7th November 2025

Simulation and Characterization of fast and radiation hard 3D silicon sensors

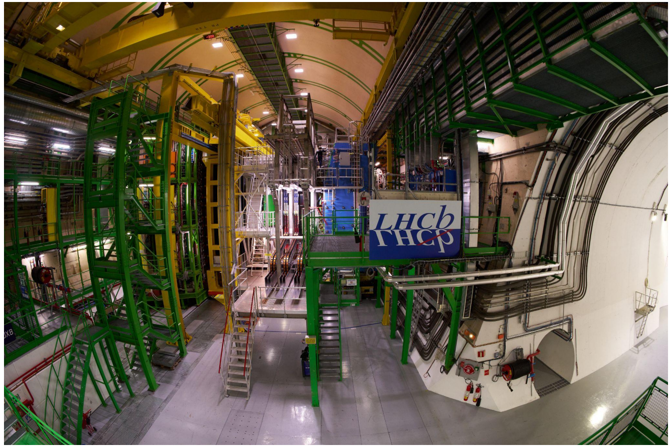
Alfonso Puicercus Gomez
on behalf of EP R&D WP1.1 at CERN and University of Groningen

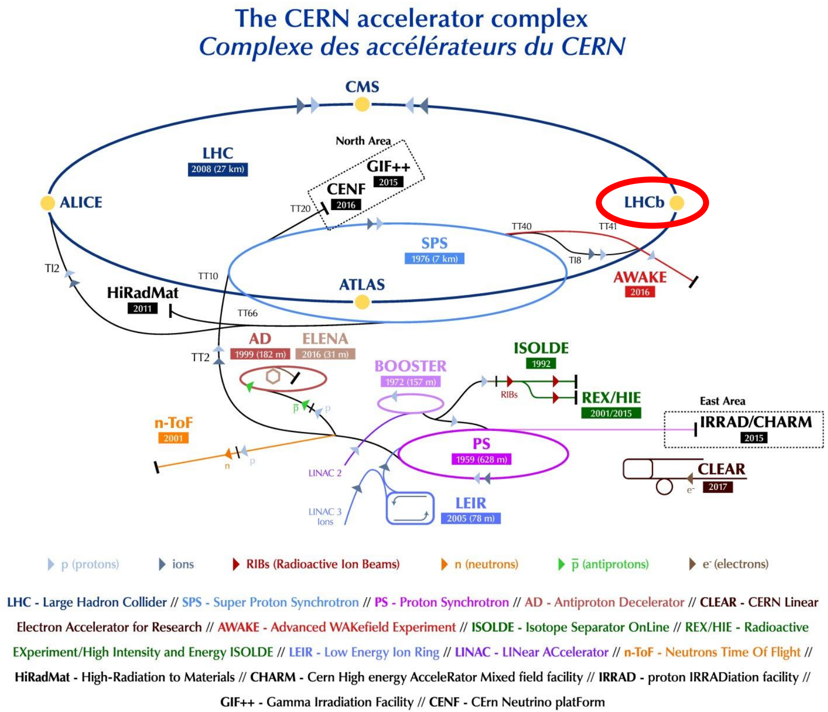
Motivation

LHCb Upgrade II

- **CERN hosts the Large Hadron Collider (LHC)**

- **LHCb is one of the four main experiments**
  - optimized for the study of heavy flavour physics and CP violation in the b- and c-quark sectors
  - Located in the forward region, LHCb operates under high particle multiplicities, requiring precise tracking and fast readout.

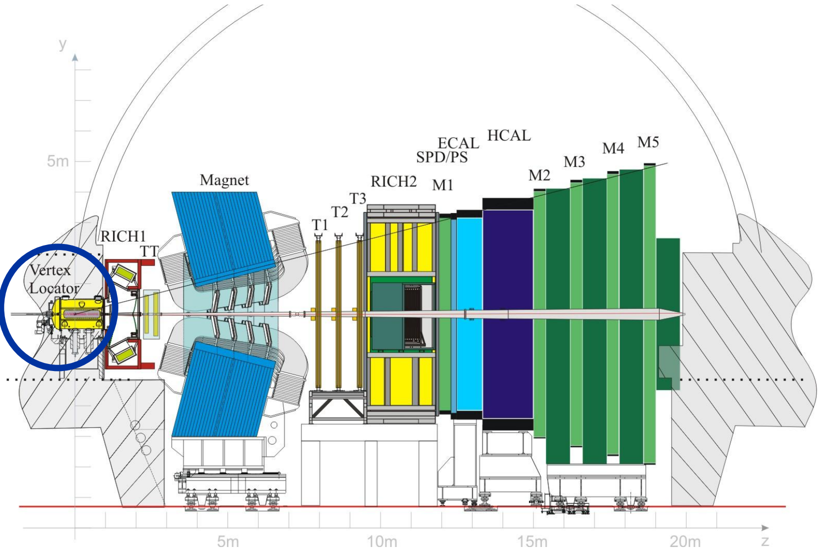


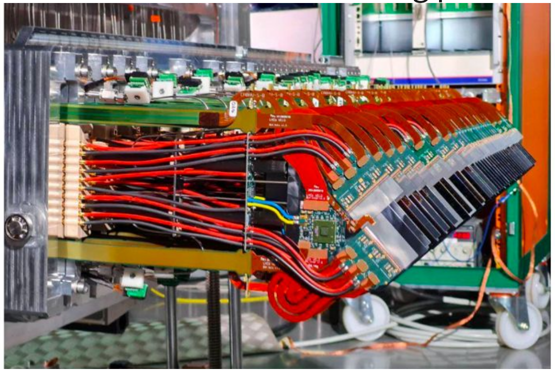


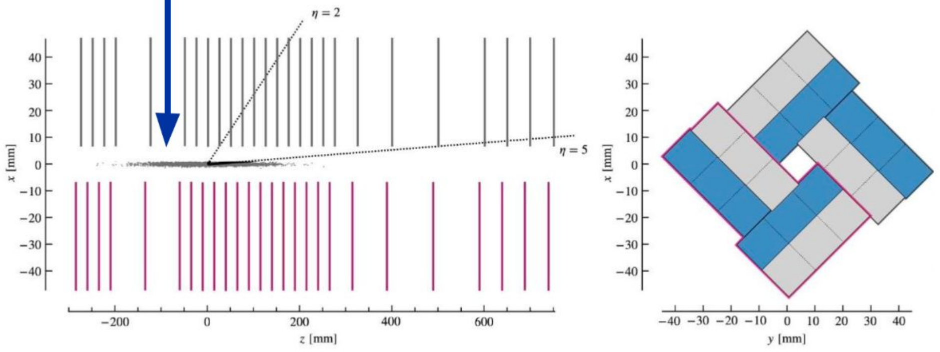
Motivation

LHCb Upgrade II

- **The VELO (Vertex Locator) is LHCb's innermost tracking subdetector:**
    - Positioned millimetres from the proton beams.
    - Provides primary and secondary vertex reconstruction with micrometre precision
- **Current VELO technology approaching limits:**
    - **Readout hybrid:** Existing electronics challenged by extreme particle fluxes.
    - **Planar sensors:** Standard sensor designs nearing radiation tolerance and timing performance limits.







Motivation

MIP detection in next generation of collider experiments

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

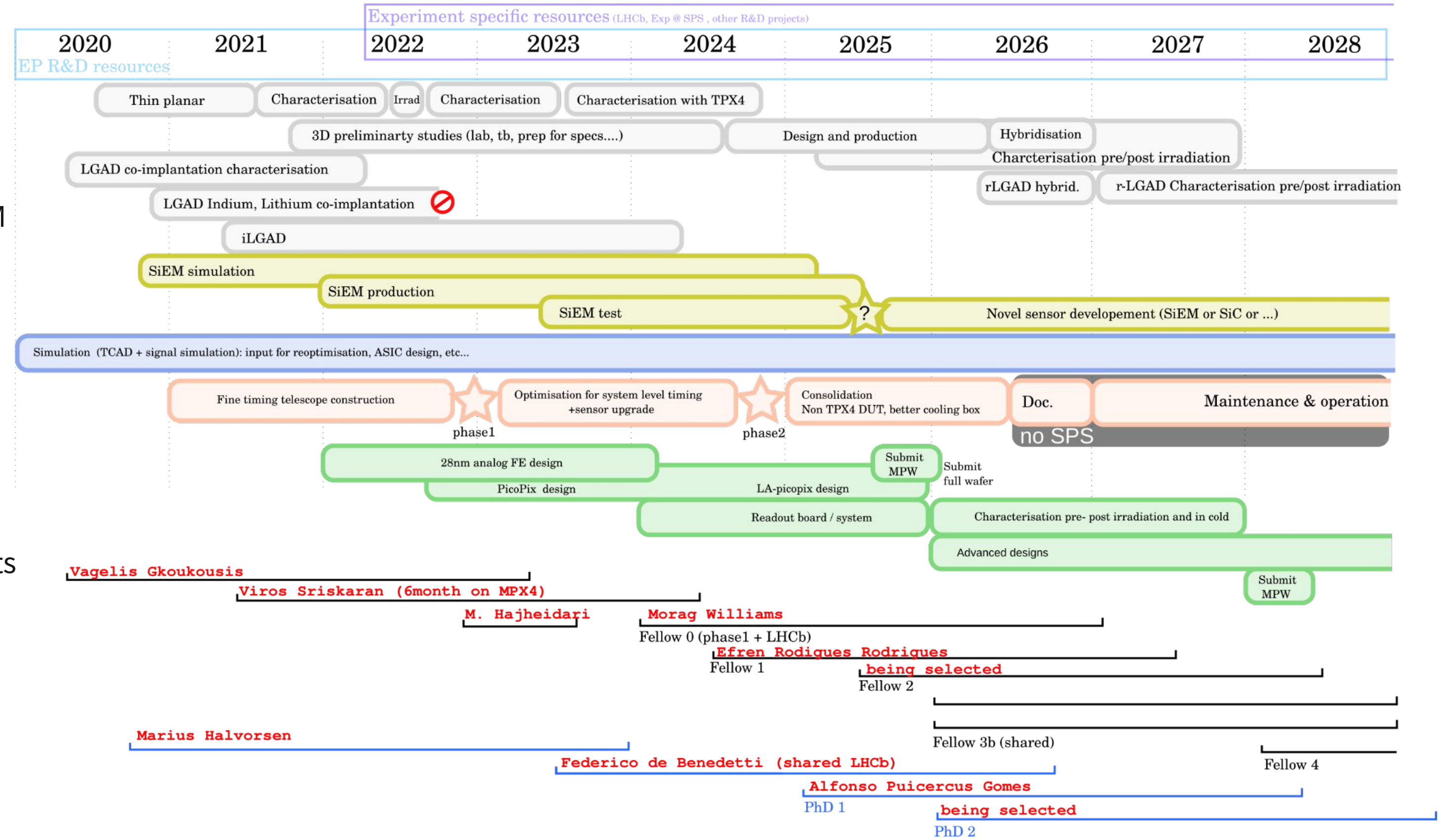
- **Time resolution 10 - 50 ps**
- **Pixel pitches down to 25 µm**
- **Fluences up to $10^{17}\ n_{eq}/cm^2/y$**
- **Max hit rate up 20 $G/cm^2/s$**

Challenges for sensor
Challenges for front-end electronics

Motivation

Timeline

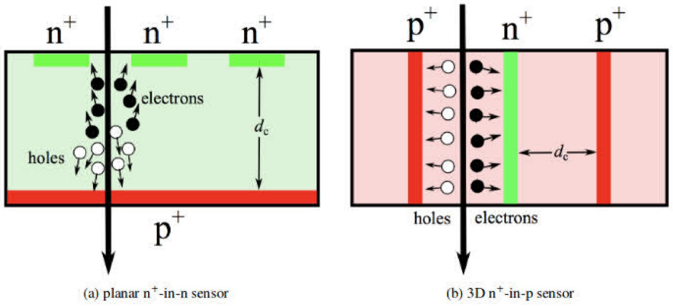
- **Sensor development:**
  - Fast 3D and SiEM
- **Simulation and characterisation:**
  - TPX4 telescope, OPTIMA, TCT setup and IV/CV
- **Readout:**
  - from picopix to LA-picopix and its readout



3D sensors

Fundamentals

- **How silicon sensors work:**
  - A silicon detector measures charged particles by collecting electron–hole pairs created when a particle crosses the silicon.
  - An electric field across a depleted region drifts these charges to electrodes → producing a measurable signal.
- **Planar sensors:**
  - Electrodes on opposite surfaces
  - E field across full thickness → charge travels through the entire bulk.
  - ✅ Mature tech, simple fabrication.
  - ❌ Slow charge collection (long drift distance).
  - ❌ High depletion voltage, especially after radiation damage.
- **3D sensors:**
  - Electrodes are vertical columns etched into the silicon
  - E field between columns
  - ✅ Shorter drift distance → faster collection.
  - ✅ Low depletion voltage & radiation hardness.
  - ❌ More complex fabrication, smaller active volume per pixel.

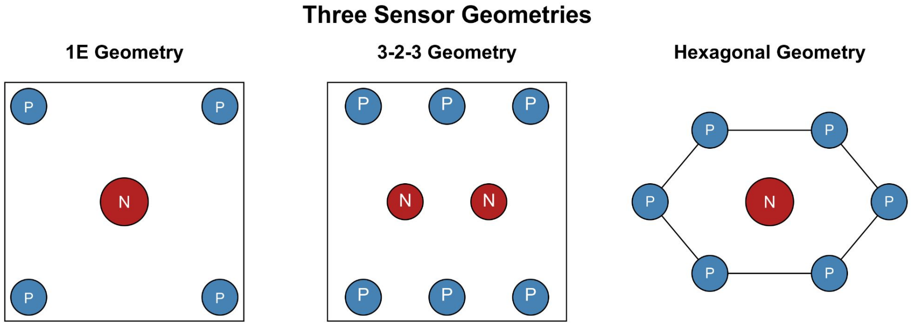


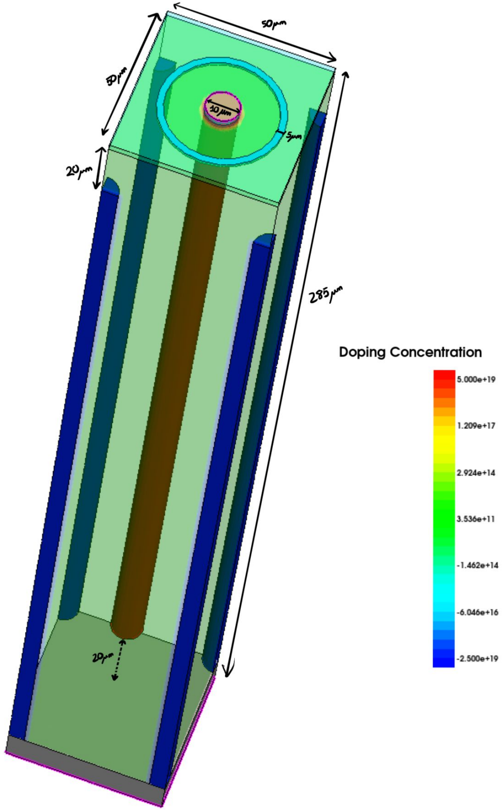
Saleem, 2019 (PhD thesis)

3D sensors

Fundamentals

- **Main parameters of interest in 3Ds:**
    - General Geometry on columns (1E, 3:2:3, Hex)
    - Fabrication process (Double vs Single Sided)
    - Thickness of bulk
    - Column diameter
    - Column gaps
    - Doping profiles
    - Isolation structures





3D sensors

Timing-Driven Sensor Design Considerations

- **Timing resolution depends on:**
  - Collected charge (signal strength)
  - Sensor capacitance (rise time, noise)

- **Design optimizations:**
  - Increase bulk thickness → more charge, reduced timewalk correction
  - Reduce column diameter → lower capacitance

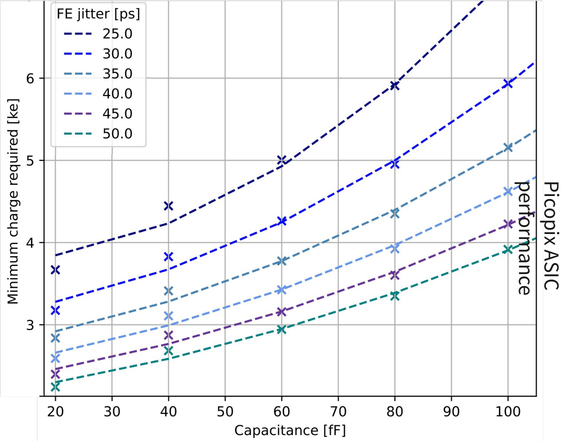
    ⇒ High AR columns required → fabrication challenge

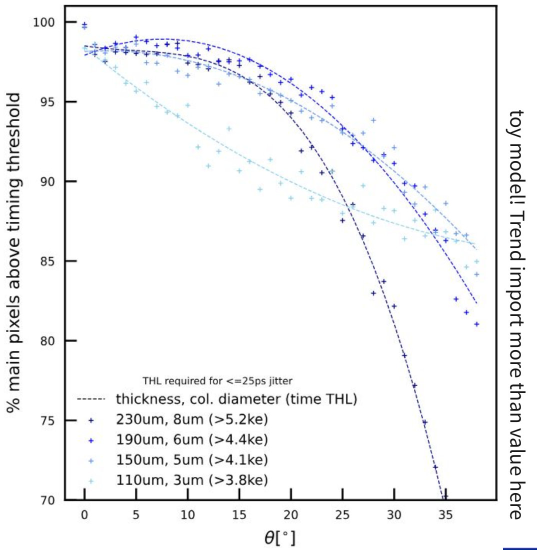
- **Larger thickness remains favourable on two fronts:**
  - higher charge reduces the error correction on the intrinsic time resolution
  - lower angle needed for optimal charge sharing (easier to design a detector)

    ⇒ thickness to be investigated

- **Investigate various column geometries:**
  - 1E, 2E, 3:2:3, hex, 50x50 (and 25x100 to be checked in simu)

- **Have large structures available to bond to Picopix and TPX4 ASICs**





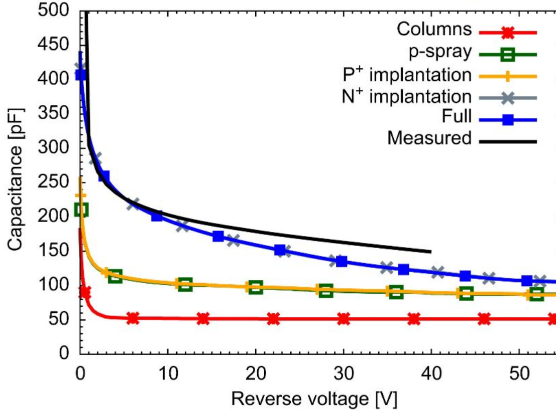
3D sensors

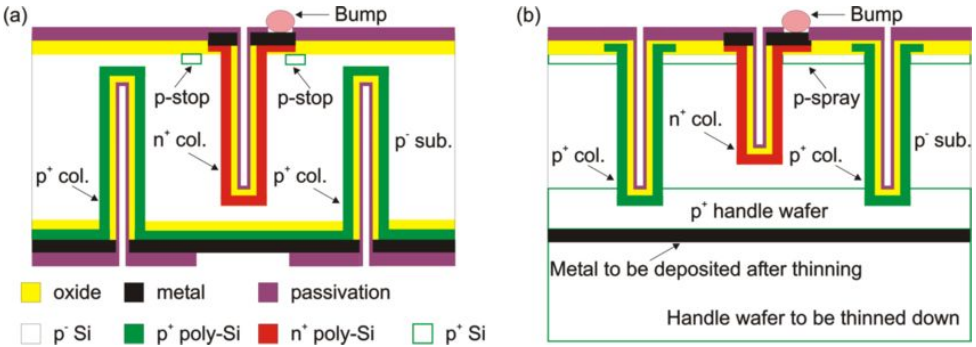
Fabrication Design Considerations

- **Double sided (DS)(a) vs Single/One sided (OS)(b)**
  - **⇒ study into choice of fabrication process**
  - possible pass-through columns for better homogeneity in response and high voltage, with a reduction in efficiency
- **Isolation structures:**
  - ***p-stop*** vs ***p-spray*** to improve HV tolerance and interpixel capacitance
    ⇒ dedicated R&D structures

Designs and studies driven by simulation studies.

M. Povoli, et al., Nucl. Instrum. Meth. A 699 (2013) 22





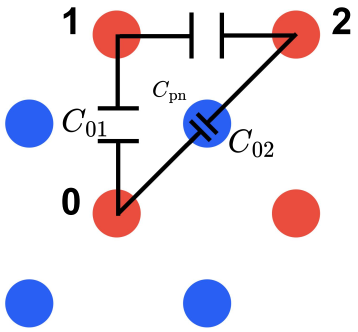
Simulations

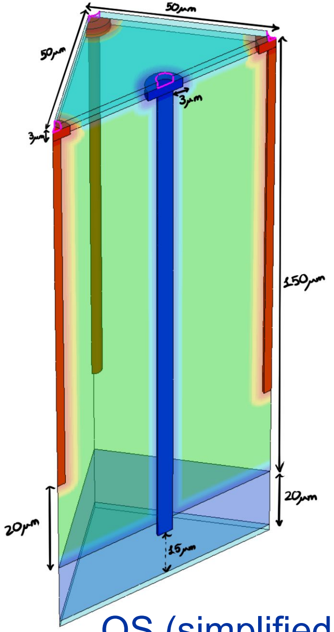
Overview

- **Support from simulation to drive the parameter space**
- **Now using this understanding as the basis to perform focused, detailed simulations of different 3D sensor designs within a full workflow:**

TCAD	Garfield++	Analog front-end integrator	PixESL
(Device simulation)	(MC simulation)	(to be integrated)	(from EP-ESE)

- **TCAD 3D models:**
  - Fully parametrized sensor design
  - Simplified model:
    - reduced computational time
    - account for neighbouring readout electrodes



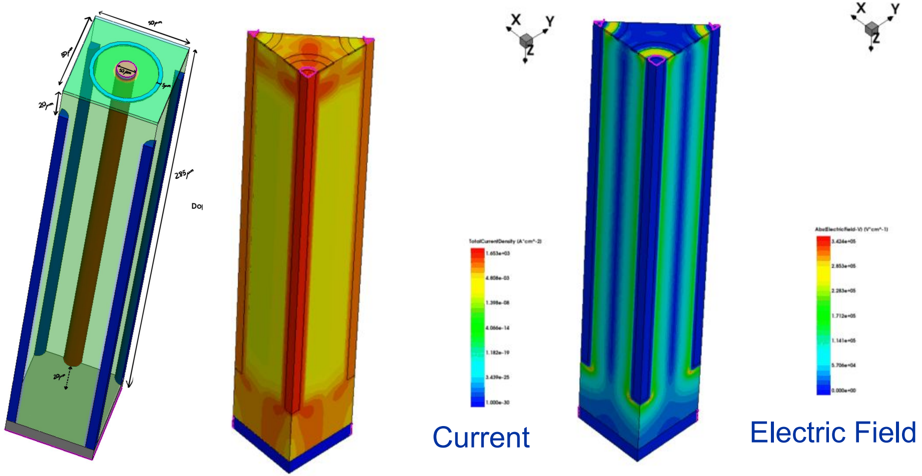


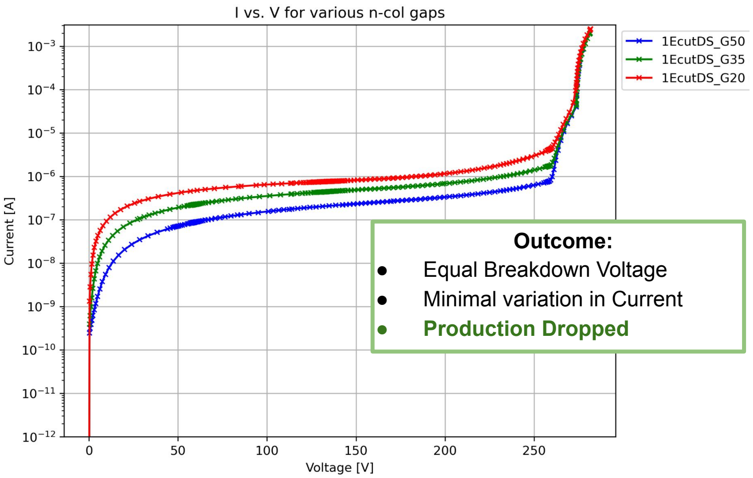
OS (simplified)

Simulations: TCAD

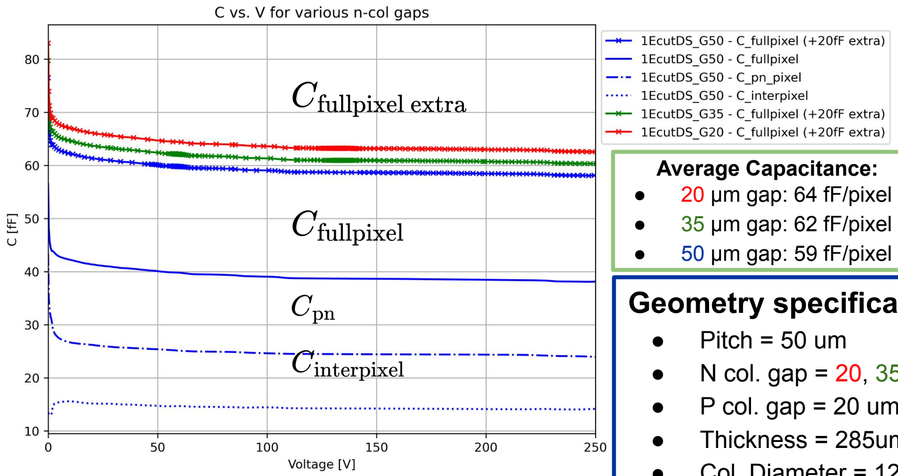
Double Sided: under n-column gap variation

- **Study:**
  - Multiple under n-column gaps considered
  - For further details see this presentation
- **Aim:**
  - Verify breakdown location within pixel
  - Study influence of shorter/larger n columns





Outcome:
- Equal Breakdown Voltage
- Minimal variation in Current
- **Production Dropped**



Average Capacitance:
- 20 μm gap: 64 fF/pixel
- 35 μm gap: 62 fF/pixel
- 50 μm gap: 59 fF/pixel

Geometry specifications:
- Pitch = 50 um
- N col. gap = 20, 35, 50 um
- P col. gap = 20 um
- Thickness = 285um
- Col. Diameter = 12 um

Simulations: TCAD

One Sided: Isolation mechanisms

- **Study:**
  - ***P-stop*** vs ***P-spray***
  - Influence of doping dosage
- **Aim:**
  - Determine benefits of each isolation mechanism

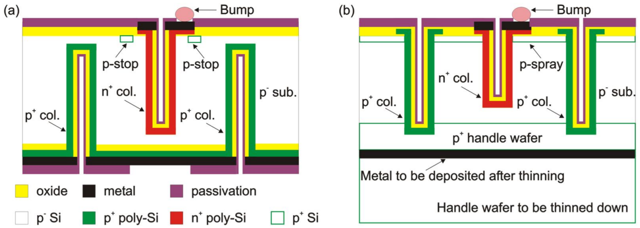
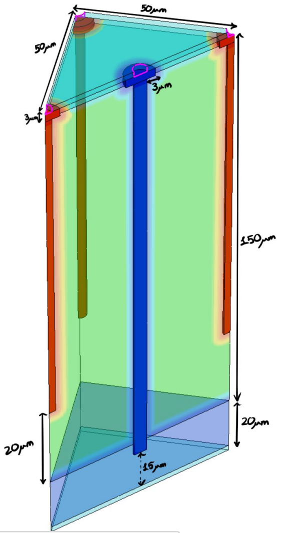
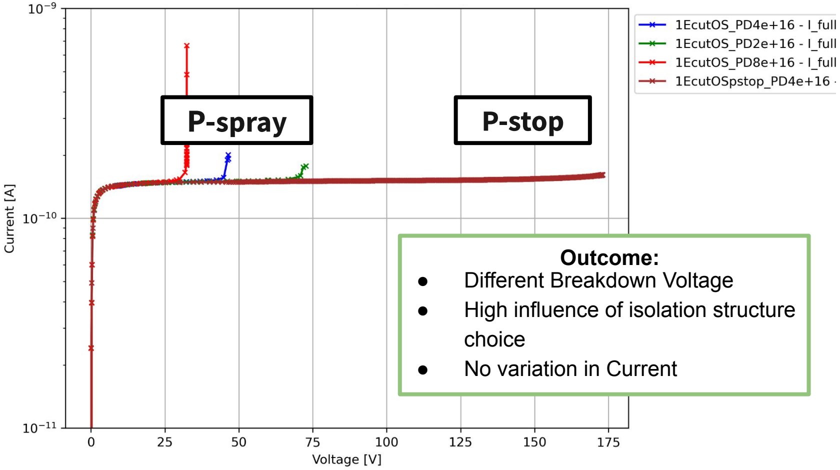


Figure 1 Schematic cross-sections of small pitch 3D sensors: (a) double-sided, and (b) single-sided.

G.F. Dalla et al. PoS (Vertex 2016) 028



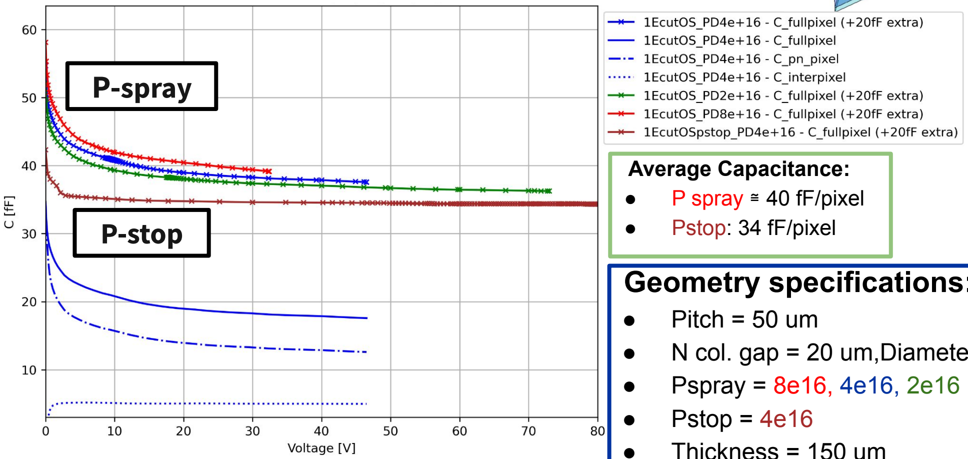
I vs V



Outcome:

- Different Breakdown Voltage
- High influence of isolation structure choice
- No variation in Current

C vs V



Average Capacitance:

- P spray ≅ 40 fF/pixel
- Pstop: 34 fF/pixel

Geometry specifications:

- Pitch = 50 um
- N col. gap = 20 um,Diameter = 5 um
- Pspray = 8e16, 4e16, 2e16
- Pstop = 4e16
- Thickness = 150 um

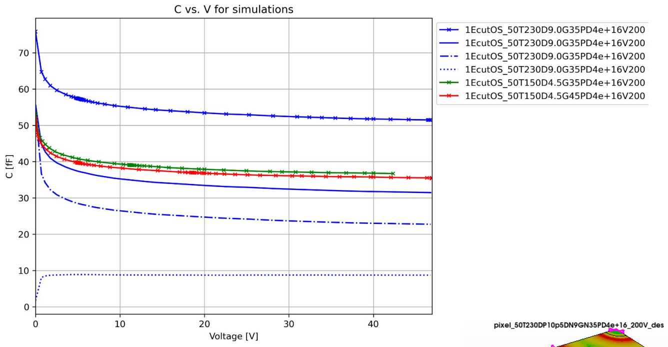
Simulations: Status and Plans

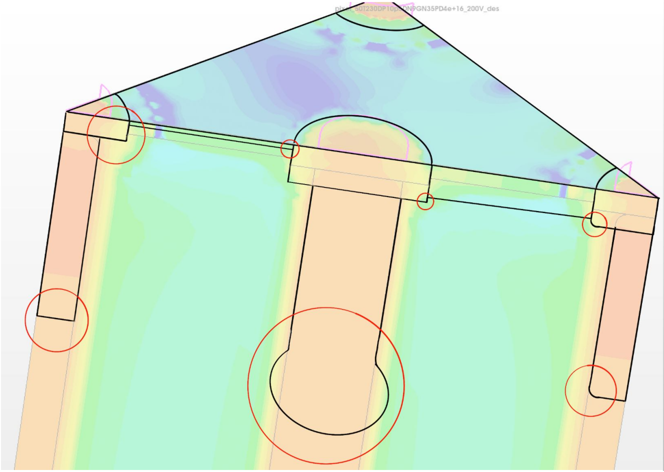
Simulation status:

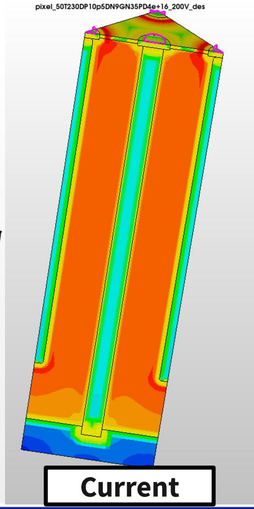
- <u>**Gap under n-columns variation:**</u> No influence in breakdown voltage, similar current and capacitance. Breakdown most likely due to surface effects and gap of p-column *(Double Sided model)*
- <u>**Isolation structures:**</u> Higher breakdown voltage and lower capacitance with p-stop than p-spray. *(Single Sided model)*

Recent and upcoming studies:

- <u>**Surface effects and isolation structures**</u>***:*** improvements seeking lower capacitance, pushing breakdown voltage…
- **Inform productions to meet expected sensor performance:** using feedback from SINTEF for model accuracy





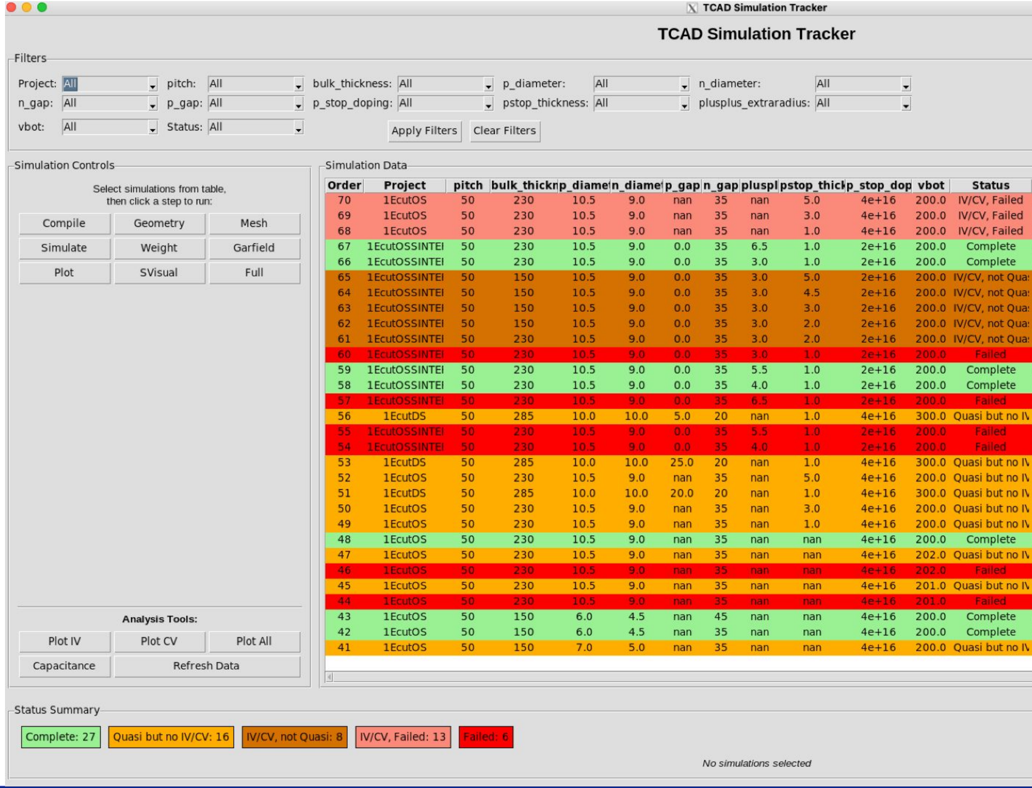


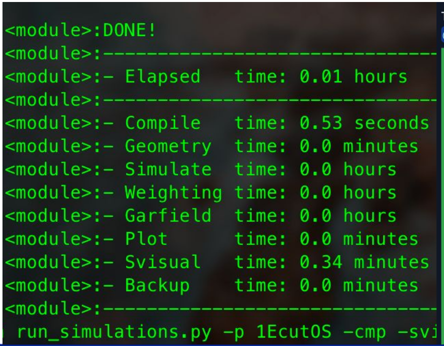
Simulations: Status and Plans

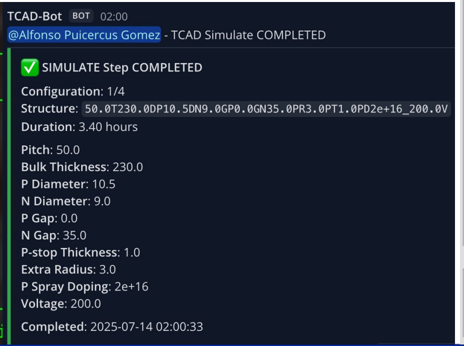
Overall Simulation Pipeline

Further improvements:

- Custom GUI and mattermost bot for planned simulation chain: easy visualisation of simulation parameters, projects, status notifications…





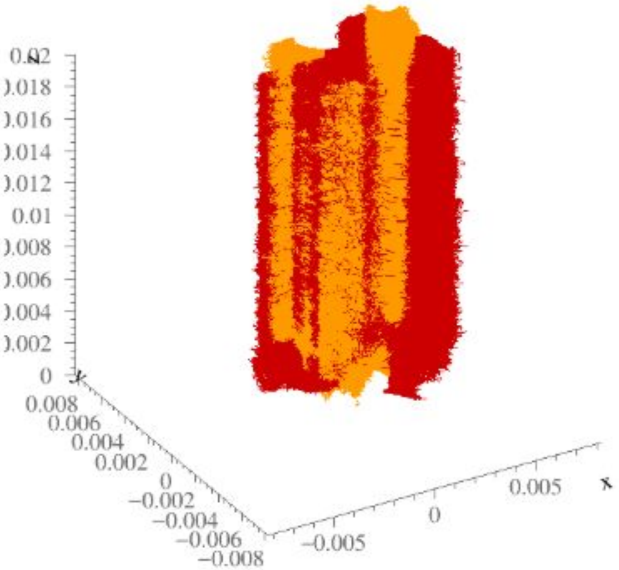


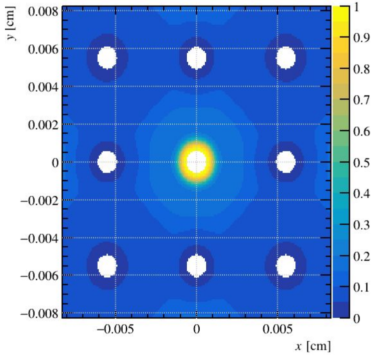
Simulations: Status and Plans

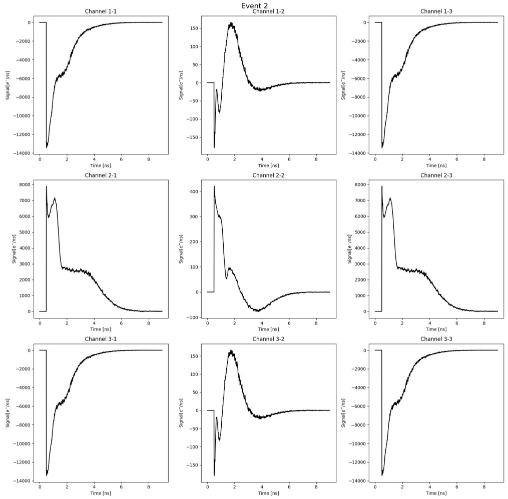
Garfield++

Progress:

- Able to place tracks at chosen or random locations+angles
- Simulation scripts ready to be used
- Some improvements to be made on Garfield++ for complete usability and accuracy



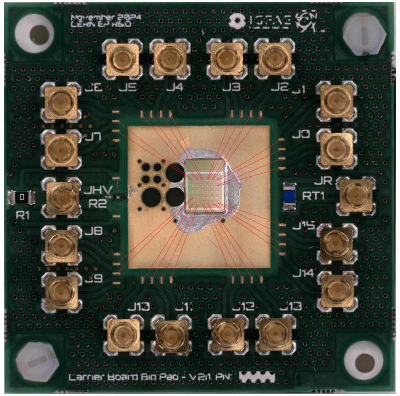


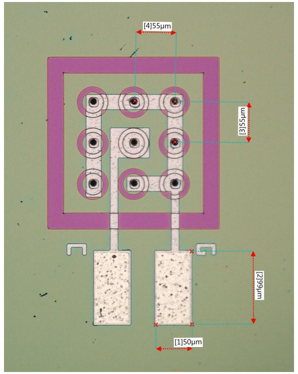


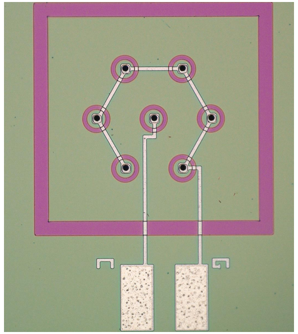
Characterisation

Planning

- **Structures from RD50 CNM fast timing 3D**
  - Already studied by other group see DRD3 Leena's talk
  - Complement the study of the signal development and timing as function of track angle
  - To be used to validate the simulation pipeline, in particular Garfield++ response
- **Wire bonding done in some structures already.**
- **Test beam using the OPTIMA boards integrated to TPX4 telescope.**
- **Irradiation campaign completed last week. IVs and wirebonding to be done, together with inclusion in next testbeam**







Special thanks to CNM for providing valuable support with a 3D double-sided TCAD model and for producing the sensors currently under study in our lab.

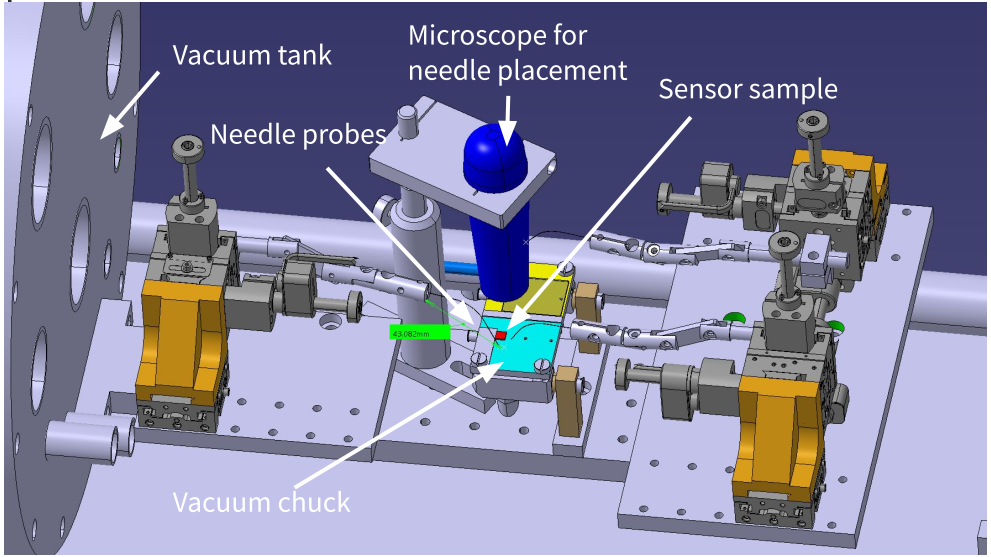
Characterisation

Setups

- **Within WP1.1, commissioning our own characterisation set-ups**: IV-CV, laser deposition, source measurements, OPTIMA / 16 channel board, test-beam telescope
- **Multiple of these set-ups exist at CERN →** idea is to **commission dedicated set-ups for the 100s of test structures** being produced within WP1.1 to **tailor characterisation process** to our needs and **optimise the time taken** per sample

IV/CV set-up

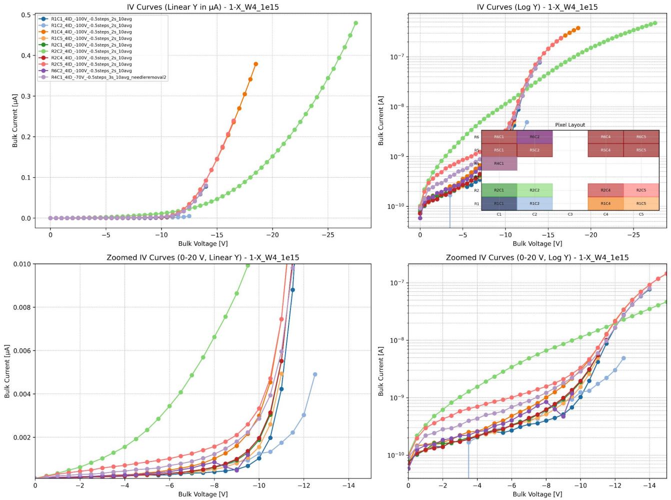
- Needles on motion stages for fast sample replacement and reproducibility inside a controlled environment.

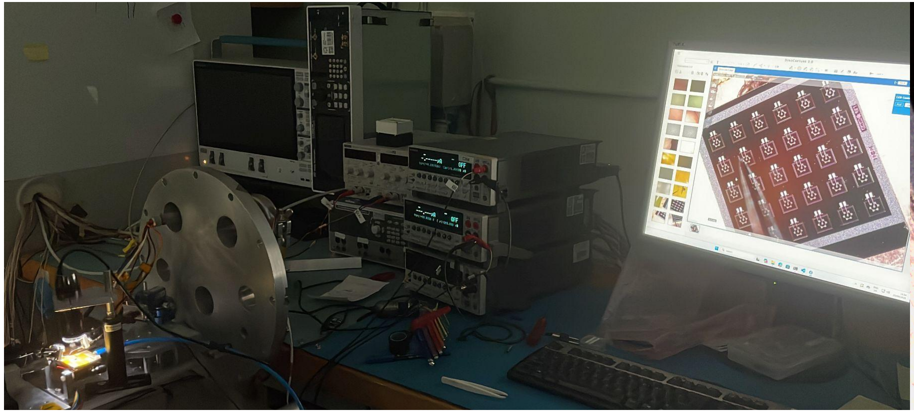


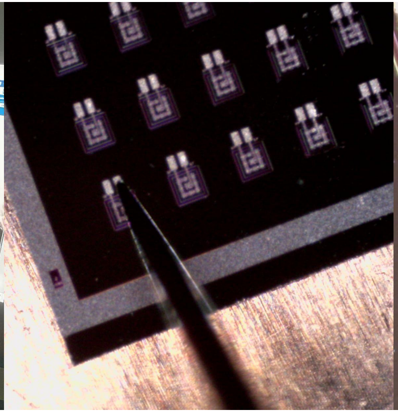
Characterisation

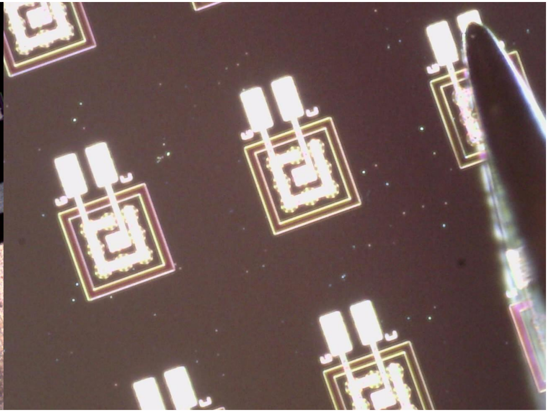
IV/CV set-up

- **First IVs taken for samples sent to irradiation:**
  - Single pixels 1E and Hexagonal geometry
  - Interconnected pixel matrices 1E geometry
- **To be characterised post irradiation**
  - Setup being commissioned with cooling and monitoring





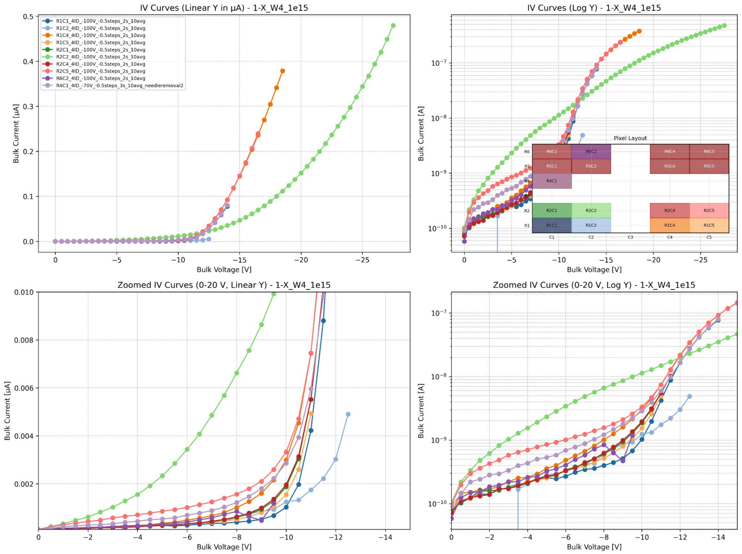


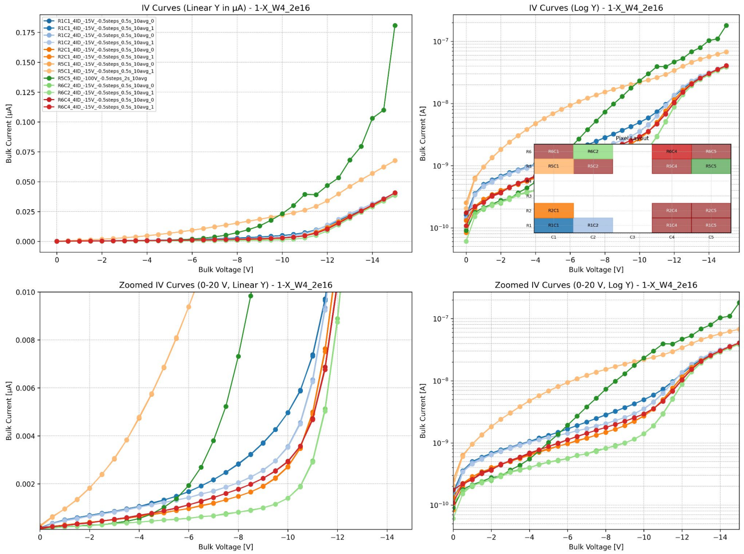


Characterisation

IV/CV set-up

- **First IVs taken for samples sent to irradiation:**
  - Significant pixel-to-pixel variation in IVs
  - Likely due to bad production, other groups also observed such behaviour

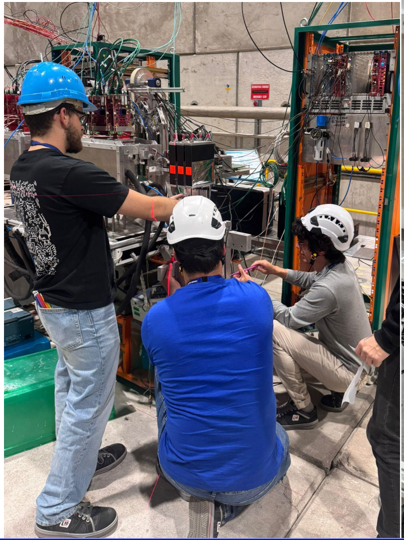


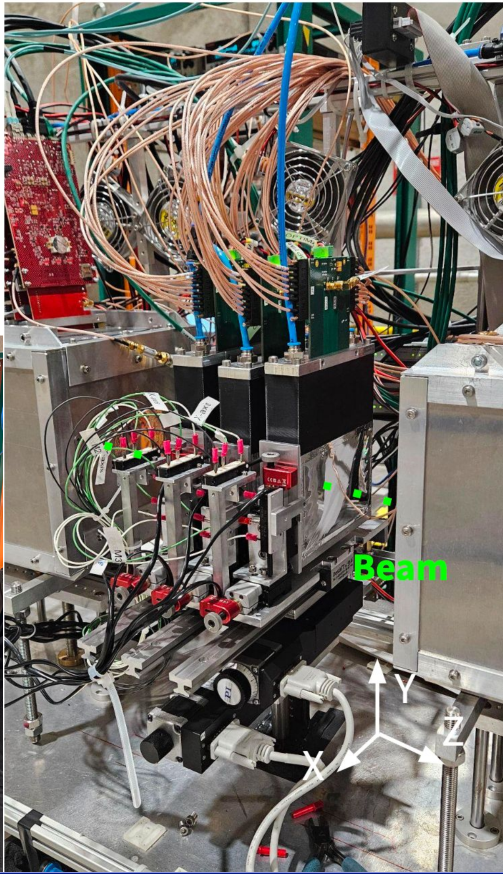


Characterisation

Test Beam May, July, October 2025

- **Test beam campaigns with Timepix4 telescope.**
- **Setup:**
  - Optima Boards on back stage
  - PCBs with **Planar, 3D, LGAD**, **SiEM** sensors
- **Issues encountered:**
  - Software: SAMPIC triggers and configuration
  - Hardware: Spatial and timing alignment
- **Outcome:**
  - Runs of data for 3D sensors for analysis:
    - Bias scan
    - Angle scan
  - To be analysed soon, aiming for:
    - Efficiency studies
    - Signal formation and shape vs angle

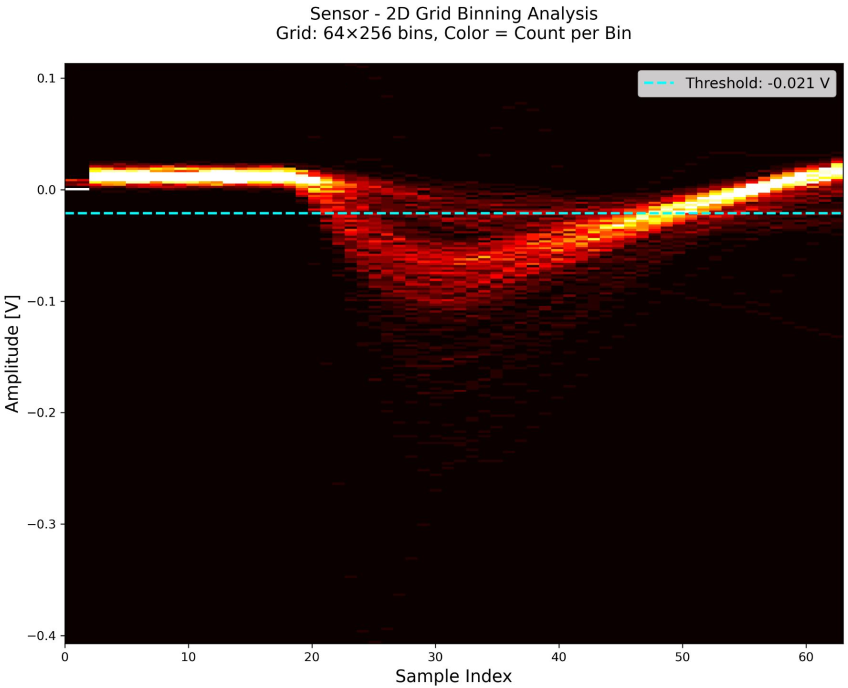


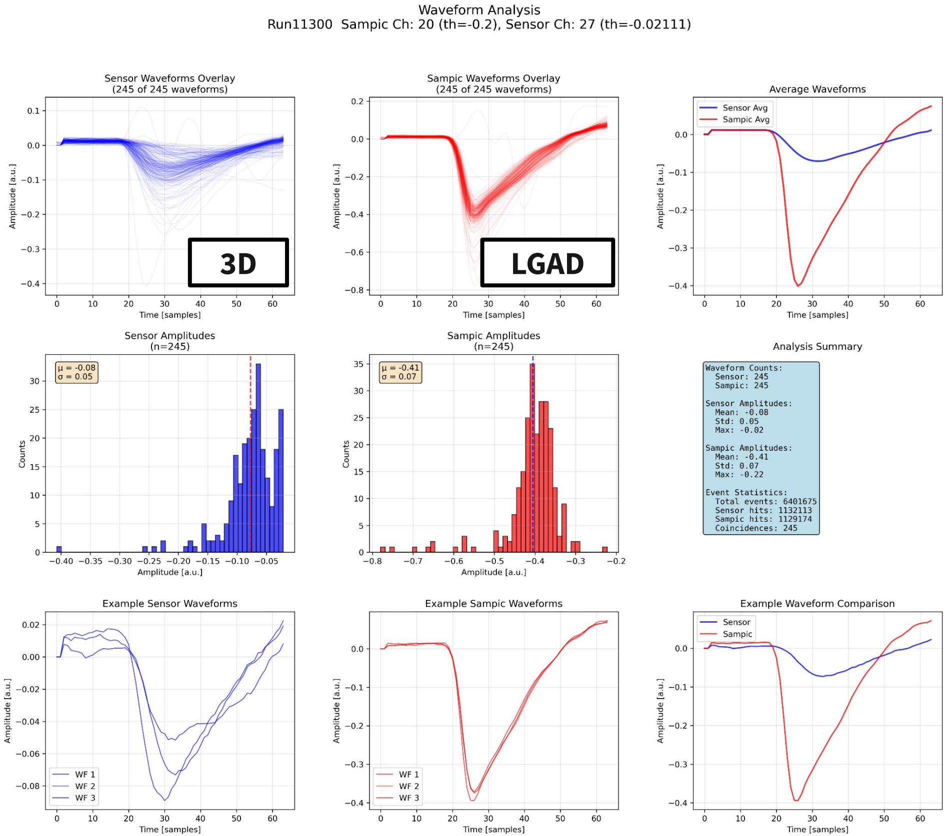


Characterisation

Test Beam July 2025

- **Some early plots:**





Outlook

Summary

- **Sensor Design & Fabrication:**
  - Simulation-driven R&D, optimization of column geometry, thickness, and isolation structures
  - Double-sided and single-sided explored
  - Focusing on single-sided *SINTEF*
- **Simulation Studies:**
  - Parametrized TCAD models and Garfield++ simulations are in an advanced stage of development.
  - Full automated simulation chain in works.
- **Characterisation and Campaigns:**
  - IV/CV, laser, and source setups being commissioned
  - Last test beam data (October 2025) expected to be good for some first results on 3Ds

Outlook

Future Work

- **Simulation Pipeline Extension:**
  - Further parameter variation to drive R&D
  - Incorporate post-irradiation effects
  - Validate signal formation using Garfield++
- **Fabrication and Testing:**
  - Within 12-14 months, large and wide variety of samples to be characterized
- **Upcoming:**
  - Test Beam data analysis
  - Irradiated sensor characterization
- **Final Goal:**
  - Build a full chain from TCAD → Garfield++ →…→ experimental validation
  - Deliver practical sensor design recommendations for VELO Upgrade II and beyond

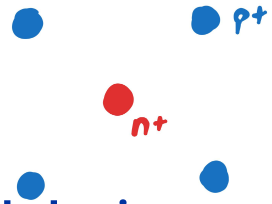
Thank you!

Backup slides

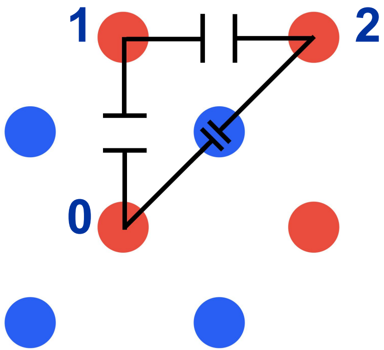
Backup

3D Sensor: Modelling and Approach

1E Geometry

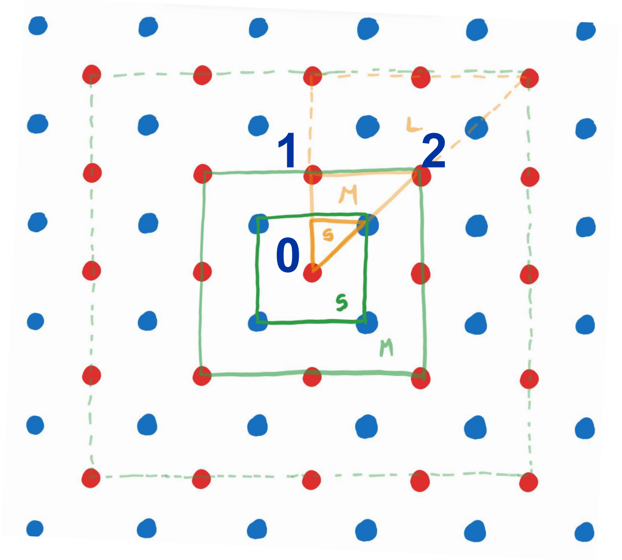


Interested in pixel behaviour *considering neighbors.*



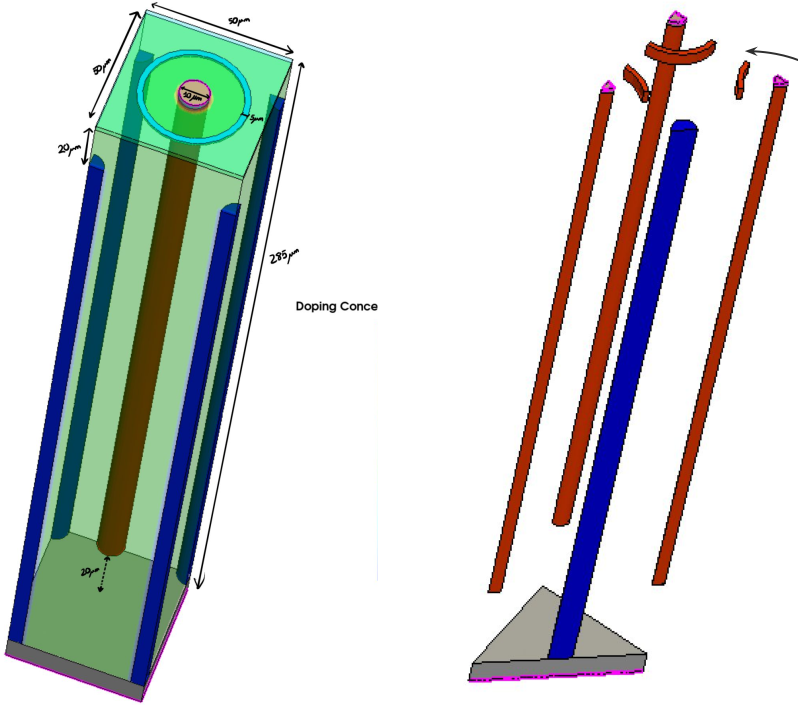
Constraints:

- Computational time is large
- Account for neighbor effects



Backup

3D Sensor: Double Sided (DS



The 3D sensor model was constructed following the CNM reference, with dimensions and features informed by the detailed specifications presented in Ò. Ferrer Naval's PhD thesis (Universitat Autònoma de Barcelona, 2024).

Characteristics:(Certain features of structure might be exaggerated for visualisation purposes)

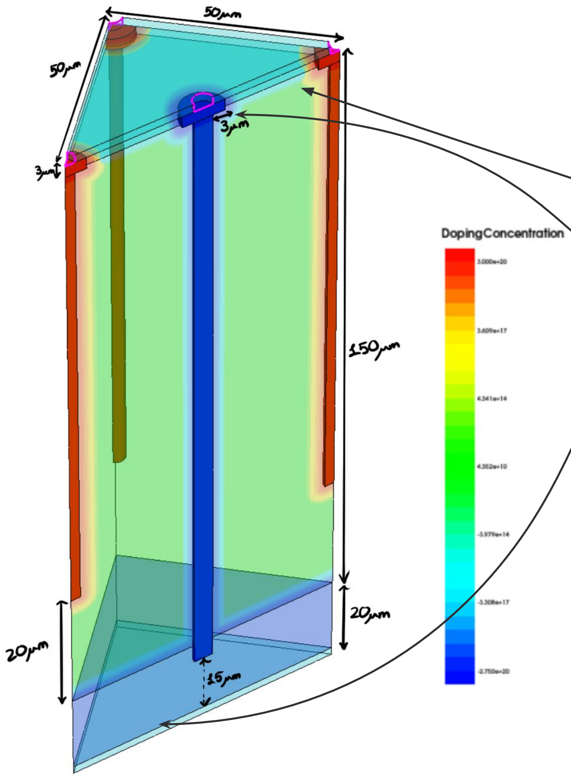
- Columns come from ***both*** sides
- p-stop ring around n cols.
- Metal at the bottom to bias p col.

Difficulties:

- Acute angles and small areas for n cols.
- P-stop ring definition influences greatly.

Backup

3D Sensor: One Sided - Single Sided (OS)



Characteristics:(Certain features of structure might be exaggerated for visualisation purposes)

- Columns come from ***same*** side
- p-spray covering surface.
- N++ and p++ on top of cols.
- P++ region at the bottom to bias

Difficulties:

- Acute angles and small areas for n cols.
- P-spray definition influences greatly.

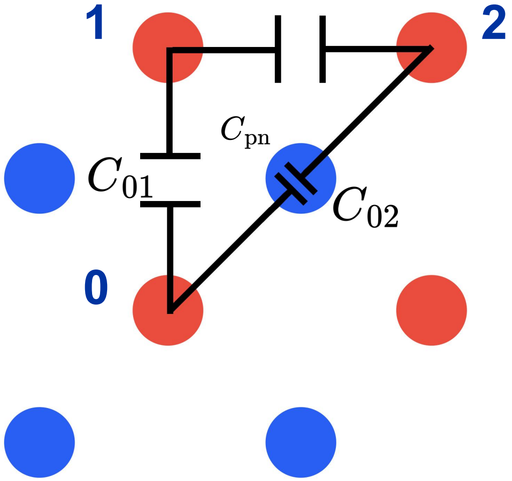
Backup

3D Sensor: Capacitance

Contributions:

- C_{pn} = Bulk capacitance within the triangle
- $C_{\text{interpixel}}$ = from neighbouring columns

$$= C_{01} + C_{02}$$



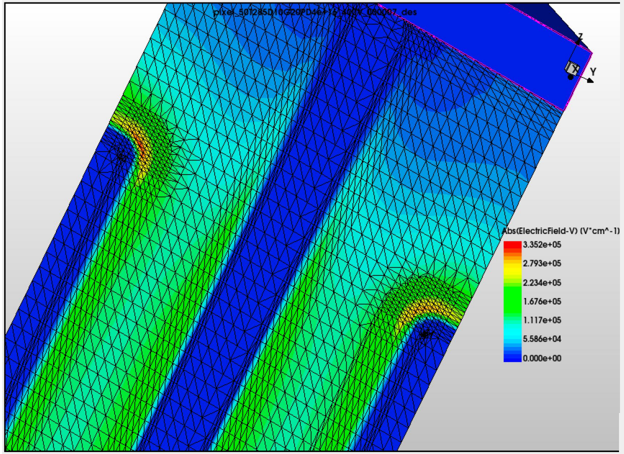
$$C_{\text{fullpixel}} = 2C_{pn} + 4C_{\text{interpixel}}$$

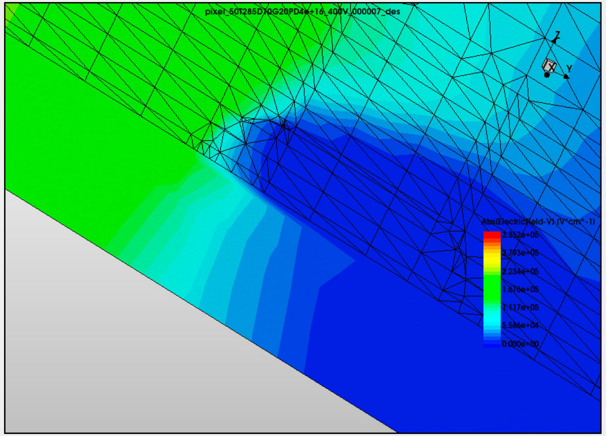
Final 1E pixel capacitance:

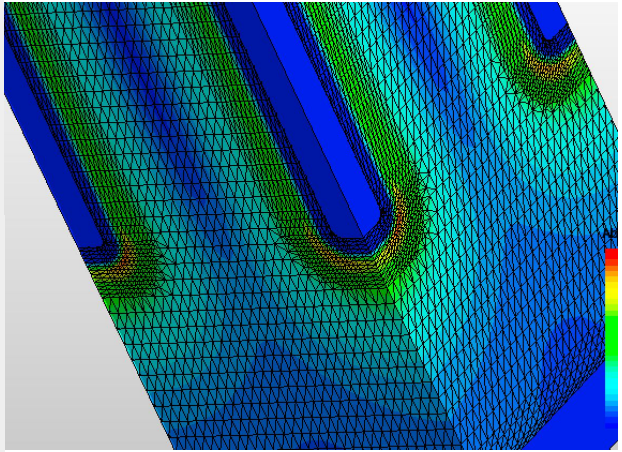
$$C_{\text{fullpixel extra}} = (2C_{pn} + 4C_{\text{interpixel}}) \times 1.2$$
$$= (2C_{pn} + 4C_{\text{interpixel}}) + 20\ [fF]$$

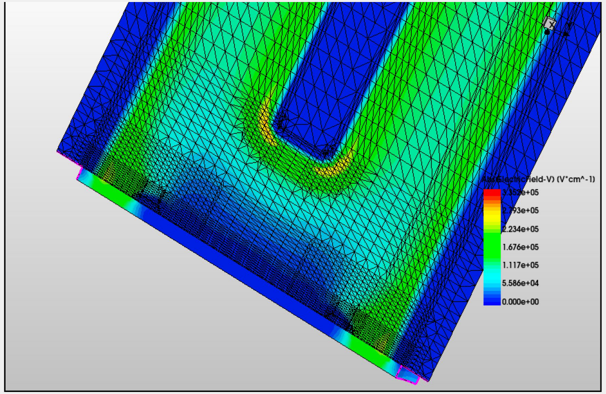
(Same papers state 20% extra contribution from geometry elements involved or approx 20fF)

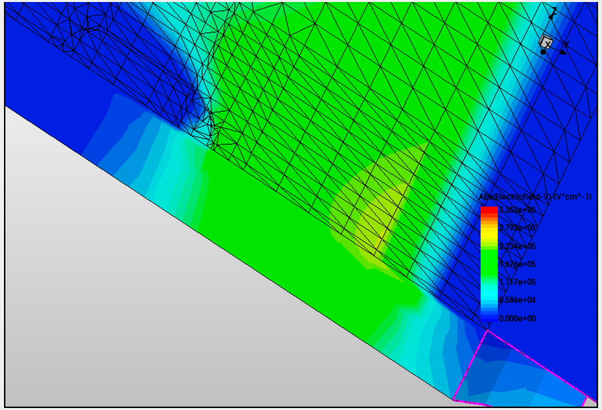
Simulations: TCAD







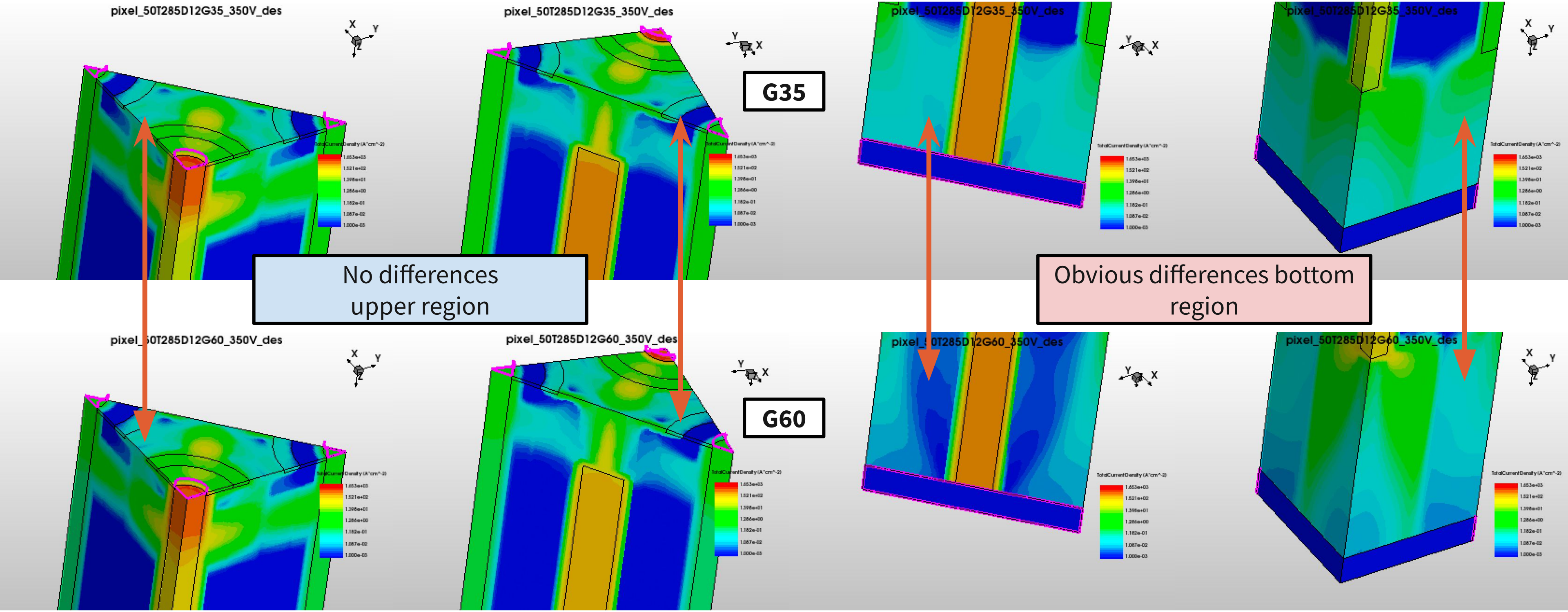




Simulations: TCAD

Double Sided: under n-column gap variation

Plots showing TotalCurrentDensity (same scale in legend)

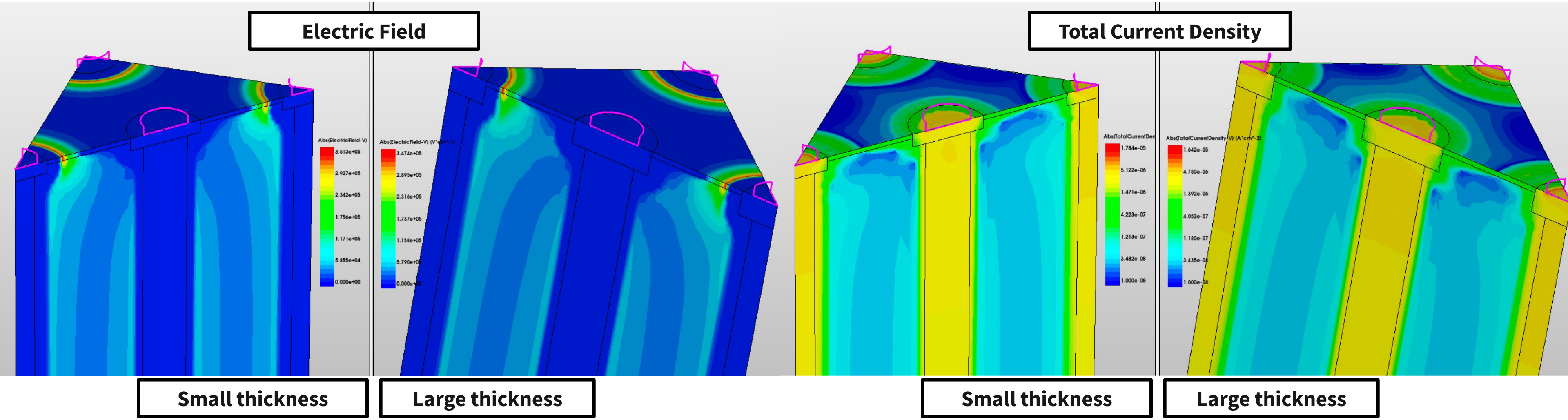


=> Breakdown occurs top of sensor <=

CERN EP R&D university of groningen

Simulations:Status and Plans

One Sided: n++ and p++ thickness



Preliminar Outcome:

For thicker n++ and p++ regions:

- Field lines spread more, not concentrating as strongly → lower chance of breakdown?

Disclaimer

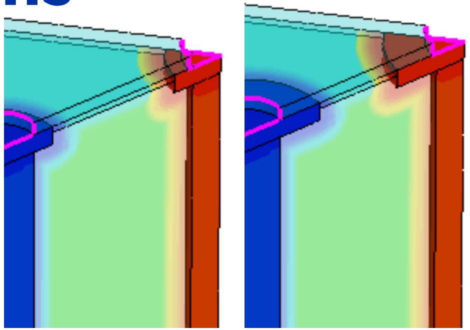
The upcoming models and results are still under construction 🚧.

Handle with care — and patience.

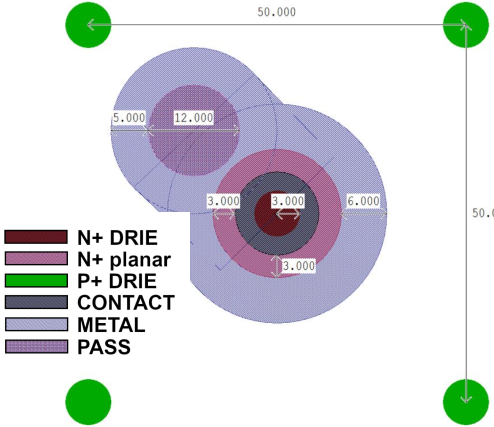
Simulations:Status and Plans

One Sided: n++ and p++ extra radius

- **Study:**
  - Column diameter kept constant
  - Variation of extra radius such that R_n++ = R_p++
- **Aim:**
  - Influence on E field and breakdown

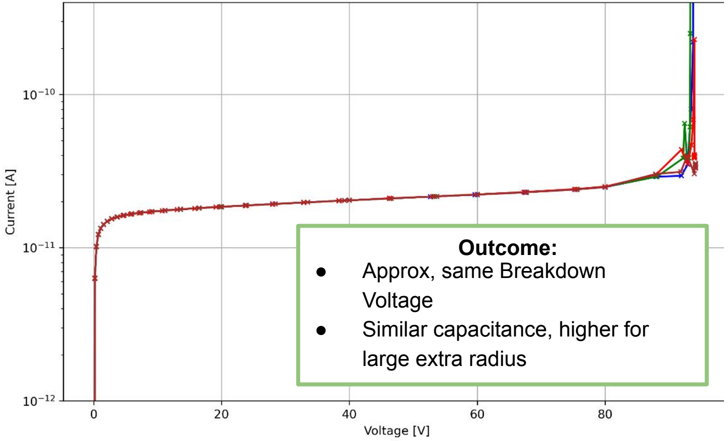


Small extraradius | Large extraradius



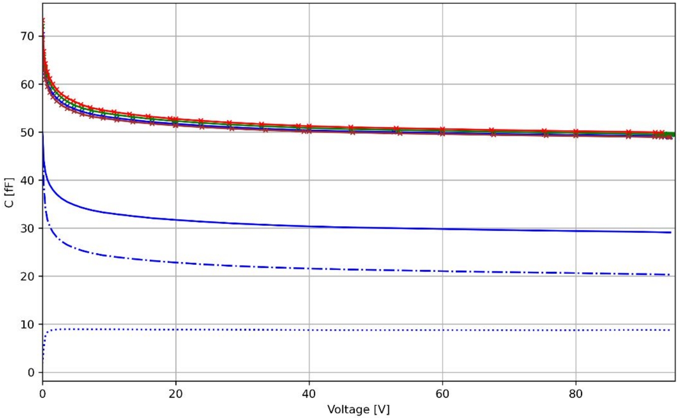
M. Povoli et al., "Sintef Overview," *VELO U2 Workshop*, CERN, Nov. 2024

I vs V



Outcome:
- Approx, same Breakdown Voltage
- Similar capacitance, higher for large extra radius

C vs V

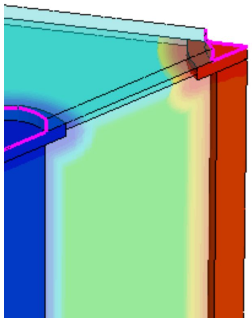


Geometry specifications:
- Pitch = 50 um
- Thickness = 230 um
- Gap p col., n col.= 0 , 35 um
- Diam. p col., n. col. = 10.5 , 9 um
- T_p++ = T_n++ = 3 um
- R_p++ = R_n++ = [3, 4, 5.5, 6.5] um
- Pspray = 1 um +diffusion, doping: 2e16

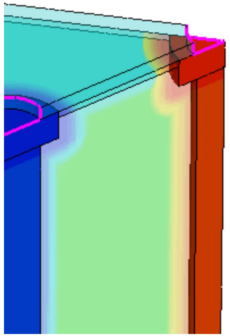
Simulations:Status and Plans

One Sided: n++ and p++ thickness

- **Study:**
  - P-spray thickness kept constant
  - Variation of thickness T_n++ = T_p++
- **Aim:**
  - Influence on E field and breakdown



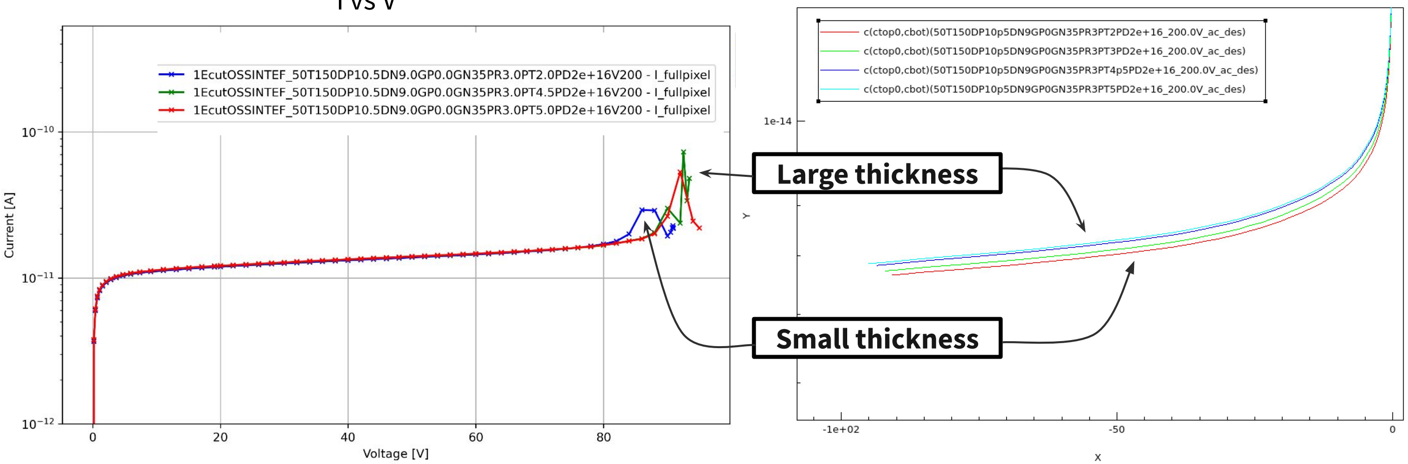
Small thickness



Large thickness

I vs V

C vs V



Outcome:

- Slightly Different Breakdown Voltage
- Higher breakdown voltage and capacitance for larger thickness

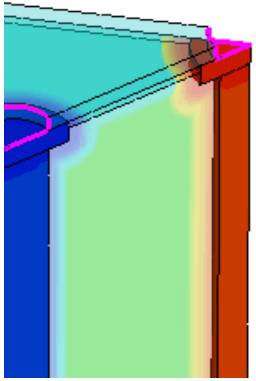
Geometry specifications:

- Pitch = 50 um
- Thickness = 150 um
- Gap p col., n col.= 0 , 35 um
- Diam. p col., n. col. = 10.5 , 9 um
- T_p++ = T_n++ = [2, 3, 4.5, 5] um
- R_p++ = R_n++ = 3 um
- Pspray = 1 um +diffusion, doping: 2e16

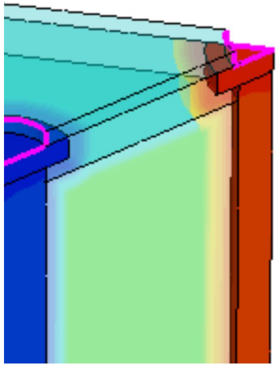
Simulations: Status and Plans

One Sided: p-spray thickness

- **Study:**
  - n++ and p++ thickness kept constant
  - P-spray thickness varied
- **Aim:**
  - Influence on E field and breakdown

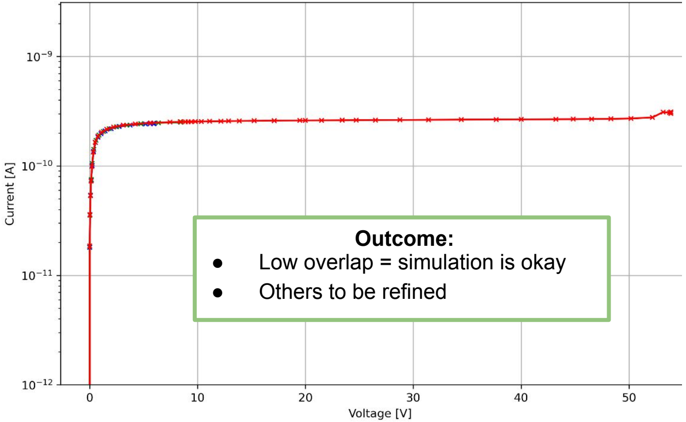


Small thickness

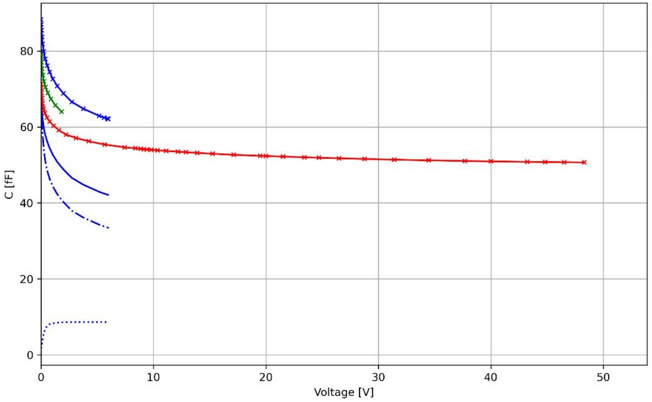


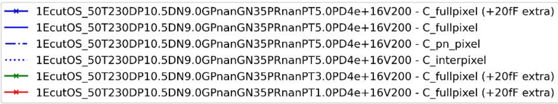
Large thickness

I vs V



C vs V





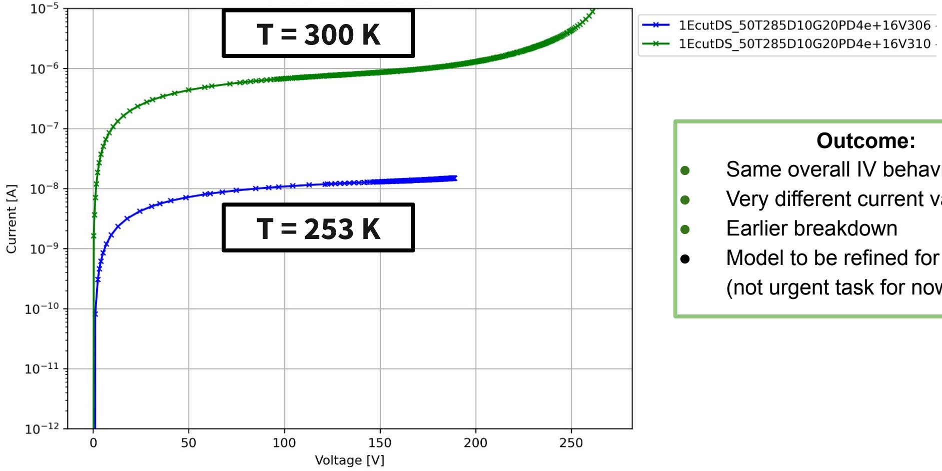
Geometry specifications:

- Pitch = 50 um
- Thickness = 150 um
- Gap p col., n col.= 0 , 35 um
- Diam. p col., n. col. = 10.5 , 9 um
- T_p++ = T_n++ = 3 um
- R_p++ = R_n++ = 3 um
- Pspray = [1, 3, 5] um +diffusion, doping: 4e16

Simulations: TCAD

Double Sided: Temperature variation

- **Study:**
  - Influence of temperature on simulation
    - Previous simulations with 300K (27°C)
    - Changed to 253K (-20°C)
- **Aim:**
  - Test physics models and math solvers used in simulation
  - Verify model capability at low temperatures for future studies



Outcome:
- Same overall IV behaviour
- Very different current value
- Earlier breakdown
- Model to be refined for low T (not urgent task for now)

- **To be improved…**
  - Test with One Sided
  - Modify temperature dependent physics models considered

Simulations: Status and Plans

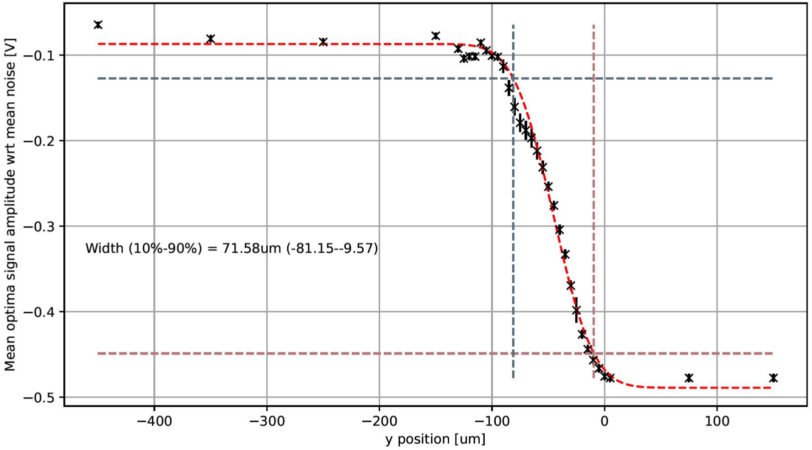
Future

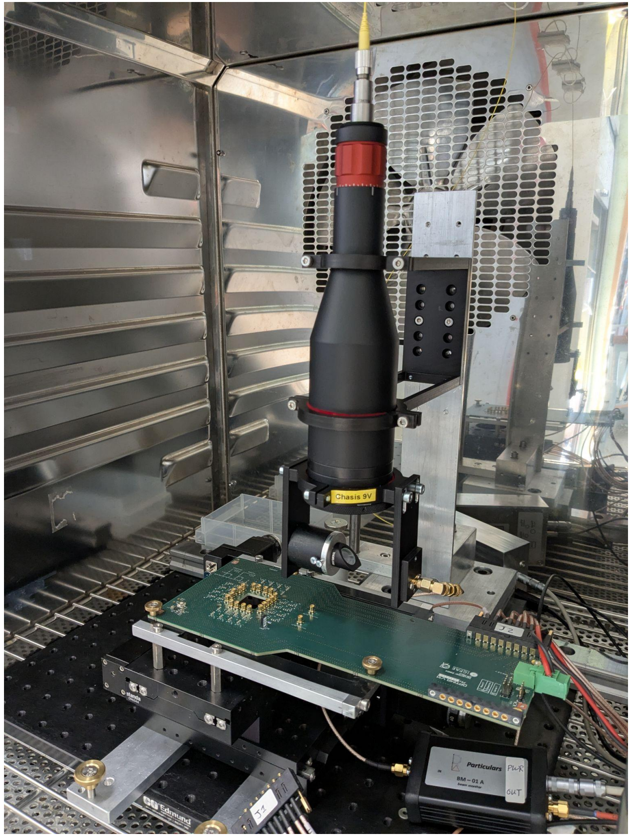
- **TCAD:**
  - Single/One Sided:
    - *Refine model with feedback from SINTEF*
    - *Complete the ongoing studies presented here*
  - Double Sided:
    - *Refine model to then compare simulations to characterization*
  - Common among models:
    - *Further improve meshing to account for all possible parameter variations, surface effects…*
    - *Incorporate radiation damage effects*
    - *Enhancing modeling at low temperatures (not critical for now)*
- **Simulation chain:**
  - Completion of Garfield ++
    - *Perform charge transport and signal induction modeling with Garfield++*
    - *Conduct semi-manual analysis of simulation output data*
  - *Begin with Analog Front End implementation*

Characterisation

Setups

- **Laser (660 nm & 1064 nm) system**
- **Set-up for source and laser tests** of samples using OPTIMA within sealed environment
- **Envisage calibration, in-pixel mapping, time resolution measurements**
- **Currently under commissioning**: focussing measurements for different DUT positions



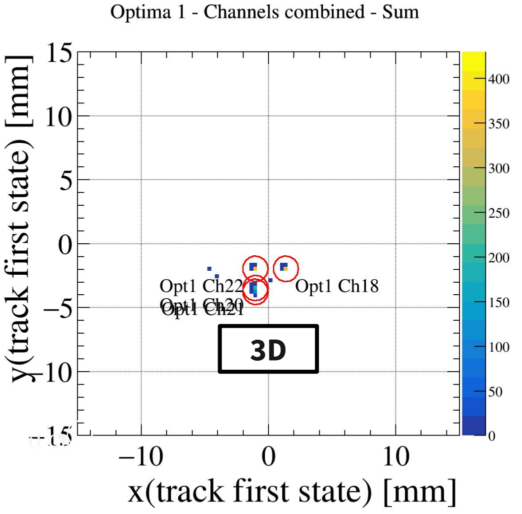


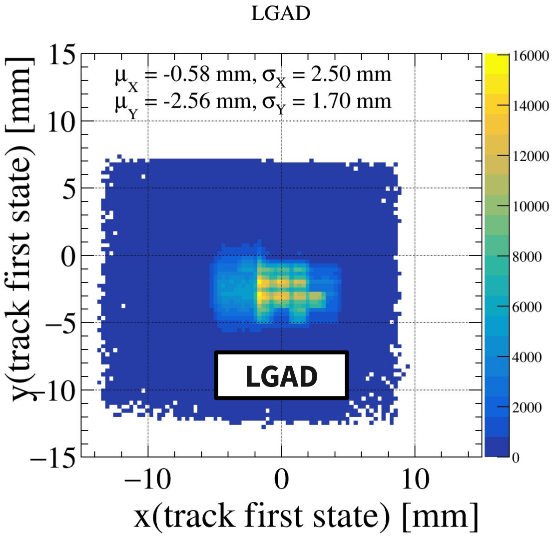
Many thanks to Leena Diehl, Raphael Dumps, and Stephane Detraz

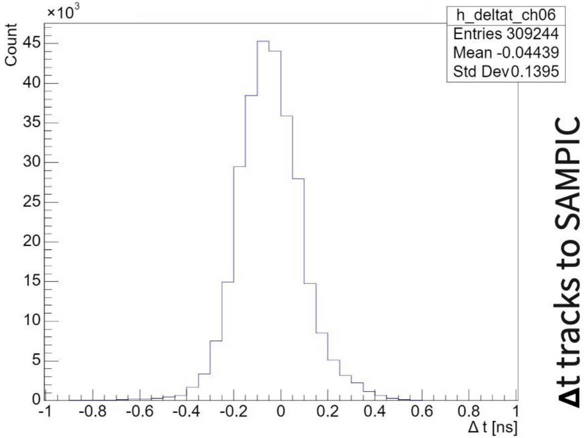
Characterisation

Test Beam July 2025

- **Some plots from operation:**
  - Spatial alignment of samples with the beam
  - Time alignment of tracks on Telescope and hits on sample







Δt tracks to SAMPIC