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

Jan Anton Hasenbichler (CERN, Vienna University of Technology)
on behalf of the ALICE Collaboration

Outline

① Tools, techniques and implementation

- Synopsys Sentaurus TCAD
- Garfield++ (https://garfieldpp.web.cern.ch/garfieldpp/)
- Simulation of pixel clusters and how to deposit X-Rays and MIPs

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

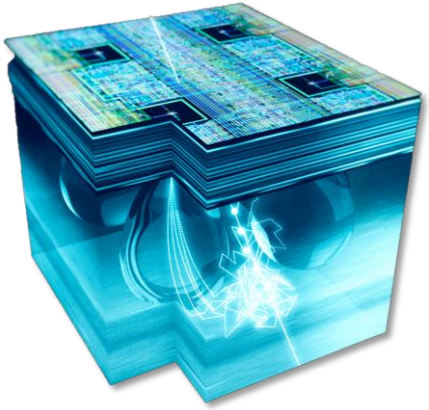
③ Summary

- Why factorize the simulations? Why Garfield++?

Introduction to ALICE, ITS2/3 and ALPIDE

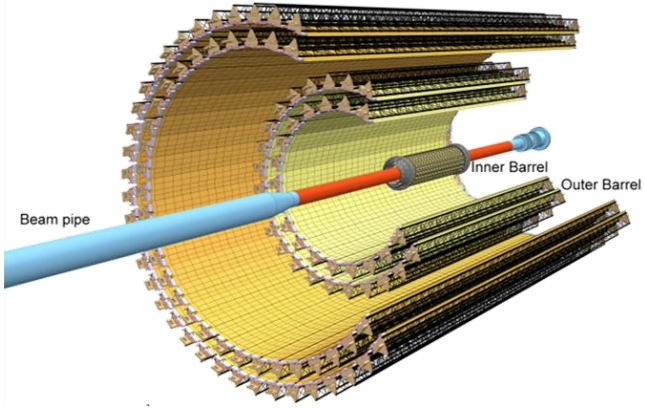
ALICE Inner Tracking System 2 (ITS2)

- 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)
  - 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 becomes feasible
- more complex design choices become possible



Concept for future Heavy Ion experiment

- full silicon detector for increased rate capability w.r.t. TPC
- improved time resolution for TOF measurements
- ultra low material budget

Tools, techniques and implementation

Garfield++

SYNOPSYS®

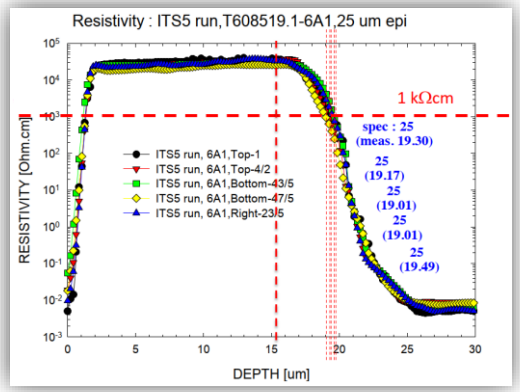
Sentaurus TCAD

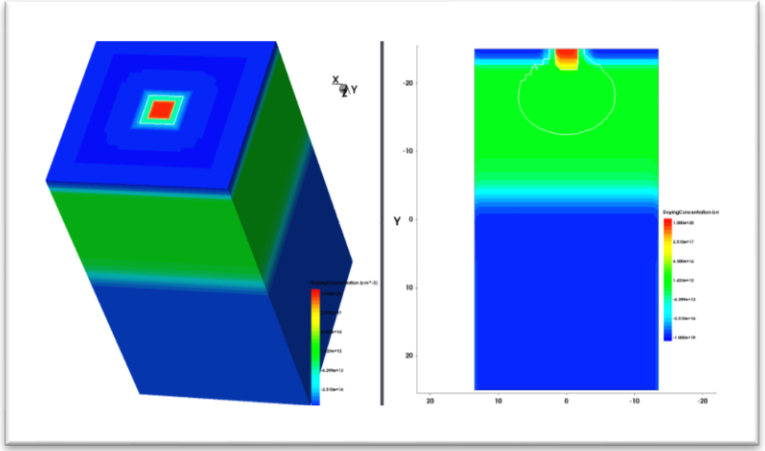
ROOT
Data Analysis Framework

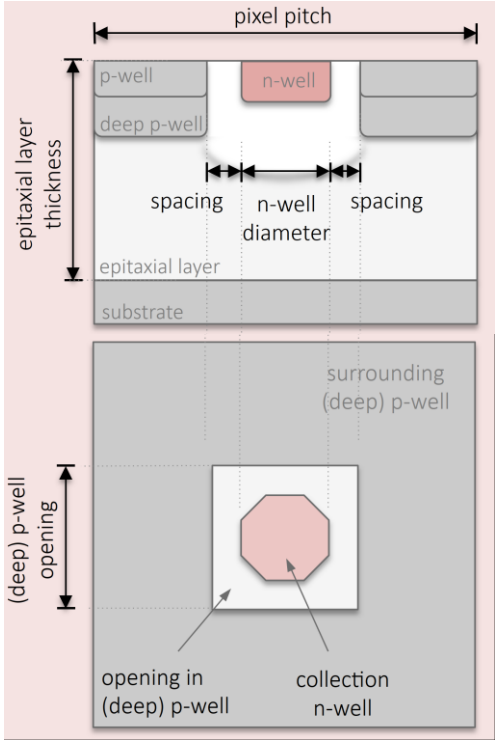
Synopsys - Sentaurus TCAD

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







Garfield++ - particle tracking and signal calculation

History

- originally written in Fortran for gas detectors
- ported to C++ and extended for silicon detectors (still actively developed)
- Available via the CERN SFT

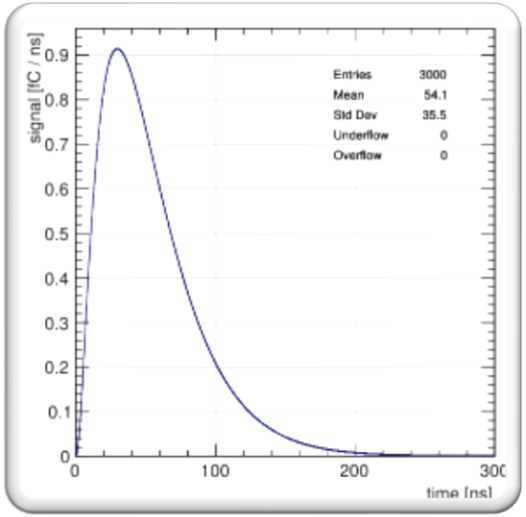
Particle tracking and signal calculation

- import of electric/weighting fields/potentials from TCAD, Ansys, COMSOL, etc.
- electron hole pairs are moved in the sensor using drift velocity and diffusion
- induced current/charge is collected along the path
- with the assumption that the drift field is not changed by the charge deposit

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)

sample plot showing induced current



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

Simulation of pixel clusters and how to depot X-Rays and MIPs

Pixel clusters – boundary conditions

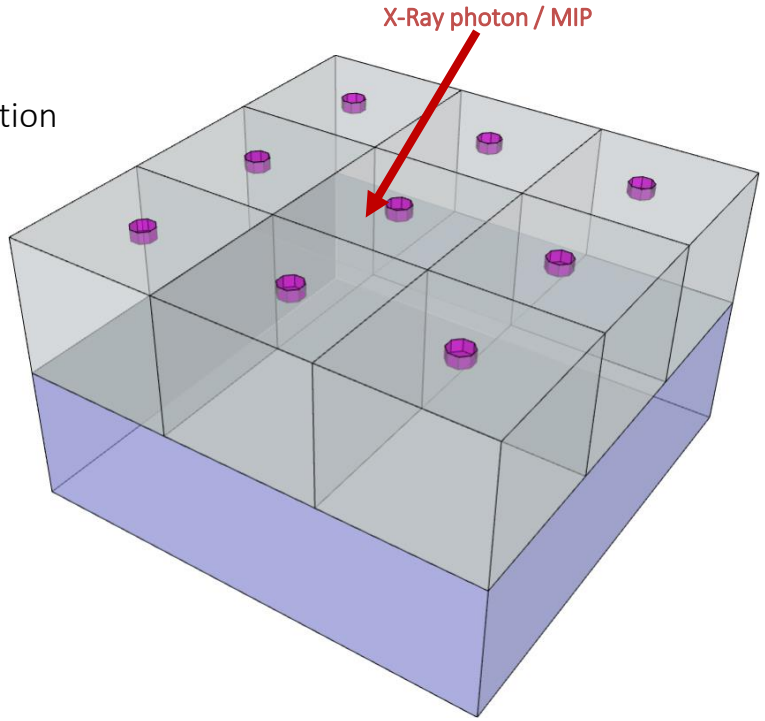
- electric field and weighting field of a single pixel are calculated
- geometry and field values allow periodicity
- fields are shifted in position to the neighboring electrode's position

MIPs

- Charge deposit of MIPs is implemented in Garfield++ using HEED (http://ismirnov.web.cern.ch/ismirnov/heed)
- Position of hit and angle have to be chosen

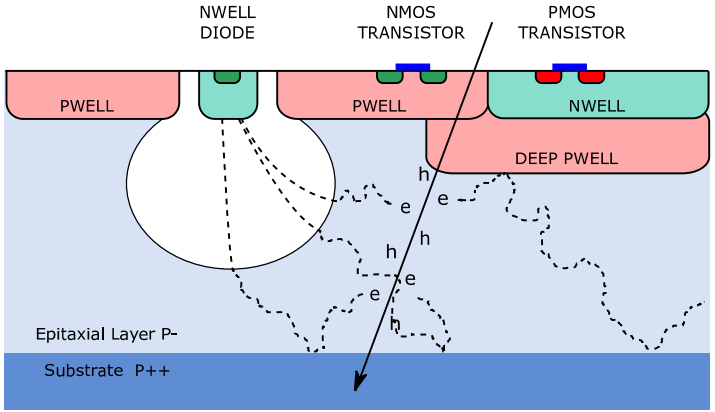
X-Rays

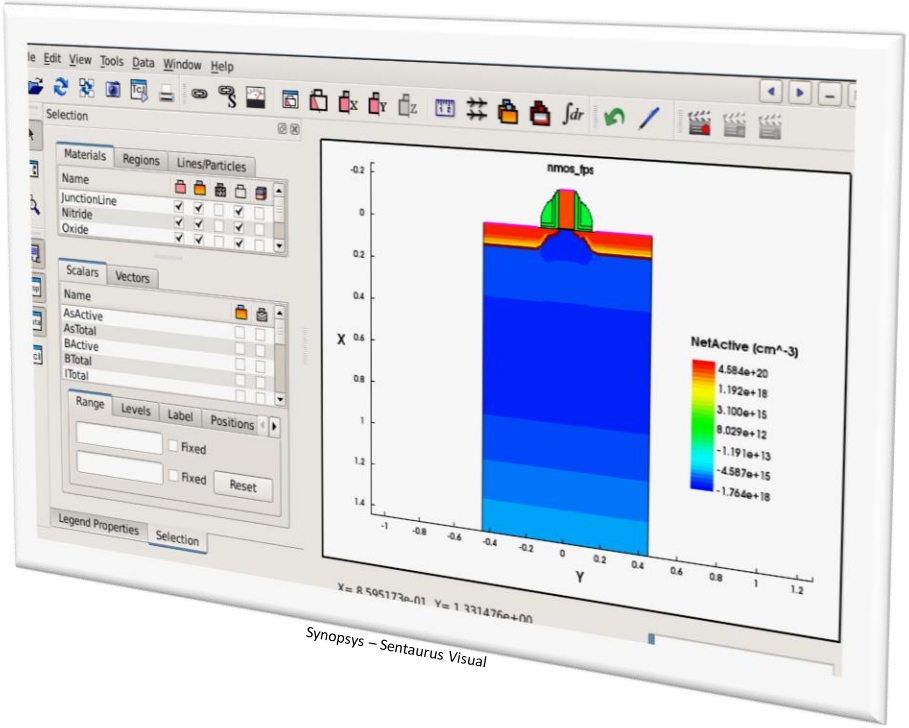
- Radioactive sources radiate photons of different energies
- Type of photon for deposit is chosen randomly given its probability during the decay
- Number of deposited electron/hole pairs is calculated from the photons energy, the band gap and smeared by the Fano factor
- depth of deposit is given by attenuation in silicon/metal layers



3x3 array of pixels getting hit by X-Rays/MIPs
The pixel which collects the largest amount of charge is called seed pixel.

Characterisation – replicating and predicting experimental results





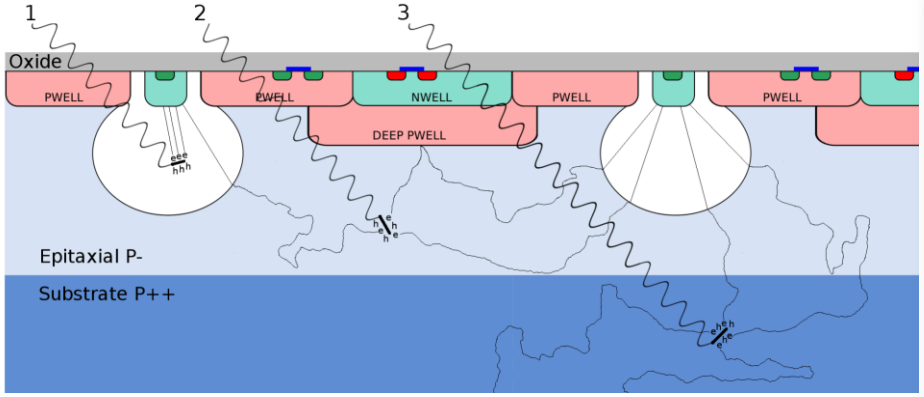
Synopsys – Sentaurus Visual

What did the characterization for ITS2 look like?

X-Ray studies of an ALPIDE like prototype chip

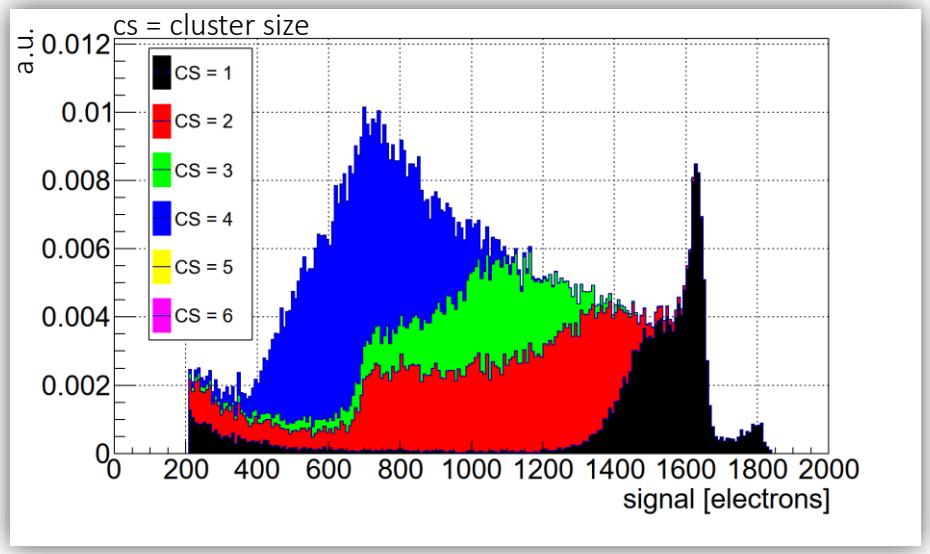
- key plots are the seed signal distribution and the cluster multiplicity
  - The seed signal refers to the amount of charge on the pixel with the largest signal
  - Cluster size refers to the number of pixels with charge above a given threshold for one event
- the main features in the seed signal distribution are the calibration peak and the charge sharing peak
  - they provide information on the amount of photons fully collected and the sensor's amount of charge sharing
- using these insights the ratio between collected charge and pixel input capacitance was optimised

Three types of X-Ray photon deposits within the sensor



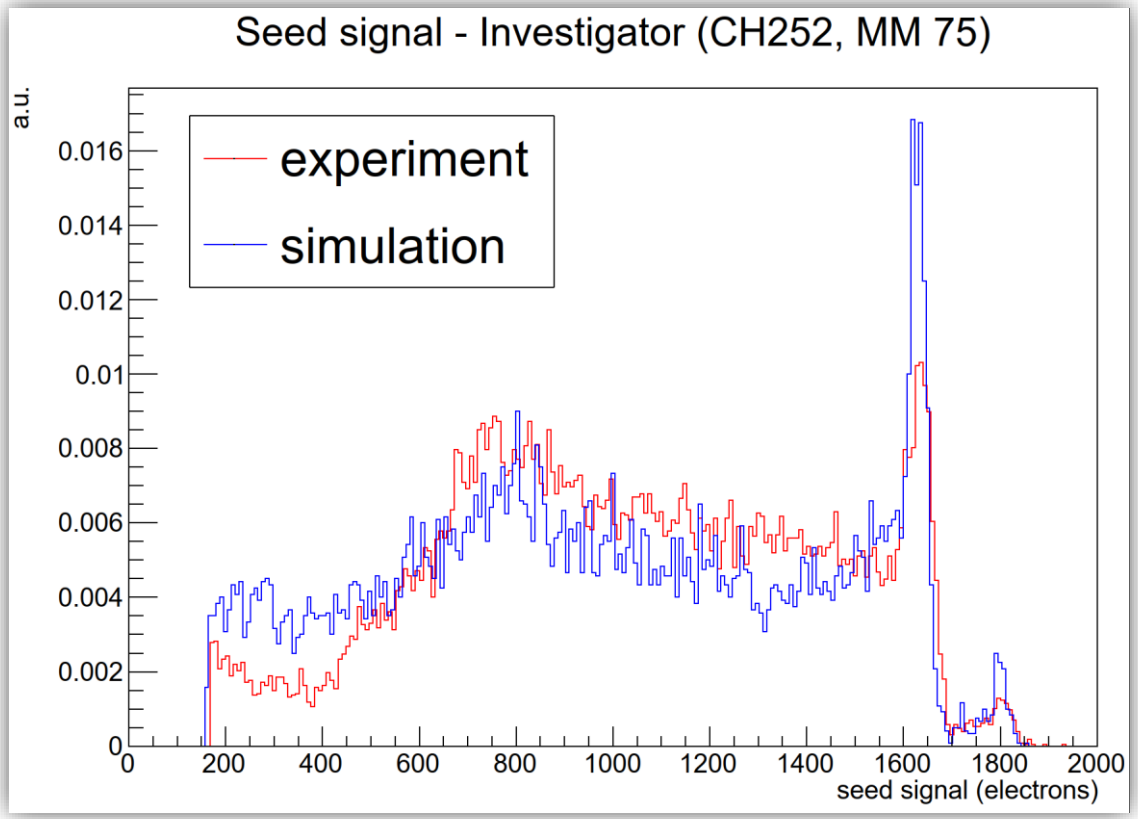
1. all charges collected by one electrode (cs = 1)
2. charges shared between pixels (full charge collection, cs = 1-4)
3. charge deposit in the substrate (charges are partially lost, cs = 1-4)

distribution of collected charge per hit event for different cluster sizes



How do the simulations compare to the experimental data?

How accurate is the simulation?



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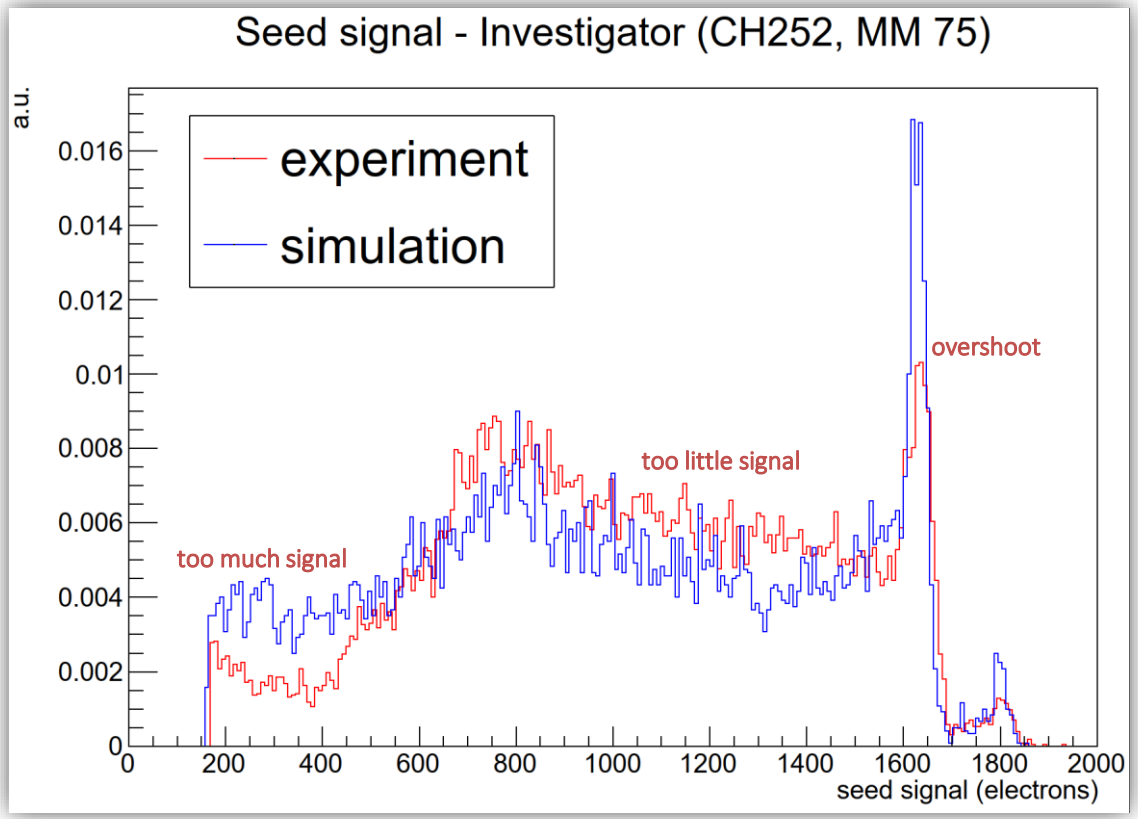
How accurate is the simulation?

- some problem areas -> mainly substrate
- simulation model improved by implementation of a doping concentration dependent carrier lifetime using the Scharfetter relation
- main effects are seen in the substrate but slight effects are also visible for the deep epitaxial layer region



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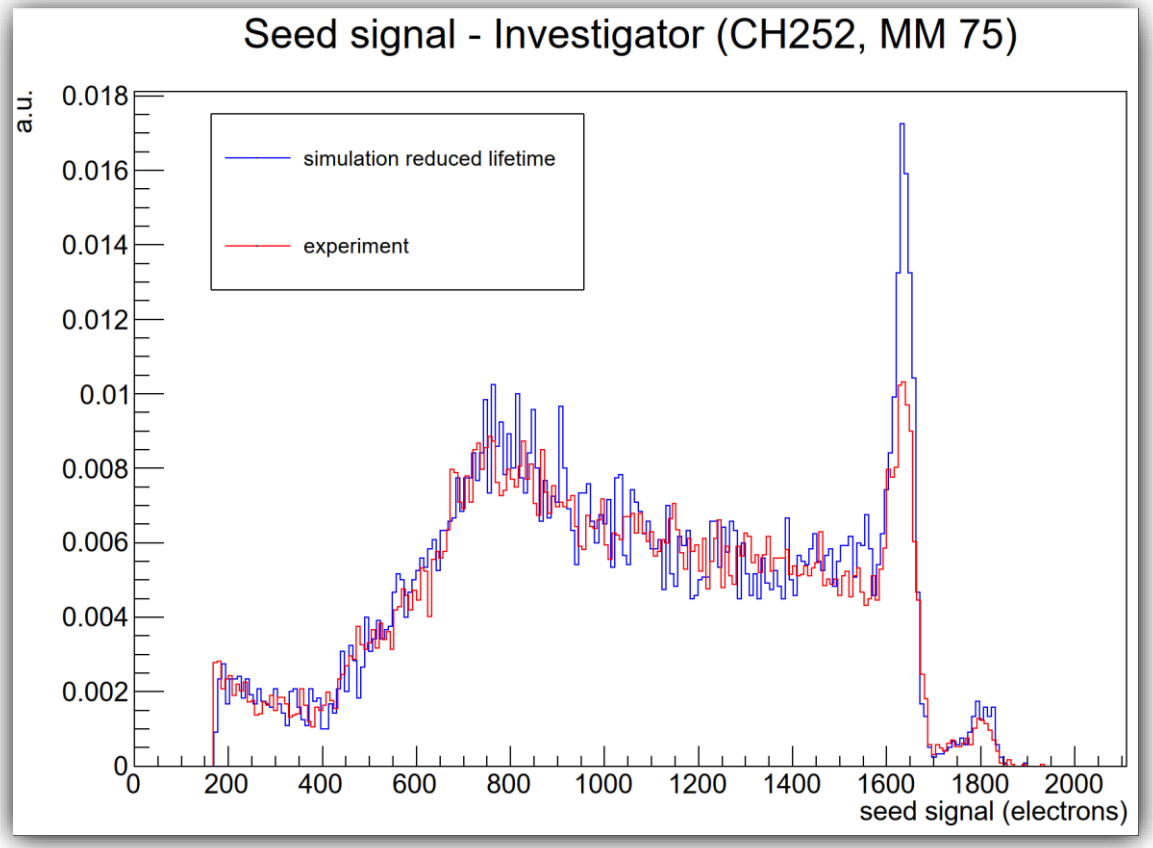

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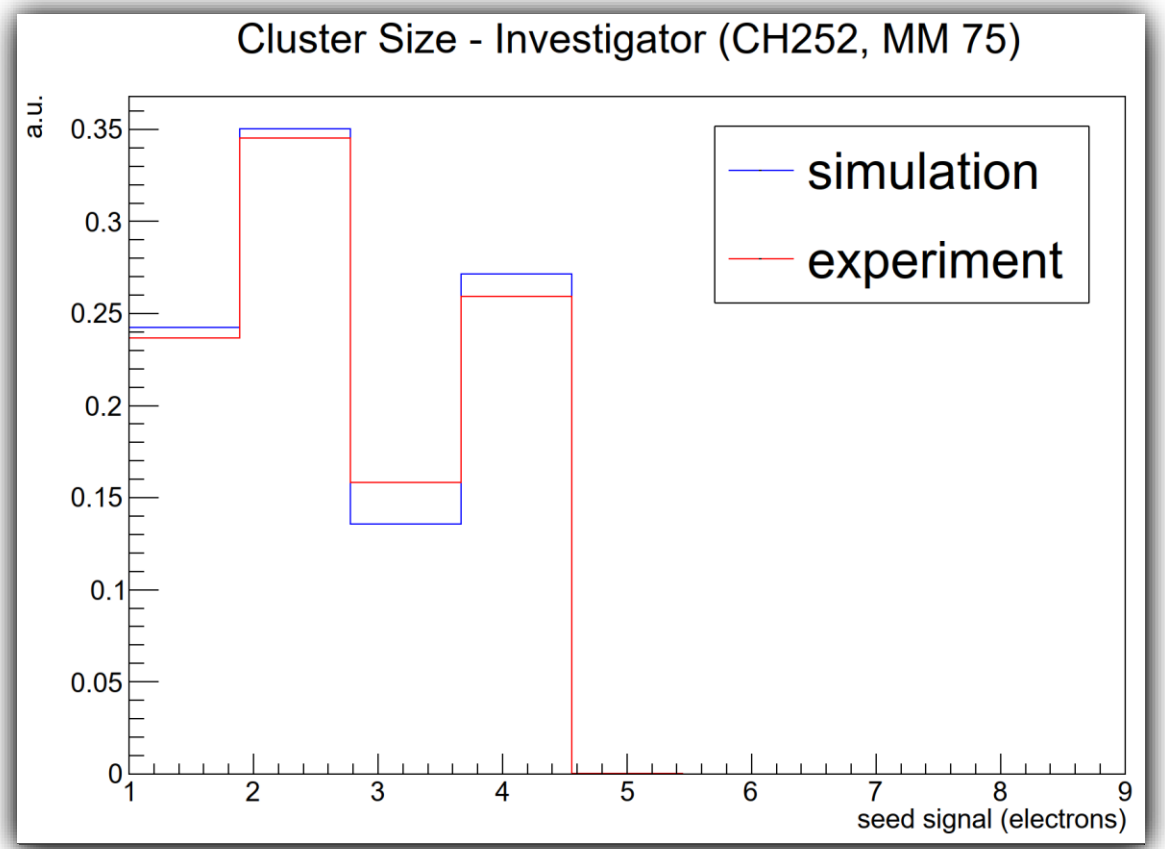
How accurate is the simulation?

- some problem areas -> mainly substrate
- simulation model improved by implementation of a doping concentration dependent carrier lifetime using the Scharfetter relation
- main effects are seen in the substrate but slight effects are also visible for the deep epitaxial layer region
- Cluster size is also well reproduced by the simulation



Next step – simulation of time resolution

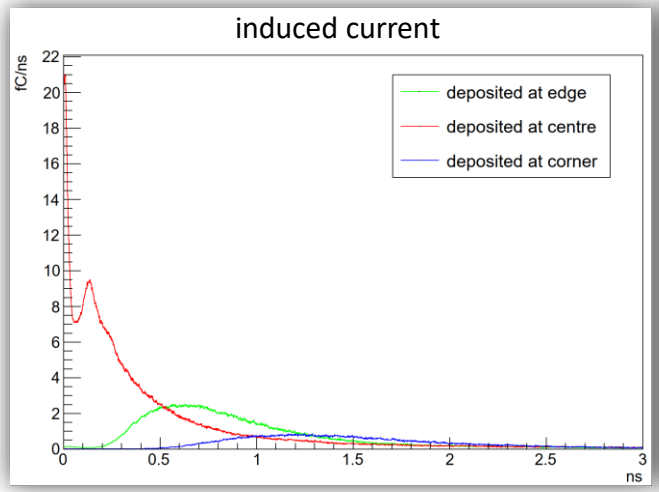
Intrinsic rise and charge collection times

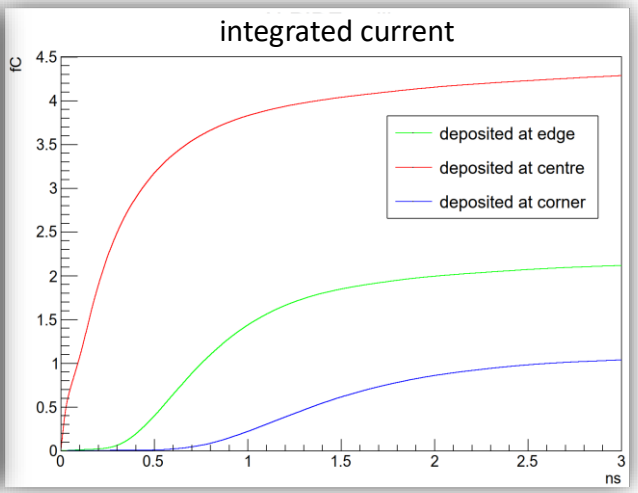
- simulation of signal shape and charge collection behavior for different geometries and voltage
- determination of efficiency and time resolution
- simulation time for a single track is in the range of seconds -> high statistics MC calculations are possible
  - all fluctuations of charge deposit, charge movement and carrier lifetime are taken into account

Time resolution

- The charge collection time or the time over threshold provide some information on the intrinsic limitations of the sensor

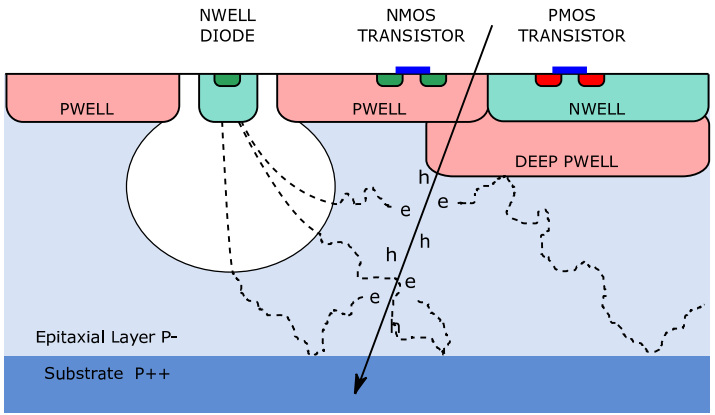
- For accurate determination of the time resolution, the amplifier transfer function, noise and method for slewing correction must be taken into account





induced current and integrated charge on the seed pixel for an ALPIDE like structure with smaller pixel pitch

Summary



Garfield++

Summary

The simulation of a MAPS detector using Garfield++ was presented

- Electric fields and weighting fields are calculated with dedicated TCAD programs and imported into Garfield++
  - Sentaurus, Silvaco, ANSYS, COMSOL, semi-analytic fields …
- Efficient MC simulation of interaction of particles with the sensor (X-Ray photon, MIPS, e/h-pairs ..) and tracking of the charges in the electric field yields the induced sensor signal.

Simulation based on first principles

- sensor fields defined by geometry and doping concentration
- charge deposit and tracking based on drift-velocity, diffusion coefficient and carrier lifetime

Direct connection to simulate connected electronics

- The induced current signals can either be used as input to analog circuit simulation programs or the signals can be convoluted with a given amplifier delta response already in Garfield++.

Garfield++

- The program has been in use for gas detector simulation since a long time and is still being developed in this context.
- The principle of signal generation in gas detector and silicon detector is the same … the extension to silicon sensor simulation is natural …

CERN

Backup slides

① Weighting field simulation

② X-Ray photon simulation – example for an FE-55 source

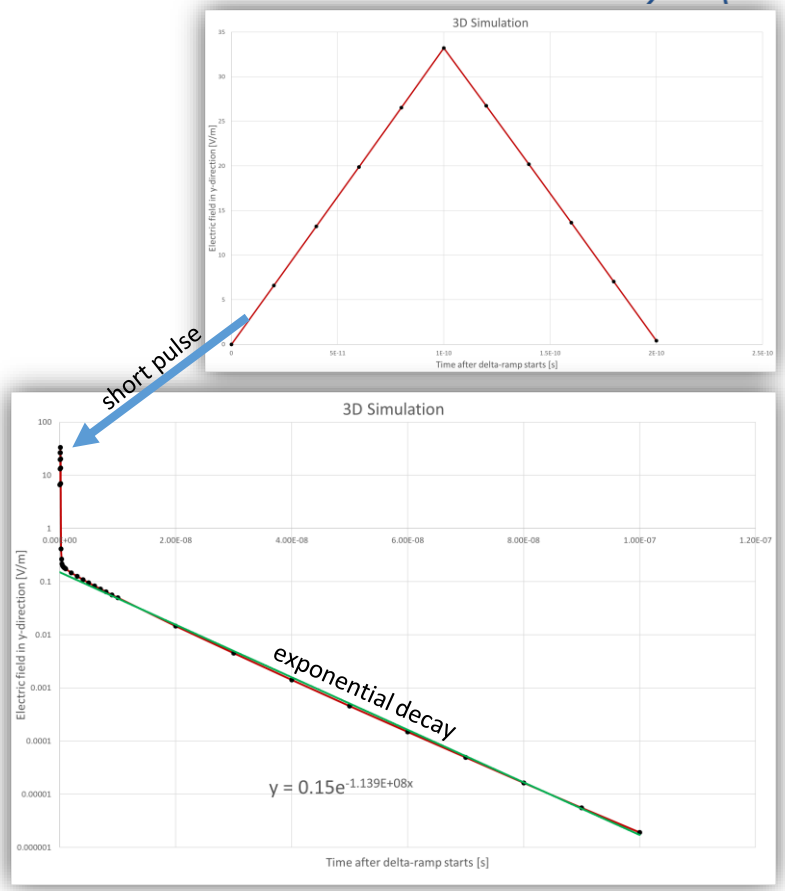
Weighting fields and potentials – static/dynamic

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