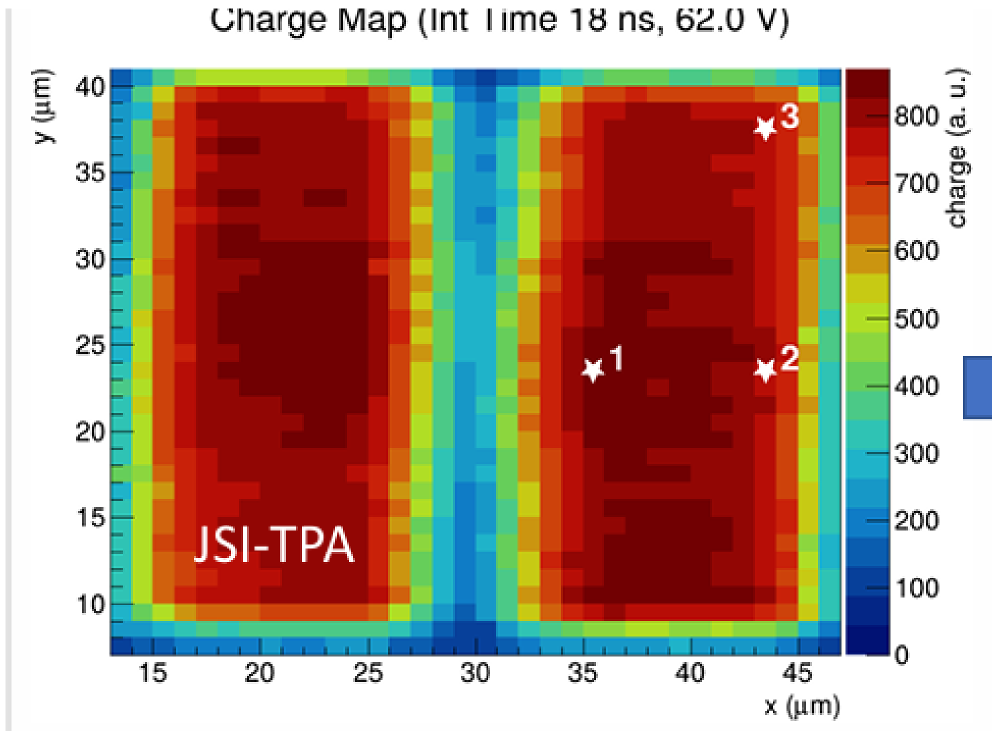
Two Photon Absorption-TCT

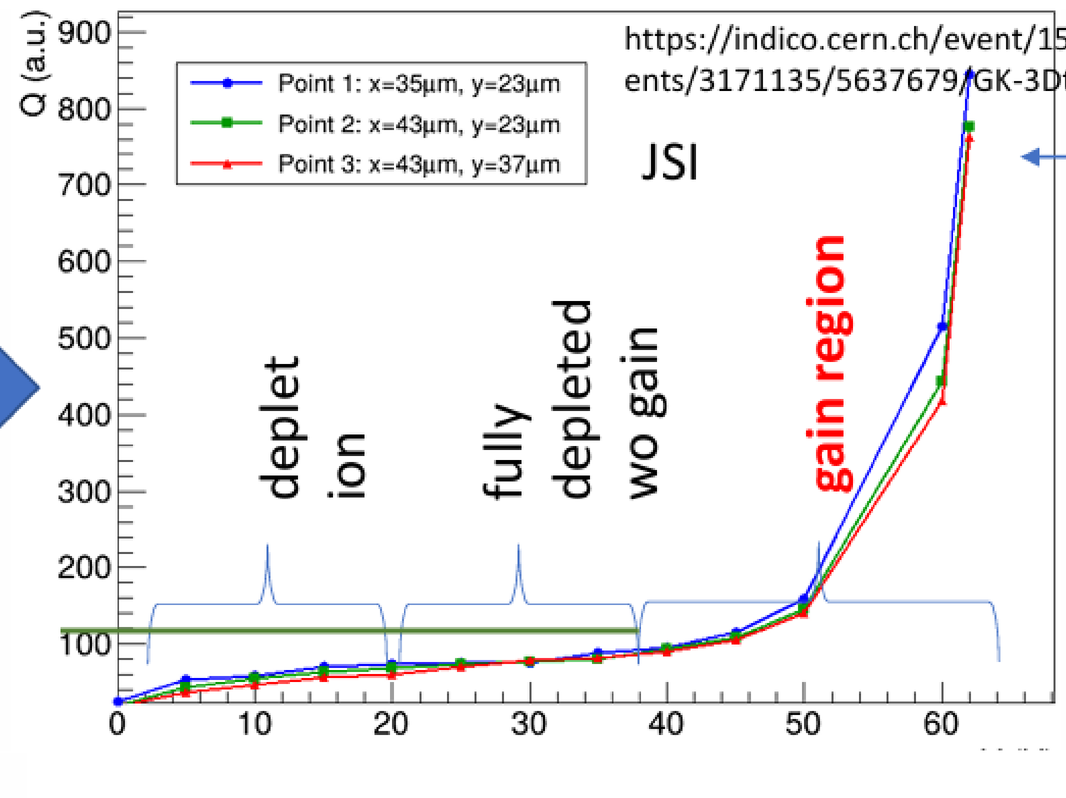
- **3D resolution** tool to scan silicon devices



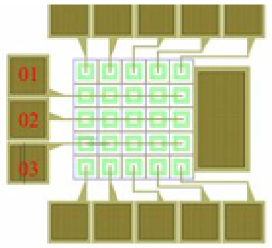


Hunting for the gain



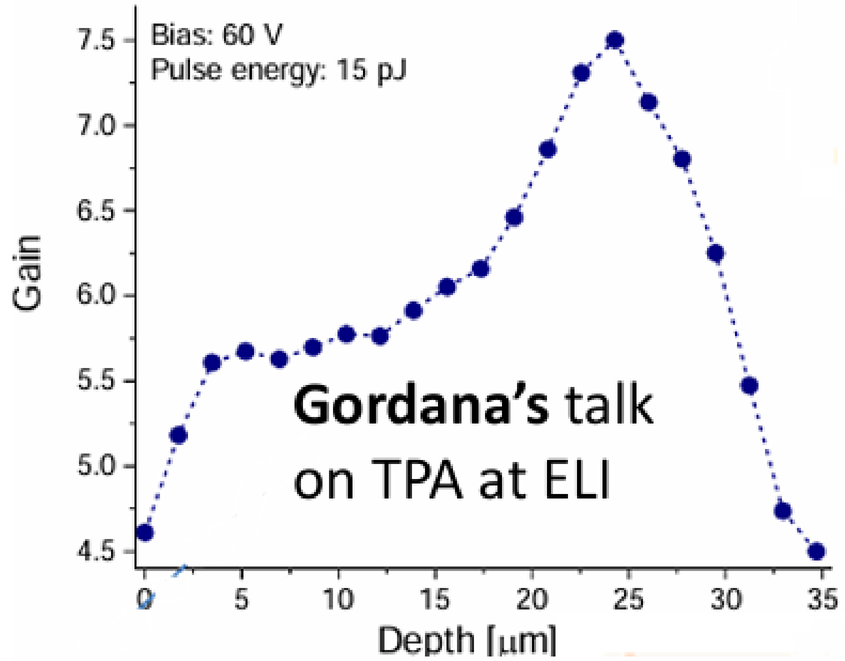


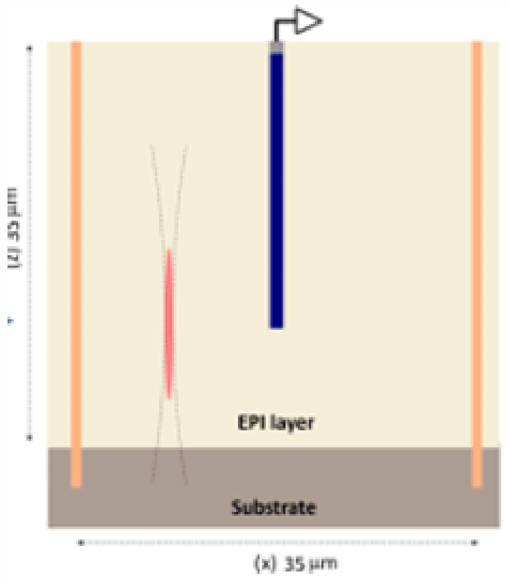
breakdown



We clearly see the gain:

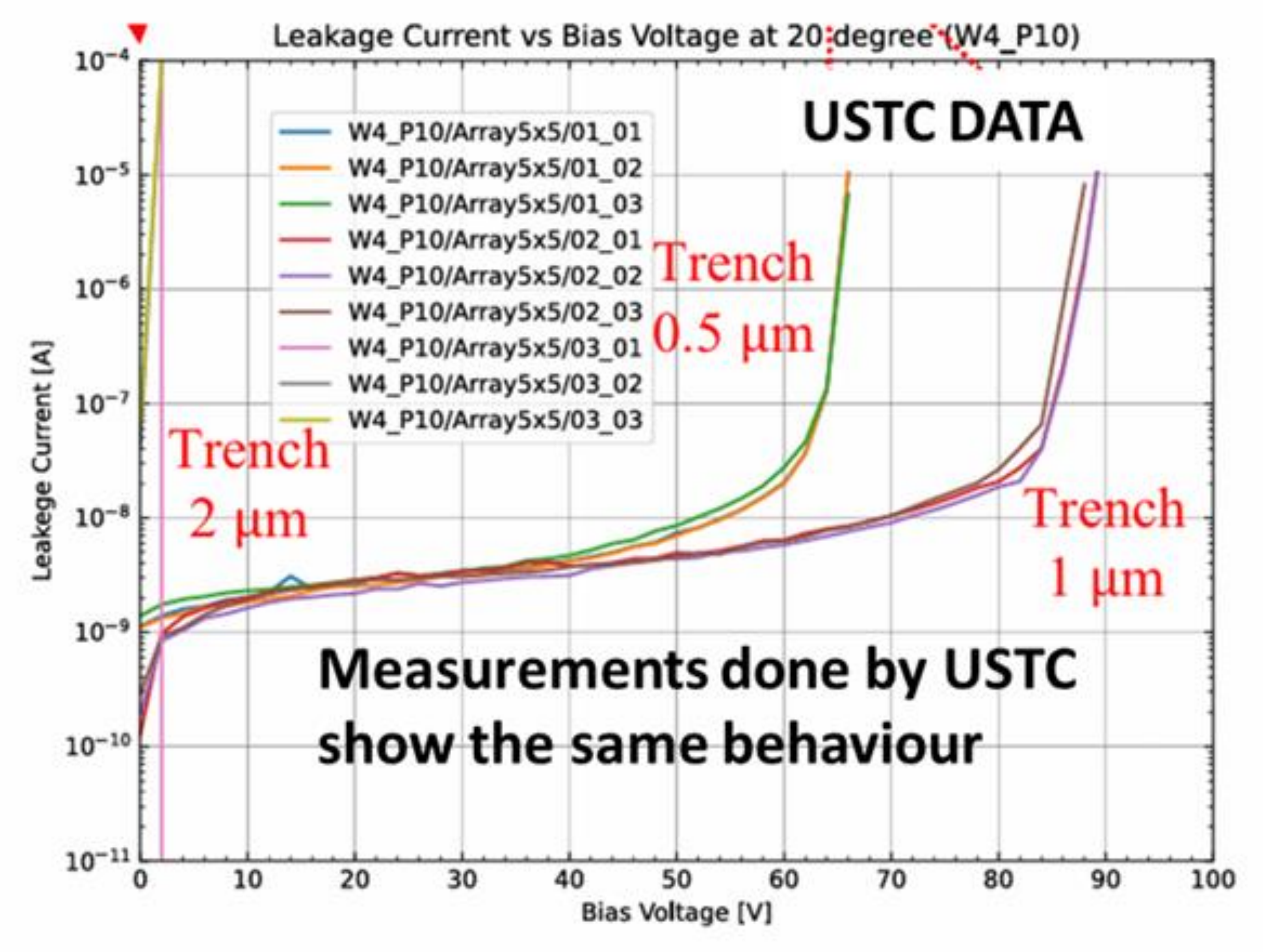
- Gain appears at ~40V
- reaches G~3-4 at 50V
- **Reaches G~8-10 at 60 V**
- Confirmed also with Sr90 measurements





We clearly see the gain these devices that comes from geometry only, unlike in LGADs where it is due to carefully tuned doping!

Reproducibility



Same structures measured at different groups (from several institutions within DRD3 Coll); **all show remarkable reproducibility** (few measured at each institute all showing the same breakdown behaviour, both in charge collection and leakage current)

→ **That shows really good control of the process**! There are also 25x25 mm2 array currently being tested also in the test beam – see test beam talk

Place for eventual Instutional Logo (if not, remove

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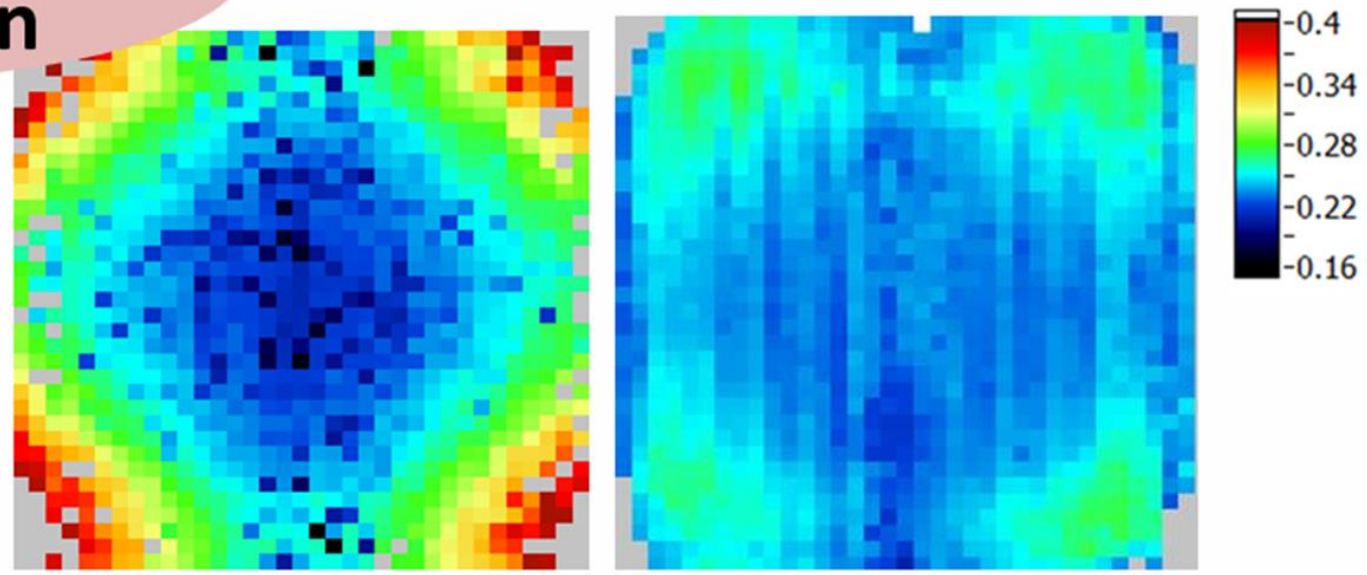
3D with Gain /Reproducibility

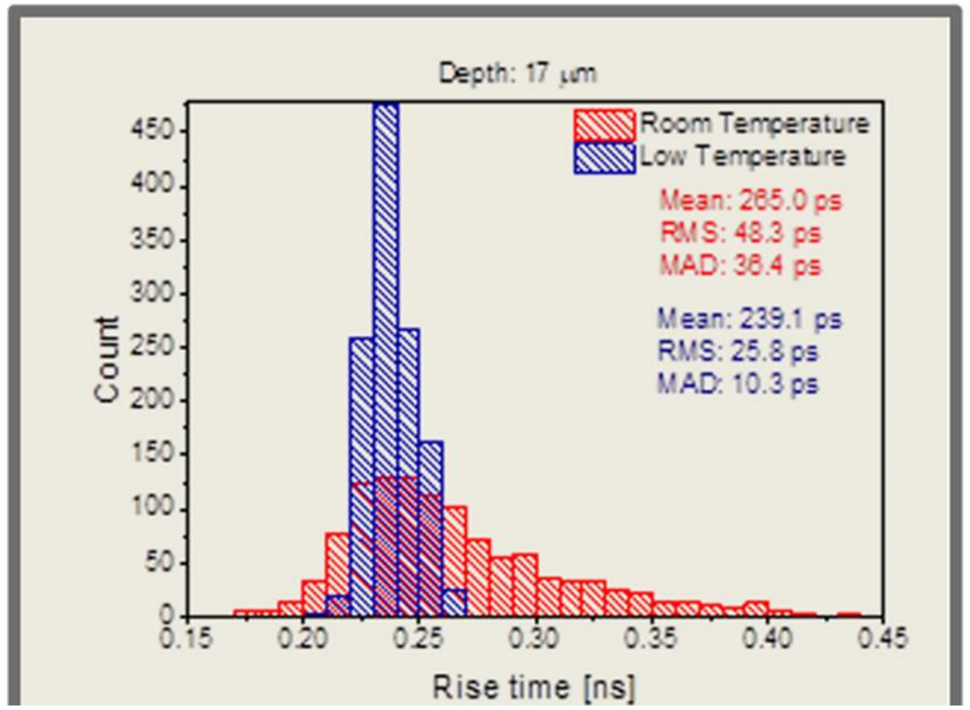
Example:
Timing before and after irradiation

RT after irradiation

2D image of Rise Time
- ✓ at RT
- ✓ -25^0C



RMS, MAD (Rise Time)
- ✓ at RT (red)
- ✓ -25^0C (blue)



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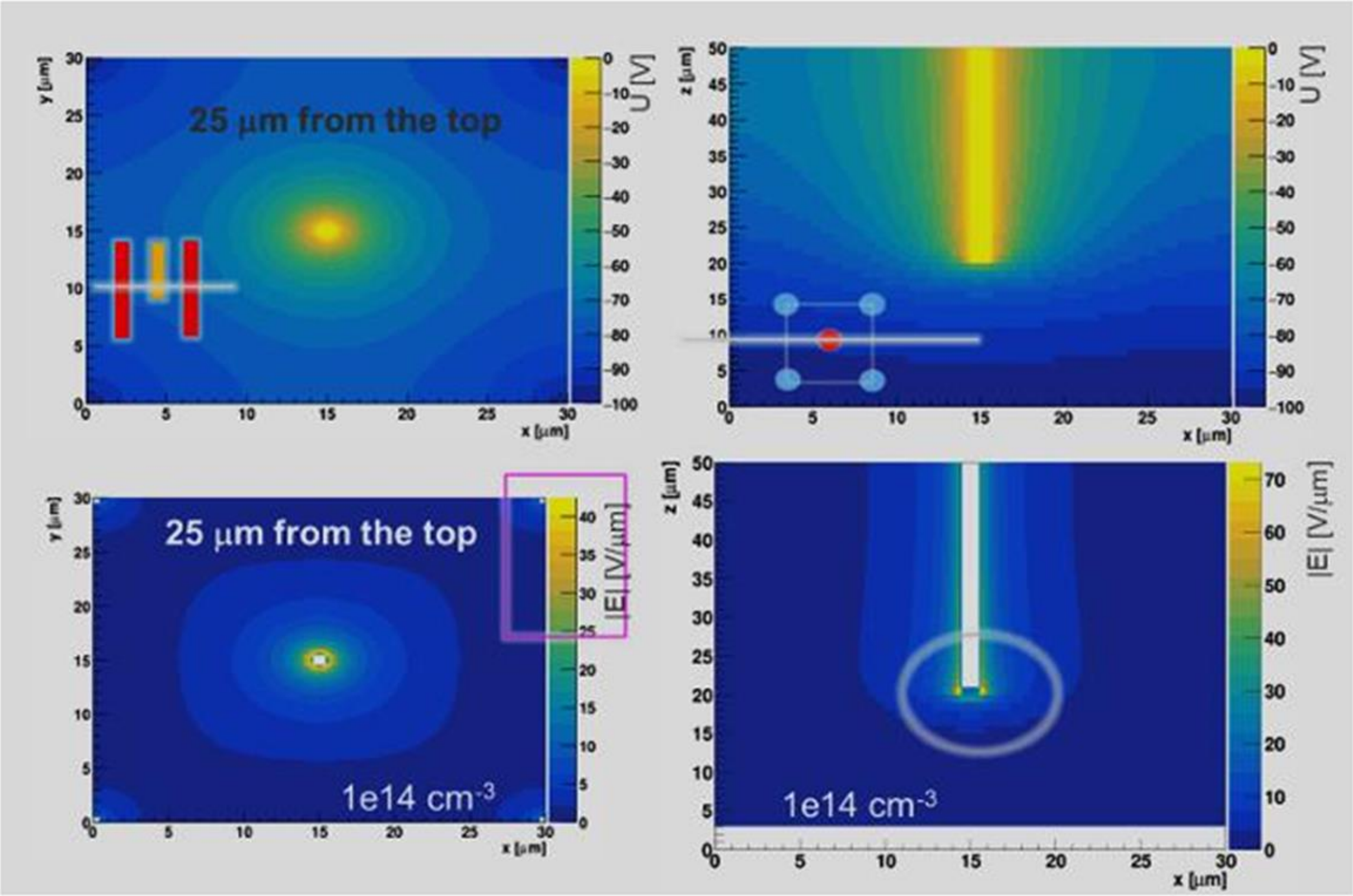
3D with Gain/Surprised observed

What was learnt beforre?



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

➢ simulations are clear

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

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

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

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

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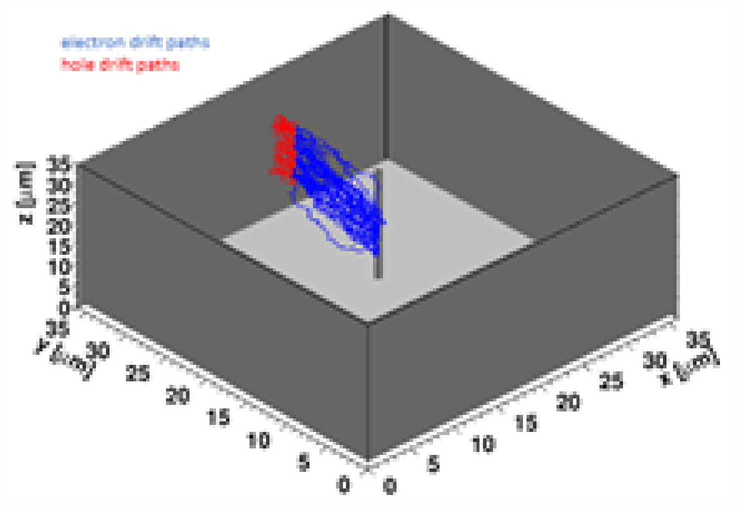
3D with Gain/Surprised observed

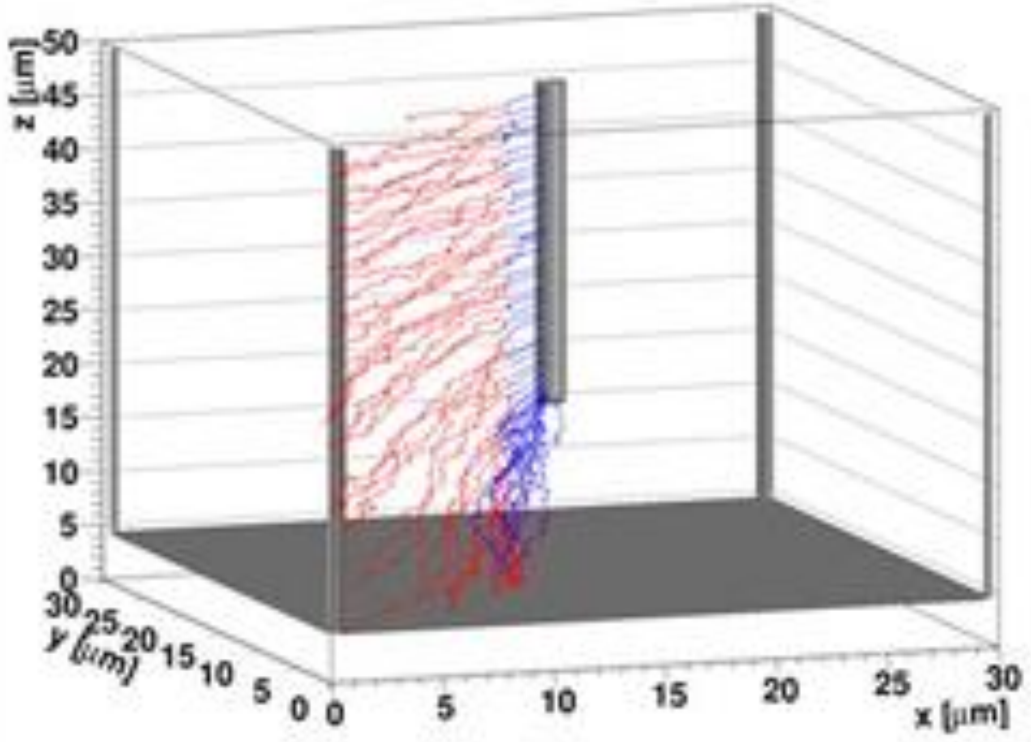
Surprised observed

We don’t see increase of ghost rates generated at break-down close to the tip

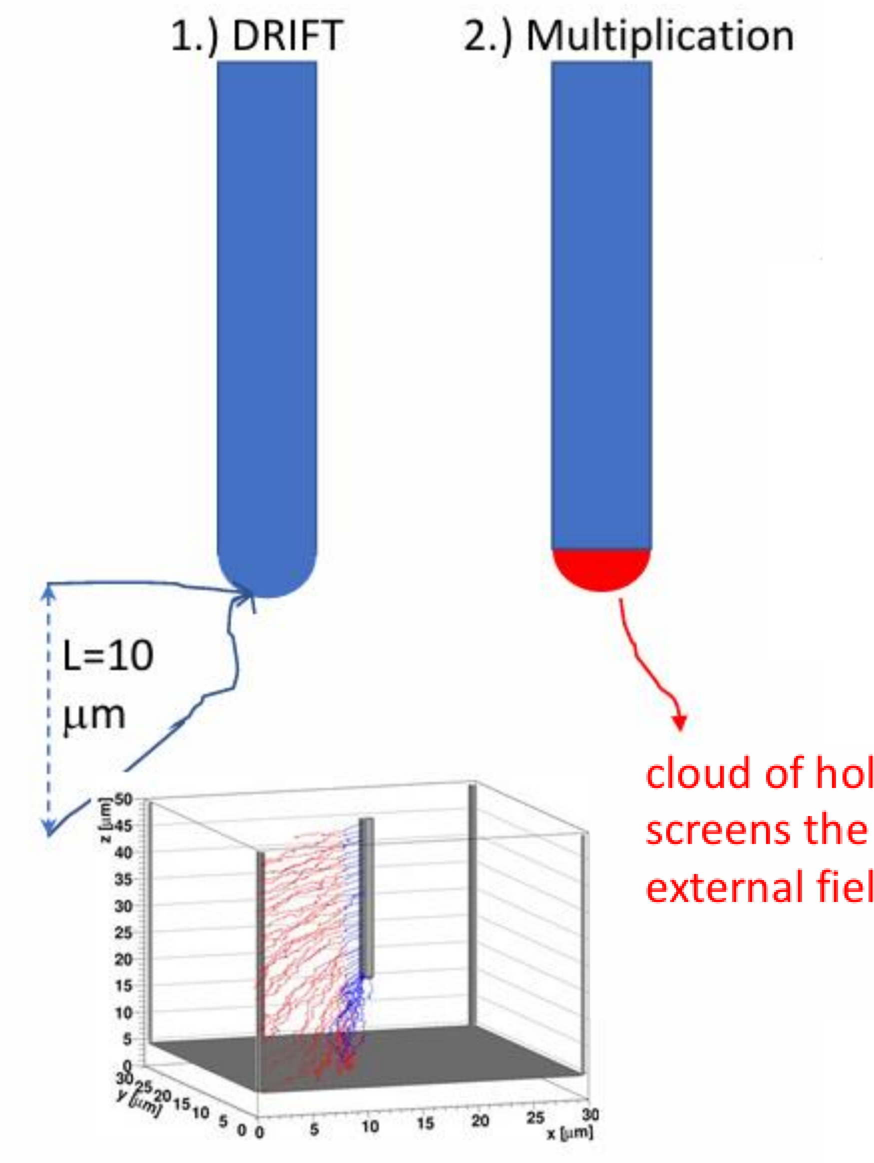
➢ We don’t see large variation of the charge with depth (~20%) even though more charges end the drift at the tip of the electrode (**next slide**)

➢ We see good agreement between Time of Arrival (ToA) in Two Photon Absorption TCT (TPA-TCT, characterization technique) and simulations– clearly the structure is not optimized for timing as it is now (trench cell is not optimum)





Advantage of small tip



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

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

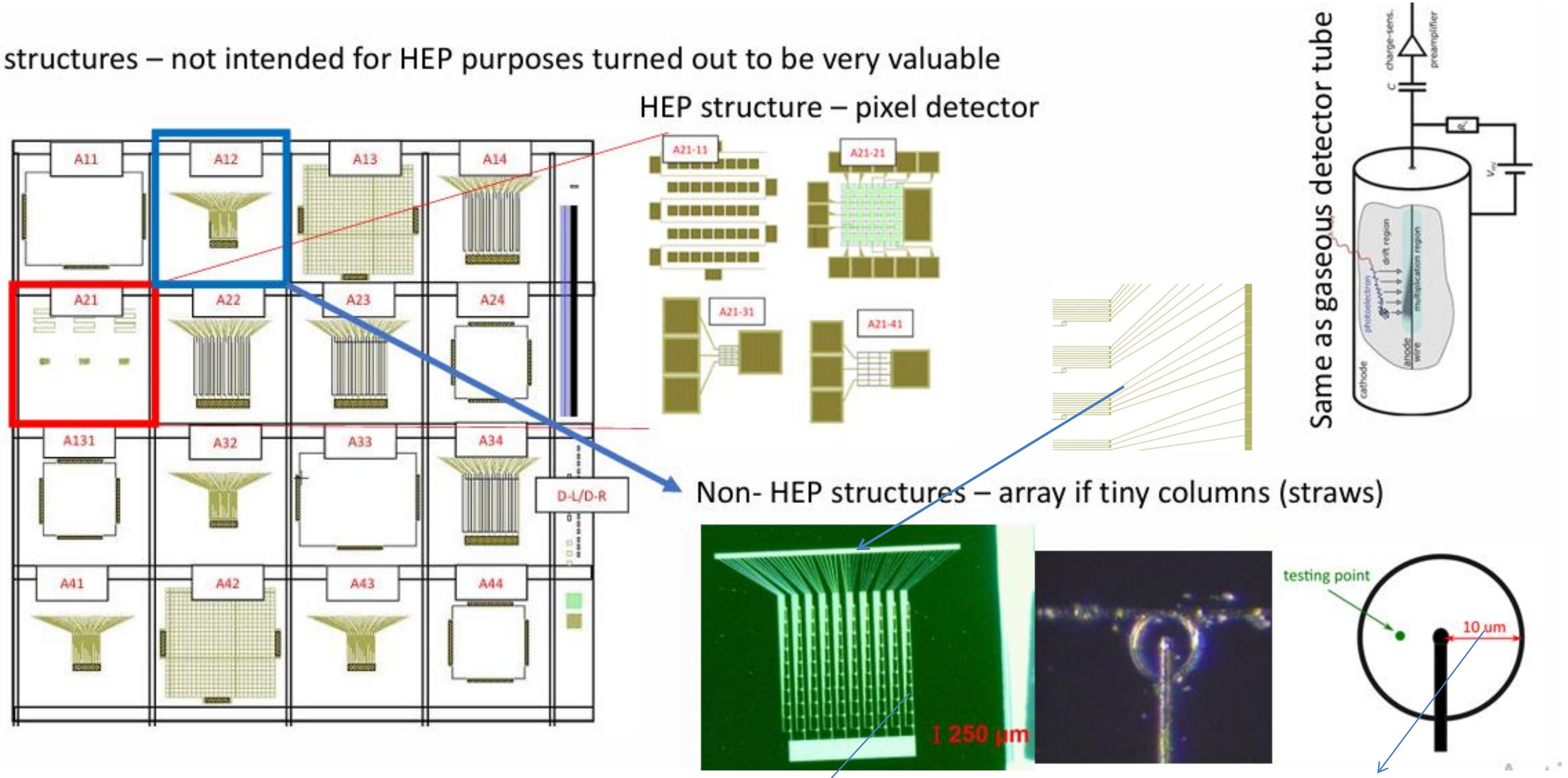
For G=10 and that taking charges from depth of around L=10 µm and all come to the tip at the same time this means multiplied holes

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

Sufficient for gain self-suppression

3D with Gain / Other IME-CAS structures we studied

The structures – not intended for HEP purposes turned out to be very valuable

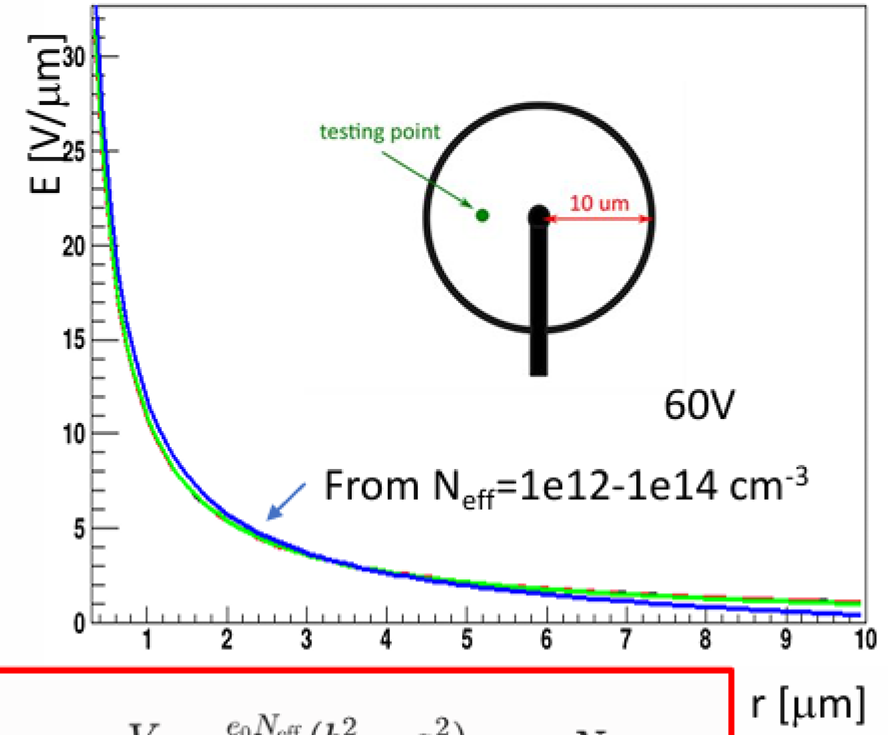


10x10 straw tubes!

Produced with diameters of 10 and 20 microns.

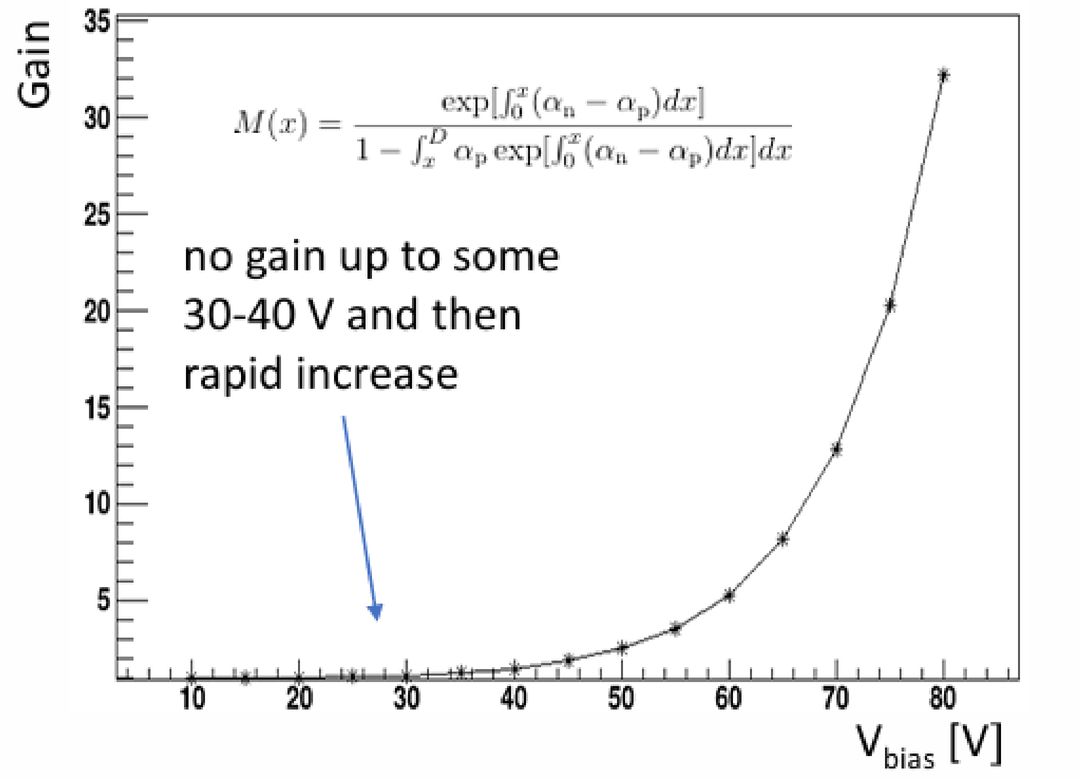
3D straw tubes

Ideal structures to study impact ionization – especially after irradiation – as the field can be solved analytically
Experimentally this is very complicated, but the project managed to do it– see next slide ! We will be able to study impact ionization at severe fluences.



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

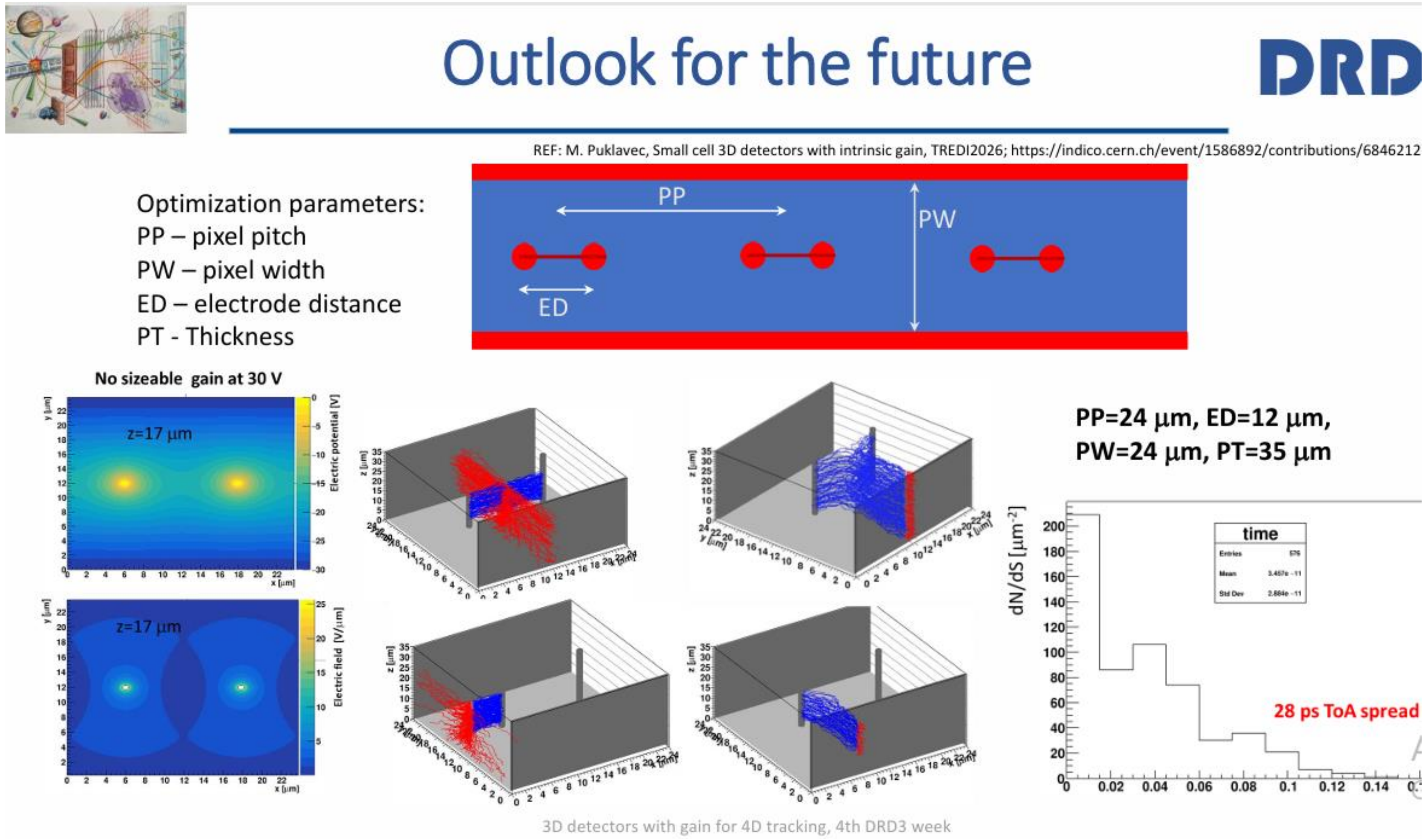
a=0.5 µm and b=10 µm



Calculated gain as a function of bias voltage (V)
At the z=15 mm one can calculate analytically the gain – so fitting and extraction of impact ionization is straightforward

3D with geometric gain/Outlook for the future

Outlook for the future



Funded by the European Union

3D with gain/Conclusions and Plans

Conclusions:

- ➢ First very small pitch and thickness 3D devices were produced with controllable gain (35x35x35 mm3 cells)
- ➢ gains of up to around 10 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
- ➢ Time resolution is not yet fully understood both in Sr90 and TB
- ➢ Single cell cylindrical devices were produced ideal to study e.g. impact ionization as well as runaway trench devices
- ➢ New runs are planned to address devices for timing (2 runs within the project with IME until the end of 2027)
    - Design and fabrication of novel 3D sensor structures based on EPI wafer;
    - Design and fabrication of novel 3D sensor structures based on thick silicon wafer;
    - Design and fabrication of large area 3D trench-column sensors based on EPI wafer.

Acknowledgement

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Acknowledgement

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Thank you ☺