Poisson Equation Solutions for Thick Fully-Depleted CCDs

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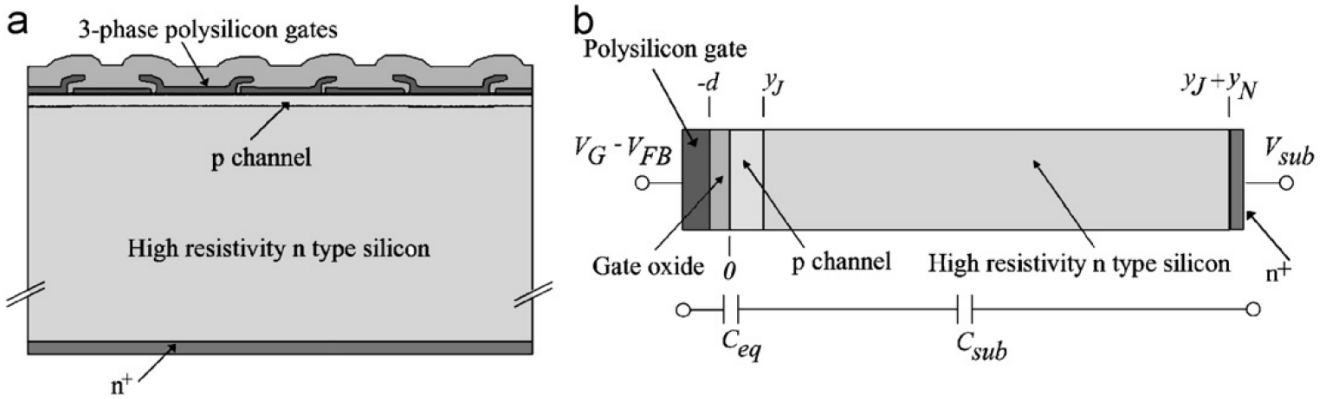
Outline

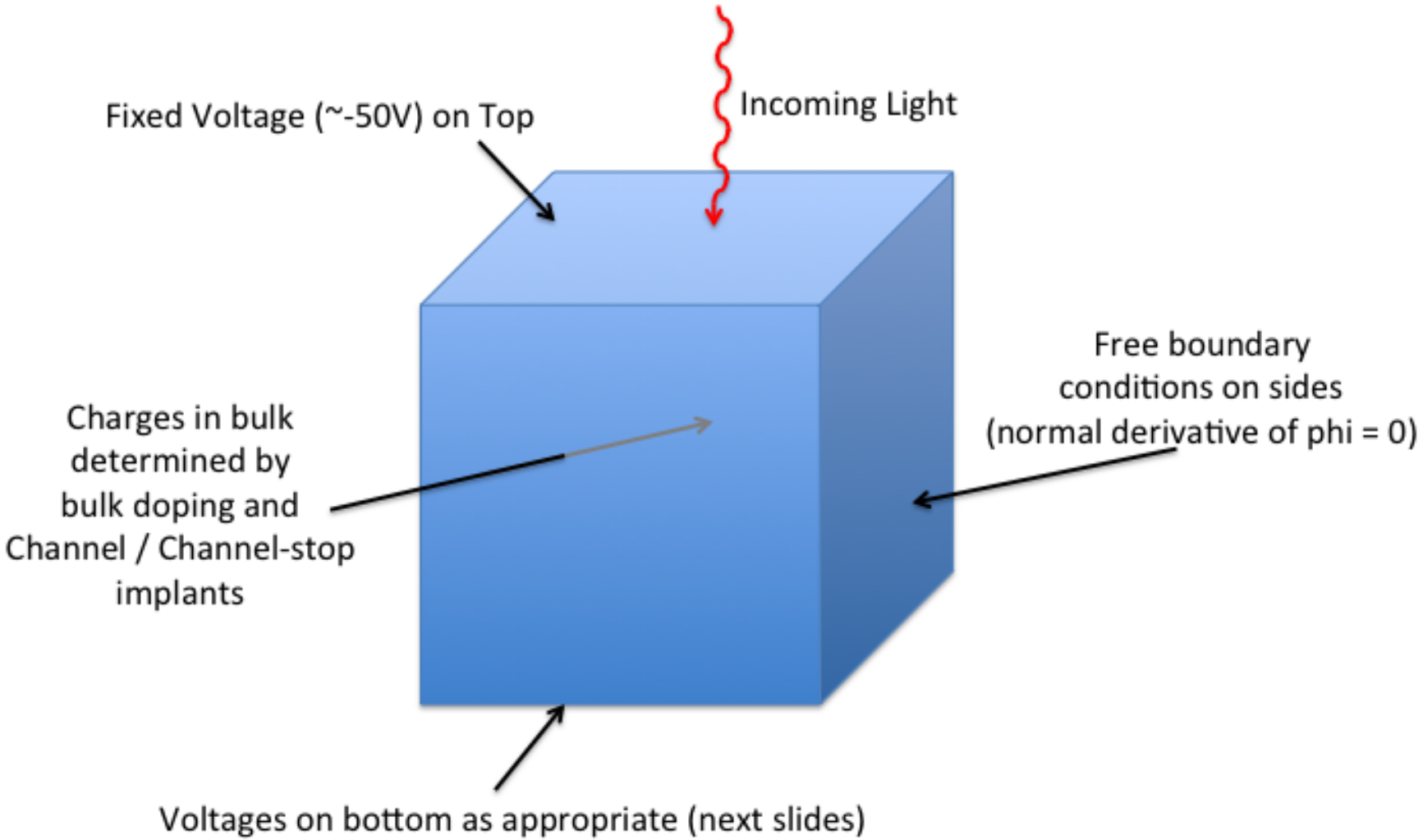
- Introduction
- Solving Poisson's Equation on a Grid
- Boundary Conditions
- Baseline Solution
- How good is our Current Dipole Model?
- Array Edge
- Incorporation into PhoSim
- Limitations and Next Steps

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

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

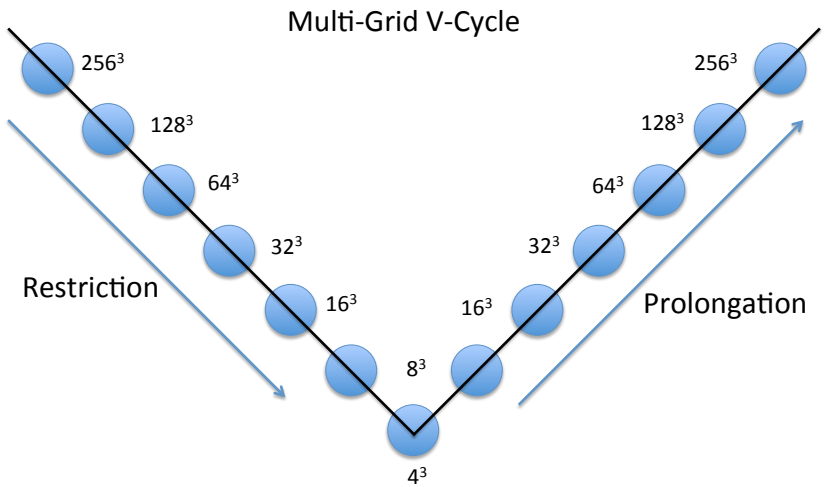
$$\frac{\partial^2 \varphi_{i,j,k}}{\partial x^2} = \frac{(\varphi_{i+1,j,k} - \varphi_{i,j,k}) - (\varphi_{i,j,k} - \varphi_{i-1,j,k})}{h^2}$$

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

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

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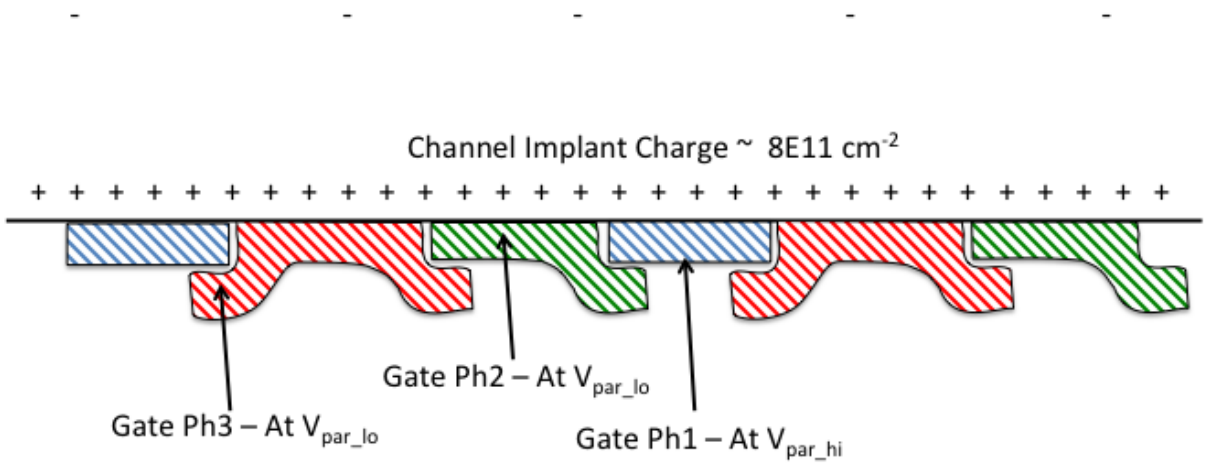
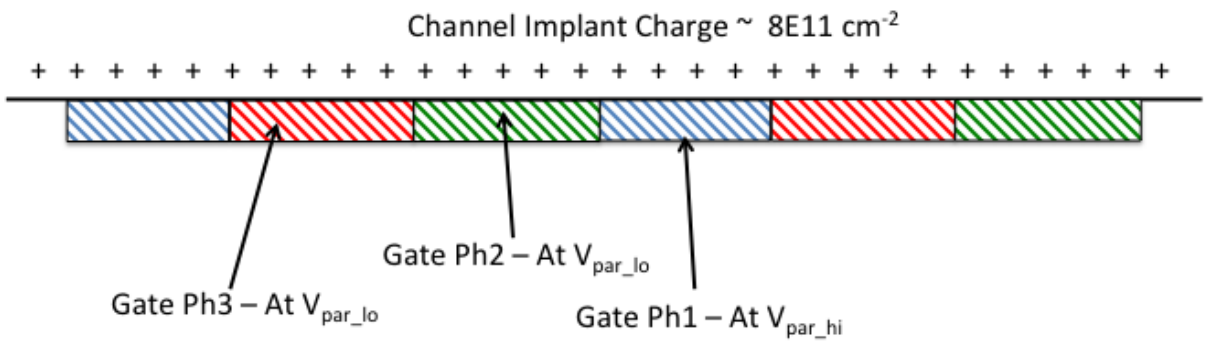
- Each successive step down is ≈ 8 times faster than the next larger grid.
- In practice, I iterate the coarsest grid to machine precision, then 2X fewer iterations at each finer grid, ending with ≈ 50 iterations at the finest grid.
- A single Vcycle suffices to converge to $1\mu\mathrm{Volt}$ accuracy.

Cross Section in Column Direction

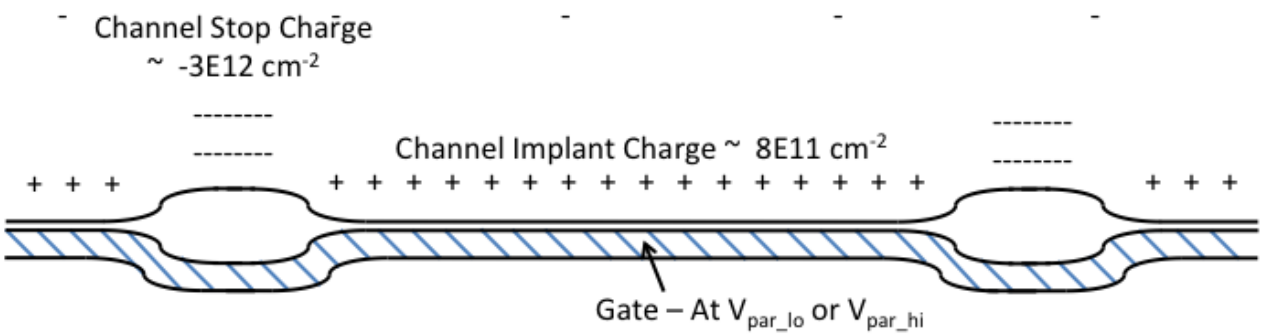


Actual Situation.

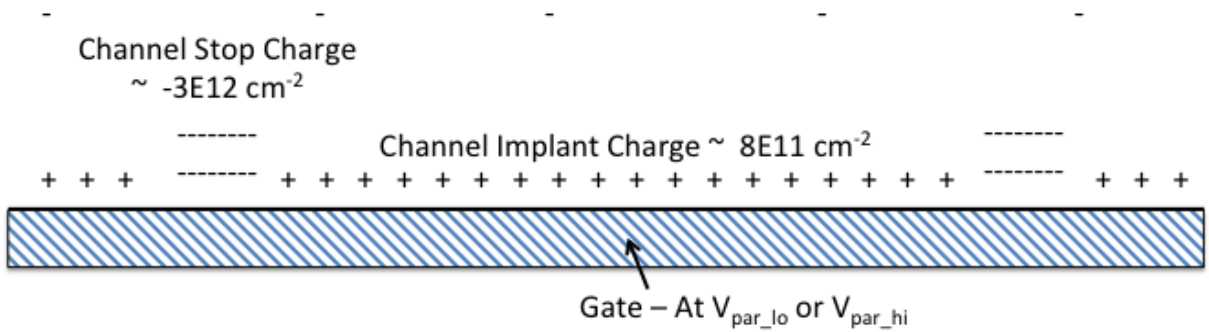


As modeled.

Cross Section in Row Direction



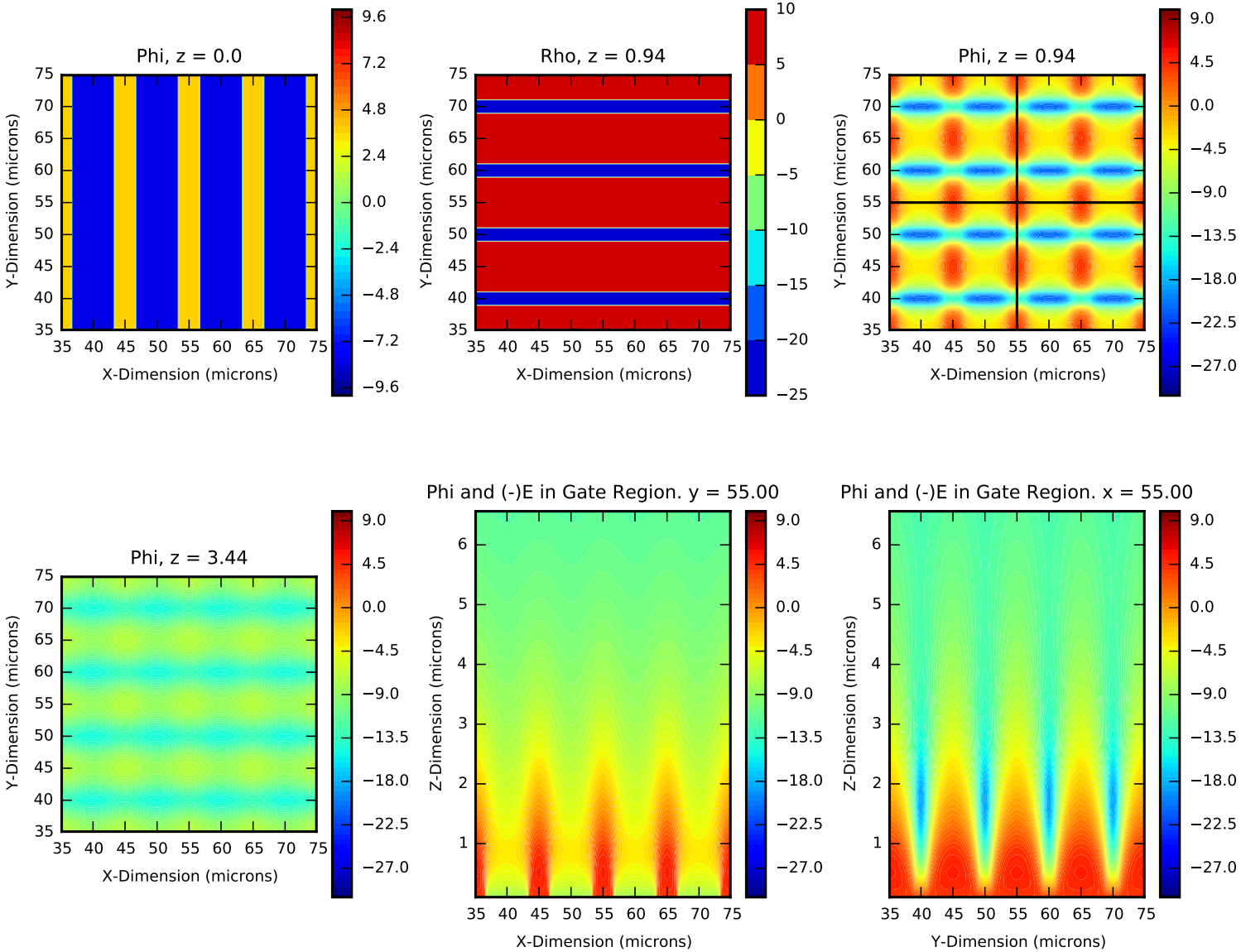
Actual Situation.



As modeled.

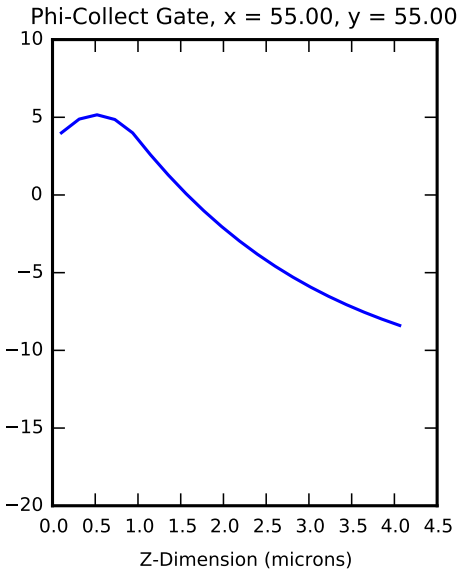
Pixel Region - All Pixels Empty

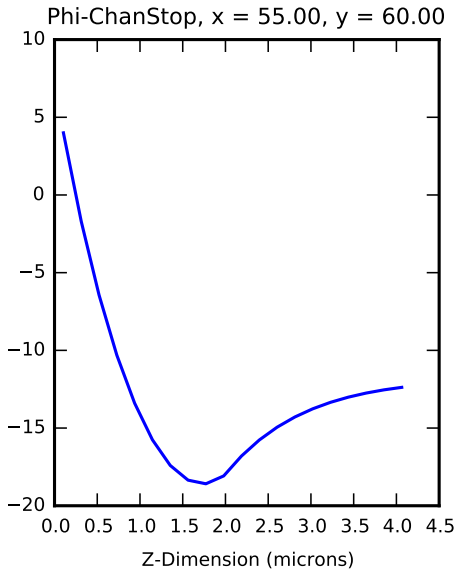
CCD Charge Collection. Grid = 512*512*512.

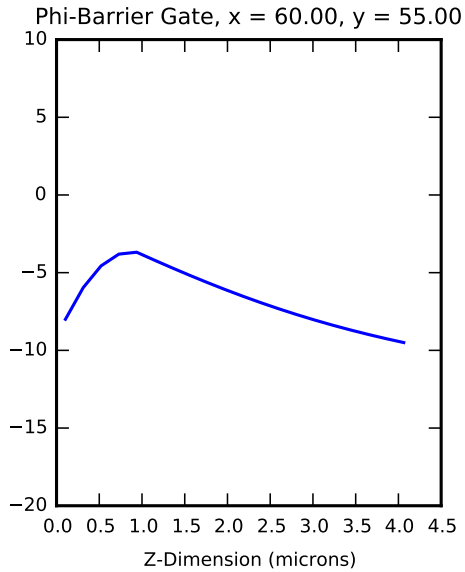


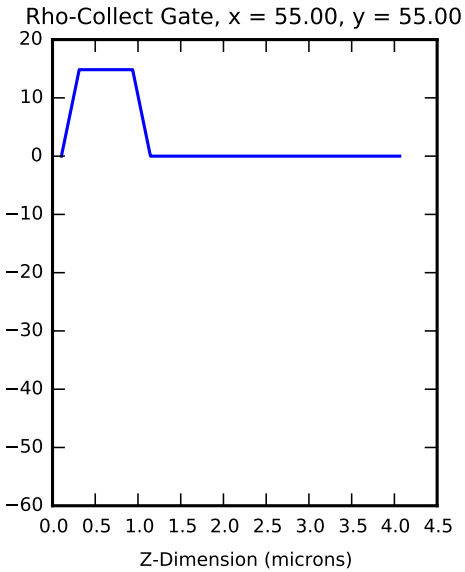
Pixel Region - All Pixels Empty

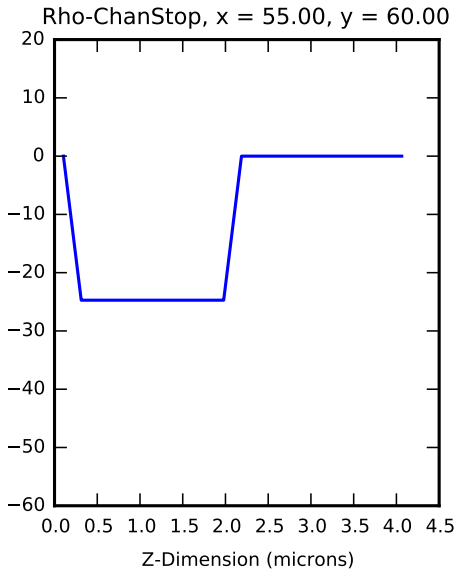
1D Potential Slices. Grid = 512*512*512.

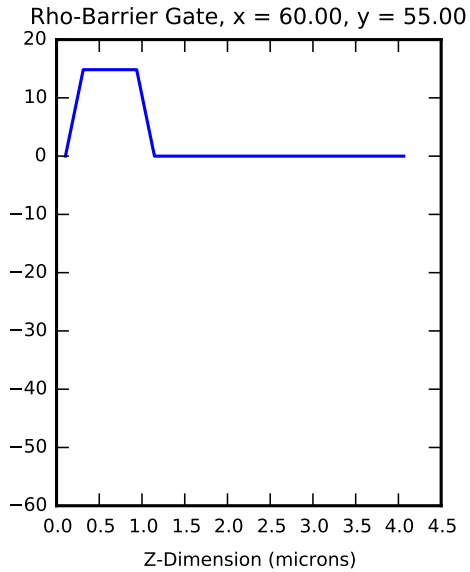






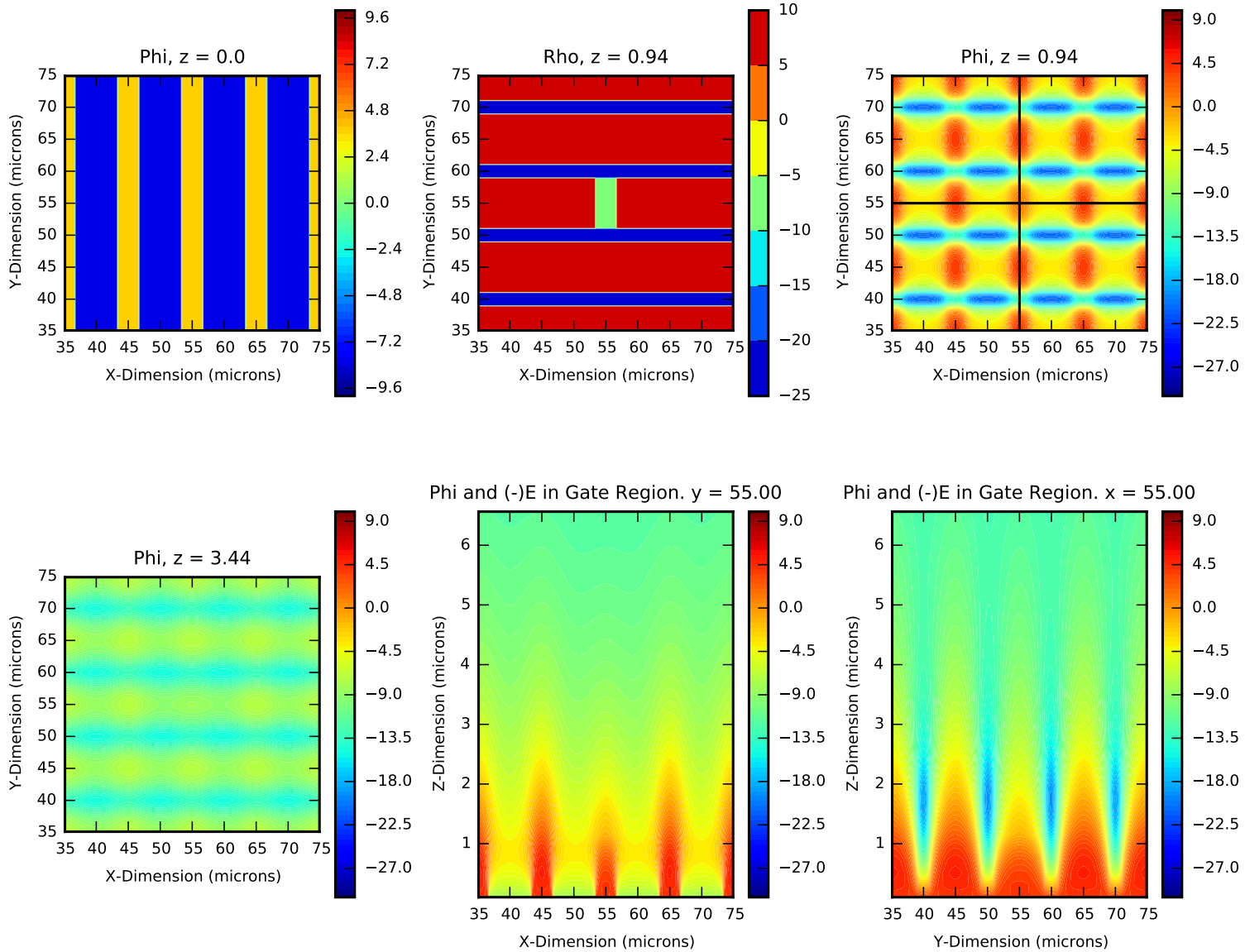




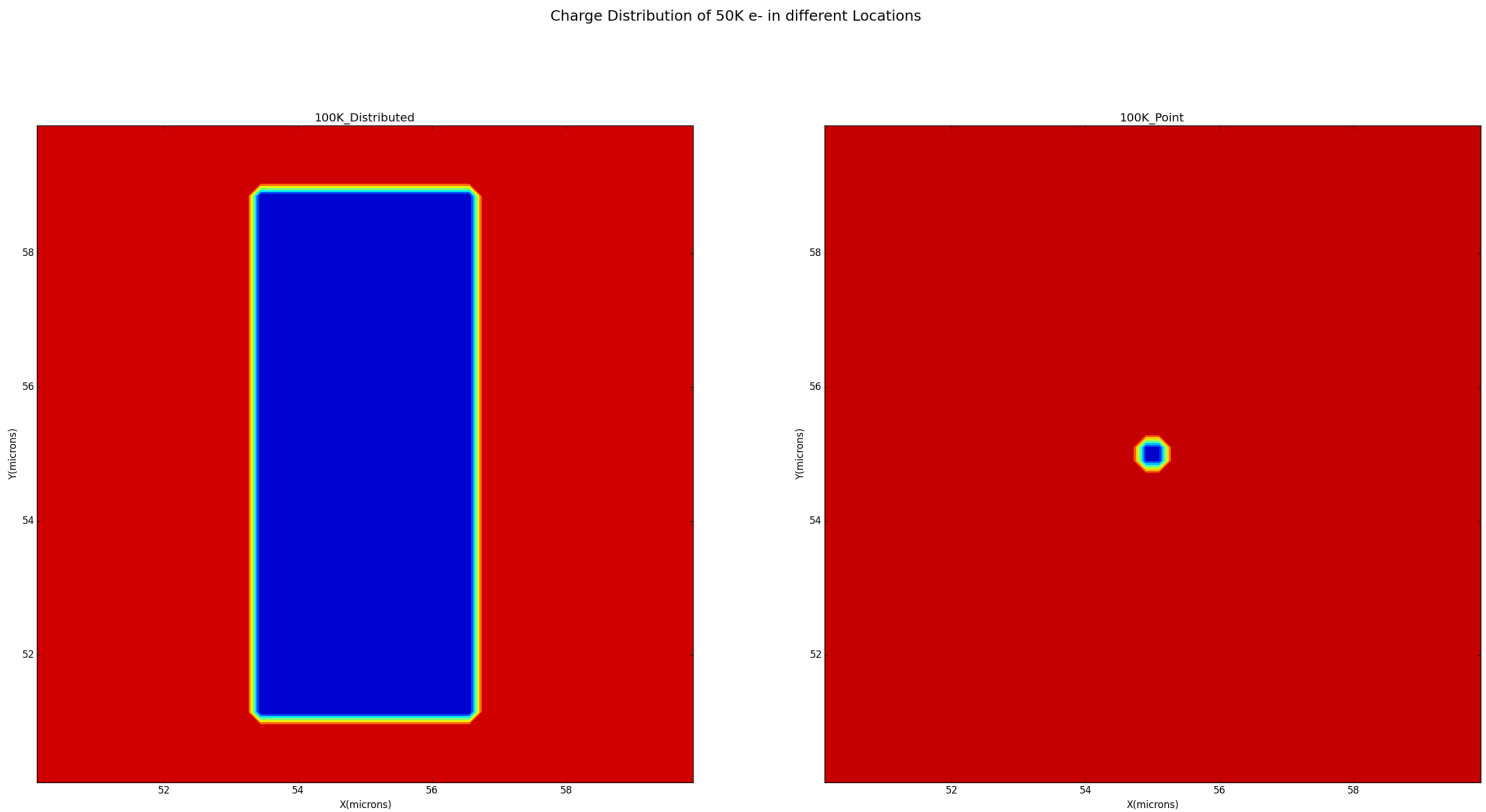


Pixel Region - One Pixel Holding 100K e-

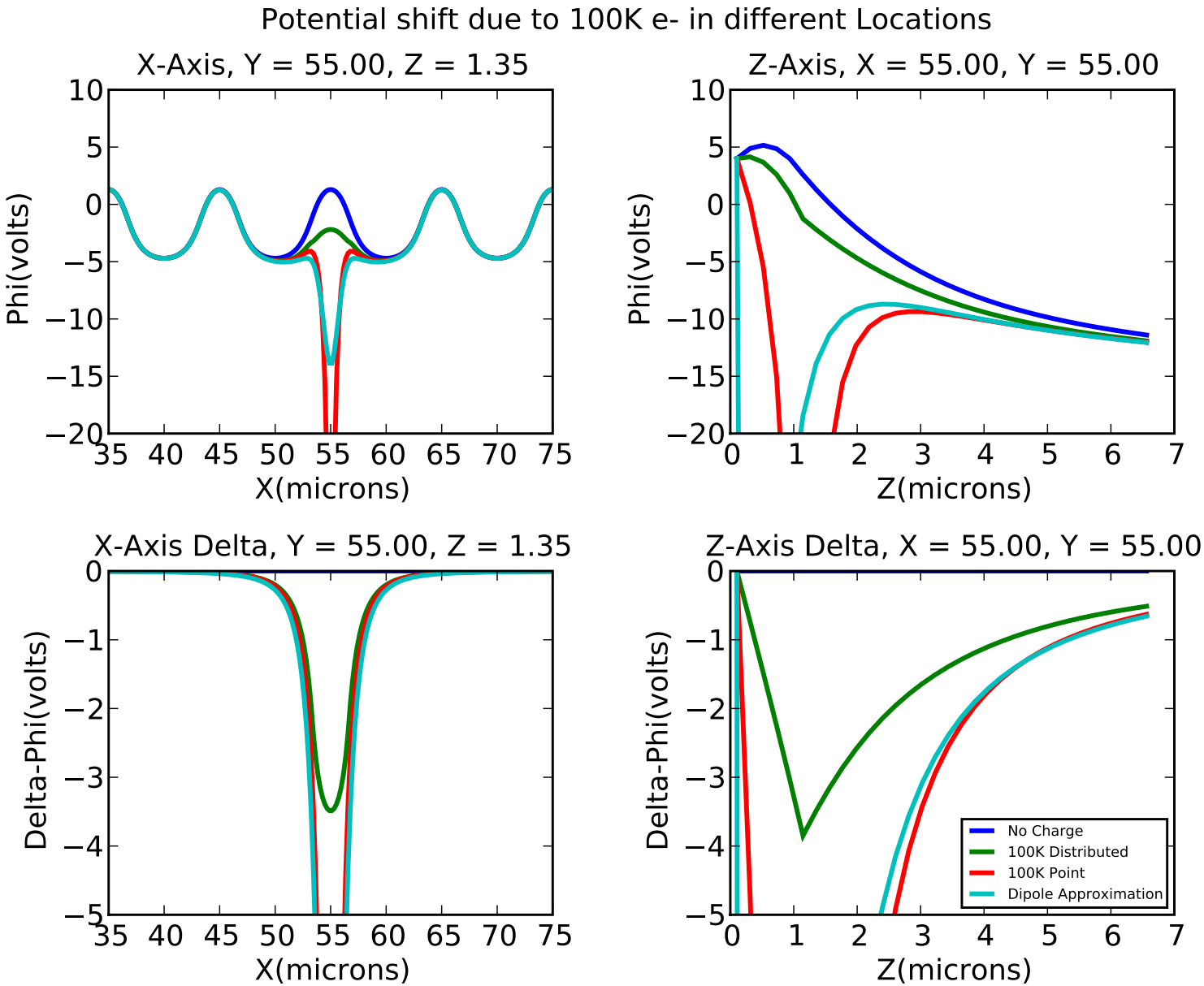
CCD Charge Collection. Grid = 512*512*512.



Test of Current Dipole Model - Charge Distribution

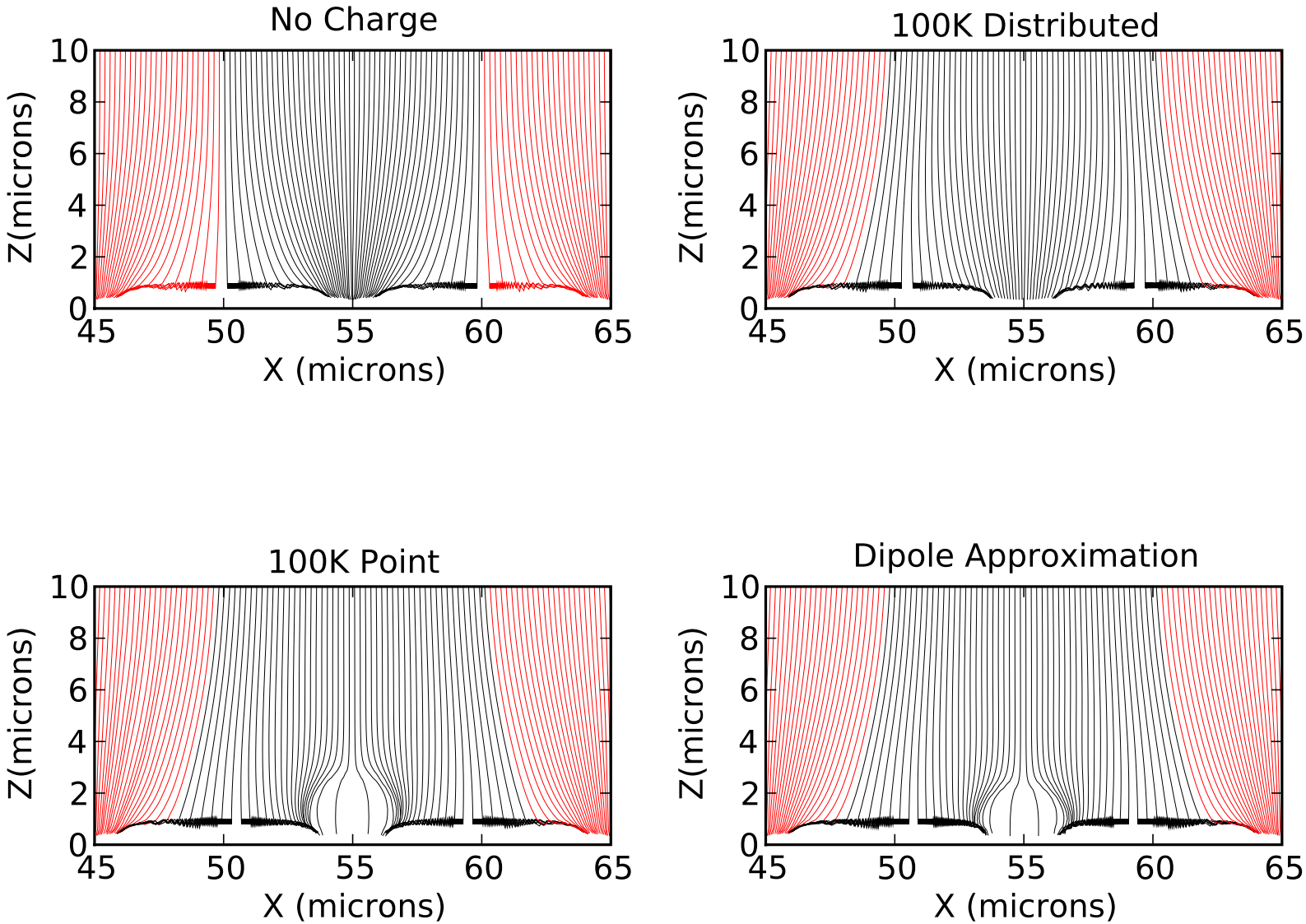


Test of Current Dipole Model - Potentials

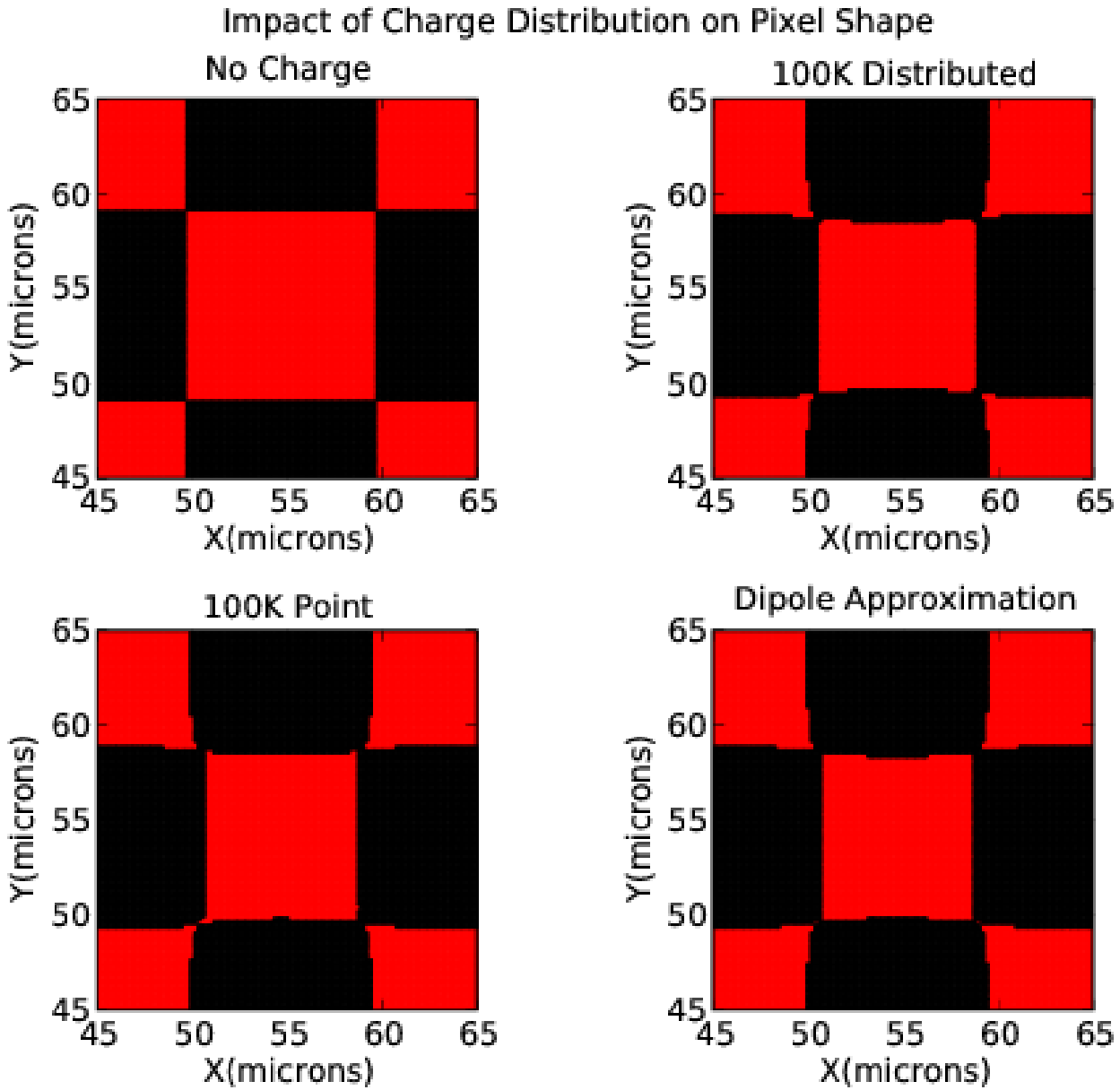


Test of Current Dipole Model - e- Paths

Impact of Charge Distribution on Electron Paths

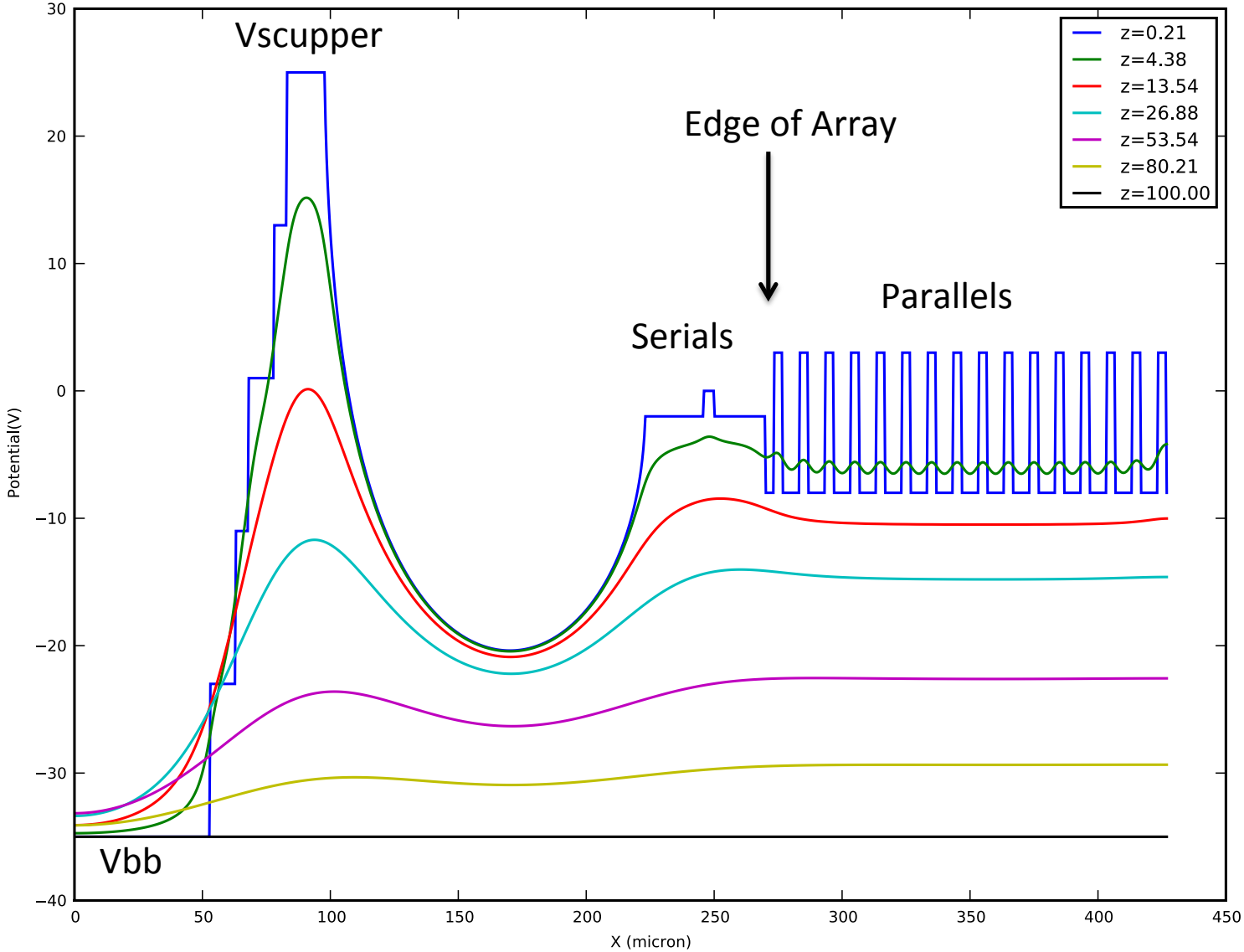


Test of Current Dipole Model - Pixel Shapes



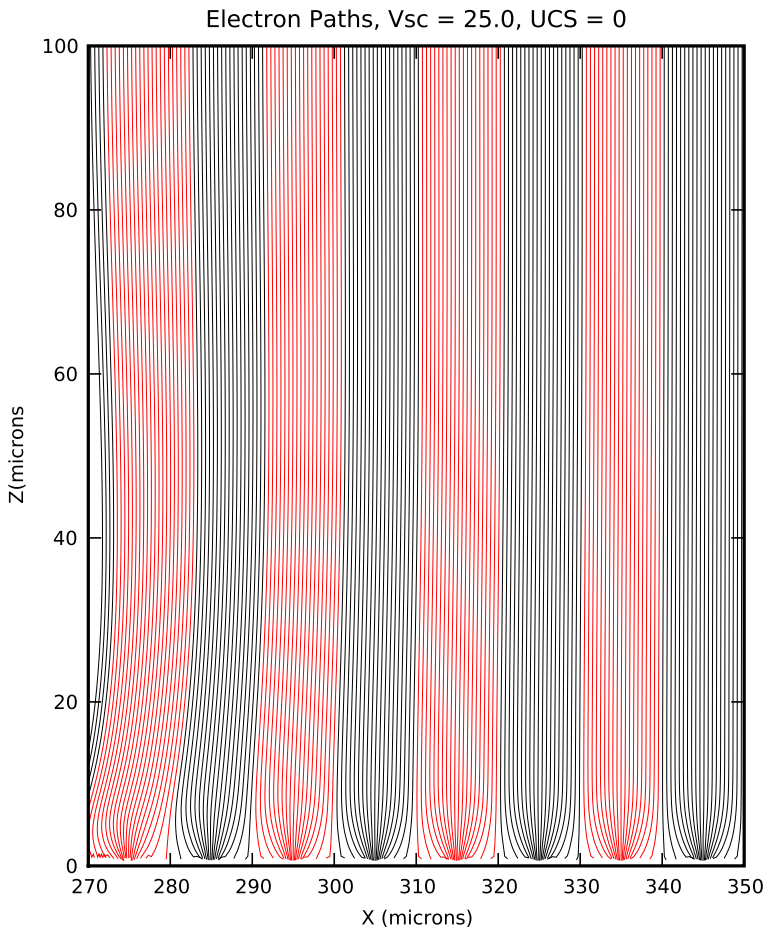
Potential Simulation at Array Edge

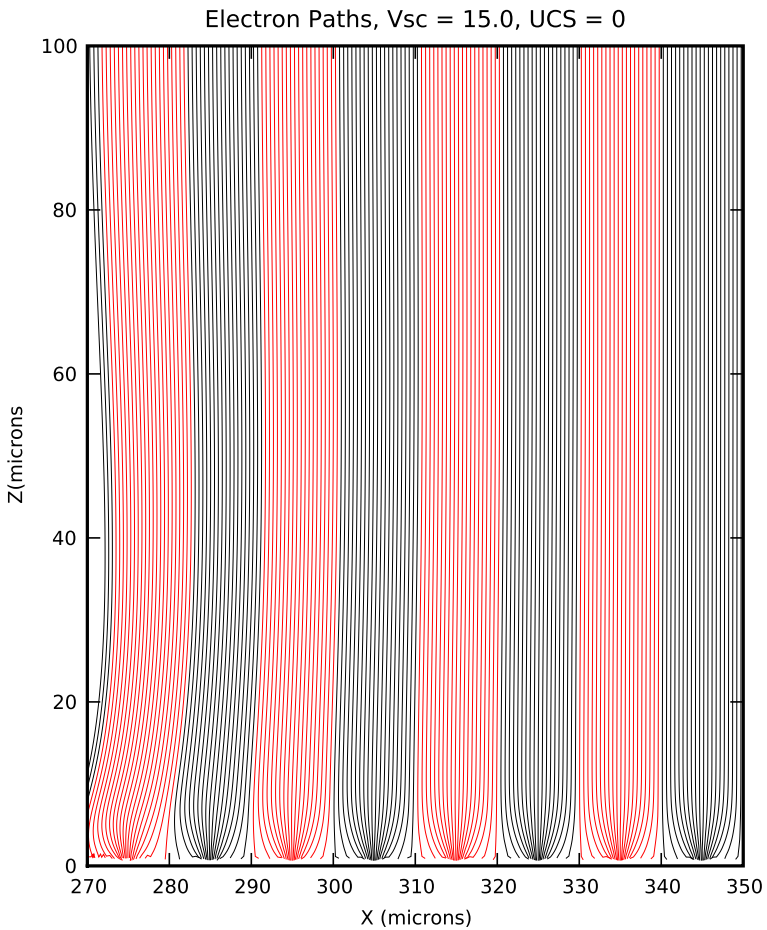
Array Center Potentials. Grid = 1024*256*256.



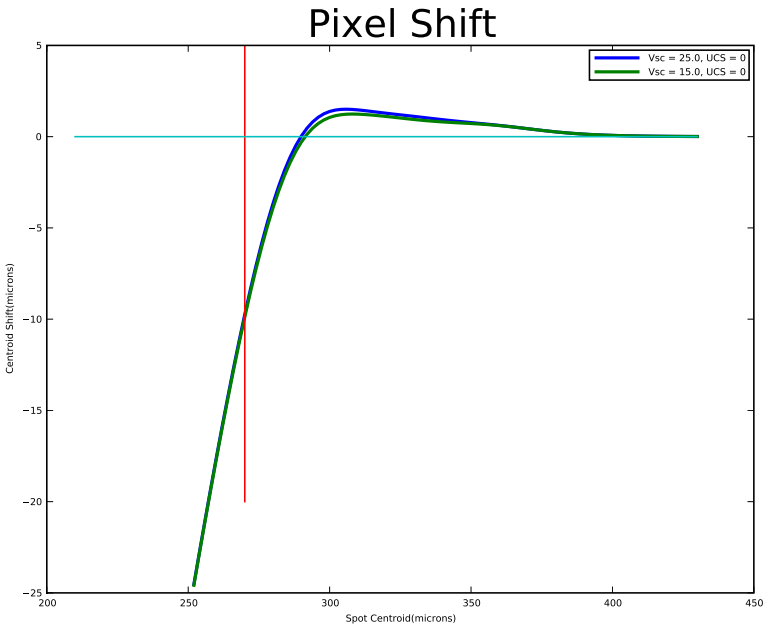
Array Edge Electron Paths

Electron Path Dependence on Voltages and Doping

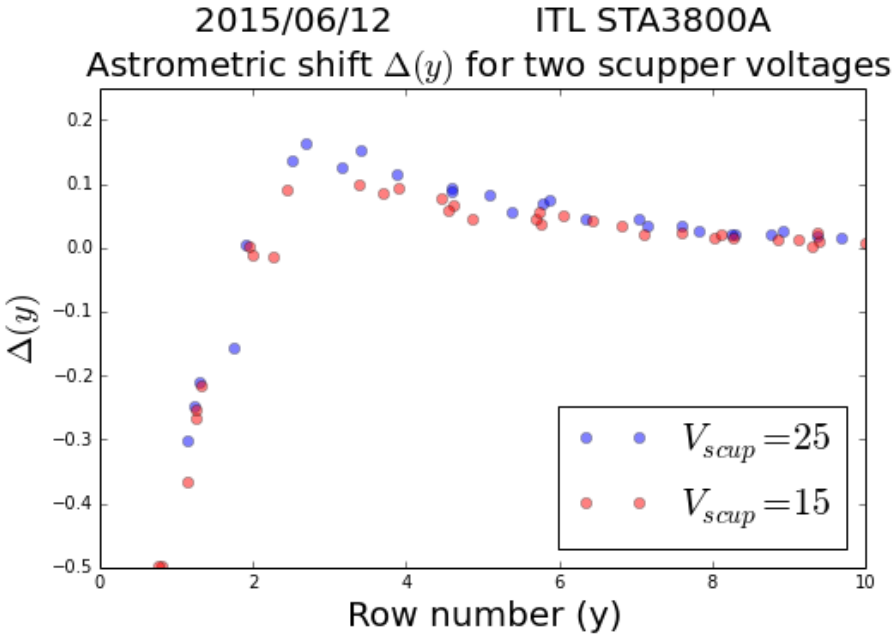




Array Edge Astrometric Shift



Simulation



Measurements (with Andrew Bradshaw)

PhoSim

- Have looked at incorporating into PhoSim.
- Electron transport calculations are much too slow.
- PhoSim (as I understand it) builds a look-up table that shifts the electron from point of creation to point of collection, based on charge in current pixel.
- Tried doing this, but electron path depends on charges stored in many surrounding pixels.
- Ideas?

Limitations and Next Steps

- Code is available at this site (https://github.com/craiglagegit/Poisson_CCD).
- 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 (can be added).
- Next Steps
  - Continue taking measurements to validate and calibrate the model.
  - Possible to incorporate into PhoSim?
  - Check channel stop region with a true device simulator (SLAC?).