# Simulating Monolithic Silicon Sensors in a 65nm CMOS Imaging Technology

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## INTRODUCTION

**Monolithic Active Pixel Sensors (MAPS)**, produced in a 65 nm CMOS imaging process, have become an attractive technology for precise vertex detectors at high energy physics experiments, and **are being considered for future lepton colliders [1].**

As part of sensor development, precise simulations are important for predicting sensor performance and guiding design improvements.

**Initial target:** high-resolution sensors for beam telescopes
**Final target:** future lepton colliders vertex detector

## PHYSICS REQUIREMENTS

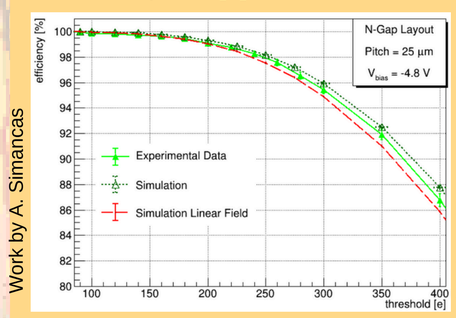
In acordance with Strategic R&D programme on technologies for future experiments **[2]**.

- **Material budget:** < 0.05% X/X0
- **Single-point resolution:** ~ 3µm
- **Time resolution:** ~ 1-10 ns
- **Rate capabilities:** 1 MHz particle rate
- **Granularity:** < 25 µm x 25 µm

## COMPARISON OF SIMULATIONS TO EXPERIMENTAL DATA

Simulations are compared to experimental data to validate the employed simulation approach.

Multiple prototype submissions with characterisation supported by simulations: **DESY MLR1, APTS [6], DESY ER1, H2M [7].**

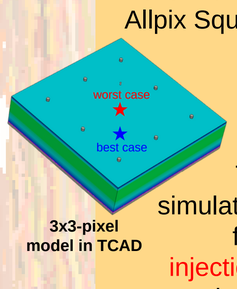



Example of comparison of simulations and test beam data of APTS chip

## TIMING STUDIES

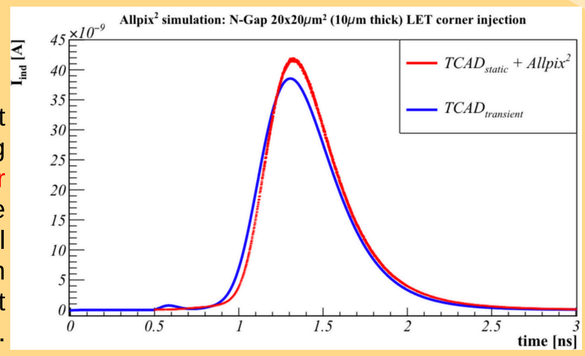
Transient simulations allow us to study the time evolution of the response of a sensor **[5]**.

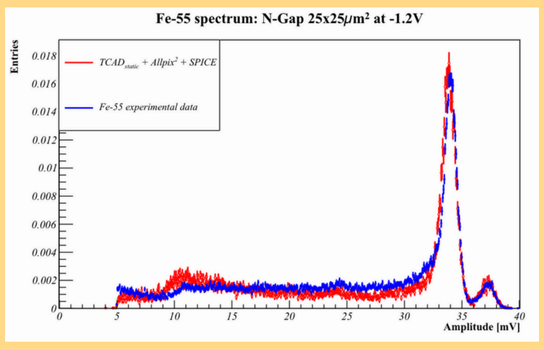
To **simulate the electronics**, the output signal from Allpix Squared is imported into **SPICE.**




3x3-pixel model in TCAD

Transient simulation using for corner injection. Pulse duration will depend on particle incident position.




The matching peaks allow for assessing the detector calibration.

## SENSOR DESIGN

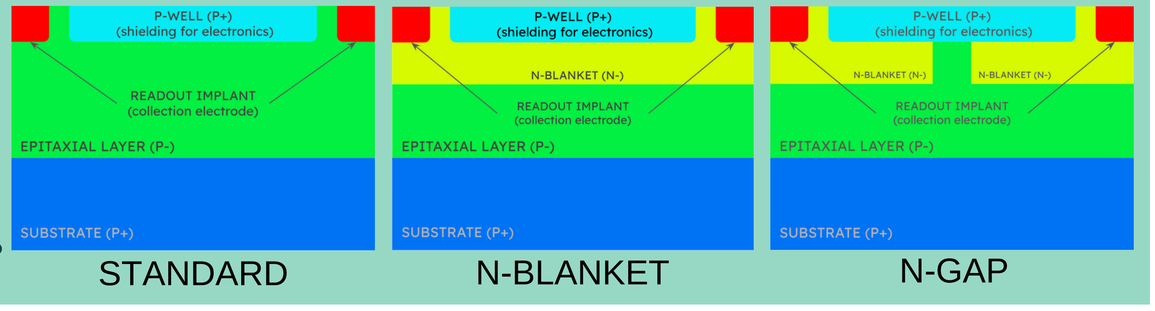
**MAPS in a 65 nm CIS** with small collection electrode

Full CMOS circuitry integrated in wells separated from collection electrode

- small pixel size → higher logic density
- small input capacitance ~fF
  - low power consumption
  - high signal-to-noise ratio

**INVESTIGATED LAYOUTS:**

FIGURES NOT TO SCALE




STANDARD | N-BLANKET | N-GAP

## DEVICE SIMULATION

**GOAL:** Accurately simulation of the charge collection behavior in the sensitive volume

**SIMULATION APPROACH:**

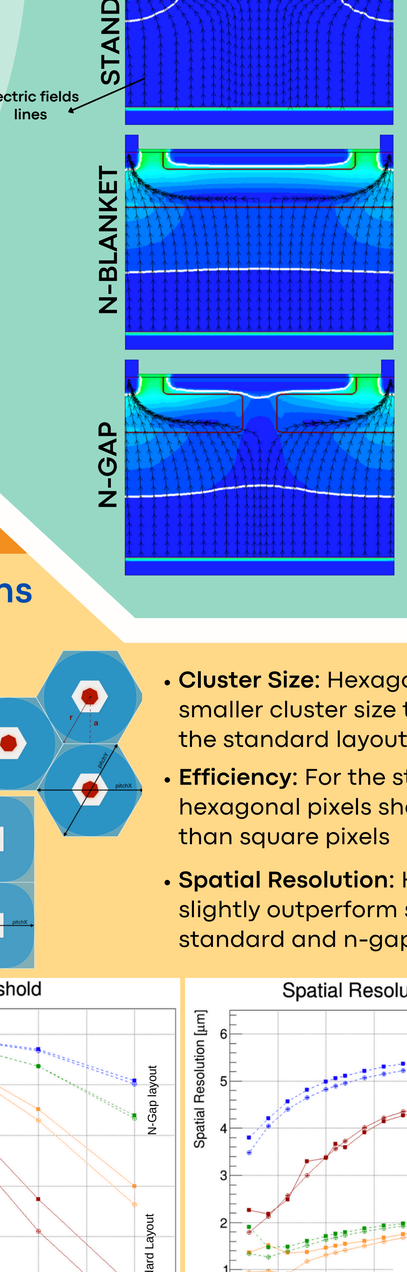
A technology-independent simulation approach **[3-4]** combines:

**Sentaurus TCAD SYNOPSYS** → **ap²** (allpix squared)

Simulation of epitaxial layer with generic doping profiles, and derivation of detailed electric field.

High-statistics MC simulation of full response of detector

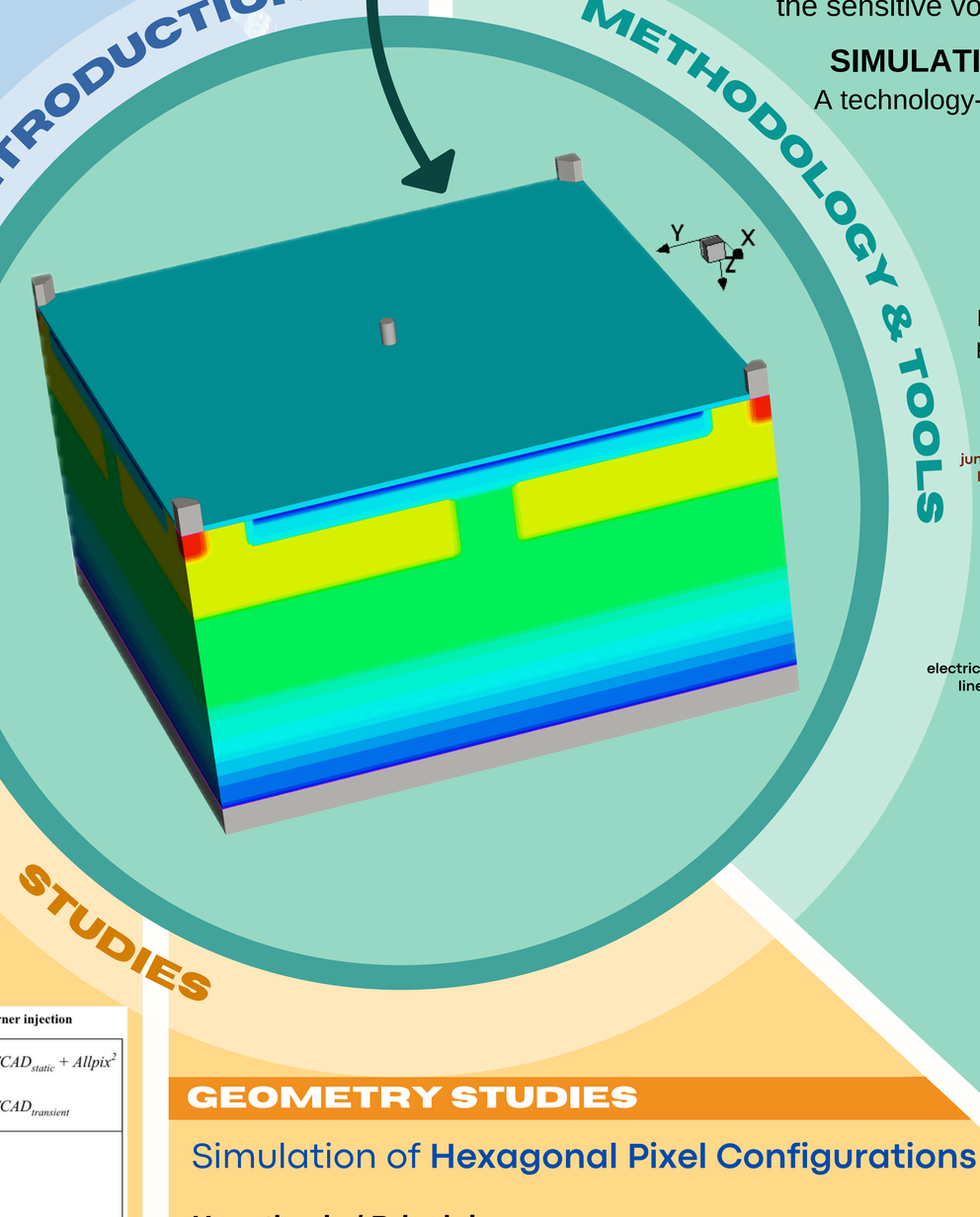
**ELECTRIC FIELD PROFILE RESULTS**




**smaller depleted volume**
- high charge sharing between pixels
- low efficiency

**larger depleted volume**
- improved efficiency
- impairment of resolution

**higher electric field in pixel corners**
- improved efficiency
- improved charge collection
- impairment of resolution

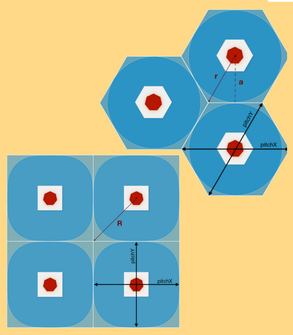



## GEOMETRY STUDIES

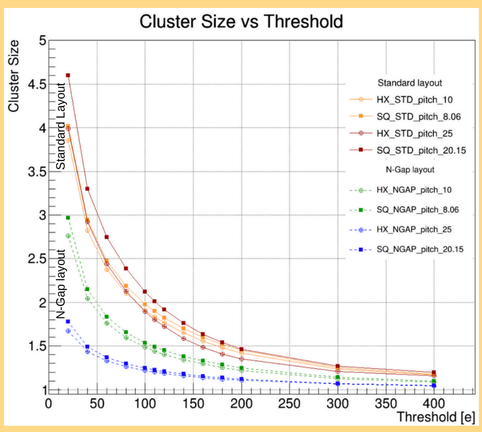
Simulation of **Hexagonal Pixel Configurations**

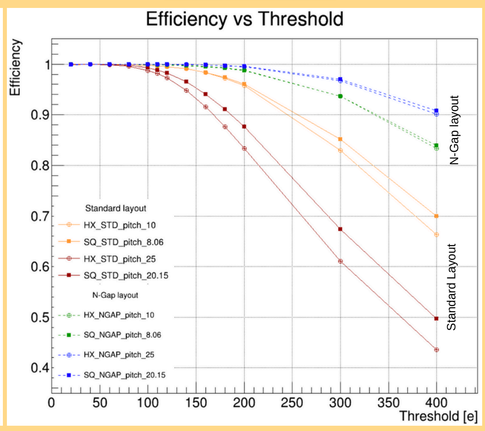
### Hypothesis / Principles

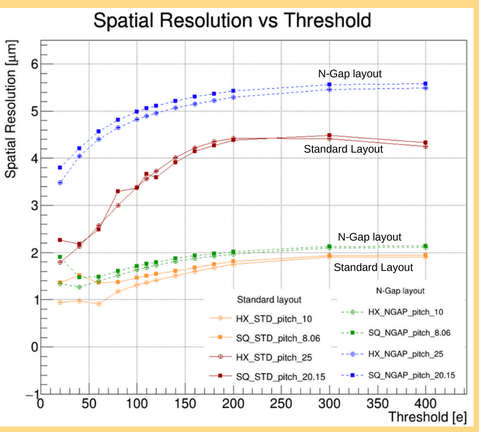
- Possibility to reduce the drift path while maintaining the area for circuitry in the p-well
- Reduced number of neighboring pixels
- Reduce electric field edge effects of square design
- More homogenous response over pixel cell → Relevant for precise timing



- **Cluster Size:** Hexagonal pixels exhibit a smaller cluster size than square pixels in the standard layout
- **Efficiency:** For the standard layout, hexagonal pixels show lower efficiency than square pixels
- **Spatial Resolution:** Hexagonal pixels slightly outperform square pixels for both standard and n-gap layouts.




## Summary & Conclusions

- **Simulations have identified key parameters for optimizing sensor design**
- Timing studies demonstrate the impact of particle incident position on amplitude, timing, and charge collection duration.
- Pixel geometry studies explore the performance of hexagonal pixel grids over square or rectangular layouts.
- Comparison with test-beam data validates the simulation approach.

[1] Chauhan, Ankur et al, Nucl. Instrum. Methods **1047**, 167821 (2023).
[2] CERN Experimental Physics Department. (2018). Strategic R&D Programme on Technologies for Future Experiments. European Organization for Nuclear Research (CERN).
[3] Simancas, Adriana et al, Nucl. Instrum. Methods **1064**, 169414 (2024).
[4] Wennlöf, Håkan et al, Nucl. Instrum. Methods **2025**, 170227 (2025).
[5] Del Rio Viera, Manuel A. et al, arXiv 2502.06675 (2025).
[6] Aglieri Rinella, Gianluca et al, Nucl. Instrum. Methods **1069**, 169896 (2024).
[7] Ruiz Daza, Sara et al, arXiv 2502.06573 (2025).

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DESY.

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