Measurements and Simulations of the Brighter-Fatter Effect in CCD Sensors

Craig Lage

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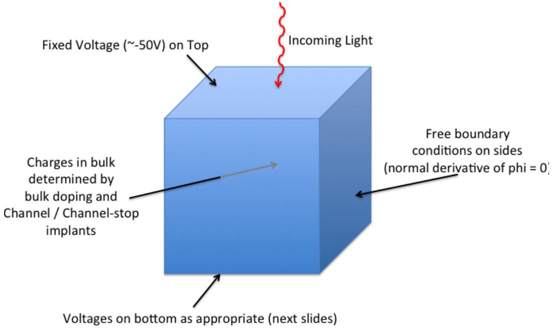
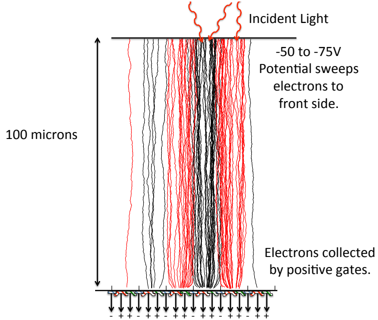
Acknowledgements:
Tony Tyson, Andrew Bradshaw, Kirk Gilmore, Perry Gee

Outline

- Solving for potentials and fields.
- Tracking electrons in the lattice.
- Spot size measurements and simulations.
- Pixel distortions and pixel-pixel correlations.
- Modeling saturation effects.
- Conclusions and next steps.

Typical Simulation $100\mu m$ Cube.





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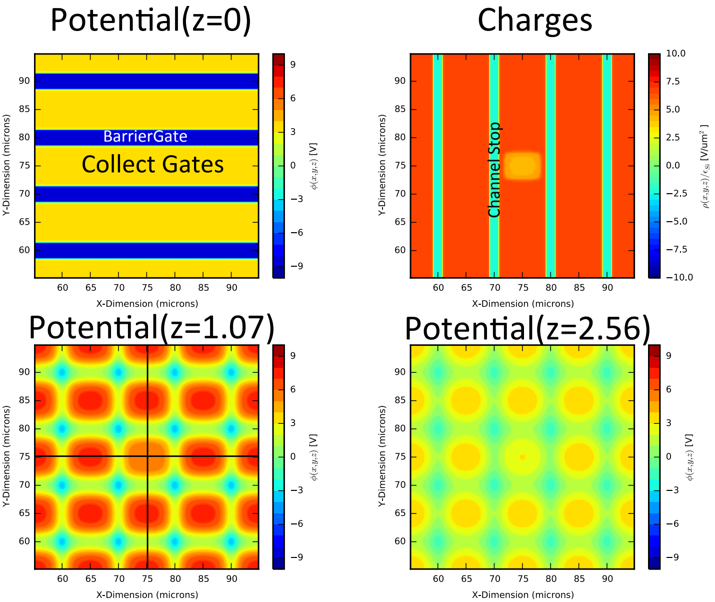
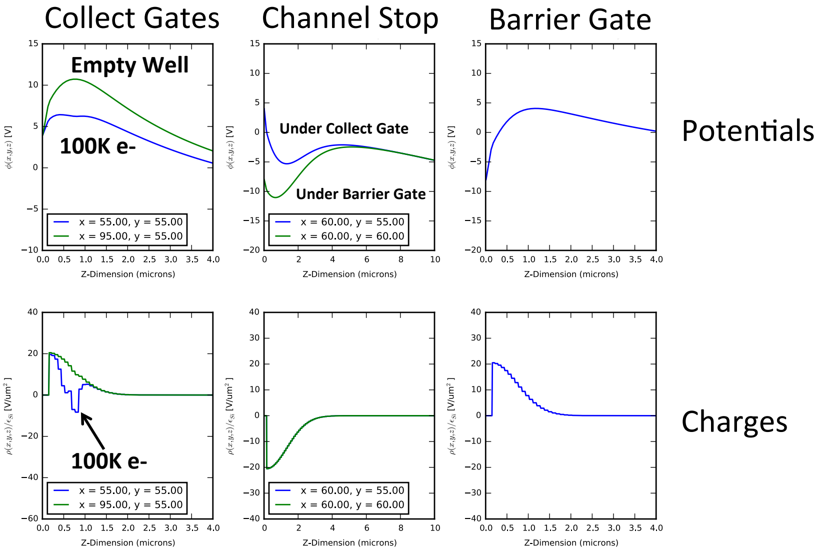
- Poisson's equation solved using multi-grid methods.
- $100\mu m$ Cube. - 10 X 10 pixels in X and Y.
- 32 grid cells per pixel - cell size $=$ 0.31 μ .
- Typical single core performance:
  - Poisson Solution $\approx$ 10 seconds.
  - Electron Tracking $\approx$ 300 e-/second.

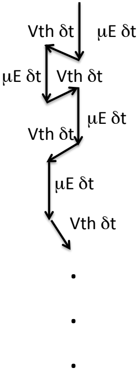
Pixel Array Summary Plot



Pixel Region Charges and Potentials

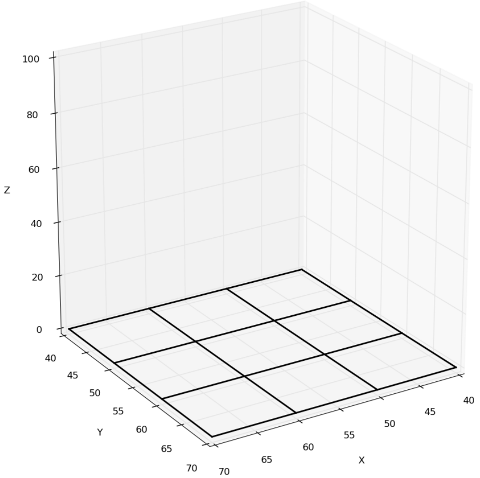


Diffusion Model

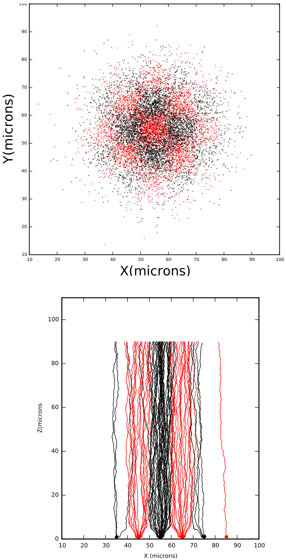


- Mobility: $\mu(E, T)$ calculated from Jacobini model
- $\mu = 1584 \frac{\mathrm{cm}^2}{\mathrm{V-sec}}$ at $\mathrm{E} = 6000 \frac{\mathrm{V}}{\mathrm{cm}}$
- Collision time:
- $\tau = \frac{\mathrm{m}_\mathrm{e}^*}{\mathrm{q}_\mathrm{e}} \mu$
- τ typically about 0.9 ps.
- $\delta \mathrm{t}$ drawn from exponential distribution with mean of τ
- $\mathrm{V}_{\mathrm{th}} = \sqrt{\frac{3\mathrm{kT}}{2\mathrm{m}_\mathrm{e}^*}}$
- $\mathrm{V}_{\mathrm{th}} \approx \mu \mathrm{E}$
- Each thermal step in a random direction in 3 dimensions.
- Typically about 1000 steps to propagate to the collecting well.

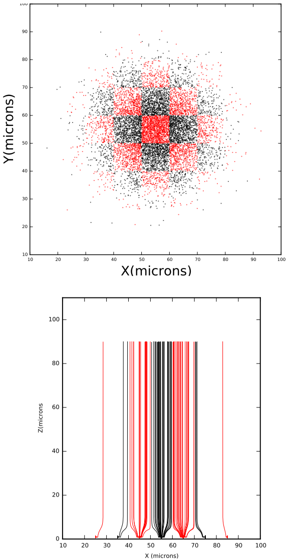
Movie of Pixel Filling - First 10,000 Electrons



Impact of electron diffusion



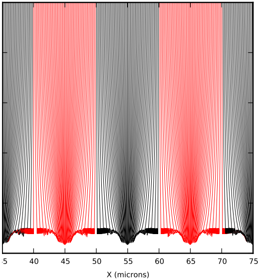
Theoretical Diffusion



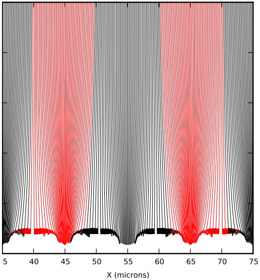
Diffusion turned off

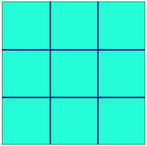
Basics of the Brighter-Fatter Effect

Diffusion turned off here.

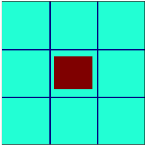


Diffusion turned off here.





Pixel empty of charge

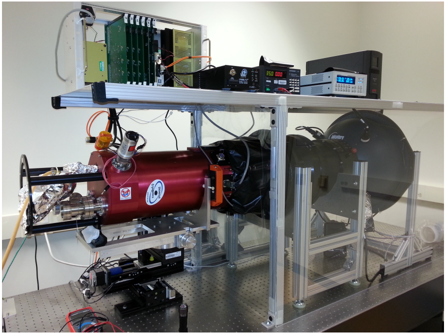


Pixel with 100K e-

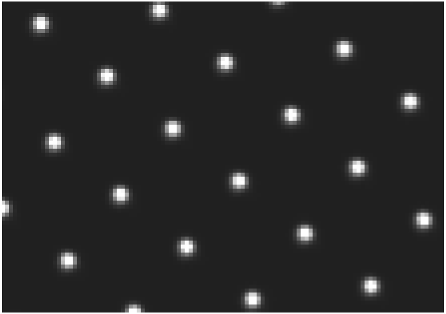
- Electrons stored in the potential well repel incoming electrons and push them into surrounding pixels.

LSST Optical Simulator and Typical Spot Images

UC Davis 1:1 Re-Imager

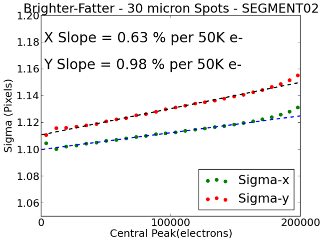


Typical Image of 30 micron Spots:

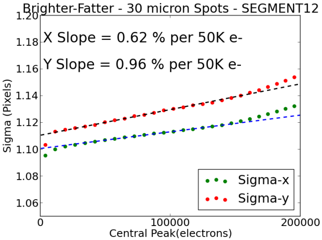


Tyson, et.al., "The LSST Beam Simulator", SPIE 9154-67 (2014), arXiv:1411.5667.

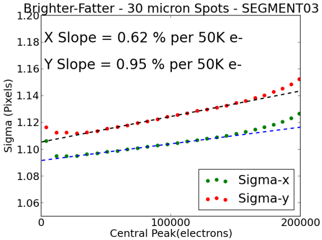
Typical Brighter-Fatter Effect Measurements - ITL 3800



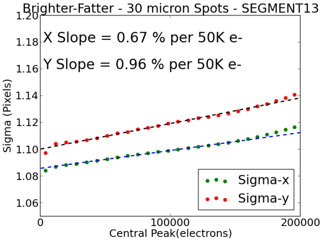
SEGMENT02



SEGMENT12



SEGMENT03



SEGMENT13

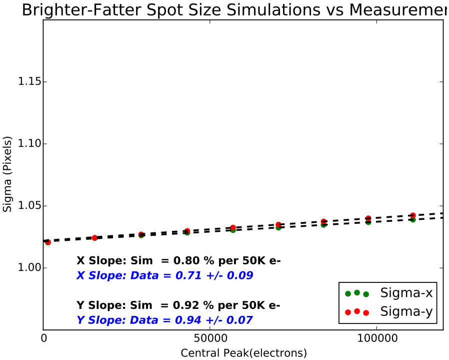
Many measurements have been made under different conditions.

Simulation Strategy for B-F effect.

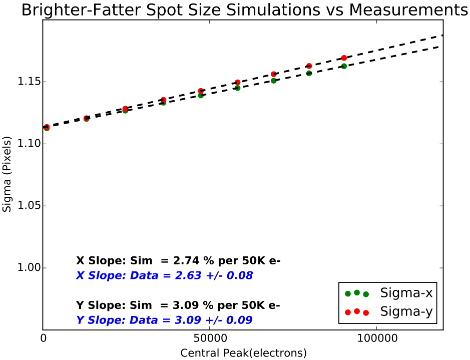
- Solve Poisson's equation for postage stamp with all pixels empty.
- Choose a random location within the central pixel.
- Determine starting locations for N electrons in a 2D Gaussian spot.
- Propagate these electrons down to their collecting gates.
- Re-solve Poisson's equation with these wells now containing the appropriate charge.
- Repeat with N more electrons.
- I have been using 10,000 electrons per step, which places about 1000 electrons in the central pixel, so about 100 iterations are needed to fill the central pixel.
- In practice, repeat for more than one spot (typically 64), each with a different central location.
- Typical run takes $\approx$ 6 hours.

Measurements vs Simulations

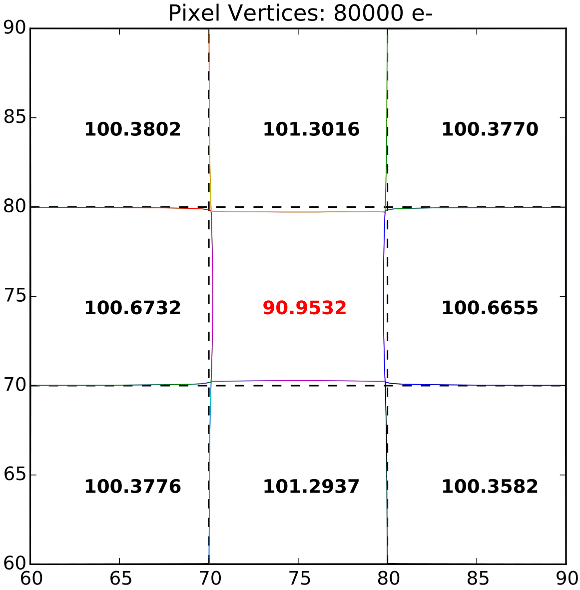
VBB = -60V



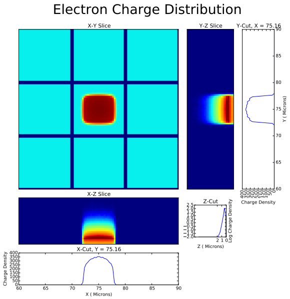
VBB = -10V

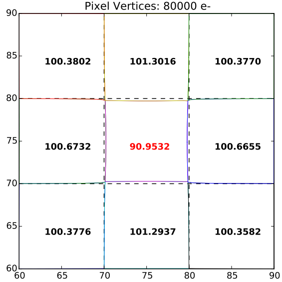


Pixel Shape Distortion due to Collected Charge

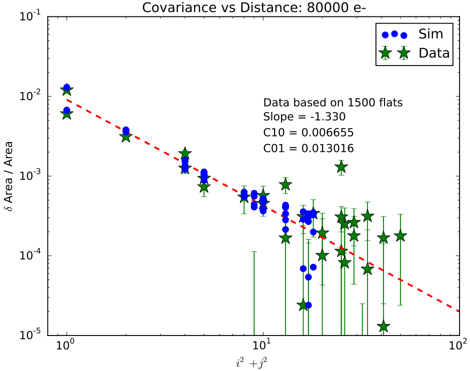


Pixel Areas and Correlations





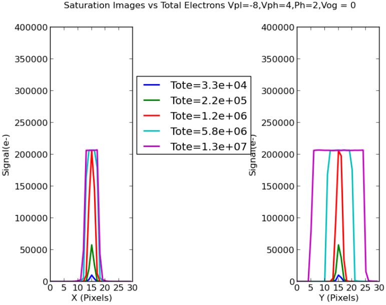
Simulations vs ITL 3800 Measurements



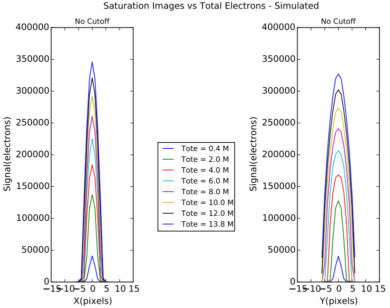
- Antilogus, et al., JINST 9C3048 (2014), arXiv:1402.0725.
- Rasmussen, A., JINST 904027 (2014), arXiv:1403.3317.

Saturated Spot Profiles

Measurements ITL 3800

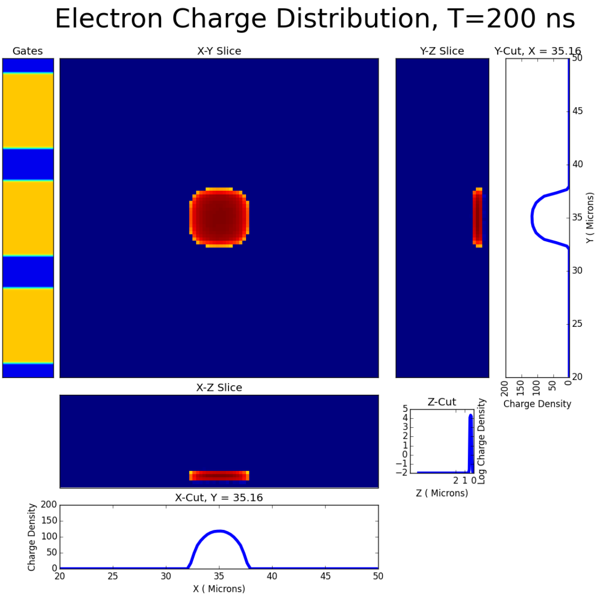


Simulation

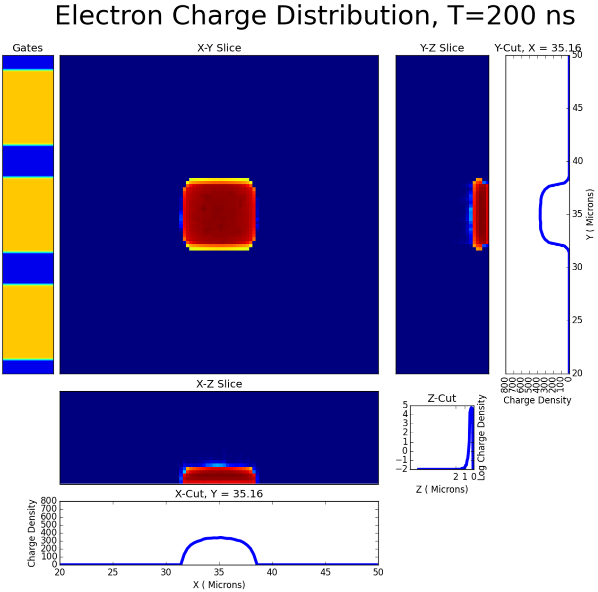


- Simulated profiles never flatten out.
- “Cutoff” may happen in charge transfer instead of charge collection, either in the array or outside the array in the serial transfer.

Movie of Charge Transfer - 50K Electrons



Movie of Charge Transfer - 200K Electrons

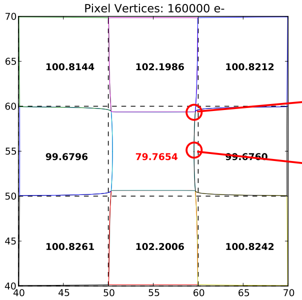


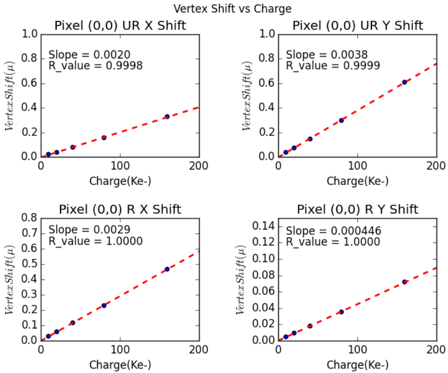
Conclusions and Next Steps

- We have had good success in simulating the Brighter-Fatter Effect:
  - Direct Spot Size Measurements.
  - Pixel Correlation Measurements.
- Biggest uncertainty concerns state of channel stop region:
  - Best fits to measurements obtained with the assumption that the channel stop region is not fully depleted, but contains free holes. However, I am still uncertain of this conclusion.
  - Plan to obtain physical measurements (SIMS) of dopant profiles.
- Simulations are not fitting saturation full well effects:
  - Attempting to determine how much of full well effect is due to charge collection, and how much is due to charge transfer.
- Latest code, with documentation and examples, is at: `https://github.com/craiglagegit/Poisson_CCD22`

Back-Ups

Pixel Vertex Movement with Charge





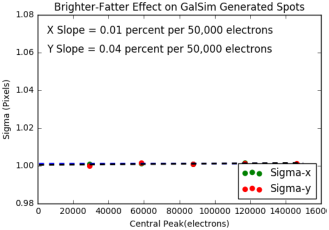
Linear relationship of vertex motion with charge implies superposition should work.

Superposition Strategy

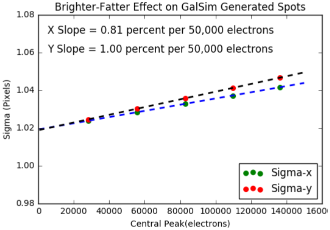
- If superposition works, we can do the following:
  - Solve (one time) Poisson's equation with one pixel containing N electrons, all surrounding pixels empty.
  - Determine displacement of pixel vertices (out to +/- M pixels away) per electron.
  - For general case where many pixels contain a varying amount of charge, sum up vertex displacements to determine pixel vertices.
  - For what follows, went up to 4 pixels away, and used 260 vertices / pixel (4 corners + 64 vertices per edge). This is probably more resolution than is needed.

GalSim Comparisons - Calculate pixel distortions every 10,000 photons

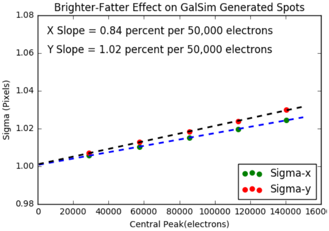
No B-F Effect



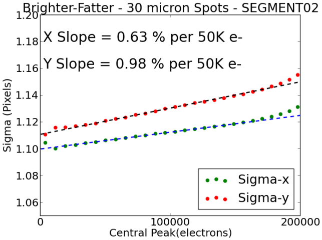
With B-F, With Diffusion



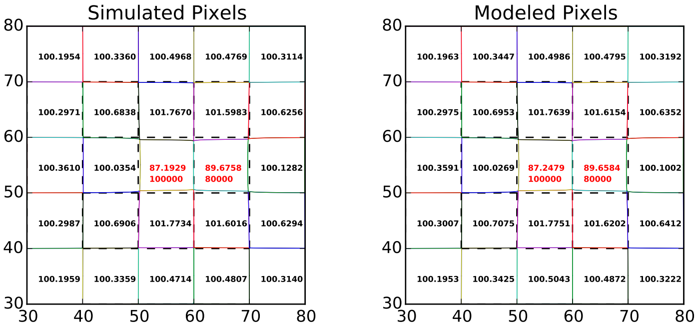
With B-F, No Diffusion



Measurements



Superposition Test 1



Average Area Error = 0.0139 percent
Average Vertex Error = 0.0003 microns
Worst Case Area Error = 0.0551 percent
Worst Case Vertex Error = 0.0669 microns

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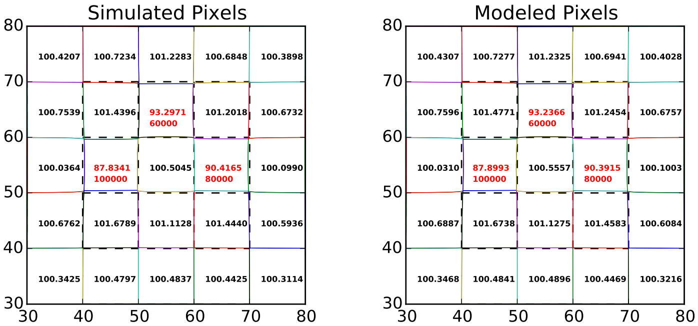
- Left - Full Physics-based simulation, solving Poisson's equation and finding pixel vertices through binary search. Simulation Time - 10's of minutes.
- Right - Take pixel vertex displacement from a single Physics-based run with one pixel containing 80K e-, and superpose the displacements for the two pixels containing charge. Simulation Time - $<< 1\text{sec}$.

Superposition Test 2



Average Area Error = 0.0242 percent
Average Vertex Error = 0.0003 microns
Worst Case Area Error = 0.0682 percent
Worst Case Vertex Error = 0.0638 microns

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- Left - Full Physics-based simulation, solving Poisson's equation and finding pixel vertices through binary search. Simulation Time - 10's of minutes.
- Right - Take pixel vertex displacement from a single Physics-based run with one pixel containing 80K e-, and superpose the displacements for the three pixels containing charge. Simulation Time - $<< 1\text{sec}$.