The University of Manchester

Development and Simulation of 3D Diamond Detectors

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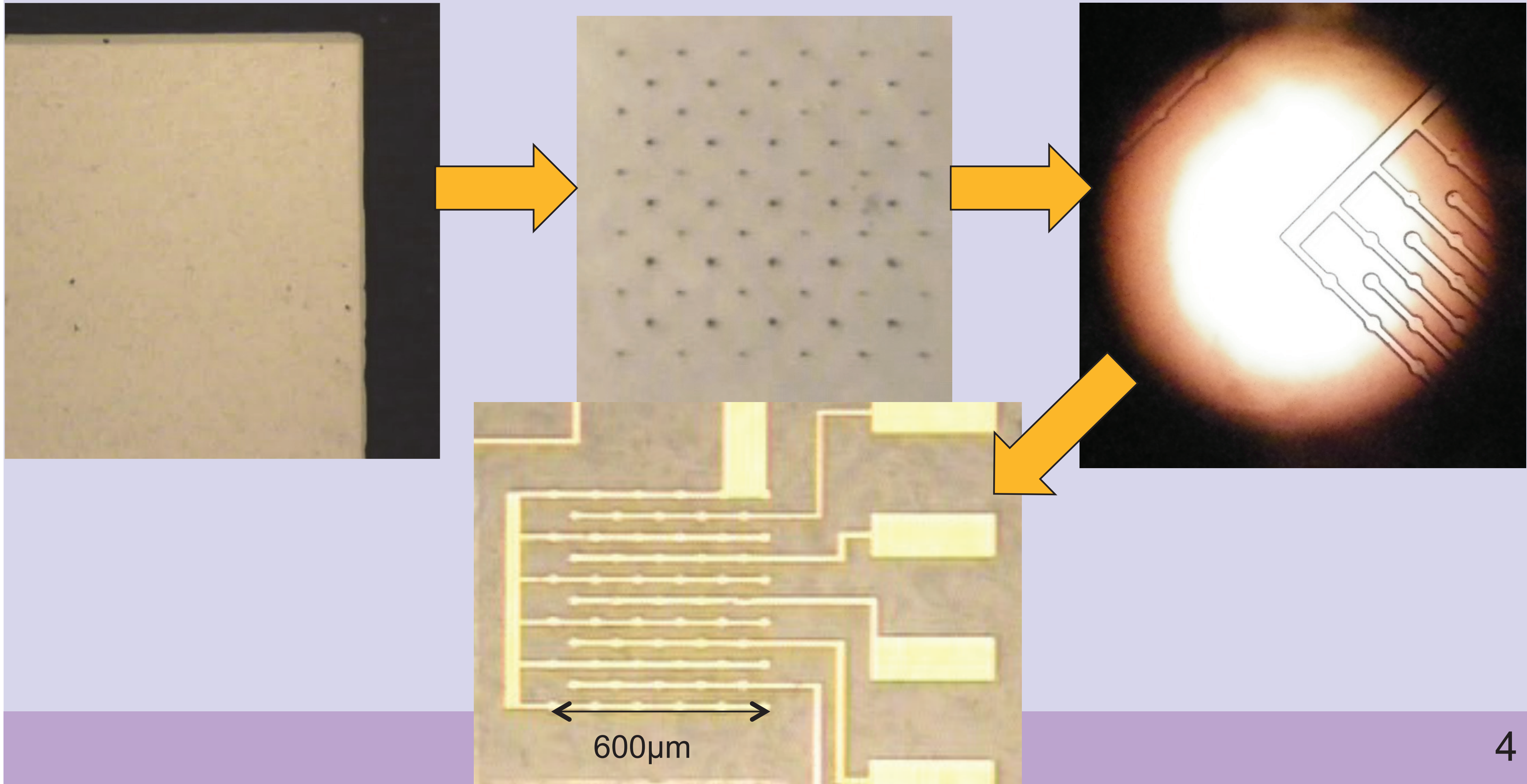
Introduction

- Manchester is working on the development of 3D Diamond Detectors
- Use laser to write graphitic wires into the Diamond bulk, possible to get features of size ~1μm (see talk by S. Murphy for details)
- Deposit metallization on samples to produce electrical contacts
- Detectors then tested and simulations used to try to understand behavior of carriers in diamond

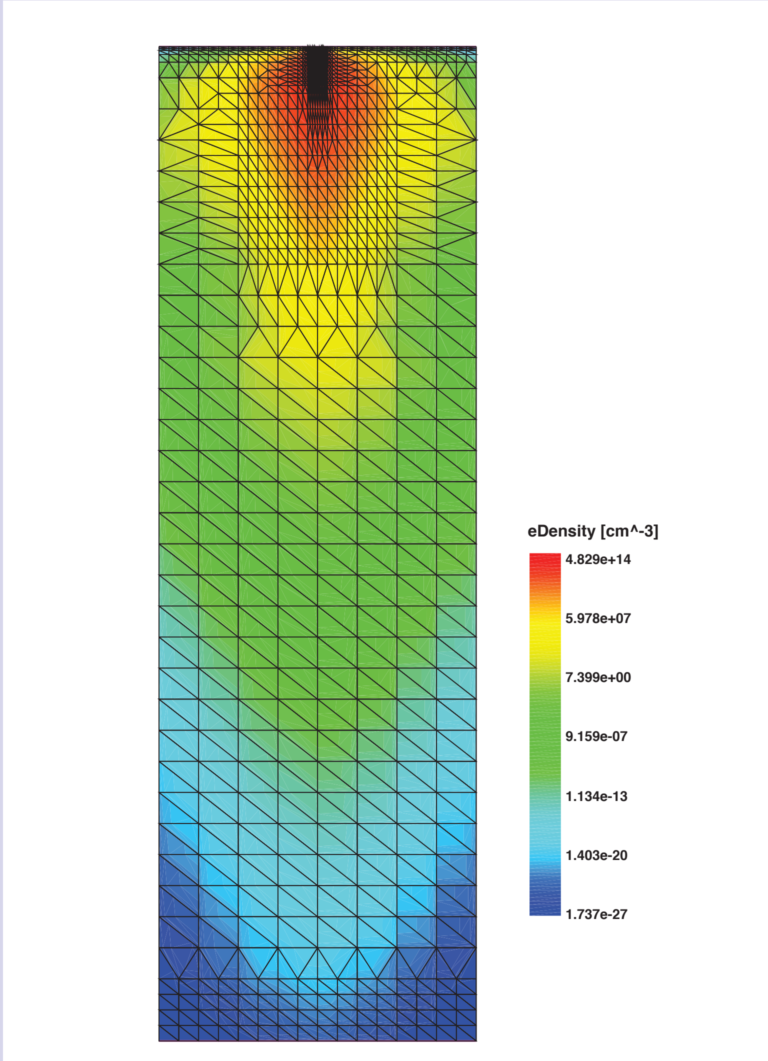
Detector Manufacture

- Laser used to produce electrodes
- Use standard photolithographic process to produce patterned metallization on diamond



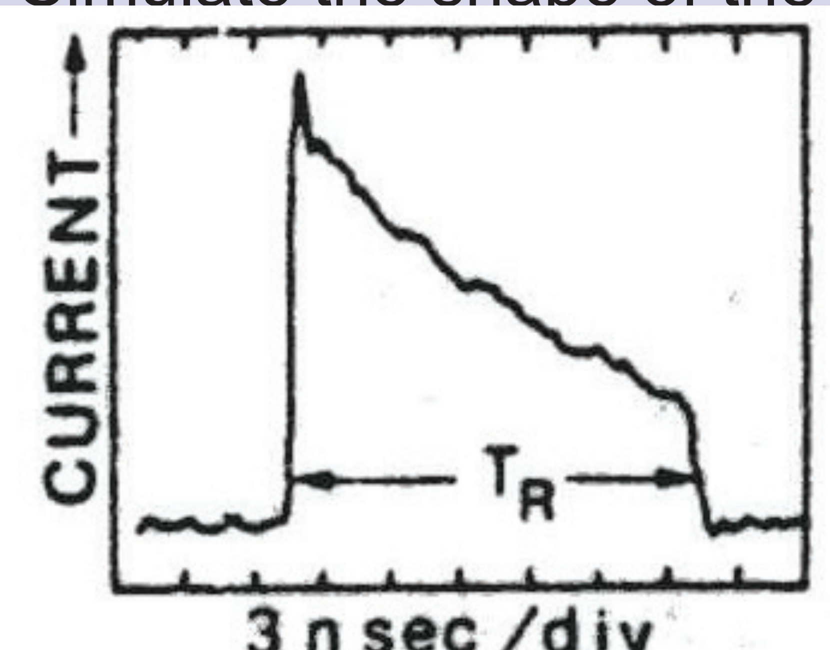
TCAD

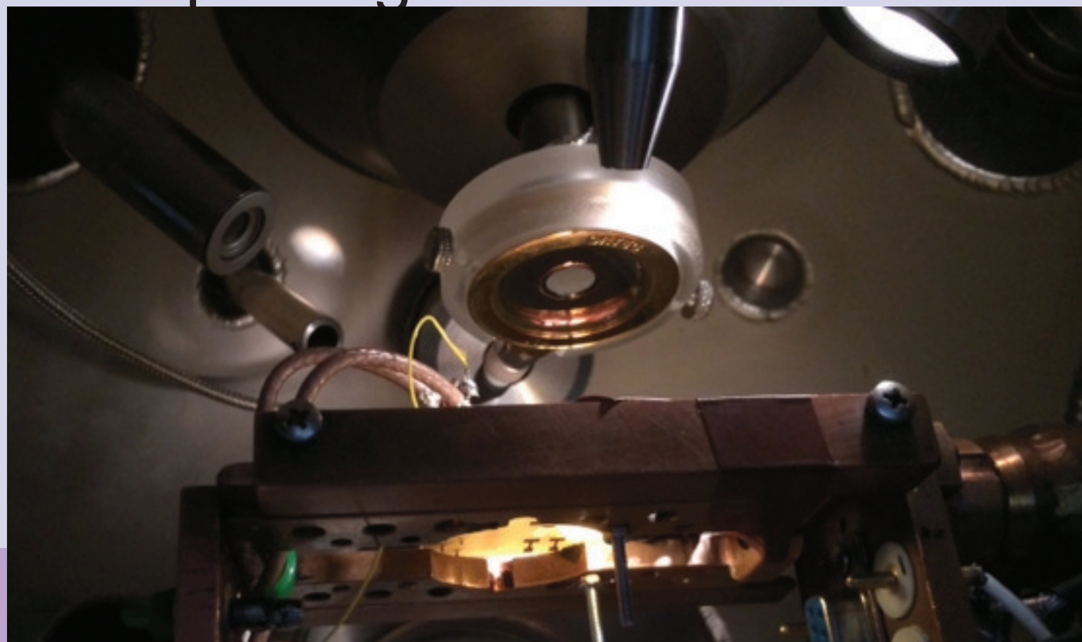
- Used Sentaurus TCAD package for simulations
- Create a mesh to approximate the structure that needs to simulated
- Apply a set of boundary conditions (e.g. electrode potentials) to find the steady state behavior of the device
- Introduce a charge density in certain regions of the device to simulate e.g. a MIP hit or an α-particle
- Iteratively solving the governing equations of semiconductors, can therefore simulate behavior such as current pulses
- Can also add more advanced Physics models such as field dependent mobility



3D Diamond TRIBIC simulations

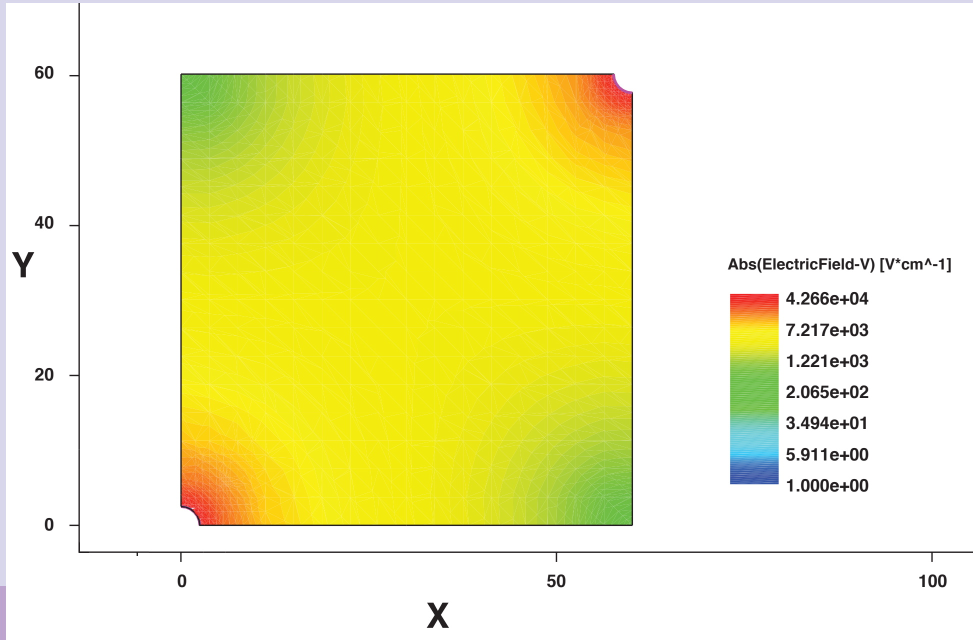
- TRIBIC (Time Resolved Ion Beam Induced Current) measurements on 3D Diamond sample
- 2013 Test beam in Zagreb, studied 3D Diamond detector with 4 MeV protons, and measured current produced
- 4MeV protons produce a Bragg peak ~80μm inside the diamond
- Self Triggered, ~ 2 μm precision
- Simulate the shape of the current pulse generated





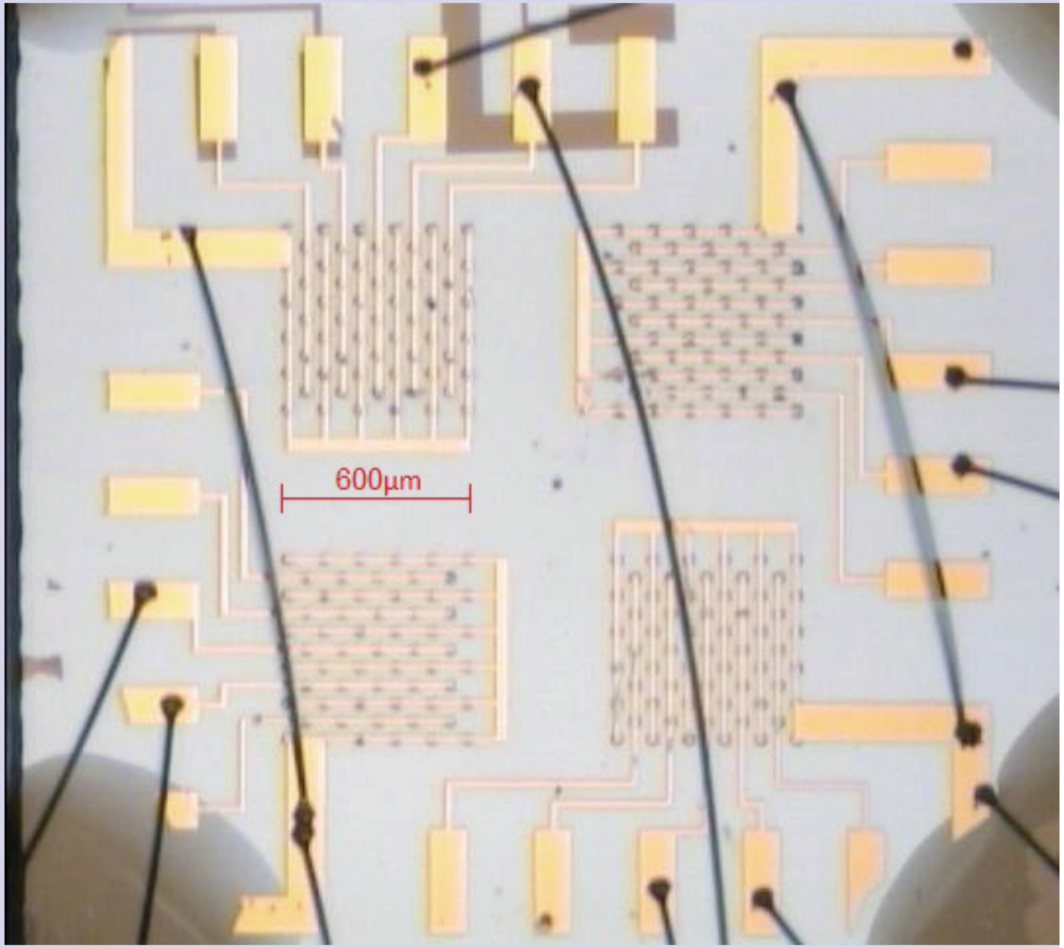
3D Diamond TRIBIC simulations

- Performed the simulations on a quarter square cell structure with 120μm pitch
- Approximated the deposited charge to a Bragg peak
- Running transient simulations to study the how the current pulse changes with different applied voltages and different hit positions



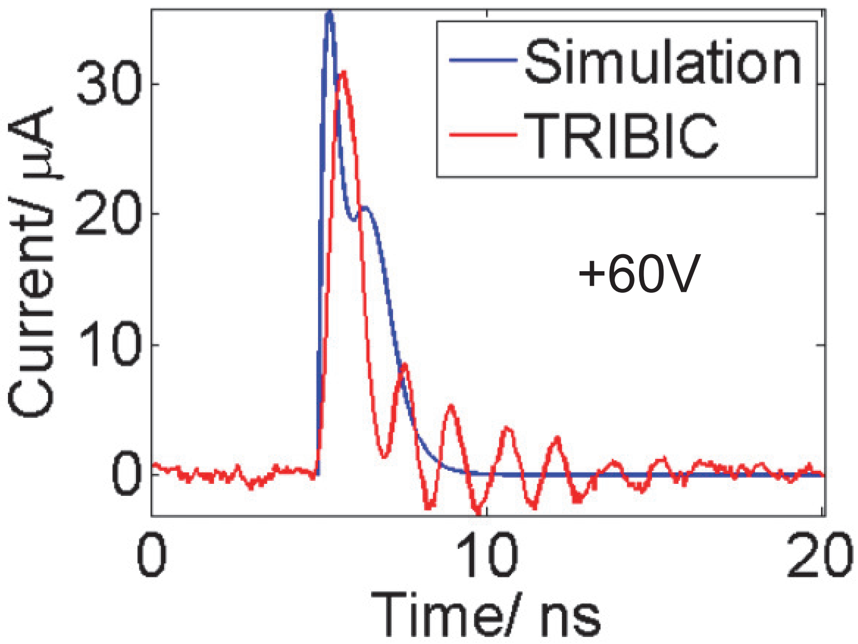
3D Diamond TRIBIC simulations

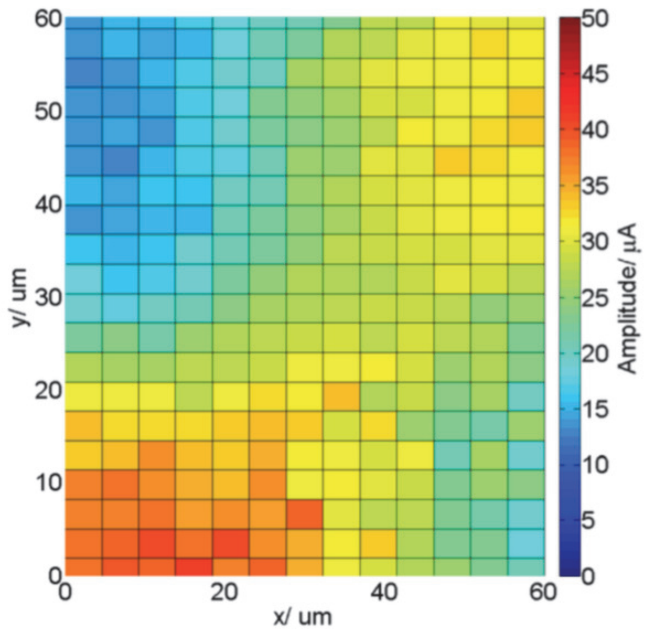
- Ran simulations at different voltages
- SC diamond, assume no traps; apply a resistance to the electrode
- Simulations included a surface metallization along the y direction to match the detector geometry used
- Applied bias voltage on the signal electrode, which was also read out; kept the HV electrode grounded

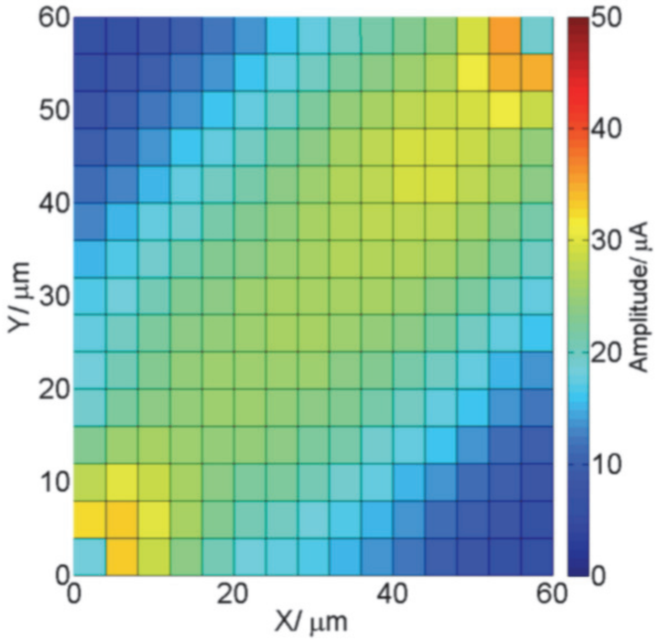


3D Diamond TRIBIC simulations

- Observed that with certain hit positions, particularly hits close to one of the electrodes, the current pulse exhibited a double peak shape due to the different travelling time of electrons and holes
- Compared pulse amplitude from experiment to simulation

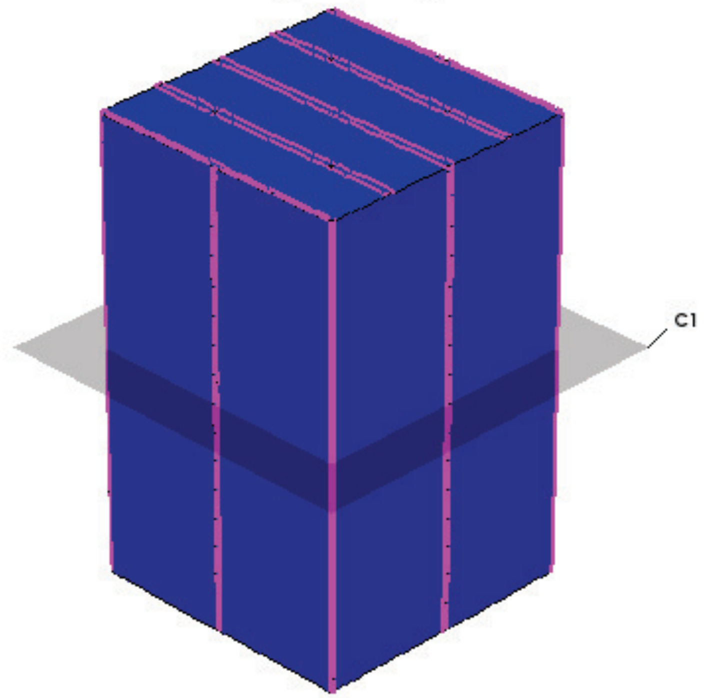


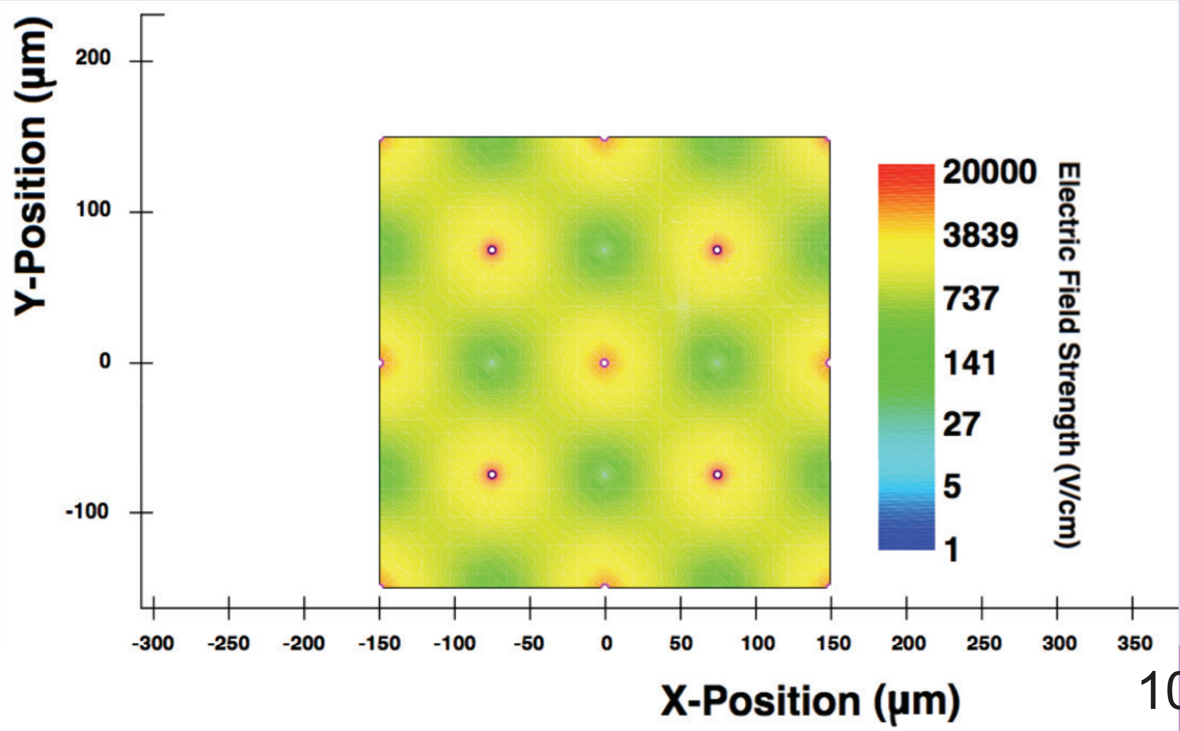




3D Diamond MIP simulations

- Produced a mesh containing several 150 µm square cells
- Signal columns were ganged together in lines along the Y-direction by surface electrode to mimic the metallization on the detector used in the experiment
- Graphitic columns modeled as perfect contacts on surface of column, with 2.5 µm radius
- Simulations performed at 25V



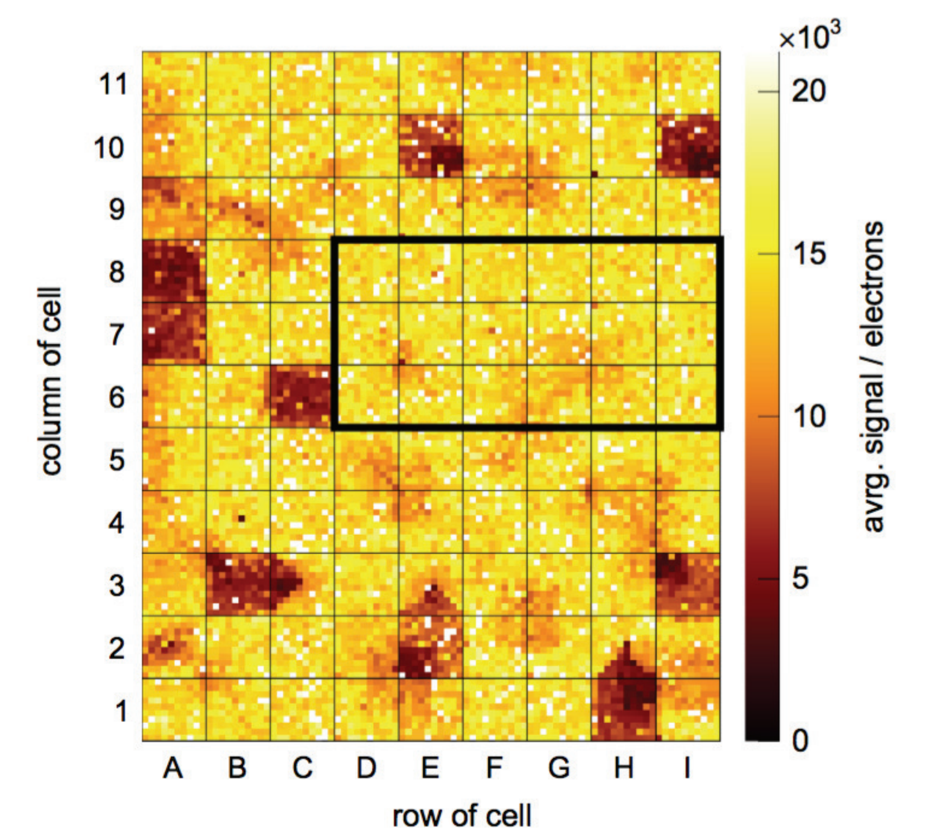


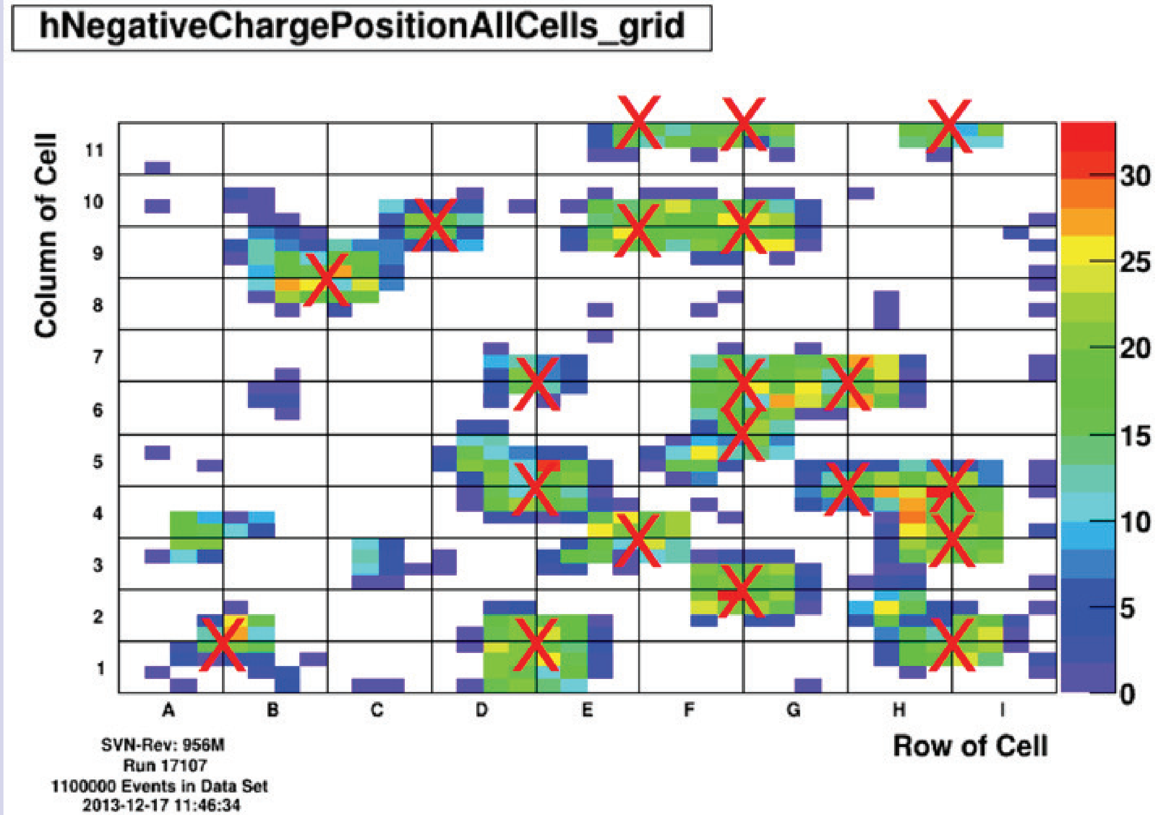
3D Diamond MIP simulations

- Better understand results of test beam with a 3D Diamond detector using 120 GeV protons*
- Understand charge sharing between neighboring cells, particularly when a bias column was missing
- Understand difference in charge collection in broken cells
- Then applied simple finite charge lifetime model to implement measured 70 ns charge lifetime

*F. Bachmair et al. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 786:97 – 104, 2015.

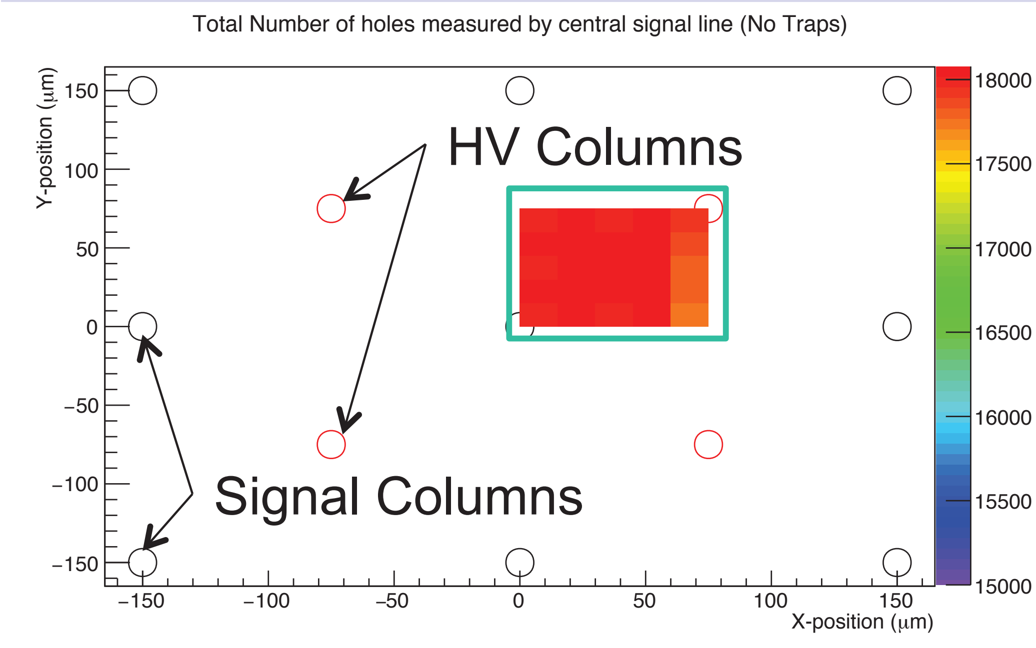
3D Diamond MIP simulations

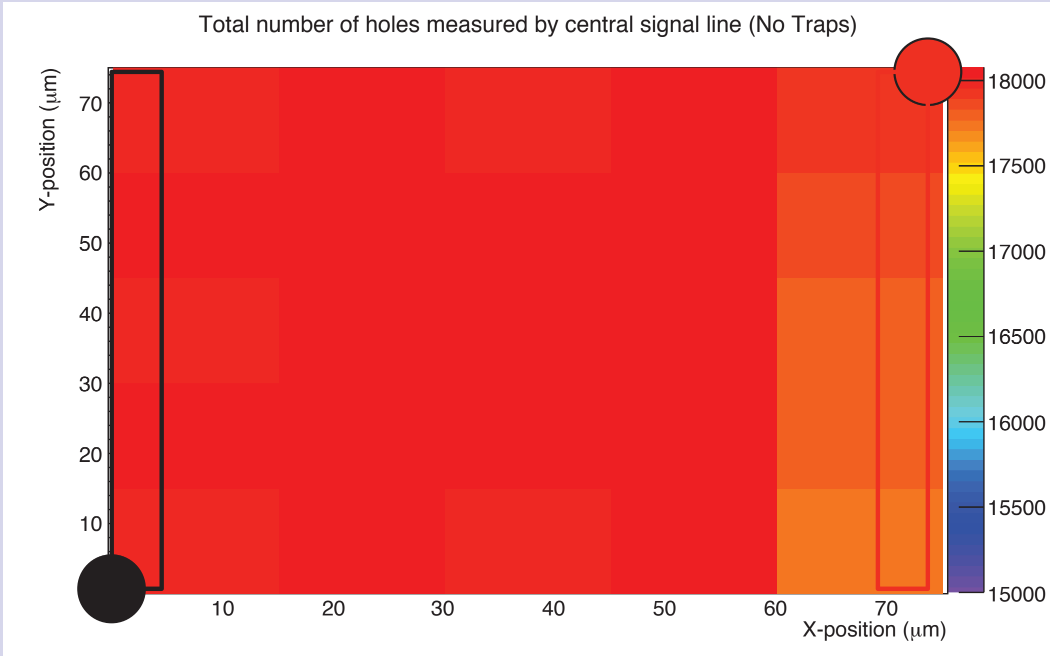




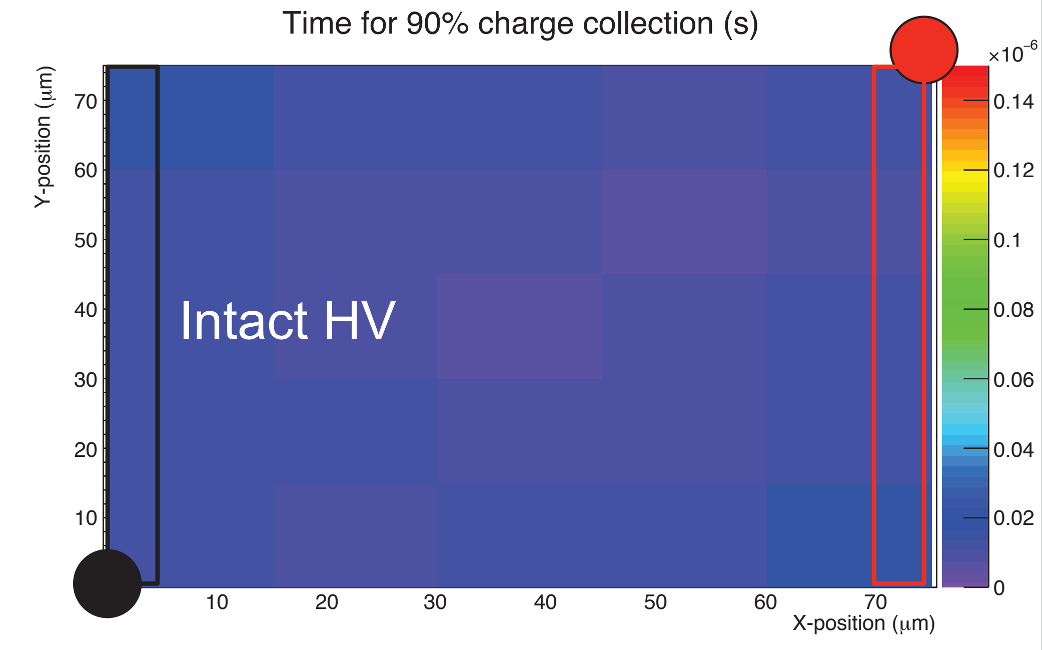
3D Diamond MIP simulations

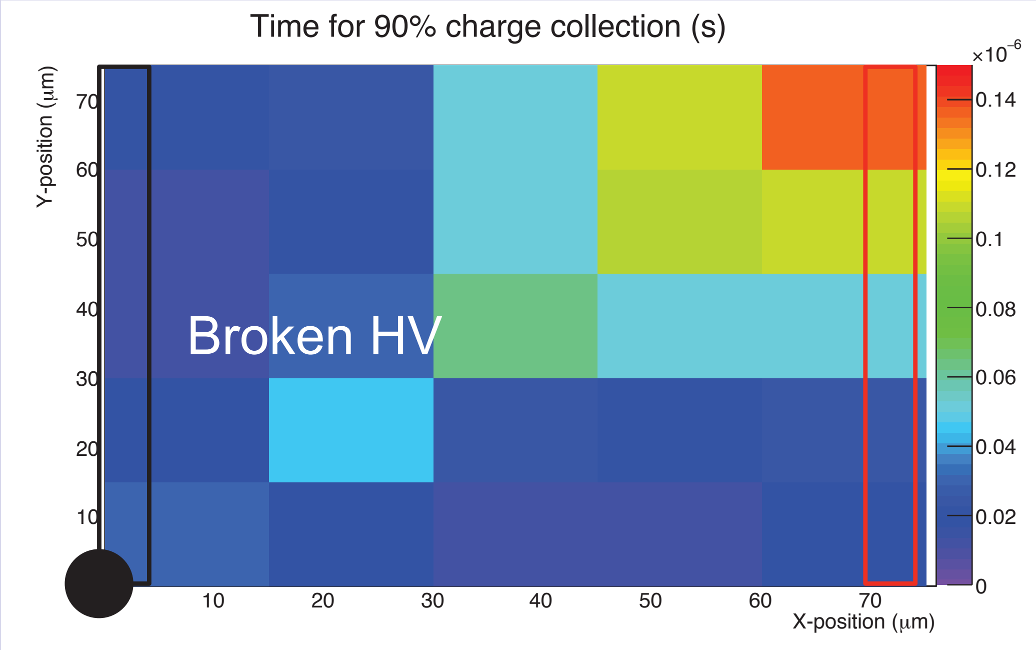
- Simulated MIPs passing through the area of a quarter cell
- Divided the quarter cell into 15x15 μm squares, and simulated a MIP hit at the center of each square
- Able to plot the charge collected as function of position





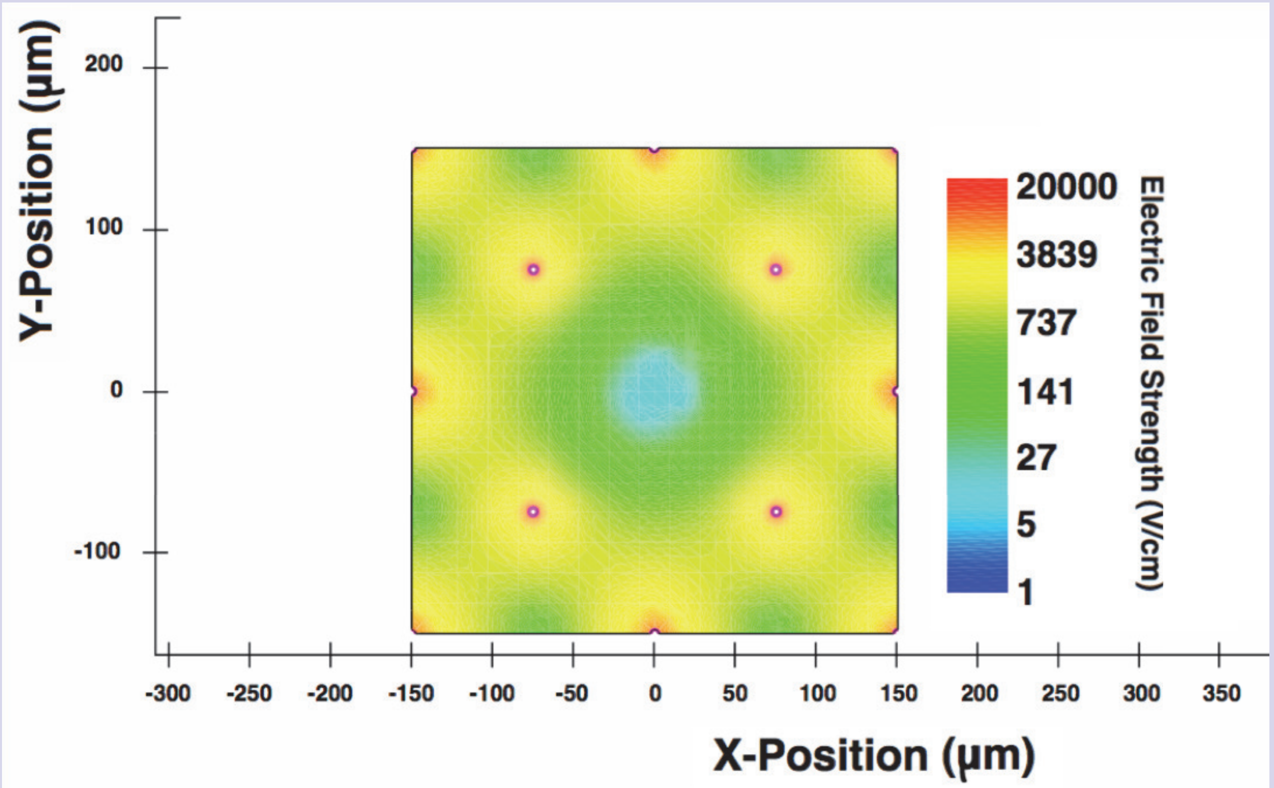
3D Diamond MIP simulations





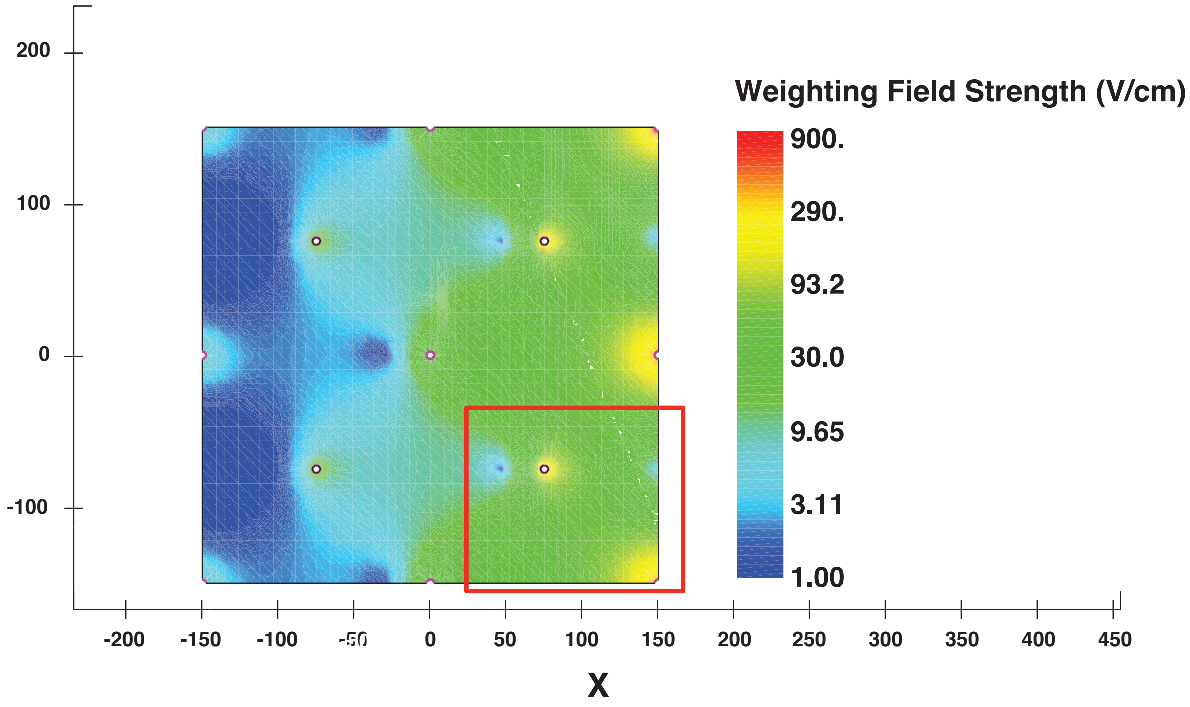
3D Diamond MIP simulations

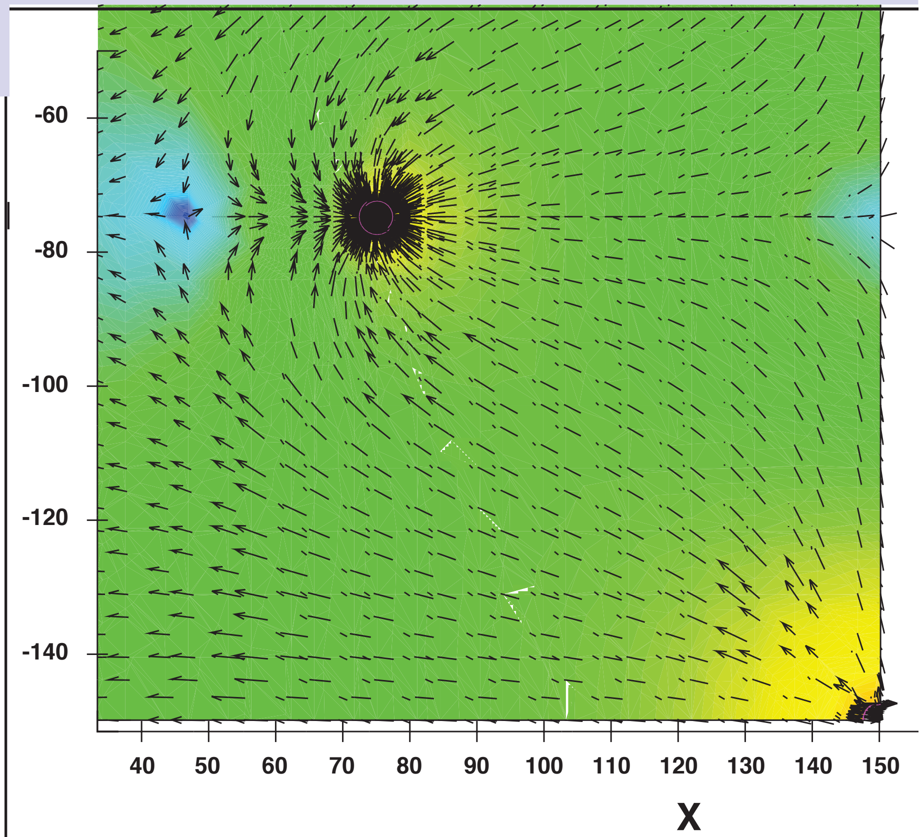
- Order of magnitude difference between charge collection times in broken cells and intact cells due to large region with low field due to missing columns



Weighting Field

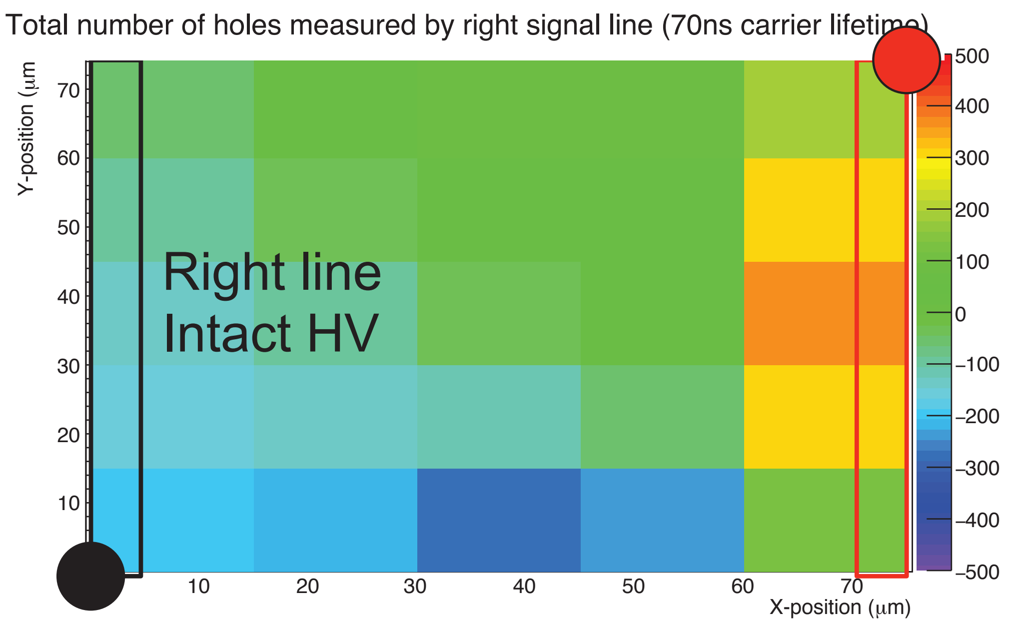
- Observed the generation of a bipolar signal in strips adjacent to the one with the hit due to the shape of the weighting field around the graphitic columns
- These signals integrate to zero due to charge conservation when no traps are present

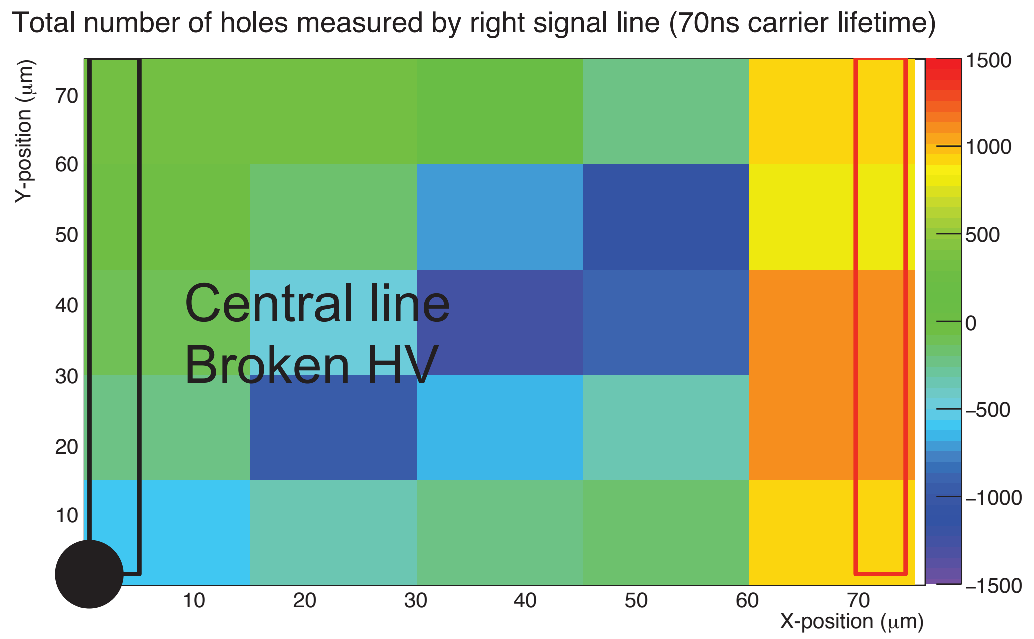




3D Diamond MIP simulations

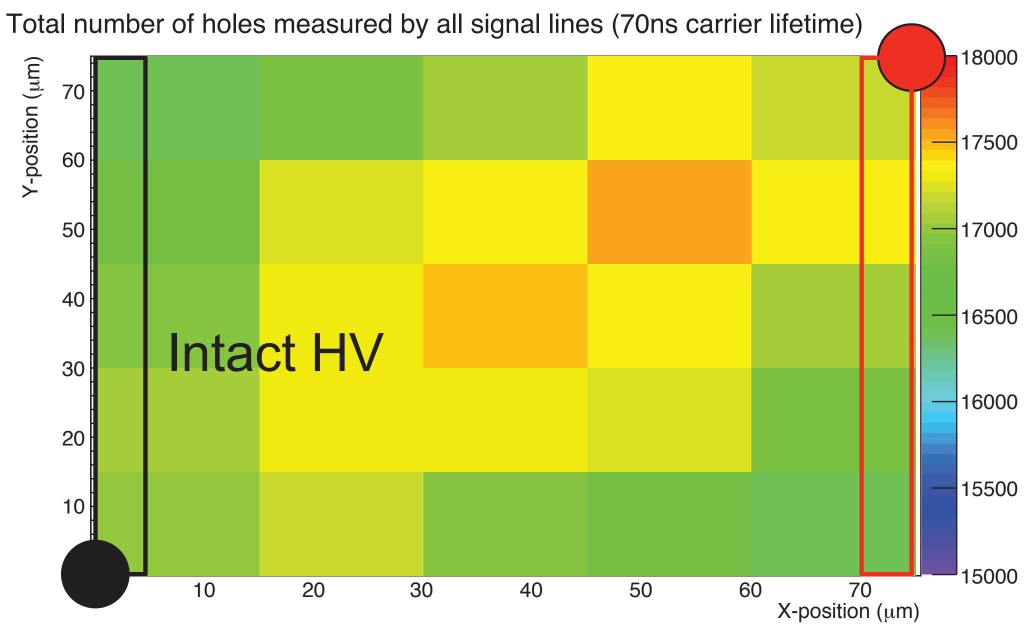
- Introduce a simple charge trapping model to mimic a 70 ns charge lifetime, now some charge is trapped before reaching electrodes resulting in a residual signal in the neighboring cells
- Negative signals observed in regions of intact cells, but below noise level
- In broken cell significantly more trapping, hence region with significant negative signals induced in neighboring cells, centered in position of missing bias column

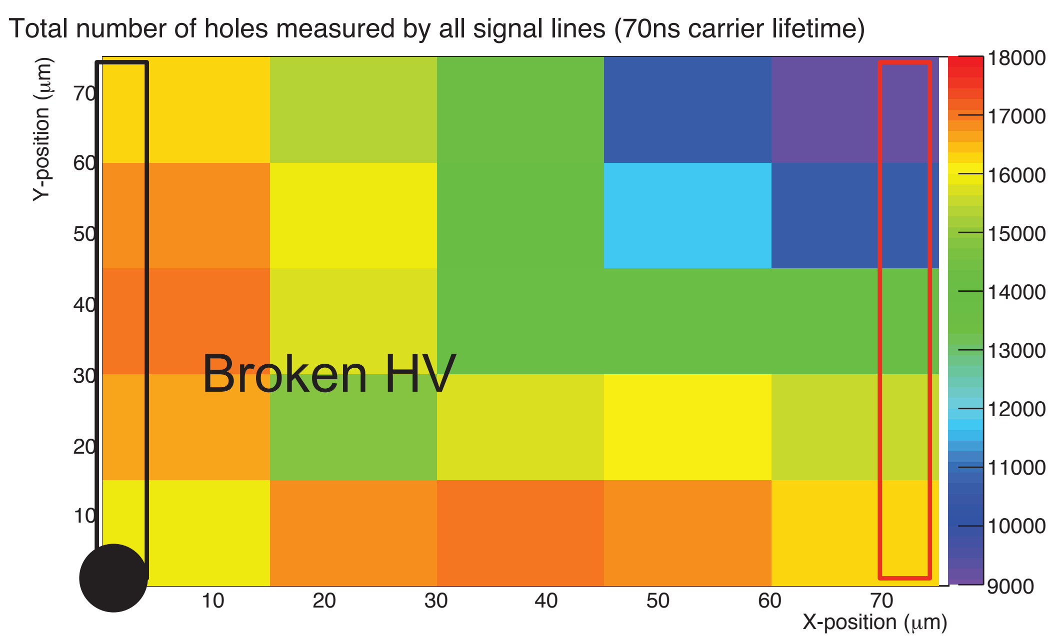




3D Diamond MIP simulations

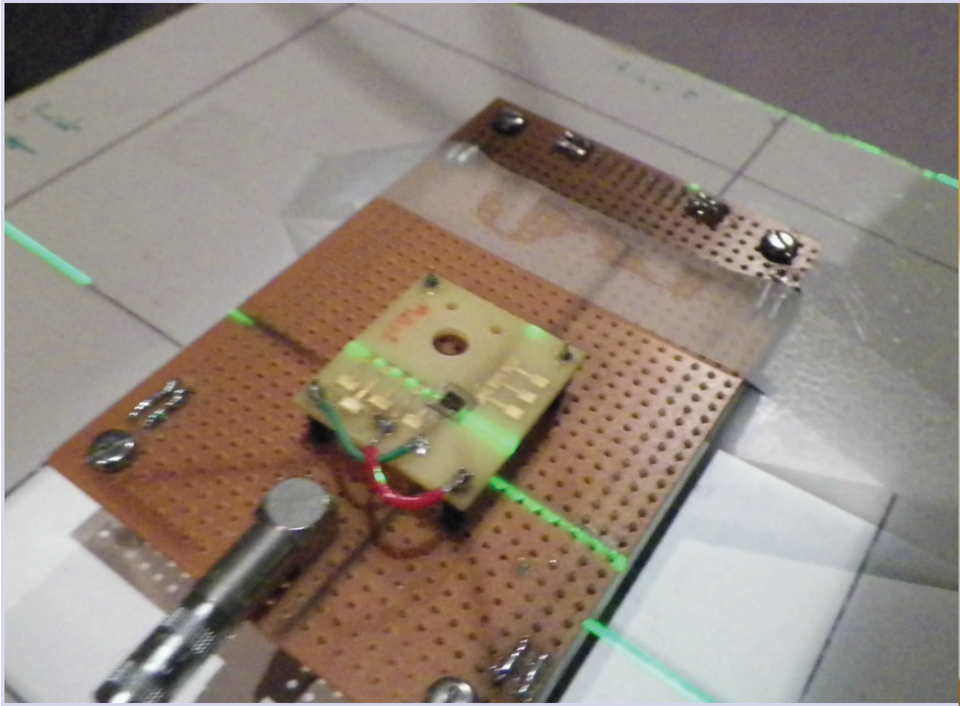
- Overall observe that relatively uniform charge collection for intact cell, even with trapping
- In case of missing HV column, region centered around column with high negative signal, and lower overall signal, as observed

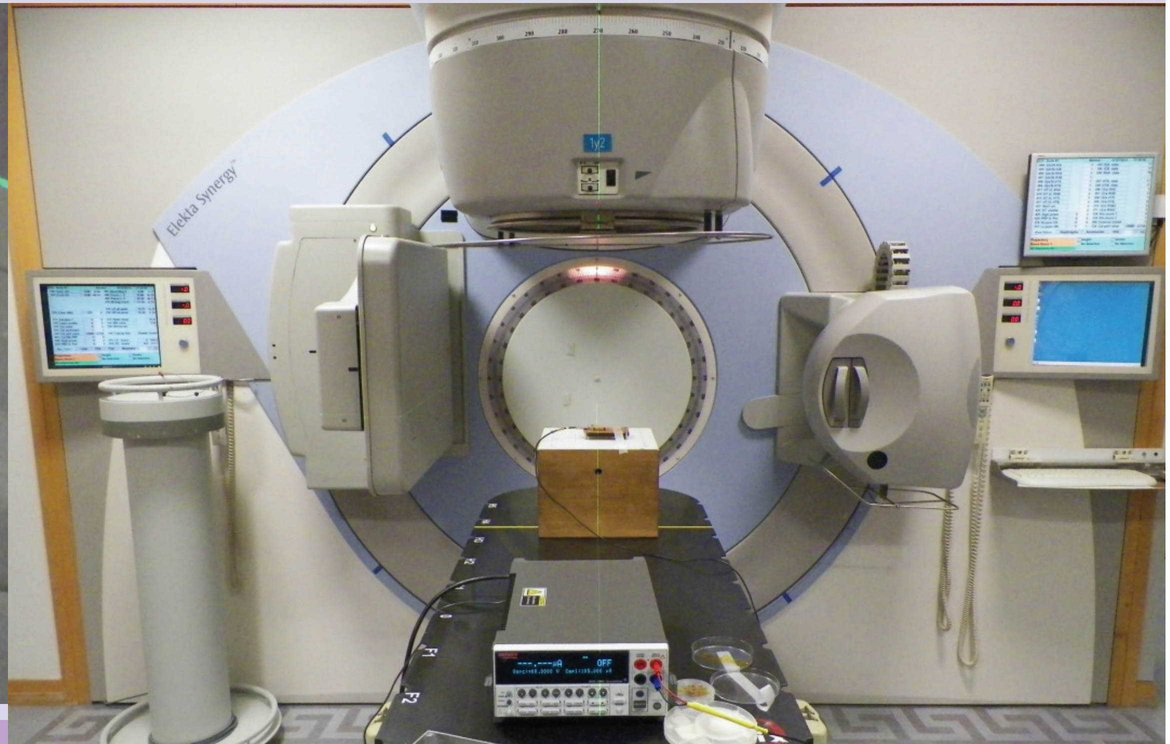




Diamonds at the Christie's

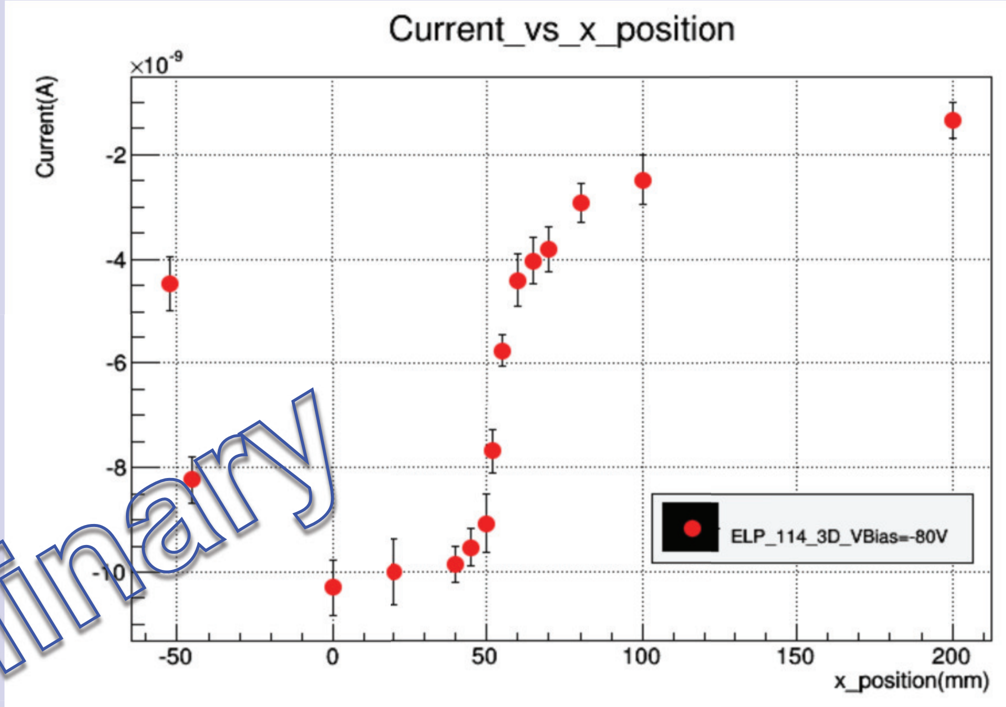
- The Christie's is a hospital that specializes in the treatment of cancer in Manchester
- Want to use 3D diamond for dosimetry in radiotherapy.
- Working in collaboration with the Christie hospital
- Goal to have detectors that allow real time, high resolution monitoring of dose received by patient

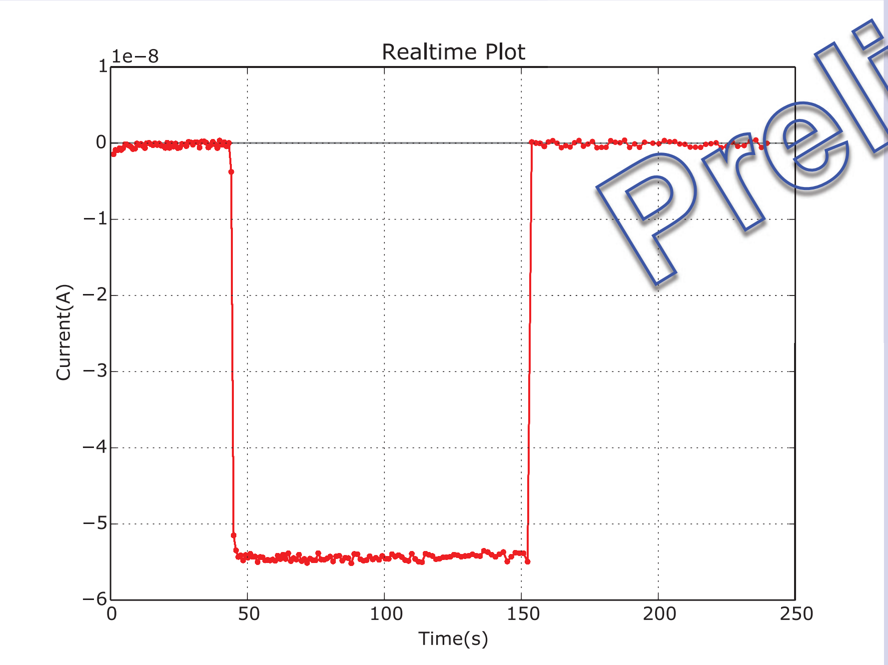


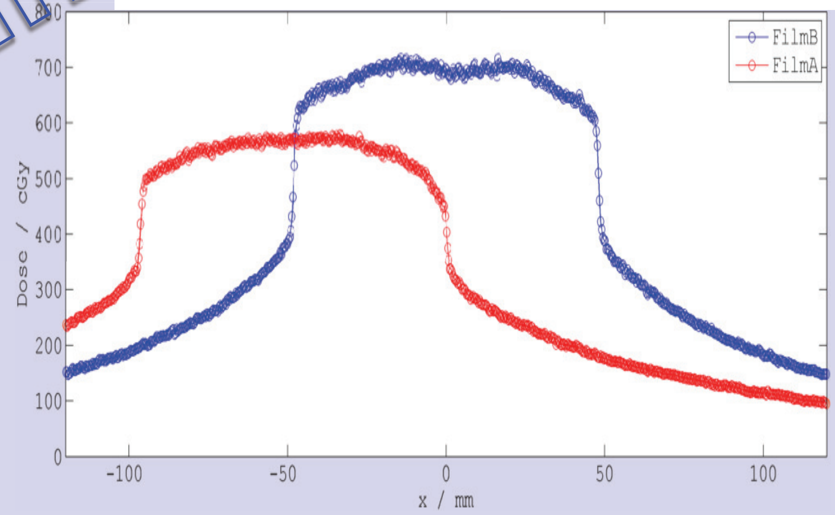


Diamonds at the Christie's

- Tried scanning different parameters
- Moved the detector to study the observed current at different positions in the beam
- Tried studying the effects of applying different voltages to both planar and 3D detectors







Preliminary

Future Plans

- Need to investigate radiation hardness of 3D Diamond, and study the effect of irradiation on the columns, sample has been irradiated; pre irradiation columns had diameter either 1.1μm or 1.4μm and respective resistances as low as ~$2.5\times10^{6}\Omega$ and ~$1.8\times10^{6}\Omega$
- Once sample is available again, will be able to compare this to column resistance post irradiation
- More measurements will be carried out at the Christie's using detectors with a purposely designed geometry
- Investigate the effects of different electrode geometries (e.g. Hexagonal, rectangular etc.) both with new detectors and more simulations
- Study the effects of varying electrode shape (e.g. branching electrodes?)

Thanks for listening

Backup Slides

Semiconductor equations

Electron Continuity Equation:

$$\frac{\partial n}{\partial t} = \frac{1}{q}\nabla \cdot J_n + (G_n - R_n)$$

Hole Continuity Equation:

$$\frac{\partial p}{\partial t} = -\frac{1}{q}\nabla \cdot J_p + (G_p - R_p)$$

Poisson Equation:

$$\nabla \cdot E = \frac{\rho_s}{\varepsilon_s}$$

- J – Current Density
- G – Carrier Generation rate
- R – Carrier Recombination rate
- ρ_s – Total space charge density
- ε_s – Permittivity of semiconductor

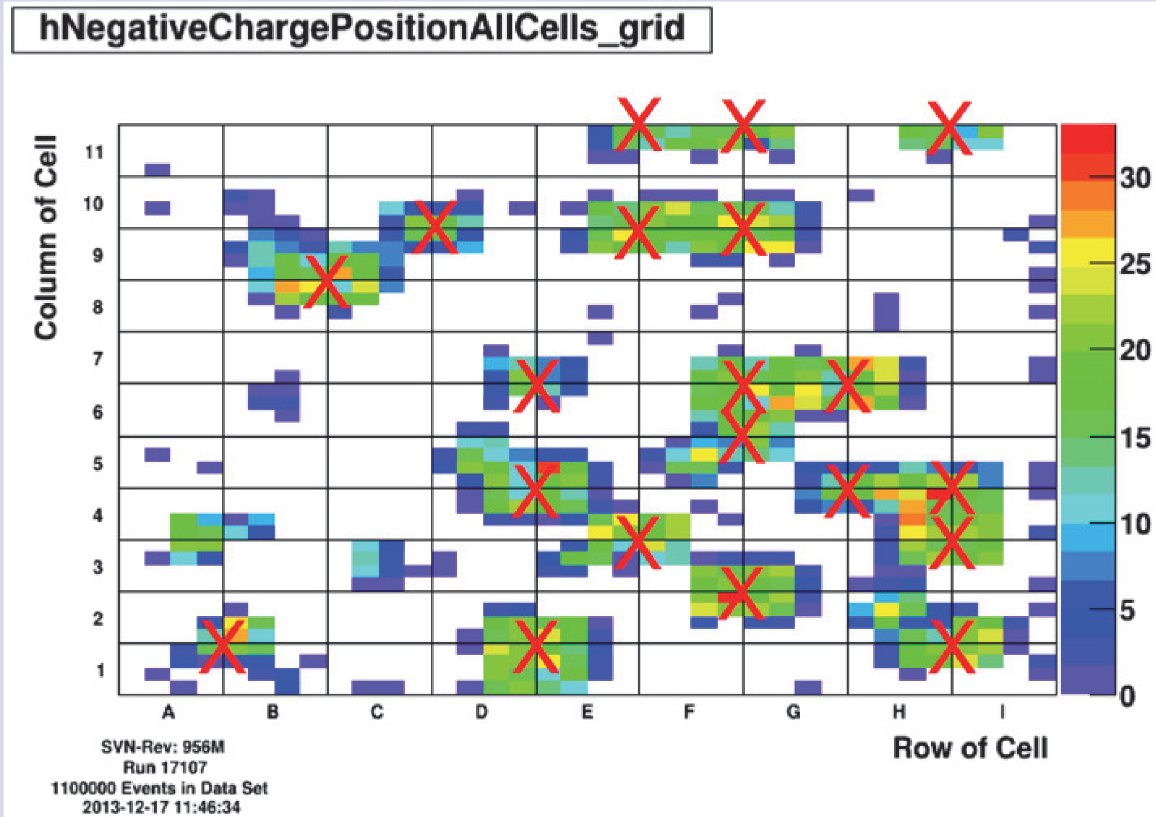
Pernegger Values

- $\mu_{low_e} = 1714\ cm^2\ V^{-1}\ s^{-1}$
- $\mu_{low_h} = 2064\ cm^2\ V^{-1}\ s^{-1}$
- $v_{sat_e} = 9.6 \times 10^6\ cm\ s^{-1}$
- $v_{sat_h} = 14.1 \times 10^6\ cm\ s^{-1}$

H. Pernegger et al. Charge-carrier properties in synthetic single-crystal diamond measured with the transient-current technique. Journal of Applied Physics, 97(7):–, 2005.

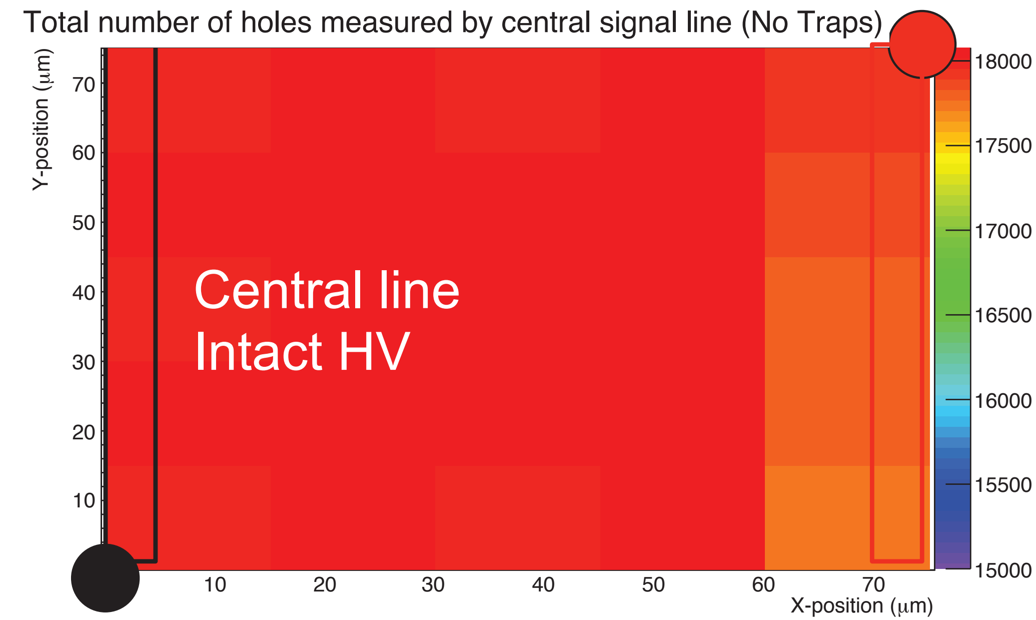
Simulation

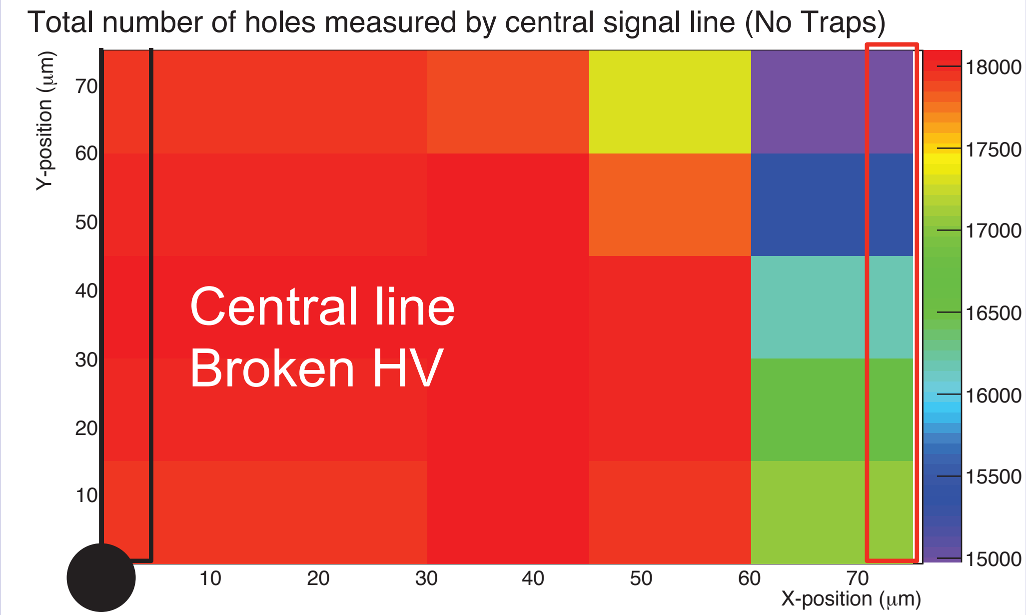
- Carried out some simulations of 3D Diamond detectors
- Wanted to investigate the effects of missing columns, and the production of a wrong sign signal pulse observed at a test beam

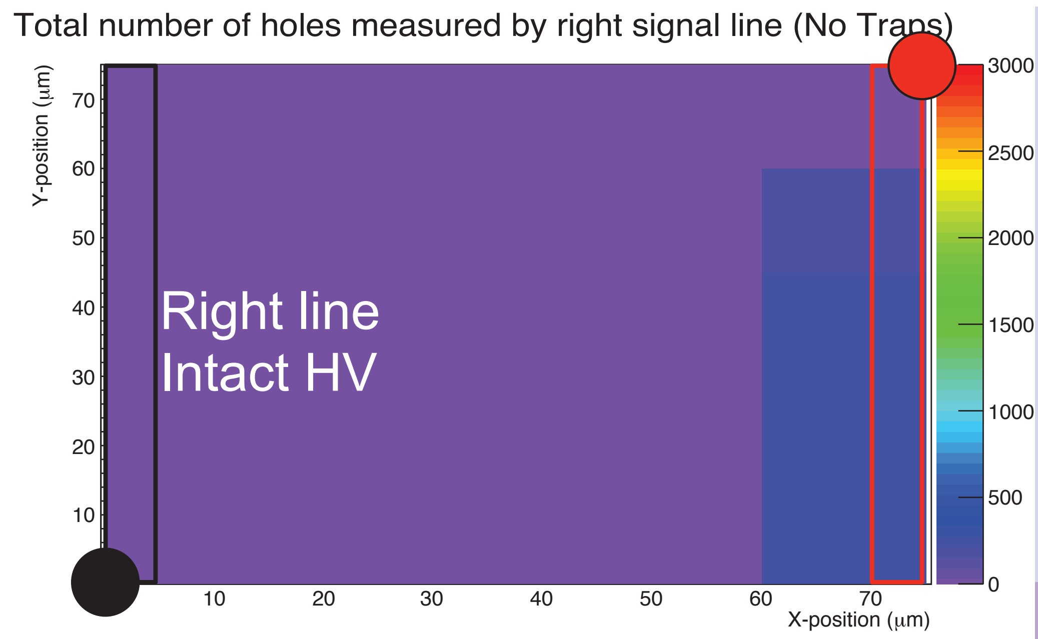


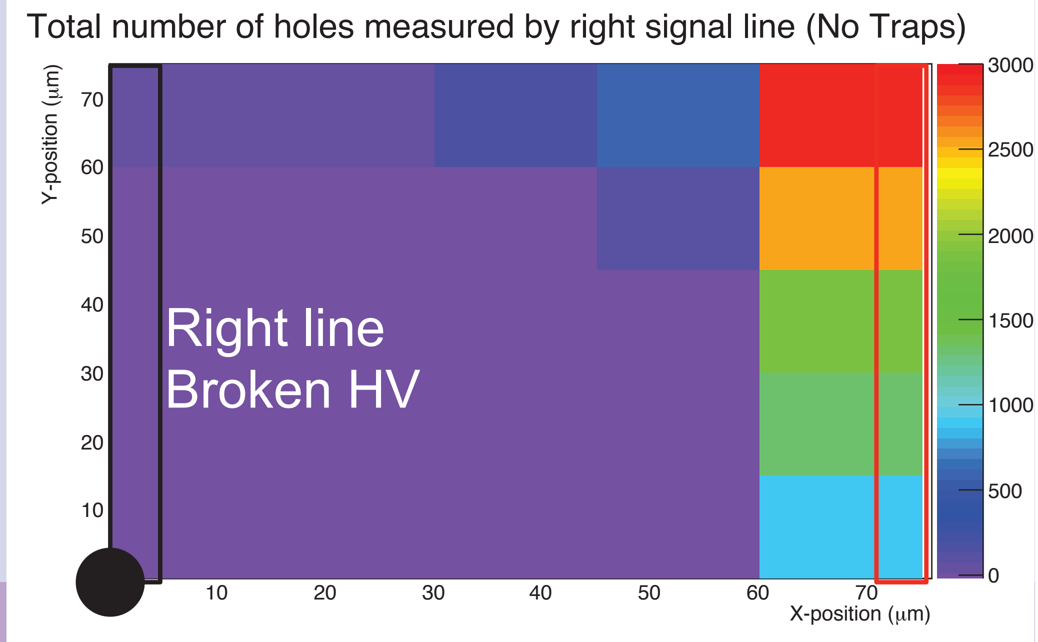
M. Pomorski, P. Bergonzo, D. Trompson, F. Bachmair, L. Baeni
I. Haughton, D. Hits, H. Kagan, R. Kass, L. Li, B. Caylar, A. Oh
Fabrication, characterization of a 3d diamond detector. 13th
Vienna Conference on instrumentation - VCI 2013, 2 2013.

3D Diamond MIP simulations









3D Diamond MIP simulations