Improving the charge collection efficiency in GridPix

Kevin Heijhoff

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Overview

GridPix Model — Amplification gap and drift region

Geometry

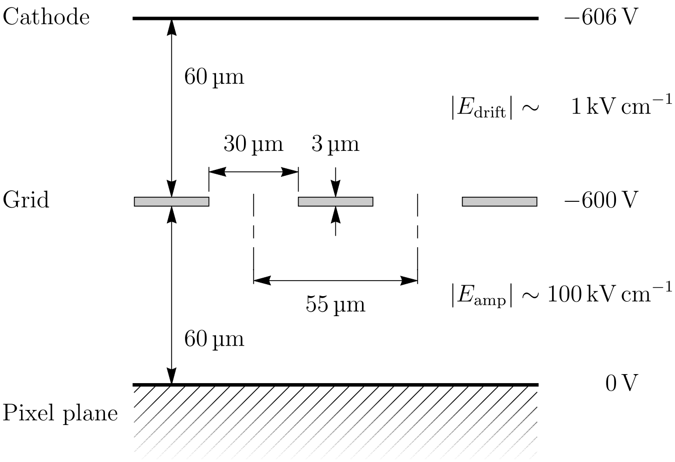
- Hole diameter: 30 µm
- Amplification gap: 60 µm

Fields

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

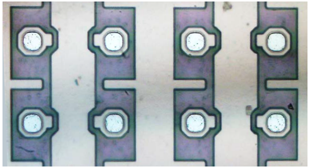
Gas

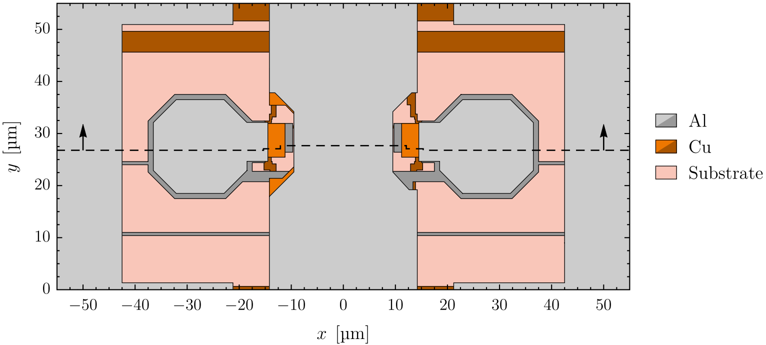
- DME(50 %)/CO_2(50 %)

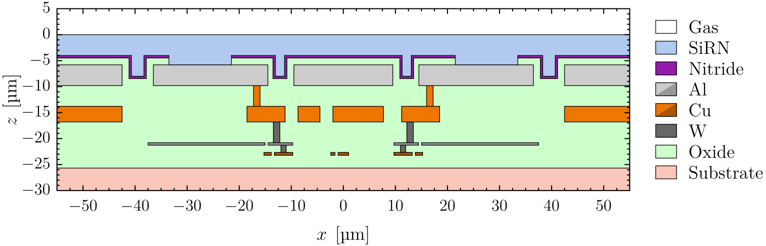


GridPix Model — TPX3 pixel chip

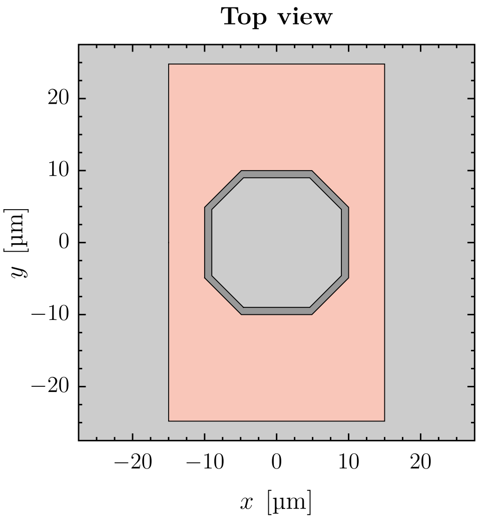
- Need pixel plane model for signal calculation
- First find out what TPX3 really looks like
- Pad diameter is 18 µm
- Passivation opening diameter is 12 µm

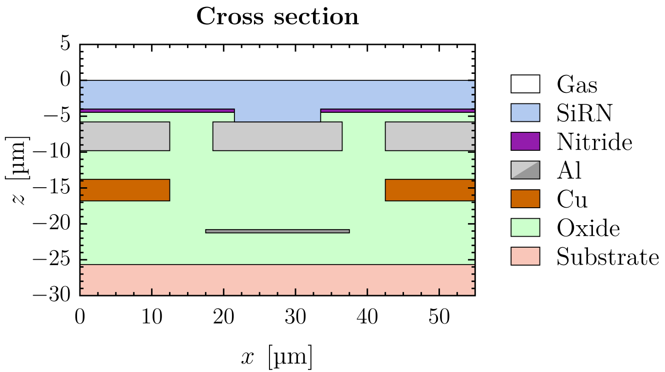




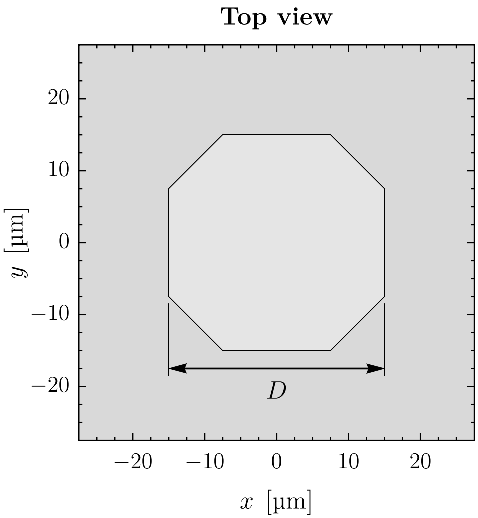


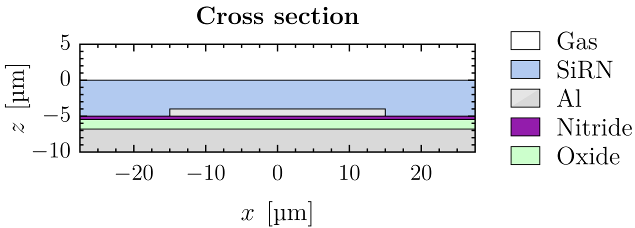
GridPix Model — TPX3 pixel chip





GridPix Model — Pixel pad enlargement





Charge Collection — Shockley-Ramo theorem

- Instantaneous current on pad:

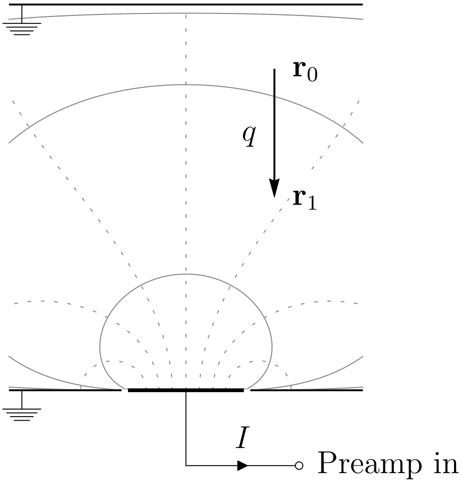
$$I = -q\,\boldsymbol{\psi} \cdot \frac{\mathrm{d}\mathbf{r}}{\mathrm{d}t}$$

with $\boldsymbol{\psi} = \frac{\mathbf{E}_\mathrm{w}}{1\,\mathrm{V}}$

- Integrated signal of charge q moving from $\mathbf{r}_0$ to $\mathbf{r}_1$:

$$Q = \int_{t_0}^{t_1} \mathrm{d}t\, I = q\left[\phi\left(\mathbf{r}_1\right) - \phi\left(\mathbf{r}_0\right)\right]$$

with ϕ such that $\boldsymbol{\psi} = -\nabla\phi$



Charge Collection — Electron ion pair

- Charge induced by electron:

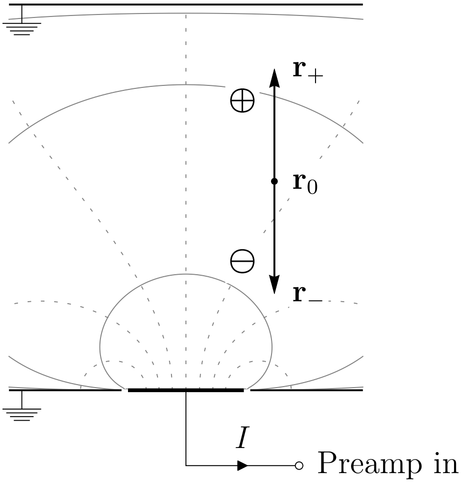
$$Q_- = [\phi_- - \phi_0]\ e^-$$

- Charge induced by ion:

$$Q_+ = [0\,\mathrm{V} - \phi_0]\ (-e^-) = \phi_0\ e^-$$

- Total signal charge:

$$Q = Q_+ + Q_- = \phi_-\ e^-$$



Charge Collection — Avalanche

- Charge induced by electron:

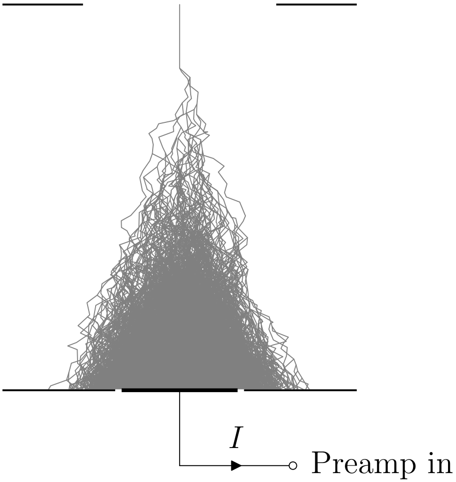
$$Q_- = \sum_{n=1}^{N} \left[\phi_{-,n} - \phi_{0,n}\right] \, e^- = \left[\bar{\phi}_- - \bar{\phi}_0\right] \, N e^-$$

- Charge induced by ion:

$$Q_+ = \sum_{n=1}^{N} \phi_{0,n} \, e^- = \bar{\phi}_0 \, N e^-$$

- Total signal charge:

$$Q = Q_+ + Q_- = \bar{\phi}_- \, N e^-$$



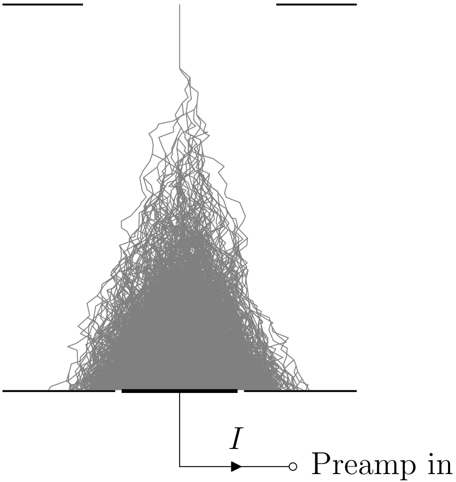
Charge Collection — Avalanche

- Electrons move very fast compared to ions

	v_{drift} [µm ns^{-1}]
electrons	230
ions	0.74

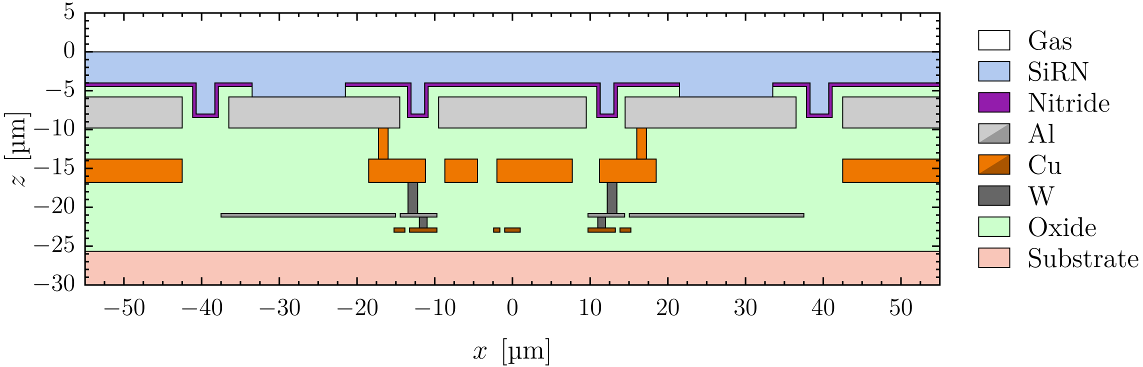
- For a 60 µm amplification gap:

$$Q\,(t = 0) = 0$$
$$Q\,(t \approx 0.26\,\text{ns}) = Q_-$$
$$Q\,(t \approx 81\,\text{ns}) = Q_+ + Q_-$$



Charge Collection — Protection layer

- Protection layer is slightly conductive
- How does this affect the signal calculation?



Charge Collection — Protection layer

- After an avalanche:

$$\sigma\left(t=0\right)=\frac{Q_{\text{ava}}}{55\times 55\,\mu\text{m}^2}$$

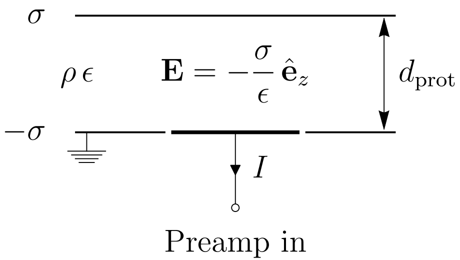
- This sets up a current density inside the protection layer:

$$\mathbf{J}=\frac{\mathbf{E}}{\rho}=-\frac{\sigma}{\rho\,\epsilon}\,\hat{\mathbf{e}}_z$$

- The surface charge now changes as

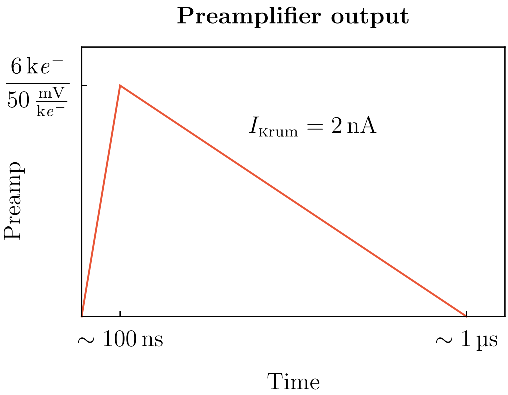
$$\frac{\mathrm{d}\sigma}{\mathrm{d}t}=\mathbf{J}\cdot\hat{\mathbf{e}}_z=-\frac{\sigma}{\rho\,\epsilon}\quad\Rightarrow\quad\sigma\left(t\right)=\sigma\left(0\right)\exp\left(-\frac{t}{\rho\,\epsilon}\right)$$

- Any change in the signal will be on a time scale of $\rho\,\epsilon$



Charge Collection — Protection layer

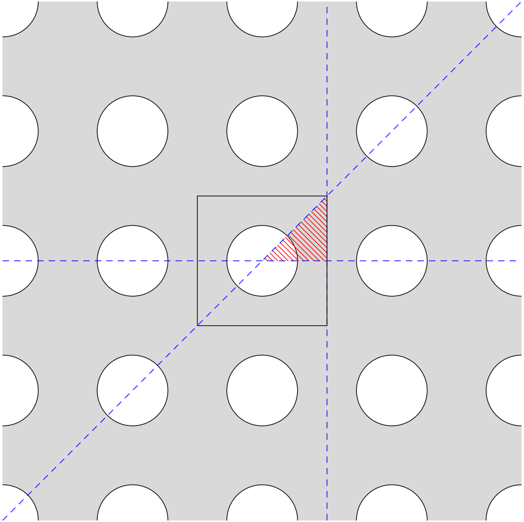
- Preamplifier output returns to baseline in $\sim 1\,\mu s$
- For SiRN, ρ is somewhere in the range of 10^9–$10^{13}\,\Omega\,m$. So, $\rho\,\epsilon$ is somewhere in the range of $60\,ms$–$600\,s$
- Therefore, we can safely regard the protection layer as an insulator for signal calculations



Meshing and electric field calculation

- 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

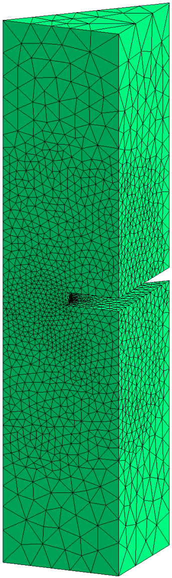
Top view



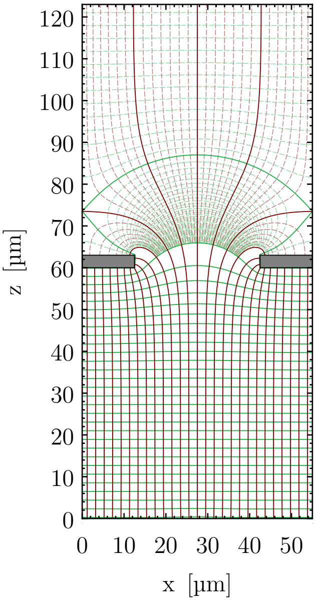
Meshing and electric field calculation

- We mesh the geometry with Gmsh
  - 3D finite element grid generator (free software)
- We use Elmer to calculate 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

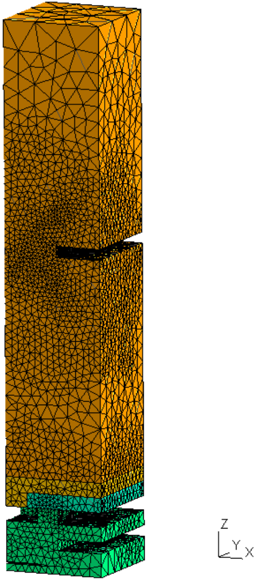


Field

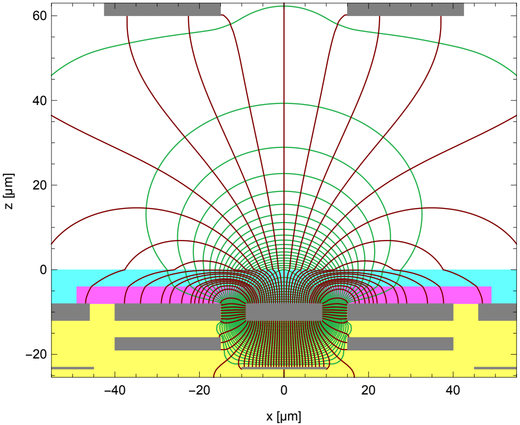


Meshing and electric field calculation — TPX3

Mesh

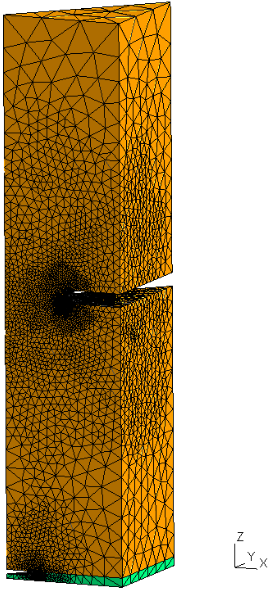


W-field

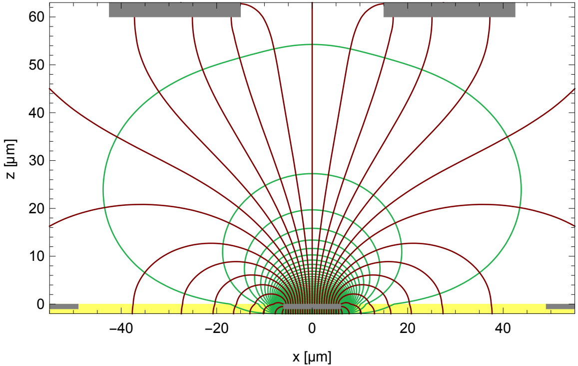


Meshing and electric field calculation — Enlarged pad

Mesh



W-field



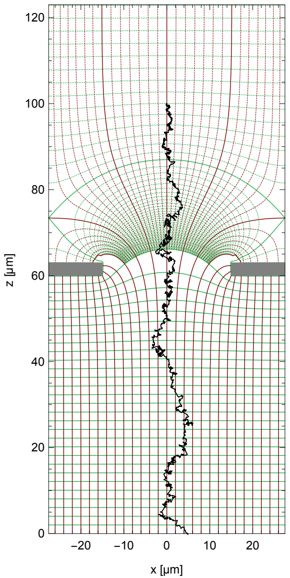
Meshing and electric field calculation — Speeding up Garfield++

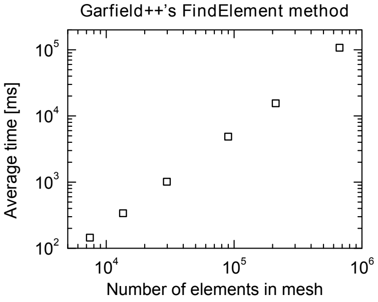
- FindElement function was taking up $> 90\,\%$ of computation time
- Measure average time to find elements along an electron track consisting of 7695 points
- Garfield++'s FindElement: $\mathcal{O}(n)$
- Improved FindElement: $\mathcal{O}(\log n)$

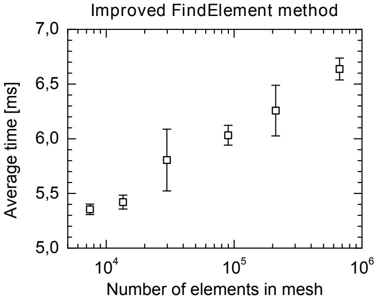
Speedup for my mesh:

- FindElement: ~ 62 times faster
- Garfield++: ~ 25 times faster

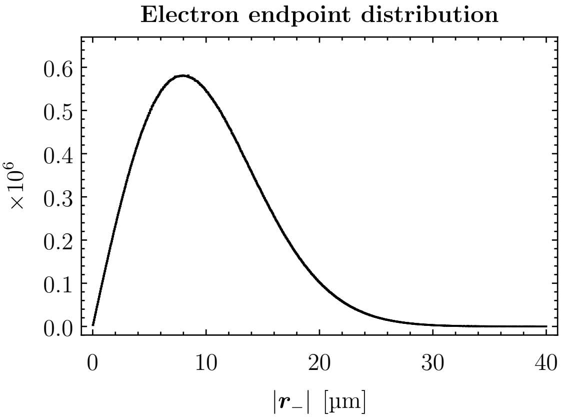
Benchmarking event

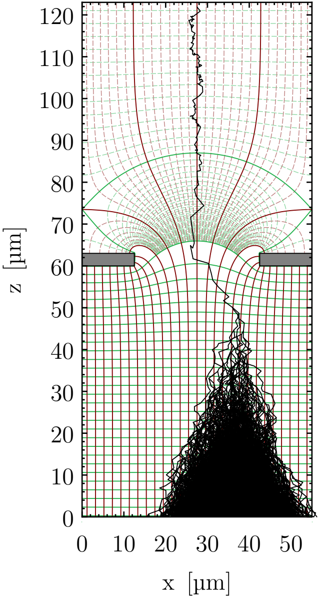




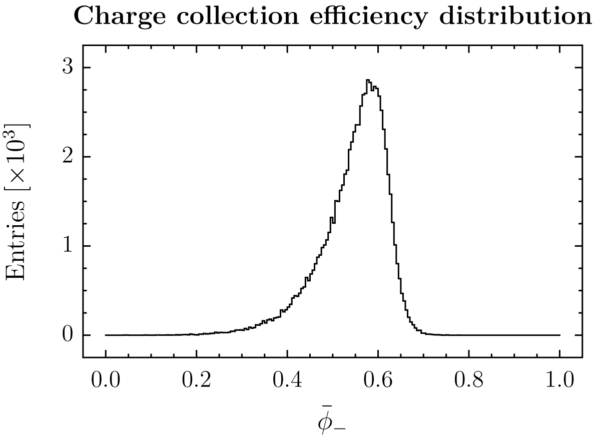


Simulating avalanches with Garfield++

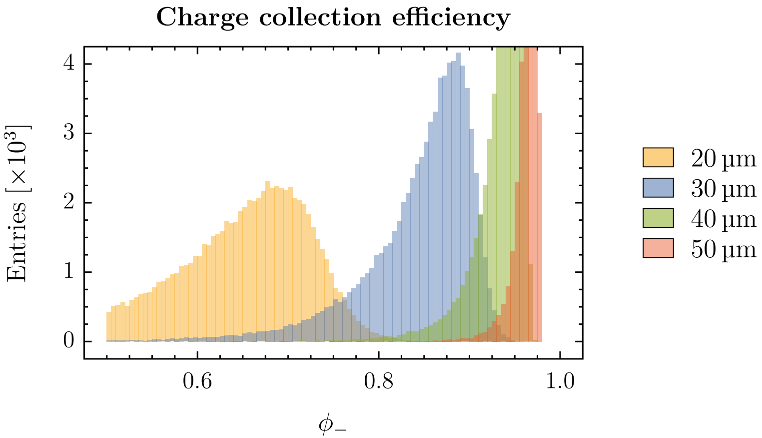




Entries	8.1×10^4
Mean	0.55
RMS	0.07



Charge collection efficiency — Enlarged pixel pad



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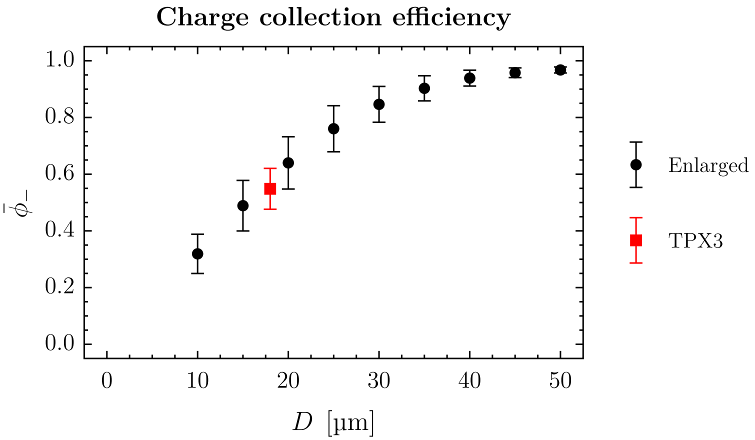
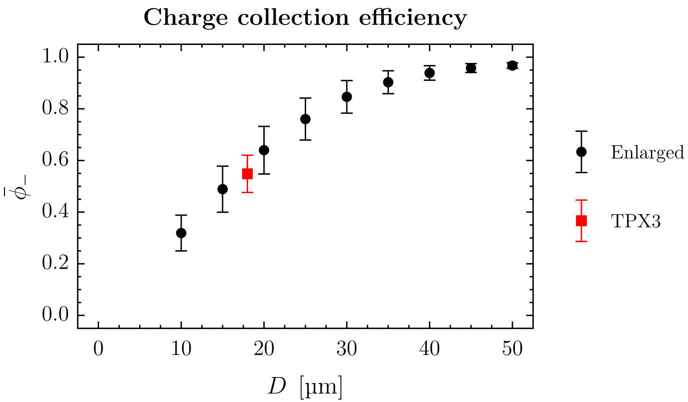


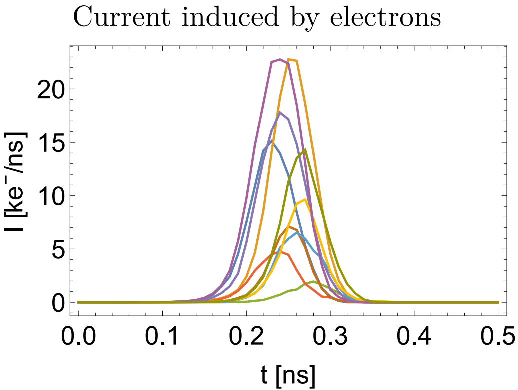
Conclusions

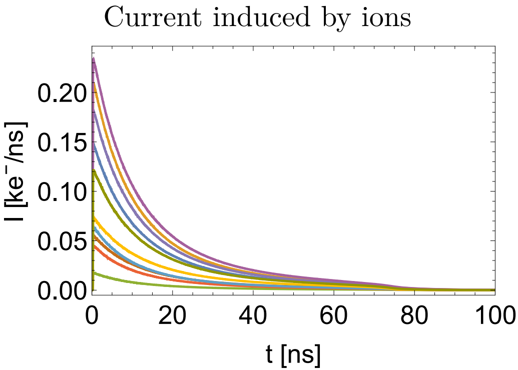
Conclusions:

- Increasing the pixel pad size will increase the charge collection efficiency
- Alternatively, the gas gain can be reduced to increase the durability



Time dependent signal





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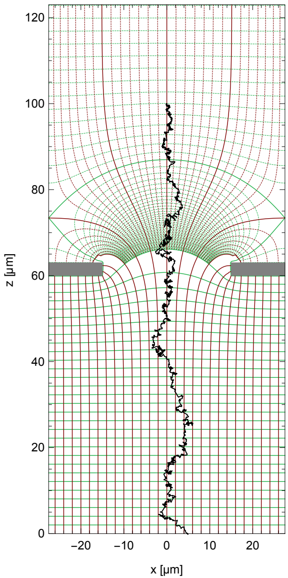

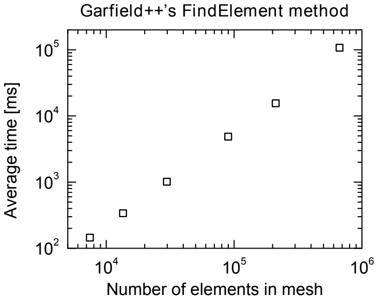

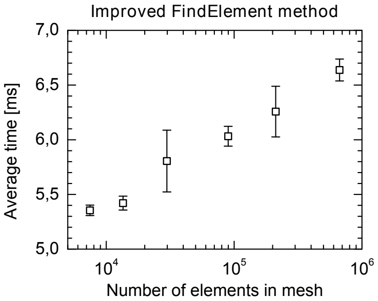

Charge buildup