Charge collection in GridPix detectors as a function of pixel pad size

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Overview

- GridPix model
- How I run Garfield++ and field simulations
- Avalanche spread
- Refine model
- Charge collection

Model

Geometry

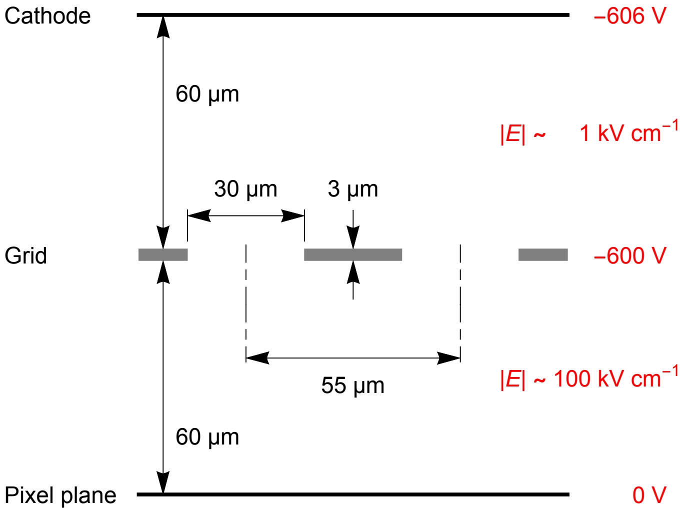
- Hole diameter: 30 μm
- Amplification gap: 60 μm

Fields

- Drift: $1\,\mathrm{kV\,cm^{-1}}$
- Amplification: $100\,\mathrm{kV\,cm^{-1}}$

Gas

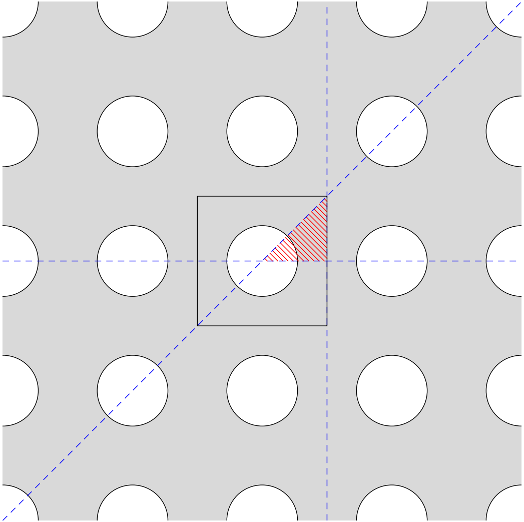
- DME(50 %)/CO_2(50 %)



Meshing and field simulation

- Use mirror symmetries to reduce number of finite elements in field and detector simulation
- Boundary condition on planes of mirror symmetry: $\nabla V \cdot \hat{n} = 0$
- Only simulate fields in shaded region

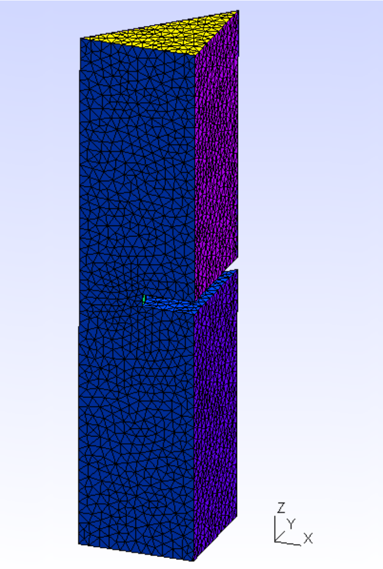
Top view



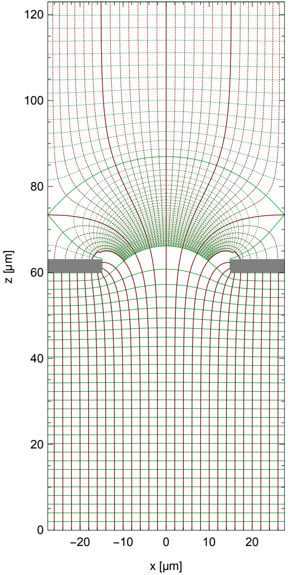
Meshing and field simulation

- We mesh the geometry with Gmsh
  - 3D finite element grid generator (free software)
- We use Elmer to simulate the field
  - Open source multiphysical simulation software mainly developed by CSC-IT Center for Science
- To save CPU, the mesh only extends up to 123 µm. Above that, the field is constant.

Mesh

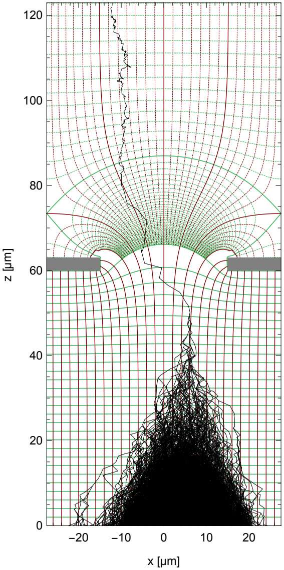


$y = 0$ plane

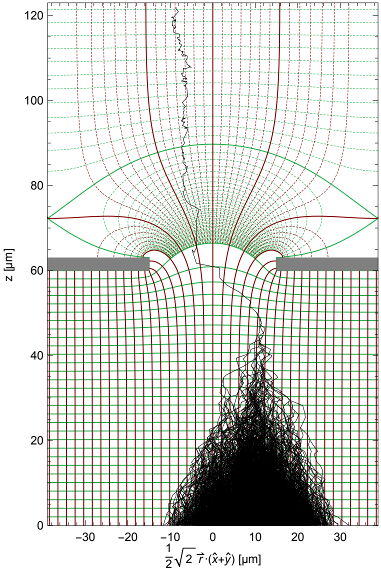


Avalanche simulation

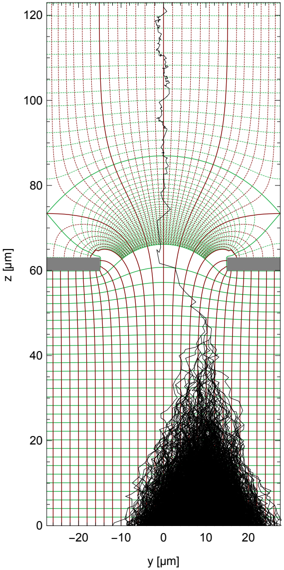
$y = 0$ plane



$x = y$ plane

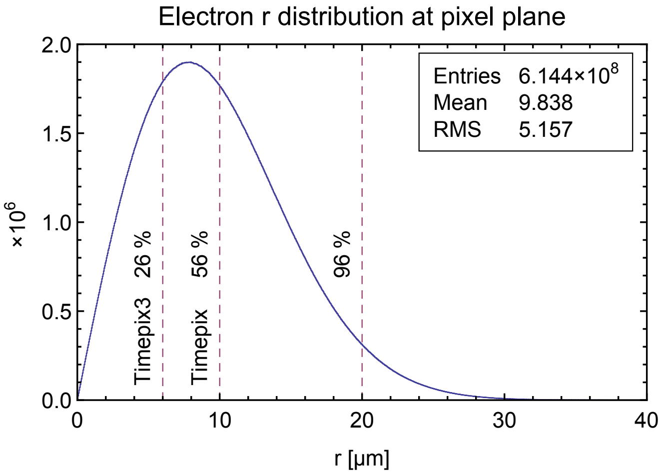


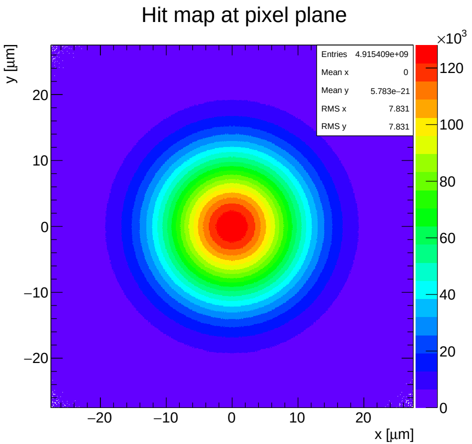
$x = 0$ plane



Secondary electron endpoints

- For this model, charge collection efficiency is 26 % for a 12 μm diameter pad
- However, in a more realistic model, not all electrons end on electrodes

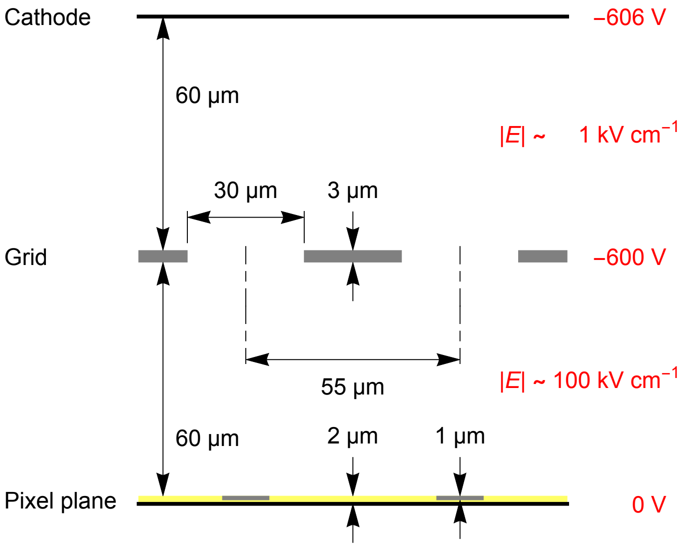




Elevated pad

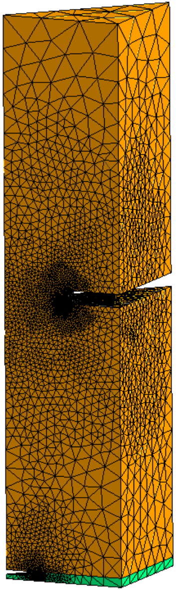
Geometry

- Added pad electrode in order to use Shockley-Ramo
- Pad embedded in SiO_2 dielectric
- Vary pad diameter

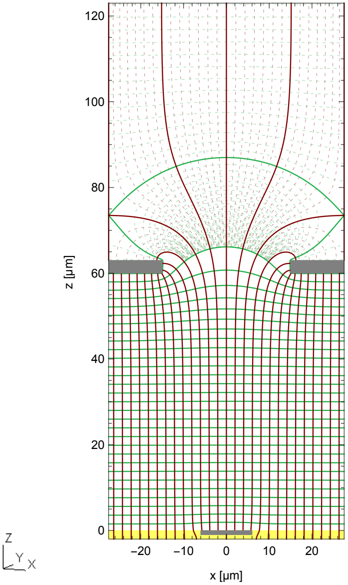


Elevated pad

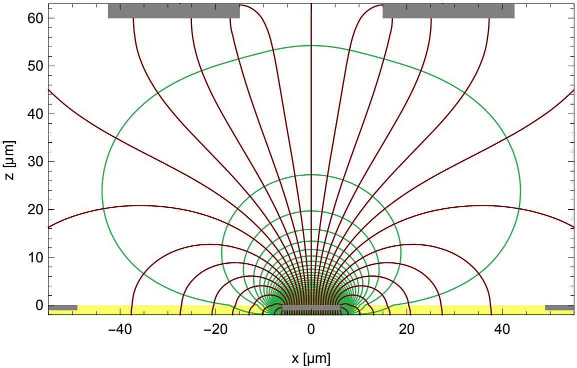
Mesh



E-field



W-field



Shockley-Ramo theorem

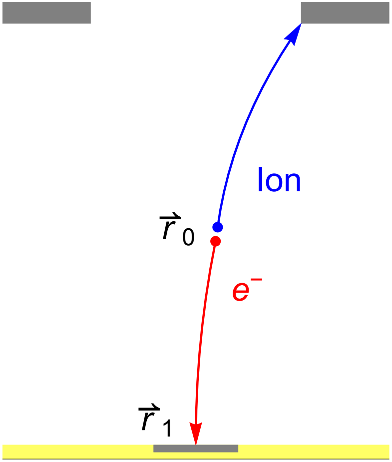
- Instantaneous current on pad given by

$$I = \frac{-q\vec{E_w} \cdot \vec{v}}{1\,\mathrm{V}}$$

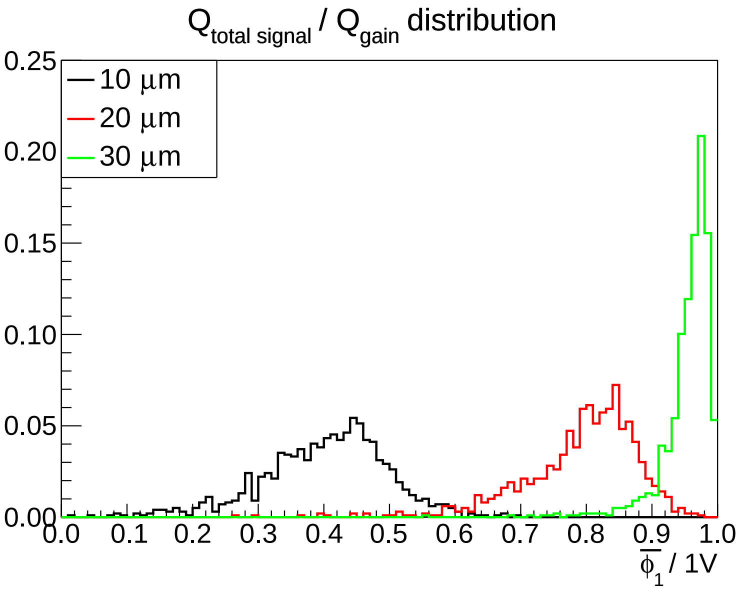
- Integrated signal:

$$\int_{t_a}^{t_b} I\,dt = \frac{q}{1\,\mathrm{V}}\left[\phi\left(\vec{r_b}\right) - \phi\left(\vec{r_a}\right)\right]$$

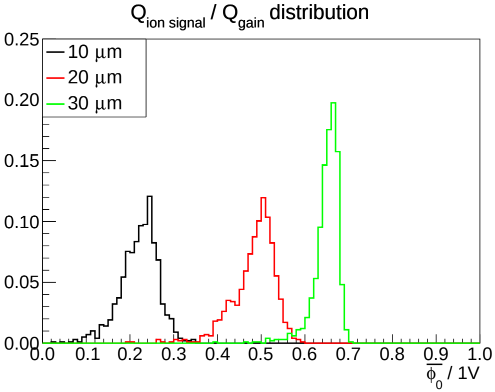
- Charge induced by electron: $Q_{e^-} = \frac{-e}{1\,\mathrm{V}}\left[\phi\left(\vec{r_1}\right) - \phi\left(\vec{r_0}\right)\right]$
- Charge induced by ion: $Q_{ion} = \frac{e}{1\,\mathrm{V}}\left[0\,\mathrm{V} - \phi\left(\vec{r_0}\right)\right]$
- Total induced charge: $Q = Q_{e^-} + Q_{ion} = \frac{-e}{1\,\mathrm{V}}\phi\left(\vec{r_1}\right)$

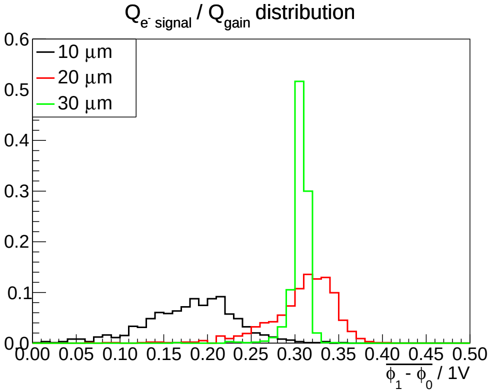


Charge collection efficiency

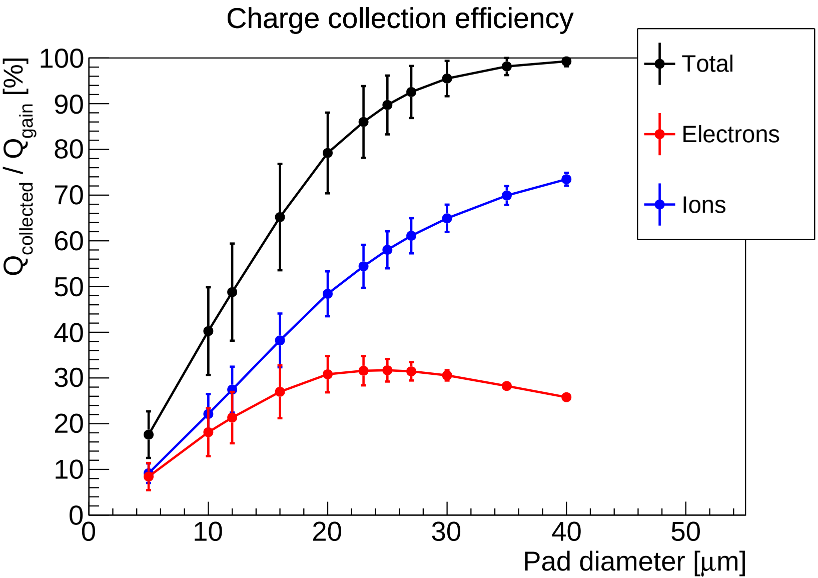


Charge collection efficiency

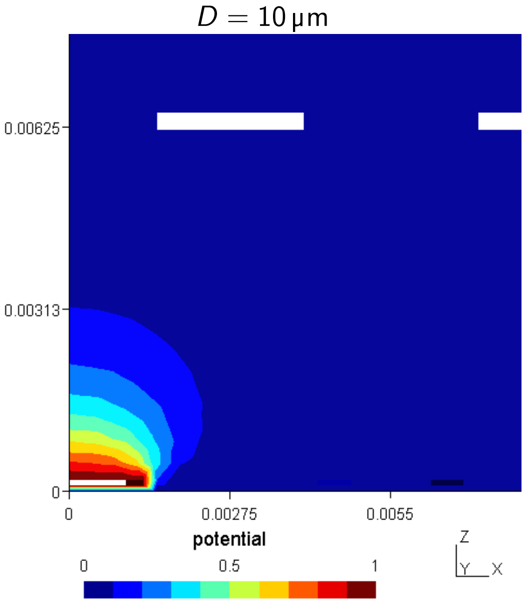


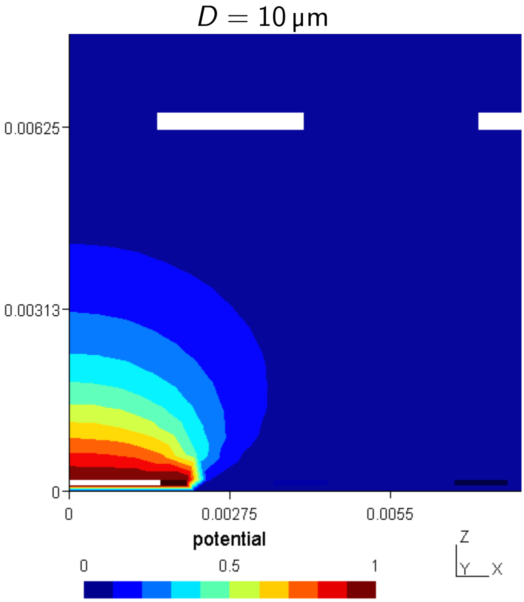


Charge collection efficiency



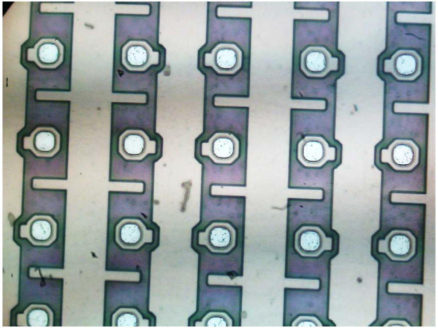
Weighting potential

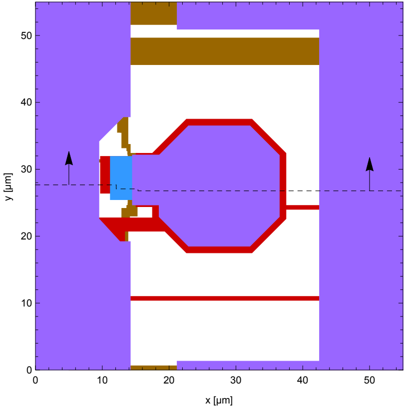


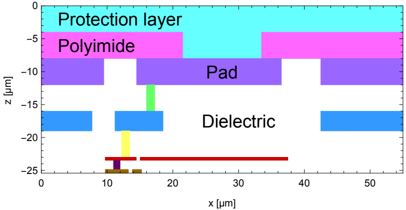


Realistic Timepix3 model

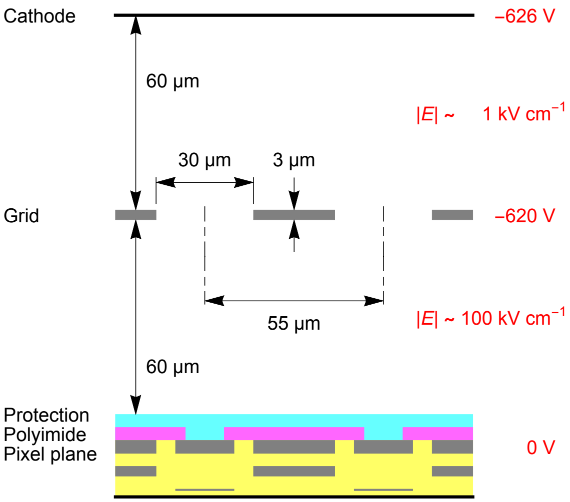
- Make an approximation of TPX3 top metal layers
- Pad is actually 18 μm in diameter, not 12 μm

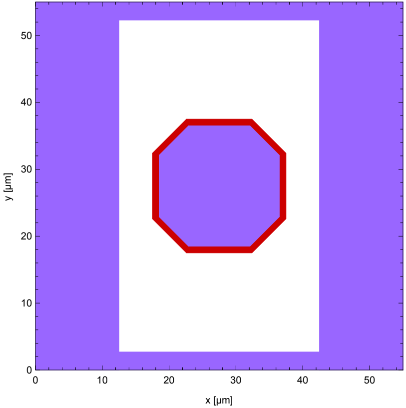


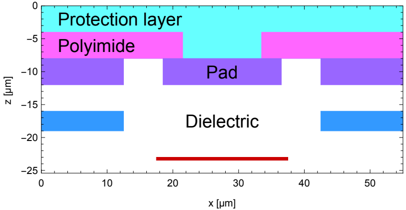




Realistic Timepix3 model

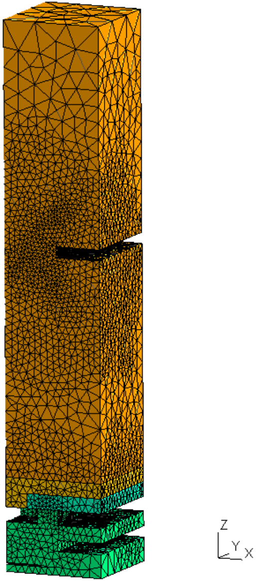




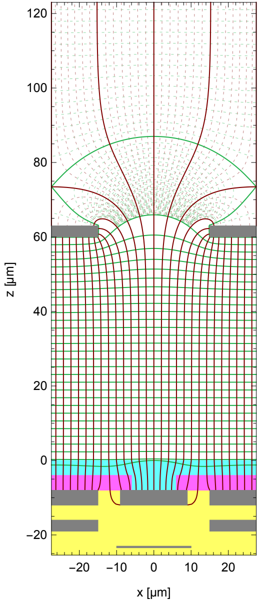


Realistic Timepix3 model

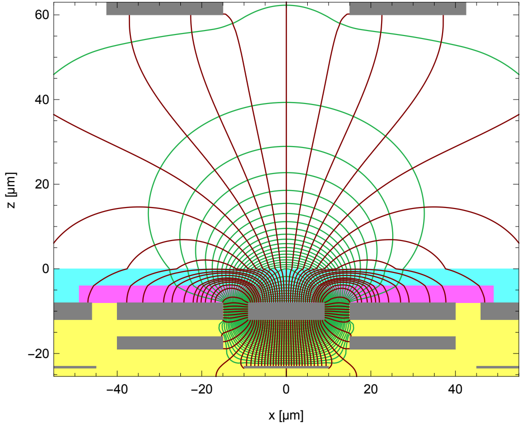
Mesh



E-field

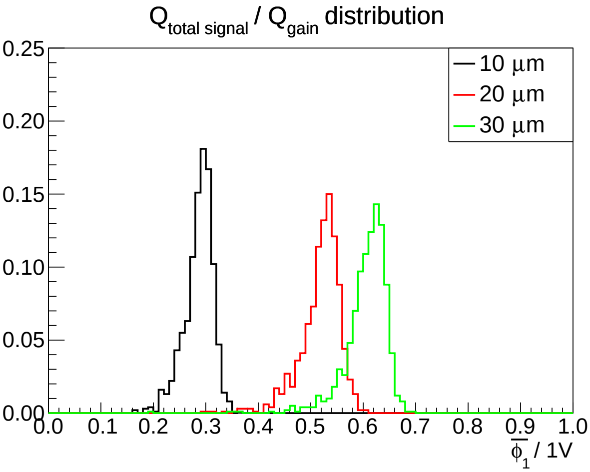


W-field

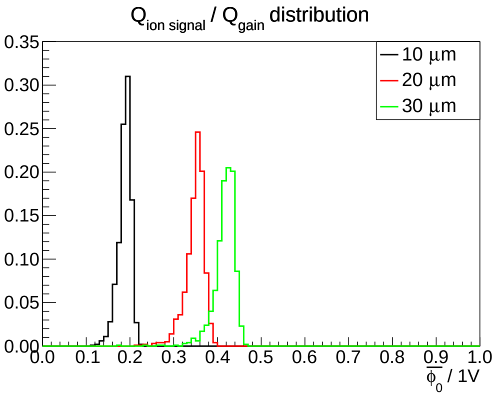


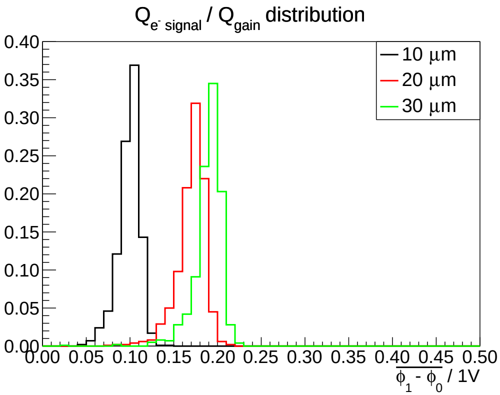
Charge collection efficiency

- Induced charged lower due to protection layers above, and metal layers around pad

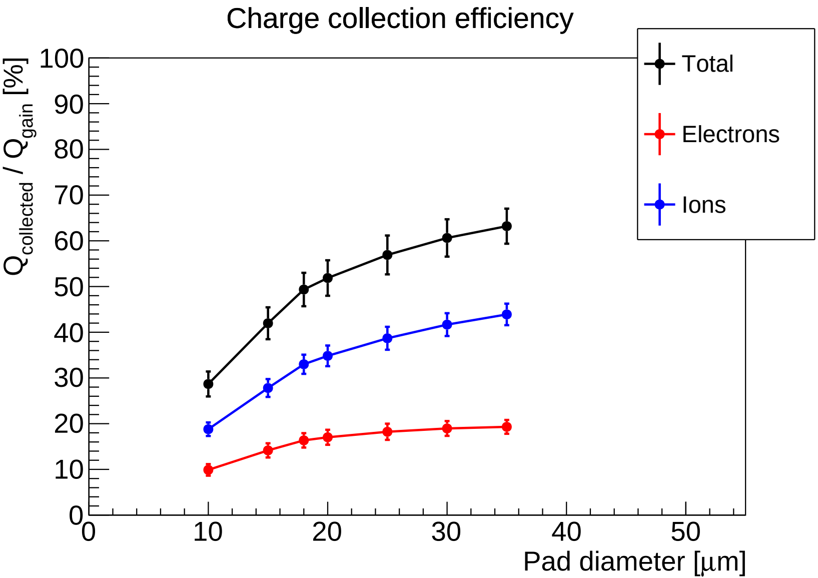


Charge collection efficiency





Charge collection efficiency



Conclusions and outlook

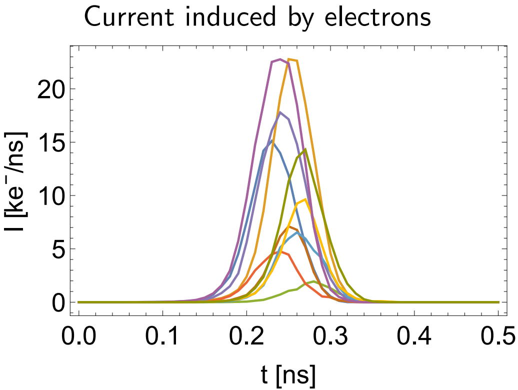
Conclusions:

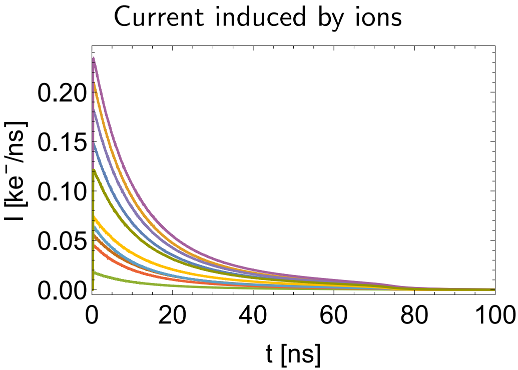
- We might see only a small part of the avalanche.
- Bigger pad size can increase the (charge-integrated) signal

Outlook:

- Model amplifier response and noise (Currently)
- Simulate how bigger pads affect noise
- See what happens when we put a bigger pad above top metal layers

Time dependent signal





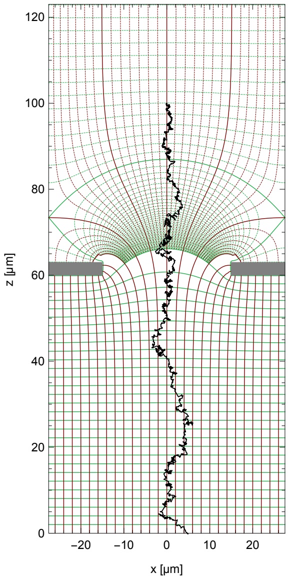
Speeding up Garfield++

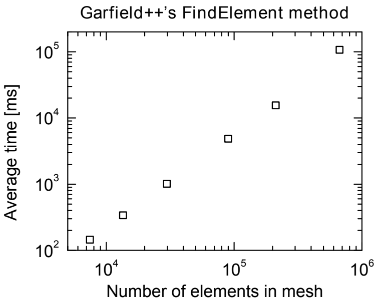
- FindElement function was taking up $> 90\,\%$ of computation time
- Measure average time to find elements along an electron track consisting of 7695 points
- Garfield++'s FindElement: $\mathcal{O}(n)$
- Improved FindElement: $\mathcal{O}(\log n)$

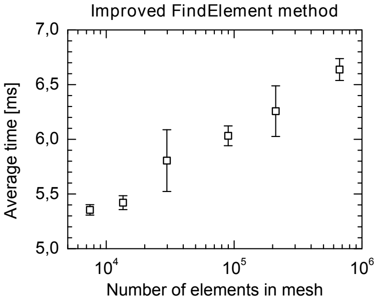
Speedup for my mesh:

- FindElement: $\sim$ 62 times faster
- Garfield++: $\sim$ 25 times faster

Benchmarking event

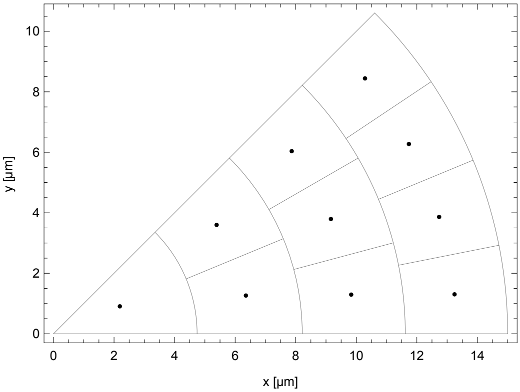






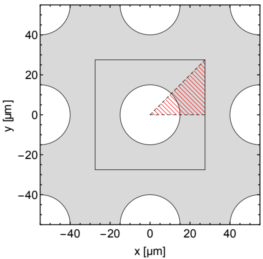
Method

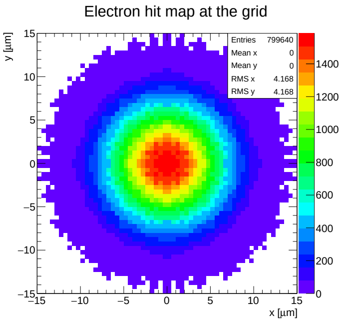
- Separate drift and gain process to decrease computation time
  1. Drift electrons to grid plane
  2. Partition grid hole into cells of equal area and simulate avalanches for each of them
- Convolve the results

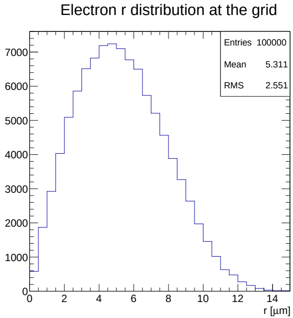


Drift process

- Generate electrons uniformly in the region $0 < x < 27.5\,\mu\text{m}$, $0 < y < x$, $63\,\mu\text{m} < z < 1\,\text{cm}$ and drift them to the grid
- Most electrons arrive at neighbouring pixel cells and are transformed back to the center pixel
- This is equivalent to generating electrons in the region $-\infty < x < \infty$, $-\infty < y < \infty$, $63\,\mu\text{m} < z < 1\,\text{cm}$ and only looking at electrons arriving at a single pixel cell
- 45 out of 100 000 electrons hit the grid



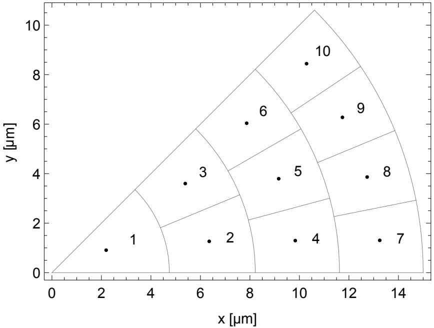


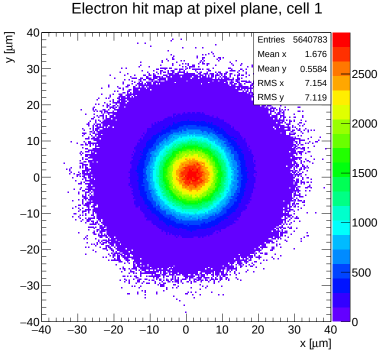


Gain process

For each cell:

- Simulate 1000 avalanches at center of cell
- Store a 2D histogram containing electron positions at pixel plane
- Store all gain values
- Note that average pixel plane position $(\overline{x}, \overline{y})$ depends on cell



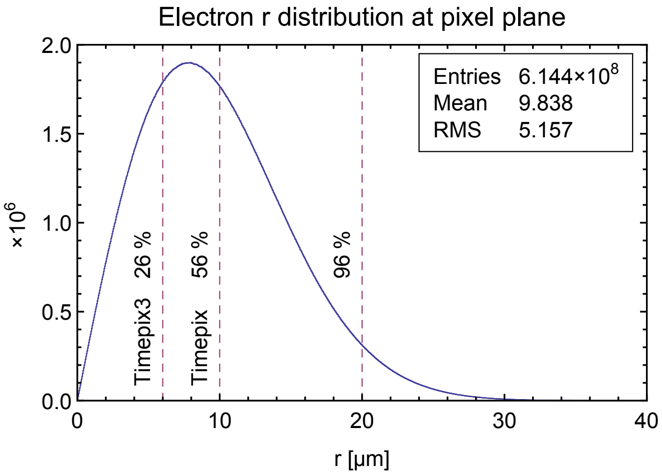


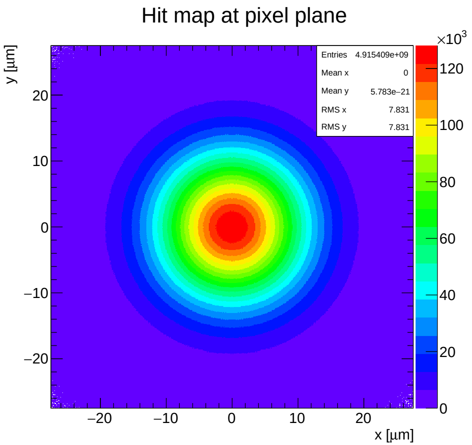
Cell	$\overline{x}$ [µm]	$\overline{y}$ [µm]
1	1.7	0.6
2	4.7	1.0
3	3.8	2.6
4	7.2	0.9
5	6.7	2.9
6	5.9	4.5
7	10	0.9
8	9.5	2.9
9	9.0	4.8
10	7.8	6.3

Convolving drift and gain results

For each drifted electron:

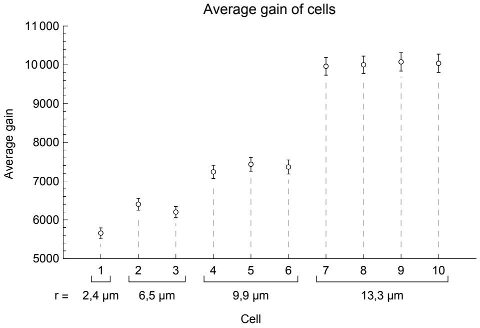
- Draw random gain N from corresponding cell
- Draw N $(\Delta x, \Delta y)$ pairs from cell hit map
- Secondary electrons hit the pixel plane at $(x + \Delta x, y + \Delta y)$

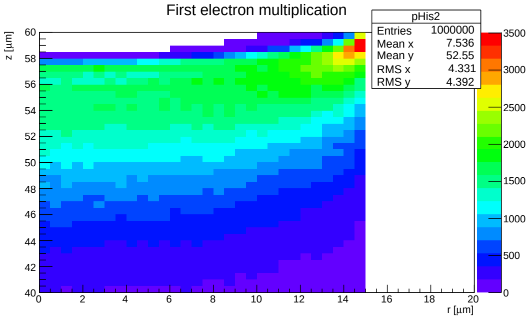




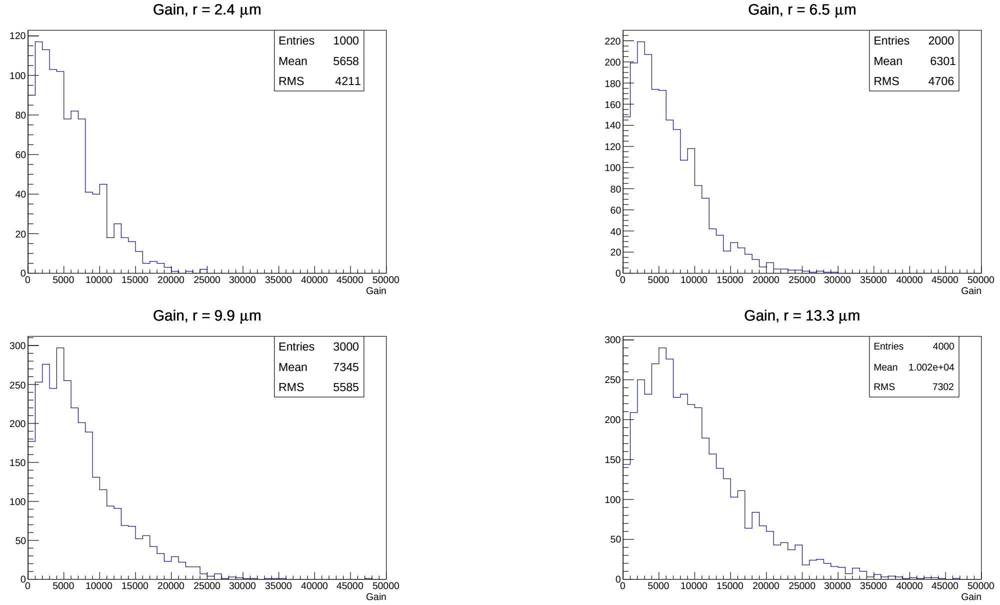
Gain variation

- Gain depends on where the electron goes through the grid hole
- A factor two difference over the grid hole

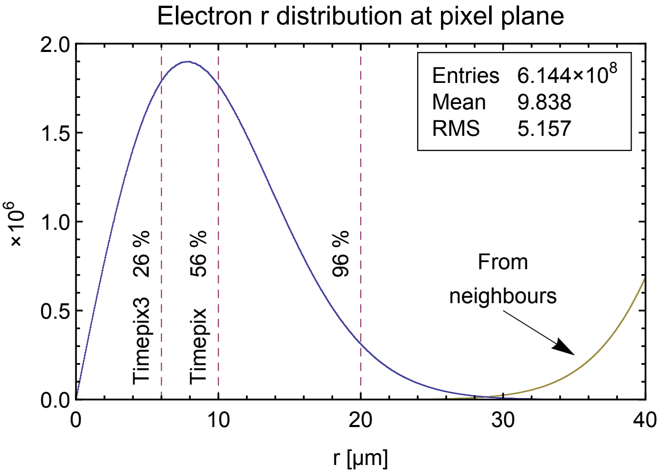




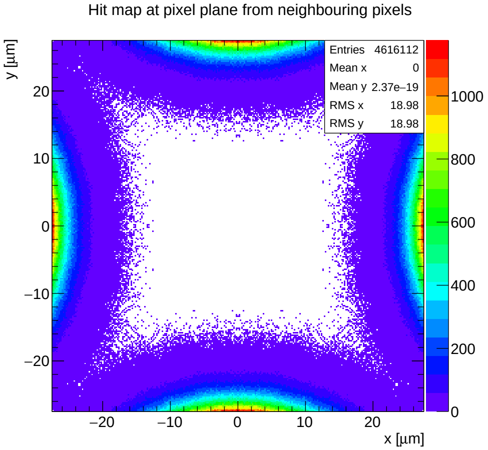
Gain histograms



Crosstalk



Electron r distribution at pixel plane
Entries 6.144×10^8
Mean 9.838
RMS 5.157
×10^6
2.0
1.5
1.0
0.5
0.0
Timepix3 26 %
Timepix 56 %
96 %
From neighbours
0
10
20
30
40
r [µm]



Hit map at pixel plane from neighbouring pixels
Entries 4616112
Mean x 0
Mean y 2.37e−19
RMS x 18.98
RMS y 18.98
y [µm]
x [µm]
20
10
0
−10
−20
1000
800
600
400
200
0

Weighted r distribution