A 3D Diamond Detector for Particle Tracking

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on behalf of the RD-42 collaboration

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Bundesministerium
für Bildung
und Forschung

Introduction

- Silicon suffers from radiation damage in regions with high particle flux (e.g. HL-LHC)

- Diamond has higher displacement energy
  $\rightarrow$ more radiation tolerant
- Larger band gap
  $\rightarrow$ less thermal noise and leakage current
- High thermal conductivity
  $\rightarrow$ less cooling needed

- Larger band gap
  $\rightarrow$ less e-h pairs created
- Trapping
  $\rightarrow$ charge loss

- Figure of merit for trapping in diamond: charge collection distance (CCD)
- CCD is the mean distance an electron-hole pair separates before being trapped
- Higher CCD $\widehat{=}$ less trapping $\rightarrow$ more signal

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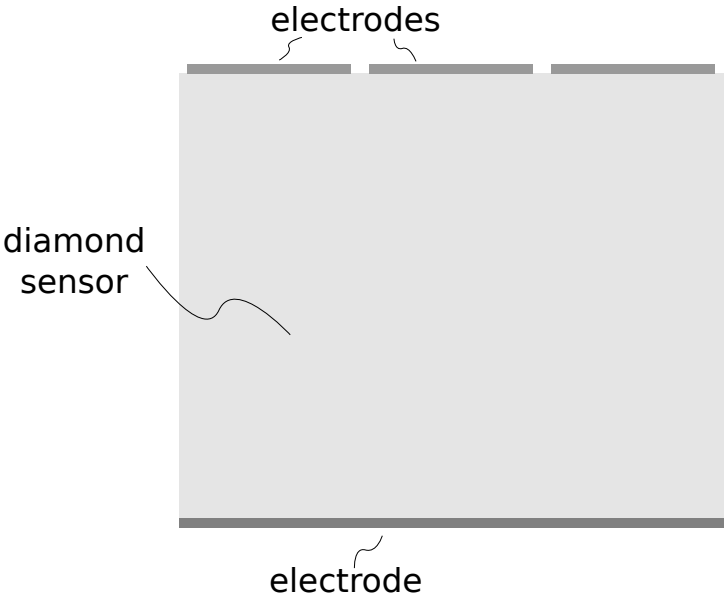
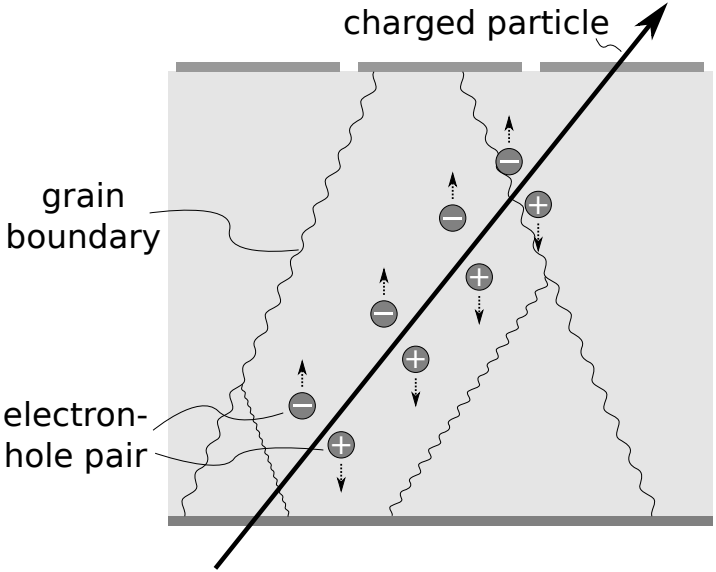
Challenge

- Charges are trapped at lattice defects
- Diamond with less defects (i.e. higher CCD) is more expensive

Planar vs. 3D



Planar vs. 3D



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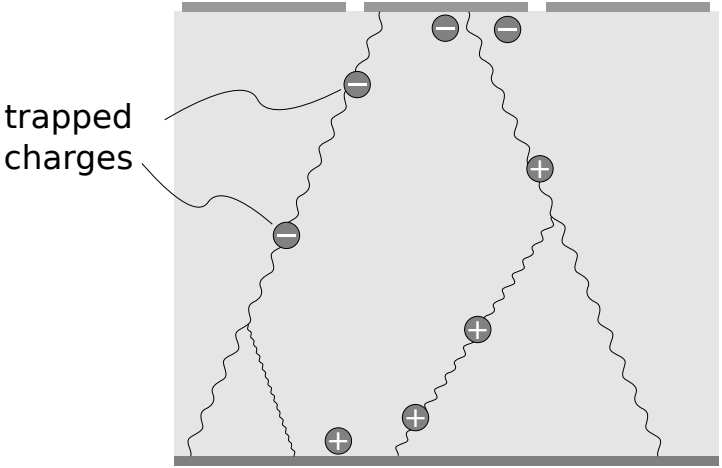

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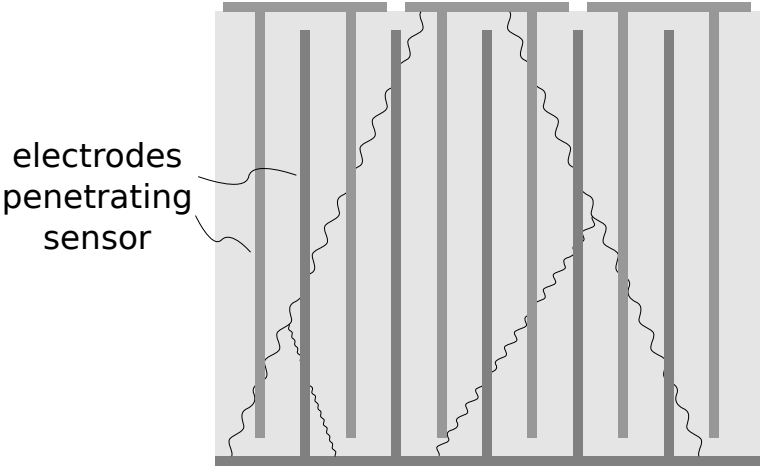

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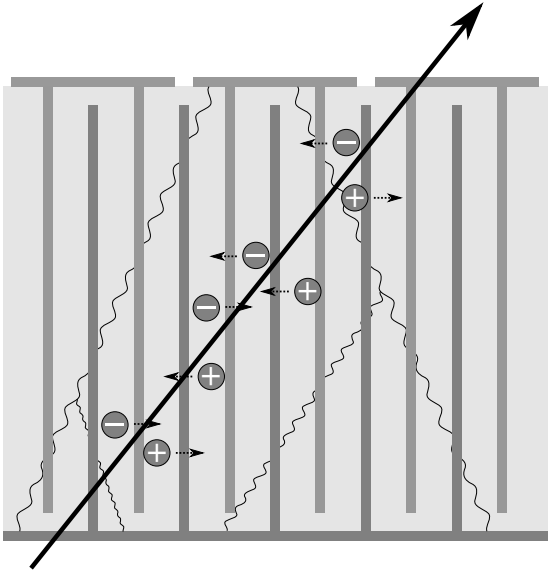

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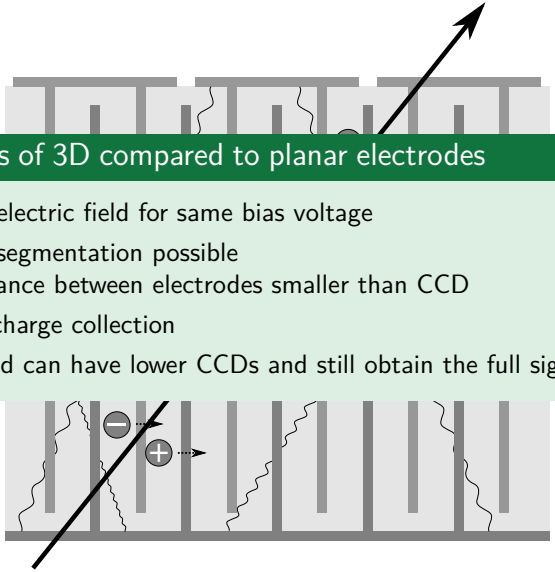
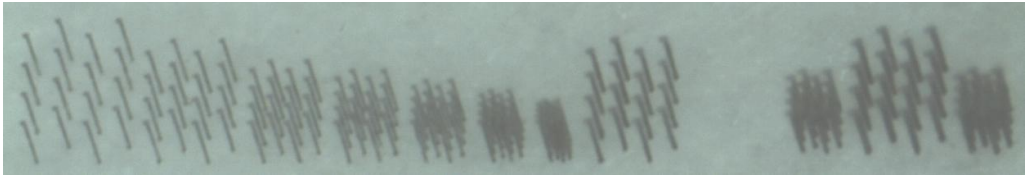


Advantages of 3D compared to planar electrodes

- Higher electric field for same bias voltage
- Higher segmentation possible
  $\rightarrow$ Distance between electrodes smaller than CCD
- Faster charge collection
- Diamond can have lower CCDs and still obtain the full signal

Producing electrodes in diamond

- Graphite is a conductor
  $\Rightarrow$ convert sp^3 (diamond) to sp^2 (graphite) using a femtosecond laser
- Move focal plane from back- to frontside through the diamond
  $\rightarrow$ seed and exit side for conductive channels
  $\Rightarrow$ electrode material is identified as combination of diamond-like carbon, amorphous carbon & graphite by resistivity measurements
- Variable growth parameter: power of laser and velocity of focal plane through diamond

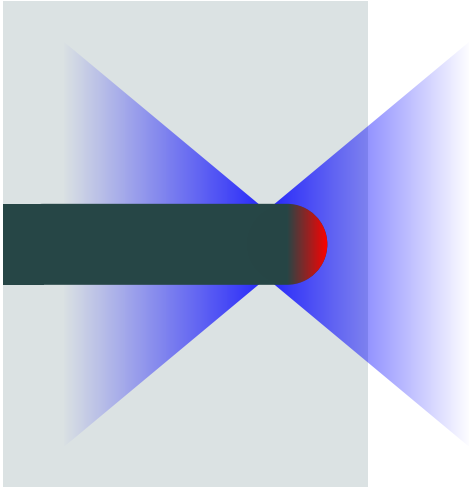


Producing conductive channels

diamond sensor

conductive channel

Producing conductive channels



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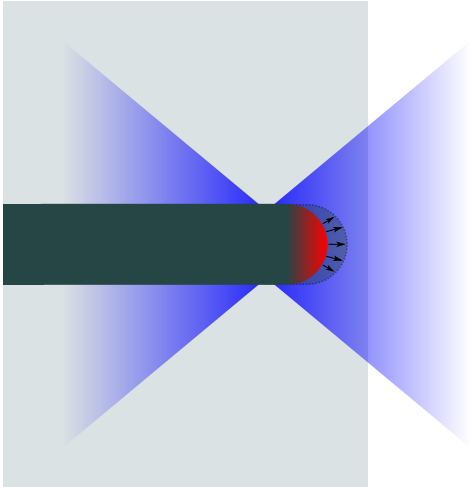
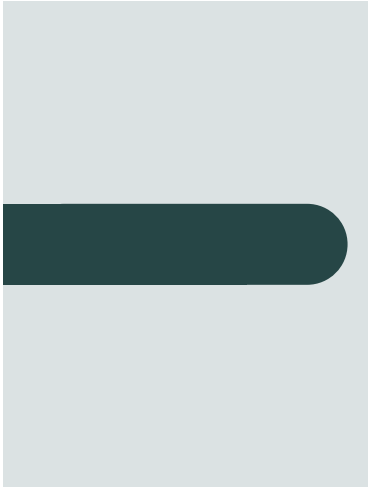
Producing conductive channels



- Tip of conductive channel heats up
- Hot electrons dissipate into the diamond
- Diamond opaque due to hot electrons
  $\rightarrow$ Laser is absorbed until phase change threshold is reached

Producing conductive channels



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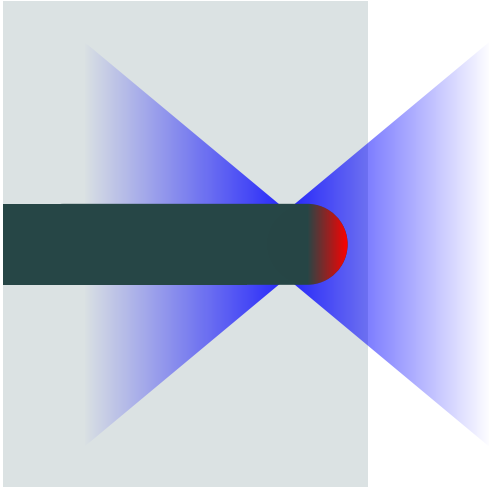

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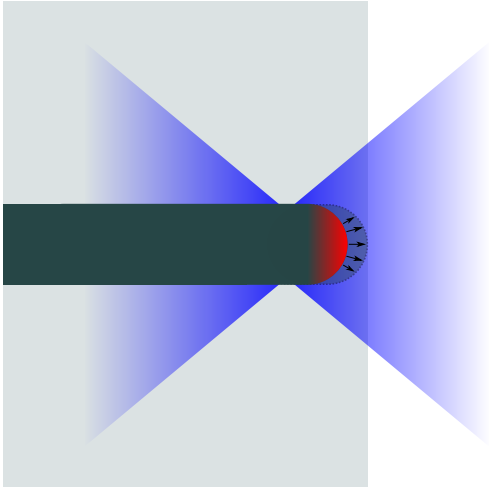

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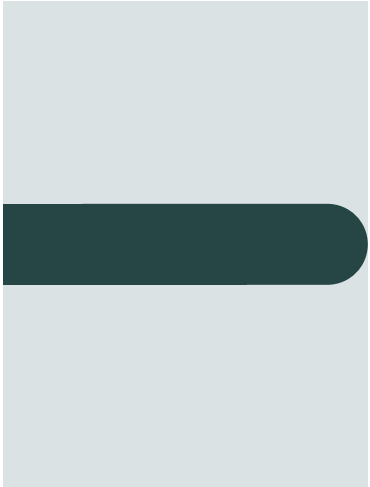

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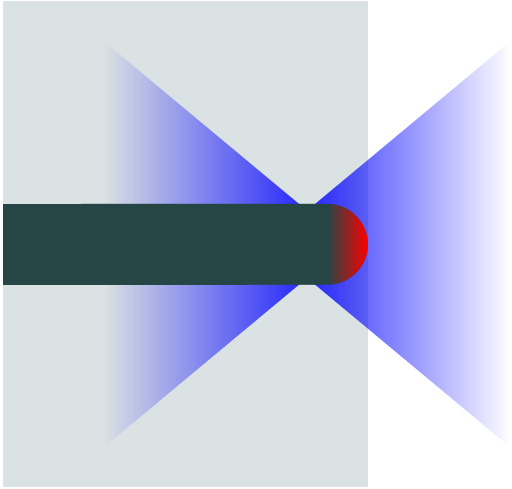

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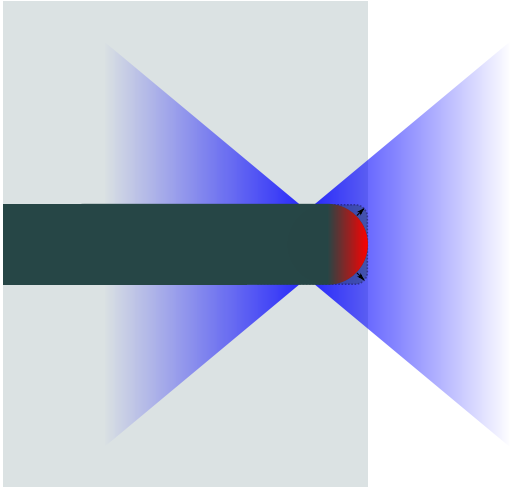

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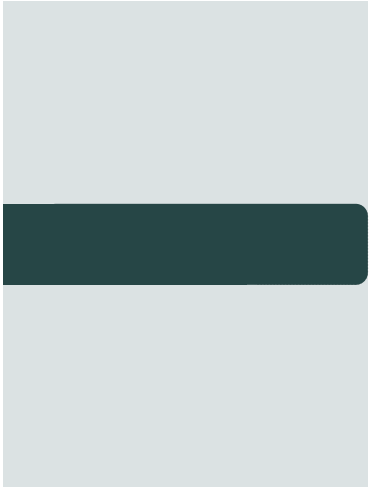

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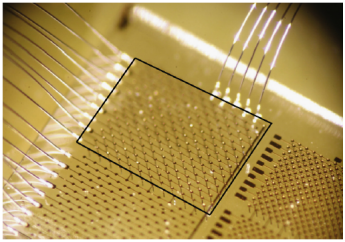
Testbeam: sample

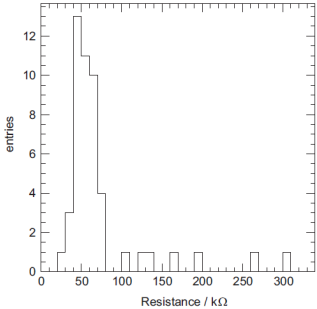
Sample properties

- scCVD electronic grade
- $4.7 \times 4.7\,\mathrm{mm}^2$, $420\,\mu\mathrm{m}$ thick
- Full charge collection only at 450 V with planar electrodes $\rightarrow$ indicative of a defect-rich material

Production of channels

- 800 nm, 100 fs Ti-Sapphire laser @ 1 kHz
- Diameter of focal plane: $4\,\mu\mathrm{m}$
- Energy density: $2\,\mathrm{J\,cm}^{-2}$
- Velocity: $20\,\mu\mathrm{m\,s}^{-1}$
- 219 channels with $92.0 \pm 0.3\%$ yield
- Cell size $150 \times 150\,\mu\mathrm{m}^2$

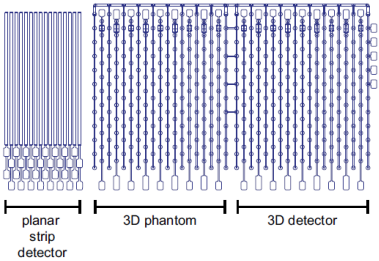


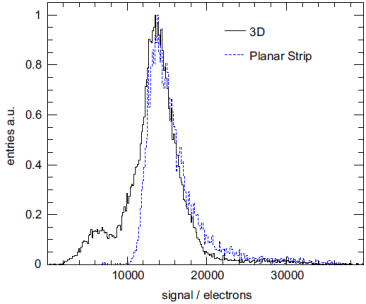


Taken from F. Bachmair et. al., "A 3D diamond detector for particle tracking", NIM A 786 (2015)

Testbeam: setup

- 3 different regions:
  - Planar strip @ 500 V
  - 3D w/o conductive channels @ 25 V
  - 3D with conductive channels @ 25 V
  - → Test different configurations on same sample
- Testbeam done at CERN SpS 120 GeV pions
- 8 layer strip telescope
- Readout via IDEAS VA2 chip ($\tau = 2\,\mu s$)





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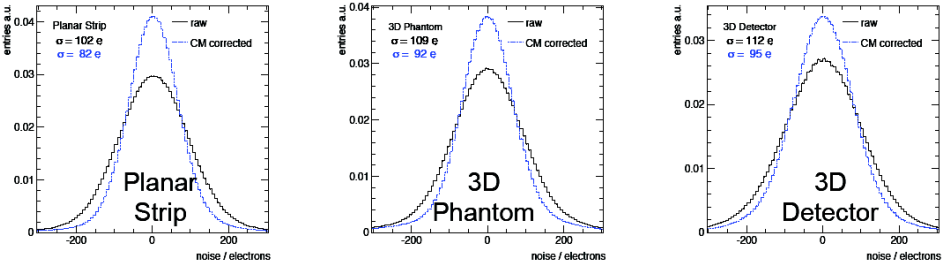
Testbeam: analysis

- Determine pedestal of each channels from first 500 events
  - Update value using "sliding window" (500 events)
  - Exclude signal events (5σ)
- Subtract pedestal and common mode noise
- Only single track events
- "Transparent" analysis:
  - No cuts on diamond signal
  - Sum of the three strips closest to track



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Testbeam: defect channels

- Negative charge contributions observed in transparent clusters
- Cut at 7σ $\rightarrow$ not due to statistical fluctuations

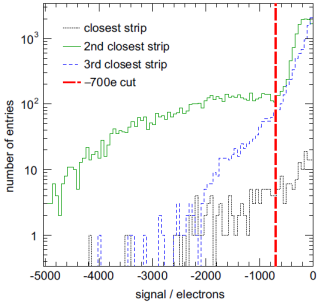
- Track position near bias channels

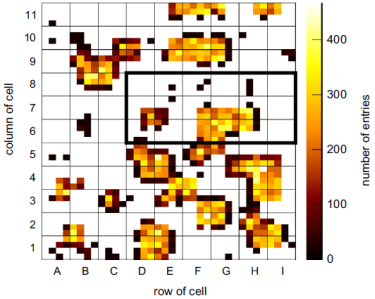
$\rightarrow$ Missing conductive channel

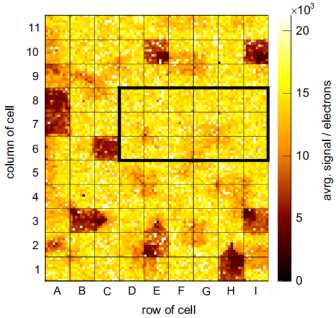
- Effect modelled in TCAD simulations

- Cells with lower charge: missing read out channels
- Verified by resistance measurements

$\Rightarrow$ Define fiducial region with few missing conductive channels







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Testbeam: results

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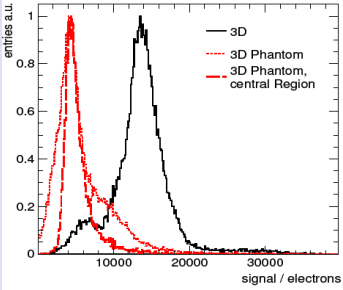
3D with vs. 3D w/o channels

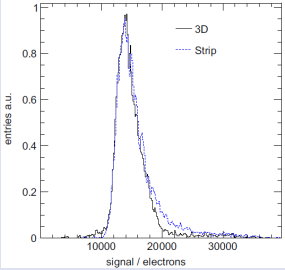
- Compare region with conductive channels to same electrode pattern w/o channels
- Significantly more charge collected with conductive channels

→ Channels do collect charge



3D vs. strip

- Strip electrodes fully collect charges
- Cut on fiducial region of 3D structure
- Cut on events with negative charge ($> 7\sigma$)
- Cluster charge from 3D and strip agrees quiet well



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Conductive channels in pCVD

- Tried to reproduce results with pCVD diamond and different laser → Goal: pixel detector
- Improve connectivity of channels

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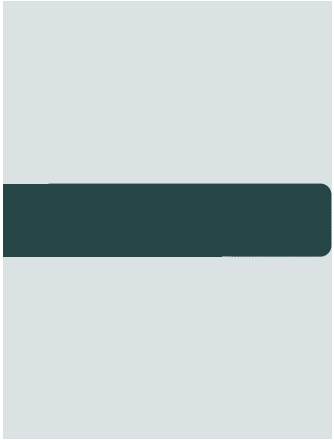

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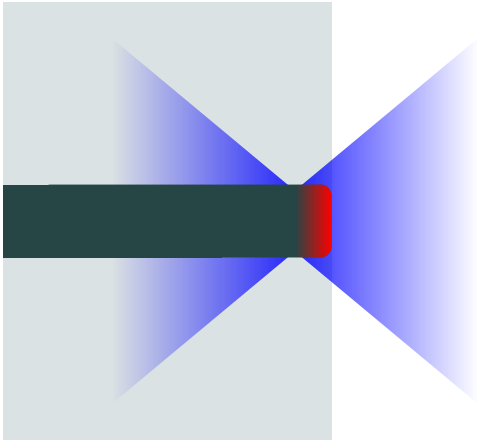

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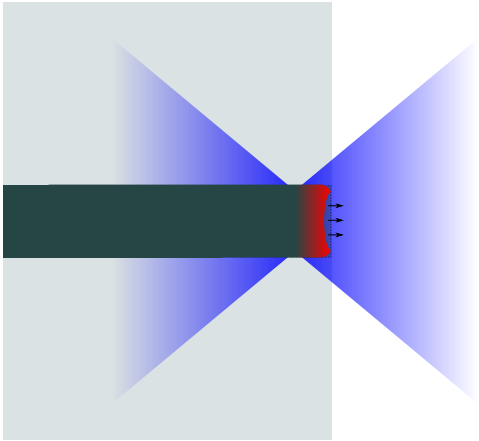

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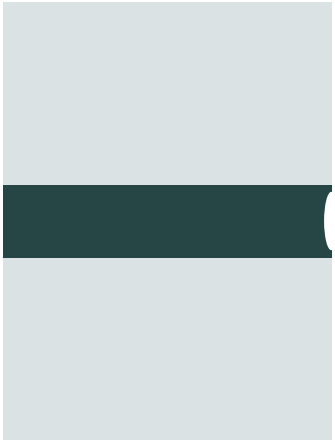

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→ Crater-like structure on the exit side

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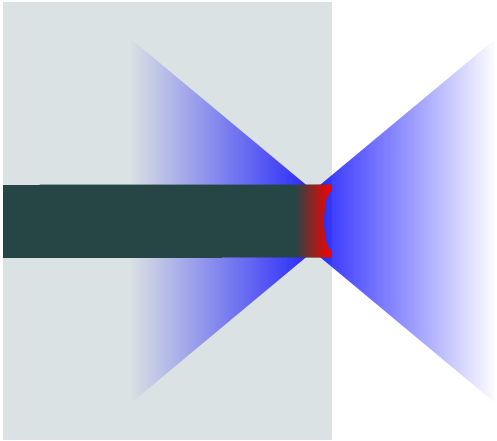

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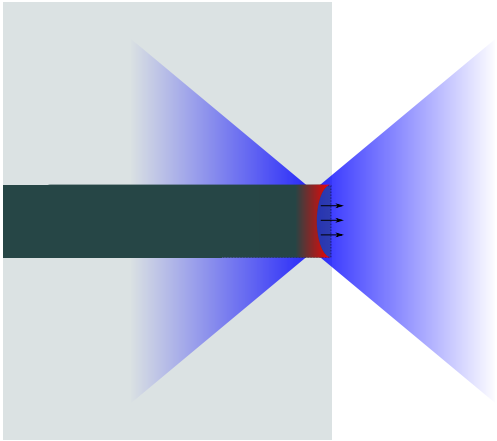

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Conductive channels in pCVD

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- Improve connectivity of channels

- At the surface the channel is exposed several times to the laser
- Material is heated up again
- Material evaporates

→ Crater-like structure on the exit side

- Different structures of conductive channels on seed and exit side

Sample preparation

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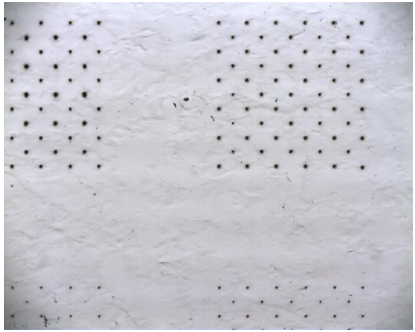
Sample properties

- pCVD
- approx. $10 \times 10\,\mathrm{mm}^2$, $500\,\mu\mathrm{m}$ thick

Production of channels

- Laser at Laser-Laboratorium Göttingen e.V. used
- 1043 nm, 290 fs Yb:YAG laser @ 200 kHz
- Diameter of focal plane: $1.6\,\mu\mathrm{m}$
- Settings of growth parameters:
  - Power: $10 - 150\,\mathrm{mW}$ ($10\,\mathrm{mW} \approxeq 2\,\mathrm{J\,cm^{-2}}$)
  - Diamond velocity: $50 - 10.000\,\mu\mathrm{m\,s^{-1}}$
- 246 channels with 88% yield (optical inspection)



Goal: Find best growth parameters for this setup

Raman spectroscopy: validation

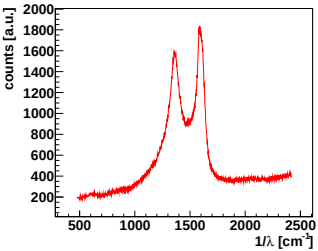
Raman spectroscopy

- Technique to investigate bound states
- Excite electrons to vibrational states
  $\rightarrow$ measure wavelength shift
- 488 nm laser setup used at geology department
- Spot size $\mathcal{O}(2\,\mu\text{m})$
  $\rightarrow$ smaller than channel diameter

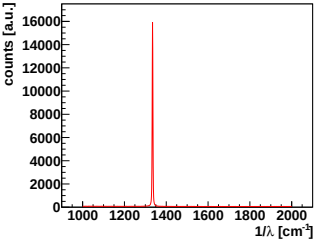
Reference measurements

- Two conductive pure graphite samples
- G- and d-peak clearly visible:

  g-peak: ordered graphite, $\approx 1580 - 1600\,\text{cm}^{-1}$
  d-peak: unordered graphite, $\approx 1350\,\text{cm}^{-1}$
- Peak at $1332\,\text{cm}^{-1}$ for pure diamond sample

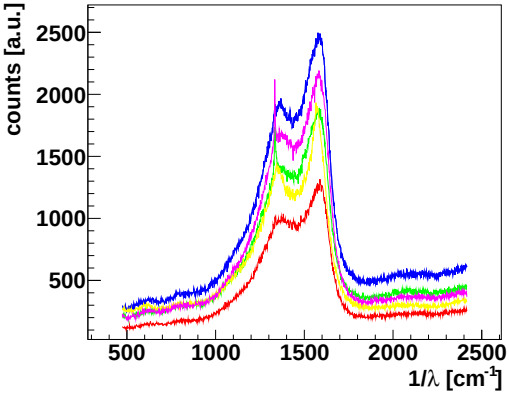


(a) Pure graphite sample

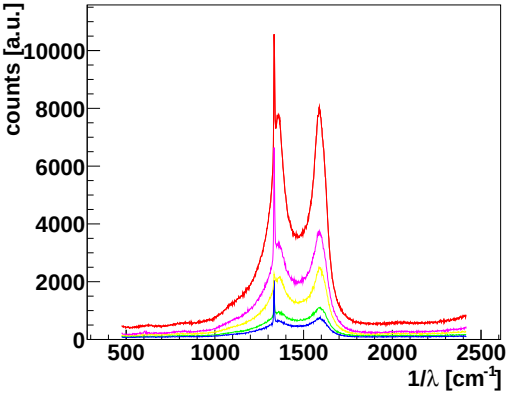


(b) Pure diamond sample

Raman spectroscopy: results



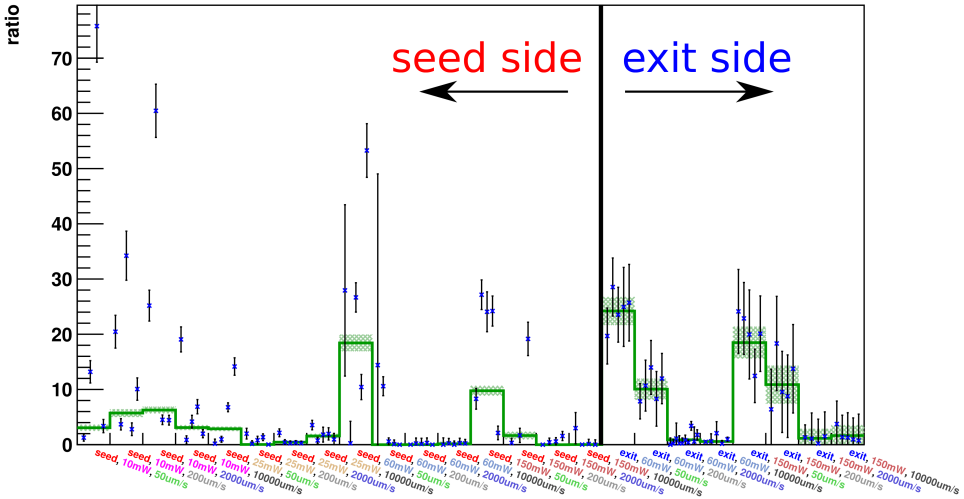
(a) Seed, 60 mW, 10 mm/s



(b) Exit, 60 mW, 10 mm/s

- At least five channels grown for each growth parameter setting (same colour $\widehat{=}$ same channel)
- Graphite contribution on both sides
- Diamond contribution more apparent on exit side $\rightarrow$ part of graphite burned away

Raman spectroscopy: results



- Ratio of diamond- to g-peak: $c_{diamond}/c_{g-peak}$
- Dots $\widehat{=}$ single measurement, bins $\widehat{=}$ weighted mean value
- Lower value $\rightsquigarrow$ less diamond, more graphite
- Better results for higher power/velocity

Conclusion

Conclusion

- Concept of 3D electrodes in diamond is working
  $\rightarrow$ allows collection of more charge from lower quality diamonds
- Electrodes produced with femtosecond laser
- Testbeam shows full charge collection
- Different structures for conductive channels on seed and exit side

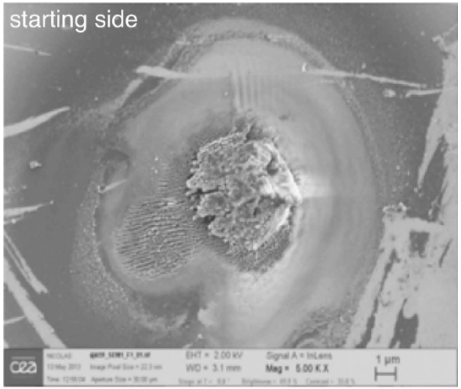
Outlook

- Use of pCVD, lower grade diamonds
- Build a module prototype:
  - Metallisation from both sides
  - Pixel-wise readout with ATLAS Pixel front end
- Address production aspects
- Explore alternatives to laser induced phase change (e.g. etching)

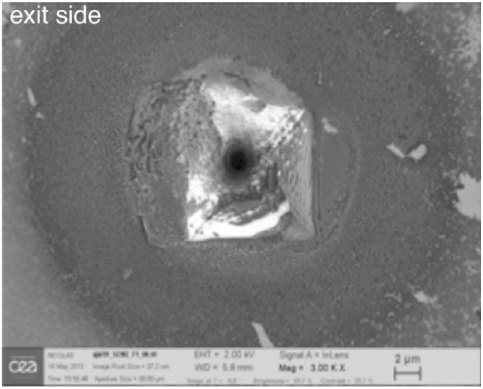
Thank you for your attention.

Backup

SEM



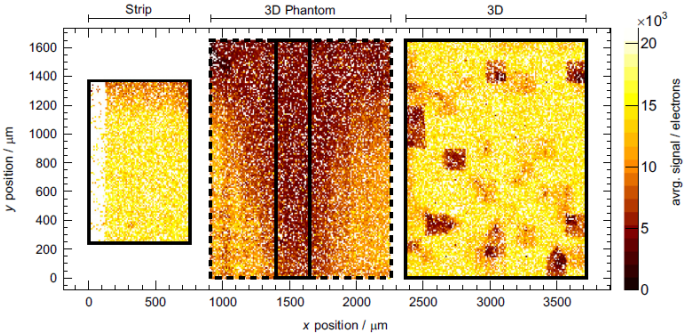
(a) Seed



(b) Exit

Taken from F. Bachmair et. al., "A 3D diamond detector for particle tracking", NIM A 786 (2015)

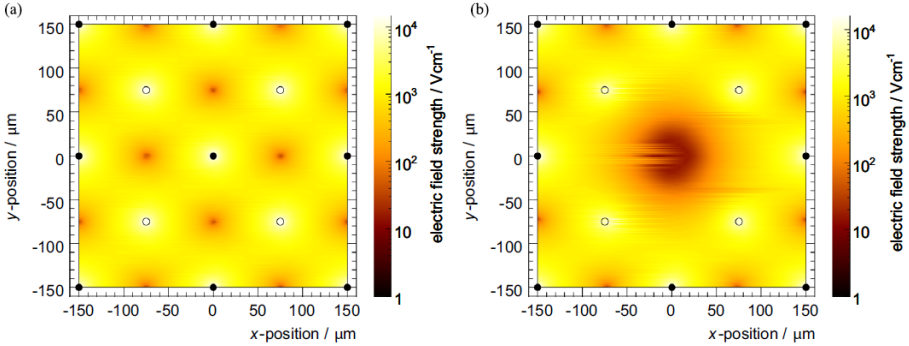
Charge map



- Average charge signal for predicted track position
- 3D phantom influenced by neighbouring detectors
  → use central strips only
- Part of strip detector outside of trigger window
- Fiducial regions marked

Taken from F. Bachmair et. al., "A 3D diamond detector for particle tracking", NIM A 786 (2015)

TCAD simulation

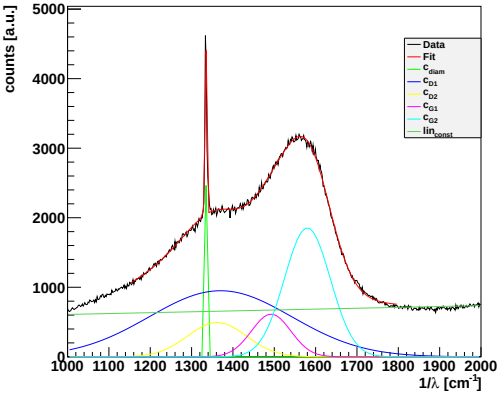


(a) Field in fully working cell

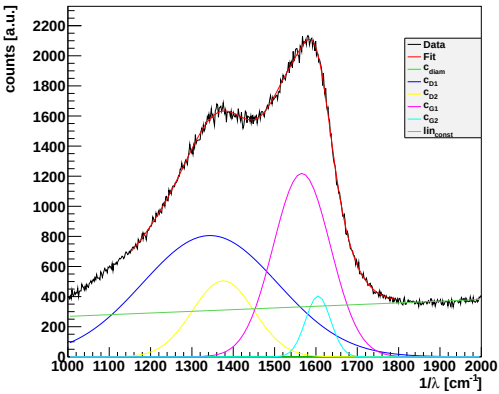
(b) Field with missing conducting bias channel in the centre

Taken from F. Bachmair et. al., "A 3D diamond detector for particle tracking", NIM A 786 (2015)

Raman spectroscopy: fitting



(a) Seed, 25 mW, 50 µm/s



(b) Seed, 60 mW, 2 mm/s

- Fit spectra with five Gaussians + linear
- Diamond peak badly modelled → extra fit on peak region