DRD1 Collaboration Meeting

Capacitive-Sharing Pixel Micromegas Detector

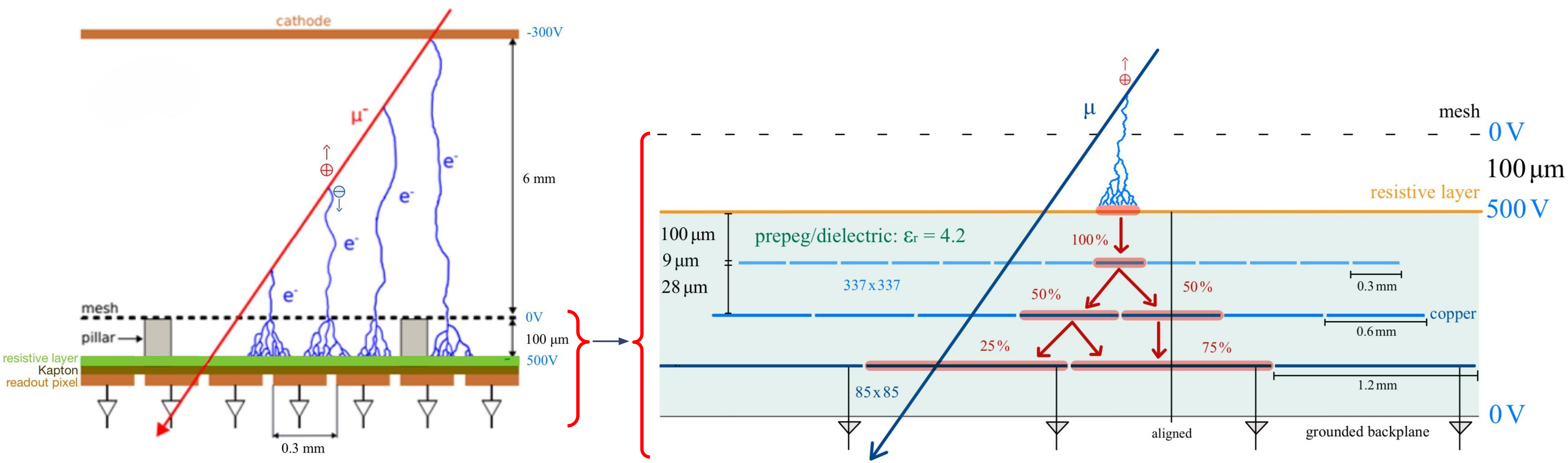
MAX MENZER
LMU: AG BIEBEL

8 October, 2025

Signal Readout - Capacitive-Sharing

<u>Goal: Reduce the number of readout channels</u>

- Multiple layers of pixels that double in size
  → no electrical contact (dielectric)
- Readout only on the biggest pixels (readout pixels)

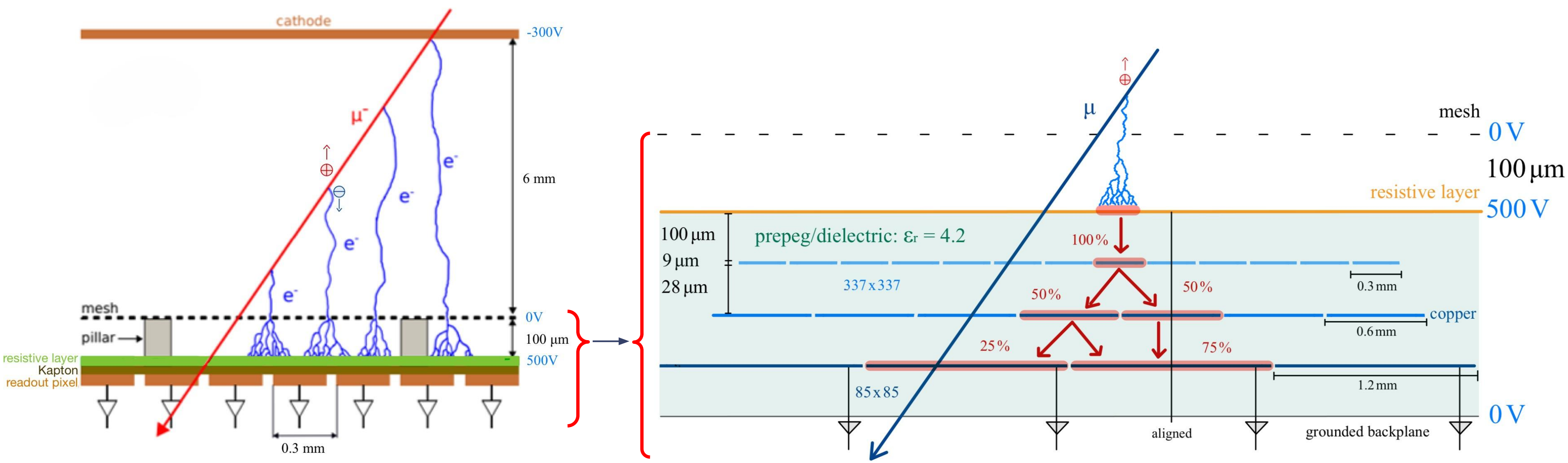


Signal Readout - Capacitive-Sharing

<u>Goal: Reduce the number of readout channels</u>

- Multiple layers of pixels that double in size
  → no electrical contact (dielectric)
- Readout only on the biggest pixels (readout pixels)

3 layers: reduce readout pixels by factor ~ 1/16:
10 cm x 10 cm detector
113 500 → 7225



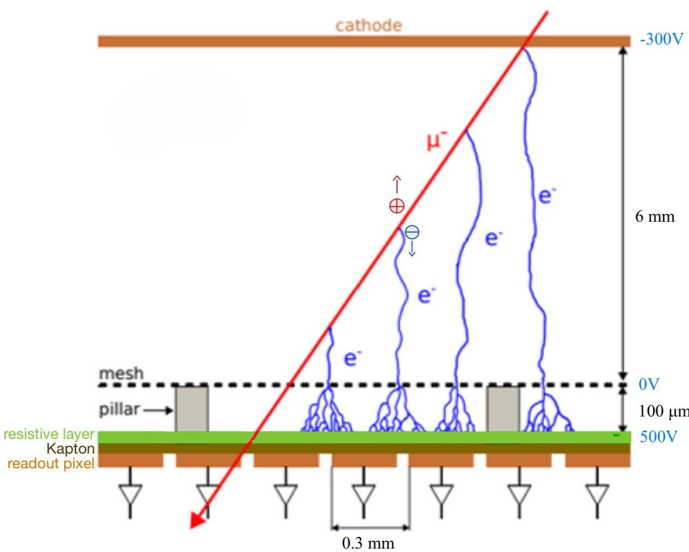
Signal Readout - Capacitive-Sharing

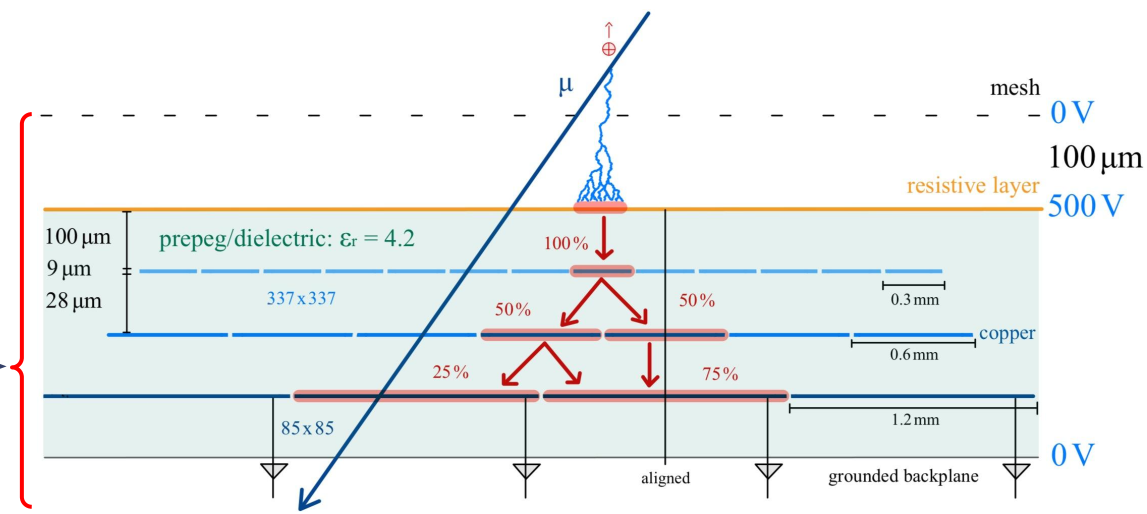
<u>Goal: Reduce the number of readout channels</u>

- Multiple layers of pixels that double in size
  → no electrical contact (dielectric)
- Readout only on the biggest pixels (readout pixels)

3 layers: reduce readout pixels by factor ~ 1/16:
10 cm x 10 cm detector
113 500 → 7225

Actual detector requires only 170 channels through a grid readout



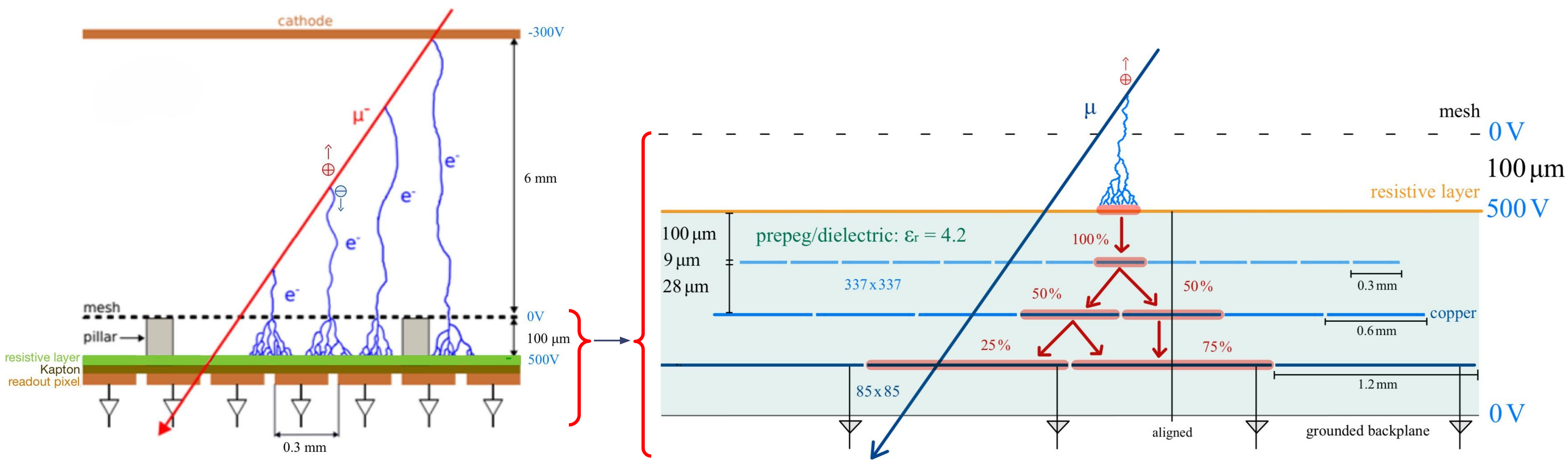


Signal Readout - Capacitive-Sharing

<u>Goal: Reduce the number of readout channels</u>

- Multiple layers of pixels that double in size
  → no electrical contact (dielectric)
- Readout only on the biggest pixels (readout pixels)
- Capacitive-Sharing allows the signal to travel downwards and split
- Unique readout for each position

3 layers: reduce readout pixels by factor ~ 1/16:
10 cm x 10 cm detector
113 500 → 7225



Signal Readout - Capacitive-Sharing

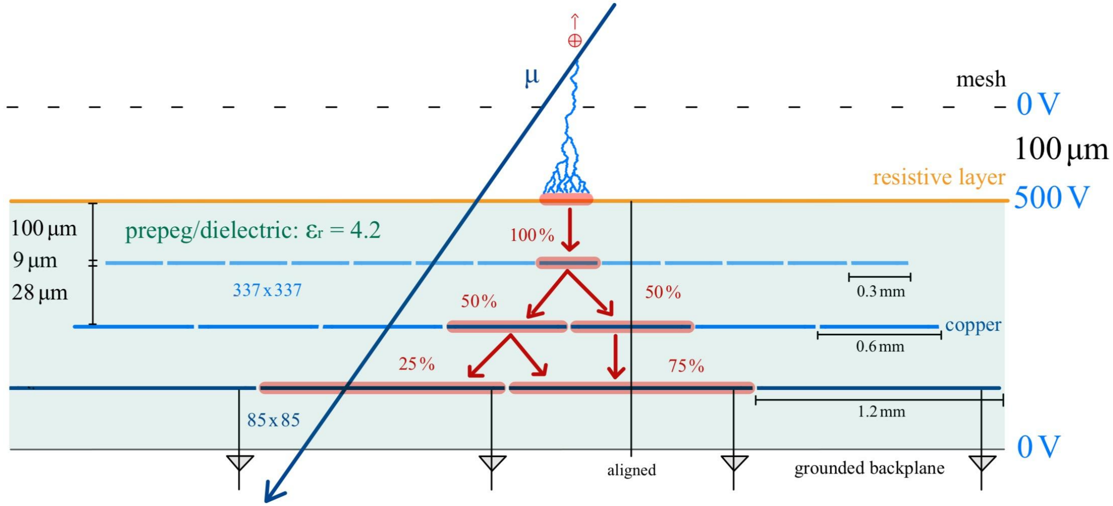
Goal: Reduce the number of readout channels

- Multiple layers of pixels that double in size
  → no electrical contact (dielectric)
- Readout only on the biggest pixels (readout pixels)
- Capacitive-Sharing allows the signal to travel downwards and split
- Unique readout for each position

3 layers: reduce readout pixels by factor ~ 1/16:
10 cm x 10 cm detector
113 500 → 7225

weighted arithmetic mean
→ resolution in the order of the smallest pixels

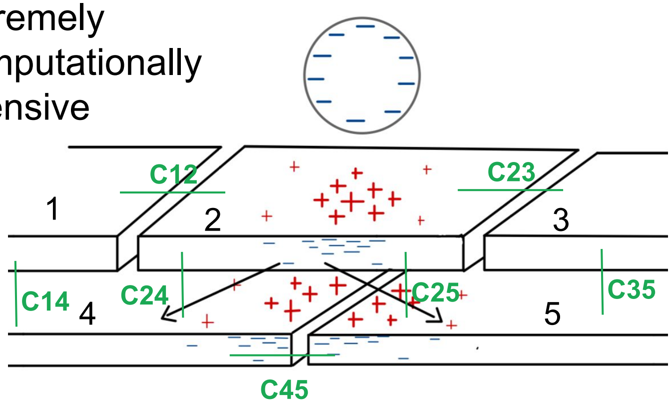
$$x_{rec} = \frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} w_i}$$

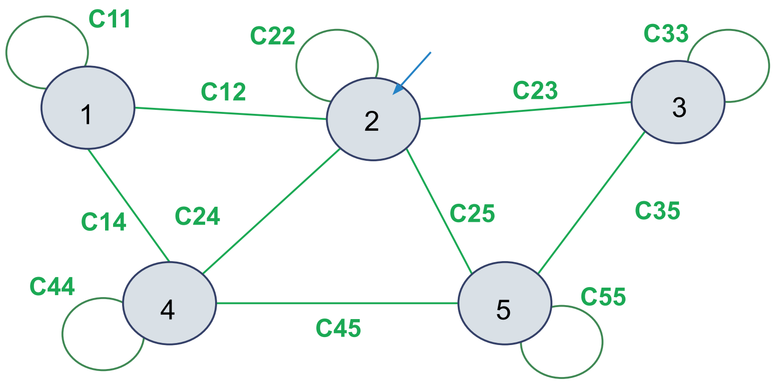


Two Theories for Capacitive-Sharing

Equivalent Circuit	Ramo-Shockley Theorem
• capacitances can be calculated between each pair of pixels • an equivalent circuit can replicate the detector • a signal can be injected (pixel 2) and its propagation observed	

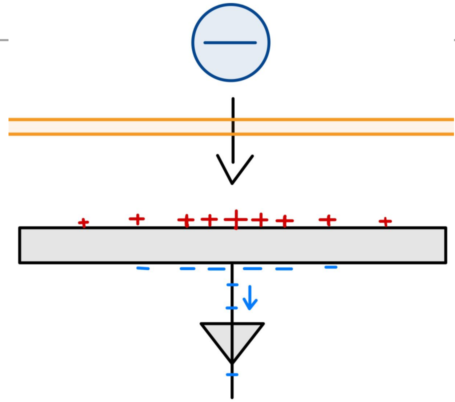
extremely computationally intensive





Two Theories for Capacitive-Sharing

Equivalent Circuit	Ramo-Shockley Theorem
• capacitances can be calculated between each pair of pixels • an equivalent circuit can replicate the detector • a signal can be injected (pixel 2) and its propagation observed	• a moving charge pushes charge carriers into the readout • weighting field is a mathematical concept and a non real electric field • ground all electrodes except electrode j, the one under consideration (1V)



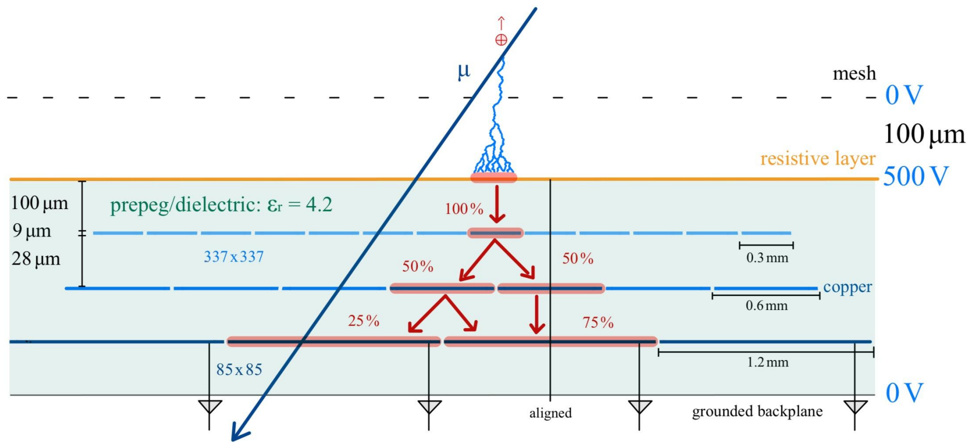
$$i_j(t) = -q\mathbf{v}(t)\mathbf{E}(\mathbf{x}(t))_{w,j}$$

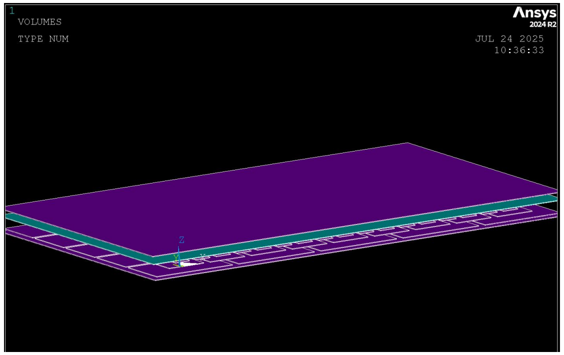
Ramo Shockley Theorem

(Notes Djunes Janssens [1])

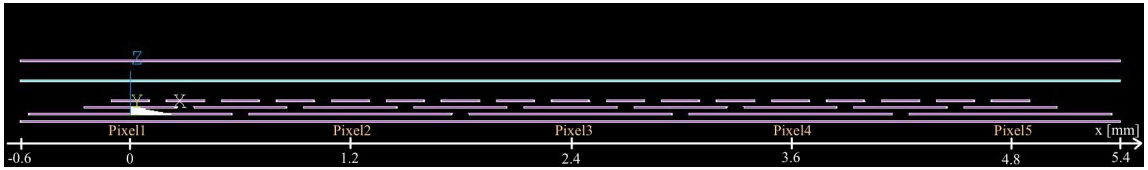
Setup for the ANSYS Simulation

<u>Focus on a section of 5x5 readout pixels</u>

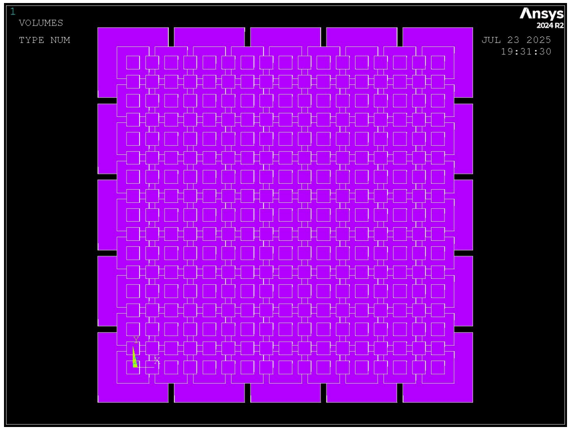




detector structure with mesh, dlc, pixels and backplane



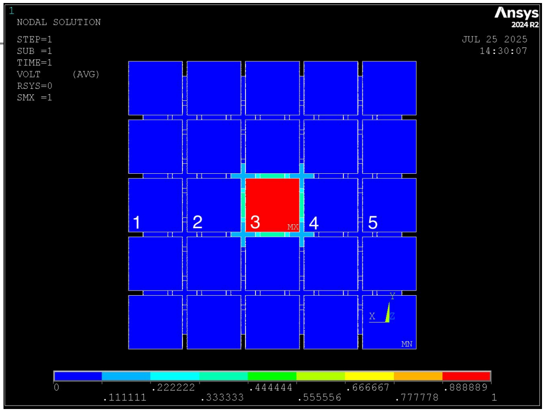
cross section with copper parts purple and dlc cyan



top view pixels only

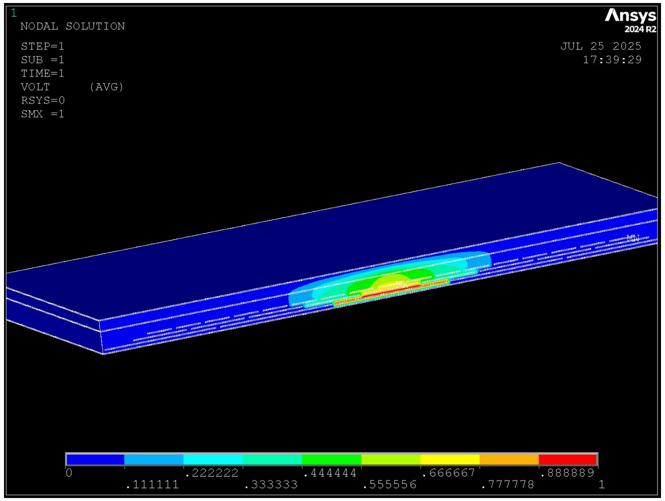
$$i_j(t) = -q\mathbf{v}(t)\mathbf{E}(\mathbf{x}(t))_{w,j}$$

Weighting field for j=3

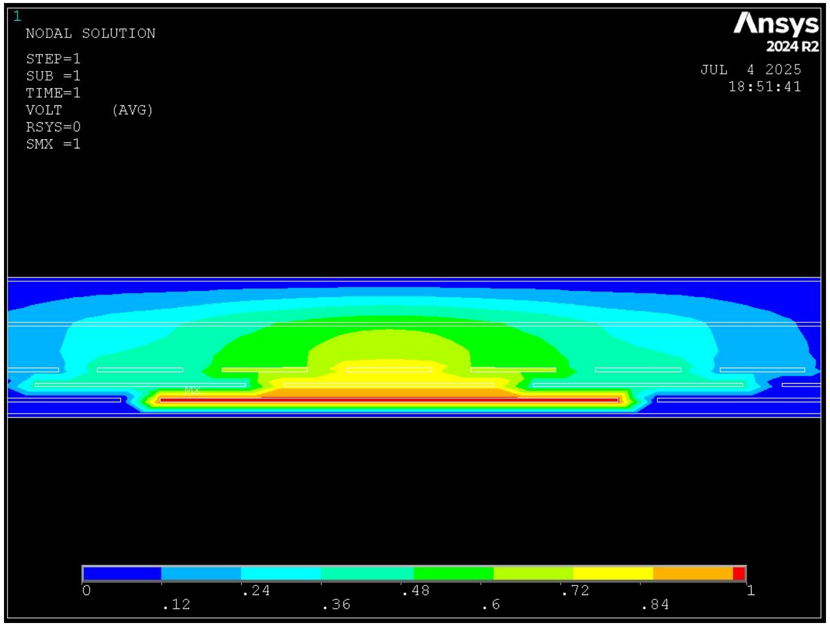


Electric potential with boundary conditions:

- Electrode/readout pixel j is set to unit potential (1V - red)
- All other electrodes are grounded
- The other pixel layers are floating



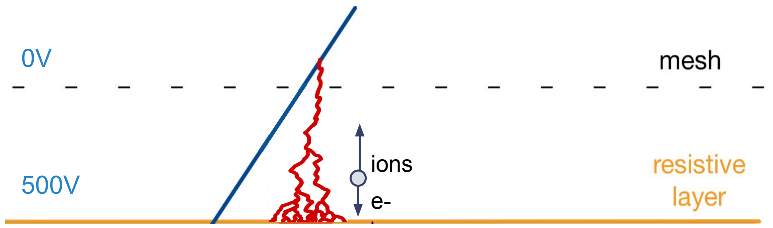
cross section along x: Readout pixels 1 to 5 visible



$$i_j(t) = -q\mathbf{v}(t)\mathbf{E}(\mathbf{x}(t))_{w,j}$$

Path integral Approach

- Electrons drift to the dlc, ions to the mesh
- Total induced charge is the integrated Ramo-Shockley current



$$Q_j = Q_{j,e} + Q_{j,i} = \int_0^{t_e} i_{j,e}(t)\, dt + \int_0^{t_i} i_{j,i}(t)\, dt$$

Electron drift gives a path integral

$$Q_{j,e} = -q \int_0^{t_e} \mathbf{v}(t)\ \mathbf{E}(\mathbf{x}(t))_w\, dt = -q \int_0^{t_e} \frac{d\mathbf{x}(t)}{dt} \nabla\phi(\mathbf{x}(t))_w\, dt = -q \int_0^{t_e} \frac{d\phi(\mathbf{x}(t))_w}{dt}\, dt$$

$$= -e\left(\phi(\mathbf{x}_{dlc})_w - \phi(\mathbf{x}_0)_w\right)$$

Add ion contribution to get total charge on readout pixel/electrode j

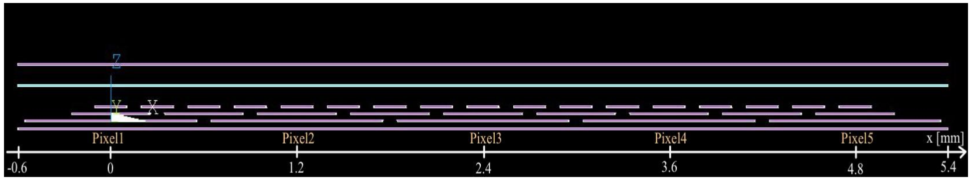
$$Q_j = -e\left(\phi(\mathbf{x}_{dlc})_w - \phi(\mathbf{x}_{mesh})\right) \sim \phi(\mathbf{x}_{dlc})$$

$$Q_j \sim \phi(\mathbf{x}_{dlc})$$

Path integral Approximation

Use charge Q_i as weighting w_i for reconstruction in one dimension

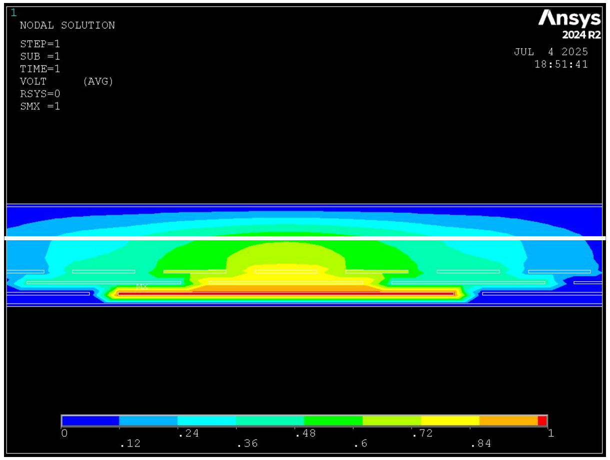
$$x_{rec} = \frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} w_i}$$



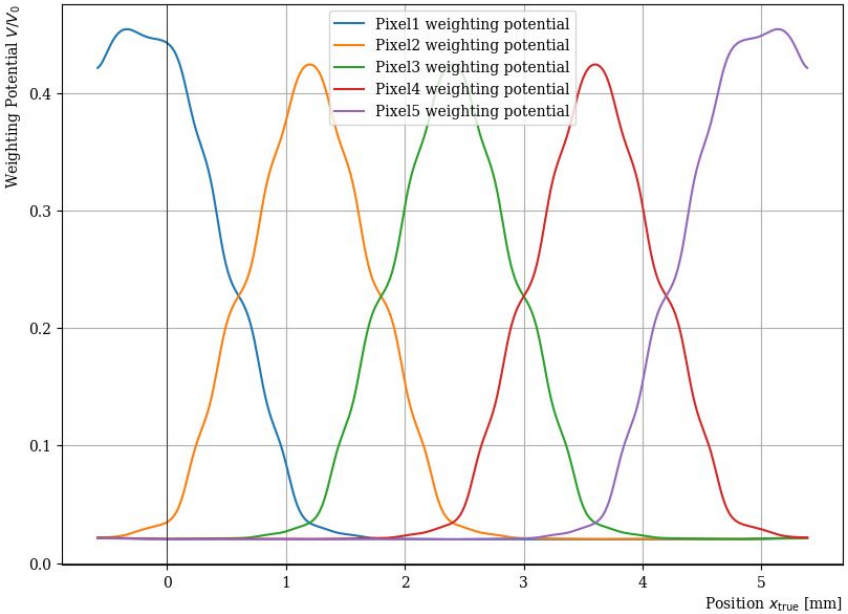
setup: cross section along x for reconstruction

Project weighting potential at the dlc onto the y axis

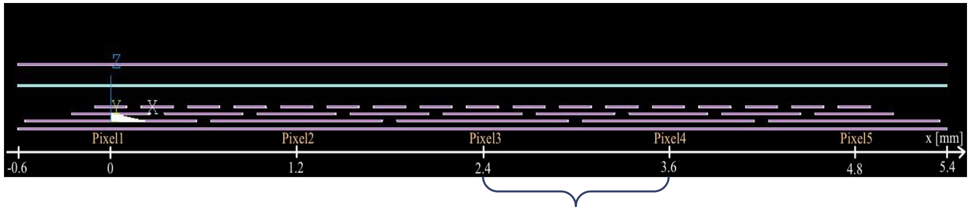
dlc



pixel3 → green



Reconstruction

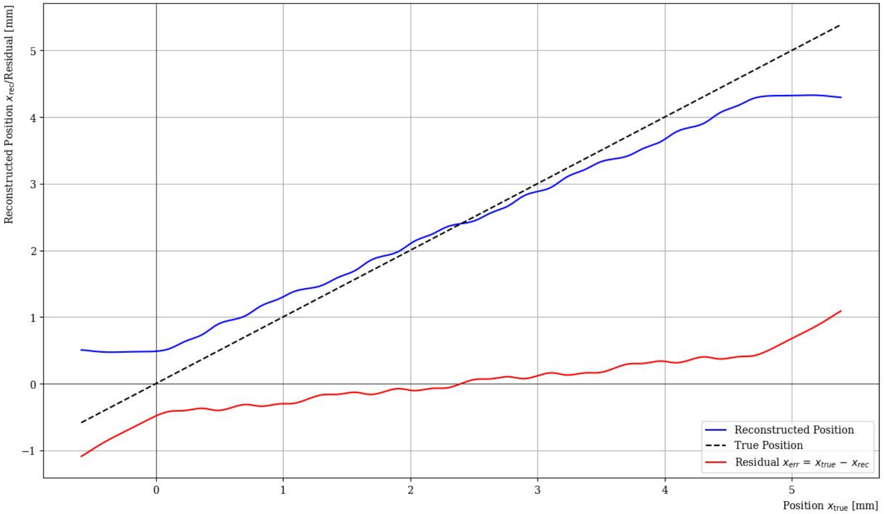


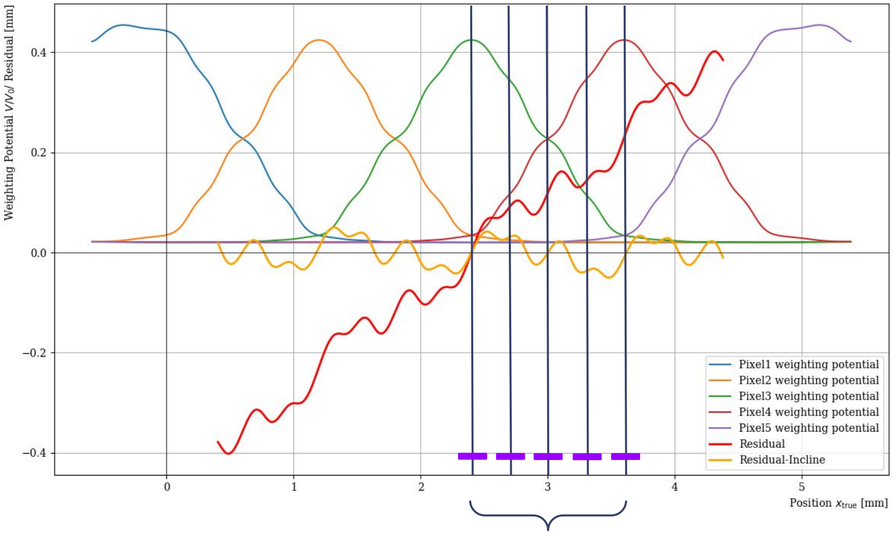
periodicity of the readout pixels or 4 smallest pixels

<u>"Move" test charge from left to right:</u>

Residual shows an inclination and oscillation

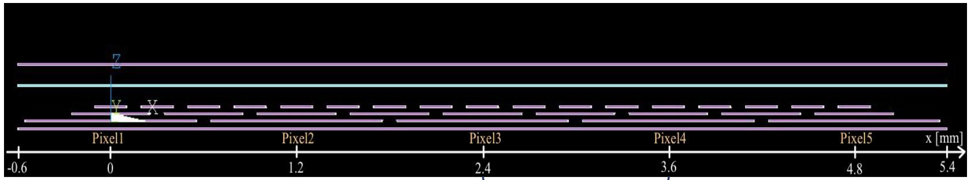
- Inclination results from limited size of the model (5x5)
- <u>Oscillation from plateaus in the weighting potential</u>





periodicity of the readout pixels or 4 smallest pixels

Reconstruction

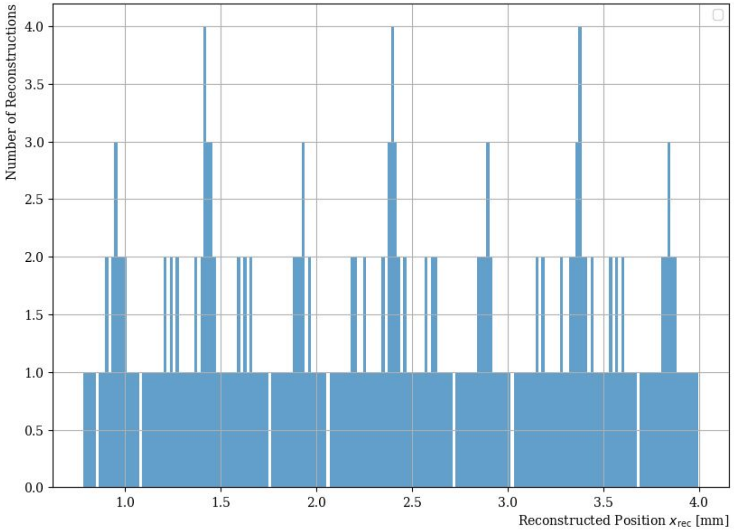


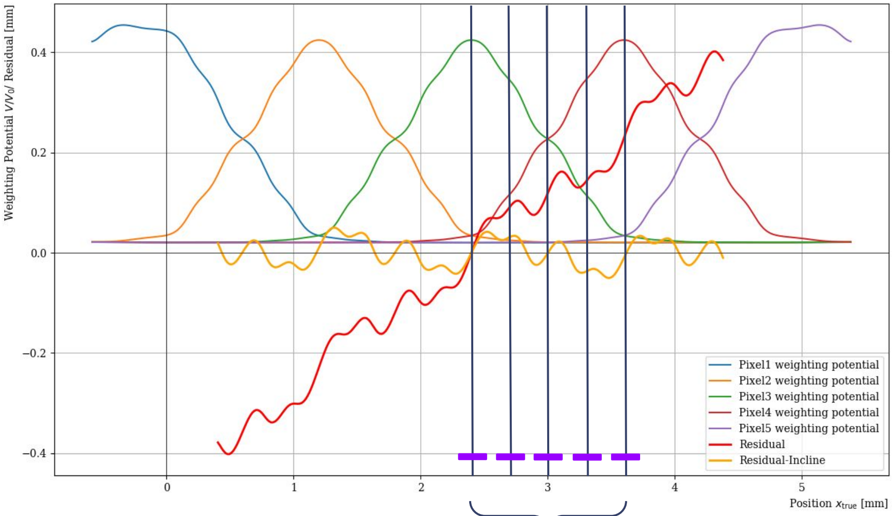
periodicity of the readout pixels or 4 smallest pixels

<u>"Move" test charge from left to right:</u>

Residual shows an inclination and oscillation

- Inclination results from limited size of the model (5x5)
- <u>Oscillation from plateaus in the weighting potential</u>

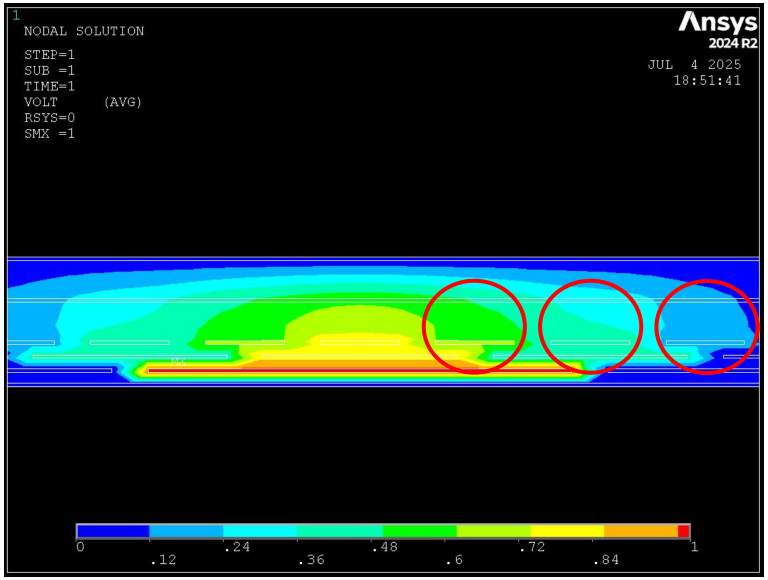


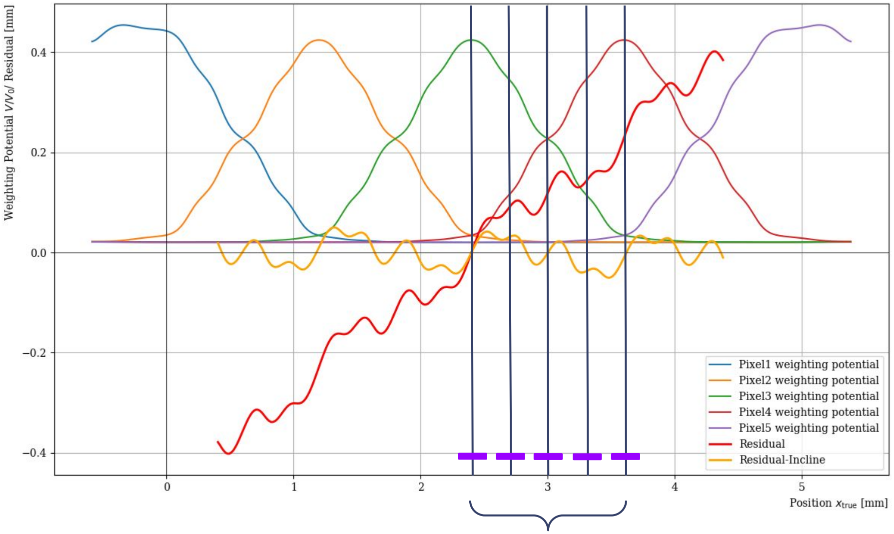


periodicity of the readout pixels or 4 smallest pixels

Oscillations of the Residual

- weighting field **E(x)** (electric field) forces floating pixels to carry a constant potential
- expands **E(x)** but also propagates upwards (plateaus)

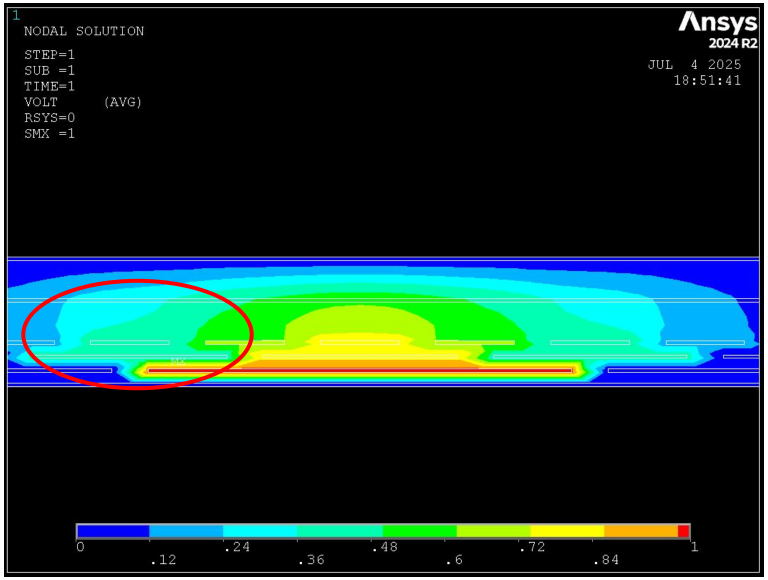


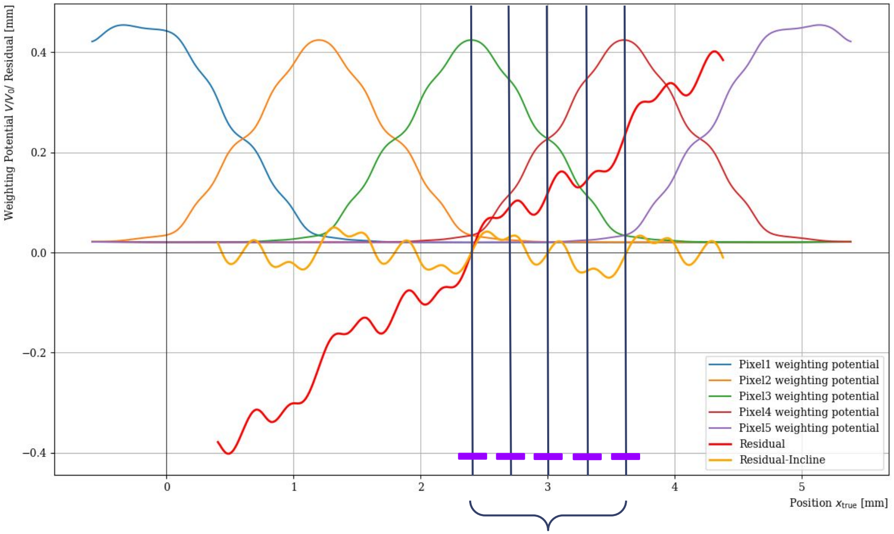


periodicity of the readout pixels or 4 smallest pixels

Oscillations of the Residual

- weighting field **E**(**x**) (electric field) forces floating pixels to carry a constant potential
- expands **E**(**x**) but also propagates upwards (plateaus)
- more prominent plateaus if pixel layers are aligned (substructure)
- substructure can be reduced by smaller pixel gap (notes Djunes)





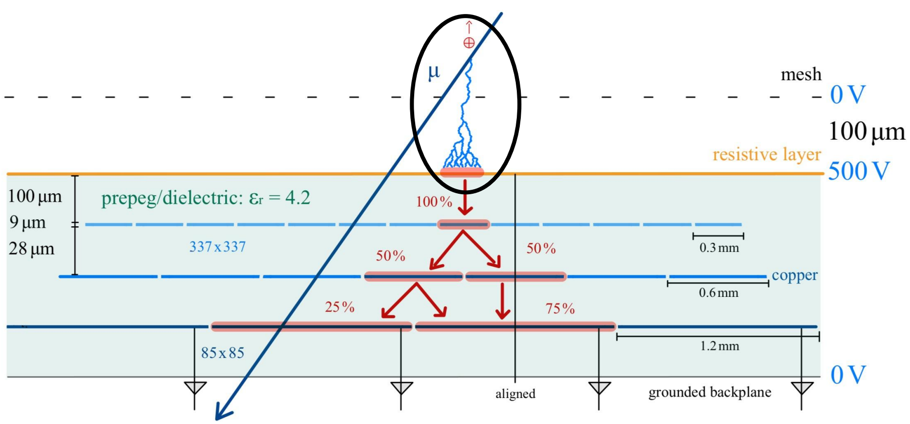
periodicity of the readout pixels or 4 smallest pixels

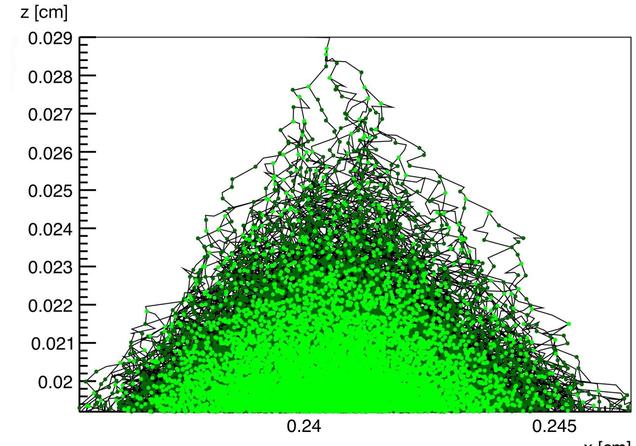
Microscopic Simulation - Garfield++

- Simulate detailed electron avalanche $\mathbf{v}(t)$
- Import weighting field $\mathbf{E}(\mathbf{x}(t))$ from Ansys

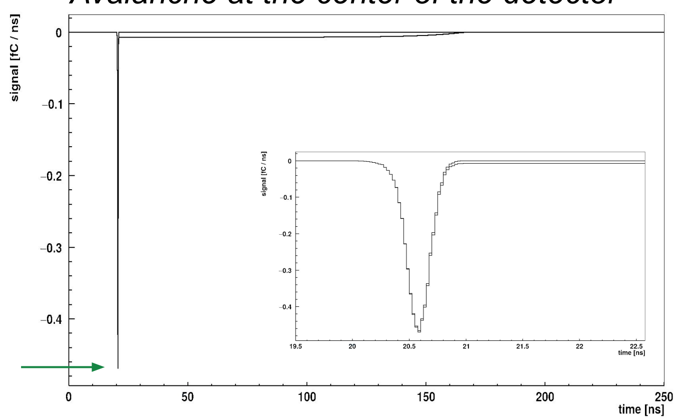
Garfield can compute the current $i_j(t)$ over time using the Ramo-Shockley Theorem

$$i_j(t) = -q\mathbf{v}(t)\mathbf{E}(\mathbf{x}(t))_{w,j}$$





Avalanche at the center of the detector



Current from e-avalanche. Intense and short electron pulse with long ion tail

Microscopic Simulation - Garfield++

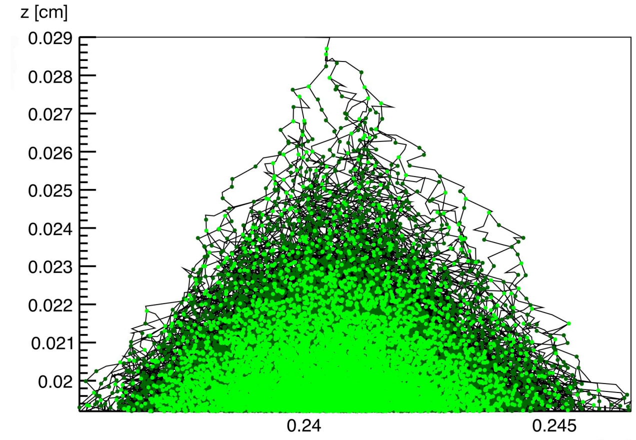
- Simulate detailed electron avalanche **v**(t)
- Import weighting field **E**(**x**(t)) from Ansys

Garfield can compute the current $i_j(t)$ over time using the Ramo-Shockley Theorem

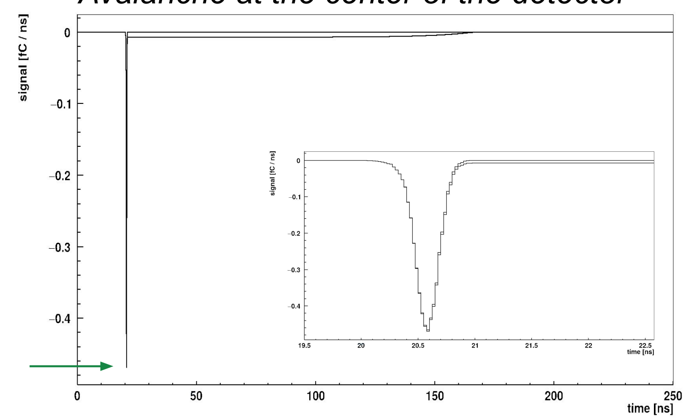
$$i_j(t) = -q\mathbf{v}(t)\mathbf{E}(\mathbf{x}(t))_{w,j}$$

Maximum current $i_j(t)$ is used as weighting w_i

$$x_{rec} = \frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} w_i}$$



Avalanche at the center of the detector

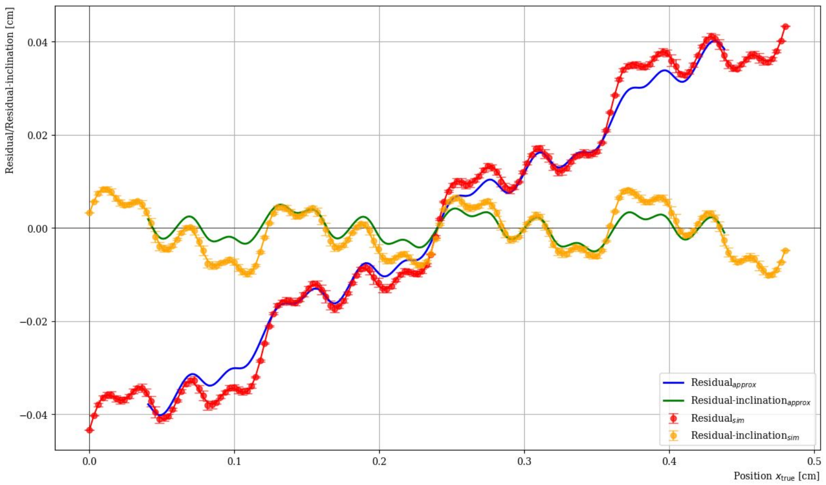


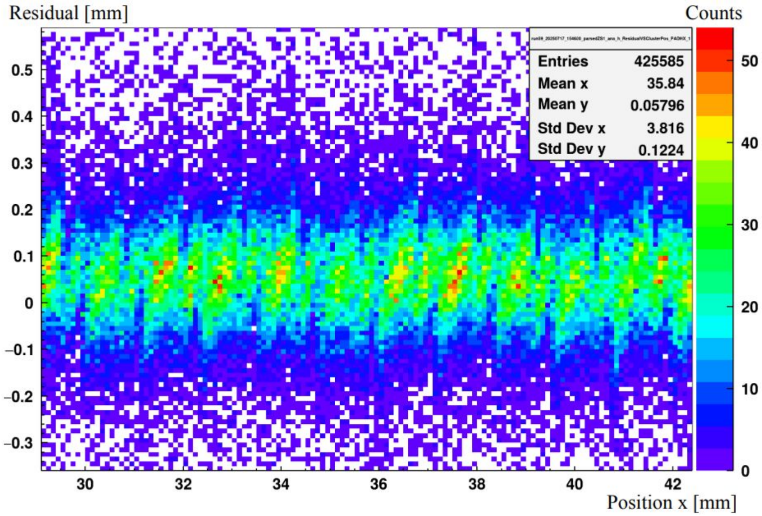
Current from e-avalanche. Intense and short electron pulse with long ion tail

Comparison and Measurement

Path integral and avalanche simulation exhibit the same behaviour as expected

Measurements H4 beamtime (CERN SPS 2025) show the same oscillations with substructure



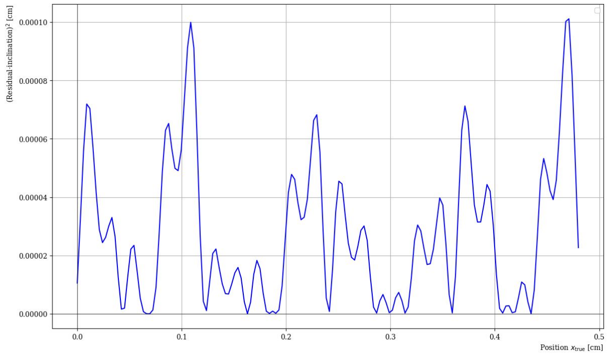


Comparison and Measurement

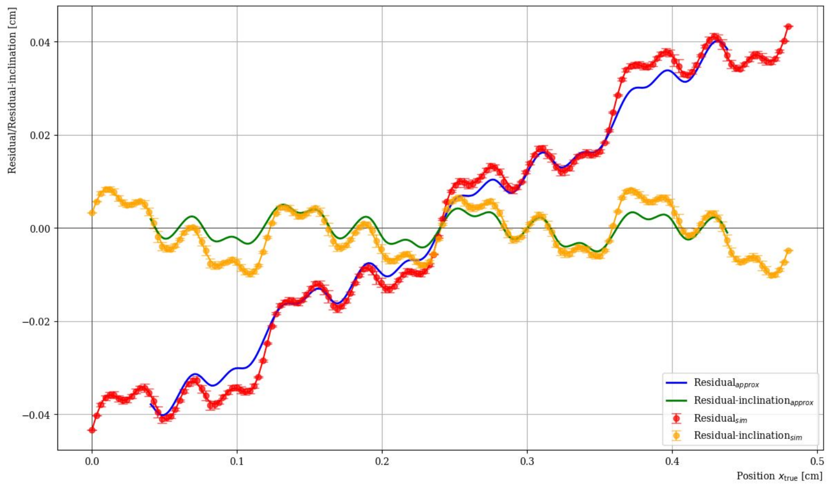
Path integral and avalanche simulation exhibit the same behaviour as expected

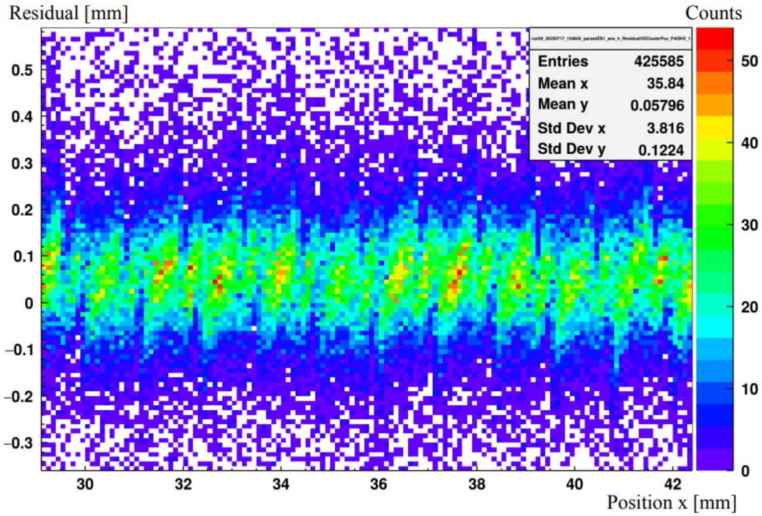
Measurements H4 beamtime (CERN SPS 2025) show the same oscillations with substructure

The resolution is comparable to a single readout of the smallest pixels

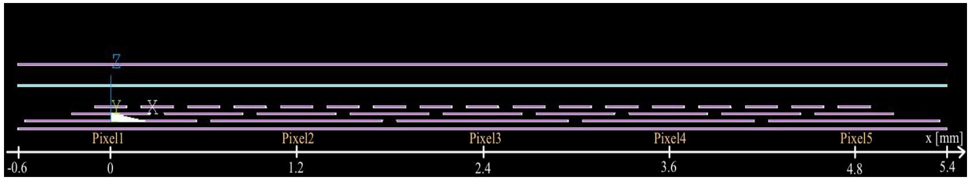


Estimated resolution using the Garfield++ simulation ~55µm

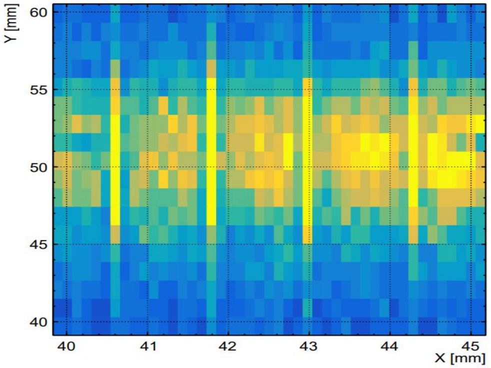




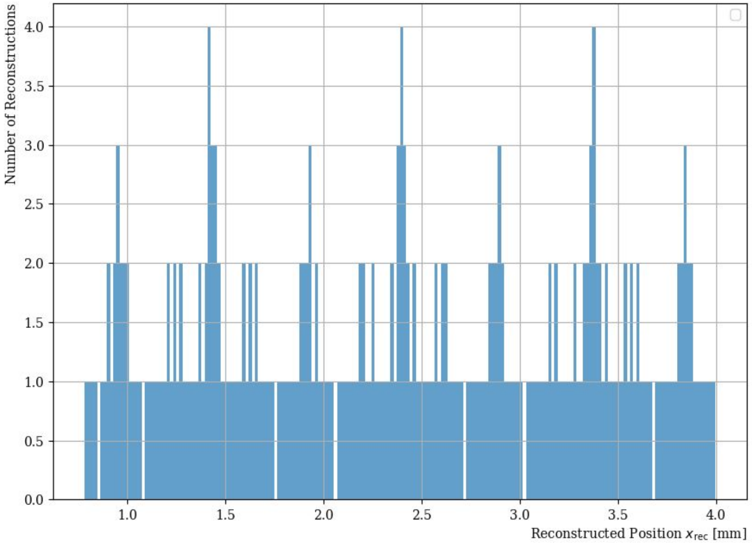
Reconstruction



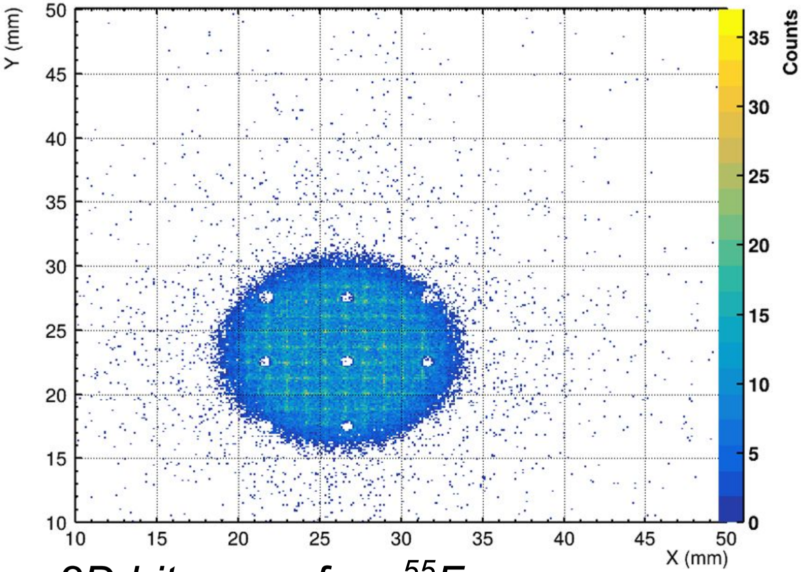
- Histogram of reconstructions and hit map show maxima in the center of the pixels
- Derivative of the residual also peaks there
- Simulation shows a slight deviation from the 1.2mm pitch (presumably limited model size)



Zoomed 1D hit map beam time



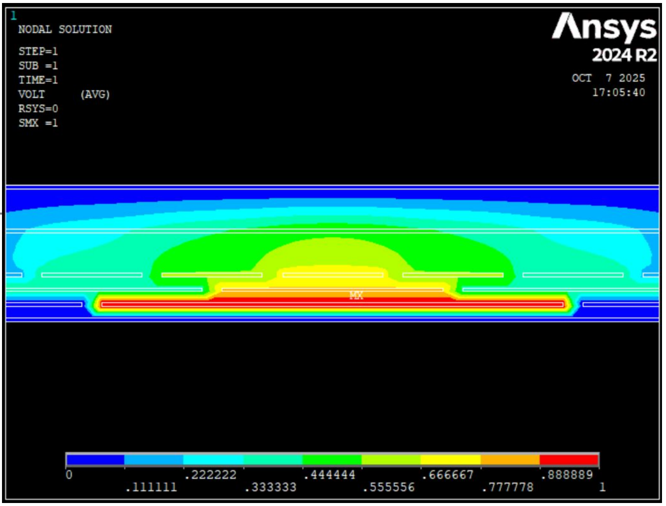
Histogram of reconstructions from simulation



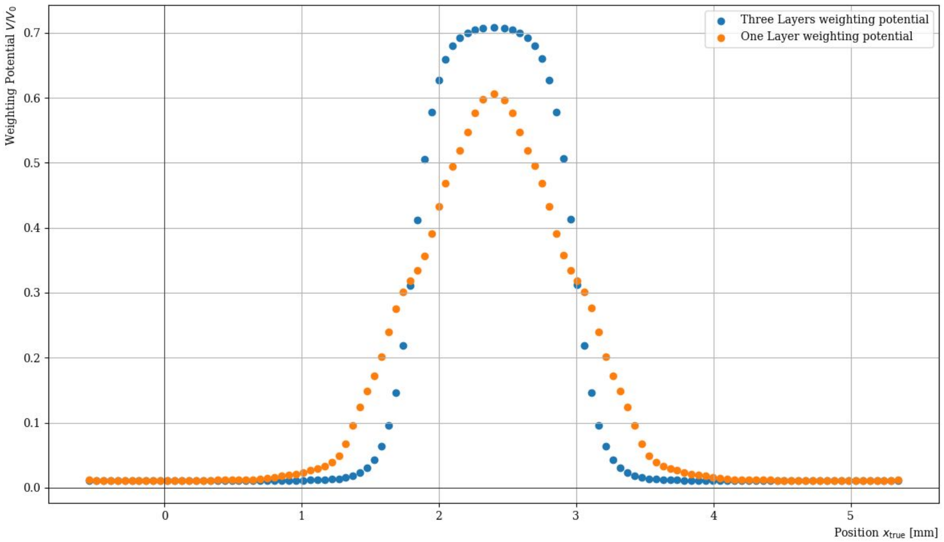
2D hit map of an ^{55}Fe source

Loss of Signal Intensity

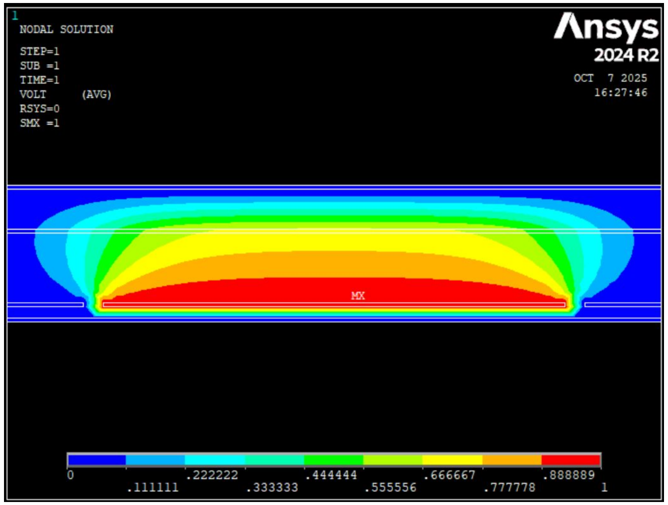
Pixel layers stretch and linearise the potential so we can use the weighted mean for reconstruction. Each layer stretches it further but also damps the signal more. Small plateaus and loss in intensity are the prize.



Weighting field with three pixel layers



Projection of weighting field at the dlc



weighting field without capacitive-sharing

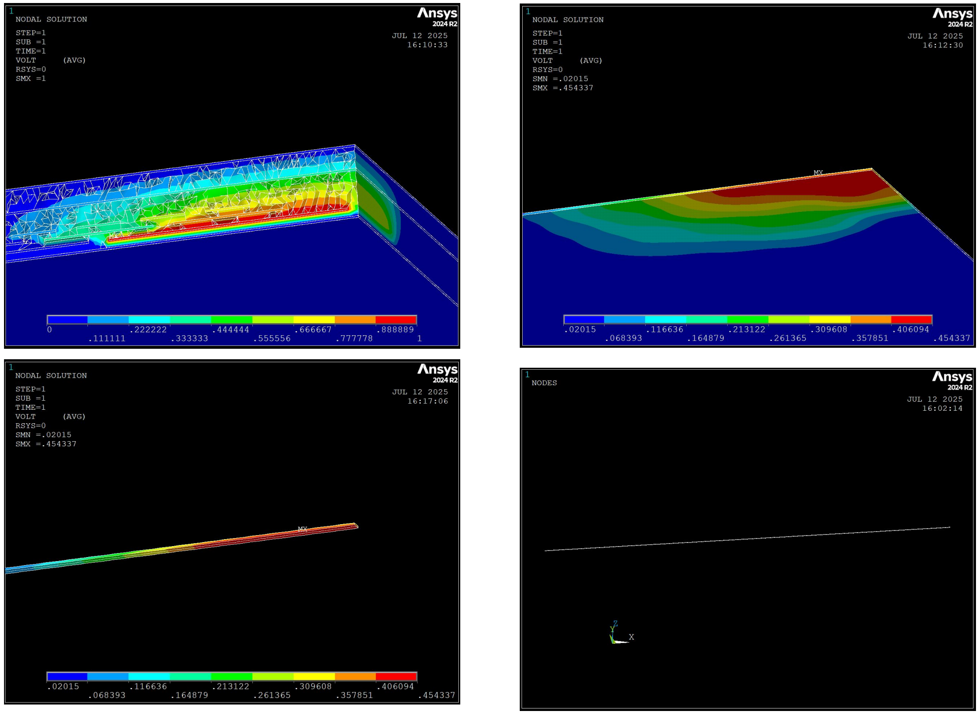
Backup

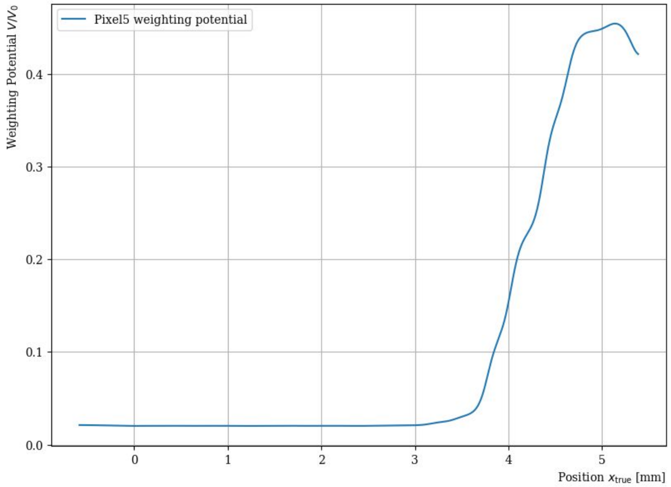
References for Capacitive Sharing

- [1] Unpublished notes and supporting ideas from Djunes Janssens (Ramo-Shockley Theorem)
- Original idea Performance of a resistive micro-well detector with capacitive-sharing strip anode readout - ScienceDirect
- Studies on capacitive sharing resistive Micromegas for Muon System at FCC-ee.pdf
- Bachelor Thesis Max Menzer 2025, supervised by Eshita Kumar bac25_mmenzer.pdf, Bachelor Theses - Elementary Particle Physics - LMU Munich

Path Integral Projection e.g. Pixel5

Weighting field in one dimension (x-axis) of pixel5 from Ansys

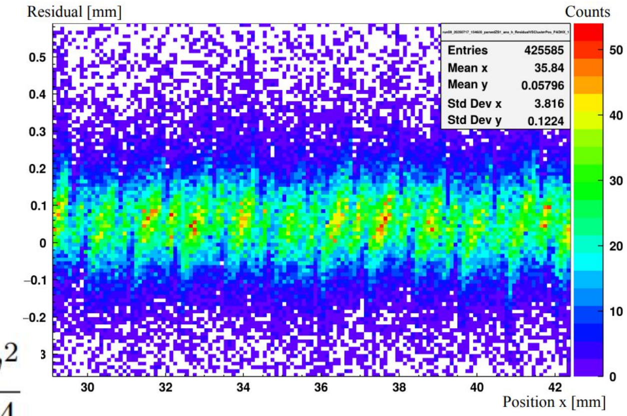




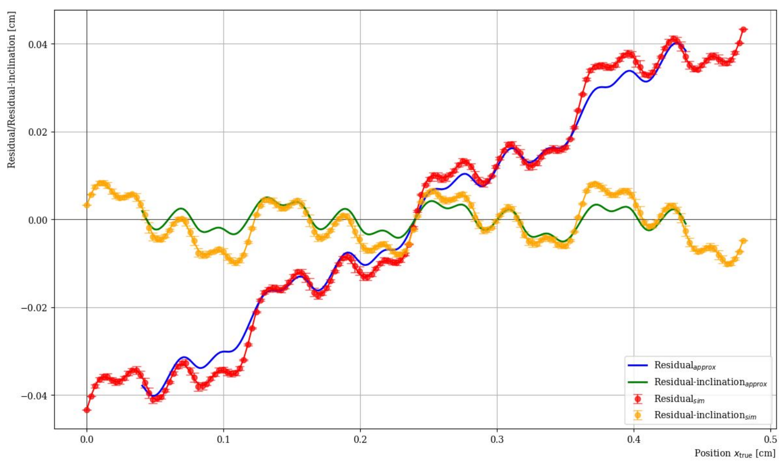
Comparison Residual

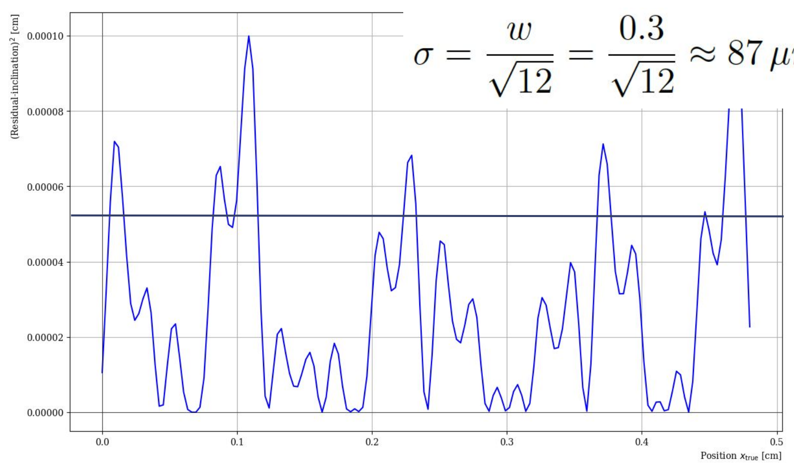
Using the residual (orange) to determine the resolution of the detector gives a limit of ~55µm

Shows that the resolution is even better than the classical readout without weighted mean



$$\sigma^2 = \frac{1}{w}\int_{-\frac{w}{2}}^{\frac{w}{2}} (x)^2\,dx = \frac{1}{w}\left[\frac{x^3}{3}\right]_{-\frac{w}{2}}^{\frac{w}{2}} = \frac{1}{w}\,\frac{(w/2)^3}{3} - \frac{(-w/2)^3}{3} = \frac{w^2}{24}$$



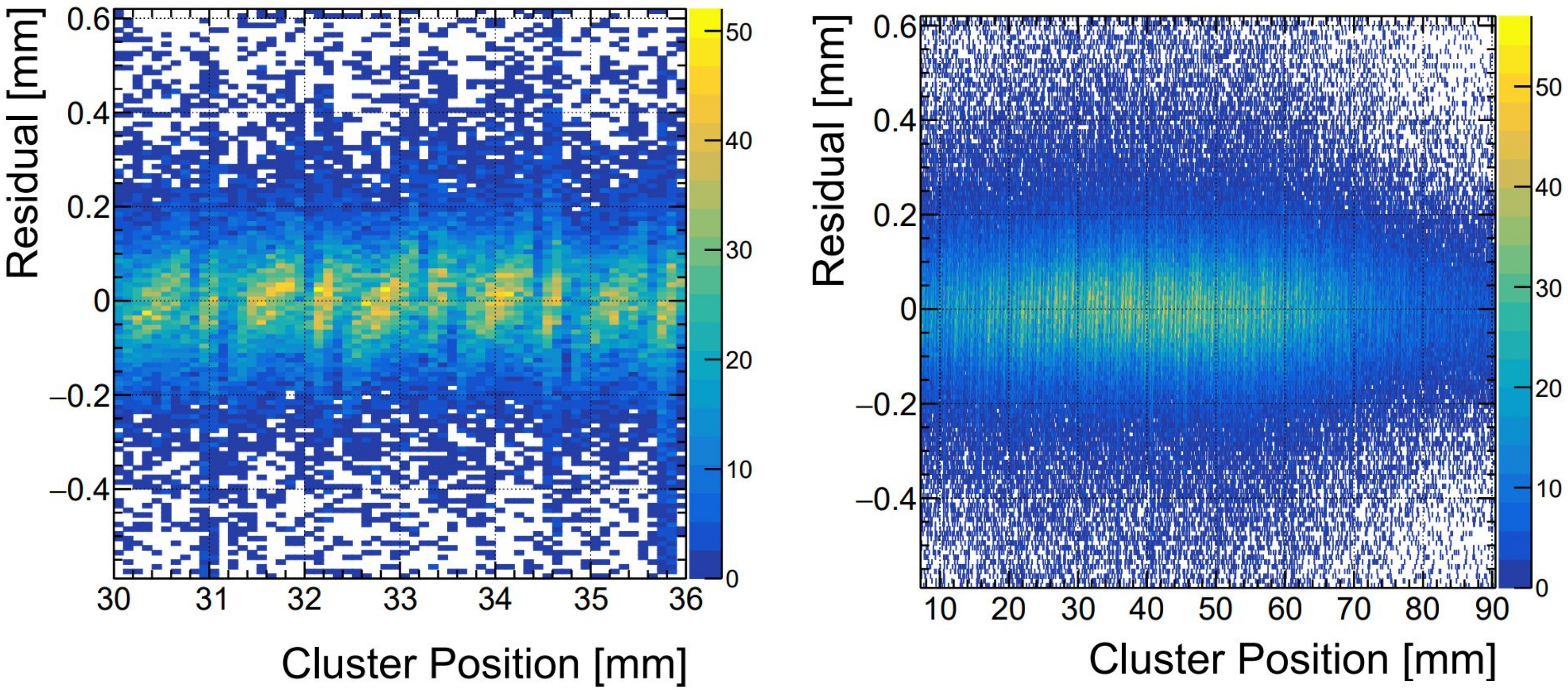


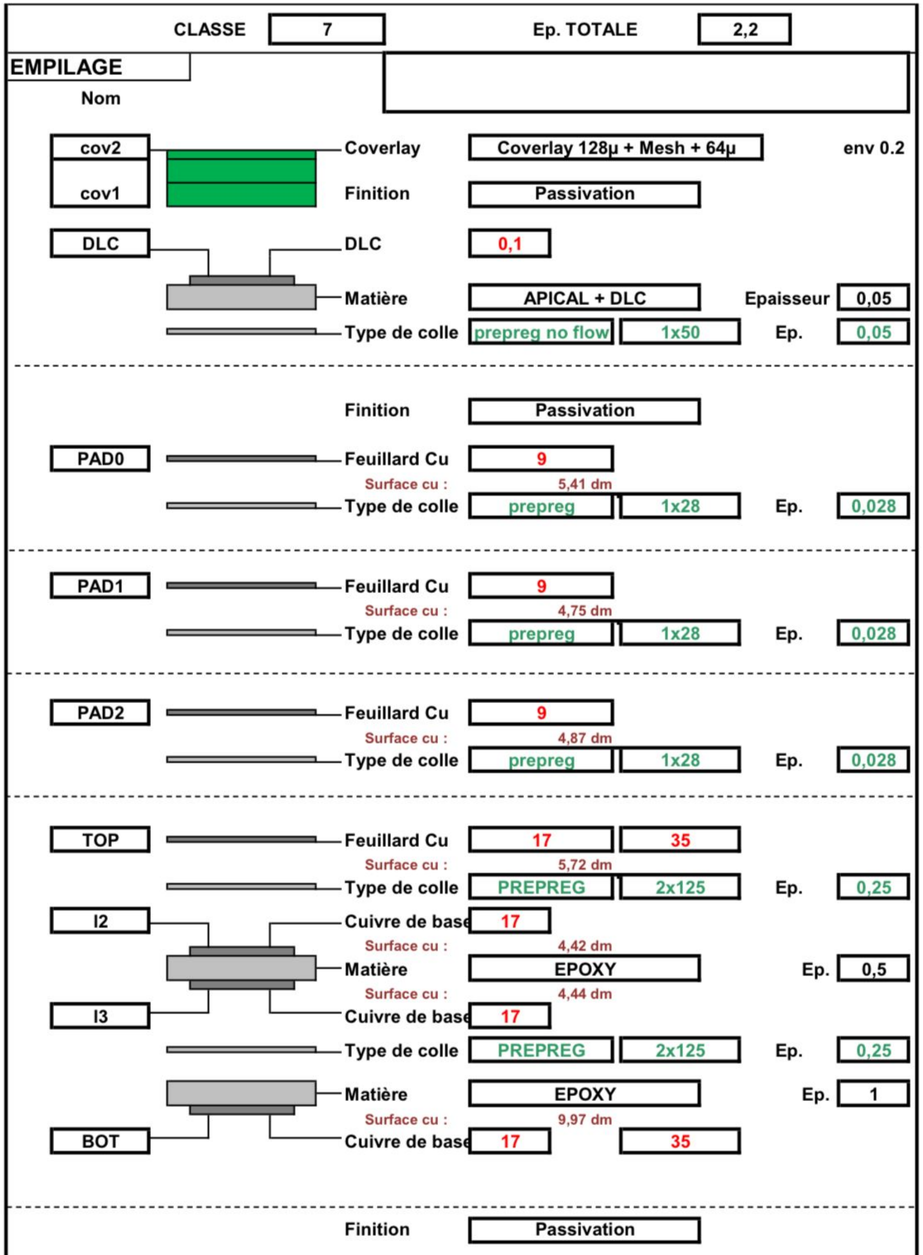
$$\sigma = \frac{w}{\sqrt{12}} = \frac{0.3}{\sqrt{12}} \approx 87\,\mu m$$

Squared residual (orange) for resolution

Additional Measurements H4 beamtime (CERN SPS25)

Measurements were carried out by Eshita Kumar and will be explained further tomorrow, Thu 09/10/25 11:45, DRD1





Stackup Three Layer Detector PADH used for measurements

MicroMegas (**Micro-Me**sh **Gas**eous Detector)

Goal: Position and Timing of particle passing through (e.g. μ)

1. Ionization and Drift region

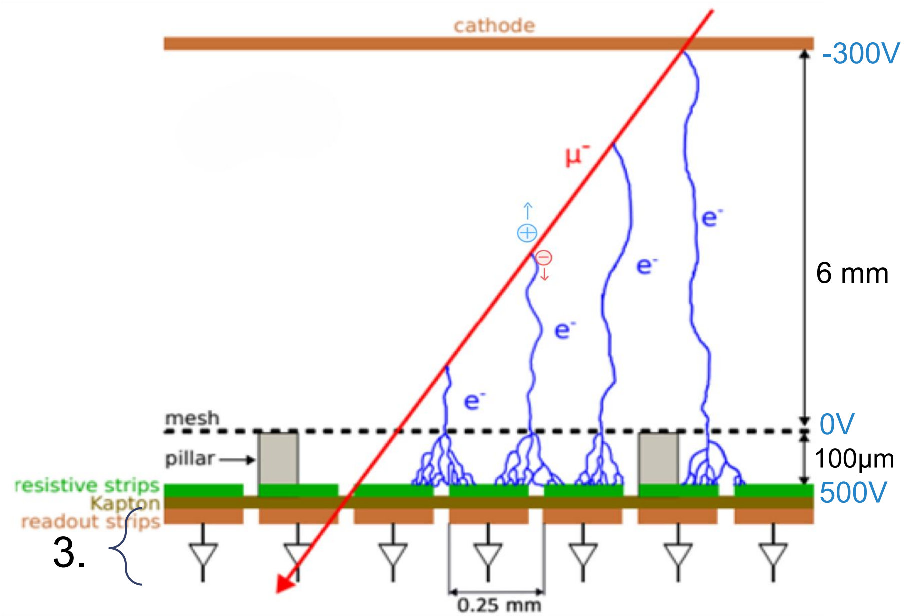
- Charged particle ionizes gas
- E-field prevents recombination of e− and ions
  → e− drift towards mesh

1. Amplification

- Strong E-field between mesh and readout
- e− avalanche
  → enough charge to detect

1. Readout

- Transform “charge cloud” into signal
- Easiest: direct readout



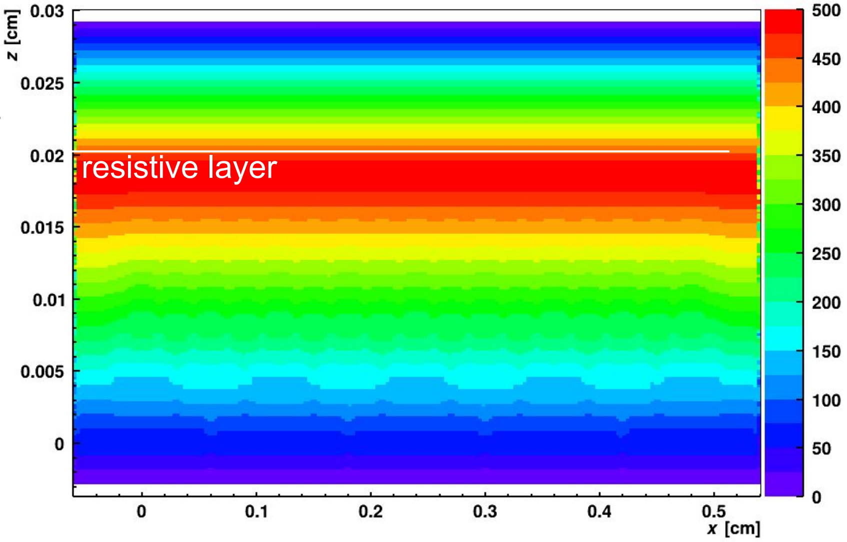
Problem:
- many readout channels (electronics)

10x10cm → ~ 150 000

Import fields to Garfield++

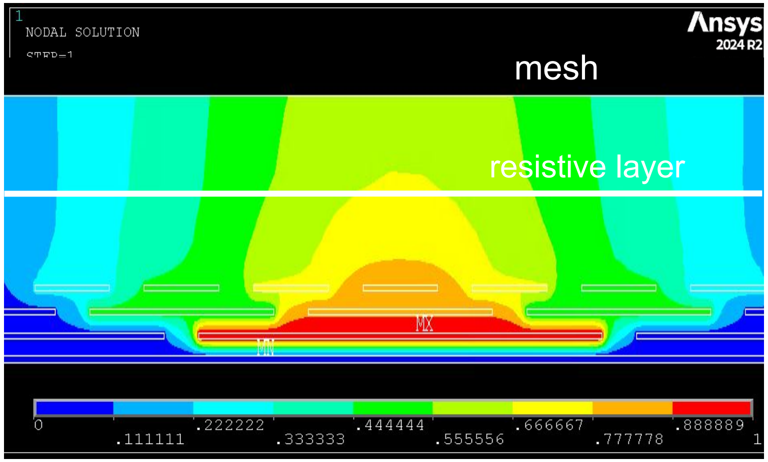
Garfield - electric field
(amplification)

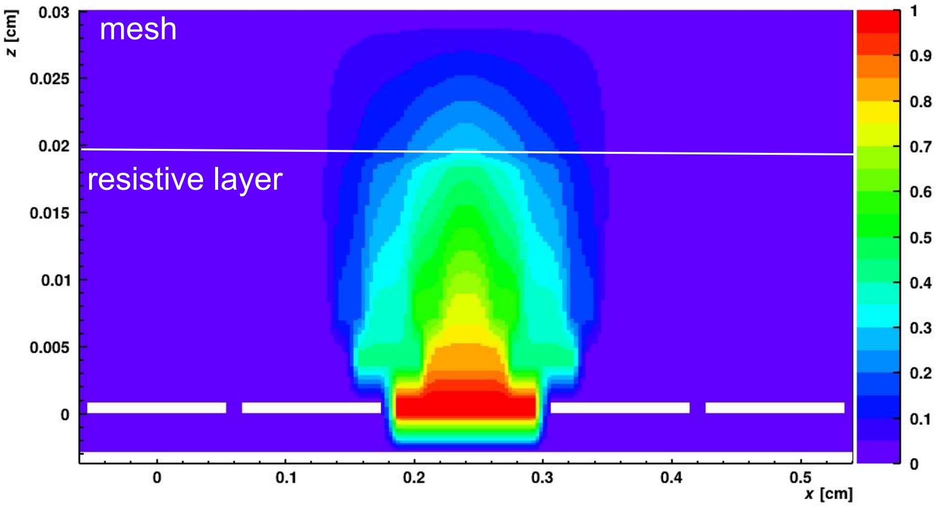
weighting field
(mathematical concept)



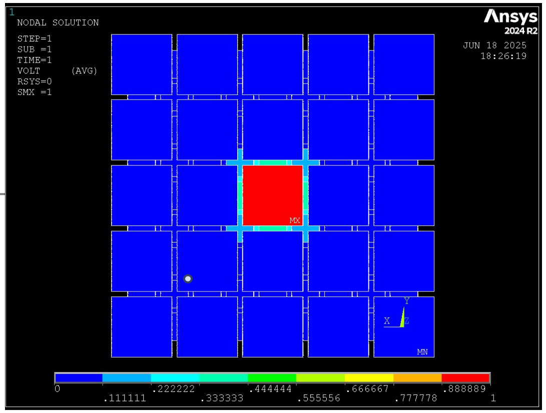
0.1 mm

0.1 mm





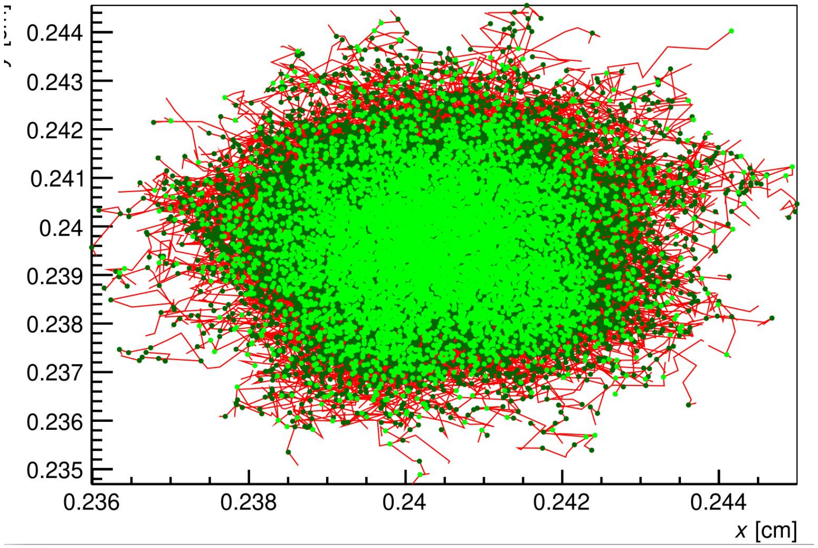
Electron avalanche



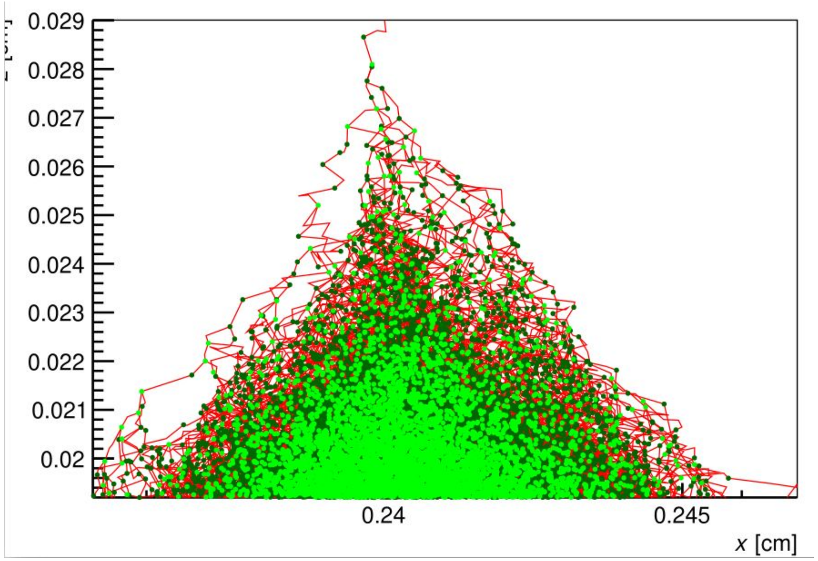
Centered above the center readout pixels

pixel size 1.2mm
avalanche spread 0.1mm

top view (xy-plane



side view (xz-plane)
cross section



Capacitive-Sharing Pixel Micromegas

Overview

- Micromegas Readout
- Capacitive-Sharing
- Explanation using the Ramo-Shockley Theorem
- Simulation using ANSYS
  - Path Integral
  - Microscopic Simulation (Garfield++)
- Comparison to Measurements