3D detector design

Angelo Loi

December 1st, 2017

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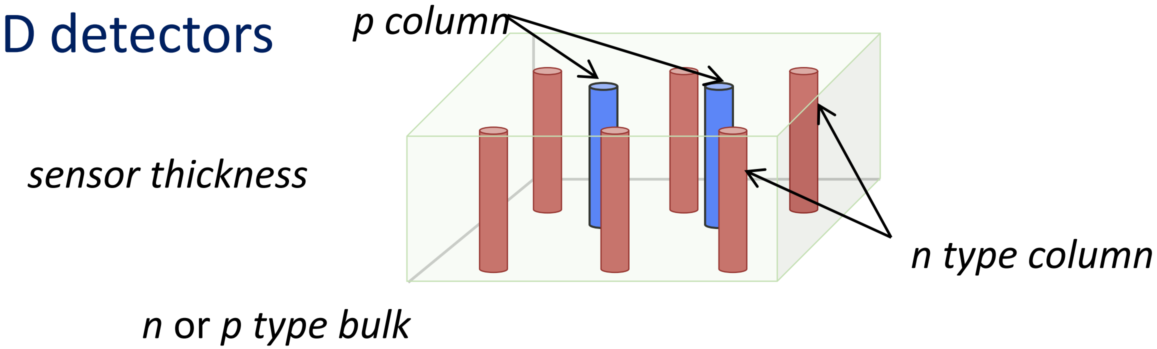
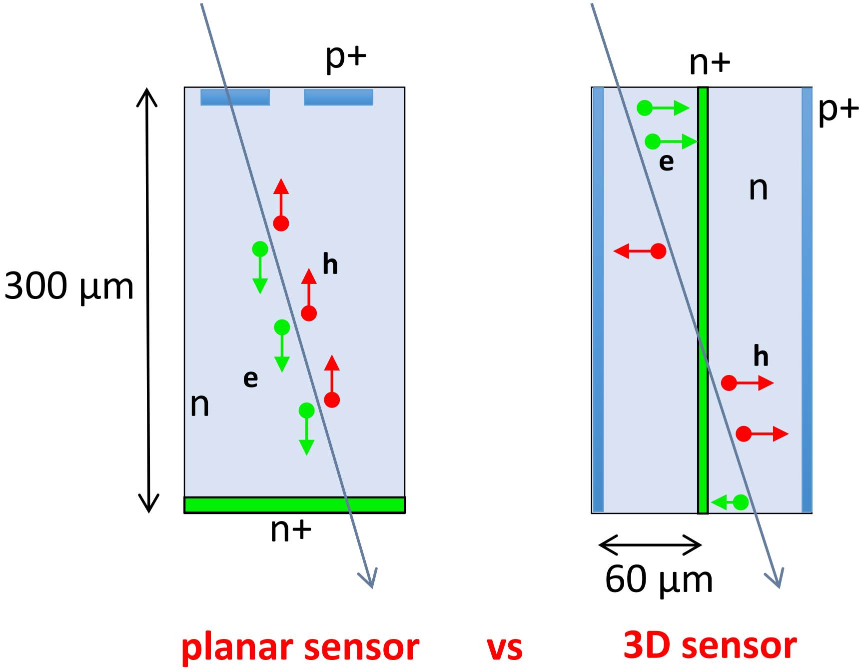
Pixel with good timing properties (1)

- What we were looking for:
  - Detector with fast charge collection (less than 500 ps)
  - Characteristic output signal shape independent from the particle track inside the silicon medium
- How can it be achieved?
  - Fast charge collection:
    - Using a detector technology which is capable of collecting electrons and holes in the requested time interval
- Chosen technology:
  - Silicon 3D detectors





Pixel with good timing properties (1)

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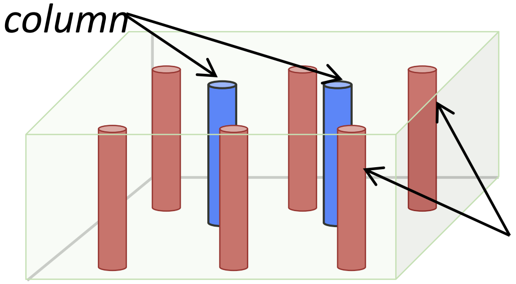
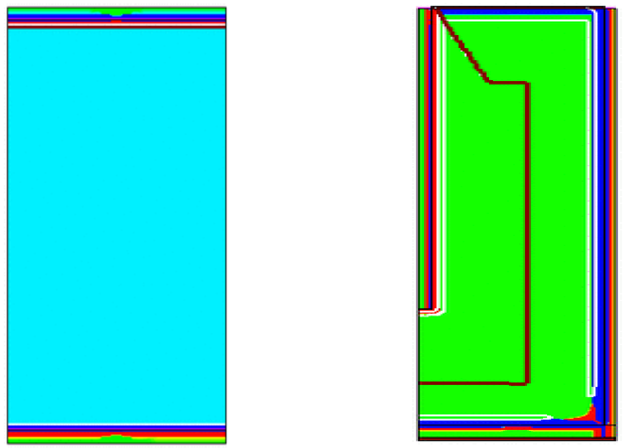
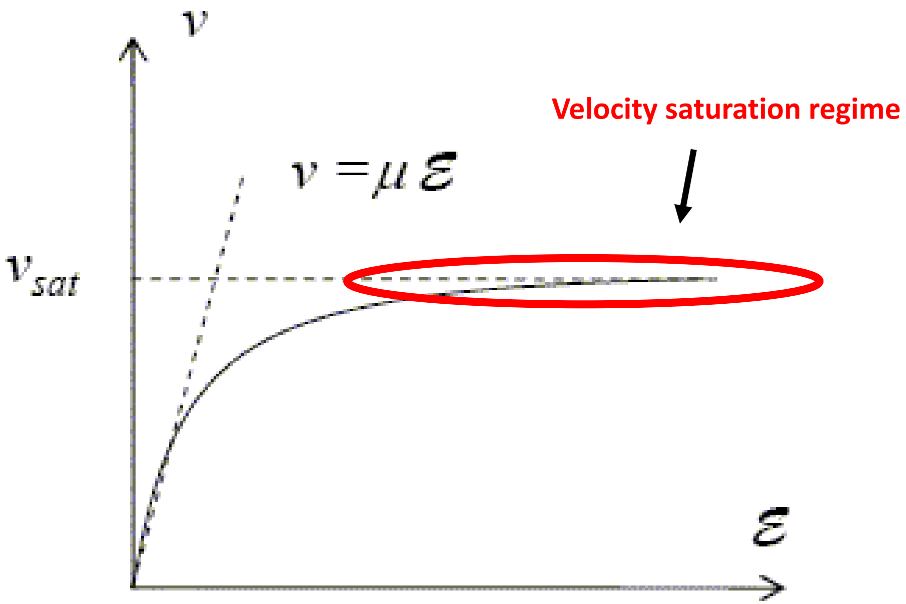




Pixel with good timing properties (2)

- How can it be achieved?
  - Signal output:
    - Following **Ramo theorem**, which describes the induced current on a electrode of a detector by a crossing particle, we need a detector with a possible constant electric field and charge velocity over the entire pixel volume.
    - V = charge velocity
    - E_w = Weighting field
- Velocity can be hold mostly constant, if detector operates at velocity saturation.
  - Electric field must be over 10 kV/cm
- Constant electric field is more challenging:
  - Need to work on the pixel geometry:
    - Form of the pixel and electrodes
    - Electrode position inside the pixel

$$i_1 = q_m \nabla\left(\frac{V_m}{V_1}\right) \cdot \mathbf{v} = -q_m \mathbf{E}_w \cdot \mathbf{v}$$



Work organization

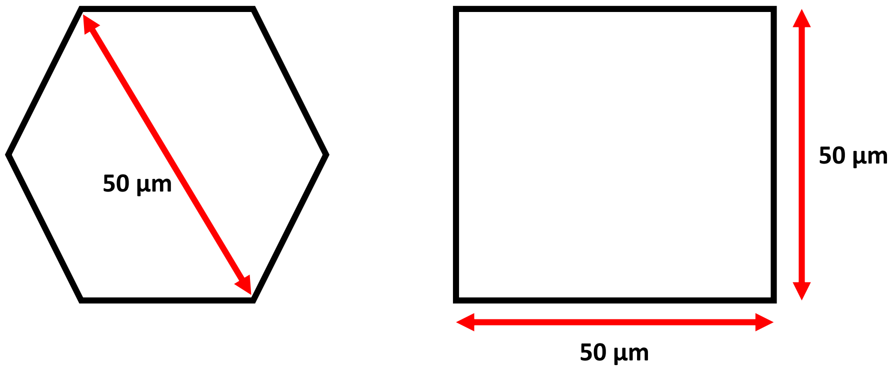
- Starting with 2D design of pixel cross-sections
  - Useful to understand carrier velocity and electric field between the electrodes
  - Less computational resources are needed
    - 2D models are defined with less than 50k points/meshes (3D models reaches easily more than 500k)
    - More geometric solutions can be explored in less time
- Selection of the geometries with the best properties
  - Evaluation of Electric field over the entire area (presence of possible low field areas)
  - Detector must operate at velocity saturation
- 3D design
  - Repeating detector design, including more structural details and repeat velocity and electric field analysis.

2D model design

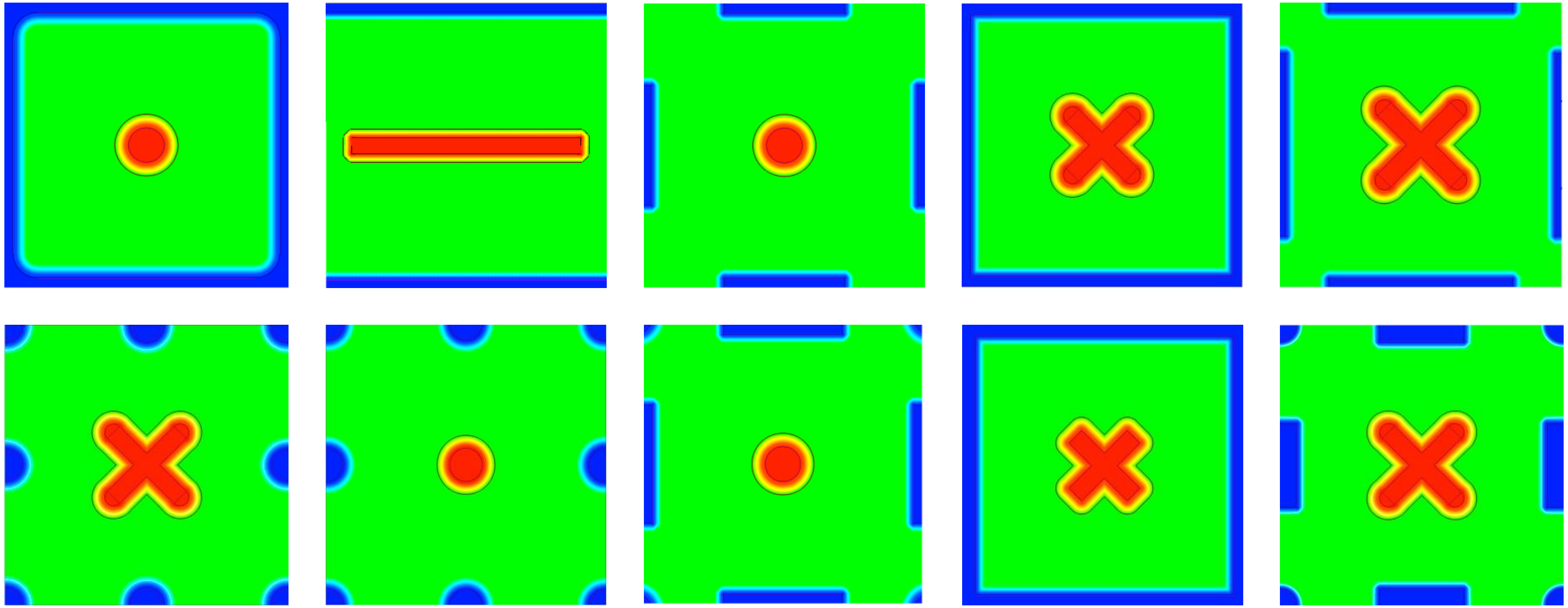
Second Title

Designed geometries

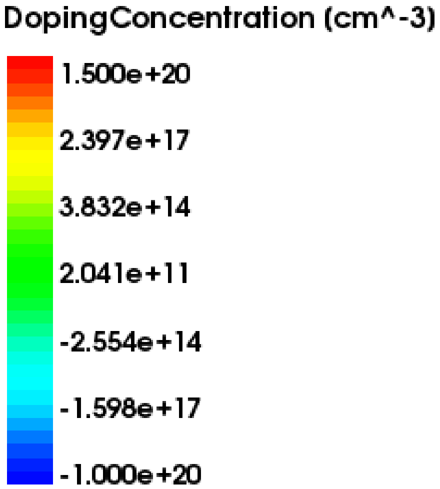
- More than **15** different geometric configurations were explored.
- Each single geometry was also designed in till 30 different ways, which means that overall there were explored **more than 200 different** pixel geometries, which are organised in two main configurations
  - **Hexagonal pixel** geometry with 50 µm in diameter (4 models)
  - **Square pixel** geometry with 50 µm x 50 µm dimension (more than 11 models)
- All designs have in common the following characteristics:
  - Doping concentrations:
    - P++/N++ doping concentration
    - P- substrate doping concentration
  - Trench dimension:
    - 6 µm and 3 µm width
  - Column dimension
    - 6 µm and 3 µm diameter
  - 2D models represent only **25%** of the entire pixel section
  - P-electrode potential is set @ -100 V

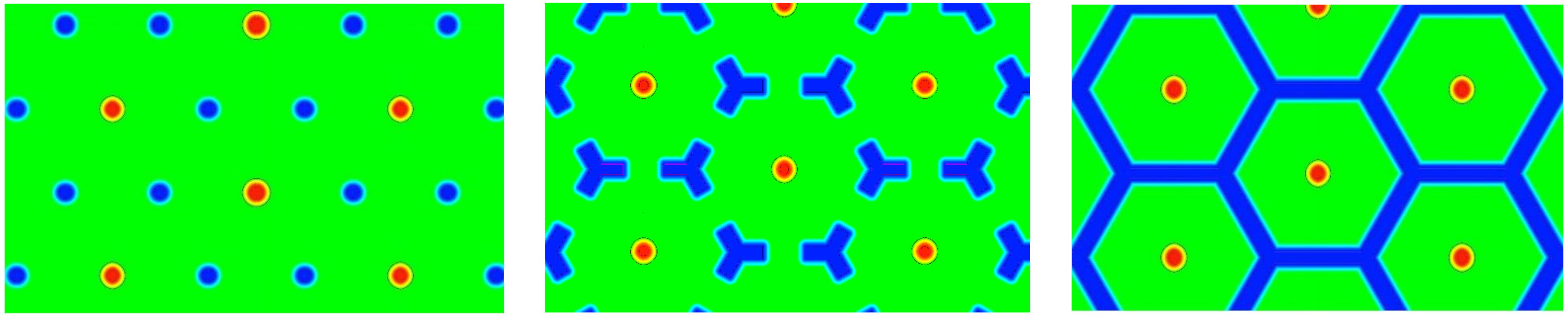


Some examples (doping maps)



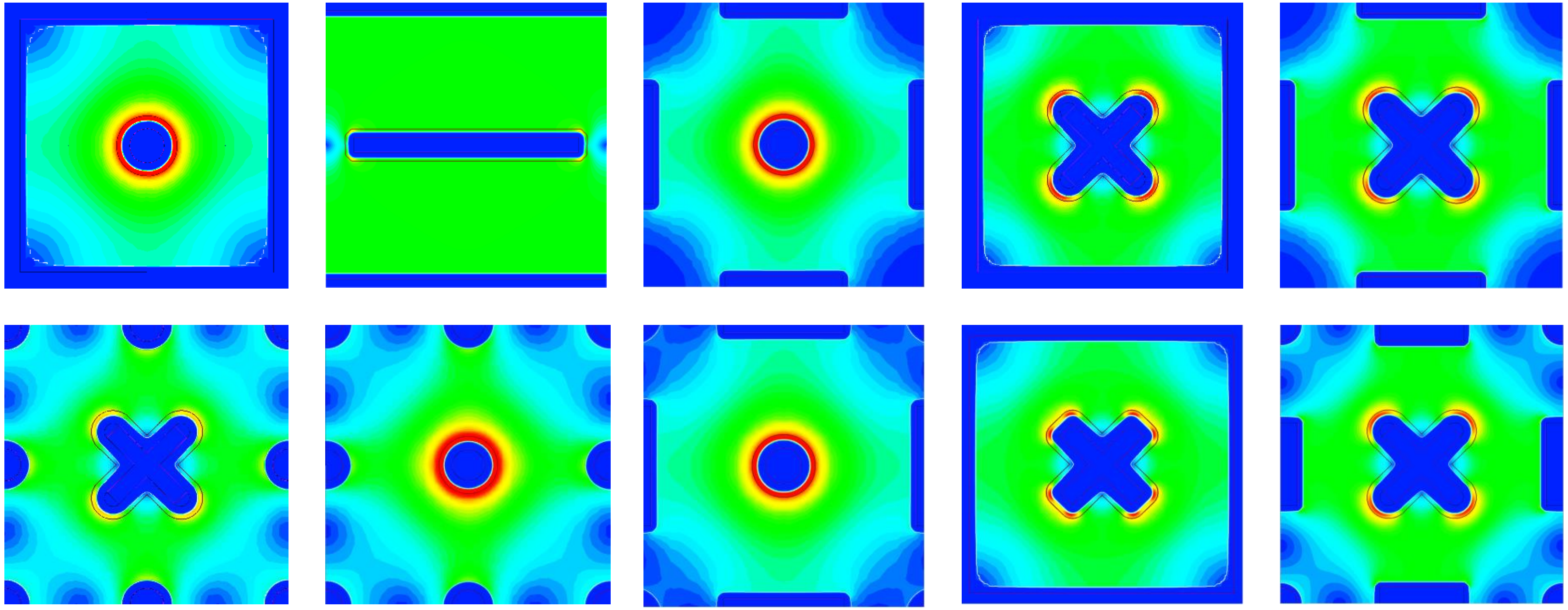
Square pixel geometries



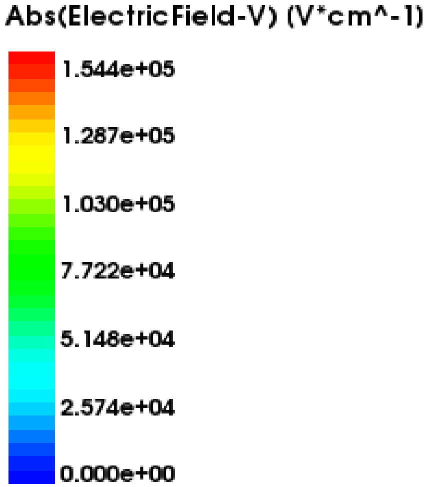


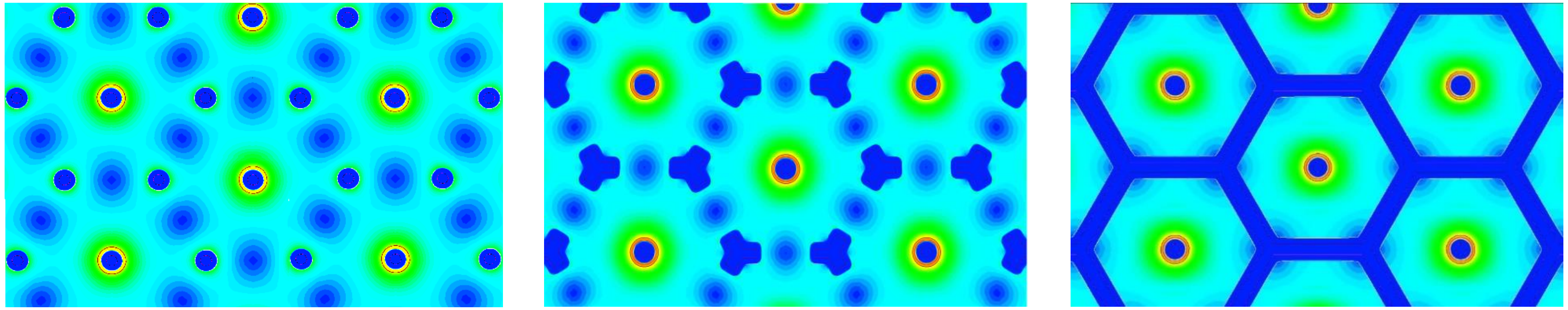
Hexagonal pixel geometries

Some examples (electric field maps)



Square pixel geometries

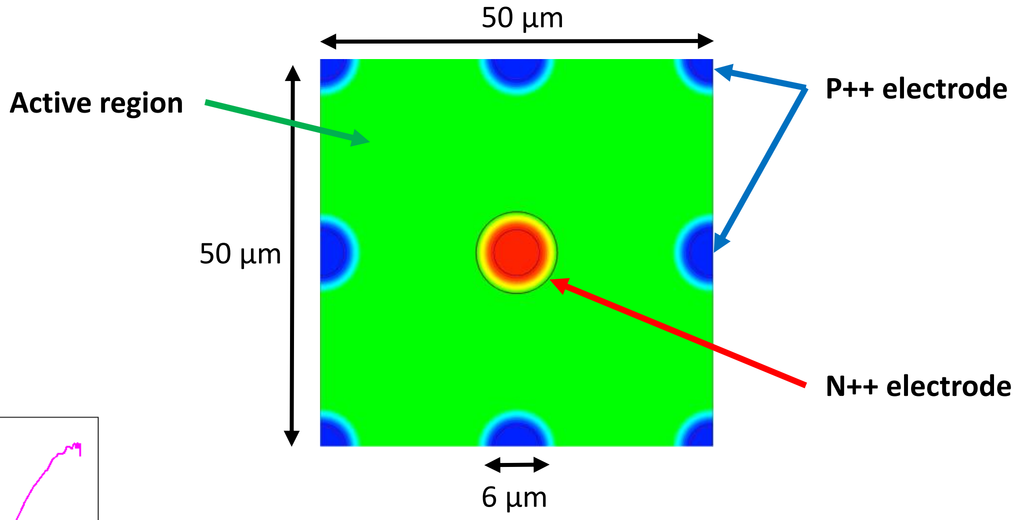


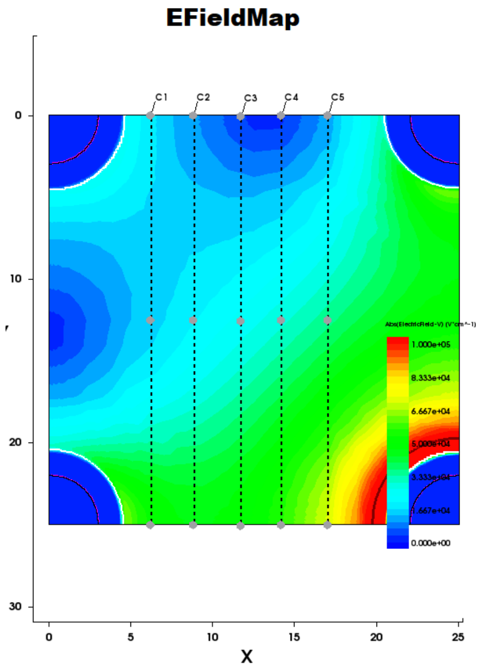


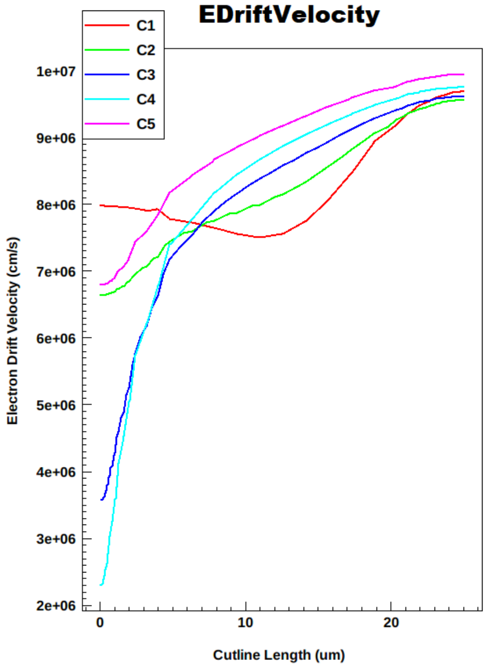
Hexagonal pixel geometries

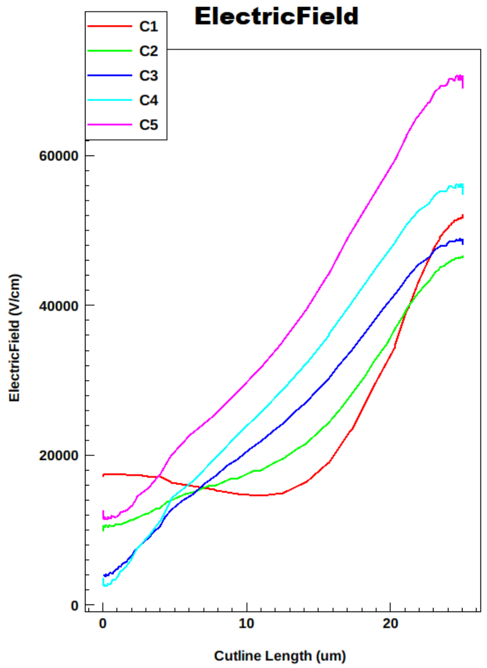
Rejected solutions, some examples (1)

- Square pixel with columnar electrodes
  - Electric field changes too much over all the pixel area.
    - 15 kV/cm over the low field area
    - Over 100 kV/cm near the collector electrode





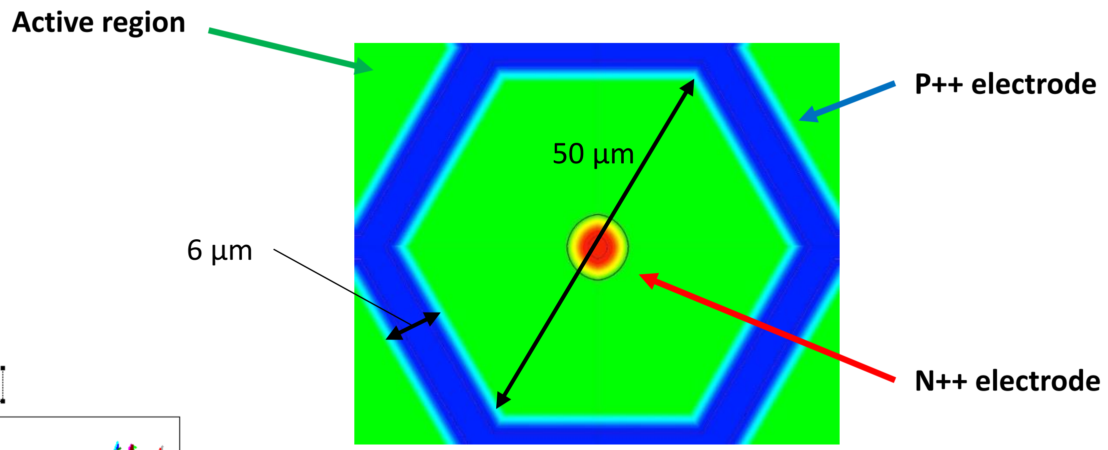


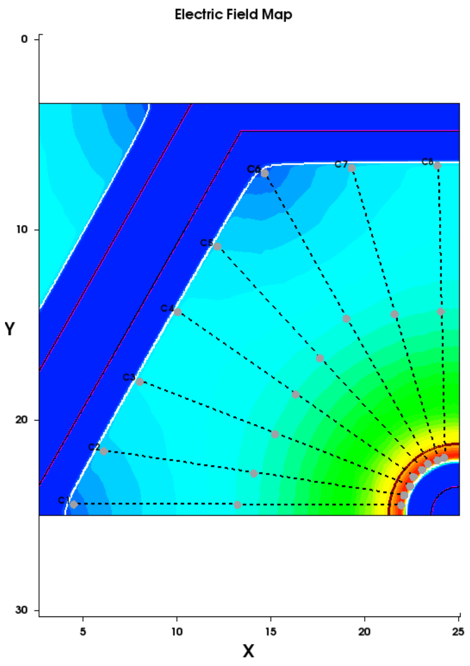


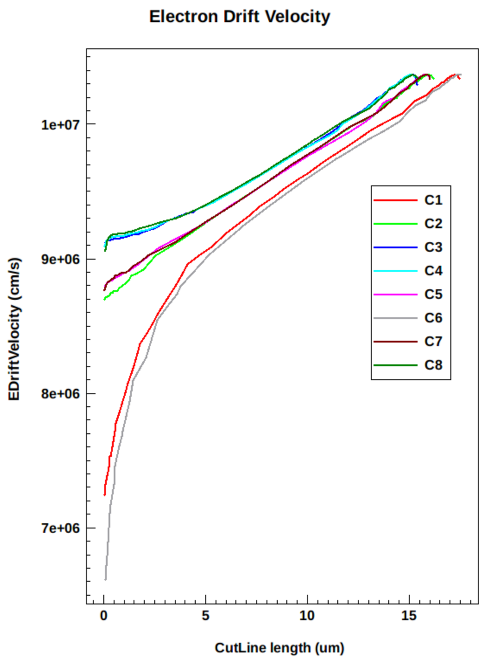
- Electric Field:
  - Electric field changes too much over all the pixel area.
- Drift Velocity:
  - Decreases too much inside the low field areas

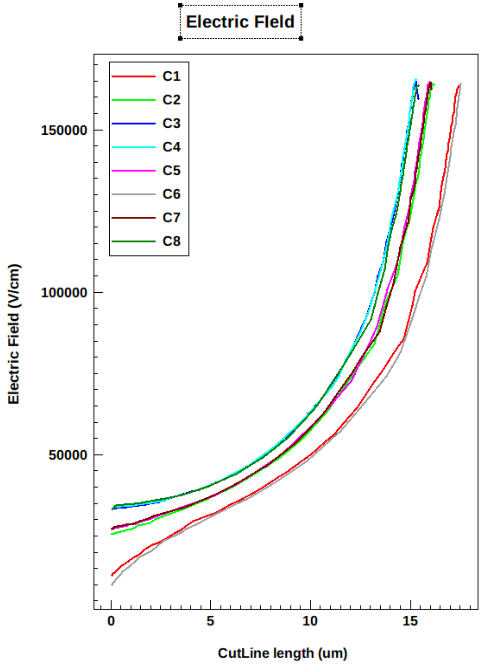
Rejected solutions, some examples (2)

- Hexagonal pixel with continuous trench frame electrode
    - Electric field changes too much over all the pixel area.
        - 15 kV/cm over the low field area
        - Over 100 kV/cm near the collector electrode





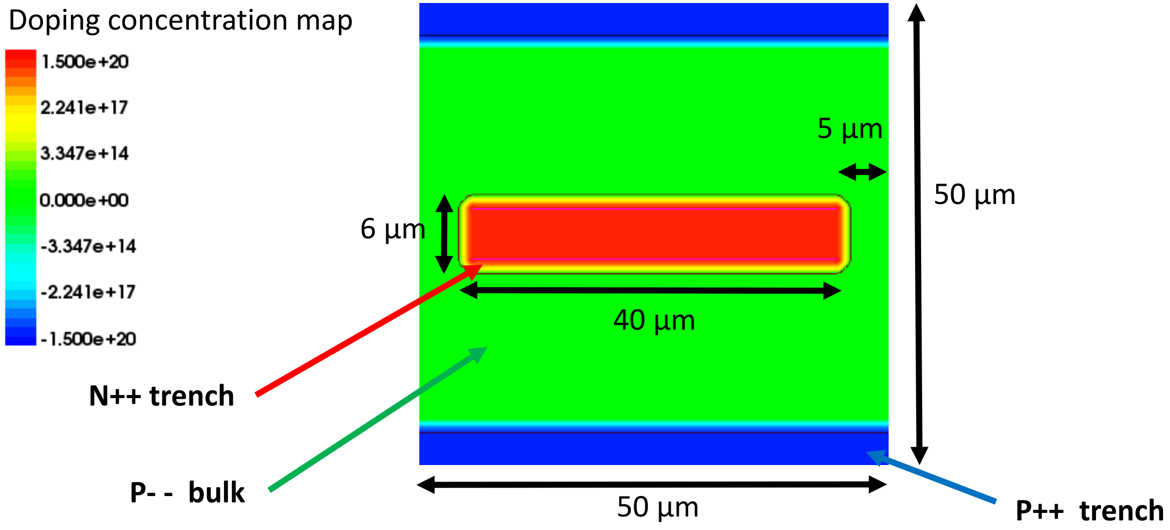




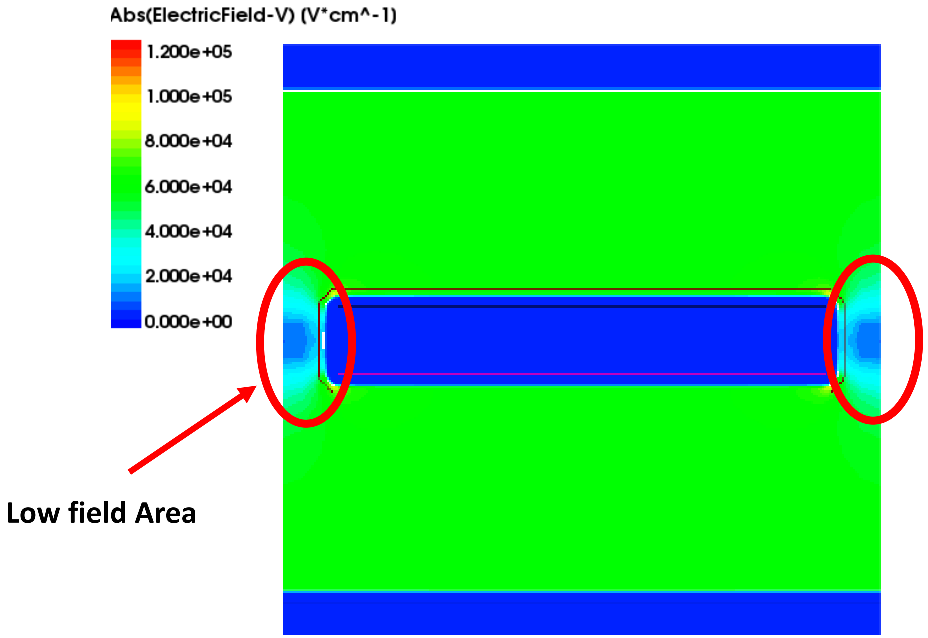
- Electric Field:
    - Electric field changes too much over all the pixel area.
- Drift Velocity:
    - Decreases too much inside the low field areas, like previous geometry.

Chosen solution: **Par trench** geometry

- Parallel trench geometry:
  - 50 µm x 50 µm pixel
  - 3 parallel trenches
    - Two external with same doping (P++) for bias
    - One 10 µm shorter central trench for signal acquisition (N++ doped trench)
  - 32 different designs were explored, changing:
    - Pixel dimension: (50 µm x 50 µm) and (100 µm x 100 µm)
    - Trench width (3 µm and 6 µm)
    - Central Trench Length (from 35 µm to 45 µm)



- Electric field:
  - Is the most uniform of all explored geometries
  - Low field areas cover ca. 1.5 % of the entire area (34 µm²)
    - Areas between two N-electrodes
    - Charge collection remains fast due to the extremely short distance to the electrodes



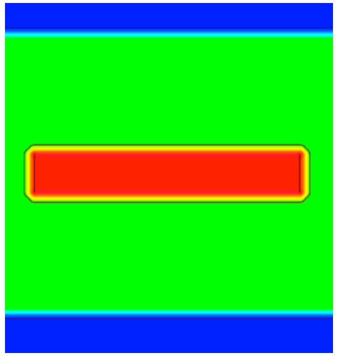
3D model design

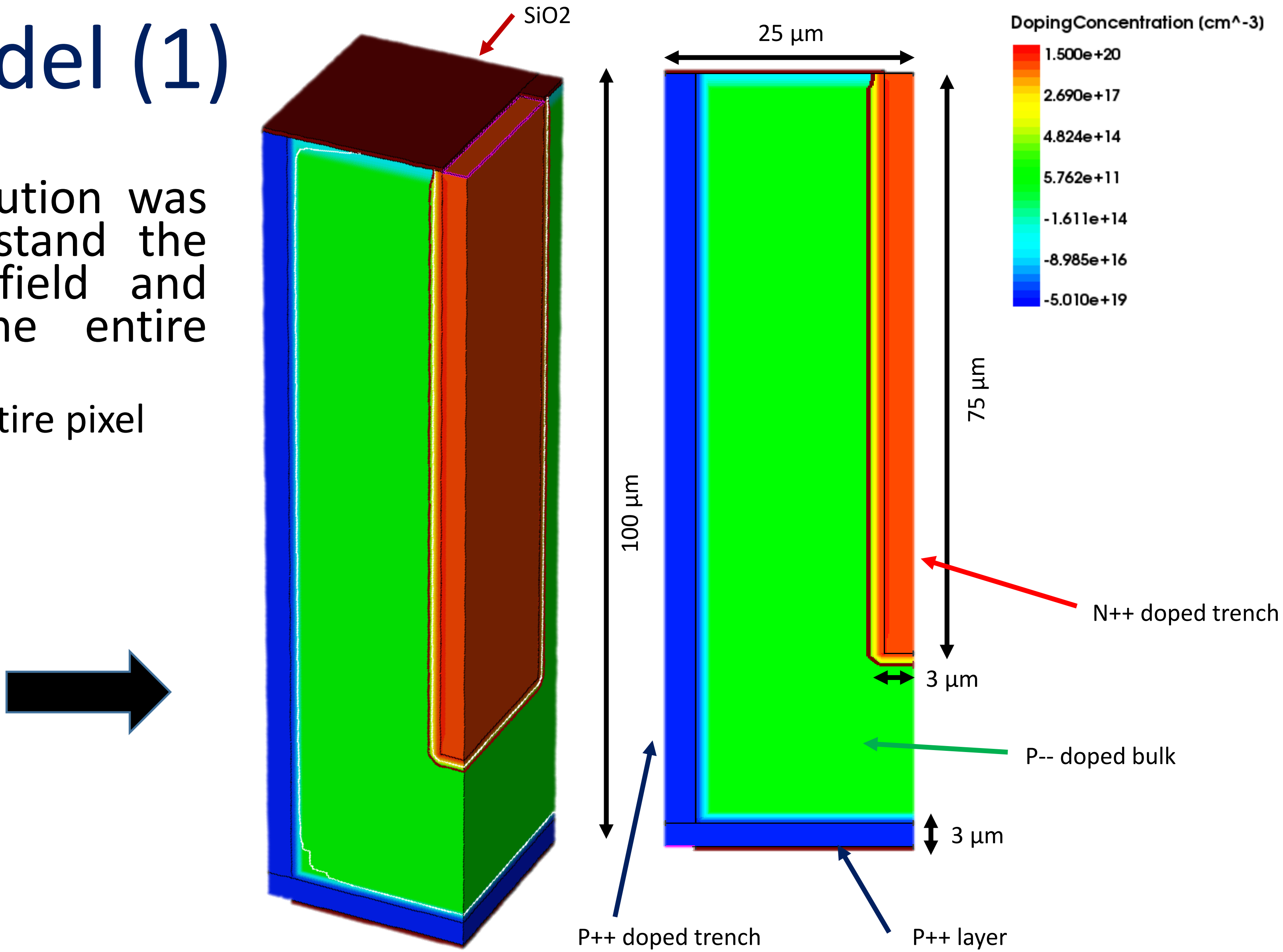
Second Title

Par trench 3D model (1)

- 3D model of the chosen solution was designed in order to understand the behaviour of the electric field and charge velocity through the entire detector volume.
  - Model represents 25% of the entire pixel

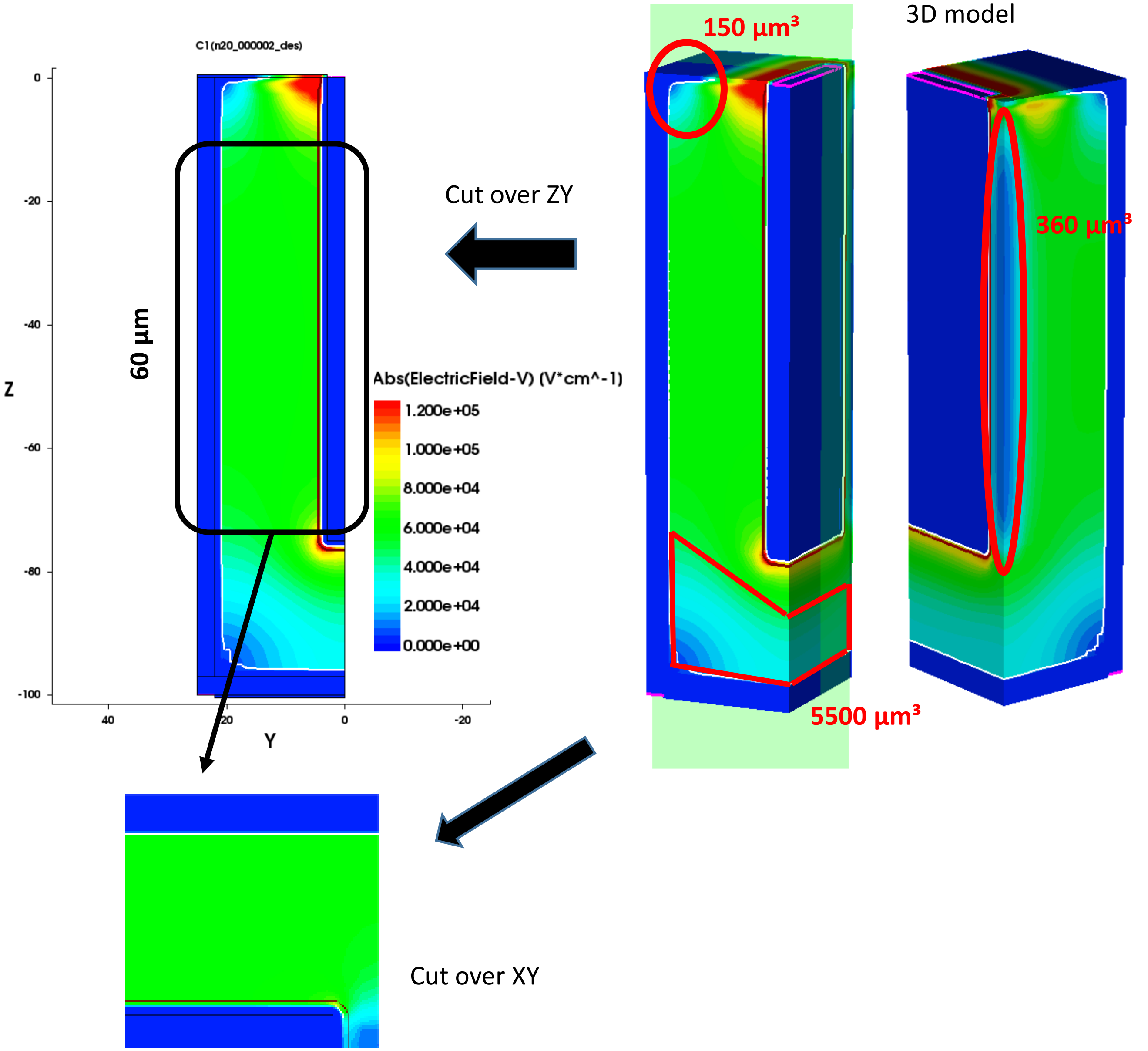
2D model along XY





Par trench 3D model (2)

- 3D simulation shows that there is a second larger low field area at the bottom of the pixel volume
  - Possibility that this area can reduce charge collection.
  - Low field regions covers ca. 10 % of the entire sensitive volume
  - Solutions must be found in order to reduce its area.

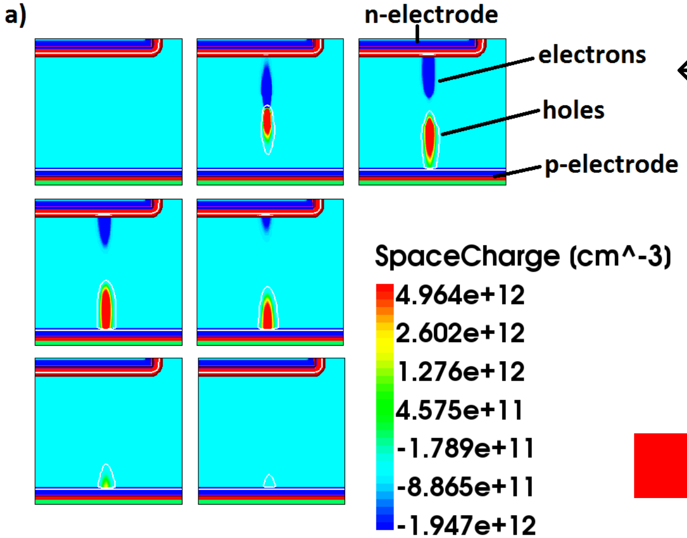


Current status

Signal generation

Signal generation on 2D models (1)

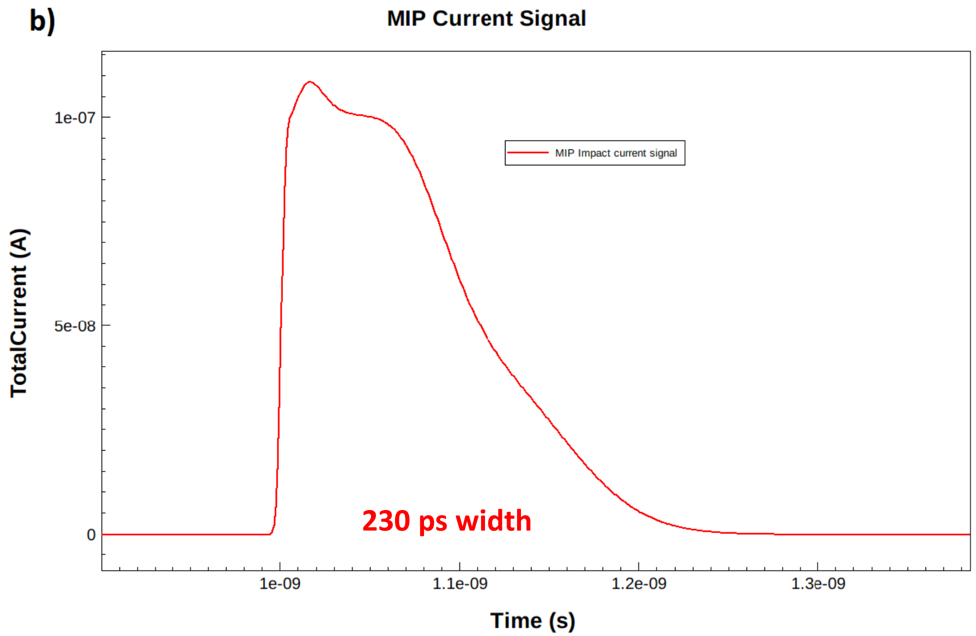
- TCAD is not specifically developed for particle detector design
- It is possible to emulate the passage of a high energy proton, by injecting charge in a specific location (or track) inside the detector during a transient simulation
  - Setting a LET of 80 electron/µm corresponds to an High energy proton passage



←Charge drift after heavy ion collision

Respective signal

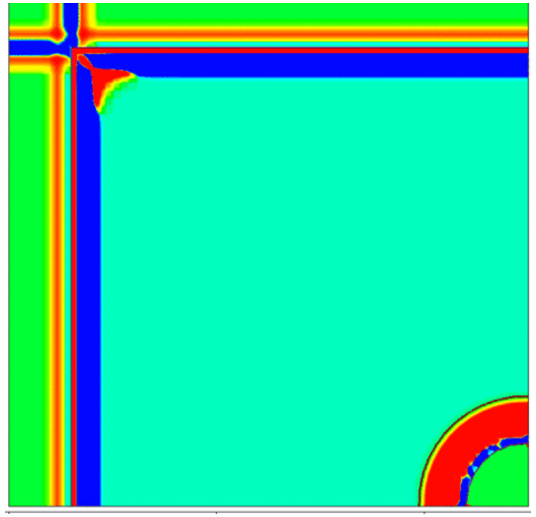
- Problems:
  - Impossible to observe the tracks of single charges
  - LET is too deterministic



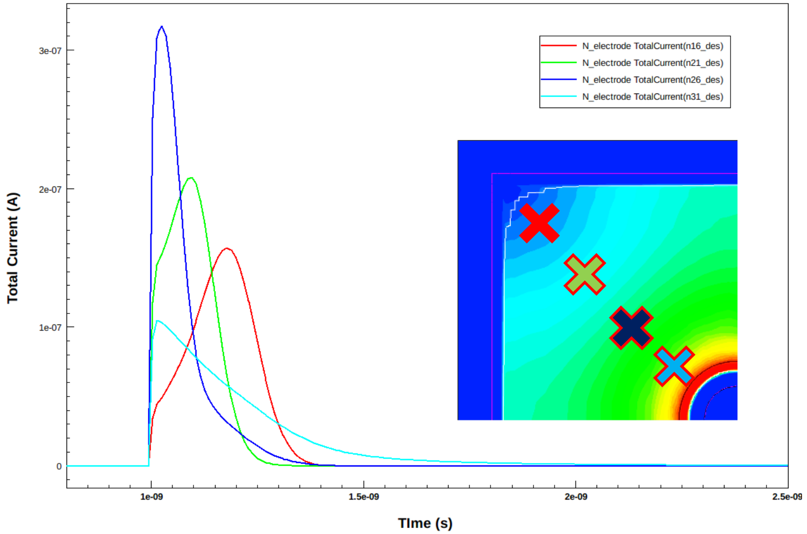
Signal generation on 2D models (2)

- Output signal shape was at first explored on 4 different 2D models
  - Dividing the area of the 2D model into approx. 25 (16) cells
  - During a transient simulation, 80 e-/h pairs were injected inside only one of the 25 cells

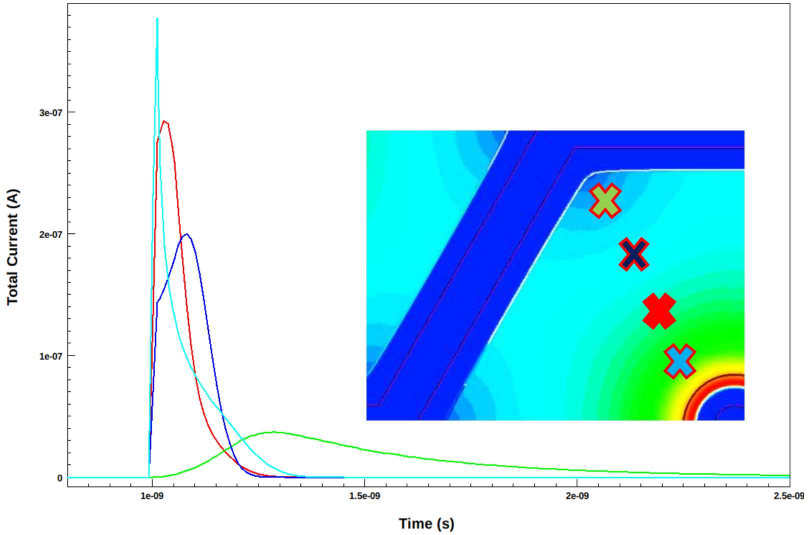
Charge density map representing 15 MIP crossing the pixel and the drift of the e-7h pair to their respective electrodes →



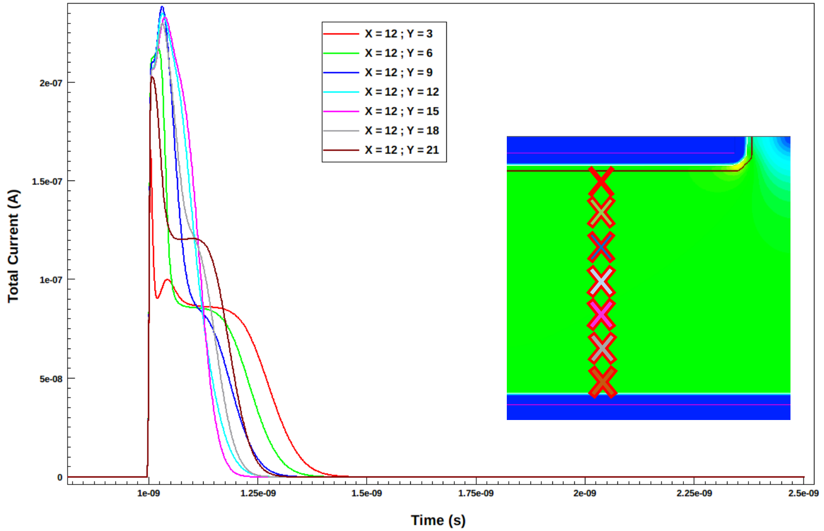
Square pixel with central column



“Closed” hexagon with central column

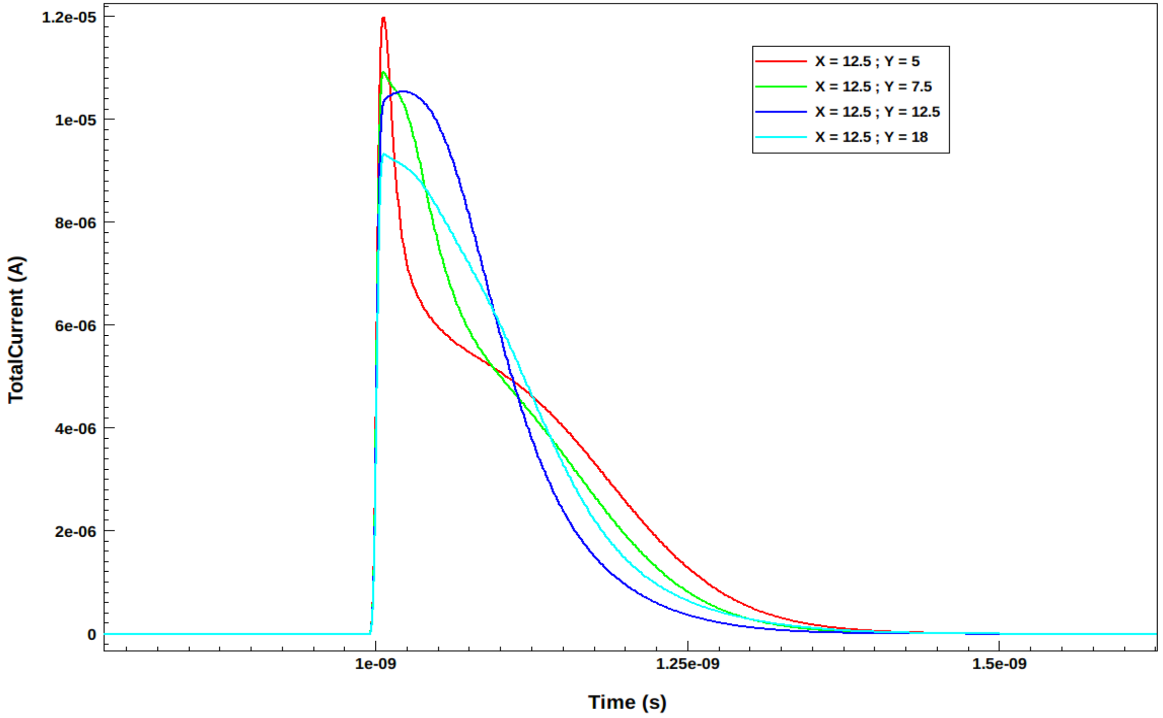


Parallel trench pixel

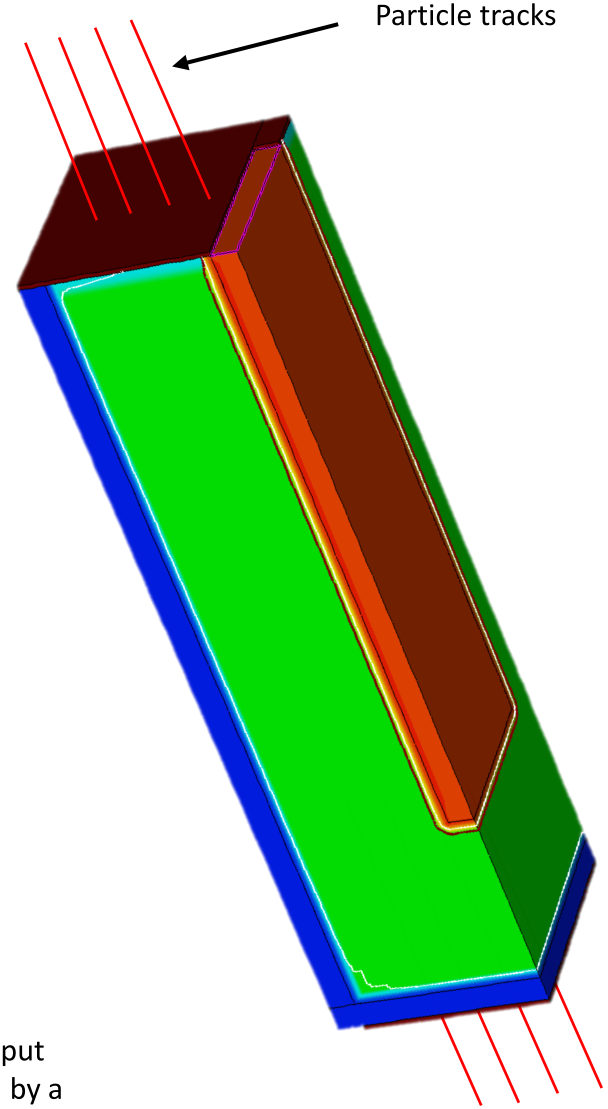


Signal generation on 3D models

- Same approach was used for the 3D model
  - Signals are more similar to each other
  - Signal width is still the same (less than 300 ps)
  - Important: There is no evidence that the low field areas are reducing charge collection.



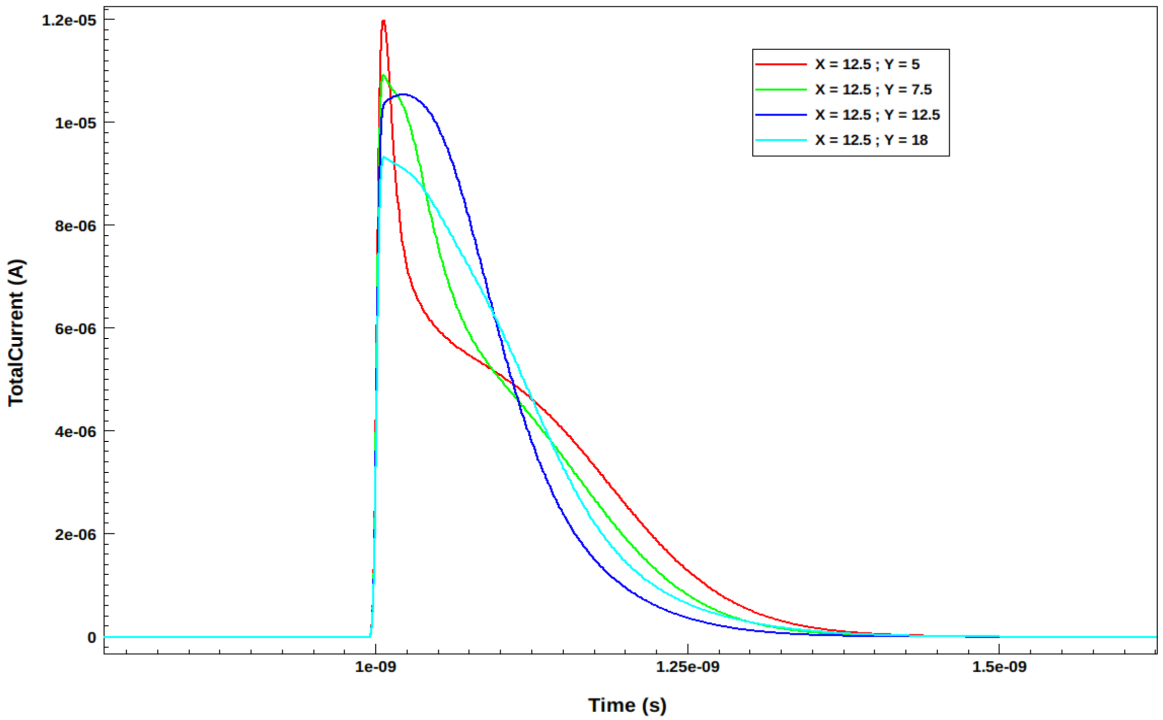
Plots watching the total current output signal of the detector when crossed by a MIP

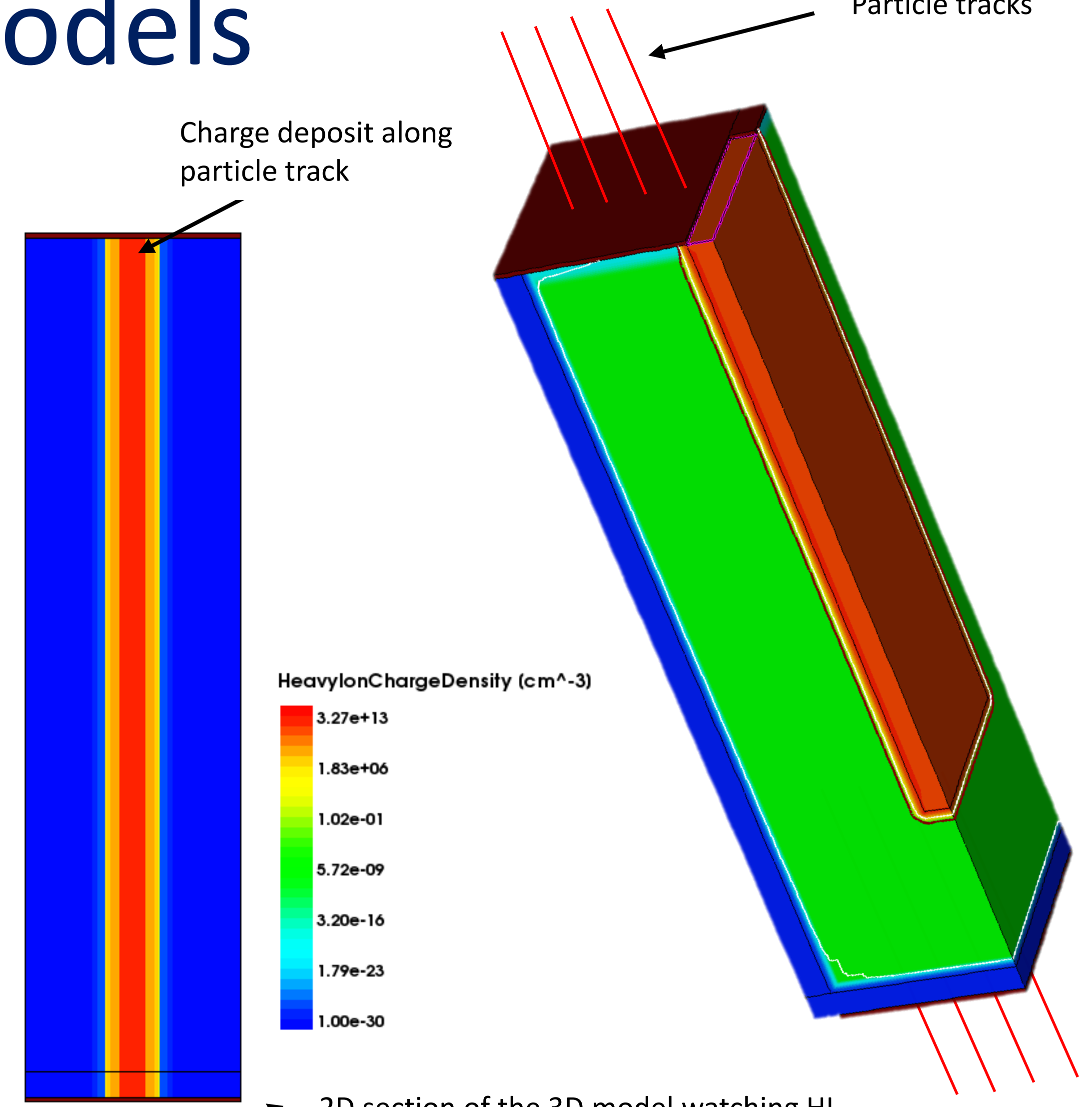


Particle tracks

Signal generation on 3D models

- Same approach was used for the 3D model
  - Energy deposit is still too uniform over all the track !
  - Need a more realistic model for the charge deposit along the particle track!





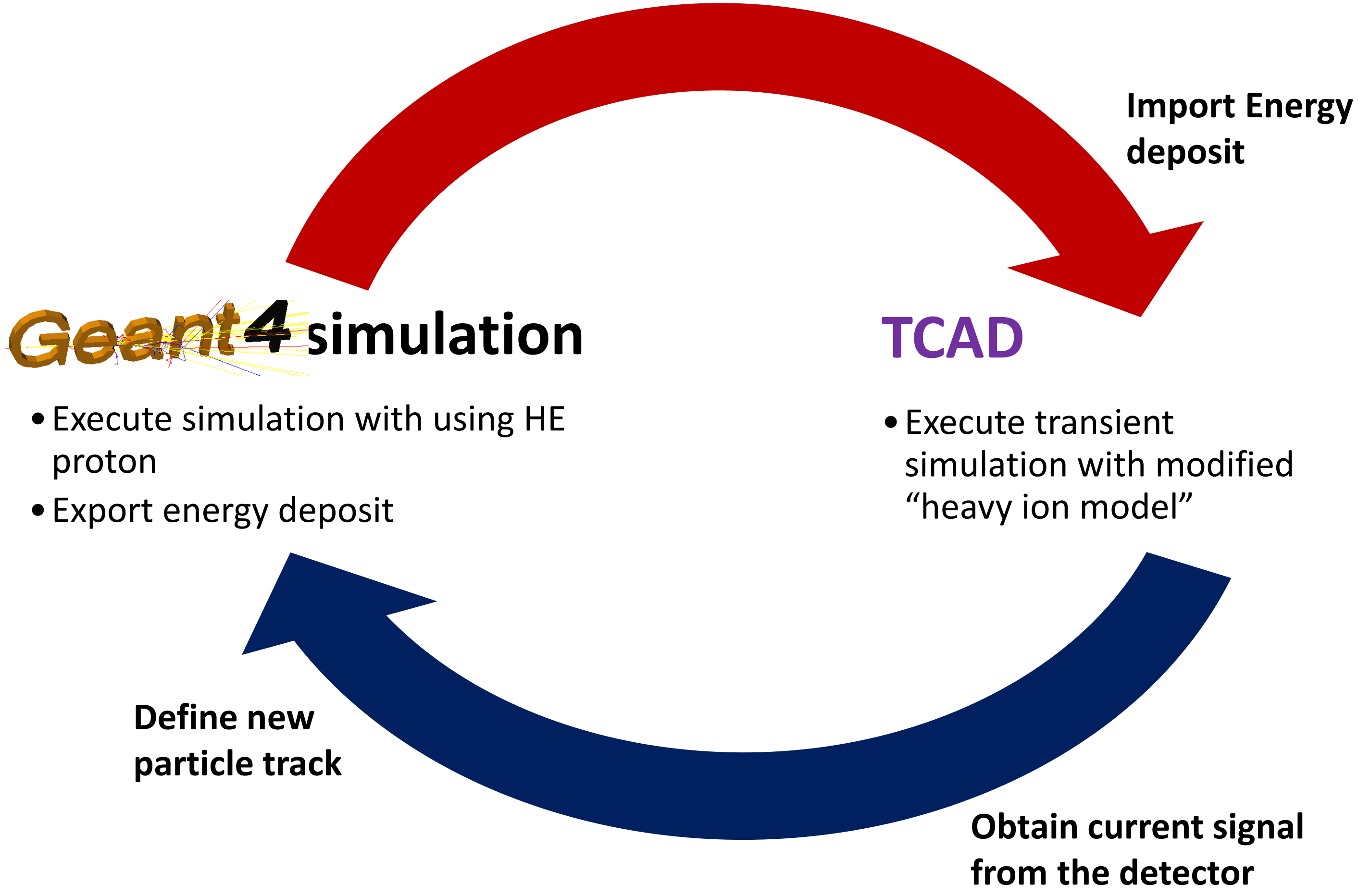
Particle tracks

Charge deposit along particle track

2D section of the 3D model watching HI charge density deposit

Signal generation using extra tools (1)

- TCAD and Geant4 approach:
  - Reproducing a same scale model of the detector in Geant4
  - Simulating the passage of an high energy proton through the pixel
  - Export the energy deposit of the particle
  - Using the energy deposit of G4 to customise the heavy ion model of TCAD on a specific ".par" file
  - Start Sdevice simulation with modified HIM



Import Energy deposit

Geant4 simulation

- Execute simulation with using HE proton
- Export energy deposit

TCAD

- Execute transient simulation with modified "heavy ion model"

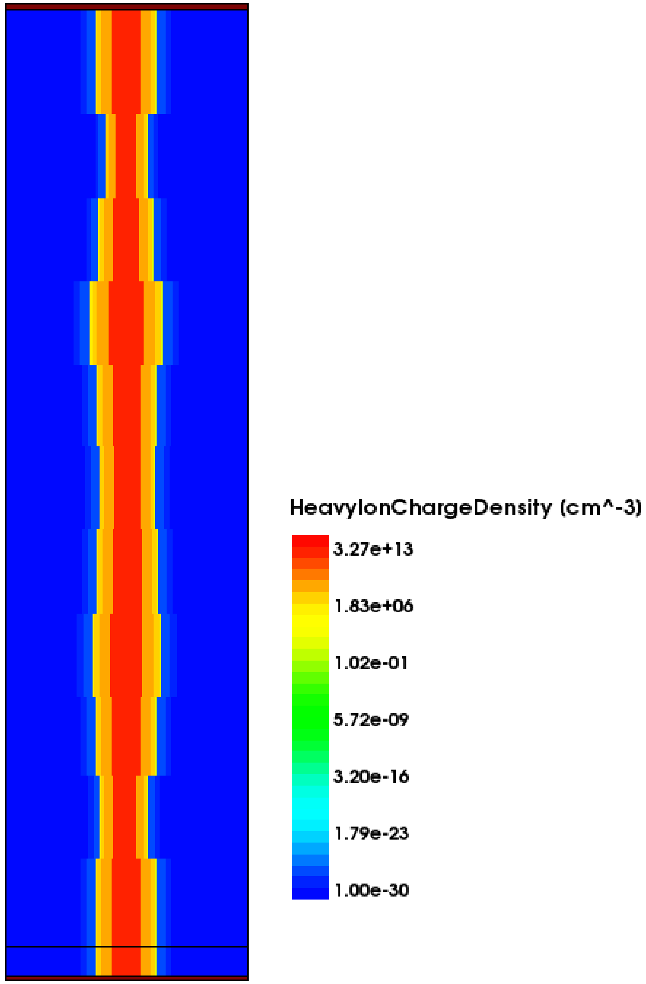
Obtain current signal from the detector

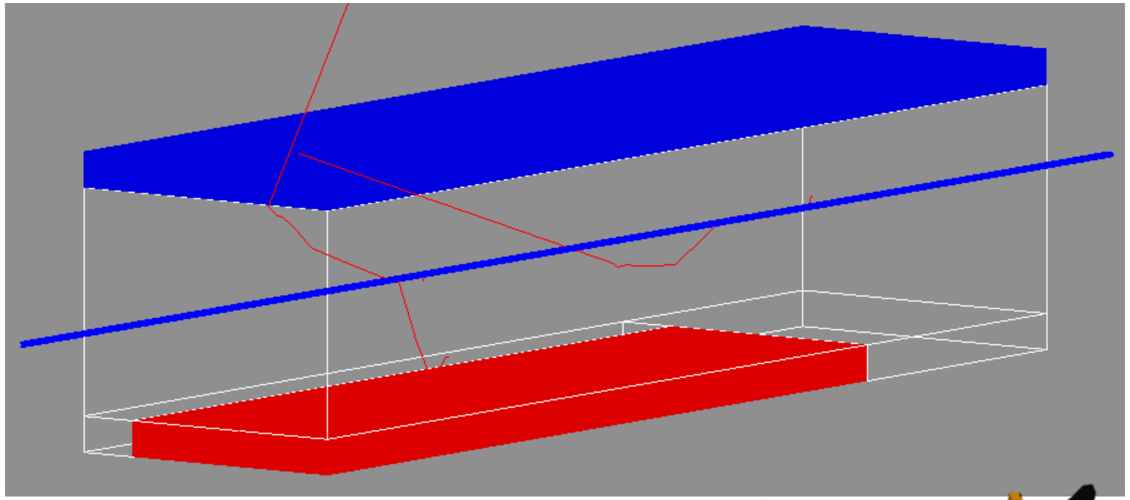
Define new particle track

Signal generation using extra tools (2)

- What is already done
  - 3D model in G4 reproduced
  - Physic is defined
    - Main physics used is the G4 microelectronics package.
  - First test simulations done
- Current work in progress:
  - Defining the sensitive volume
  - Find a way to export the energy deposit in a .root file

What I’m expecting to see after importing the energy deposit in TCAD →





← Geant4 Simulation watching the passage of an 5 GeV proton (blue track) through the pixel. Red tracks represents negative charged fast particles generated by the passage (already done).

Conclusions

Second Title

Conclusions

- Started to explore a geometry solution for a 3D silicon detector
  - Starting from 2D models
  - Select the geometry with the best parameters
  - 3D model of the solution was designed and tested too.
- Pixel output signal was simulated
  - Starting only using TCAD
  - Improving simulation using Geant4 to define the energy deposit

Backup

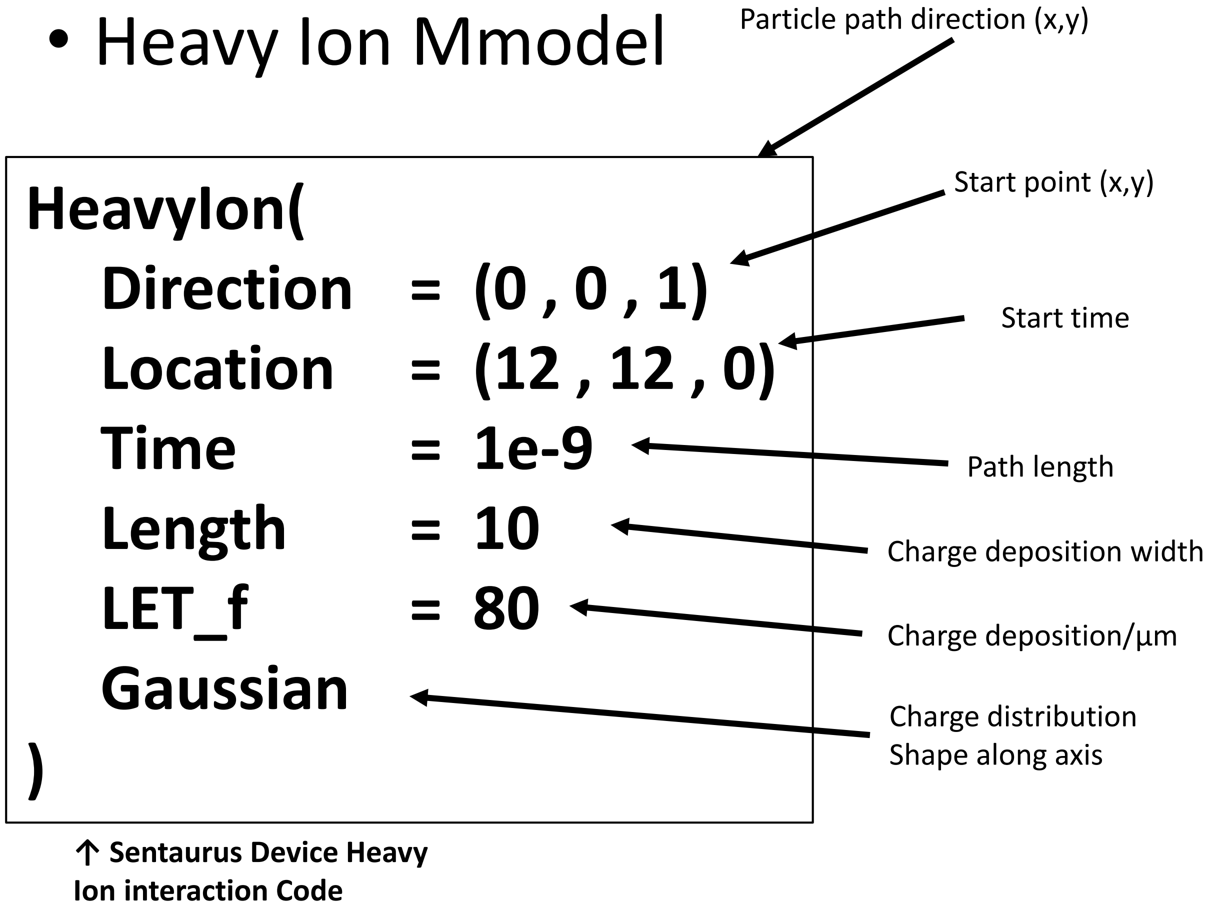
Second Title

1) Heavy Ion Model

Short Description

Heavy Ion model

- Heavy Ion Mmodel



Particle path direction (x,y)

```
HeavyIon(
    Direction    =  (0 , 0 , 1)
    Location     =  (12 , 12 , 0)
    Time         =  1e-9
    Length       =  10
    LET_f        =  80
    Gaussian
)
```

Start point (x,y)

Start time

Path length

Charge deposition width

Charge deposition/µm

Charge distribution
Shape along axis

↑ **Sentaurus Device Heavy Ion interaction Code**

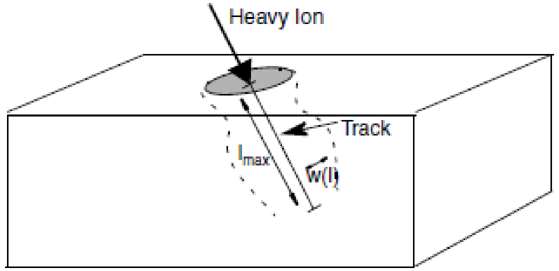


Figure 53 A heavy ion penetrating a semiconductor; its track is defined by a length and the transverse spatial influence is assumed to be symmetric about the track axis

Generation rate: → $G(l, w, t) = \underline{G_{\mathrm{LET}}(l)}R(w, l)T(t)$

$$G_{\mathrm{LET}}(l) = a_1 + a_2 l + a_3 e^{a_4 l} + k'\left[c_1(c_2 + c_3 l)^{c_4} + \mathrm{LET\_f}(l)\right] = \mathrm{LET\_f}(l)$$

Normal HIM

Table 112 Coefficients for carrier generation by heavy ion (HeavyIon parameter set)

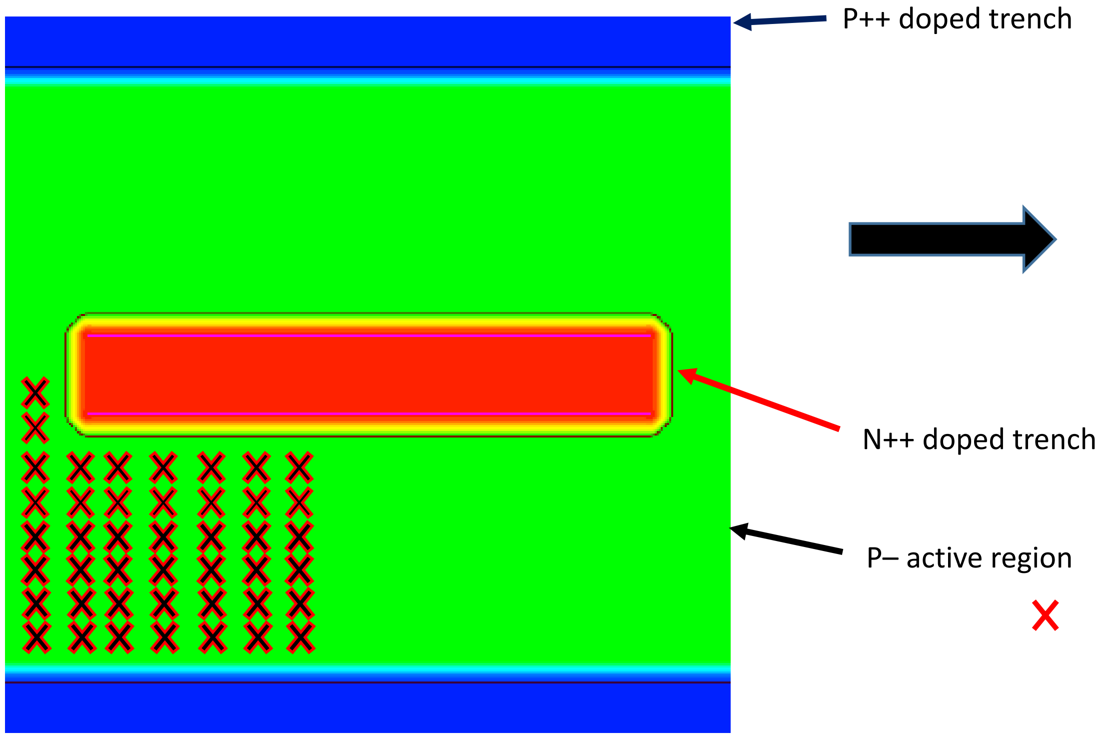
	s_{hi}	a_1	a_2	a_3	a_4	k	c_1	c_2	c_3	c_4
Keyword	`s_hi`	`a_1`	`a_2`	`a_3`	`a_4`	`k_hi`	`c_1`	`c_2`	`c_3`	`c_4`
Default value	2e-12	0	0	0	0	1	0	1	0	1
Default unit	s	pairs/cm^3	pairs/cm^3/cm	pairs/cm^3	cm^{-1}	1	pairs/cm^3	1	cm^{-1}	1
Unit if PicoCoulomb is chosen	s	pairs/cm^3	pairs/cm^3/µm	pairs/cm^3	µm^{-1}	1	pC/µm	1	µm^{-1}	1

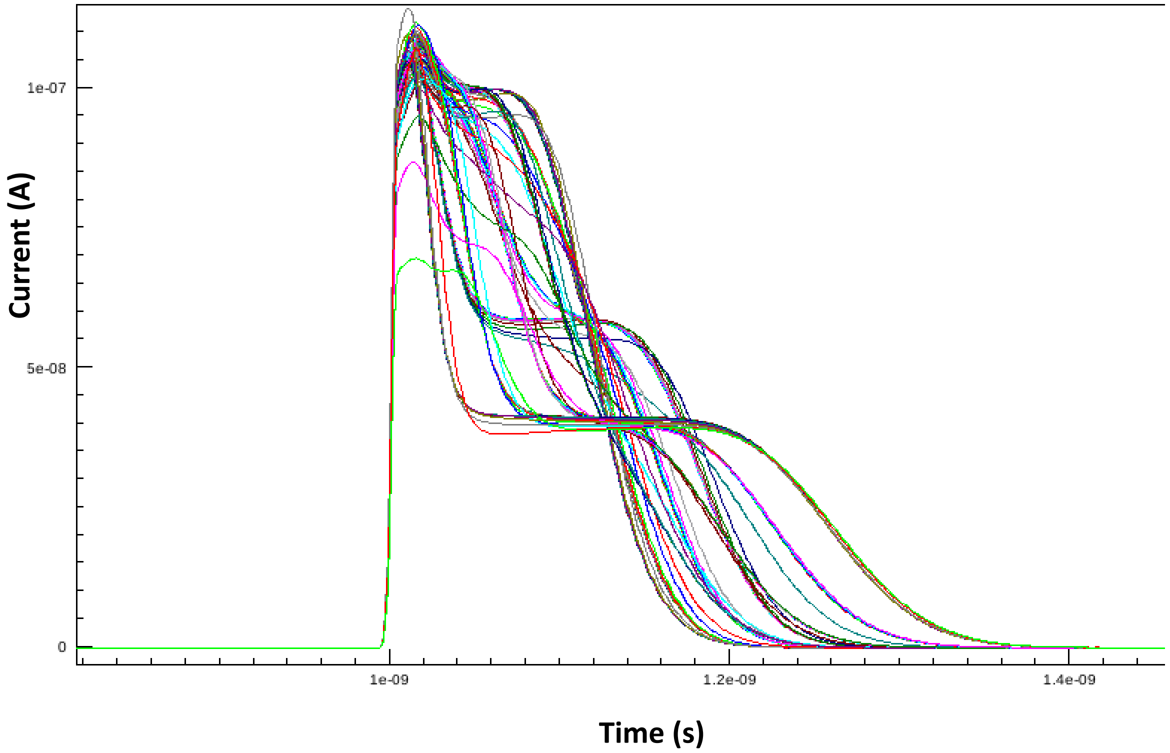
2) 2D Signal simulation

All generated curves for the par trench design

Signal generation

- Charge injection points and respective output current signals

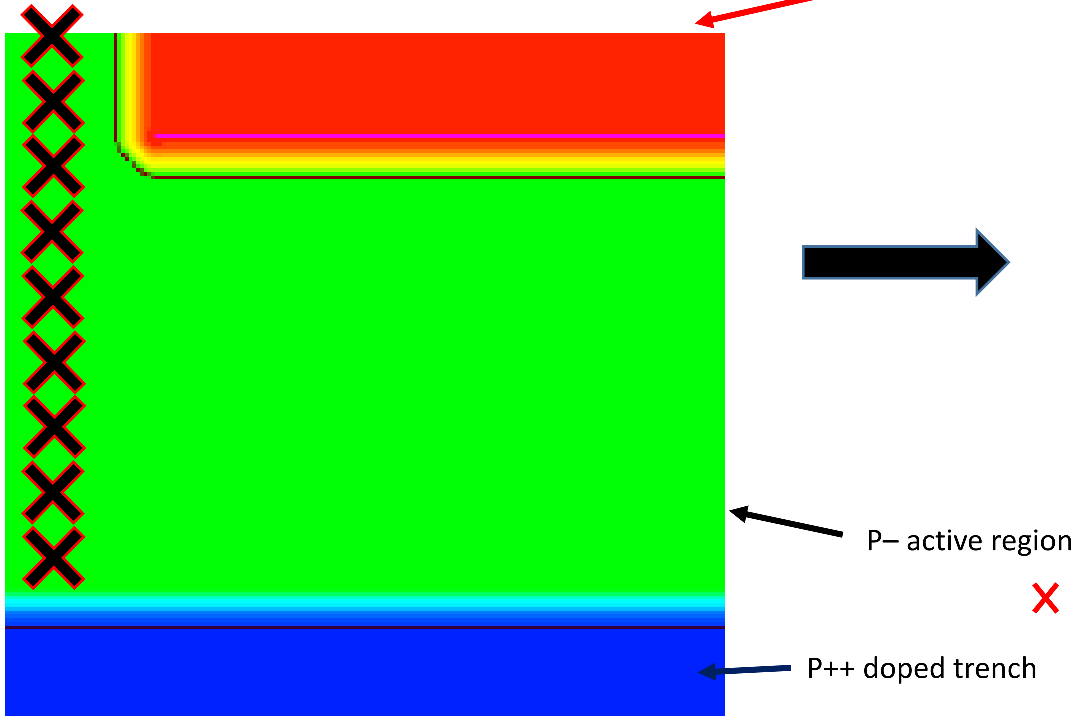




Doping concentration map

Signal generation

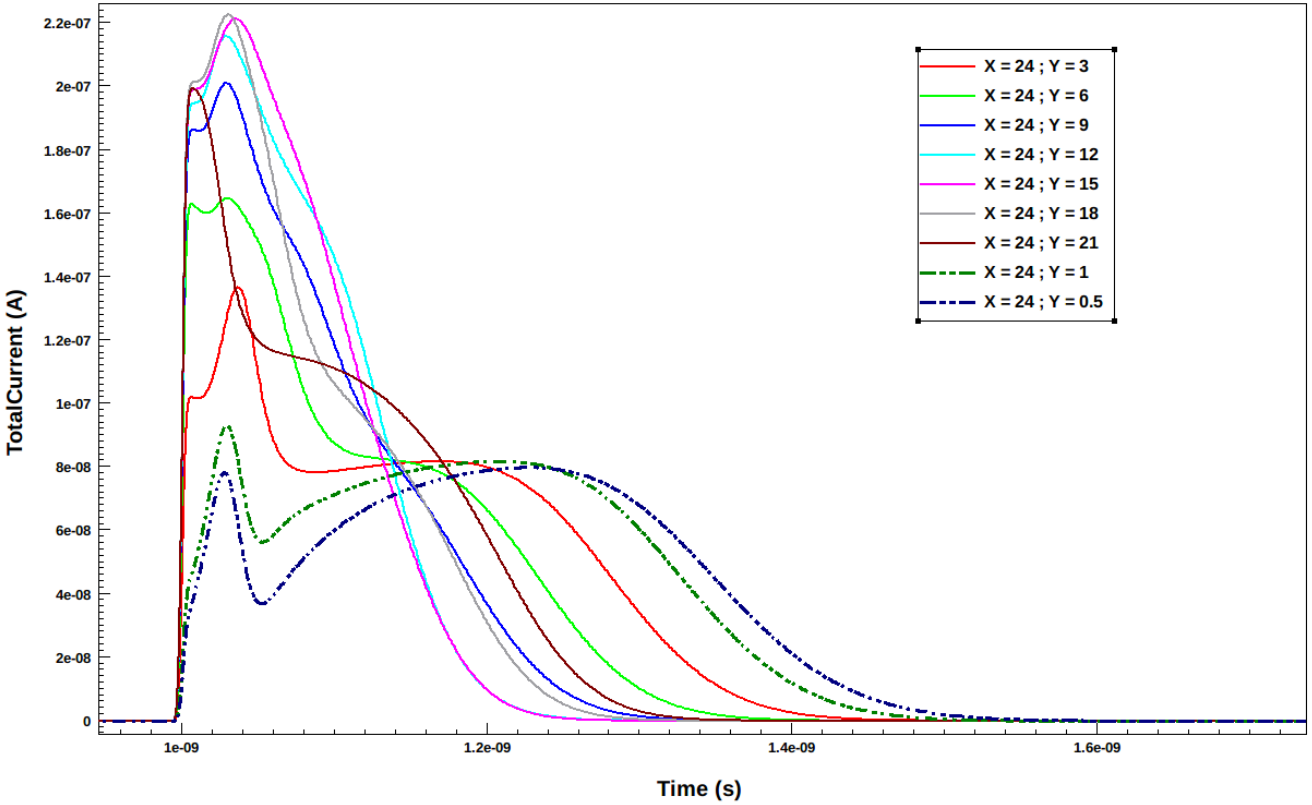
- Charge injection points and respective output current signals:
  - Signals produced along the low field region


N++ doped trench

P– active region

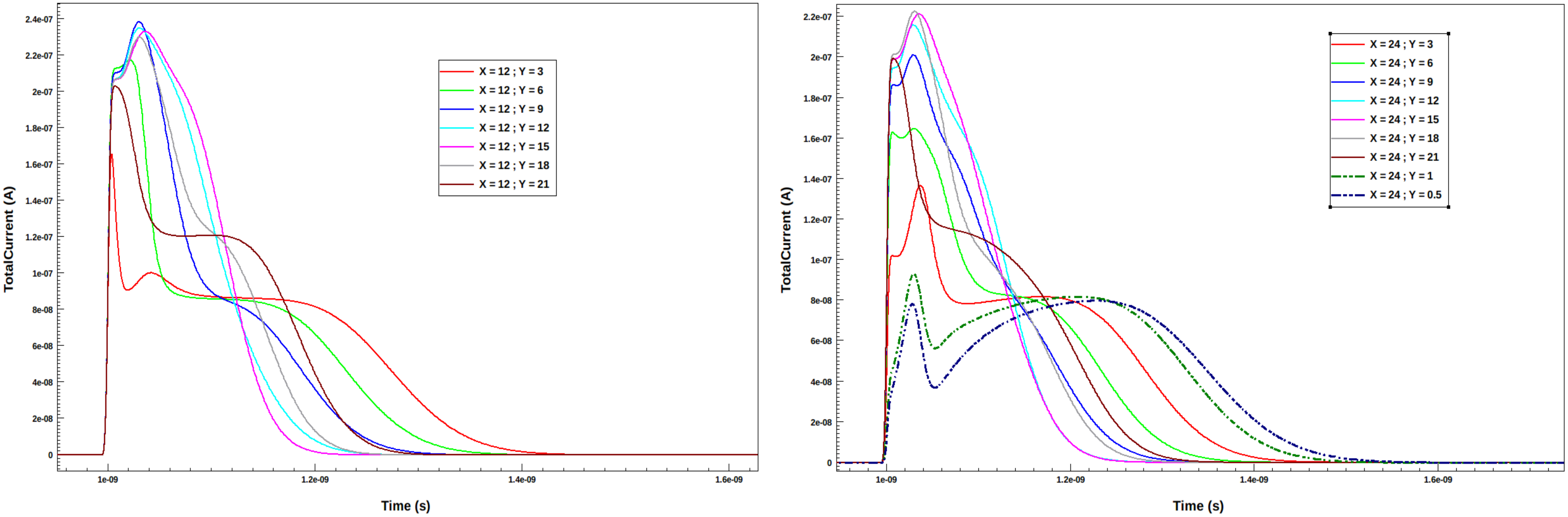
P++ doped trench

Doping concentration map



Signal generation

- Charge injection points and respective output current signals
  - Centre of the 2D model (left) vs low field region (right)



Backup