Simulation of Hexagonal Pixel Configurations in Monolithic Active Pixel Sensors

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HELMHOLTZ UNIVERSITÄT BONN

The Tangerine Project
TowArds the Next GEneRation of SIlicoN DEtectors

- Research and development of **new silicon sensors** for future lepton colliders and test beam telescopes.

- Part of the **Work Package 1 (WP1):**
  Development MAPS in 65 nm CMOS Imaging Technology:
  - Increase logic density
  - Allow smaller pixels
  - Decrease overall power consumption
  - Low noise/threshold
  - Reduction of costs

MAPS = Monolithic Active Pixel Sensor

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A combination of **detailed simulations** and **prototype testing** can be used to **efficiently guide the way in sensor developments**

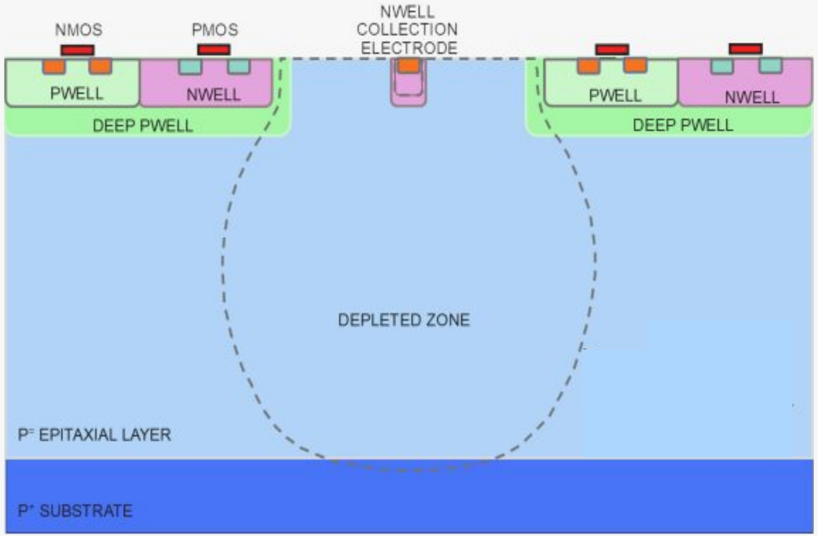
MAPS = Monolithic Active Pixel Sensor

Sensor Layouts Under Study

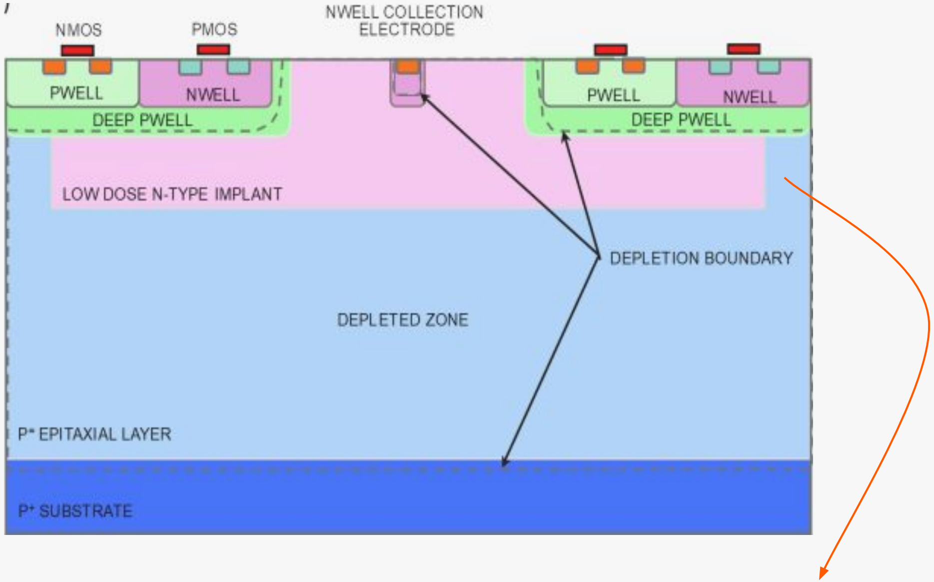
Monolithic Active Pixel Sensors (MAPS) with small collection electrode

W._Snoeys
https://doi.org/10.1016/j.nima.2017.07.046

Standard Layout



N-Gap Layout



structures not in scale !!

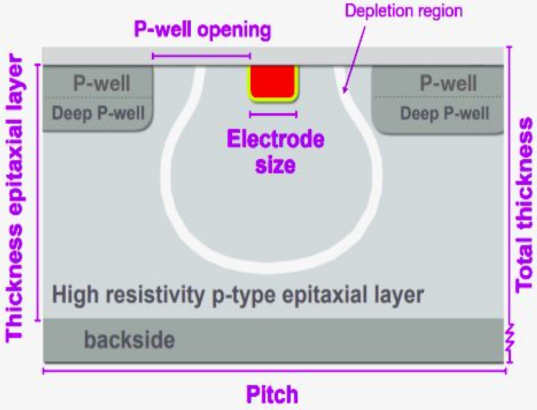
Space ("Gap") in Continuous N-type Implant

Silicon sensor simulation

Goal: Accurate simulation of the charge collection behaviour in the sensitive volume of **MAPS 65 nm CMOS Imaging Technology**

Issue: The access to manufacturing process information is extremely **limited**

Solution: Development of a technology-independent simulation approach using generic properties

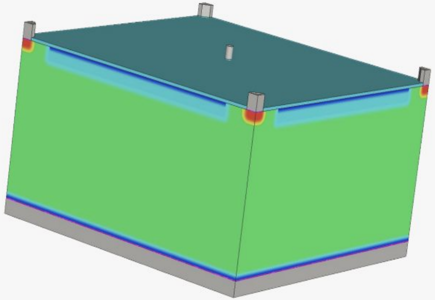


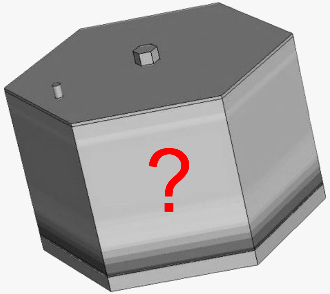
Schematic cross section of a single pixel cell in the CMOS process under investigation. Source: Modified from [*D Dannheim et al., Combining TCAD and Monte Carlo methods to simulate CMOS pixel sensors with a small collection electrode using the Allpix 2 framework*]

- Impose constraints on **implant depth**, **doping concentrations**, **input voltages**, etc.
- Perform parameter scans, varying it within a range, and observe the behavior of the **electric field** and **depleted volume** to identify working point

Silicon sensor simulation

Execute **highly detailed** simulations for studying the possibility of using **hexagonal pixels** within a 65 nm CMOS imaging technology for MAPS, with small collection electrodes.





what improvements can we make by changing the pixel shape?

Simulation approach

Sentaurus TCAD — SYNOPSYS® Silicon to Software™

Technology **C**omputer-**A**ided **D**esign

+

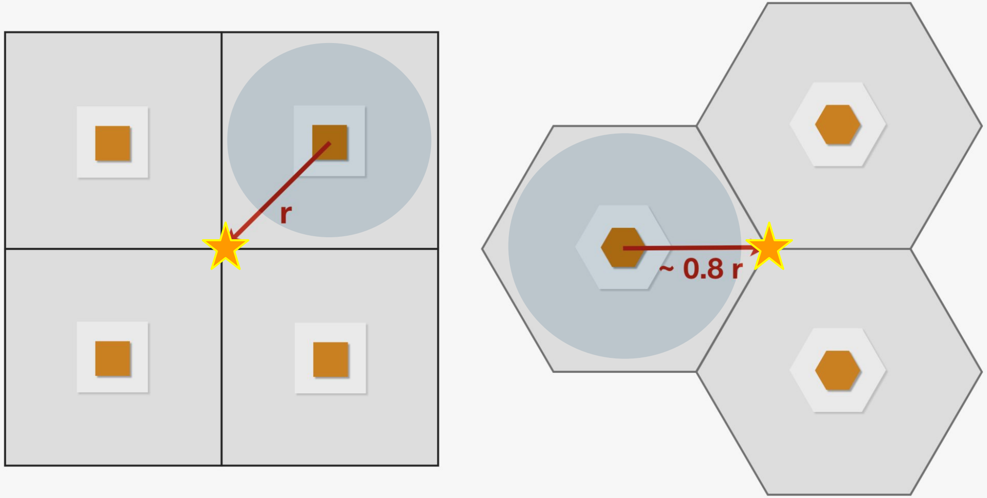
ap² allpix squared — Allpix²: Monte Carlo Simulations for Semiconductor Detectors

https://doi.org/10.1016/j.nima.2018.06.020

Finite element simulation | **Monte Carlo simulation**

Silicon sensor simulation

Why hexagons?



Principles:

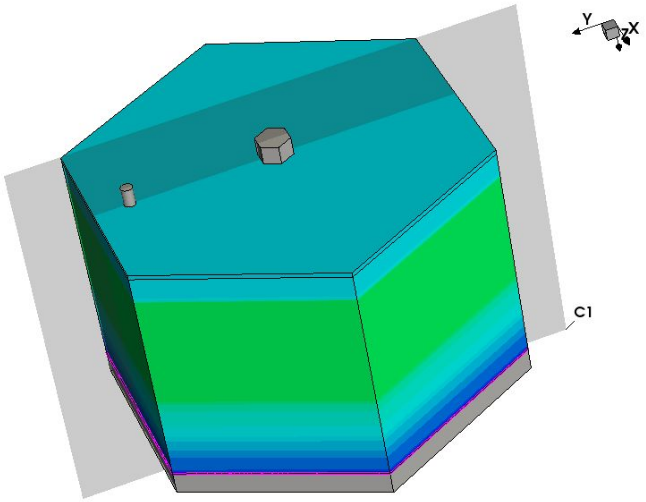
- Reduce the drift path while **maintaining area for circuitry**
- Reduced number of neighboring pixels

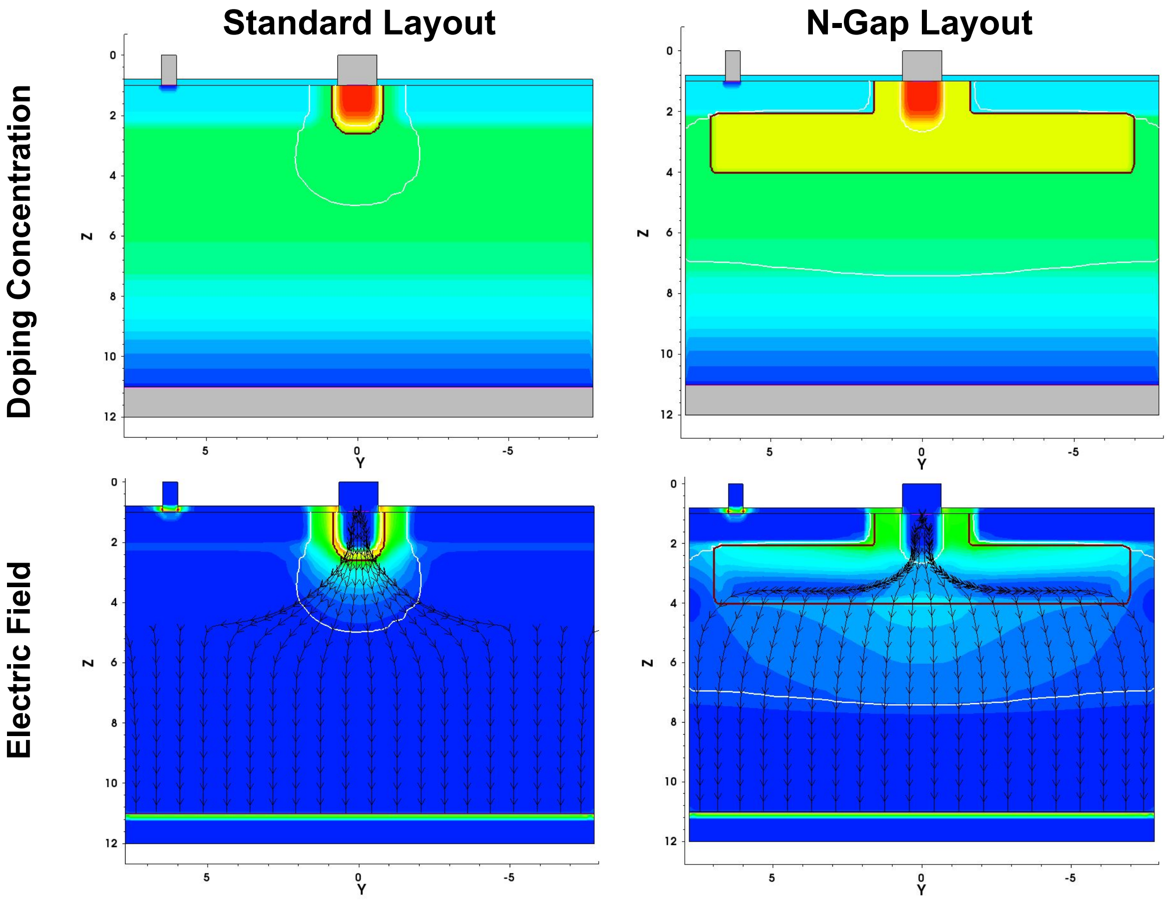
Reduce electric field edge effects of square design

More homogenous response over pixel cell → *Relevant for precise timing*

Simulation results

Finite element simulation results

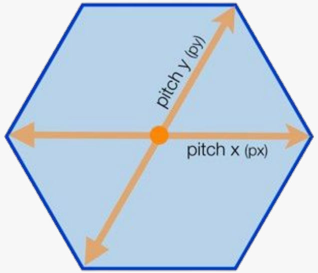




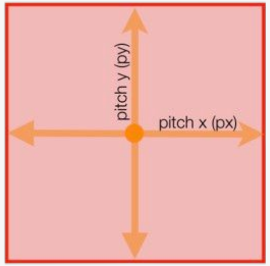
Monte Carlo simulations

Allpix²simulation results using TCAD fields

- Simulations allow for the analysis of multiple observables: **cluster size, efficiency and spatial resolution**.
- Tests have been performed **comparing square pixels and hexagonal pixels,** maintaining the pixel area
  - *The space available for readout electronics thus remains the same per pixel*



18 µm



14.5 µm

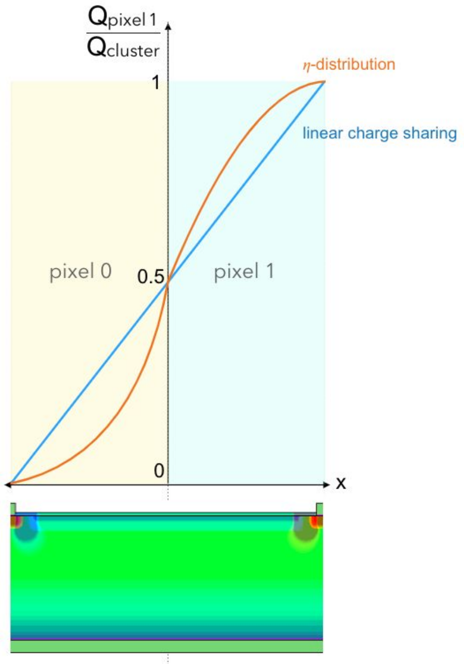
Key Element	Value
number_of_events	100,000
particle_type	e-
source_energy	5 GeV
beam_size	100 um
electronics_noise	10e
threshold	multiple values scanned
threshold_smearing	5e
physics models	Masetti-Canali model, Shockley-Read-Hall Auger recombination

Monte Carlo simulations

Eta-correction (η-correction)

To correct for non-linear charge sharing effects

Standard Layout



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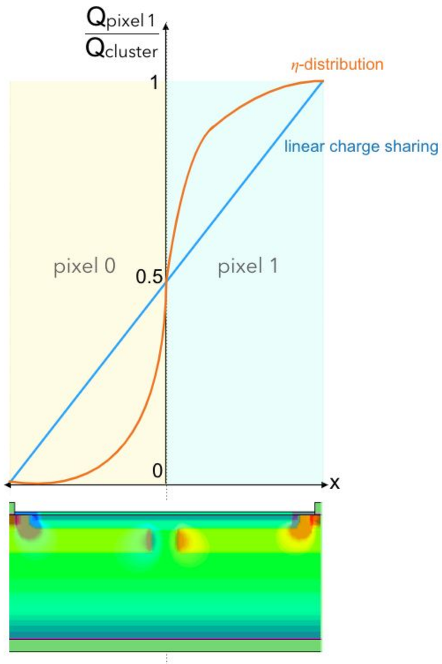

Reference position: Center of lowest, leftmost pixel in cluster

Algorithm for two and three pixel clusters

$$\Delta\varphi = \varphi_{\text{particle}} - \varphi_{\text{cluster}}$$

$$r_{\text{track, projected}} = r_{\text{track}} \cdot \cos(\Delta\varphi)$$

$$\varphi\text{Dist}_{\text{track, projected}} = r_{\text{track}} \cdot \sin(\Delta\varphi).$$

- ***r_track***: radial distance of the local intercept of the MC particle track from the reference pixel
- ***r_cluster***: radial distance of the cluster's center position from the reference pixel

Monte Carlo simulations

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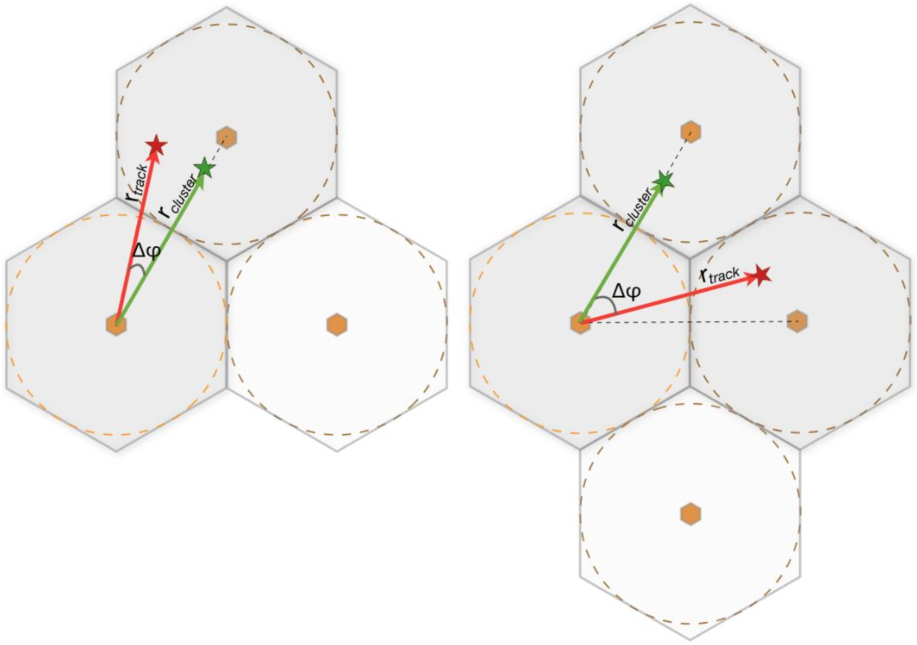

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residual in r: $r_{\text{track, projected}} - r_{\text{cluster}}$

residual in ϕ: $r_{\text{track}} \cdot \sin(\phi)$

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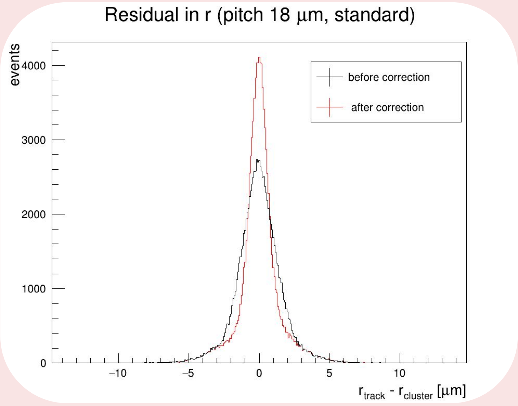

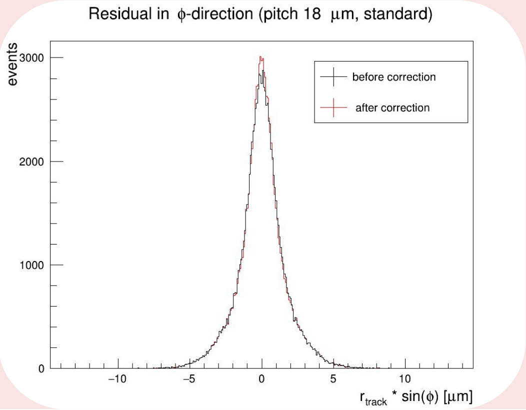

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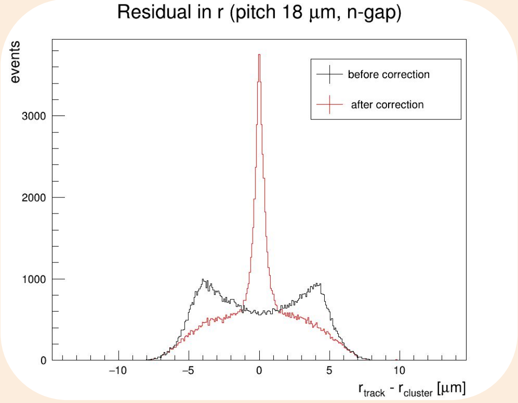

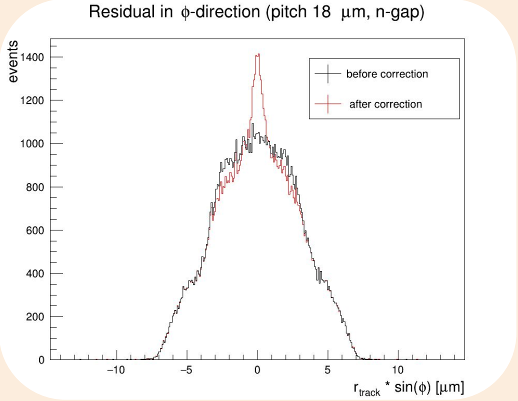

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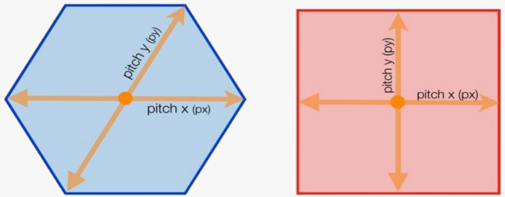
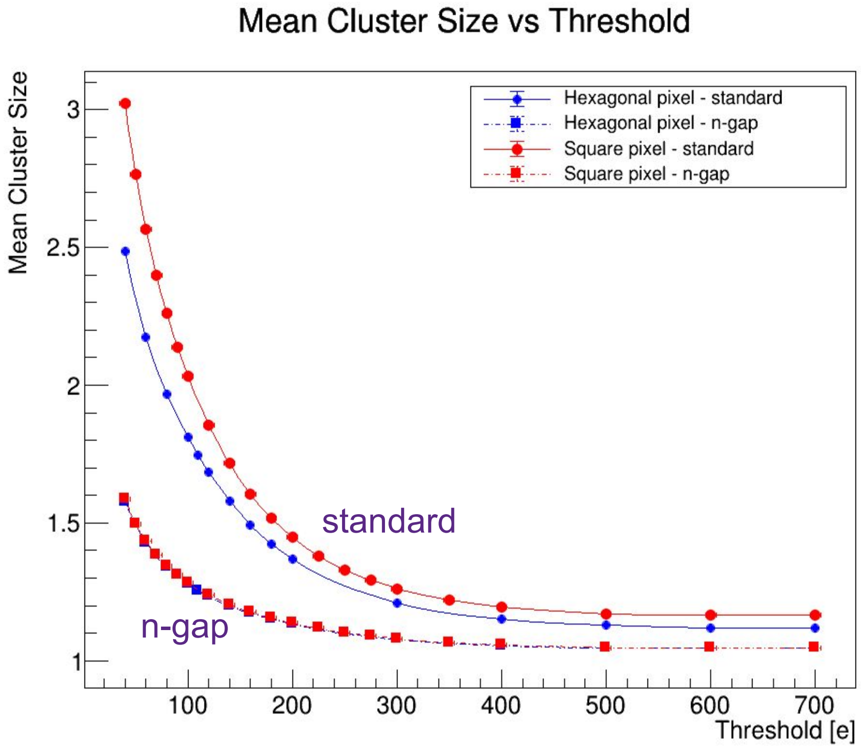


18 µm **14.5 µm**



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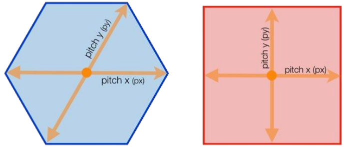
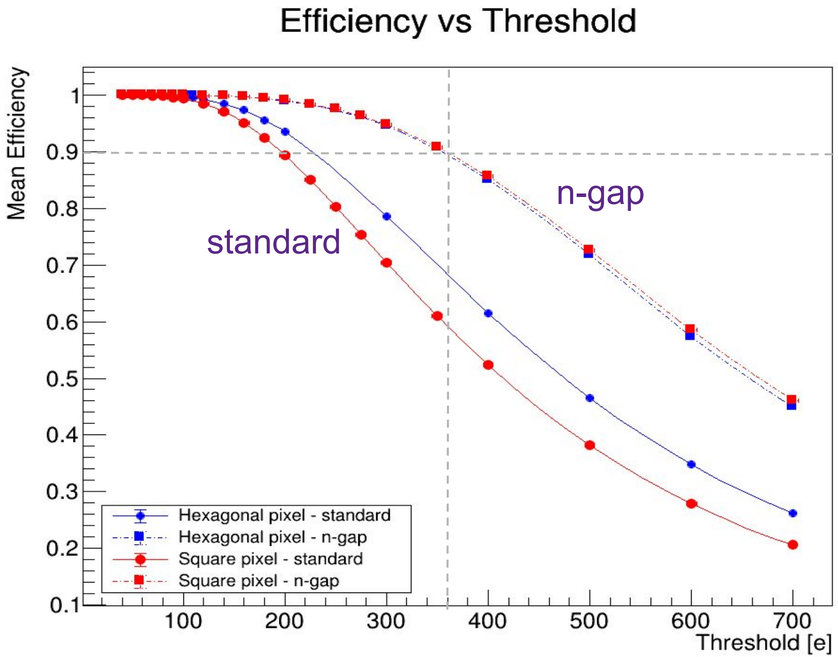
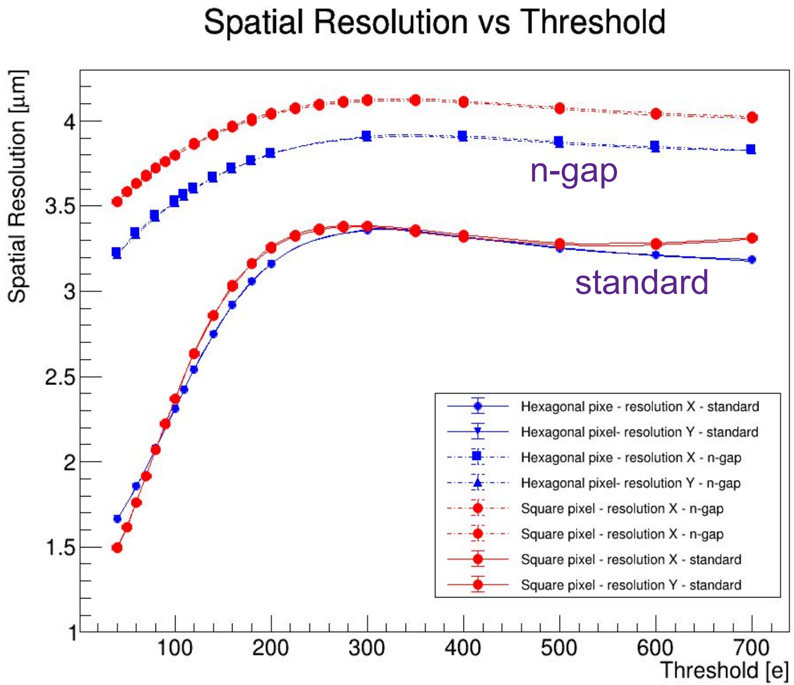


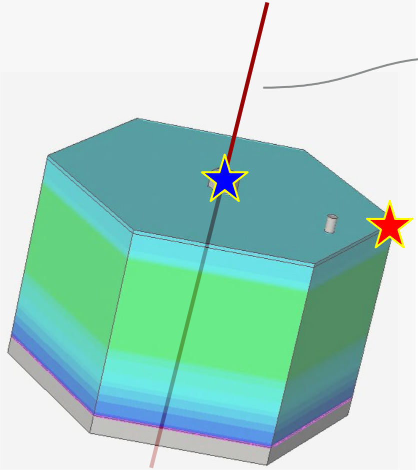




Transient Simulations
with TCAD

- Extracting the **time-dependent induced signal** on the collection electrodes, from traversal of a MIP

- **GOAL:** Investigate both pixel **corner** incidence and pixel **centre** incidence
    - Gives indication of "**worst case**" and "**best case**" particle hit scenarios



Heavy Ion Model on TCAD

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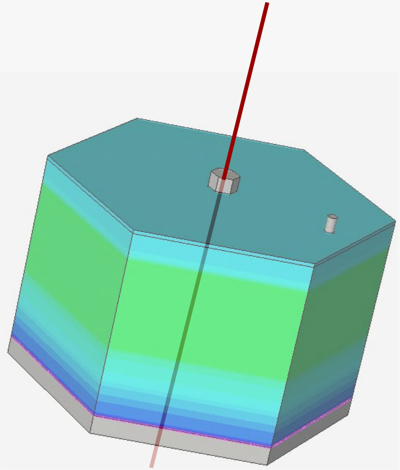
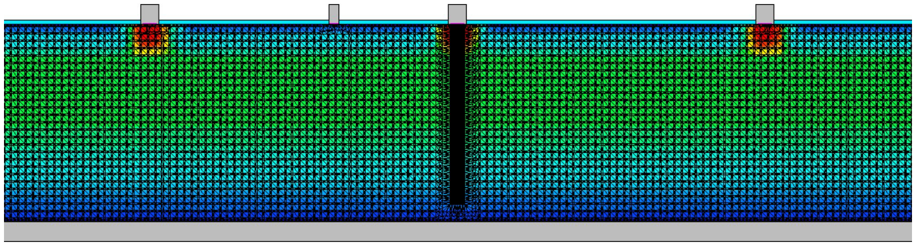
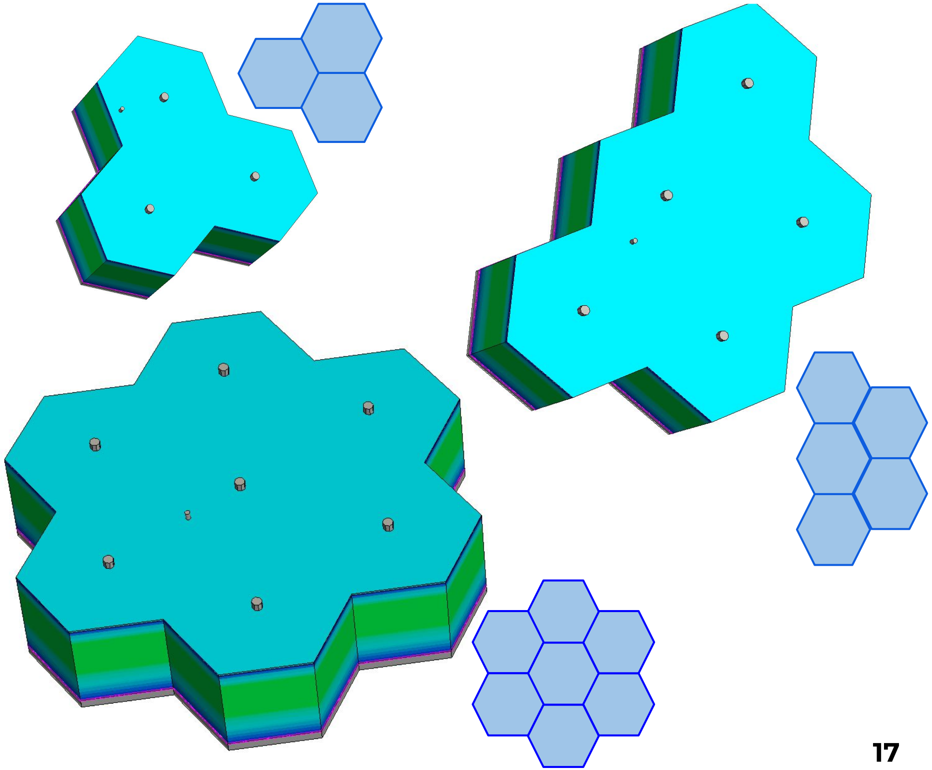
STATUS:

optimizing pixel cell design and meshing

for both **Standard** and **N-Gap** layouts







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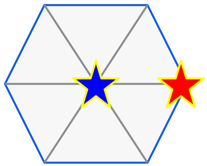

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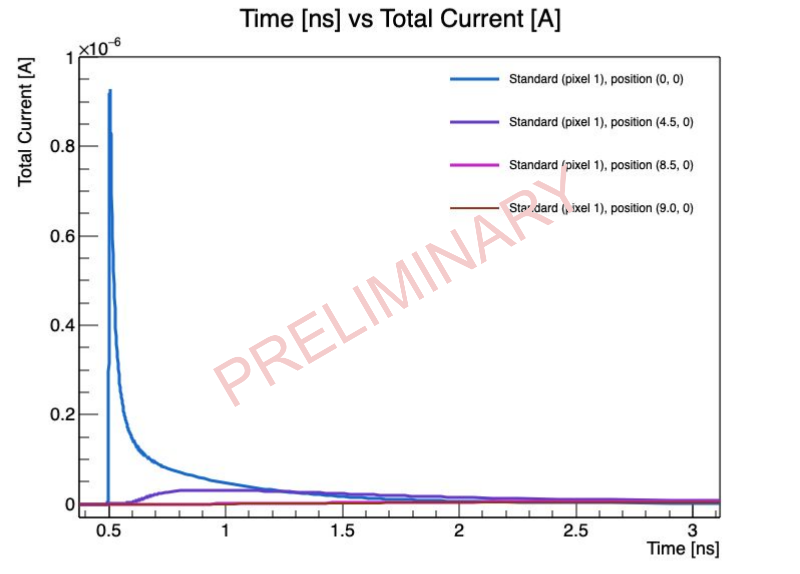

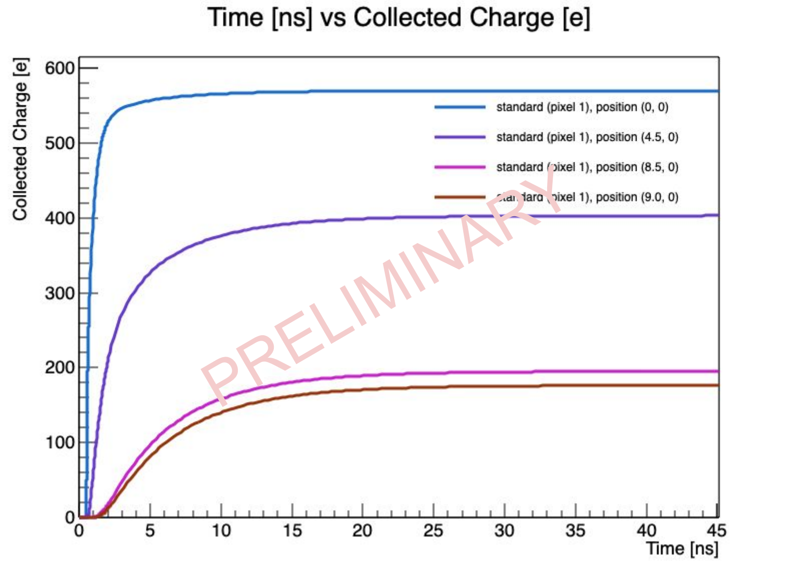

Conclusions and outlook

With **hex pixels** we can combine advantages of MAPS with a small collection electrode (low cost & material, reduced production effort, small sensor capacitance) with precise spatial resolution and fast and complete charge collection

- A hexagonal layout leads to reduced charge sharing in pixel corners and a reduced distance from pixel boundary to pixel centre
  - *Allows efficient operation at higher thresholds, and* ***better spatial resolution and fast charge collection***

Next steps

- Simulate different scenarios (e.g. different hit positions and pixel sizes)
- Compare timing performance on **both pixel geometries**
- Capacitance measurements to be considered
- Detailed timing studies → See M. A Del Rio Viera's presentation

thank you