ARCADIA fully-depleted monolithic active pixel sensors optimised for sub-nano second timing

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on behalf of the ARCADIA collaboration

18th Trento Workshop on Advanced Silicon Radiation Detectors

ARCADIA monolithic sensors

ARCADIA (**A**dvanced **R**eadout **C**MOS **A**rchitectures with **D**epleted **I**ntegrated sensor **A**rrays) R&D project

SPACE APPLICATIONS

- very low power consumption (< 20 mW/cm^2)
- scalable matrix size

MEDICAL APPLICATIONS

- fast timing (time resolution below 10 ns)
- low voltages
- low material budget

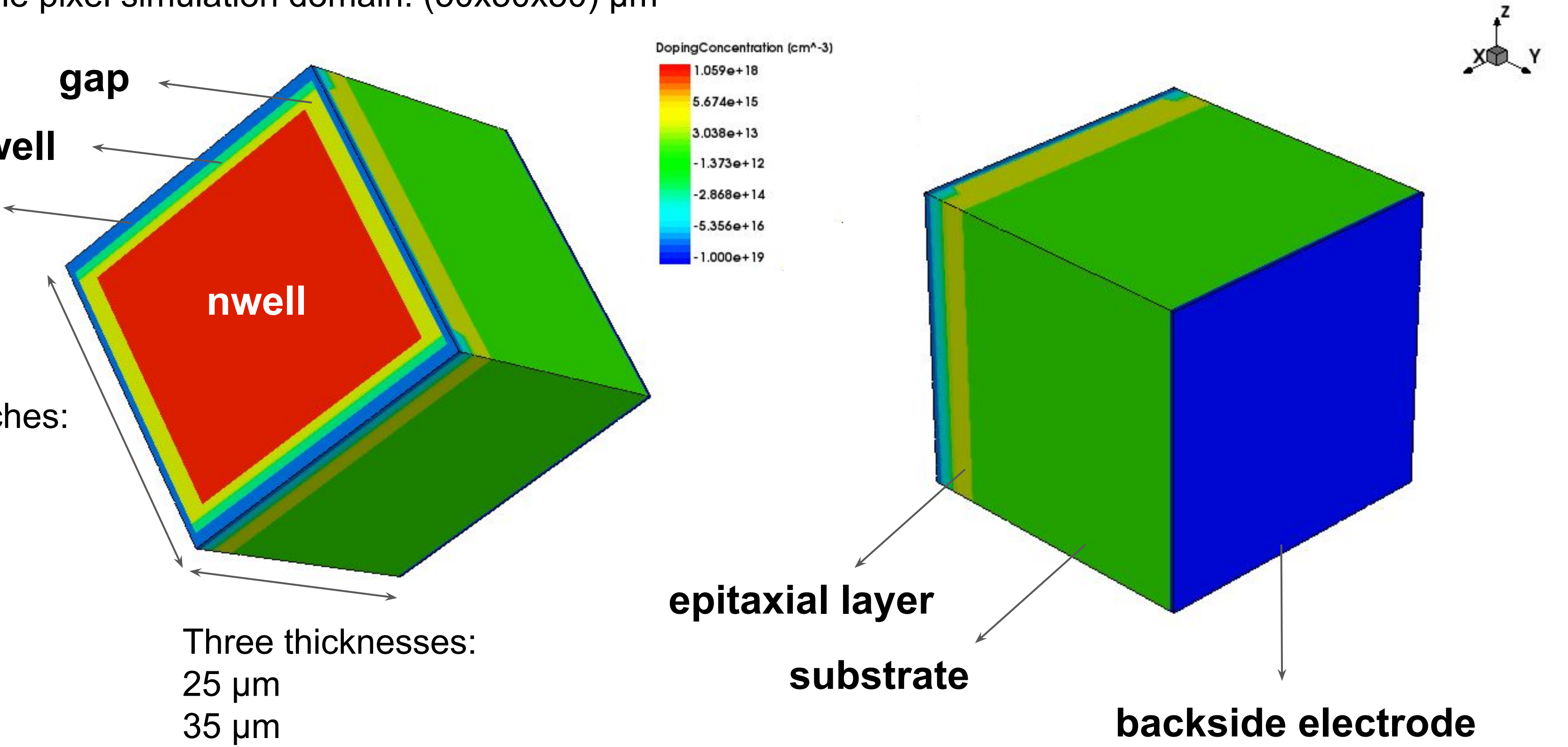
HIGH ENERGY EXPERIMENTS

- low power consumption
- fast timing
- low voltages
- high radiation hardness (1Mrad)
- improved spatial resolution (pixel pitch 20-25 μm, thickness 50-100 μm)
- scalability

- *Fully depleted Monolithic Active Pixel Sensor* (FD-MAPS) profit from a low material budget and cost
- Charge collection by drift: fast and uniform response over all the pixel matrix
- Innovative sensor design based on a modified 110 nm CMOS process with backside bias to improve charge collection efficiency and timing

ARCADIA pad diode monolithic sensor

TCAD single pixel simulation domain: (50x50x50) μm³

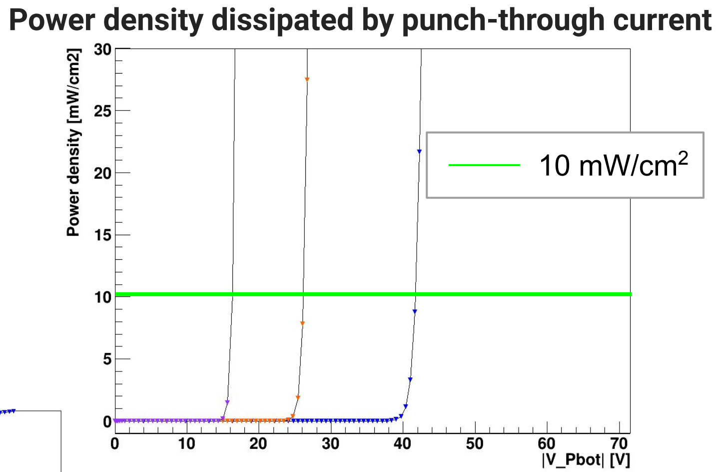


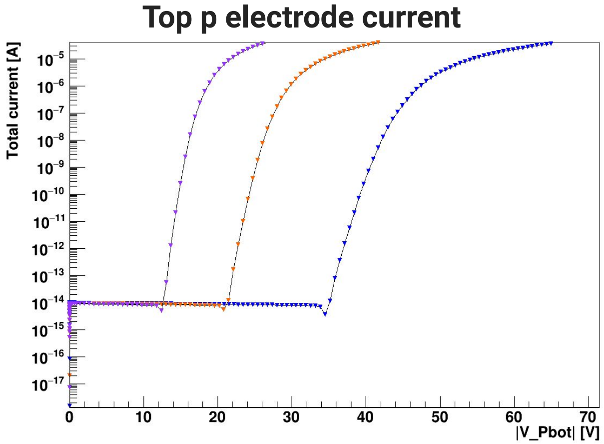
Four pitches:
50 μm
100 μm
150 μm
200 μm

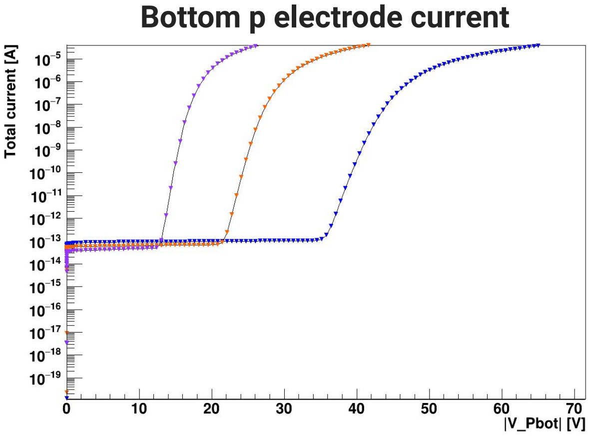
Three thicknesses:
25 μm
35 μm
50 μm

Punch-through current and power density @ 10 mW/cm^2

Pixel pitch [um]	Thickness [um]	Vn [V]	|Vpt| [V]	|Vpd| @ 10 mW/cm^2 [V]
50	**50**	3.3	34.5	41.7
50	**35**	3.3	20.8	26.2
50	**25**	3.3	12.4	16.3







Pixel pitch 50 μm

- 50 μm thickness
- 35 μm thickness
- 25 μm thickness

SIMULATION TOOLS

TCAD

- Numerical simulation tool for sensor modeling
- Describes carriers motion and electromagnetic fields
- Very demanding on computing time

Synopsys® Sentaurus TCAD

ALLPIX^2

- Monte Carlo simulations
- High statistics
- Geant4 for energy deposition
- Telescope and complex detector geometries

ap^2 allpix squared

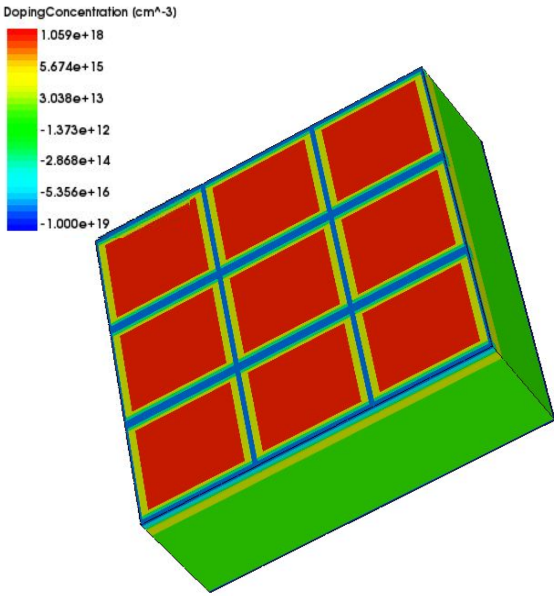
Allpix^2: a modular simulation framework

- Modular, Monte Carlo based simulation framework for detectors built in CMOS technologies
- Possibility to combine TCAD-simulated electric fields with a Geant4 simulation of the particle interaction with matter, taking into account the stochastic nature of the initial energy deposition
- Static electric field

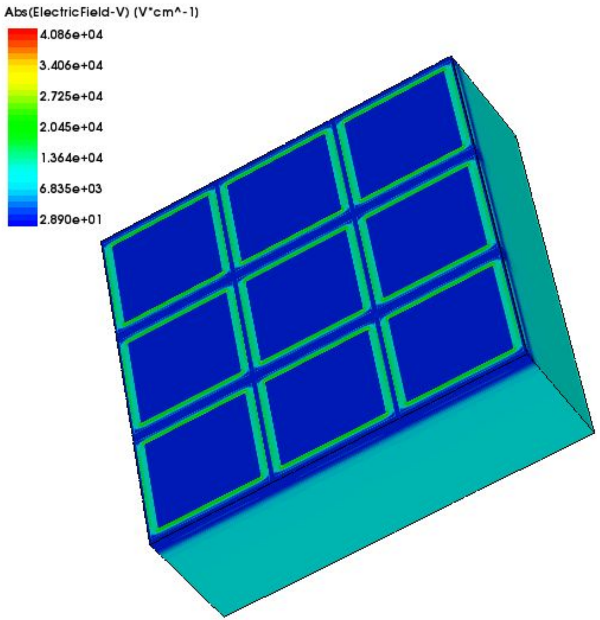
TCAD simulated electric field → Mesh Converter tool → Allpix^2 Signal simulation → High statistic of particle-sensor interaction → Sensor model to compare with tests on silicon

TCAD simulated electric field

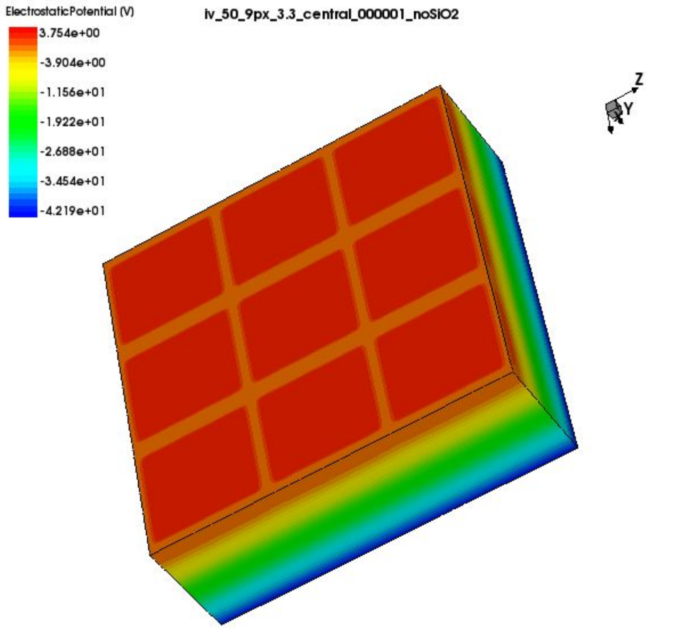
TCAD 3x3 simulation domain



Doping

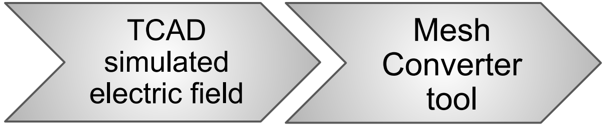


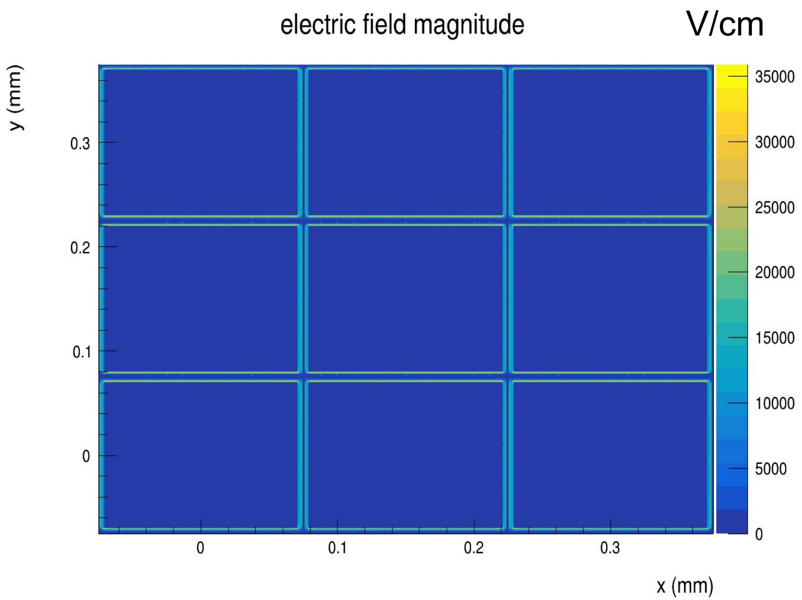
Electric Field

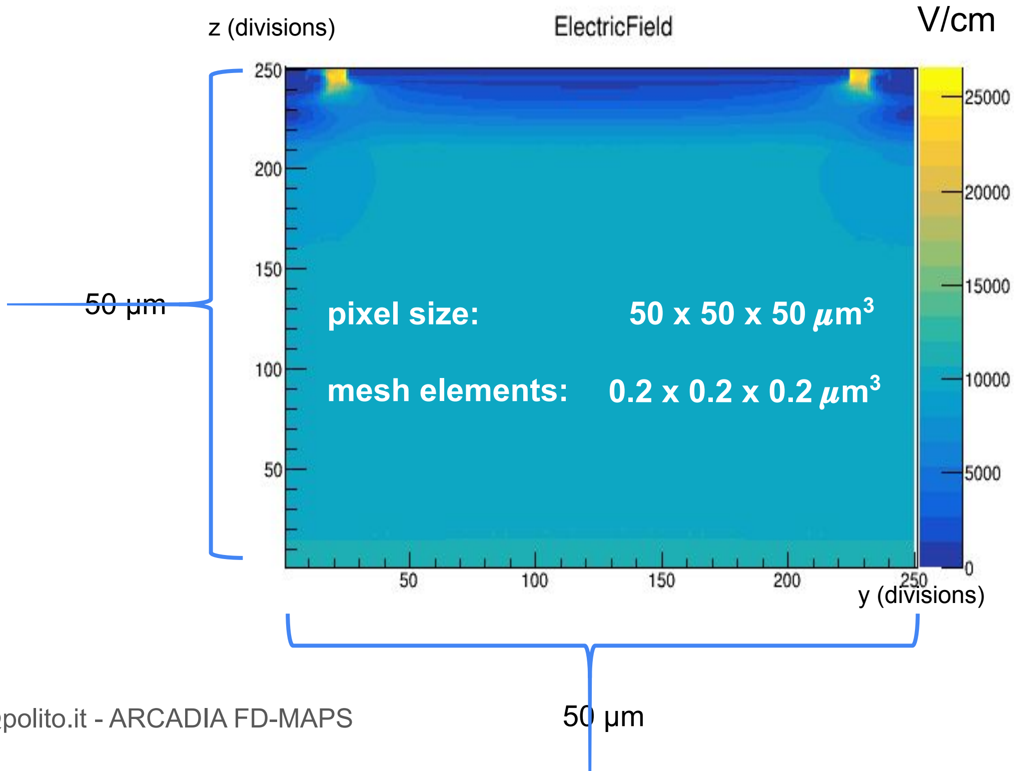


Electrostatic Potential

Electric field - single pixel domain 50 μm pitch

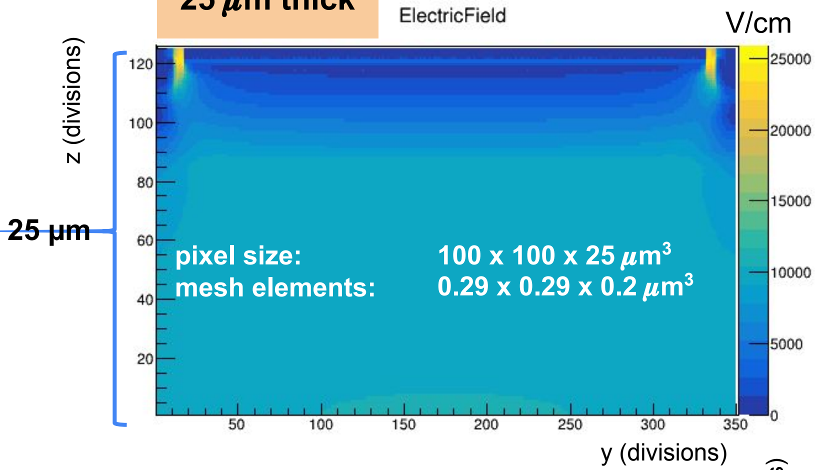




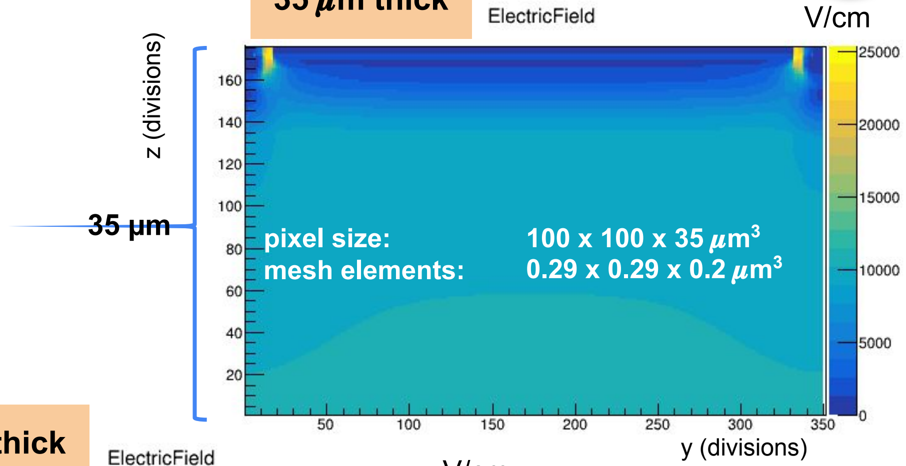


Electric Field - single pixel domain 100 μm pitch

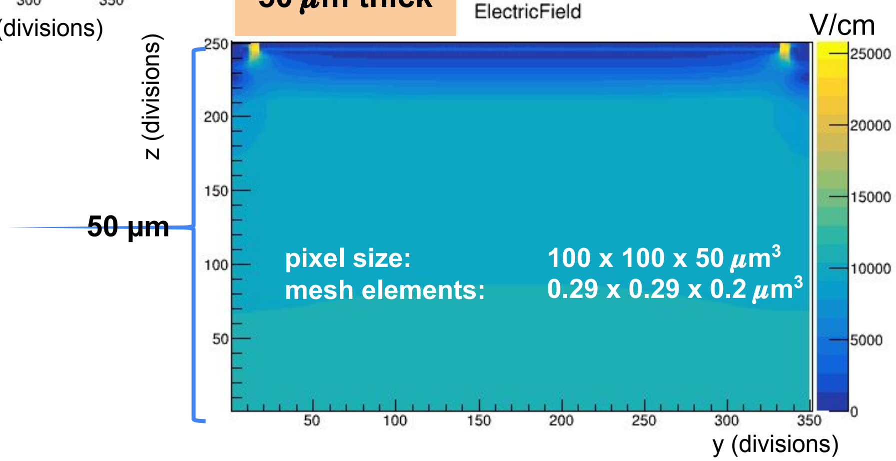
25 μm thick



35 μm thick



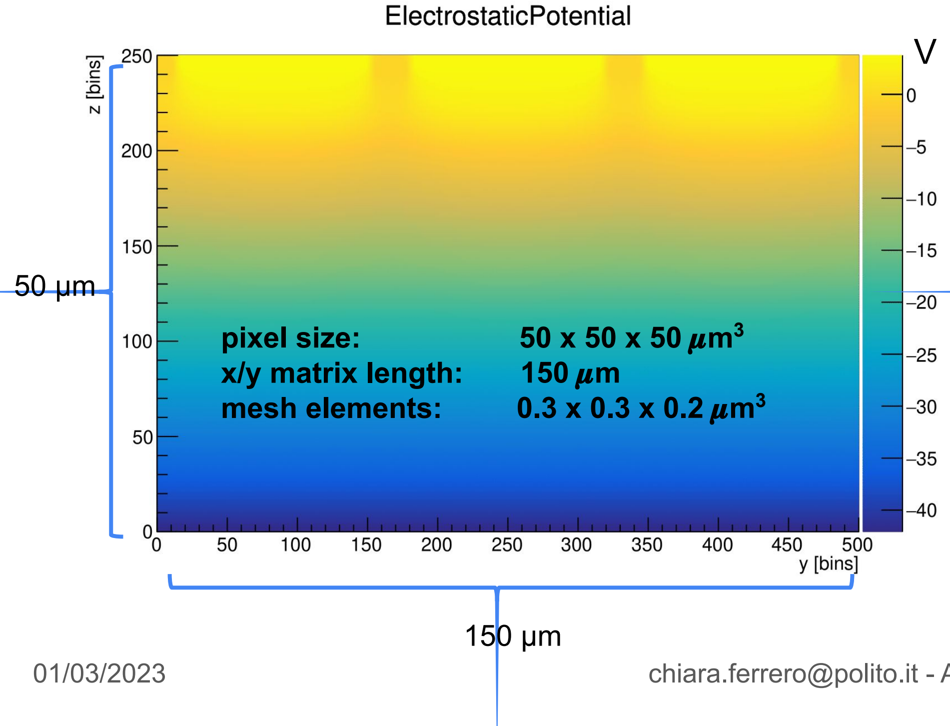
50 μm thick

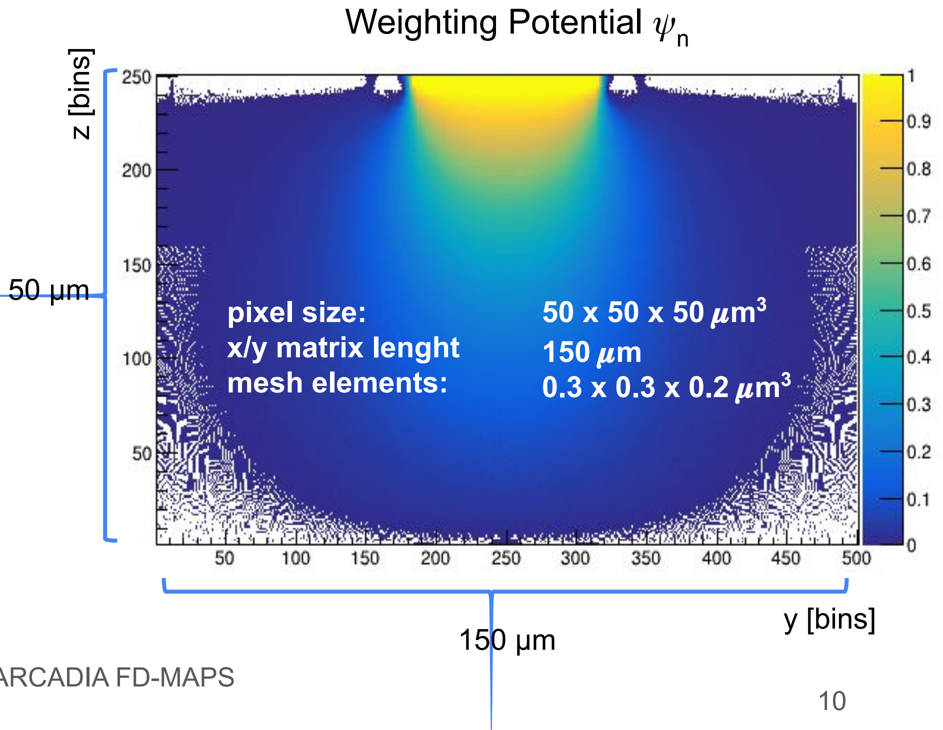


Induced signals from Ramo-Shockley theorem

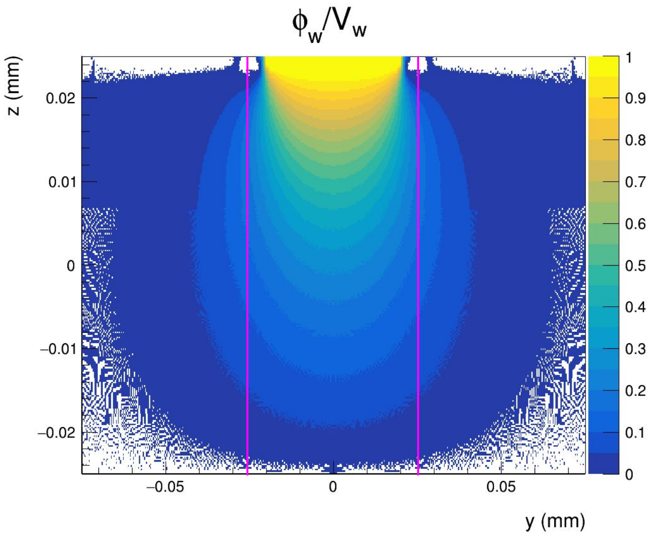
$$Q_n = \int_{t_0}^{t_1} dt\, I_n^{ind}(t) = -\frac{q}{V_w}\int_{t_0}^{t_1} dt\, \boldsymbol{E}_n(\boldsymbol{x}(t))\dot{x}(t)$$

$$= \frac{q}{V_w}\left[\psi_n(\mathbf{x}_1) - \psi_n(\mathbf{x}_0)\right]$$



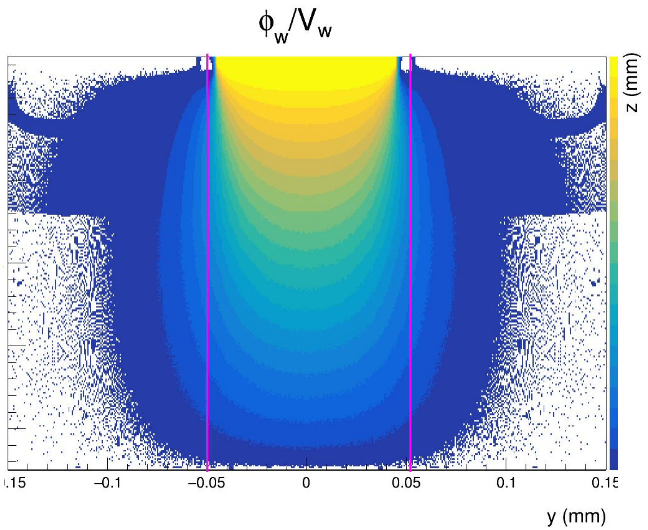


Weighting Potential - 3x3 simulation domain
50 / 100 / 150 μm pitch



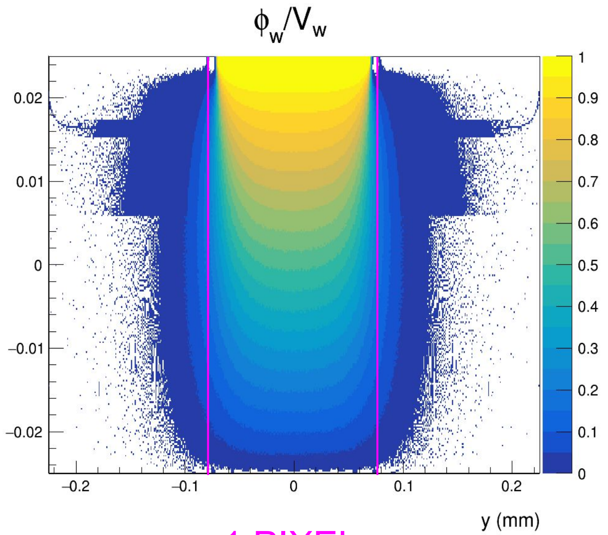
1 PIXEL

50 μm pitch



1 PIXEL

100 μm pitch

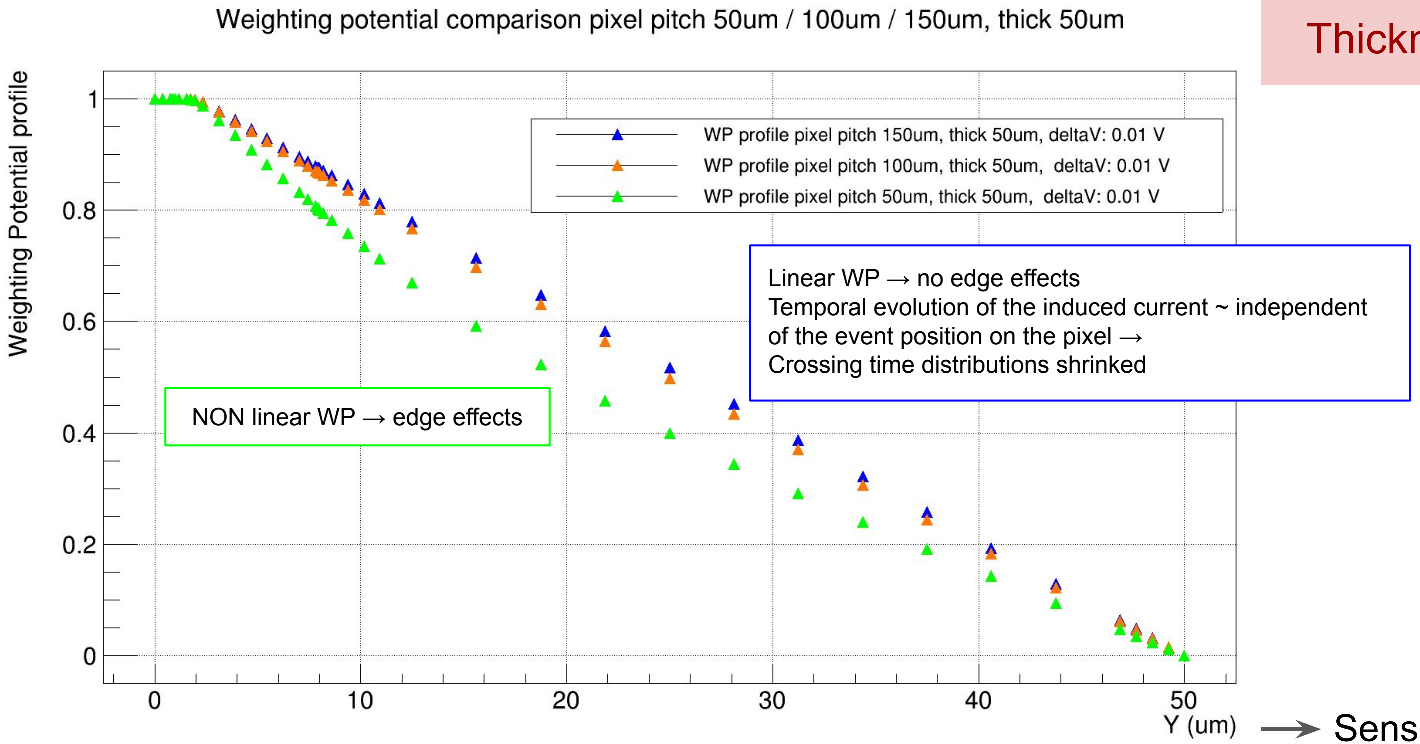


1 PIXEL

150 μm pitch

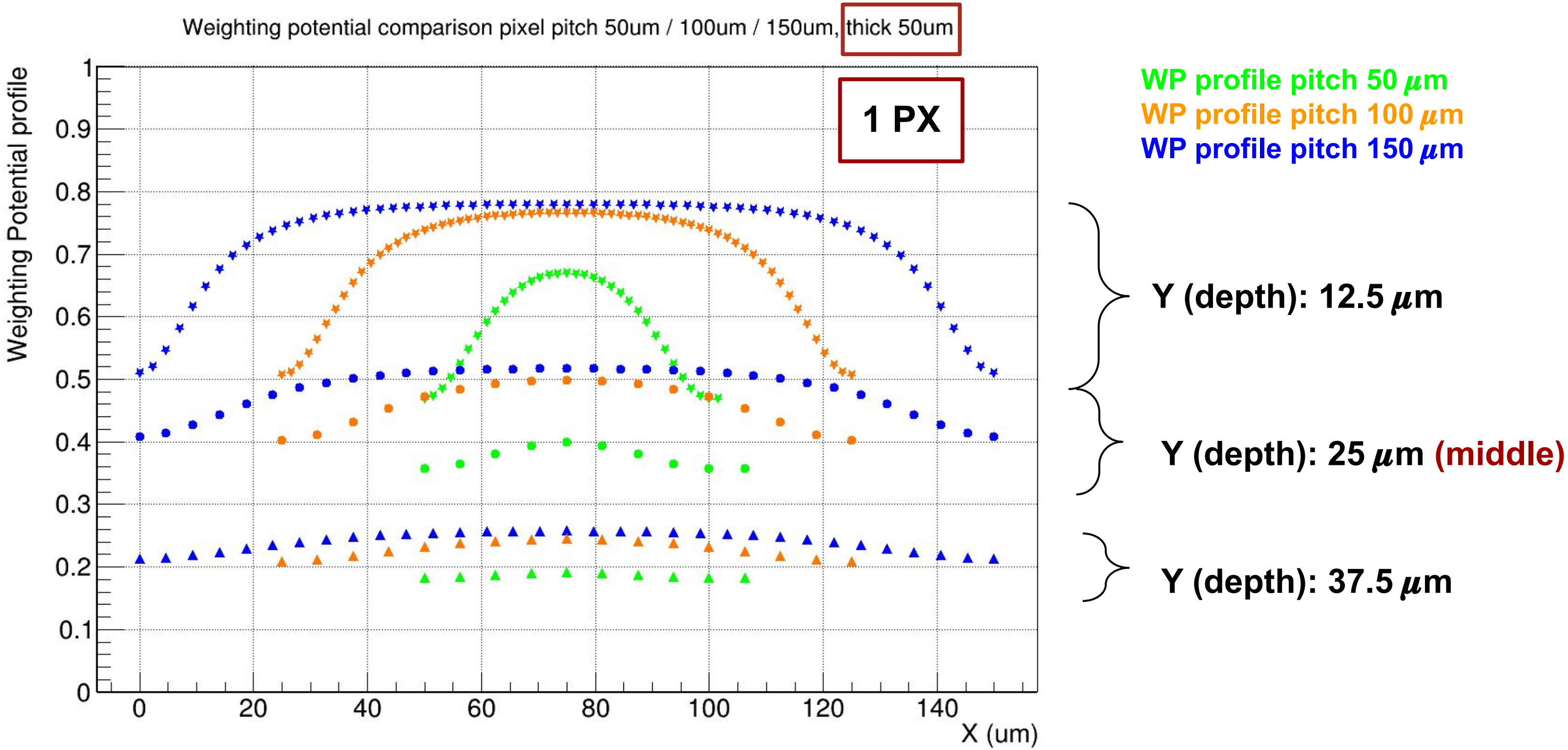
Weighting Potential investigation
vertical line in the center of the 3x3 simulation domain **50 / 100 / 150 μm pitch**

Thickness 50 μm

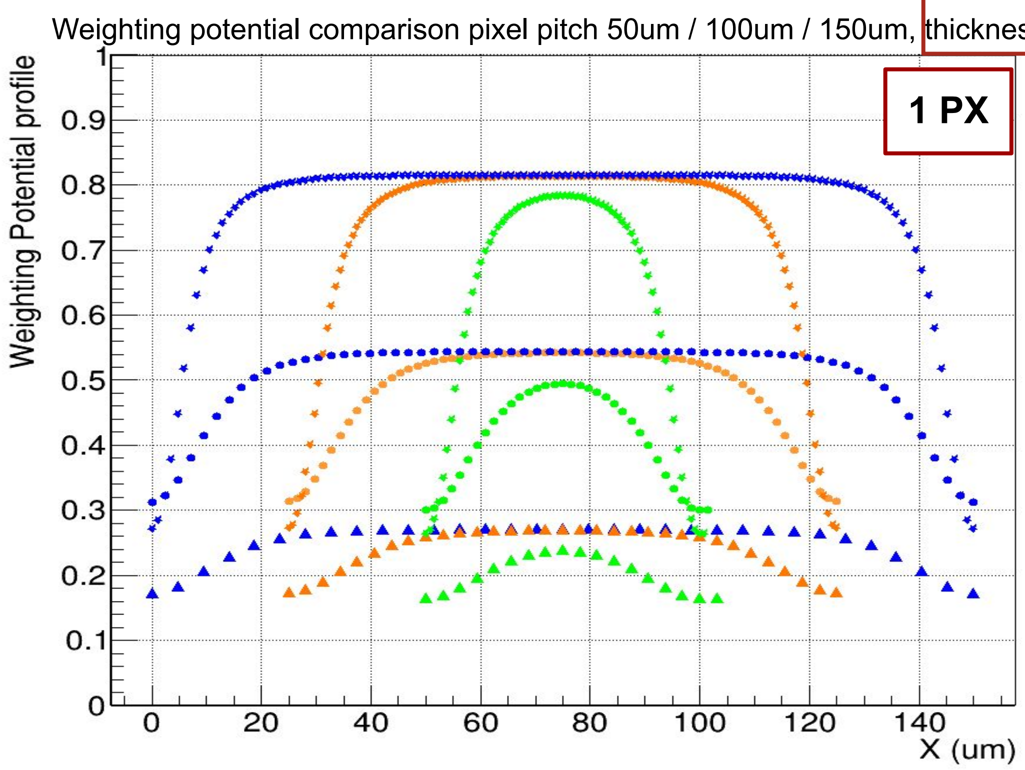


→ Sensor thickness

Weighting Potential investigation on the transverse coordinate for **50 / 100 / 150 μm pitch**



Weighting Potential investigation on the transverse coordinate for **50 / 100 / 150 μm pitch**



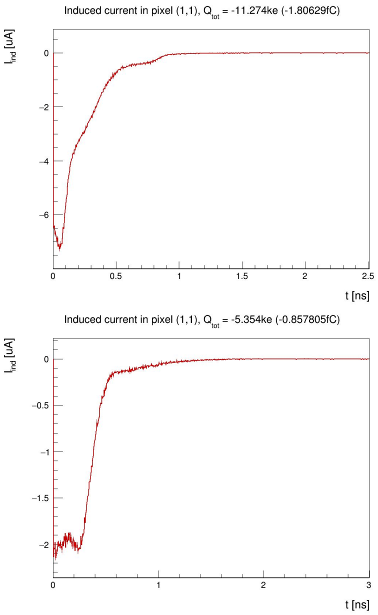
WP profile pitch 50 μm
WP profile pitch 100 μm
WP profile pitch 150 μm

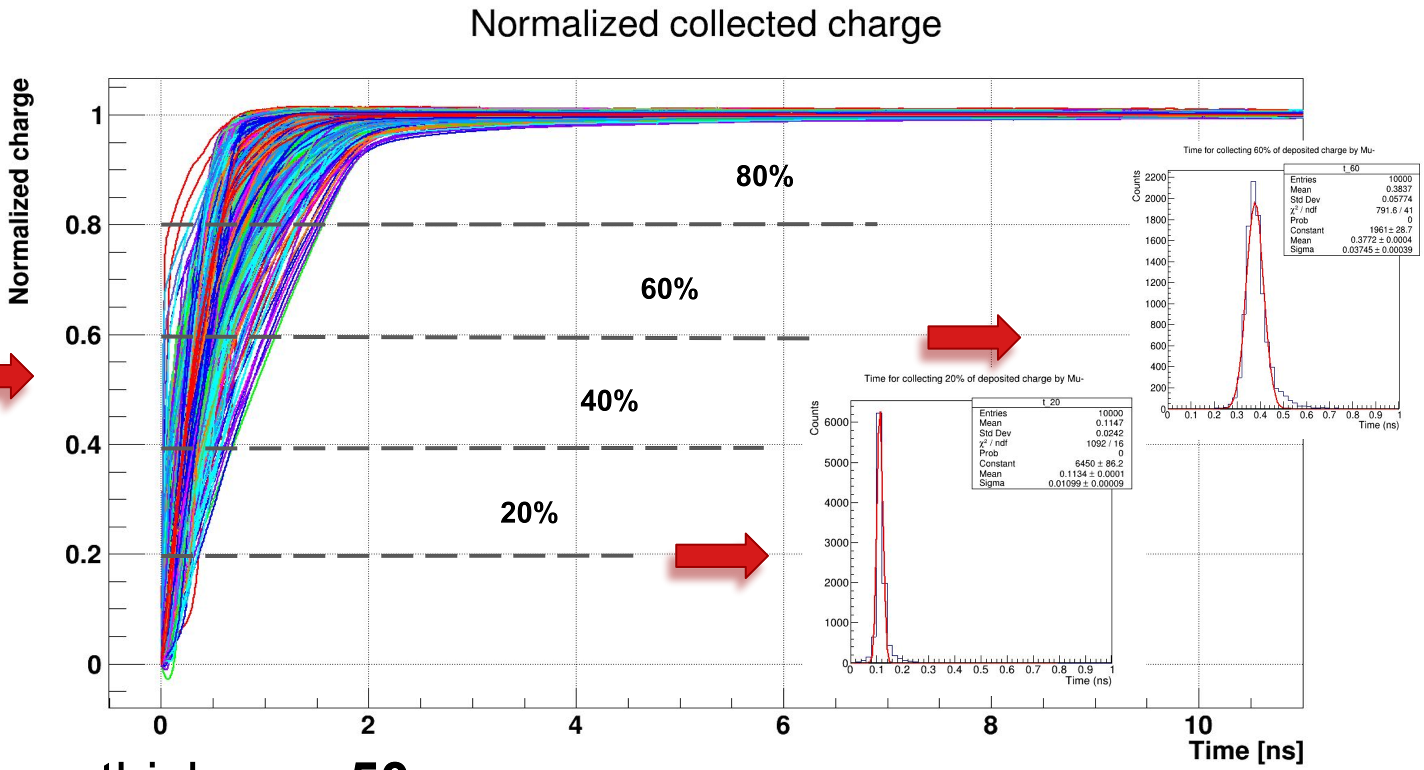
Y (depth): 6.25 μm

Y (depth): 12.5 μm (middle)

Y (depth): 18.75 μm

Time resolution evaluation: CFD method on 10k events

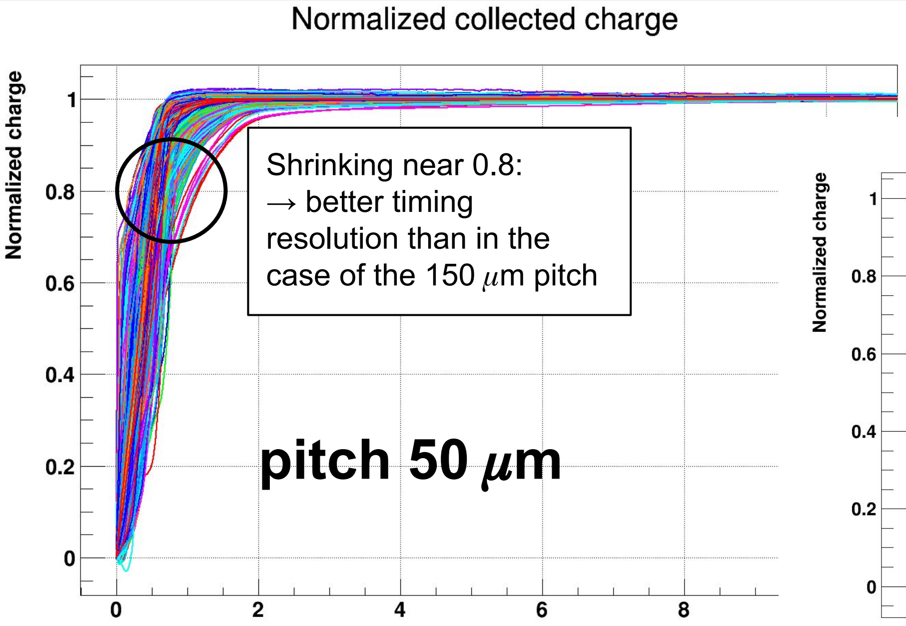


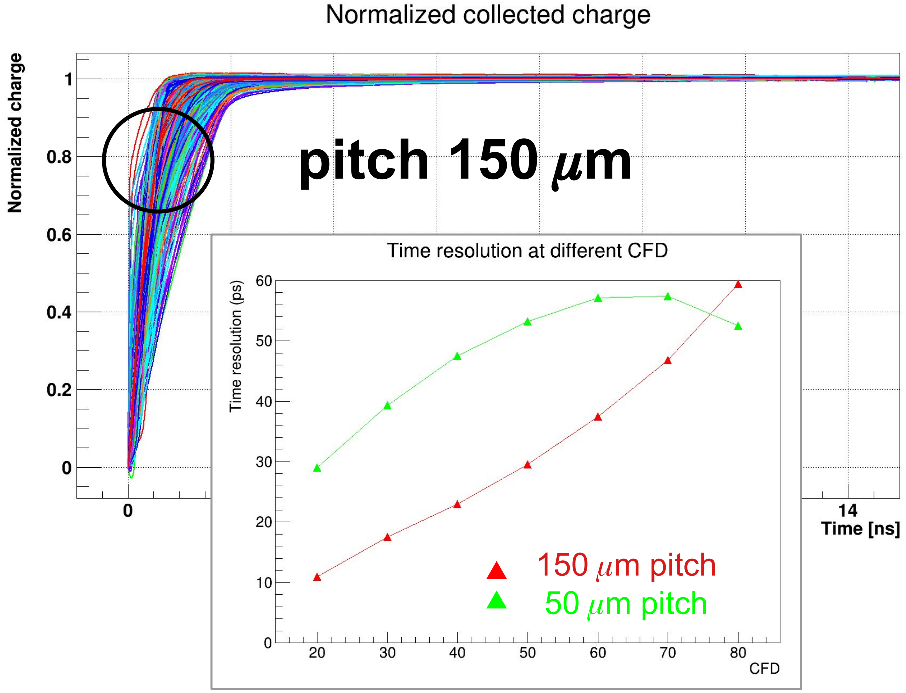


Allpix^2
Signal simulation

thickness **50 μm**

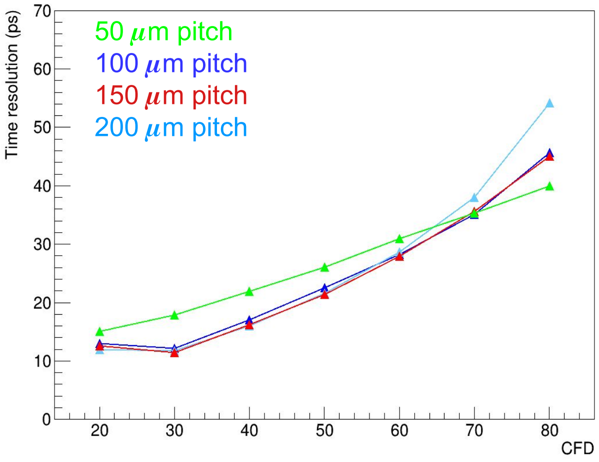
Time resolution evaluation 10k events performance comparison **50 / 150 μm pixel pitch**



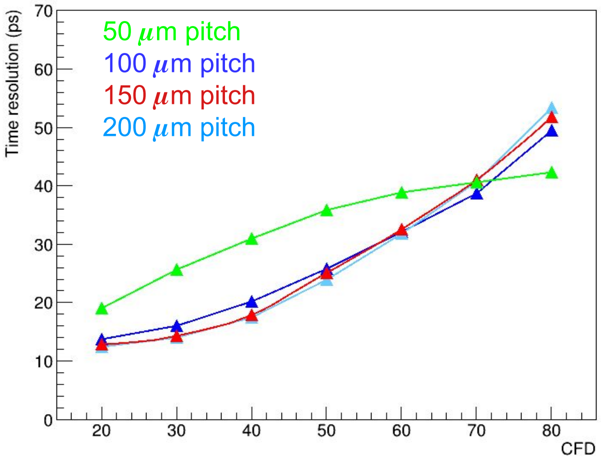


thickness 50 μm

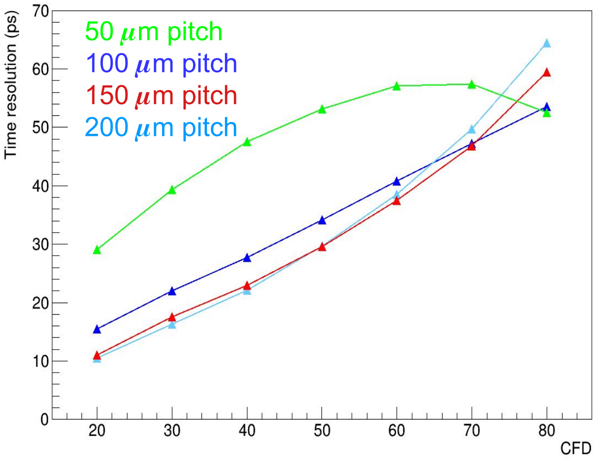
Time resolution with CFD method



Thickness **25 μm**



Thickness **35 μm**



Thickness **50 μm**

Conclusions and next steps

- The timing performances of FD-MAPS in 110 nm CMOS process with pixel pitch from 50 μm to 200 μm and 25 / 35 / 50 μm thickness have been simulated

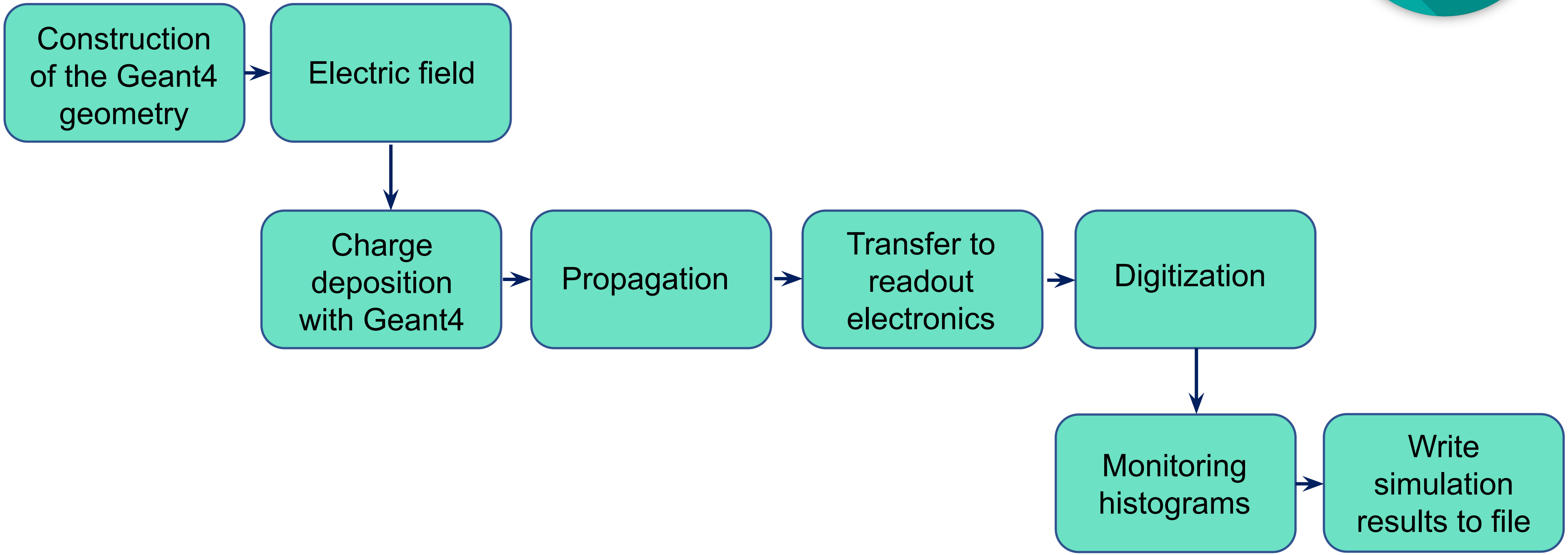
- For 25 μm thickness and below, sensors with pixel pitch ≥ 100 μm are suitable for optimal timing resolution

- Integrated electronics with simulated electronics jitter below 100 ps has been designed and fabricated, test starting in March

- Work in progress: simulation of timing resolution using TCAD and Allpix^2 frameworks on monolithic sensors with additional gain layer

BACKUP SLIDES

Allpix^2 simulation chain



Simulation of the induced signals from Ramo-Shockley theorem using the weighting potential

The weighting field of an electrode can therefore also be calculated by leaving all electrodes at the bias voltages and adding the voltage V_0 to the electrode in question and then taking the difference of the fields

Riegler, W. An application of extensions of the Ramo-Shockley theorem to signals in silicon sensors, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, Oct *2019*

- Two simulations of the sensor at different voltages at the readout electrode (V_0 and $V_0 + \Delta V$) with V_0 = 3.3V and ΔV = 0.01V

  Subtract the two electrostatic potentials and normalize the difference $\frac{(3.31 - 3.3)V}{0.01V} = 1$ at the electrode of interest

- For the weighting field, same procedure but with the two electric fields (x, y, z directions)