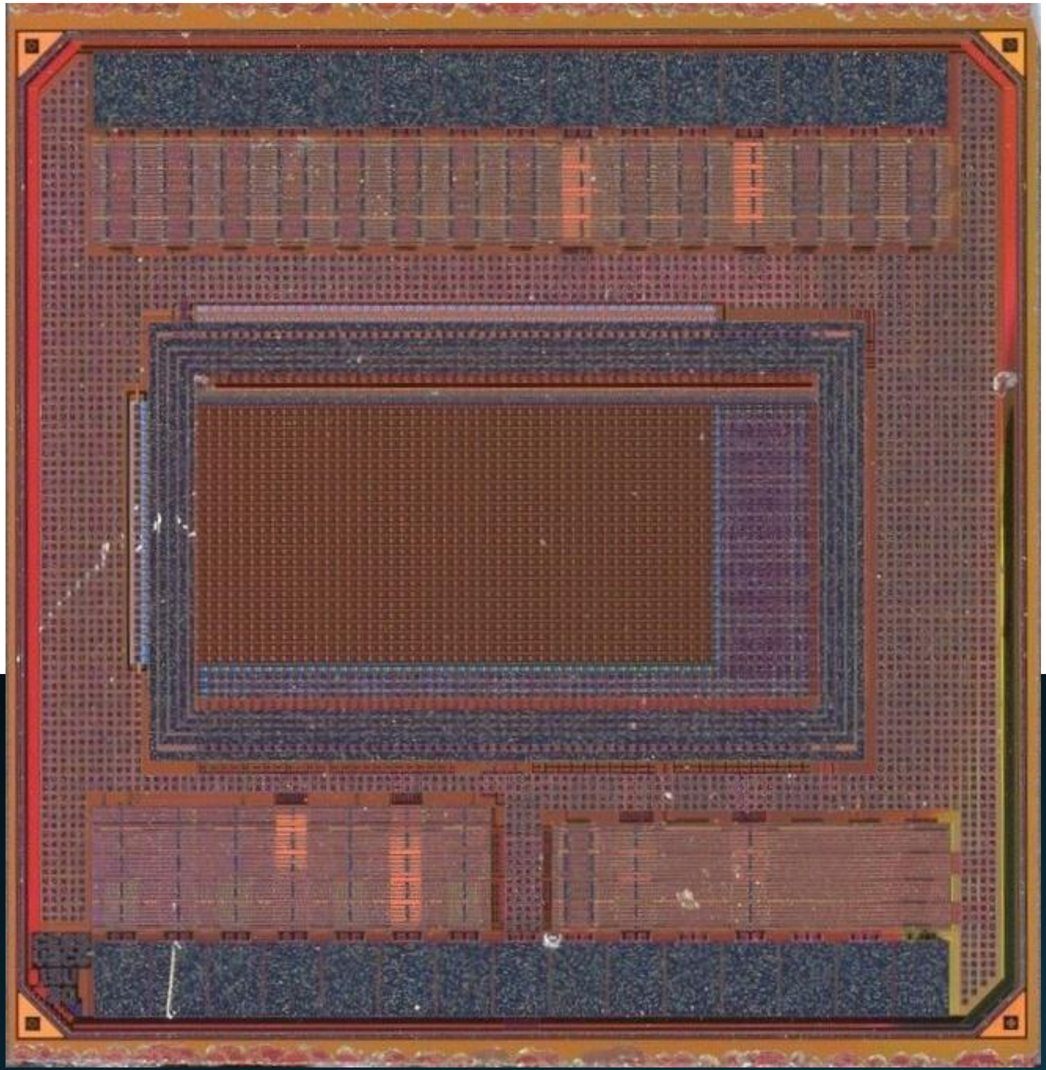
Performance studies of the CE-65v2 MAPS prototype structure

2nd DRD3 week on Solid State Detectors R&D

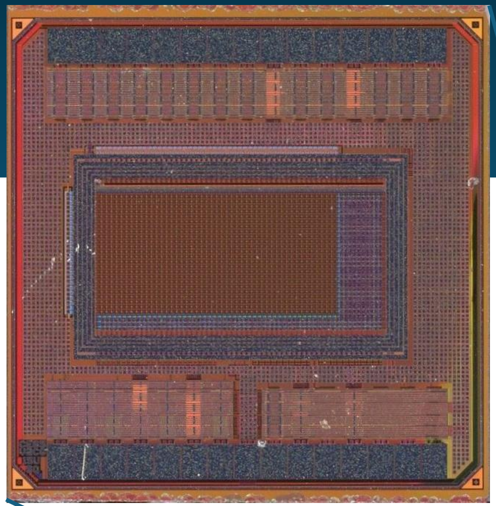


Alessandra Lorenzetti
on behalf of the CE-65 team

Universität Zürich UZH

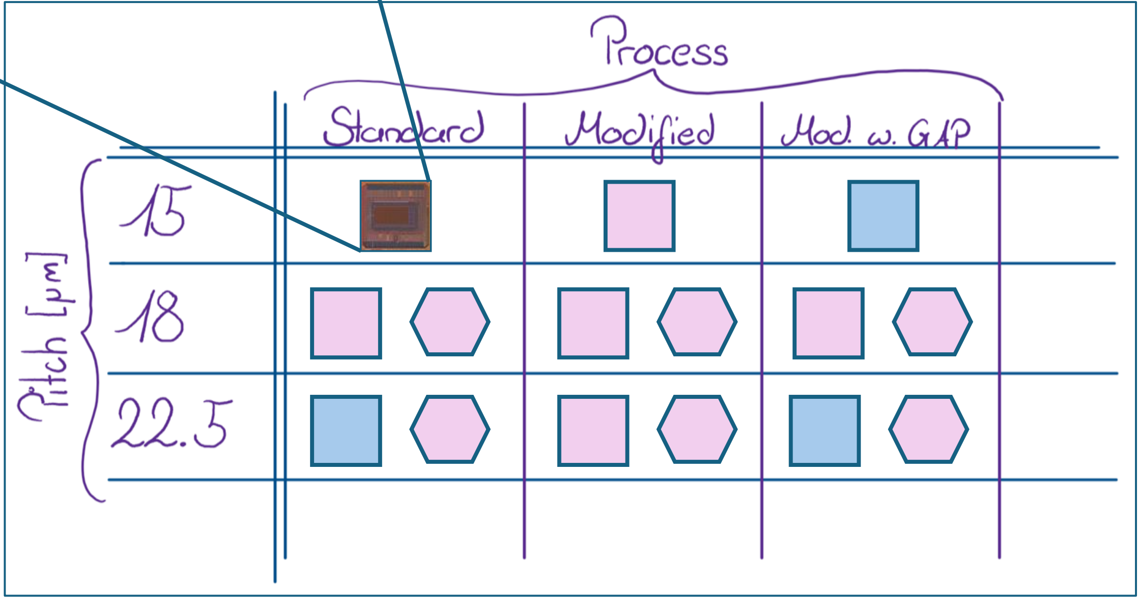
Talk based on poster at Pixel 2024

CE 65 v2



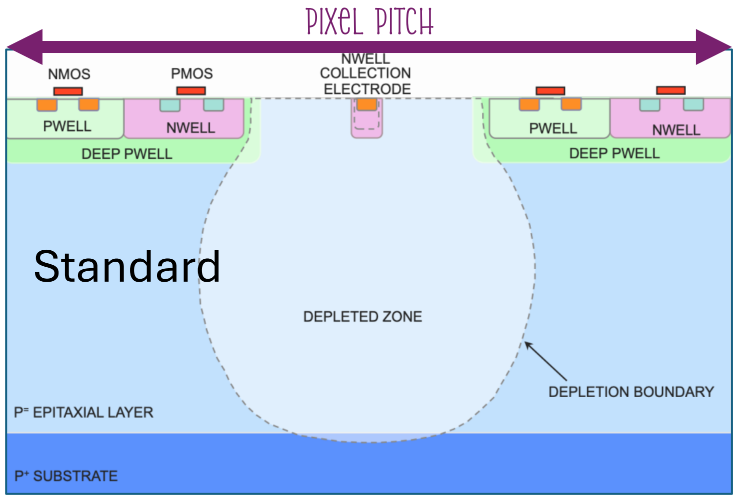
- 65 nm MAPS
- Designed by IPHC
- AC coupling
- Analog rolling shutter readout
- 48x24 pixel
- Different pitches, processes and pixel arrangements

S. Bugiel et al., Charge sensing properties of monolithic CMOS pixel sensors fabricated in a 65 nm technology, NIM-A: Accelerators, Spectrometers, Detectors and Associated Equipment **1040**, 167213 (2022). (DOI)



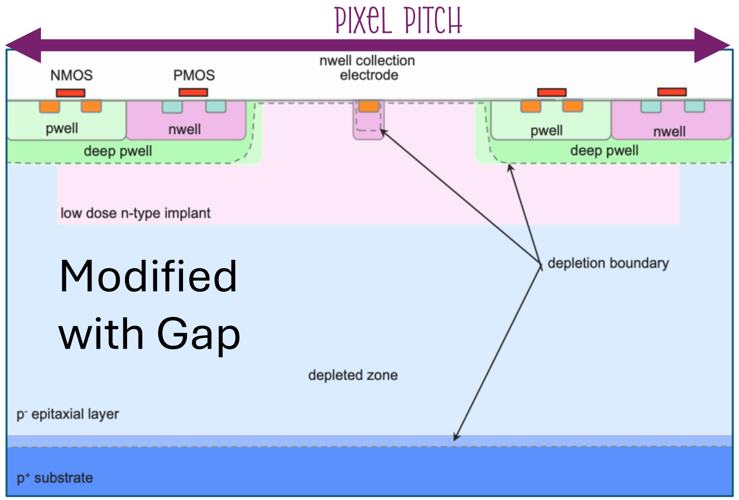
K. Gautam and A. Kumar, Characterisation of analogue MAPS fabricated in 65 nm technology for the ALICE ITS3, NIM-A: Accelerators, Spectrometers, Detectors and Associated Equipment **1068**, 169787 (2024). (DOI)

Different kinds of processes



Faster charge collection

More charge sharing



Undepleted regions at the pixel edges
→ Charge collection is *diffusion-dominated*

- High charge sharing between neighb. Pixels
- Slow charge collection
- ➢ subject to charge trapping, less radiation tolerant

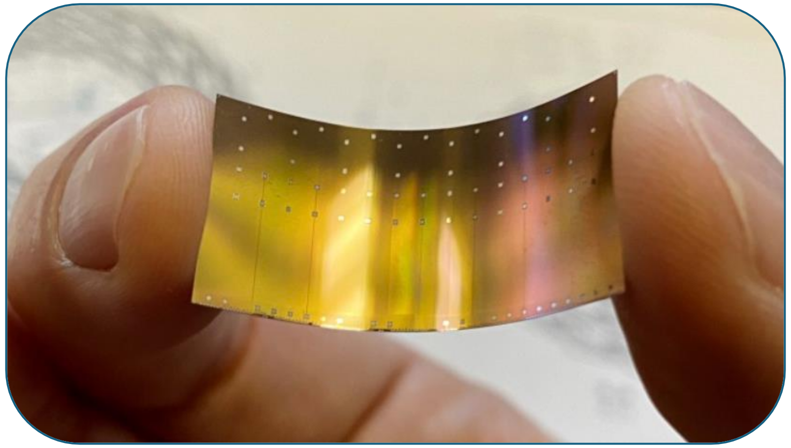
Electric field expands laterally due to gap in low dose n-type implant at pixel edges
→ Charge collection is *drift-dominated*

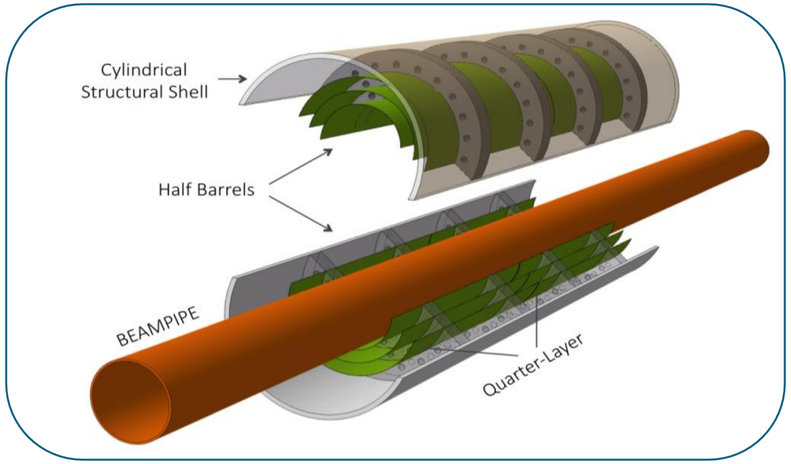
- Low charge sharing
- Even at the edges fast charge collection
- ➢ More radiation tolerant

W. Snoeys et al., Optimization of a 65 Nm CMOS Imaging Process for Monolithic CMOS Sensors for High Energy Physics, in Proceedings of 10th International Workshop on Semiconductor Pixel Detectors for Particles and Imaging — PoS(Pixel2022), Vol. 420 (SISSA Medialab, 2023),

ALICE ITS3

- Upgrade of the Inner Tracking System, installation in 2027-30
- Three innermost layers of ITS2 will be replaced with wafer-scale, thin, bent sensors
- Ultra-light design to minimise multiple Coulomb scattering
- CE-65 originating from ALICE ITS3 R&D, to go beyond ITS3





ALICE Collaboration, link accessed 30.10.2024.

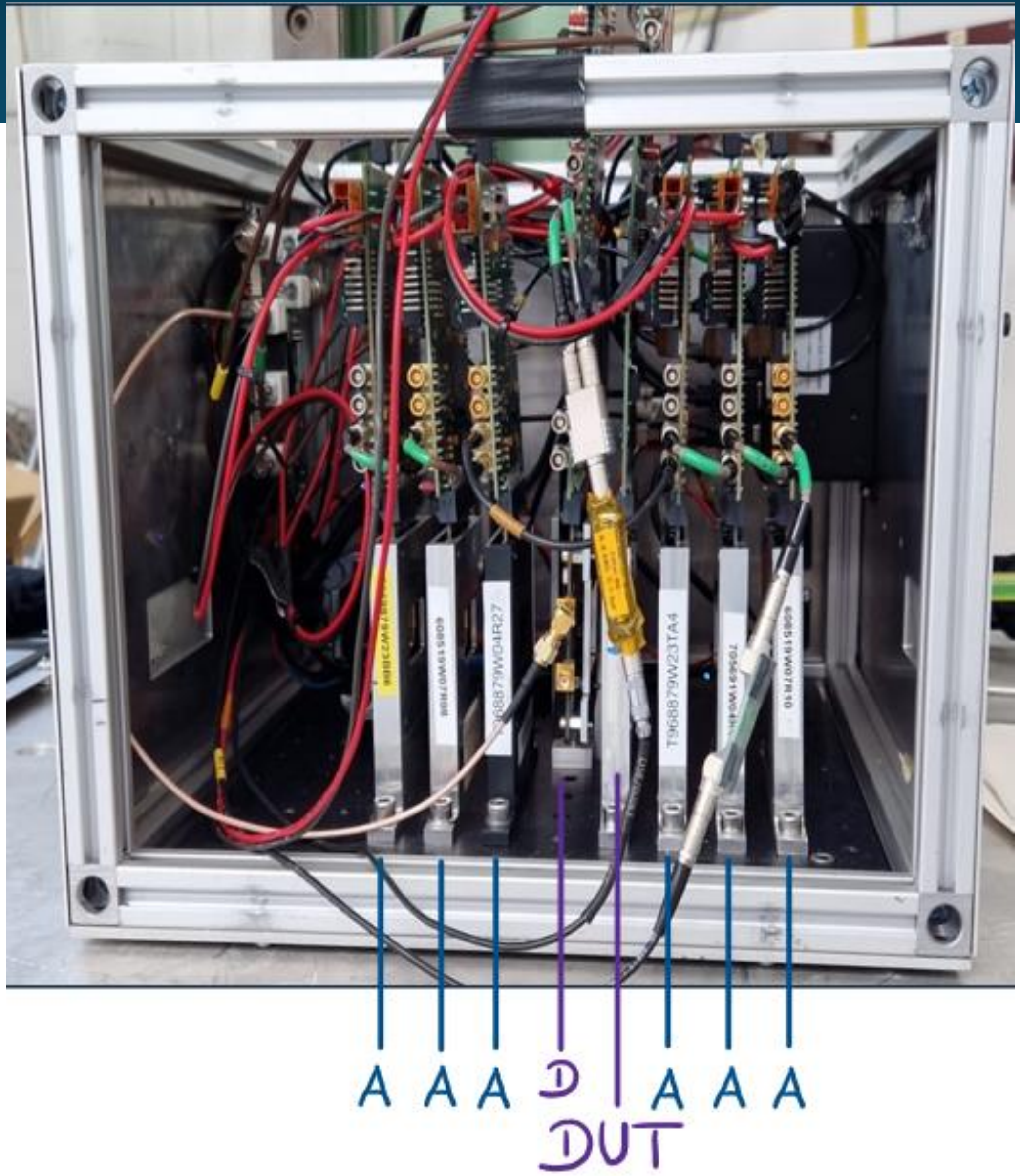
ALICE and FCC?

Requirements	ALICE ITS3	FCC-ee vertex
Sensor spatial resolution	5 µm	3 µm
Material budget per layer [X_0]	0.07 %	< 0.3 %
Radiation tolerance [1MeV n_{eq}/cm^2]	10^{13}	~ 10^{14} per year
First layer radius rmin	19 mm	13.7 mm
Power density	40 mW/cm^2	≲ 50mW/cm^2
Particle hit density in 1st layer	8.5 MHz/cm^2	~ 250 MHz/cm^2

ALICE collaboration, Technical Design report for the ALICE Inner Tracking System 3 - ITS3 ; A bent wafer-scale monolithic pixel detector, (2024).
Full report on the FCC Feasibility Study mid-term review. Scientific Policy Committee - Three-Hundred-and-Thirty-Sixth Meeting, (2023).

Testbeam at CERN SPS

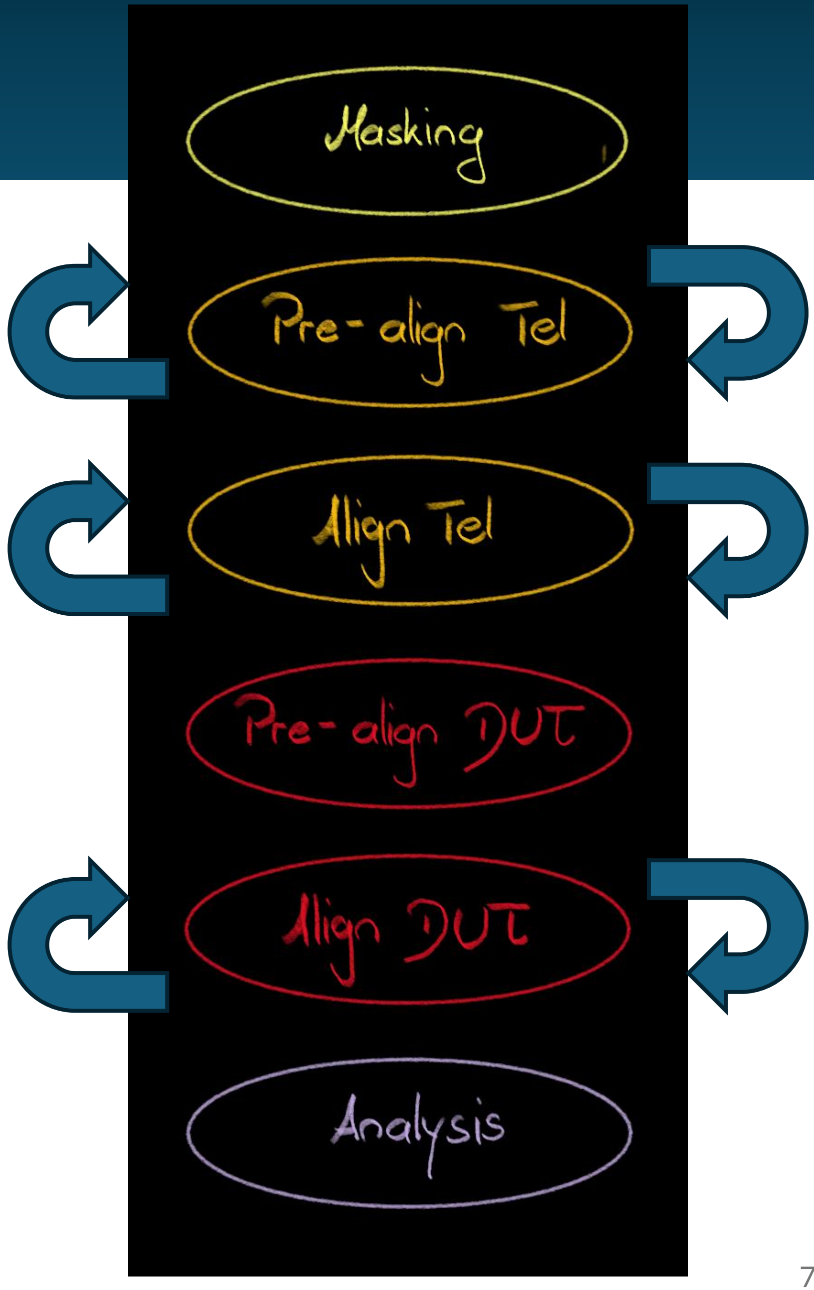
- Mixed hadron beam
- Telescope consists of:
  - 6 ALPIDE planes A
  - DPTS as trigger D
  - 2.2 μm resolution of telescope



Analysis

- Mask noisy pixels on ALPIDE planes
- Mask noisy pixels on DUT (next Slides)
- Pre-align the telescope
- Align the telescope
  - Require hit on all ALPIDE planes
- Pre-align DUT
- Align DUT
  - “Cluster” clustering method
  - Seed charge at thresholds:

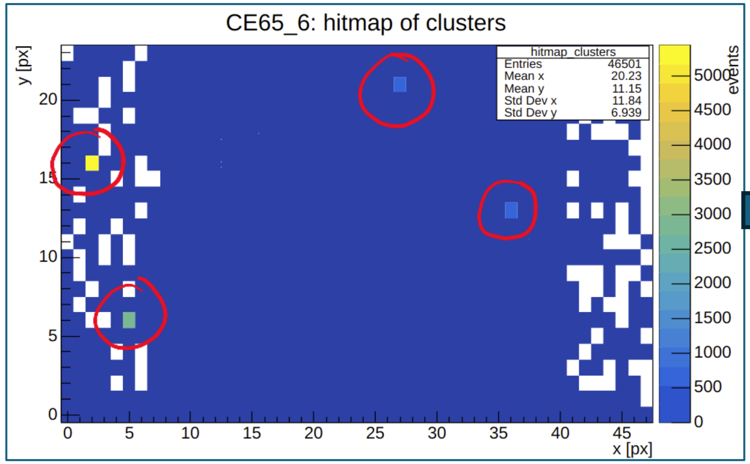
  90, 110, 130, 170, 210, 250, 290, 330, 370, 390
- Analysis
  - Cut on ROI



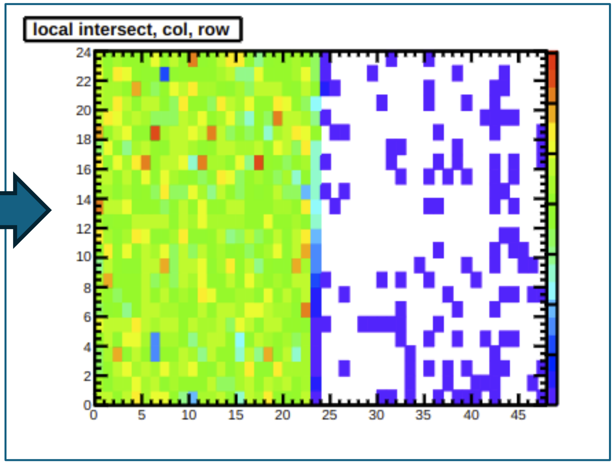
Problem with DUT pixels in all 4V GAP 15 runs

At seed charge threshold = 290 electrons, the analysis failed:

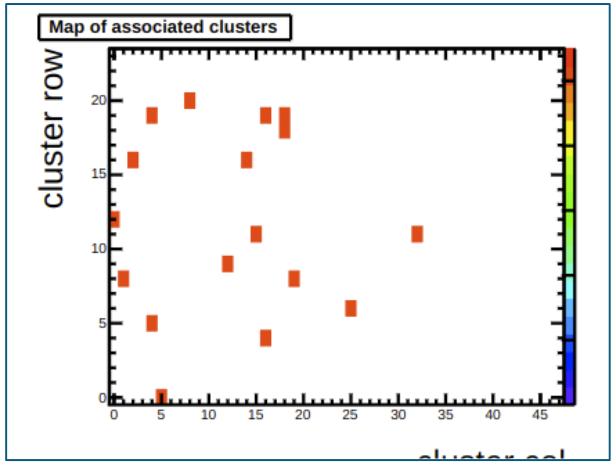
Efficiency = 0.1 ±0.0%



Map of hits



Alignment Shifted



Clustermap

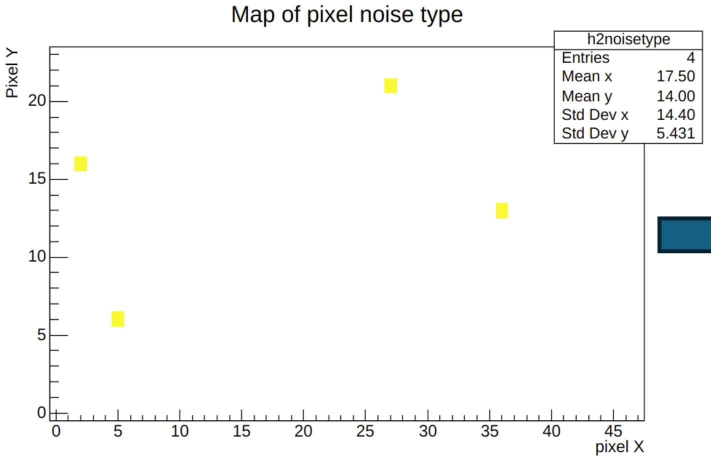
From the plot on the left, one can see that there are 4 noisy pixels which cause the alignment to be shifted and thus the efficiency and the clustering to be bad.

=> Mask noisy DUT pixels!

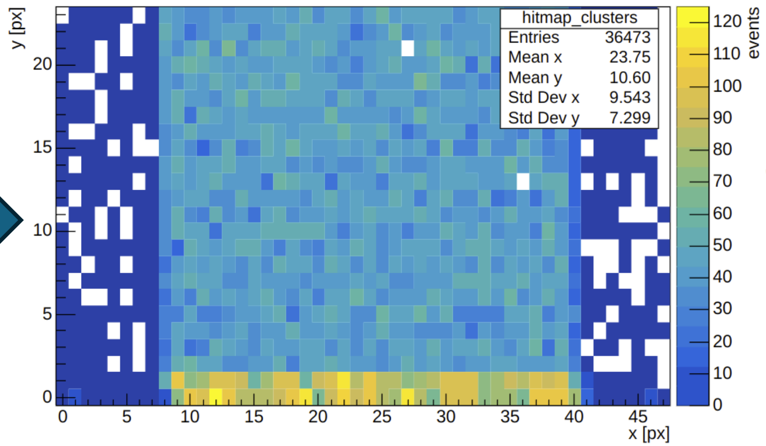
done by increasing the cut on the noise per pixel

Mask DUT pixels, noise cut = 400

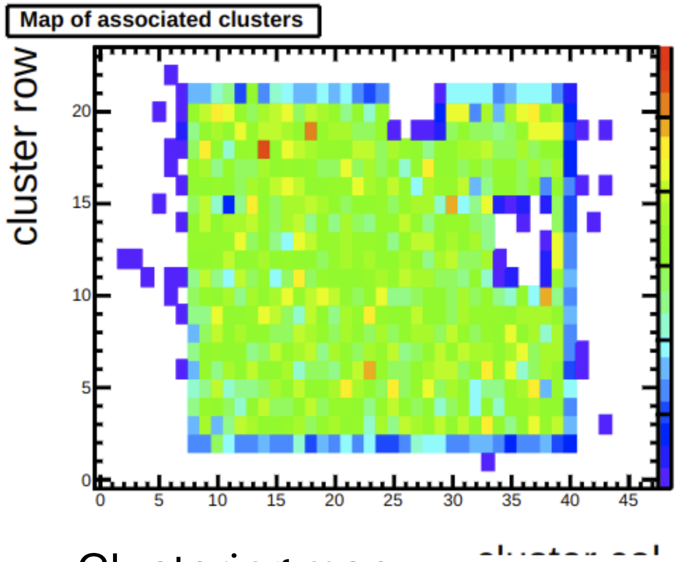
Cut away 4 noisiest pixels to ensure the clustering still works well.
Also checked this threshold for the other chips and for HV 10, for safety reasons changed it to 380. Didn’t change the efficiencies
Efficiency = 93.9 ± 0.2 %



Pixels cut away



Pixels left after cut

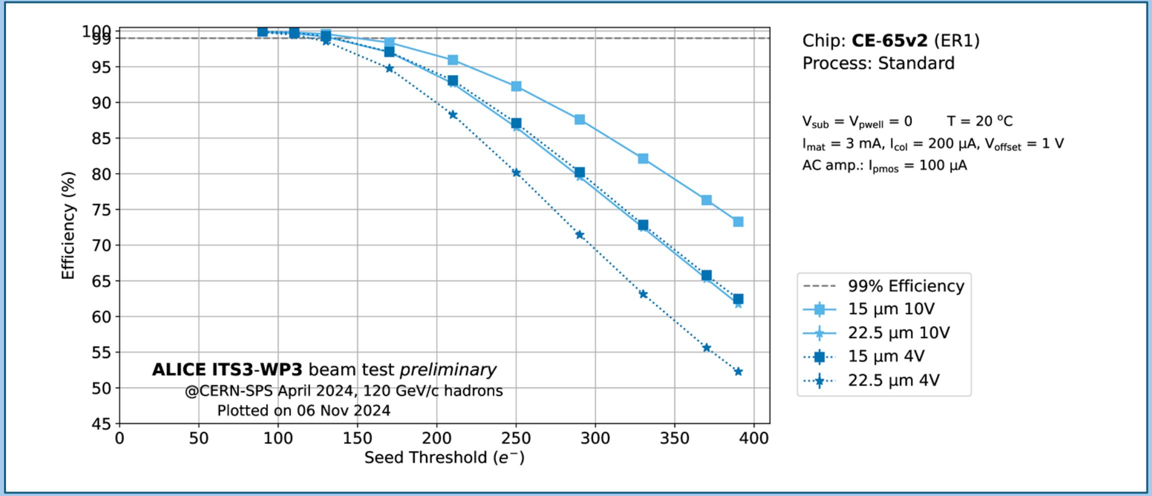


Clustering map

Test beam analysis: global efficiency

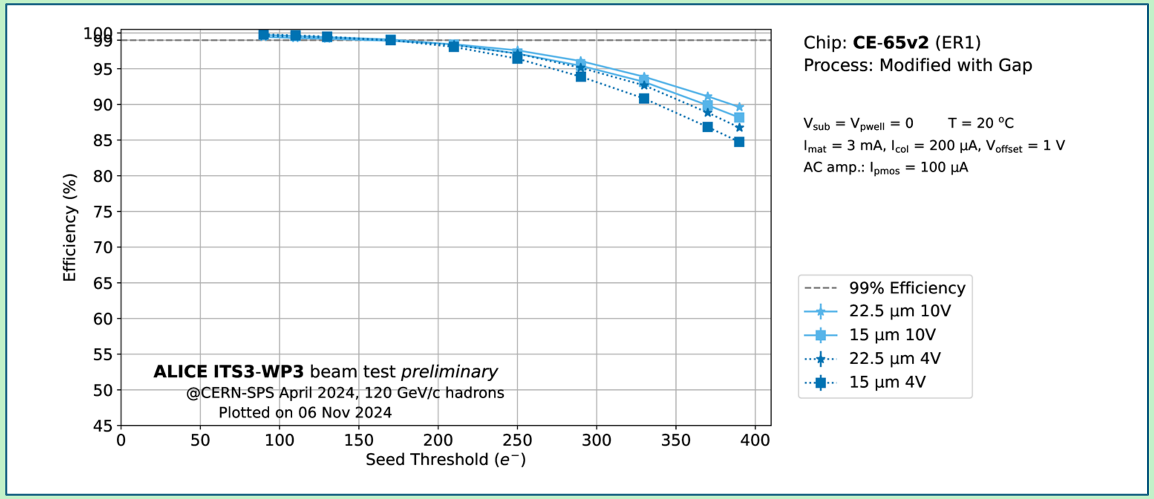
- Mask noisy pixels on reference and DUT
- Telescope pre-alignment and alignment → DUT pre-alignment and alignment → Analysis
- *Cluster* method with $\text{threshold}_{nbh} = \text{threshold}_{seed}$
- First seed threshold at 3 x RMS noise (90 e^-)
- Subtract telescope resolution in quadrature

Standard



Better efficiency for 10V than 4V

Modified with Gap

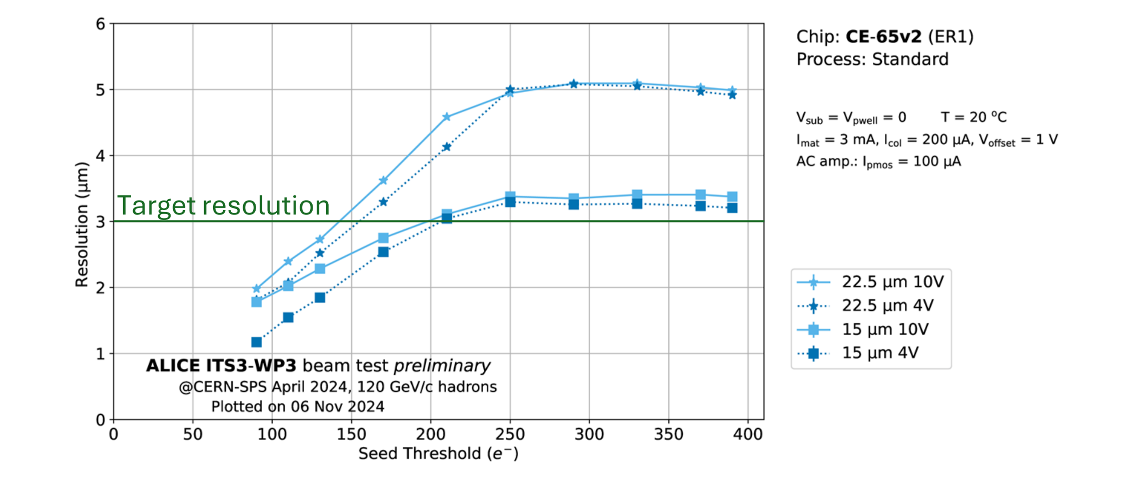


Negligible impact of higher voltage

Test beam analysis: global resolution

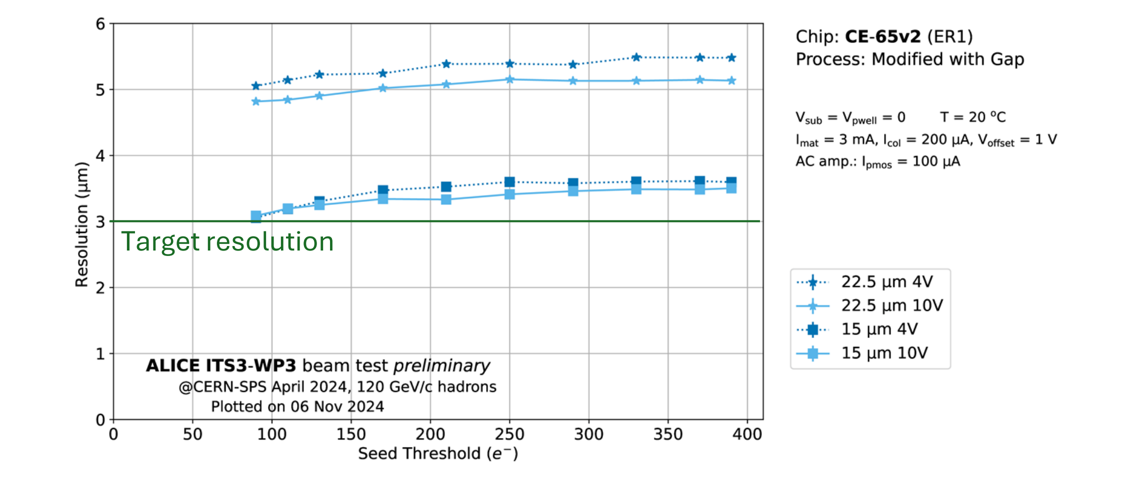
- Mask noisy pixels on reference and DUT
- Telescope pre-alignment and alignment → DUT pre-alignment and alignment → Analysis
- *Cluster* method with threshold_{nbh} = threshold_{seed}
- First seed threshold at 3 x RMS noise (90 e^-)
- Subtract telescope resolution in quadrature

Standard



< 2.5 µm and < 3.5 µm resolution for 15/22.5 µm pitch at efficiencies > 99%

Modified with Gap

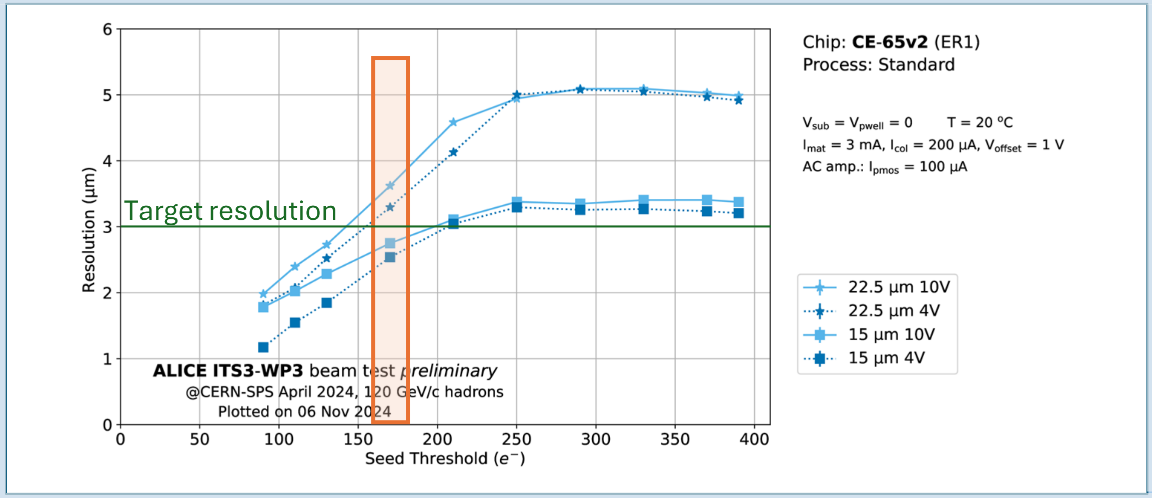


< 3.5 µm and < 5.5 µm resolution for 15/22.5 µm pitch at efficiencies > 99%

Test beam analysis: global resolution

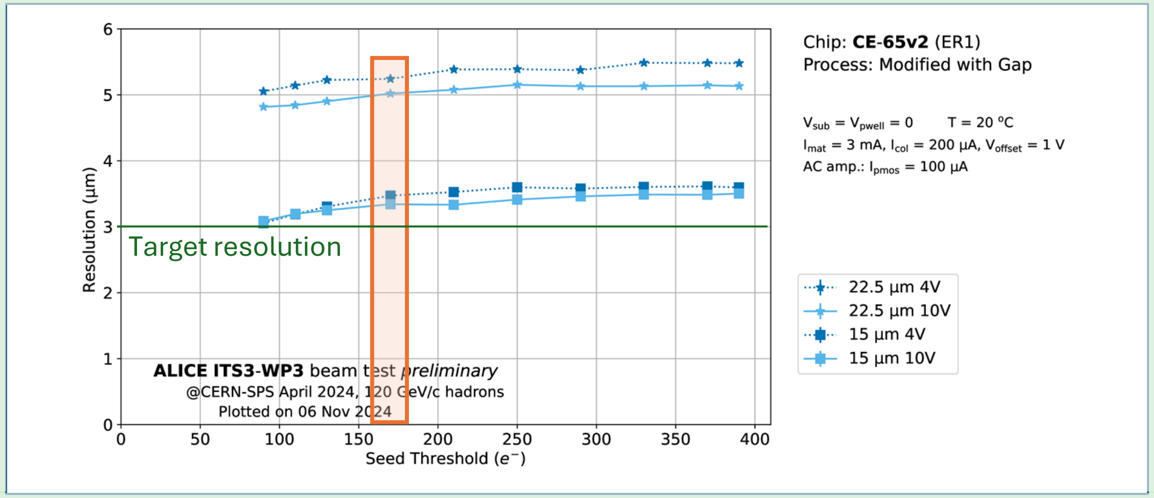
- Mask noisy pixels on reference and DUT
- Telescope pre-alignment and alignment → DUT pre-alignment and alignment → Analysis
- *Cluster* method with $\text{threshold}_{nbh} = \text{threshold}_{seed}$
- First seed threshold at 3 x RMS noise (90 e^-)
- Subtract telescope resolution in quadrature

Standard



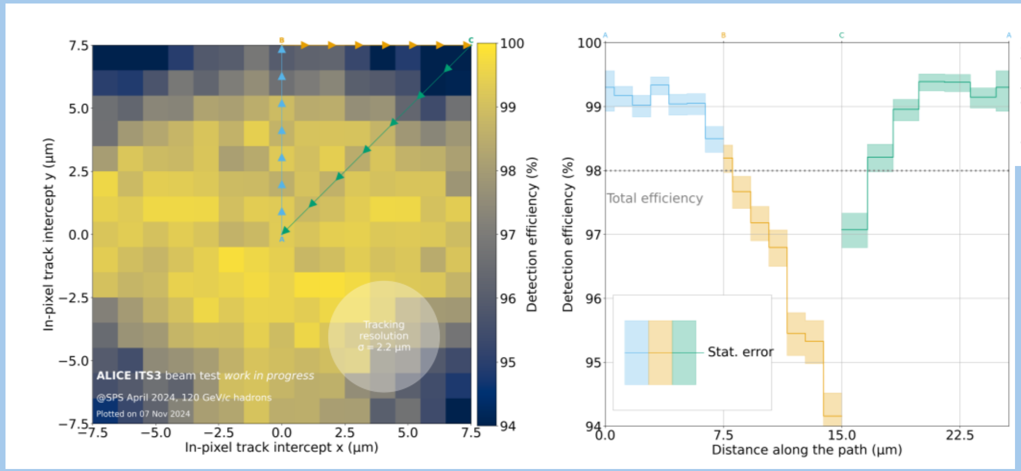
< 2.5 µm and < 3.5 µm resolution for 15/22.5 µm pitch at efficiencies > 99%

Modified with Gap

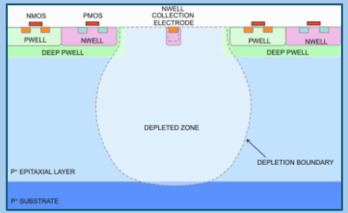


< 3.5 µm and < 5.5 µm resolution for 15/22.5 µm pitch at efficiencies > 99%

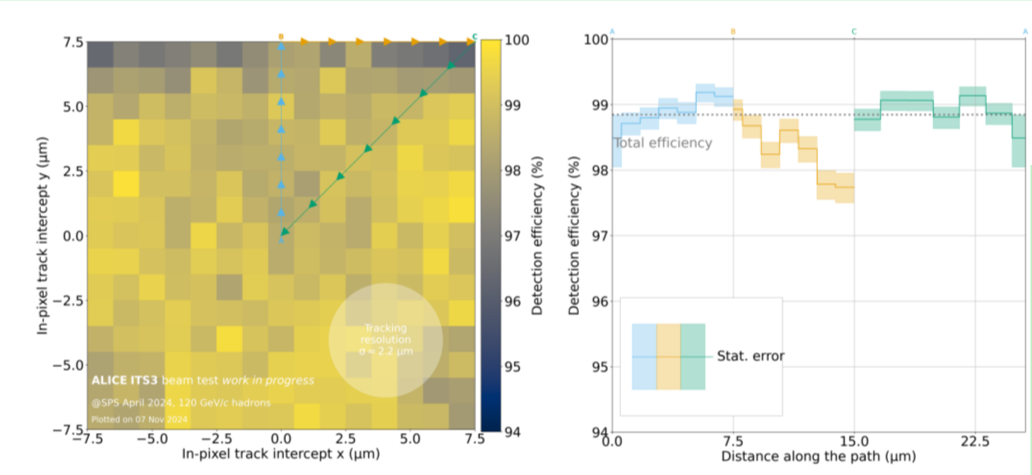
Test beam analysis: In-pixel efficiency



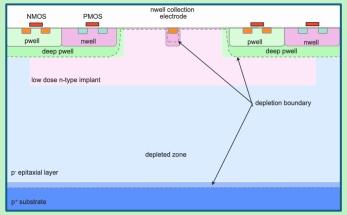
Standard



- Seed threshold at 170 e^-
- *Cluster* method with $threshold_{nbh}$ = $threshold_{seed}$

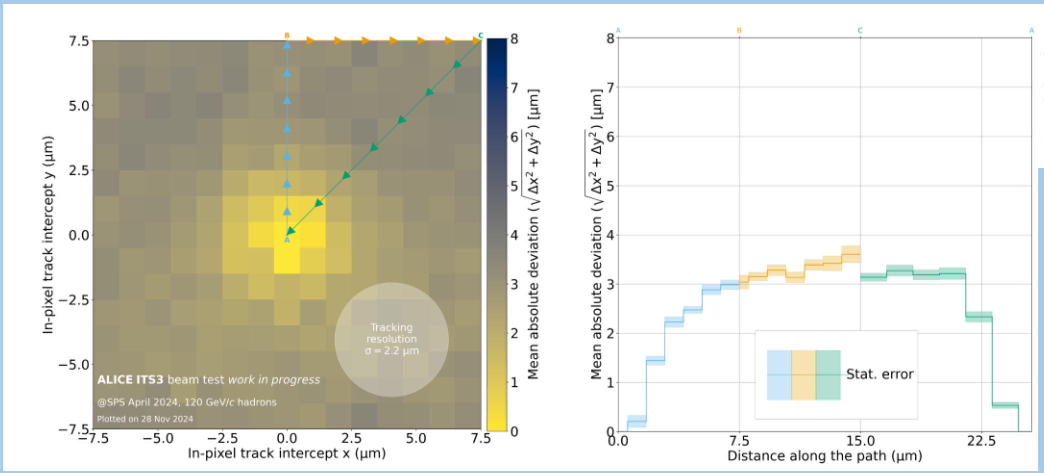


Modified with Gap

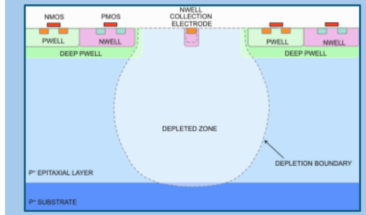


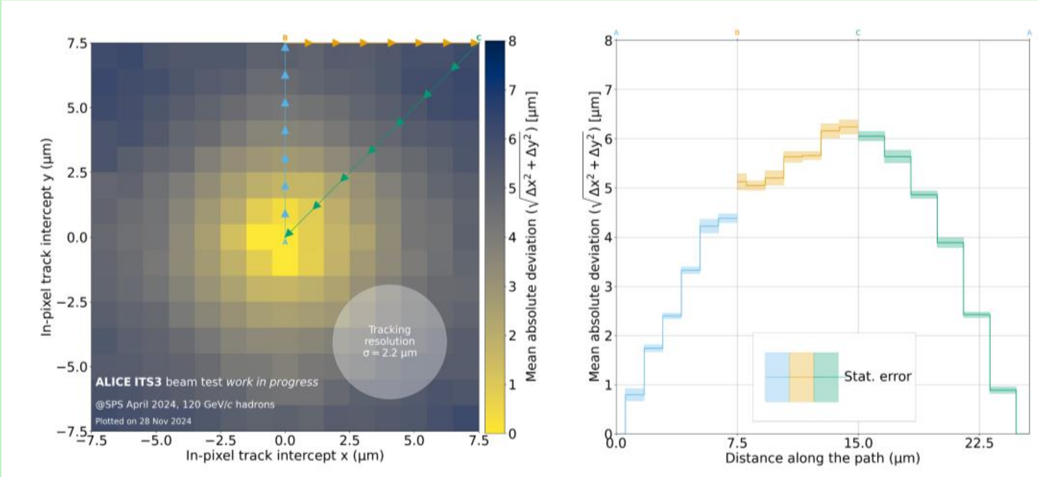
Modified with gap process has higher efficiency at the edges and corners, but performs slightly worse in the centre

Test beam analysis: In-pixel resolution

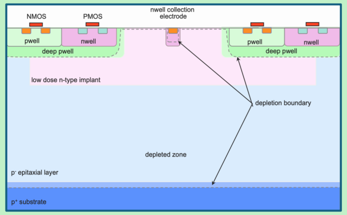


Standard





Modified with Gap



- *Window* method: $threshold_{nbh} = 0$
- Seed threshold of 170 e^-
- 5x5 window around seed to define cluster
  - See backup for in-pixel resolution with cluster method
- Subtract telescope resolution in quadrature

Better resolution in standard process comes from edge and corner regions, thanks to charge sharing

Importance of beyond-binary analog-to-digital conversion when having strong charge sharing

See link for benefits of having more than one threshold to benefit from charge sharing

Conclusion

- Analog resolution for pitch size of 15 μm < 2 μm (STD process) resp. 3 - 3.5 μm (modified with gap process), efficiency greater than 99% at thresholds larger than 3 × RMS noise
  - Compatible with FCC-ee vertex spatial resolution requirement. Further development needed to fulfil other requirements
  - Nota bene: Spatial resolution in fully-functional sensor is heavily influenced by analog-to-digital conversion scheme
- Able to efficiently perform detailed in-pixel studies thanks to large matrix size. Result confirming previous findings on process variations

Outlook

- CE-65 v2 characterisation almost finished
  - Radiation tolerance of CE-65 under investigation (May 2024 test beam at DESY)
  - Analysis of staggered pixel mimicking hexagonal pixels arrangement ongoing
  - Request for SPS test beam in 2025 to test 18 µm pitch and modified process in detail
- Great starting point for DRD3 WG1/WP1 project OCTOPUS (Optimized CMOS Technology for Precision in Ultra-thin Silicon), see this link for more information on OCTOPUS, this link to an article on tracking and vertexing detectors at FCC-ee vertex, or this link to a presentation at Pixel conference 2024 concerning the vertexing challenge at FCC-ee

Thanks for your attention!

Special thanks to

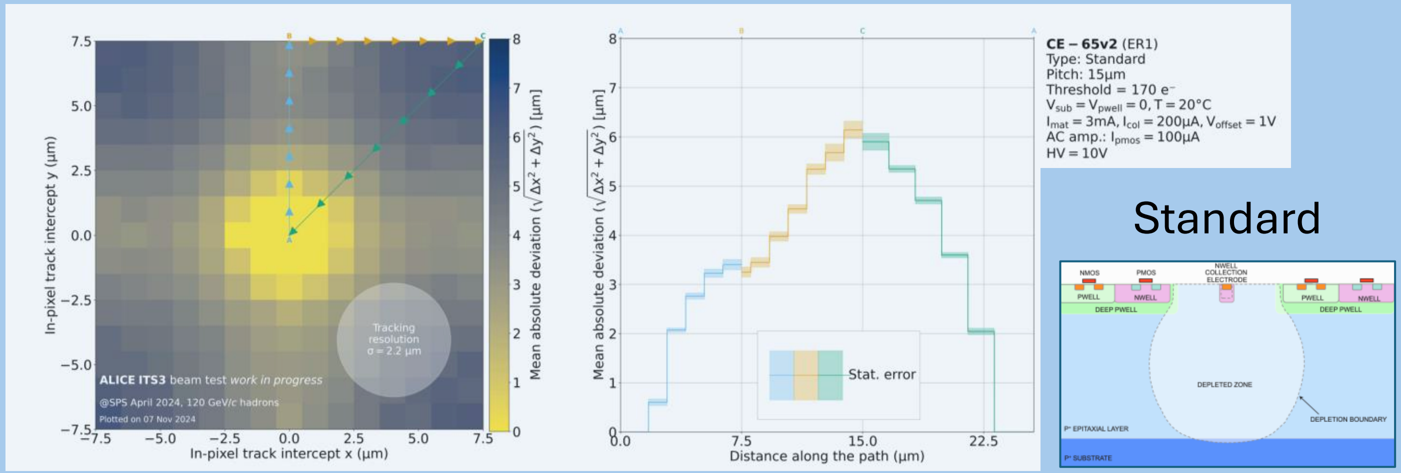
Ajit Kumar, Alex Kluge, Andrei Dorokhov, Anna Macchiolo, Armin Ilg, Christine Hu-Guo, Claude Colledani, Daito Shibata, Felix Reidt, Hitoshi Baba, Jerome Baudot, Jonghan Park, Kimmo Jaaskelainen, Lukas Tomasek, Magnus Mager, Mathieu Goffe, Miljenko Sulic, Pavel Stanek, Serhiy Senyukov, Shingo Sakai, Szymon Bugiel, T. Chujo, Taku Gunji, Towa Katsuno, Walter Snoeys, Yitao Wu, Yorito Yamaguchi, Ziad El Bitar, Auguste Besson, Hasan Shamas, Isabelle Valin

Bibliography

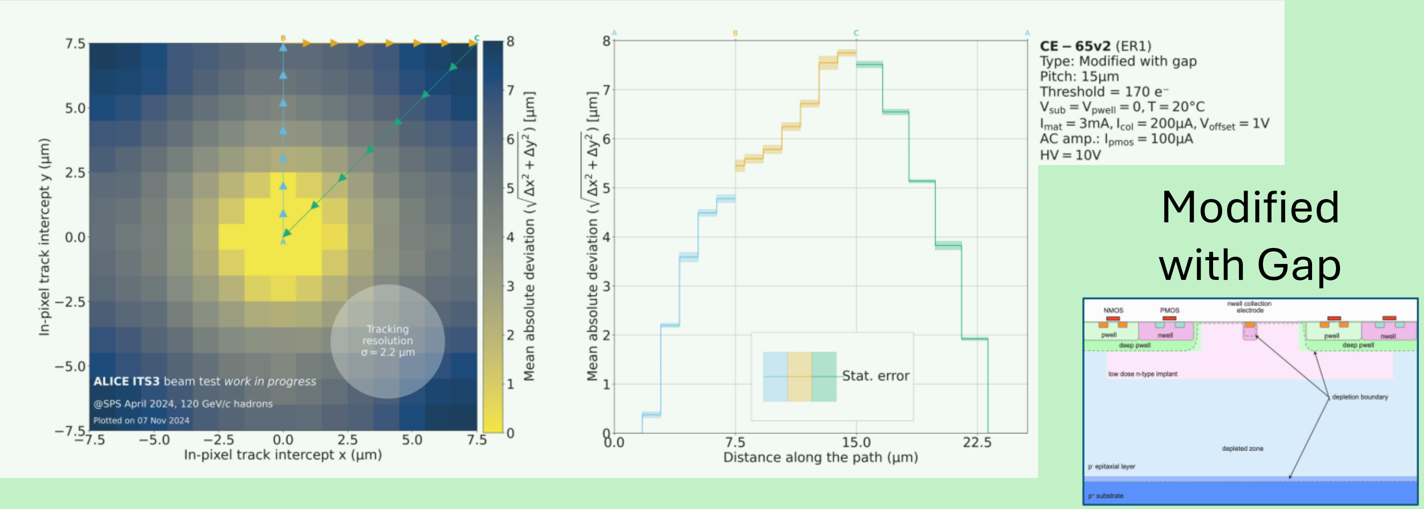
- K. Gautam and A. Kumar, Characterisation of analogue MAPS fabricated in 65 nm technology for the ALICE ITS3, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **1068**, 169787 (2024).
- The ALICE collaboration, Technical Design report for the ALICE Inner Tracking System 3 - ITS3 ; A bent wafer-scale monolithic pixel detector, (2024).
- Full report on the FCC Feasibility Study mid-term review. Scientific Policy Committee - Three-Hundred-and-Thirty-Sixth Meeting, (2023).
- S. Bugiel et al., Charge sensing properties of monolithic CMOS pixel sensors fabricated in a 65 nm technology, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **1040**, 167213 (2022).

Backup

Test beam analysis: In-pixel resolution



Standard



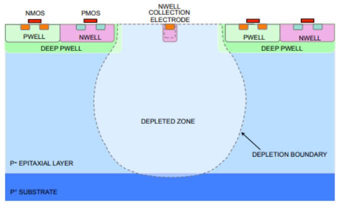
Modified with Gap

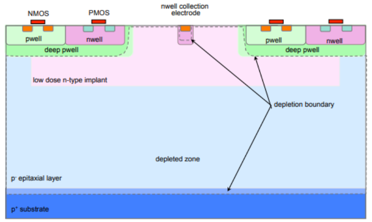
- *Seed threshold of 170 e^-*
- *Cluster* method with $\text{threshold}_{neibhbour} = \text{threshold}_{seed}$
- Subtract telescope resolution in quadrature

Better resolution in standard process comes from edge and corner regions, thanks to charge sharing

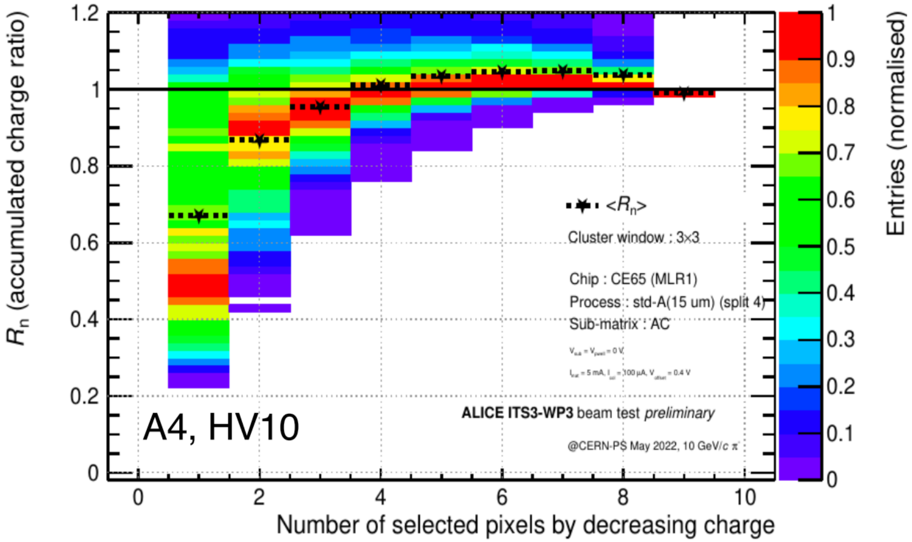
Quantification of charge sharing

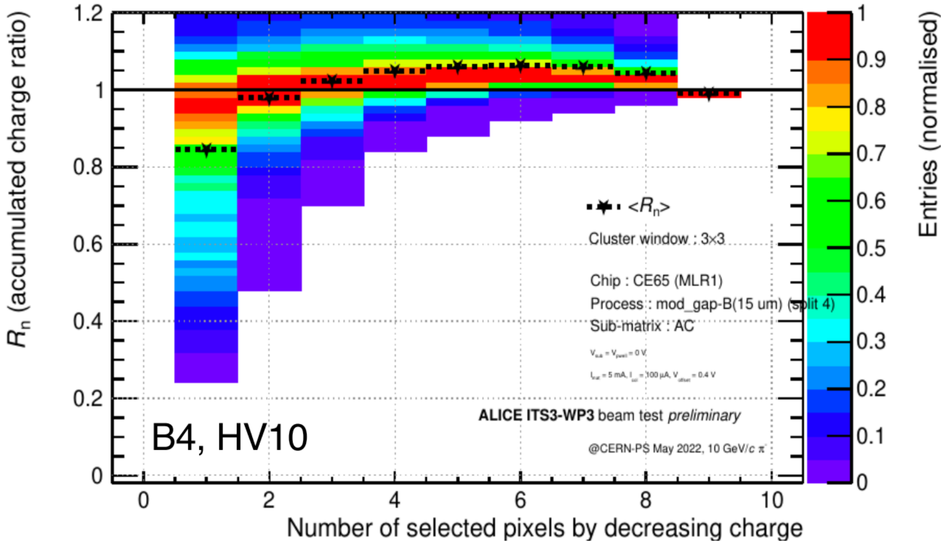
Standard





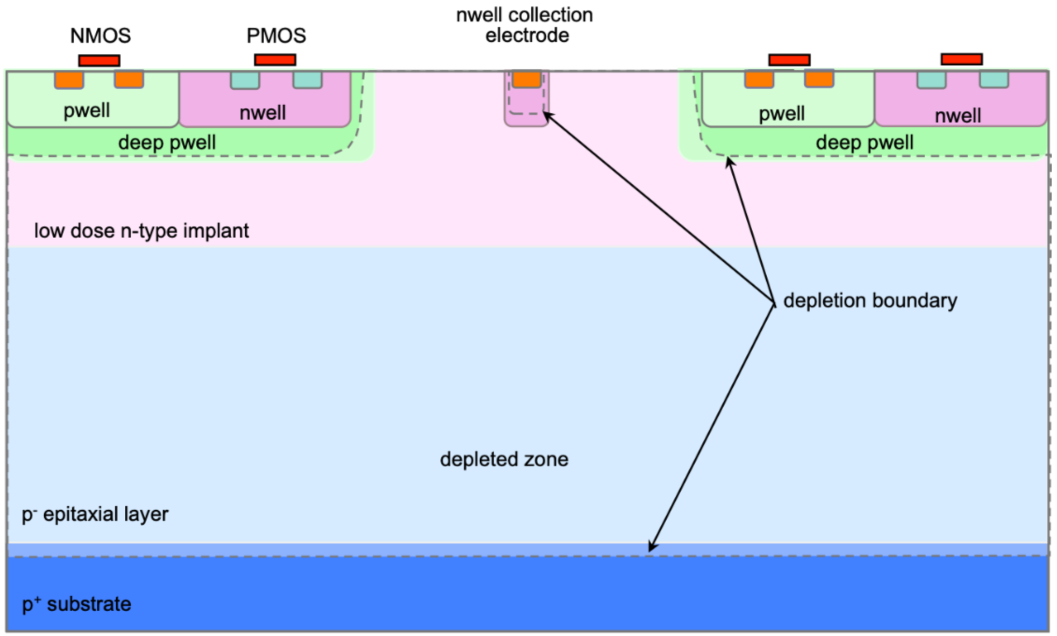
Modified with Gap





These figures quantify the level of charge sharing by providing the number of pixels collecting a charge significant in average

Modified process



With a deep blanket low dose n-type implant.

- Full depletion allows for drift-dominated charge collection
- In 180 nm this increased the radiation tolerance to 10^{14} MeV n_{eq} cm^{-2} but not beyond
- The very low lateral field near pixel edges allows for charge trapping

ALICE collaboration, Technical Design report for the ALICE Inner Tracking System 3 - ITS3 ; A bent wafer-scale monolithic pixel detector, (2024).