3D Diamond Detector Development

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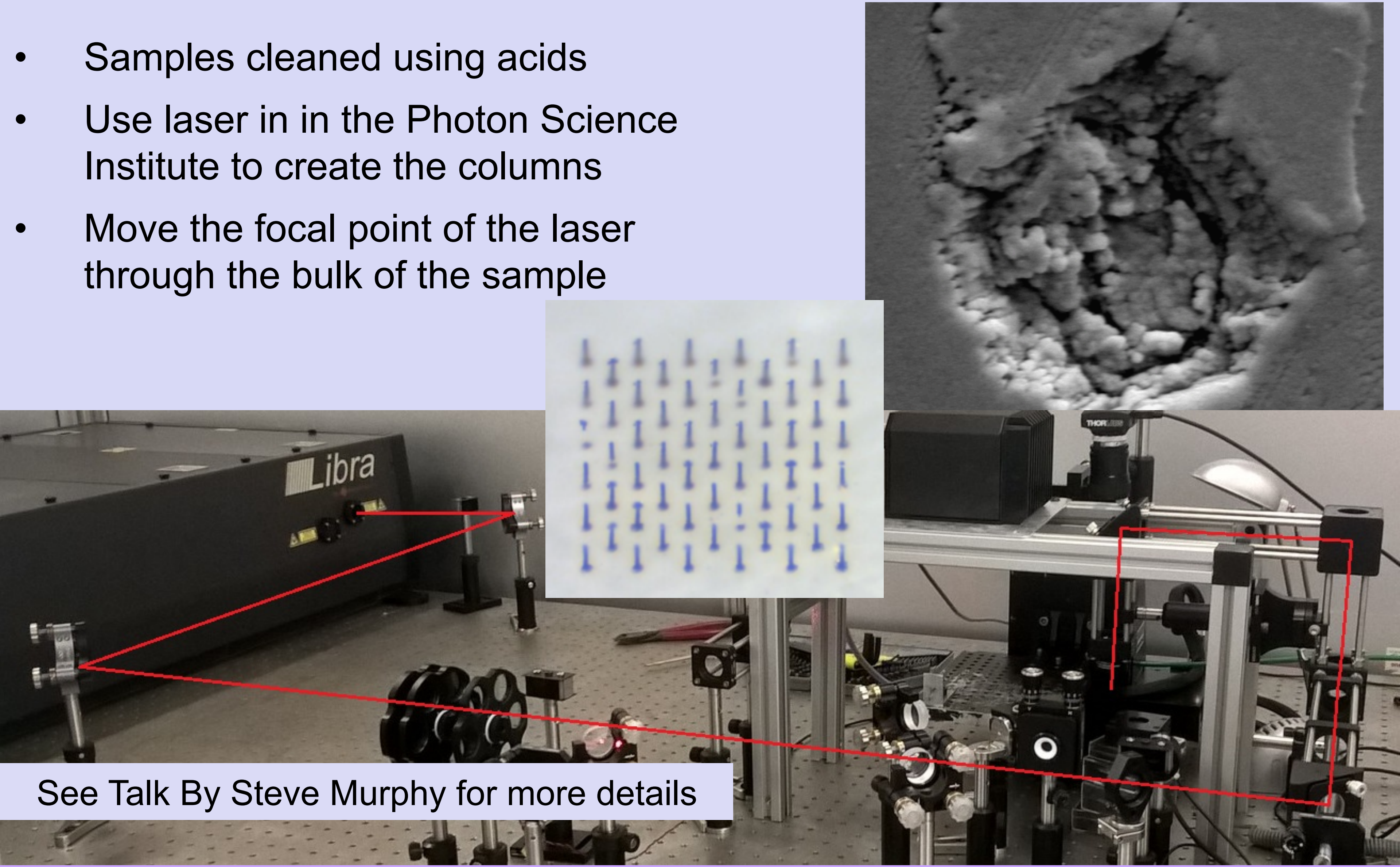
Manufacture

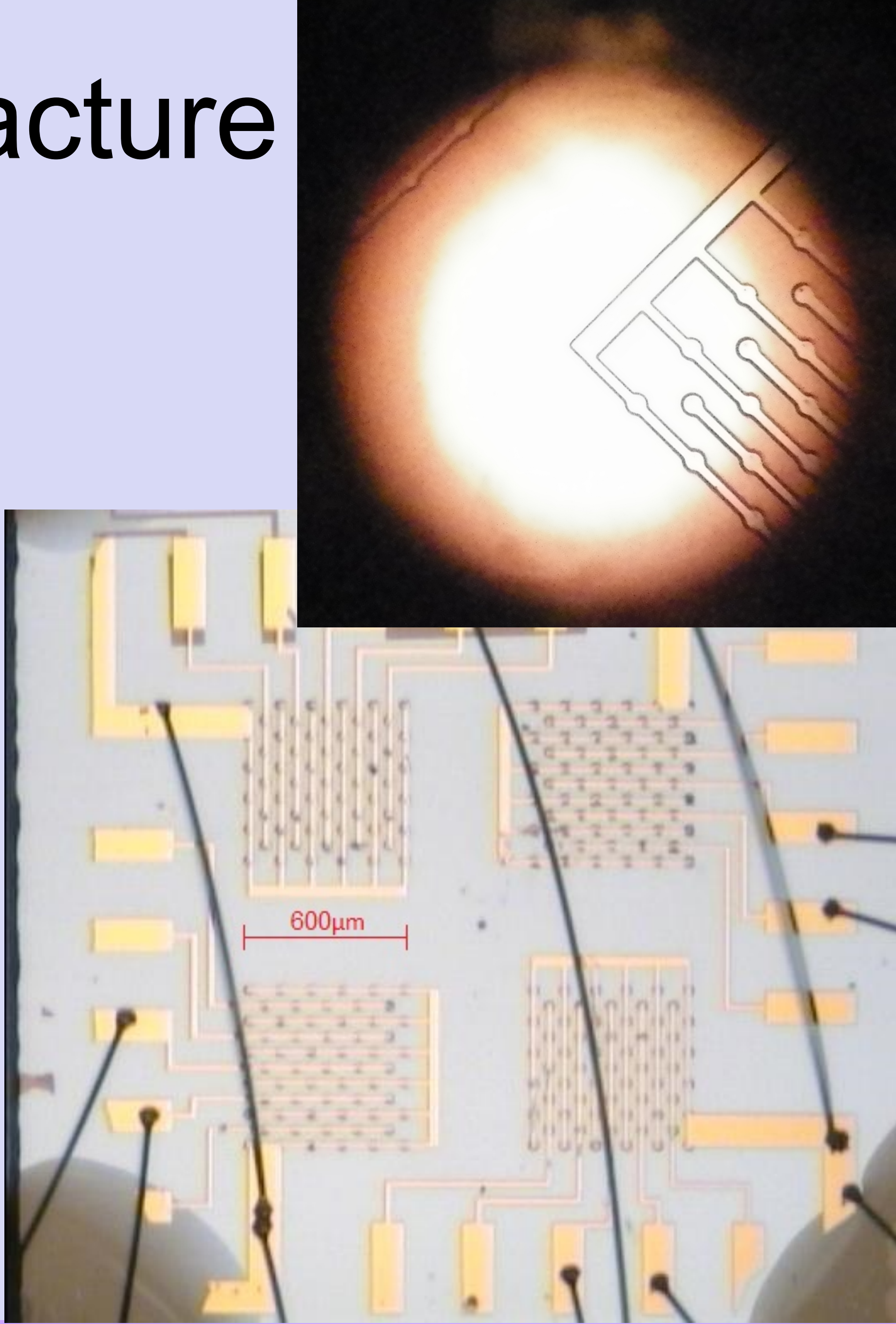
- Samples cleaned using acids
- Use laser in in the Photon Science Institute to create the columns
- Move the focal point of the laser through the bulk of the sample



See Talk By Steve Murphy for more details

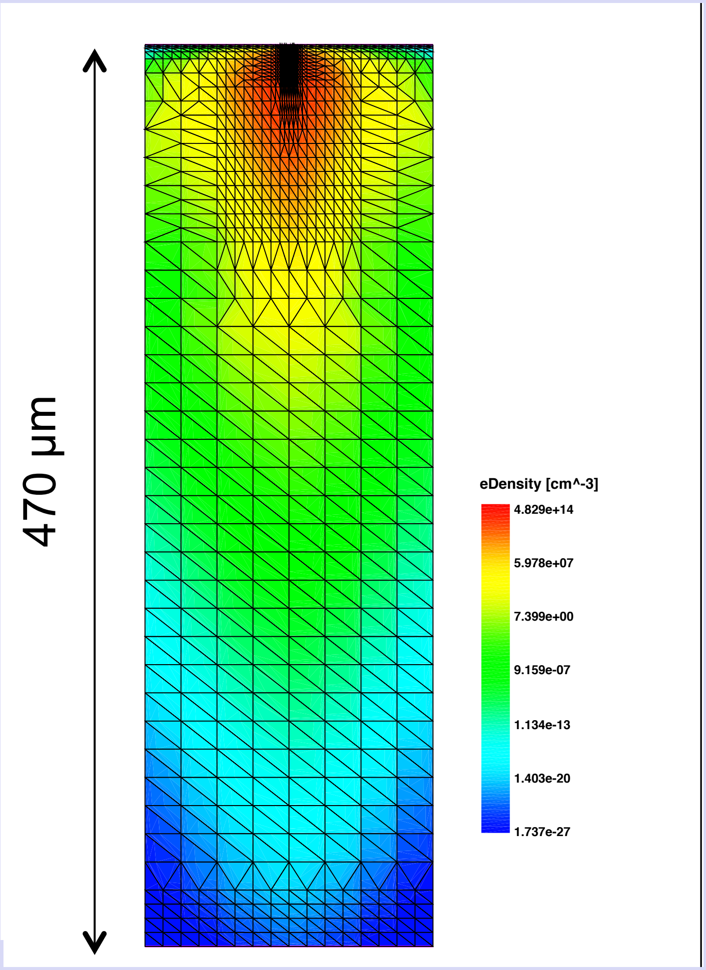
Manufacture

- Use a photolithographic process
- Apply photoresist to sample
- Expose to UV light
- Develop the pattern
- Treat the surface with a plasma
- Evaporate/sputter the desired pattern on the surface
- A number of detectors have so far been successfully produce in Manchester

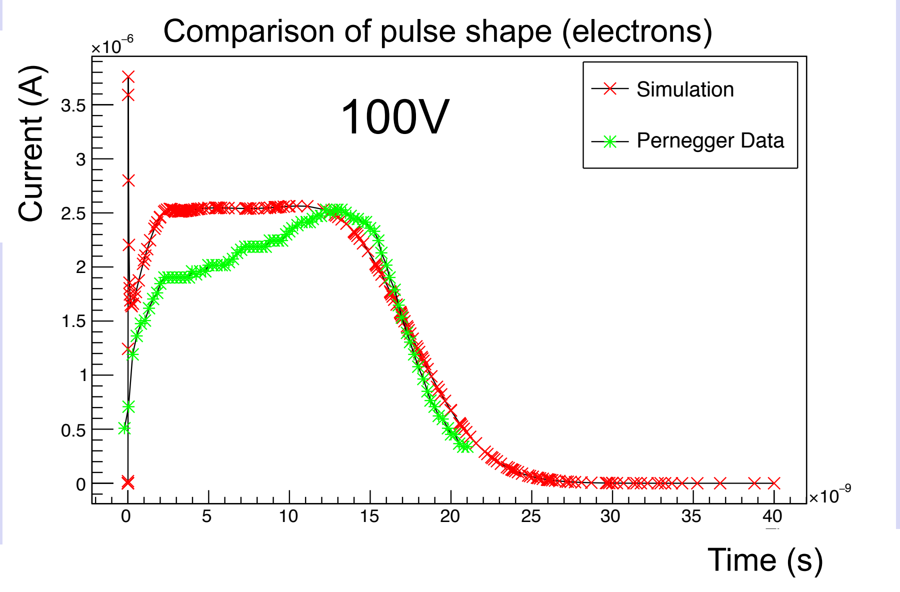


Device simulation

- Used Sentaurus TCAD package for simulations
- Create a mesh to model the device that needs to be simulated as a set of discreet points
- 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



Diamond Model



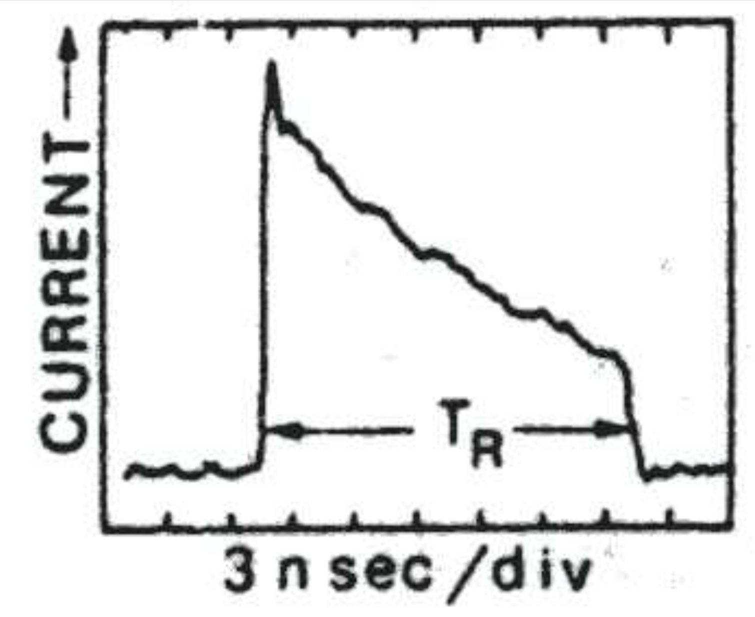
- Need to first add the parameters of diamond to the model as they are not present in TCAD
- Define new material with diamond properties
- Compare results from simulation to the data to verify the accuracy of the model
- Interested mainly in timing, good agreement between simulation and experimental data

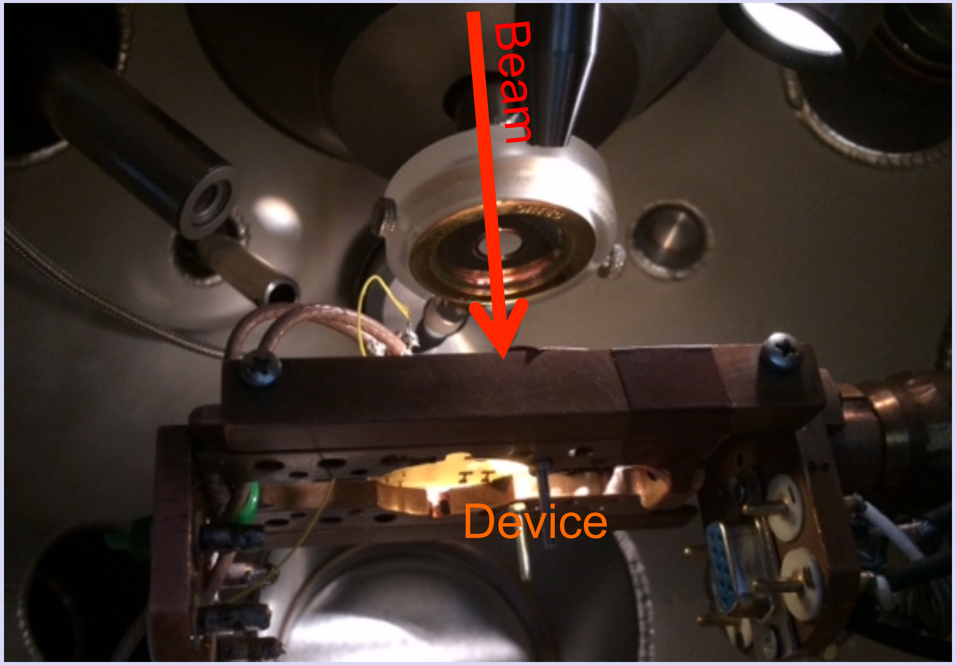
(*)Simulations compared to H. Pernegger et al. Charge-carrier properties in synthetic single-crystal diamond measured with the transient-current technique. Journal of Applied Physics, 97(7):–, 2005.

3D Diamond TRIBIC

- 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 80-100 μm inside the diamond
- Self Triggered, ~ 2 μm precision
- Simulate the shape of the current pulse generated

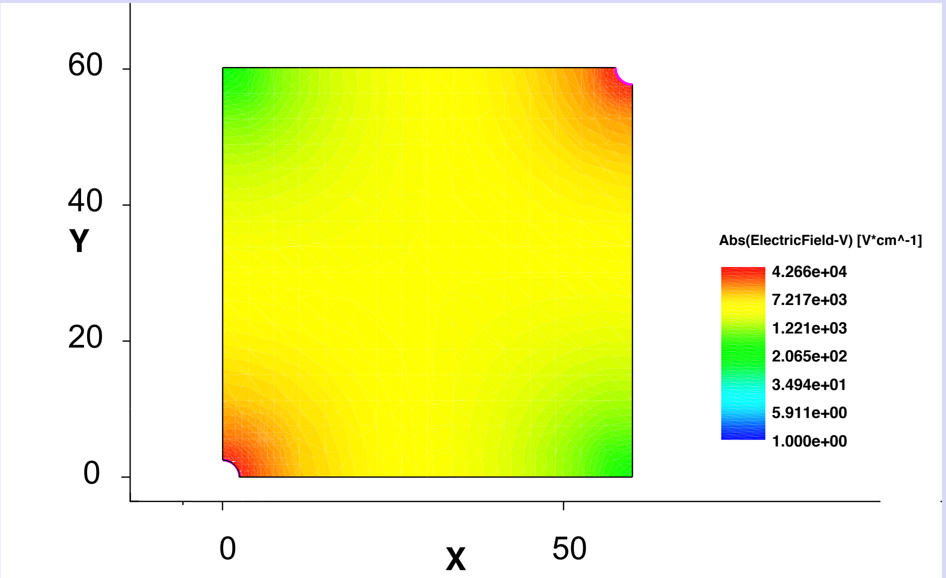
G. Forcolin, V. Grilj, B. Hamilton, L. Li, M. McGowan, S. Murphy, A. Oh, N. Skukan, D. Whitehead, A. Zadoroshnyj, Study of a 3d diamond detector with photon and proton micro-beams, Diamond and Related Materials 65 (2016) 75 – 82





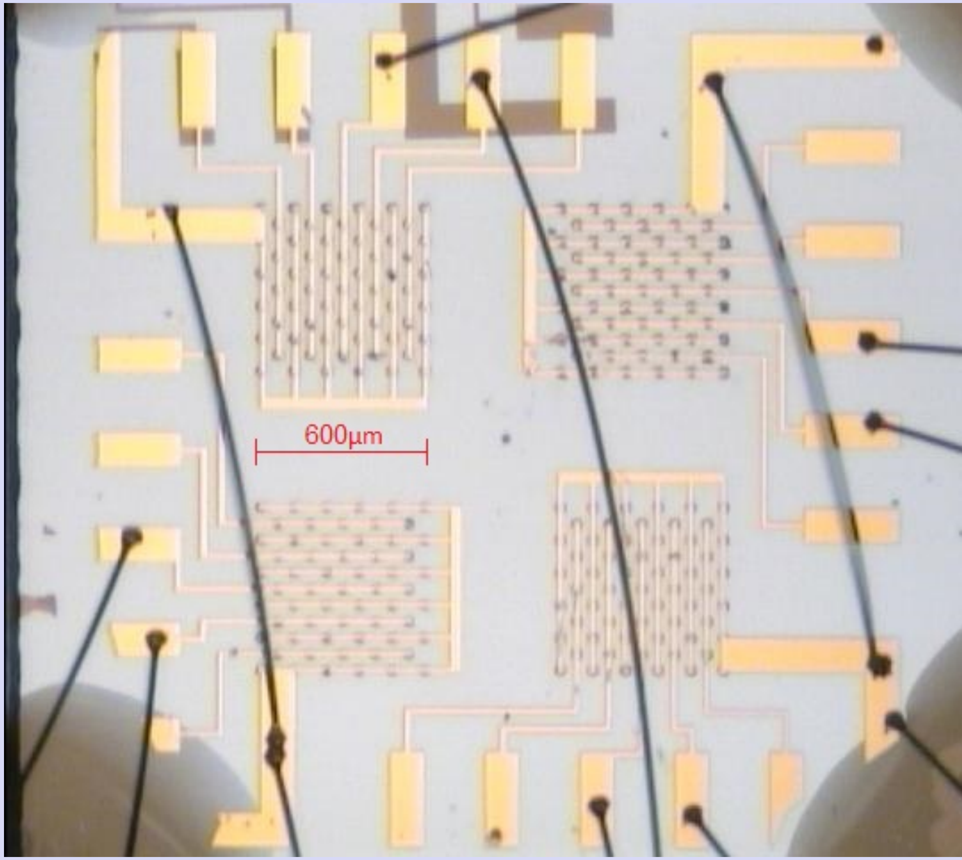
3D Diamond TRIBIC simulations

- 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



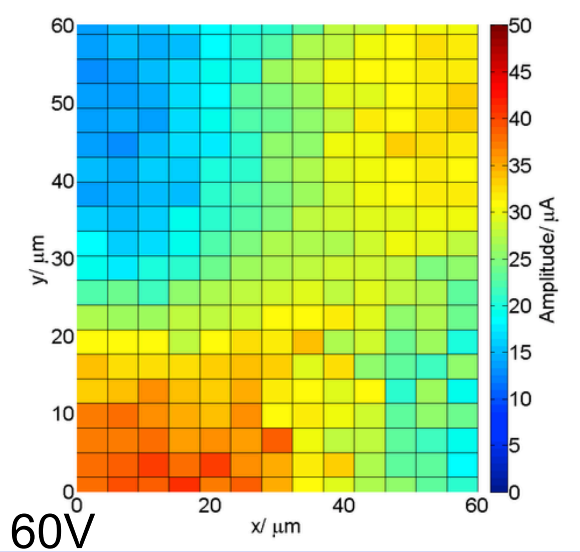
3D Diamond TRIBIC simulations

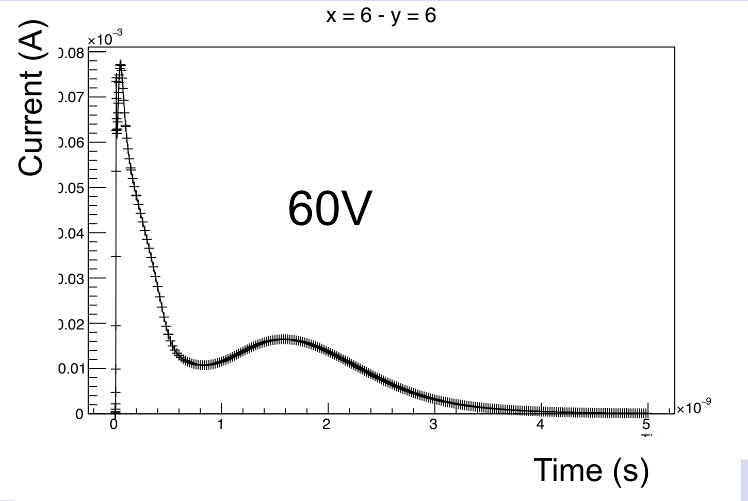
- Ran simulations at different voltages
- Simulations do not include traps
- Simulations included a surface metallization along the y direction to match the detector geometry used
- Applied bias voltage on the signal electrode, which was also read out; kept the HV electrode grounded

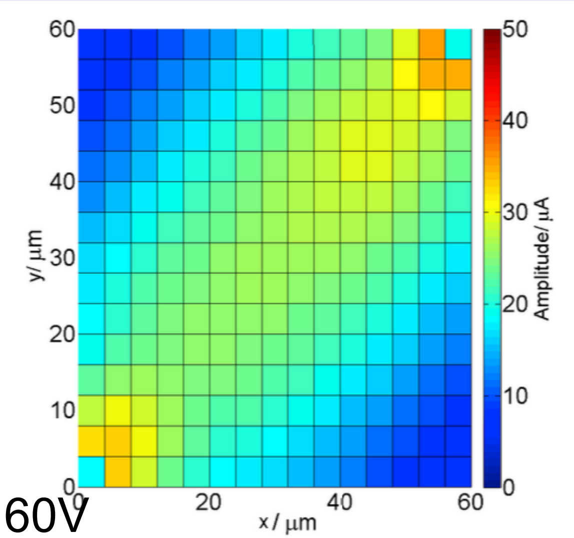


3D Diamond TRIBIC simulations

- Observed that with certain hit positions, double peak shape due to the different travelling time of electrons and holes
- Observed strong dependence of height and shape of the signal on the position of the hit due to non-uniformity of electric field within cell
- Amplitude plotted as an analogue for charge collection time

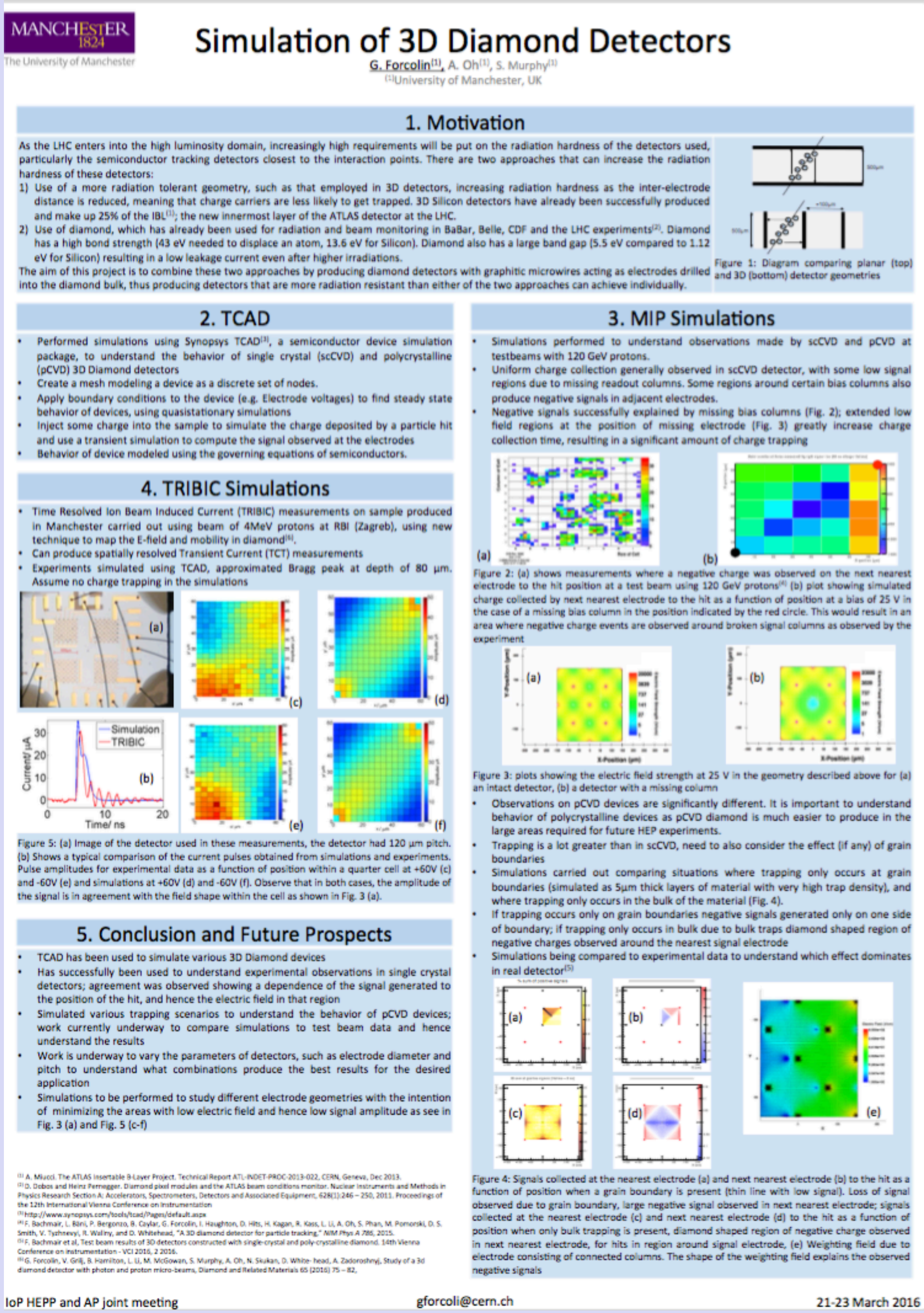






3D Diamond Simulations

- Single crystal and polycrystalline 3D Diamond detectors studied at test beams
- Use simulations to understand observed behavior
- Single crystal behavior reasonable well understood
- Polycrystalline behavior not as straightforward, but good progress is being made towards understanding it
- More details in poster presentation



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Simulation of 3D Diamond Detectors

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1. Motivation

As the LHC enters into the high luminosity domain, increasingly high requirements will be put on the radiation hardness of the detectors used, particularly the semiconductor tracking detectors closest to the interaction points. There are two approaches that can increase the radiation hardness of these detectors:

1) Use of a more radiation tolerant geometry, such as that employed in 3D detectors, increasing radiation hardness as the inter-electrode distance is reduced, meaning that charge carriers are less likely to get trapped. 3D Silicon detectors have already been successfully produced and make up 25% of the IBL[1]; the new innermost layer of the ATLAS detector at the LHC.
2) Use of diamond, which has already been used for radiation and beam monitoring in BaBar, Belle, CDF and the LHC experiments[2]. Diamond has a high bond strength (43 eV needed to displace an atom, 13.6 eV for Silicon). Diamond also has a large band gap (5.5 eV compared to 1.12 eV for Silicon) resulting in a low leakage current even after higher irradiations.

The aim of this project is to combine these two approaches by producing diamond detectors with graphitic microwires acting as electrodes drilled into the diamond bulk, thus producing detectors that are more radiation resistant than either of the two approaches can achieve individually.

Figure 1: Diagram comparing planar (top) and 3D (bottom) detector geometries

2. TCAD

- Performed simulations using Synopsys TCAD[3], a semiconductor device simulation package, to understand the behavior of single crystal (scCVD) and polycrystalline (pCVD) 3D Diamond detectors
- Create a mesh modeling a device as a discrete set of nodes.
- Apply boundary conditions to the device (e.g. Electrode voltages) to find steady state behavior of devices, using quasistationary simulations
- Inject some charge into the sample to simulate the charge deposited by a particle hit and use a transient simulation to compute the signal observed at the electrodes
- Behavior of device modeled using the governing equations of semiconductors.

4. TRIBIC Simulations

- Time Resolved Ion Beam Induced Current (TRIBIC) measurements on sample produced in Manchester carried out using beam of 4MeV protons at RBI (Zagreb), using new technique to map the E-field and mobility in diamond[6].
- Can produce spatially resolved Transient Current (TCT) measurements
- Experiments simulated using TCAD, approximated Bragg peak at depth of 80 µm. Assume no charge trapping in the simulations

Figure 5: (a) Image of the detector used in these measurements, the detector had 120 µm pitch. (b) Shows a typical comparison of the current pulses obtained from simulations and experiments. Pulse amplitudes for experimental data as a function of position within a quarter cell at +60V (c) and -60V (e) and simulations at +60V (d) and -60V (f). Observe that in both cases, the amplitude of the signal is in agreement with the field shape within the cell as shown in Fig. 3 (a).

5. Conclusion and Future Prospects

- TCAD has been used to simulate various 3D Diamond devices
- Has successfully been used to understand experimental observations in single crystal detectors; agreement was observed showing a dependence of the signal generated to the position of the hit, and hence the electric field in that region
- Simulated various trapping scenarios to understand the behavior of pCVD devices; work currently underway to compare simulations to test beam data and hence understand the results
- Work is underway to vary the parameters of detectors, such as electrode diameter and pitch to understand what combinations produce the best results for the desired application
- Simulations to be performed to study different electrode geometries with the intention of minimizing the areas with low electric field and hence low signal amplitude as see in Fig. 3 (a) and Fig. 5 (c-f)

3. MIP Simulations

- Simulations performed to understand observations made by scCVD and pCVD at testbeams with 120 GeV protons.
- Uniform charge collection generally observed in scCVD detector, with some low signal regions due to missing readout columns. Some regions around certain bias columns also produce negative signals in adjacent electrodes.
- Negative signals successfully explained by missing bias columns (Fig. 2); extended low field regions at the position of missing electrode (Fig. 3) greatly increase charge collection time, resulting in a significant amount of charge trapping

Figure 2: (a) shows measurements where a negative charge was observed on the next nearest electrode to the hit position at a test beam using 120 GeV protons[4] (b) plot showing simulated charge collected by next nearest electrode to the hit as a function of position at a bias of 25 V in the case of a missing bias column in the position indicated by the red circle. This would result in an area where negative charge events are observed around broken signal columns as observed by the experiment

Figure 3: plots showing the electric field strength at 25 V in the geometry described above for (a) an intact detector, (b) a detector with a missing column

- Observations on pCVD devices are significantly different. It is important to understand behavior of polycrystalline devices as pCVD diamond is much easier to produce in the large areas required for future HEP experiments.
- Trapping is a lot greater than in scCVD, need to also consider the effect (if any) of grain boundaries
- Simulations carried out comparing situations where trapping only occurs at grain boundaries (simulated as 5µm thick layers of material with very high trap density), and where trapping only occurs in the bulk of the material (Fig. 4).
- If trapping occurs only on grain boundaries negative signals generated only on one side of boundary; if trapping only occurs in bulk due to bulk traps diamond shaped region of negative charges observed around the nearest signal electrode
- Simulations being compared to experimental data to understand which effect dominates in real detector[5]

Figure 4: Signals collected at the nearest electrode (a) and next nearest electrode (b) to the hit as a function of position when a grain boundary is present (thin line with low signal). Loss of signal observed due to grain boundary, large negative signal observed in next nearest electrode; signals collected at the nearest electrode (c) and next nearest electrode (d) to the hit as a function of position when only bulk trapping is present, diamond shaped region of negative charge observed in next nearest electrode, for hits in region around signal electrode, (e) Weighting field due to electrode consisting of connected columns. The shape of the weighting field explains the observed negative signals

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[1] A. Miucci. The ATLAS Insertable B-Layer Project. Technical Report ATL-INDET-PROC-2013-022, CERN, Geneva, Dec 2013.
[2] D. Dobos and Heinz Pernegger. Diamond pixel modules and the ATLAS beam conditions monitor. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 628(1):246 – 250, 2011. Proceedings of the 12th International Vienna Conference on Instrumentation
[3] http://www.synopsys.com/tools/tcad/Pages/default.aspx
[4] F. Bachmair, L. Bäni, P. Bergonzo, B. Caylar, G. Forcolin, I. Haughton, D. Hits, H. Kagan, R. Kass, L. Li, A. Oh, S. Phan, M. Pomorski, D. S. Smith, V. Tyzhnevyi, R. Wallny, and D. Whitehead, "A 3D diamond detector for particle tracking," *NIM Phys A 786*, 2015.
[5] F. Bachmair et al, Test beam results of 3D detectors constructed with single-crystal and poly-crystalline diamond. 14th Vienna Conference on Instrumentation - VCI 2016, 2 2016.
[6] G. Forcolin, V. Grilj, B. Hamilton, L. Li, M. McGowan, S. Murphy, A. Oh, N. Skukan, D. White- head, A. Zadoroshnyj, Study of a 3d diamond detector with photon and proton micro-beams, Diamond and Related Materials 65 (2016) 75 – 82,

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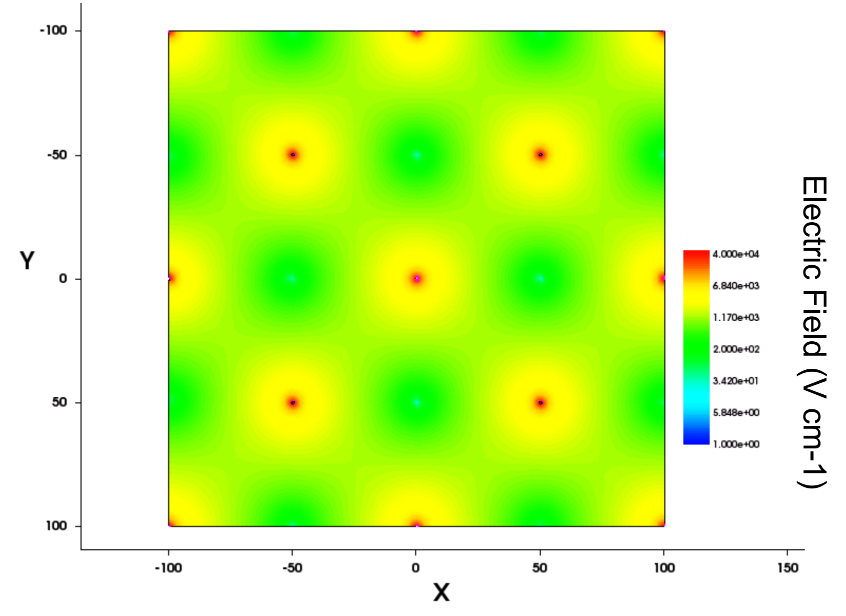
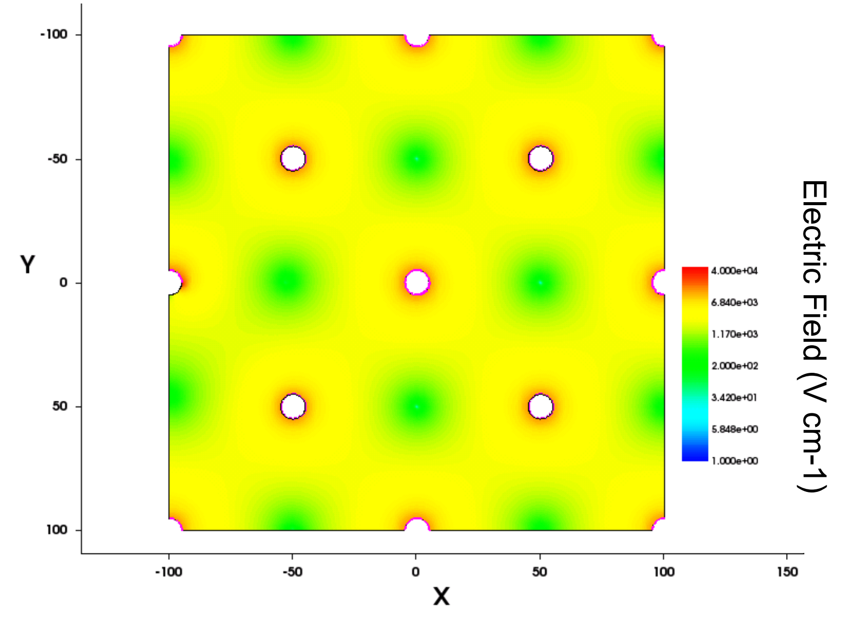
3D Diamond Simulations

- Simulations can also be used to understand effects of different fabrication parameters on the performance of the detectors, and hence can be used to optimize the design
- Various parameters are being studied, such as the size of the electrodes
- Want to reach good compromise between having a high active area, and keeping the field high enough throughout the detector

25V, 0.5μm column radius, 100μm pitch

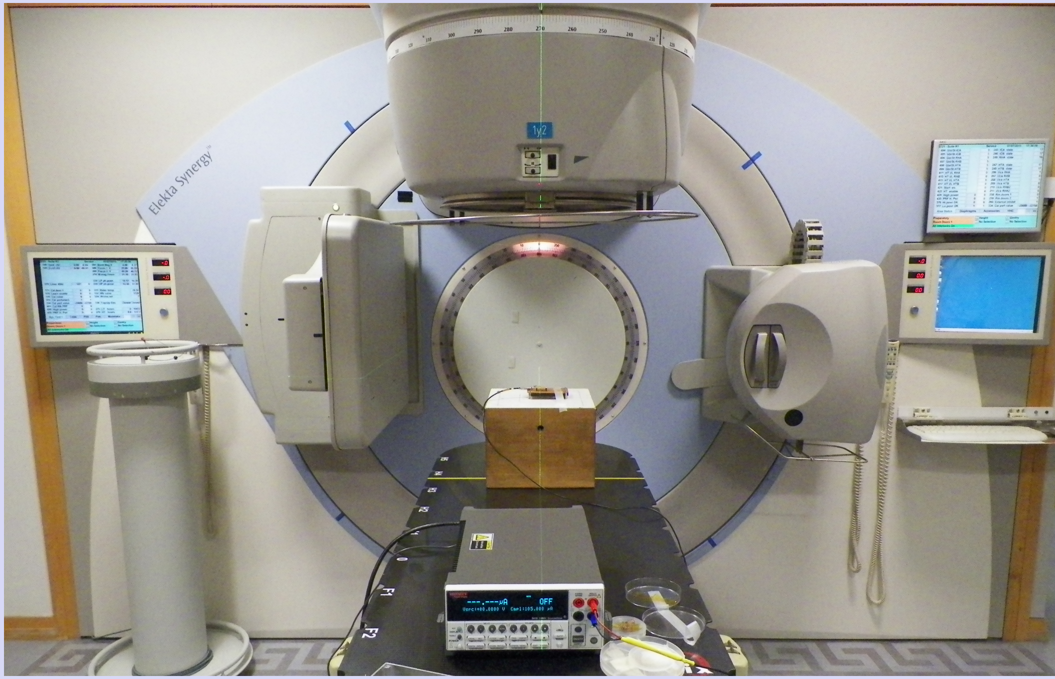


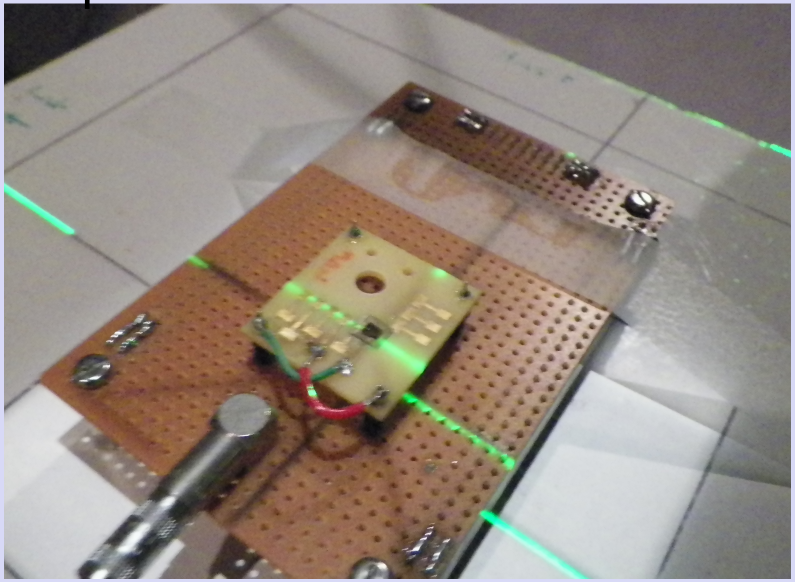
25V, 5μm Column radius 100μm pitch



Diamonds at the Christie's

- 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

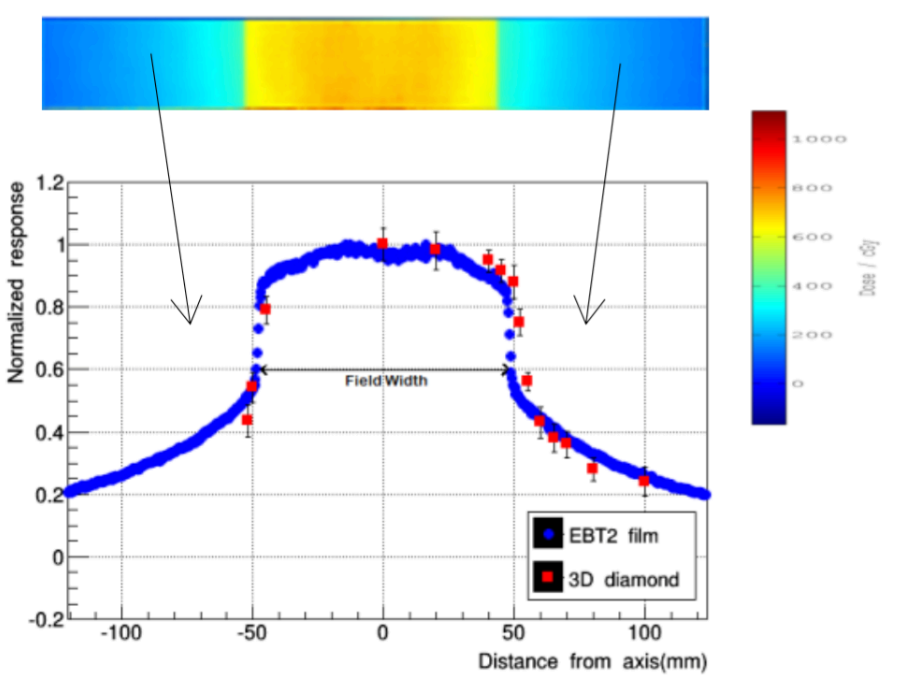


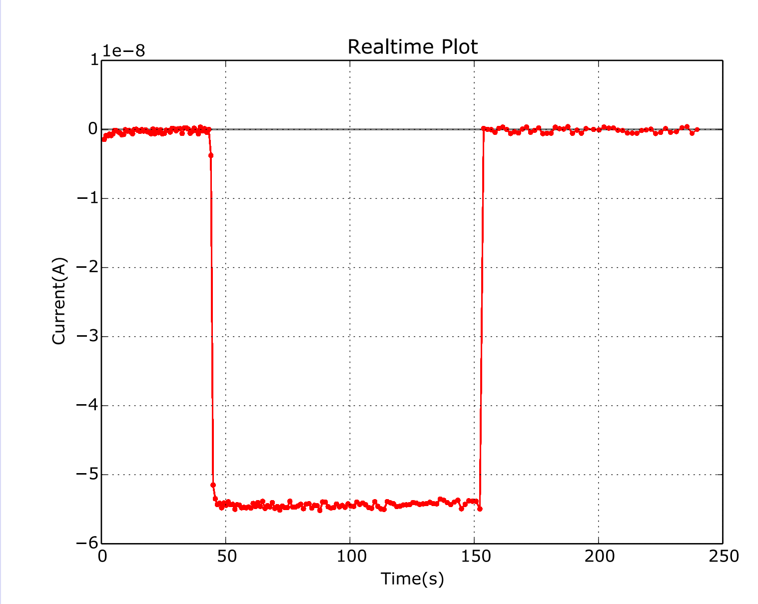


- Diamond is radiation hard, non toxic, and tissue equivalent.
- 3D geometry allows operation at low voltage

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





K. Kanxheri, L. Servoli, A. Oh, F. Munoz Sanchez, G. T. Forcolin, S. A. Murphy, C. J. Moore, A. Aitkenhead, D. Passeri, A. Morozzi, S. Sciortino, S. Lagomarsino, M. Bellini, C. Corsi, Investigation of 3D diamond devices for medical radiation dosimetry, SBDD XXI, Hasselt Diamond Workshop 2016

Future Plans

- Need to test radiation hardness of 3D Diamond, and study the effect of irradiation on the columns
- Sample irradiated at CERN-PS, properties of columns have been measured before irradiation, will be re-measured once sample has cooled down
- More measurements will be carried out at the Christie’s using detectors with a purposely designed geometry
- Analysis to be complete on pCVD diamond test beam data, and comparison to simulations will be published in the coming months

Thank You for listening!

Backup Slides

Diamond Model

- Need to first add the parameters of diamond to the model as they are not present in TCAD
- Define new material with diamond properties
- Include a high field saturation mobility model based on the TCT results reported by Pernegger et al(*)
- Compare results from simulation to the data to verify the accuracy of the model

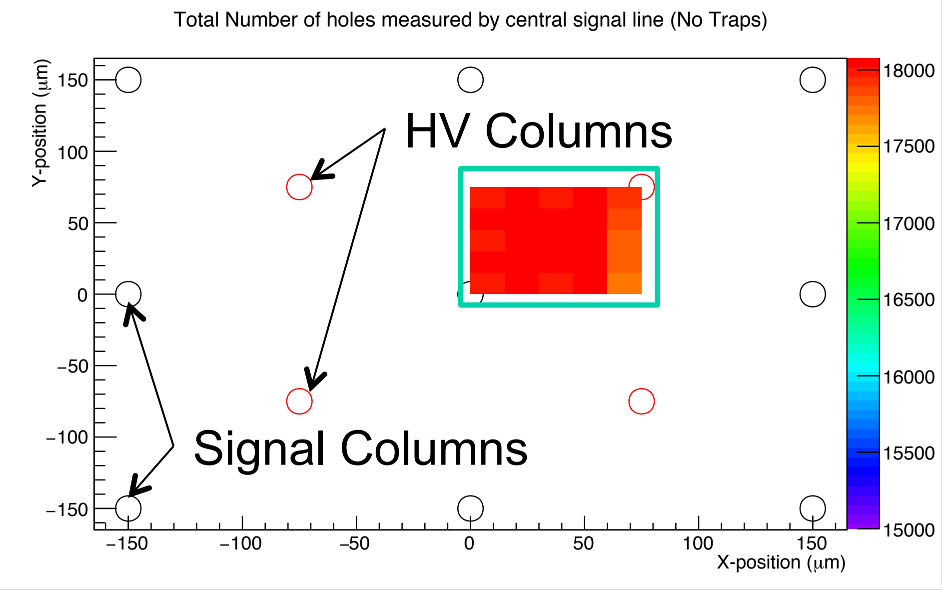
(*)H. Pernegger et al. Charge-carrier properties in synthetic single-crystal diamond measured with the transient-current technique. Journal of Applied Physics, 97(7):–, 2005.

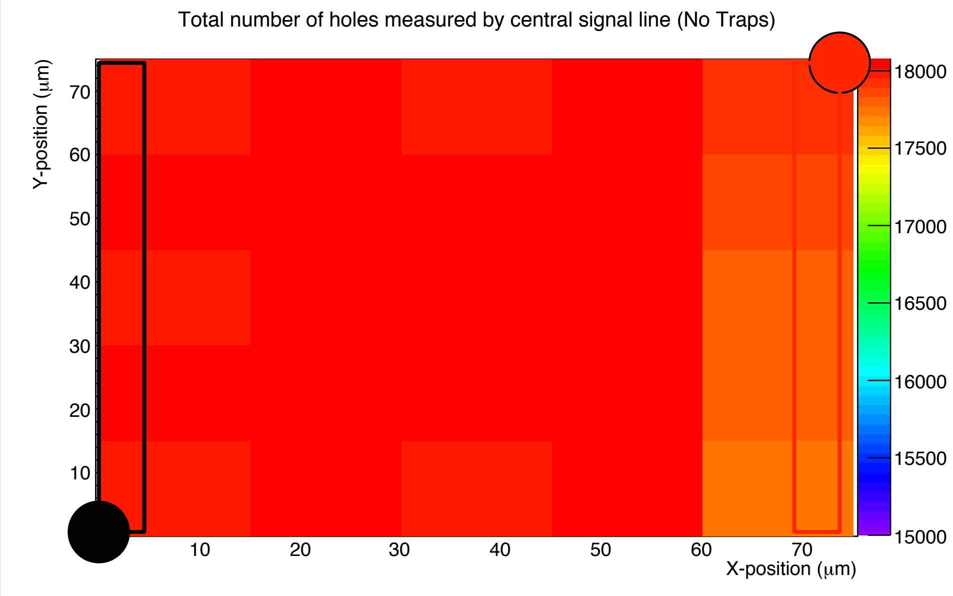
3D Diamond MIP simulations

- Better understand results of test beam with a 3D Diamond detector using 120 GeV protons (MIPS)
- 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

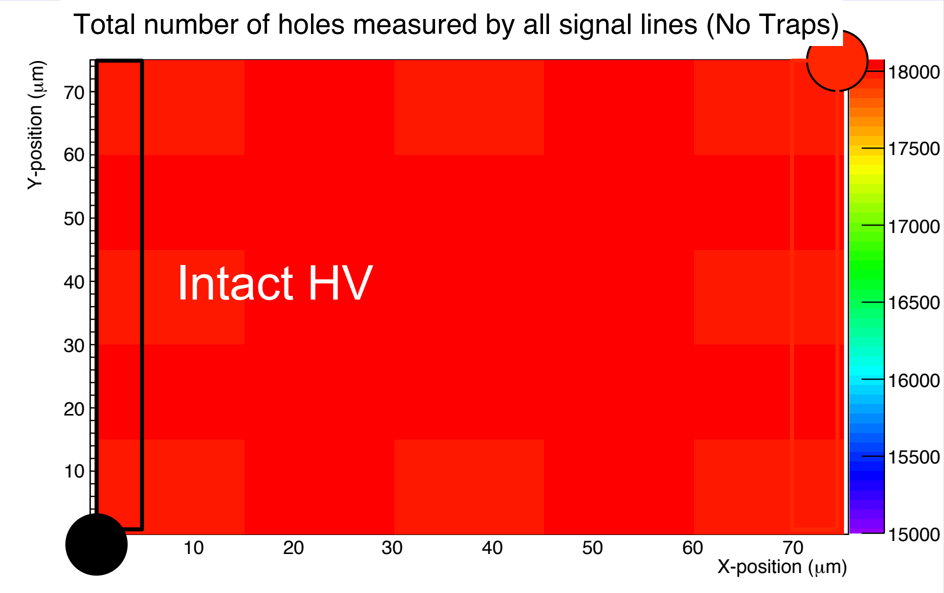
3D Diamond MIP simulations

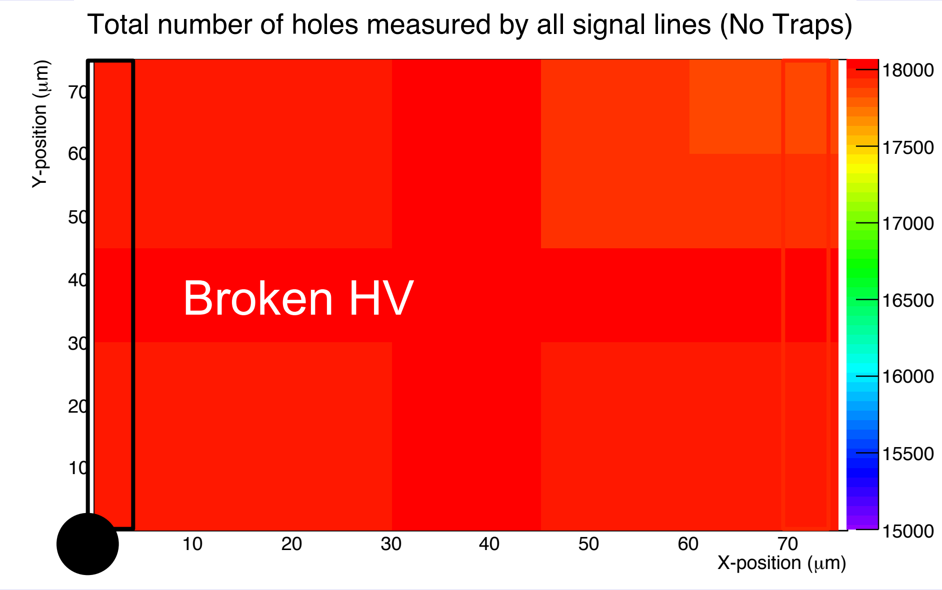
- Simulated MIPs passing through the area of a quarter cell
- Divided the quarter cell into 15x15 µm squares, and simulated a MIP hit at the center of each square
- Able to plot the charge collected as function of position





3D Diamond MIP simulations


Total number of holes measured by all signal lines (No Traps)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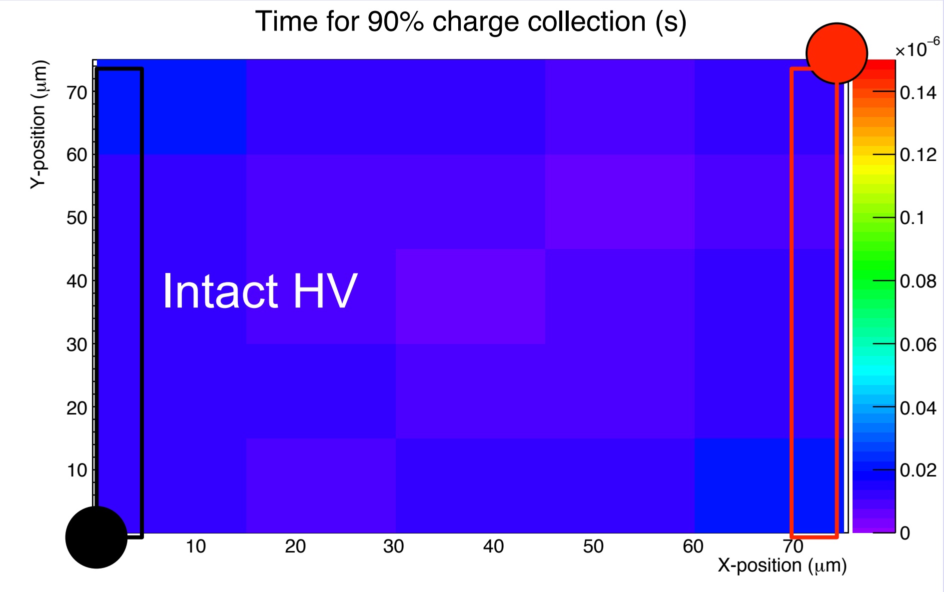
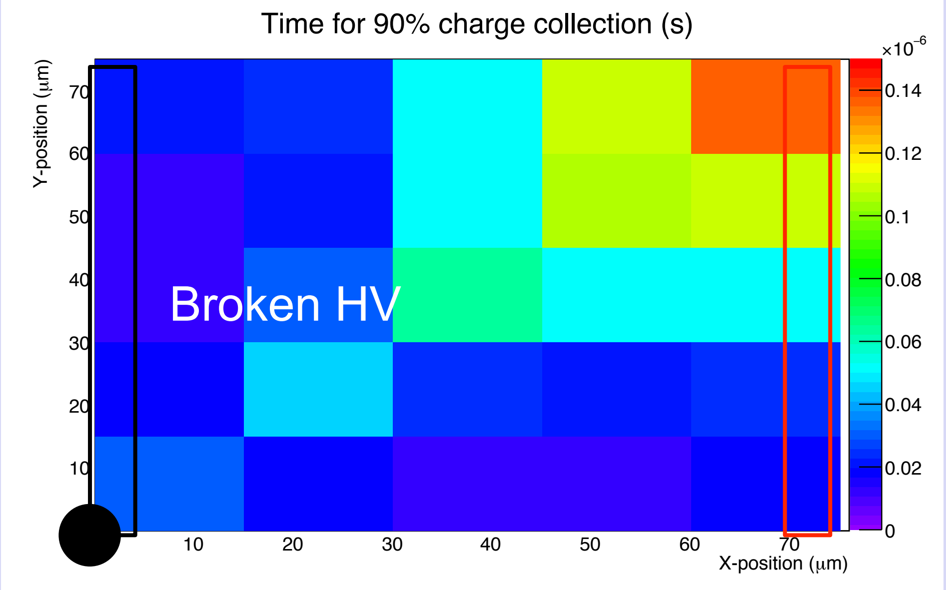
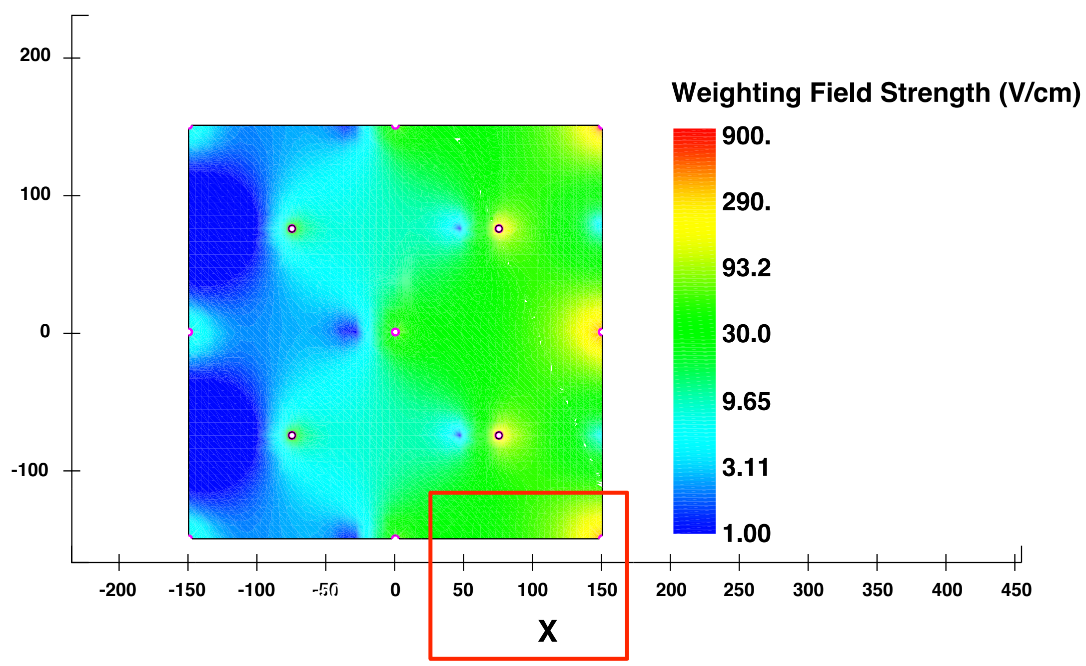
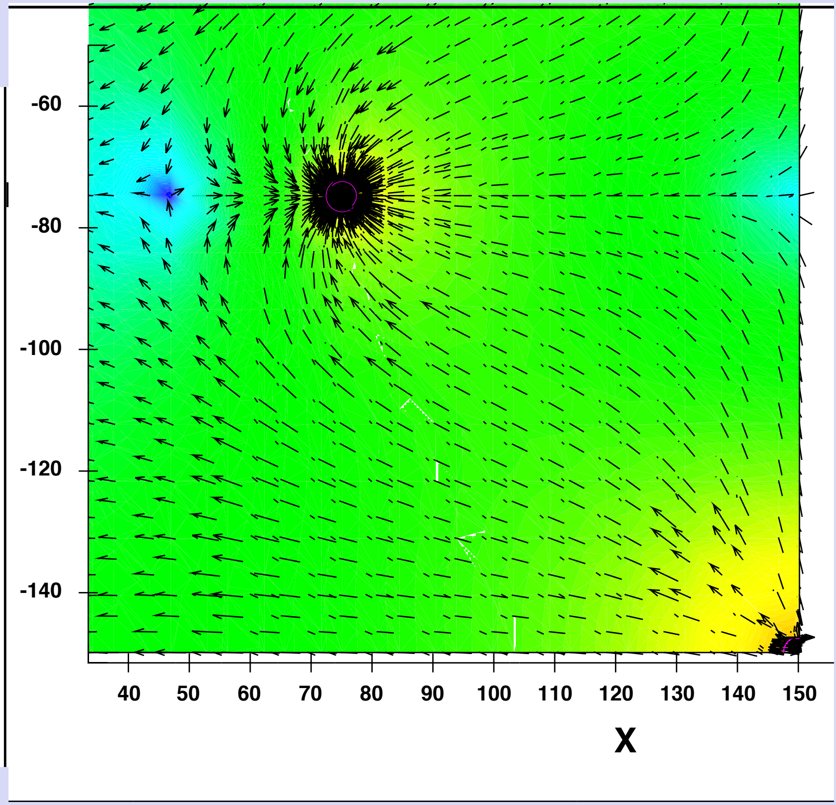

Time for 90% charge collection (s)


Time for 90% charge collection (s)

Weighting Field

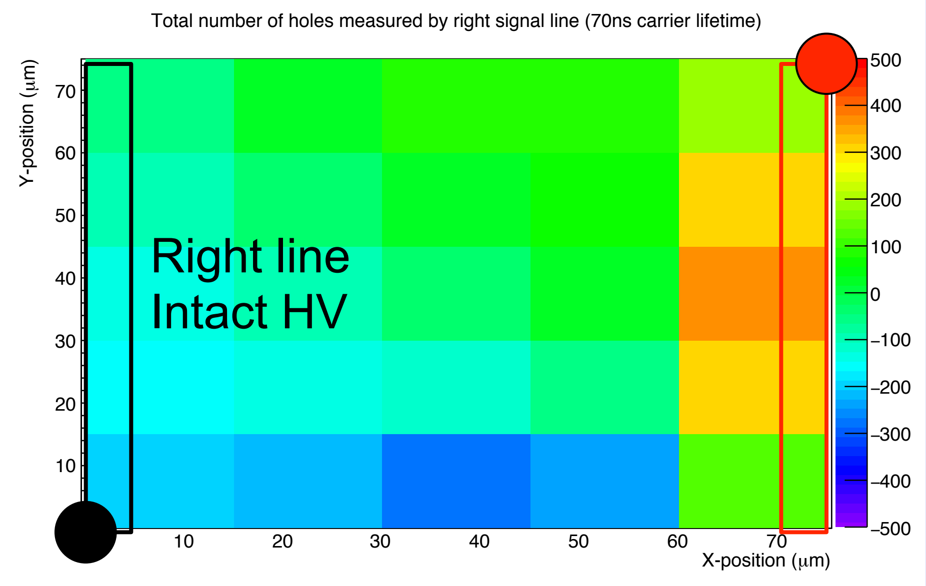
- Observed the generation of a bipolar signal in strips adjacent to the one with the hit due to the shape of the weighting field around the graphitic columns
- These signals integrate to zero due to charge conservation when no traps are present

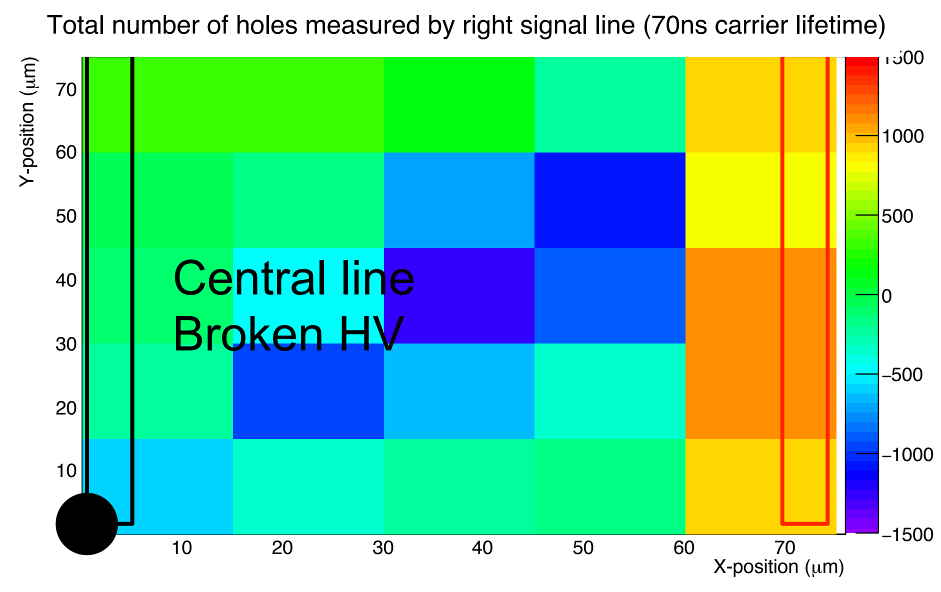




3D Diamond MIP simulations

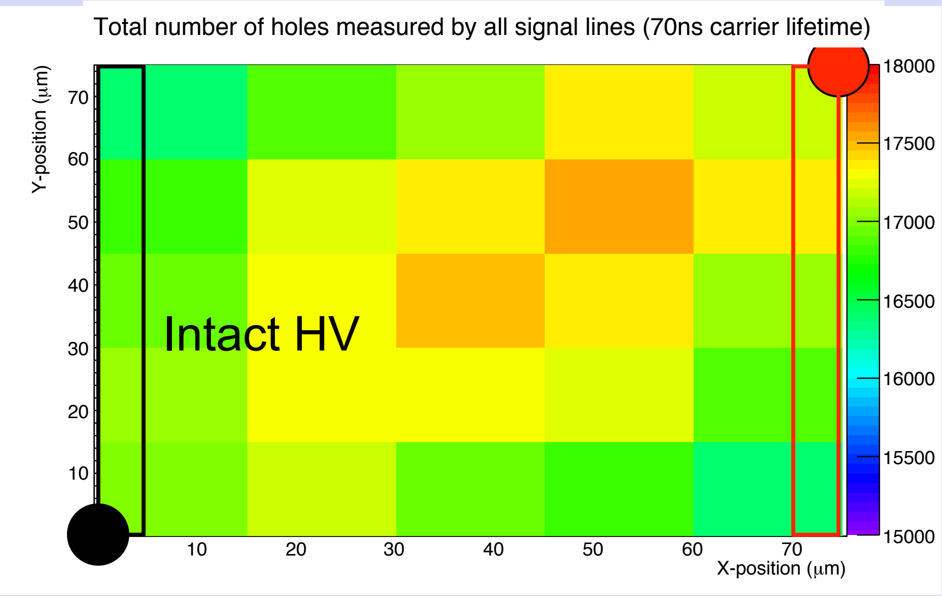
- Introduce a simple charge trapping model to mimic a 70 ns charge lifetime, now some charge is trapped before reaching electrodes resulting in a residual signal in the neighboring cells
- Negative signals observed in regions of intact cells, but below noise level
- In broken cell significantly more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

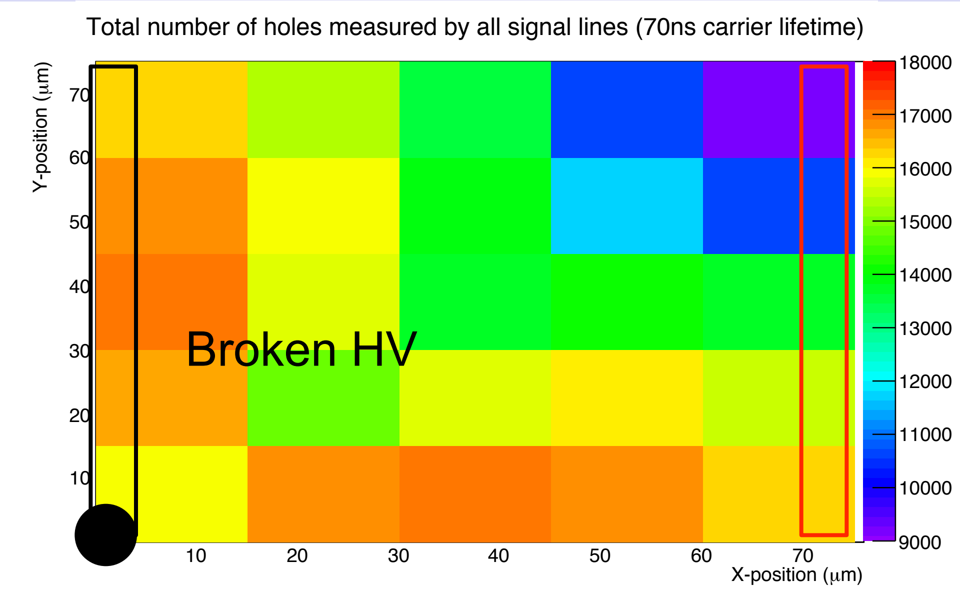




3D Diamond MIP simulations

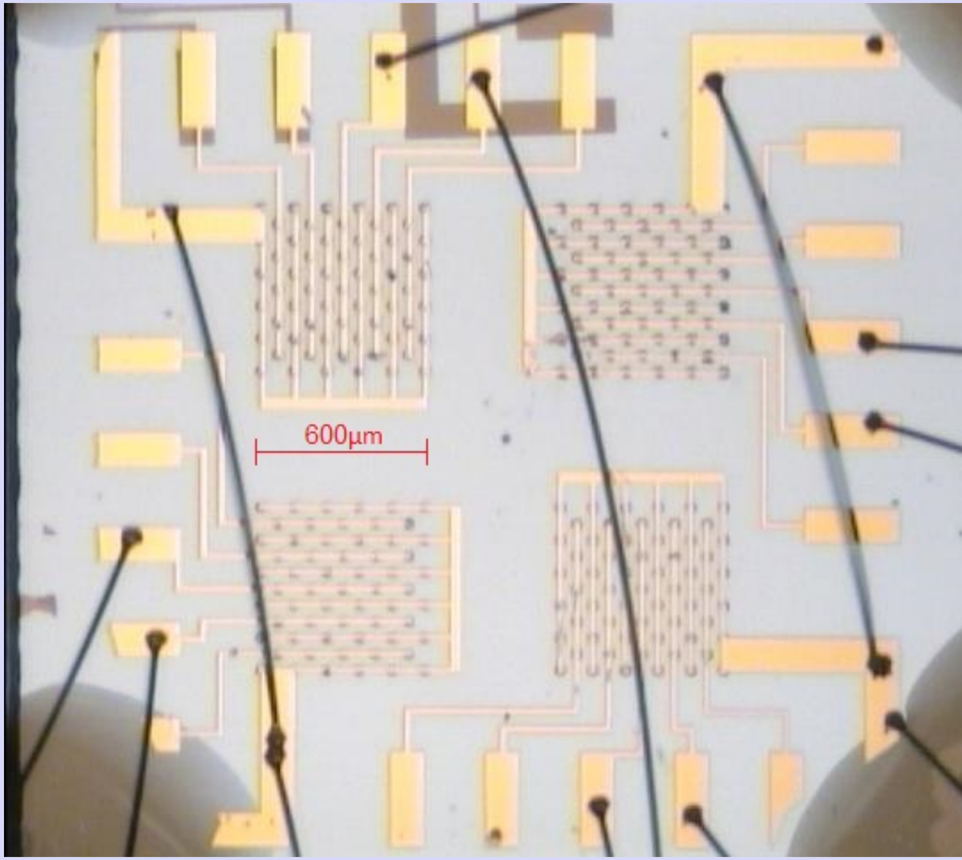
- Overall observe that relatively uniform charge collection for intact cell, even with trapping
- In case of missing HV column, region centered around column with high negative signal, and lower overall signal, as observed





3D Diamond TRIBIC simulations

- Ran simulations at different voltages
- Simulations do not include traps (yet)
- 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



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

- $\mu_{\mathrm{low}_e} = 1714\ \mathrm{cm}^2\ \mathrm{V}^{-1}\ \mathrm{s}^{-1}$
- $\mu_{\mathrm{low}_h} = 2064\ \mathrm{cm}^2\ \mathrm{V}^{-1}\ \mathrm{s}^{-1}$
- $v_{\mathrm{sat}_e} = 9.6 \times 10^6\ \mathrm{cm\ s}^{-1}$
- $v_{\mathrm{sat}_h} = 14.1 \times 10^6\ \mathrm{cm\ s}^{-1}$

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.