Development of fast-timing sensors and multichannel characterisation board

Morag Williams on behalf of CERN EP R&D WP1.1, LHCb, and collaborating institutes

20th February - VCI2025

Motivation for fast-timing detectors

from the CERN Strategic R&D Programme on Technologies for Future Experiments [CERN-OPEN-2018-006]

[fineprint in CERN-OPEN-2018-006]	HL-LHC	SPS	FCC-ee	FCC-hh
Total fluence [$n_{eq}cm^{-2}\ s^{-1}$]	$5x10^{16}$	10^{17}	10^{10}	10^{17}
Max Hit rate [$cm^{-2}\ s^{-1}$]	2-4G	8G	20M	20G
Material budget per layer [X_0]	0.1-2%	2%	0.3%	1%
Pixel size [μm^2] inner trackers	50x50	50x50	25x25	25x25
Temporal hit resolution [ps] inner trackers	~50	~40	-	~10

Need for high-resolution, radiation-hard, fast-timing sensor technologies across the board

see Efren's talk from Tuesday for more details

Example: LHCb Upgrade II

- To reconstruct events under heavy pile-up HL-LHC conditions → timing required within vertex detector, VELO.
- VELO UII design→ balance of spatial resolution and radiation hardness.

Sensor technologies for VELO Upgrade II:

Fast-timing	Radiation hardness	High granularity
≤50ps res. per plane	6 x 10^{16} 1MeV $n_{eq}/cm^2/y$	pixel pitch ≤50μm

→ Hybrid sensor R&D for fast timing sensors is on-going within the CERN EP R&D working group 1.1

Presenting today : SiEM, 3D, multichannel characterisation board

Silicon electron multiplier (SiEM) sensor

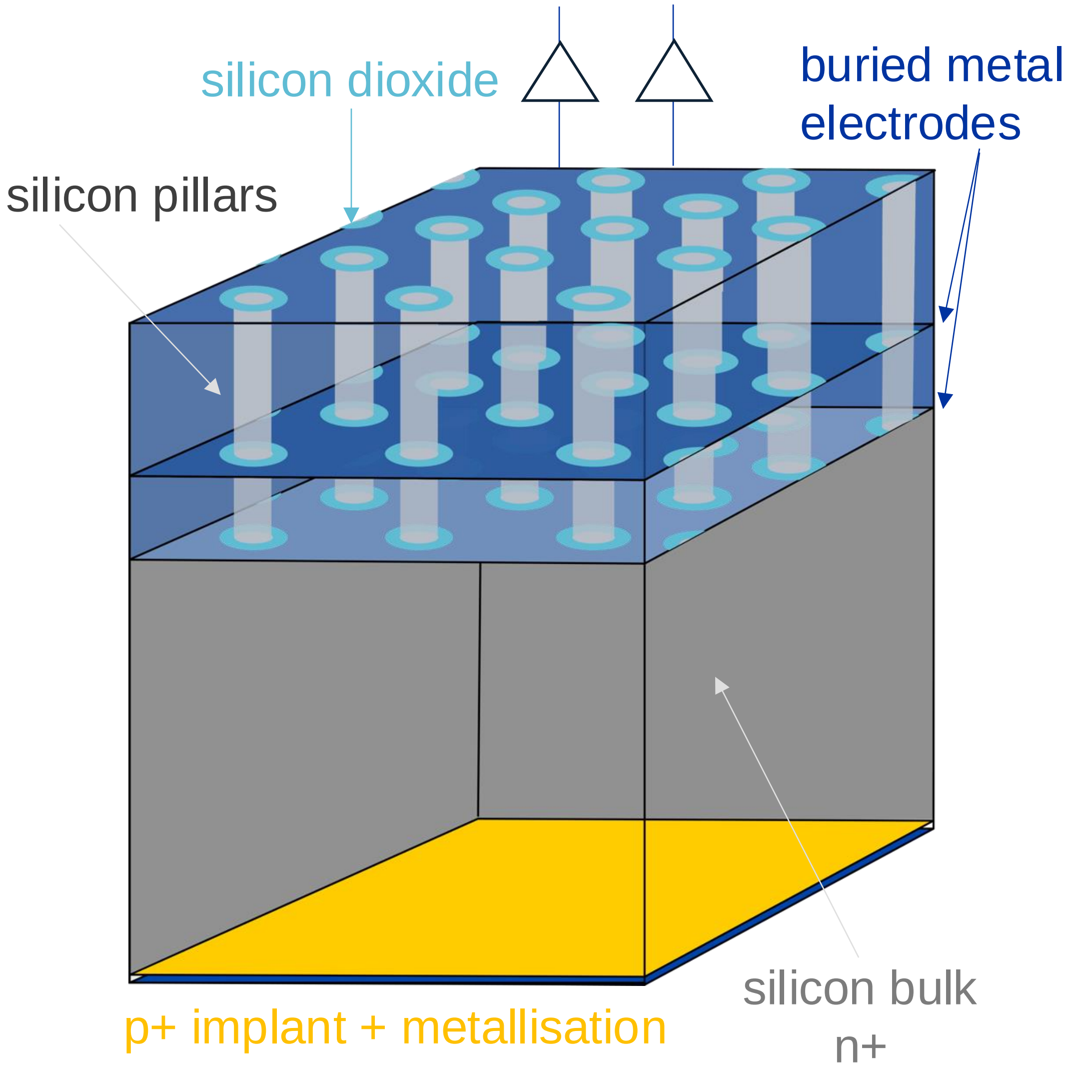
SiEM sensor has **high E field** region in part of sensor thickness, created by potential difference over metallic electrodes

→ drifting electrons are **multiplied** and signal induced on readout electrode(s)

→ pillars can be individually read out (∼5-10μm) or can be interconnected (∼50μm)

→ geometry can be strips or individual columns

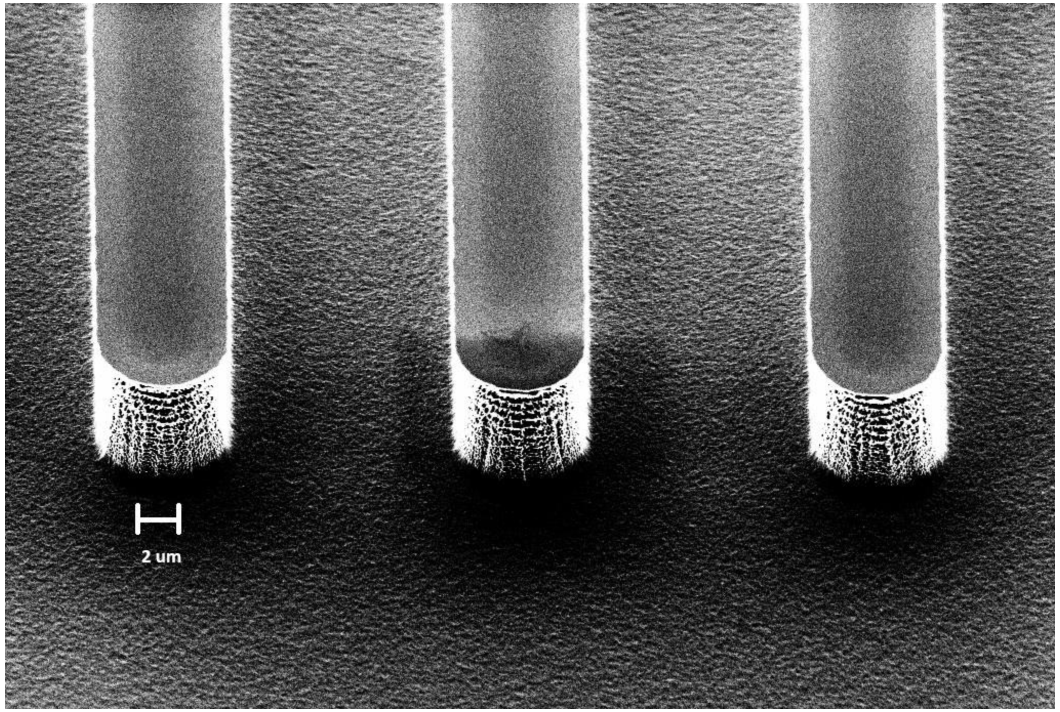
→ aims to achieve **internal gain**, **fine pitch**, and **radiation hard** gain mechanism

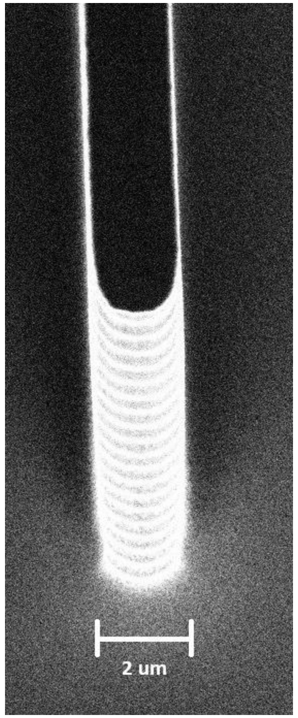


SiEM demonstrator

Deep reactive ion etching (DRIE) production with CNM and AIDAinnova Blue Sky R&D:

Images from CNM





- Pillar width expected to be 2, 3 and 4μm
- Electrodes are deposited using an evaporative aluminium process
- First gain electrode: deposited in the trench on top of an atomic layer deposition of HfO_2
- Second gain electrode: deposited into the trench and insulated using SiO_2

Fabrication currently on-going at CNM.

Previously investigated production with PSI using metal assisted chemical etching (MacEtch): NIM.A. 1041(167325) (2022)

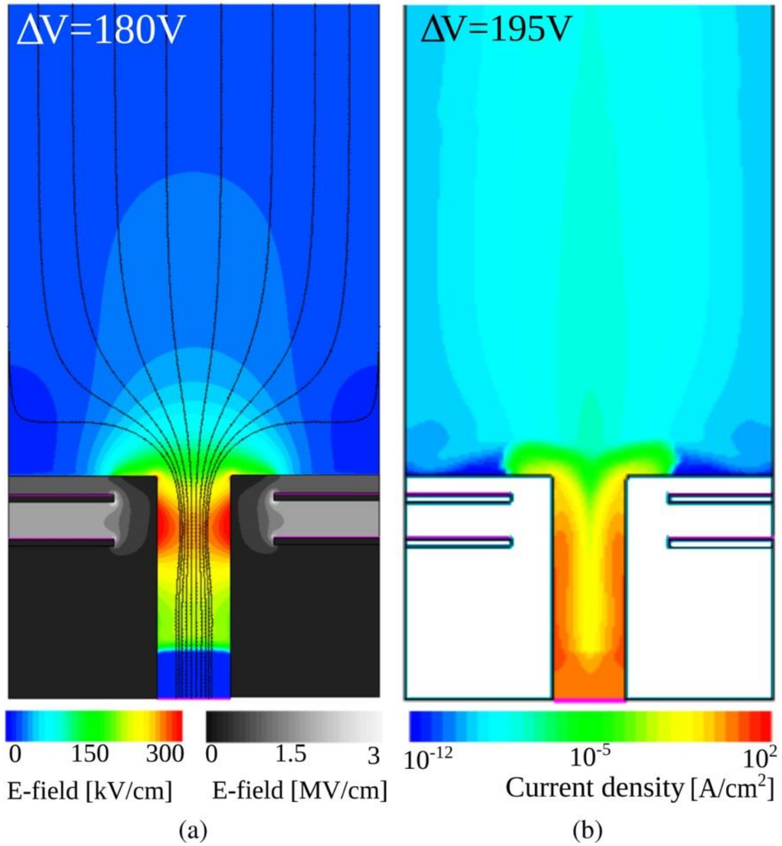
SiEM TCAD simulations

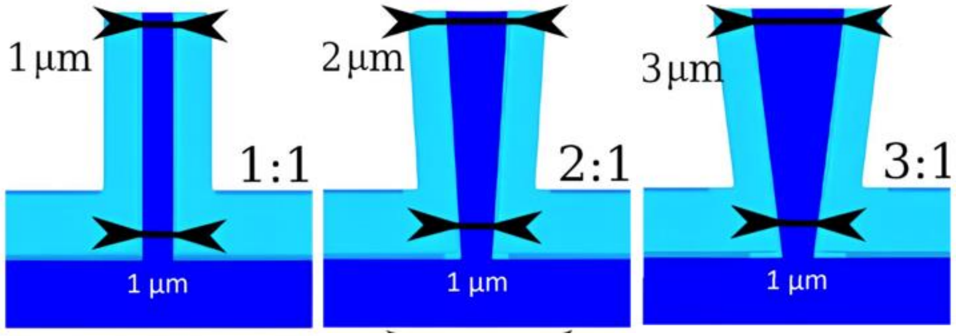
Detailed TCAD simulations performed to be compared to demonstrator

- → Simulations indicate gain >x10 and time resolution O(10ps), depending on geometry

Column width at the base is found to drive the gain. Production constraints mean that the column shape could be pyramidal:

- → Investigations show gain >x10 can still be achieved with this geometry
- → Gain dominated by electrode retraction from the pillar leading to higher HV requirement

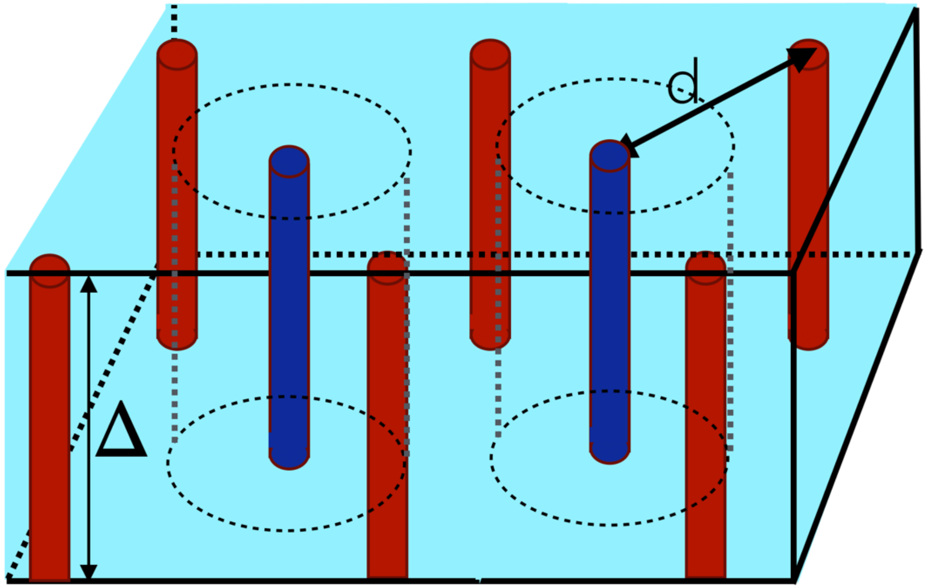




Column 3D sensors

- Intrinsically fast and radiation hard due to lateral charge transport in high E fields
- Signals induced closer in time than in planar sensors
- Non-uniform E field, ‘dead’ regions at the columns, and relatively large capacitances

Within work package, pursing production and simulation of 3D column sensors with timing-motivated designs



Reference: S. Parker et al. IEEE TNS 58(2) (2011)

3D design considerations

Many configurable parameters in 3D sensor design:

- Column width (N,P)
- Column depth (N)
- Pixel pitch
- Column geometry
- Sensor thickness
- Production method(s)

and operational parameters:

- Bias voltage
- Detection threshold
- ASIC readout mode
- Incident track angle

impact longest charge drift path, amount and placement of dead material, non-uniformity of E field, sensor capacitance, etc.

Each 3D sensor design choice has important impact on **timing resolution, spatial resolution**, and **efficiency**

3D design investigations

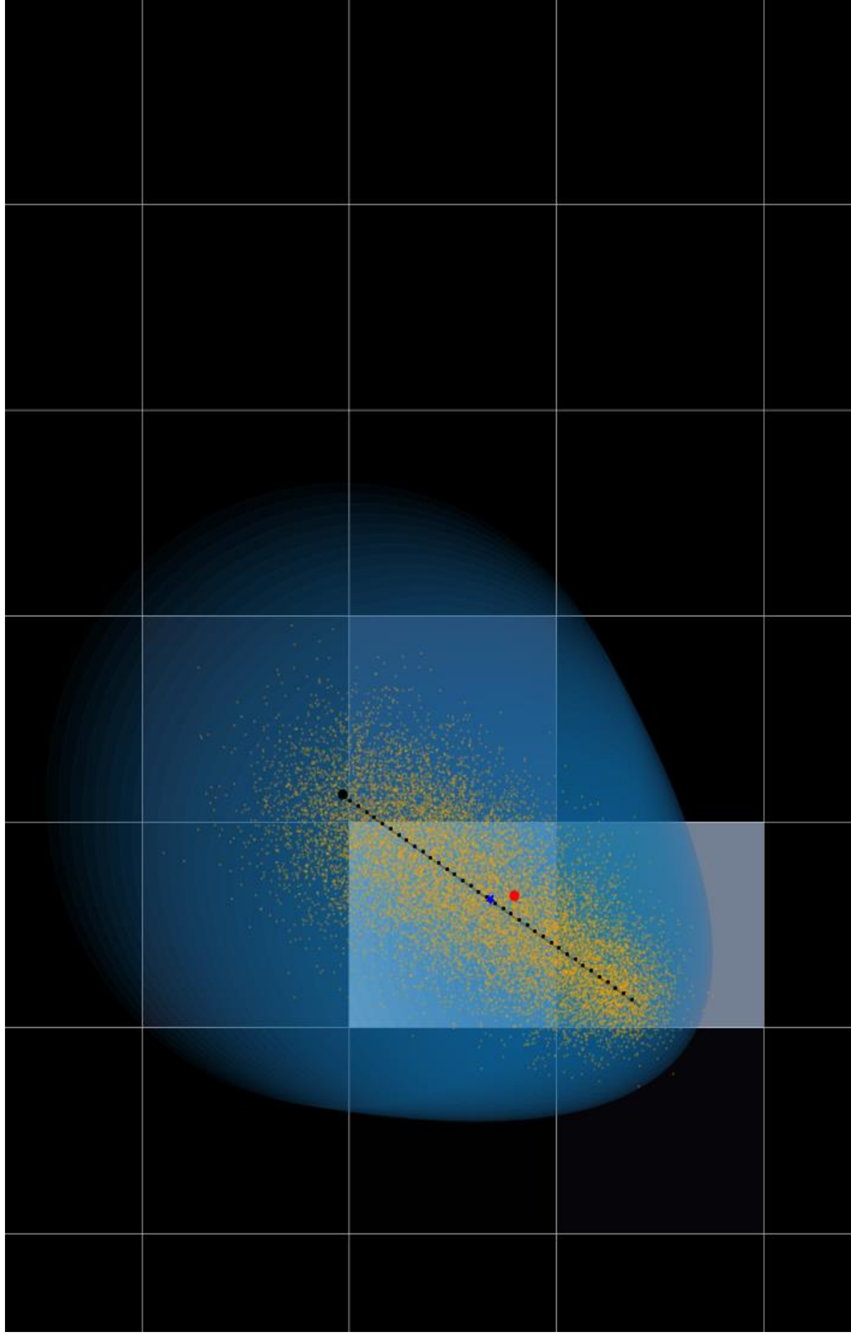
To understand the interplay of design parameters and additional ASIC effects, the chain of **TCAD + MC simulation+ TCoDE/PixESL** is very **time-intensive**

→ idea to investigate **wide parameter space of sensor design** with simpler simulation model that still includes many of the additional detector effects to be investigated

→ developed **fast and configurable toy model** using simplifying assumptions to inform more detailed studies

Python toy model (git, docs): charge deposition along randomly angled (ϕ, Θ) straight line tracks within a mimicked 3D sensor plane.

- Includes: adaptable 3D square-column design, inefficient column regions, large pixel array, langaus fluctuations of charge, detection threshold, clustering algorithms, sensor capacitance and front-end jitter estimation

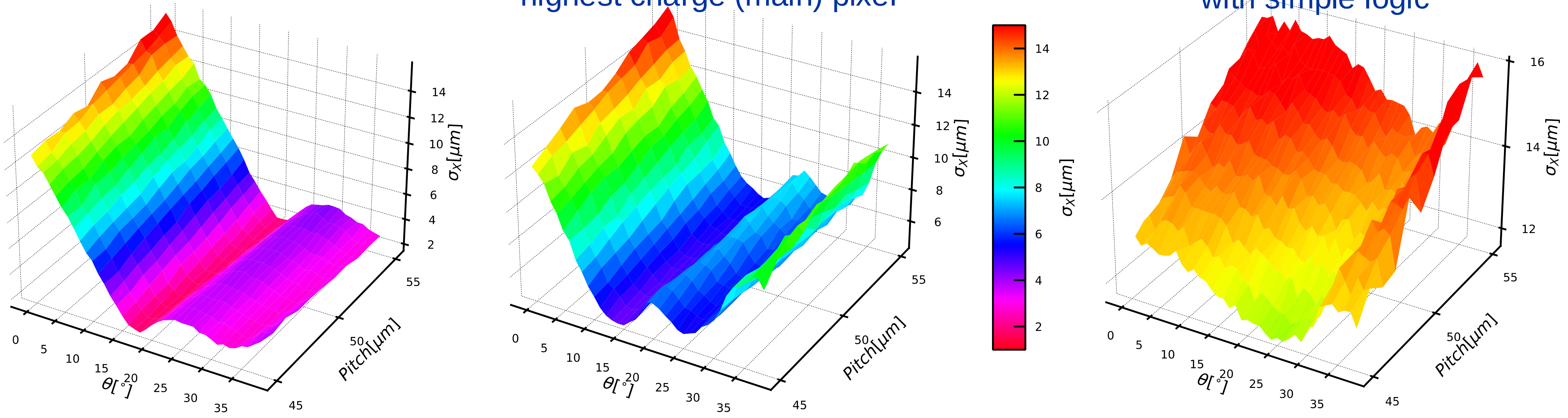


Spatial resolution

Well-known that inherent inefficiency of 3D sensors can be compensated by angling detector plane with respect to incident particles → How does spatial resolution compare?

In addition, future data rates likely mean experiments are unable to readout full charge information per-pixel → How does partial charge information affect spatial resolution with angle?

Barycentre | Cluster shape + position of highest charge (main) pixel | Cluster position calculated on chip with simple logic



→ important to consider this aspect when optimising sensor design for theoretical gains of spatial resolution

Timing resolution

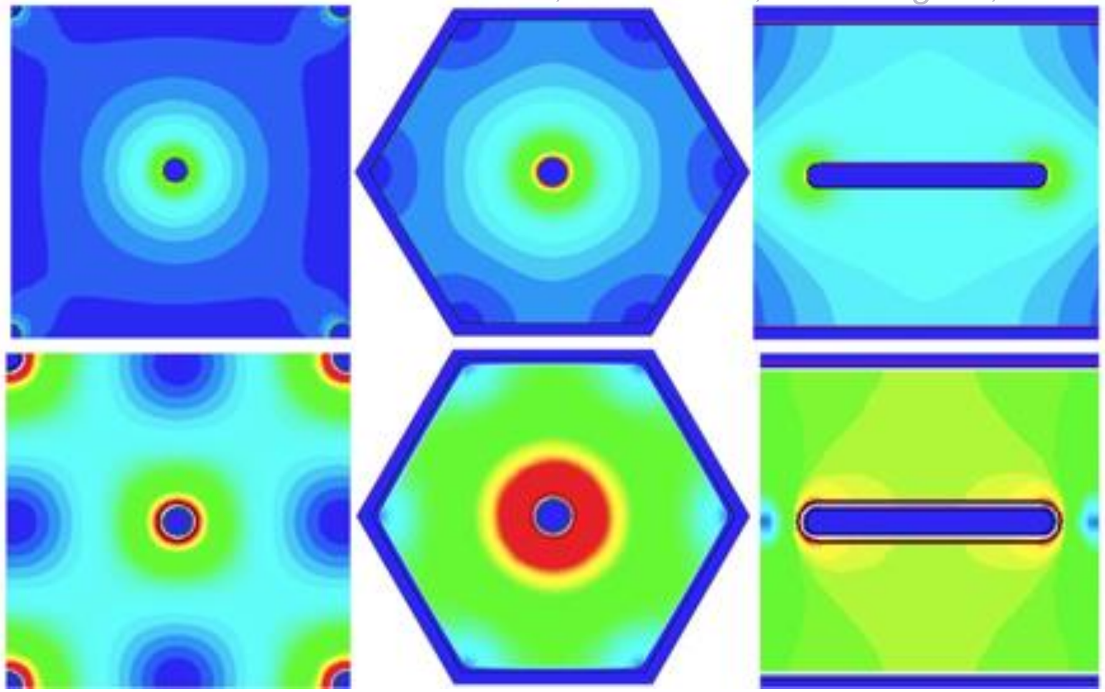
Drift of charges within highly non-uniform electric field → non-trivial to determine timing resolution of 3D sensors

Detailed TCAD studies performed by Timespot (see previous presentation) and others show inherent timing resolution of some 3D sensor designs.

Contributions to overall time resolution comes from both **sensor dynamics** and **electronic response:**

→ focus for a moment on **front-end jitter** and **per-pixel hit-dependent time resolution**

A. Loi, PhD thesis, U. of Cagliari, 2020



estimated values from X. Llopart for Picopix ASIC

$$\boxed{\sigma^2_{t,singleplane} = \sigma^2_{t,sensor} + \sigma^2_{t,ASIC}}$$

50ps 40ps rms 30ps rms

$$\boxed{\sigma^2_{t,ASIC} = \sigma^2_{t,analogFE} + \sigma^2_{conversion} + \sigma^2_{clock}}$$

$(<)25ps$ $11.5ps$ $(<)10ps$

Timing resolution

For front-end timing jitter of <25ps, a minimum amount of deposited charge is required

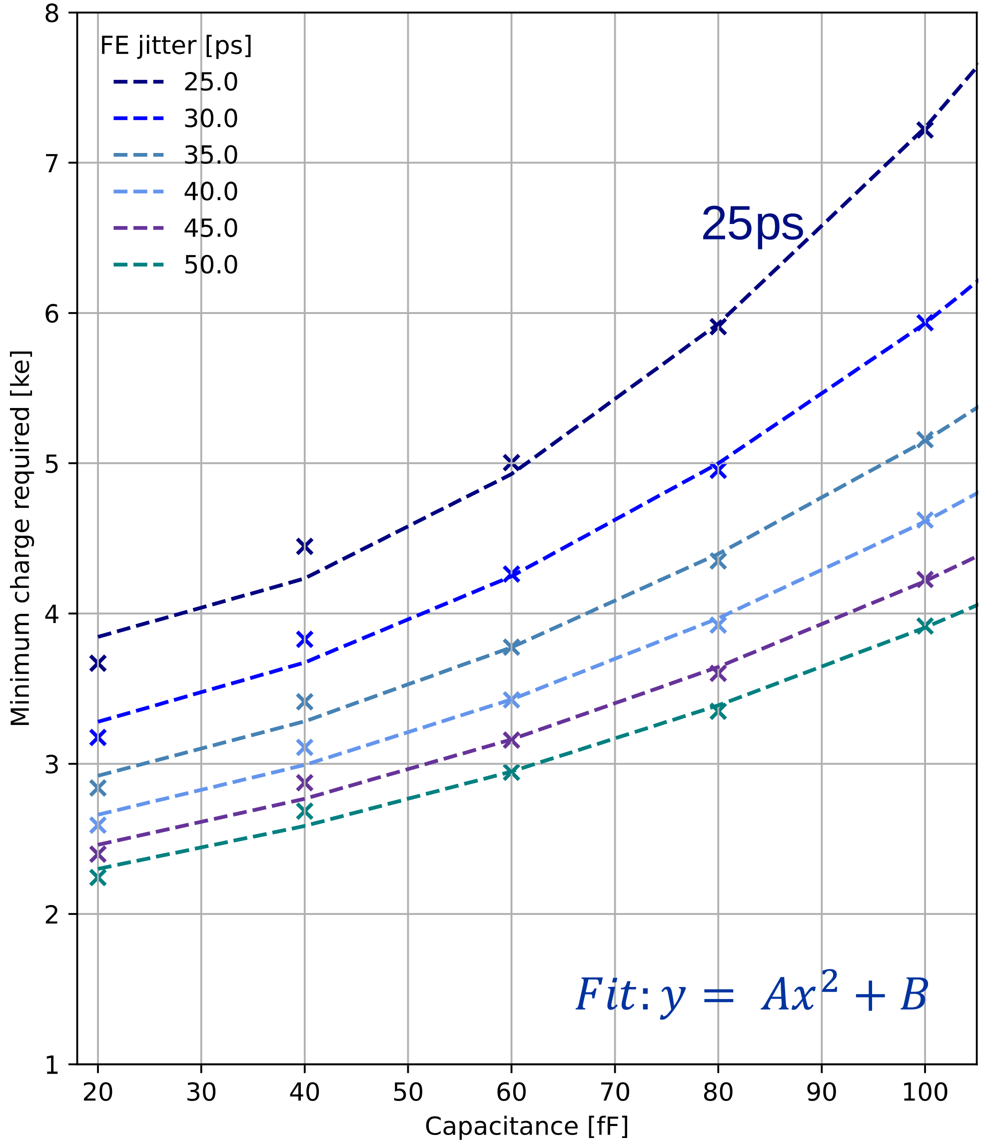
→ analytical timing threshold determines what is a **reliable** timestamp

→ **per-pixel charge dependent** timing resolution

N.B.: considering timing resolution of highest charge pixel in each cluster

Timing threshold ∝ input capacitance, ∴ dependent on almost all 3D sensor **design parameters** and by **different proportionality factors**

Simulation for Picopix ASIC FE provided by Viros Sriskaran



Timing resolution

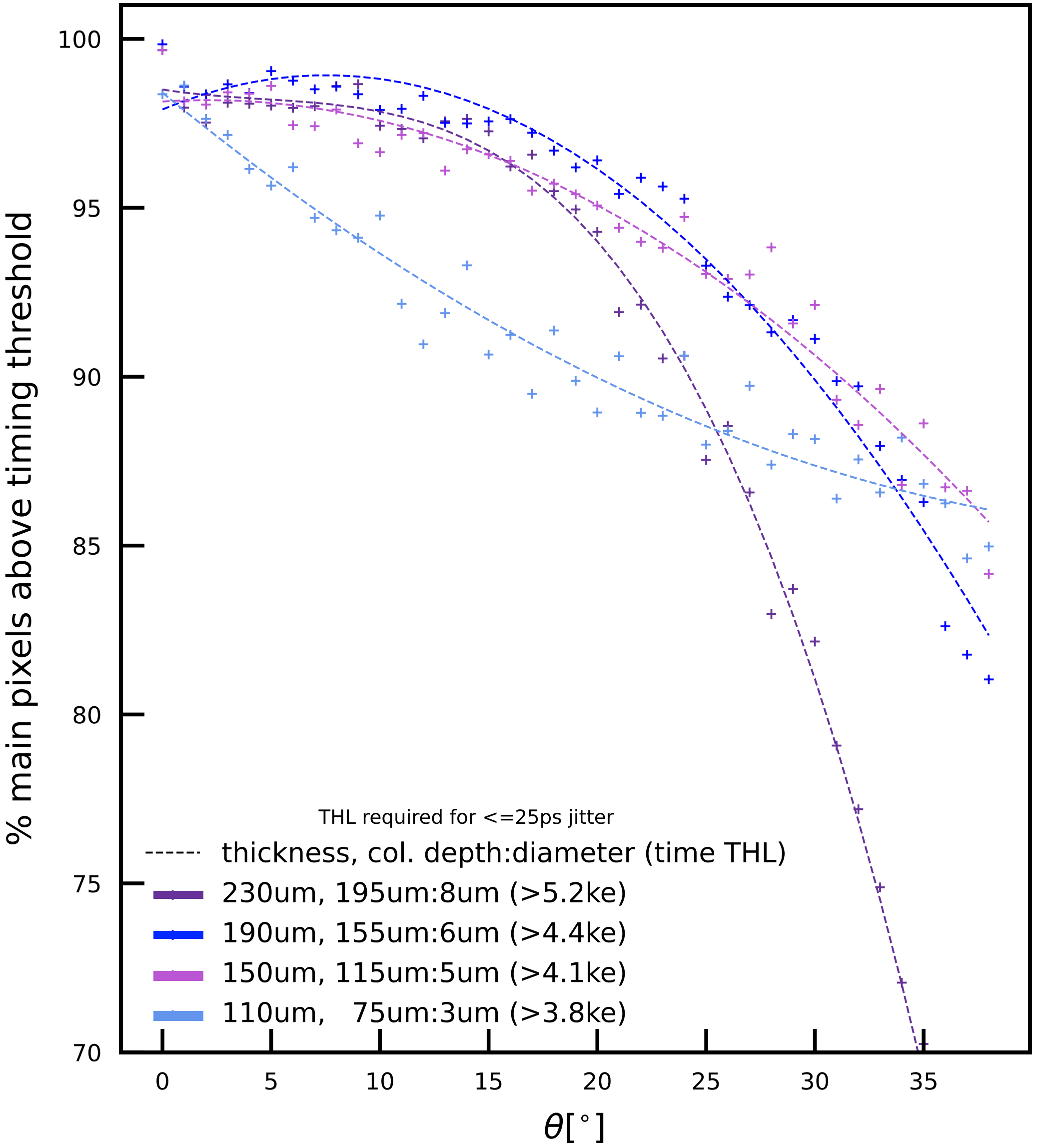
Example 1: Sensor aspect ratio column depth : column diameter of approx. 1:25 with 35um under N-column gap.

Sensor Thickness [um]	230	190	150	110
Column Depth [um]	195	155	115	75
Column Diameter [um]	8	6	5	3
Calculated Capacitance [fF]	62.9	45.2	32.9	19.9

→ affects both the amount of deposited charge per pixel and the timing threshold to be surpassed

→ which one wins?

Thicker 3D sensors could be more interesting for timing than first expected due to increased charge per pixel for angles <20°



Python toy simulation: 3D 1E sensor with column depth : diameter AR of ~1:25. Pitch 50um, threshold 1ke, gap 35um, barycentre clustering using per-pixel charge info

Timing resolution

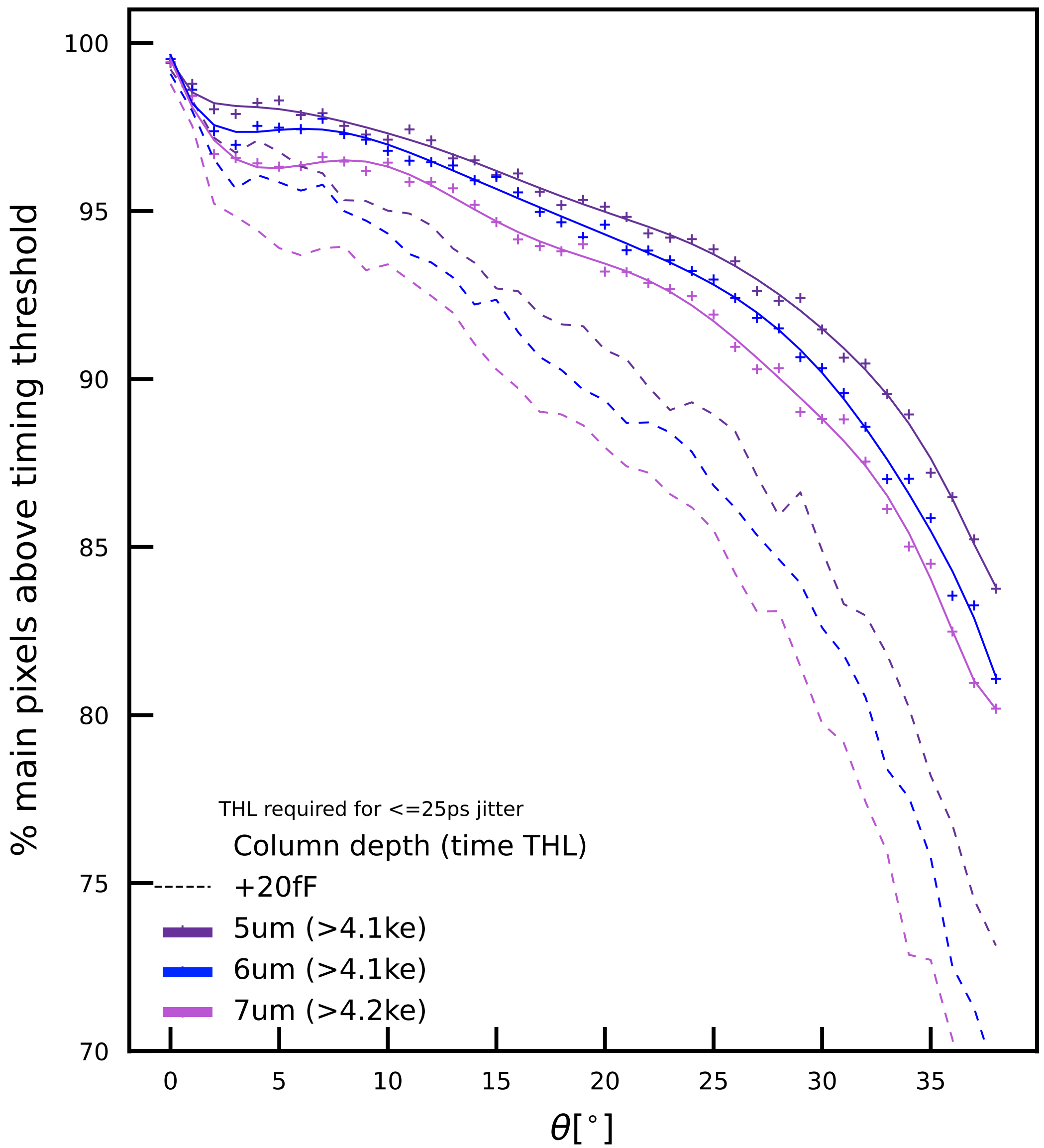
Example 2: Varying column diameter (N and P) for a fixed sensor thickness

Sensor Thickness [um]	150	150	150
Column Diameter [um]	5	6	7
Calculated Capacitance [fF]	32.9	35.7	38.4

→ increased capacitance has critical, non-linear impact on the number of clusters with a reliable timestamp

→ highlights impact of manufacturing process: for example, choice of p-stop or p-spray can change capacitance by order of 20fF → large effect

Verification through simulation and test-beam analysis on-going.



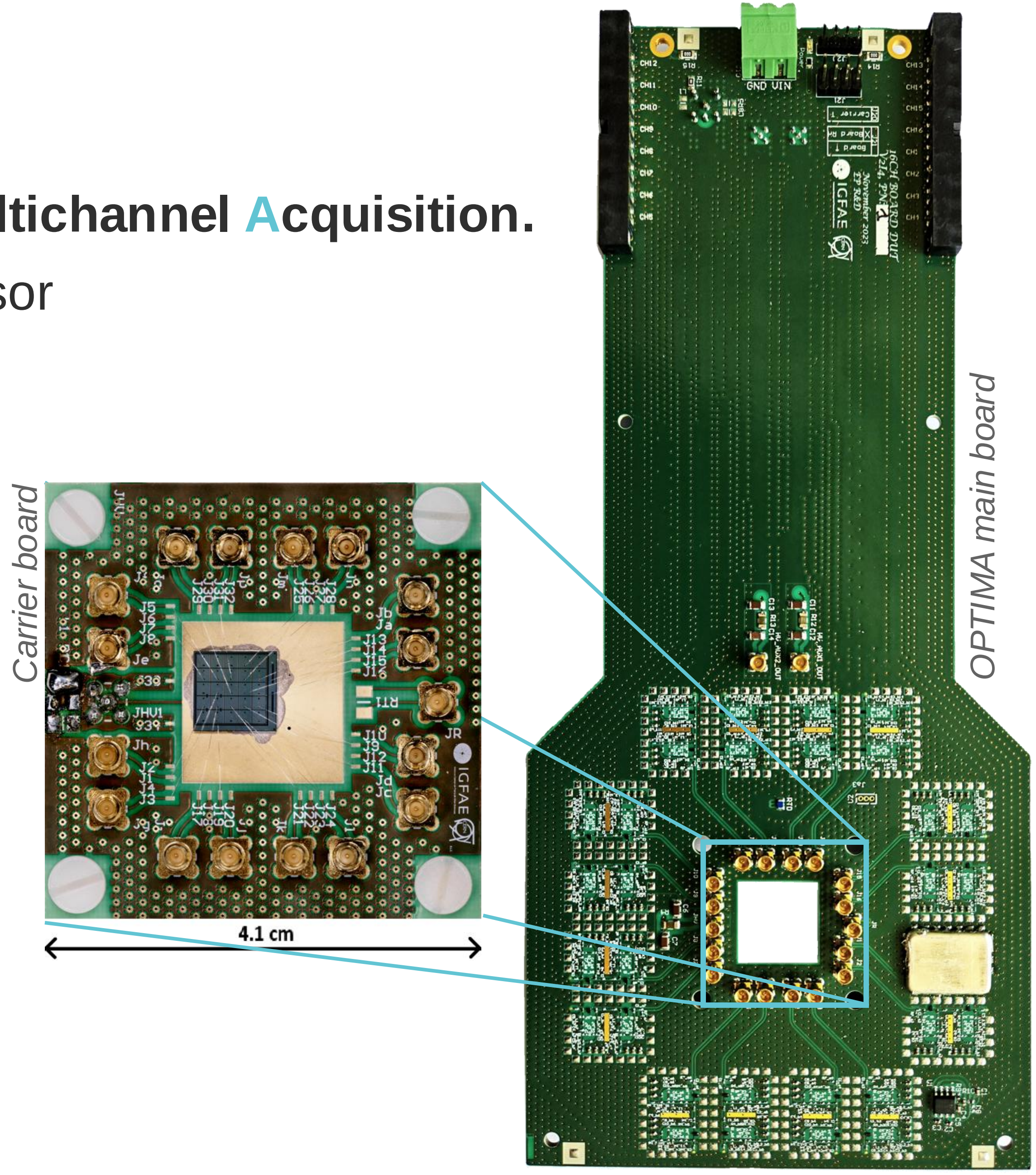
Python toy simulation: 3D 1E sensor of thickness 150um. Pitch 50um, threshold 1ke, gap 35um, clustering using main pixel position and cluster shape

OPTIMA

A board for Optimised Precision TIming for Multichannel Acquisition.

→ designed for characterisation of fast silicon sensor

- Based on a dual-stage SiGe NPN Transimpedance Amplifier (TIA).
- Capable of acquiring data from up to **16 channels simultaneously**.
- Hot-swappable carrier boards enable fast prototyping and irradiation campaigns.
- Laboratory tests show a **gain of O(x70)** and a **rise time of O(500) ps**.



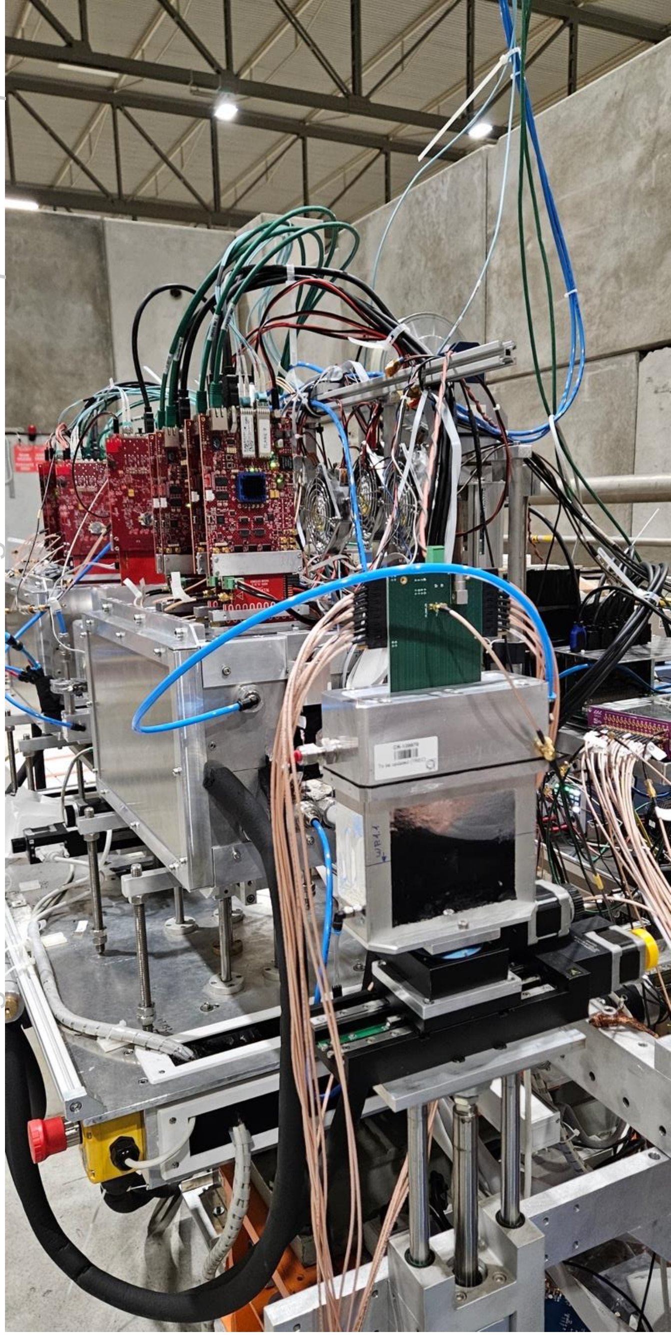
OPTIMA

Preliminary test beam campaigns:

- OPTIMA has been integrated into the Timepix4 telescope set-up and time correlation with tracks has been validated.

  → see presentation “Recent results from the Timepix4 Telescope” from Tjip Bischoff presented 18/2 of VCI2025 for more on the telescope

- Time resolution measurement used a LGAD structure from CMS, **rated 30 ps** using a Micro Channel Plate (MCP) as a time reference.

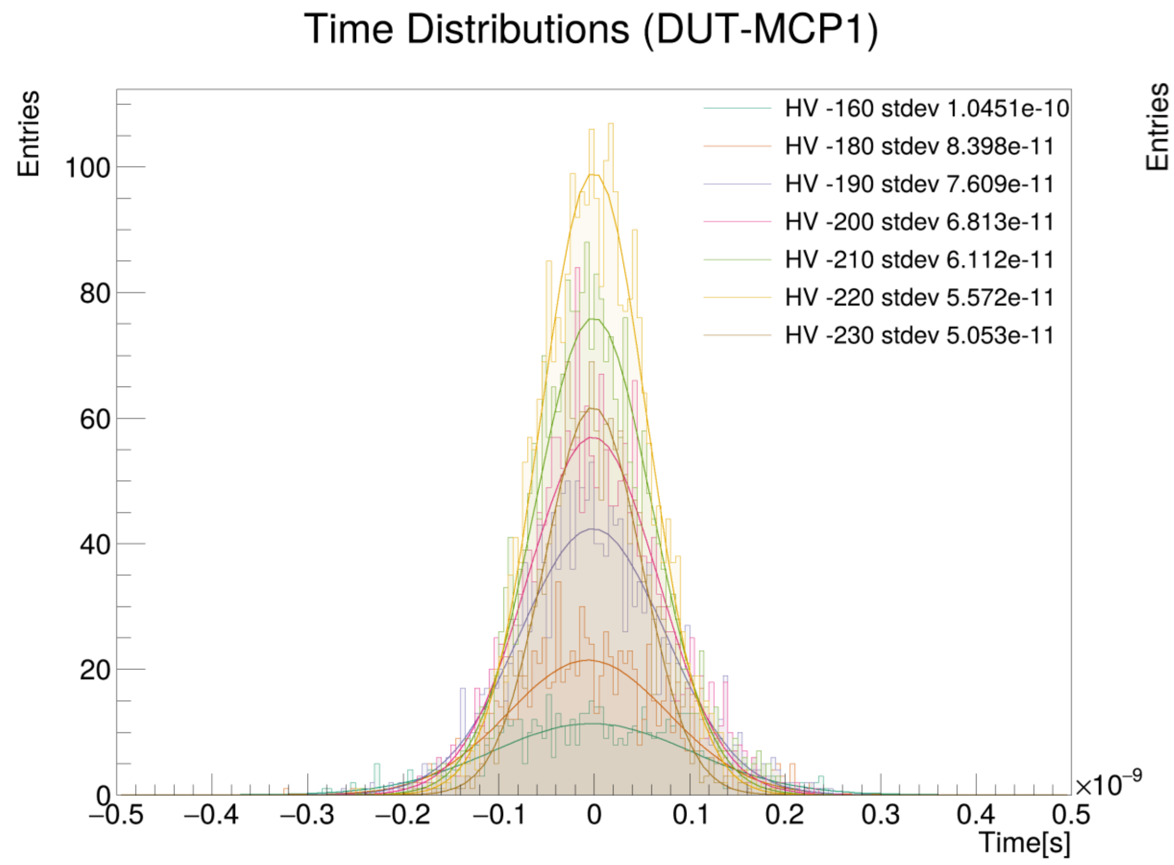


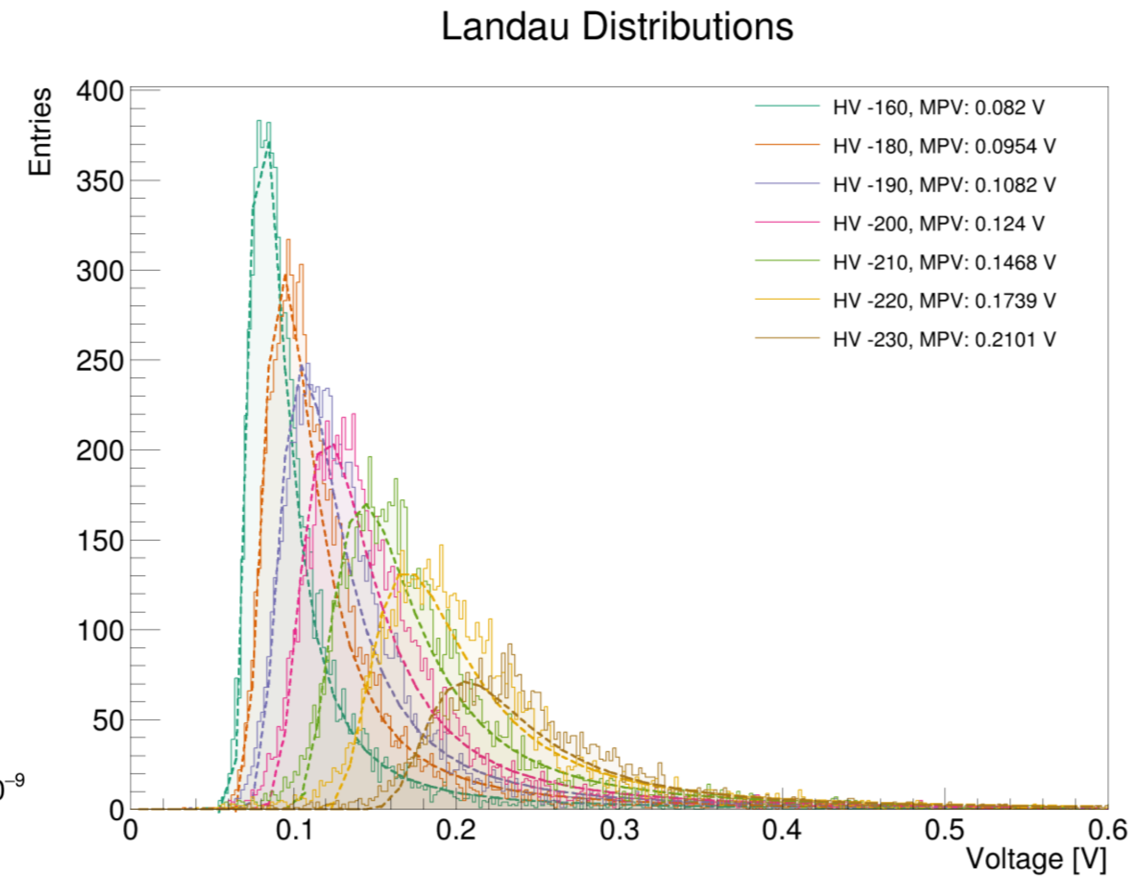
OPTIMA board integrated into downstream stage of LHCb Timepi4 telescope

OPTIMA

Preliminary test beam campaigns:

- Initial results with OPTIMA demonstrate an excellent **signal-to-noise ratio SNR>10** and a time resolution of **O(50) ps**.





Conclusions

Need in high energy physics for fast timing sensors for future experiments with fine pitch and radiation hard.

Activities within EP R&D WP1.1 overviewed:

SiEM

- Promising sensor with a radiation-hard gain mechanism and fine pitch.
- DRIE-based production on-going with CNM with 2-4µm pillars.
- Detailed TCAD simulations performed to compare to laboratory tests.

3D column sensors

- Toy simulation investigating impact of design parameters on figures of merit, used to inform focus of further studies.
- Indicates importance of considering sensor capacitance in timing performance, and impact of partial charge information and angle on spatial resolution.

OPTIMA

- Board for fast-sensor characterisation with 16 simultaneous channels.
- Testbeam analysis of OPTIMA with LGAD sensor. Initial results: time resolution O(50)ps, SNR >10, and gain of O(70) in laboratory measurements.

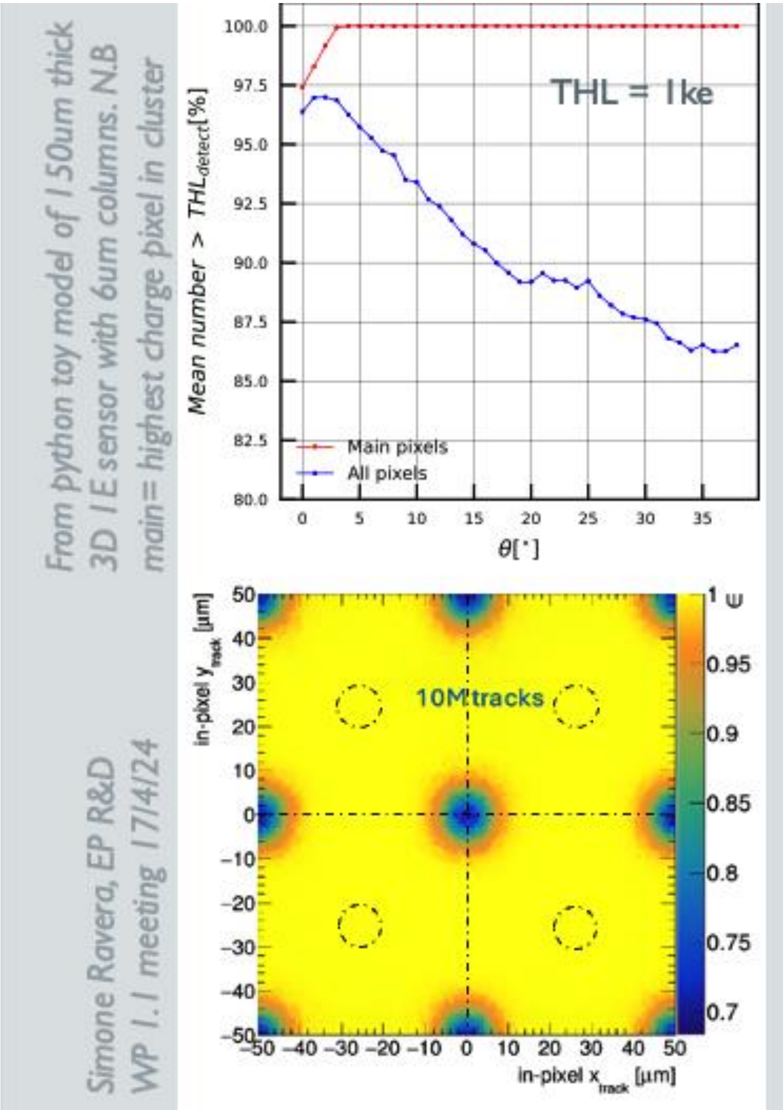
home.cern

References and further materials

- LHCb VELO upgrade II workshop (November 2024):
  "Sensor and ASIC characterisation overview"- F de Benedetti
  "VELO sensor studies for R&D"- M Williams
- EP R&D WP 1.1 meetings: https://indico.cern.ch/category/13627/
- TREDI 2025: "Development of the Silicon Electron Multiplier (SiEM) Sensor and Fast-timing Readout Tools For Sensor Characterization" - F de Benedetti
- DRD3: "OPTIMA, a board dedicated to Optimized Precision Timing for Multichannel Acquisition"- F de Benedetti
- EP R&D Day March 2024: "Hybrid Silicon sensors" – M Williams

Morag Williams, LHCb VELO upgrade II workshop, November 2024, “VELO simulation drivers for 3D sensor production”

slide 7



slide 9

SPATIAL RESOLUTION

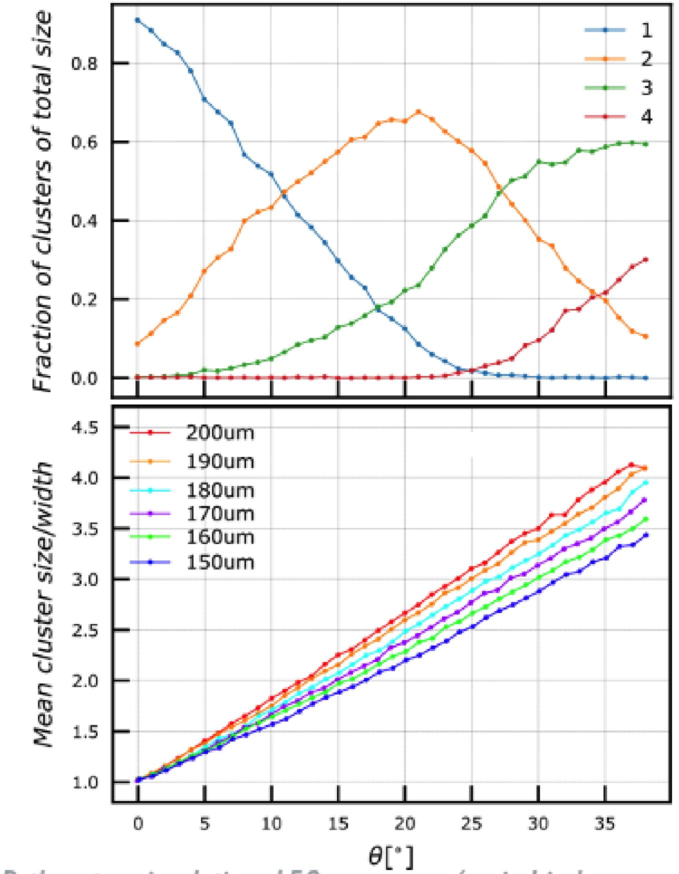
- Readout of full charge information from each pixel/cluster is not guaranteed in VELO upgrade II due to foreseen output high data rates

→ need cluster centre position calculation using partial information

- Position calculation methods with partial information have in-built assumptions of charge deposition within clusters of different shapes and sizes

→ reduced cluster charge information and cluster geometries will affect spatial resolution

Presented previously in here and here



Python toy simulation: 150um sensor (varied in lower plot), 3D 1E with 6um thick columns, pitch 50um.

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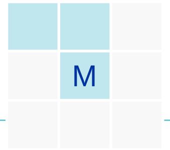
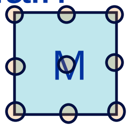
Morag Williams, 113th LHCb week: VELO parallel session, September 2024, “LHCb upgrade II simulation”, slide 5

Considered clustering algorithms with different levels of charge info

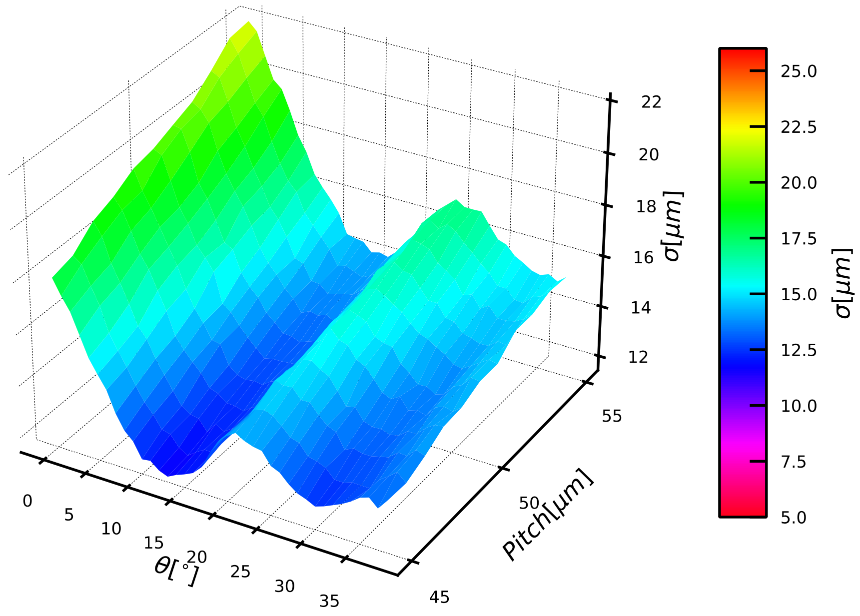
Data packet	Output	Cluster position calculation
Full charge info	ToT of every pixel	Analog-weighted centre of gravity of hit pixels (barycentre)
‘Binary’ cluster shape info off-chip	Binary hitmap (8bit) + highest-charge pixel position 	Weighted centre of gravity of hit pixels, where main pixel has configurable weight (=1,2,…) and other pixels in cluster = 1
‘Binary’ cluster shape info on-chip	Highest-charge pixel position + fractional calculated cluster position (2bit)	Main pixel position, but with a possible half-pixel pitch shift up/down and/or left/right depending on cluster geometry and main pixel configurable weight (=0,1,2,…) 

How does partial charge information effect spatial resolution for a single plane?

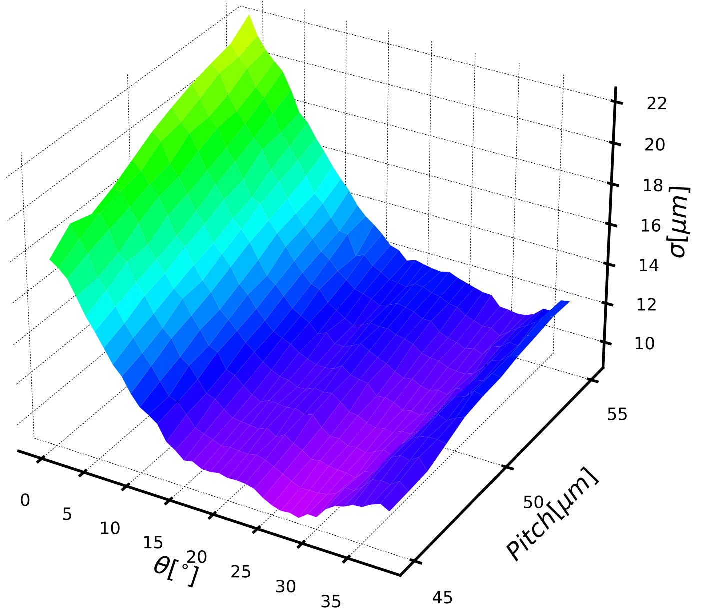
→ stand-alone single-sensor Python toy model developed to investigate effect of partial charge information for different sensor designs and particle track angles

Morag Williams, LHCb VELO upgrade II workshop, November 2024, “VELO simulation drivers for 3D sensor production”
Slides 21 and 22 combined

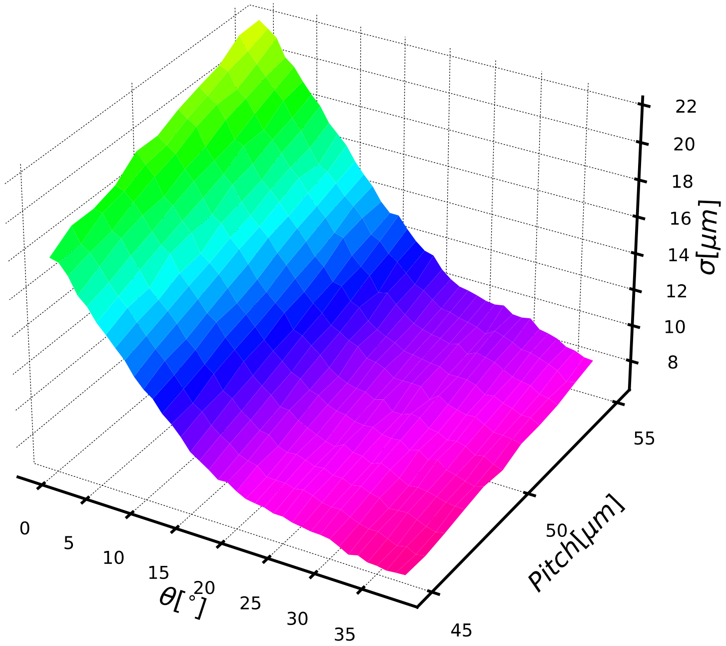
N.B. σ is combined XY



Using fractional calculated cluster position (on-chip, w=0)



Using ‘binary’ hitmap (off-chip, w=2)



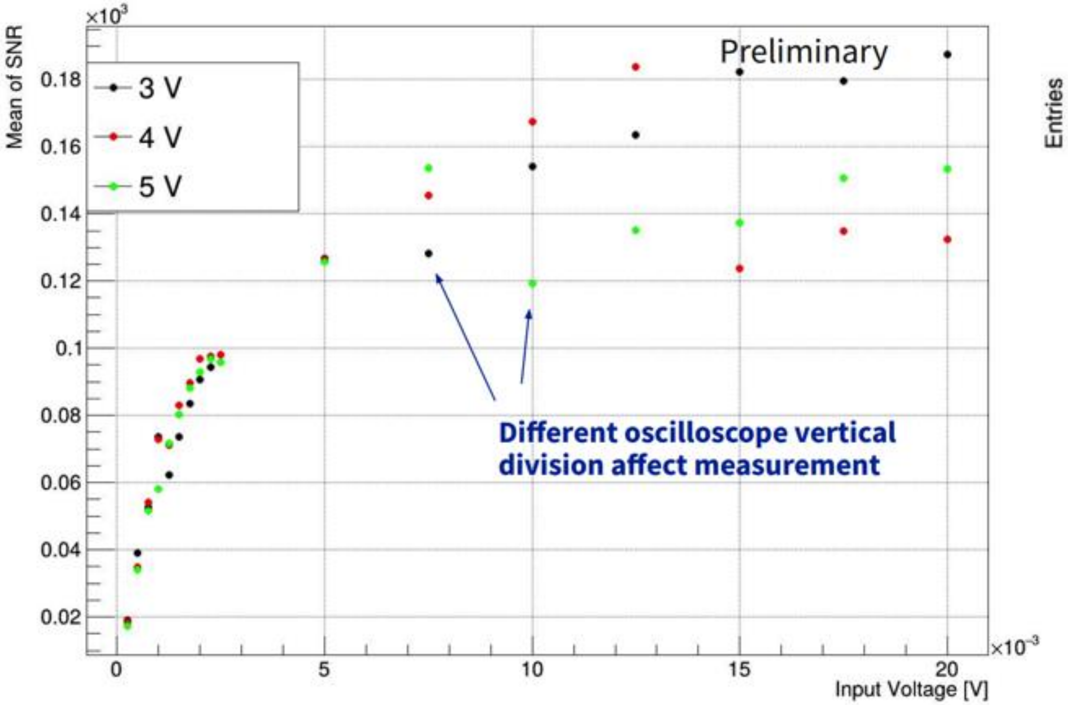
Barycentre

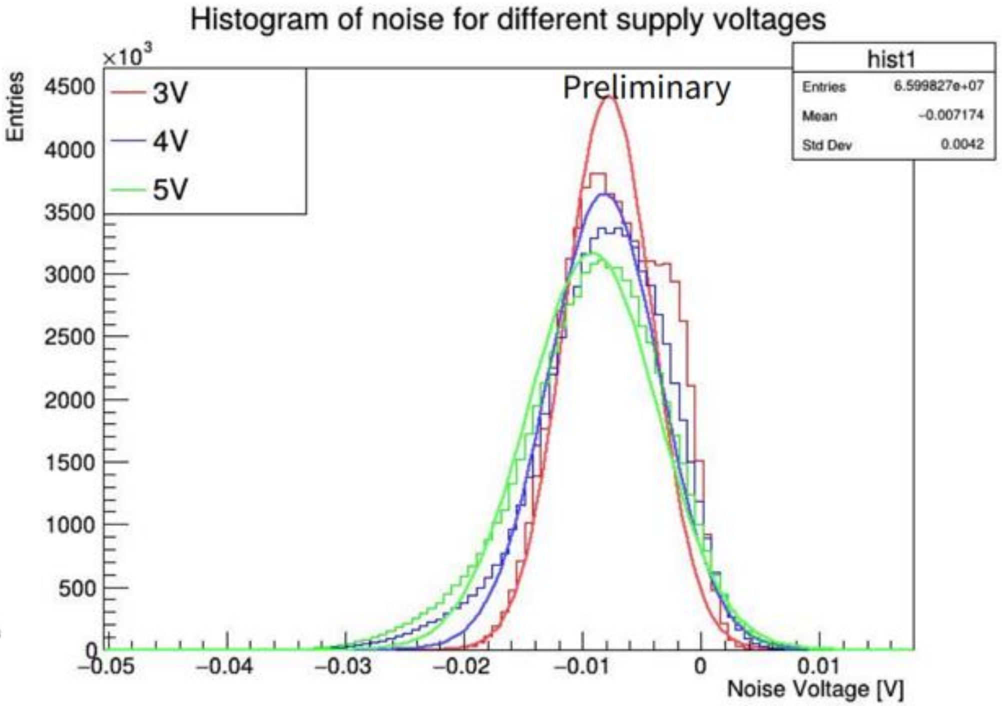
Federico de Benedetti, DRD3 week Dec 2024, “**OPTIMA, a board dedicated to Optimized Precision Timing for Multichannel Acquisition**”, slide 8

Lab Tests

SNR

- Noise is fairly independent on the power supply setting
- SNR is always >10 even for very low input signals (<1mV)





TCAD capacitance measurements from U. of Cagliari and Timespot, presented at PIXEL 2024 by Angelo Loi, “Design and production of timing optimised 3D silicon sensors for future LHC experiments and beyond”