Simulation of 3D Diamond Detectors

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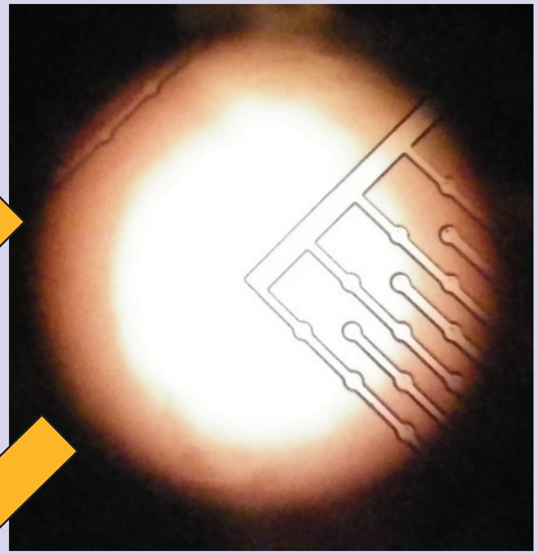
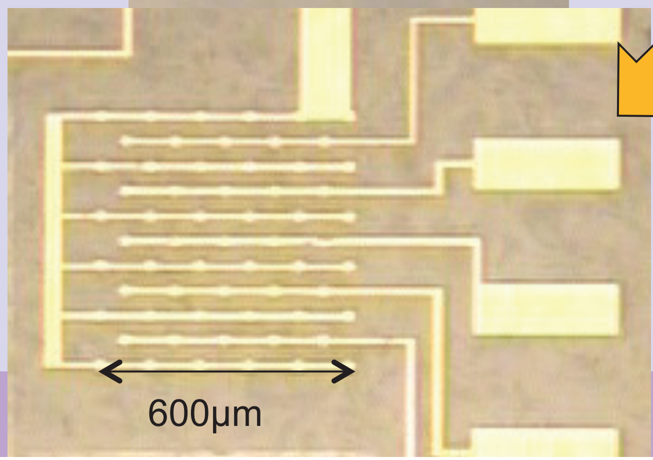
Introduction

- 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 I. Haughton 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

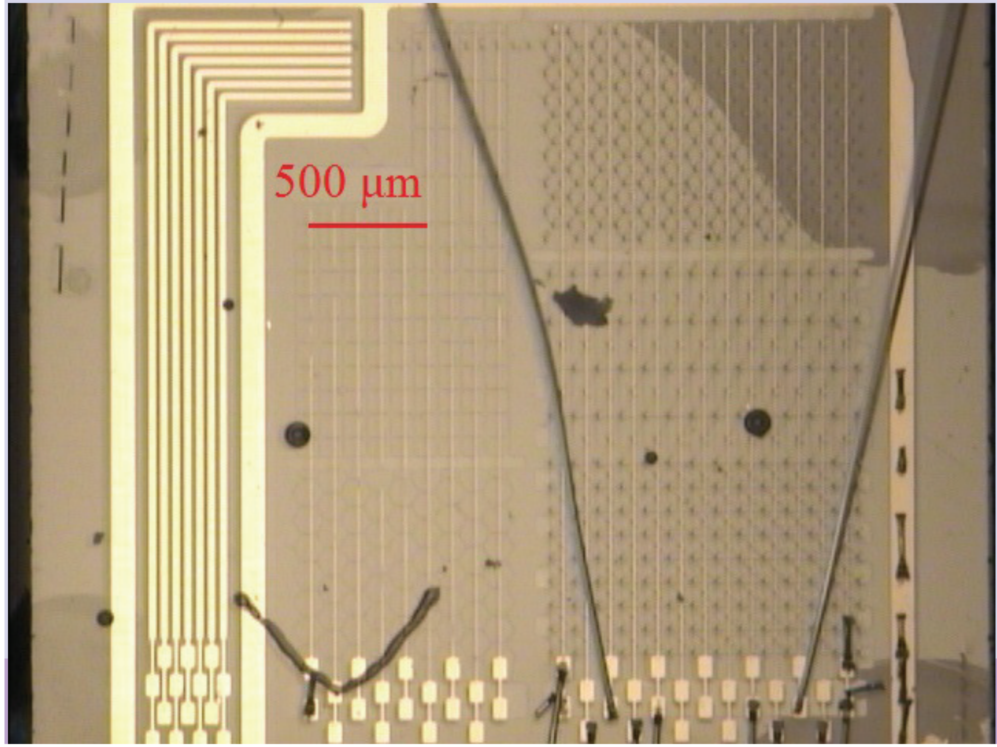
- Laser used to produce electrodes
- Use standard photolithographic process to produce patterned metallization on diamond

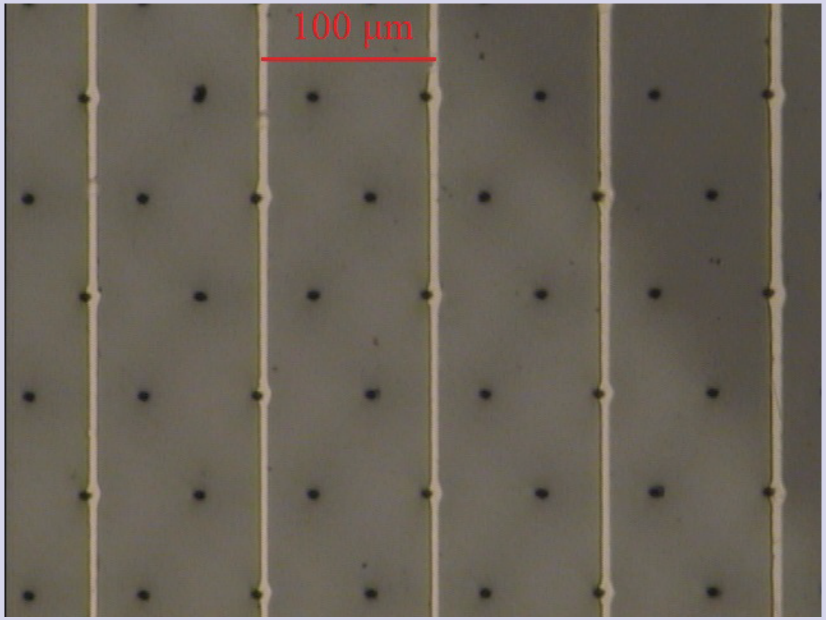




3D Diamond TRIBIC

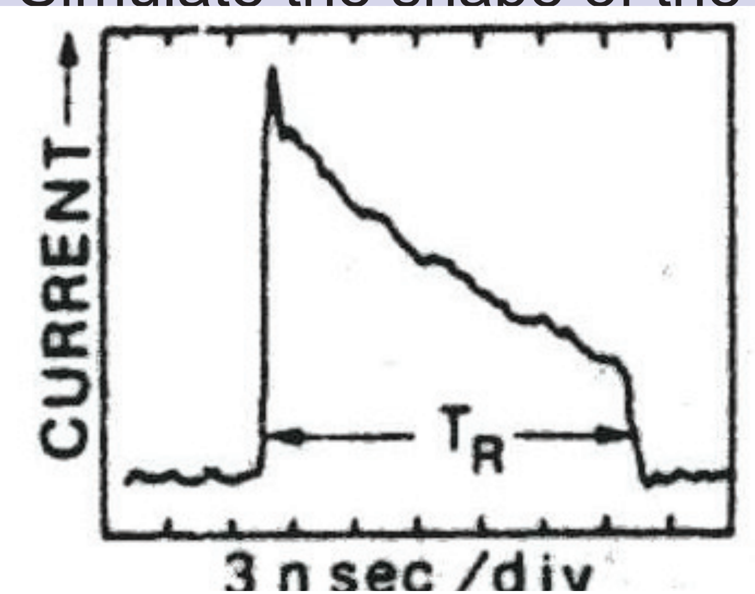
- Detector fabricated, columns drilled in Oxford, metallized in Manchester
- IBIC and TRIBIC measurements carried out in Zagreb (see Iain's talk)
- Recorded pulses for a range of positions in the detector
- Different cell geometries available for studies

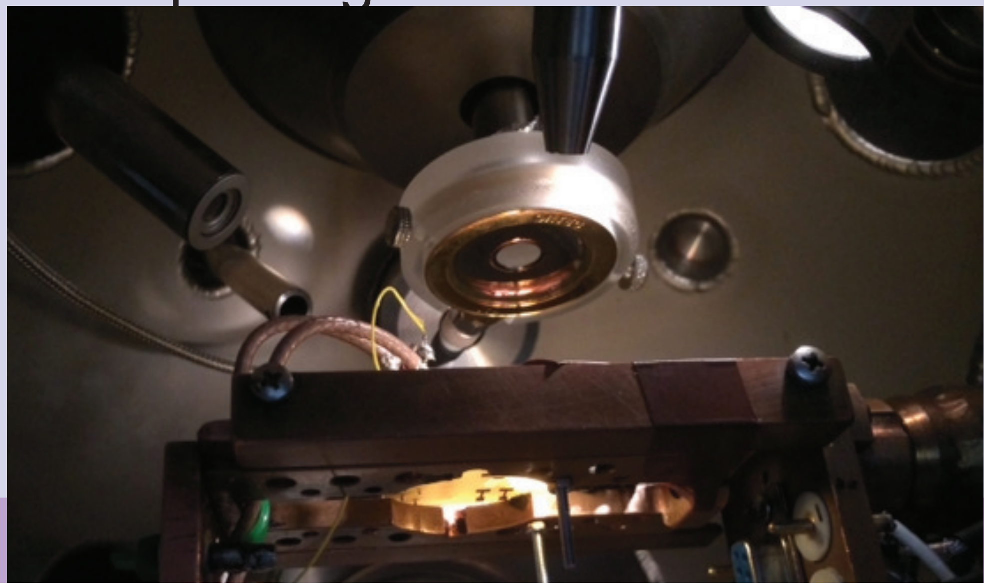




3D Diamond TRIBIC simulations

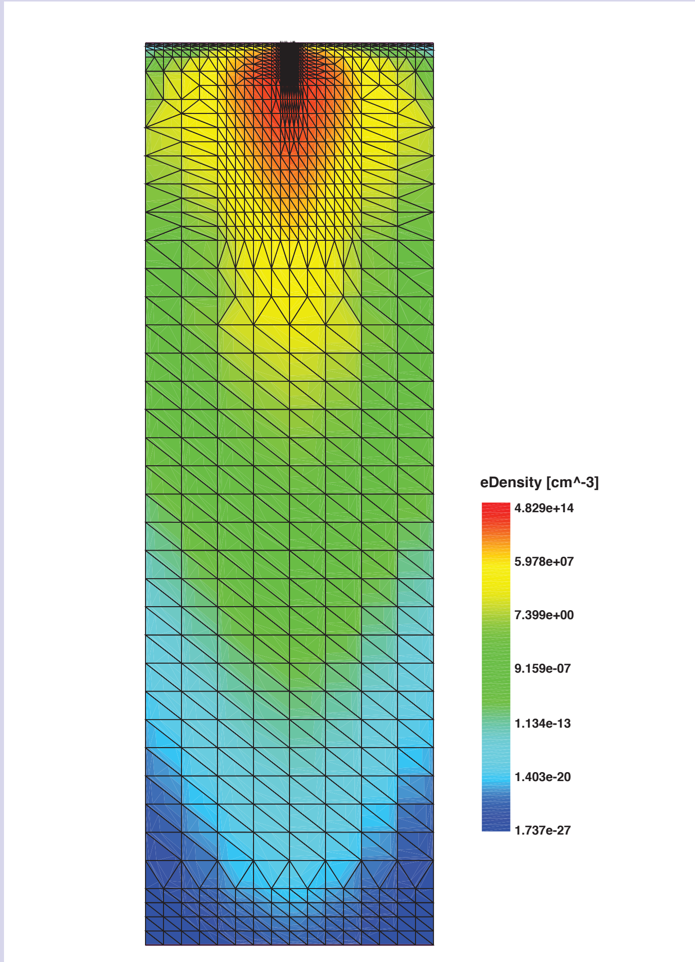
- TRIBIC (Time Resolved Ion Beam Induced Current) measurements on 3D Diamond sample
- 2016 Test beam in Zagreb, studied 3D Diamond detector with 4.5 MeV protons, and measured current produced
- 4.5MeV protons produce a Bragg peak ~80µm inside the diamond
- Self Triggered, ~ 2 µm precision
- Simulate the shape of the current pulse generated





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 (for these simulations used Pernegger parameters*)



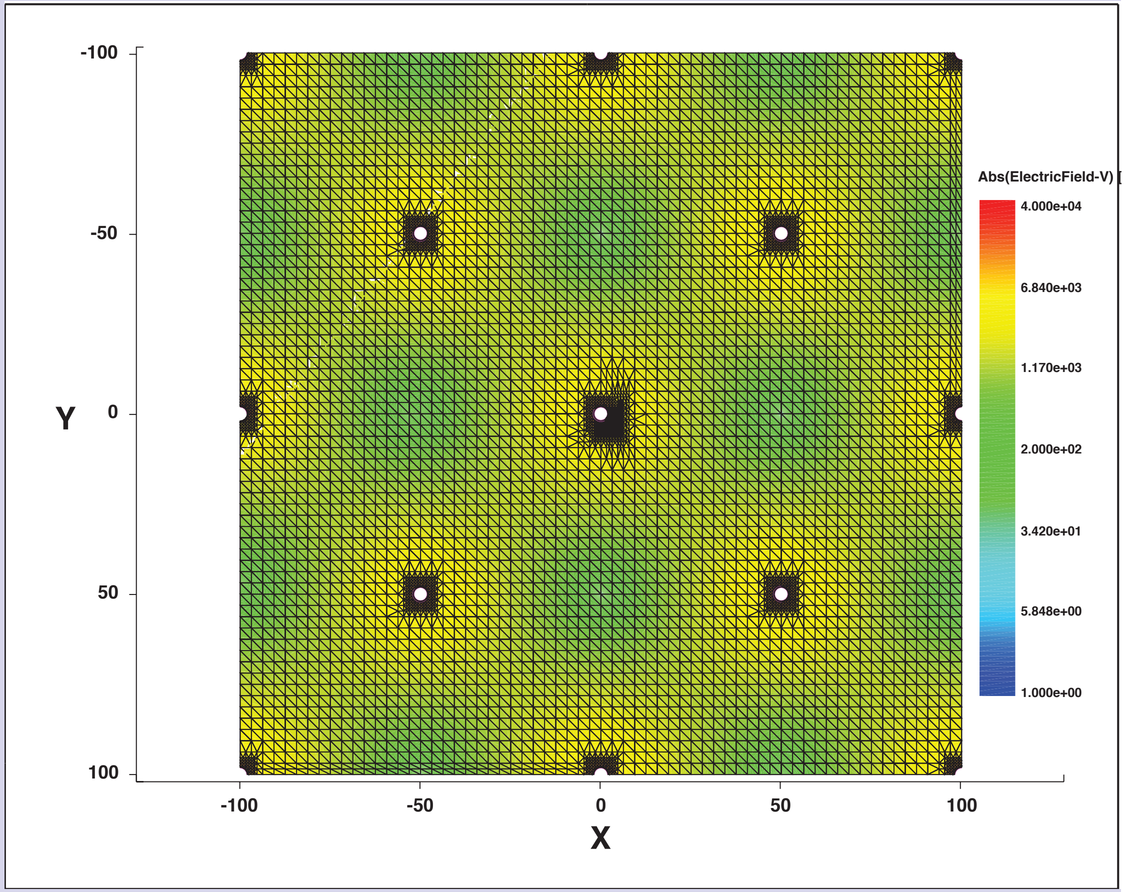
*H. Pernegger et al. Journal of Applied Physics, 97(7):–, 2005.

TCAD

- SC diamond, assume no traps; apply a resistance to the electrodes
- Applied bias voltage on the signal electrode, which was also read out; kept the HV electrode grounded, as this is how experiment was carried out
- Simulations performed on 2D mesh due to time issues, so do no include surface metallization

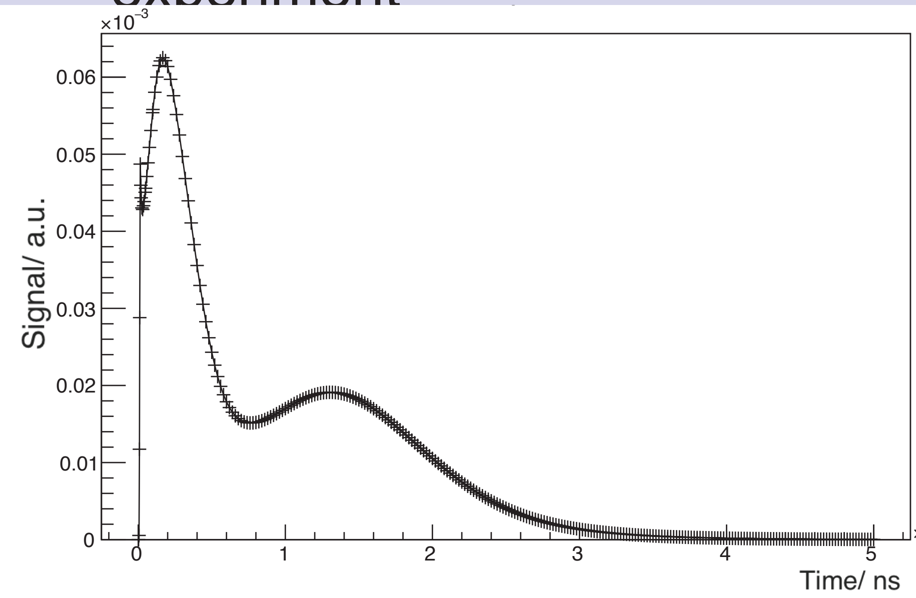
3D Diamond TRIBIC simulations

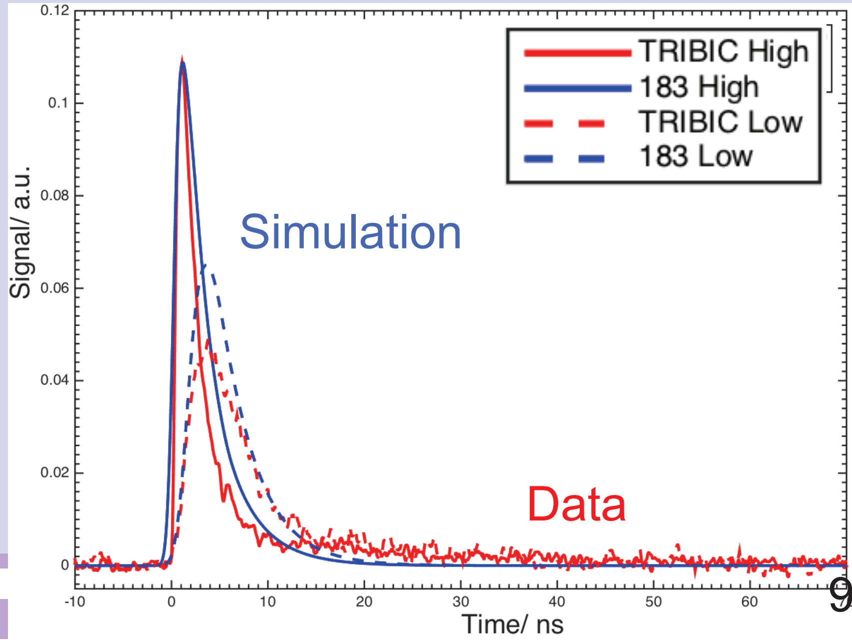
- Simulations performed on 2D mesh containing a 2x2 array of cells 100 micron pitch
- Run Transient simulations to study how different parameters affect the shape of the pulses generated
- Compare to TRIBIC data at 20V



3D Diamond TRIBIC simulations

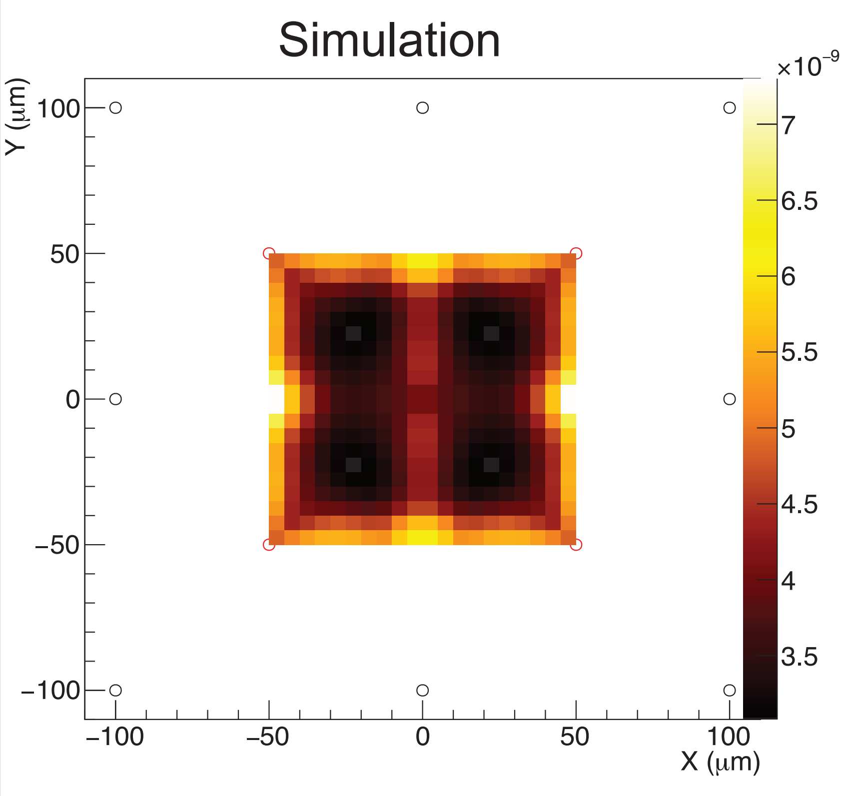
- Expect a 2 peak structure (left) when hit is close to electrode and electrode resistance is low, some of which is lost due to finite response time of amplifier
- This is not observed in the data, increasing electrode resistance (and thus the RC time constant) in the simulation increases the duration of the pulse and reduces the 2 peak structure of the pulses, so we can deduce that the pulse structure in the data is dominated by the RC time constant. Good agreement between data and experiment

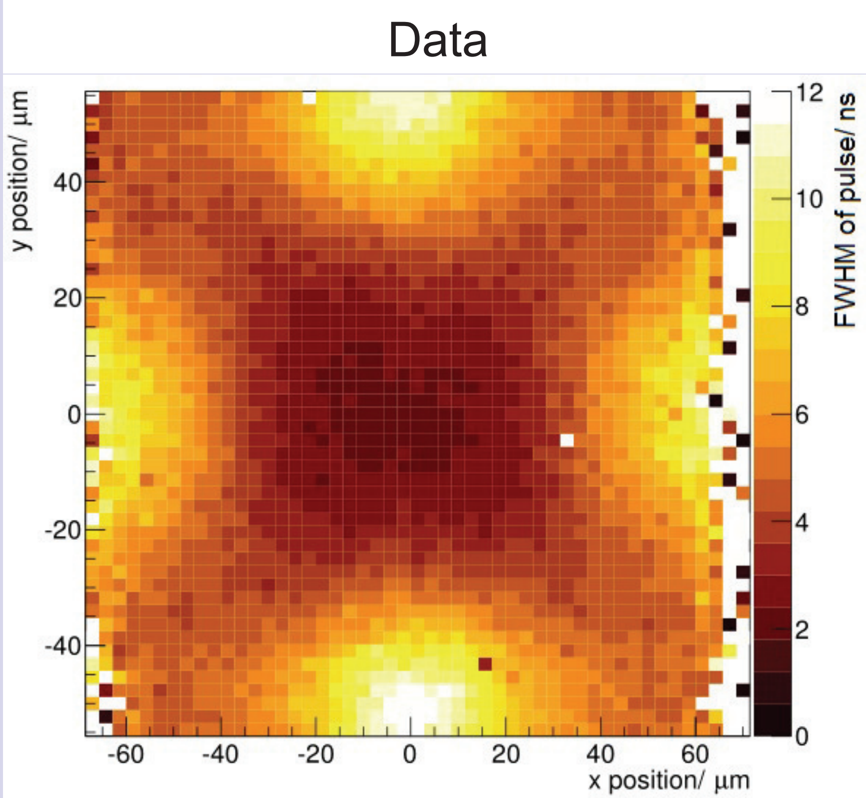




3D Diamond TRIBIC simulations

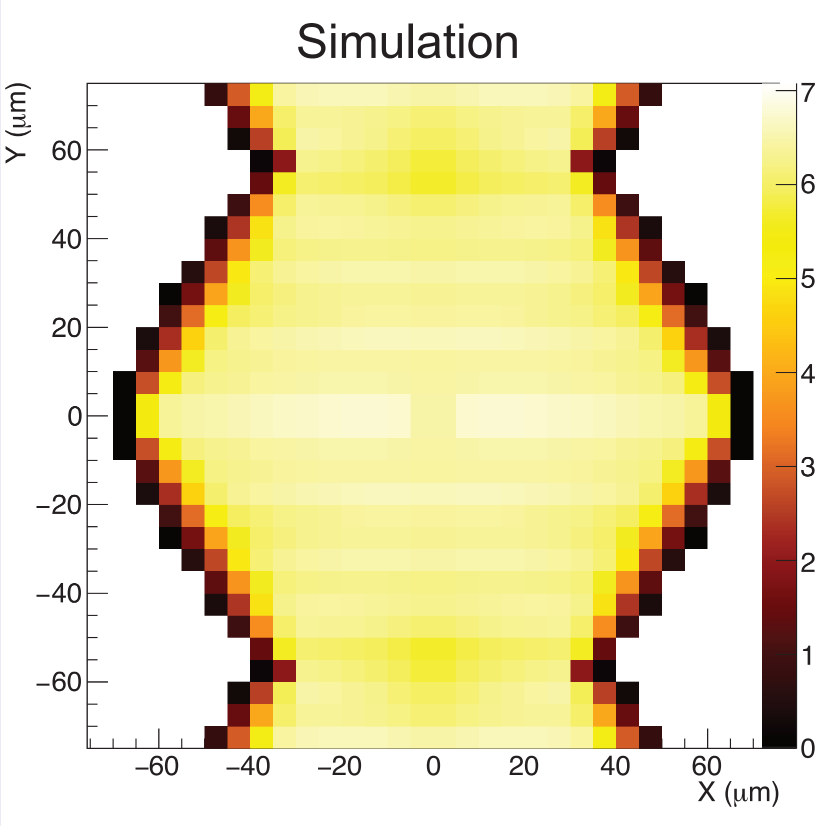
- Also compare the width of the pulses (time between pulse rising above 50% of amplitude and falling below 50% of amplitude) in the simulation and experiment as a function of position. Structure observed in rough agreement, but still more work needed to understand some features of the simulation

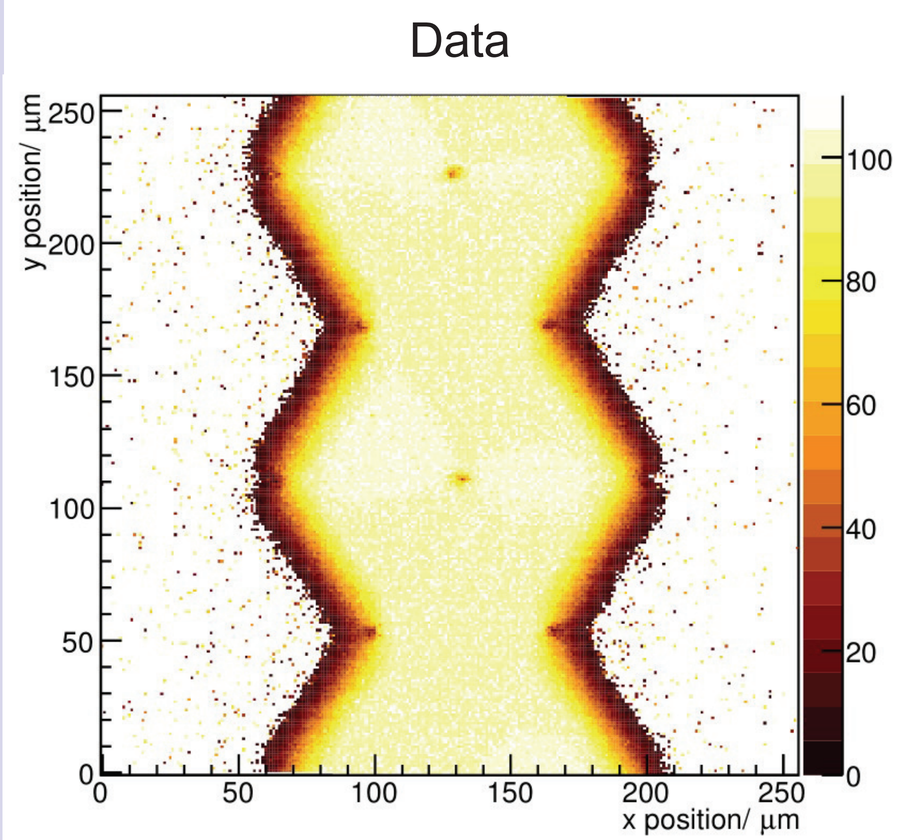




3D Diamond TRIBIC simulations

- Also compared IBIC measurements made on Hex cells, plotting integral of pulses as a function of position
- Fairly uniform throughout with some structure present. More work needed to fully understand the structure observed





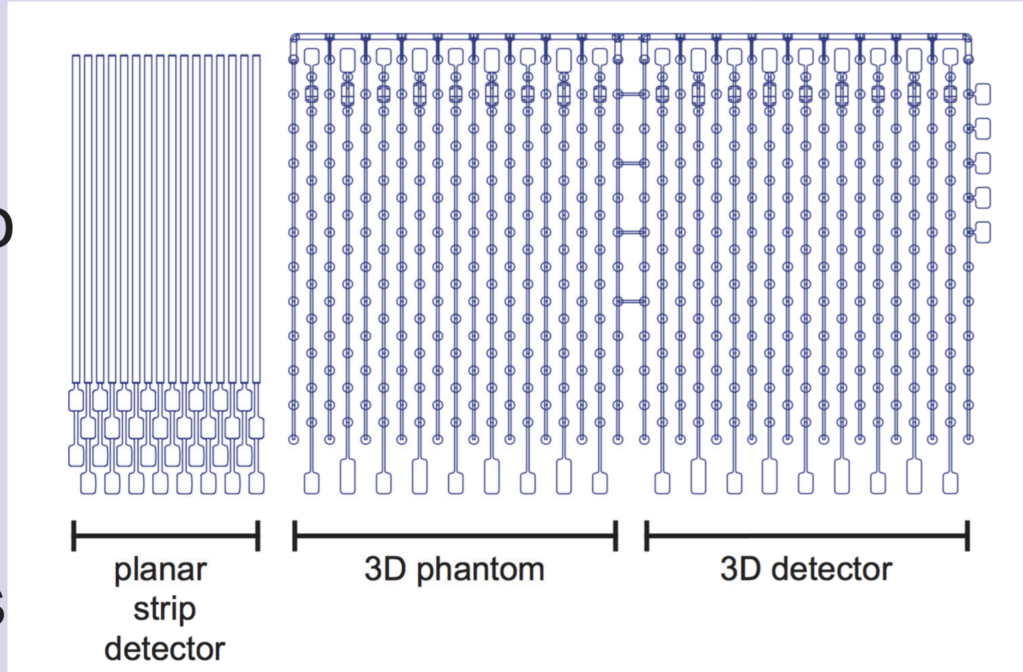
3D Diamond MIP simulations

- Better understand results of test beam with a 3D pCVD Diamond detector using 120 GeV protons*
- Observed somewhat regular diamond shaped regions around most signal columns where negative charge events are recorded in neighboring electrodes
- Wanted to understand if these observations are due to charge trapping in pCVD material.

*Details of experiments and analysis: F. Bachmair. CVD Diamond Sensors In Detectors For High Energy Physics. PhD thesis, ETH Zurich, Zurich, 2016.

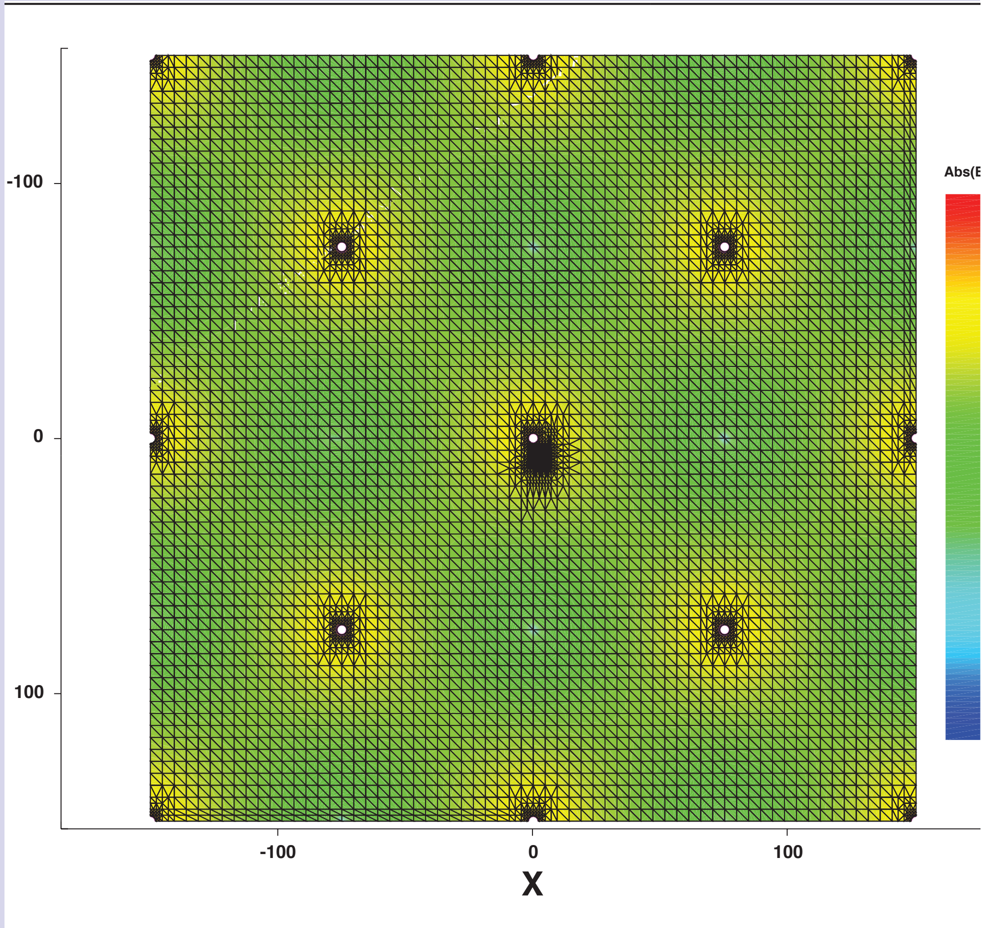
3D Diamond MIP simulations

- Experiments carried out on small area pCVD detector, adjacent to a phantom detector and strip detector in order to study the diamond and effects of metallization
- Columns connected in vertical strips and strips read out individually



3D Diamond MIP simulations

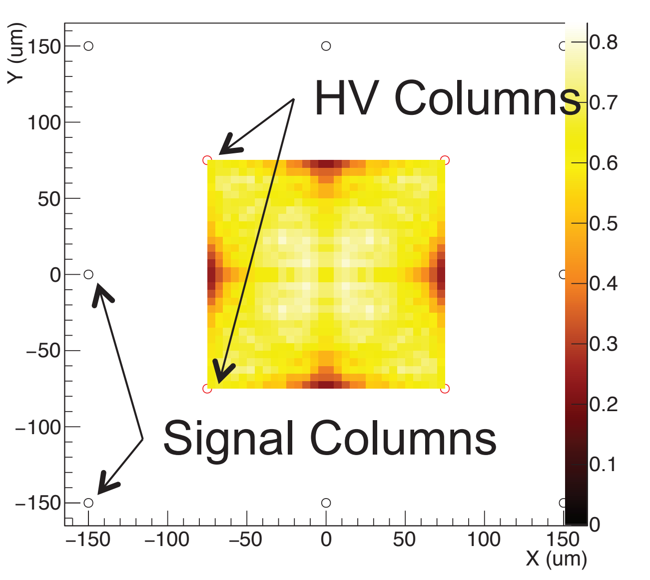
- Produced a 2D mesh containing 2x2 array of 150 µm square cells
- Signal columns were ganged together in lines along the Y-direction as in the detector used in the experiment, metallization not included
- Graphitic columns modeled as perfect contacts on surface of column, with 2 µm radius



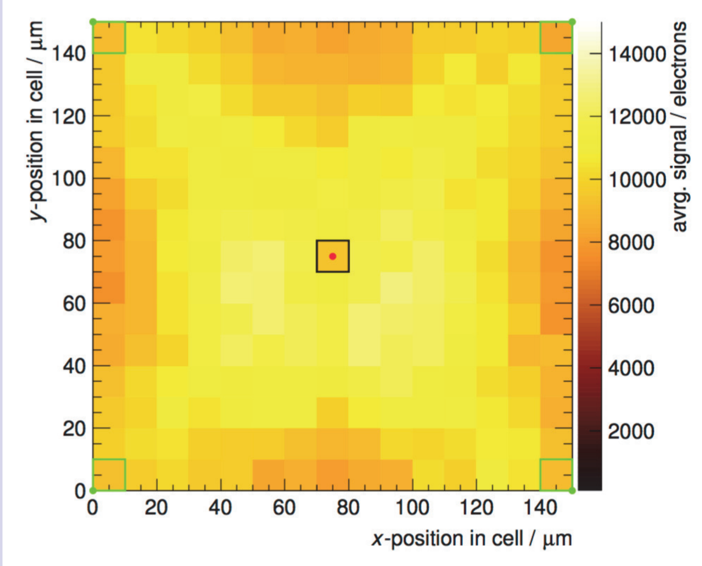
3D Diamond MIP simulations

- Simulated MIPs passing through the area of a quarter cell
- Divided the cell into 7.5x7.5 μm squares, and simulated a MIP hit at the center of each square, introduce a finite charge lifetime to simulated effect of charge trapping
- Able to plot the charge collected as function of position, good agreement between features observed in simulation and data

Simulation



Data

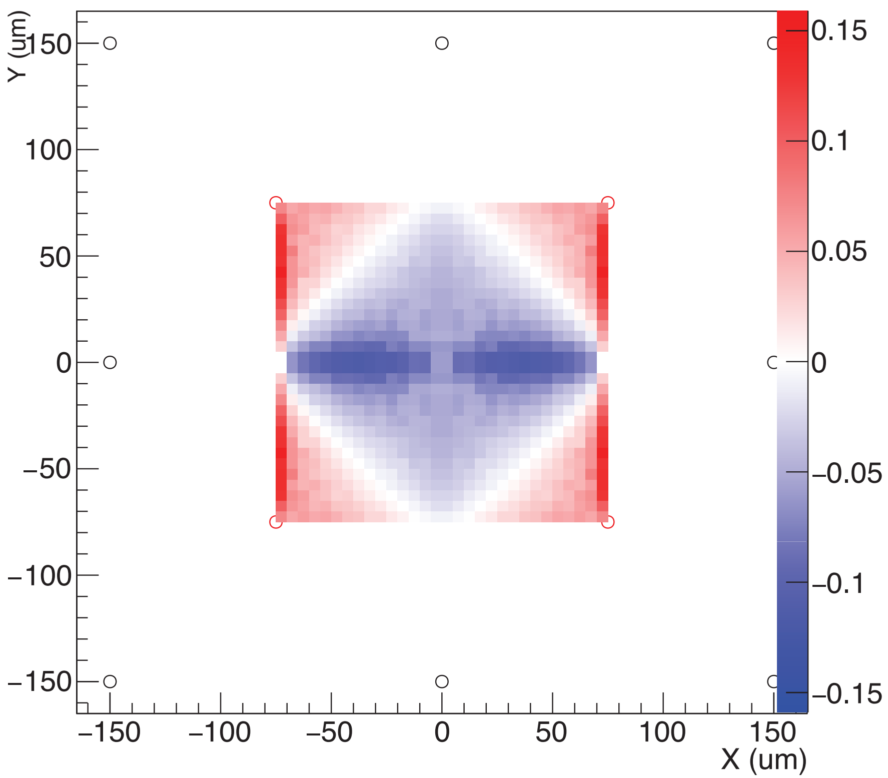


F. Bachmair. CVD Diamond Sensors In Detectors For High Energy Physics. PhD thesis, ETH Zurich, Zurich, 2016.

3D Diamond MIP simulations

- Observed good agreement between observed negative charge regions in simulation and experiment.

Simulation



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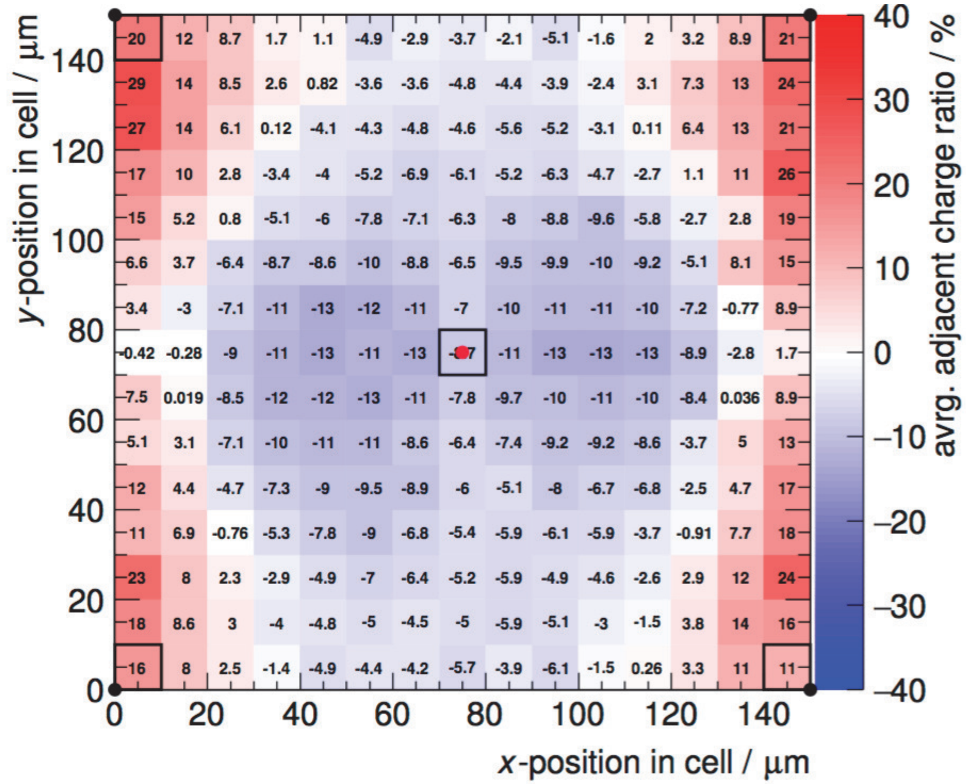


F. Bachmair. CVD Diamond Sensors In Detectors For High Energy Physics. PhD thesis, ETH Zurich, Zurich, 2016.

3D Diamond MIP simulations

- Observed good agreement between simulation and data
- Diamond shaped regions with observed negative signals in good agreement with experiment
- From this can deduce that, at least on average, pCVD material can be treated as high trap density scCVD material for simulation purposes
- Simulation results are imperfect, but provide a good qualitative understanding of the processes involved

Conclusion

- Simulations have been performed with Sentaurus TCAD to understand various measurements performed on 3D Diamond
- Pulse shape in TRIBIC simulations generally in good agreement with experiment in high field and low field regions, but work still to be done to improve the agreement
- MIP simulations have produced good agreement with experiment, simulations are imperfect but allow good qualitative understanding of observations

Future Plans

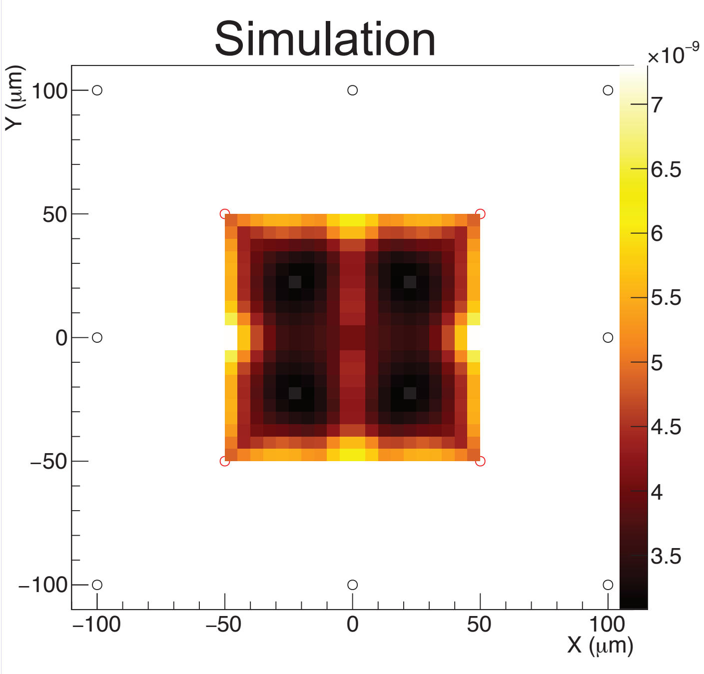
- Finish work on TRIBIC simulations in the next few weeks/ month
- pCVD and TRIBIC results will hopefully be published soon
- Continue looking at the possibility of 3D Diamond detectors for dosimetry applications
- Continue investigating the effects of different electrode geometries with new detectors and more simulations
- Make and test some 3D Pixel detectors

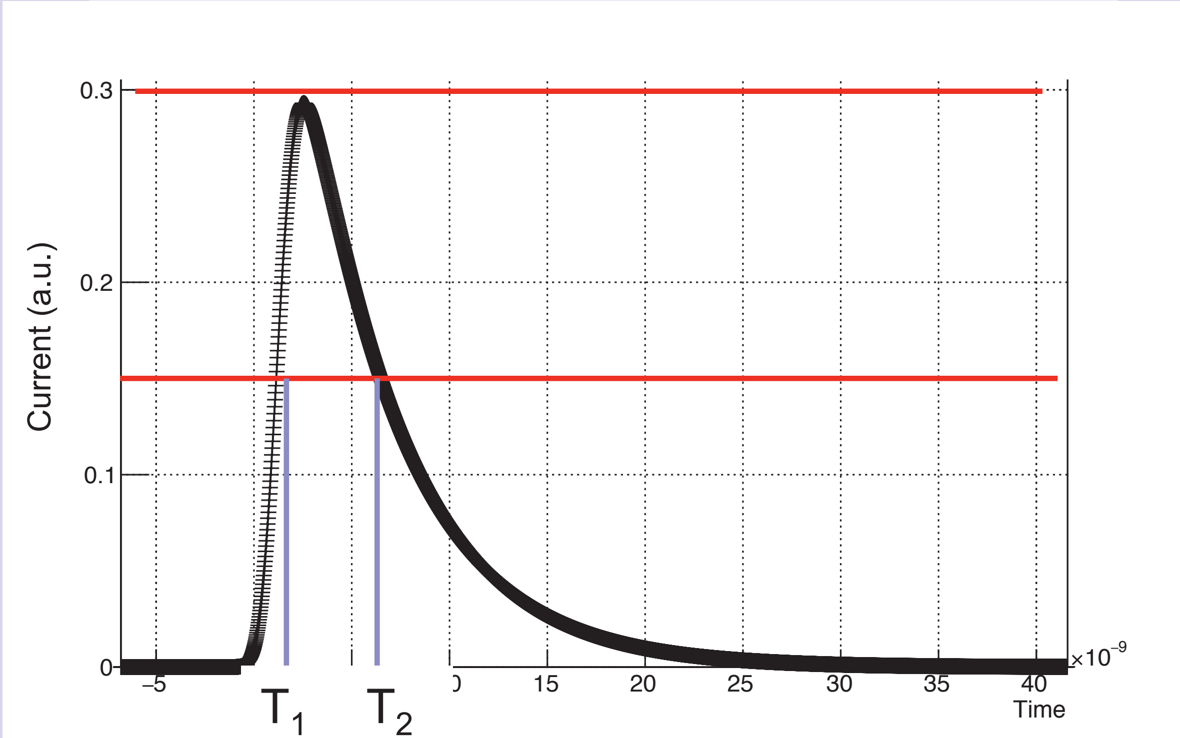
Thanks for listening

Backup Slides

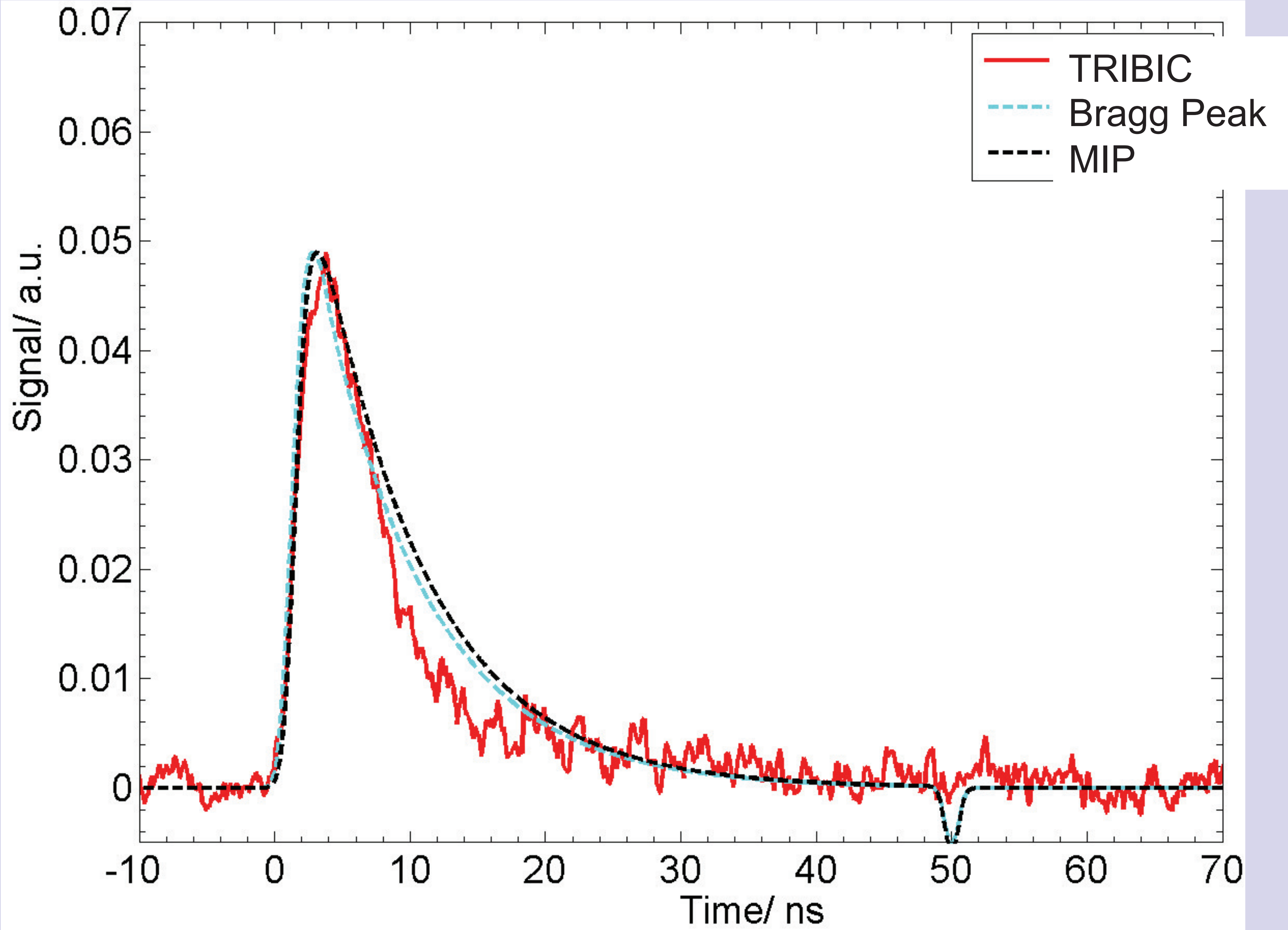
3D Diamond TRIBIC simulations

Width = $T_2 - T_1$



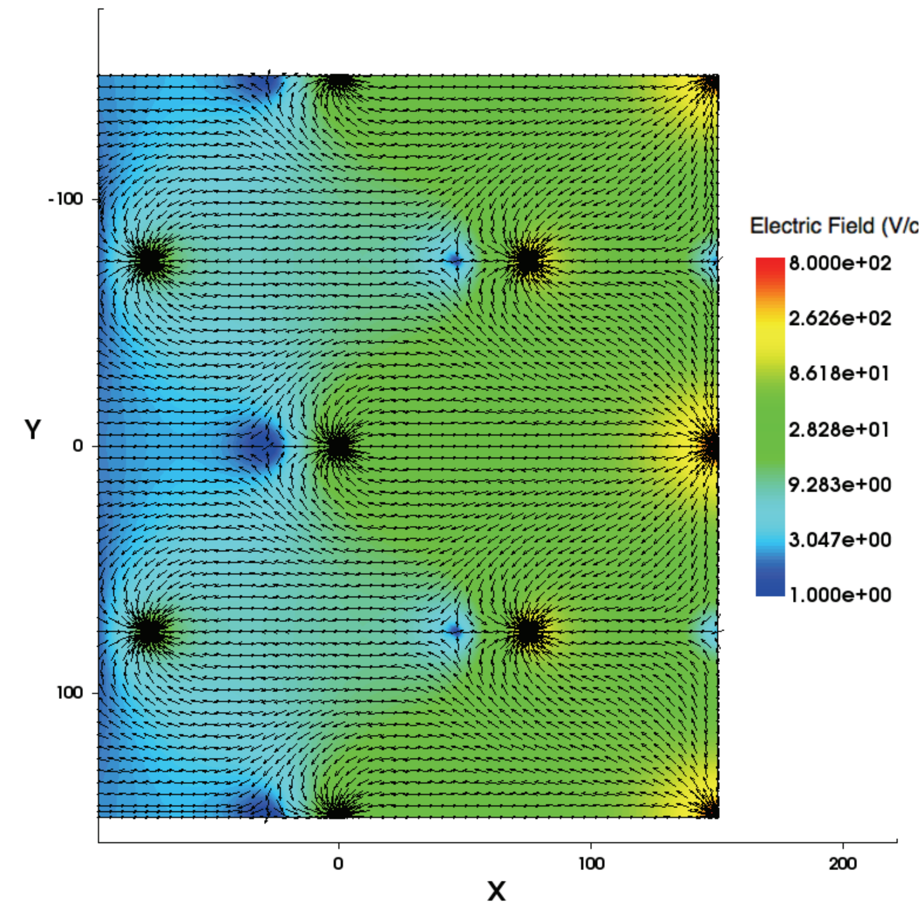


3D Diamond TRIBIC simulations



3D Diamond MIP simulations

- Shape of region with negative signal observed by adjacent electrode due to high amount of trapping due to pCVD material, in combination with weighting field in the detector



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.