CERN – EP Department

Simulation of signal creation in MAPS to speed up the characterization and development of sensors

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Outline

① Tools, techniques and implementation

- Synopsys Sentaurus TCAD
- Garfield++ (https://garfieldpp.web.cern.ch/garfieldpp/)
- X-Rays/MIPS implementation and reusability of events

② Simulations – replicating and predicting experimental data

- What did the characterization look like for ITS2?
- How do the simulations compare to the experimental data?
- Next step – simulations on time resolution

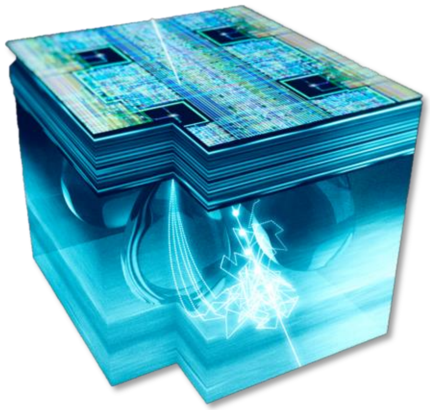
③ Summary

- Why Simulations? Why Garfield++?

Introduction to ALICE, ITS2/3 and ALPIDE

ALICE Inner Tracking System 2 (ITS2)

- The currently deployed ITS2 tracker will consist of 7 layers, all using Monolithic Active Pixel Sensors (MAPS) using TowerJazz' 180nm CMOS process
- The sensor developed for the ITS2 is called the ALice PIxel DEtector (ALPIDE)
- The chip size is 30x15mm² and the pixel dimensions are 27x29µm²



ITS3 and the switch to the 65nm process node

- wafer scale sensors (300mm) and bendable silicon
  - M. Mager - The LS3 upgrade of the ALICE Inner Tracking System based on ultra-thin, wafer-scale, bent Monolithic Active Pixel Sensors
- smaller electronics in n/p-well free up space
- shrinking the pixel pitch to 20µm, 15µm or even 10µm possible
- more complex design choices become possible

ITS4 and beyond

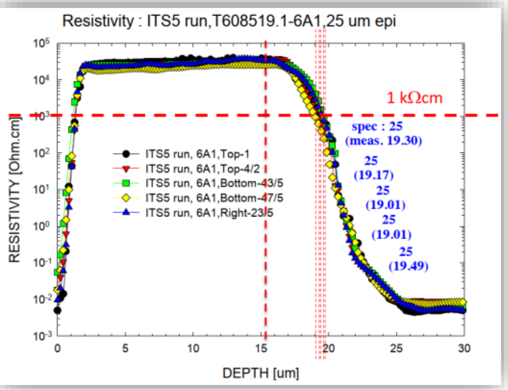
- better time resolution and more radiation hardness
- probably full silicon detector?

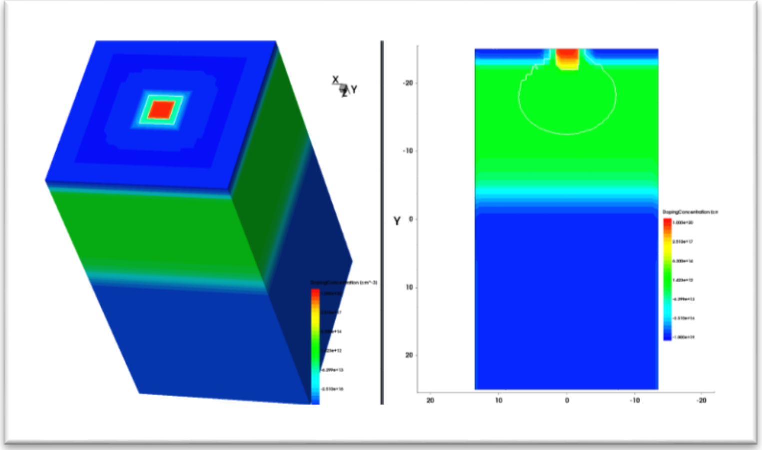
Tools, techniques and implementation

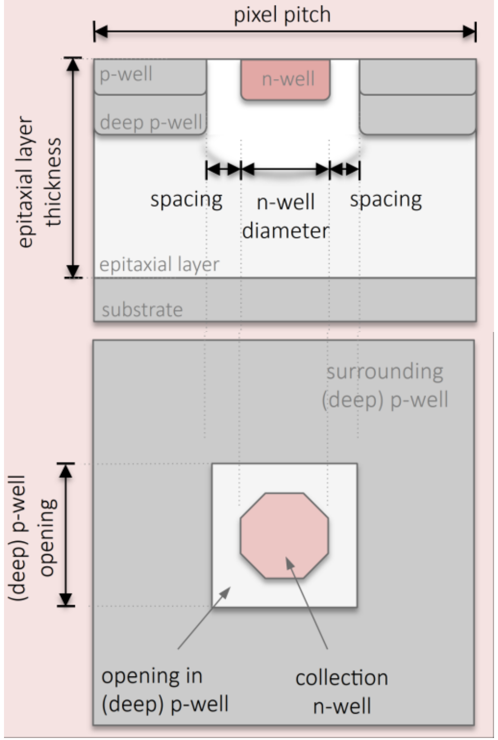
Synopsys - Sentaurus TCAD

3D representation of the physical sensor/pixel

- Geometry definition of one or several pixel
  - sensor thickness and epitaxial layer thickness
  - n-well diameter, form (rectangular or octagonal) and spacing
  - voltage applied to n-well and p-well
  - periodicity/boundary conditions
- Doping concentration / resistivity profile
- Definition of the simulation procedure
  - (quasi)-static or transient
- Visualisation and data taking







ALPIDE telescope – J. van Hoorne

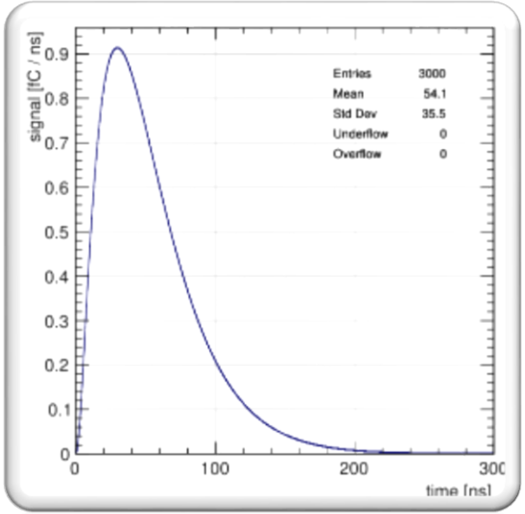
Garfield++ - particle tracking and signal calculation

History

- originally written in Fortran by Rob Veenhof for gas detectors
- ported to C++ by Heinrich Schindler
- extended also for silicon detectors (still actively developed)

Particle tracking and signal calculation

- import of electric and weighting fields/potentials from TCAD, Ansys, COMSOL, etc. (see backup slides for further detail)
- point like electron hole pairs are tracked through the sensor using drift velocity and diffusion
- induced current/charge is collected along the path



Possibility to simulate the behavior of connected electronics

- (semi)-analytic convolution of the signal with a transfer function possible
- or export of the signal and input into electrical simulation software (Cadence, Spice)

https://garfieldpp.web.cern.ch/garfieldpp/

Implementation of X-Rays/MIPS and reusability of events

X-Rays

- Radioactive sources are used in many experiments -> photons of different energy are created
- Position of hit defined or chosen randomly. Depth is given by attenuation in silicon/metal layers
- See backup slides for the modelling of an Fe-55 source

MIPS

- different types of MIPS are implemented in Garfield++ using HEED
- Position of hit and angle have to be chosen

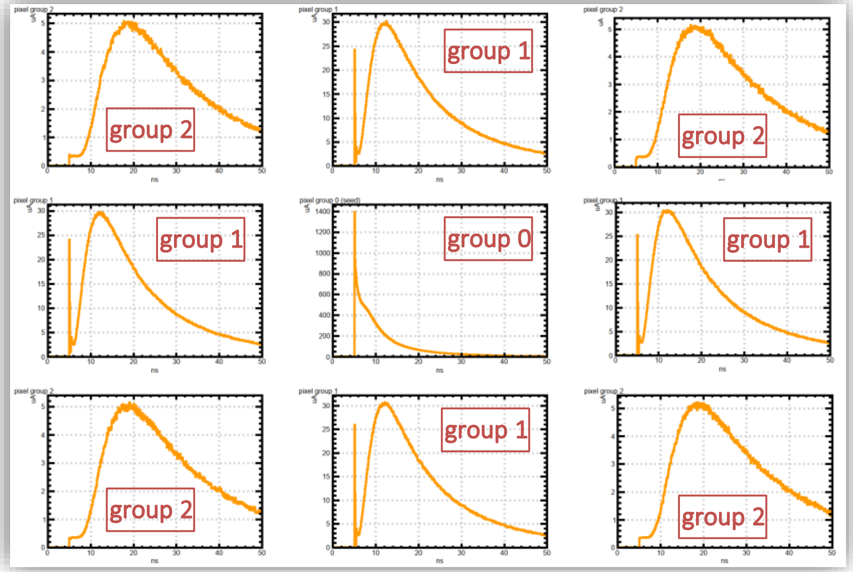
Pixel clusters – boundary conditions

- electric and weighting field only for one pixel needed.
- boundary conditions allow signal for neighbouring pixels
- grouping of electrodes is possible

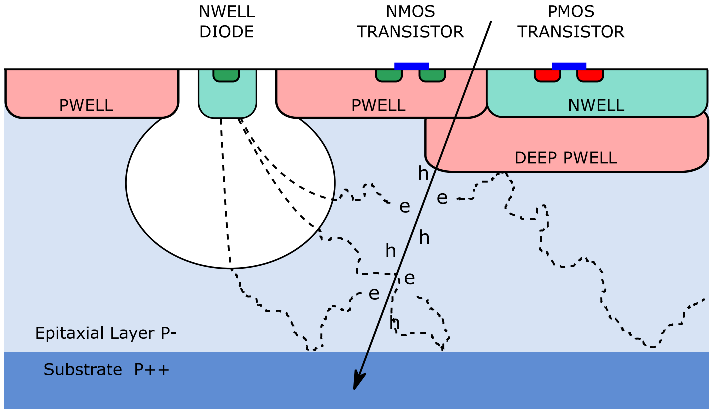
Reusability of events

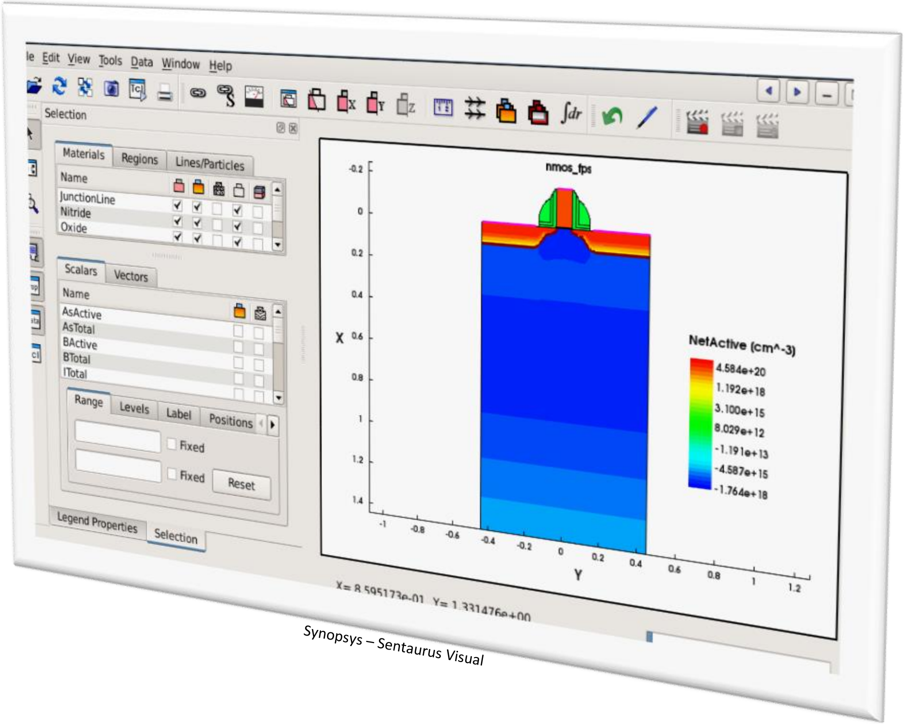
- Signals from events (X-Ray, MIPS) can be written to file
- Big time save as one geometry only has to be simulated once due to reusability of this data

3x3 array of pixels showing the average signal created by MIPS passing through



Characterisation – replicating and predicting experimental results





Synopsys – Sentaurus Visual

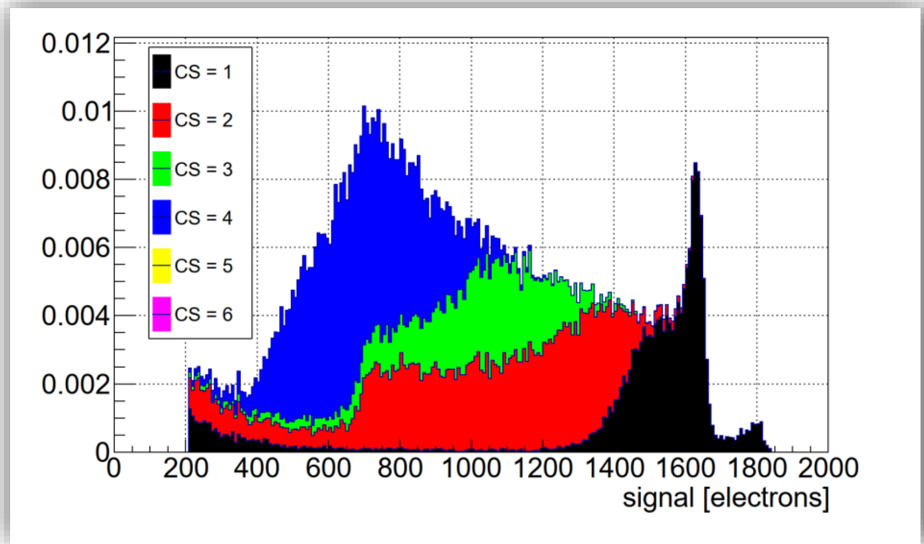
What did the characterisation for ITS2 look like?

Sensitivity studies using the INVESTIGATOR chip

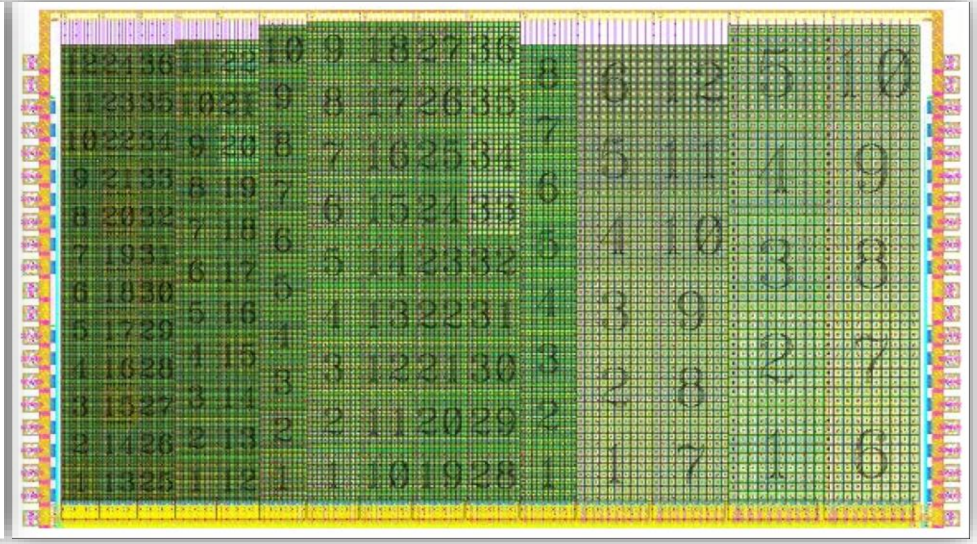
- 134 mini-matrices on one sensor with different pixel pitches, epi thicknesses and electrode geometries to maximize the ratio between collected charge and pixel input capacitance

- Beam studies to characterize the seed signal distribution, cluster multiplicity or charge collection efficiency

distribution of collected charge per hit event for different cluster sizes



INVESTIGATOR chip with 134 mini-matrices

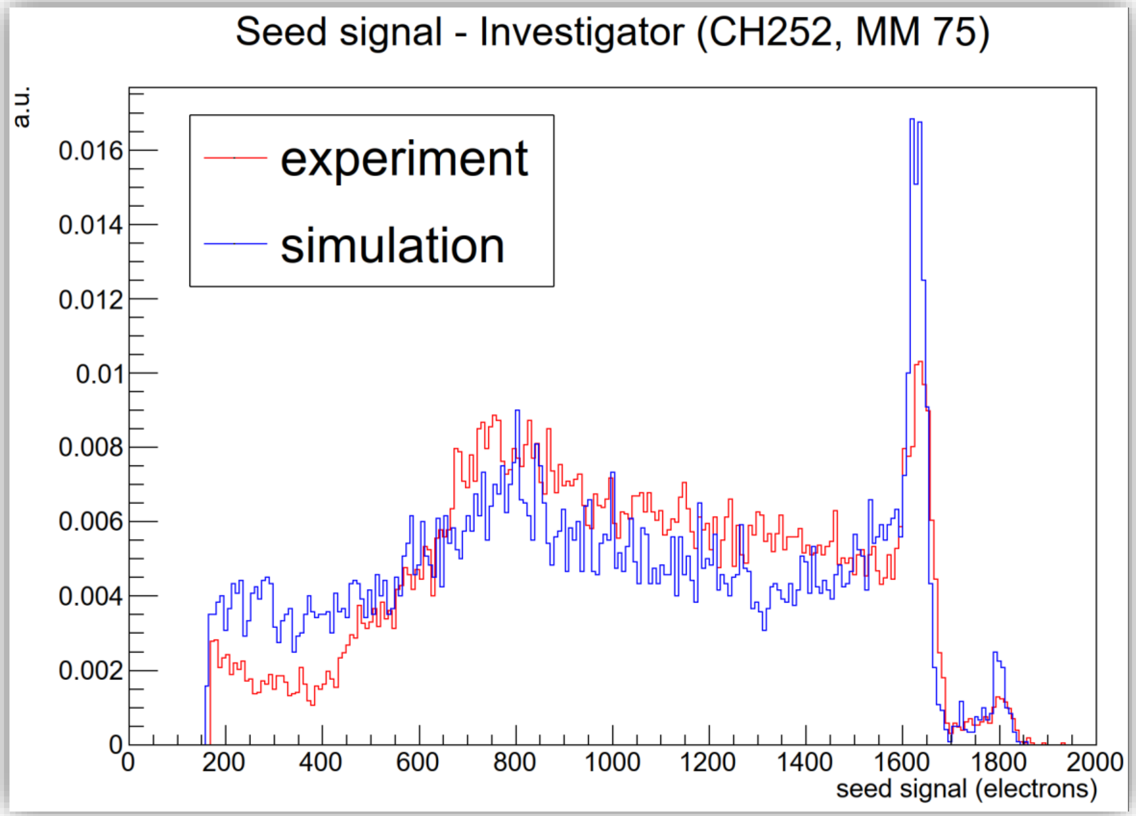


M. Šuljić - Study of Monolithic Active Pixel Sensors for the Upgrade of the ALICE Inner Tracking System

How do the simulations compare to the experimental data?

How accurate is the simulation?

- Immediately pretty good results



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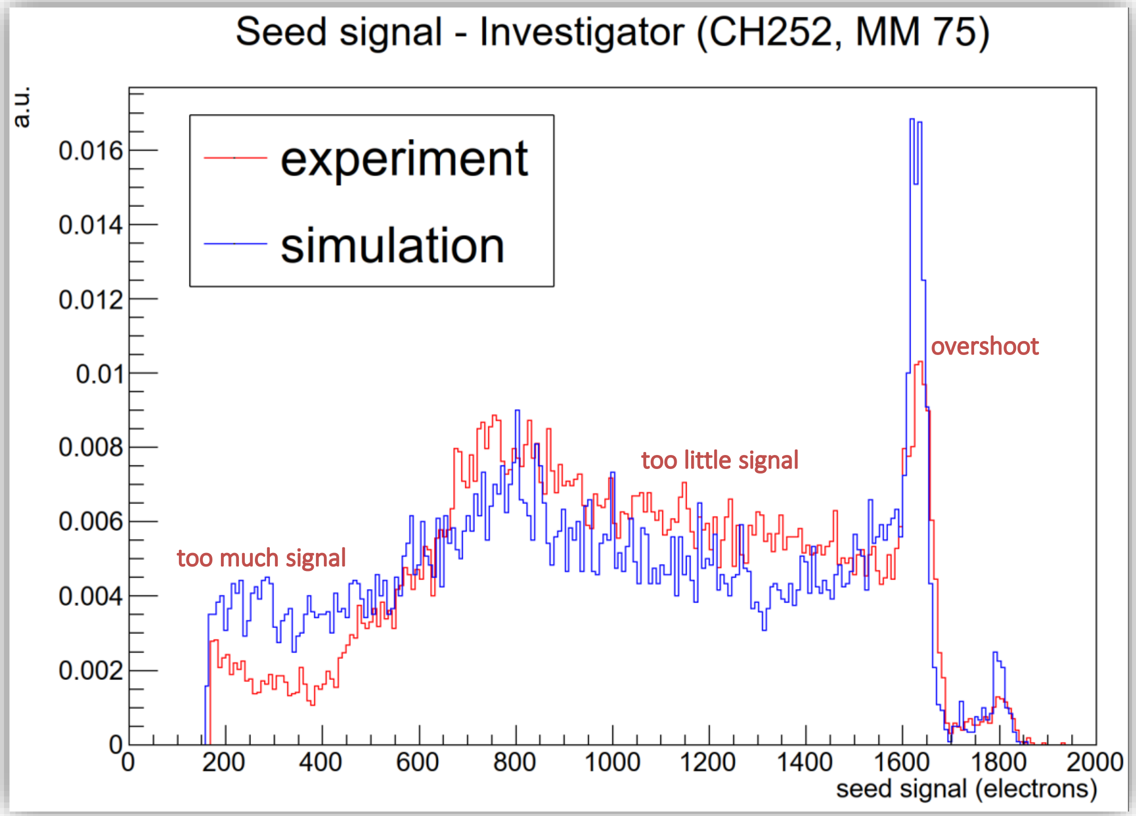

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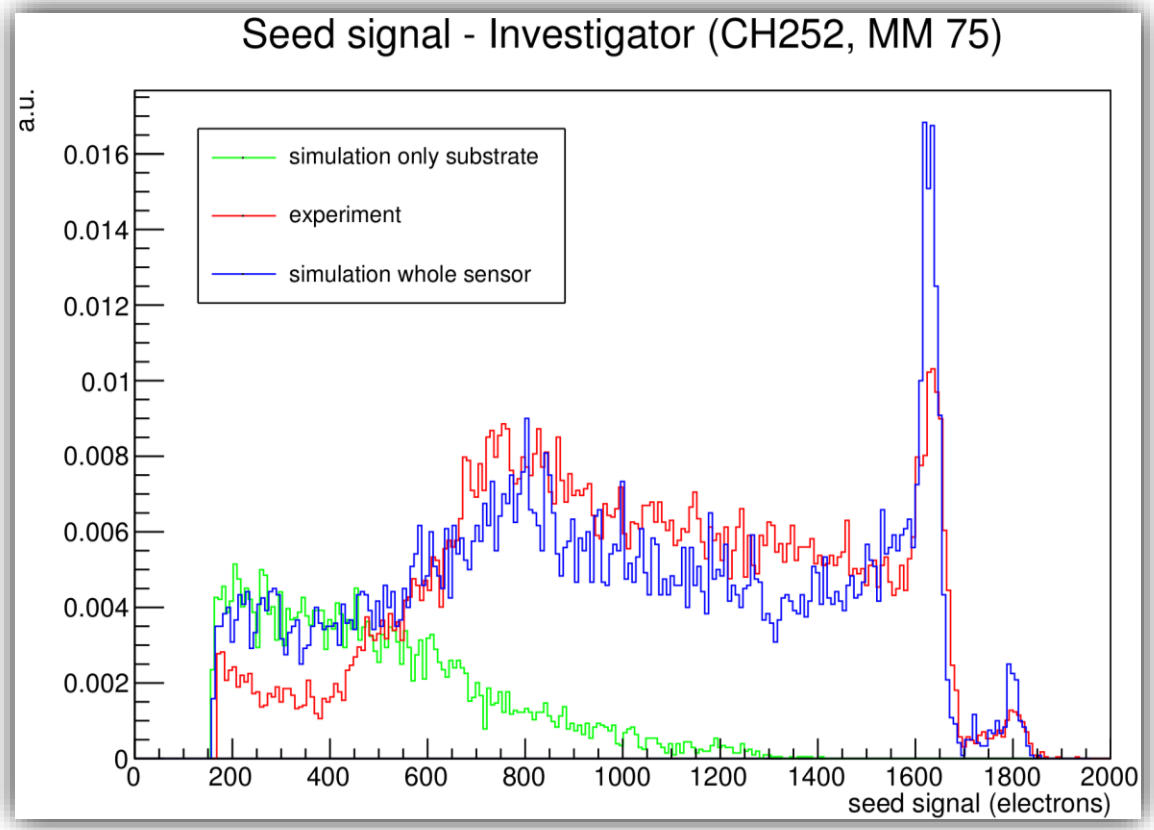

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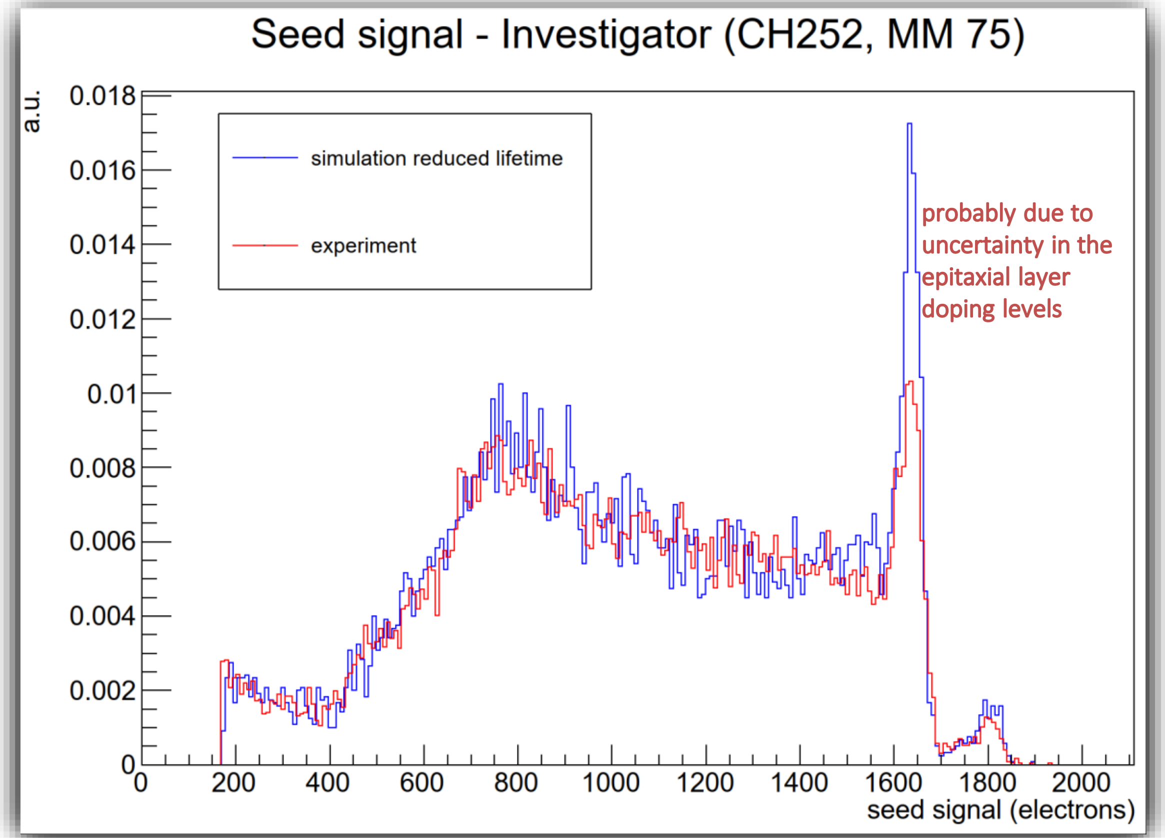

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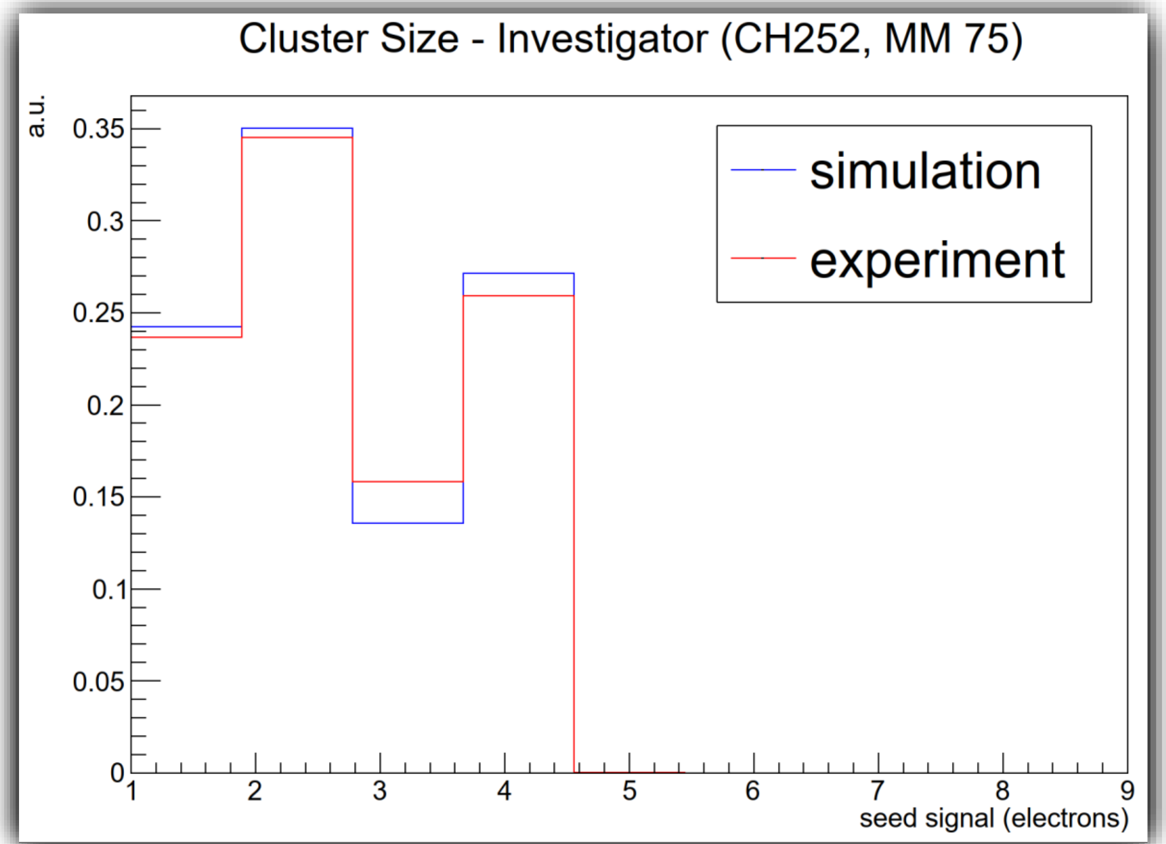
- nearly perfect results –> higher peak most probably due to uncertainty in the doping concentration and therefore in the extent of the depletion area and electric fields
- Great match between simulation and experiment is also seen in the cluster size distribution
- All of that is achieved without any fit parameters!



Next step – simulations on time resolution

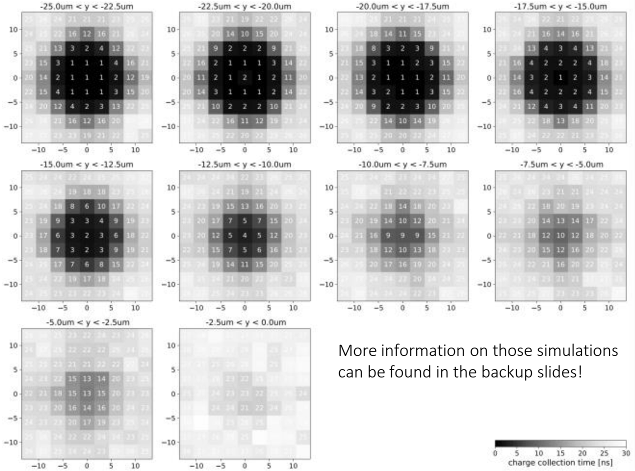
Intrinsic rise and charge collection times

- Signal rise and charge collection behavior for each scenario can be simulated
- Efficiency of collection compared to deposited charges is tracked

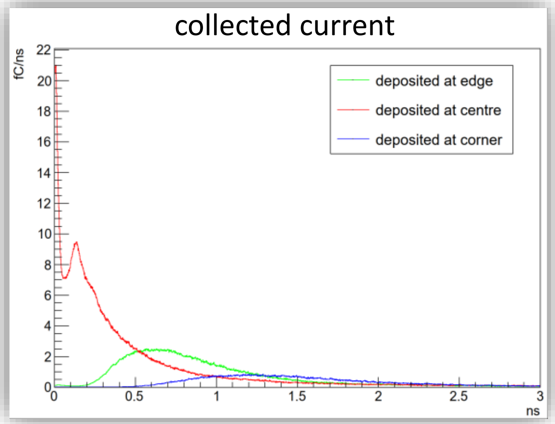
Time resolution – does it intrinsically even exist?

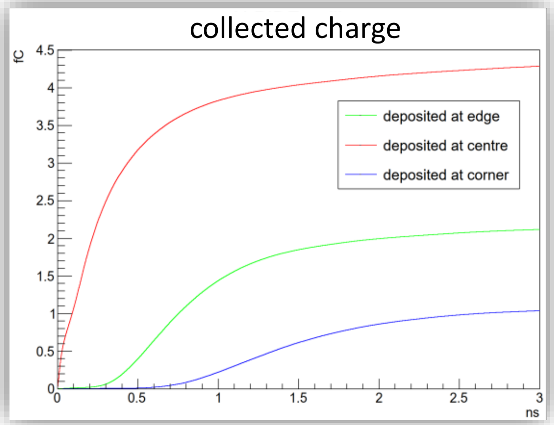
- The charge collection time or the time over threshold provide information on the intrinsic limitations of your sensor
- Only the intrinsic limitations in combination with the connected electronics and its noise let's you define the sensor's time resolution
- Therefore, Garfield++ provides the possibility to reuse the signals as input of electronics simulation software.

charge collection times of one pixel divided into 810 voxels

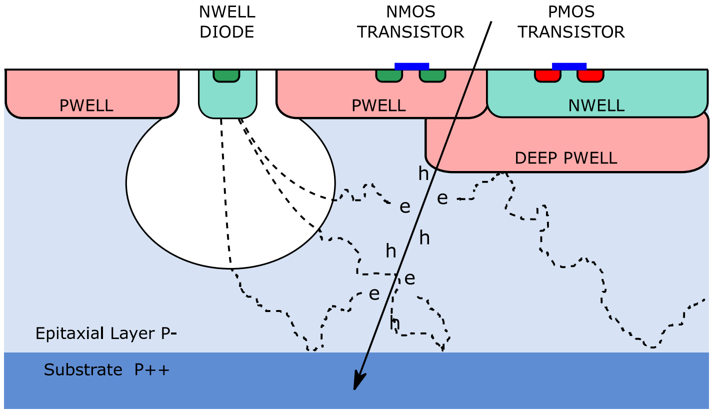


More information on those simulations can be found in the backup slides!





Summary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Epitaxial Layer P-
Substrate P++

Why Simulations? Why Garfield++?

No redundancy in simulations as the simulation process is split into two parts

- Each geometry only has to be simulated once to get the electric/weighting fields
  - Results are therefore independent of your device simulation tool
  - Sentaurus, Silvaco, ANSYS, COMSOL, semi-analytic fields… everything works
- Signal of each deposited X-Ray photon, MIPS, e/h-pair from Garfield++ can be reused

No fitting parameters and no unphysical assumptions

- electrons and holes and tracked individually, solely using the electric field
- simulated by foundry's description of geometry and doping concentration

Direct connection to simulate connected electronics

- via current input into software tools like SPICE, Cadence etc or via convolution with a given transfer function

Why Garfield++?

- Implementation has been used and verified countless of times over the last few decades
- Semiconductor is in fact just a tiny extension of Garfield's roots for gas detectors

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Backup slides

1. Weighting field simulation
2. X-Ray photon simulation – example for an FE-55 source
3. MIPS simulation in Garfield++
4. Charge collection time extremely accurate simulation
5. Sensor efficiency extremely accurate simulation

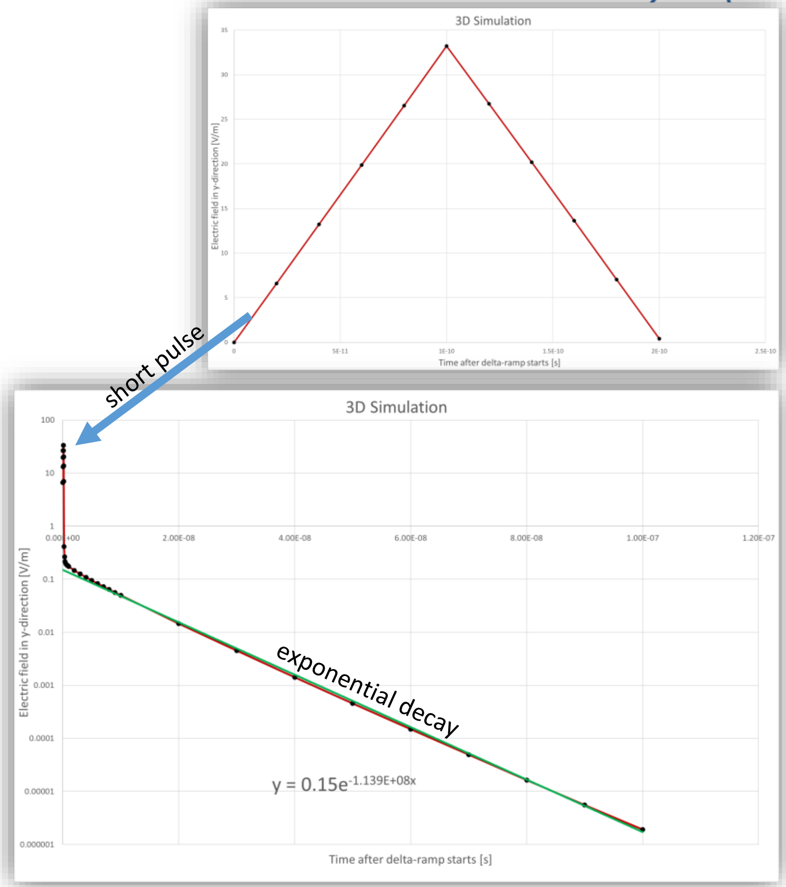
Weighting fields and potentials – static/dynamic

static weighting field/potential

- two (quasi)-static simulations of the sensor at different voltages at the readout electrode (V_0 and $V_0+\Delta V$)
- Weighting field
  - get the two electric fields (x-, y-, z-direction)
  - subtract the two electric fields and normalize the difference
- Weighting potential
  - same procedure as with fields, but with the two potentials

delayed weighting field/potential

- short (triangle) voltage pulse on readout electrode
- delayed electric field effects due to non infinite conductivity
- small field strength, but long lasting effects
  - for parallel plates this corrects the static signal by up to 20%
- effects negligible for the MAPS sensors in ALICE
  - short time / fast collection in high field regions -> no effect
  - long time / slow collection in low field regions -> no effect



Riegler https://www.sciencedirect.com/science/article/pii/S0168900219309015?via%3Dihub

Correct Simulation of X-Ray deposits – Physics and Implementation

Fe-55 decay probabilities [1]

- 5.89/5.9keV photon – 16.57/8.45%
  - 25.02% in total, as energy difference can't be resolved
- 6.51keV photon – 3.40%
- 0.64keV photon – 0.52%
- rest is Auger electrons etc.

X-ray attenuation in air [2]

- 5.90keV photon has 23.7g/cm – factor of 0.031/cm
- 6.51keV photon has 17.7g/cm – factor of 0.023/cm
- 0.64keV photon has 3600g/cm – factor of 4.68/cm
  - no photons hit the sensor as source is a few cm away

X-ray attenuation in silicon [2]

- 5.90keV photon has 154.7g/cm – factor of 36045/m
  - 60% / 83.5% will be deposited within 25µm/50µm
- 6.51keV photon has 119.7g/cm – factor of 27895/m
  - 50.1% / 75.2% will be deposited within 25µm/50µm

Photon type selection

- Random number [0,1] decides the photon energy
- 5.9keV if rnd < 0.8804 (88.04% are 5.9keV photons)
- 6.51keV else (11.96% are 6.51keV photons)

Deposition depth selection

- exponentially correct random number W needed
- random number U [0,1] is created
- transformation due to attenuation is $W = -\frac{1}{\mu}\ln(U)$
- U can't be arbitrarily small, otherwise selected depth would be >50µm
- Umin = 0.165 for 5.9keV, Umin = 0.248 for 6.51keV

Deposition of electron/hole pairs

- 1636 or 1808e/h-pairs are deposited according to the random depth and their energy (5.9keV or 6.51keV)
- x-/z-position of the deposit is randomized in the cell to get better statistics

[1] http://www.nucleide.org/DDEP_WG/Nuclides/Fe-55_tables.pdf and http://www.nucleide.org/Laraweb/index.php
[2] https://www.nist.gov/pml/xcom-photon-cross-sections-database and https://physics.nist.gov/PhysRefData/XrayMassCoef/ComTab/air.html

MIPS simulation with and without angle

Simulation setup

- MIPS are defined using HEED in Garfield++. For 50µm silicon the most probable value ≈ 3160e/h pairs
- Angle is defined using angles of spherical coordinates (θ, ϕ) to cover the whole range of possible angles
- Random numbers define the x/z position of the MIPS entering the sensor as well as the two angles
- For very shallow angles, cutoff depending on the experimental design has to be chosen
- Signal is only collected individually for the first neighbours
  - seed pixel – signal group 0
  - direct neighbour – signal group 1
  - diagonal neighbour – signal group 2
- Each and every event is written to file. The signals of those events can be recombined later.
- Signal can be convoluted using a transfer function directly within Garfield++ or used as input in electrical simulation software like Cadence or SPICE
- Time over Threshold and Constant Fraction Discrimination can be used in Garfield++ as well

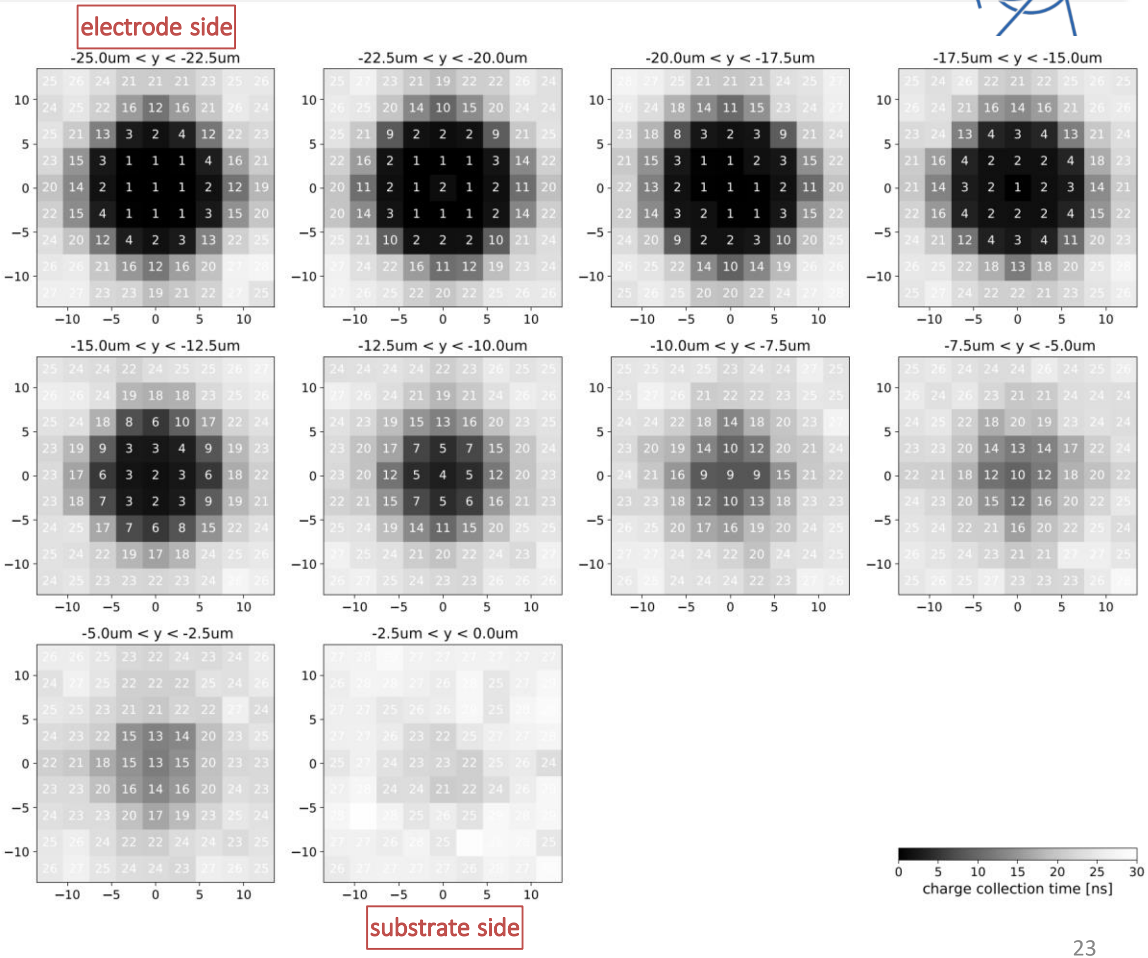
Charge collection time

Setup

- epitaxial layer divided into 9x9x10 cells
- -25µm is at the electrode, 0µm is at the boundary to the substrate
- Fe55 photons of 5.9keV = 1636e/h pairs deposited in each cell at random positions
- e/h pairs tracked to the electrode

Extreme accuracy of sensor behavior

- Experiments will never provide so much detail, so for optimization such simulations crucial
- Questions like "what is the substrate contribution" can be answered this way



Signal pixel efficiency

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Definition of seed pixel efficiency

- electrons that reach the seed electrode

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