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A Systematic 3D Simulation Study of BNL's 3D-Trench Electrode Detectors

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Introduction - Past Silicon Pixel Detectors

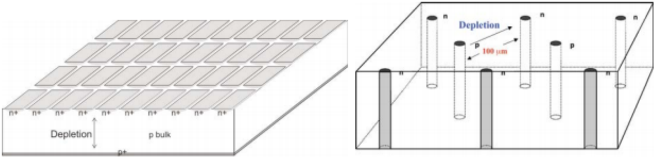


Fig 1a. ***Typical planar pixel detector.***

Fig 1b. ***Standard 3-D detector.***

C. Kenny, S. Parker, et al. IEEE, NS46 (4), 1999

- Planar pixels (left) have limited depletion zone close to the electrodes at moderately high voltages after high radiation exposure
- The Column 3D detector (right) solved this problem, but introduced a saddle point in the potential and nonhomogeneity in $\vec{E}$, meaning it introduced a θ dependence.

3D

Advantages of 3D

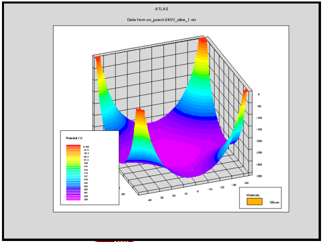
- Decouples depletion from thickness
- Reduces depletion voltage by decreasing the electrode spacing

Column 3D Limitations

- High electric field along junction at the column
- Columns create inhomogeneities in $\vec{E}$

We want to:

- Remove the saddle point in the potential.
- Remove θ dependence
- Make each cell independent of its neighbors



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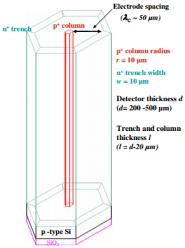
Our High Energy 3D-Trench Electrode Detector



Z. Li, NIMA Vol 658, Issue 1 (2011)

- Electrode spacing: 50 μm
- Shape: Hexagon

- Depth: 500 μm - Simulated: 300 μm
- Width of trench: 10 μm
- Diameter of column: 10 μm
- Depth of doping: Simulated - 270/300 μm
- When simulated with radiation, treated after $\Phi_{eq} = 10^{16}$ 1 MeV n_{eq}/cm^2
- Doping:
  - p+ column
  - n+ trench
  - p type bulk (simulates after SCSI)

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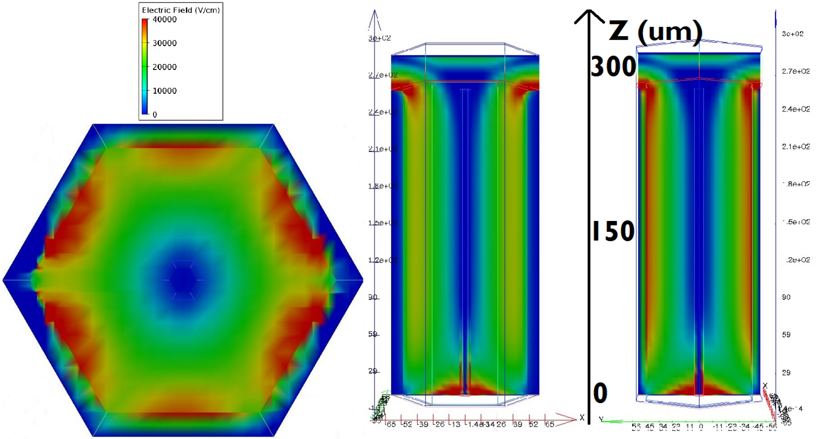
Simulation Specifics

- Used commercial software from Silvaco (TCAD's programs - Devedit 3d, Device 3d, Atlas, etc) to simulate the detectors' electrical properties.
- Simulate the detector after high radiation by changing the effective doping concentration of the bulk.
- In the future, will use explicit radiation defects in Silicon
- This gives us first order effects.

Electric Field at Full Depletion - 95V

Full Depletion Voltage was simulated to be 95 V. Electrode spacing is $50\mu m$ Treated with $\Phi_{eq} = 10^{16}$ 1 MeV n_{eq}/cm^2



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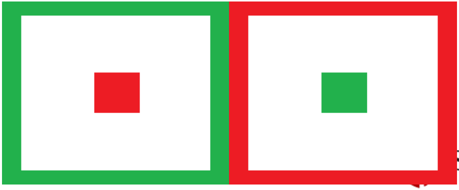
The different types of detectors possible

The different doping does not matter in the column detectors, since differences would just correspond to a translation.

- For our detectors, different doping will cause significant changes in the potential's shape
- We choose:
  - Doping of the center column
  - Doping of the cylindrical-shaped trench in each cell
  - Doping of bulk n (green) and p (red)

1. Outer trench is n+ and center column is p+
2. Outer trench is p+ and center column is n+



4 Combinations

- Now for both of the previous two, there are two more versions with the type of doping of the bulk Si
  1. n-type
  2. p-type
- Under high radiation, the bulk material may undergo space charge sign inversion (SCSI). This "type inversion" turns n-type doping into "p-type equivalent"
- **This determines where the junction is, at the trench or at the column**
- Junction at the column makes high electric field, while having the junction at the trench allows for more uniformity and a lower absolute maximum $\vec{E}$

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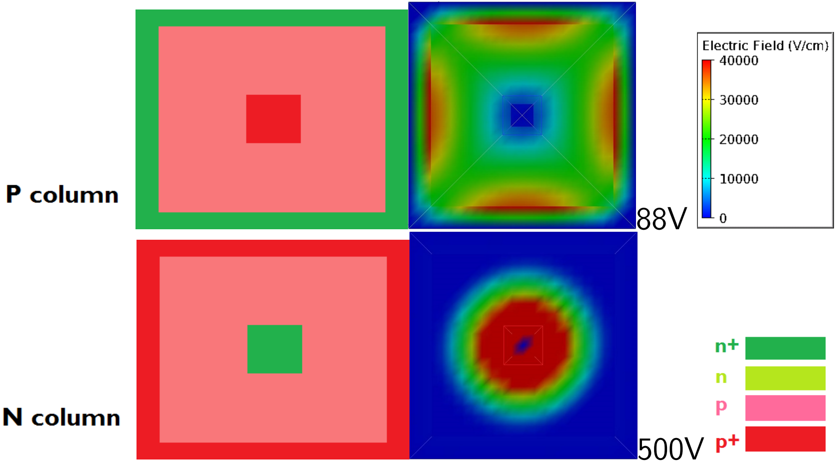
Electric Fields, Fully Radiated

The electrode spacing is 50 μm, and is simulated with $\Phi_{eq} = 10^{16}$ 1 MeV n_{eq}/cm^2. Top is fully depleted, bottom is not.

P Type



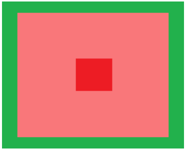
Type Comparison Results

The electrode spacing is 50 μm, and is simulated with $\Phi_{eq} = 10^{16}$ 1 MeV n_{eq}/cm^2

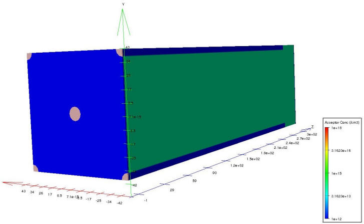
Table: Comparison of Different Doping schemes

column, bulk, trench	V_{dep}	Junction	Dep Direction
n+, n, p+	90 V	trench	inward
n+, p, p+	> 500 V	column	outward
p+, n, n+	> 500 V	column	outward
p+, p, n+	88 V	trench	inward

After $\Phi_{eq} = 10^{14}$1 MeV n_{eq}/cm^2 the n-type will type invert, so we might as well start off with p-type. Therefore, we use p+ column with p-type bulk and n+ trench.



Column 3D Detector

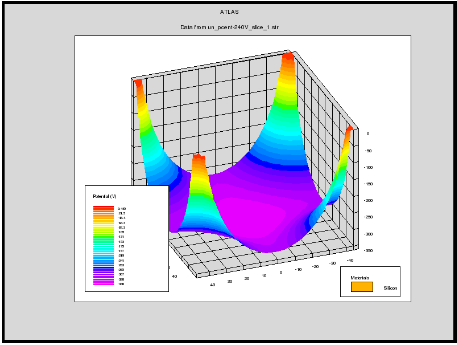


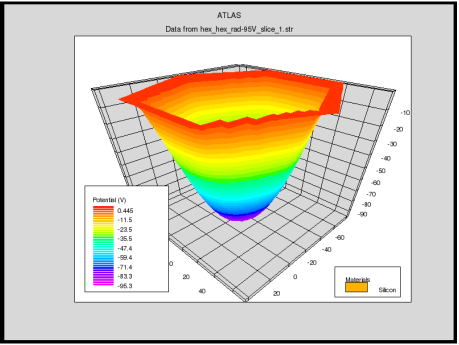
- Electrode spacing: 50 μm
- Depth: 300 μm
- Shape: Column
- Diameter of doping columns: 10 μm
- When simulated with radiation, treated after $10^{16} n/cm^2$
- Doping:
  - p+ center column
  - n+ corner columns
  - p type bulk (simulates after SCSI)

Column Vs. BNL's

Potential at Full Depletion

Column (250 V)　　　　BNL's (95 V)





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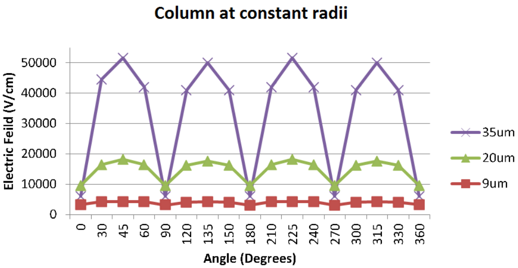
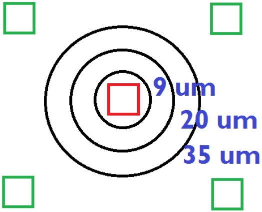
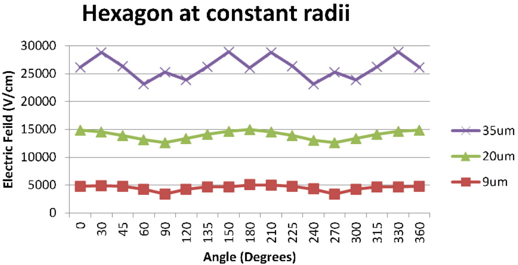
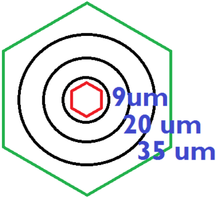
Electric Field's θ Dependence



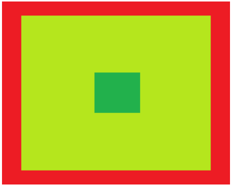






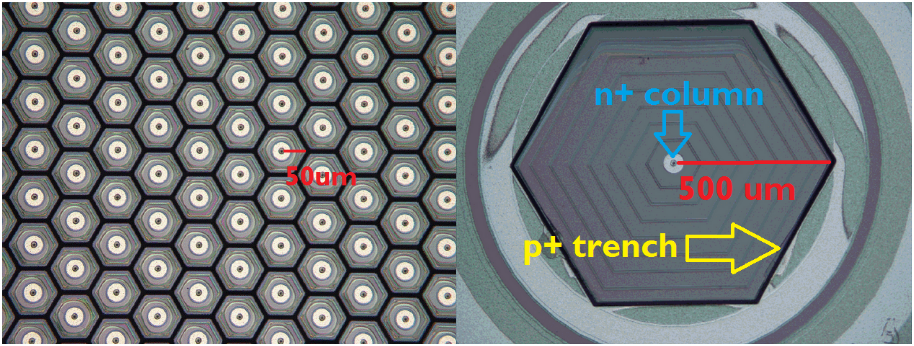
Photon Sciences

- Also useful for X-ray detection at the National Synchrotron Light Source II at Brookhaven National Laboratory.
- The natural separation of cells is good for spectrometry
- Radiation is no longer an issue, simulated at a much lower bulk doping concentration.
- The cell size is $\approx 500\mu m$ which means it is much larger than the High Energy cells (x10 larger)
- In our first prototype the Trench and center column have a width of 10 μm and a depth of 200 μm
- Chose n+ column with n-type bulk and p+ trench



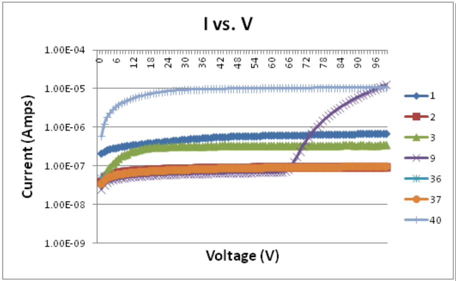
Prototypes

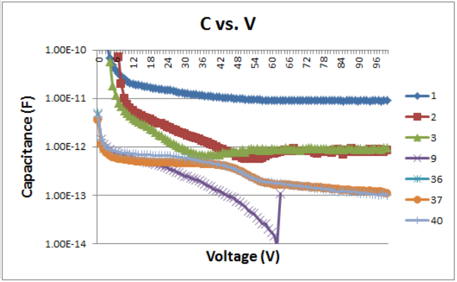
Being manufactured by CNM (National Centre for Micro-electronics)



Array of High Energy pixels on left, and a single Photon Science pixel on right.

Electric Properties of Good Prototypes





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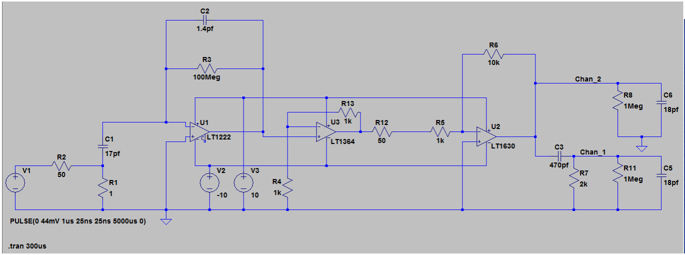
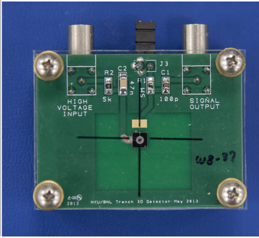
Charge Collection Efficiency Measurements

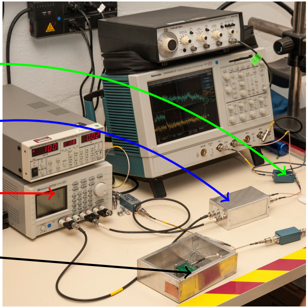
- Am241 Source placed on detector inside Faraday cage
  - Signal is readout by a commerical cremat preamplifier
  - Trigger on equivalent voltage of 59.5 keV γ particle signal (16,500 e^-)
- The output is sent into the oscilloscope in two channels:
  1. Inline CR filter for noise reduction
  2. No inline filter (can apply software filters in labview)
- Collected 1000 events
- Schematic view of experiment below on left, picture of detector on right





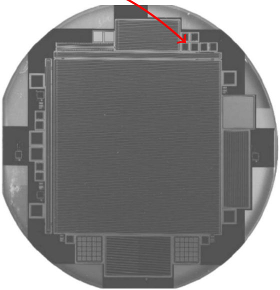
Experimental Setup

- Inline CR filter
- Read Out Electronics
- Power Supplies
- Detector

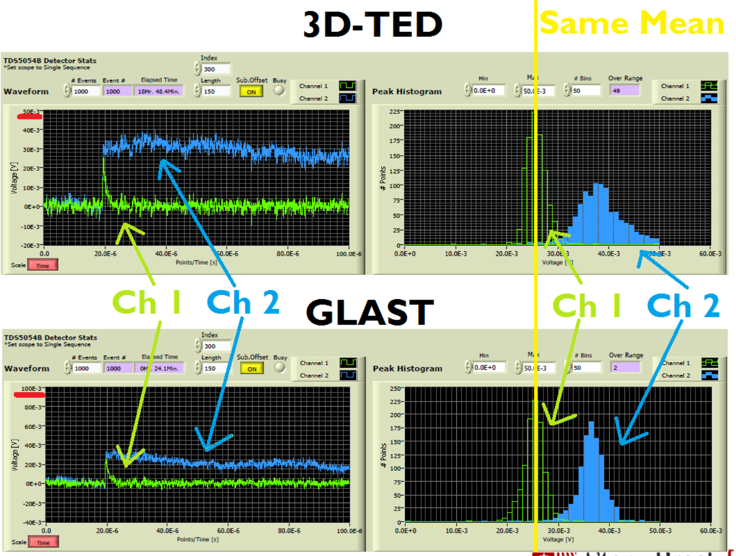


Glast Detector

- Glast mini-square detector
- Well-known characteristics (T. Ohsugi et. al, NIMA Vol 541, Issues 1-2, 2005) so it provides a baseline
- Less than full charge collection at perimeter of active region
- Provided to us by Hartmut Sadrozinski (Thank you!)

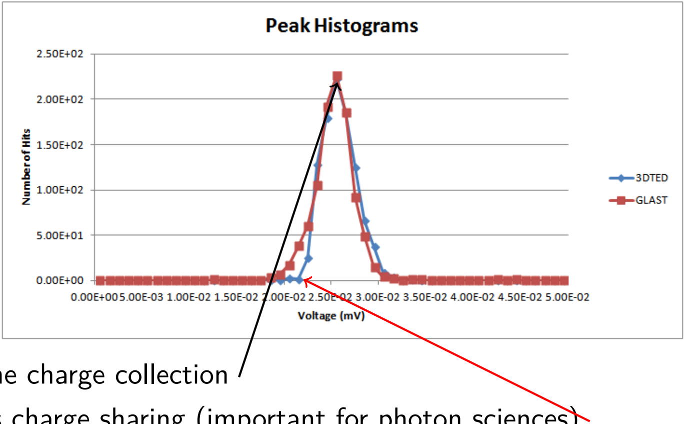


CCE Raw Data



Same mean shows collection is identical. Different vertical scales on left.

3D-TED isolation from charge sharing



- Same charge collection
- Less charge sharing (important for photon sciences)
- More isolation details to be studied with laser injection

CCE results

- The two detectors had similar peaks (peak value $\propto$ Energy deposited)
- The peak mean values are consistent, meaning they are collecting roughly the same amount of charge
- Consistent over different voltages (plots in back-up slides)
- Approximate signal to noise ratios are decent and similar to each other (glast $\approx$ 15, 3D-Trench-Electrode $\approx$ 13.5)
- We see that the 3D-Trench-Electrode detector is more noisy. Expected because of its higher leakage current
- We expect CCE to depend on location. Will be studied more closely with laser injection.

Summary

- Simulated 3D-Trench-Electrode Detector has a depletion voltage of 95V, about $\frac{2}{5}$ of the column detectors.
- One can also see that the electric field is more uniformly distributed in the 3D-Trench Electrode Detectors than in the column 3D.
- Preliminary electrical and charge collection efficiency measurements from the first prototypes are done.
- We see full charge collection and much reduced charge sharing with the 3D-Trench-Electrode Detector
- Will do simulations with simulated radiation defects
- Will do higher resolution CCE measurements with laser injection.
- CNM has started the next round of prototypes.

Thank you for your attention!

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Nuclear Instruments and Methods in Physics Research A, Vol 658, Issue 1 2011.
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Radiation damage effects in Si materials and detectors and rad-hard Si detectors for SLHC.
Journal of Instrumentation, 4 P03011 2009.

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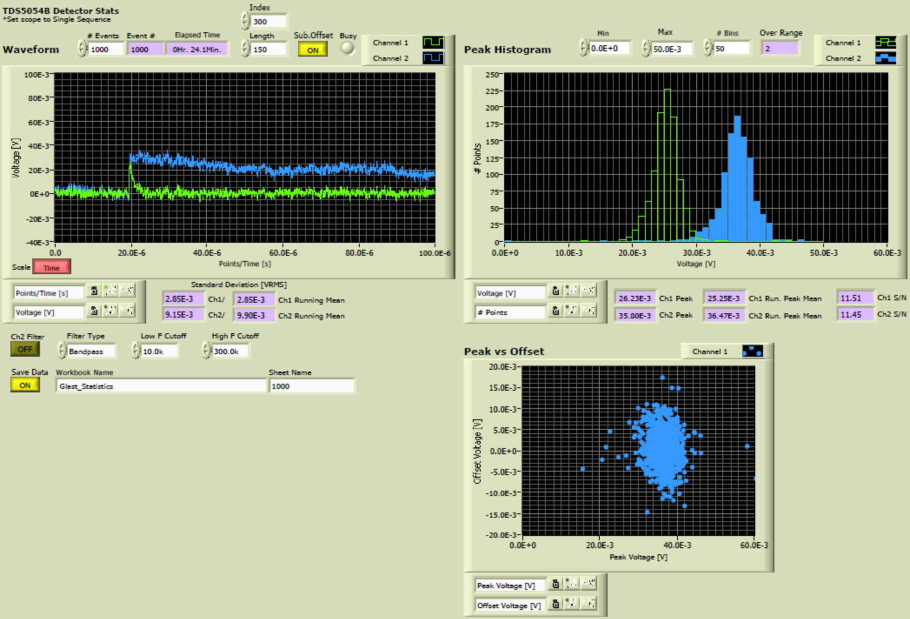
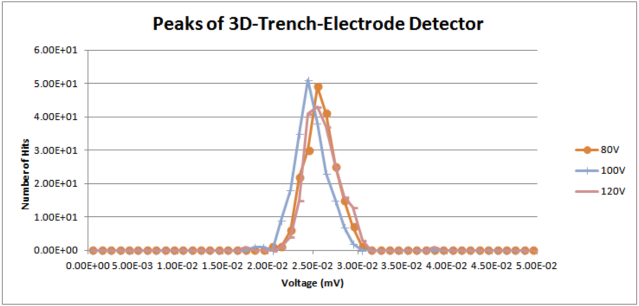
Electrons Versus Holes

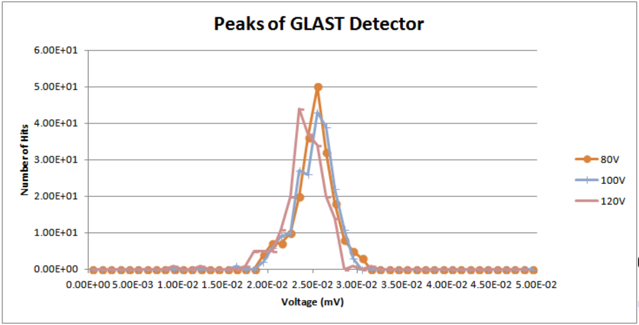
- There is a difference between collecting and reading out electrons versus holes because of their mobility
- But because of the high $\vec{E}$, we don't see the mobility difference over such a small distance
- This is because we are near the saturation
- There is only a 20% difference in this case, so it is not significant

Glast Detector Results



Peaks at different voltages





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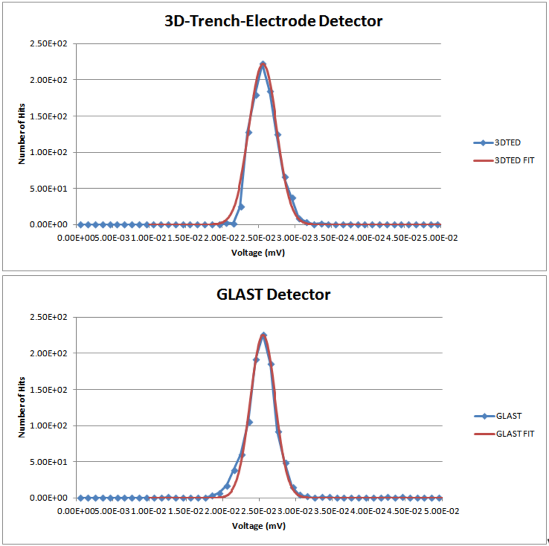
Rough Fits



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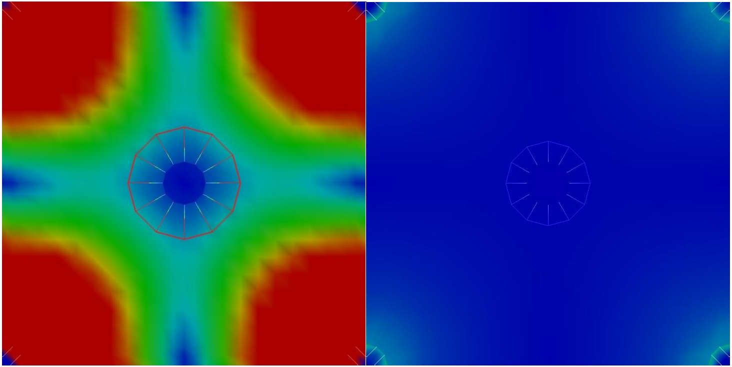
Column

Full Depletion Voltage was simulated to at 250 V.
$\Phi_{eq} = 10^{16}$ 1 MeV n_{eq}/cm^2,electrode spacing: $50\mu m$



On the left, the maximum (red) is 40,000 V/cm while on the right the maximum is almost 1,300,000.