Signal formation in Vertical Drift

DUNE – France Analysis workshop

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Vertical drift design

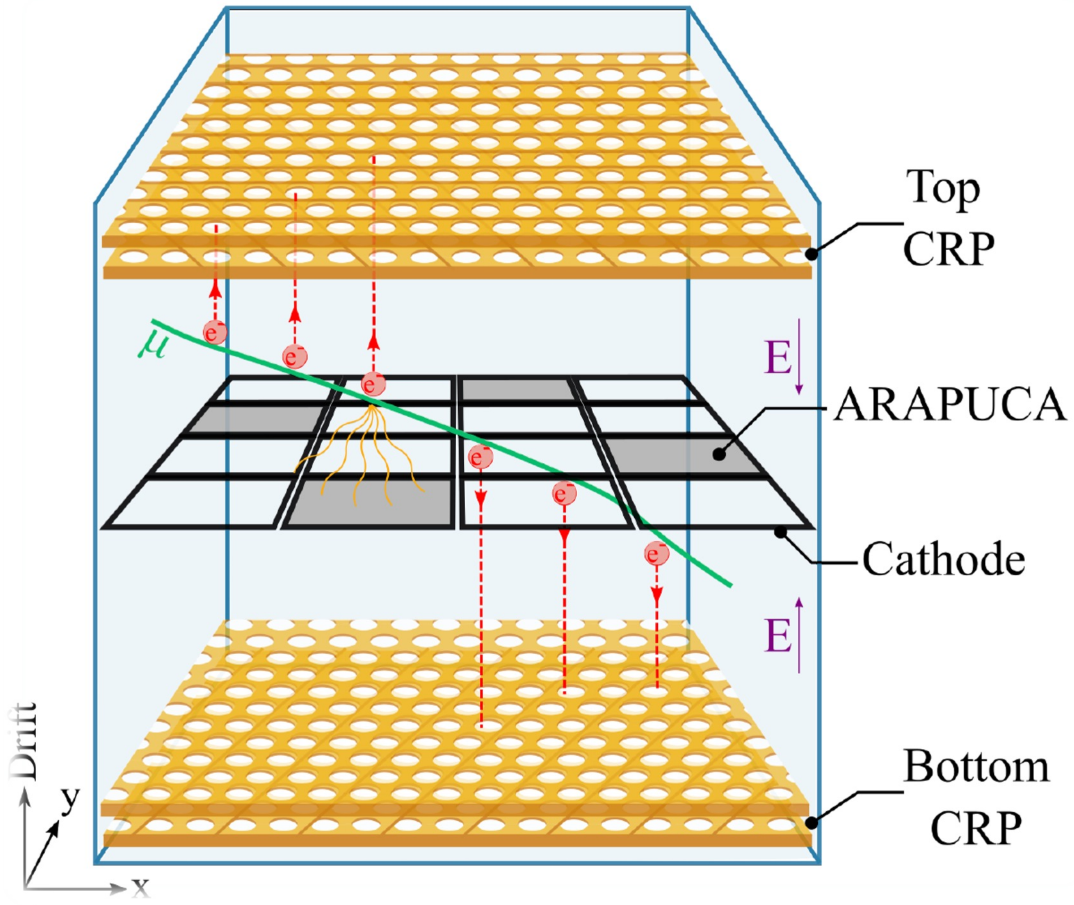


Diagram by L. Zambelli

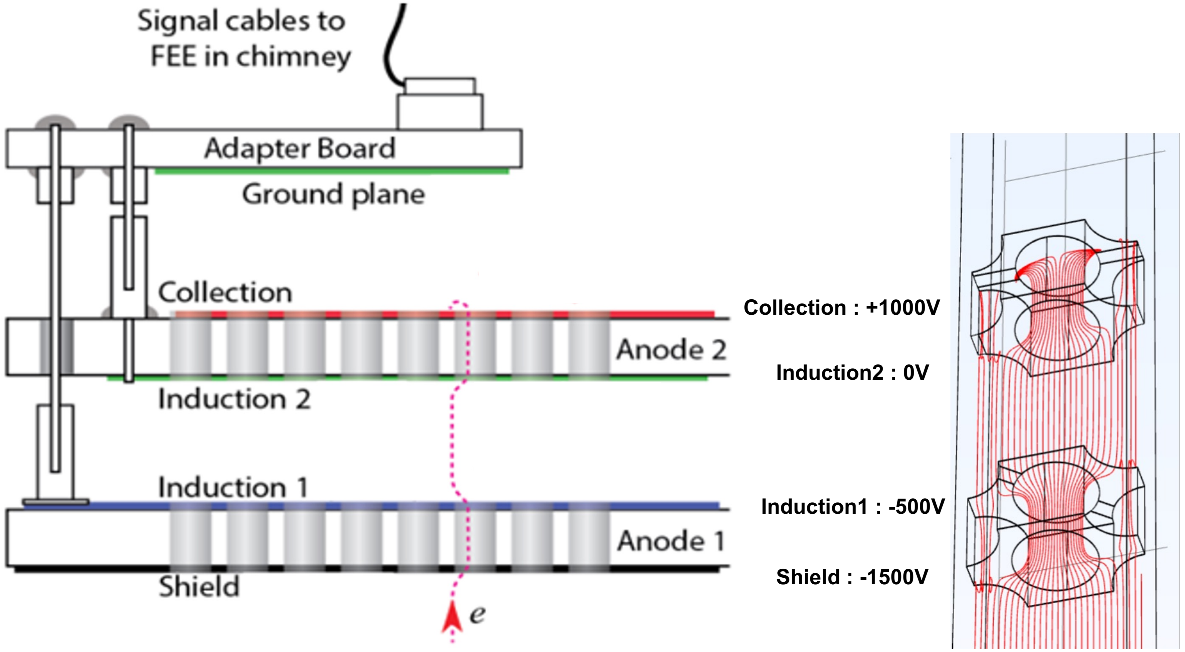
- 2 volumes split by a cathode
  - Electric drift field: $|\vec{E}| = 0.5\ kV/cm$
- X-ARAPUCA* for light detection on the cathode
- The new perforated anode technology
  - Stack of 2 perforated Printed Circuit Boards (PCB)
  - Etched copper electrode strips on each PCB face
  - A sub-centimeter spatial resolution
  - Module called Charge-Readout Planes (CRP) ~ 3x3 m
- DUNE Far detector at SURF:
  - 80 module CRPs for each top and bottom TPC
  - Half will be produced at Grenoble

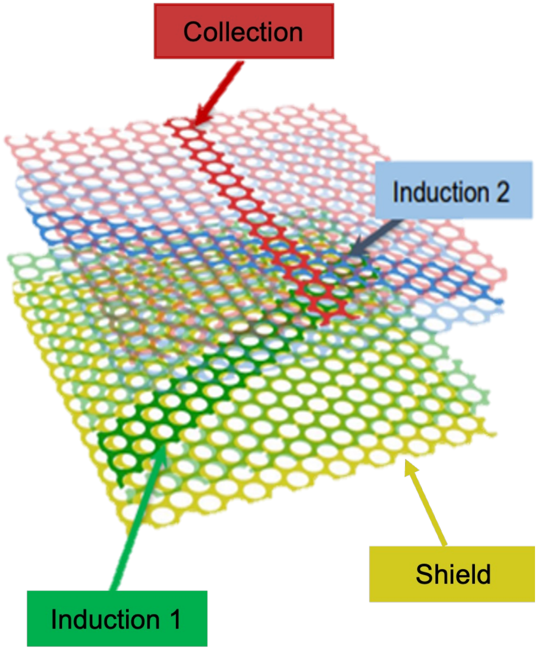
** Light detector device*

The perforated anode technology

➢ Shield + 3 different charge readout layers:

- **Induction 1 (view 0)** – strip orientation -30° wrt beam axis
- **Induction 2 (view 1)** – strip orientation +30° wrt beam axis
- **Collection (view 2)** – strip orientation 90° wrt beam axis



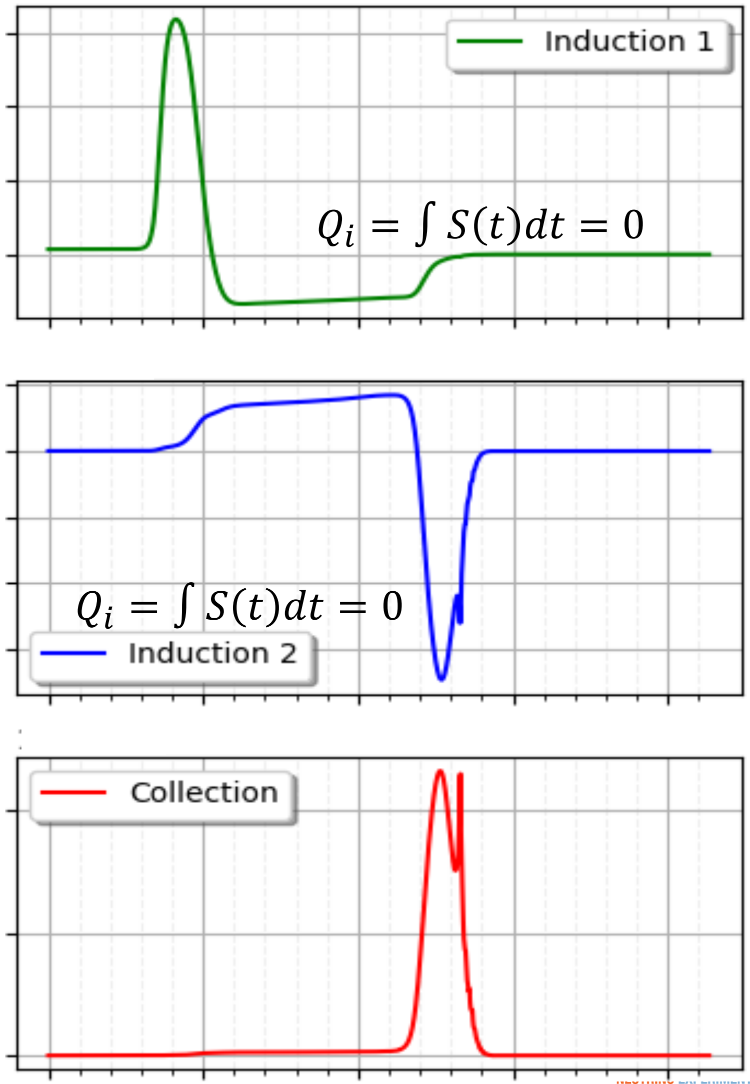


➢ **Induction views:** Bipolar signals

➢ **Collection view:** Unipolar signal

$$Q_{coll} = \int S(t)dt = N_e \times e$$

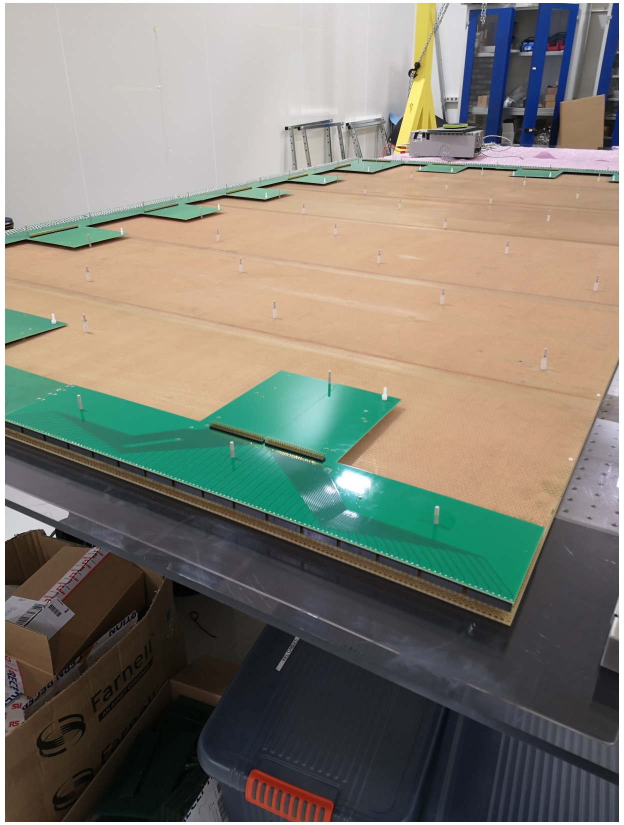
➢ Signal before convolution



Signal formation study on anodes

- **Problematic:**
  - Use of new anode technology
  - Important to know the deposited energy in the detector to measure the neutrino oscillation parameters
  - Important to reconstruct the particle tracks from collected charge

- **My work:**
  - Understanding the waveforms based on energy, track angle and position
  - Understanding the charge lost in the anodes
  - Estimate the different systematics
  - **Study of induced signal formation on the anode**



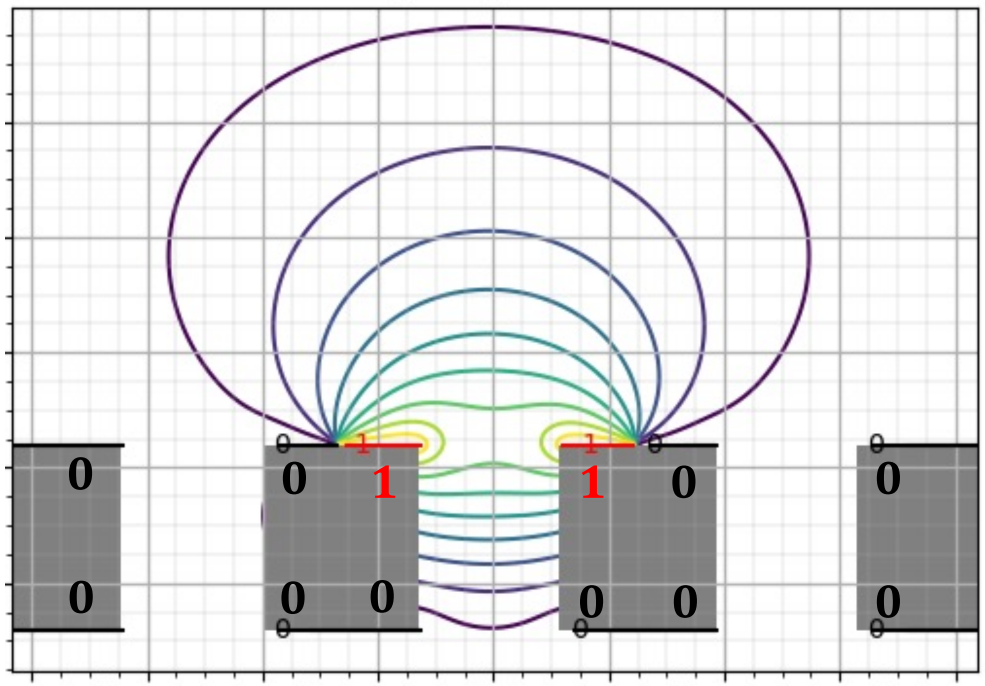
CRP assembly at CERN

Modeling signal formation

➢ Shockley-Ramo theorem:

$$i(t) = q\,\vec{E}_w \,.\, \vec{v}_D$$

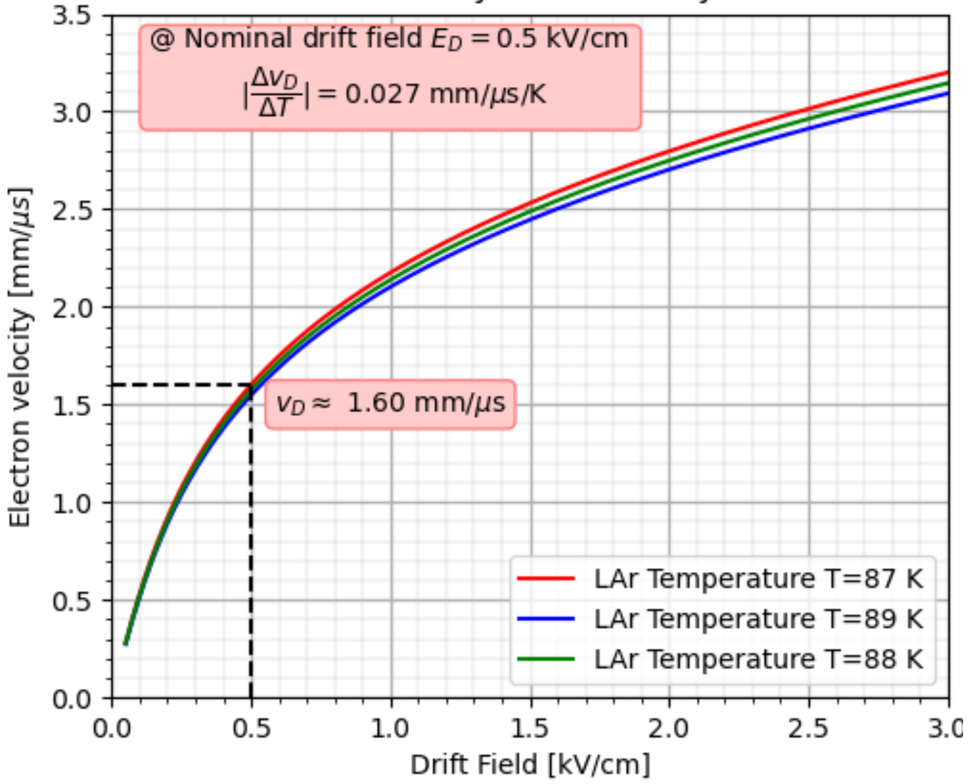
➢ Weighting Field $\overrightarrow{E_w}$ is virtual field defined when the **reading strip equal 1 V** and **all others fixed to 0 V**



$\left\{ \begin{array}{l} \overrightarrow{E_w}\text{: geometry factor} \\ \overrightarrow{v_D}\text{: physics factor} \end{array} \right.$

➢ **Drift velocity:**

$$\overrightarrow{\mathrm{v_D}} \equiv \overrightarrow{v_D}\,(\overrightarrow{E_D}, T)$$



➢ **<u>The instantaneous current is induced by charge motion only</u>**

➢ **Need simulation for complex geometry**

https://lar.bnl.gov/properties/trans.html

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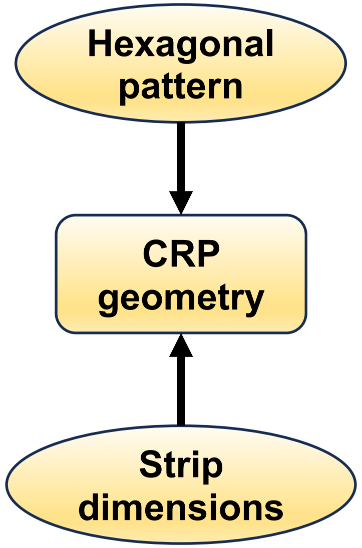
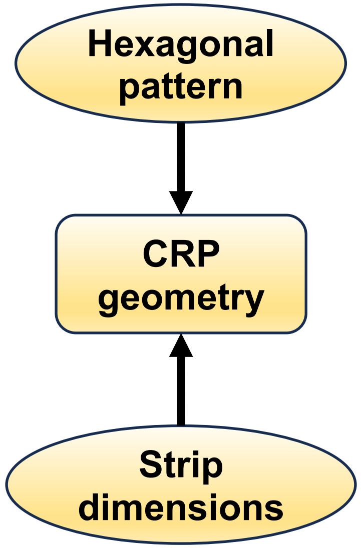
Induced signal simulation

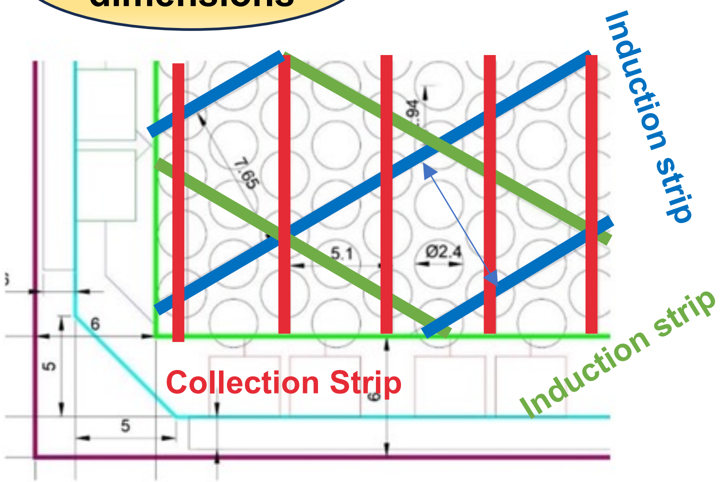
- Design of a simulation on Python



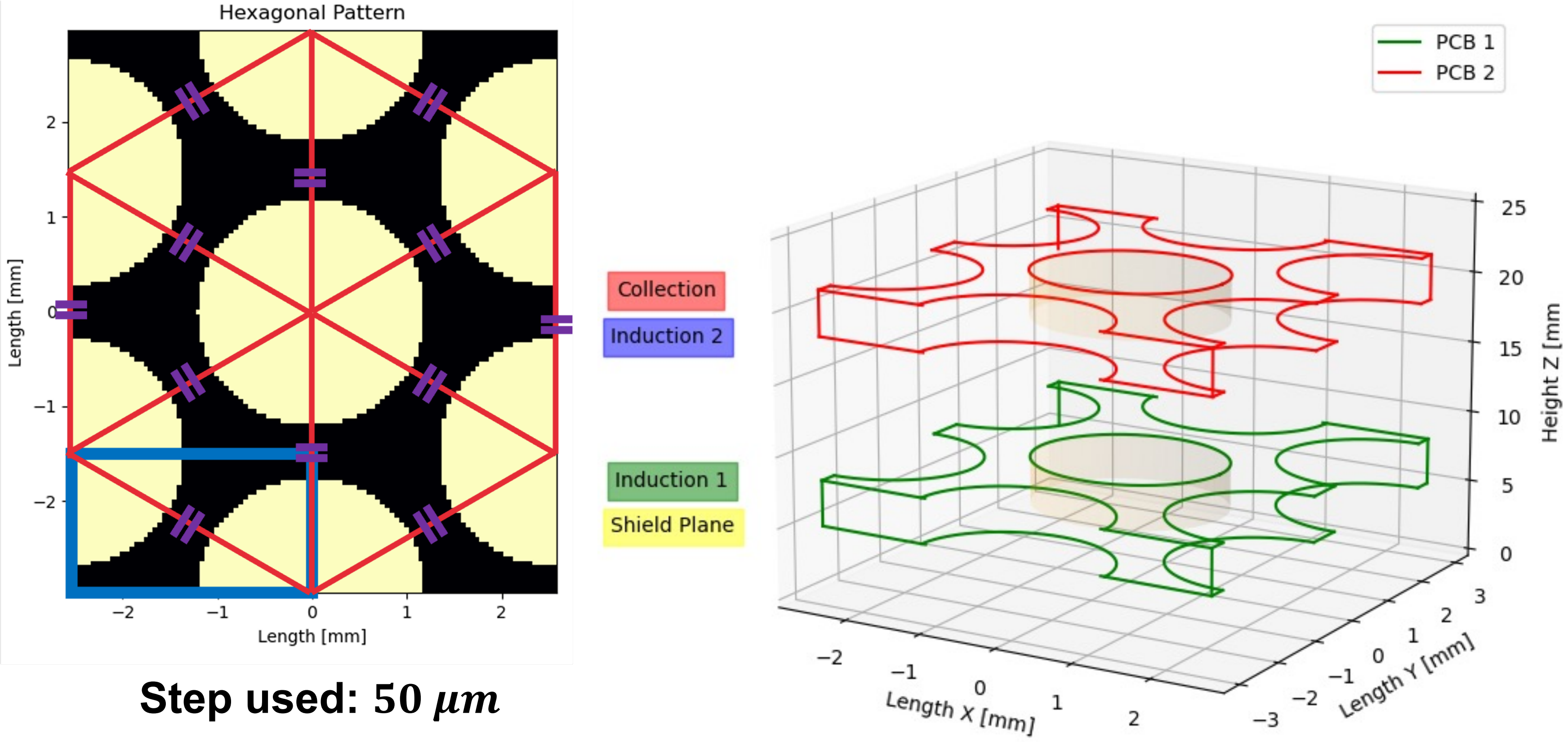
Induced signal simulation

- Numerical simulation on Python





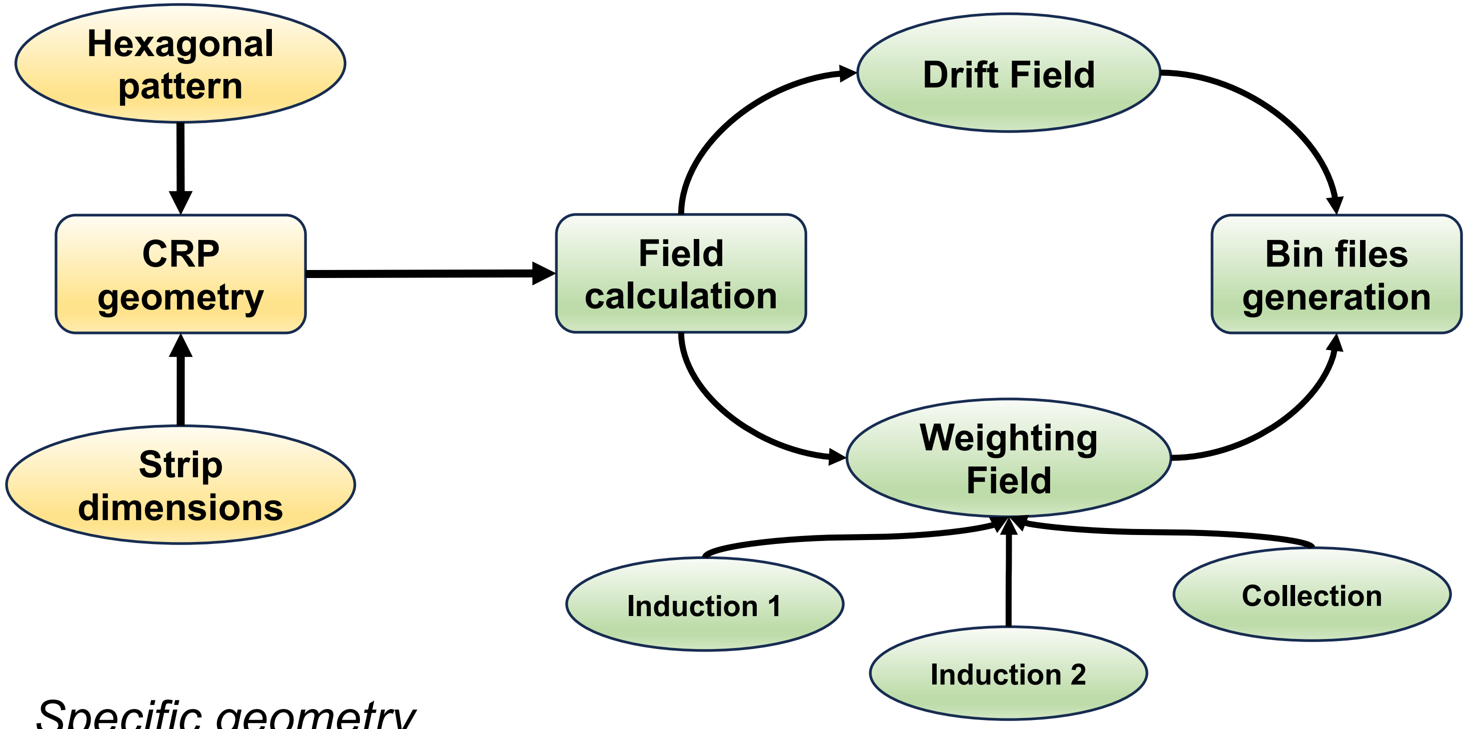
- Implement CRP geometry hexagonal pattern, width strips, 2 Printed Circuit Boards, 4 equipotential planes



Step used: $50\ \mu m$

Induced signal simulation

- Design of a simulation on Python



1. *Specific geometry setting up*

- Induced signal on the readout strips:

$$i(t) = q\,\overrightarrow{E_W}.\overrightarrow{v_D}$$

  - Weighting field $\overrightarrow{E_W}$
  - Drift Velocity Field:
    $\overrightarrow{v_D} = \mu(\,|\overrightarrow{E_D}|, T)\times\overrightarrow{E_D}$

- Solving Laplace's equation in 3D:

$$\Delta\phi(x, y, z) = 0$$

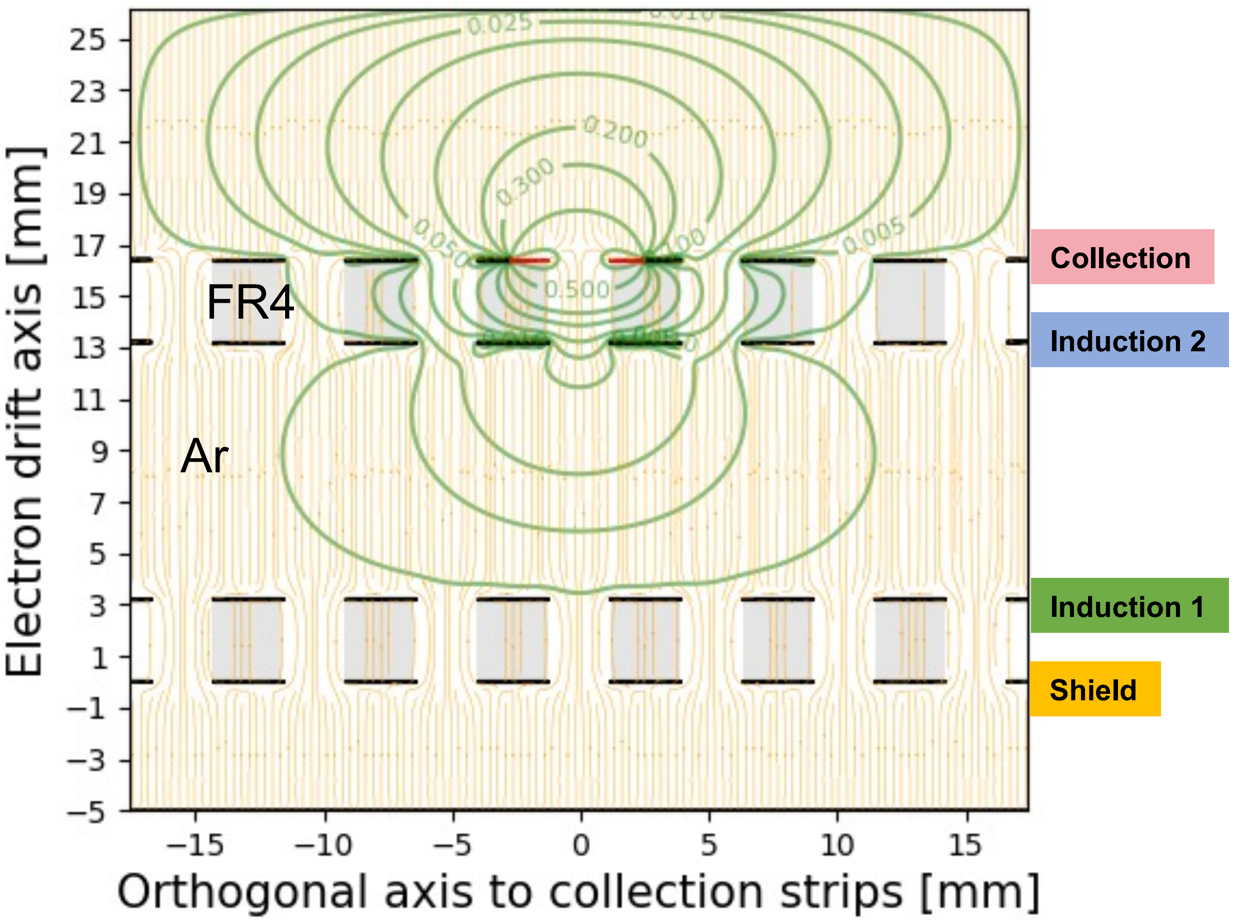
- 3D Finite element method (FEM):

$$\phi_{i,j,k} = \frac{\phi_{i\pm1,j,k} + \phi_{i,j\pm1,k} + \phi_{i,j,k\pm1}}{6}$$

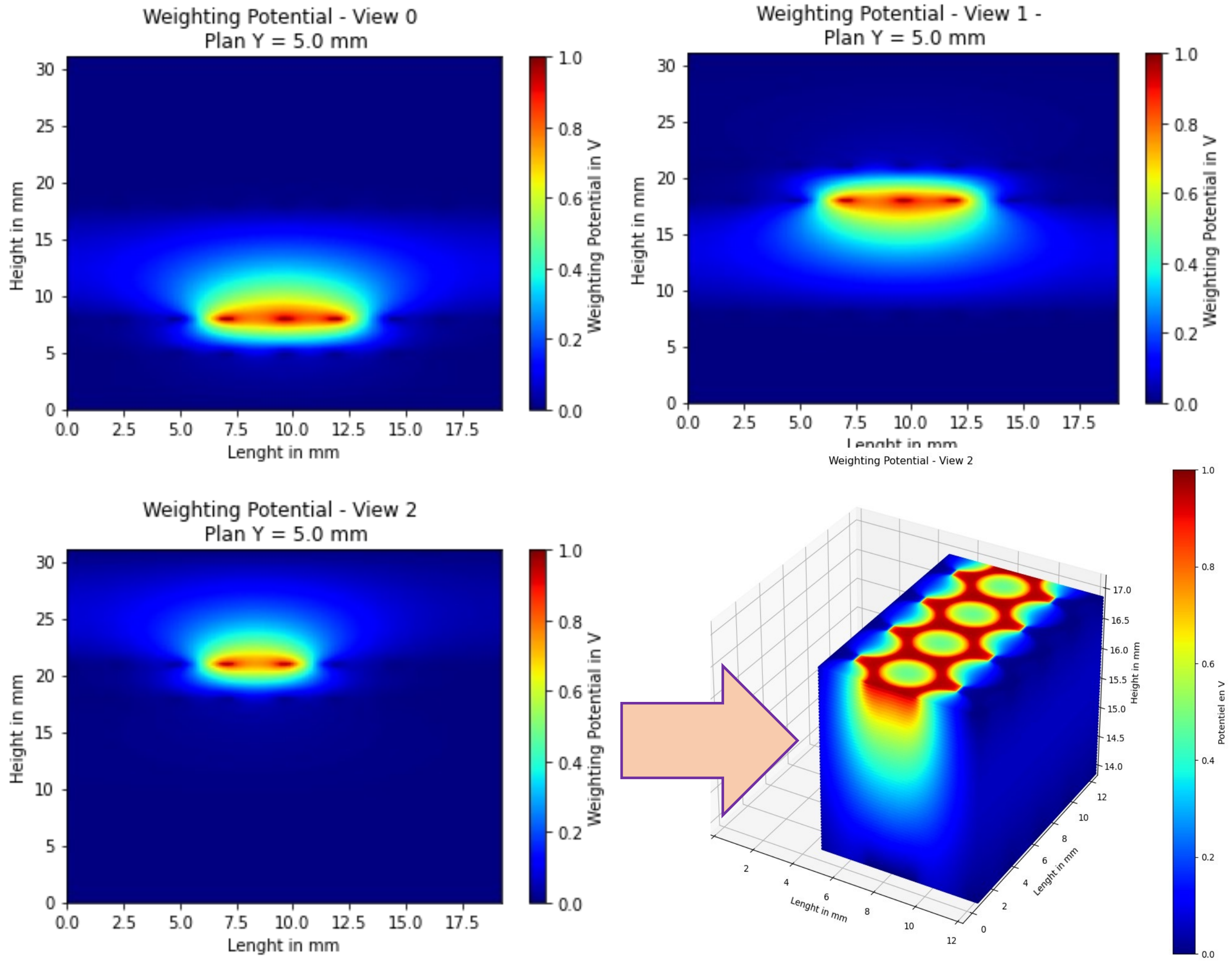
- Iterative method, step by step

Field results

- 2D projection of drift field lines and weighting equipotential



- **Weighting Potential**

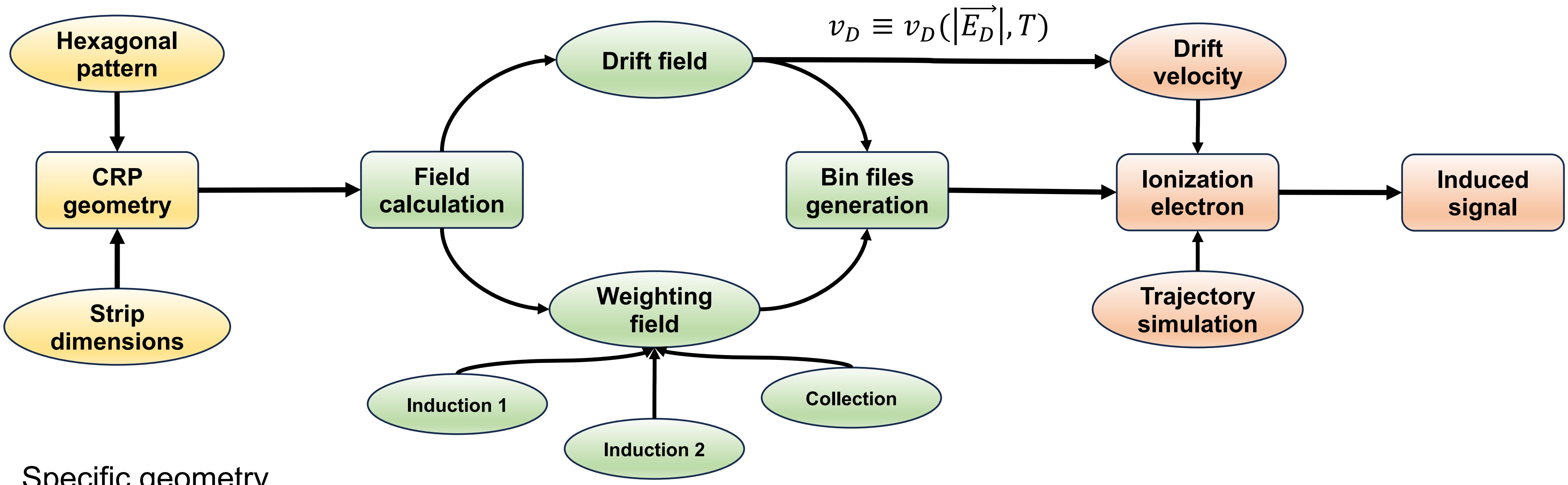


- Induced signal in the nearby strips

Induced signal simulation

- Design of a simulation on Python

$\left|\overrightarrow{E_D}\right| \in [0.5\,;4\,]$ kV/cm



1. Specific geometry setting up

2. Field generation with CRP geometry

Ionization electron generation

- Thermal electron
  - Trajectory follow drift field lines
- The electron trajectory is perfectly defined

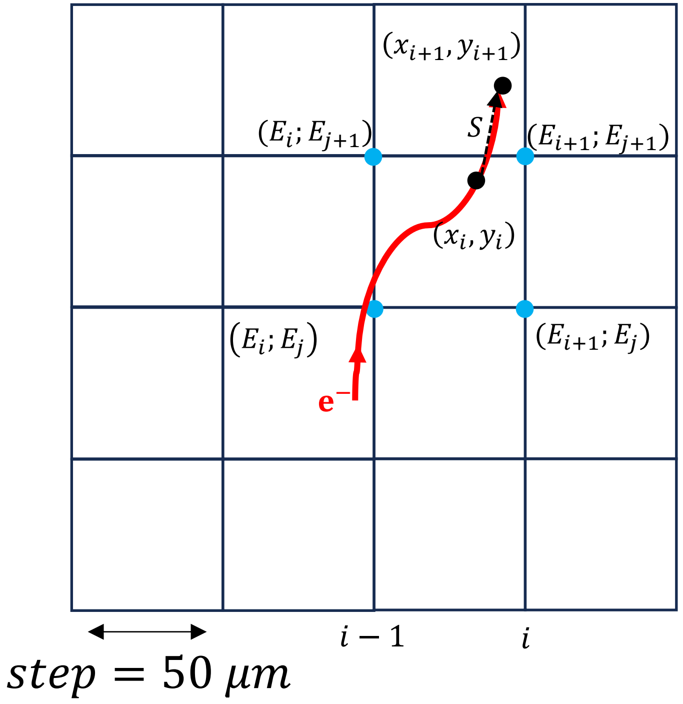
- Runge Kunta like simulation

$$x_{i+1} = x_i + \frac{E_x^{interp}(x_i, y_i)}{|E(x_i, y_i)|} \times S$$

$$y_{i+1} = y_i + \frac{E_y^{interp}(x_i, y_i)}{|E(x_i, y_i)|} \times S$$

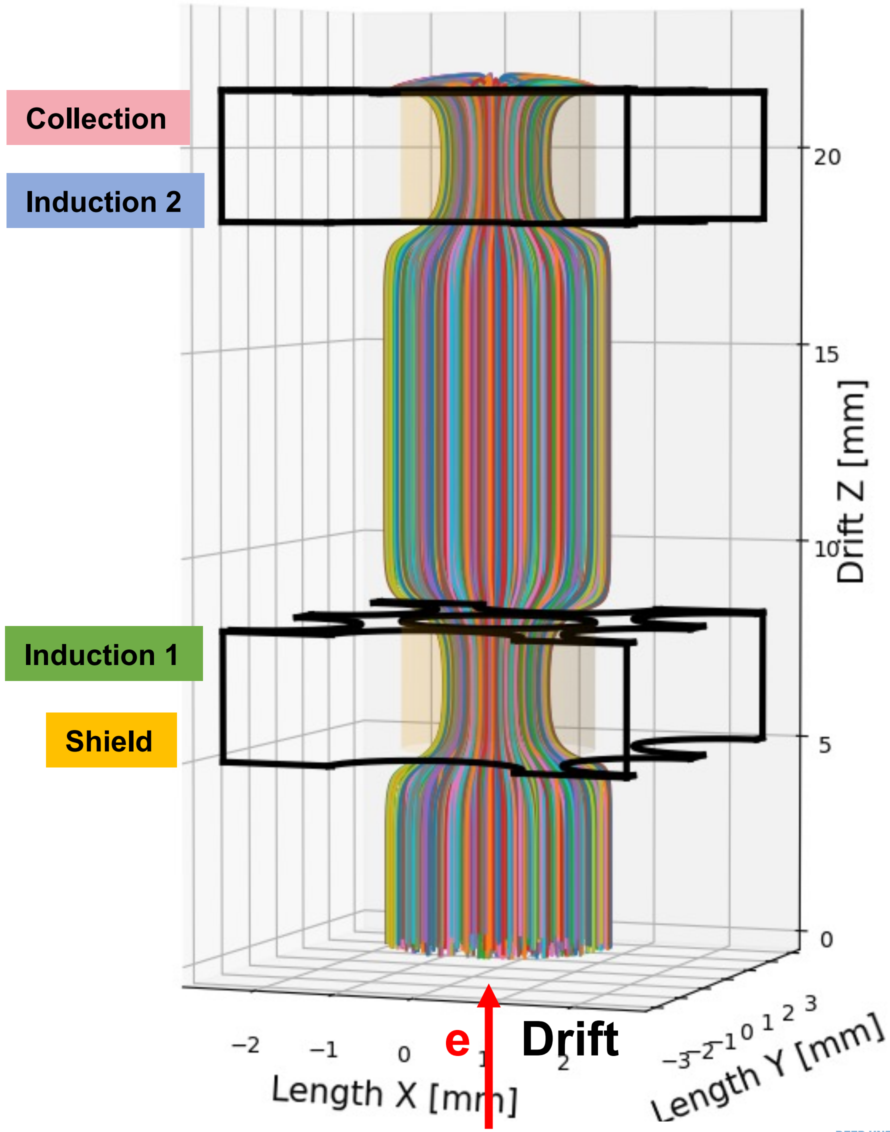
- E^{interp}: 3D linear interp

- Drift simulation 5 mm

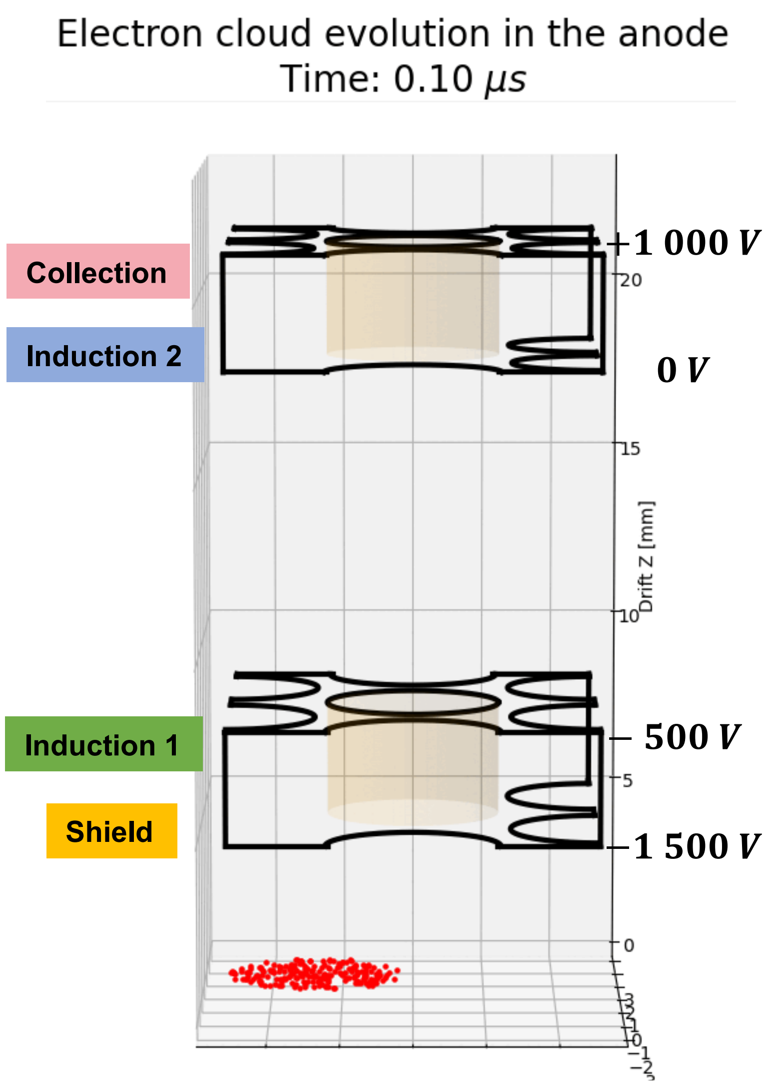


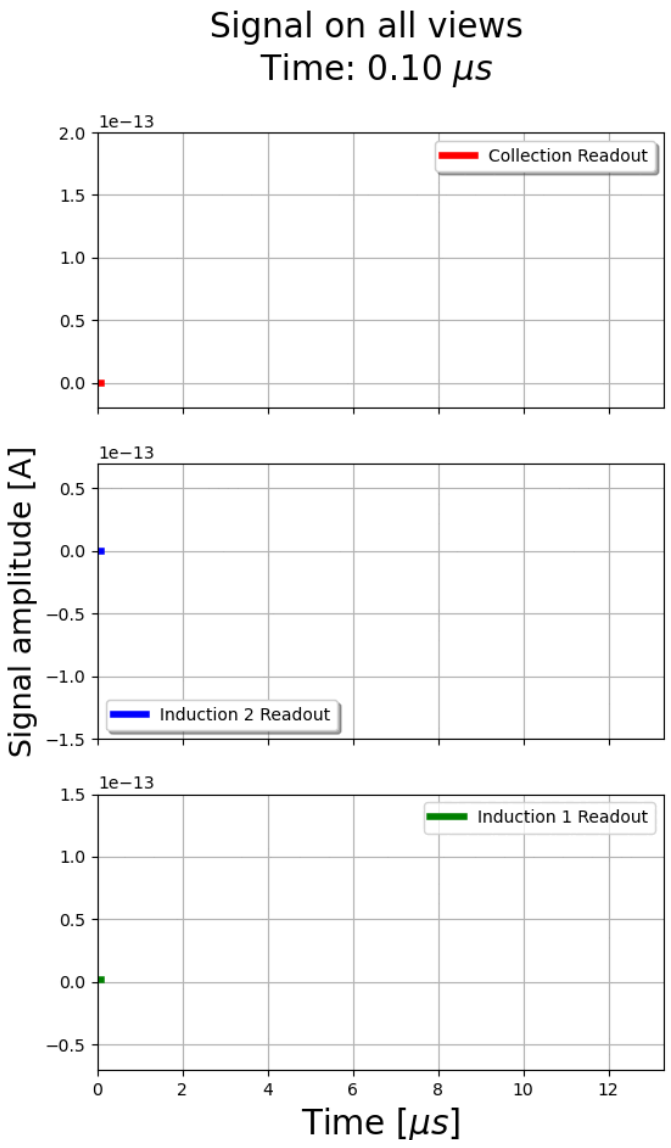
- Grid of the mesh used for the field calculation

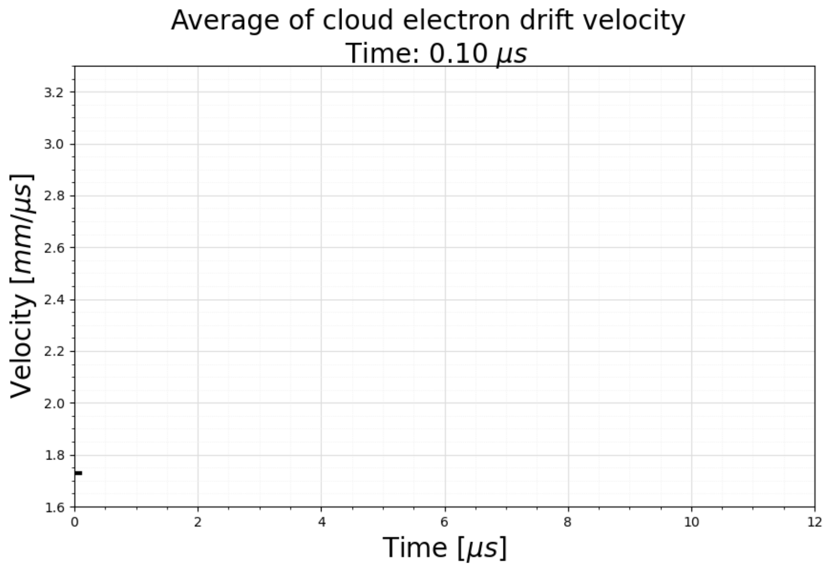
- Electron trajectories passing through a CRP's hole



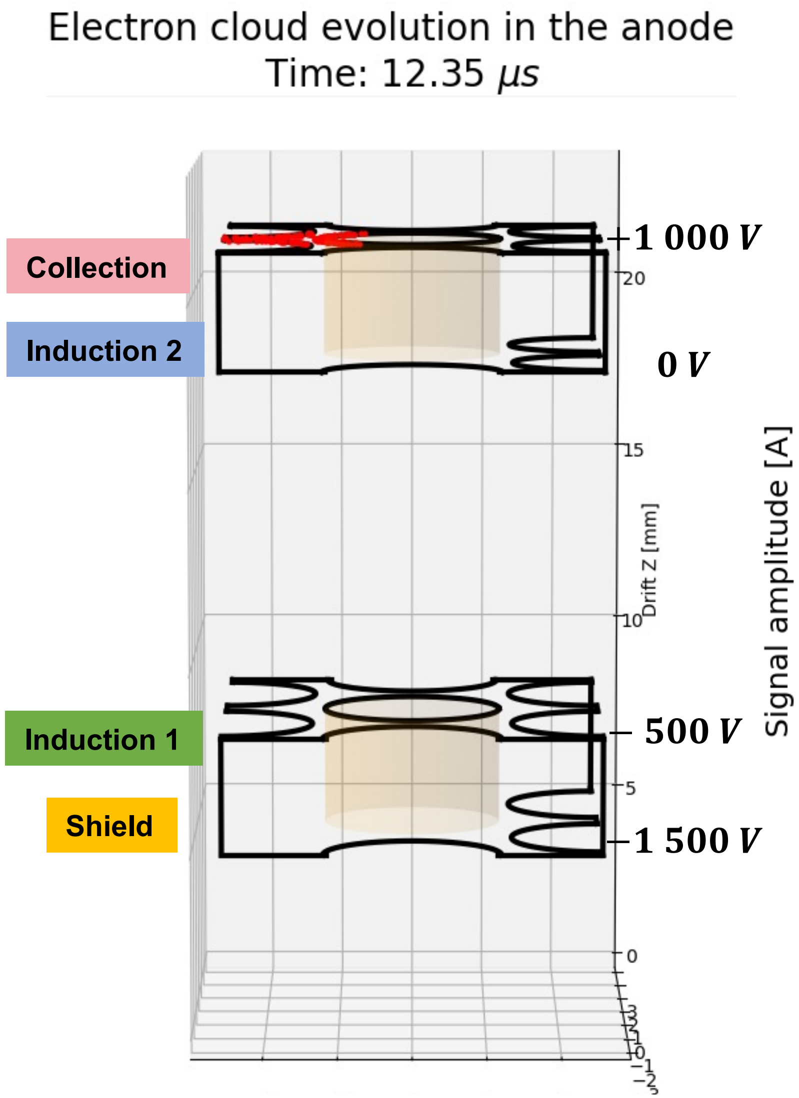
Electron cloud simulation

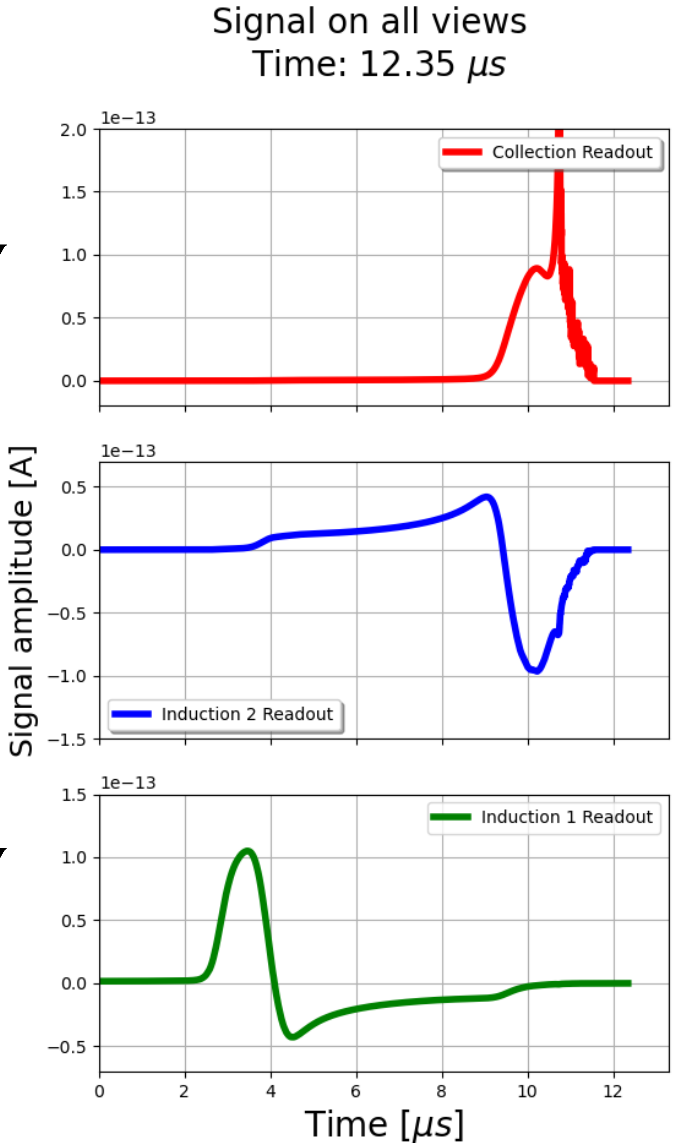


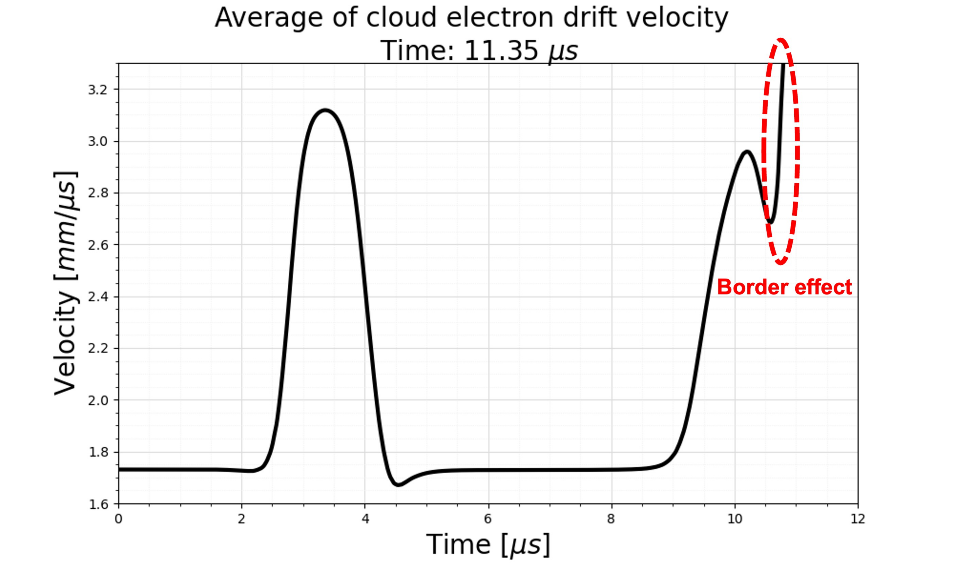




Electron cloud simulation

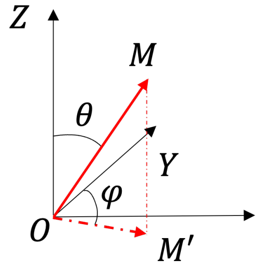




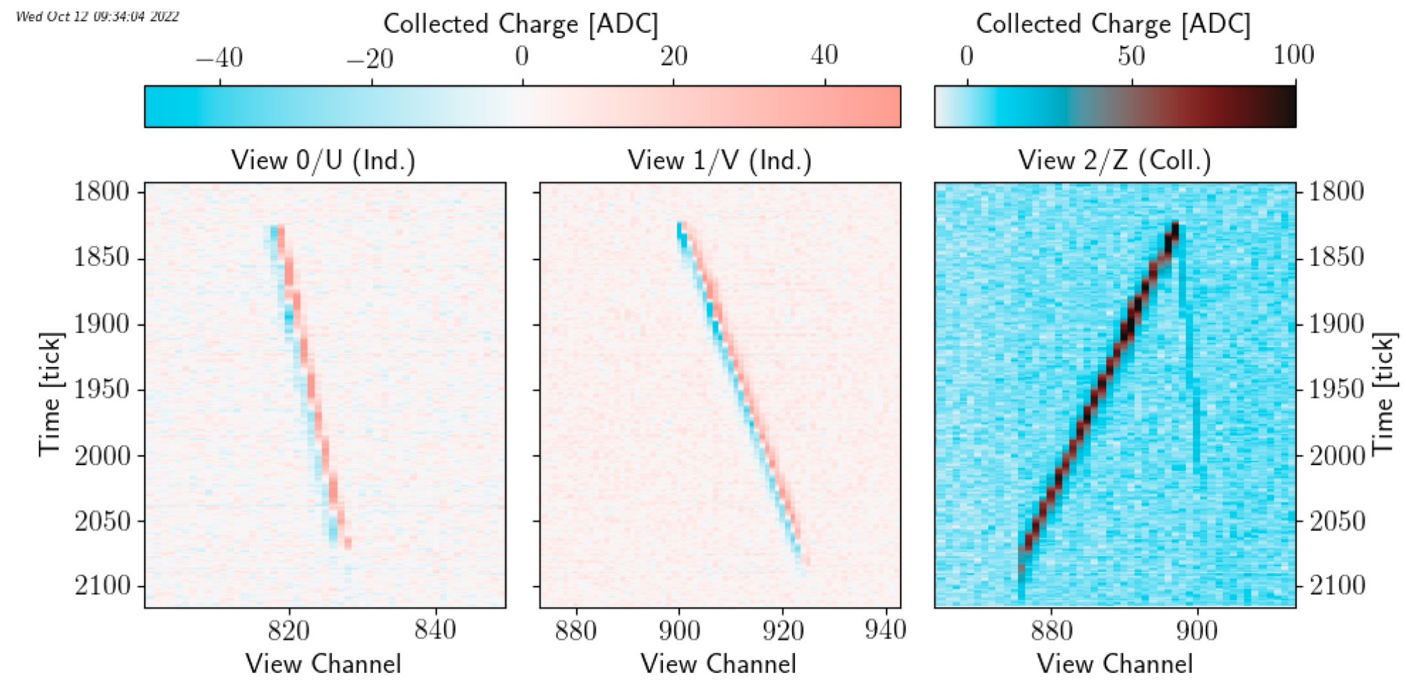


- Border effect near to the collection electrode
- The field takes $\propto 1/r^2$ dependancy which will induce a high frequency signal
- Electronic response will smooth the readout induced current

Data extraction



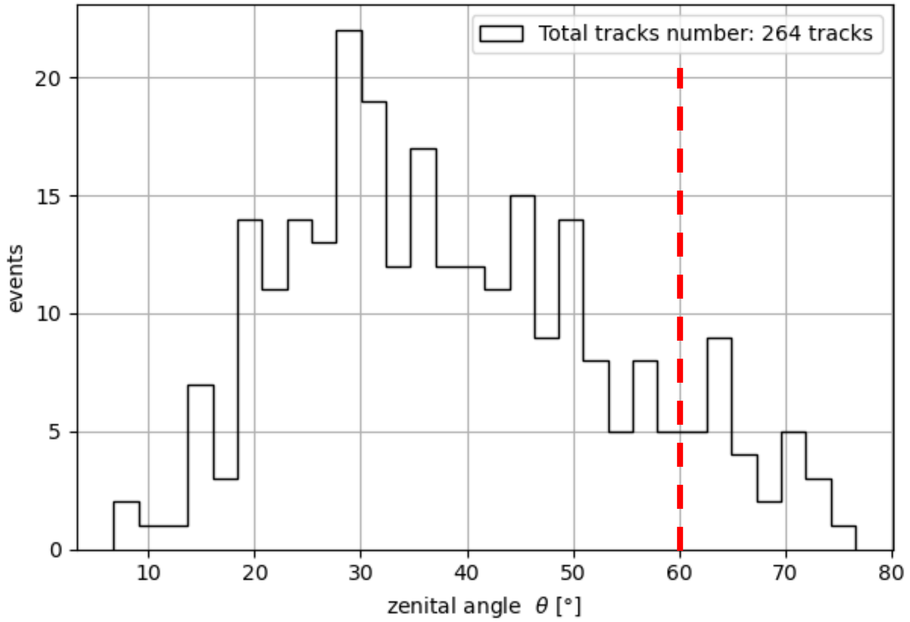
- **Event Display**
  - An example of cosmic ray track from the Coldbox



- Bipolar signals induction view
- Muon events

- **Coldbox's data cuts**
  - Tracks with reconstructed angle $\theta > 60°$
  - φ in the cone with $45°$ from the strip readout
  - Track lengths $> 20\ cm$

Reconstructed zenithal angle distribution

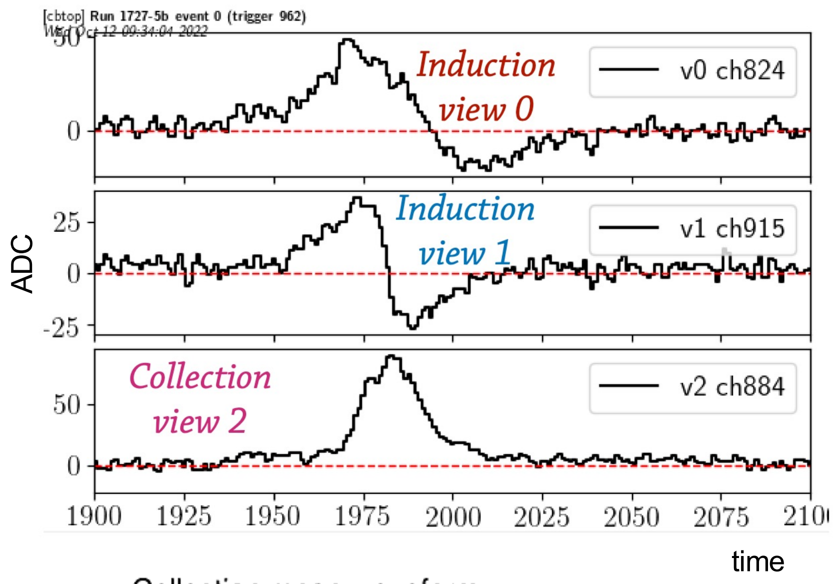


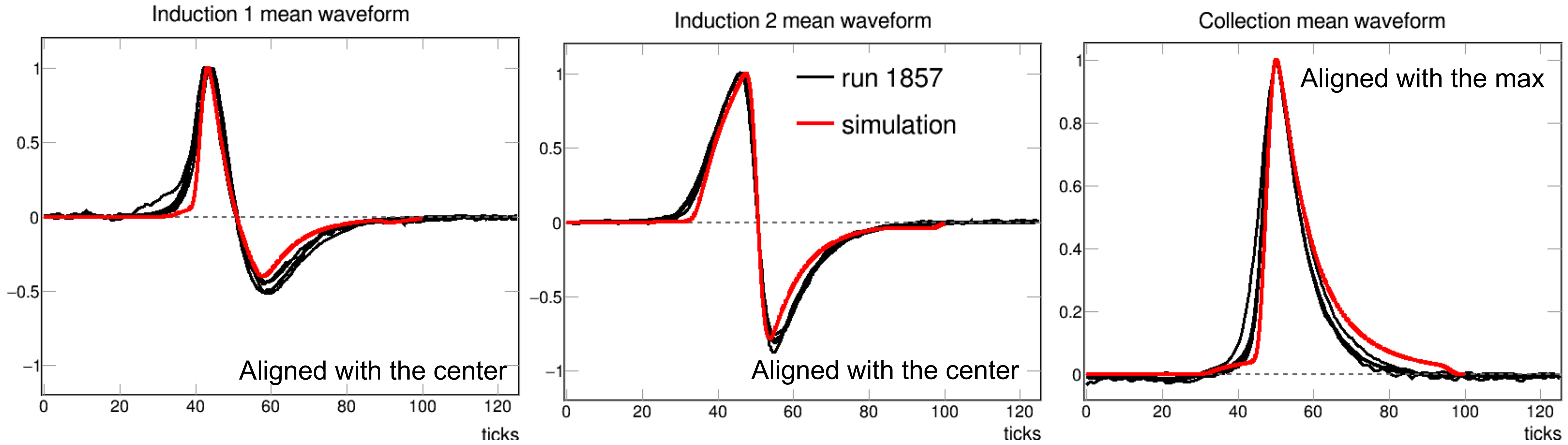
- Data reconstruction with LARDON (software developed by L. Zambelli)

- **Select horizontal track to compare with simulation**

Comparison data VS simulation

- **Mean waveform**
  - Signals summation on each readout channel
    → To reduce the incoherent noice
  - Mean signal calculation for each track

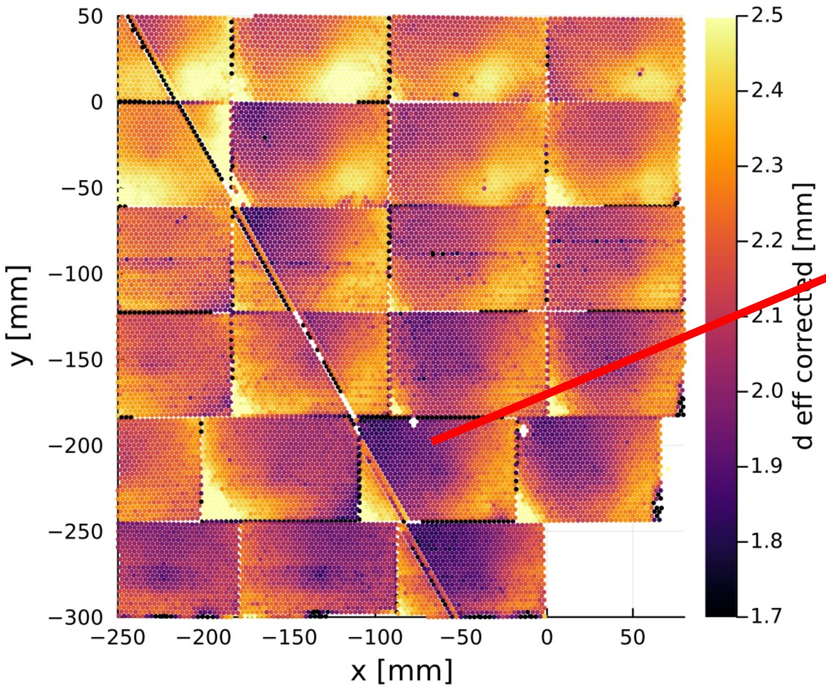


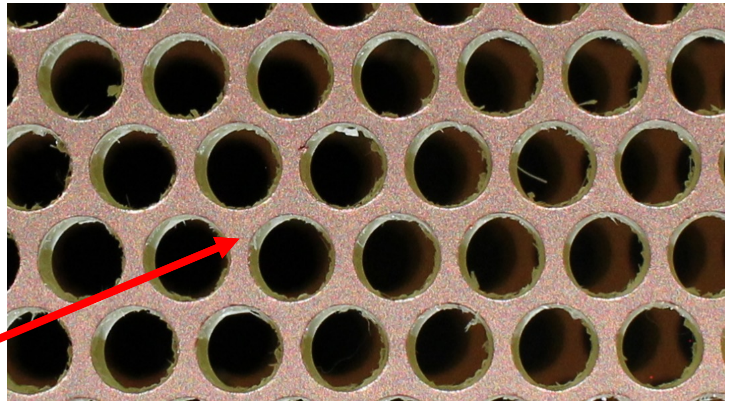


→ **Simulated waveforms in agreement with data**

CRP 6 data explanation

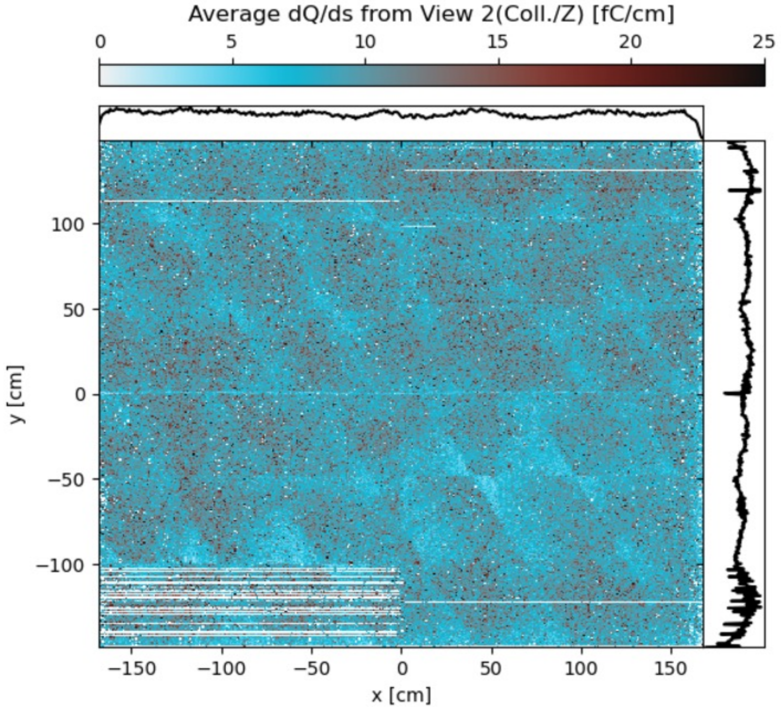
Luis' work*





- Effective hole diameter modified
- PCB shifted between shielding and view 0
- Probably glue inside the holes

Laura's work**



- Consequences: charge lost
- Draw a pattern along the induction strips
- An effect that would seem to be a "charging-up"

Problem: no charge lost in the simulation and no "charging-up" effect

** Photo analysis for QA/QC of CRP anodes – Luis Manzanillas*

*** https://indico.fnal.gov/event/64225/contributions/288494/attachments/176651/240155/cb_crp6_iii_first_look.pdf*

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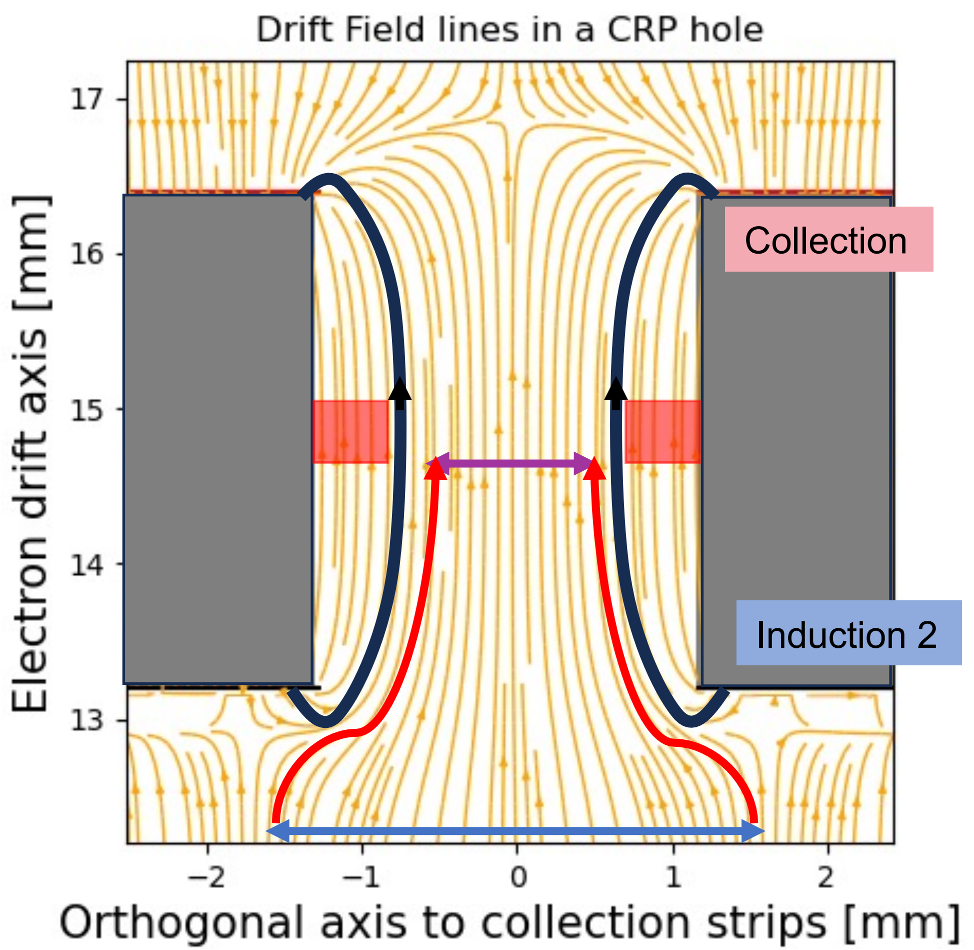
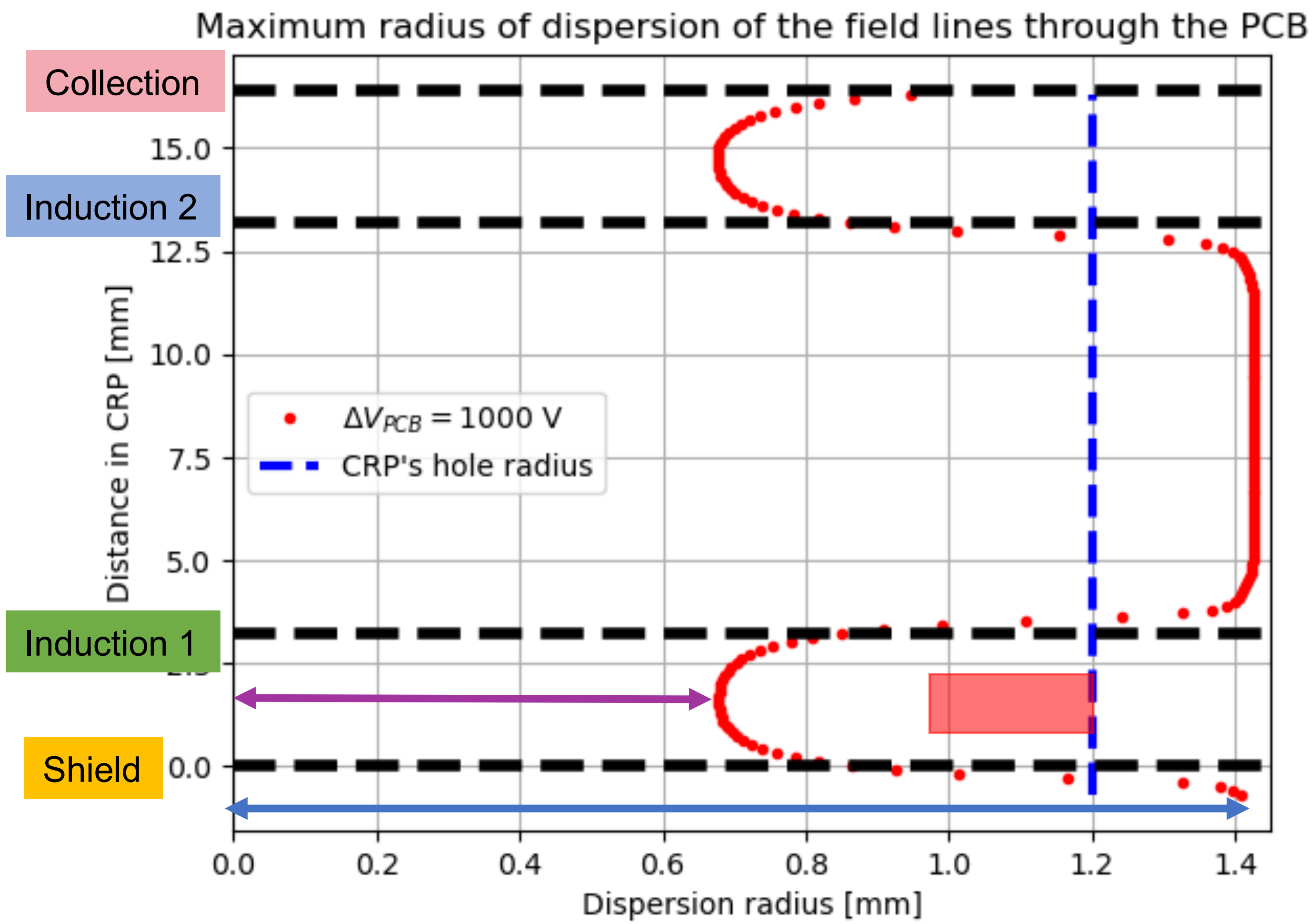
Holes covering and loss charge

- ➢ Focalization of drift field lines in the CRP hole





- ➢ Field line too focused to explain the loss of charge
  → **Electron diffusion**

Electron diffusion

- **Transverse electron diffusion could cause a loss of charge in the CRP**

$$\frac{\partial n}{\partial t} = D_L \frac{\partial^2 n}{\partial z^2} + D_T \left(\frac{\partial^2 n}{\partial x^2} + \frac{\partial^2 n}{\partial y^2} \right)$$ **Fick's equation**

- Gaussian spatial distribution of the electrons over time
- Average diffusion length given by:

$$\sigma_{L,T} = \sqrt{2 D_{L,T} t}$$

- Longitudinal and transverse diffusion coefficient:

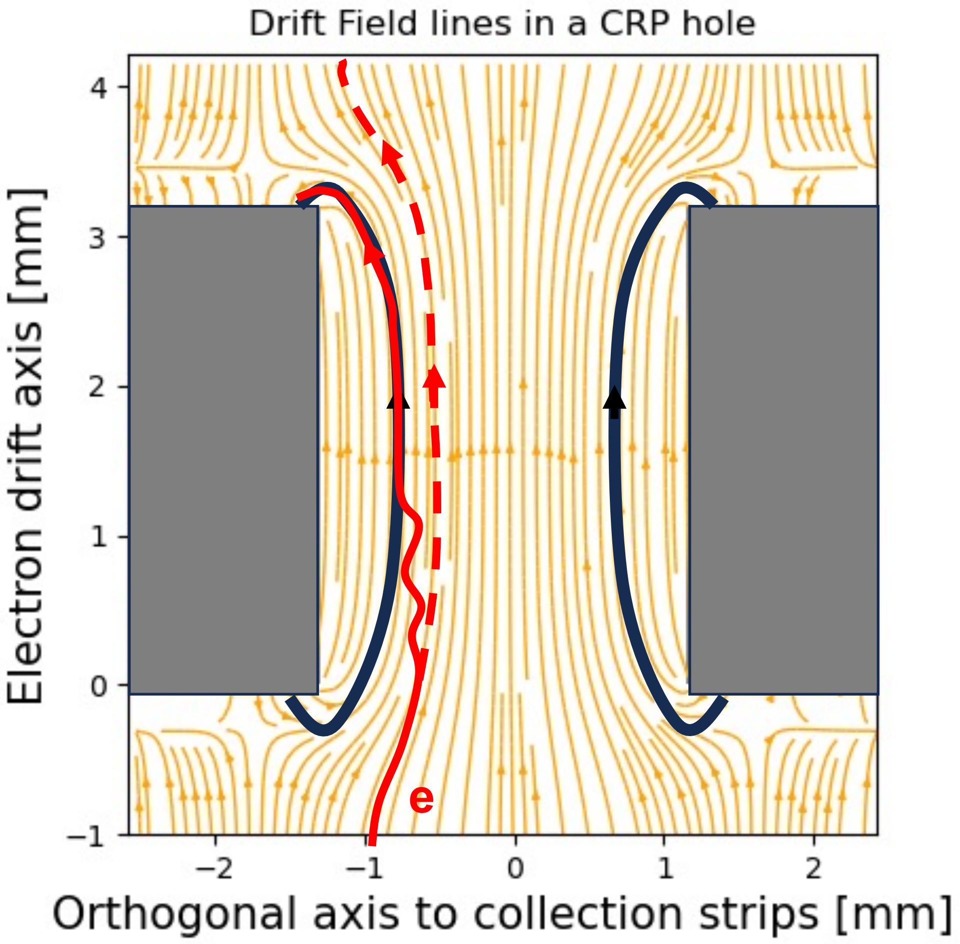
(Einstein's relation) $$D_L = \frac{\epsilon_L \mu}{e}$$

ϵ_L: longitudinal effective electron energy
μ: electron mobility

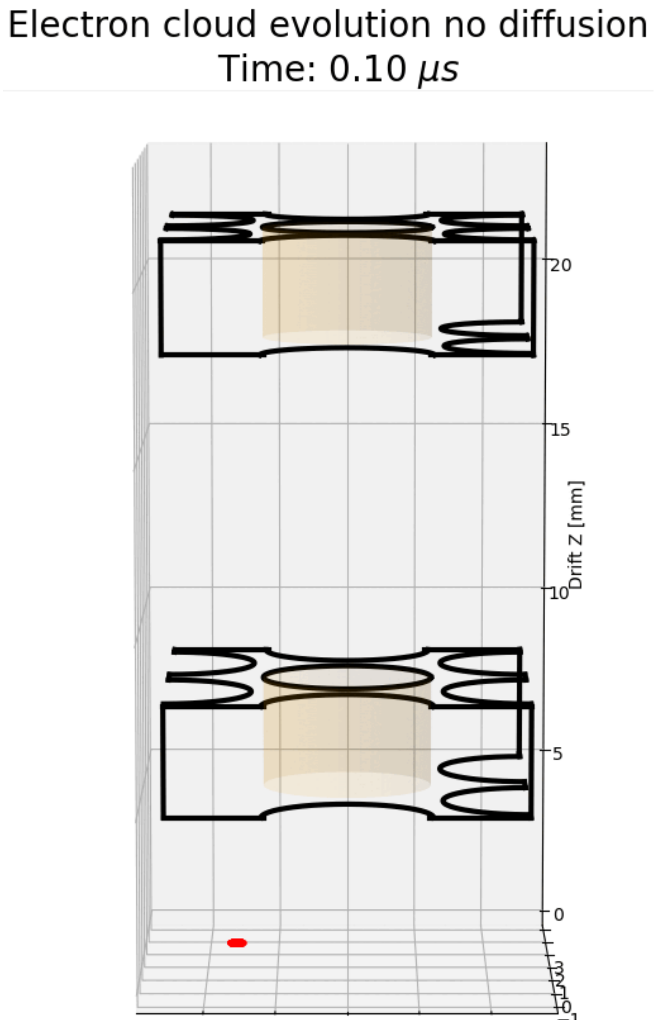
$$\frac{D_L}{D_T} = 1 + \frac{E}{\mu} \frac{\partial \mu}{\partial E}$$

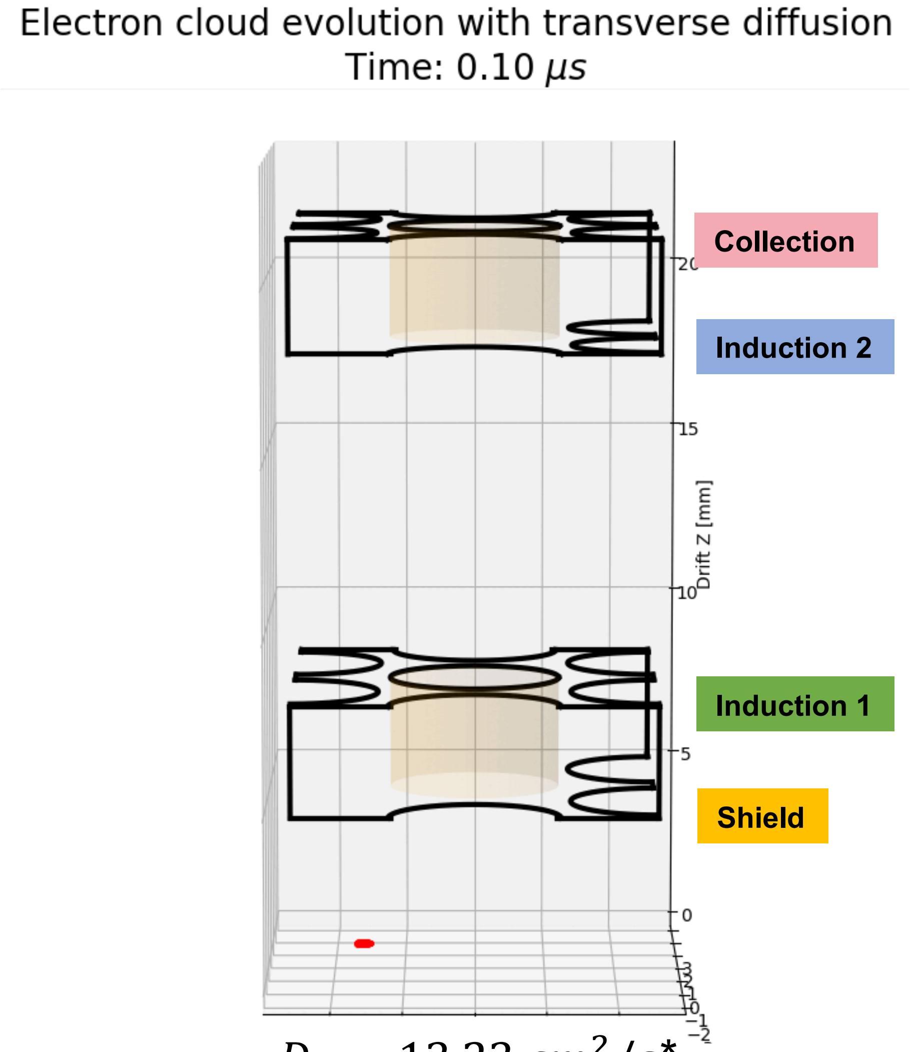
- For next: only transverse diffusion is used (work in progress)

- Electron loss on view 0 due to the diffusion



Transverse electron diffusion only





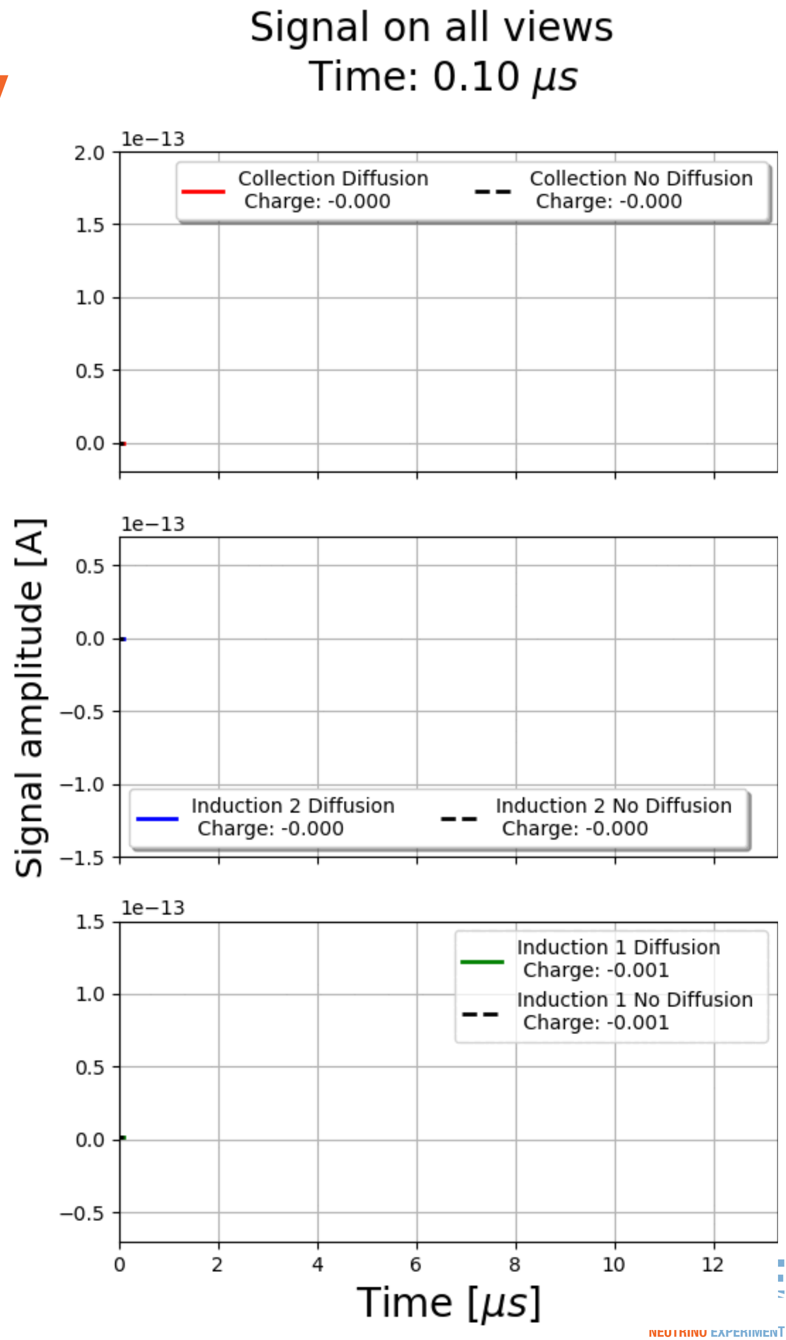
Collection

Induction 2

Induction 1

Shield

$D_T = 13.23\ cm^2/s$*



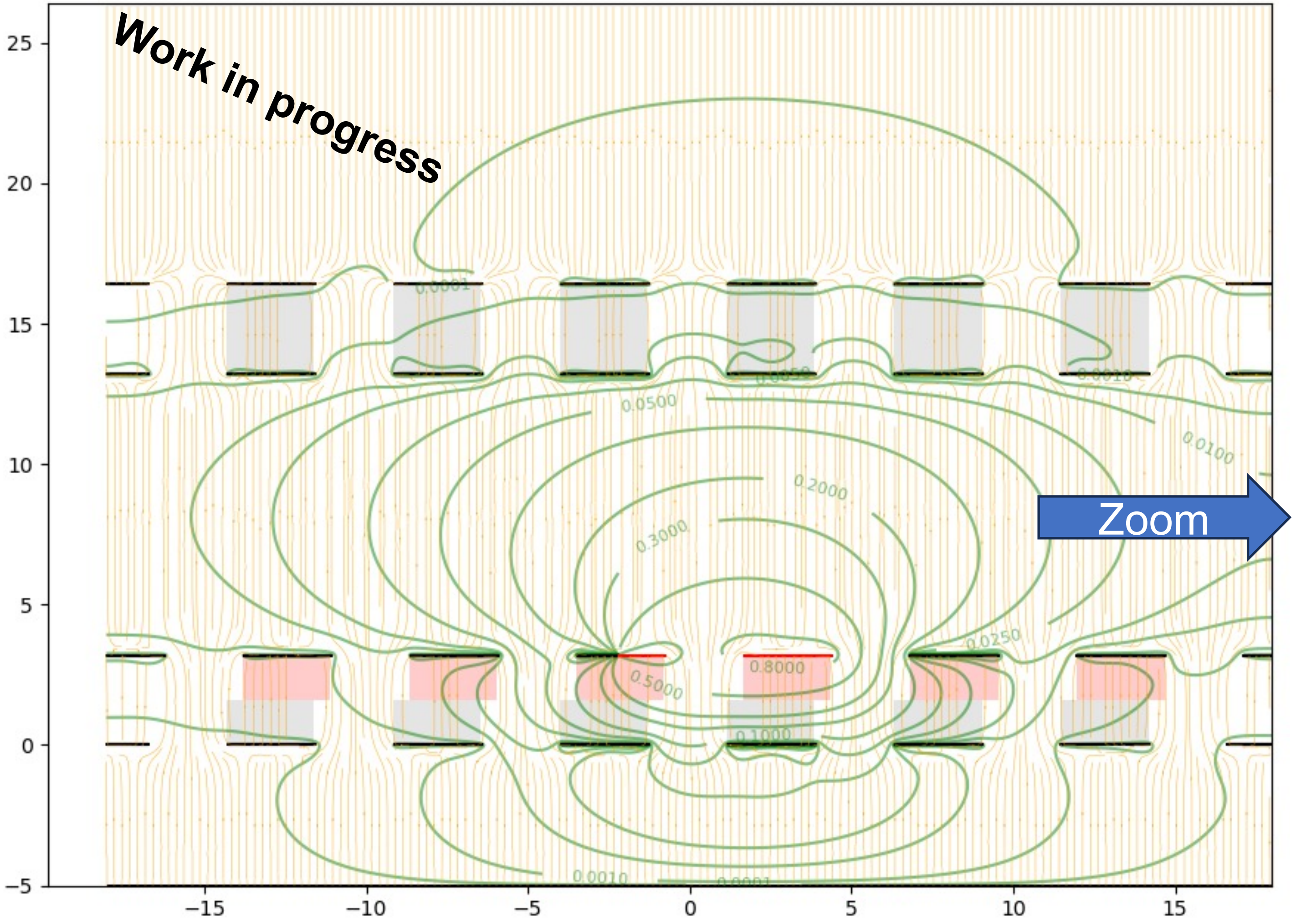
* *https://lar.bnl.gov/properties/trans.html*

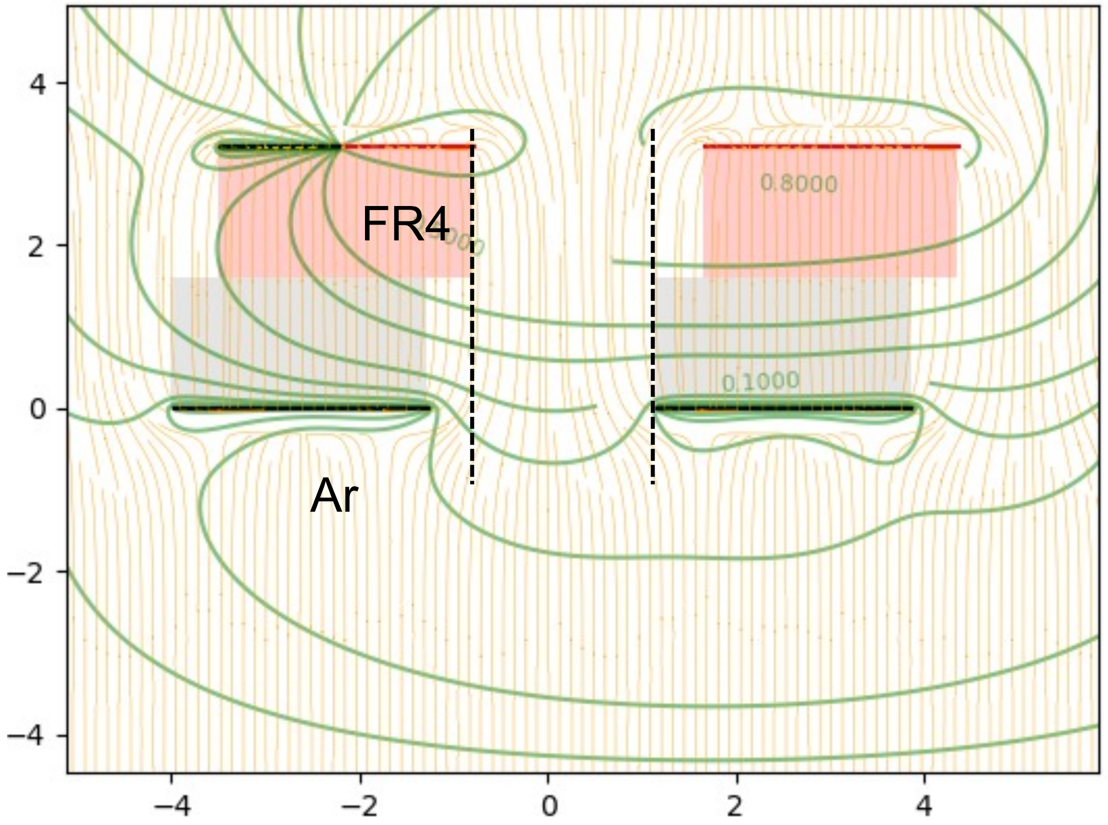
Field with hole shifted

- Covering exact area given by:

$$\mathcal{A}_{analytic} = 2R^2\left[\arccos x + 2x\sqrt{1-x^2}\right]$$

with $x = \frac{\sqrt{R^2-(x_0/2)^2}}{R}$, x_0: shifting, $R = 1.2\ mm$

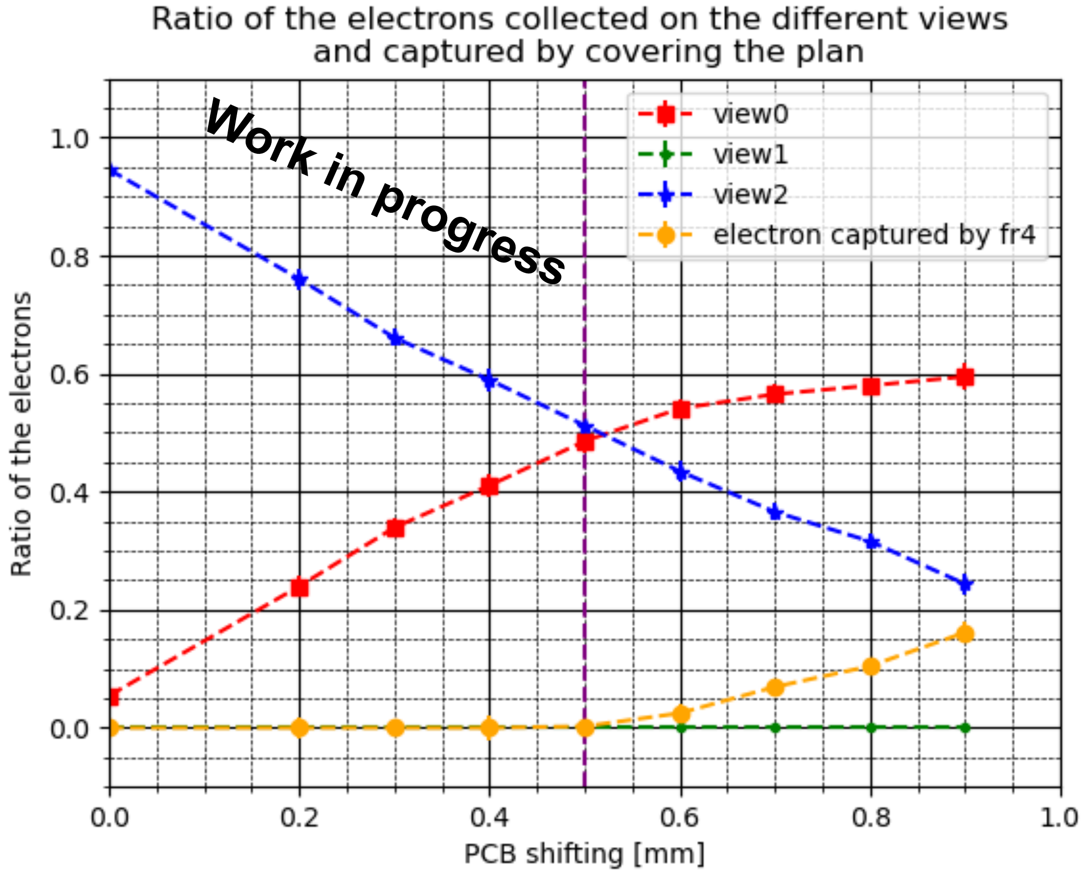


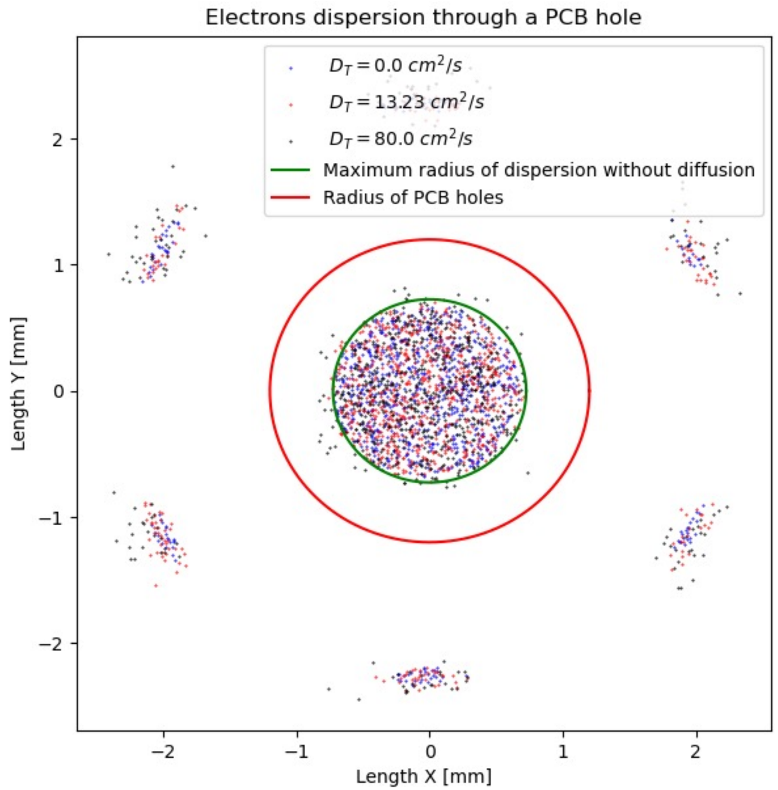


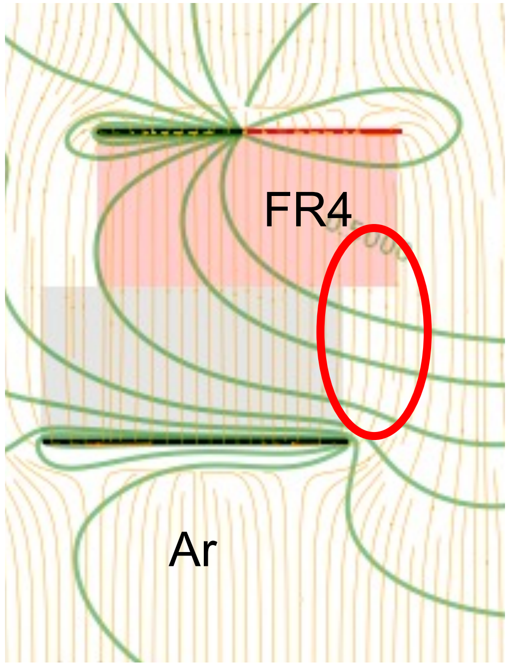
$x_0 = 0.5\ mm$

Covering area : 52 %

CRP6 transparency (simulation)







→ Have to implement the dielectric constant for the FR4

- Increased charge loss
- Charging-up effect can be explain that if the electrons are captured by the FR4.
- i.e. **shifting > 0.5 mm**
- But Luis has **measured a shifting max ~ 0.35 mm**

➢ Even with diffusion: electron dispersion through a hole is insufficient

➢ too focused to explain charging-up
→ **Electron diffusion**

Summary

➢ **Work done:**

- Numerical simulation conception to understand the formation of induction signals of all views

- Coldbox's data extraction → **simulation is good agreement with this**

➢ **What's next ?**

- Keep working on the electron diffusion and the impact on the loss charge

  - Same study with longitudinal diffusion
  - Implement the drift field dependance → $D_L(\overrightarrow{E_D}, T)$, $D_T(\overrightarrow{E_D}, T)$

- Implement the dielectric matrix to discriminate the change of medium (FR4 into Ar and vice versa)

  - Solving Generalized Poisson's equation in 3D:

$$\vec{\nabla}.(\varepsilon_r\left(\vec{\nabla}\phi(x,y,z)\right) = 0 \text{ (no source)}$$

- Extend the simulation in a bigger volume → track angle studies and position in the TPC (boundary conditions)