Advances in Development of 3D Silicon Detectors with CMS Pixel Readout

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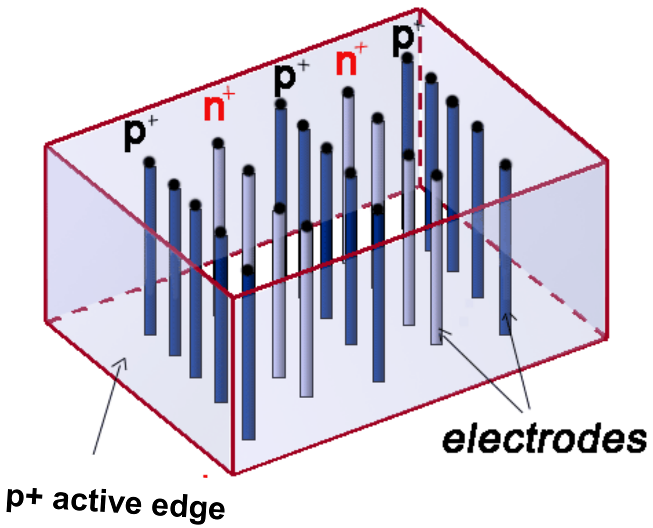
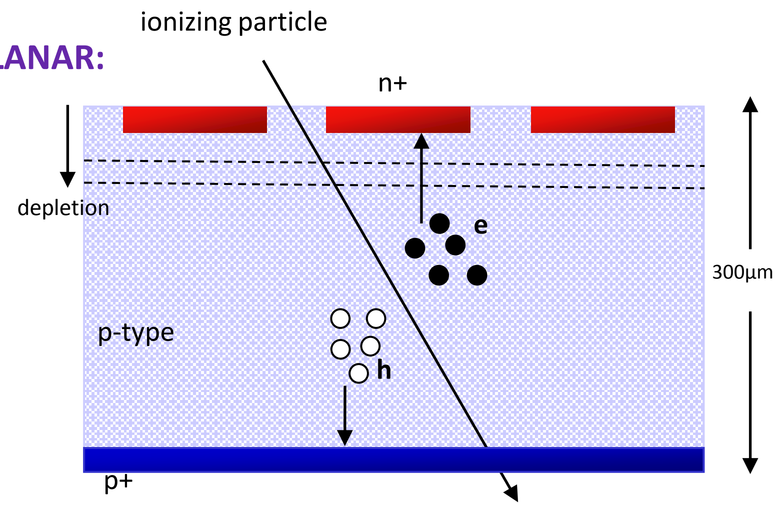
3D Silicon Detectors

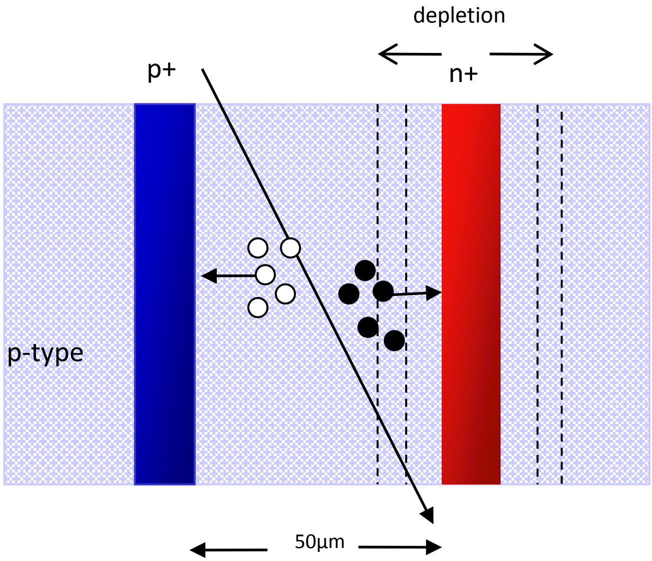
- p+ and n+ electrodes are arrays of columns that penetrate into the bulk
- Lateral depletion
- Charge collection is sideways
- Superior radiation hardness due to smaller electrode spacing:
  - smaller carrier drift distance
  - faster charge collection
  - less carrier trapping
  - lower depletion voltage
- No guard rings required (active edge) ➡ Reduced dead volume
- Higher noise
- Complex, non-standard processing



PLANAR:

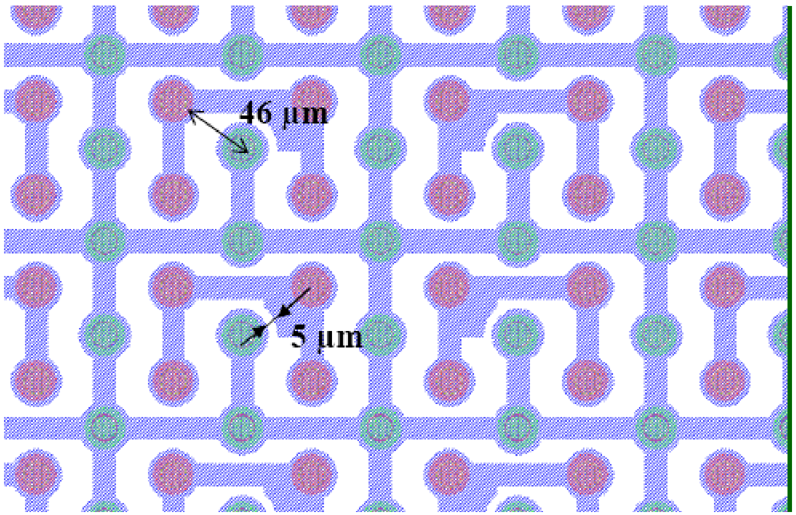


3D:



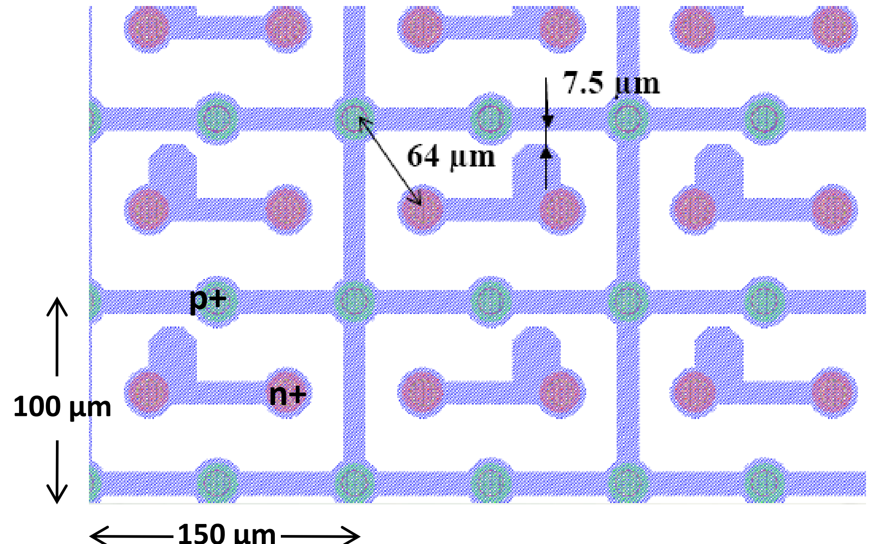
3D CMS Pixel Layouts

4 readout electrodes per pixel (4E)



- ✓ Lower depletion voltage
- ✓ Faster response
- ✓ Lower signal loss

2 readout electrodes per pixel (2E)

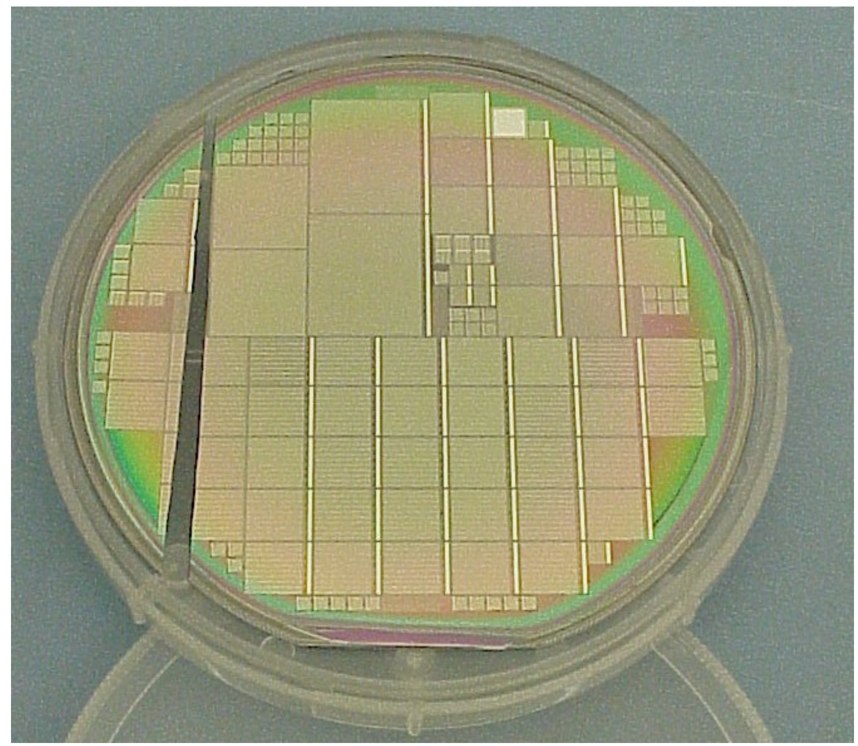


n+: readout **p+: bias**

- ✓ Lower electronic noise
- ✓ Less dead volume

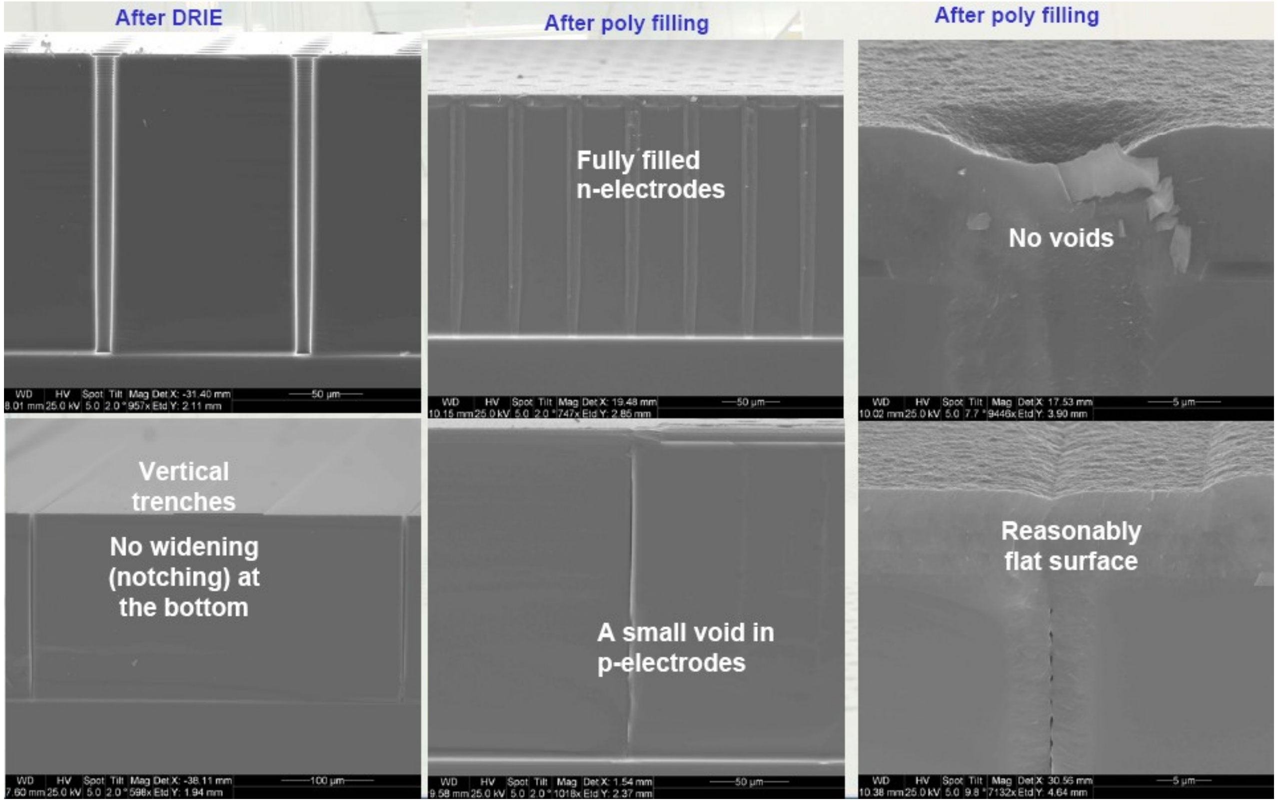
3D Sensor Wafer Layout

- Includes ATLAS, CMS, and MediPix devices
- CMS chips cover ~15% of wafer area
- p-type silicon wafers with resistivity > 10 kΩ.cm
- 200 μm and 285 μm thick wafers processed in parallel
- Well-performing sensors mostly located near the center of the wafer



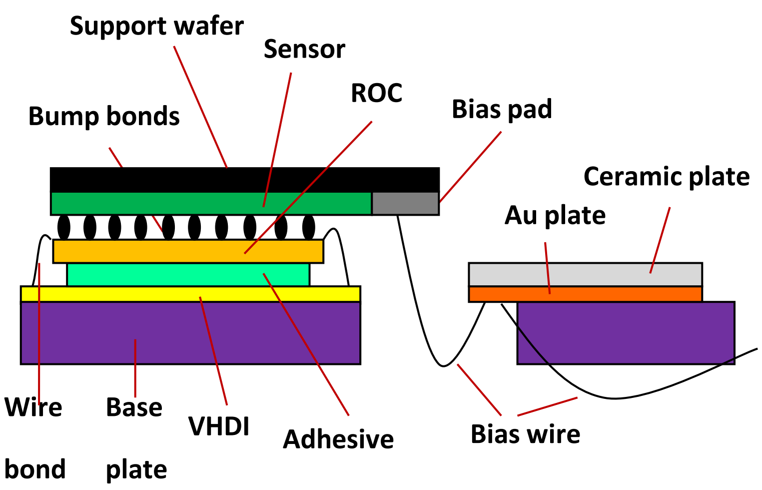
Fabrication of 3D detectors at SINTEF

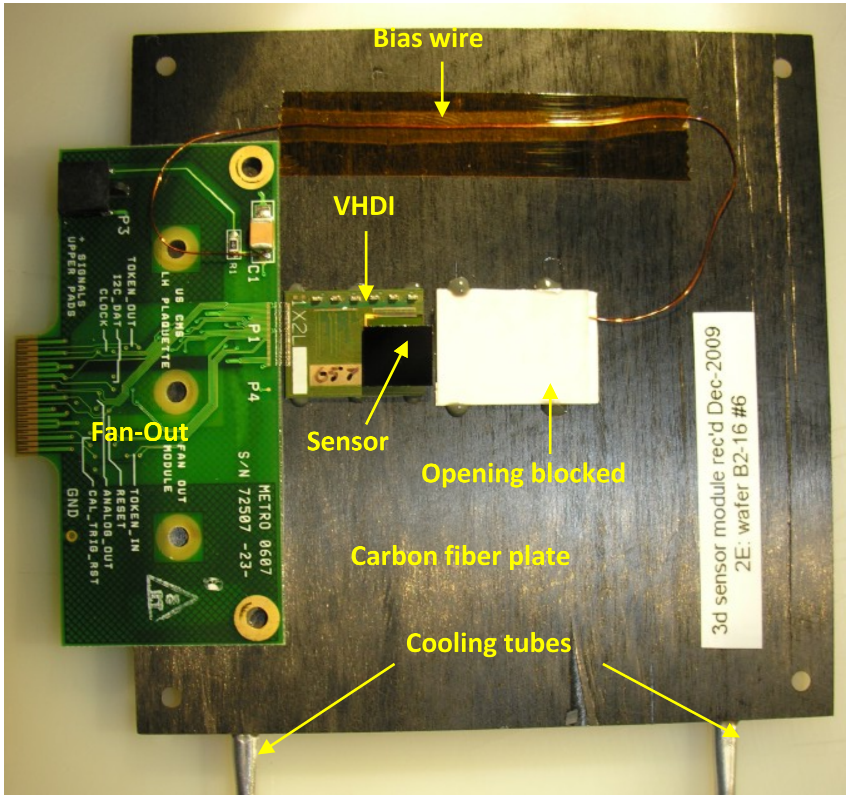
- P-spray inter-electrode isolation
- Wafer bonded to a support wafer by Si-Si fusion bonding
- Columns and active edge etched by deep reactive ion etching (DRIE)
- Holes and active edge trench filled with polysilicon and doped
- Column diameter: 14 µm & active edge width: 5 µm



3D Detector Module Assembly

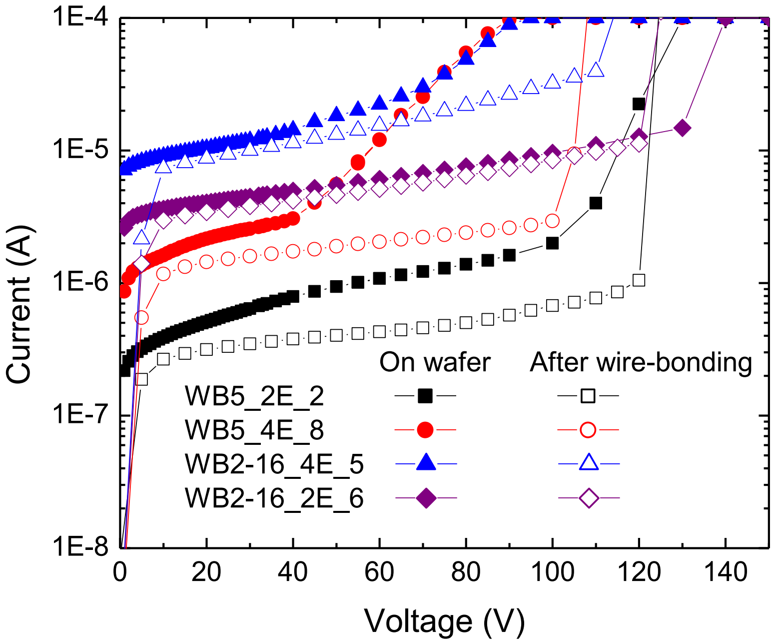
- 3D sensors bump-bonded to CMS Pixel Readout Chip (PSI46v2) via Pb-Sn (IZM) or In bumps (SELEX)
- Assembly of 3D modules was similar to the production FPIX modules except HV bias wiring
- Small opening was made through carbon fiber plate at the end of the VHDI
- Gold-ceramic piece was used as intermediate pad for HV wire-bonding between sensor and Fan-Out
- Carbon-fiber plate was inverted on wire-bond machine to make HV bias wiring



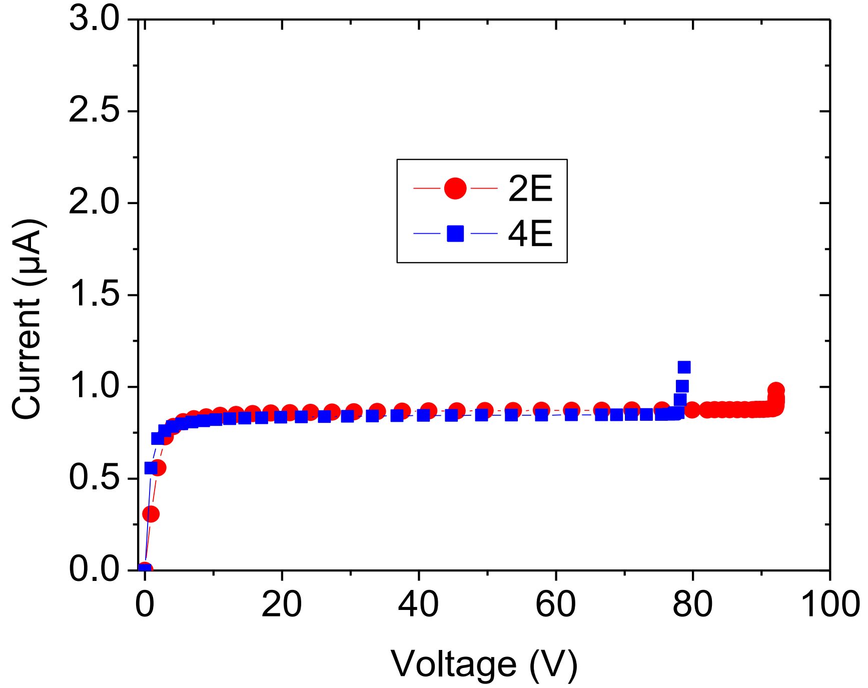


I-V Characteristics

Measurement



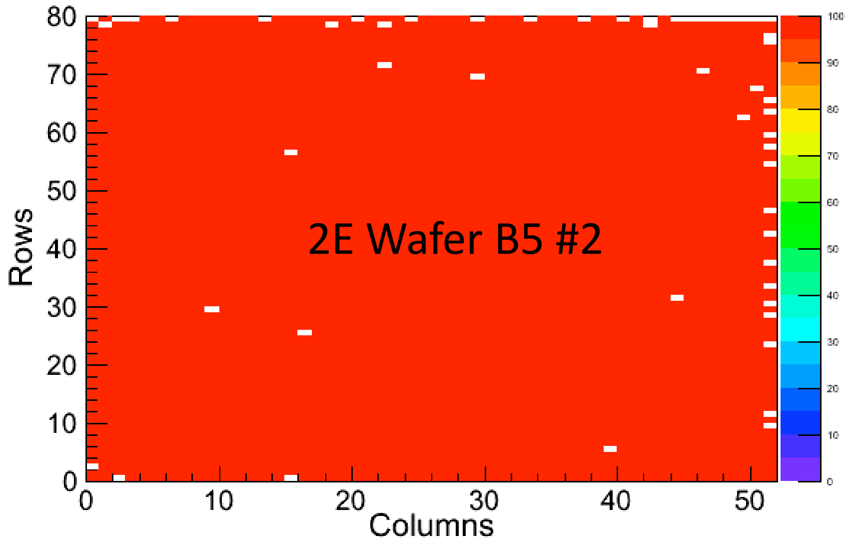
TCAD simulation

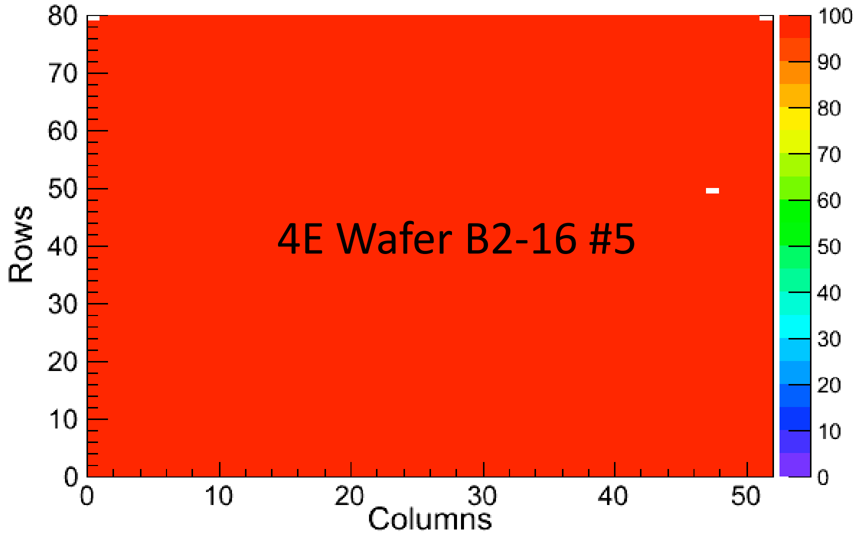


- Measurements done at room temperature (no cooling)
- Post-assembly leakage current is lower than wafer level leakage current
  - Wafer level measurements were done with a temporary metal layer connecting all n-type columns. This forms an MOS structure introducing extra surface leakage current.
- Predictions of simulations are in a reasonable agreement with measurement results

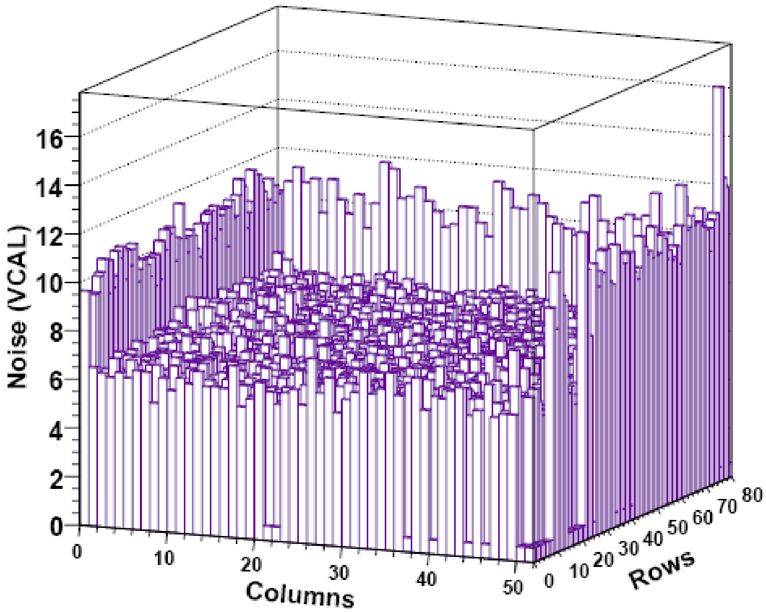
Bump-Bond Quality

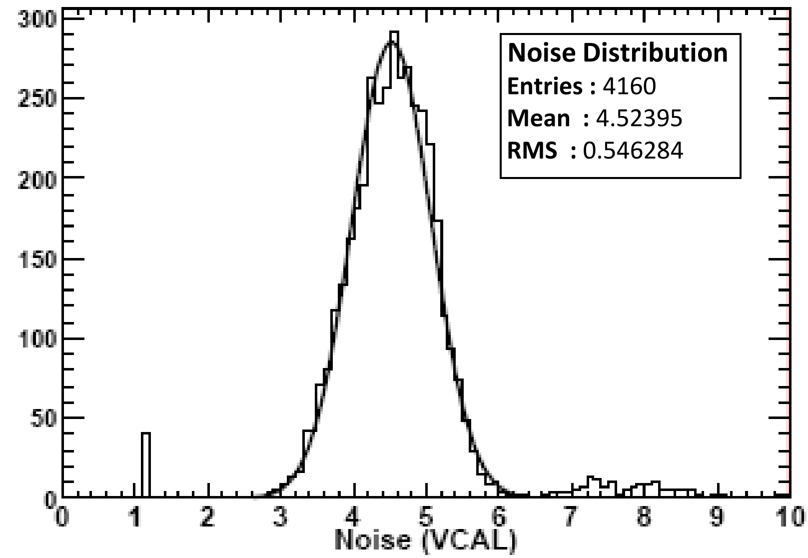
- Tests done by "Modified External Calibration"
- No radioactive or light source used
- All sensors showed perfect bump-bond quality except one

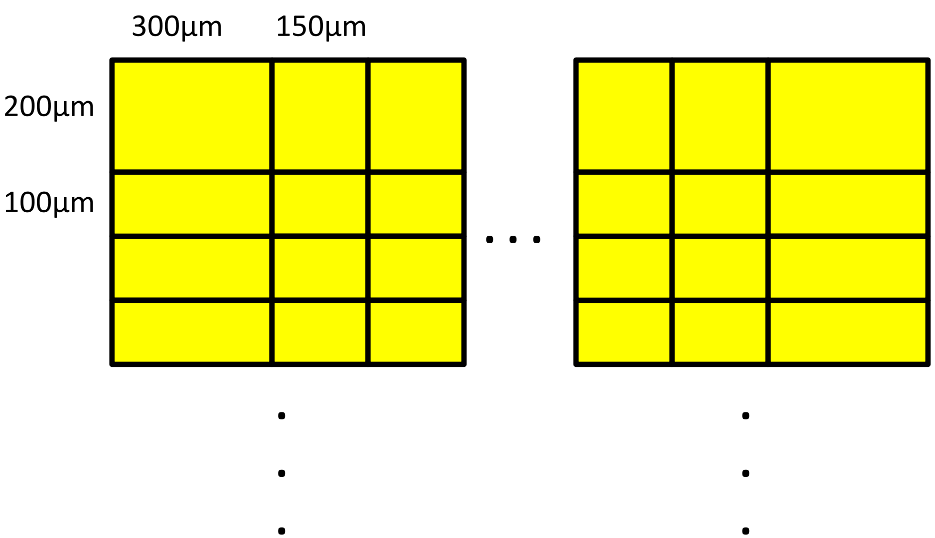




Noise





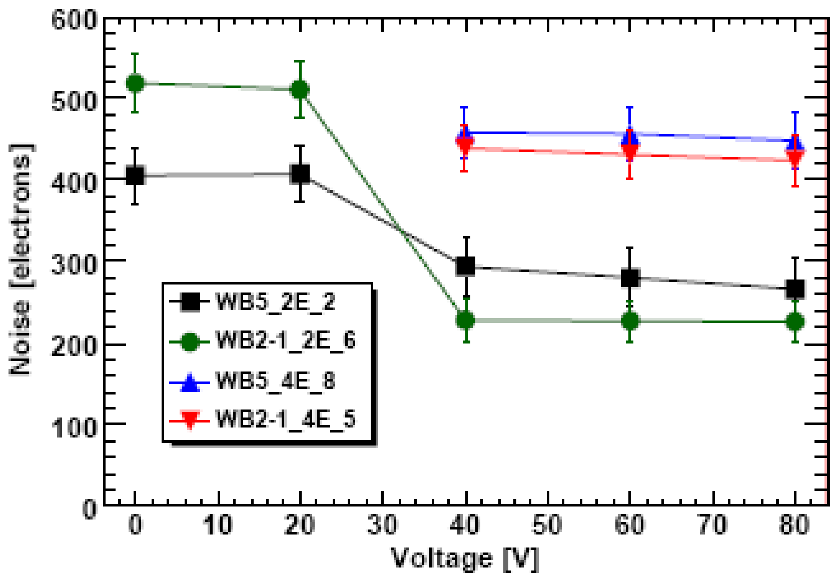


- Sensor:

  WB5_2E_2 (2E design, 285 µm thick)

- V_{bias}=-40V
- 1 VCAL= 65.5 electrons

Noise and Threshold



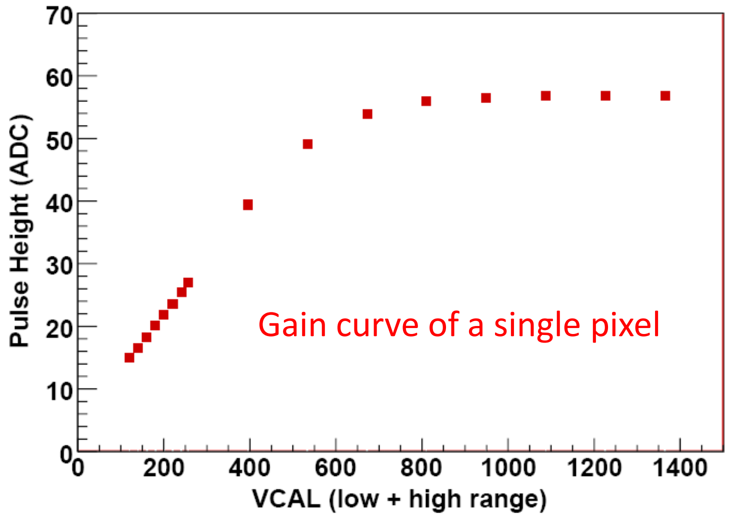
Noise:

FPIX planar	BPIX planar	3D with 2E configuration	3D with 4E configuration
110	155	250-300	~450

Threshold:

FPIX planar	BPIX planar	3D with 2E configuration	3D with 4E configuration
2870	2910	3200-5500	3200-5500

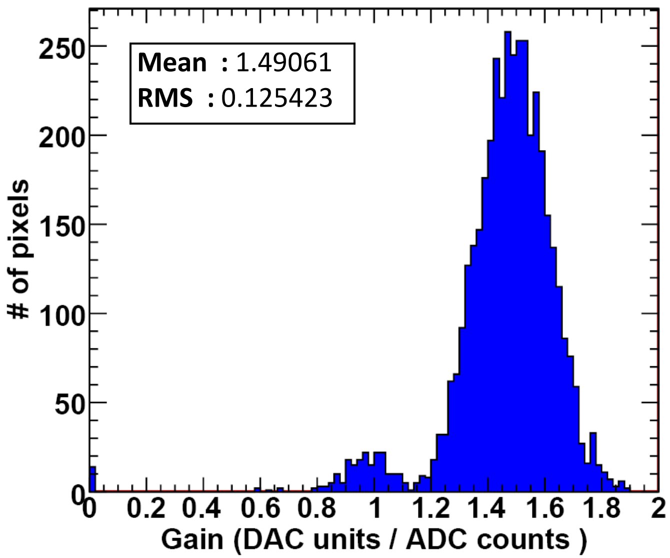
Gain Calibration

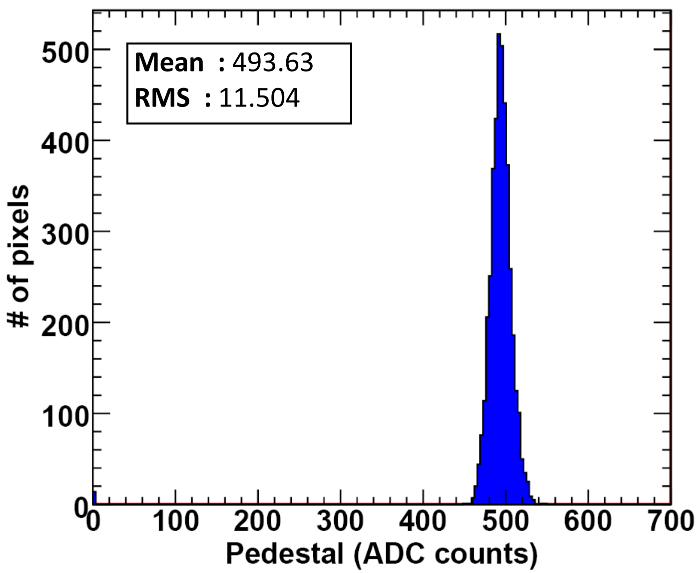


2E configuration, 285 µm thick

- Gain determined from slope and pedestal determined from the offset of linear region by fitting the curve with the function:

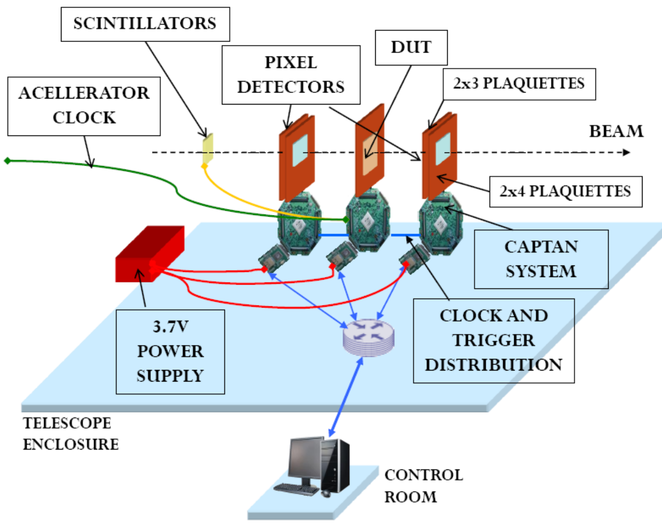
$$ADC = p_3 + p_2 * \tanh(p_0 * VCAL - p_1)$$

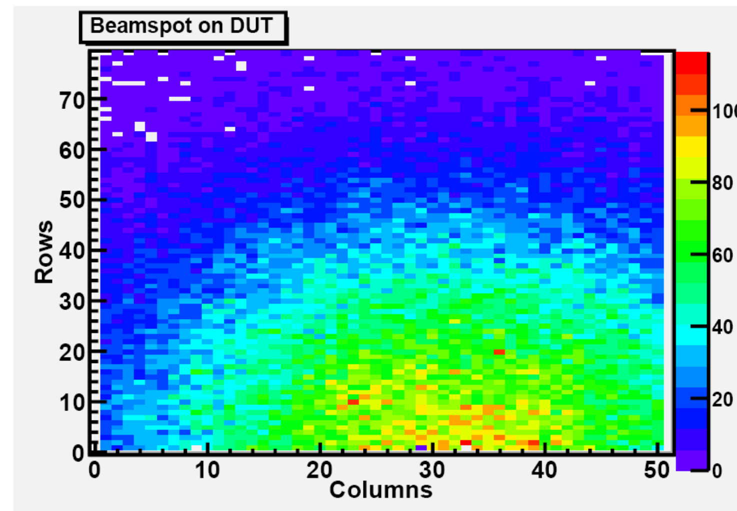




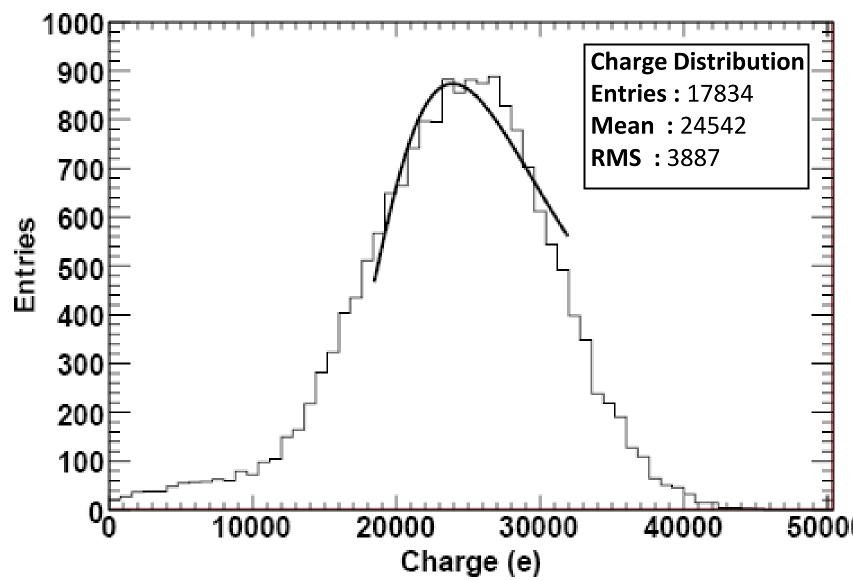
Efficiency Studies with Test Beam at FNAL

- 120 GeV protons
- No magnetic field





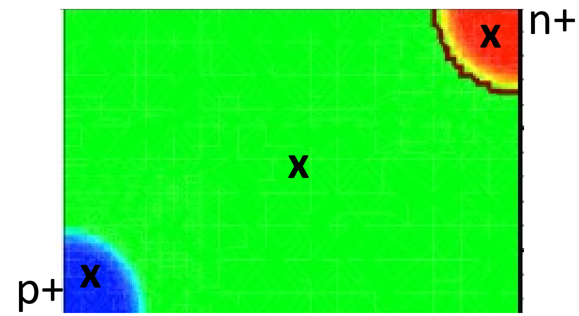
2E configuration, 285 μm thick



- V_{bias}=-40V
- ADC to electron conversion:
  VCAL (DAC) = ADC x gain – pedestal
  Charge (e-) = VCAL x 65.5 – 410
- Charge distribution does not have a very good convoluted Landau and Gaussian shape
  - Gain calibration needs improvement

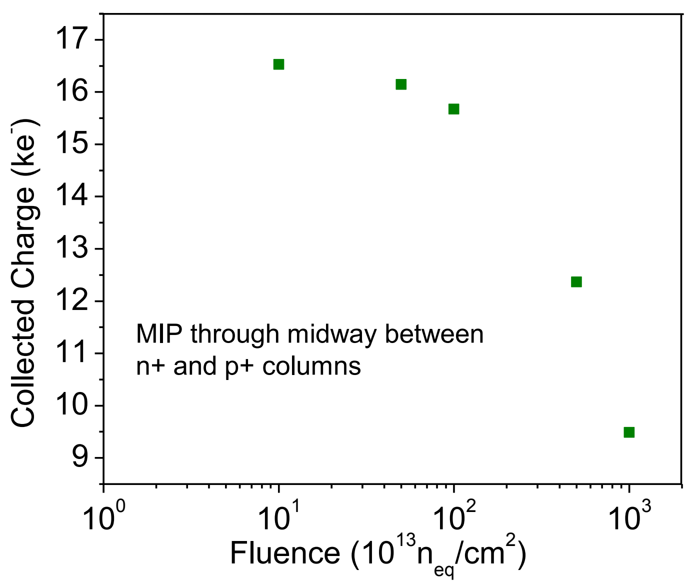
Efficiency Simulations

Substrate thickness = 200 µm



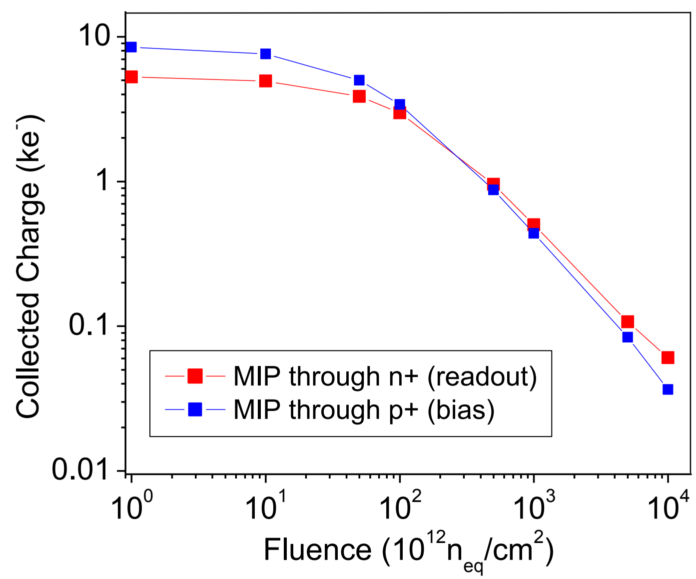
- Minimum Ionizing Particle (MIP):
  - Travels vertically through substrate thickness
  - Track generates 80 electron hole pairs per micron
  - Gaussian lateral profile with 1µm standard deviation
  - > 99.99% of charge generated within a radius of ~2.1µm

Efficiency= ~100% before irradiation



Efficiency= ~ 35% before irradiation

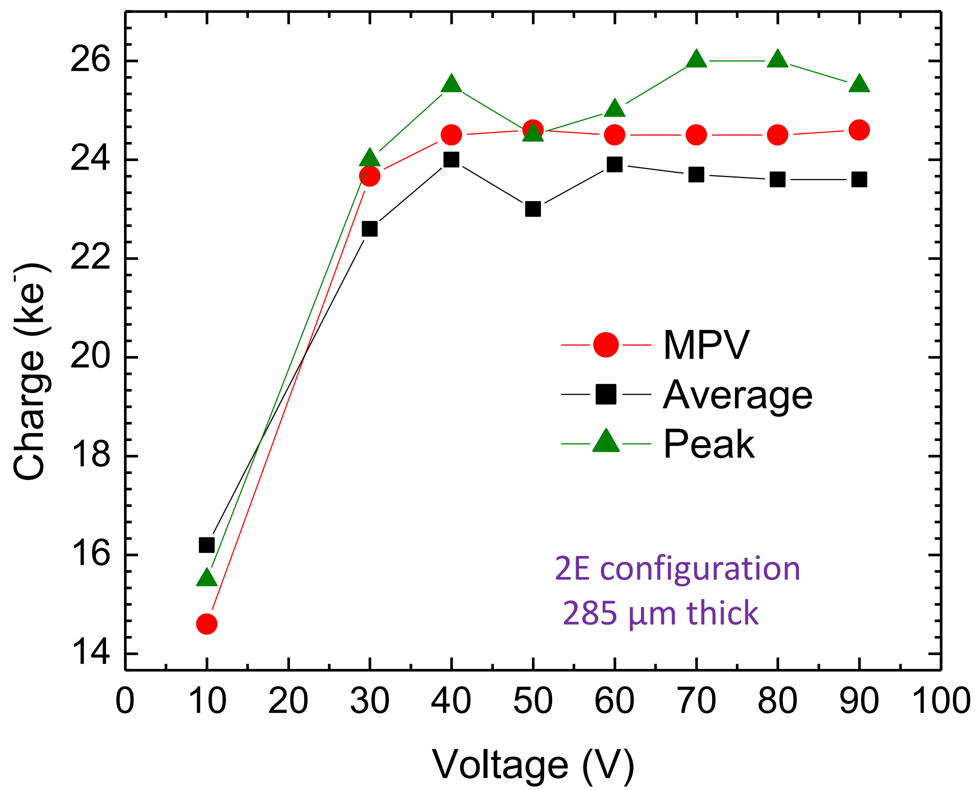
Efficiency= ~ 55% before irradiation



$$\text{Average Efficiency} = \begin{Bmatrix} 97.8\% \\ 95.6\% \end{Bmatrix} \text{ for } \begin{Bmatrix} 2E \\ 4E \end{Bmatrix} \text{ before irradiation}$$

Efficiency Studies

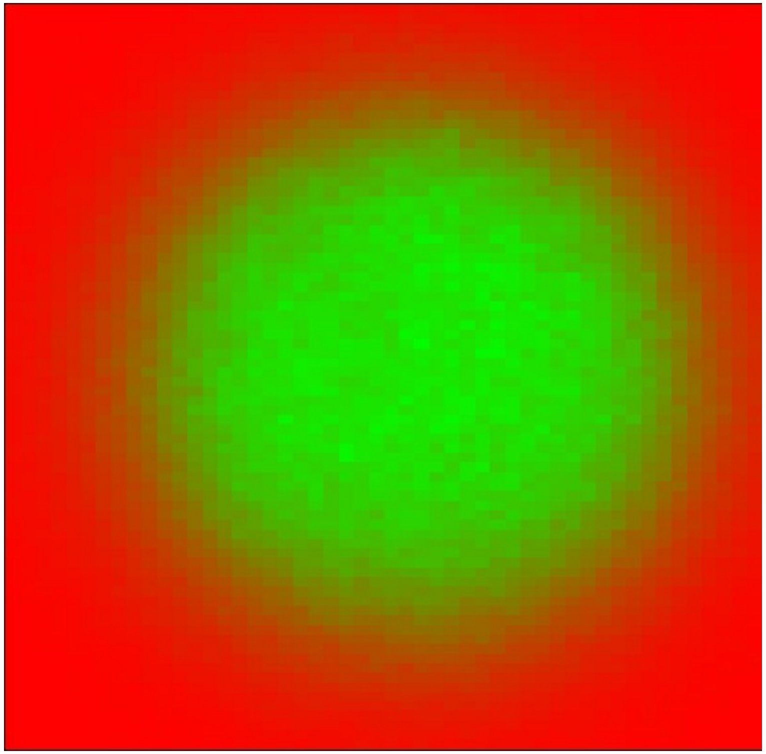
Test beam

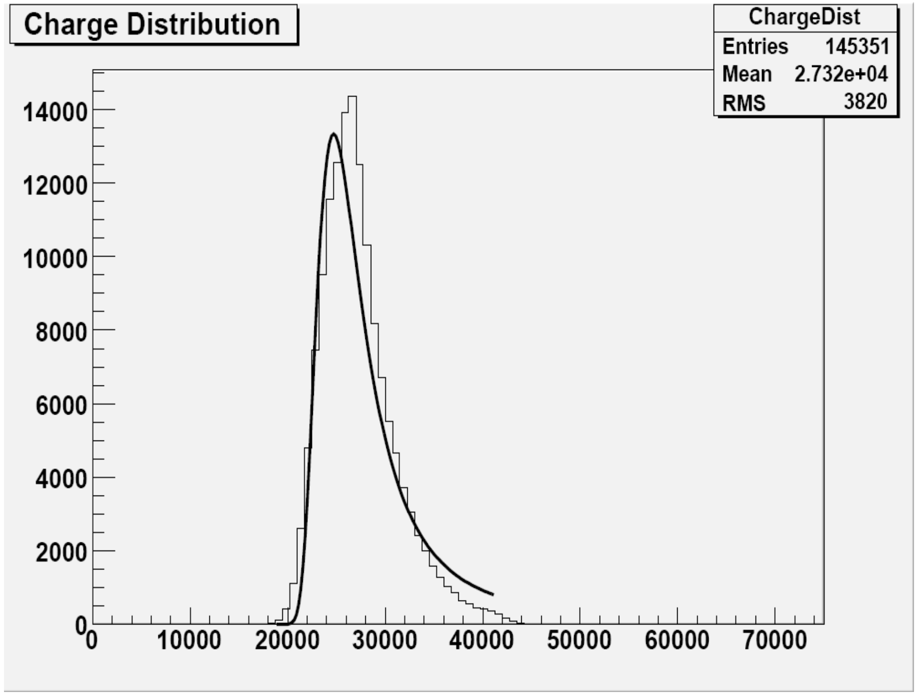


Prediction of simulation:

Collected charge = 22.3 ke- if MIP charge is 80 electron-hole pairs per micron

Efficiency Studies with Radioactive Source (^{90}Sr)





Summary and Next Plans

- Promising results
- Noise: 250-300 electrons for 2E (S/N=~90), ~450 electrons for 4E (S/N=~55)
- Threshold: 3200-5500 electrons
- Bump-bonding with In at SELEX is problematic
- Gain calibration needs to be improved
- Resolution studies in progress
- 3D sensors irradiated by 1.2×10^{14}, 2×10^{15}, 4.7×10^{15} (1MeV n_{eq}/cm^2)
- Test beam at FNAL two weeks later