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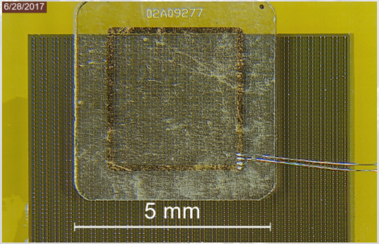

Diamond Detector Technology: Status and Perspectives

EPS Conference (Venice, Italy)

Michael Reichmann
on behalf of the RD42 Collaboration

7th July 2017

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Section 1

Motivation

Motivation

- innermost layers → highest radiation damage (100 MHz/cm^2 to 200 MHz/cm^2)
- current detector is designed to survive ∼12 month in High-Luminosity LHC
- → **R&D for more radiation hard detector designs and/or materials**

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- → **R&D for more radiation hard detector designs and/or materials**

Diamond as Detector Material:

- properties
  - radiation tolerance
  - isolating material
  - high charge carrier mobility
  - smaller signal than in silicon

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Diamond as Detector Material:

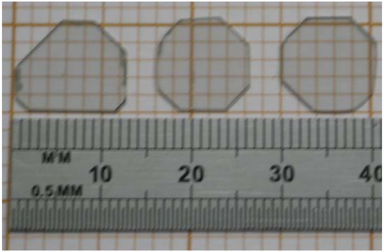
- properties
  - radiation tolerance
  - isolating material
  - high charge carrier mobility
  - smaller signal than in silicon
- investigation of the signal independence/dependence on incident particle flux in various detector designs:
  - pad → full diamond as single cell readout
  - pixel → diamond sensor on pixel chips
  - 3D → strip/pixel detector with clever design to reduce drift distance

Section 2

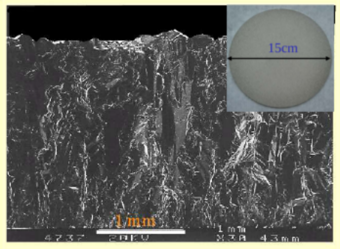
Diamond Types

Diamond Types

- diamonds artificially grown with chemical vapour deposition (CVD)
- investigation of two different diamond types:



(a) single-crystalline CVD



(b) poly-crystalline CVD (courtesy of E6)

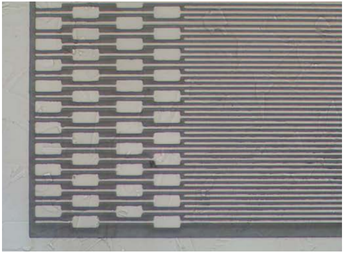
- only small sizes ($\sim$0.25 cm^2)
- large wafers (5″ to 6″ ⌀)

- pCVD signals smaller than scCVD (1:2) in planar configuration

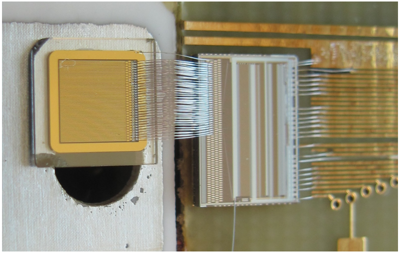
Section 3

Radiation Tolerance

Devices



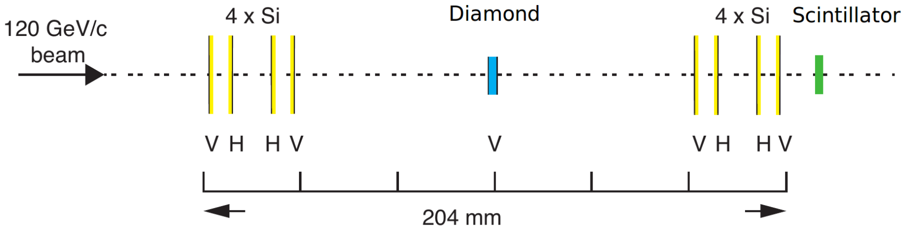
(a) strip metalisation pattern



(b) mounted diamond with amplifier

- patterning the diamonds → create pad, strip and pixel devices
- metalisation on both sides → almost edgeless
- segmentation critical for radiation studies → charge & position

Schematic Beam Test Setup



- characterisation of irradiated devices in beam tests
- transparent or unbiased hit predictions from telescope

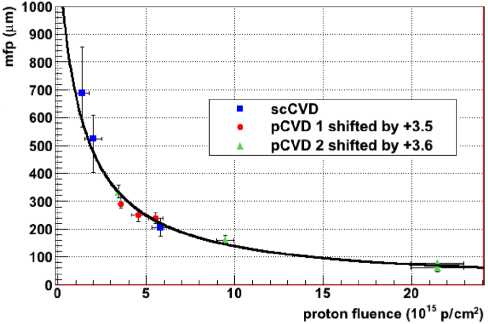
Irradiation at CERN PS with 24 GeV protons

damage equation:

$$n = n_0 + k\phi$$

$$\frac{1}{mfp} = \frac{1}{mfp_0} + k\phi$$

n_0 – initial number of traps
mfp_0 – initial mean free path
k – damage constant
ϕ – fluence



- assume same mean free path for electrons and holes
- results up to 2.2×10^{16} p/cm^2 (~500 Mrad)
- same damage curves and constant (k) for scCVD and pCVD diamonds
- larger mfp_0 performs better at any fluence

Charge Collection Distance (ccd) vs. Mean Free Path (mfp)

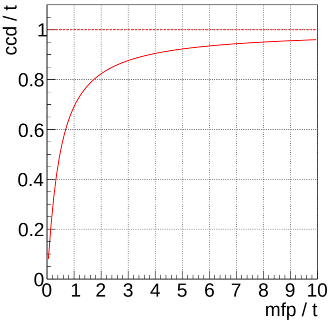
- ccd = average distance between electron and hole until trapped
- for scCVD: ccd $\sim$ thickness, for pCVD: ccd $<$ thickness
- ccd direct measurement (no correction)
- mfp correct theory $\rightarrow$ correct data with assumptions (i. a. $\mathrm{mfp_e} = \mathrm{mfp_h}$)

equation for ccd:

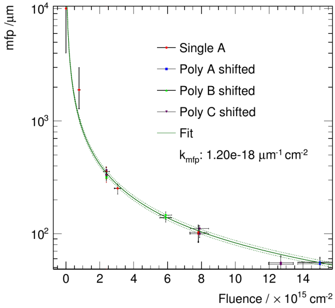
$$\frac{\mathrm{ccd}}{\mathrm{t}} = \sum_i \frac{\mathrm{mfp}_i}{\mathrm{t}} \left(1 - \frac{\mathrm{mfp}_i}{\mathrm{t}} \left(1 - e^{-\frac{\mathrm{t}}{\mathrm{mfp}_i}}\right)\right)$$

t – thickness

i – electrons & holes



Summary of Proton, Neutron and Pion Irradiation



(a) irradiation at LANL with 800 MeV protons (up to 1.4×10^{16} p/cm^2)

Particle	Energy	Relative k
Proton	24 GeV	1.0
	800 MeV	1.79 ± 0.13
	70 MeV	2.4 ± 0.4
	25 MeV	4.5 ± 0.6
Neutron	1 MeV	4.5 ± 0.5
Pion	200 MeV	$2.5 - 3$

(b) summary

Section 4

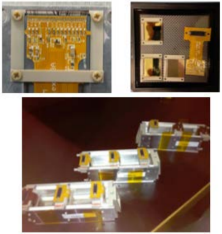
Diamond Devices in Experiments

Diamond Devices in Experiments

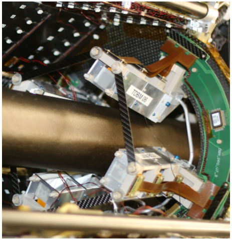
- beam condition/loss monitors
  - essential in all modern collider experiments
- current generation pixel detectors
  - **ATLAS Diamond Beam Monitor (DBM)**
- future HL-LHC trackers
  - **3D diamond detectors**
- future beam condition/luminosity monitor
  - multipad design BCM'

ATLAS DBM

- diamond pixel detectors in ATLAS (tracking)
- total production of 45 diamonds (t $= 500\,\mu m$) on FE-I4b chips
- module assembly at CERN
- installed during LS1
- 8 telescopes (2 Si & 6 Diamond) symmetric around ATLAS IP
- thresholds tuned to $\sim$2500 e



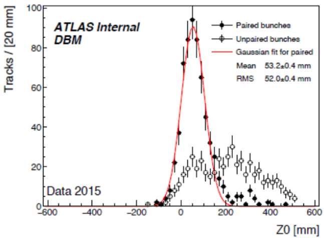
(a) cable, detectors, telescopes



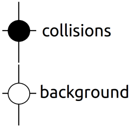
(b) 4 mounted telescopes

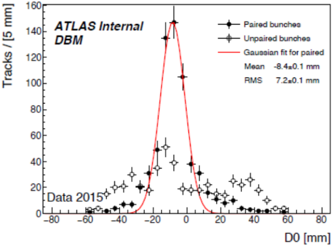
Tracking

- reconstruction of tracks from hits of 3 modules



(a) longitudinal distance to IP





(b) radial distance to IP

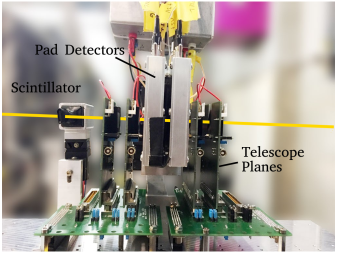
- plots with initial alignment
- clear discrimination between background and collisions
- loss of modules (Si/D)
  - successful re-commissioning of surviving modules
- diamond and Si modules now part of ATLAS data taking

Section 5

Rate Studies

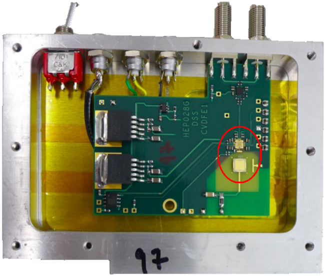
Setup

- rate studies conducted with 260 MeV/c π^+ at Paul Scherrer Institute (PSI)
- tunable particle fluxes from $\mathcal{O}\left(1\,\mathrm{kHz/cm^2}\right)$ to $\mathcal{O}\left(10\,\mathrm{MHz/cm^2}\right)$
- detectors tested in ETHZ beam telescope (based on CMS-Pixel-Chips)

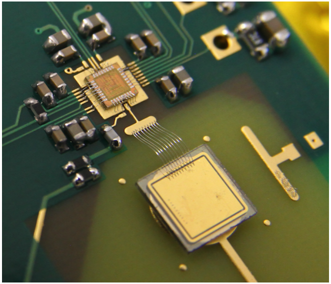


- 4 tracking planes with particle trigger
- scintillator for precise trigger timing $\rightarrow \mathcal{O}\left(1\,\mathrm{ns}\right)$

Pad Detectors



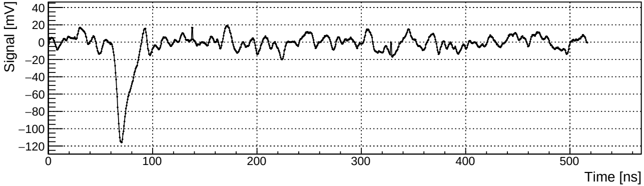
(a) fast amplifier box

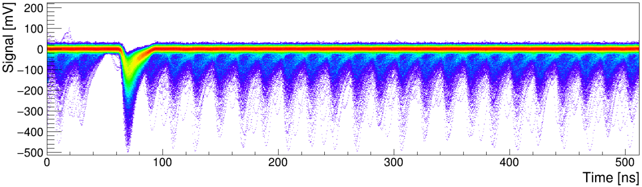


(b) diamond and fast amp

- diamonds in custom built amplifier boxes from Ohio State University (OSU)
- cleaning, photo-lithography and Cr-Au metallisation at OSU
- low noise, fast amplifier with $\mathcal{O}(5\text{ns})$ rise time
- prototype for HL-LHC BCM/BLM

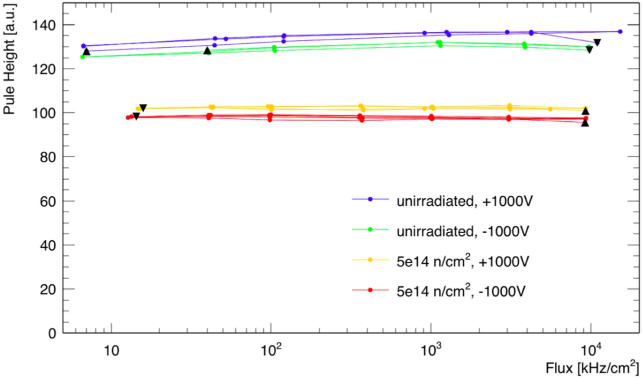
Waveforms





- fast amplifier and good timing resolution → resolve bunch structure of PSI beam
- bunch spacing of 19.8 ns clearly visible

Results



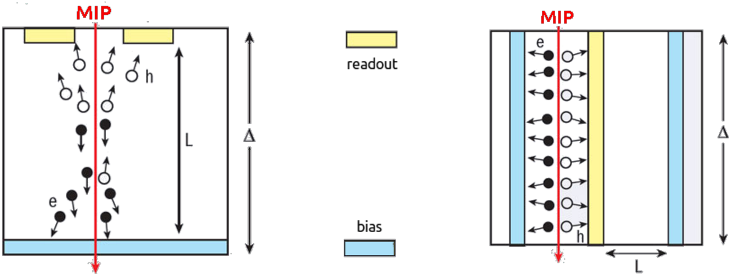
- no rate dependence observed in pCVD diamonds up to 10 MHz/cm^2
- no absolute pulse height and noise calibration yet
- extending radiation doses to 1×10^{16} n/cm^2

Section 6

3D Detector Development

Detector Concept

- after large irradiation → all detector materials trap limited (mfp $< 75\,\mu m$)
- **keep drift distances smaller than mean free path**

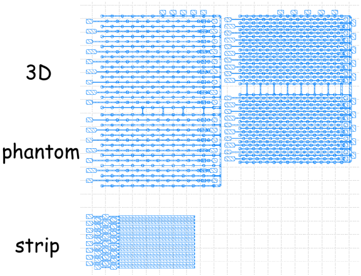


(a) planar detector (b) 3D detector

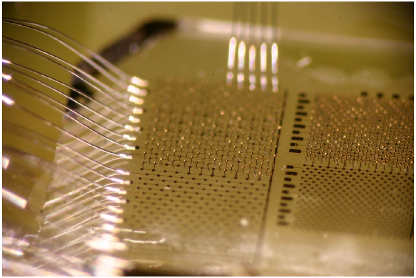
- bias and readout electrode inside detector material
- same thickness Δ → same amount of induced charge → shorter drift distance L
- electrode columns drilled with 800 nm femtosecond laser
- convert diamond into resistive mixture of carbon phases

3D Multi Detector (2015)

- pCVD diamond with 3D, phantom and strip detector on single sensor
- 3D column efficiency of 92 %
- 3D cell size: 150 µm × 150 µm
- signal read out as ganged cells



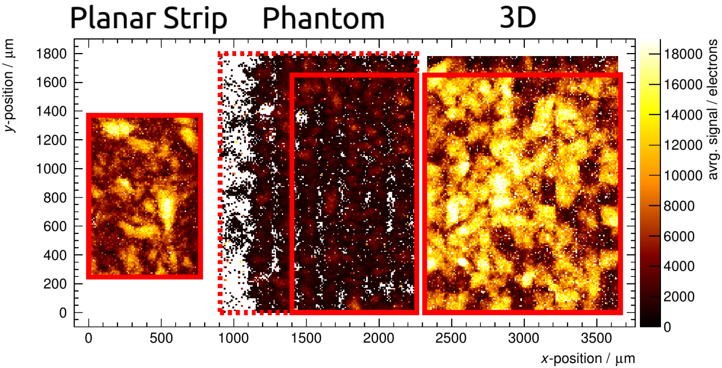
(a) metalisation pattern



(b) photograph

3D Multi - Signal Map

- square cells visible (9 broken cells)
- signals in 3D already bigger by eye
- phantom (no columns) → no pulse height

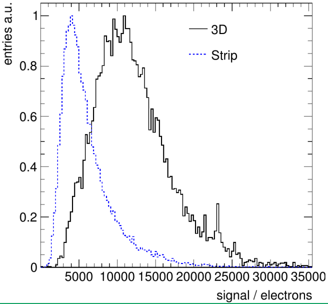


3D Multi - Result

- measured signals for diamond thickness 500 μm:

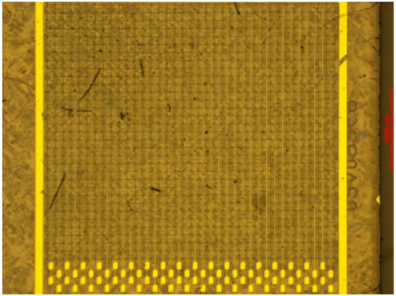
Device	Mean Charge [e]	ccd [μm]
planar strip	6900	192
3D	13500	350 – 375*

- $^*ccd_{eq}$ - equivalent ccd to observe same charge in planar device
- **collect > 75 % charge in pCVD for the first time**

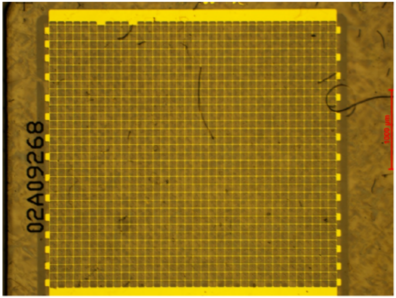


Full 3D Detector (May/Sep 2016)

- 3 dramatic improvements compared to 3D Multi:
  - an order of magnitude more cells: from 99 to 1188
  - smaller cell size: 100 μm × 100 μm
  - higher column efficiency: from 92 % to 99 %



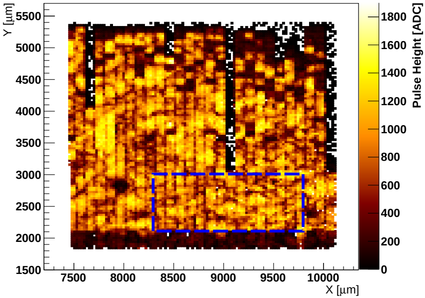
(a) readout side



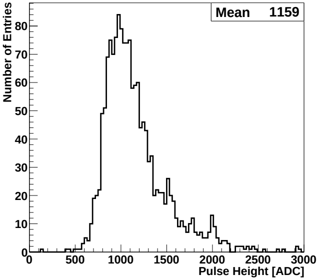
(b) bias side

Full 3D Preliminary Results

- analysis in progress
- device seems to perform well
- see charge in entire detector
- largest charge collection in pCVD yet
  - **>85 % over contiguous region**



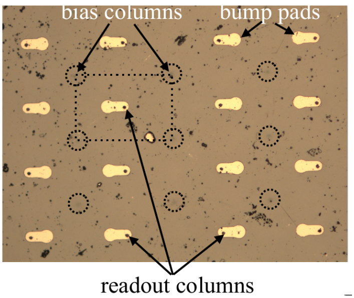
(a) charge map



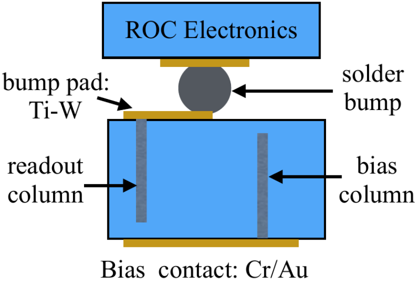
(b) charge distribution

3D Pixel Detector - Fabrication

- cleaning and photo-lithography
- connect to bias and readout with surface metallisation
- bump and wire bonding

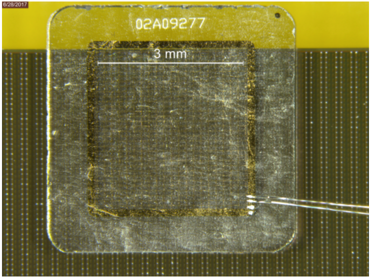


(a) pixel readout metalisation

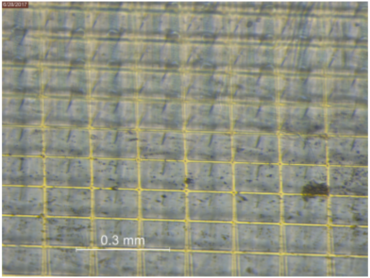


(b) final scheme

3D Pixel Detector



(a) detector bonded on CMS-Pixel-Chip



(b) bias grid and R/O columns

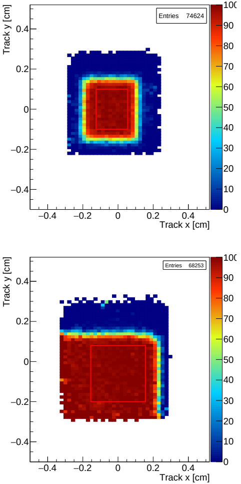
- successful production of a working 3D pixel detector

3D Pixel Detector - Preliminary Results

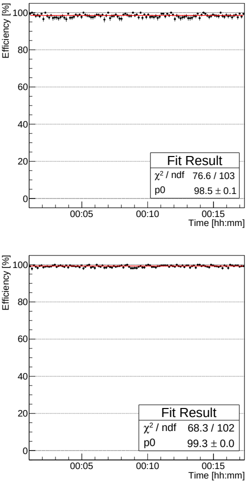
3D Diamond Pixel
→ **98.5 % Efficiency**

- efficiencies flat in time
- pixel threshold: 1500 e
- lower efficiency in diamond probably due to due to low field regions

Planar Silicon Pixel (Ref)
→ **99.3 % Efficiency**



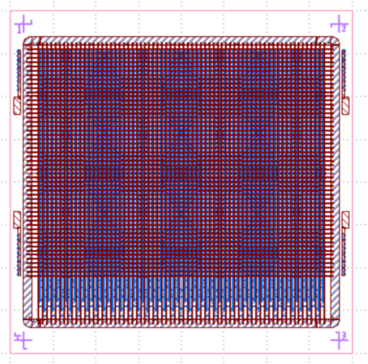
(a) efficiency maps



(b) hit efficiencies

3D Pixel Detector - New Design

- currently producing 3500 cell pixel prototype with 50 µm pixel pitch
- two independent drillings (Oxford - complete, Manchester - in progress)
- bump bonding at Princeton (CMS) and IFAE (ATLAS)
- CMS device probably ready for August beam tests



Section 7

Conclusion

Conclusion

- impact of diamonds in LHC is increasing
- one of the first pixel projects started taking data:
  - ATLAS DBM re-commissioned for 13 TeV collisions
- quantification and understanding of the rate effects in diamond
  - pCVD shows no rate effect up to 10 MHz/cm^2
  - shown for fluence up to 5×10^{14} n/cm^2
- great progress in 3D detector prototypes
  - 3D works in pCVD diamond; scale up and smaller cells also worked
- production and successful test of 3D diamond pixel devices
  - efficiency looks good; pulse height in progress