Physics Models and Simulations of Sensors

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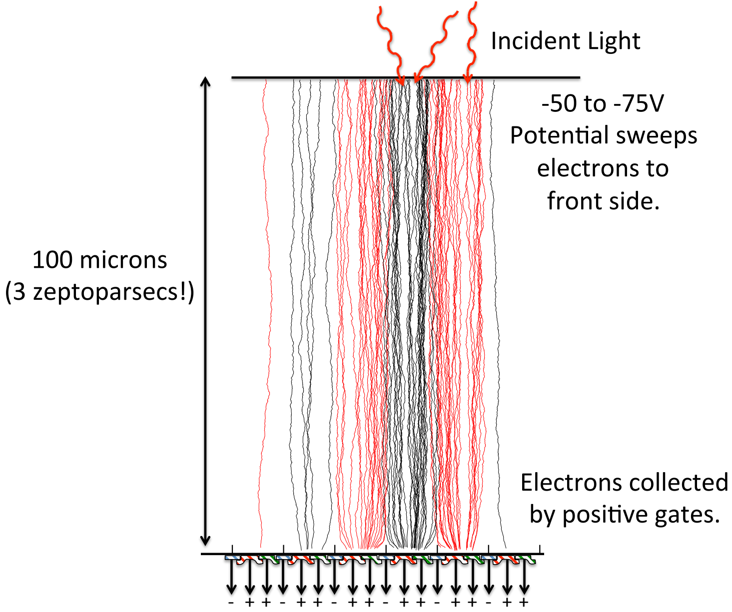
Acknowledgements:
Tony Tyson, Andrew Bradshaw, Kirk Gilmore, Perry Gee

Outline

- Introduction
- Why build a physics-based model of the sensor?
- Simulating the sensor.
- Simulation successes:
  - Edge effects.
  - Diffusion effects.
  - Brighter-Fatter effect
    - Direct measurements
    - Correlation measurements
- Conclusions and next steps.

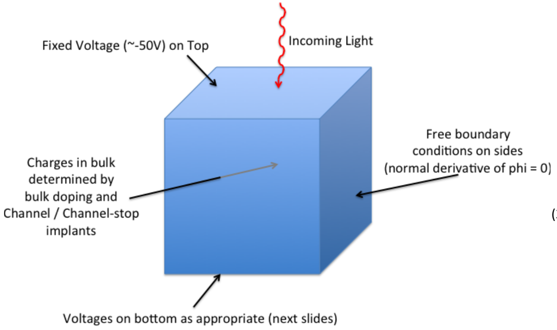
The last 3 zeptoparsecs!

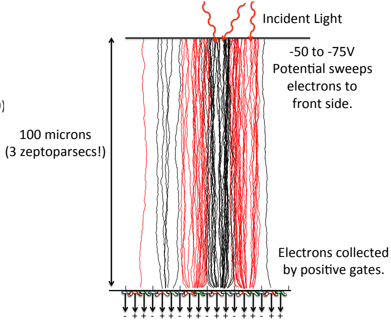


Why build a physics-based simulation of the sensor?

- Allows one to turn physical effects (such as diffusion) on and off.
- Allows study of small effects without interference from extraneous problems:
  - Noise
  - Crosstalk
  - Optical Distortion, ...
- Allows study of the impact of sensor differences:
  - Doping
  - Thickness
  - Vendor, ...
- Allows study of the impact of environmental effects:
  - Temperature
  - Voltage, ...

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





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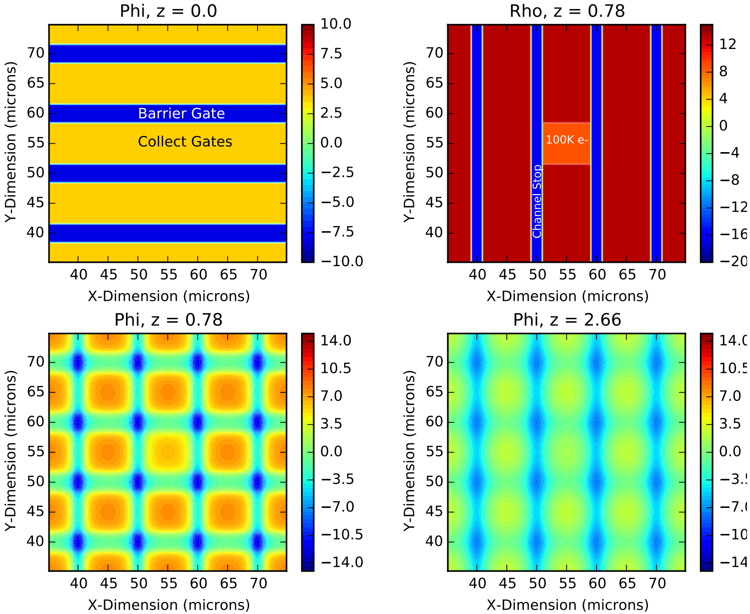
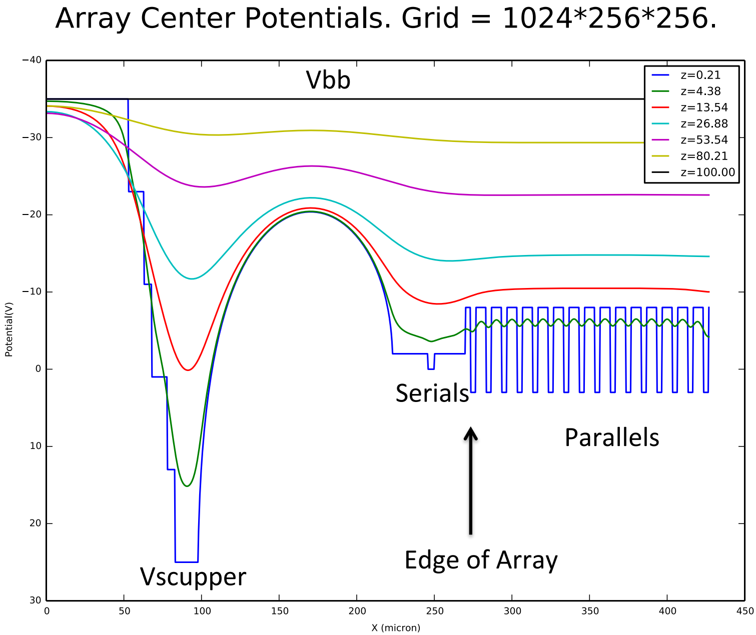
- $100\mu\mathrm{m}$ Cube. - 10 X 10 pixels in X and Y.
- 32 grid cells per pixel - cell size $=$ 0.31 μ .
- A B-F run with 256 spots, 3 million electrons (300,000 in central spot) takes about 6 hours.

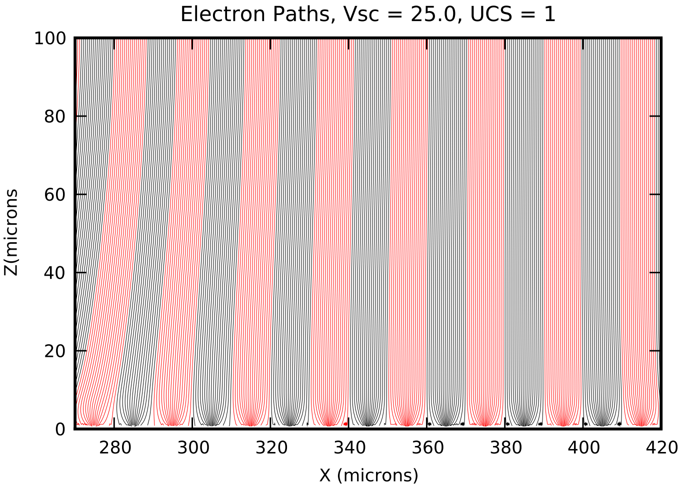
Pixel Array Summary Plot



Potential Simulation at Array Edge

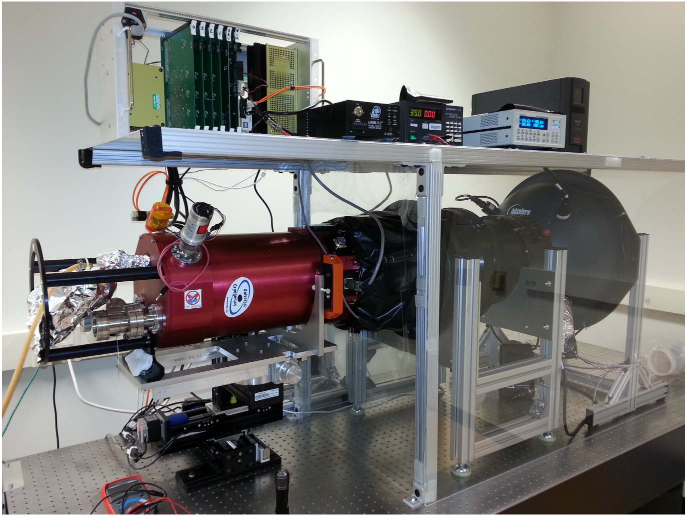


Array Edge Electron Paths



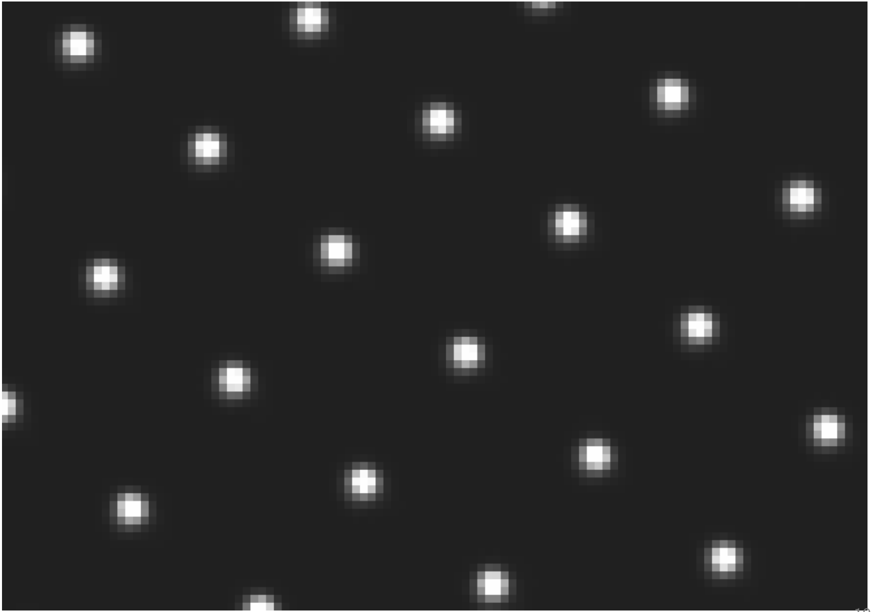
Shift at edge of array greater than 1 pixel!

LSST Optical Simulator

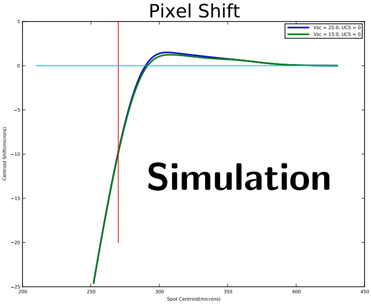


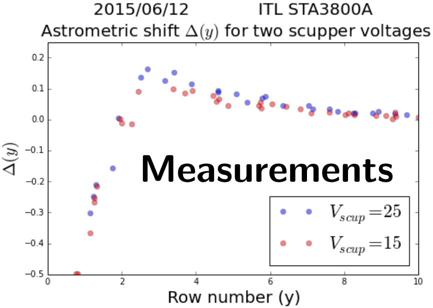
Tyson, et.al., "The LSST Beam Simulator", SPIE 9154-67 (2014), arXiv:1411.5667.

Typical Image of 30 micron Spots



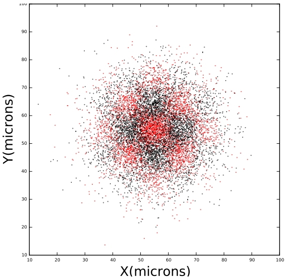
Array Edge Astrometric Shift

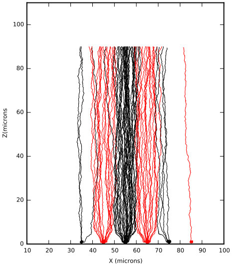




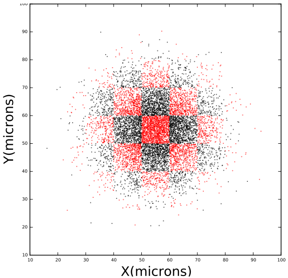
Bradshaw, et al., JINST 10C4034B (2015), arXiv:1507.02683.

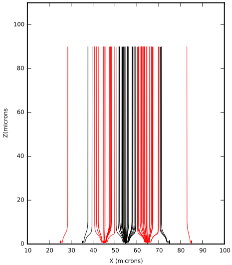
Impact of electron diffusion





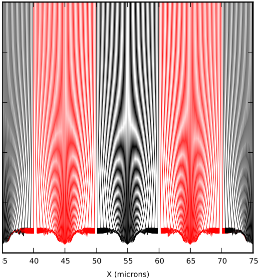
Theoretical Diffusion

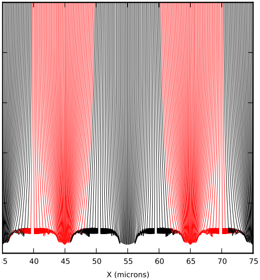


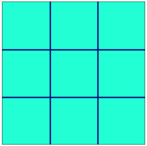


Diffusion turned off

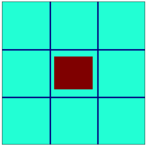
Basics of the Brighter-Fatter Effect







Pixel empty of charge



Pixel with 100K e-

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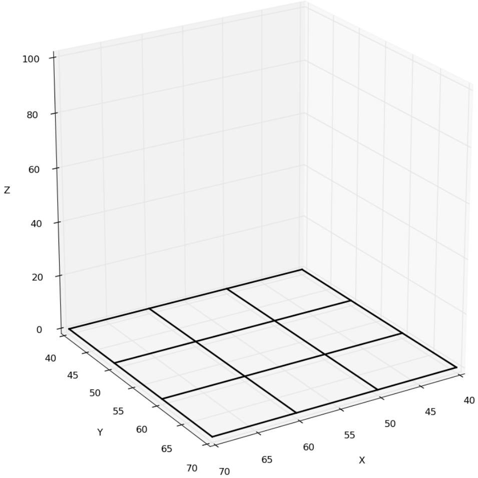
- Electrons stored in the potential well repel incoming electrons and push them into surrounding pixels.

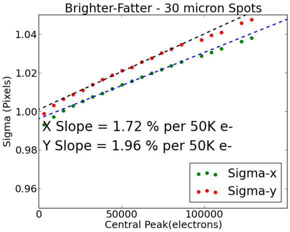
Simulation Strategy for B-F effect.

- 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 (typical 256), each with a different central location.

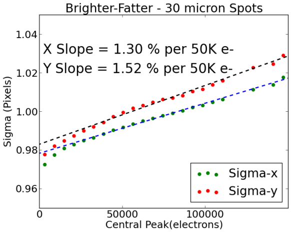
Movie of Pixel Filling - First 10,000 Electrons



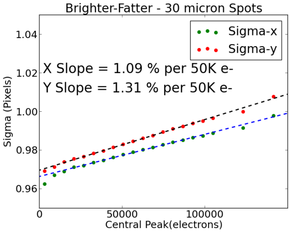
B-F Slopes vs VBB, Measurements and Simulations - Assumed Charge Location



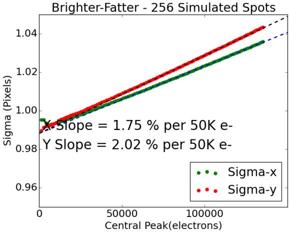
VBB:-30V - Measured



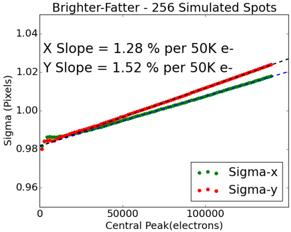
VBB:-45V - Measured



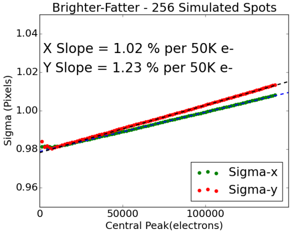
VBB:-60V - Measured



VBB:-30V - Simulated

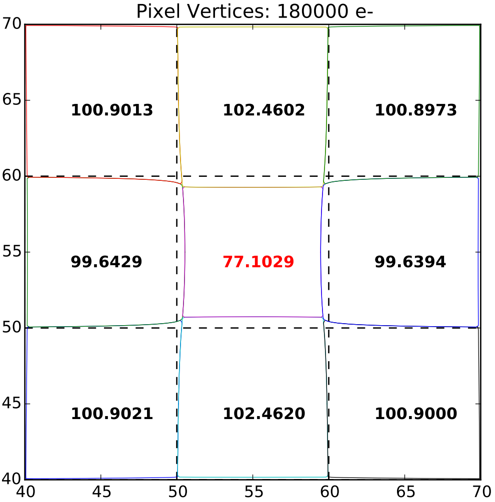


VBB:-45V - Simulated



VBB:-60V - Simulated

B-F Effect and pixel correlations in CCD flats.



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

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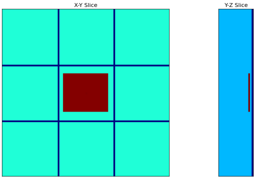
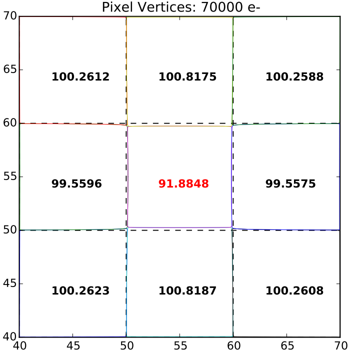
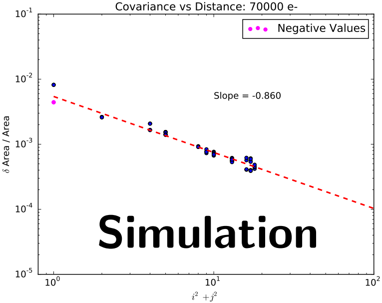
- A pixel that receives an excess of electrons causes surrounding to pixels grow slightly in area, leading them to also receive a slight excess in electrons.

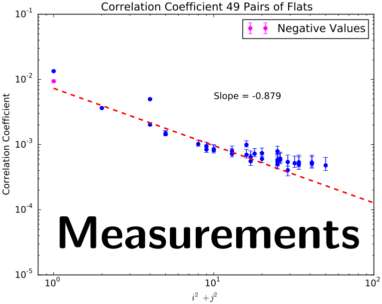
Pixel Areas and Correlations - 70,000 e- in Central Pixel



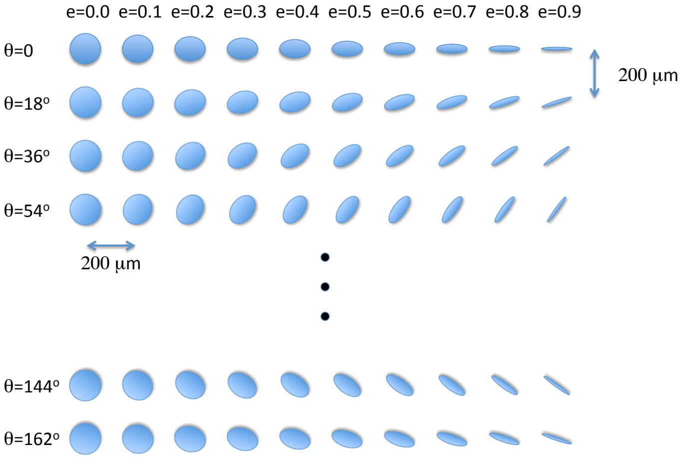
Charge Distribution (Assumed)







Preliminary Future Plans for Spot Masks



- A range of ellipses with different ellipticities and orientations.
- Image, extract shapes with dm stack and compare to input.
- Future masks will include mock galaxies with different light profiles.

Conclusions and Next Steps

- Physics-based simulations are a powerful tool for studying astrometric and photometric distortions in CCDs.
- We are having good success in simulating some important effects:
    - Edge effects.
    - Brighter-Fatter effects.
    - Diffusion effects.
- Future plans include:
    - Continued refinement of the physics-based model with additional measurements:
      Voltages, Collecting phases, Saturation, ...
    - Extension to both CCD vendors.
    - More complex masks to allow tests with simulated stars and galaxies.
    - Incorporation of the learning into PhoSim.