A Novel 2D Position Sensitive Silicon Detector with Micron Resolution for Heavy Ion Tracking

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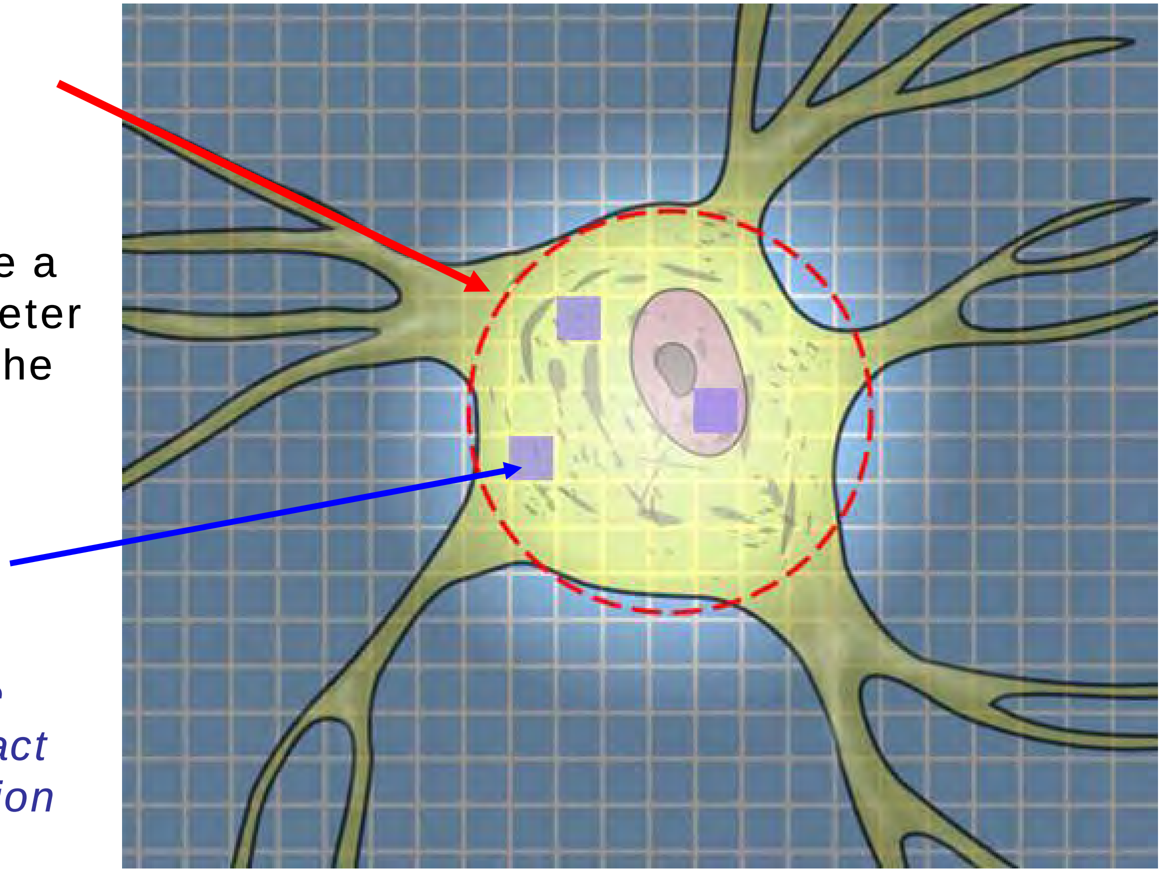
The Application and Requirements

Radiation effects studies of single heavy ions on single cells in the central nervous system

A microbeam of heavy ions (e.g. iron) at energies up to 3 GeV/nucleon. The microbeam would have a sufficiently small diameter (σ~10μm) to localize the ions to a single cell.

*An electronic position sensitive detector for heavy ions with a **position resolution ~ 1μm**, to localize the position of an ion impact within a particular region of the cell.*



A Microphotograph of the Cell Samples

~500µm

The Concept: Stripixel Detectors

Individual pixels are alternately connected by X and Y readout lines (strips)

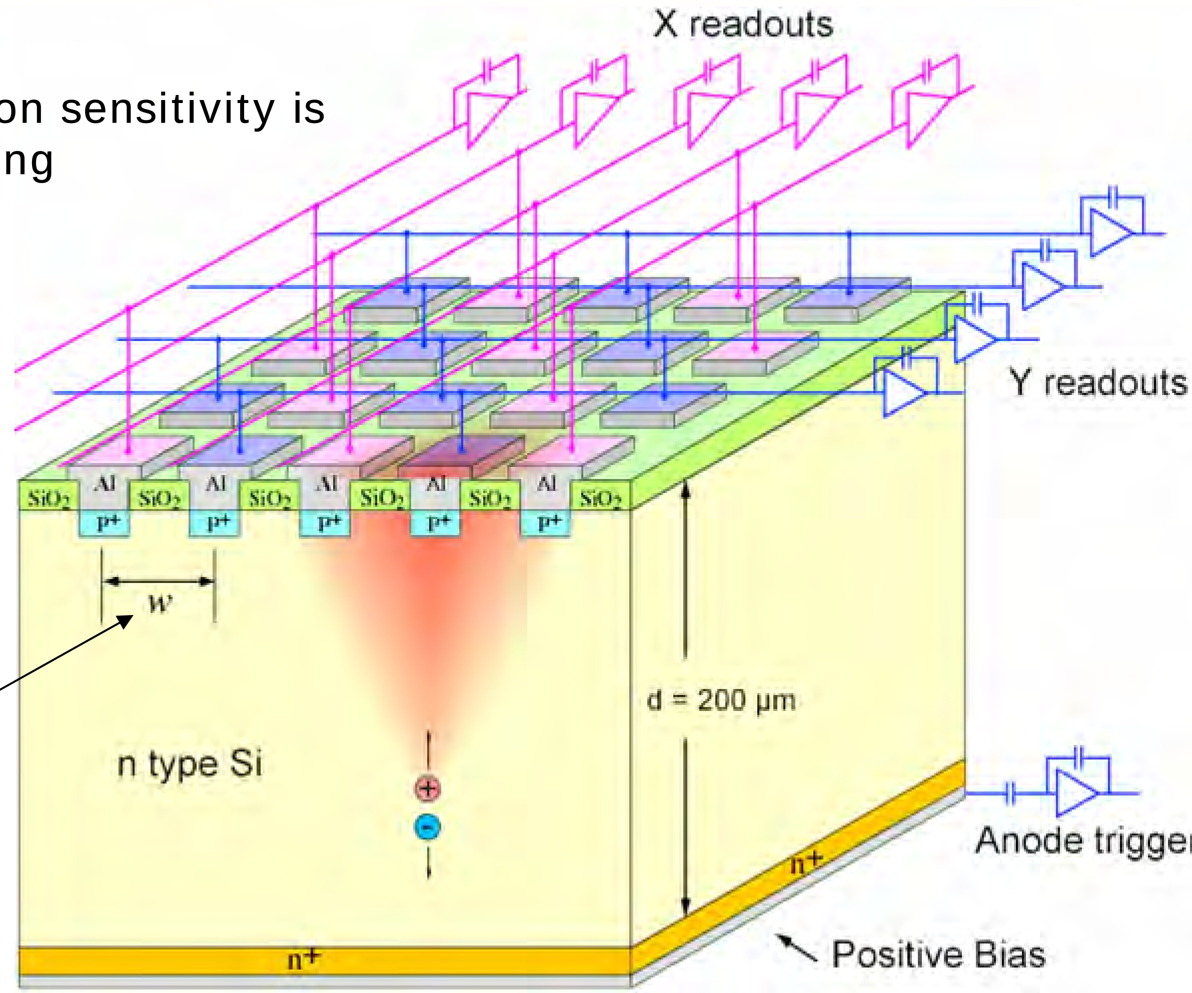
- Two dimensional position sensitivity is achieved by charge sharing between X and Y pixels
- Single sided process
- The pixel pitch must not be larger than the size of charge cloud

Interpolating readout:

$$\frac{\sigma_x}{w} \approx \frac{2}{S/N}$$

Pixel pitch

Interpolation factor: w/σ_x~10-100



Z. Li, NIM A518, p738 (2004)

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Position Resolution vs. Number of CF Channels

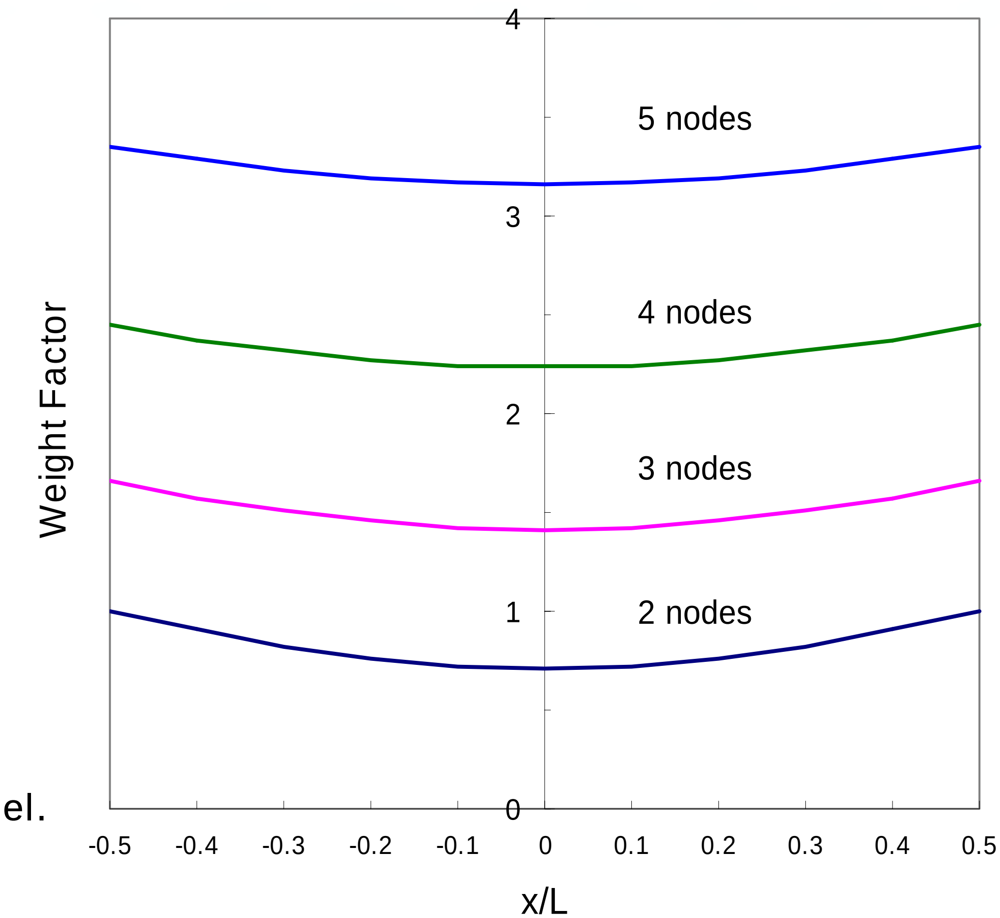
Using the simple center of gravity formula:

$$x = L\frac{\sum i \cdot Q_i}{\sum Q_i}$$

L is the distance between readout nodes.

The noise contribution to the relative position resolution is:

$$\frac{\Delta x}{L} = \frac{\Delta Q}{Q_T} \cdot a$$



ΔQ is the noise from a single channel. It is assumed to be non-correlated and equal for all channels.

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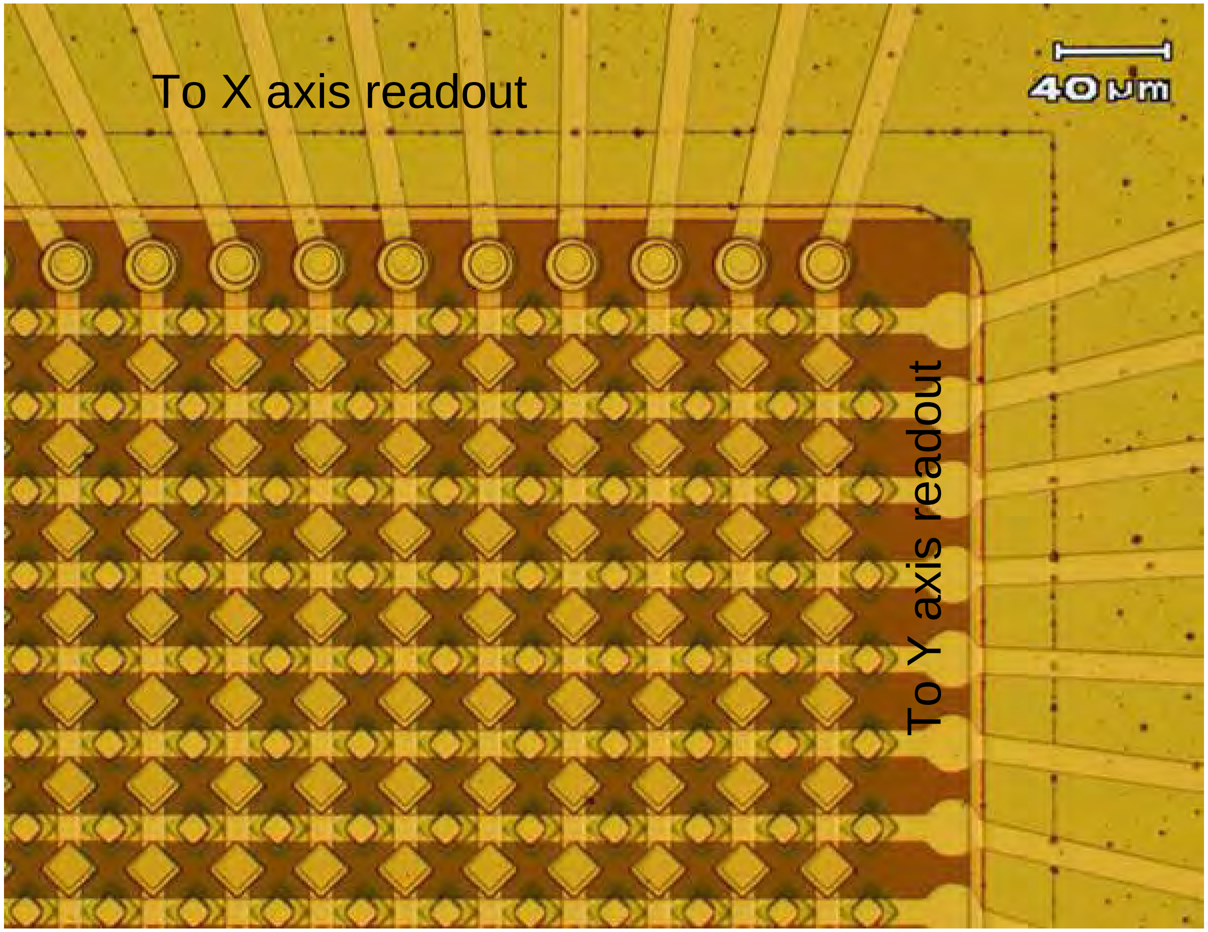
Detector Design: Alternating Stripixel (ASD)

30µm pitch, square pixels



Detector Design: Interleaved Stripixel (ISD)

40µm pitch, interleaved pixels

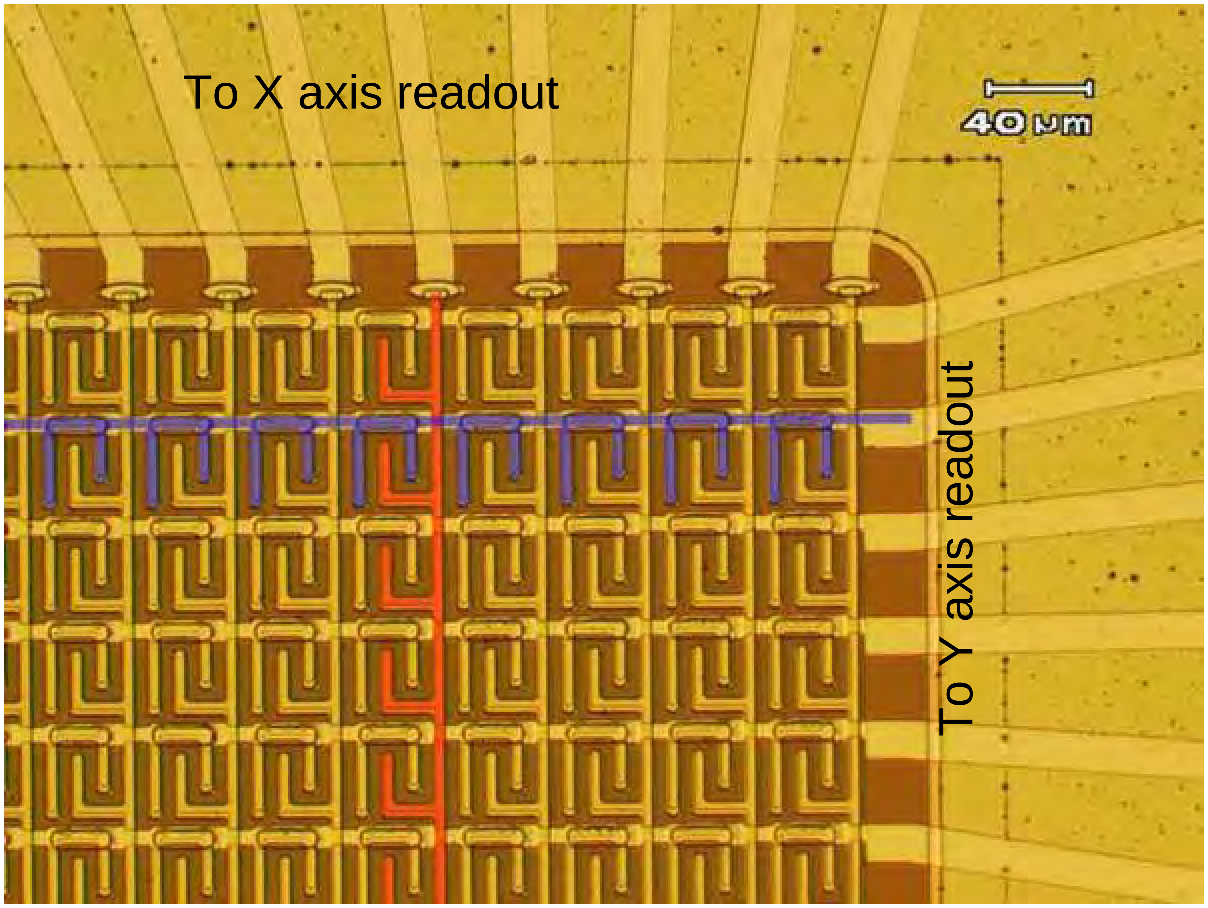


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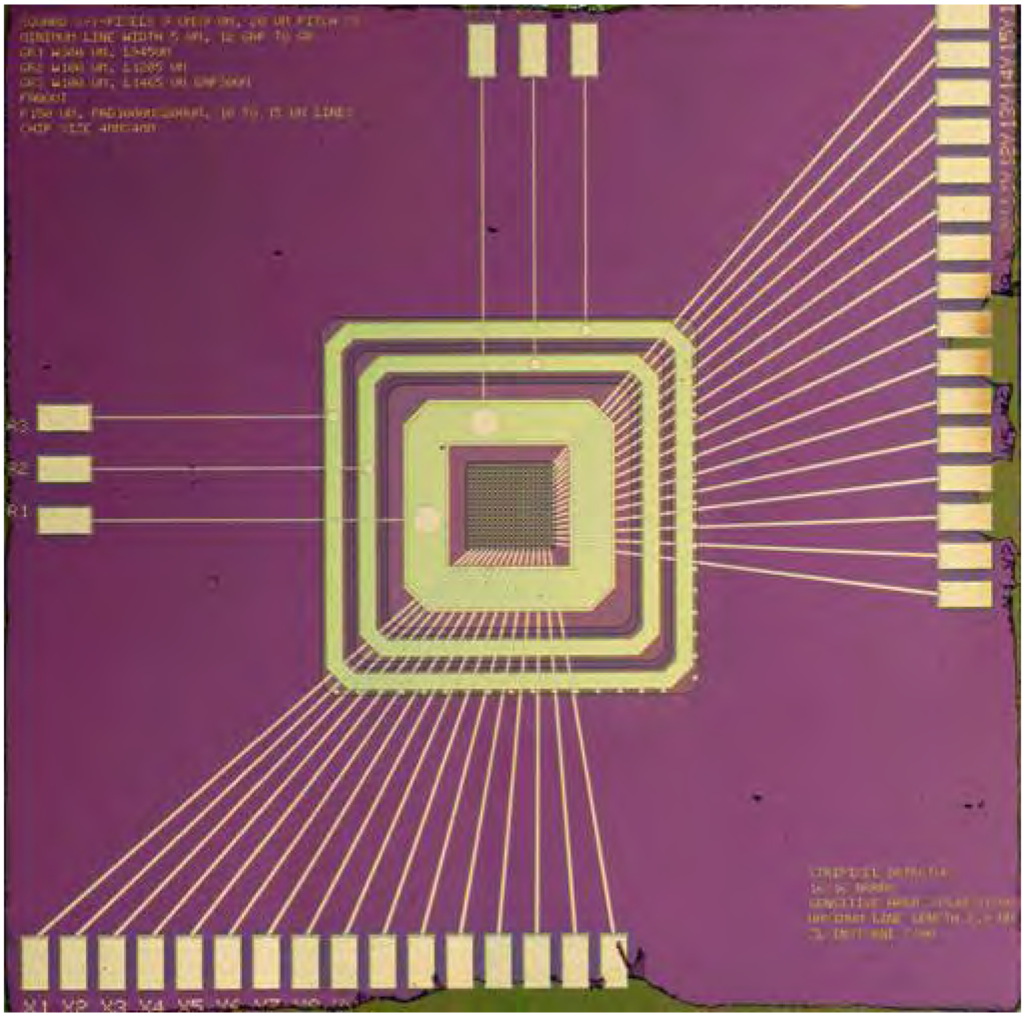
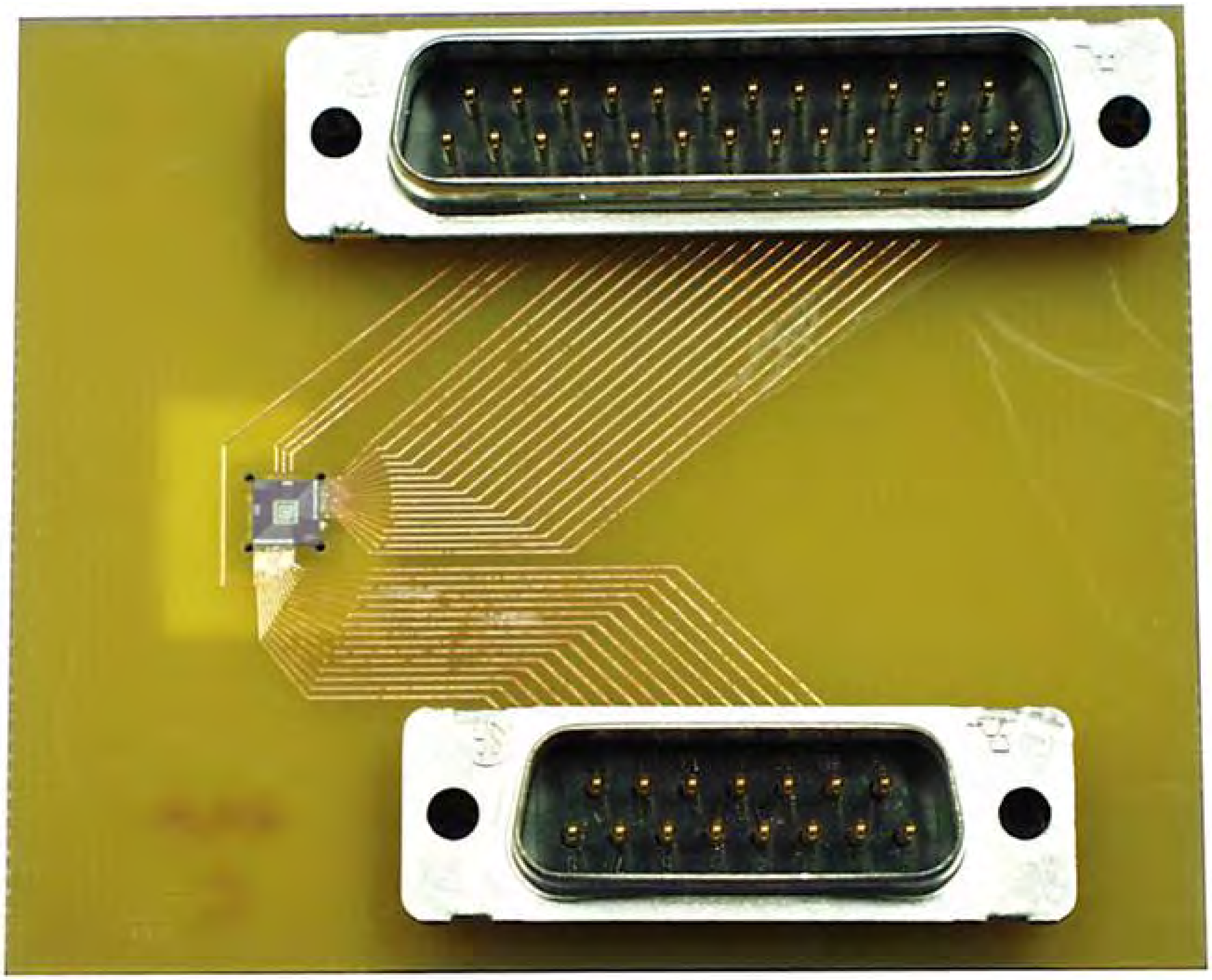
Photo of a Stripixel Die with a 20µm Pitch



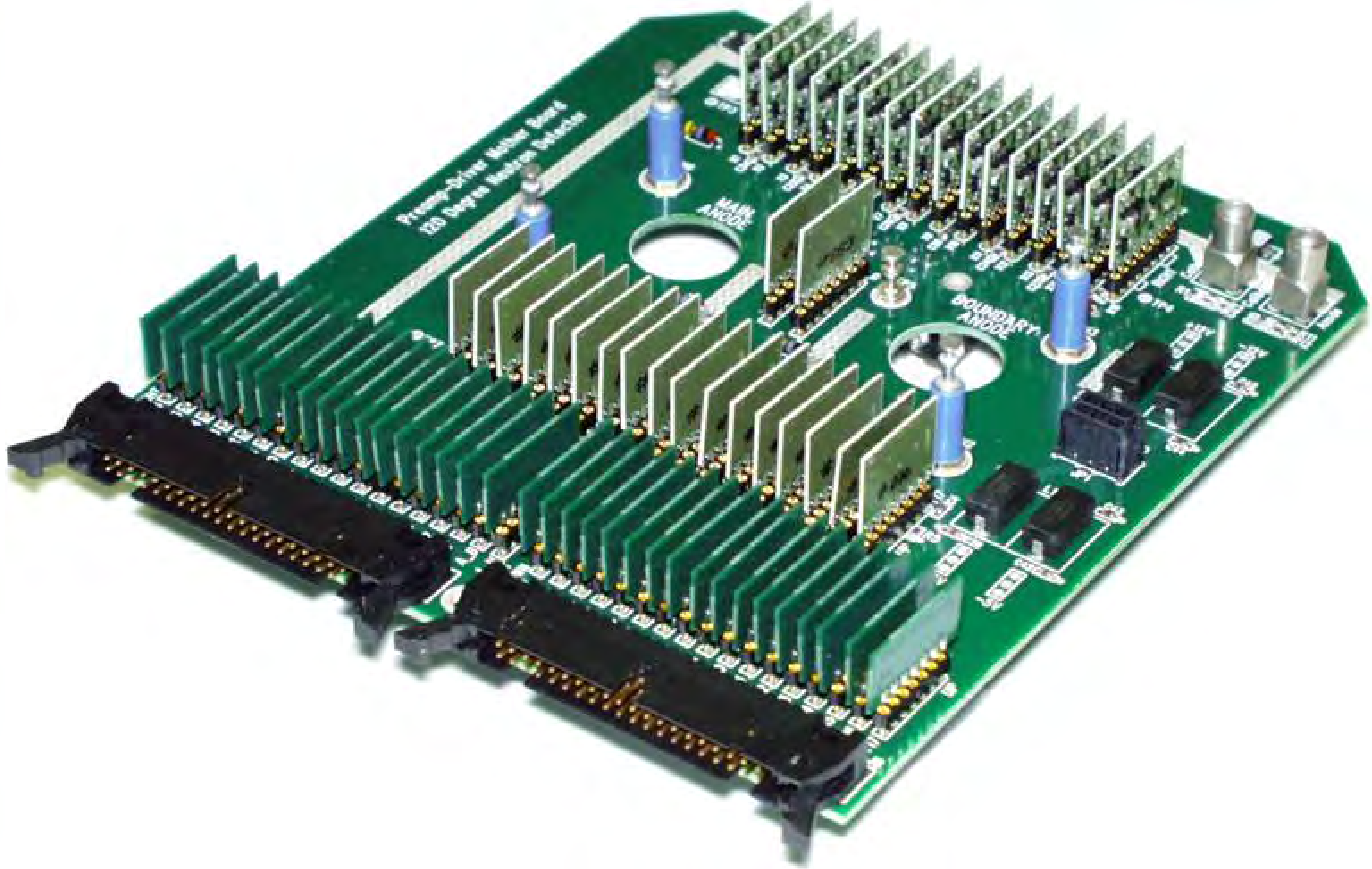
Active area:
0.3mm x 0.3mm

Number of Channels:
16X + 16Y

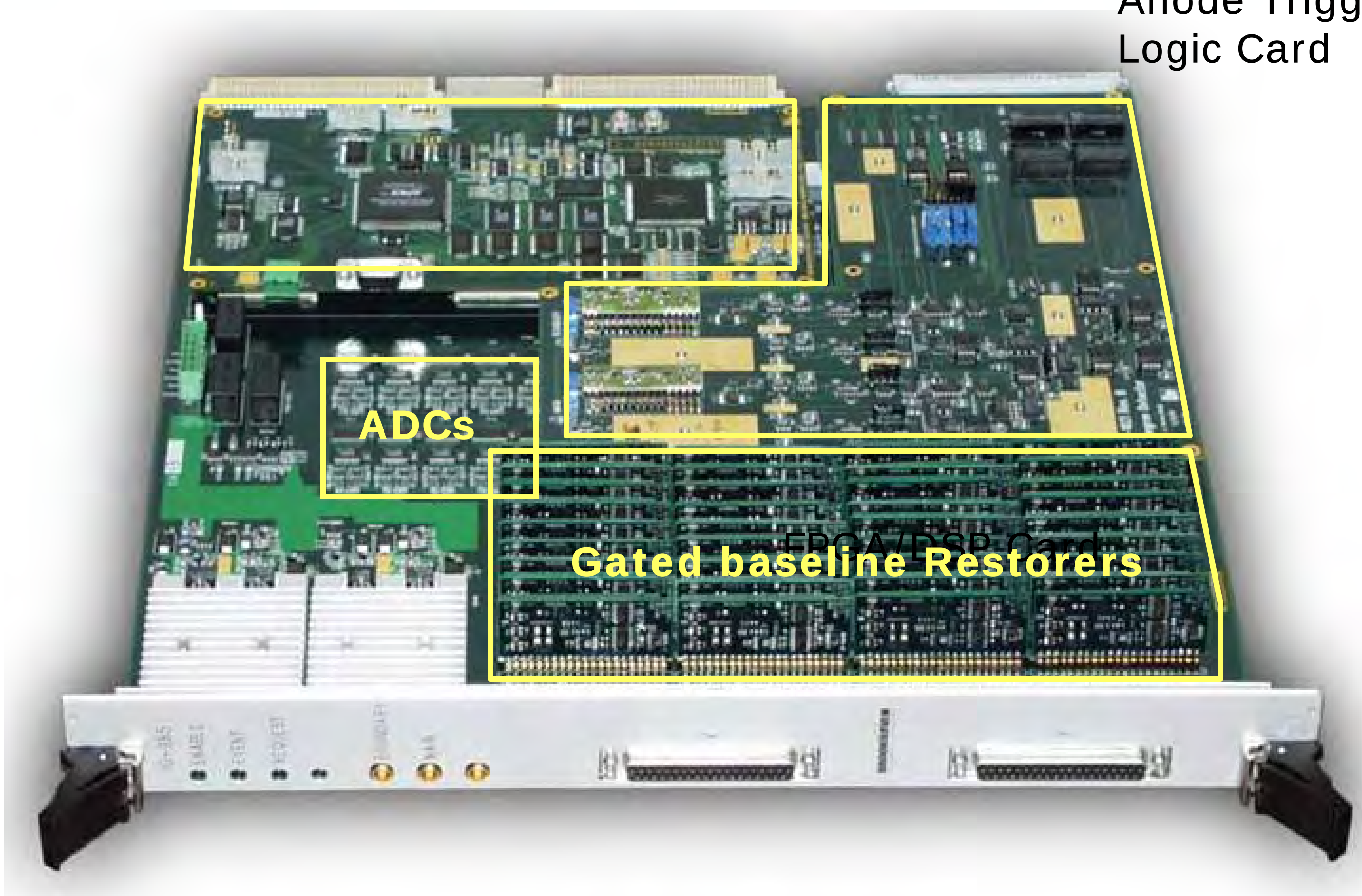
Detector Bonding Board



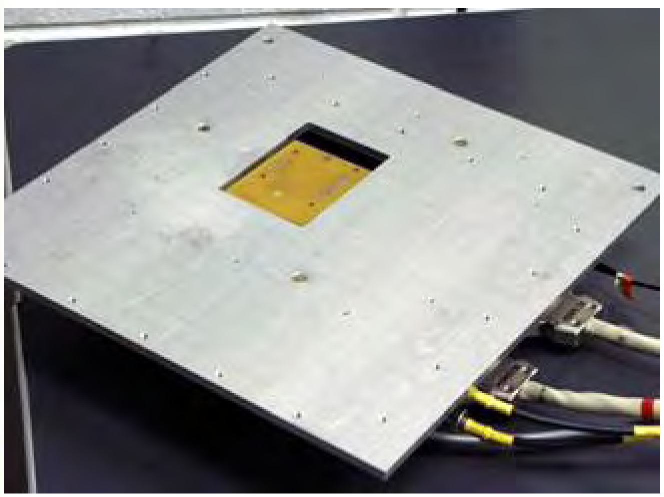
Front-End Electronics (120° Neutron Detector)

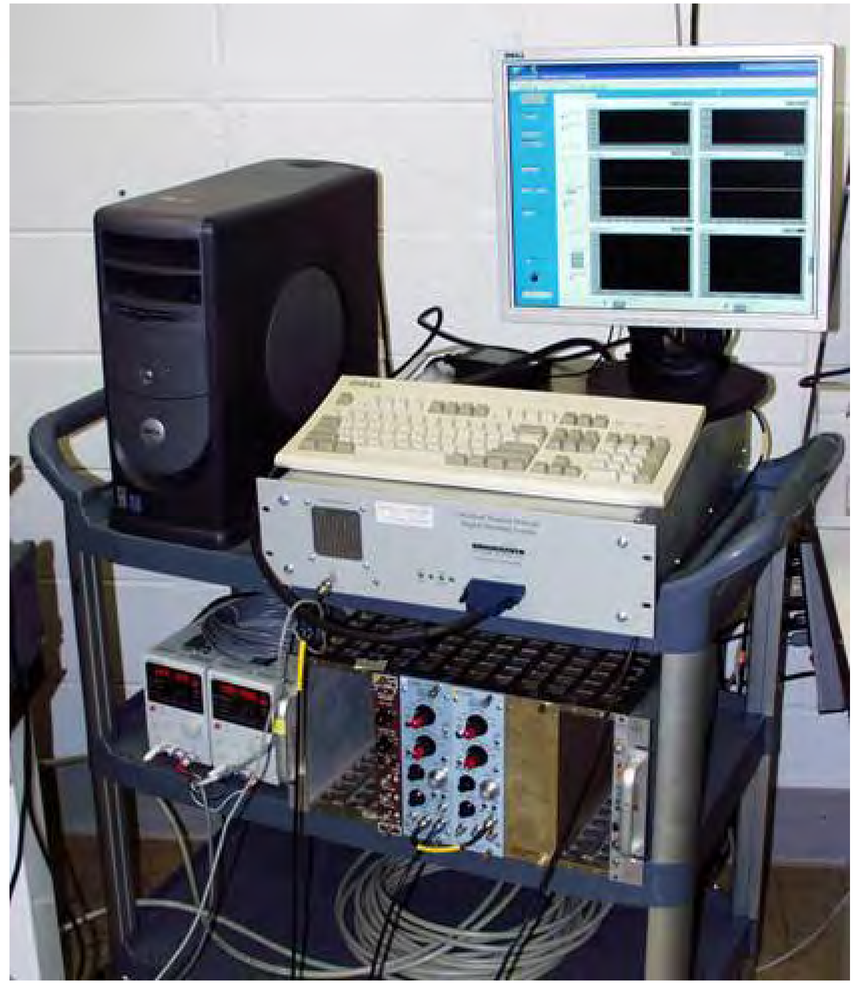


Digital Centroid Finding System (Neutron Detector)



Complete Detector System





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Fe Ion Interaction with Si

Expected effects on energetic Fe ions due to the traversal of 200µm of Si. The estimates are based on TRIM simulations by Peter Thieberger.

Energy per nucleon (MeV/amu)	**1000**	**800**	**600**	**400**	**200**
Average energy loss (MeV)	55.4	58.4	64.0	75.9	112.1
RMS energy loss fluctuation (MeV)	3.81	3.41	2.93	2.51	2.23
dE/dx (MeV/µm)	0.277	0.292	0.320	0.379	0.561
RMS exit distance from incident ion trajectory (µm)	0.024	0.030	0.048	0.076	0.131
RMS exit angle (mrad)	0.20	0.28	0.37	0.56	1.15

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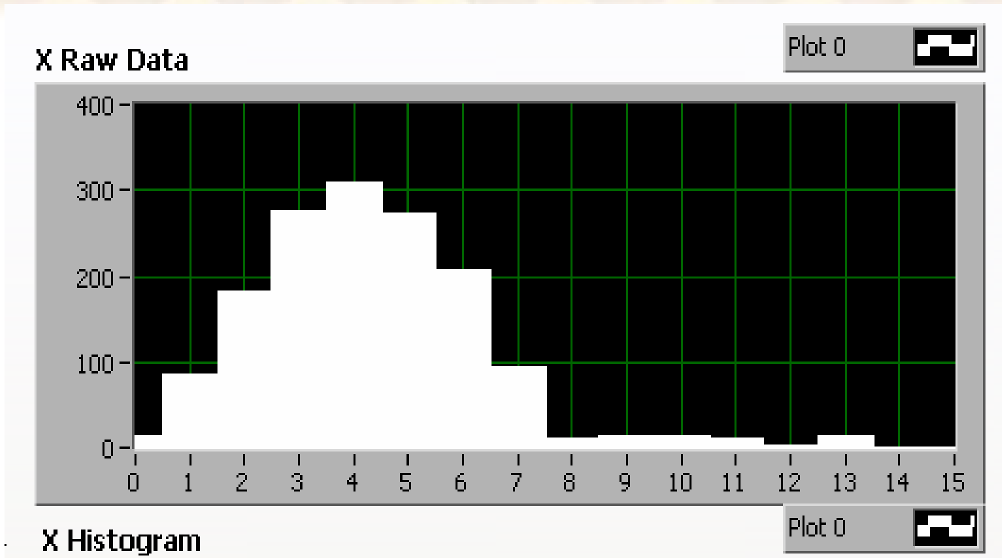
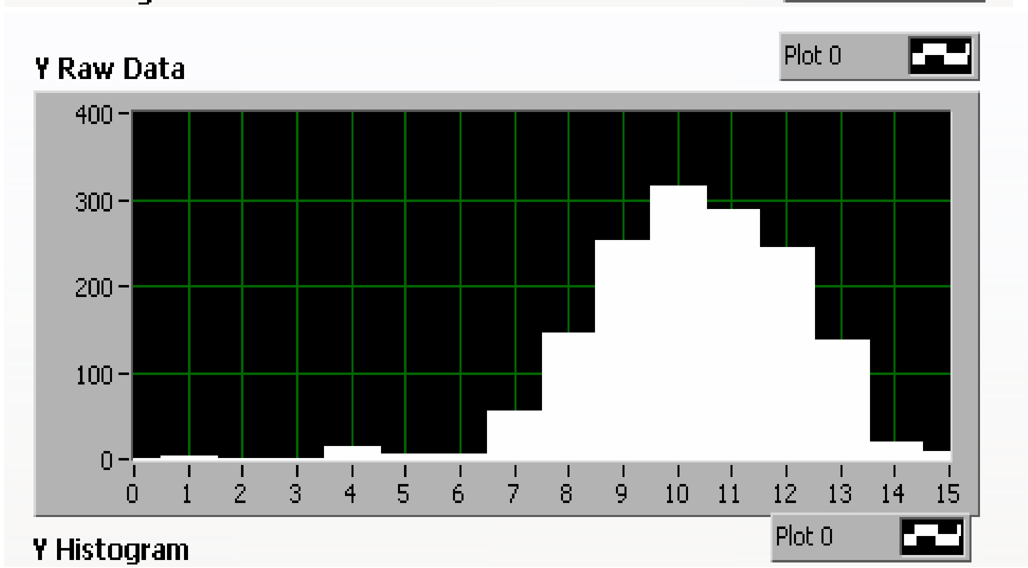
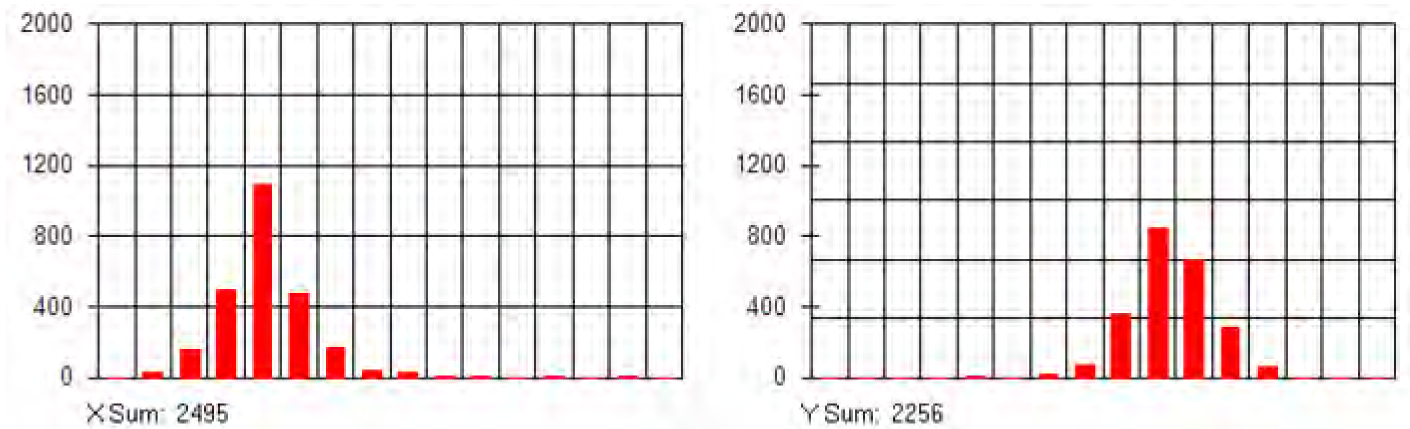
Laser Pulse Signal Display





635nm red laser on 20µm pixel pitch. Beam spot ~ 7µm

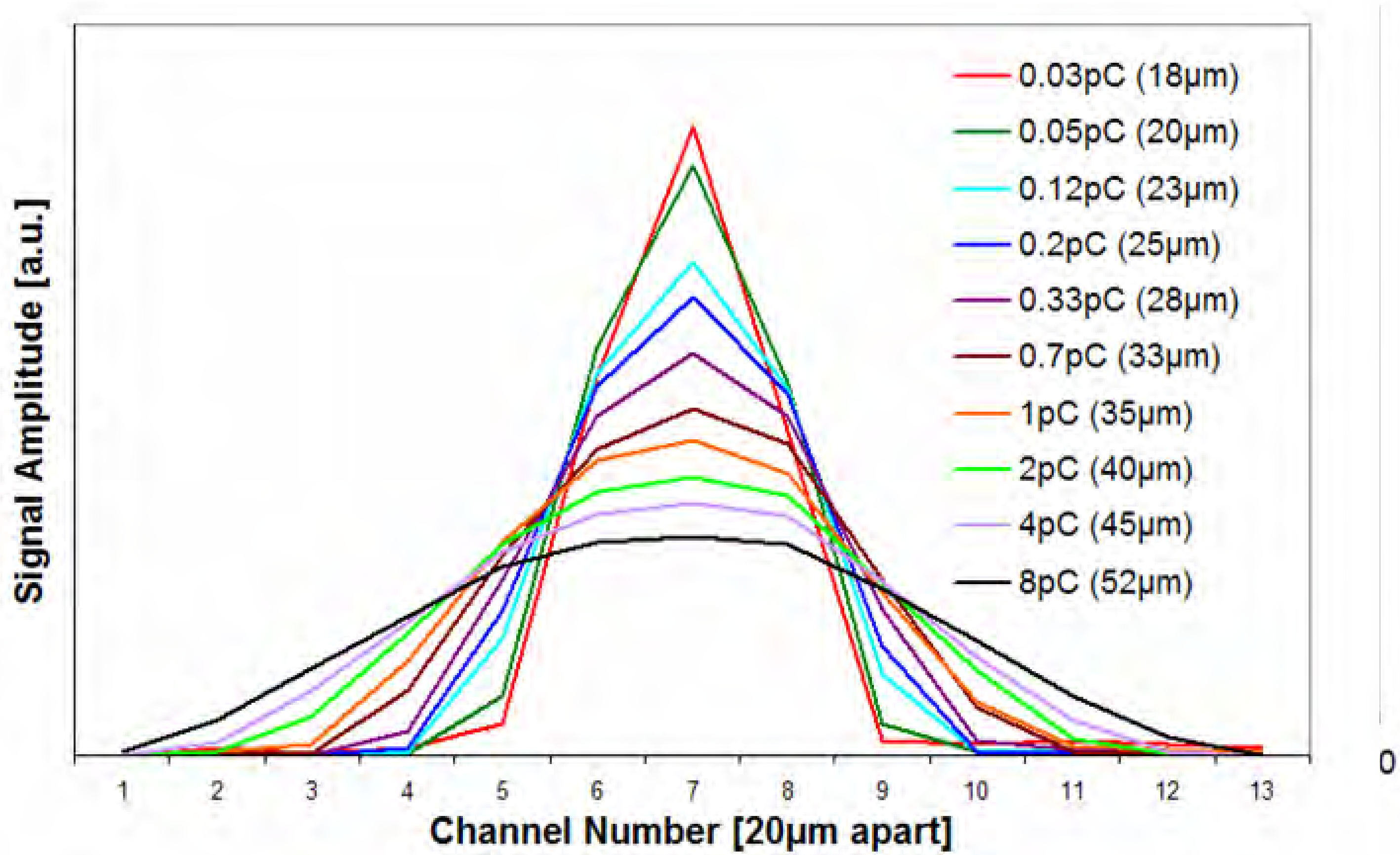
Heavy Ion Event Signal Display



Example of the signal charge collected from all channels on both axes of a stripixel detector with 20µm pitch. The incident particle is a 1GeV/n Fe ion. The total charge deposited on both axes is about 2.4pC (55MeV).

Spread of Signal Charge under Red Laser Beam

20µm pixel pitch, 635nm laser on back side, 60V bias, normalized area. The numbers in parentheses are the sigmas of a gaussian fitted to the distributions



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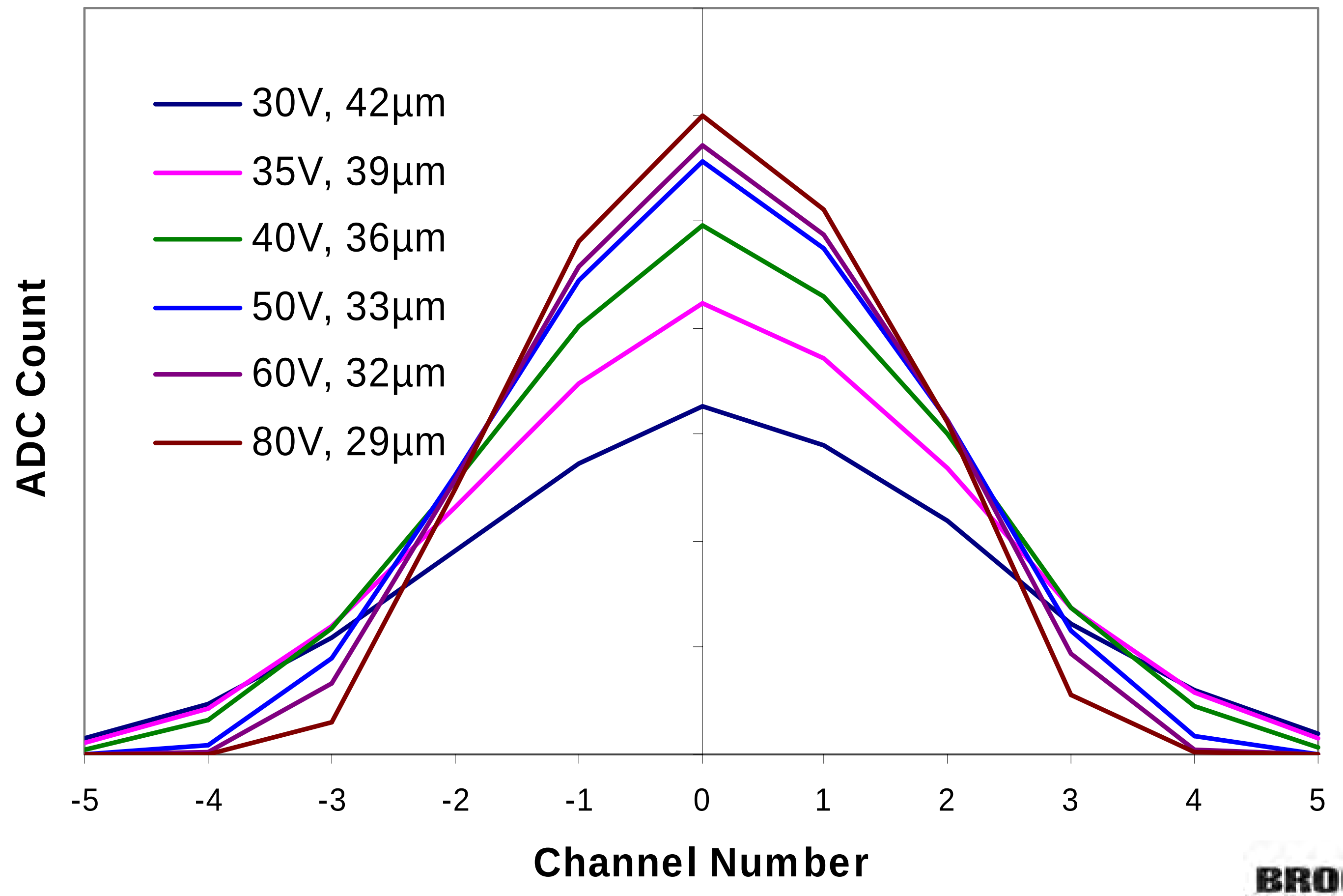
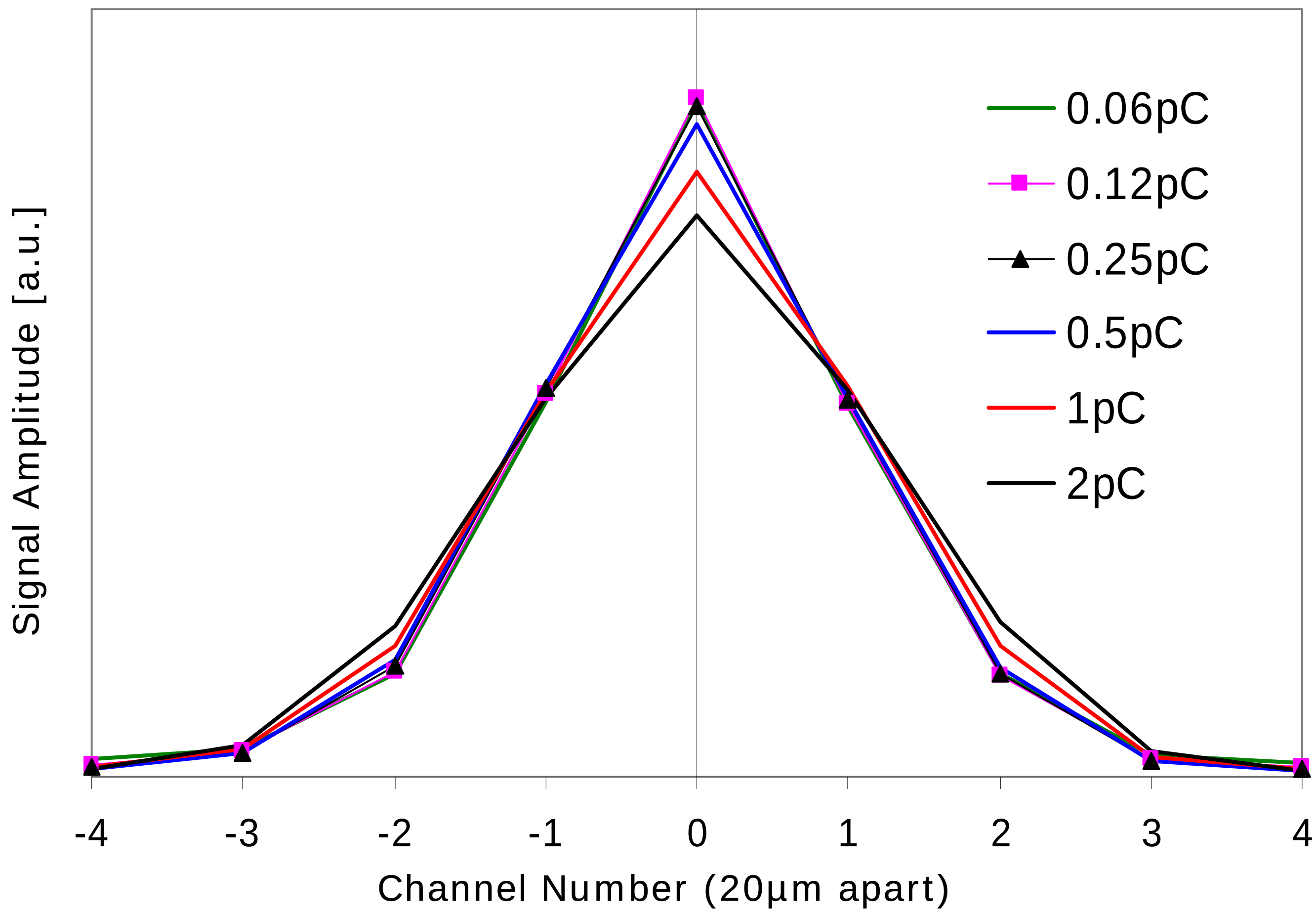
Charge Spread vs. Bias (Red Laser)

20µm pixel, red laser through window, q~0.6pC



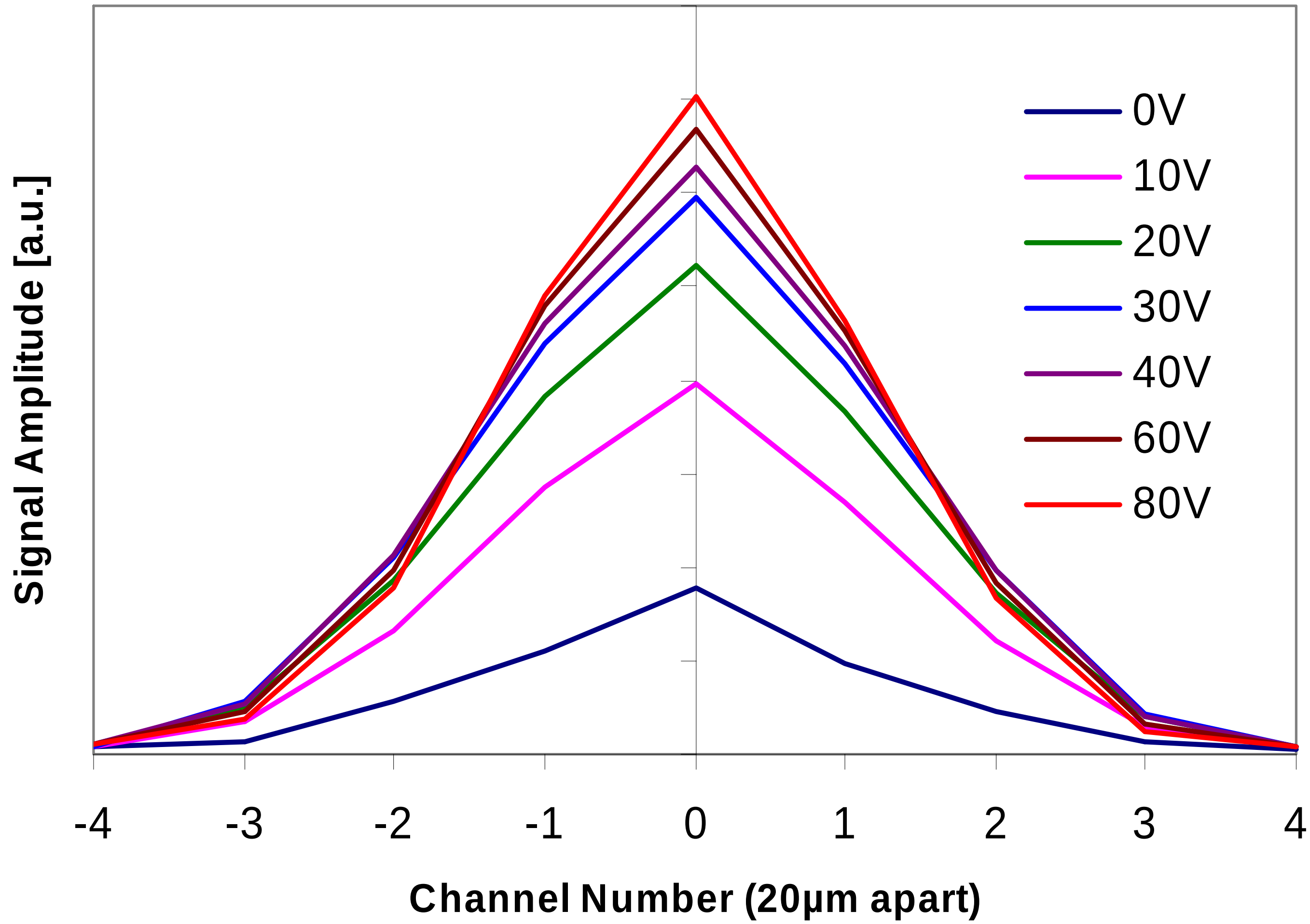
Spread of Signal Charge under IR Laser Beam

20µm pixel pitch, 1060nm laser on back side, 60V bias, normalized area.

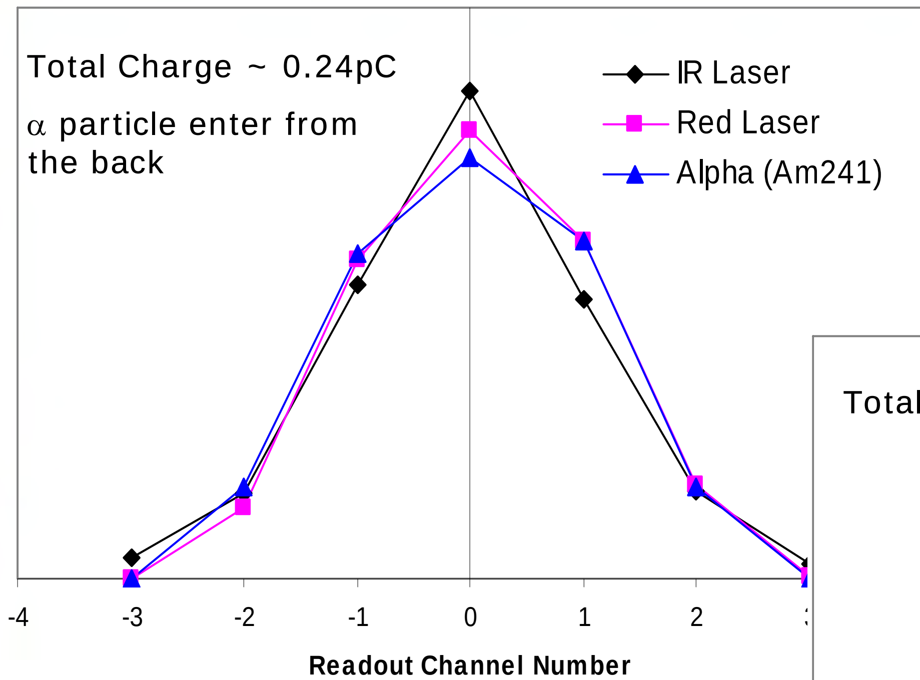


Charge Spread vs. Bias, IR Laser Beam

20µm pixel pitch, 2pC charge total charge.



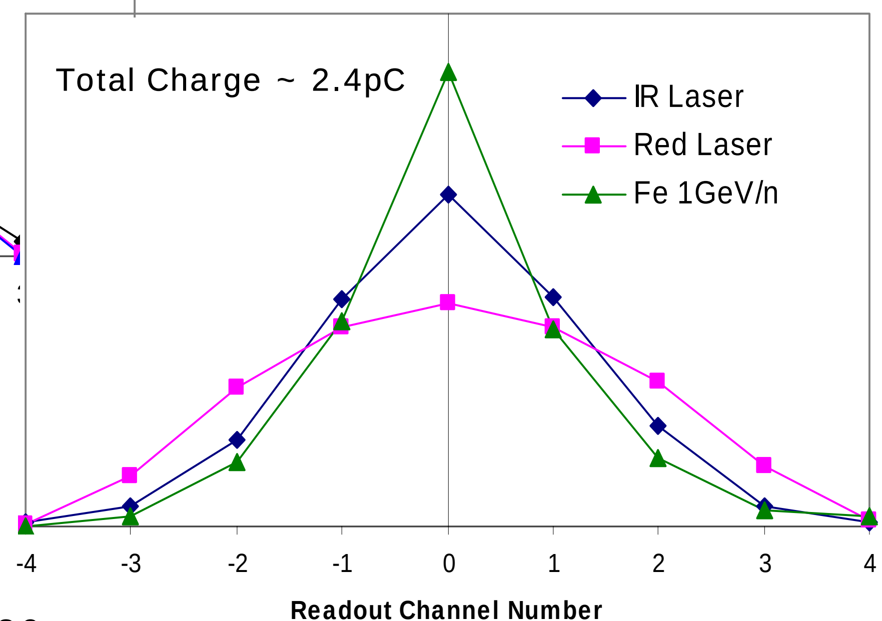
Charge Spread Profile vs. Type of Radiation



Red Laser: 635nm

Infra-red Laser: 1060nm

Beam Spot ~ 5µm



20µm pixel pitch, 200µm thick, 60V bias

The IR laser profile fits a gaussian with σ~26µm

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Nuclear Instruments and Methods in Physics Research A253 (1987) 393–399
North-Holland, Amsterdam

DYNAMICS OF ELECTRONS IN DRIFT DETECTORS*

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N electrons initially distributed as a Dirac delta function in an infinite homogeneous mediam:

$$Q(r,t) = \frac{r^3}{3(\frac{\mu}{4\pi\varepsilon})t}\left[U(r) - U(r - r_0(t))\right] + qN \cdot U(r - r_0(t))$$

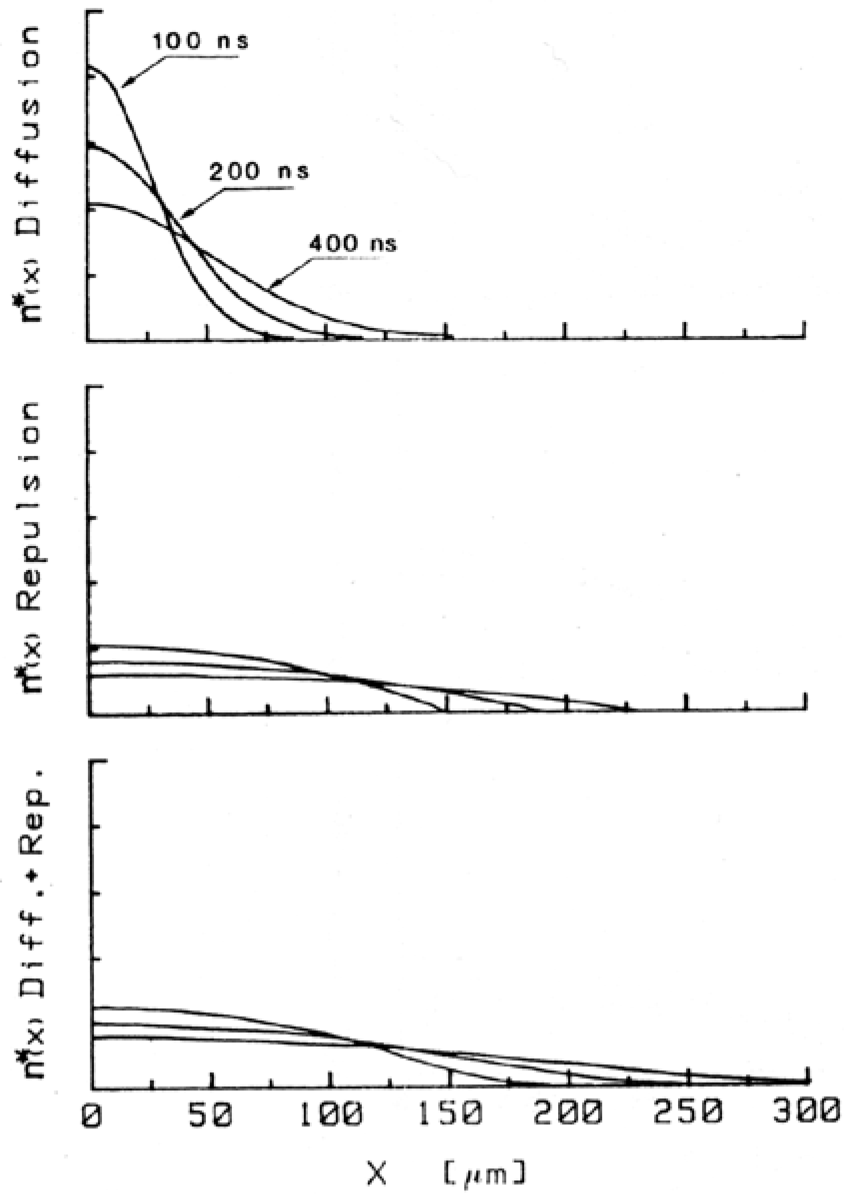
U(r) is the step function.

All N electrons are contained in an expanding sphere, with a radius of:

$$r_0(t) = \sqrt[3]{3\frac{\mu q}{4\pi\varepsilon}Nt}$$

Calculated charge density distribution, with 900,000 electrons

From E. Gatti et al., NIM A253 (1987) p393



Diffusion only

Repulsion only

Diffusion + Repulsion

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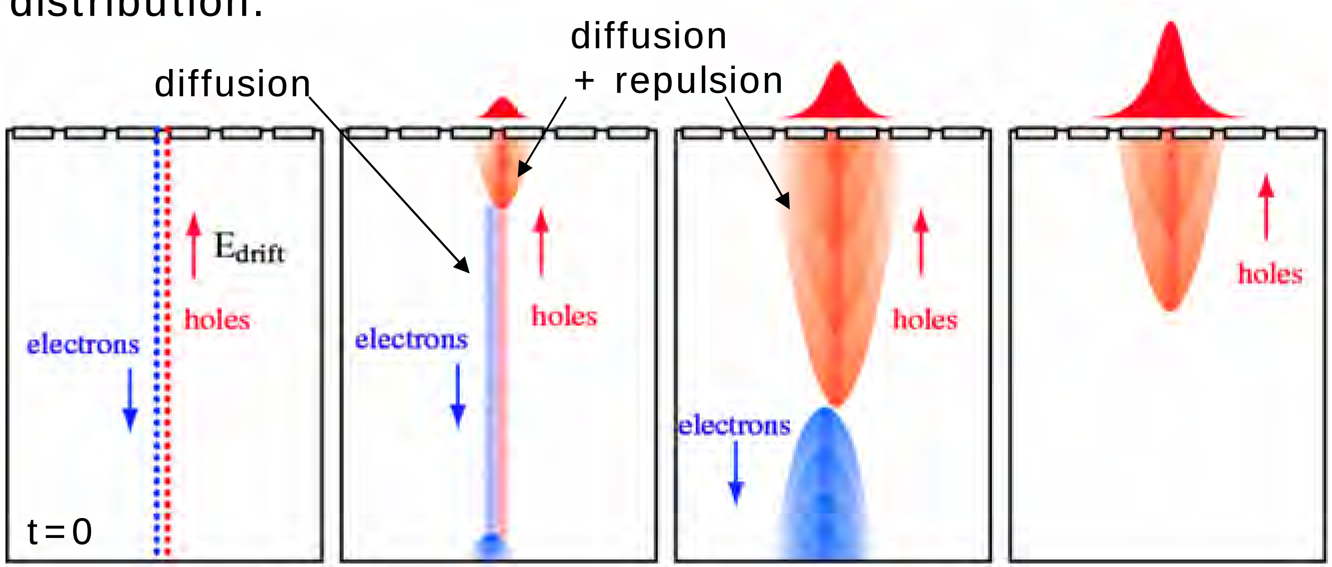
Charge Cloud Spread, the Contributors

- When ionization is from heavy ions (including alpha particles), the ionization density in silicon is so large that the natural diffusion of the charge carriers is no longer the main contributor to the charge spread.
- Under such conditions, the charge cloud expands rapidly under its own repulsive force, results in much greater spread than that from diffusion.
- The final charge distribution on the pixel plane from a heavy ion track is the result of a convolution from a series of distributions, driven mostly by repulsion, with increasing ranges. This gives a broad, but narrowly peaked distribution.



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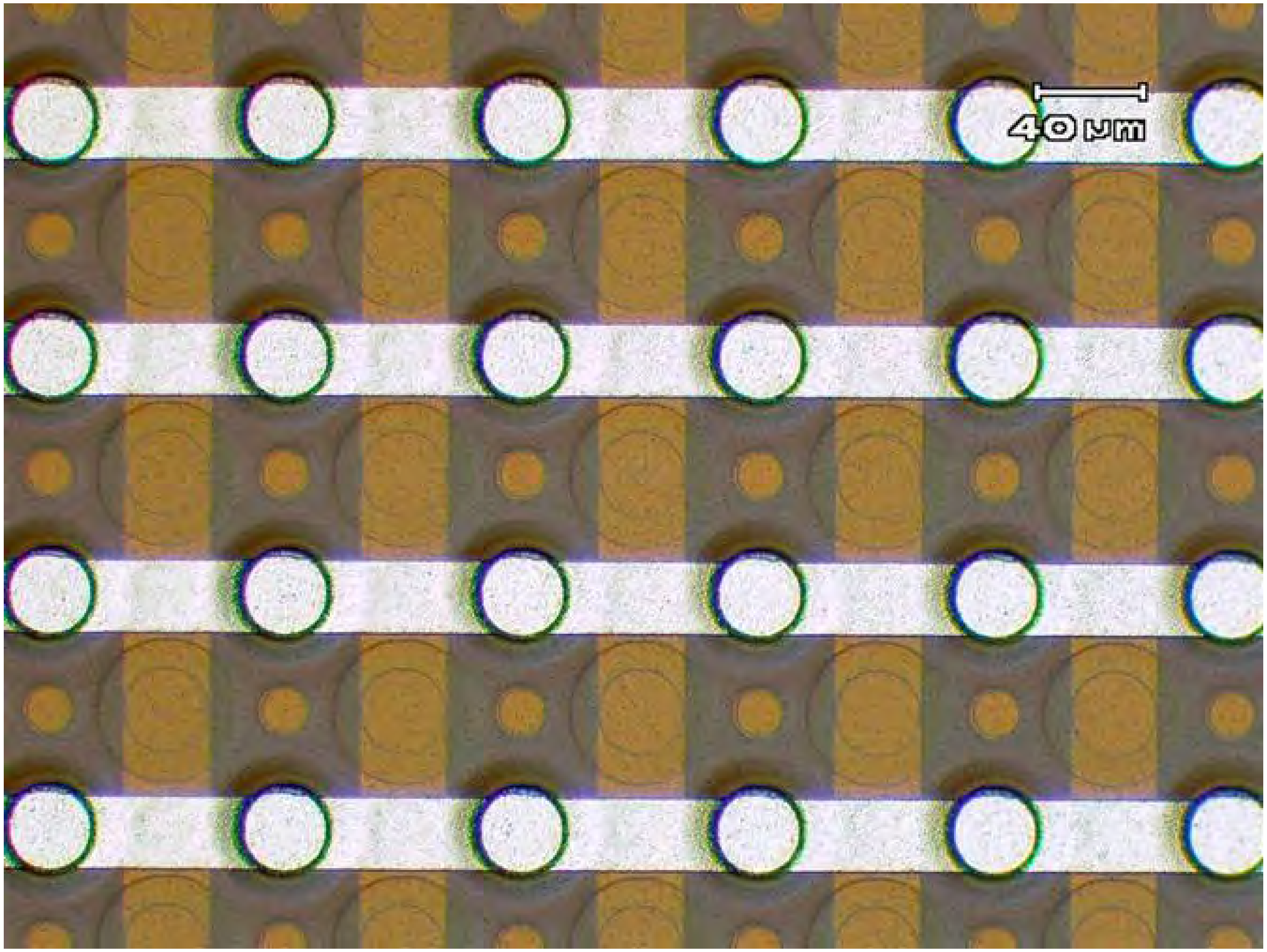
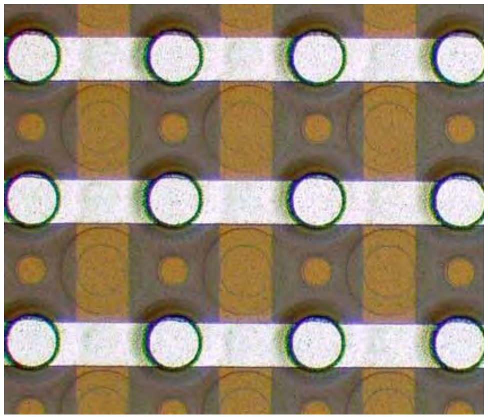
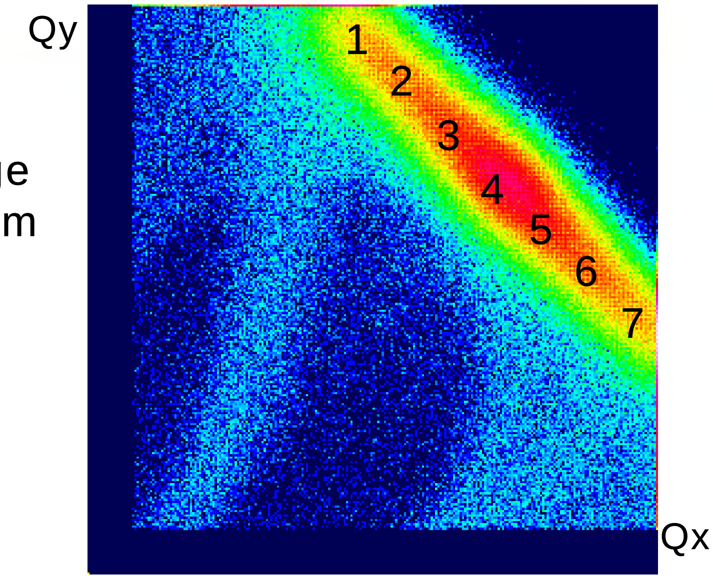
85µm Circular Pixel



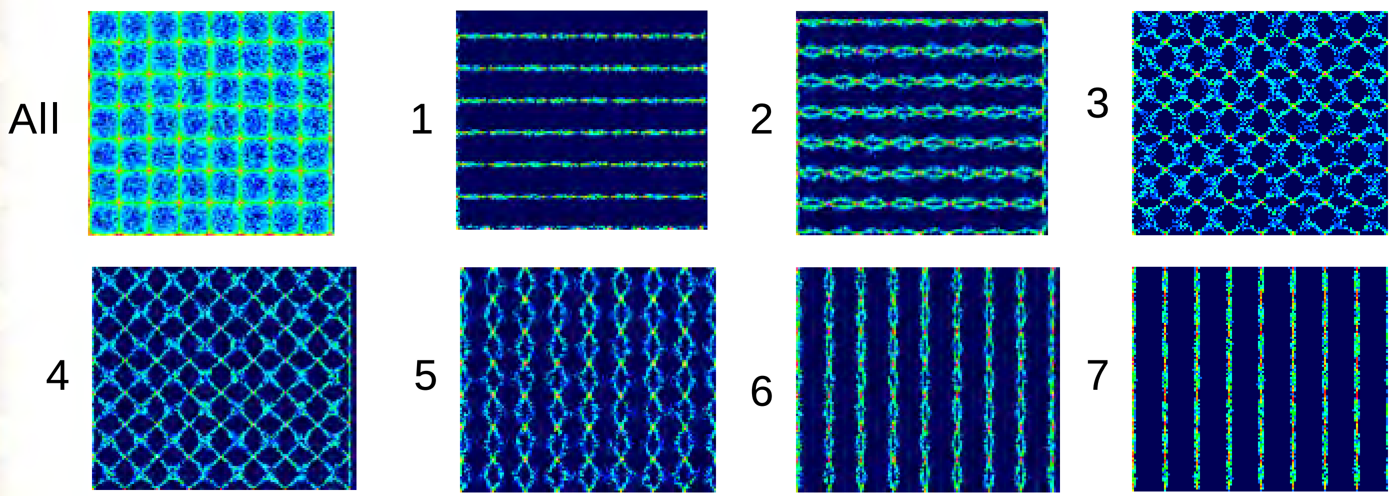
Asymmetric Charge Sharing (85µm circular pixel)



X-Y axis charge correlation from uniform Alpha irradiation



Reconstructed positions from events in selected regions



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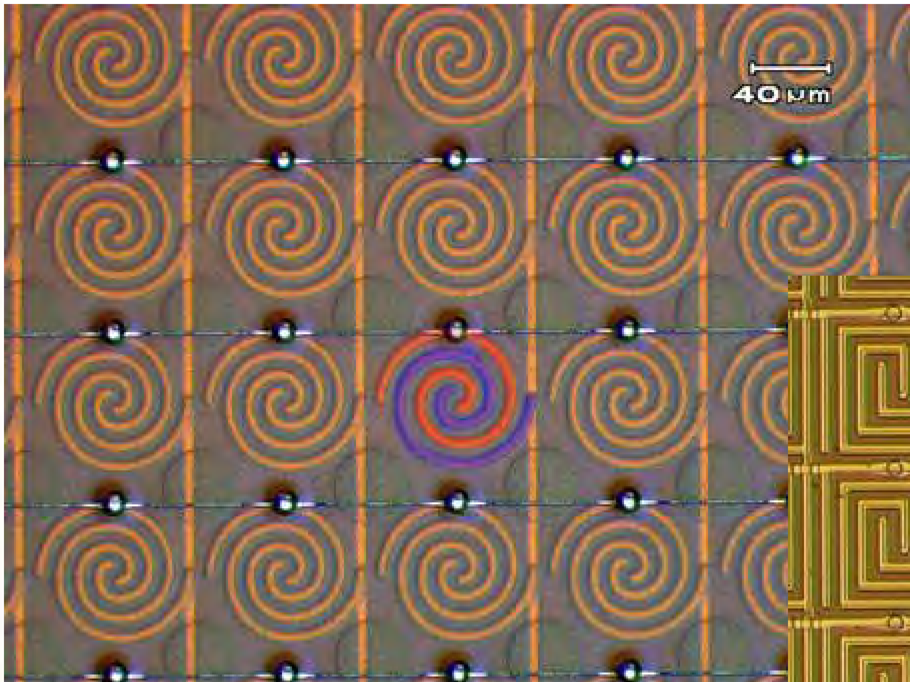
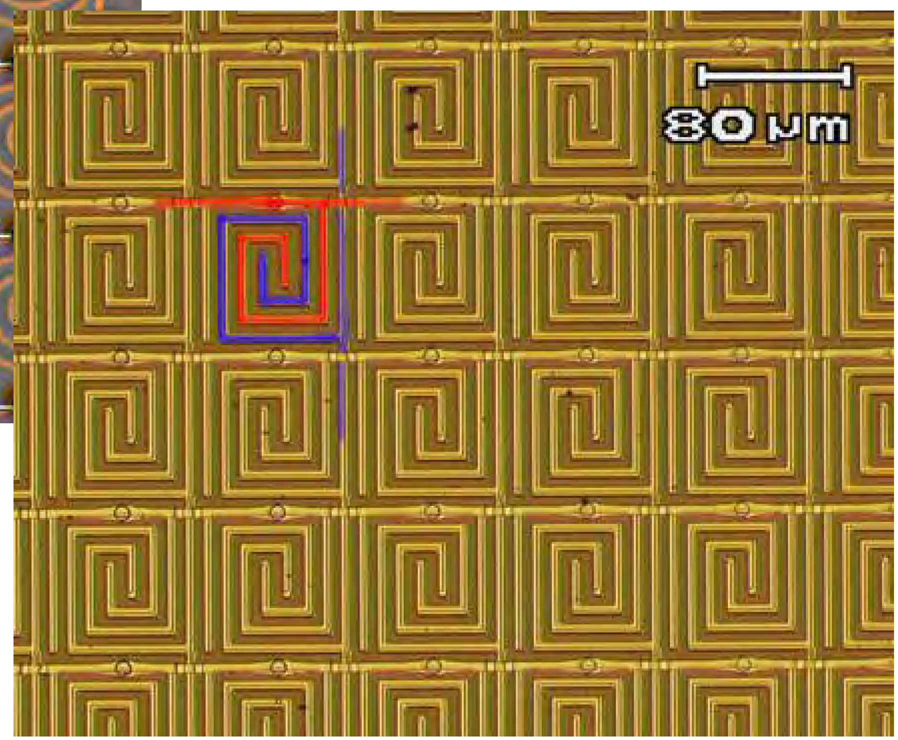
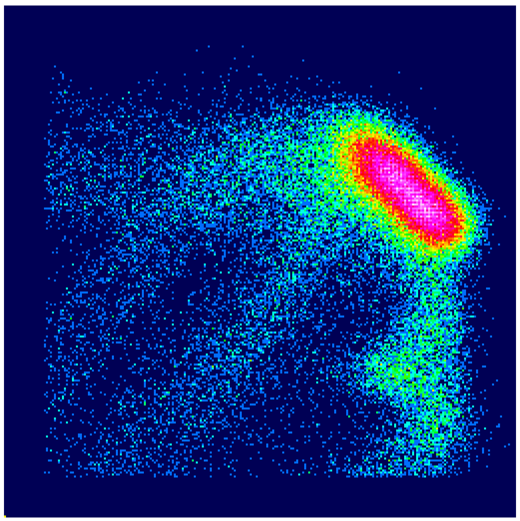
85µm Circular and Square Spiral Pixels



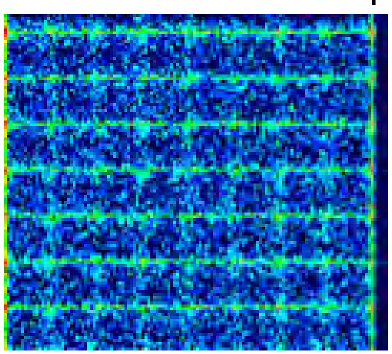


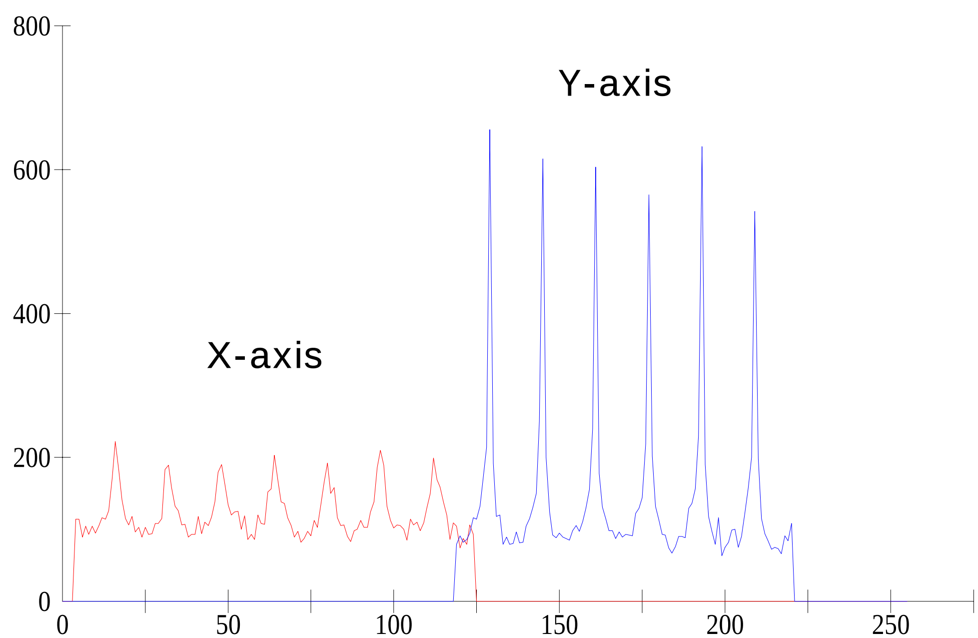
85µm Circular Spiral Pixels, Alpha Test Results

X-Y axis charge correlation



Uniform irradiation response





Uniform irradiation response

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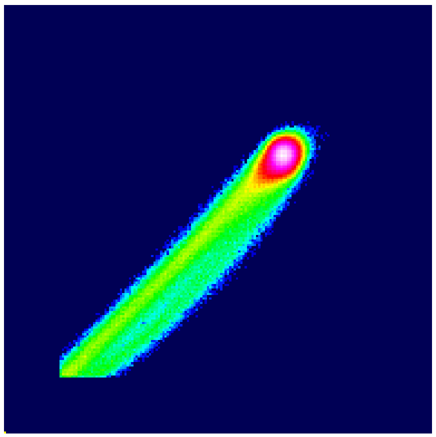
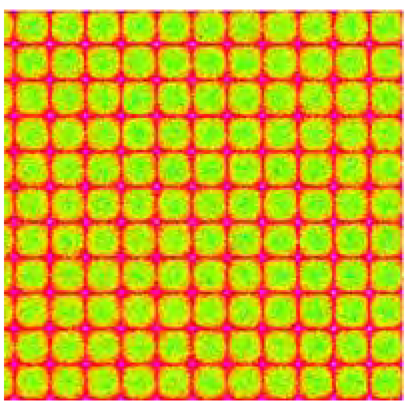
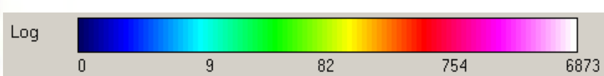
85µm Square Spiral Pixels, Alpha Test Results

Two axis charge correlation

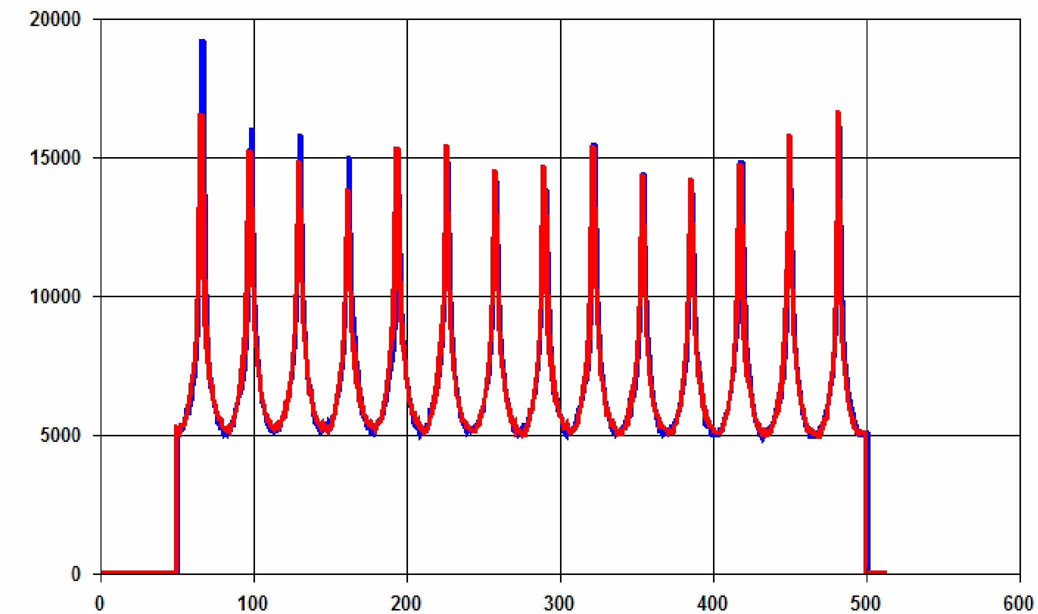


Uniform Irradiation Response



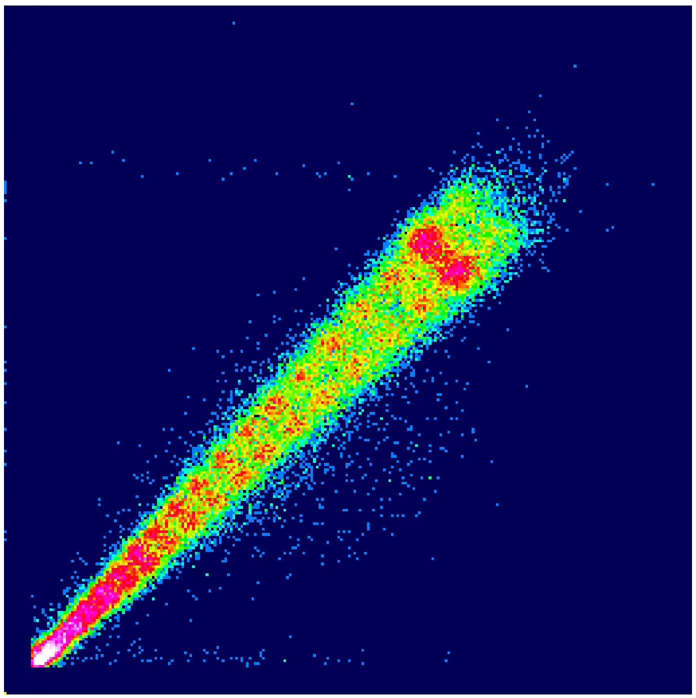


Uniform Irradiation Response

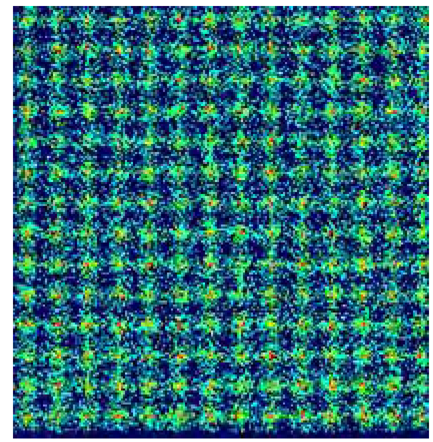


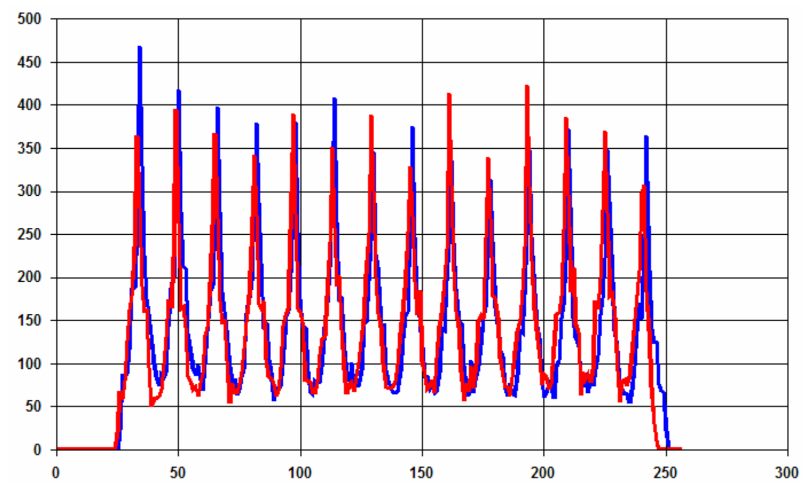
85µm Square Spiral Pixels, Fe Beam Test Results

Two axis charge correlation



Uniform Irradiation Response





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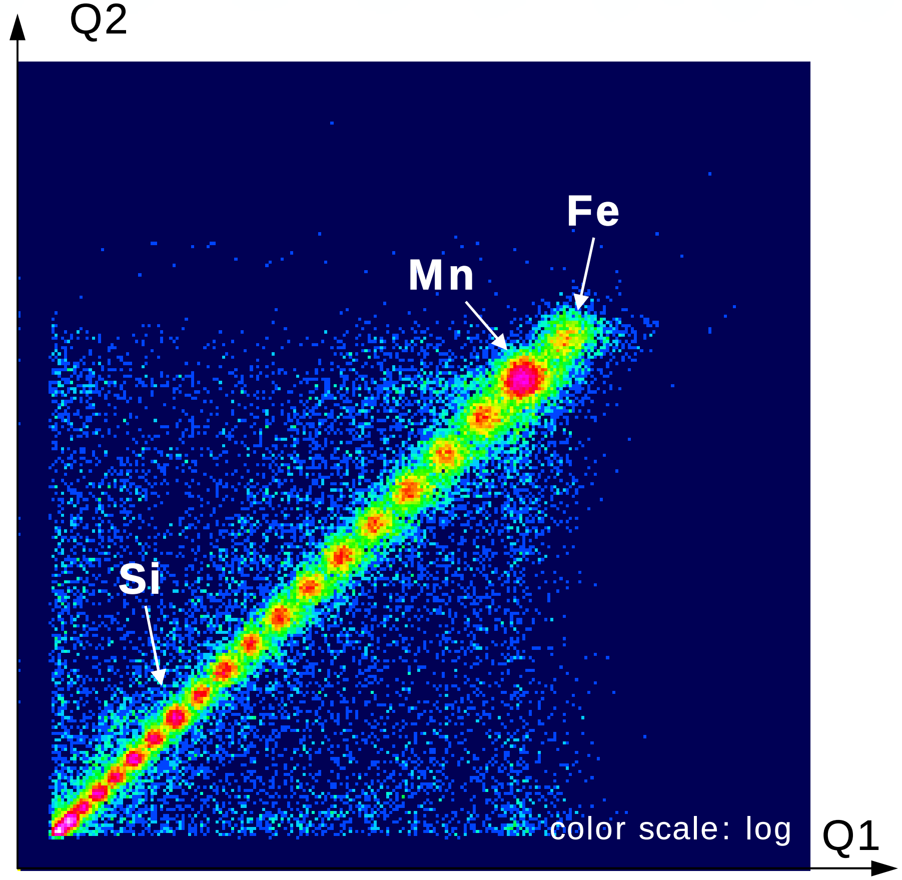
Particle Identification

Good intrinsic energy resolution and large de/dx from heavy ions have made the detector capable of resolving the ion species. This is very beneficial to the study of radiation effect on single cells.

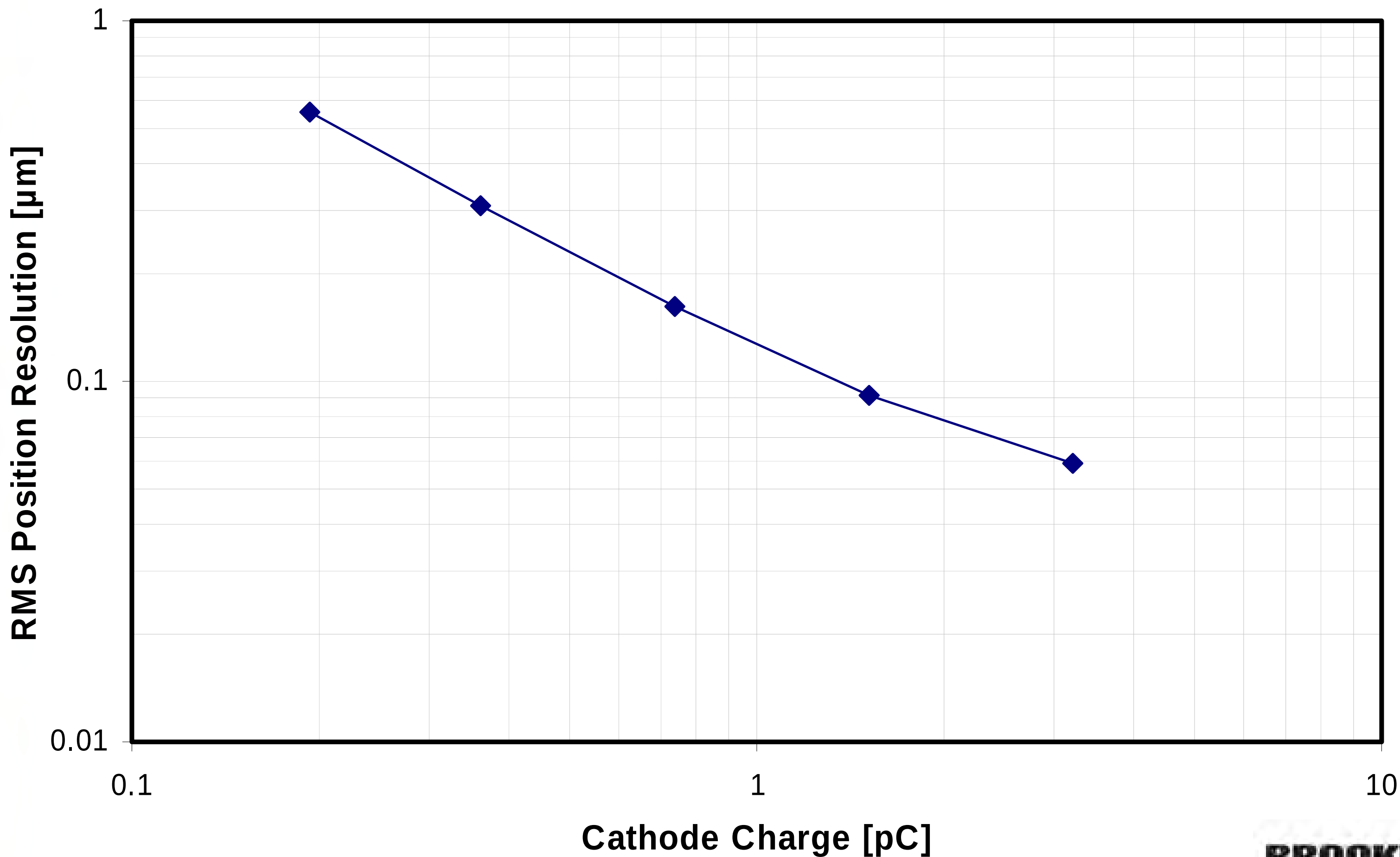
This figure shows the correlation between the total charge collected from one detector versus that of the another from coincidence events in a double detector setup.

During this particular run, the beam was heavily fragmented. The spots show the presence of every element from N to Fe (there was a cutoff in our DAQ for events with lower signals)



Position Resolution vs Charge

20µm pixel pitch, 635nm laser, 60V bias, 5ch centroid finding formula



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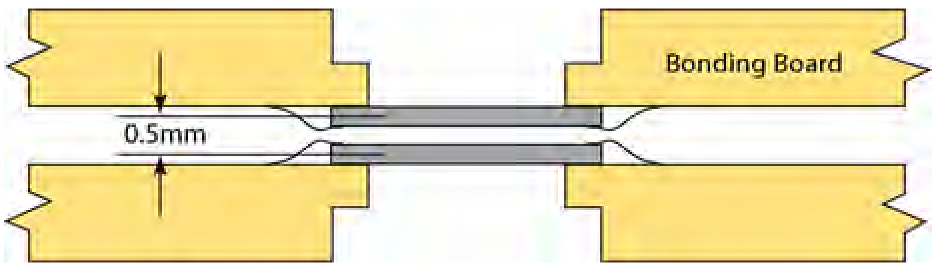
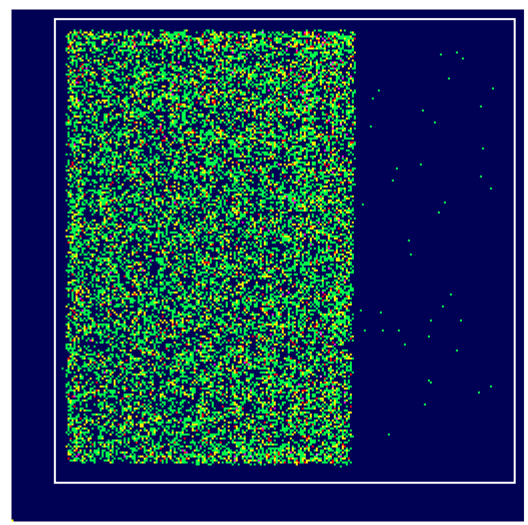
Position Resolution for Fe Ion Beam (1GeV/n)

- Tests Performed at the NASA Space Radiation Laboratory (NSRL) at BNL.
- Two identical detectors with 30µm pitch were used to measure position resolution for Fe ions @ 1GeV/n.
- The dominant limiting factor in measuring position resolution down to micron level is the parallax error due to multiple scattering of the beam (~0.5mrad at the location of the detector)

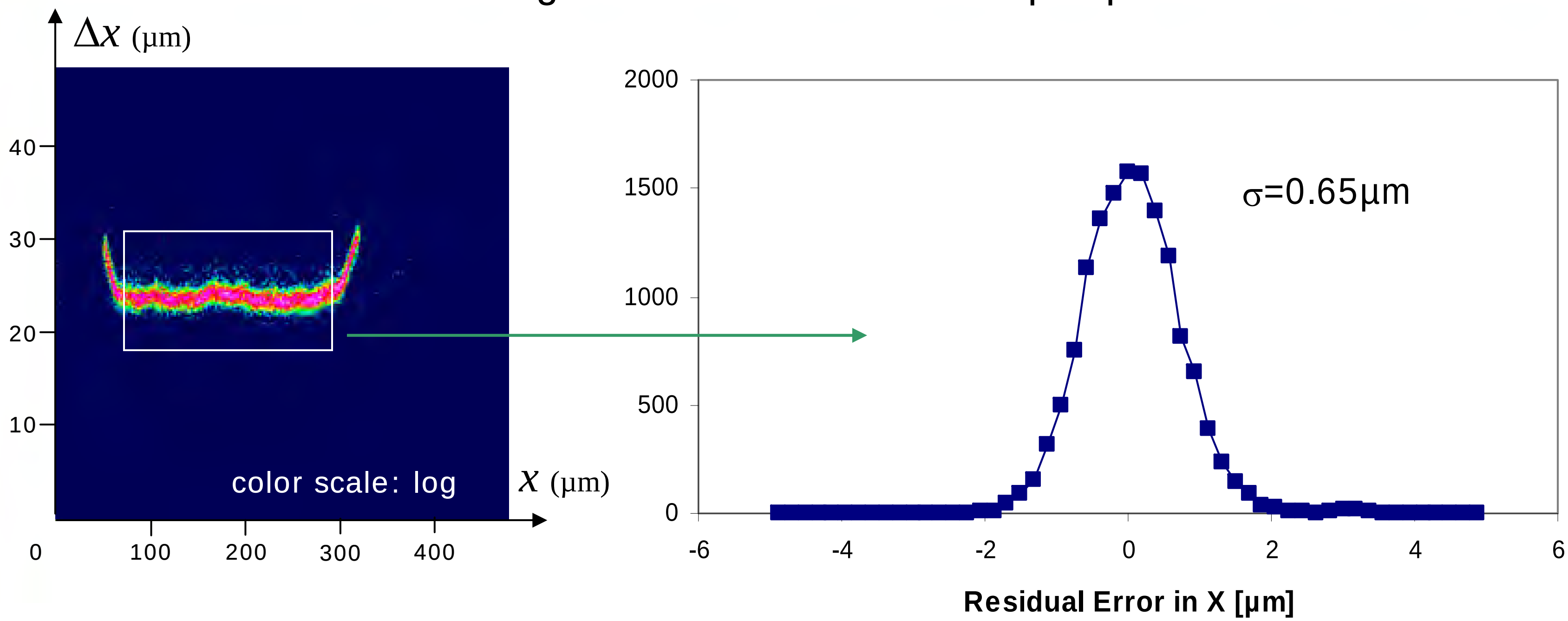




Area of the overlap between the two detectors (~15,000 coincidence events)

Position Resolution with 1GeV/n Fe Beam

Residual error along X axis between two 30µm pitched detectors:



The single detector rms resolution is:

$$\frac{0.65\mu m}{\sqrt{2}} = 0.46\mu m$$

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Outlook

- Explore additional charge division methods to further increase the detectors' interpolation factor, and therefore the active areas
- Develop customized readout electronics (ASICs) and data acquisition system to improve the portability of the detector system
- Develop a suitable detector package to make the system user friendly for non-detector experts working on biomedical experiments

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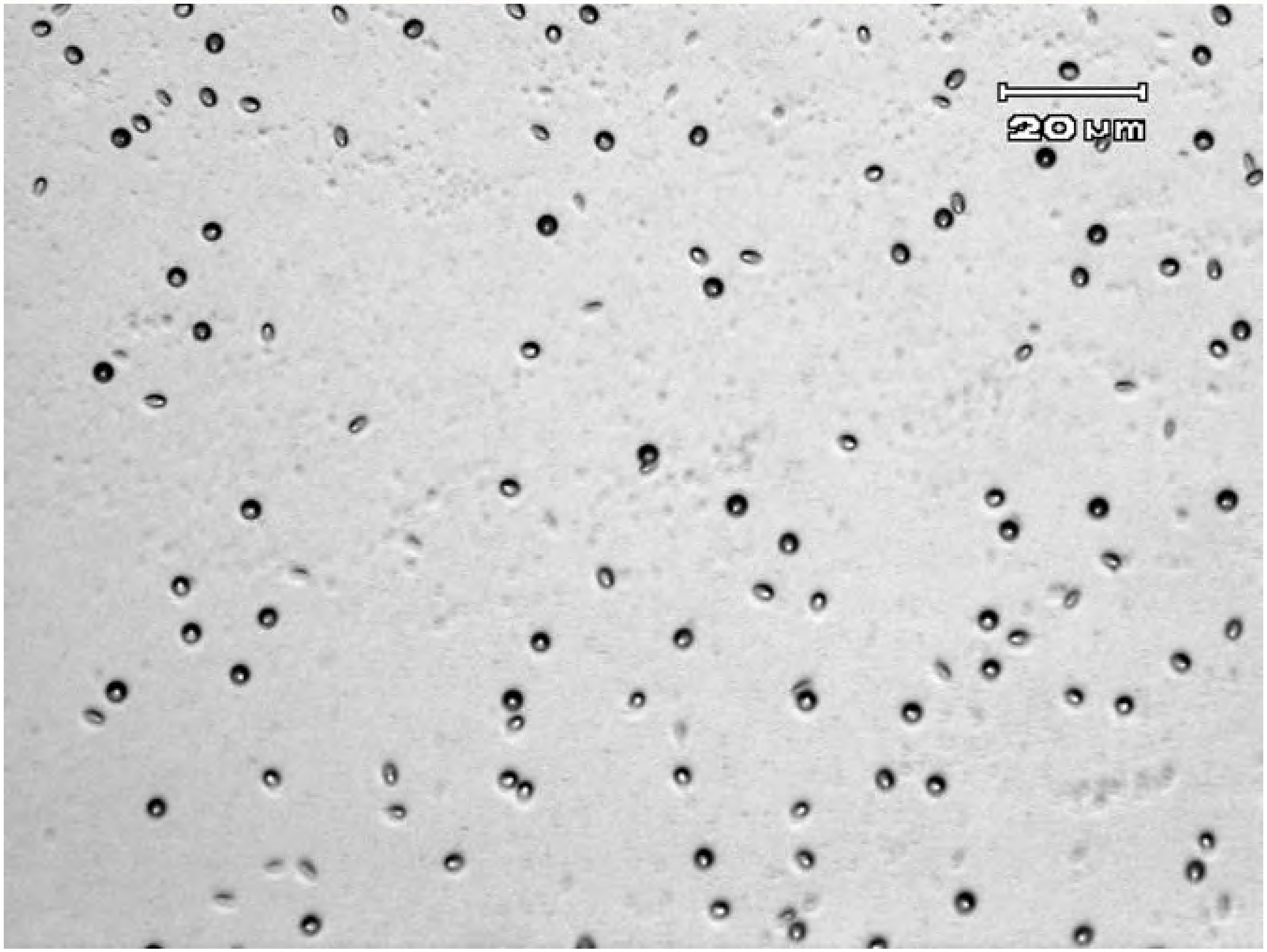
Plastic Nuclear Track Detector (PNTD)



CR39 plastic exposed to Alpha particles, developed in NaOH solution.

Silicon Detector Processing