ETH zürich

Test beam results of 3D detectors based on scCVD and pCVD diamonds

Felix Bachmair on behalf of the RD42 collaboration

VCI 2016, 18th February 2016

ETH Institute for Particle Physics

The RD42 Collaboration

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31 Institutes

Overview

- Diamond as a sensor material
  - Newest developments in chemical vapor deposition (CVD) diamonds
- 3D diamond detectors
  - Single-crystalline (sc)CVD diamond
  - Polycrystalline (p)CVD diamond
- Summary & Outlook

Why diamond?

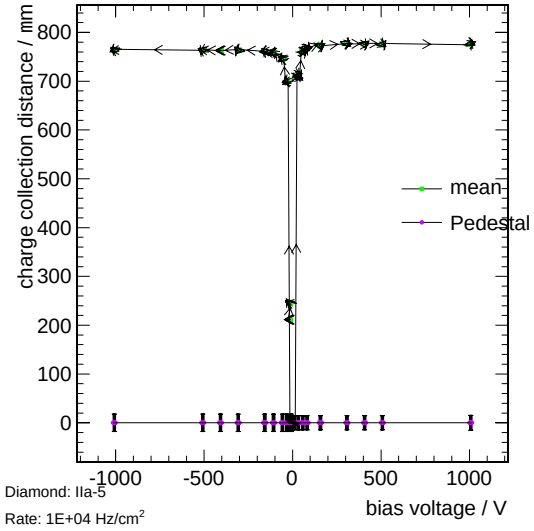
- advantages of diamonds w/r/t silicon
  - large displacement energy → Radiation hard
  - large bandgap → less leakage current & noise
  - high thermal conductivity → less cooling, good heatspread
- there are some disadvantages though
  - Large bandgap → less signal
  - Size of diamonds (scCVD) → R&D: Material more expensive than Si

Diamond Manufacturers

- In the past diamonds via DDL from ElementSix (De Beers)
  - DDL out of business, now directly via ElementSix
- Two new suppliers

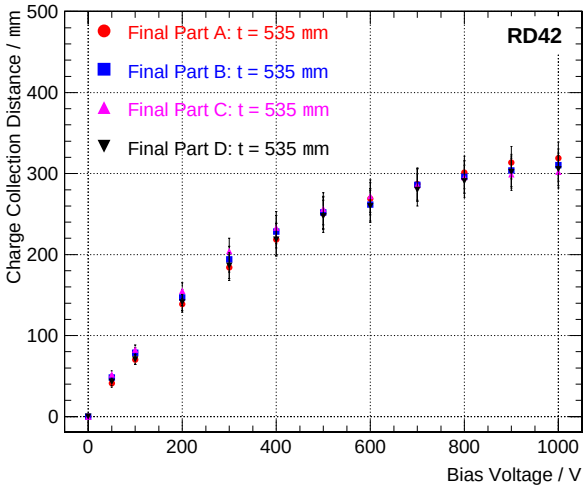
IIa-Technologies

- Right now: high quality scCVD
- In the future: pCVD



II-VI Incorporated

- High quality pCVD
- Finished detector parts typically reach 275 - 300 µm charge collection distance



3D diamond detectors

Supported by
US DoE Grant DE-SC0010061,
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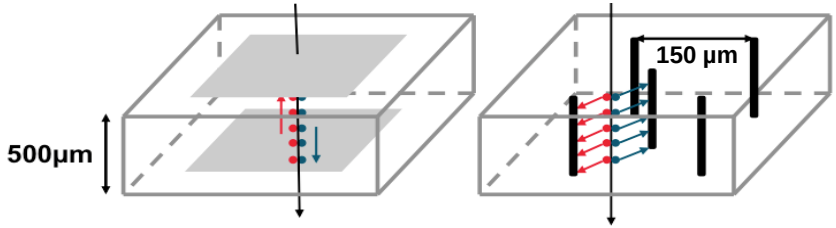
3D diamond detectors

- Improve charge collection by reducing the drift distance of the charge carriers

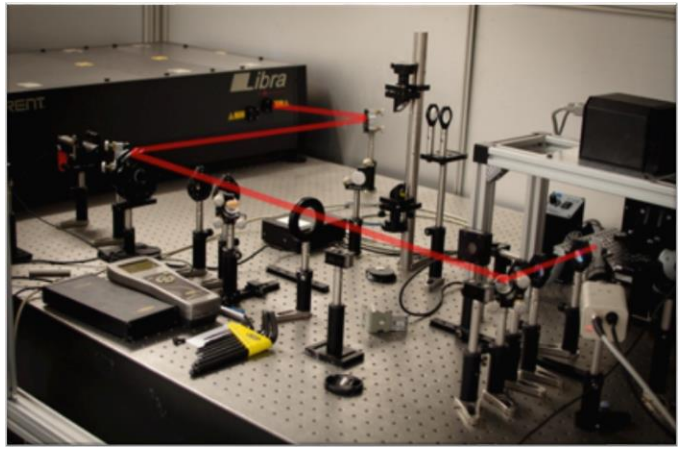


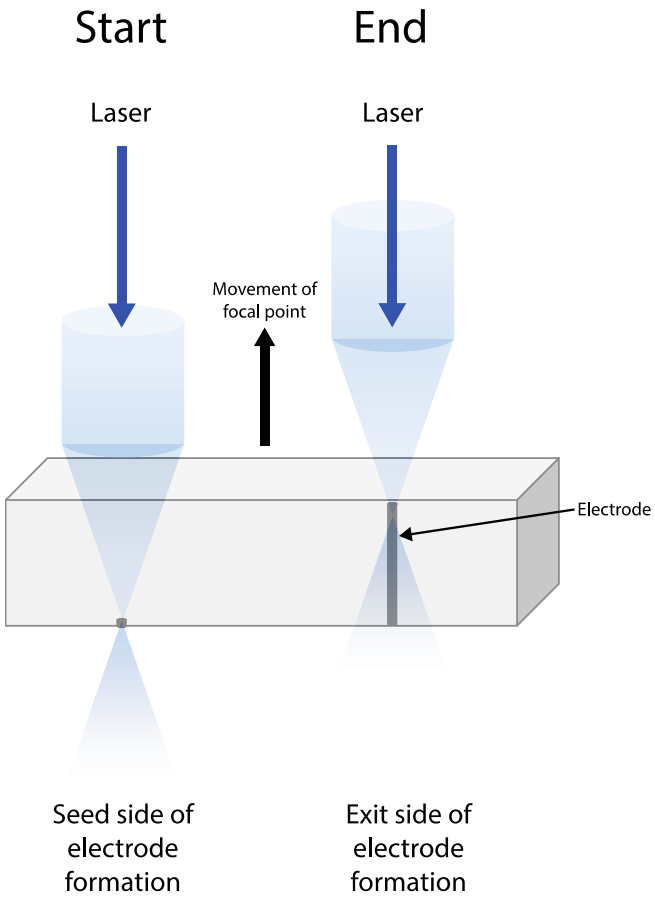
- Tested Cell Sizes: 150 x 150 µm
- Drift distance shorter than in planar (< 100 µm vs. 500 µm)
- Comparable to mean free path of charge carriers in irradiated diamond

Poster by Steven Murphy: Laser processing in 3D Diamond Detectors

Fabrication

- Using a femto second laser
- phase transition of diamond into a combination of
  - diamond-like carbon,
  - amorphous carbon
  - graphite





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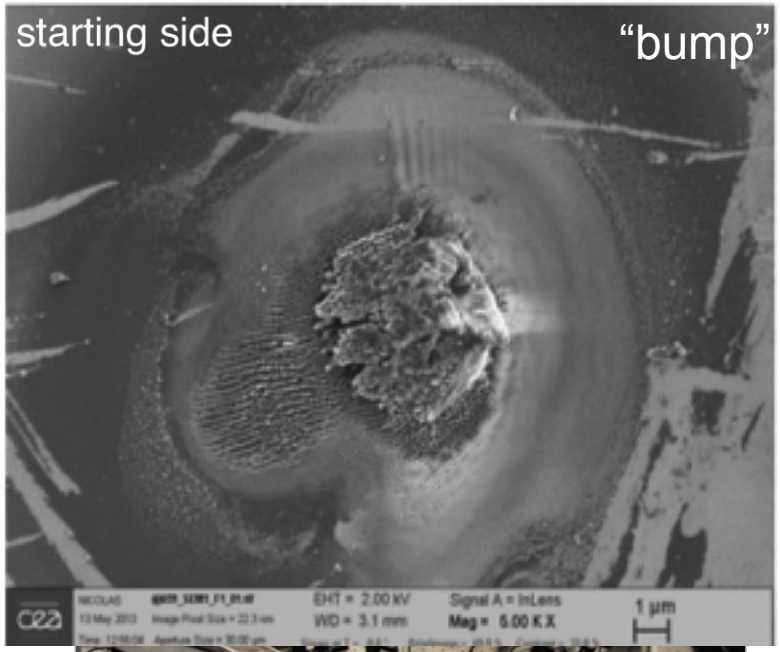
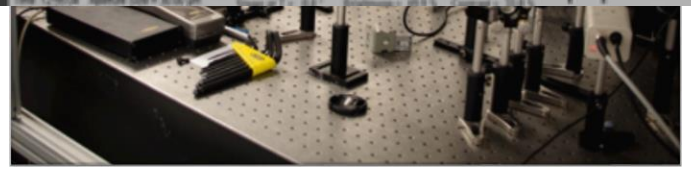
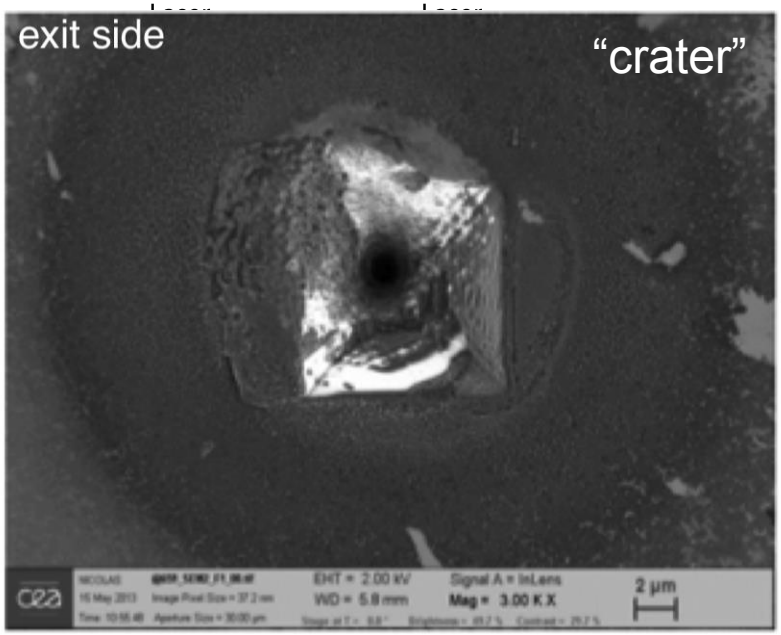




Start

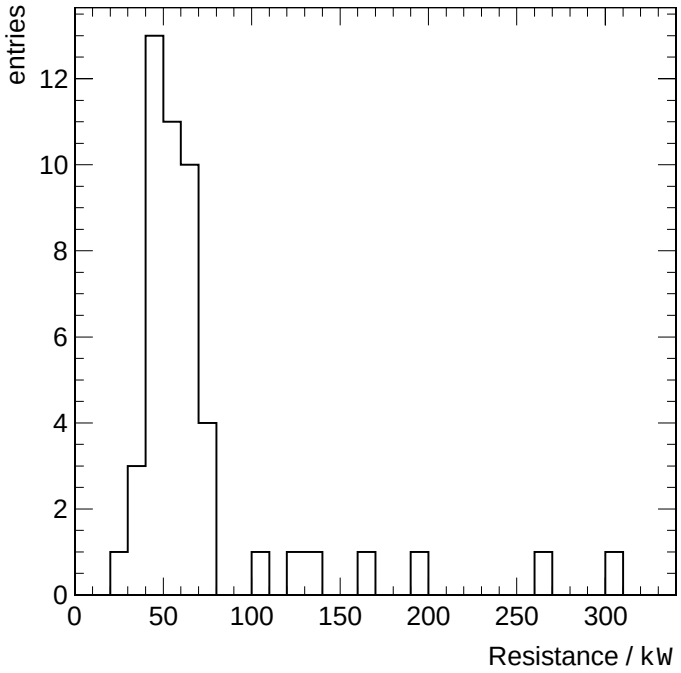
End



Seed side of electrode formation

Exit side of electrode formation

Conducting Columns - Resistivity

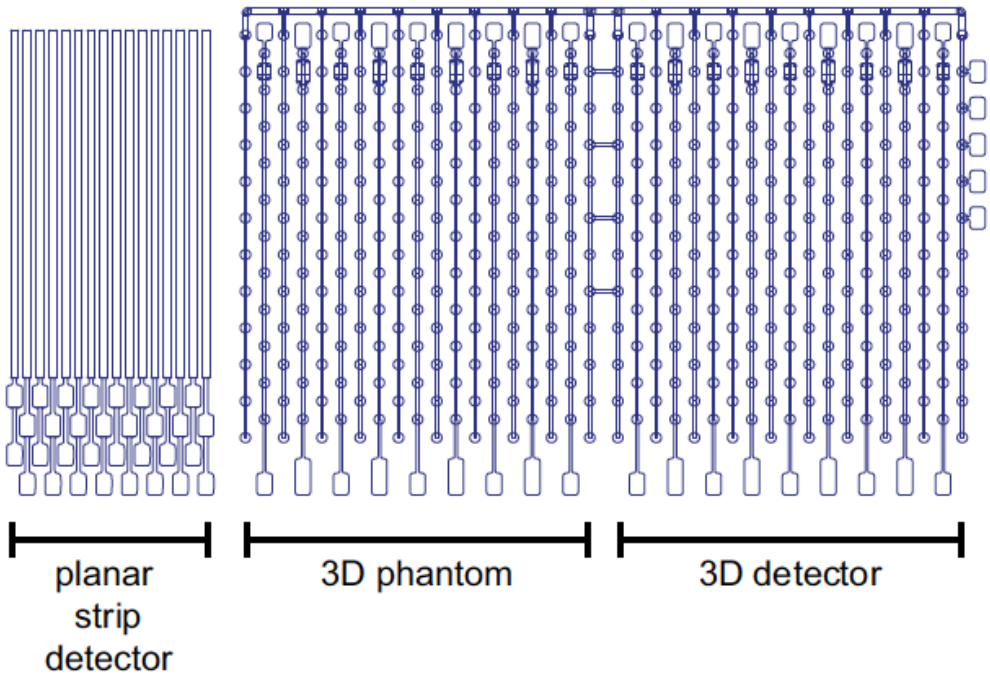


- Resistance: 45 kΩ & Electrode Diameter: 6 µm

➔ Conductivity: 0.29 ± 0.1 Ωcm for a typical electrode

Fabrication – Mask Layout

Three different detector regions on one diamond sensor for comparison

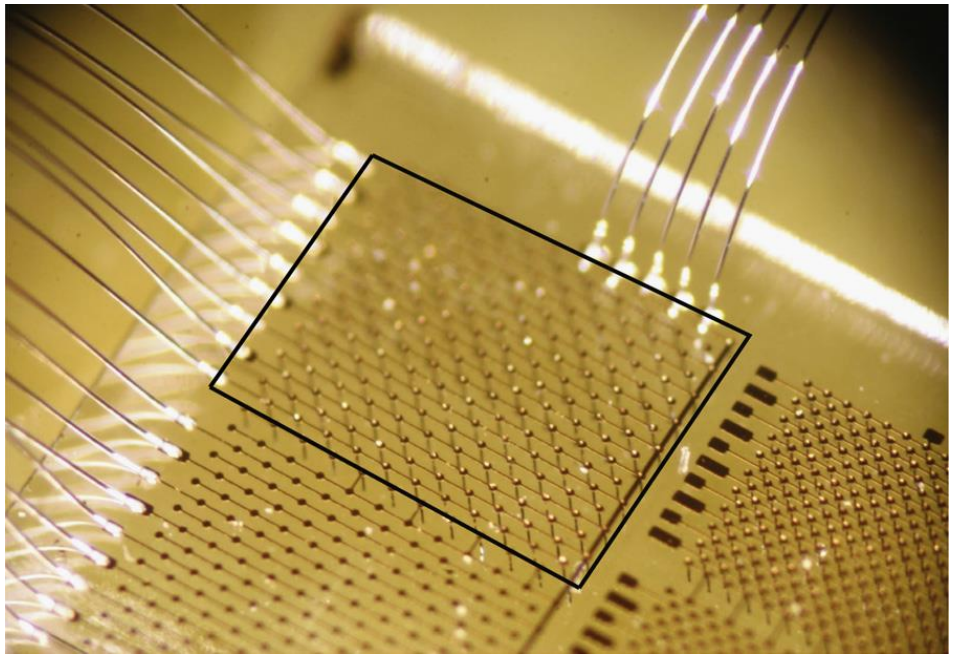


strip pitch 50 µm
Bias: 500V

3D Cell size: 150 x 150 µm^2
Bias: 25V

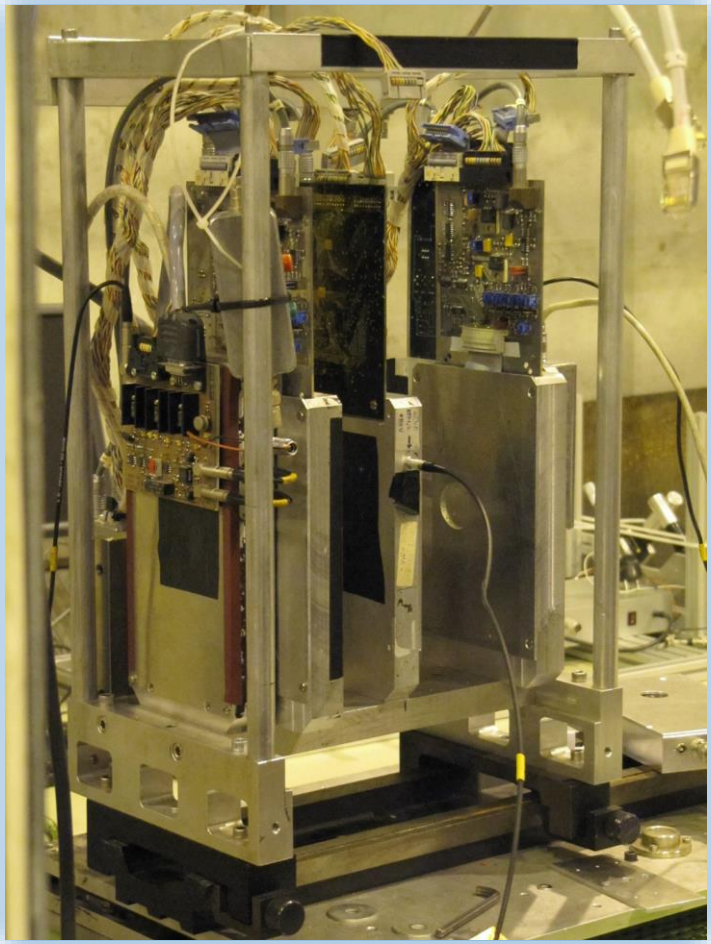
Fabrication

Cr – Au Metallization for contacting – Wire bonding of sensor



Test Beams at CERN

- H6 Beam Line at CERN
  - 120 GeV/c protons
- Strasbourg Telescope for Tracking
  - 4 X + 4 Y Silicon Reference Strip Detectors
  - Resolution: < 5µm at the DUT
- Tested
  - scCVD: Autumn 2012
  - pCVD: Autumn 2015



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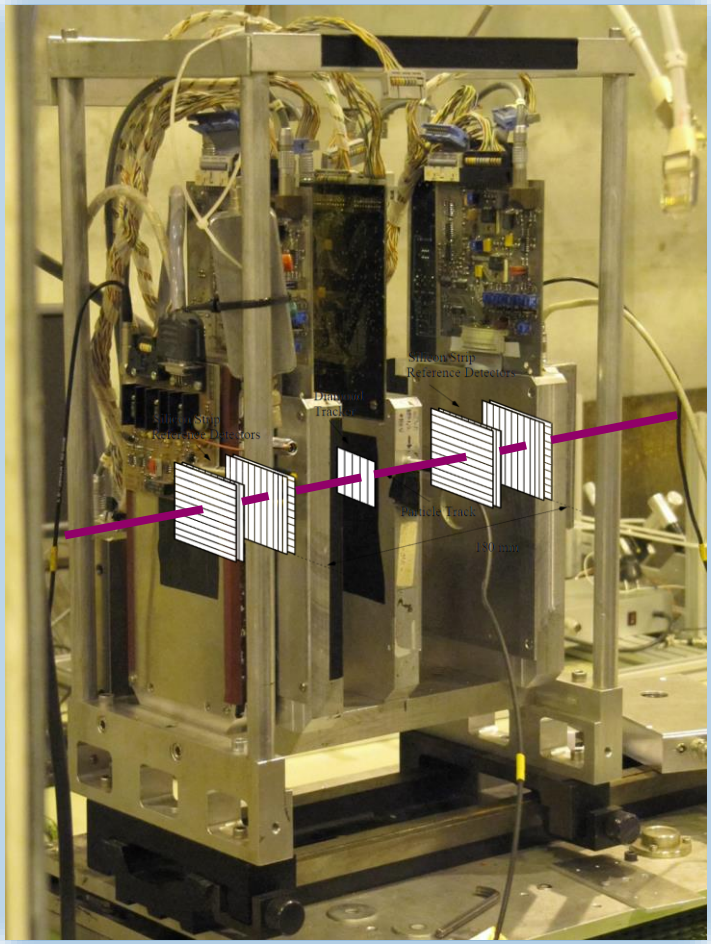
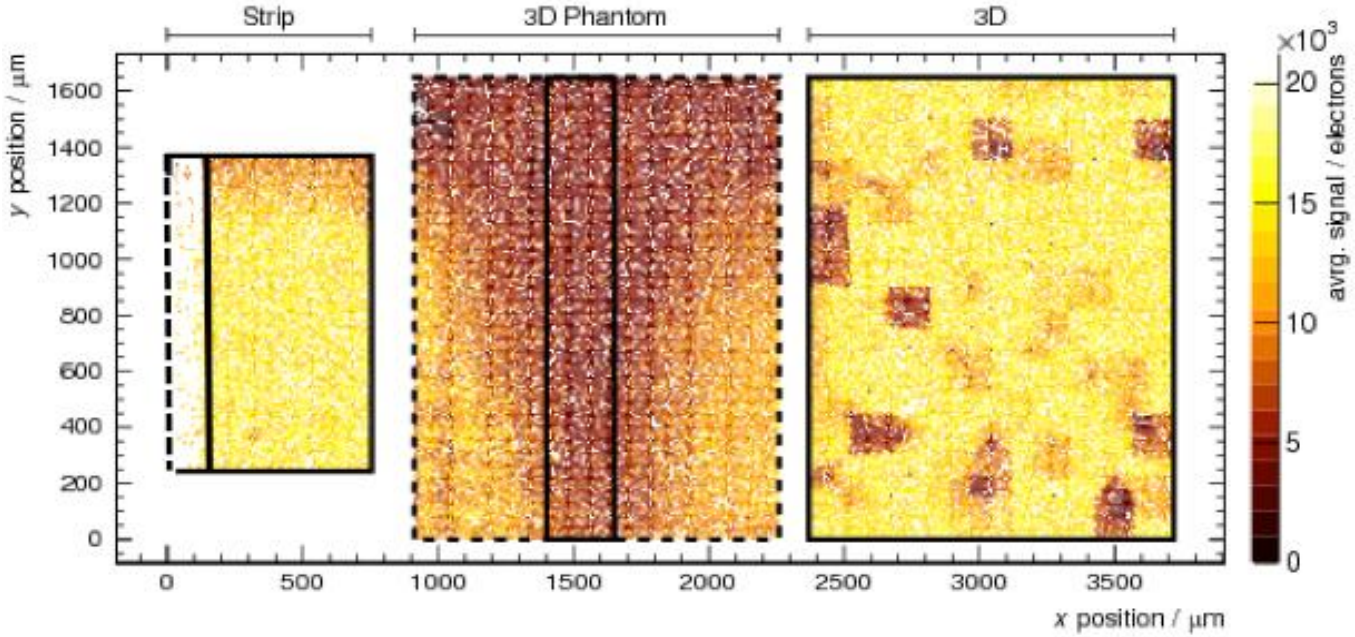


Results



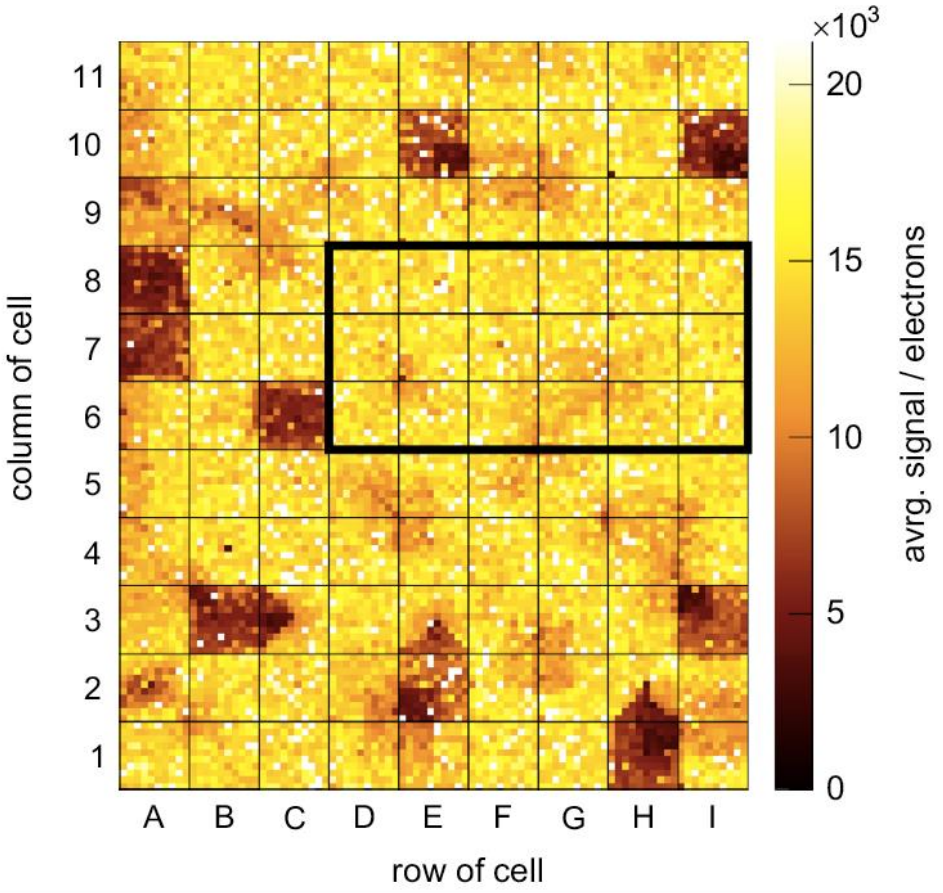
strip pitch 50 µm
Bias: +500V

3D Cell size: 150 x 150 µm^2
Bias: +25V

scCVD results published in NIM A 786 (2015) p97

3D diamond detectors

- Missing charge around ~9 broken readout columns
  - In agreement with other measurements
- See effects of missing bias columns



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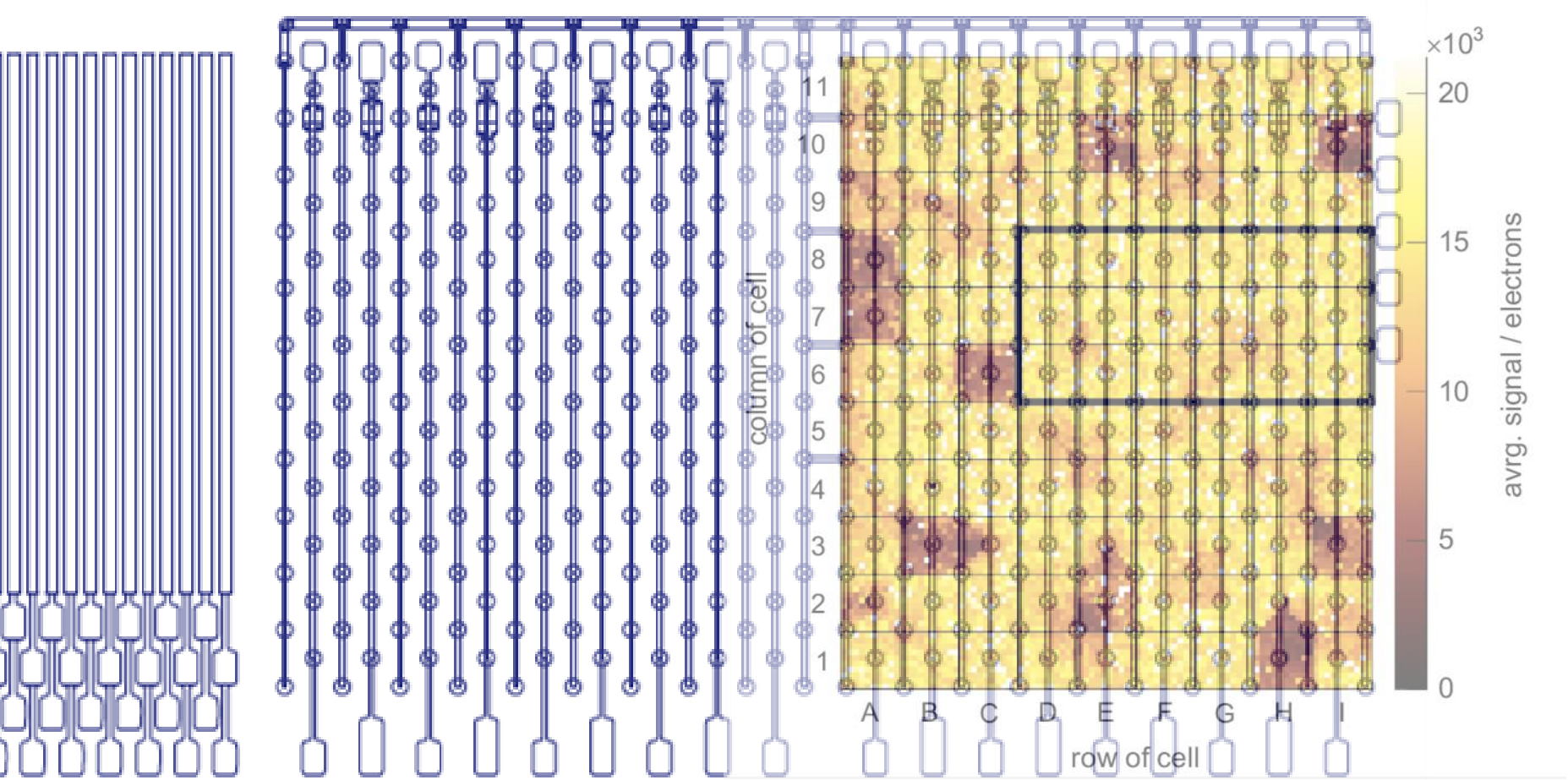

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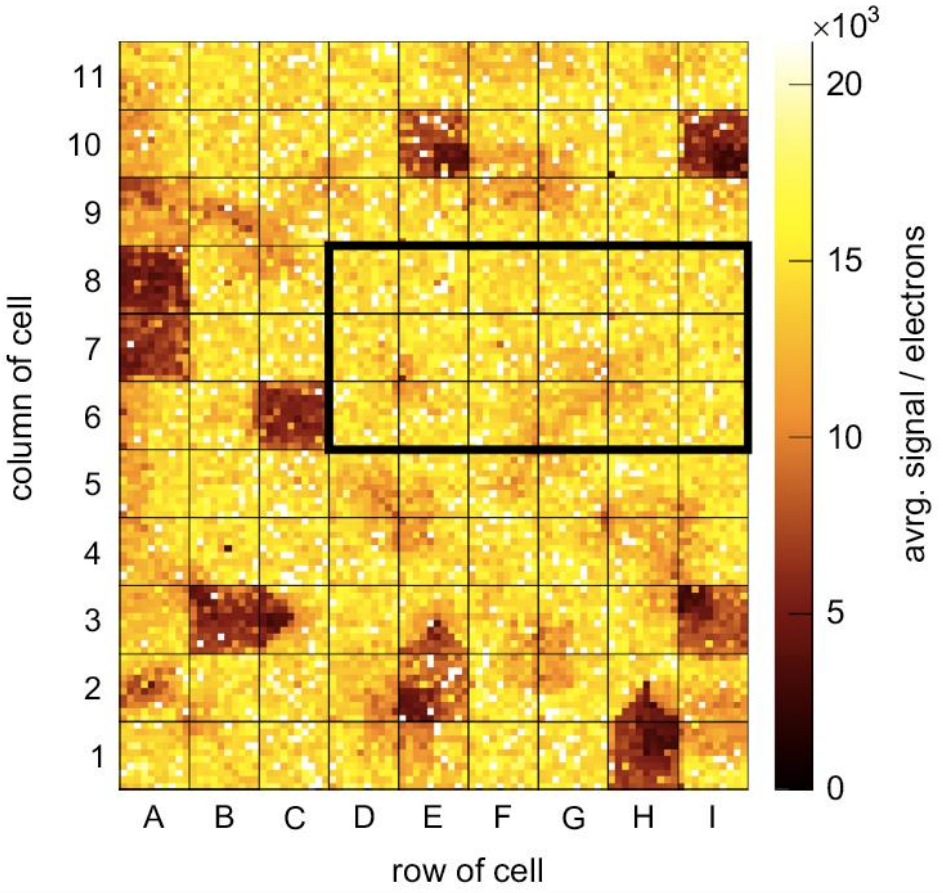

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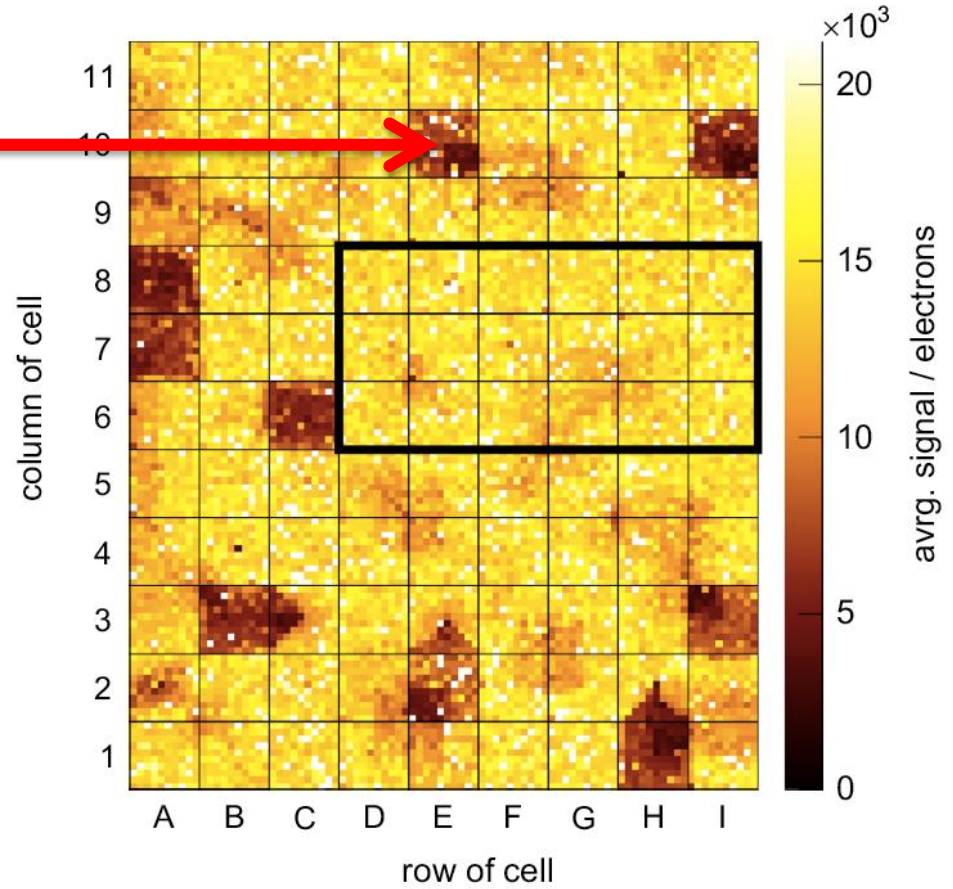

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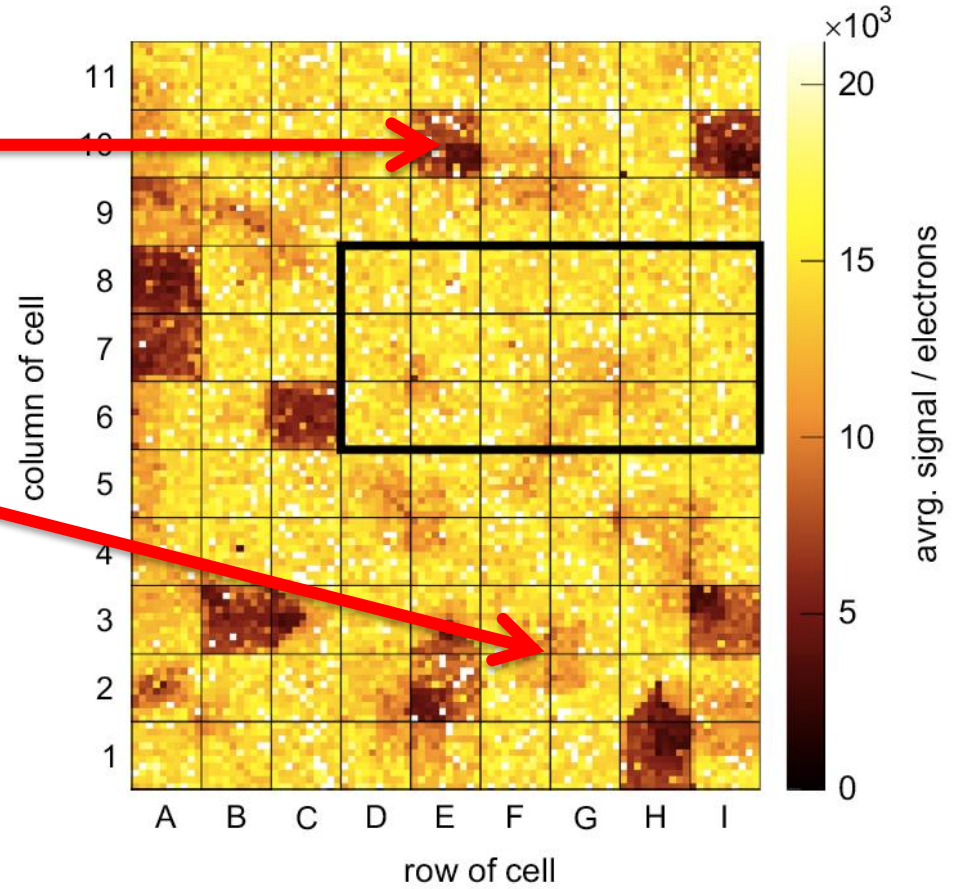
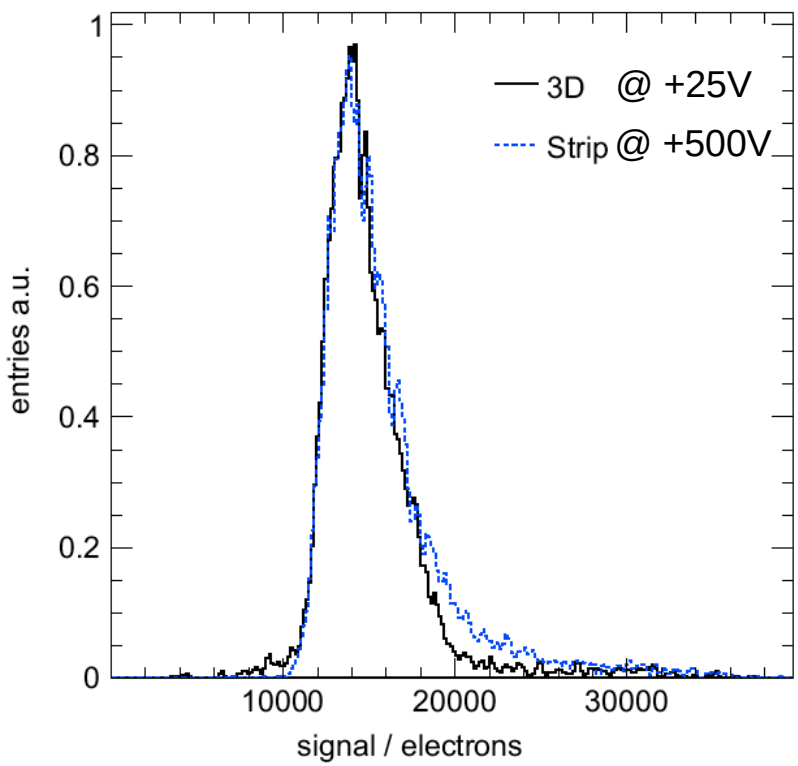


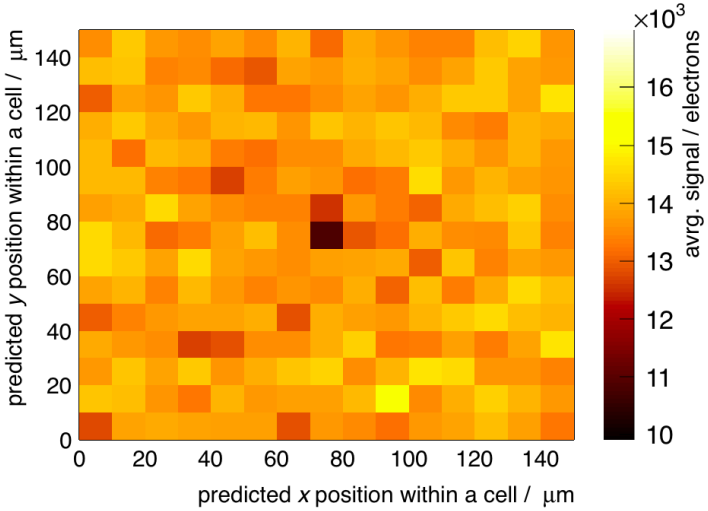
3D diamond detectors

- Full Charge Collection for both detectors
- Remarkable agreement between signals in 3D and planar strip geometries
- full charge at lower avrg. E-Field
  - 3D: 25 V , < 100 µm
  - Planar: 500 V, 440 µm



Uniformity and resolution

- split each cell into 10 x 10 µm^2 and overlay each subcell
  - nice uniformity ~3% across cell observed (ignoring cells with columns)



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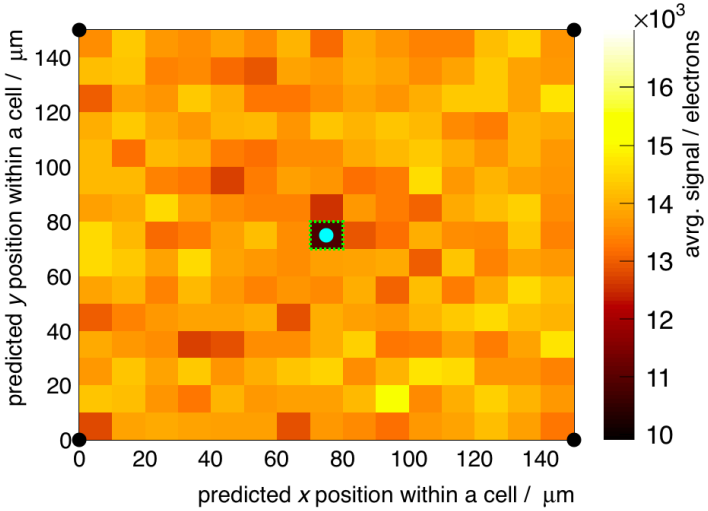

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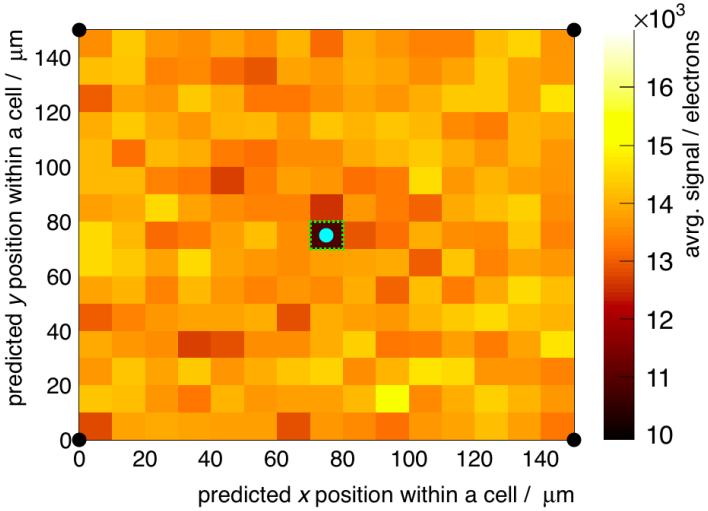
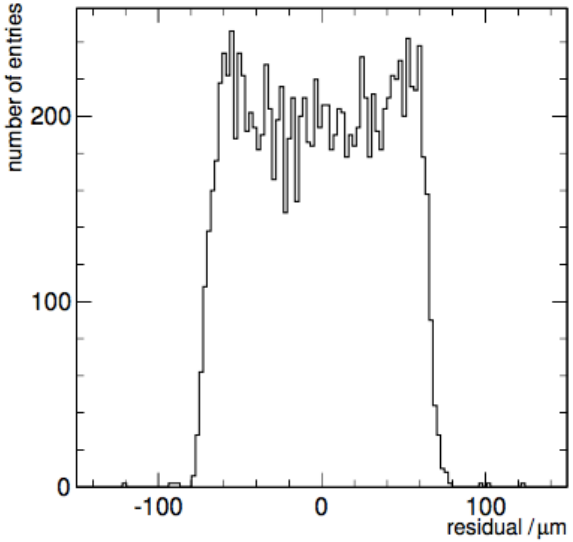


- Residual distribution
  - 2 Strip - Charge Weighted
  - 40.2 ± 0.3 μm (expect 43 μm for digitial)
  - Very little charge sharing

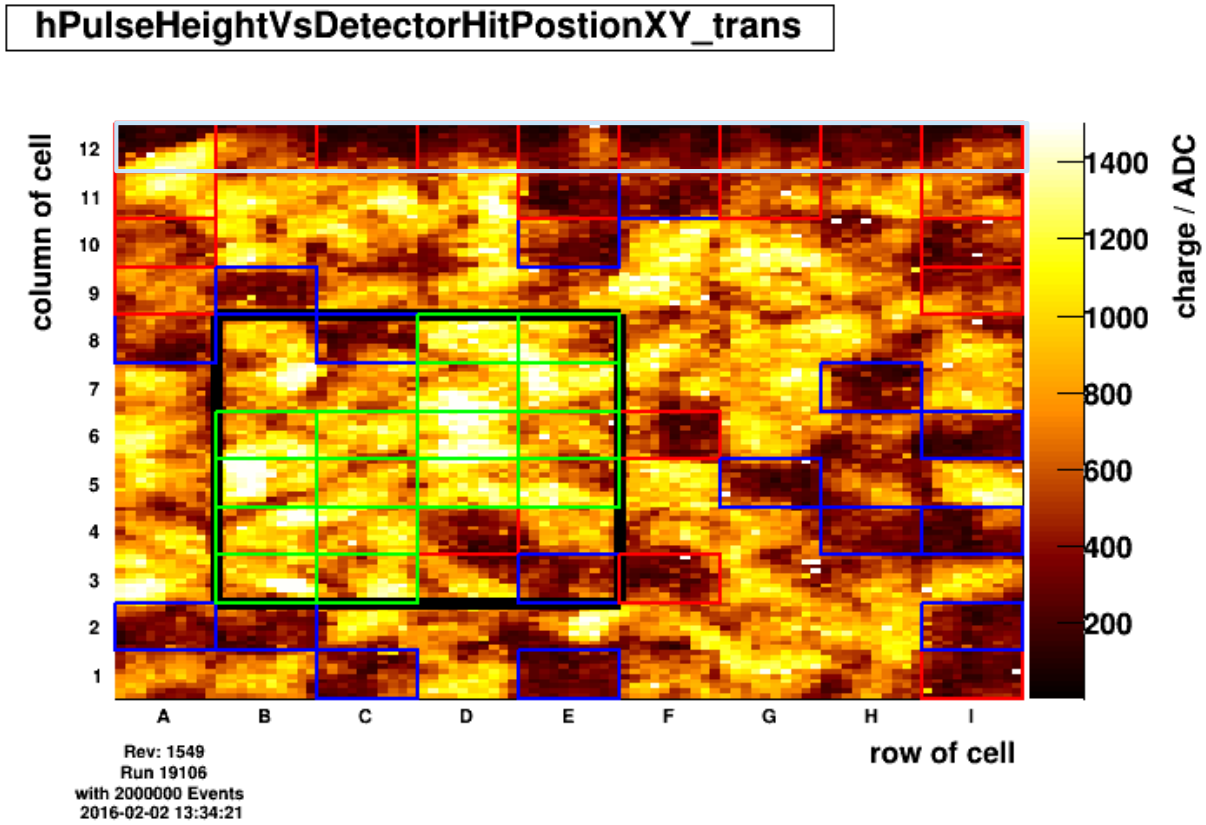


Test of first 3D pCVD diamond detectors

- Same layout/mask as for 3D scCVD diamond
  - Planar Strip @ 500V
  - 3D-Phantom @ 75V
  - 3D-Detector @ 75V
- Smaller yield in fabrication & contacting of columns than for scCVD
- Preliminary result without calibration to electrons
  - 3D-Detector & 3D-Phantom biased @ 75V, planar strip @ 500V
  - Comparison between 3D detector and planar strip
  - First results on residual/charge sharing

Selection of Good Cells

- Selected 16 adjacent cells



Poster by Giulio Forcolin: Simulation of 3D Diamond Detectors

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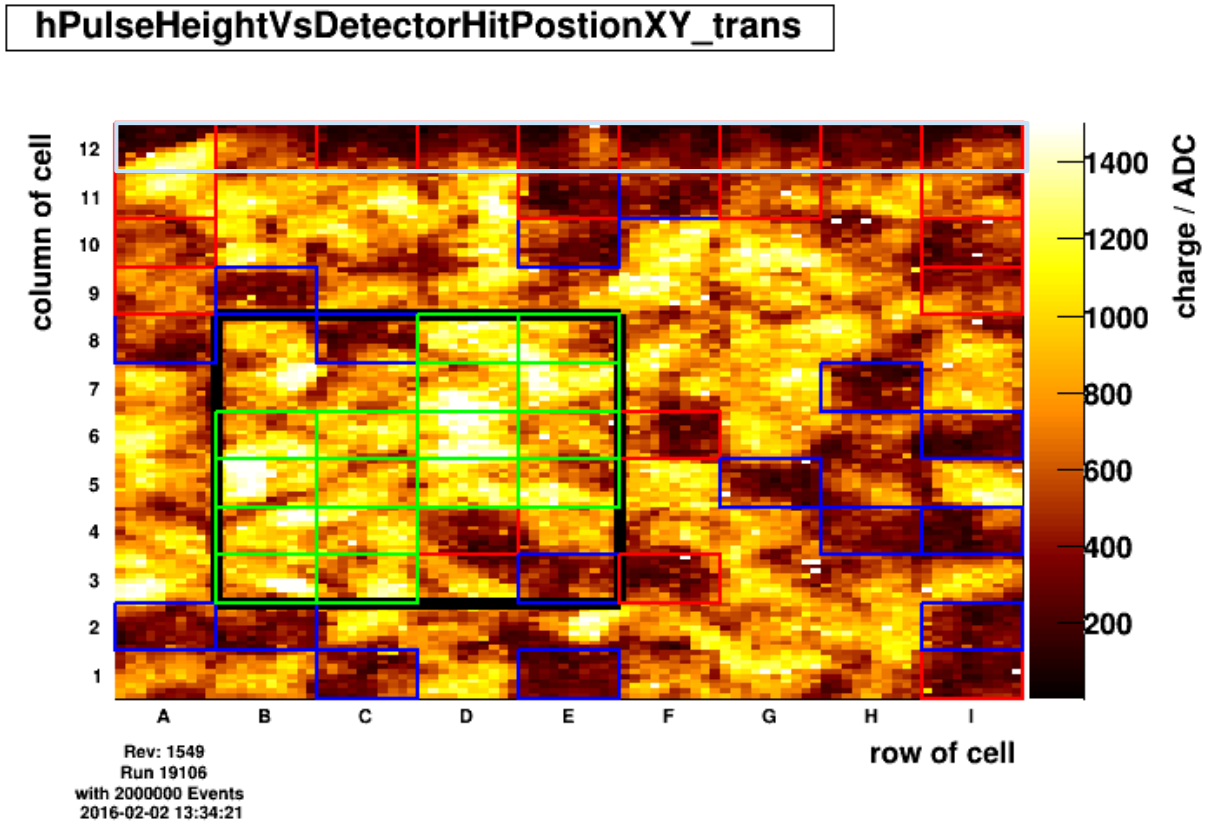
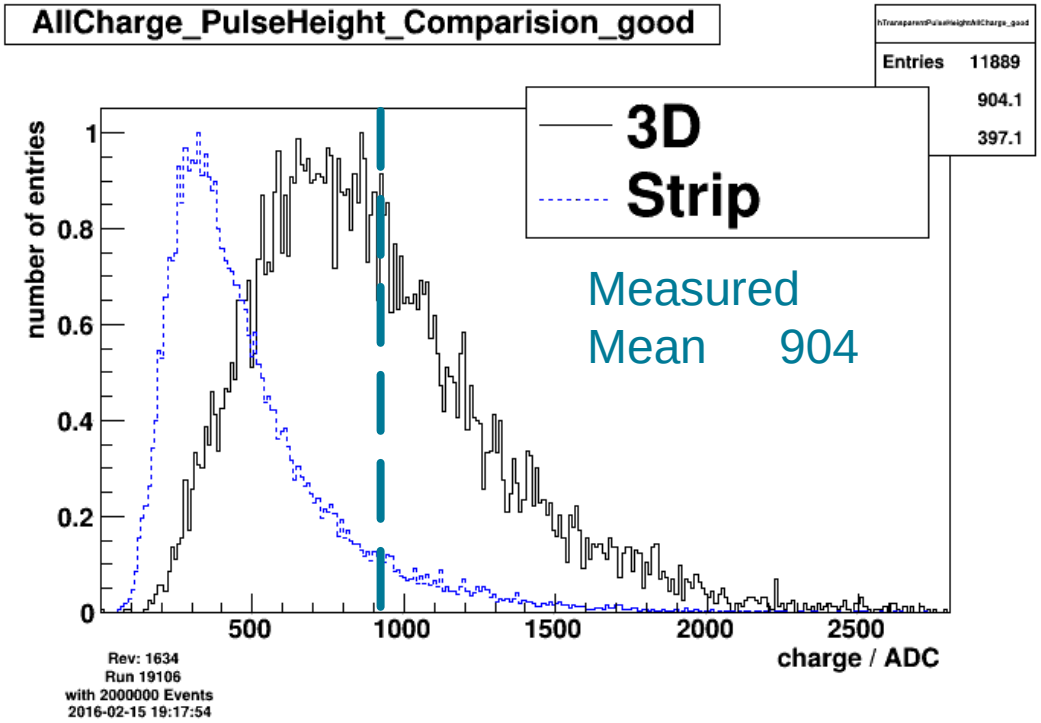


Final Comparison

- Low estimate for charge collection



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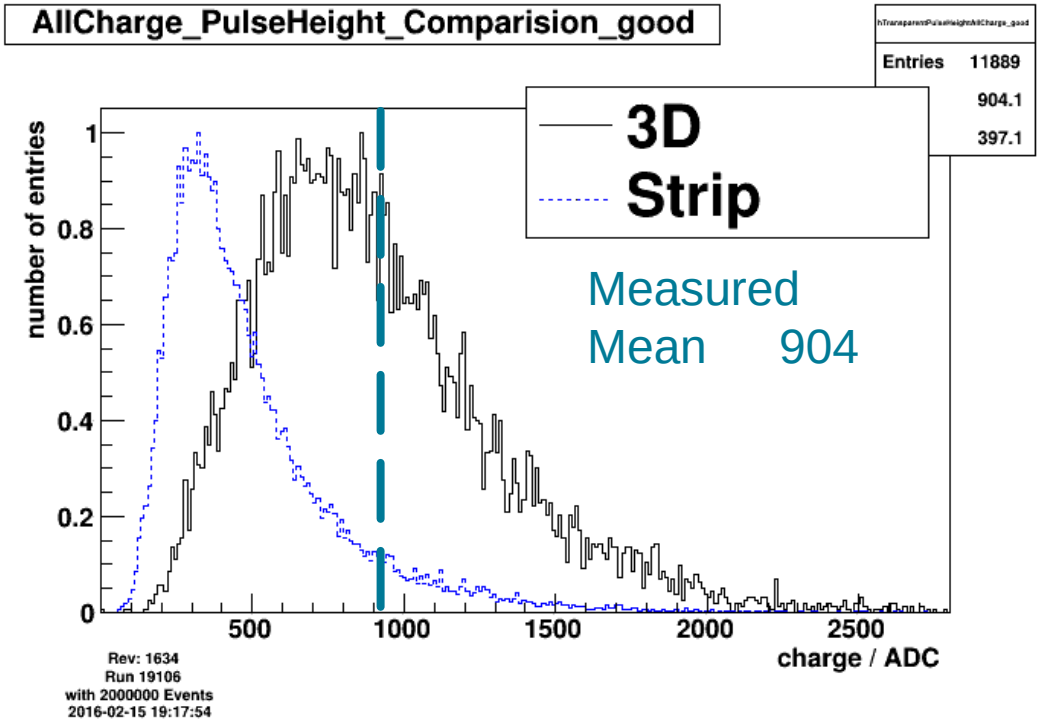
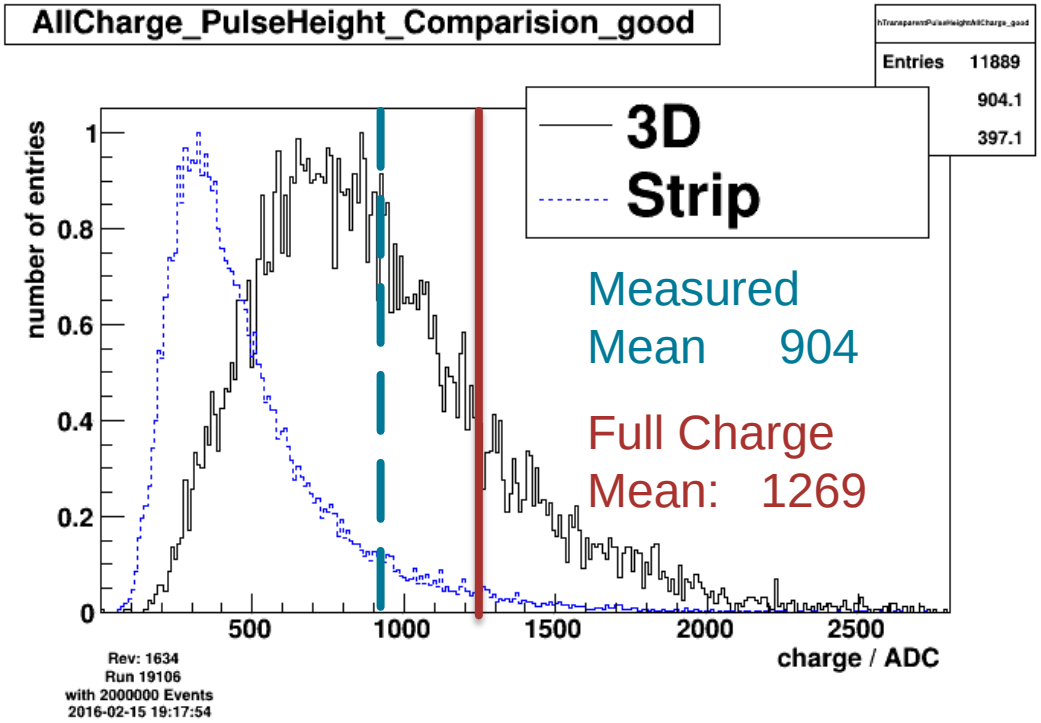


Better charge collection than planar (mean 488 ADC)

Final Comparison

- Red line estimate the Mean for Full Charge Collection (500µm)



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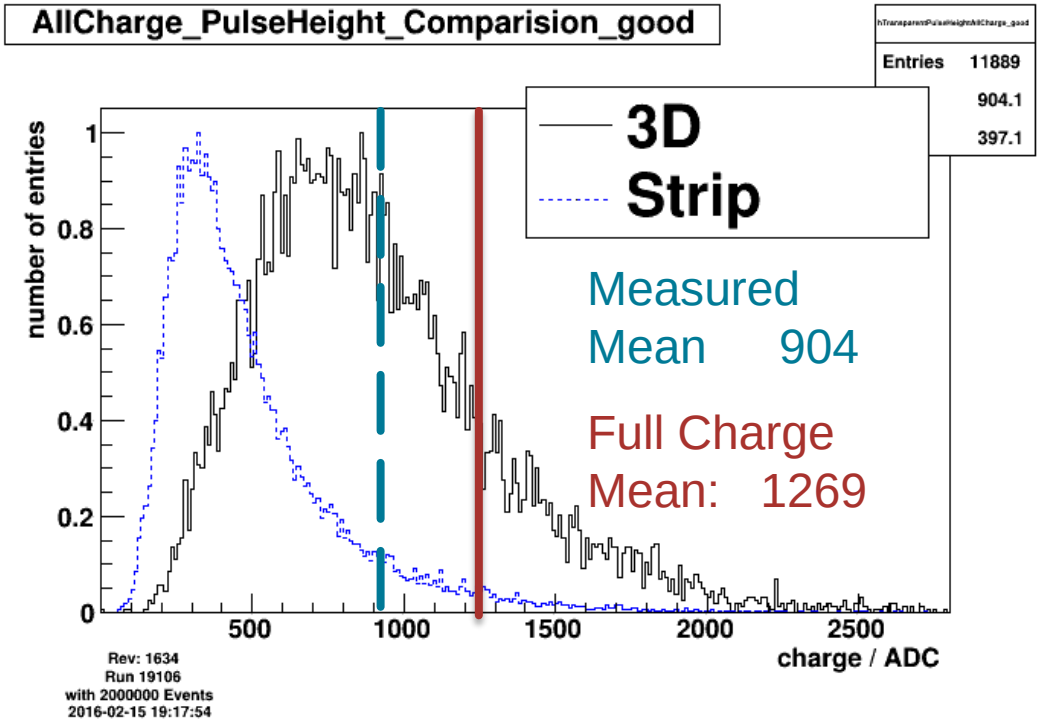
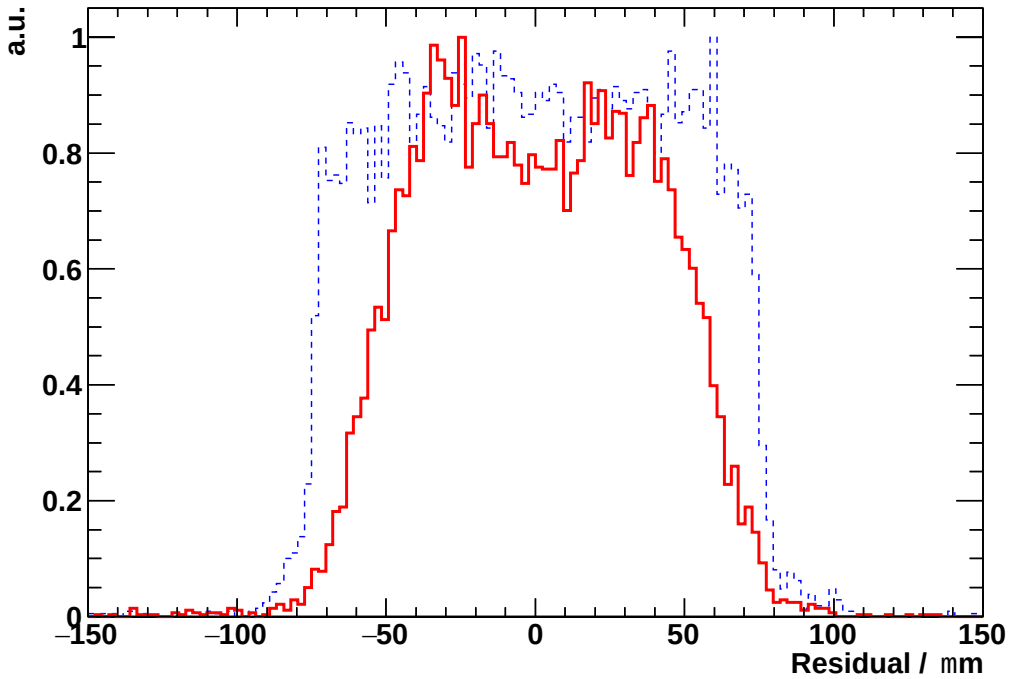


71% of Full Charge Collection, corresponding to 356 µm

Highest charge collection ever measured for pCVD diamonds

Residual



Blue: 1 Strip
(digital)
σ = 44.0 μm

Red: 2 Strip
Charge Weighed
σ = 36.8 μm

Slight improvement due to small charge sharing in between the cells

Summary

- New diamond suppliers, IIa & II-VI, improved situation on the market
- Quality of diamonds has improved strongly over the last years
  - Now reaching 275 - 300 µm CD in pCVD diamonds

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- Results for 3D scCVD diamond have been published
  - Collecting same charge as planar configuration at a much smaller bias voltage (25 V vs. 500V)

Summary

- New diamond suppliers, IIa & II-VI, improved situation on the market
- Quality of diamonds has improved strongly over the last years
  - Now reaching 275 - 300 µm CD in pCVD diamonds
- Results for 3D scCVD diamond have been published
  - Collecting same charge as planar configuration at a much smaller bias voltage (25 V vs. 500V)
- Results of first 3D pCVD diamond look very promising
  - Highest Charge Collection measured in pCVD diamond
  - ≧ 71% of full charge collection (356µm) at 75 V
  - Slight Charge Sharing between cells

Outlook

- Further improvement of diamond quality in cooperation with suppliers
- R&D on 3D devices
  - Improve micromachining for conductive columns
    - Higher yield
    - Smaller resistivity
    - Bigger detectors
  - Test of different cell structures
    - Honeycomb, rectangular
    - Different sizes
  - TCAD Simulations 3D diamond detectors
  - Studies of irradiated 3D CVD diamonds

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Poster by Giulio Forcolin: Simulation of 3D Diamond Detectors

Thank you

BACKUP

Why diamond?

	Si	diamond
Band Gap [eV]	1.12	5.45
Electron Mobility [$cm^2/V\ s$]	1450	2200
Hole Mobility [$cm^2/V\ s$]	500	1600
Saturation Velocity [cm / s]	$0.8 \cdot 10^7$	$2 \cdot 10^7$
Breakdown Field [V / m]	$3 \cdot 10^5$	$2.2 \cdot 10^7$
Resistivity [Ohm]	$2.3 \cdot 10^5$	$> 10^{11}$
Dielectric Constant	11.9	5.7
Displacement Energy [eV]	13-20	43
e-h creation energy [eV]	3.6	13
Average e-h pairs per MIP per µm	89	36
Charge Collecting Distance [µm]	~full	scCVD: ~full pCVD: ~ 250-300
Thermal conductivity [W/cm K]	1.5	22

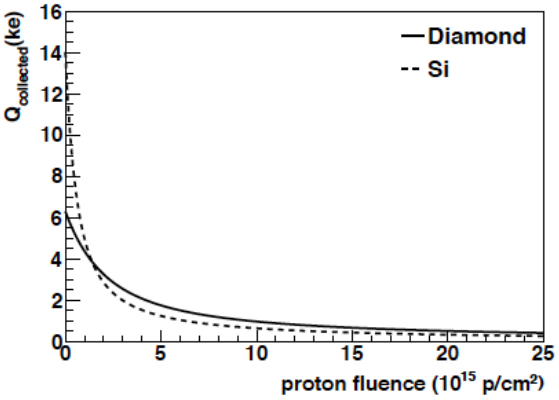
+ Low leakage current
+ Low capacitance
+ Operation at high voltages
+ Operation without cooling
+ Radiation tolerant

- Lower signal
- Single crystals small in size
- Efficiency < 100% (pCVD)
- More expensive

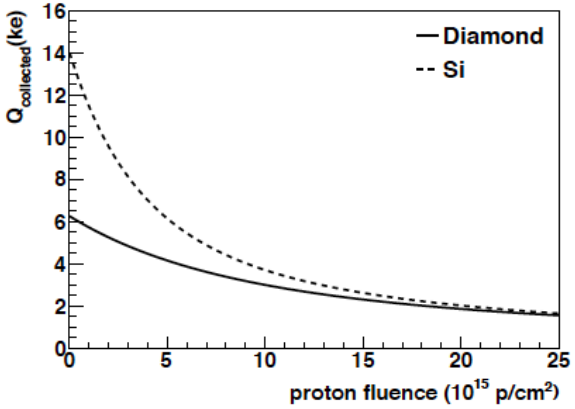
Diamond vs. Silicon

- Expected signals (MPV) of MIP for 200 um sensor
- ENC vs. irradiation – simulation & measurement (25 MeV)

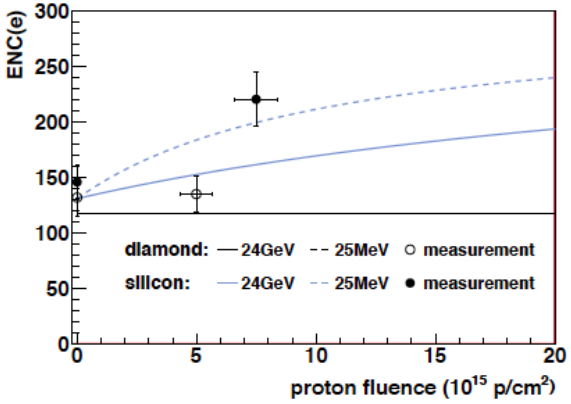
25 MeV proton irradiation



24 GeV proton irradiation



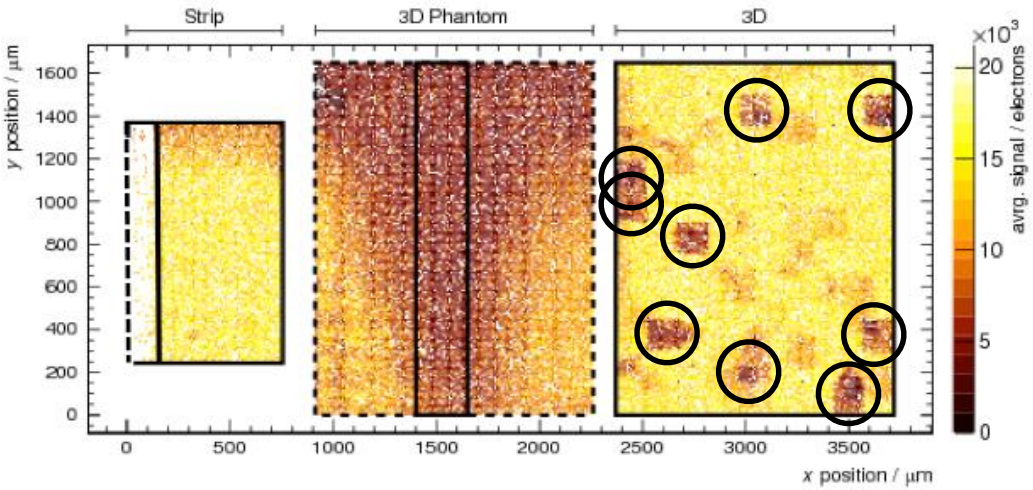
ENC for Si & Dia



arxiv.org/pdf/1206.6795v2.pdf

pulse height maps

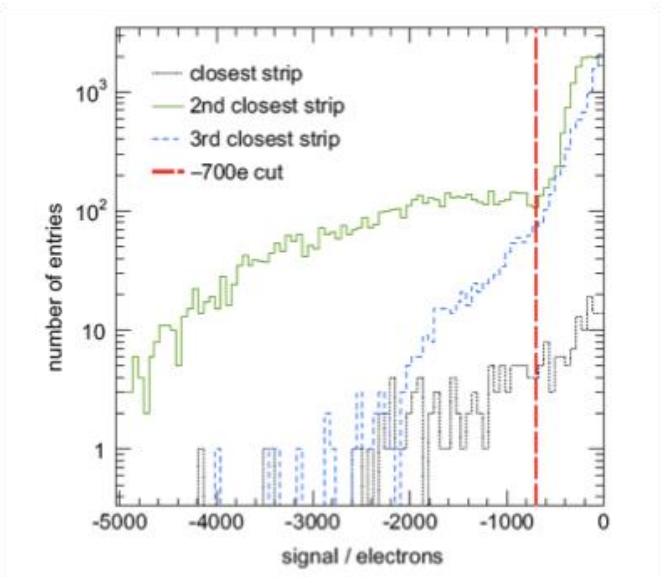
- first check if the diamond works: map of pulse height
- small fiducial loss due to scintillator trigger

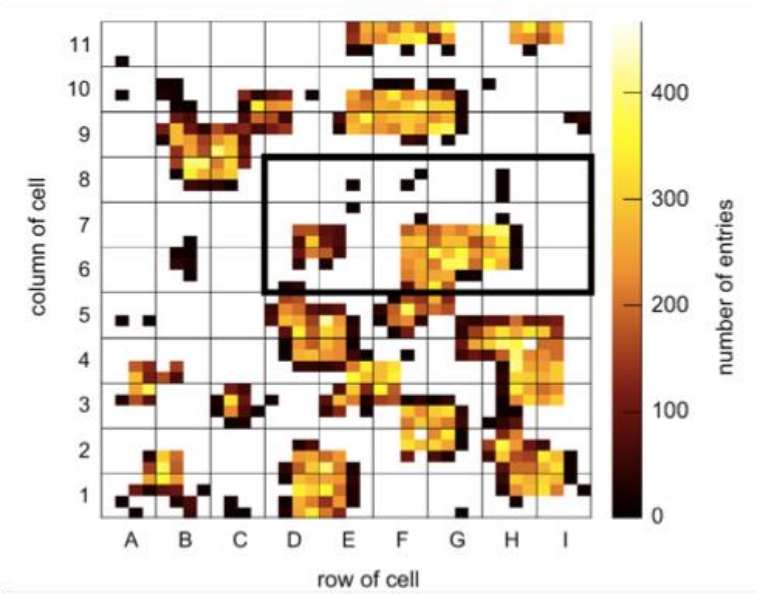


- dead cells already visible due to faulty readout columns
- roughly 9 broken readout columns (expect 8 from 92% efficiency)

3D Diamonds – Negative Charges

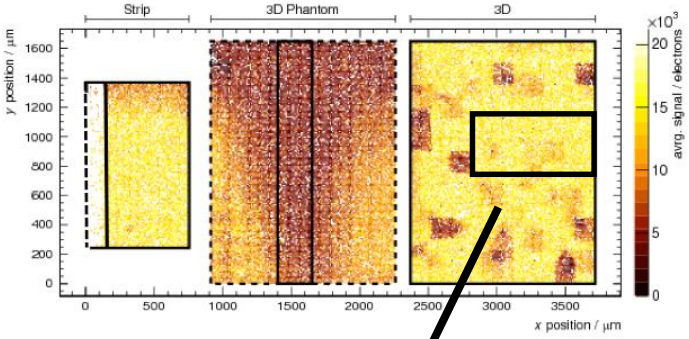
- Observed unexpected negative charge tail
- Negative charge clustered around center of cells
- Identified to be due to missing bias column

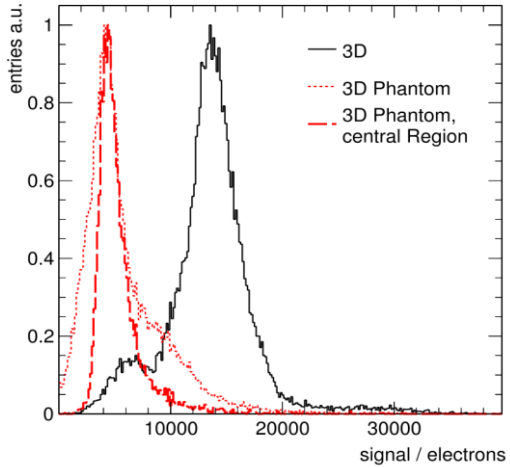


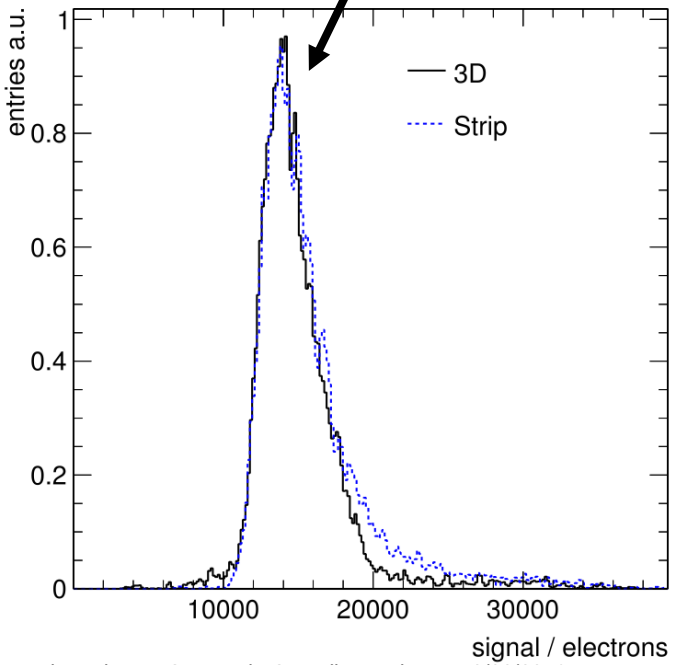


results on charge collection

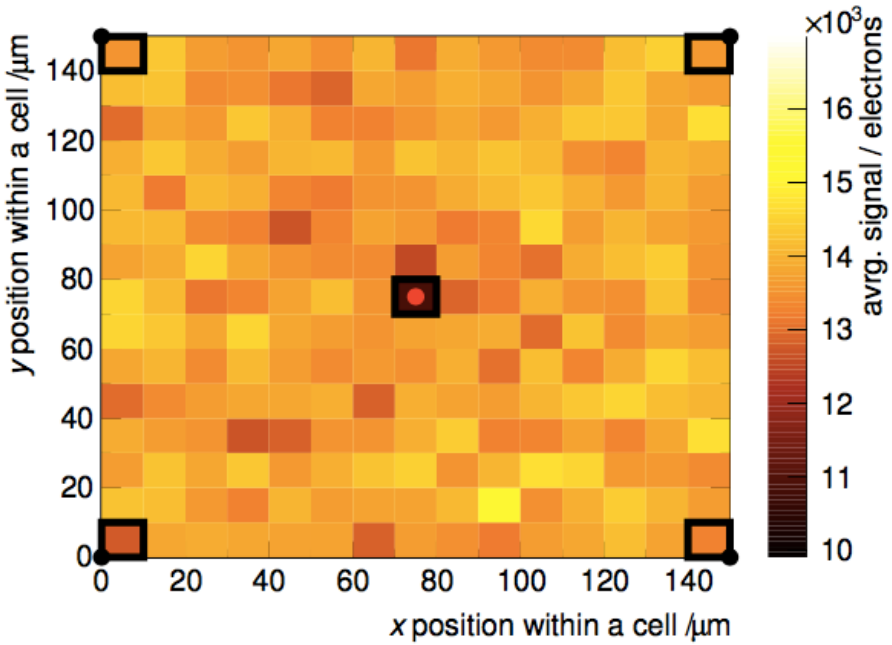
- strip part should collect full charge at 450 V
  - this expectation is confirmed
- 3D collects same charge at 5% of the voltage!
  - great confirmation of expectation
- 3D phantom collects significantly less charge
  - theory is that it collects charge only at surface, not in the bulk

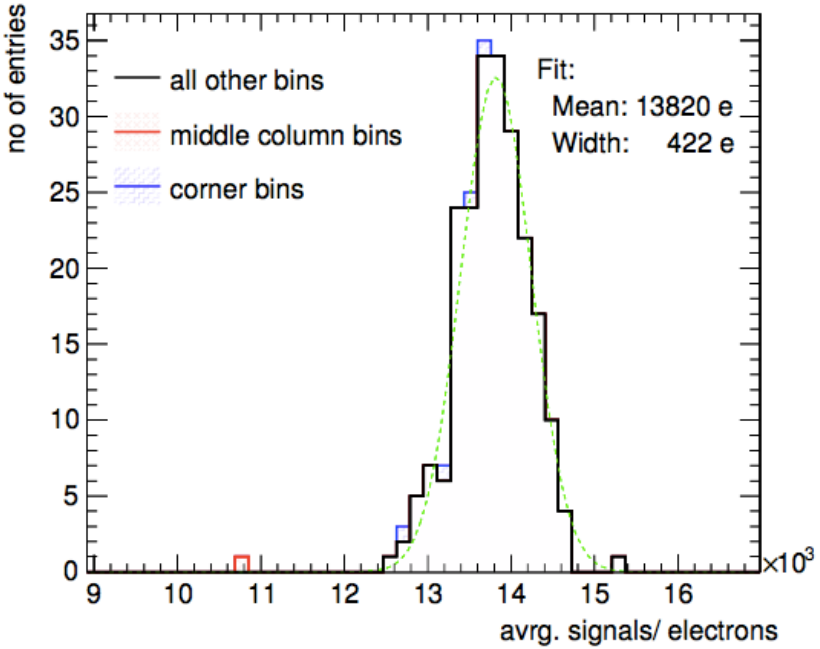






Uniformity

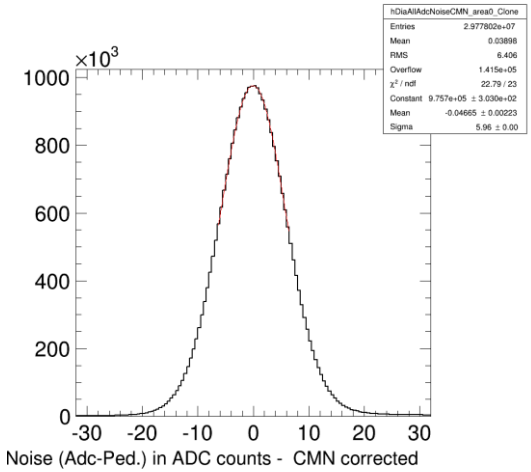

y position within a cell /µm
x position within a cell /µm
avrg. signal / electrons
×10³
0
20
40
60
80
100
120
140
10
11
12
13
14
15
16


no of entries
avrg. signals/ electrons
×10³
all other bins
middle column bins
corner bins
Fit:
Mean: 13820 e
Width: 422 e
0
5
10
15
20
25
30
35
9
10
11
12
13
14
15
16

3D pCVD Results

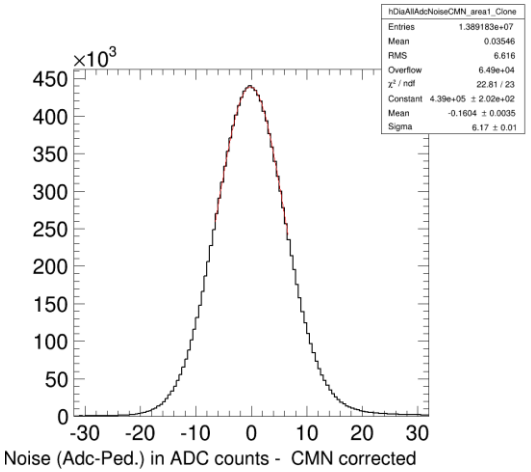
- pCVD diamond from II VI
  - Thickness 500 µm
- Noise

Strip



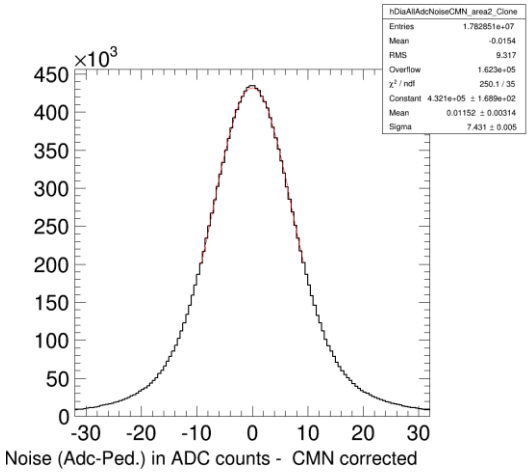
σ = 5.96 ADC

3D Phantom



σ = 6.17 ADC

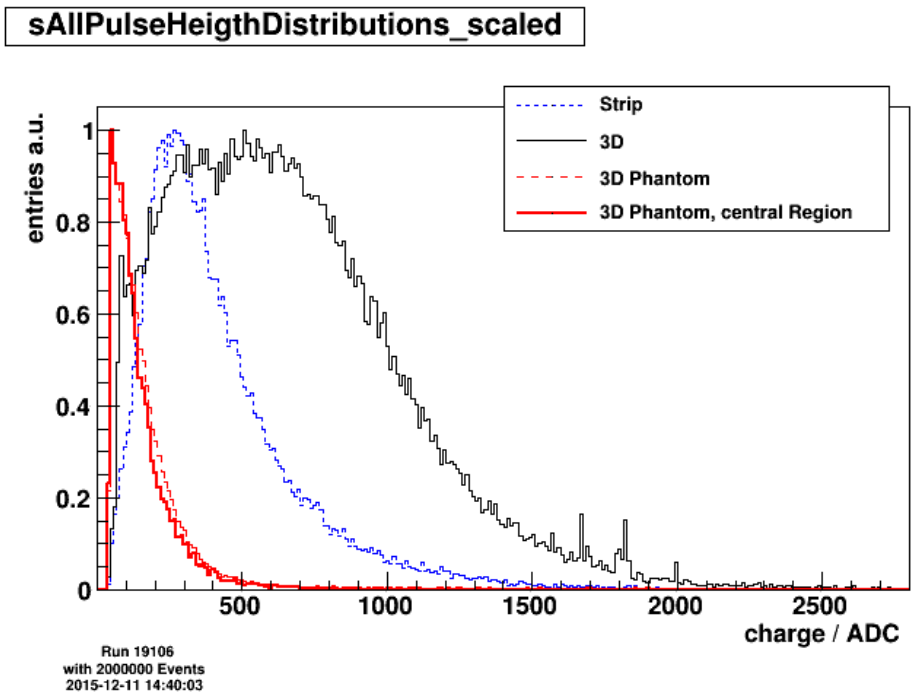
3D Detector



σ = 7.43 ADC

Charge in whole detector

- Cluster analysis:
  - strip detector: Landau
  - 3D Phantom: very low signals
  - 3D Detector: Wide distribution
    - More charge in 3D detector than within strip detector
- Region of ‘working Cells‘ must be selected



Final Comparison

- All Cells
- Good Cells (16 cells)