Poisson Equation Solutions for Thick Fully-Depleted CCDs

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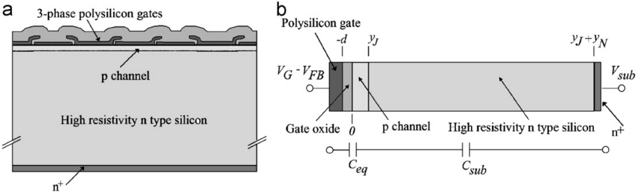
Outline

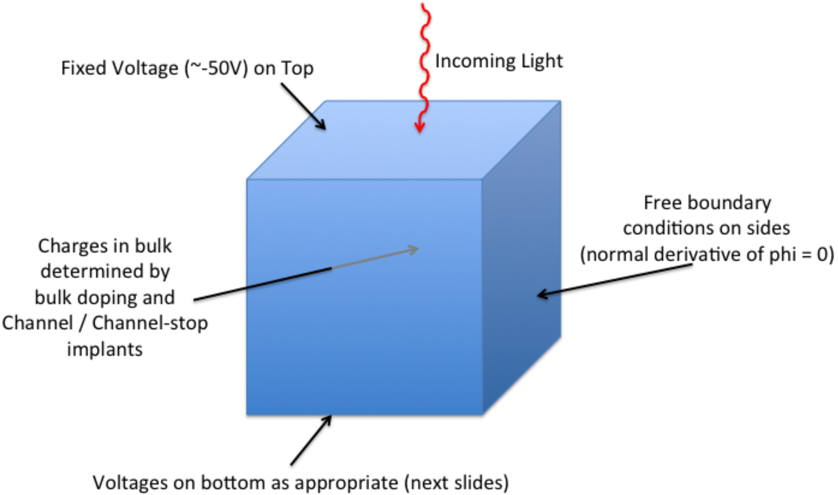
- Introduction
- Solving Poisson's Equation on a Grid
- Boundary Conditions
- Baseline Solution
- How good is our Current Dipole Model?
- Array Edge
- Array Center
- Limitations and Next Steps

Basic Device Structure



- From Holland, et.al., 2007, “Fabrication of back-illuminated, fully depleted charge-coupled devices”.
- Our devices are n-channel instead of p-channel, so all polarities are reversed.

Boundary Conditions - Typical Simulation $100\mu\mathrm{m}$ Cube.



Solving Poisson's Equation on a Grid

$$\nabla^2 \varphi = \rho$$

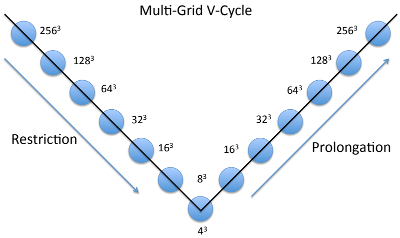
$$\frac{\partial^2 \varphi_{\mathrm{i,j,k}}}{\partial \mathrm{x}^2} = \frac{(\varphi_{\mathrm{i+1,j,k}} - \varphi_{\mathrm{i,j,k}}) - (\varphi_{\mathrm{i,j,k}} - \varphi_{\mathrm{i-1,j,k}})}{\mathrm{h}^2}$$

$$(\varphi_{\mathrm{i+1,j,k}} + \varphi_{\mathrm{i-1,j,k}} + \varphi_{\mathrm{i,j+1,k}} + \varphi_{\mathrm{i,j-1,k}} + \varphi_{\mathrm{i,j,k+1}} + \varphi_{\mathrm{i,j,k-1}} - 6 * \varphi_{\mathrm{i,j,k}}) = \mathrm{h}^2 * \rho_{\mathrm{i,j,k}}$$

$$\varphi_{\mathrm{i,j,k}} = \frac{1}{6} * (\varphi_{\mathrm{i+1,j,k}} + \varphi_{\mathrm{i-1,j,k}} + \varphi_{\mathrm{i,j+1,k}} + \varphi_{\mathrm{i,j-1,k}} + \varphi_{\mathrm{i,j,k+1}} + \varphi_{\mathrm{i,j,k-1}} - \mathrm{h}^2 * \rho_{\mathrm{i,j,k}})$$

- Conceptually, we simply iterate until convergence.
- In practice, it converges very slowly - millions of iterations are required.

Multi-Grid Methods to the Rescue



Finest Grid	Cells/Pixel	Grid Spacing	Time (laptop)
128^3	12	0.83 micron	5 sec.
256^3	24	0.41 micron	45 sec.
512^3	48	0.20 micron	5 min.

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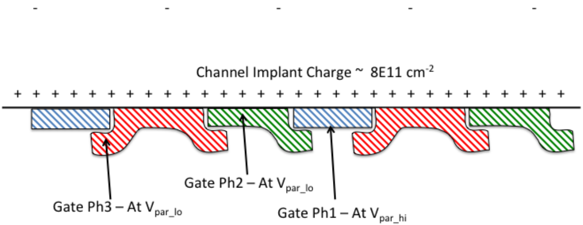
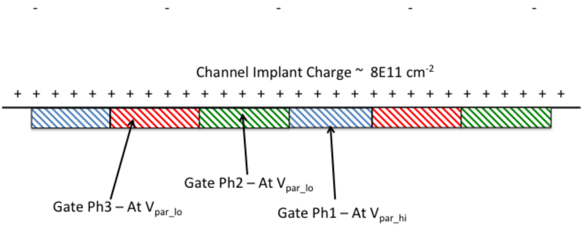
- Each successive step down is ≈ 8 times faster than the next larger grid.
- In practice, I iterate the coarsest grid to machine precision, then 2X fewer iterations at each finer grid, ending with ≈ 50 iterations at the finest grid.
- A single Vcycle suffices to converge to $1\mu\mathrm{Volt}$ accuracy.

Cross Section in Column Direction

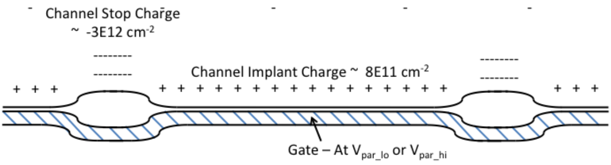


Actual Situation.

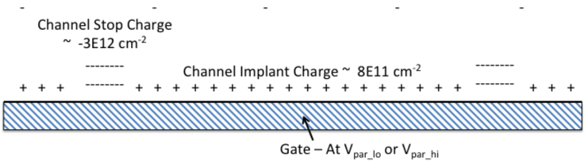


As modeled.

Cross Section in Row Direction

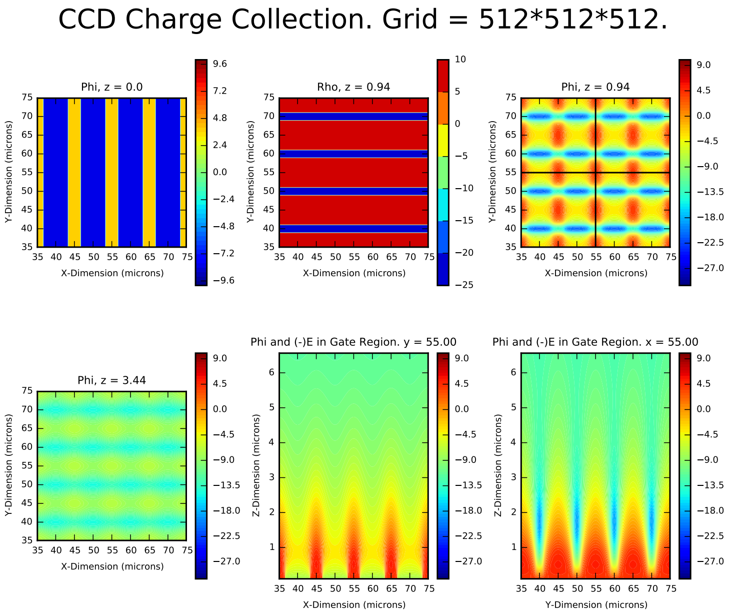


Actual Situation.

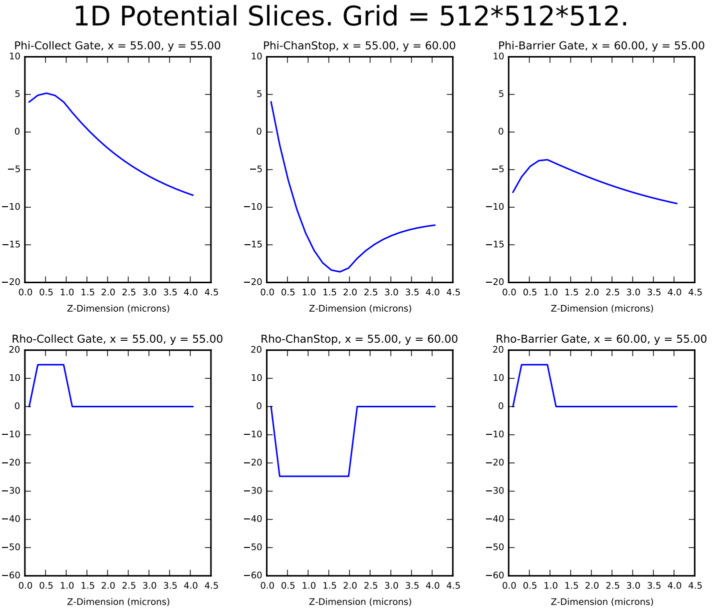


As modeled.

Pixel Region - All Pixels Empty

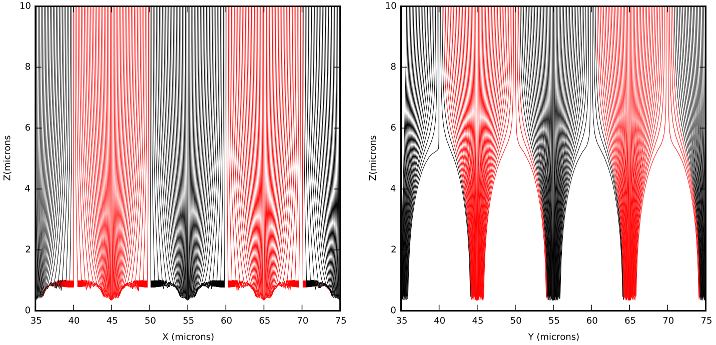


Pixel Region - All Pixels Empty

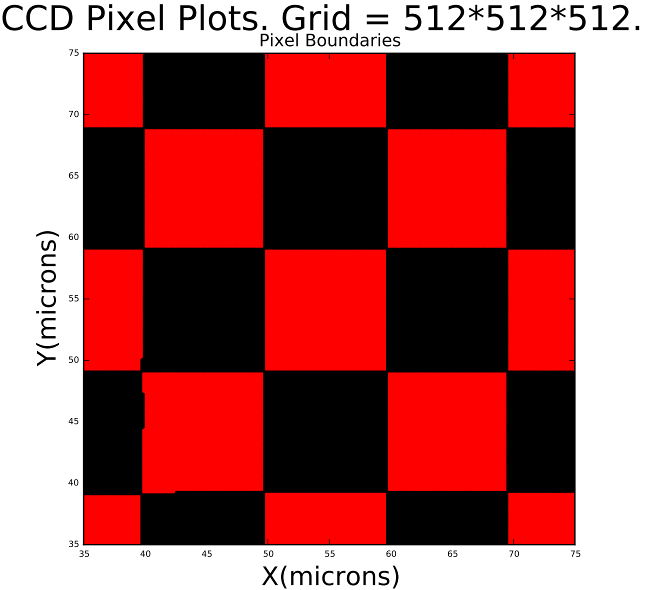


Pixel Region - All Pixels Empty

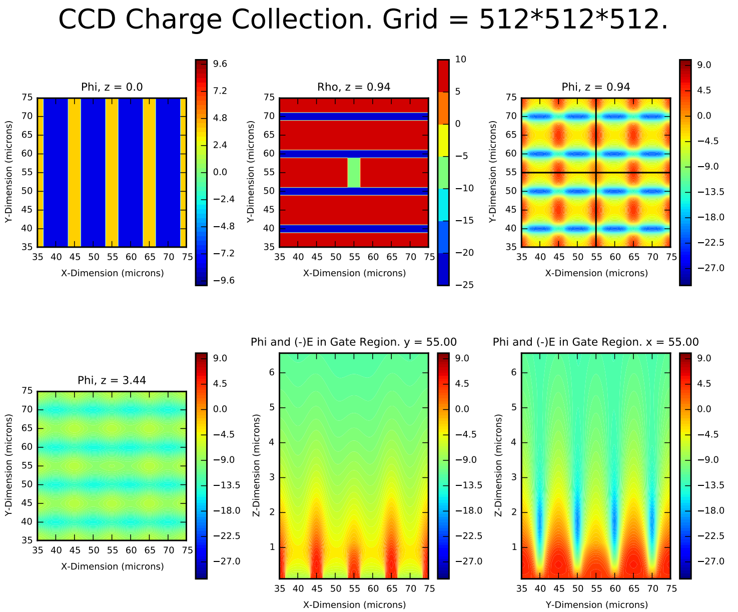
Electron Path Plot - Vertical Zoom = 4



Pixel Region - All Pixels Empty

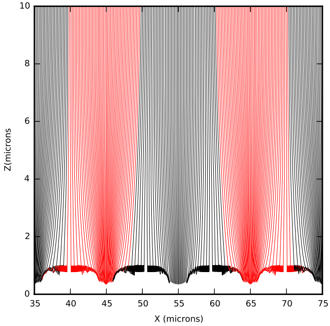


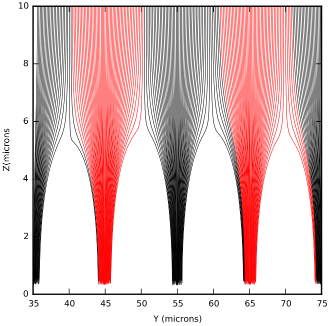
Pixel Region - One Pixel Holding 100K e-



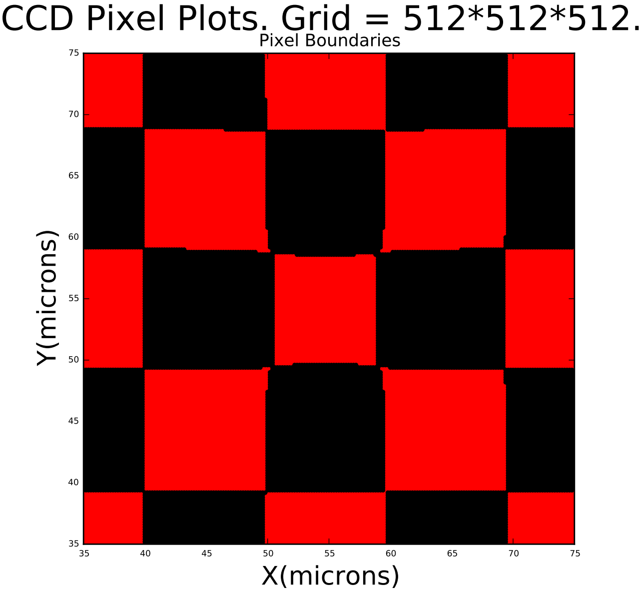
Pixel Region - One Pixel Holding 100K e-

Electron Path Plot - Vertical Zoom = 4

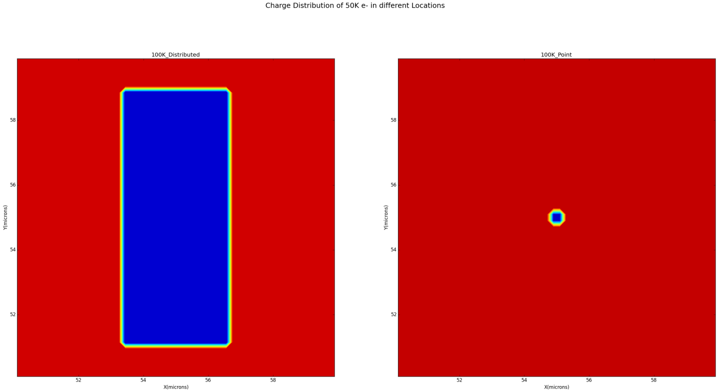




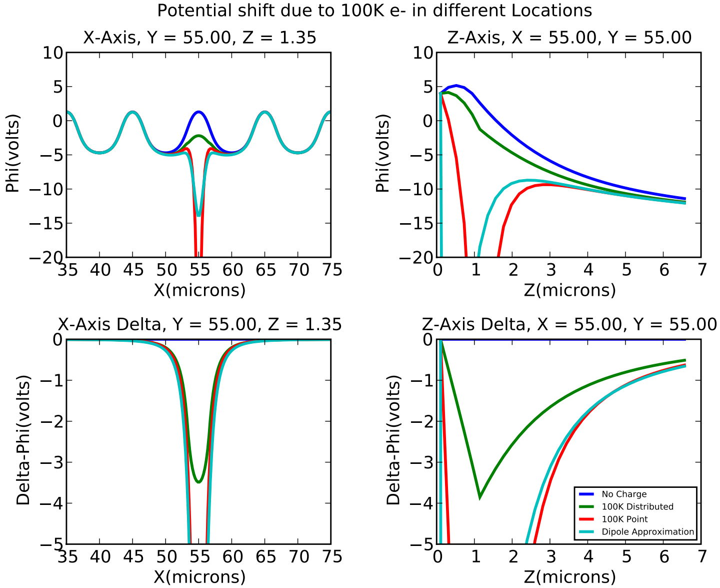
Pixel Region - One Pixel Holding 100K e-



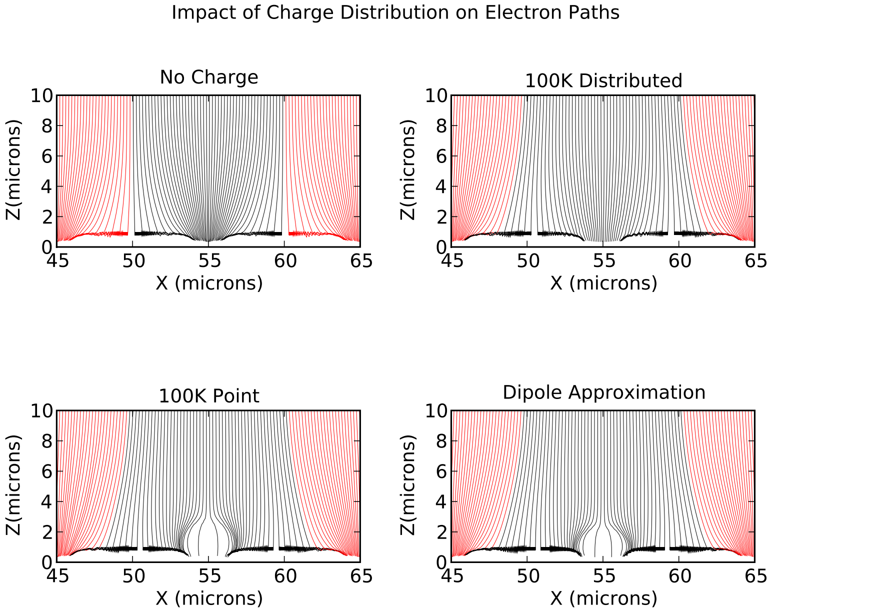
Test of Current Dipole Model - Charge Distribution



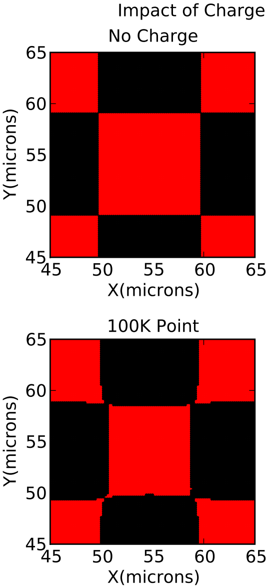
Test of Current Dipole Model - Potentials



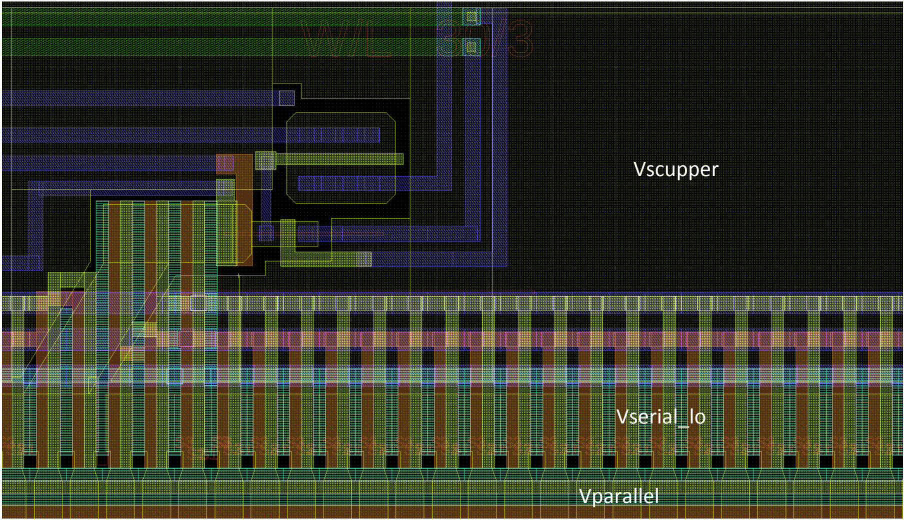
Test of Current Dipole Model - e- Paths



Test of Current Dipole Model - Pixel Shapes

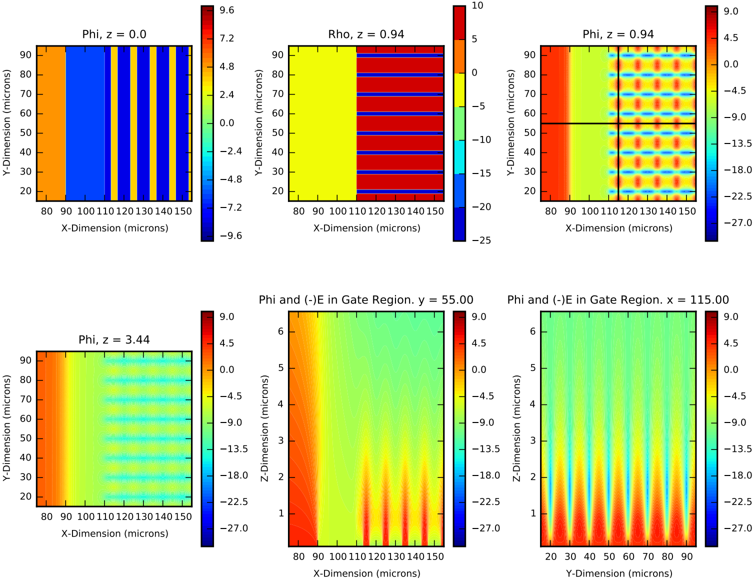


Array Edge Layout



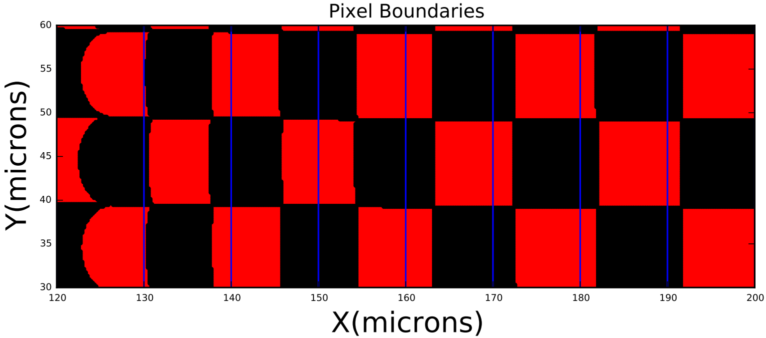
Array Top Edge Simulation

CCD Charge Collection. Grid = 1024*512*512.

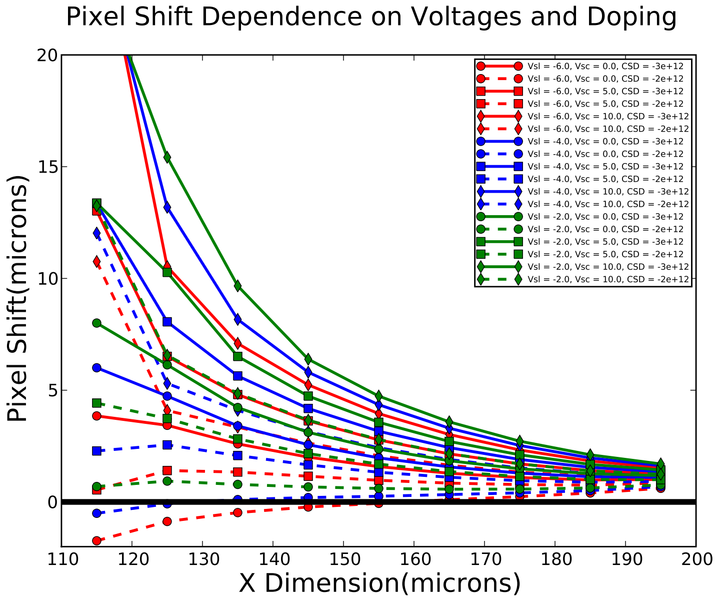


Array Top Edge Pixel Shift

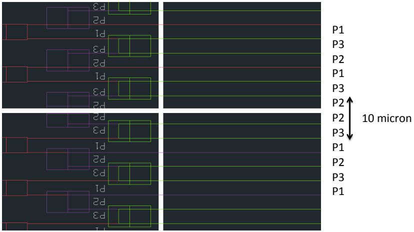
CCD Pixel Plots. Grid = 1024*512*512.



Array Top Edge - Impact of Surrounding Voltages



Array Center - Impact of Collecting Phase



- Top and bottom arrays are mirror images.
- If P3 is the collecting phase, then the arrays are on a regular 10 micron spacing.
- If P2 is the collecting phase, one array has a -6.7 micron shift relative to the other.
- If P1 is the collecting phase, one array has a +6.7 micron shift relative to the other.
- P3 is the best choice.
    - Is this widely known?
    - Is the e2V chip the same way?

Limitations and Next Steps

- Limitations
  - Charge distributions are assumed, rather than solved self-consistently.
  - Channel stop region is uncertain (fully depleted or not?).
  - Carrier transport by drift only, no diffusive scatter.
- Next Steps
  - Start taking measurements to validate and calibrate the model.
  - Make the code available for others to use and critique.
  - Work with Pho-Sim and SAWG teams to improve dipole model.
  - Check channel stop region with a true device simulator (SLAC?).