Design of 3D silicon sensors for high resolution time measurements

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On behalf of the TIMESPOT project

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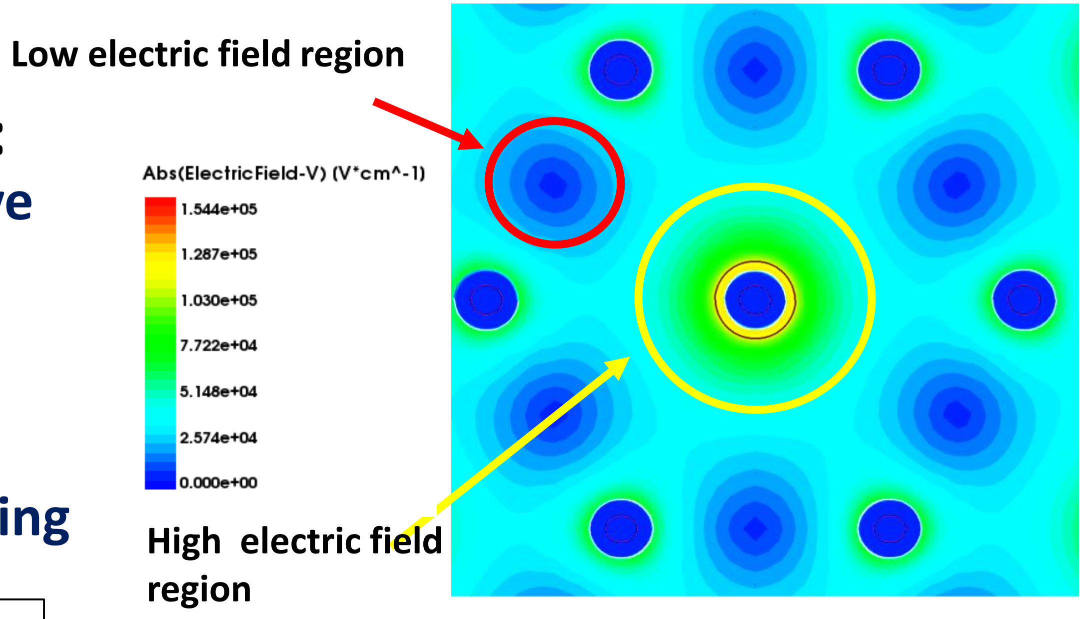
Introduction

Introduction

- **Importance of 3D sensor design for fast timing:**
  - **Unlike planar silicon sensors, 3D sensors do not have commonly a uniform electric field between their electrodes**
    - **The electric field can change much from point to point.**
  - **Effects of a non uniform field influence strongly the shape of the output current signal, following Ramo theorem, which also is a crucial factor for a fast timing sensor**

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



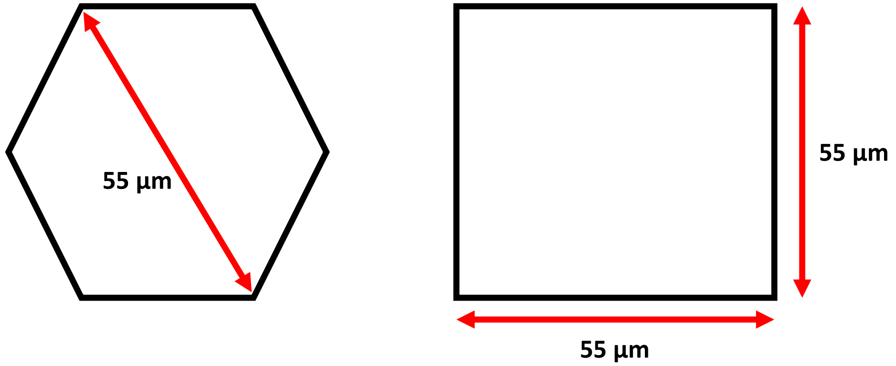
↑ Electric field map for a hexagonal pixel with a electrode geometry of 5 corner electrodes for electric field bias and a central diode electrode for signal output. Between same kind electrodes the field goes down to 0 V/cm which is a critical factor for timing

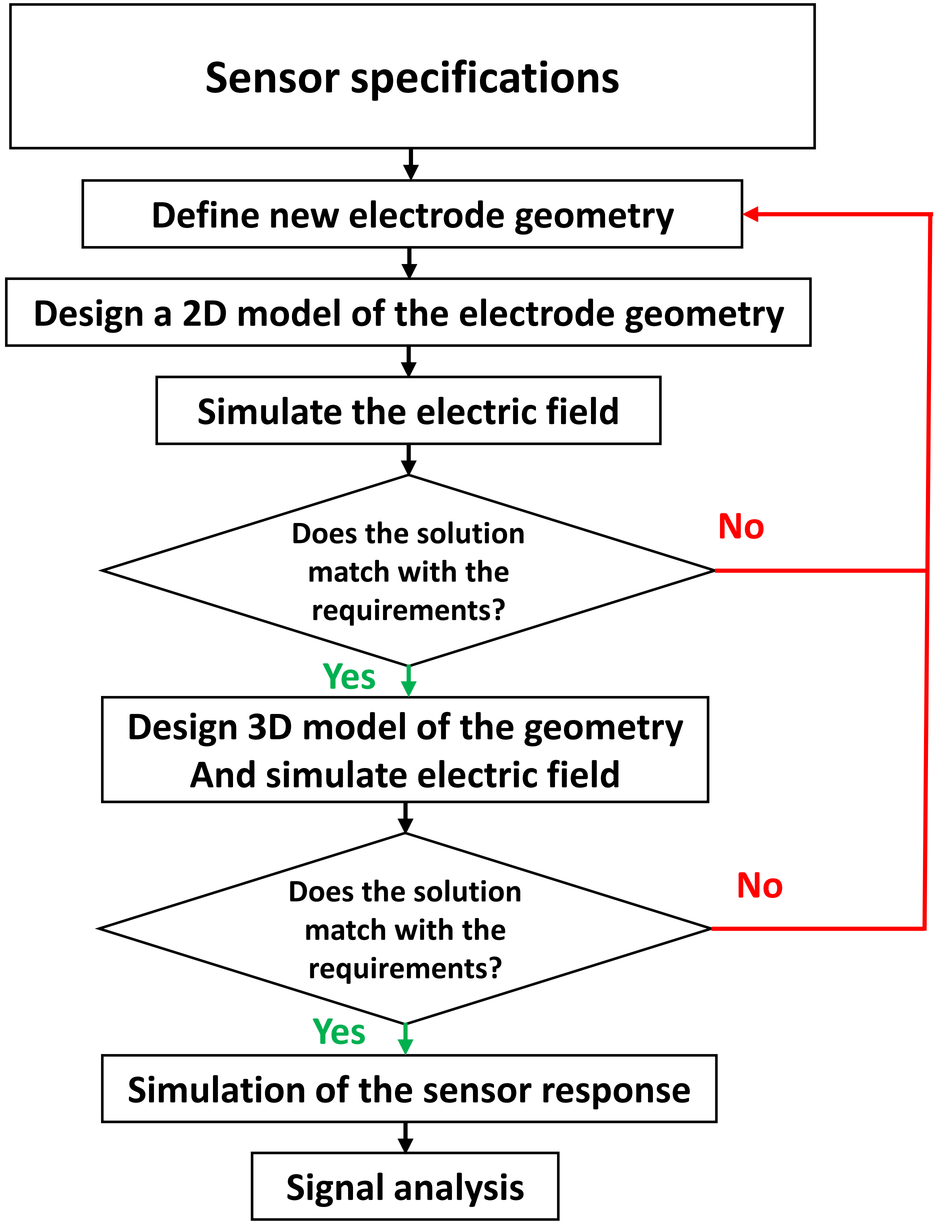
- **Research activity is part of the TIMESPOT project**
  - **3 years long, from (INFN) financed research initiative, started in 2018.**
  - **Purpose: Develop a first prototype for a 4D (space and time) tracking detector for future high luminosity experiments**
    - **Project includes also the development of its own fast readout electronics and fast tracking algorithm.**

Model design and simulation

Design approach

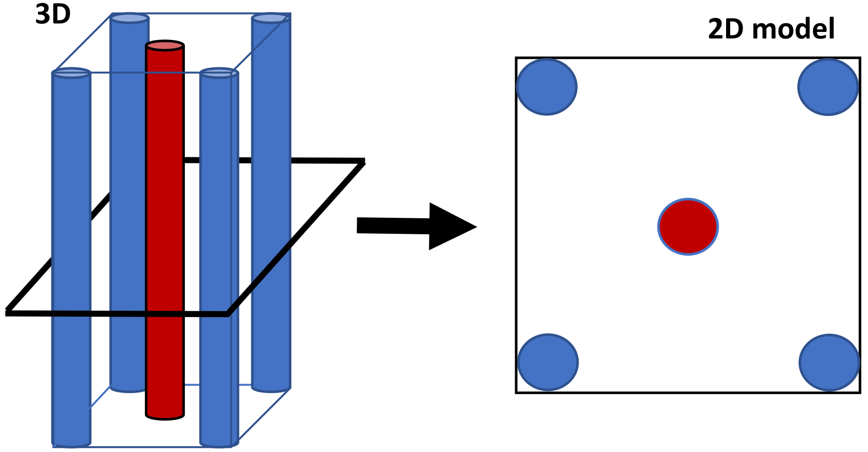
- **Following specifications:**
  - Pixel sensor for tracking measurements in 4D (space and time) in high luminosity environment
  - Resolution:
    - Resolution in space around 50 um
    - Resolution in time possible less than 100 ps
  - Possible shapes and dimensions:
    - Square pixel, 55 um x 55 um pitch
    - Hexagonal pixel with 55 um diagonal





2D model design

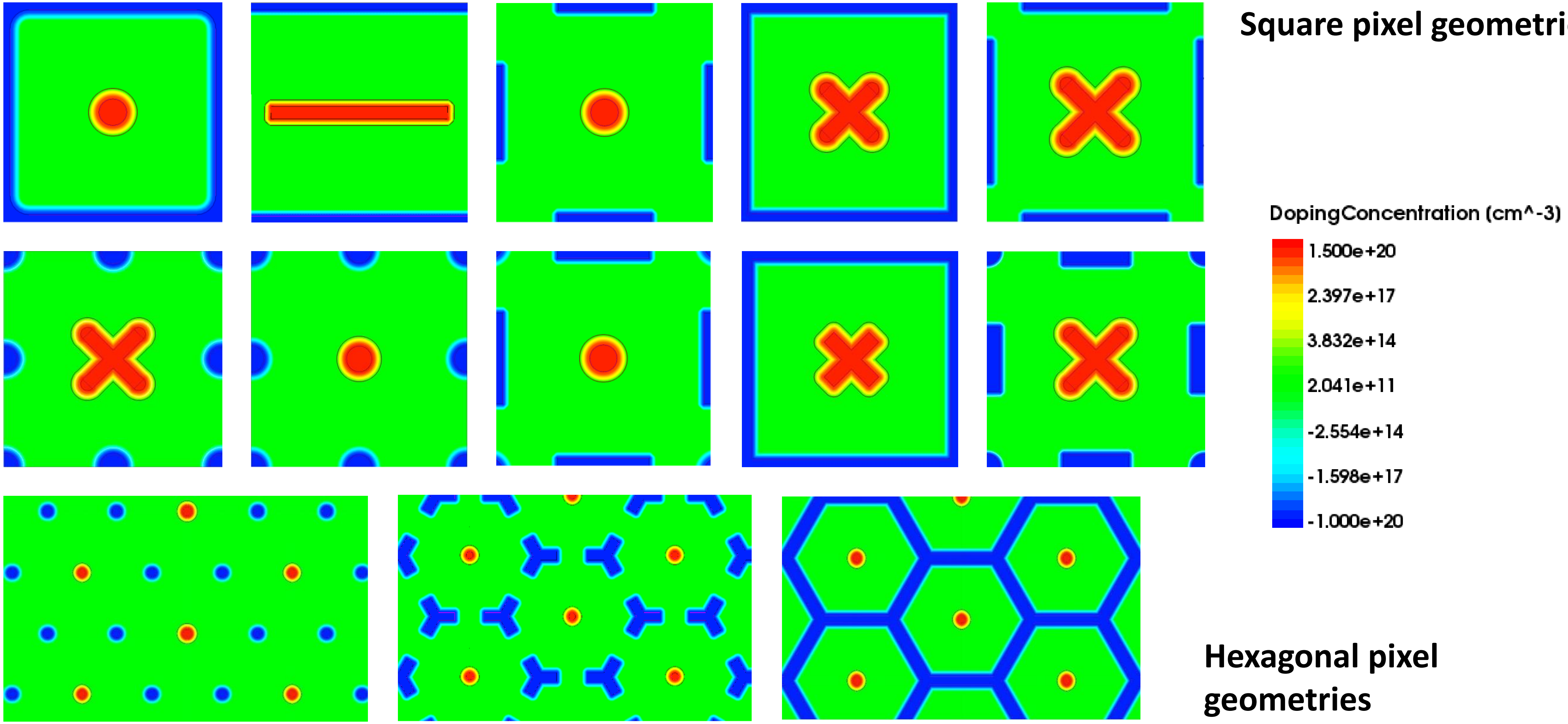
- **Motivations:**
  - **3D modelling and simulation is very time consuming**
    - **3D models have an average of 1 M points instead of 2D, which are defined by an average of 10 k points**
  - **Explore as much as possible geometric electrode configurations in order to find the solution which better matches to the requested performances**
- **Steps to do:**
  - **Design the geometry**
  - **Simulate the electric field between the electrodes**
    - **Using a voltage ramp from 0 V to -100 V**
    - **Use bias @ -100 V as reference**
  - **Analyse electric field behaviour**
    - **Presence of low field areas and their effects**



↑ Instead of modelling the entire pixel, only a cut section of it is designed in a 2D, which is enough to have first information about the electric field behaviour between the electrodes

2D model design approach: Some solutions

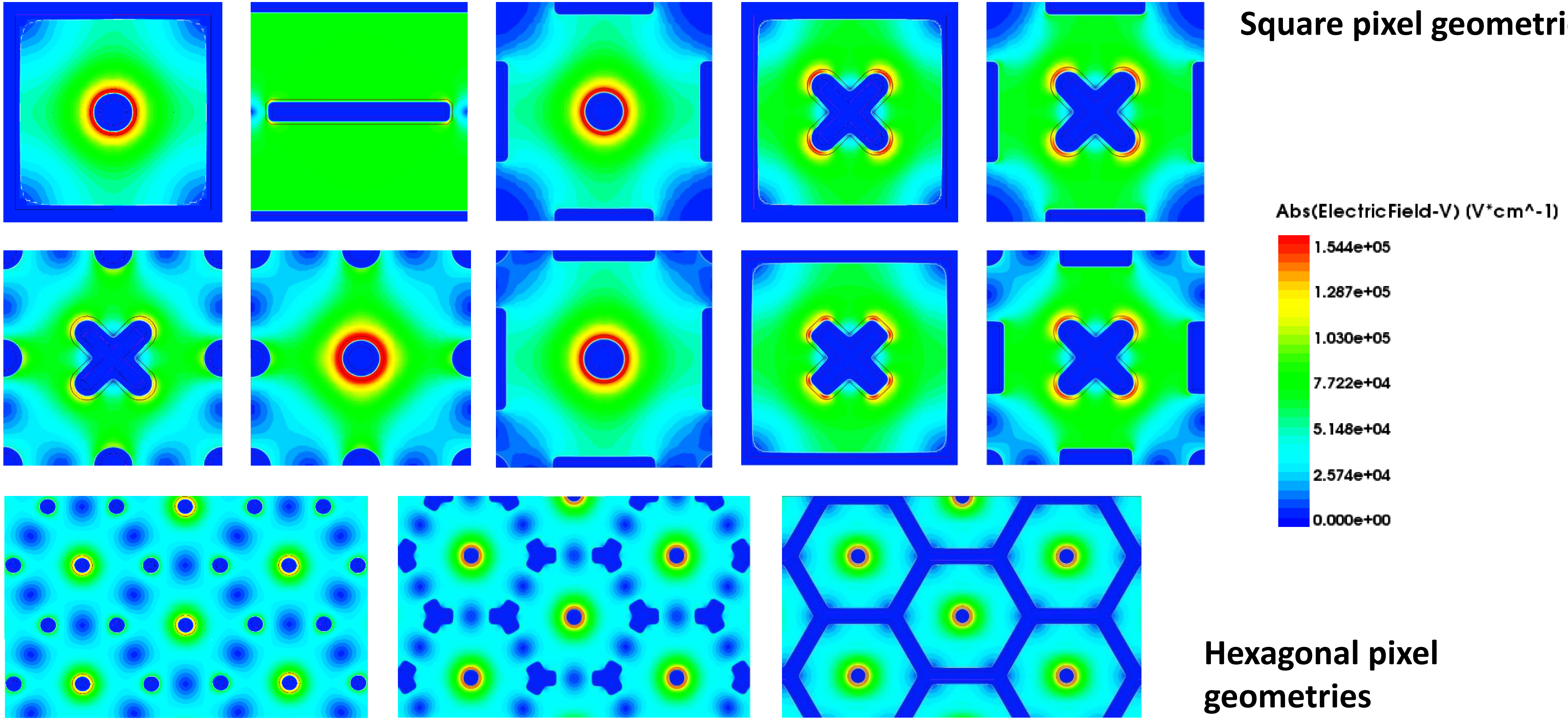
Square pixel geometries



Hexagonal pixel geometries

2D model design approach: Electric field

Square pixel geometries

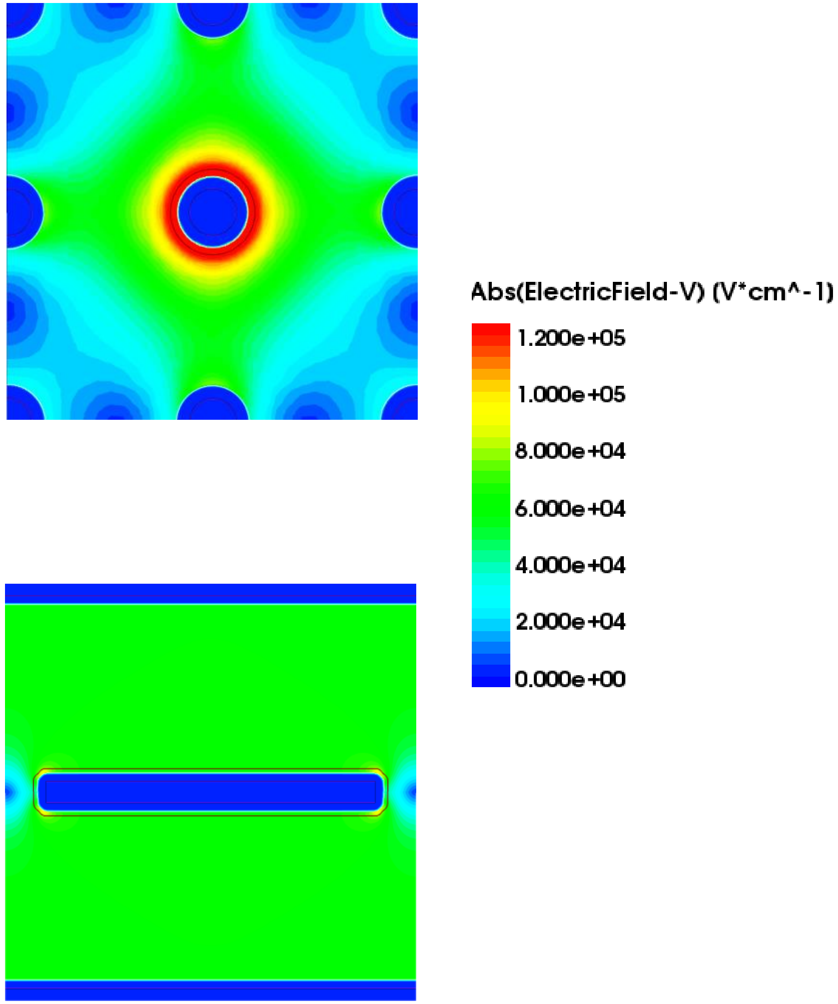


Hexagonal pixel geometries

Electric field analysis, some examples

- **Rejected solution: Square pixel with columnar electrodes**
  - **Electric field is uniform only between different electrodes**
  - **Electric field changes much along the corner regions**
  - **Electric field goes down to 0 V/cm between boarder electrodes**

- **Selected configuration: Square pixel with parallel trench configuration**
  - **Electric field is uniform, with little exceptions, over all the entire pixel**
  - **Two low field regions are present between the diode electrodes**
    - **Charge collection is not heavily affected because the region is close to the electrode**



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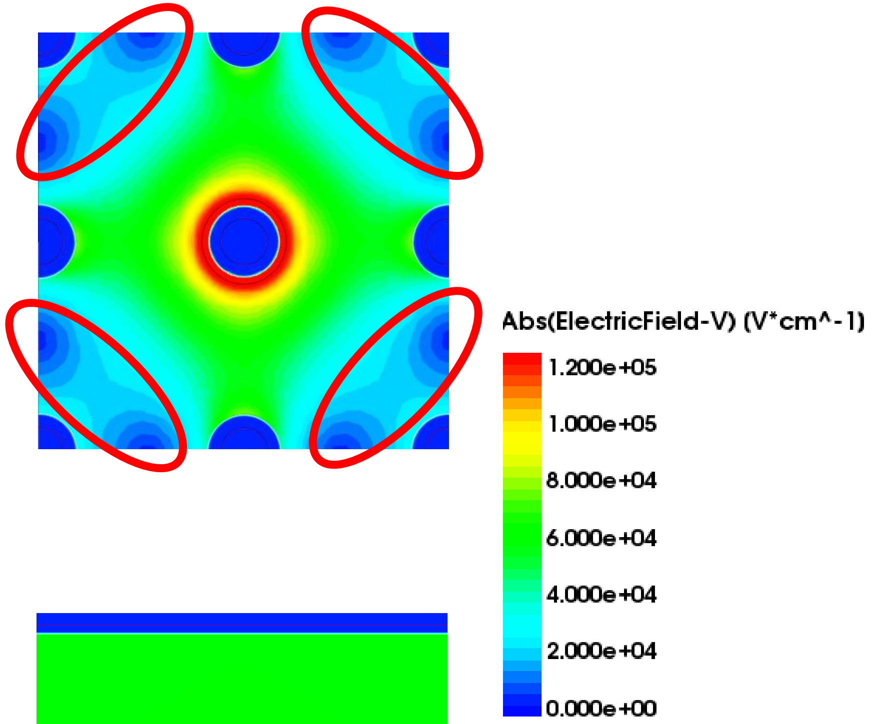

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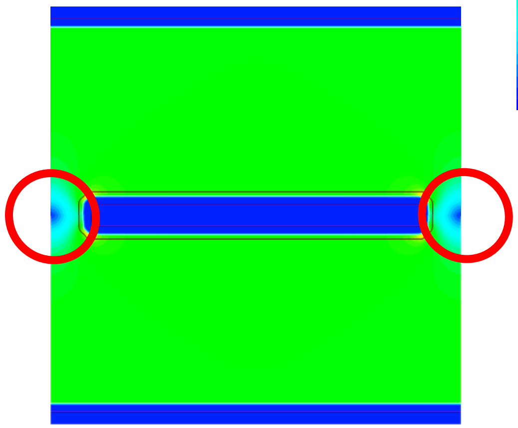
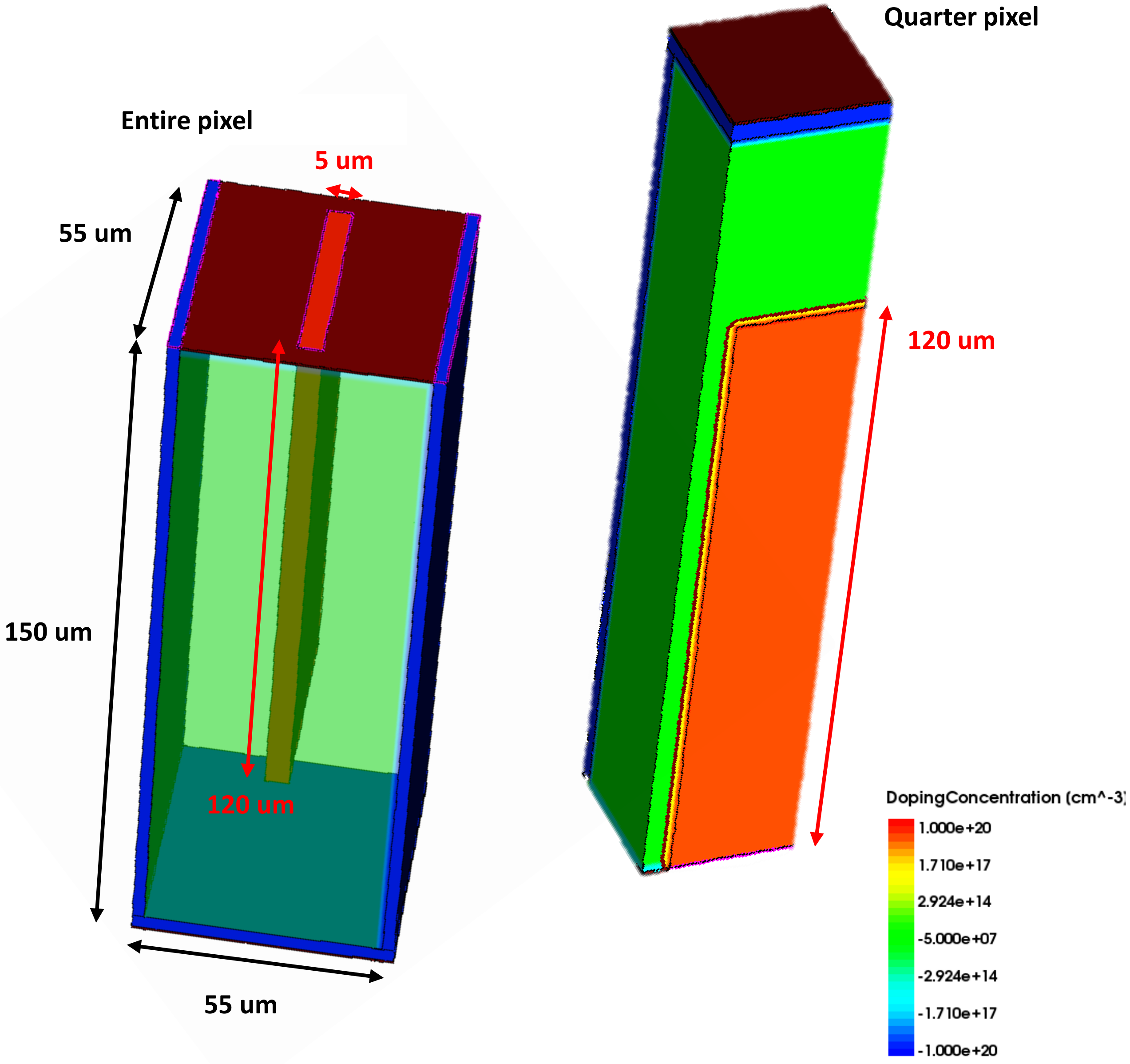


3D modelling approach

- **Two different models were edited**
  - **One complete pixel**
    - **Which will be used later for signal simulation**
    - **2.8 million points**
      - **Critical if I want to use it to simulate hundreds of signals**
  - **One quarter pixel**
    - **Useful if I want to save computing time (1/4 times less points compared to complete model)**



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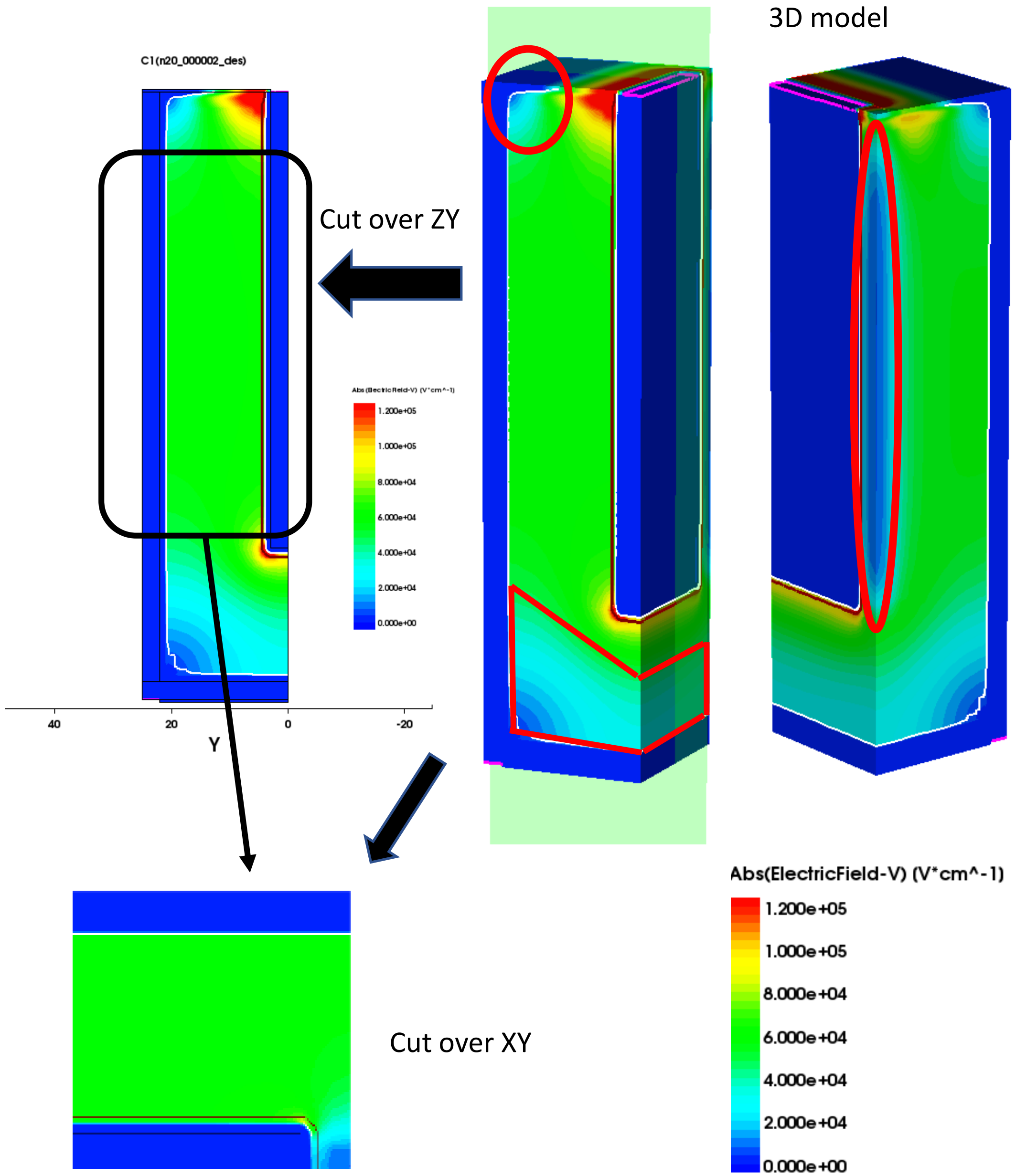
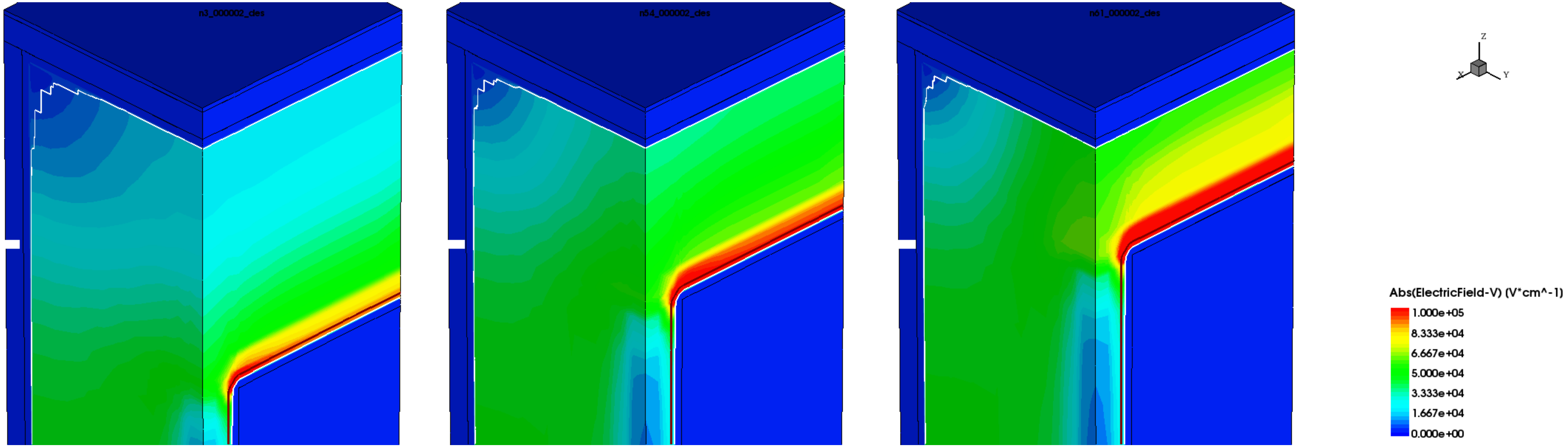
    - **Useful if I want to save computing time (1/4 times less meshes compared to complete model)**
- **Electric field analysis**
  - **Presence of a low field areas at the bottom of the diode trench**



3D design approach

- **Low field area needs to be reduced**
  - **Trying 3 electric field simulations with different diode trench depth**
  - **Low field area becomes less influent for trench depths down to 130 um**

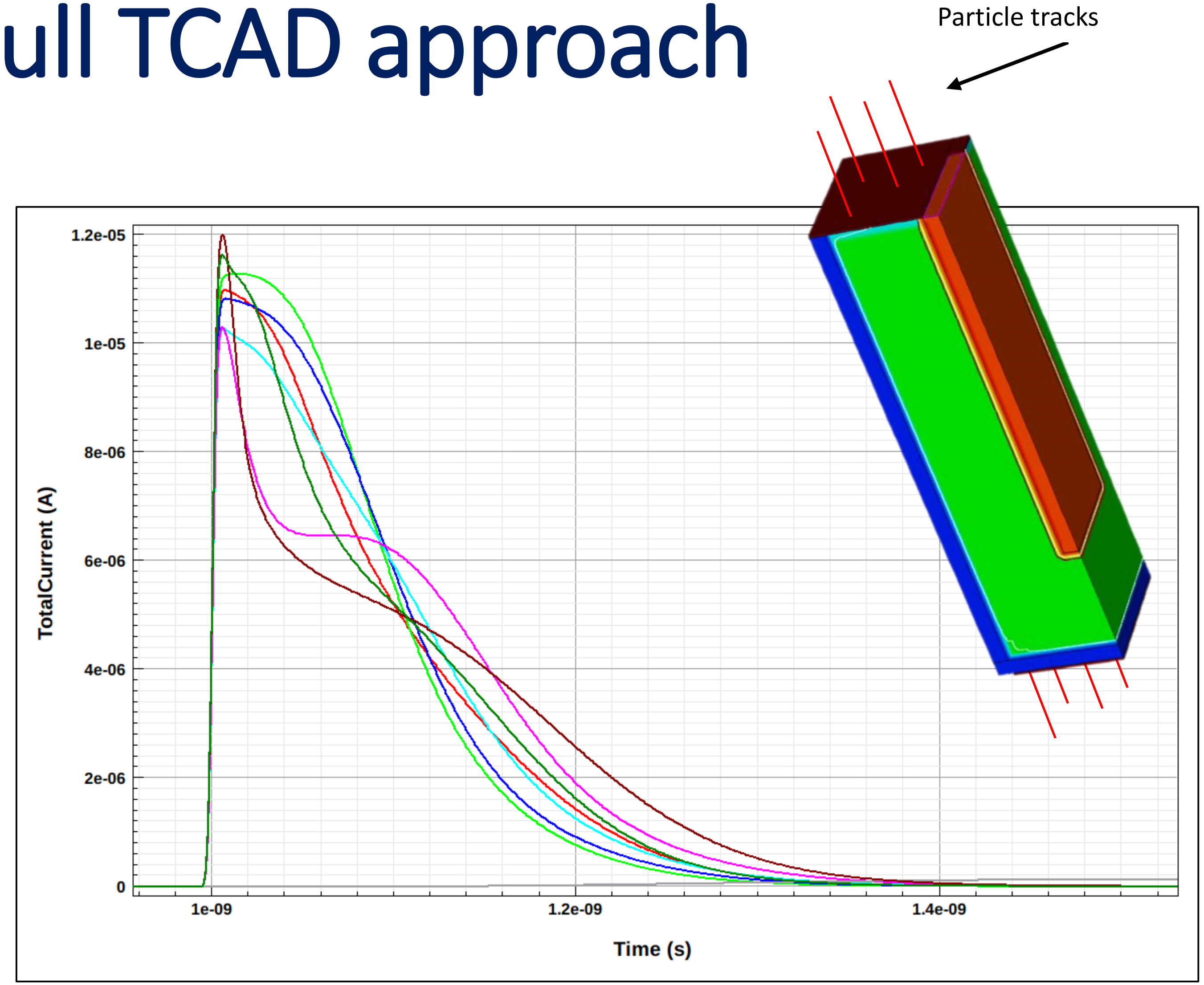


120 um **130 um** **135 um**

Signal simulation

First signal simulation: Full TCAD approach

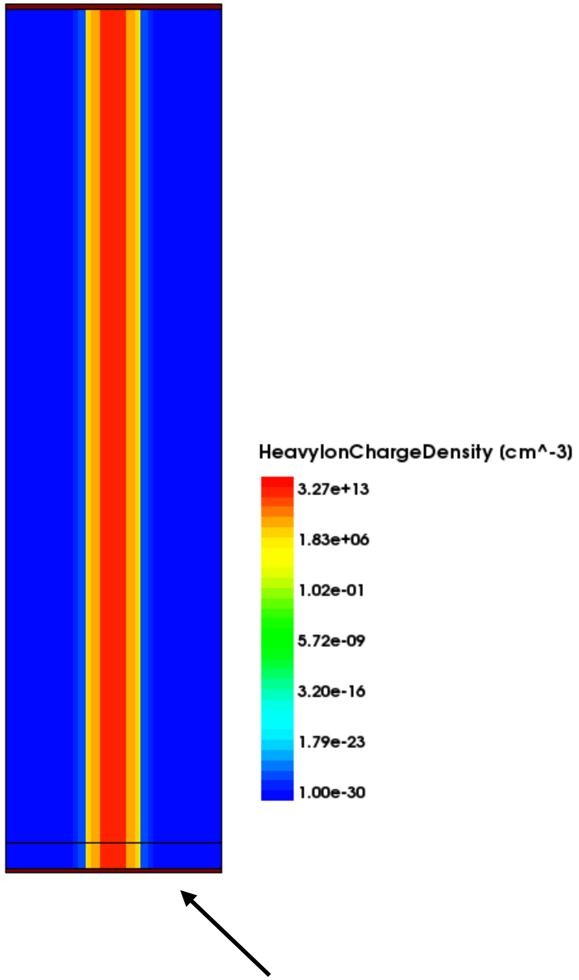
- **Possibility to emulate with TCAD the charge generated by the ionisation of a crossing high energy particle**
  - sdevice "HeavyIon" model
- **First simulation approach**
  - Particle direction was set parallel to the trenches
  - Start point was changed few times to see possible differences of the shape in function of the ionised region
  - Energy deposit was set at 80 e-h couples/um
    - Average number of charges generated by ionisation from high energy particle in Si



Geant4 assisted 3D model signal simulation

- **The TCAD HeavyIon model does not provide further information about:**
  - **Energy deposit variation along the particle track**
  - **Generation of possible secondary particles and their energy deposit**
    - **For example delta rays**

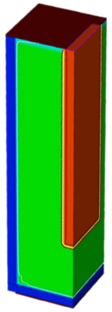
- **In order to add those information, a Geant4 simulation was developed with the following characteristics:**
  - **It simulates the interactions of a high energy particle which crosses a same scale replication of the pixel model from TCAD**
  - **All the information about particle paths and their energy deposit is used to write a TCAD simulation file**
  - **At the end of the simulation the simulation file will be executed by TCAD which simulates the output signal of the pixel in response of those interactions**



2D section of the 3D model watching charge density deposit from the ideal heavyIon model set at 80eh/um

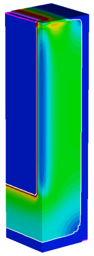
Program structure

TCAD device construction



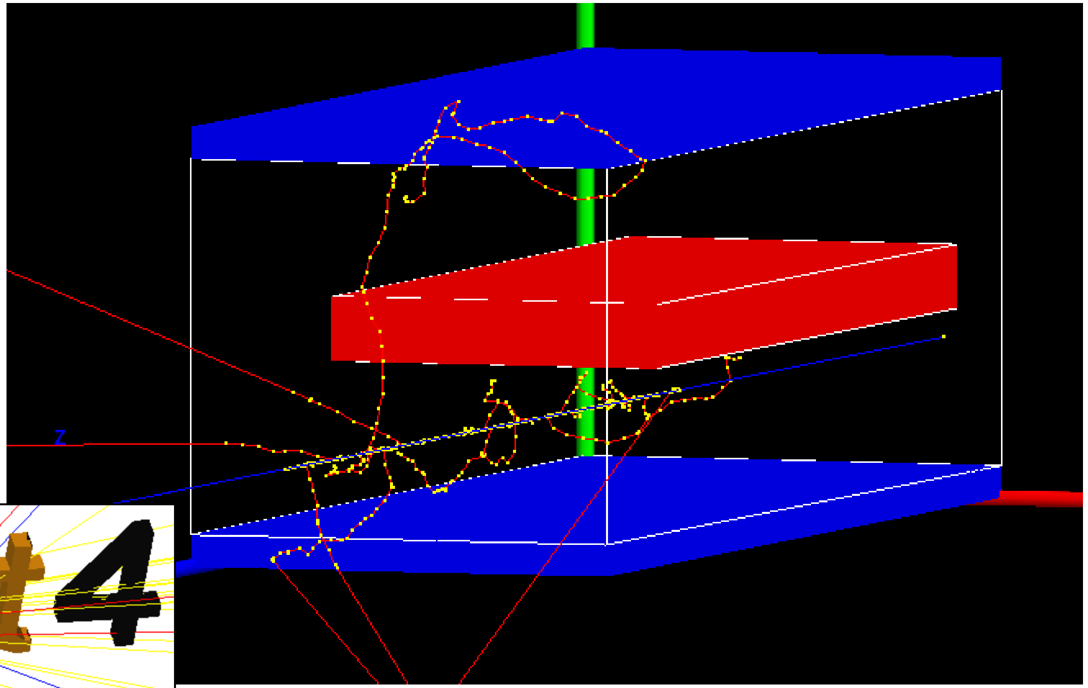
TCAD electric field simulation @ 100 V

Saves electric field map @ 100 V



TCAD HeavyIon transient simulation

Geant4 Simulation



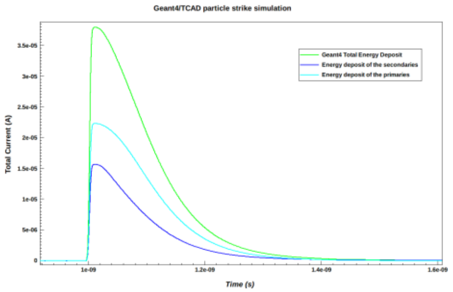
Entire Pixel
Projectile: single pi+ @ 20 GeV
Random angle
Different particle path

Define sdevice command file

Start next Geant4 Simulation

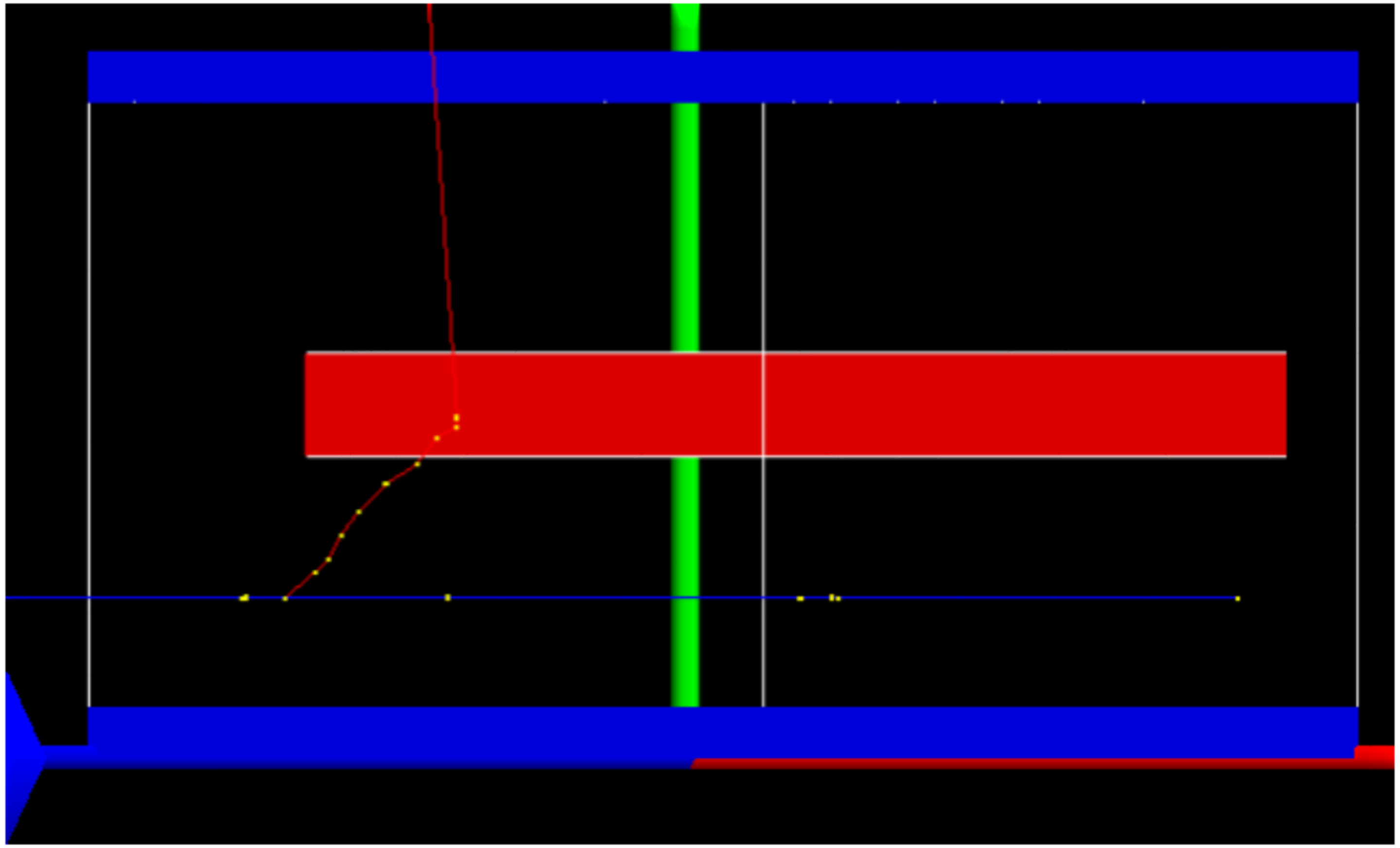
Plot current vs time

Saves data



First results and comparison to normal TCAD HeavyIon simulation

- **First test results:**
  - **Primary particle and energy:**
    - **Pion @ 20 GeV**
  - **Source location and direction:**
    - **(12.5 ; 12.5 ; -100) um**
    - **Path along z axis**
  - **Number of secondaries:**
    - **3**
  - **Total number of observed tracks**
    - **4 primary**
    - **11 secondaries**



↑ Complete simulation of a single pi+ at 20 GeV shot against the pixel model. The blue track belongs to the pion, the red one belongs to a low energy electron.

First results and comparison to normal TCAD HeavyIon simulation

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    - **Path along z axis**
  - **Number of secondaries:**
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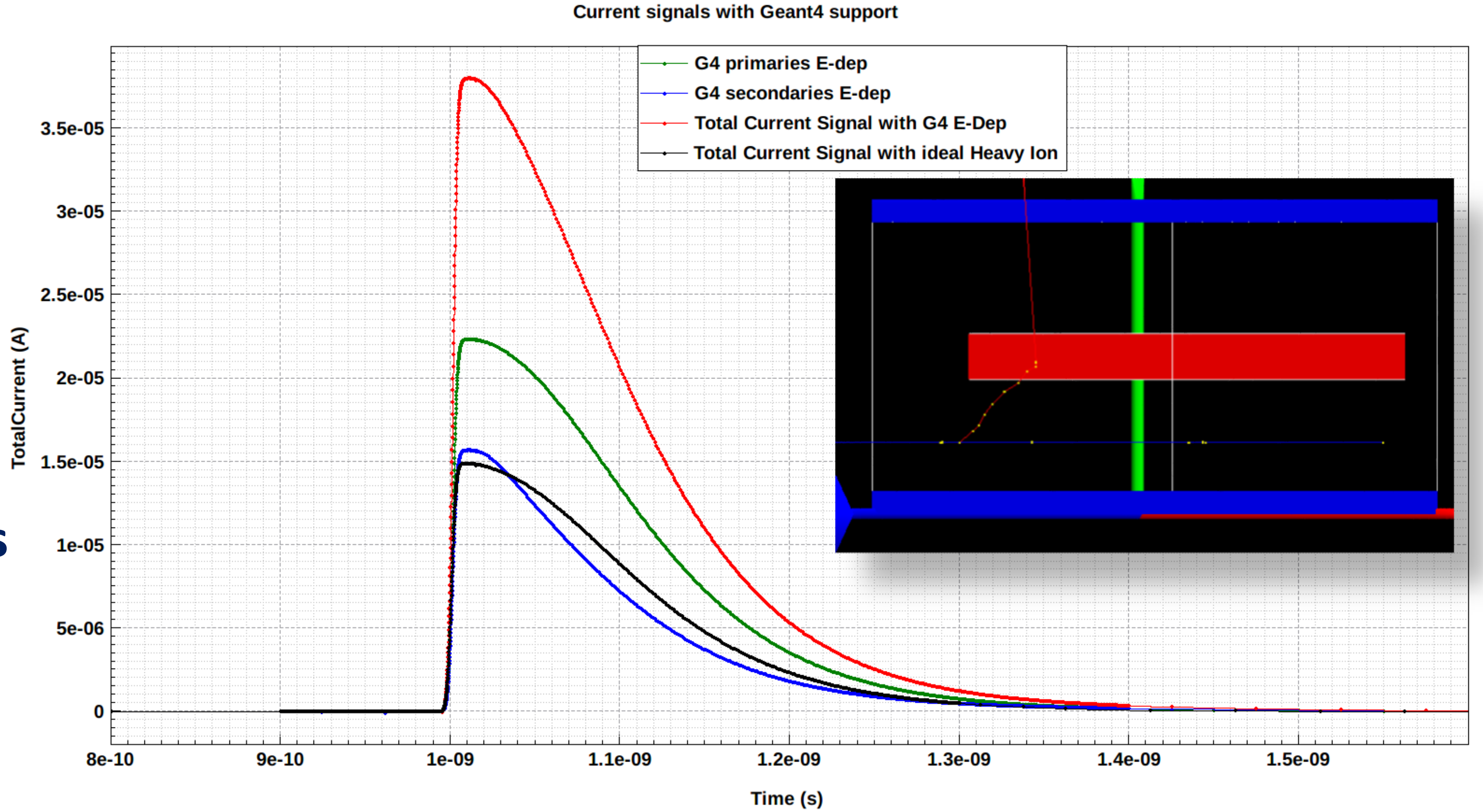
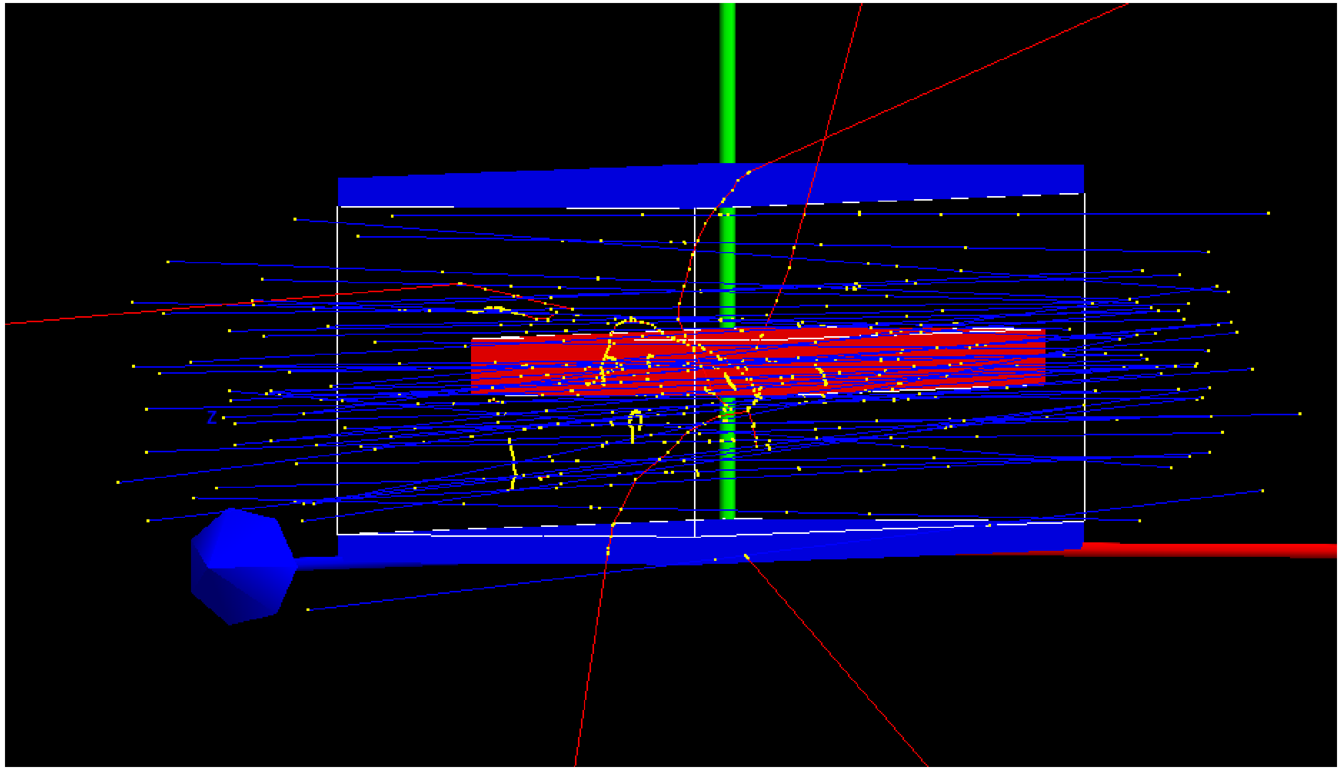
  - **Comparison with standard HI →**
    - **80 e/h pairs / um**



↑ Total current signal generated by multiple HeavyIon codes defined using the Geant4 simulation (*red curve*), compared with the previous HeavyIon simulation (*black curve*). Green curve describes the contribution of the primaries and the *blue* one of the secondaries.

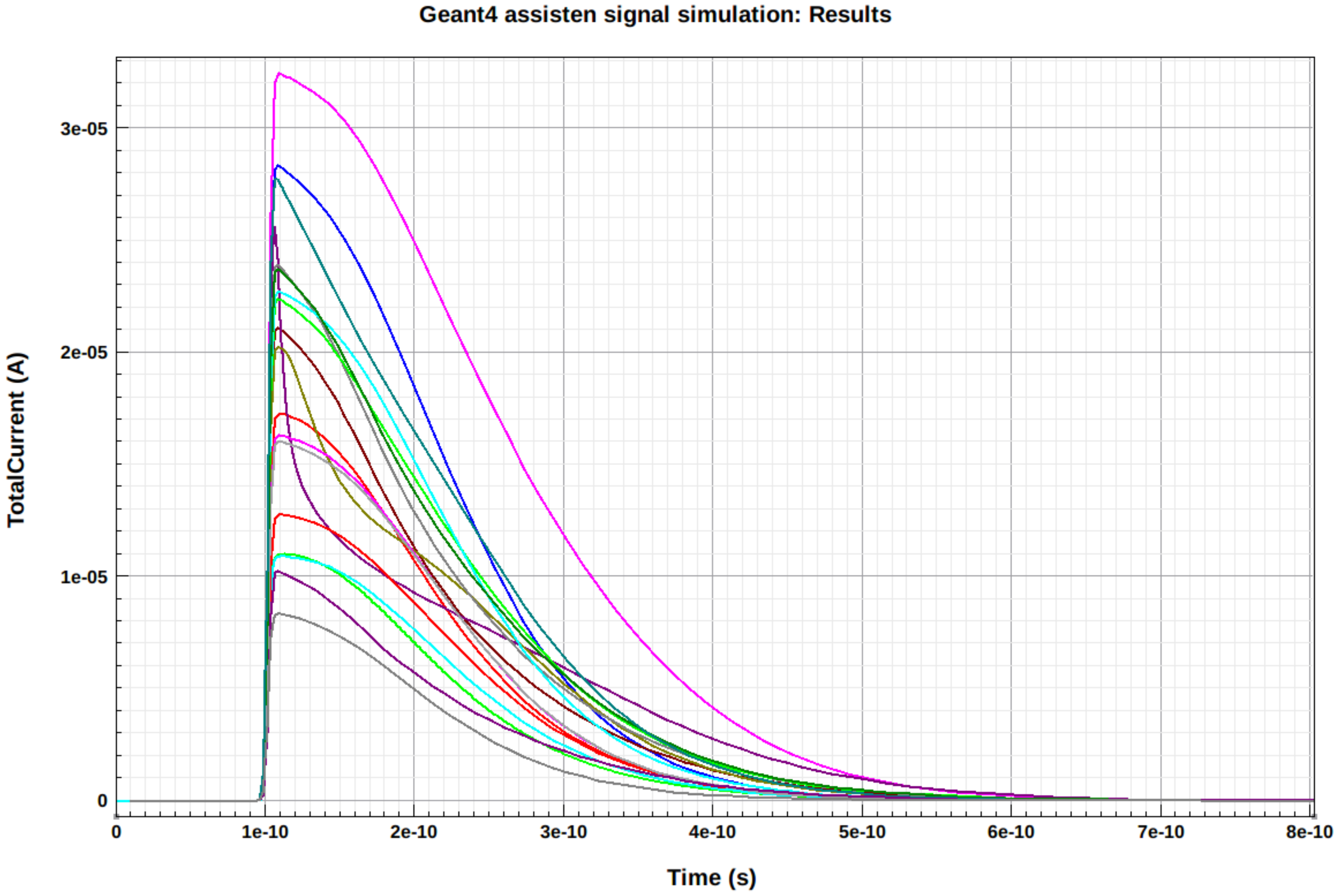
First signal set

- **Currently 100 interactions are simulated pi+ @ 20 GeV are shot against the pixel**
  - Trajectory
    - is parallel to central diode trench
    - Crosses only ¼th of the region of the pixel
  - Primaries
    - Describes an average of 3-5 tracks
  - Secondaries
    - Average case traverls few nanometers
    - Every 8-10 pions, one e- travels for more than 10 um



First signal set

- **Current status:**
  - 18 observed signals
    - Simulation is still running
- **Signal shape**
  - Is independent…
    - From track length
    - Track angulation
    - Primary energy deposit
    - Secondaries energy deposit
- **Time information**
  - Charge collection lower than 1 ns
  - Risetime in less than 20 ps



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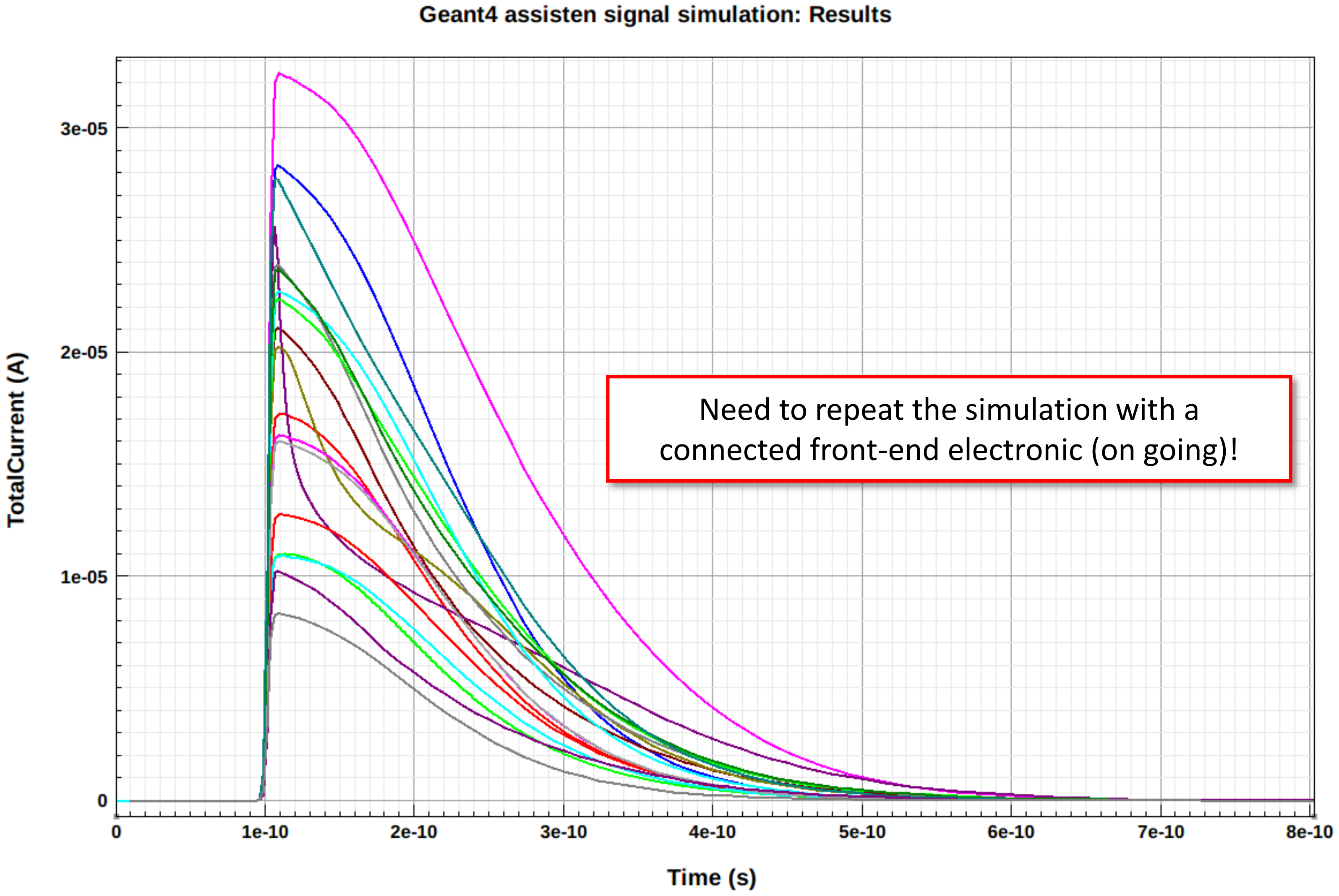


Need to repeat the simulation with a connected front-end electronic (on going)!

Summary

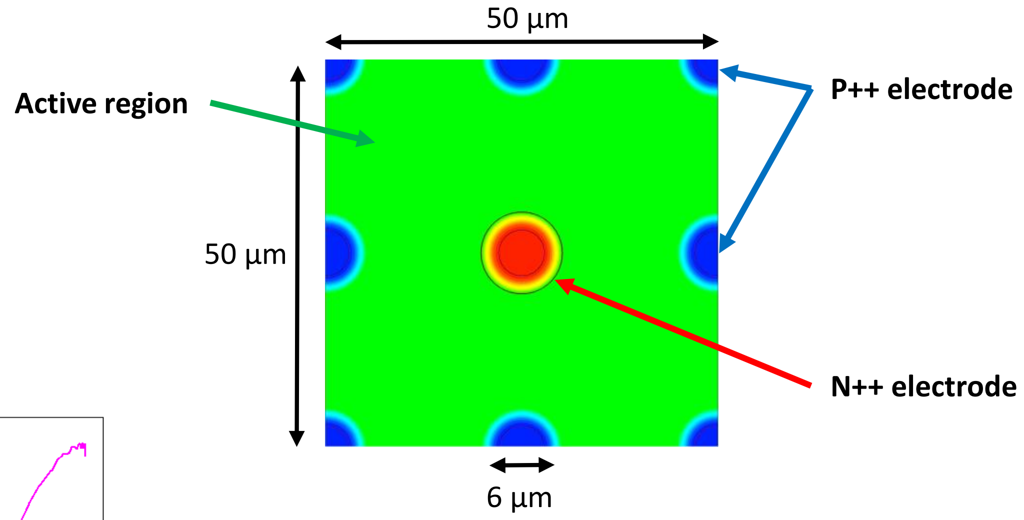
Summary

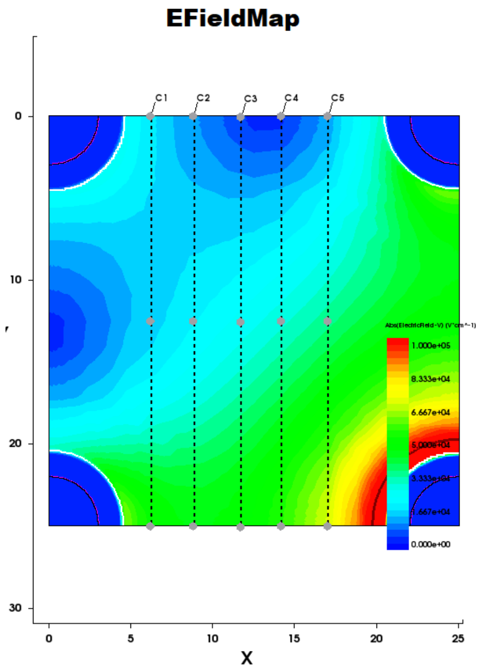
- For the TIMESPOT project a 3D sensor for fast timing tracking measurements is needed
- A first selection of geometric configurations was done in order to find the one with the best electric field characteristics
  - Starting with 2D modelling and selecting the solution which was build in a 3D model
- 3D model is then used for signal simulation
  - Using only TCAD is not recommended if you want further information about energy deposit and particle track inside the sensor
  - Geant4 can help to correct those aspects by adding more information about track and energy deposit.
- Next step is to simulate the output signal with a connected front-end

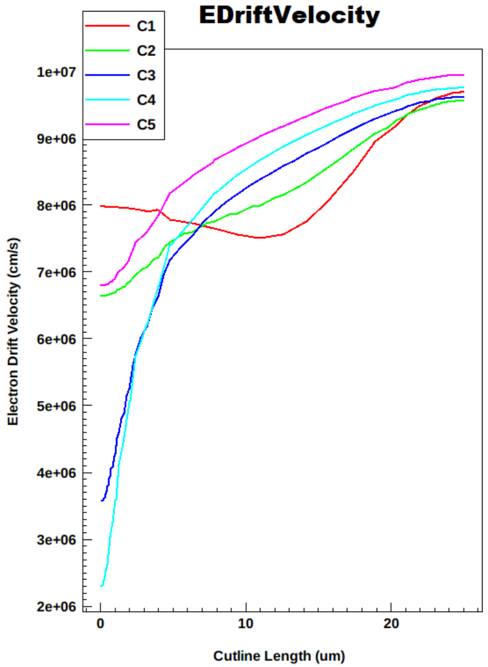
Backup

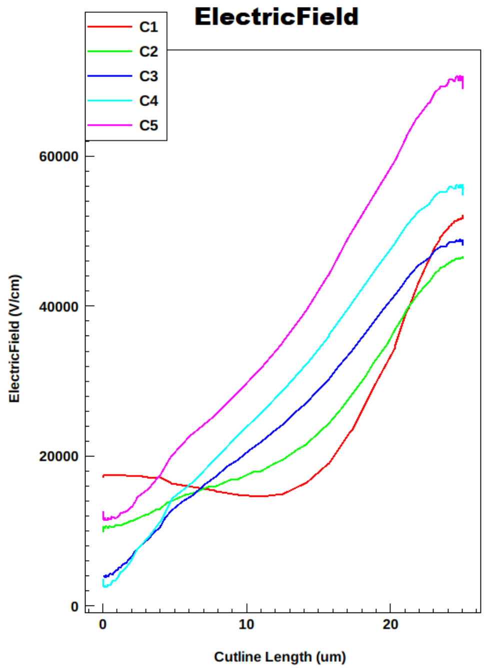
Rejected solutions, some examples (1)

- **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**





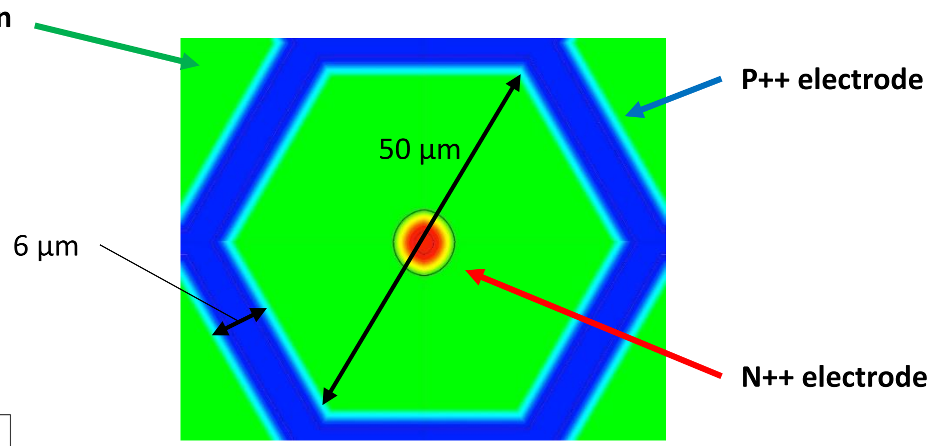


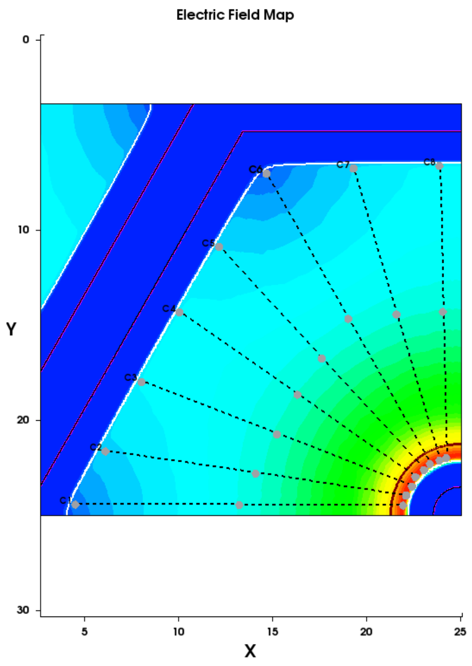


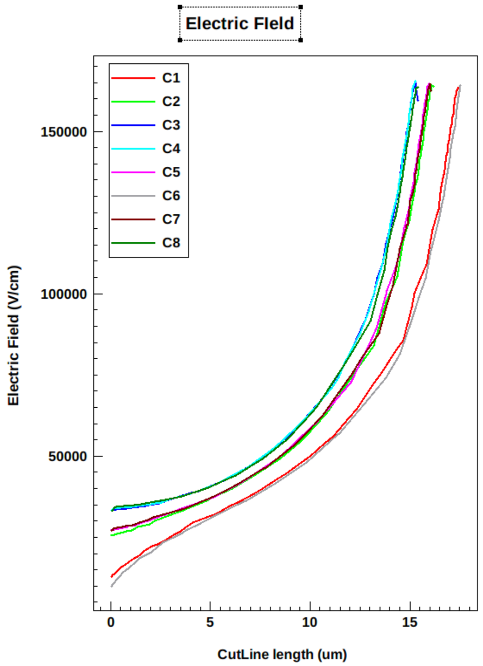
- Electric Field:
  - Electric field changes too much over all the pixel area.
- Drift Velocity:
  - Is not saturated @ 100 V

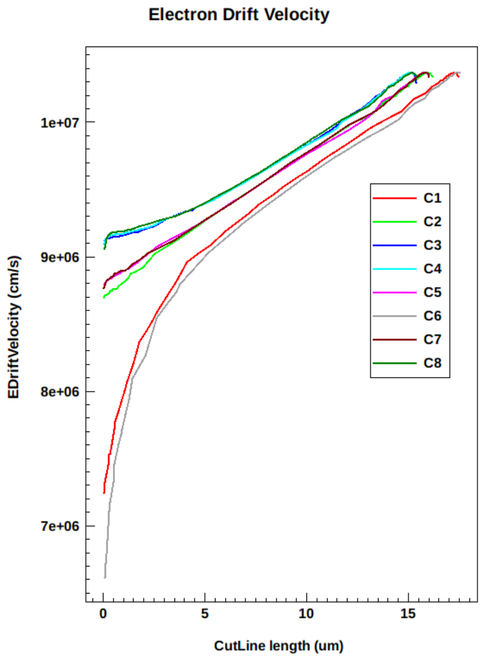
Rejected solutions, some examples (2)

- **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:
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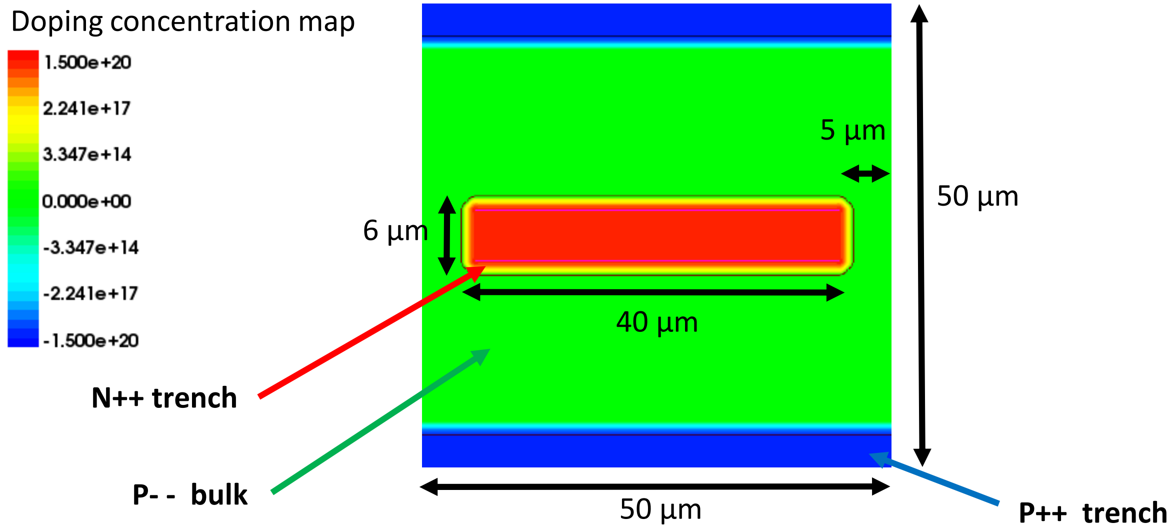
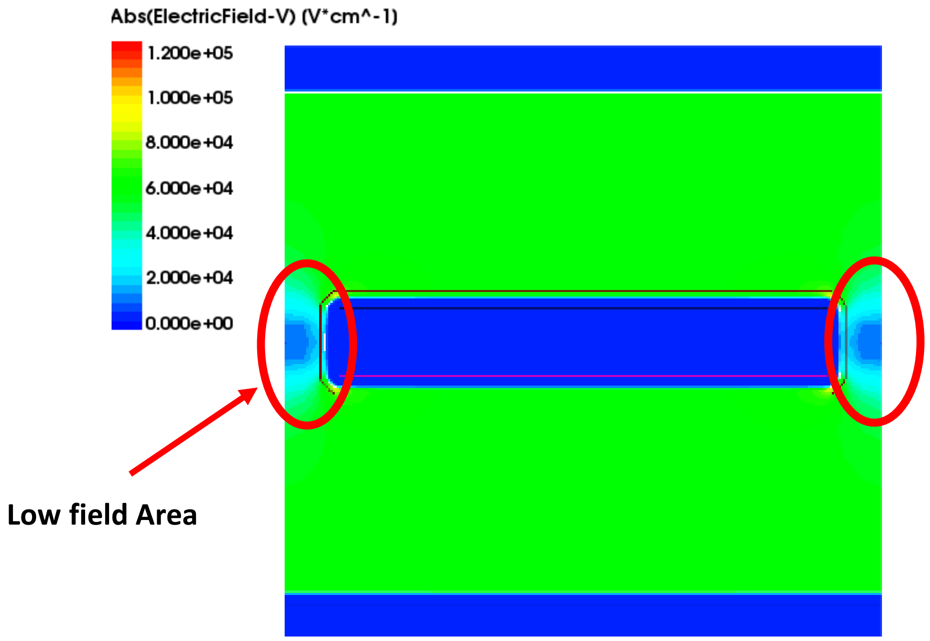
Selected solutions, some details

- **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 45 µm to 35 µm)

- **Electric field:**
  - Is the most uniform of all explored geometries
  - Low field areas covers ca. 1.5 % of the entire area (34 µm^2)
    - Areas between two N-electrodes
    - Charge collection remain fast due to the extremely short distance to the electrodes





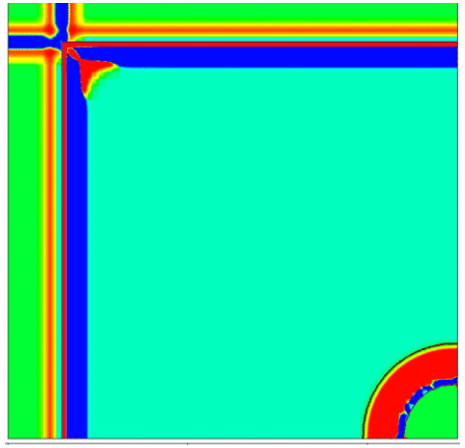
Signal generation: low field area and signal generation

- **2D model signal simulation (test)**
  - **80 e/h couples are injected in specific points**
  - **Signal shape changes from point to point**
    - **Amplitude becomes lower**
    - **Risetime slower**
    - **Signal width larger**

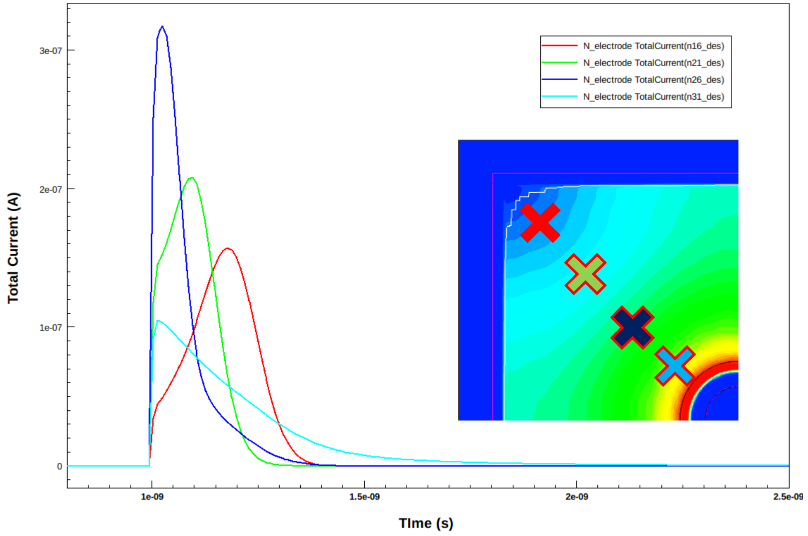
$$i_1 = q_m \nabla\left(\frac{V_m}{V_1}\right) \cdot \mathbf{v} = -q_m \mathbf{E}_w \cdot \mathbf{v}$$

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

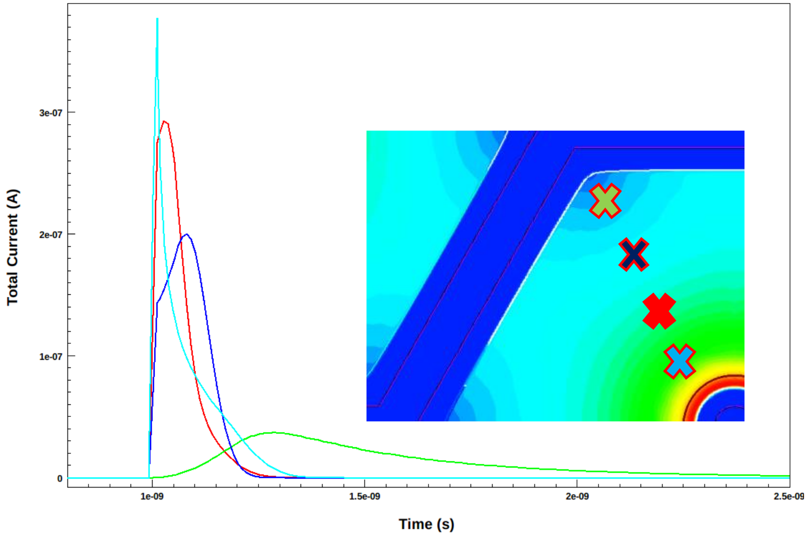
←Ramo Theorem gives the explanation of the different signal shapes



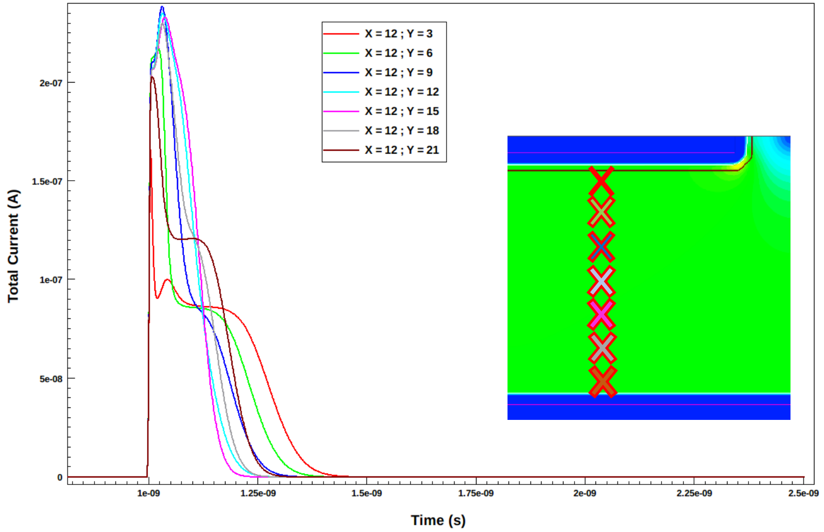
Square pixel with central column



"Closed" hexagon with central column



Parallel trench pixel



TCAD HeavyIon model

- **Heavy Ion Mmodel**

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

Particle path direction (x,y)

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**

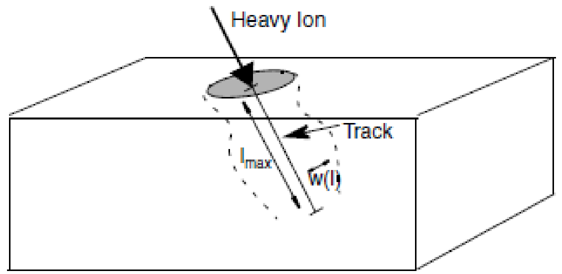


Figure 53 A heavy ion penetrating a semiconductor; its track is defined by a length and the transverse spatial influence is assumed to be symmetric about the track axis

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

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

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