Fine-tuning of MAPS Simulations with Hexagonal Pixel Designs

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ATLAS Final Presentation

2024 DESY Summer Student Program

August 28, 2024

Index

- Motivation
- Monolithic Active Pixel Sensor (MAPS)
- TCAD and Allpix^2 Simulation
- Figures of Merit (FOM)
- Simulation Setup
- Results
- Conclusion

Motivation

TANGERINE (Towards Next Generation Silicon Detectors) project aims the development of 65 nm CMOS MAPS (Monolithic Active Pixel Sensor) for future lepton collider and test beam telescopes.
(by simulations and prototype chip tests)

	(HL-) LHC (ATLAS/CMS)	**Future Lepton Colliders**
Material budget	10% X_0	< 1% X_0
Single-point resolution	~ 15 µm	≤ 3 µm
Time resolution	25 ns	~ ps – ns
Granularity	50 µm x 50 µm	≤ 25 µm x 25 µm

S. Spannagel, 93rd PRC

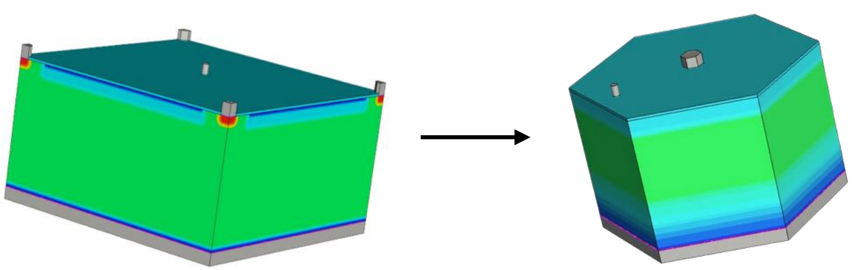
TANGERINE requirements

Parameter	Value
Single-point resolution	$< 3\ \mu m$
Time resolution	1 - 10 ns
Granularity	$< 25\ \mu m \times 25\ \mu m$
Particle rate	1 MHz
Material budget	$< 0.05\%\ X_0$

Hexagonal pixels

- Fewer number of neighboring pixels
- Reduced electric field effects from corners
- Reduced path between the corner and the electrode in the same area of pixels

For studying the possibility of using hexagonal pixels, we use the detailed simulations.

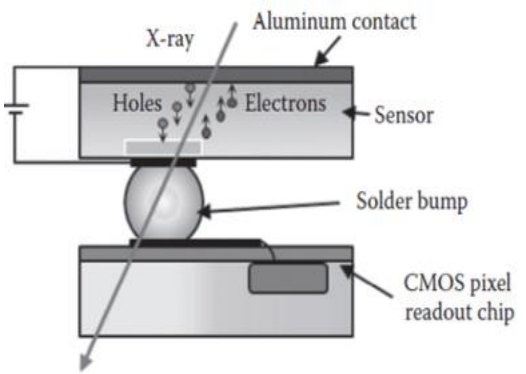


Larissa Mendes

Monolithic Active Pixel Sensor (MAPS)

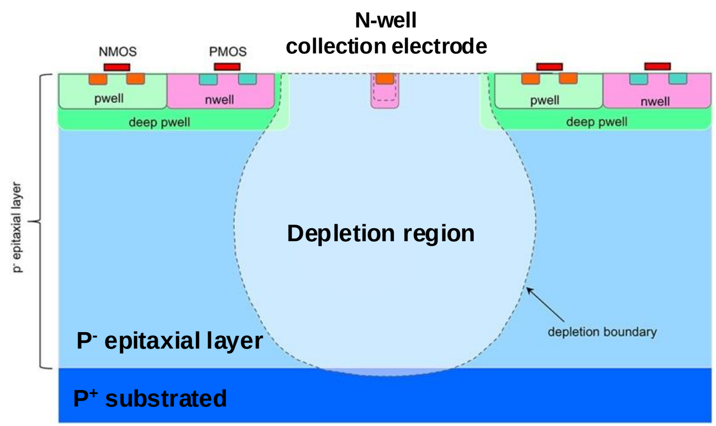
- P-type substrate
- Reverse bias voltage
- Not fully depleted

Conventional hybrid pixel detector



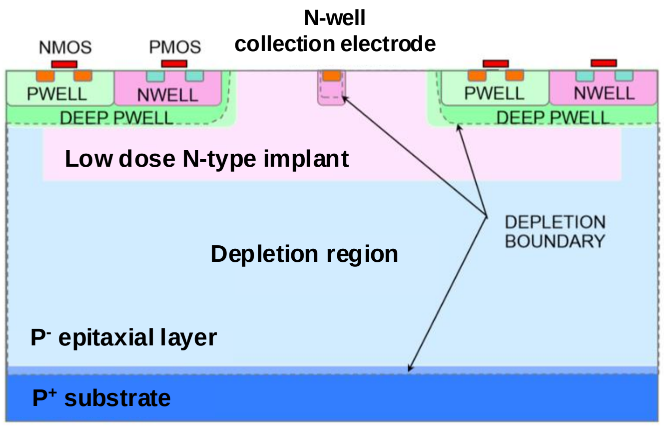
https://doi.org/10.1109/NSSMIC.2017.8533085

MAPS Standard



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

MAPS N-gap



https://doi.org/10.3390/instruments6040051

- ❑ P-type epitaxial layer (epi-layer) with lower doping concentration than p-type Si substrate
→ **high-resistivity, depletion region***

- ❑ Small n-well collection electrode

- ❑ Employing commercial CMOS circuitry for readout electronics (NMOS, PMOS)
→ **low material budget, compactness**

- ❑ N-gap: low dose n-type implantation
→ **larger depletion region, higher efficiency**

*** Depletion region (backup #25)**
Let's think about the PN junction.
We can assume that there're **no mobile charge carriers** in the middle of the n-side and p-side.
Any electron or hole entering this area **will be swept out by the electric field**.
→ In this area, charges **move by drift not by diffusion.**
It attracts charges fast and strongly.
When the **reverse bias** is applied to the PN diode, **depletion region gets wider.**

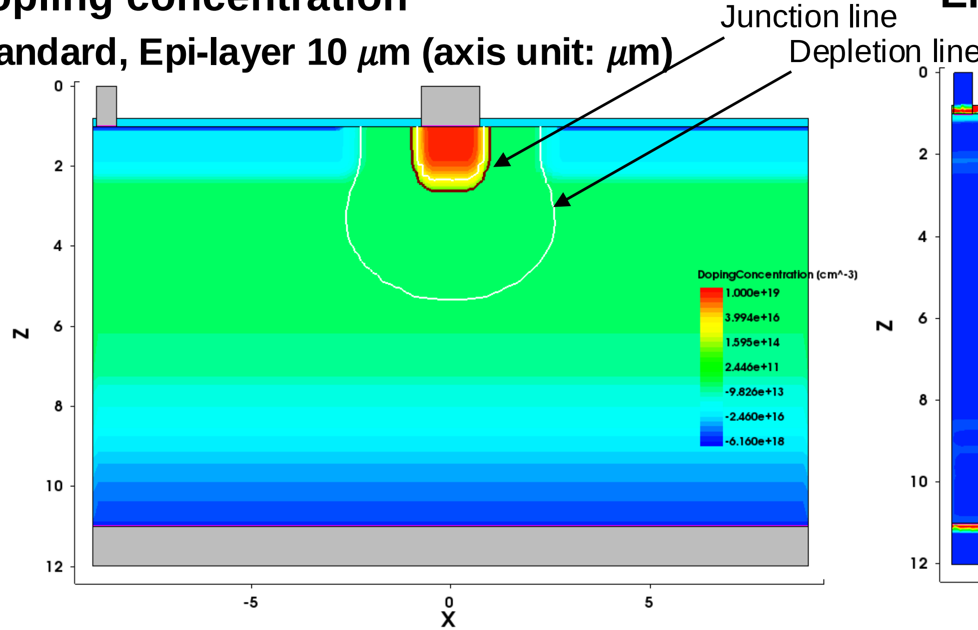
Doping Concentration and Electric Field

Sentaurus TCAD

SYNOPSYS

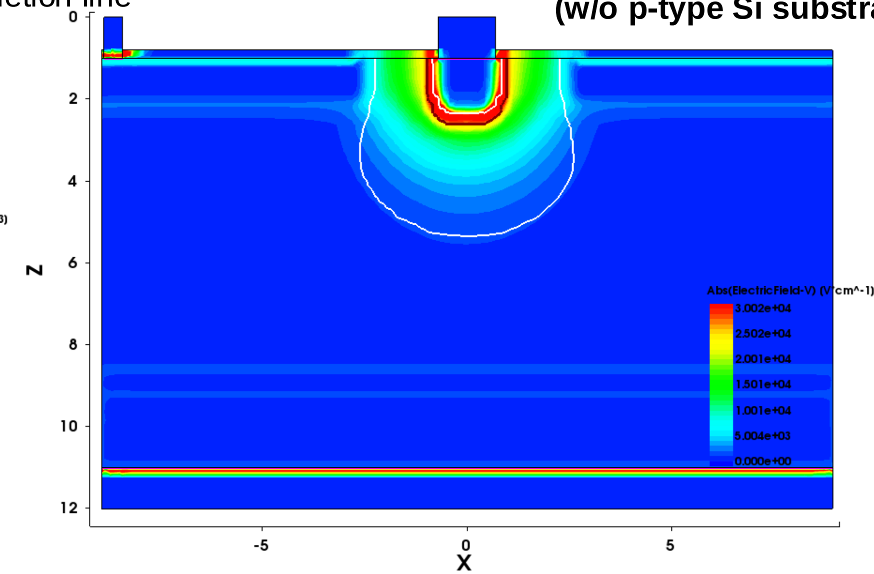
Dopling concentration

Standard, Epi-layer 10 μm (axis unit: μm)

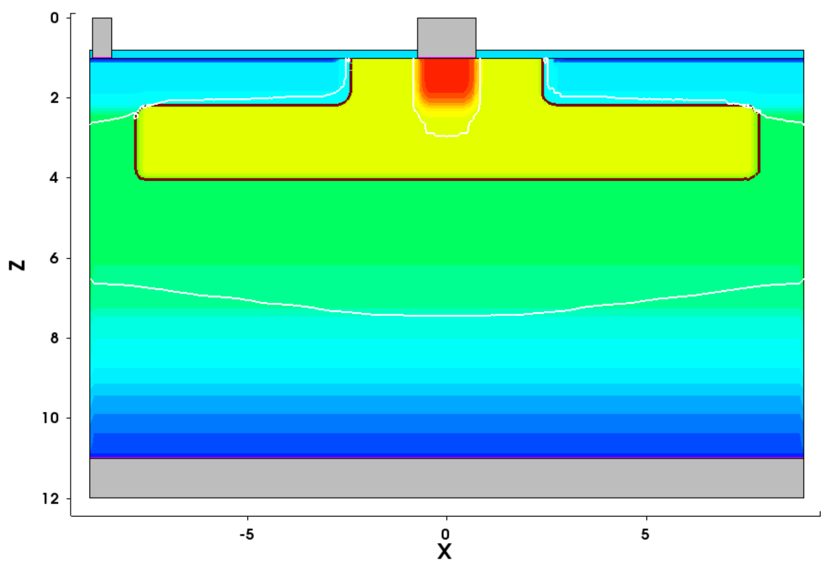


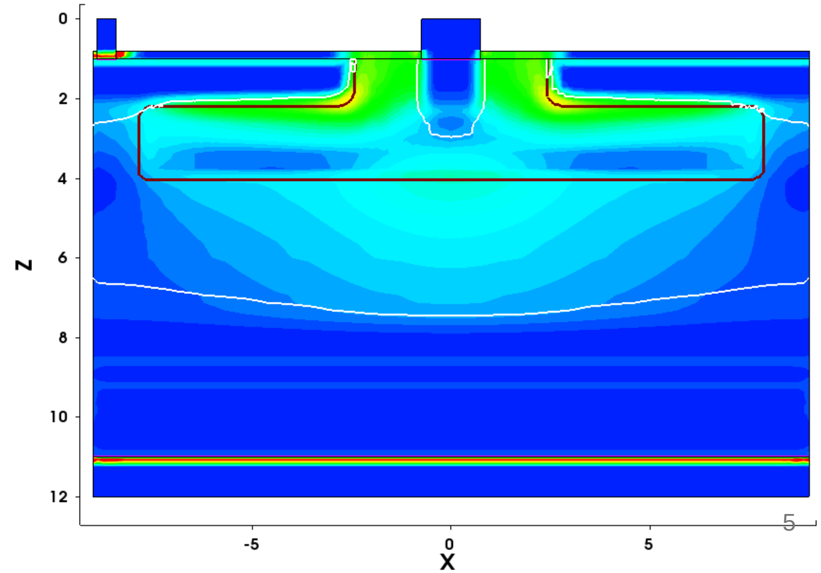
Electric field

Run by Larissa Mendes (w/o p-type Si substrate)



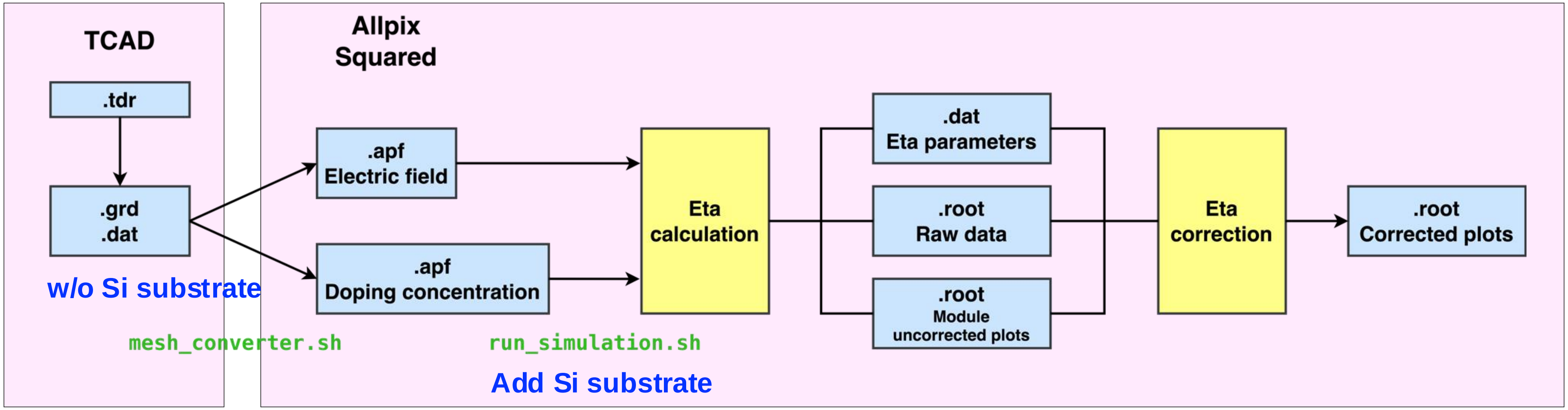
N-gap, Epi-layer 10 μm





Simulation

Data flow in Allpix²

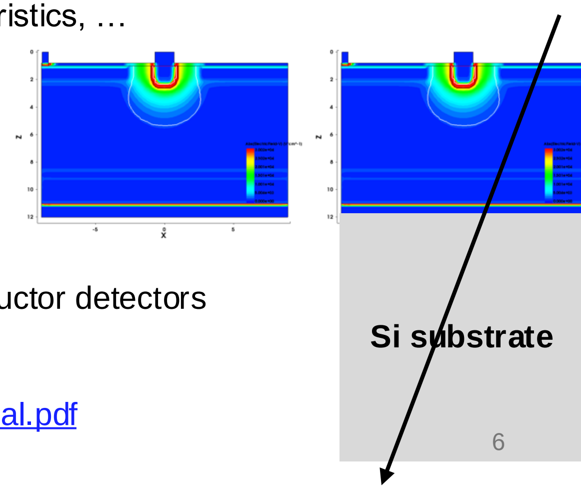


Sentaurus TCAD

- **SProcess**: fabrication process simulation
- **SDevice**: simulates numerically the electrical behaviour of a single semiconductor device
- **SDE**: 2D and 3D device structure editor, geometric operations

SYNOPSYS

→ Doping concentration, electric field, mobility, electrical characteristics, …
https://www.synopsys.com/manufacturing/tcad.html



ap² allpix squared

Monte Carlo simulations
for semiconductor tracker and vertex detectors [2]

- Simulation of **charge deposition and transport** in semiconductor detectors
- **Digitization** to hits in the frontend electronics
- Using **Geant4 and ROOT**

https://project-allpix-squared.web.cern.ch/usermanual/allpix-manual.pdf

Figures of Merit

: a quantity to characterize the performance of the MAPS

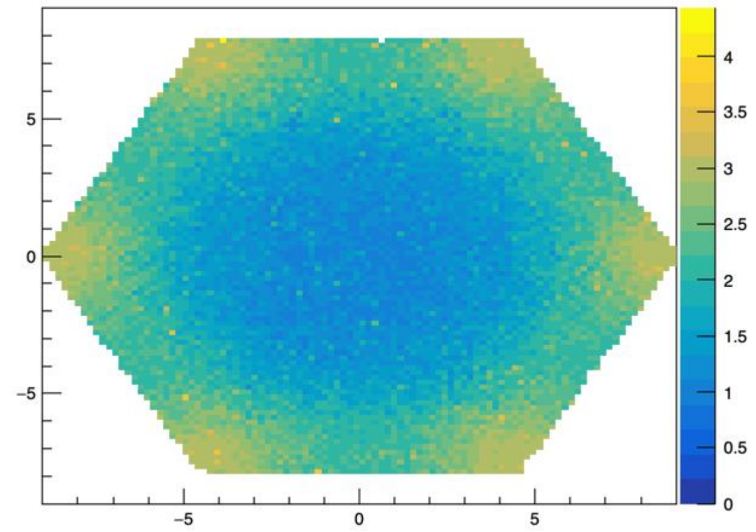
1. Cluster size

- ❑ Number of pixels in each reconstructed cluster (> 1)

- ❑ Shows the degree of charge sharing

→ Larger cluster size means higher charge sharing

- ❑ Mean cluster sizes across the full pixels are in the graphs.



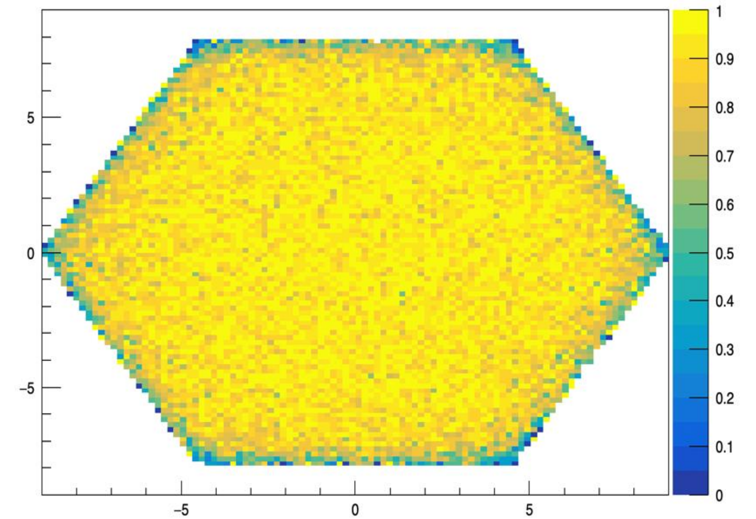
Cluster map

2. Efficiency

- ❑ How many particles generate signals compared to the number of the incident particles.

- ❑ 0 ~ 1 (or 0 ~ 100 %)

- ❑ Mean efficiency across the full pixel are in the graphs.

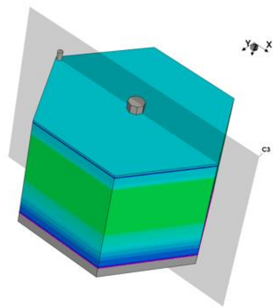


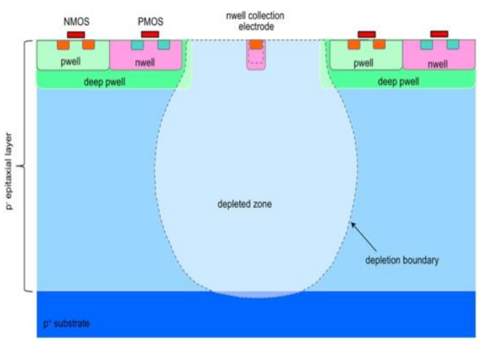
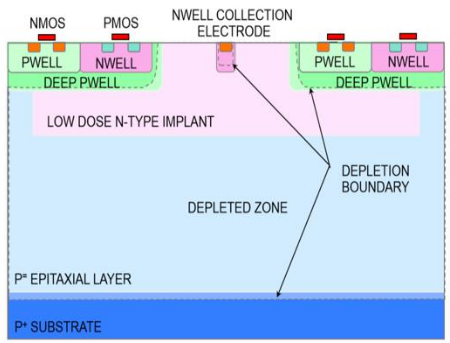
Efficiency map

3. Spatial resolution

- ❑ Difference between reconstructed cluster position and real particle position (residual)

Simulation Setup



Standard	N-gap
	
https://doi.org/10.1016/j.nima.2017.07.046	https://doi.org/10.3390/instruments6040051

Simulation type
Electrostatic

Incident particle
5 GeV electron beam

Geometry
Hexagonal

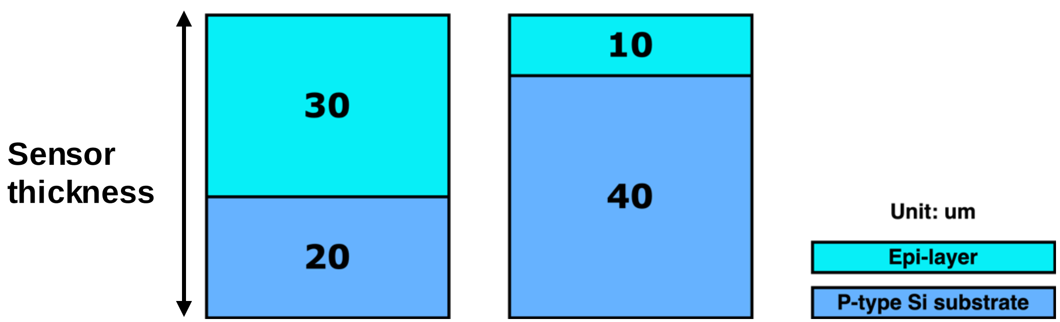
Events
100,000

Voltage supply
Collection electrode 1.2 V
Backside electrode -1.2 V
Contact electrode -1.2 V

Pitch
10.00 μm
18.00 μm
25.00 μm

Layout and epi-layer

Standard,	Epi 30 μm
Standard,	Epi 10 μm
N-gap,	Epi 30 μm
N-gap,	Epi 10 μm



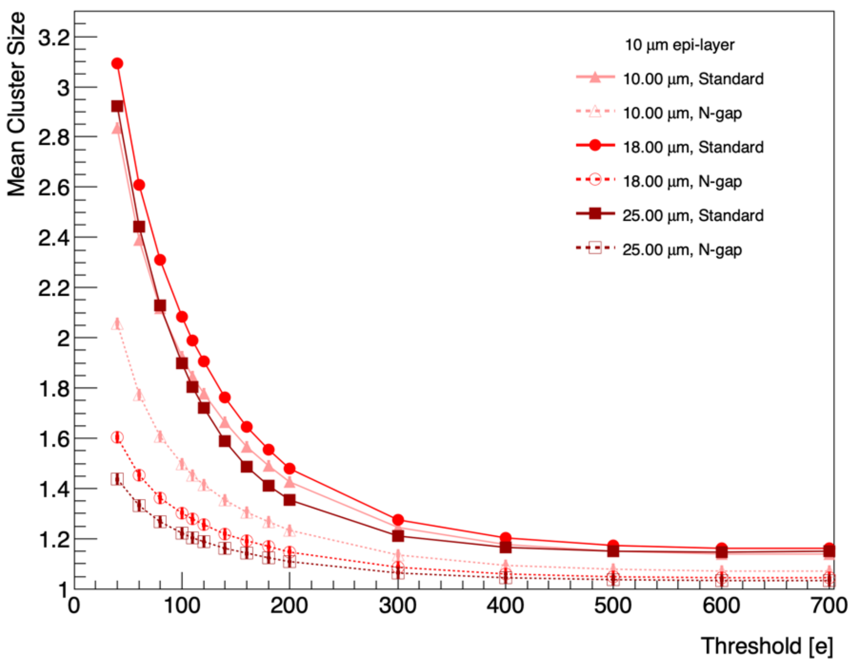
1. Pitch and layout comparison
at 10 μm epi-layer

2. Epi-layer and layout comparison
at 18.00 μm pitch

+ Integration time comparison
25 ns
40 ns
5 μs

Pixel size and Layout Comparison
(10 μm epi-layer)

Cluster Size



25.00 μm pitch has smaller cluster size for both layouts.

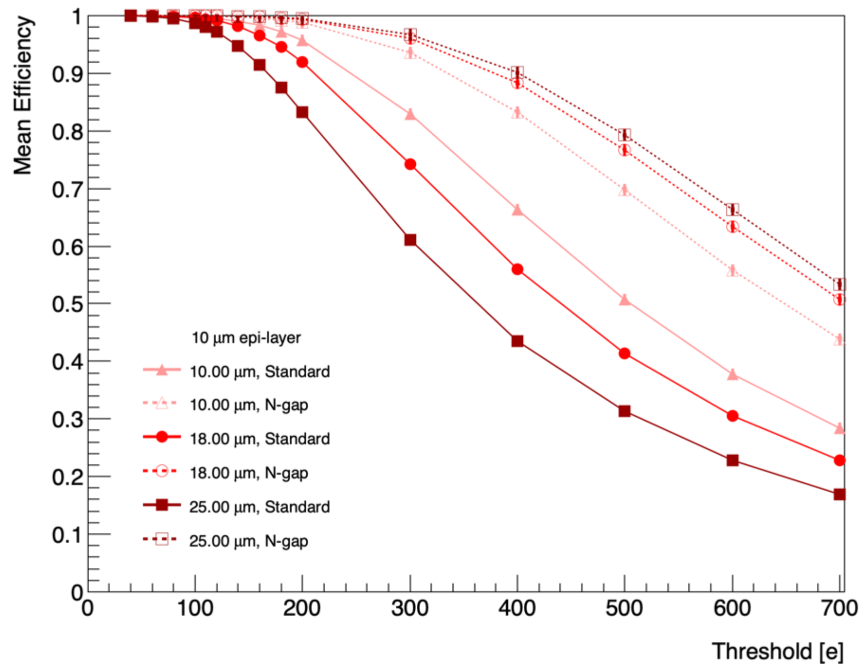
N-gap

- N-gap has smaller cluster size (less charge sharing) *as expected*
- Cluster sizes are inversely proportional to the pitch.

Standard

- Cluster sizes are not proportional to the pitch.

Efficiency



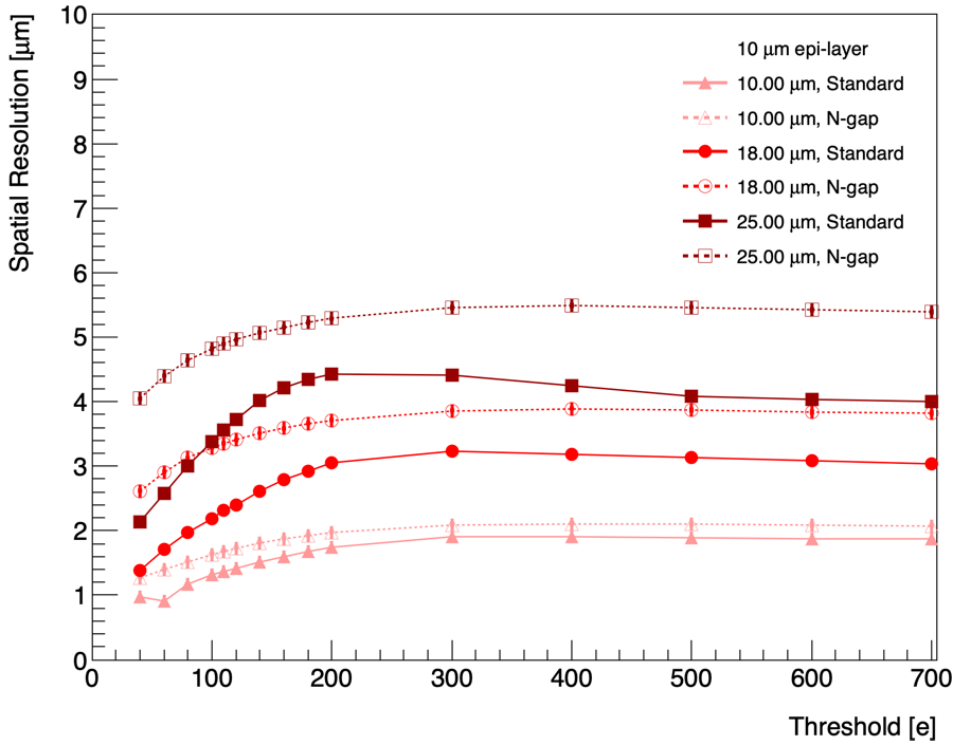
The highest efficiency in 25.00 μm N-gap

- N-gap has higher efficiency than Standard *as expected.*
- N-gap efficiency is proportional to pitch size.
- Standard efficiency is inversely proportional to pitch size.

*** More details are in the slide #20 (backup)*

Residual in X: Spatial Resolution

(10 μm epi, multiple pitch sizes)



No significant differences between X and Y *as expected.*

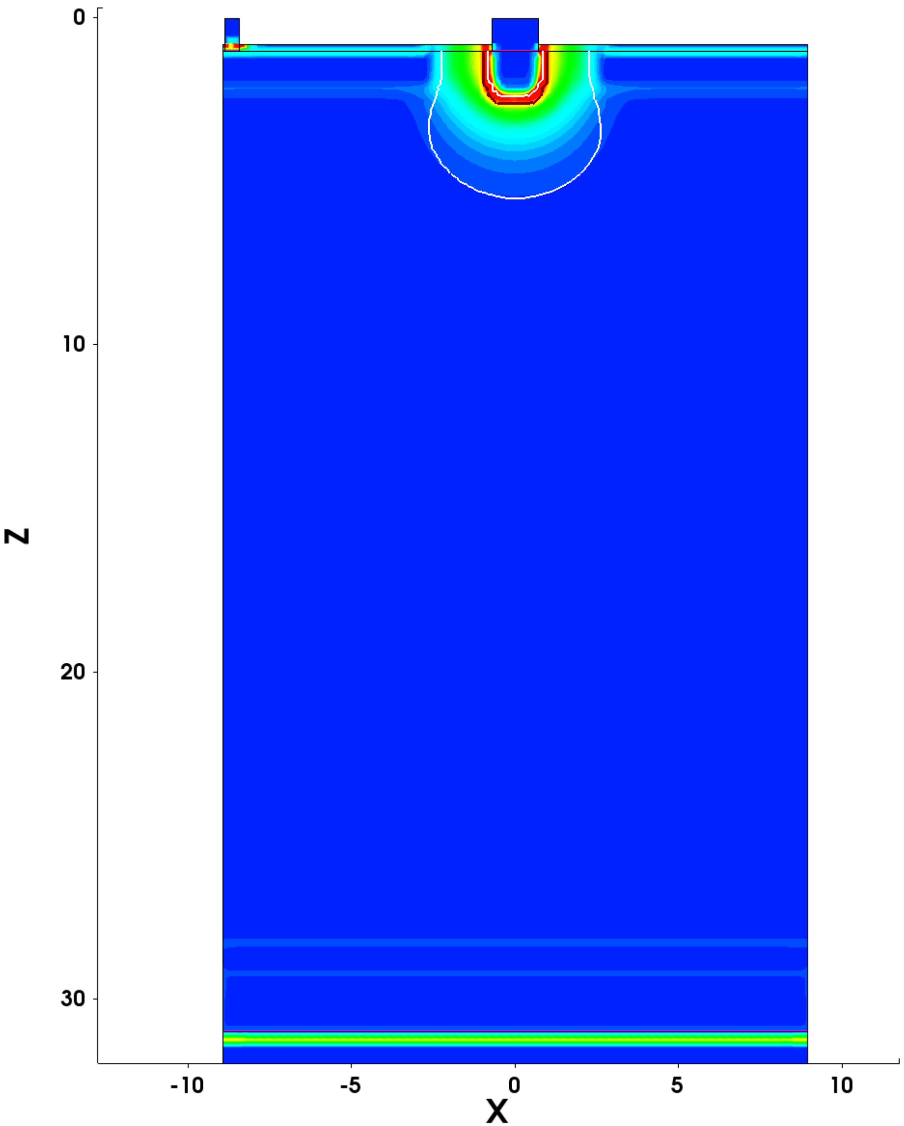
- Standard has higher spatial resolution than N-gap *as expected.*
- If we use the smaller pitch we can overcome the layout differences *as expected*.

N-gap is more stable under 200e threshold.

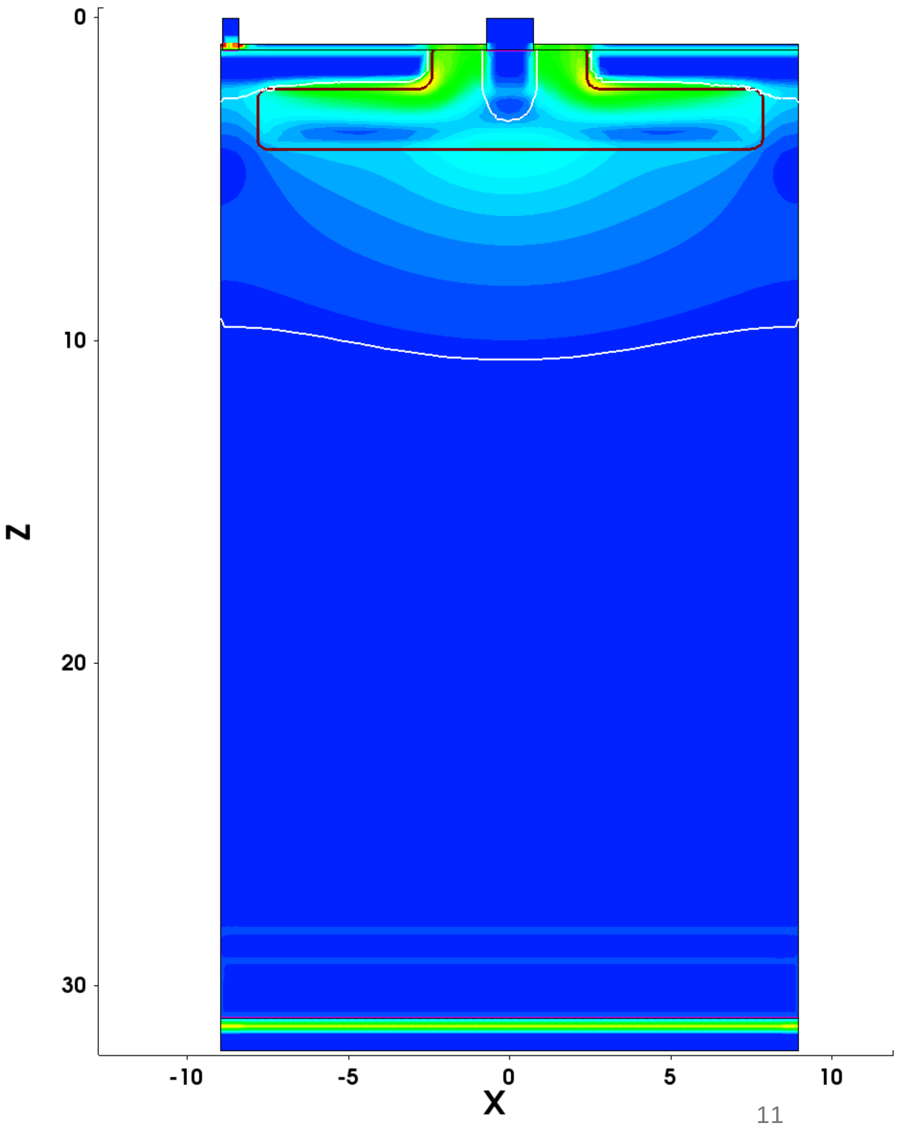
Electric Field in 30 μm Epi-layer

Run by Larissa Mendes
(w/o p-type Si substrate)

Standard (axis unit: μm)



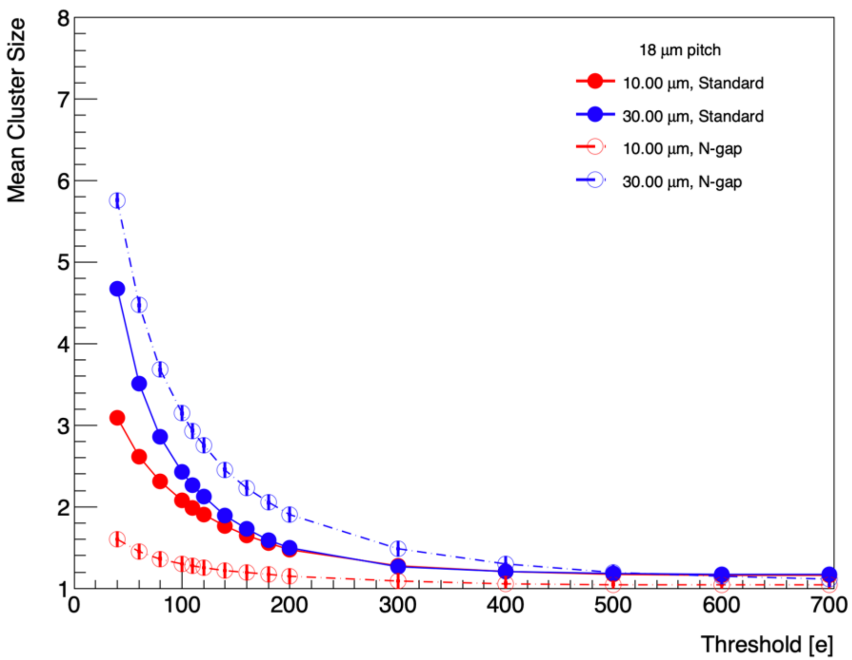
N-gap



Epitaxial Layer and Layout Comparison

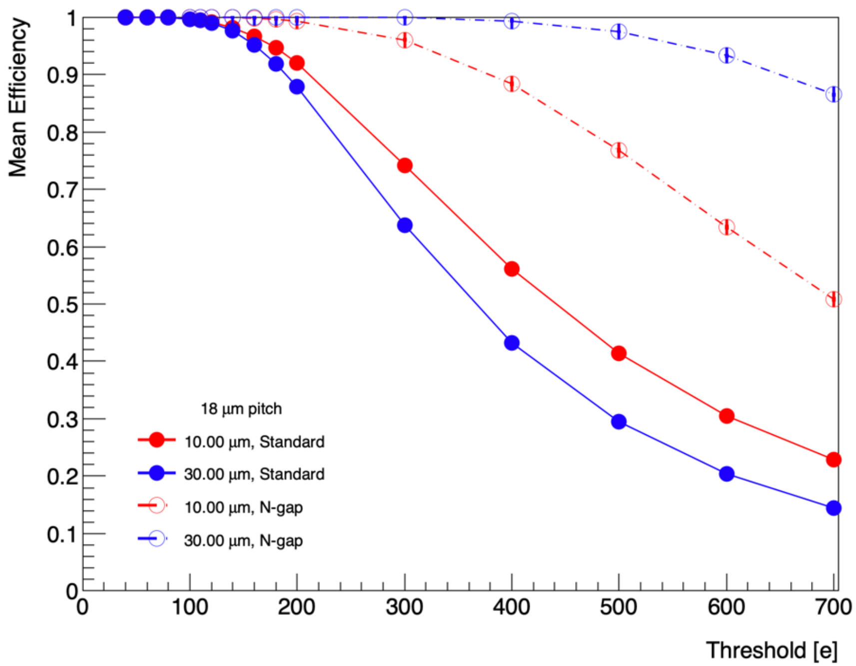
(18 μm pitch, 25 ns integration time)

Cluster Size



- 10 μm has smaller cluster size than 30 μm.

Efficiency

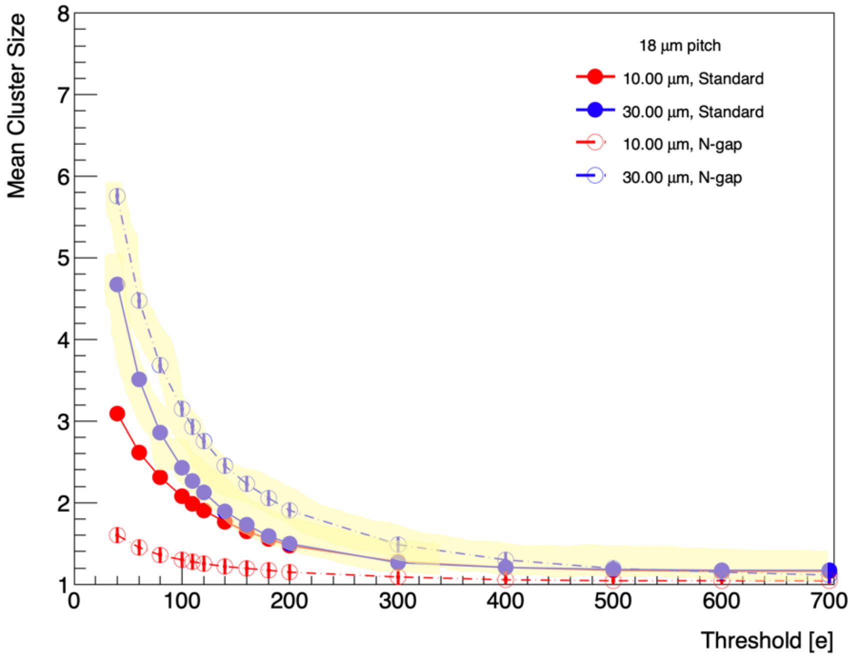


- The highest efficiency in 30 μm N-gap
- N-gap has higher efficiency than Standard.

Out of Expectation

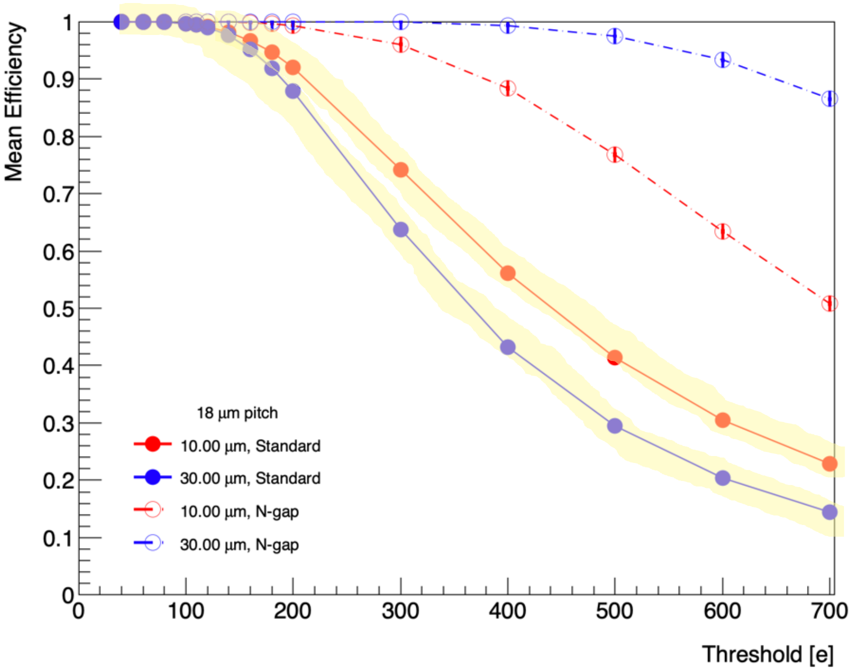
(18 μm pitch, 25 ns integration time)

Cluster Size



- 10 μm has smaller cluster size than 30 μm.
- **In 30 μm, N-gap has bigger cluster size than Standard.**

Efficiency

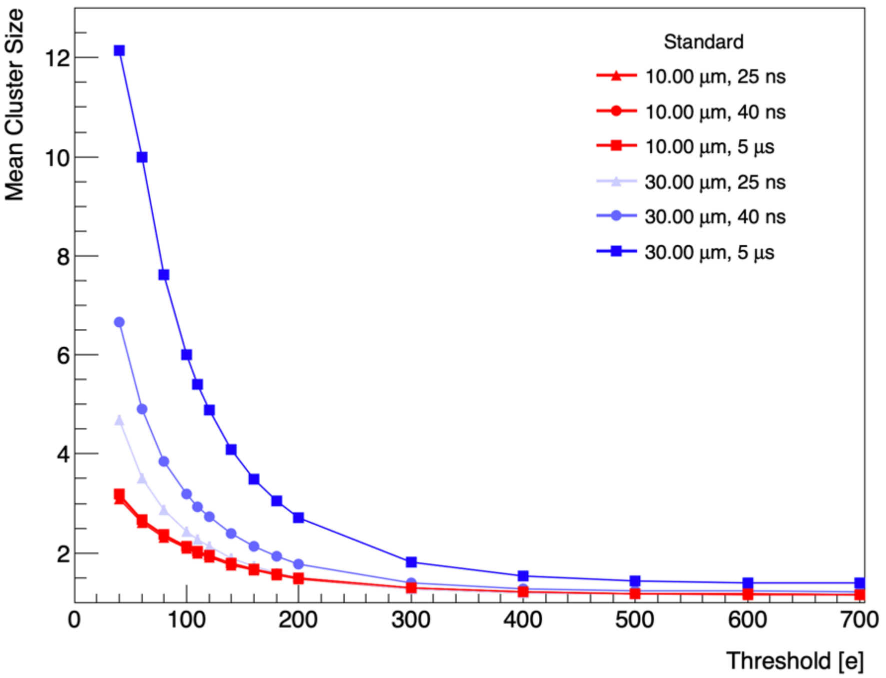


- The highest efficiency in 30 μm N-gap
- N-gap has higher efficiency than Standard.
- **In Standard, 10 μm is more efficient than the 30 μm.**

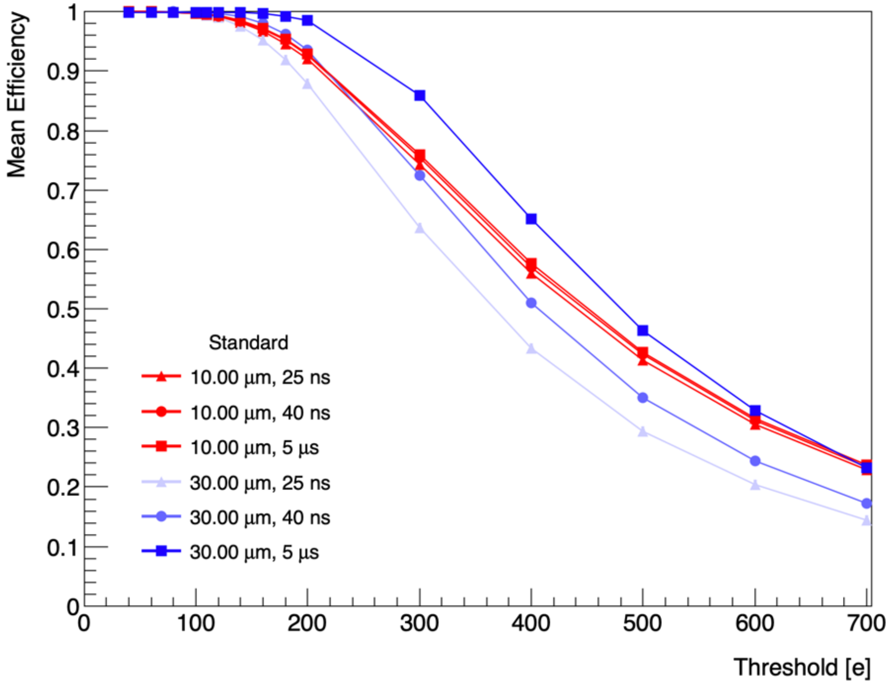
Integration Time Comparison

: 25 ns, 40 ns, 5 μs in both epi-layer (standard, 18 μm pitch)

Cluster Size



Efficiency



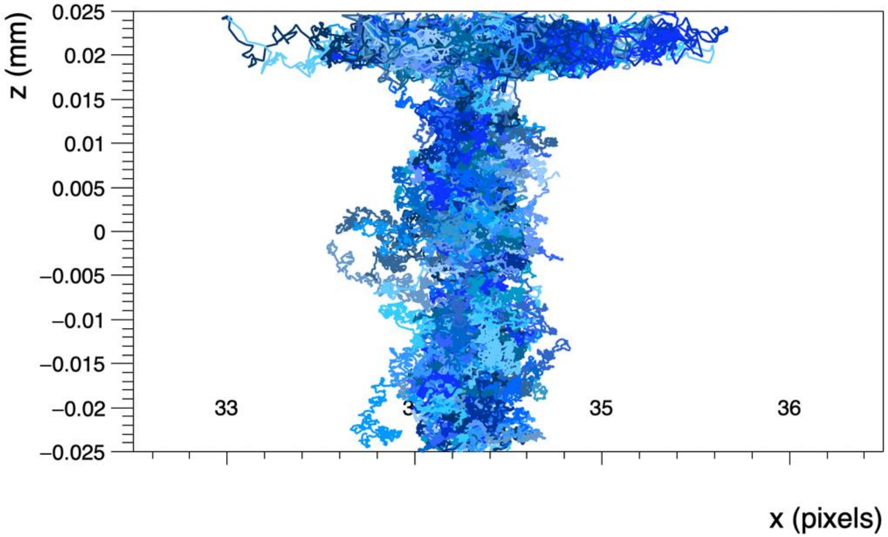
(No significant change in 10 μm epi-layer.)

- **In 30 μm, cluster size and efficiency increases with the integration time.**
- 30 μm exceeds 10 μm in efficiency at 5 μs.

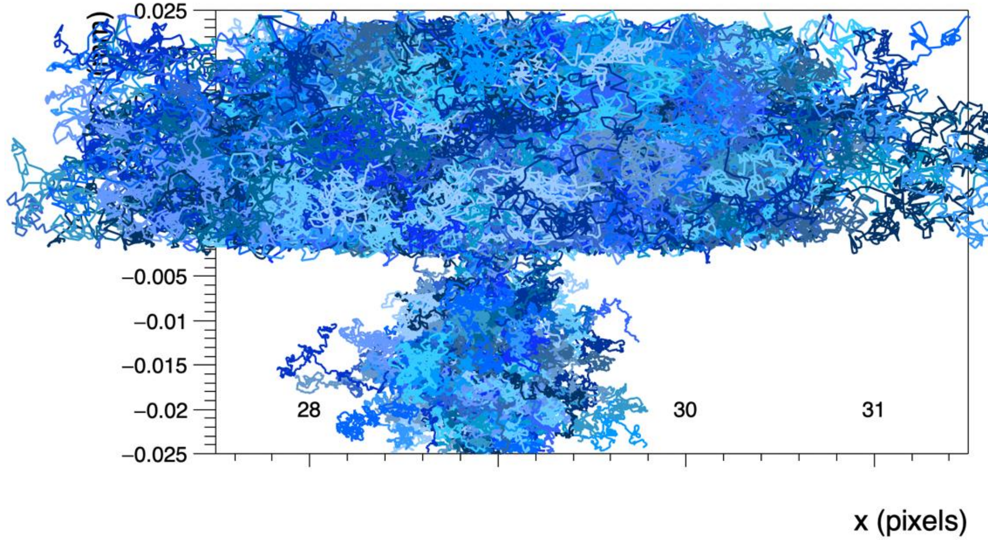
Linegraphs for Standard (40 ns)

threshold: 60e

10 μm epi-layer

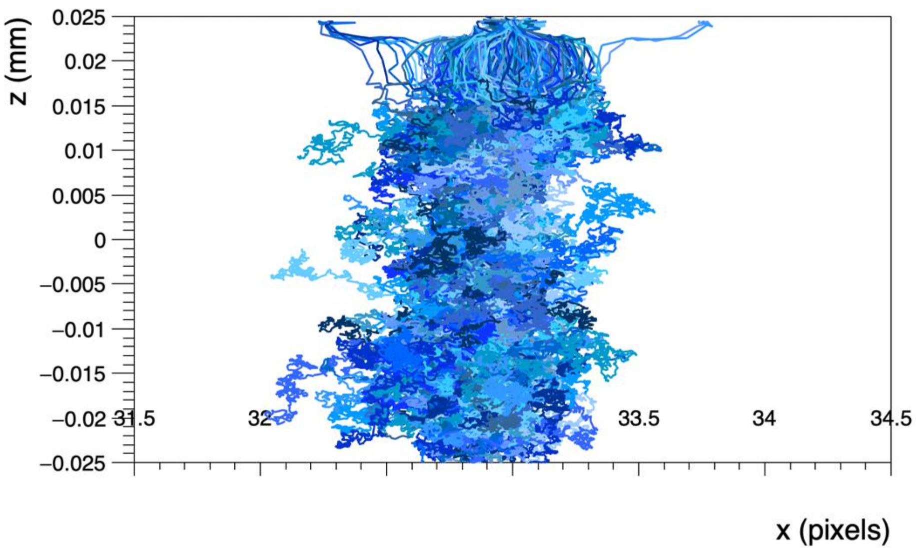


30 μm epi-layer

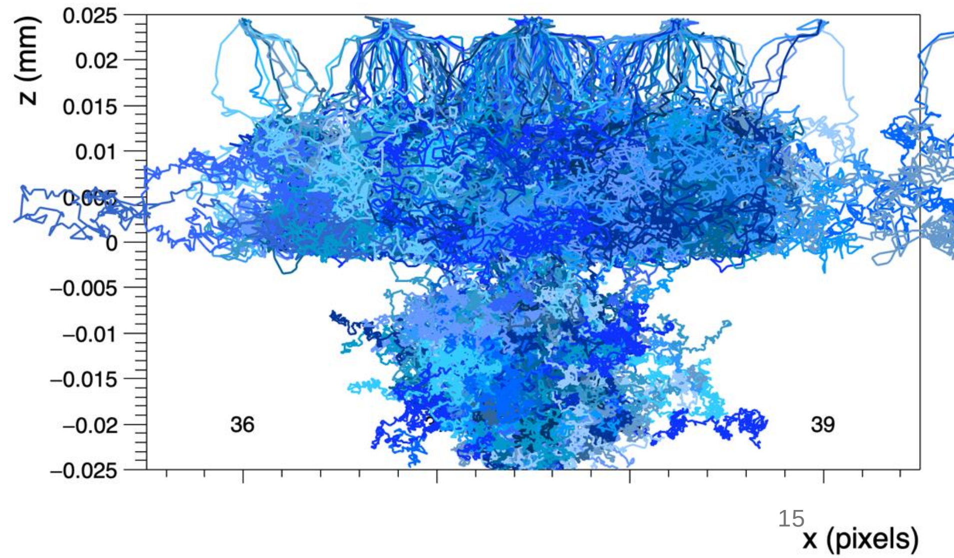


Linegraphs for N-gap (40 ns)

10 μm epi-layer



30 μm epi-layer

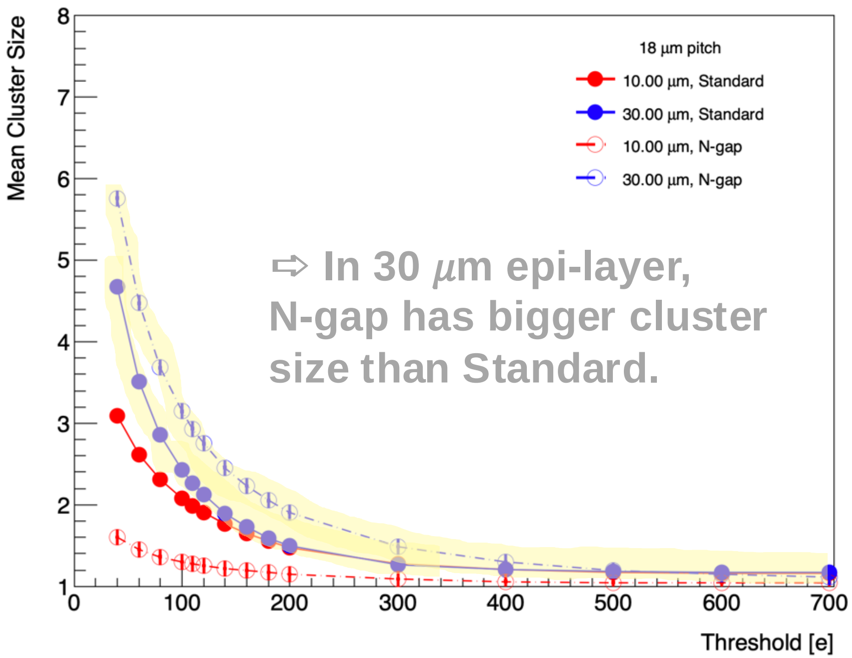


Now We Can Understand ..

(10 and 30 μm epi-layer, 18 μm pitch)

Cluster Size

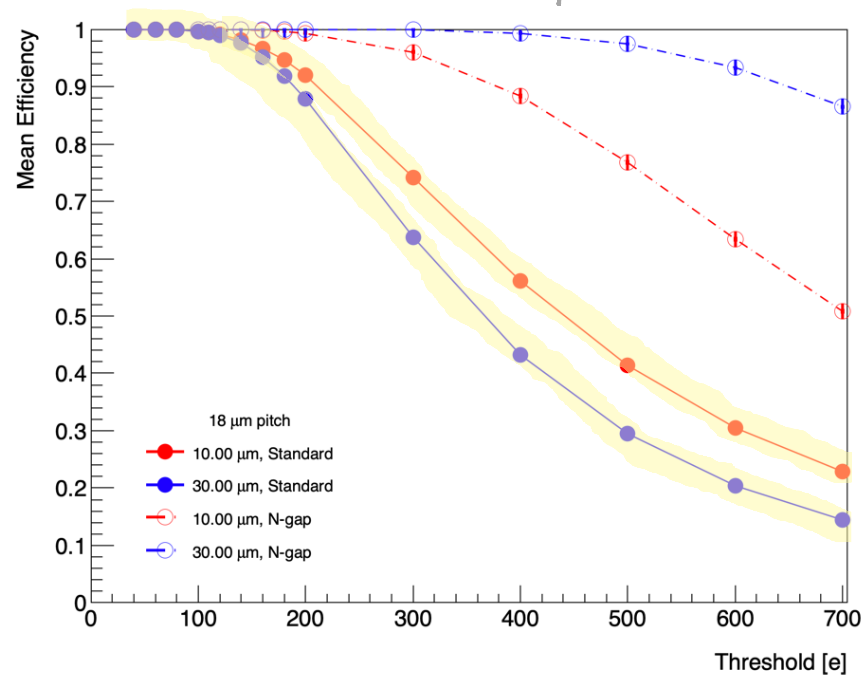
25 ns



Efficiency

25 ns

⇨ In Standard, 10 μm is more efficient than the 30 μm.



Explanation of 30 μm: It makes wide diffusion

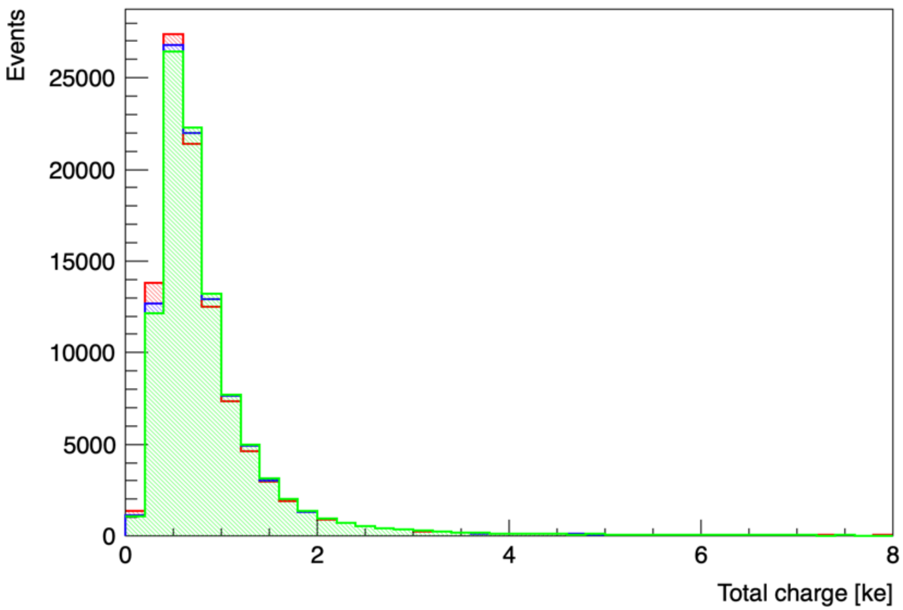
- ❑ In Standard, many charge carriers can be recombined before reaching the depletion region of the far pixel. That's why we lose efficiency rapidly as the thresholds increase.
- ❑ But in N-gap, it has larger depletion region. Thus, although they move widely by diffusion, carriers can easily reach the depletion region in far pixels and generate signals.
- ❑ We can also explain why only the 30 μm epi-layer is influenced by the integration time.

Total Charge Per Event

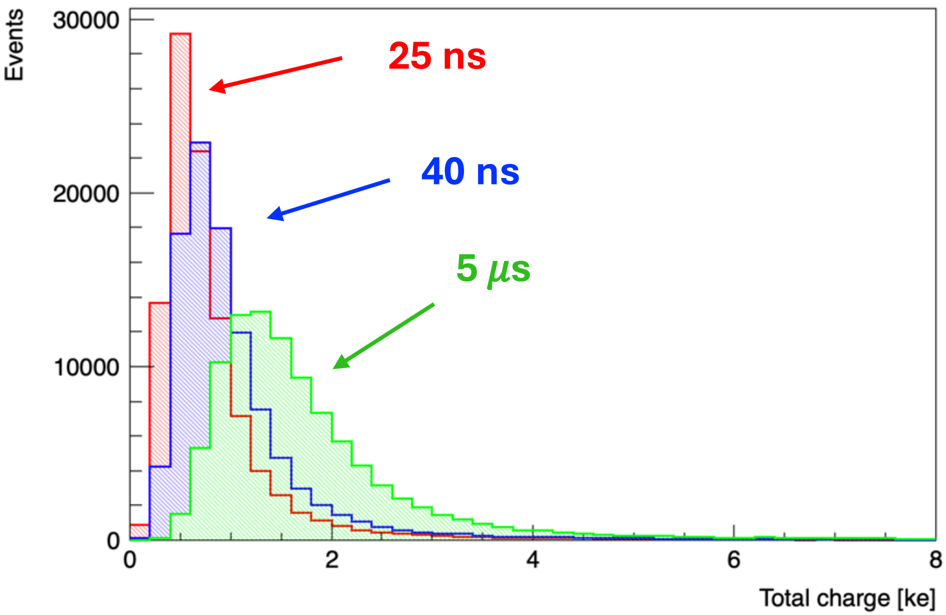
(25 ns, 40 ns, 5 μs for standard in both epi-layer)

* Fit function: Landau distribution

10 μm epi-layer



30 μm epi-layer



Most probable value

10 μm		30 μm	
25 ns	5.00e-1	25 ns	4.96e-1
40 ns	5.10e-1	40 ns	6.45e-1
5 μs	5.15e-1	5 μs	1.16

In 30 μm, charges diffuse for a long time going far pixels, and they couldn't be collected in the integration time.

This also supports our explaination!

Conclusion

1. In 10 μm epi-layer, N-gap has smaller cluster size and higher efficiency.
However, it shows worse spatial resolution compared to the Standard.
(It's because larger cluster size makes reconstruction position more precise)

2. 30 μm epi-layer shows unexpected behaviors in cluster size and efficiency.
- In 30 μm, N-gap has bigger cluster size than Standard.
- In Standard, 10 μm is more efficient than the 30 μm.

➔ To investigate, we changed integration time and checked the charge and linegraphs.
:Only in the 30 μm, cluster size and efficiency increases with the integration time.

➔ It's because 30 μm epi-layer makes carriers diffuse widely and the Standard cannot collect them due to its small depletion region.

Backup

More Details

10 um epi-layer (slide #9, 10)

Efficiency proportionality
- ❑ N-gap: bigger pitch offers larger space for charge collection (depletion region)
- ❑ Standard: bigger pitch makes larger space out of depletion region. It worsens the efficiency.

This also can explain why the cluster sizes change easily with the pitch in N-gap compared to Standard.

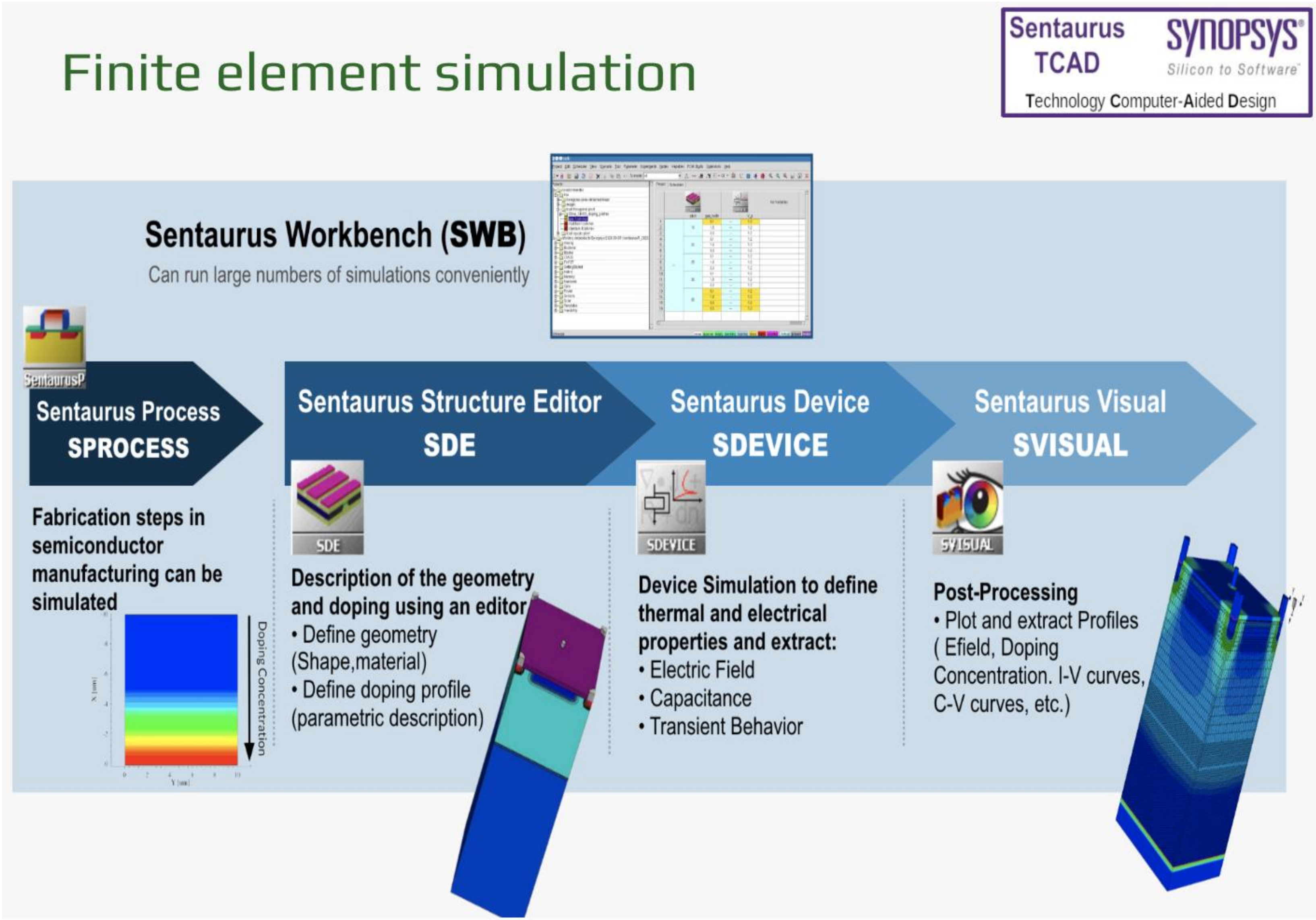
**** Comments from Håkan**

Cluster size changes with pitches

As the pitch increases, there will be smaller room for charge sharing.

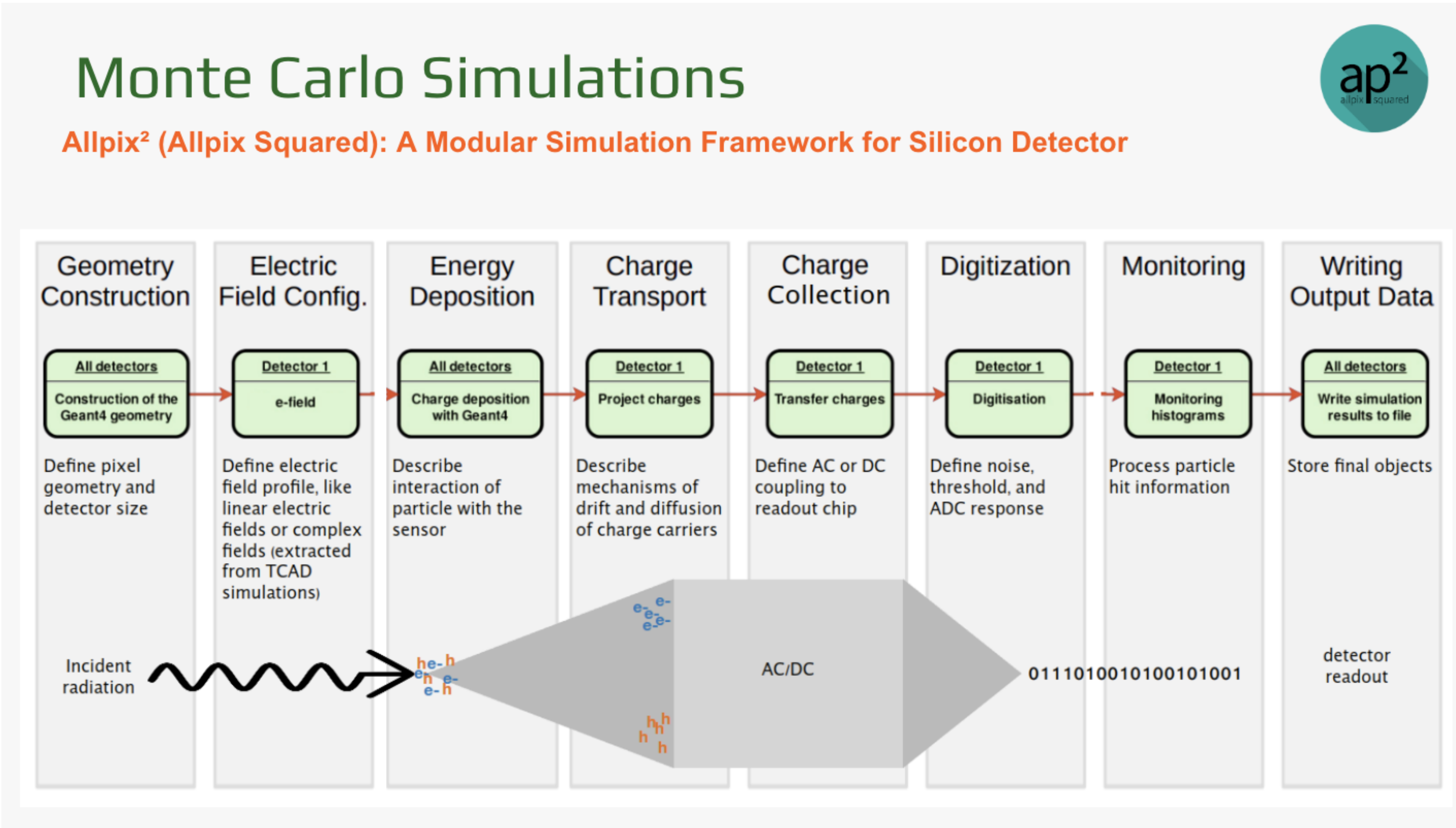
When efficiency gets lower, we also lose cluster size.

TCAD



Finite element simulation
Sentaurus TCAD
SYNOPSYS
Silicon to Software
Technology Computer-Aided Design
Sentaurus Workbench (SWB)
Can run large numbers of simulations conveniently
SentaurusP
Sentaurus Process
SPROCESS
Sentaurus Structure Editor
SDE
Sentaurus Device
SDEVICE
Sentaurus Visual
SVISUAL
Fabrication steps in semiconductor manufacturing can be simulated
Doping Concentration
SDE
Description of the geometry and doping using an editor
• Define geometry (Shape,material)
• Define doping profile (parametric description)
SDEVICE
Device Simulation to define thermal and electrical properties and extract:
• Electric Field
• Capacitance
• Transient Behavior
SVISUAL
Post-Processing
• Plot and extract Profiles (Efield, Doping Concentration. I-V curves, C-V curves, etc.)

Allpix^2


Monte Carlo Simulations
Allpix² (Allpix Squared): A Modular Simulation Framework for Silicon Detector
ap²
Geometry Construction
Electric Field Config.
Energy Deposition
Charge Transport
Charge Collection
Digitization
Monitoring
Writing Output Data
All detectors
Construction of the Geant4 geometry
Detector 1
e-field
All detectors
Charge deposition with Geant4
Detector 1
Project charges
Detector 1
Transfer charges
Detector 1
Digitisation
Detector 1
Monitoring histograms
All detectors
Write simulation results to file
Define pixel geometry and detector size
Define electric field profile, like linear electric fields or complex fields (extracted from TCAD simulations)
Describe interaction of particle with the sensor
Describe mechanisms of drift and diffusion of charge carriers
Define AC or DC coupling to readout chip
Define noise, threshold, and ADC response
Process particle hit information
Store final objects
Incident radiation
AC/DC
0111010010100101001
detector readout

Spatial Resolution

- RMS of 3σ (99.7 %) residual distribution

- Residual: difference between reconstructed cluster position and real particle position

In Allpix² simulation,

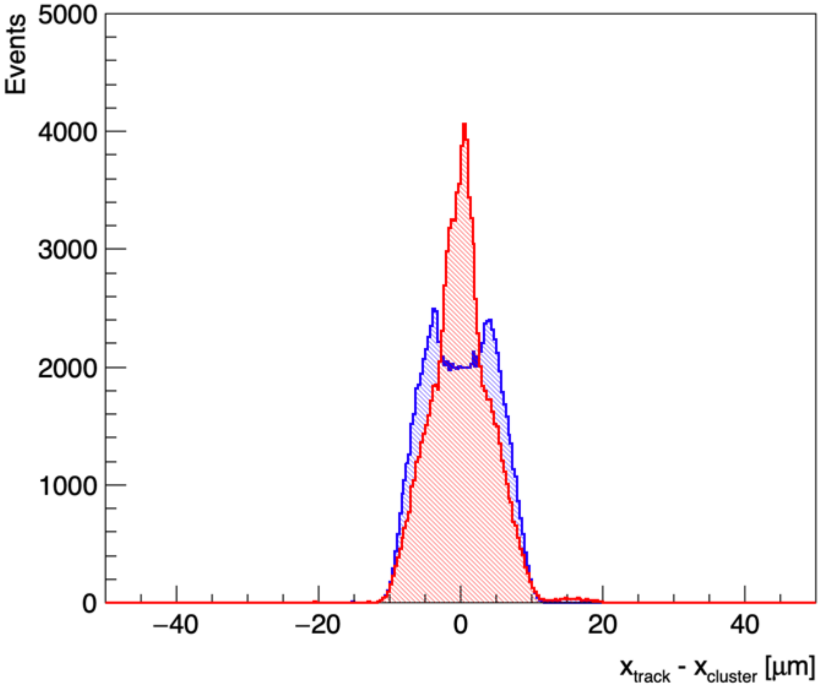
- Reconstructed cluster position: charge-weighted mean of a cluster

$$x = \frac{\sum_i x_i q_i}{\sum_i q_i}$$

- Real particle position: randomly drawn position from a Gaussian distribution

- Bigger cluster size leads to the smaller spatial resolution because it makes more precise reconstructed position

- We use an η-correction



Residual distribution
: Before (blue) and after (red) η-correction

Deep P-well

In real, NMOS, PMOS → p-well → deep p-well structure.
(In TCAD simulation, we use it without CMOS.)
P-well is bigger than deep p-well for more space for charge collection.

Epitaxial Layer

Epitaxy (prefix *epi*- means "on top of") refers to a type of crystal growth or material deposition in which new crystalline layers are formed with one or more well-defined orientations with respect to the crystalline seed layer.

TCAD Files

*.grd: grid file. Structure of mesh.

*.dat: contain variables such as e-field potential and carrier concentrations at every mesh point in the device.

Depletion Region

With the reverse bias voltage (ref. G. Lutz, Semiconductor Radiation Detectors)

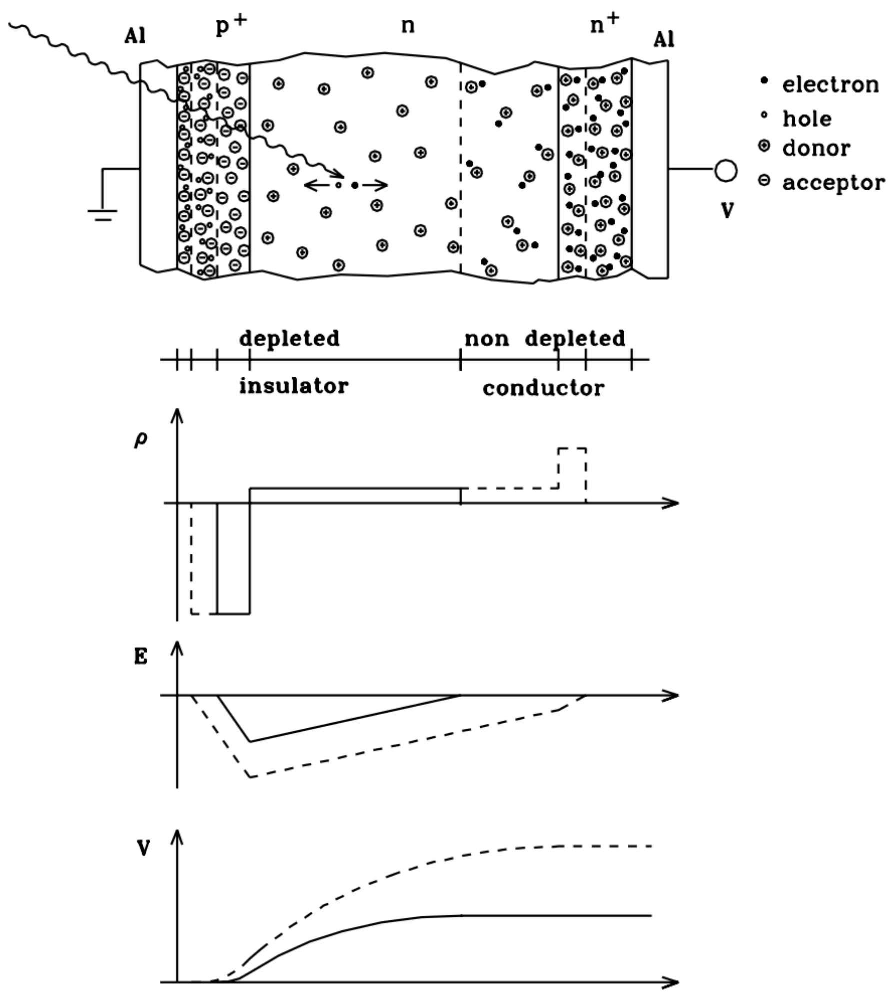


Fig. 5.2. A p–n diode junction detector: charge density, electric field and potential for partial (*continuous line*) and full (*dashed line*) depletion