BERKELEY LAB Lawrence Berkeley National Laboratory

U.S. DEPARTMENT OF ENERGY

T3-based MAPS’ in CMOS 130nm

CPIX14 – Bonn – September 14-16, 2014

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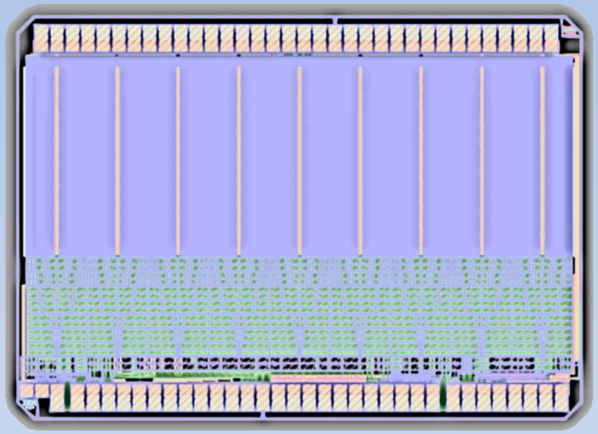
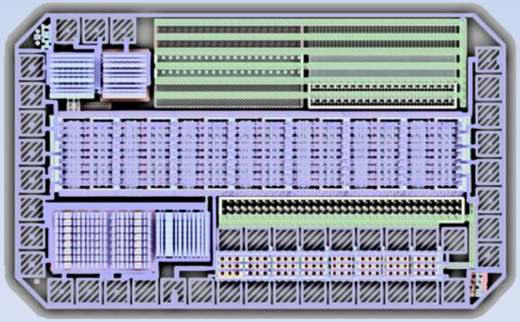
September 16, 2014

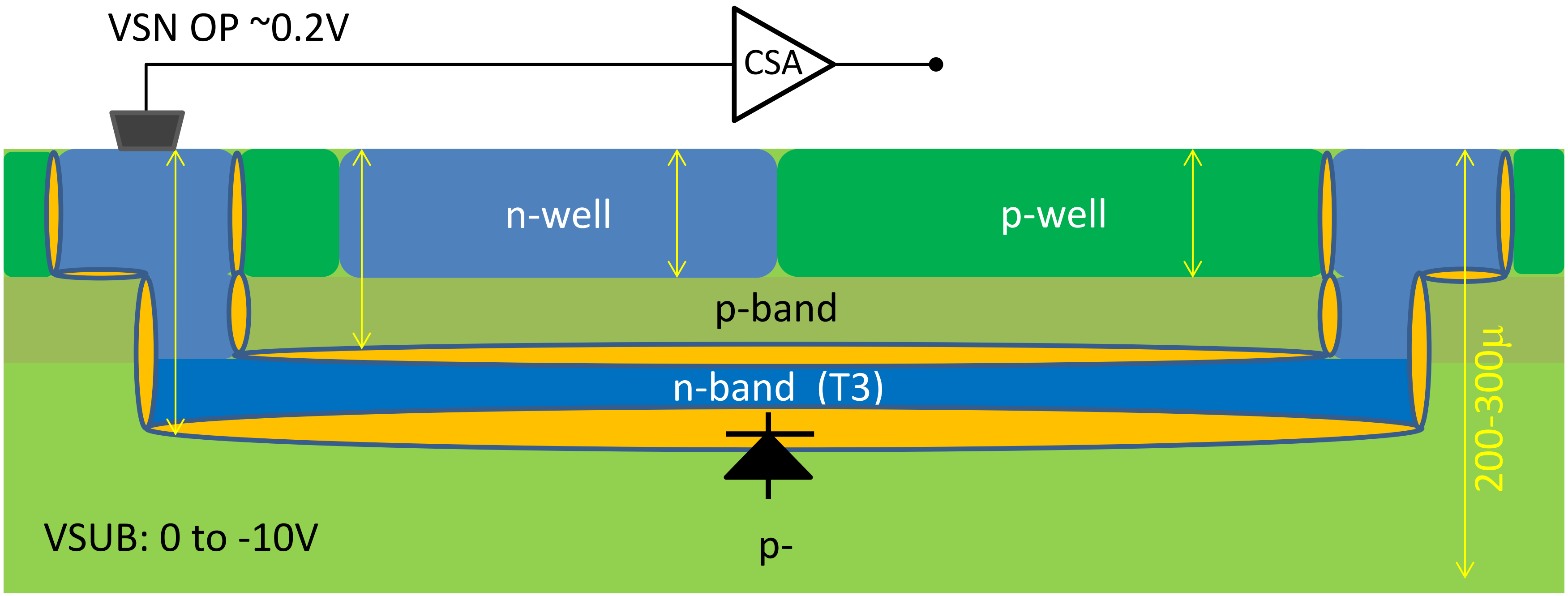
Outline

- **General intro**
  - APS structure and design target
- **Test chip 1**
  - Description (diagrams+layout+sims)
  - Rad source & beam tests
  - Rad Tolerance
  - Analysis & Modeling
- **Test chip 2**
  - Description (layout)
  - IV & CV measurements
  - Current Status
- **Conclusions**
  - Open questions
  - Future plans



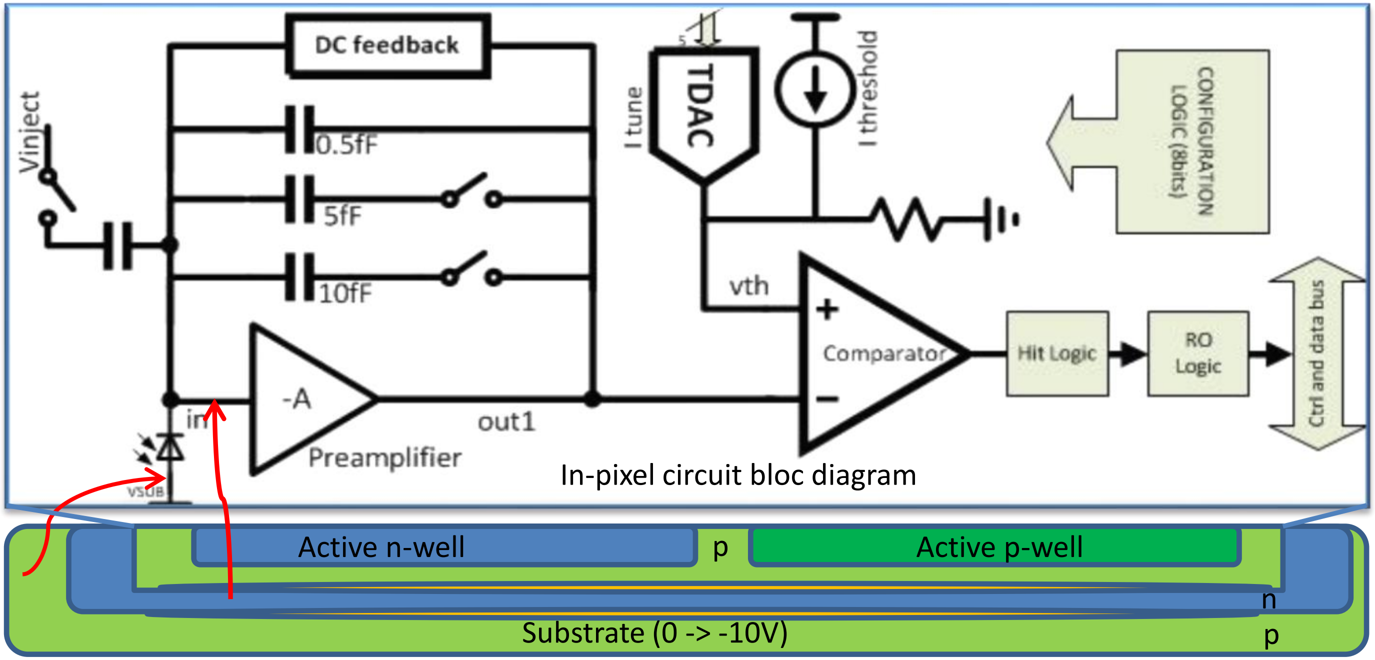


Introduction: Sensor Structure



- Using deep n-band (T3) electrode as sense node
- Doping and implant thickness not specified in process docs
  - Some info from models…
- Several junction of different nature contribute to sense node
  - Substrate doping higher than ideal…

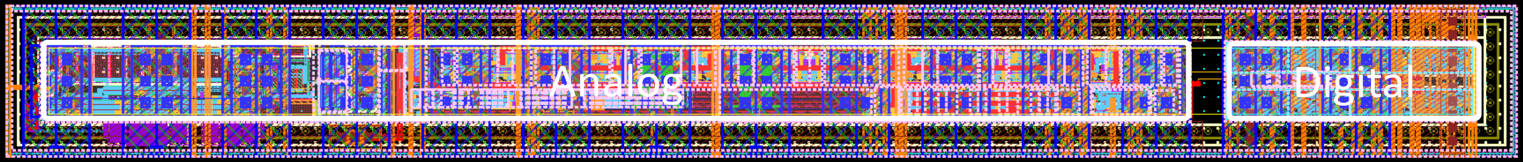
Design: Pixel Electronics

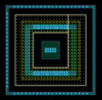


- Based on FE-I4 TOT design w/ additional gain configuration
- Minimalistic low-risk digital pixel for hit counting and digital cross-talk tests

Design: Pixel Layout

Large-pixel (17x221 um^2) - different 'flavors'



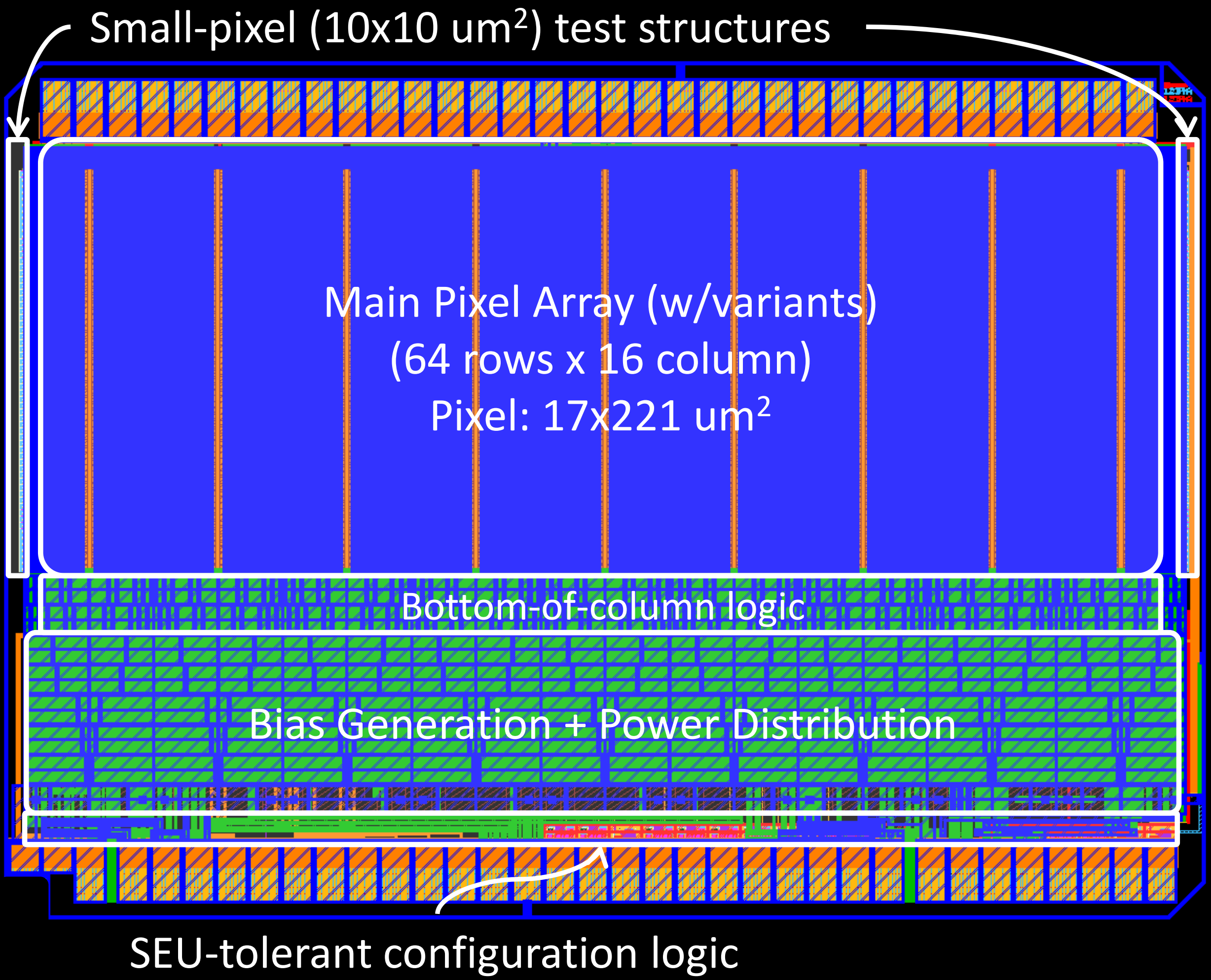


Small-pixel (10x10 um^2)

- Adaptation of FE-I4 frontend
- Minimal full-custom logic in pixel
  - Hit count
  - Digital crosstalk tests
- Sensor layout variants:
  - Optimized for crosstalk
  - Optimized for capacitance
  - No DRC violation

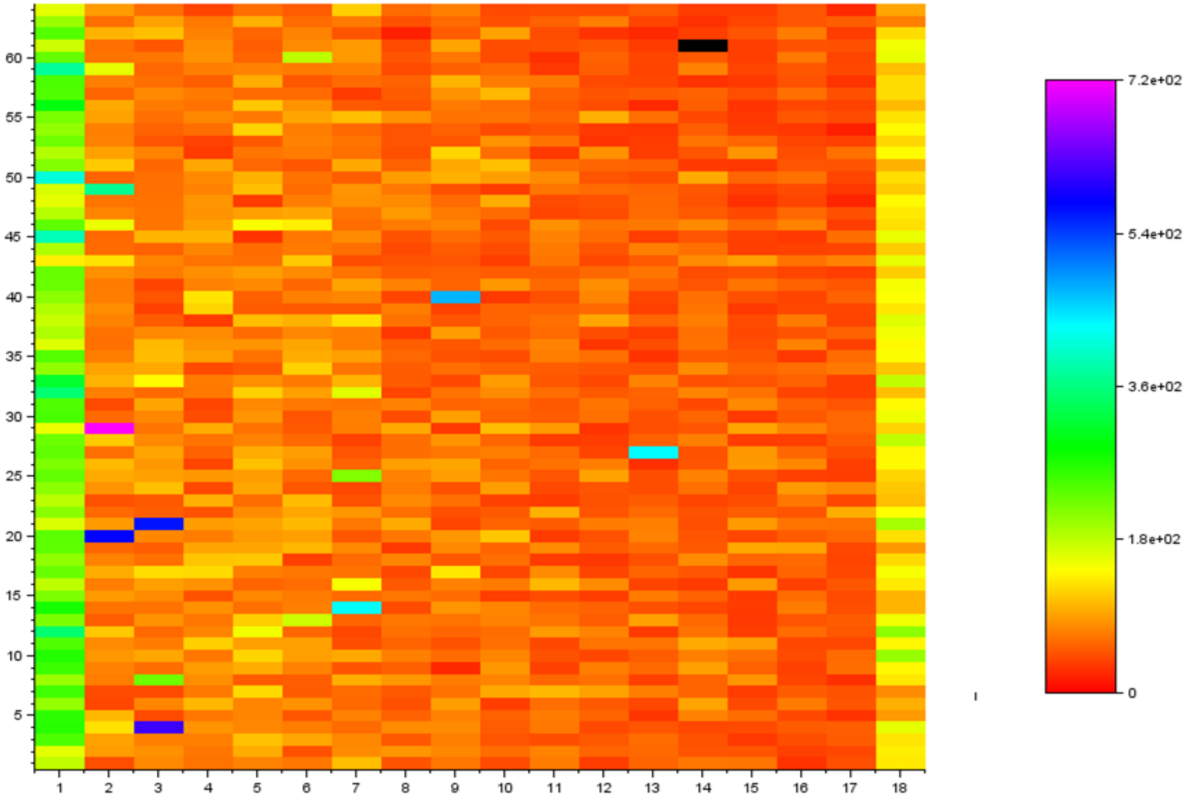
- Minimum size pixel
  - Minimal noise test
  - Spectroscopy

Design: T3MAPS_P1 Layout



- Adapt existing FE, BOC and IO structures from FE-I4
- Minimal full-custom logic in pixel
- Test sensor:
  - Efficiency
  - Hybrid collection effects
  - Charge-sharing
  - Crosstalk
- Test electronics
  - Analog front-end
  - Layout variants

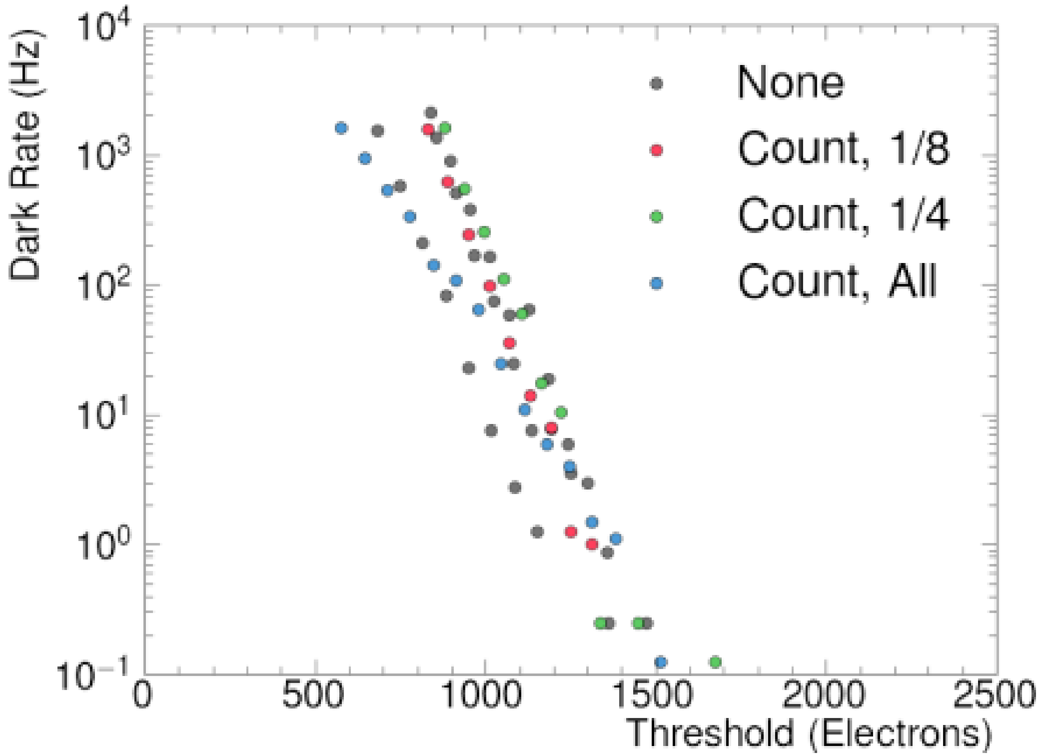
Experimental: Array Hit Map

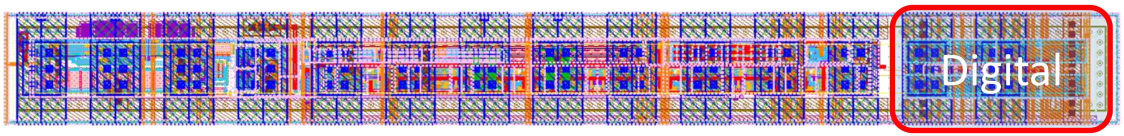


Sealed source hit test:

- Reasonable yield
- Reasonable threshold uniformity before tuning
  - Side columns instrument micro-pixels
- Non-quantitative analysis for efficiency

Experimental: Digital Cross-talk

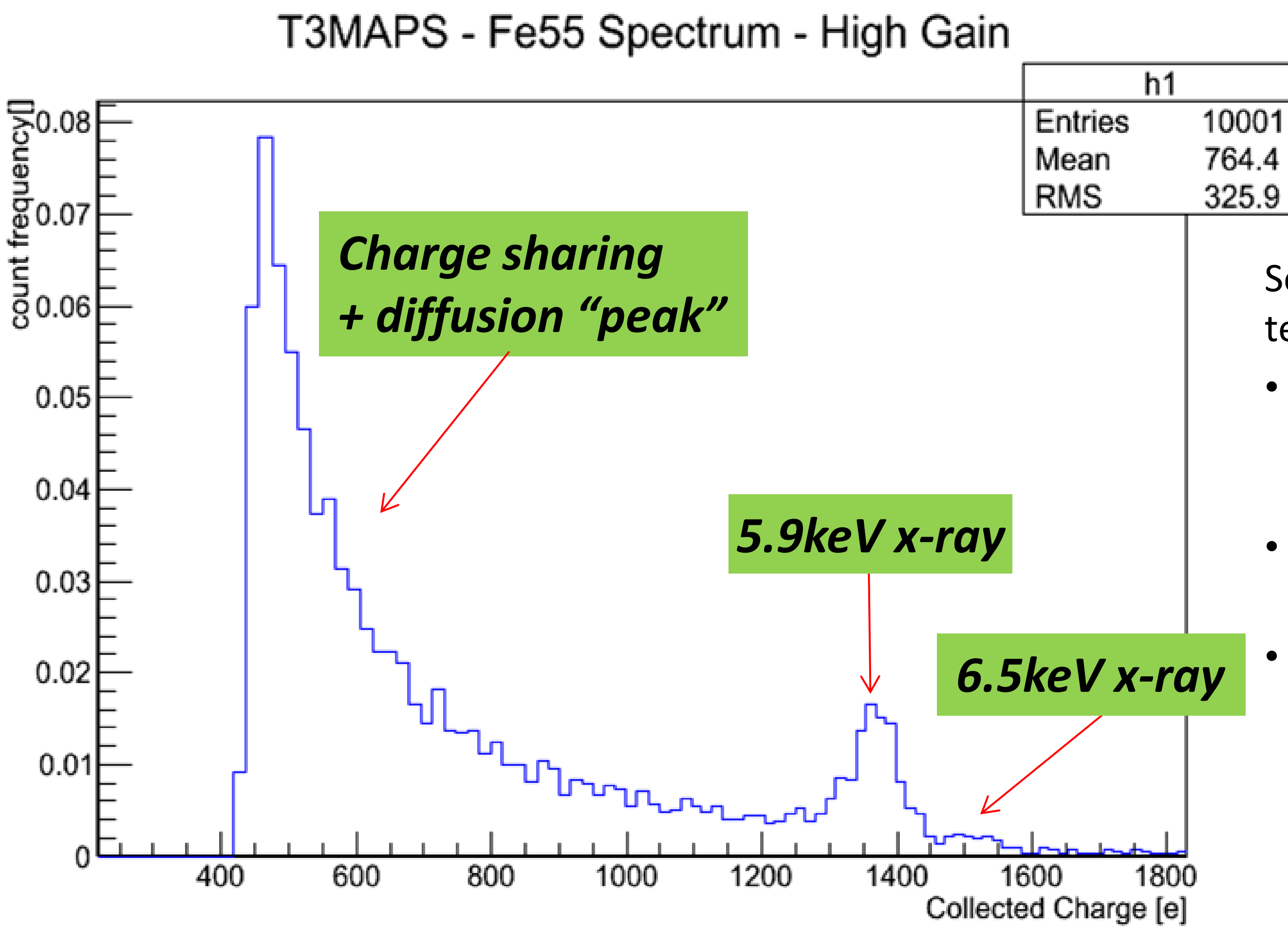




Dark noise hit test:

- Negligible influence of digital activity
- Possible mitigation technique possible but not needed

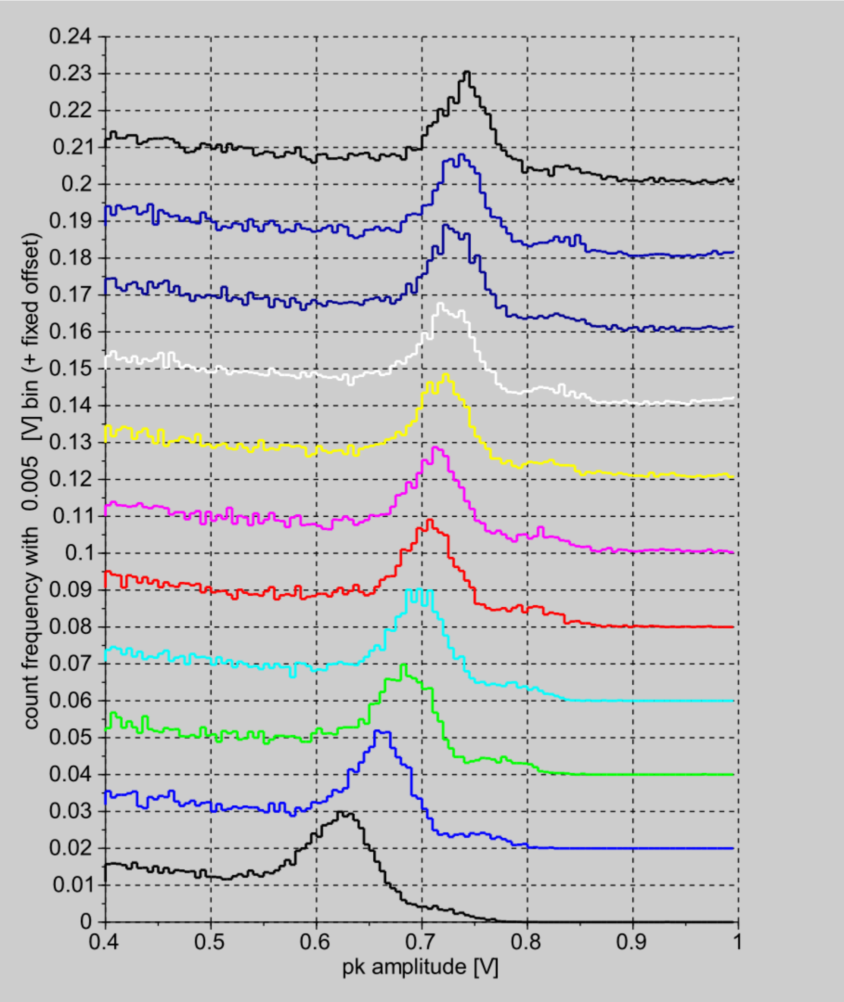
Experimental: small pixel spectra



Sealed source spectrum test:

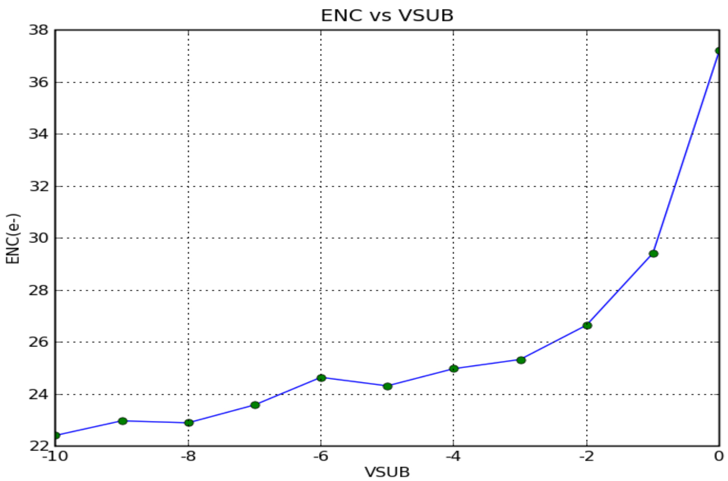
- Charge calibration based on injection cap (known to +/-20%)
- Output follower non-linearity for large signal
- Confirms
  - Dominant diffusion contribution
  - Critical role of threshold level

Experimental: Reverse Bias Effect

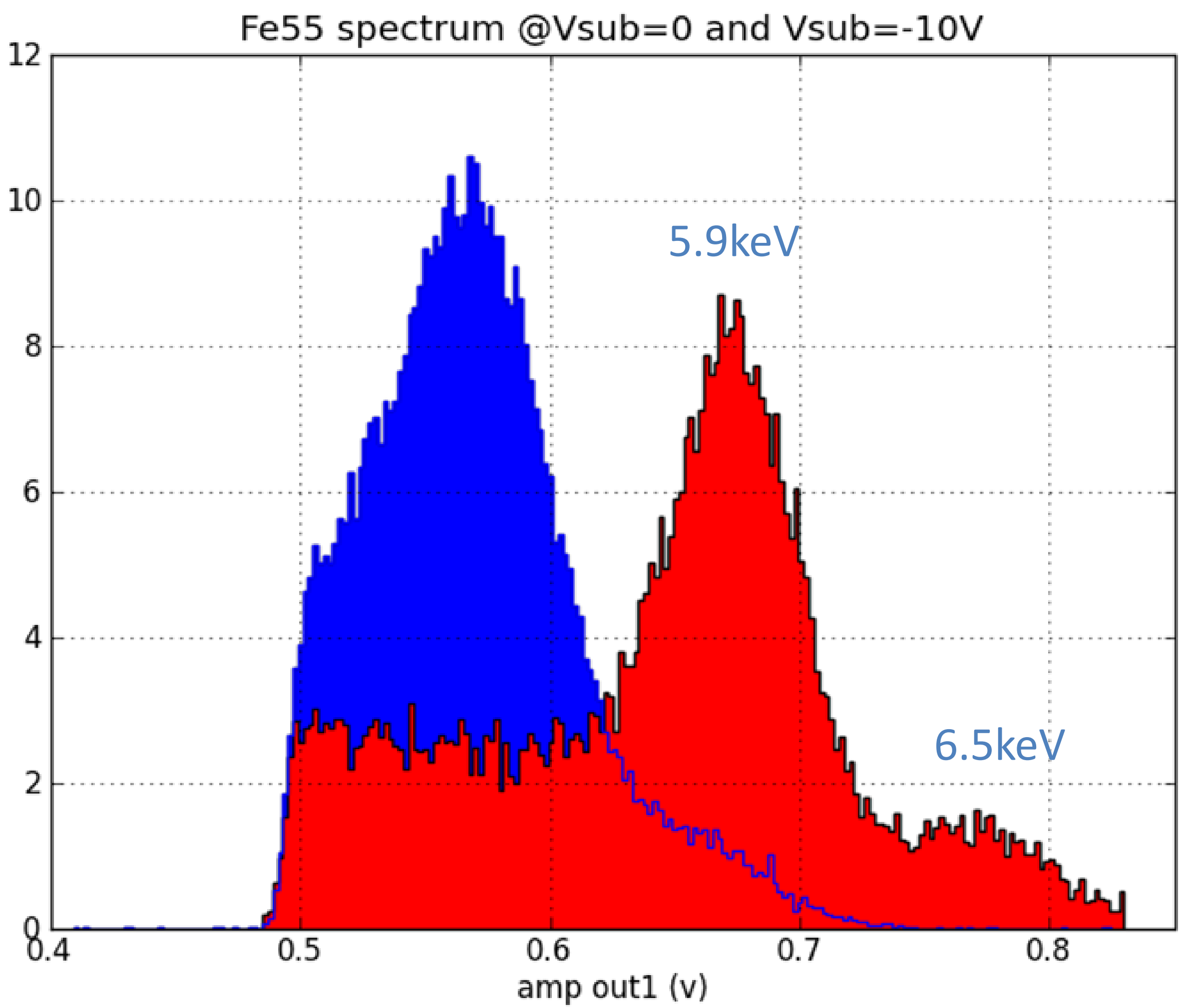


Sealed source hit test:

- Increase in gain and resolution as a function of reverse bias voltage
- Increase in ‘large’ hits above max expected energy
  - pile-up OR
  - avalanche effects (?)



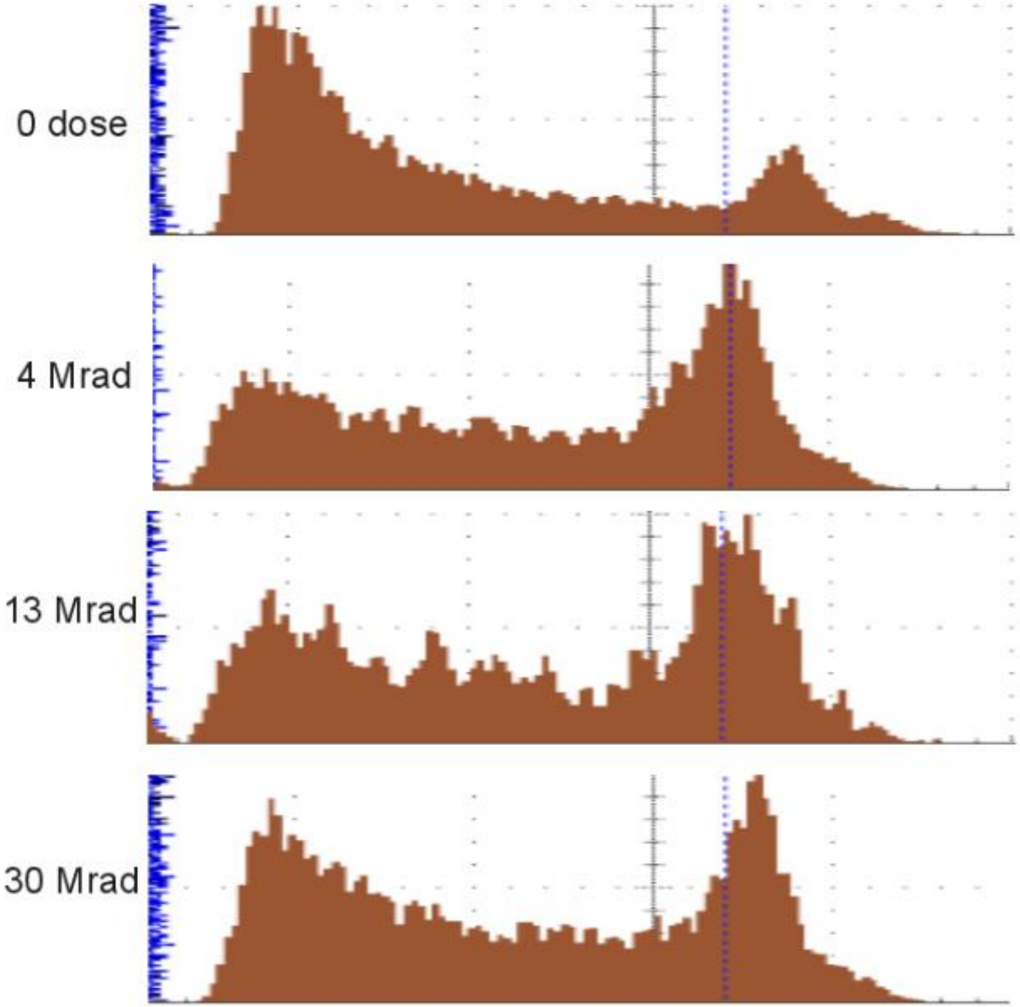
Experimental: small pixel spectra



Sealed source spectrum test:

- Small pixel low noise level allows for resolving Fe55 double peak
- Confirms
  - charge calibration
  - noise level
  - substrate bias effect

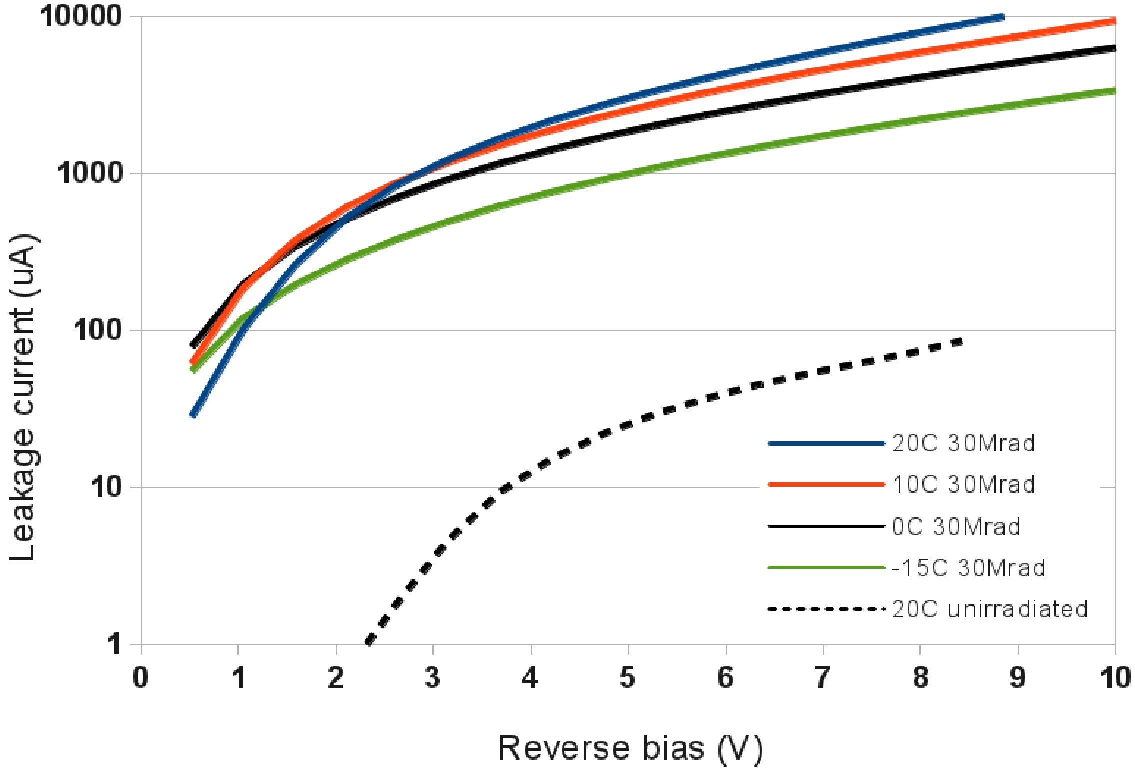
Experimental: total dose effects



Fe55 detection after 800MeV proton irradiation:

- Significant variation in the ratio of drift-to-diffusion signal
  - Trap-induced reduction in diffusion length (?)
- Slight increase in noise
  - Harder to resolve Fe55 double peak
  - Based on similar exposure times…

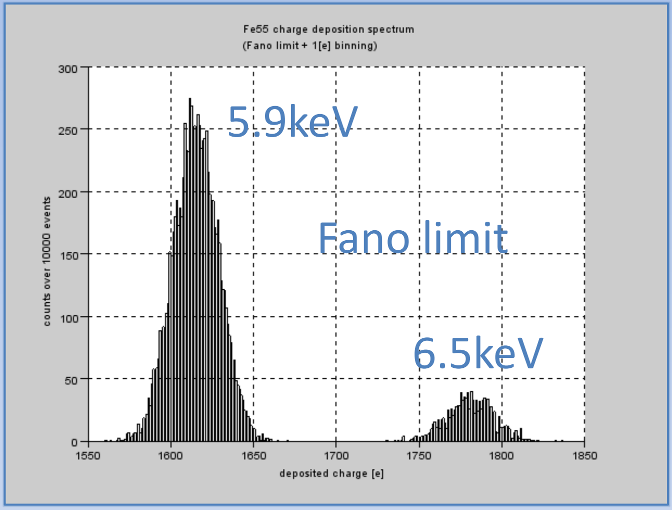
Experimental: total dose effects



Biasing after gamma irradiation:

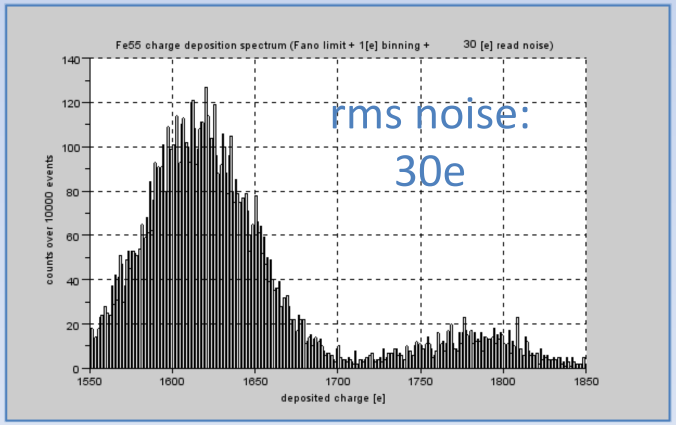
- 2 orders of magnitude increase in leakage current
- Limited improvements at lower temperatures

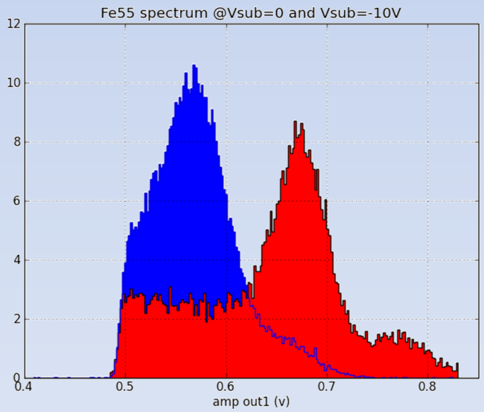
SIM: Drift Contribution

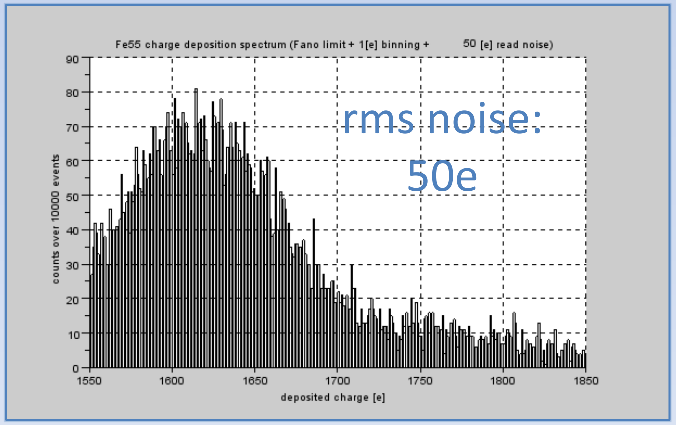


Montecarlo sim of drift signal from Fe55 source as a function of readout noise (for a fixed number of hits):

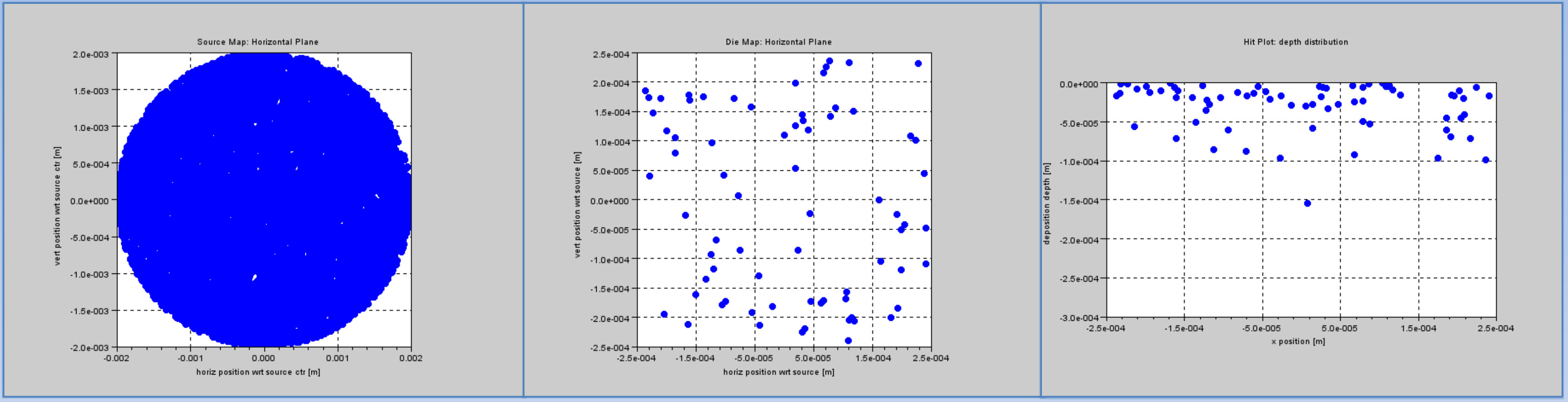
- Confirms input-referred noise magnitude (~30e)
- Confirms correct interpretation of spectrum peaks







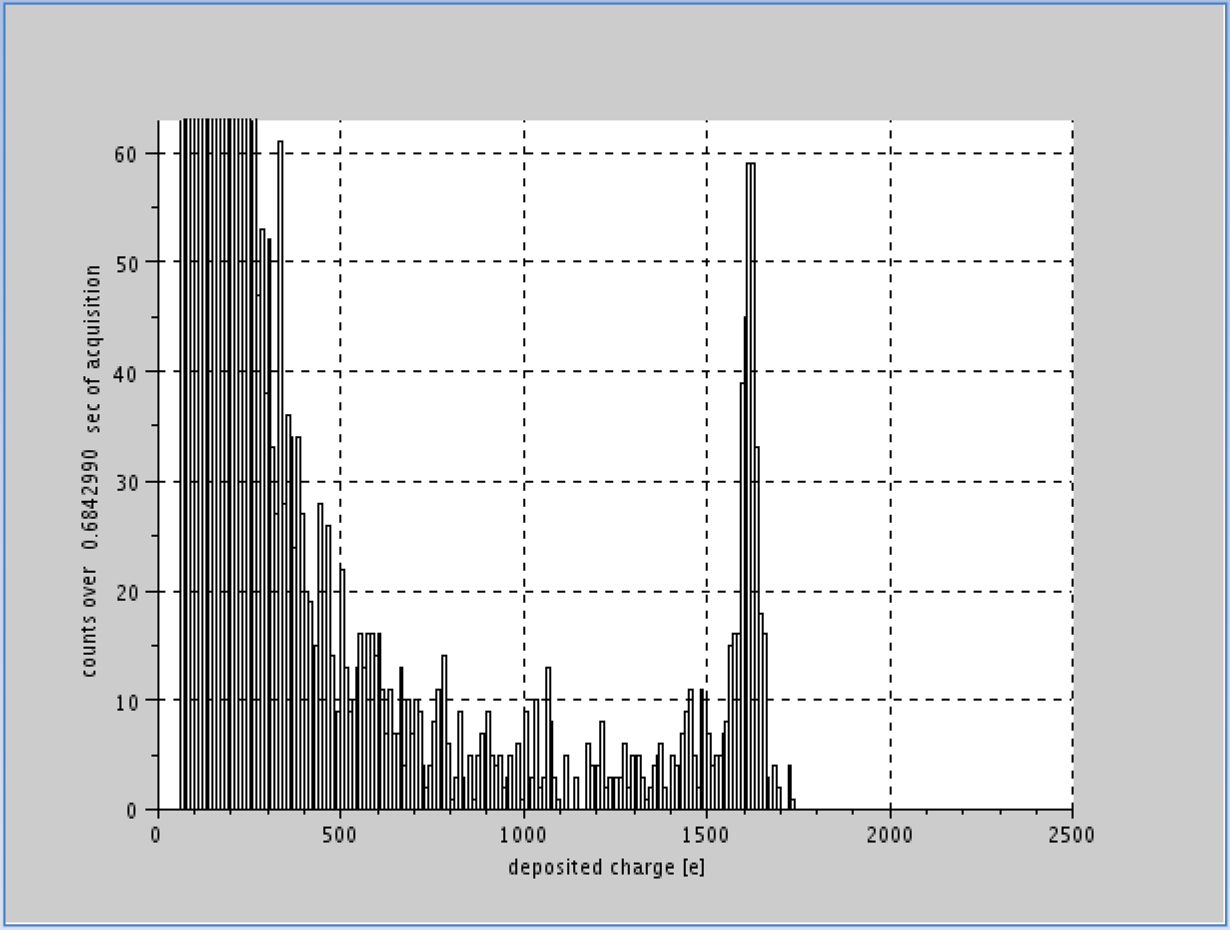
SIM: Diffusion-Drift Spectrum



Montecarlo sim of diffusion signal from sealed Fe55 source:

- Only 5.9keV photons propagated
- Photon statistics
- Source activity and geometry
- Interposed materials
- Stat. charge deposition from photons in Si
- Stat. of charge diffusion-recombination

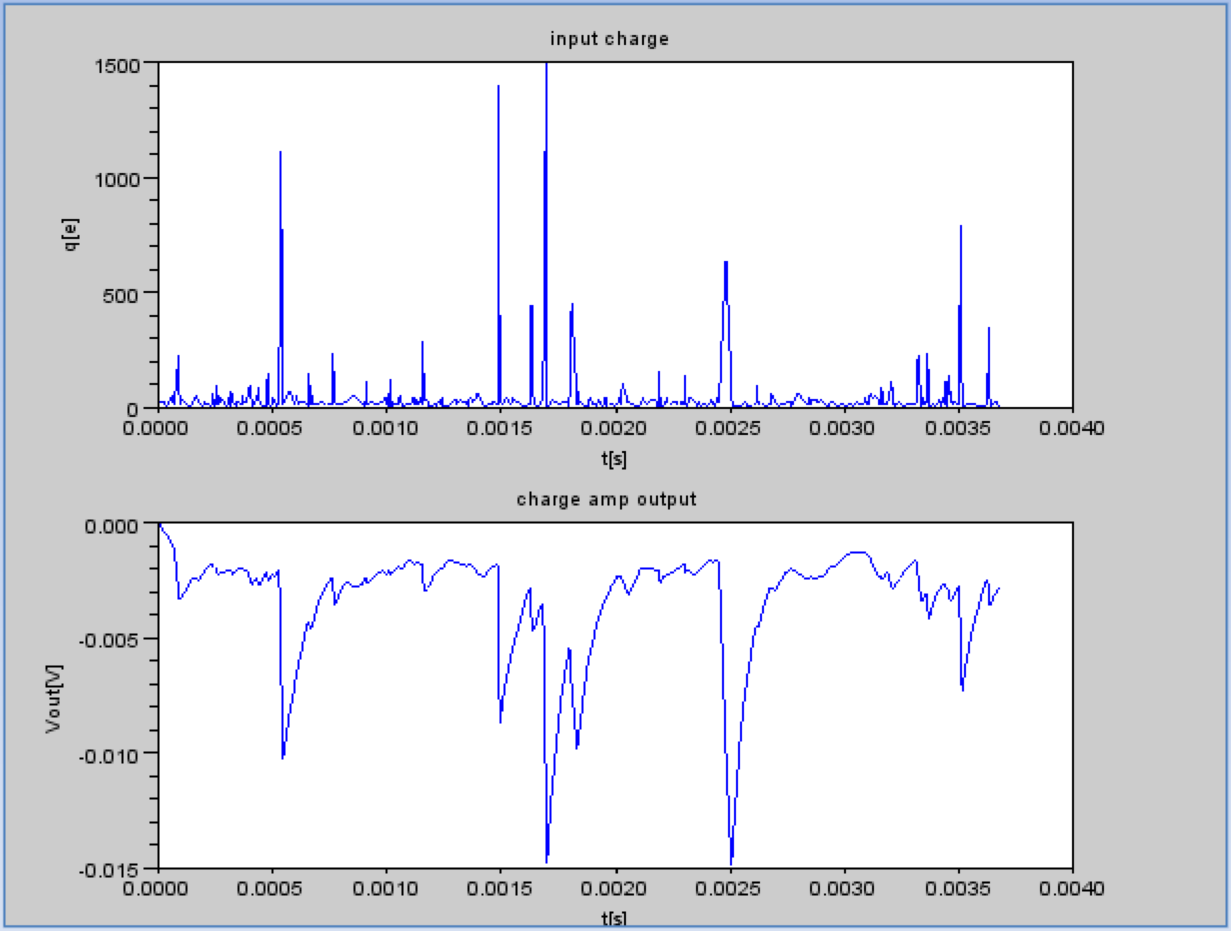
SIM: Diffusion-Drift Spectrum



Montecarlo sim of diffusion signal from sealed Fe55 source:

- Only 5.9keV photons propagated
- Accounts for
  - Source geometry
  - Pixel geometry
- Silicon deposition statistics
- Limited accuracy on recombination simulation
  - Negligible impact in our conditions
- Confirms (qualitatively) hybrid spectrum structure

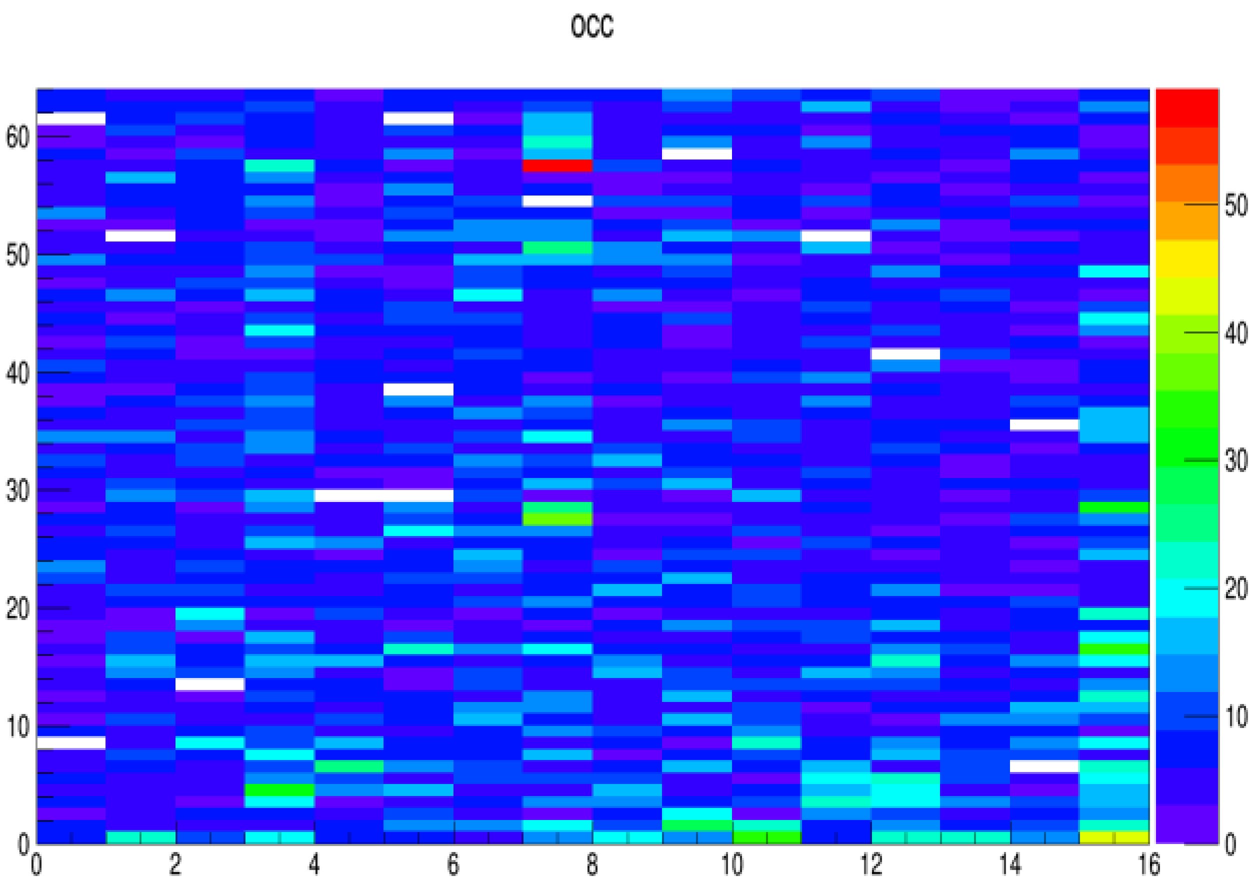
SIM: Collected Charge and CSA Signal



Montecarlo sim of diffusion signal from sealed Fe55 source:

- Continuous flow of small amounts of diffusion charge creates a drifting baseline output
- Occasional drift signal can easily pile-up
- Diffusion signal at high rates becomes 'noise' for drift signal
- Shaping useful to minimize pileup and restore baseline

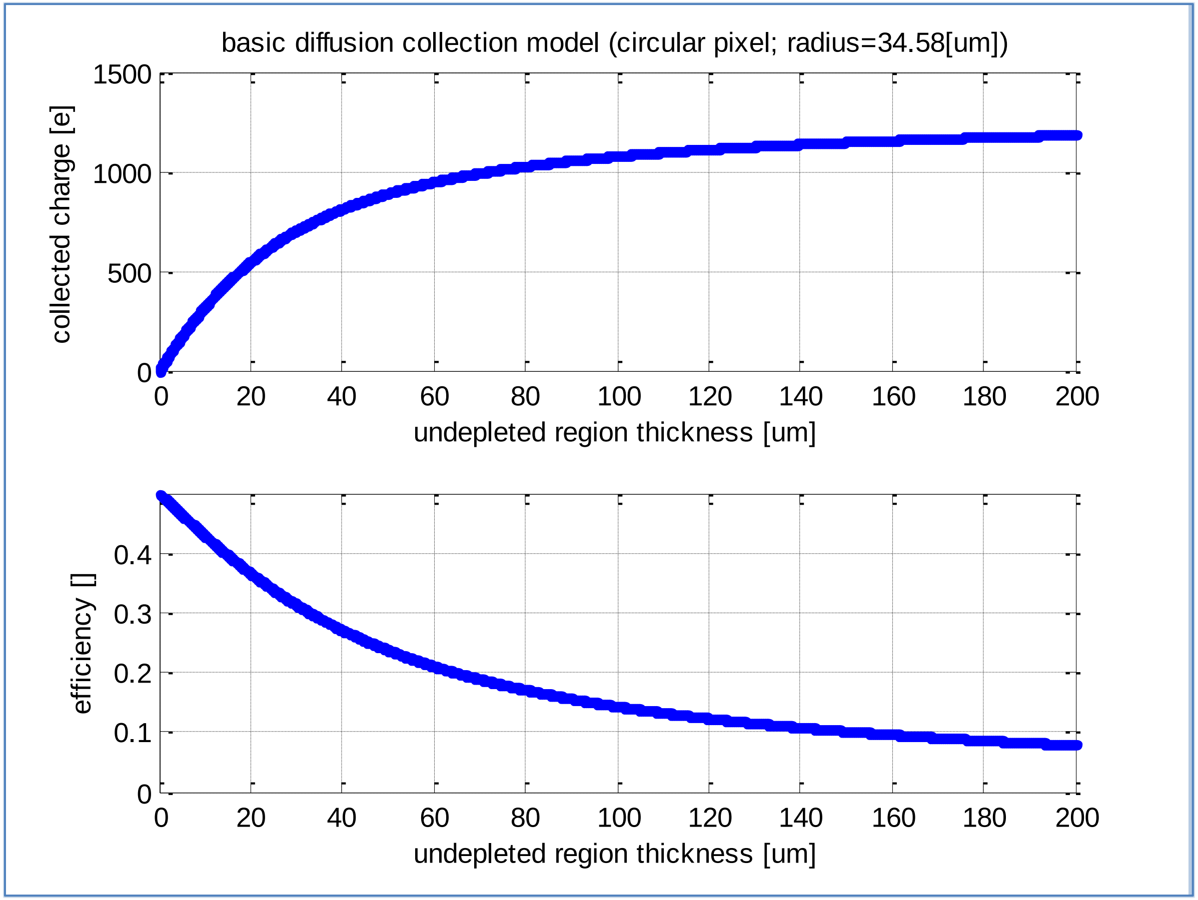
Experimental: recent MIPs irradiation results



T3MAPS_P1 occupancy map w/i a 10Gev electron beam at SLAC:

- Threshold set to minimum value before firing on noise.
  - Adjustment done pixel by pixel…
- Comparison with IBL tracker indicates 50% hit efficiency
- Estimate threshold about 1700e- (slide 8)
  - suggests that MIP signal median was also about 1700e-

Preliminary: Analytical Models for Collection-by-Diffusion



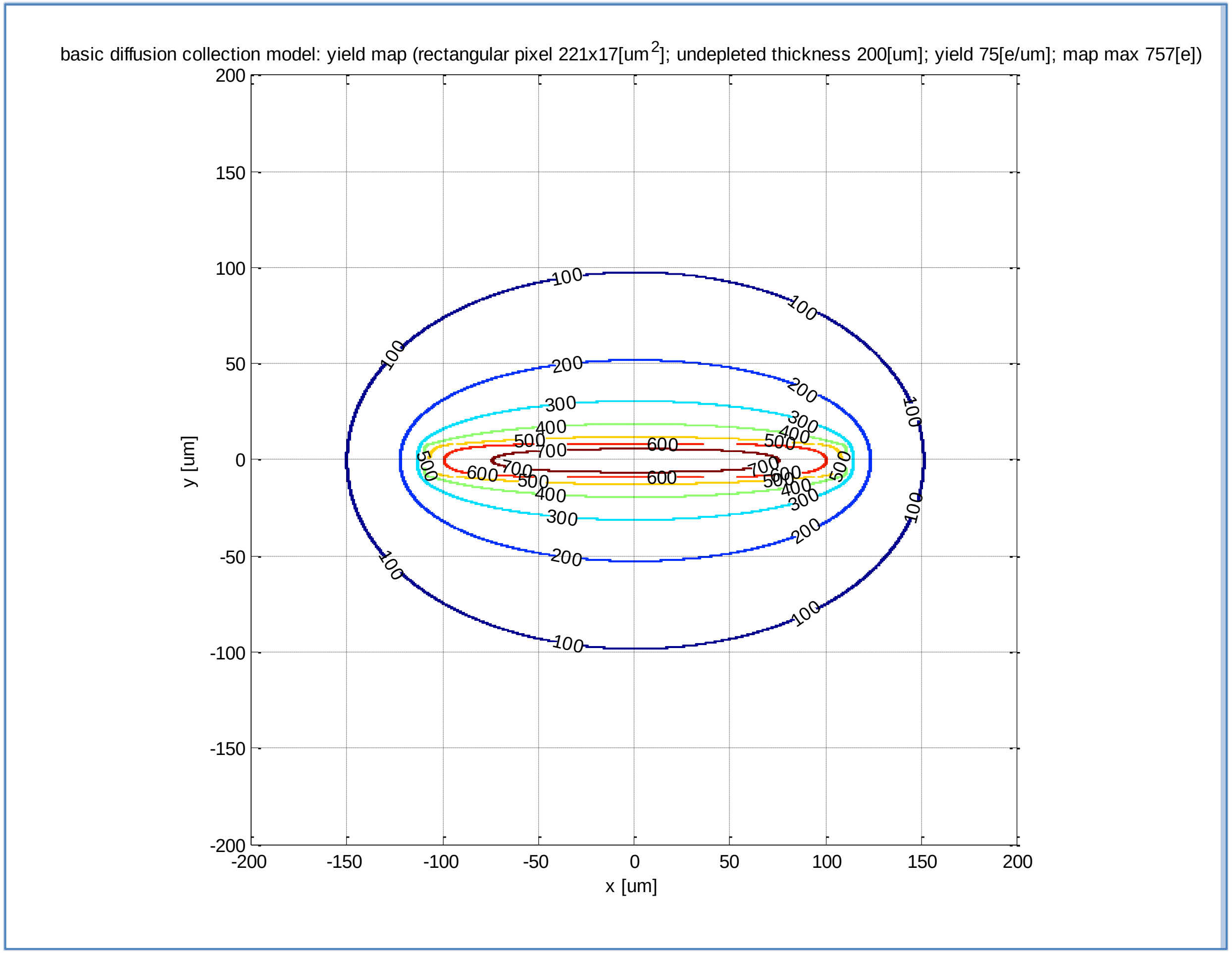
Analytical model of diffusion signal from MIP beam:

- Round pixel
- Orthogonal track
- Pixel center
- 221x17um^2 area-equivalent

Behavior vs deposition depth:

- Efficiency (wrt drift) quickly drops from 0.5 to 0 as $1/z^2$
- Collected charge saturates to a value lin dep on pixel size

Preliminary: Analytical Models for Collection-by-Diffusion



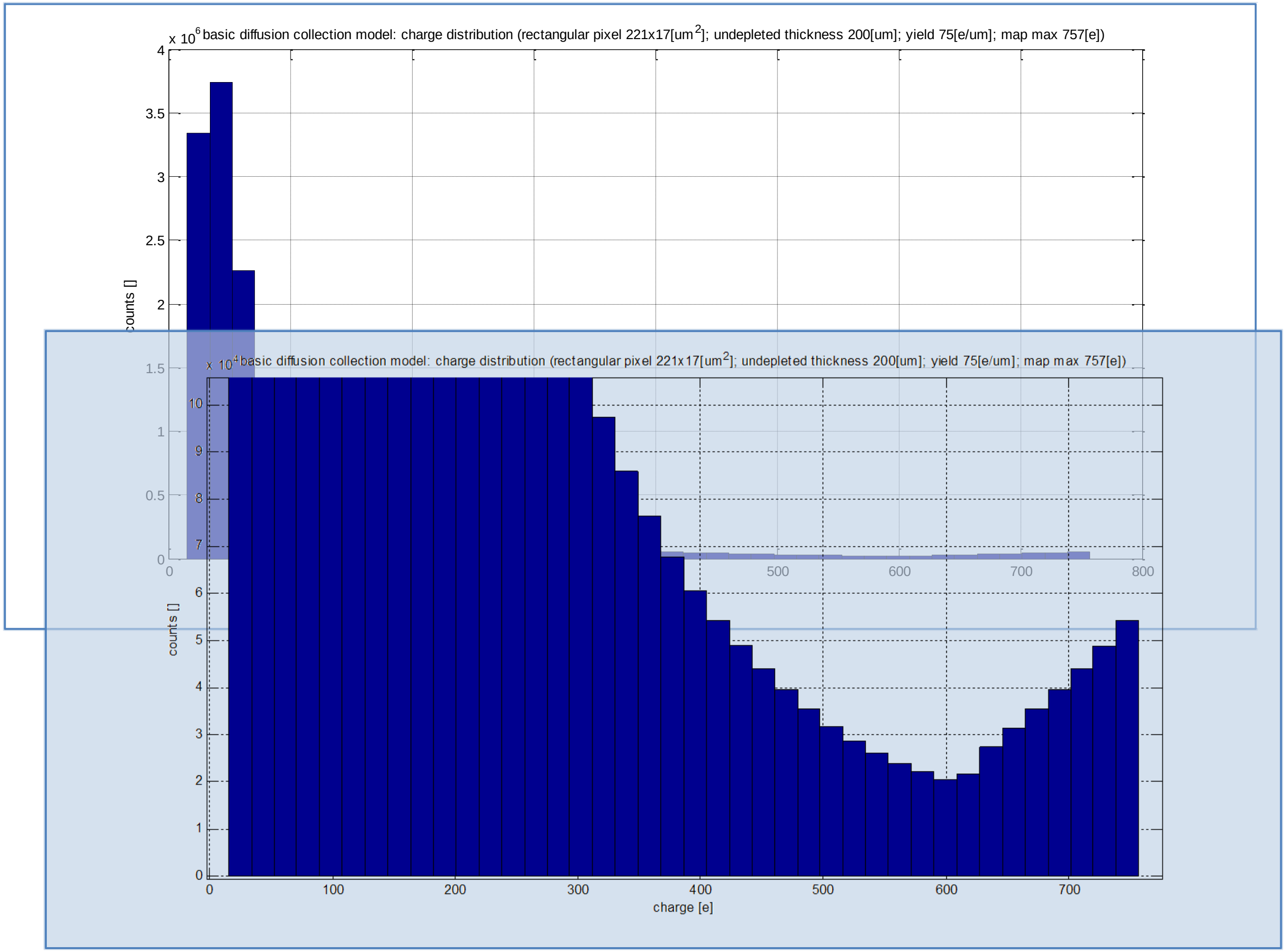
Analytical model of diffusion signal [e] from MIP beam:

- Rectangular pixel
- Orthogonal tracks
- 221x17um^2

Behavior vs track transversal distance:

- Charge-sharing can be significant
- Threshold can help limiting PSF
- Will be problematic at high rates

Preliminary: Analytical Models for Collection-by-Diffusion



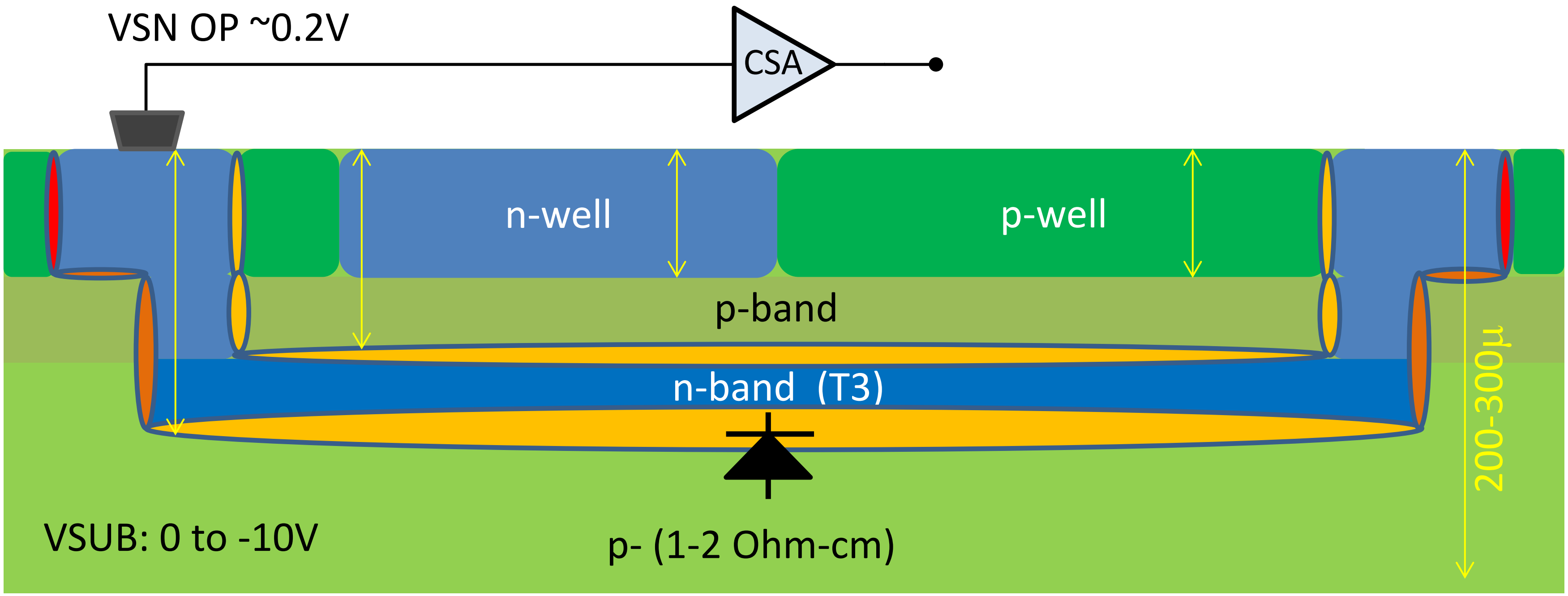
Analytical model of diffusion signal [e] from MIP beam:

- Rectangular pixel
- Orthogonal tracks
- $221x17um^2$

Collected charge distribution:

- Threshold is fundamental in limiting PSF
- high rates can be a significant problem…

Sensor limitations

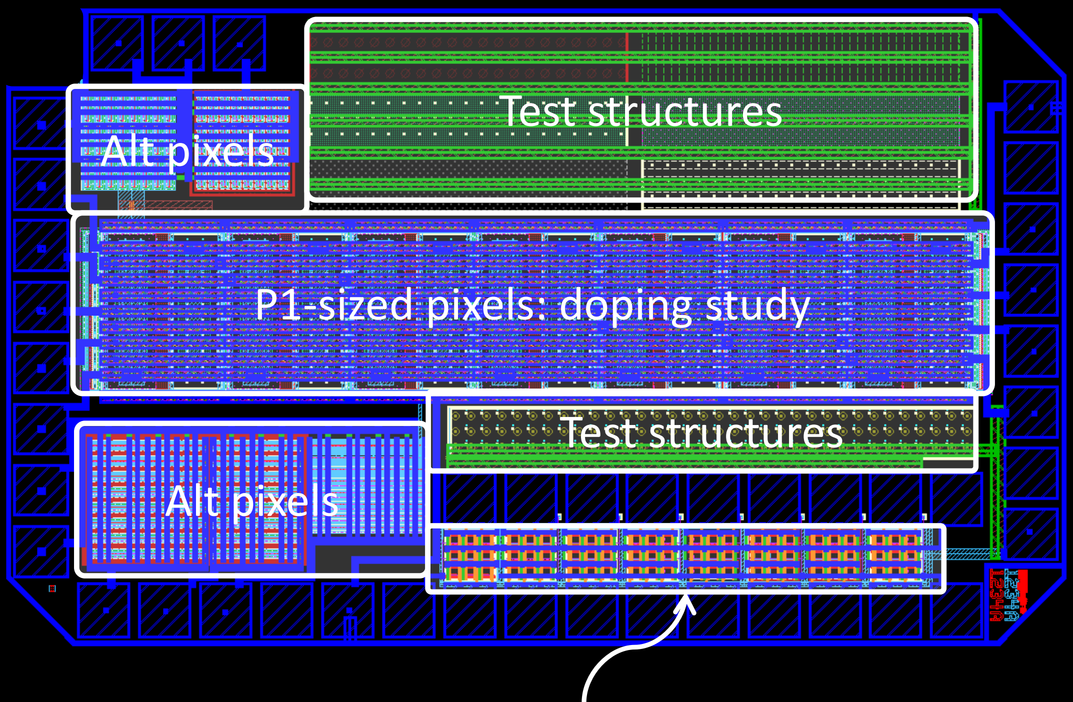


- S/N benefit from higher drift signal component
  - Increase depletion width
  - Increase BV (HR wafer were not available)
- Reasonable to assume surface twin-well junction determines BV
  - Limited silicon simulation data available…
- Intrinsic cap limitations from inner junction
  - CSA is DC-coupled…

First prototype results

- Sensor
  - Detection efficiency is limited by depletion layer thickness
  - Depletion width limited by substrate doping AND breakdown voltage
  - Foundry was not open to high-resistivity runs
  - Try custom devices options to increase breakdown voltage (assuming doping and not geometry is limiting factor)
  - Lost silicon simulation capability…
- Electronics
  - Operated as expected from simulation
  - Digital crosstalk into sensing node is negligible
- Open Questions
  - Avalanche effects
  - Rad tolerance
  - Possible BV optimization w/i process options
  - BV mechanism

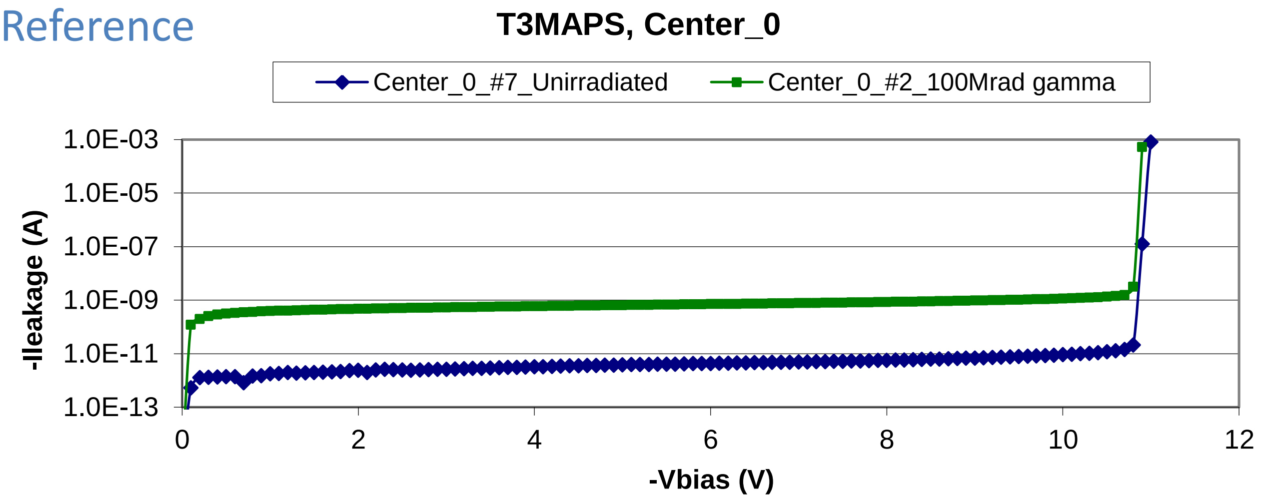
T3MAPS_P2: Layout



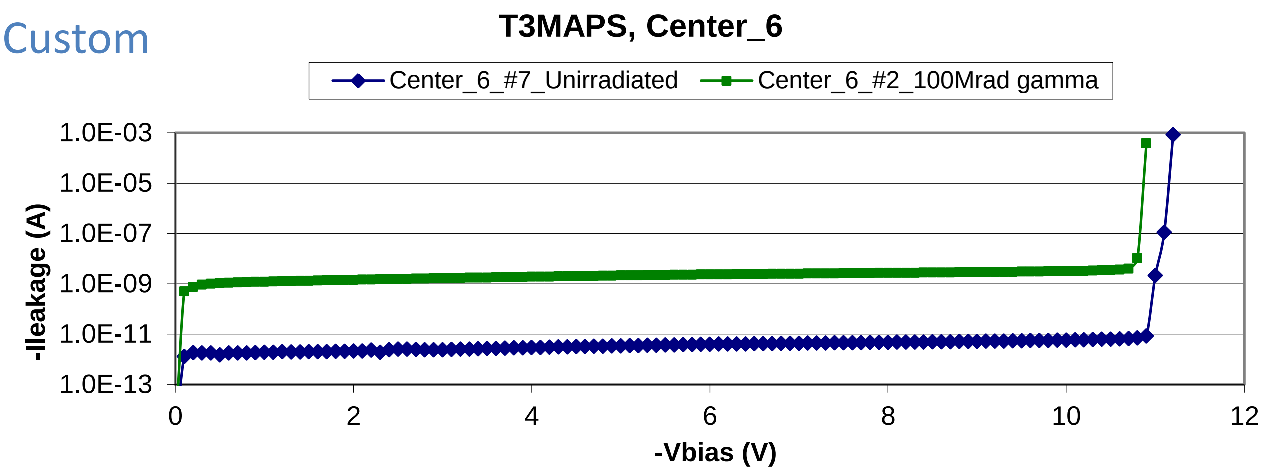
- Pixel optimization and process study
- Test sensor:
  - Breakdown optimization
  - Radiation tolerance
- Test Process:
  - Junction and implant measurements

Experimental: rad effects on I-V curves

Reference



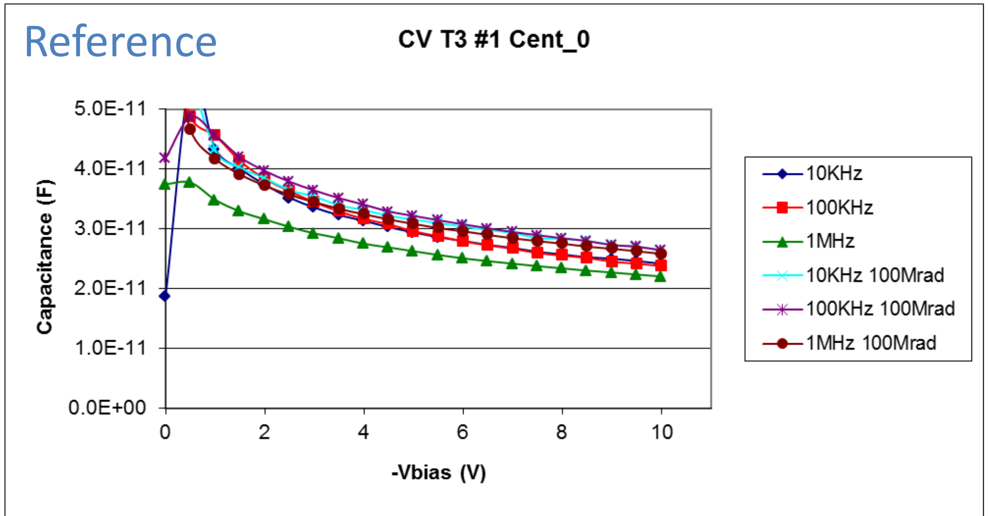
Custom

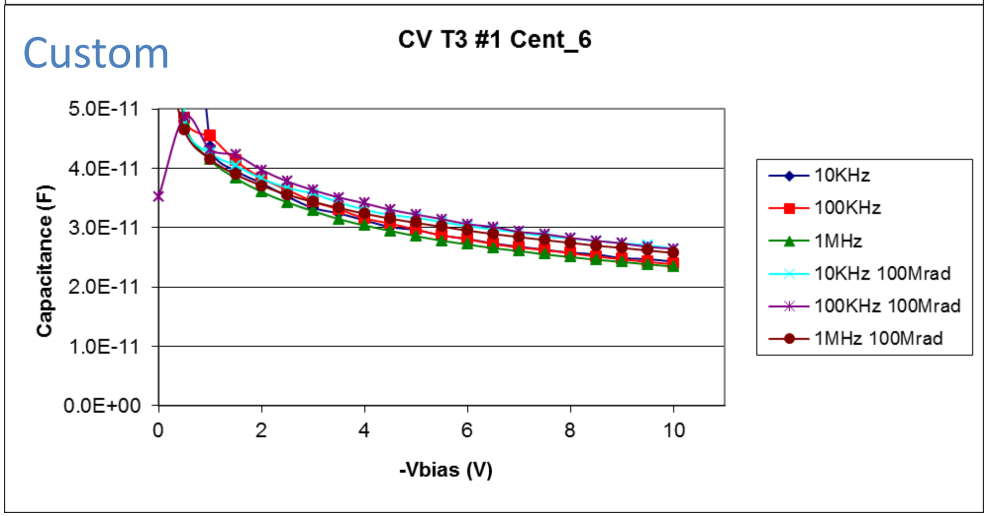


100Mrad gamma:

- Std junction
  - BV seems unaffected by irradiation
  - Leakage current increases by 2-3 orders of magnitude
- Custom junctions
  - BV effect are visible but minor
  - Similar levels of leakage increase
  - Not what we hoped for…

Experimental: rad effects on C-V curves

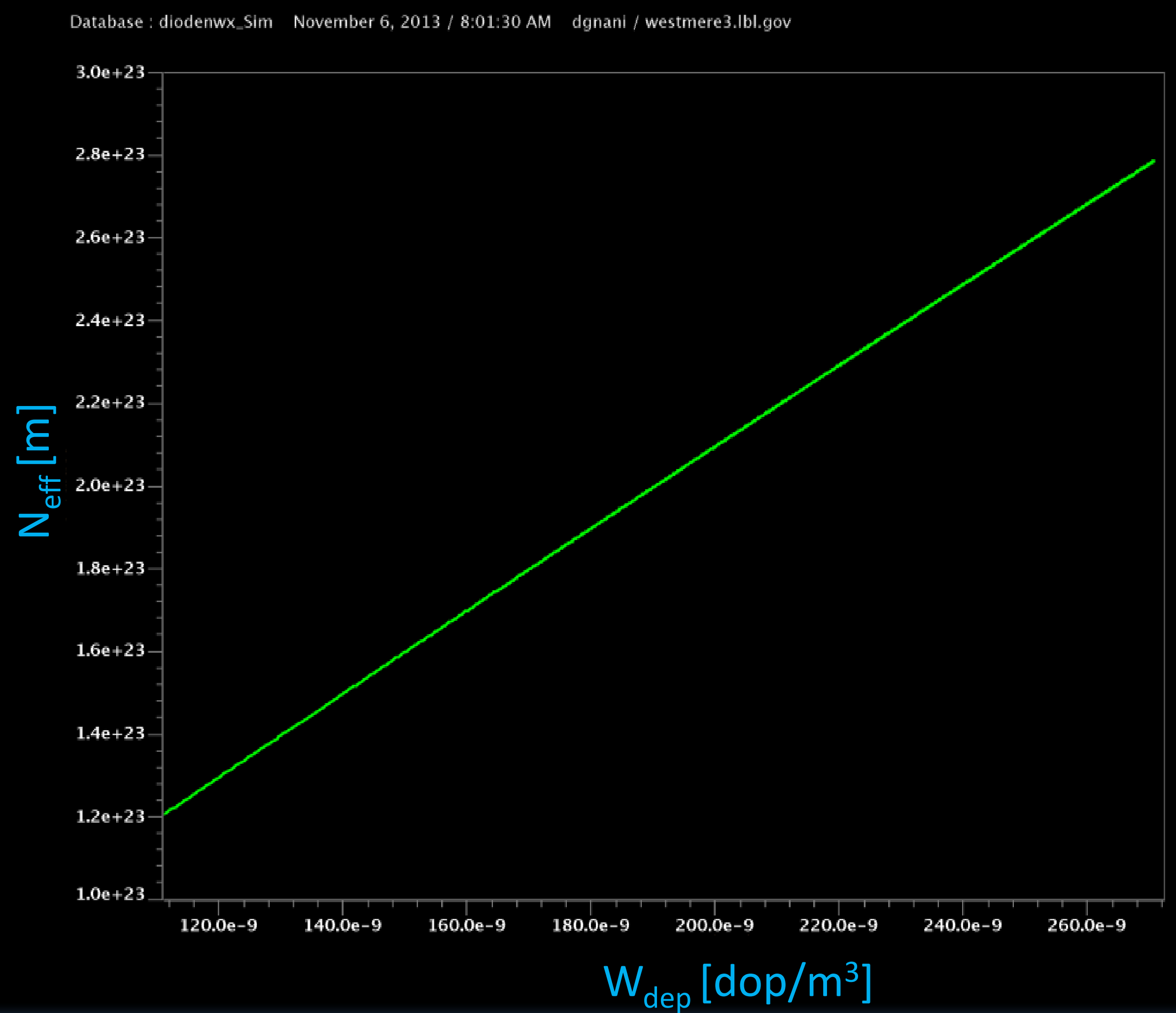




100Mrad gamma:

- Std junction
  - Irradiation causes a small increase in capacitance
  - Electrode resistance artifact in high freq measurements
- Custom junctions
  - No significant difference in sense node cap
  - Inner depletion dominates… still we were expecting some perimeter effects..

SIM: process info from models



N_{eff} vs W_{dep} curve:

- Limited accuracy due to approximations
- Indicates orders of magnitude

Second prototype results

- Breakdown voltage
  - None of the implant-based solutions in the pixels tested so far was able to achieve significant BV increase
  - Possible explanations:
    - Junction geometry determines BV rather than doping
    - Undocumented foundry layer ops suppressed layers in custom structures
  - Additional structures present in the prototype were not tested
- Radiation Tolerance
  - Regular sense-node junction leakage is limited to 2-3 orders of magnitude at 100Mrad
  - Additional
- Process
  - Additional results could come from the analysis of C-V curve for approximate Wdep extraction
  - Additional test structures not analyzed
- Open Questions
  - Avalanche effects
  - BV mechanism
  - Performance of more complex structures

Conclusions

Main results

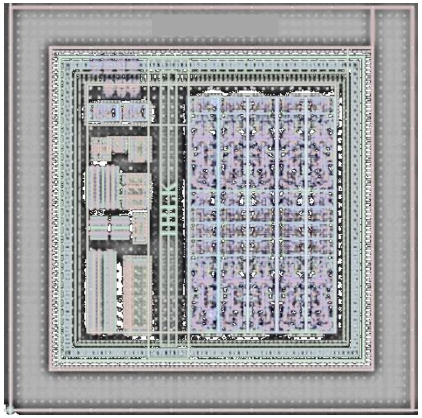
- Sensor and in-pixel electronics work but…
  - efficiency is limited
  - sense node cap too high
  - need higher ρ substrate

Open questions

- Unclear what prevented increase in BV
  - Suppression by logic op?
  - Junction curvature?
- Avalanche effects?

Future Plans

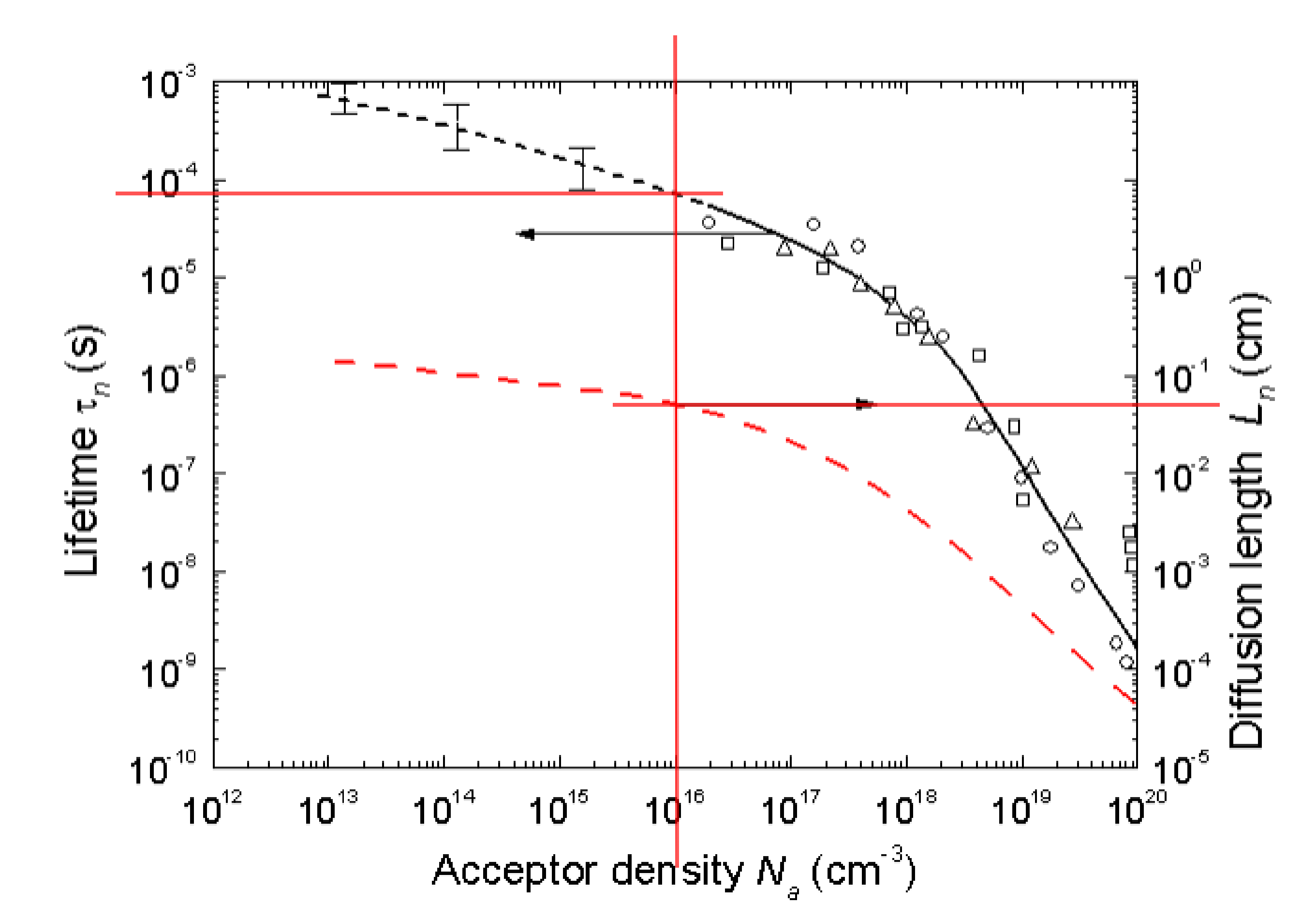
- New run using 50um square pixels
- Hope to use high resistivity substrate



Non-essential slides: details, very preliminary results, …

ADDITIONAL SLIDES

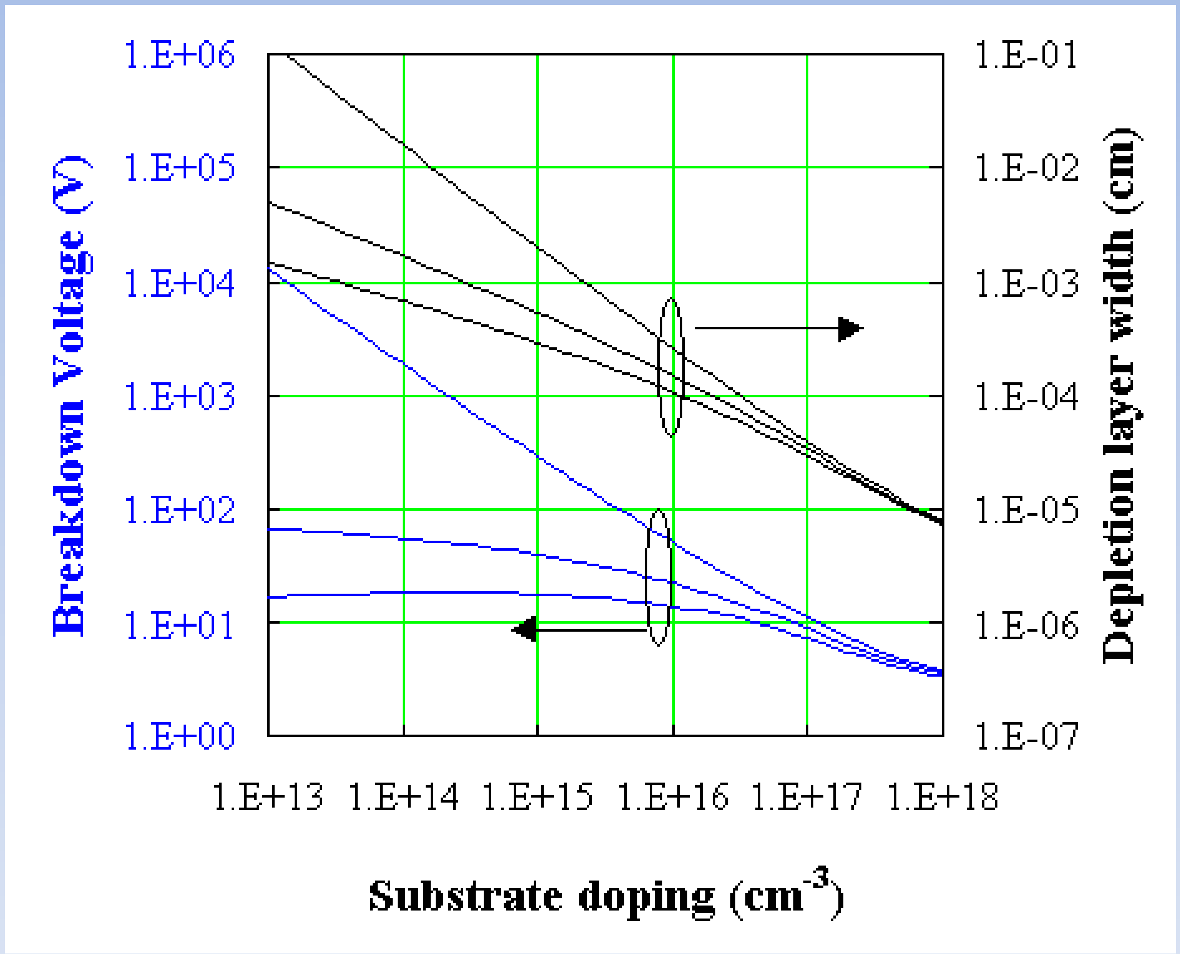
Phys: Diffusion in Si



Diffusion length and minority carrier recombination time in p-doped Si:

- Ld_e~500um
- Tau_e~70us

Phys: Abrupt junction curvature



Effect of flat, cylindrical and spherical curvature on BV and Wdep in an abrupt junction:

- Spherical junction
  - BV saturates below 10^{16}at/cm3 doping level
  - Depletion width scaling goes from (almost) linear to increasingly sublinear

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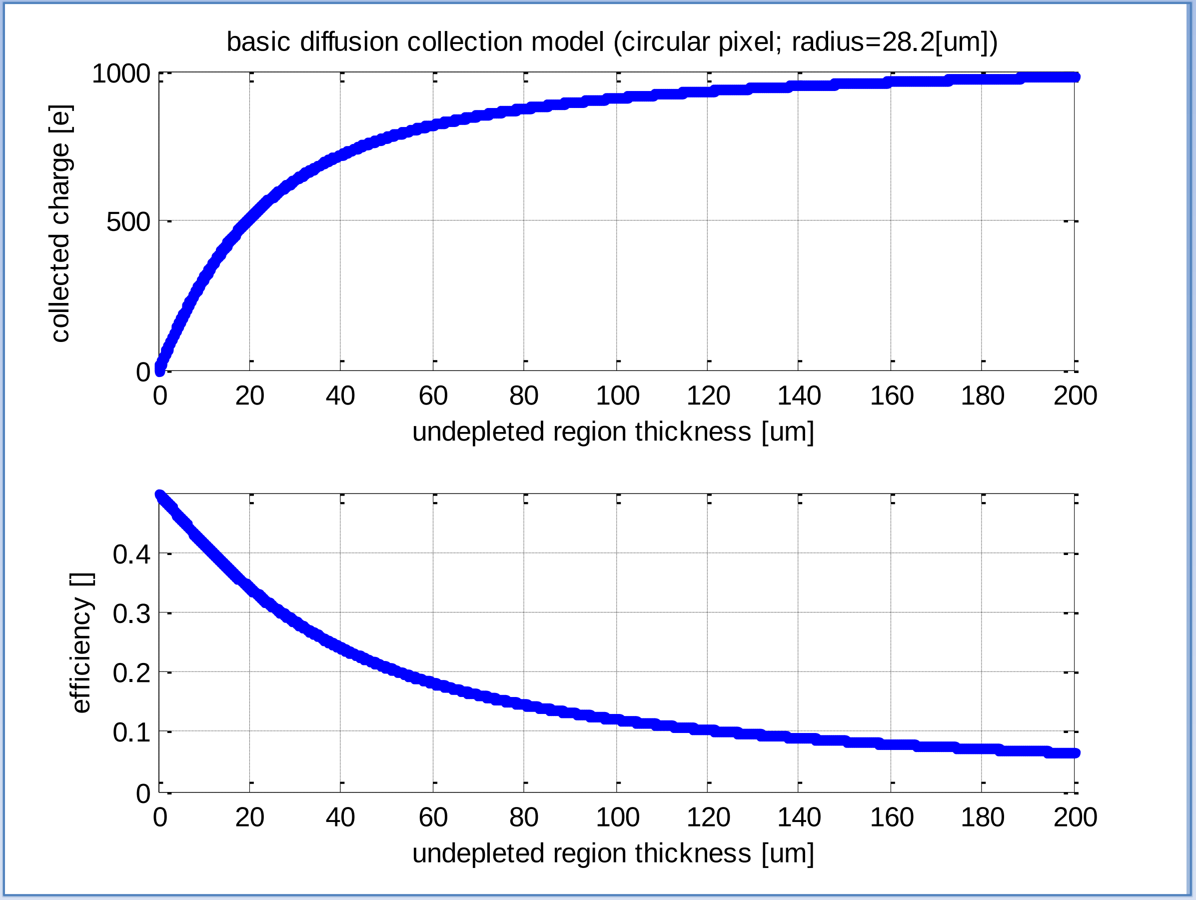

Analytical model of diffusion signal from MIP beam:

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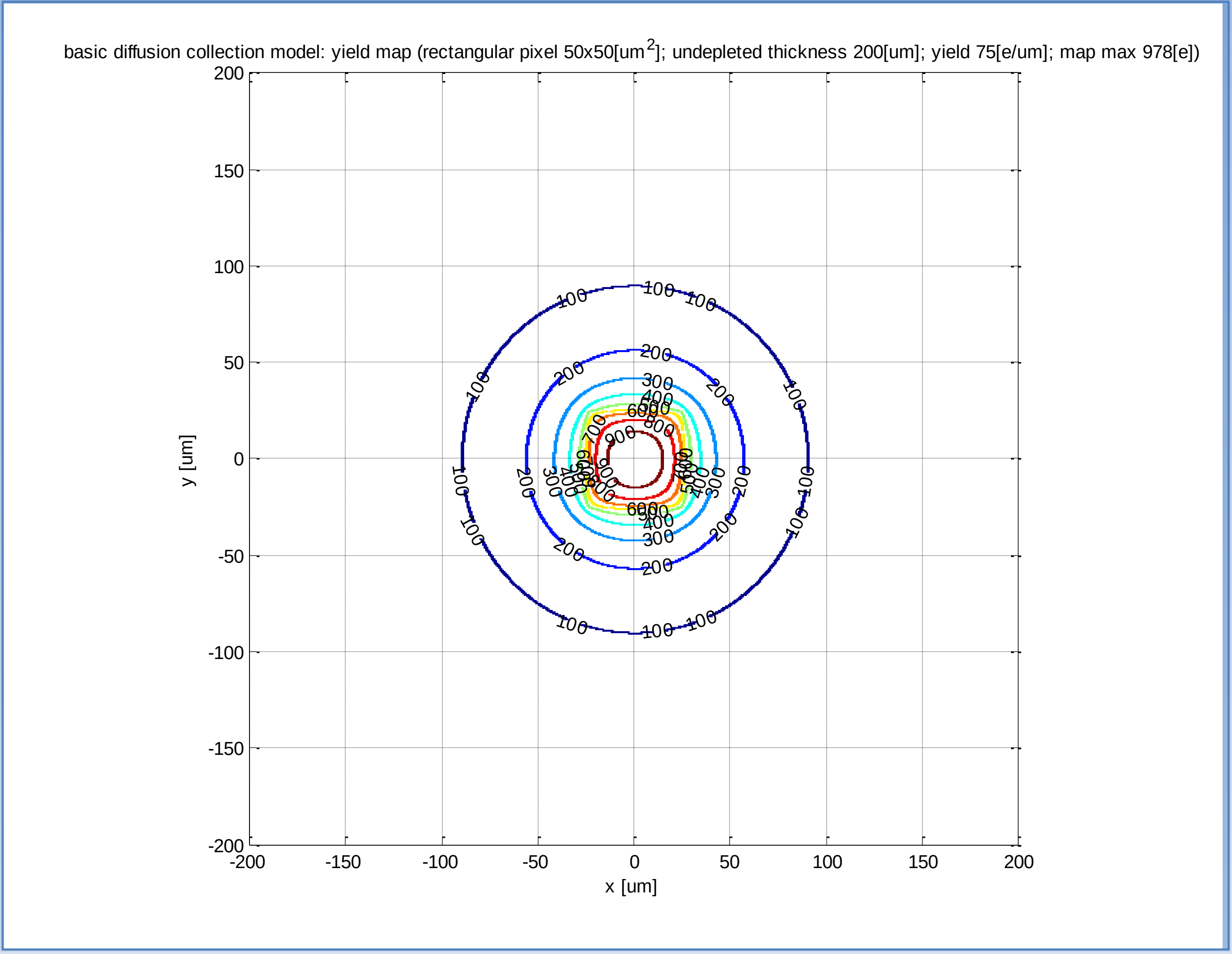

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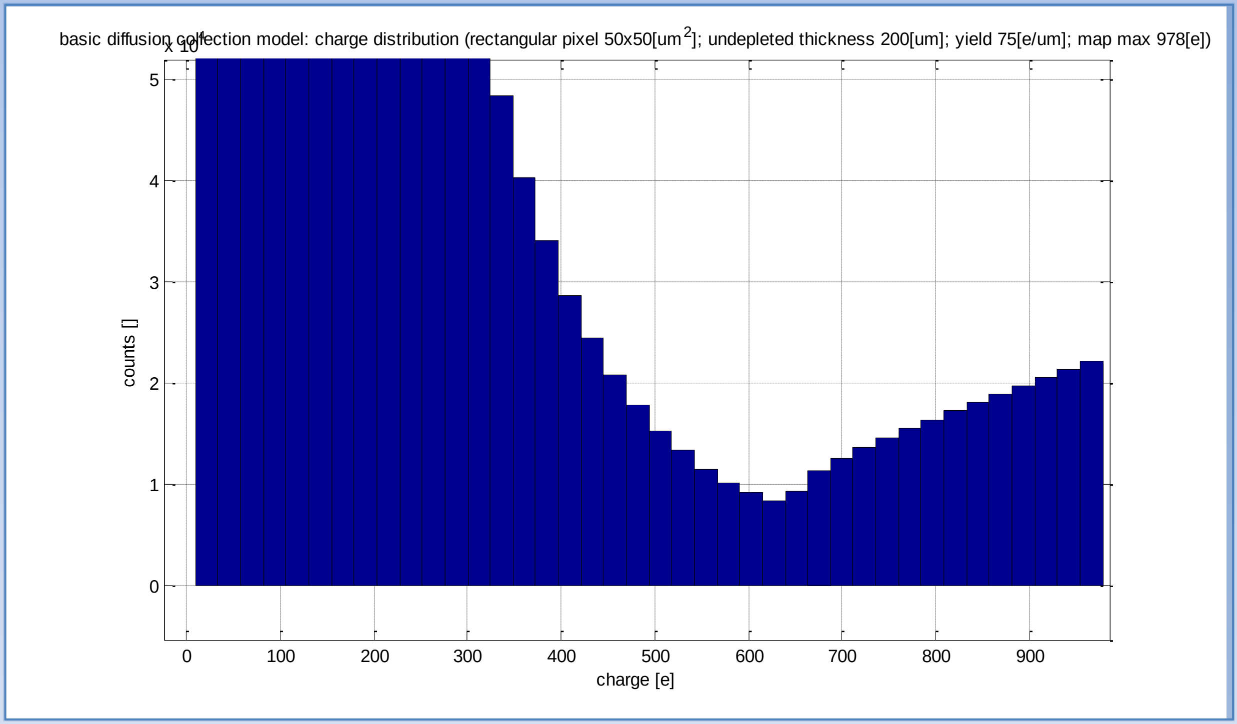

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- Orthogonal tracks
- $50x50um^2$

Collected charge distribution:

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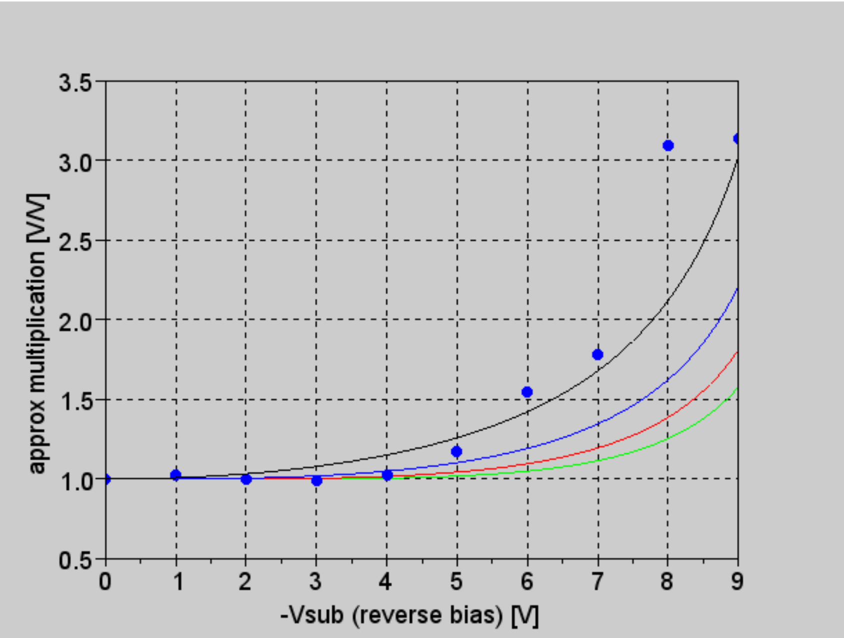
- high rates can be a significant problem…

Experimental: High energy Tail



Sealed source hit test:

- ‘large’ hits above max expected energy
  - pile-up
    OR
  - avalanche effects
- Require better statistics (high threshold spectrum)
  - …