

## New Beam Test Results of 3D Pixel Detectors Constructed With Poly-Crystalline CVD Diamond

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## Section 1

### Motivation

# Diamond as Detector Material

- innermost tracking layers  $\rightarrow$  highest radiation damage  $\mathcal{O}$  (GHz/cm<sup>2</sup>)
- current detectors is designed to survive  $\sim 12$  month in High-Luminosity LHC
- $\rightarrow$  **R&D for more radiation tolerant detector designs and/or materials**

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## Diamond as Detector Material:

- properties
  - ▶ radiation tolerant
  - ▶ isolating material
  - ▶ high charge carrier mobility
  - ▶ smaller signal than in silicon with same thickness (large bandgap)
  - ▶ after  $1 \cdot 10^{16}$  n/cm<sup>2</sup> the mean drift path in diamond larger than in silicon

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## Work of RD42:

- investigate signals and radiation tolerance in various detector designs:
  - ▶ Pad Detectors  $\rightarrow$  whole diamond as single cell readout
  - ▶ Pixel Detectors  $\rightarrow$  diamond sensor on pixel readout chip
  - ▶ 3D Pixel Detectors  $\rightarrow$  3D diamond detector on pixel readout chip

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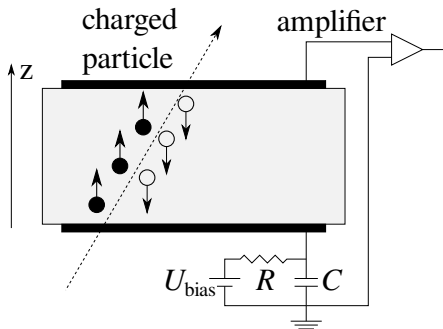
- investigate signals and radiation tolerance in various detector designs:
  - ▶ Pad Detectors
  - ▶ Pixel Detectors
  - ▶ 3D Pixel Detectors  $\rightarrow$  this talk

## Section 2

### 3D Diamond Detector



# Diamond as Particle Detector



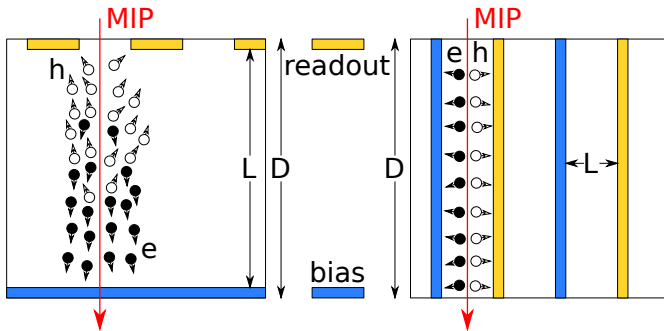
(a) Detector Schematics



(b) 15 cm  $\varnothing$  pCVD Diamond Wafer

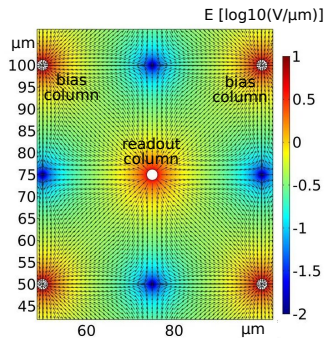
- detectors function as ionisation chambers
- metallisation on both sides
- poly-crystals produced in large wafers

# Working Principle



- after large radiation fluence all detectors become trap limited
- 3D = bias and readout electrode inside detector material
- same thickness  $D \rightarrow$  same amount of induced charge  $\rightarrow$  shorter drift distance  $L$
- **increase collected charge in detectors with limited mean drift path (Schubweg)**

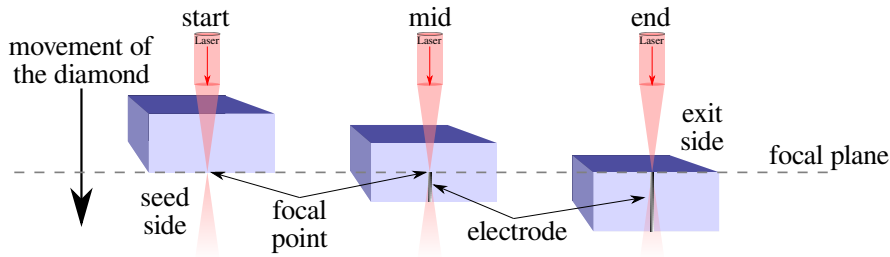
# Electric Field Simulation



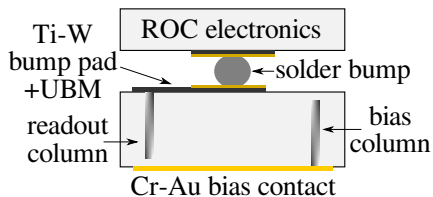
- simulation with 30 V bias voltage and periodic boundary conditions
- electric field  $\sim 1 \text{ V}/\mu\text{m}$  over a large area in the cell
- low field region in between the electrodes

# Laser drilling

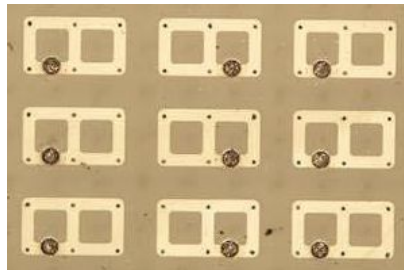
- “drilling” columns using 800 nm fs-LASER (Oxford)
- convert diamond into resistive mixture of carbon phases (i.a. DLC, graphite, ...)
- usage of Spatial Light Modulation (SLM) to correct for vertical aberration
- initial column yield  $\sim 90\%$   $\rightarrow$  now  $\geq 99\%$
- initial column diameter  $6 \sim 10\ \mu\text{m}$   $\rightarrow$  now  $2.6\ \mu\text{m}$



# Bump Bonding



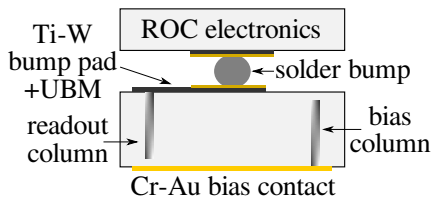
(a) Bump bond schematics



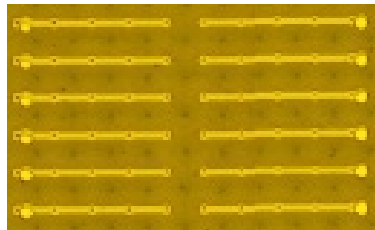
(b)  $3 \times 2$  bump pads

- connection to bias and readout with surface metallisation
- ganging of cells to match pixel pitch of readout-chip (ROC)
- small gap ( $\sim 15 \mu\text{m}$ ) to the surface to avoid a high voltage break-through

# Bump Bonding



(a) Bump bond schematics



(b)  $1 \times 5$  bump pads

- connection to bias and readout with surface metallisation
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# Progress in Diamond Detectors

## 3D Detectors - History in Diamonds:

- proved that 3D works in pCVD diamond
- scale up the number of columns per detector:  $\mathcal{O}(100) \rightarrow \mathcal{O}(1000)$  (x40)
- reducing the cell size:  $150\text{ }\mu\text{m} \times 150\text{ }\mu\text{m} \rightarrow 50\text{ }\mu\text{m} \times 50\text{ }\mu\text{m} \rightarrow 25\text{ }\mu\text{m} \times 25\text{ }\mu\text{m}$  (soon)
- reducing the diameter of the columns:  $6 \sim 10\text{ }\mu\text{m} \rightarrow 2.6\text{ }\mu\text{m} \rightarrow 1 \sim 2\text{ }\mu\text{m}$  (soon)
- $\rightarrow$  increasing column yield:  $\sim 90\% \rightarrow \geq 99\%$
- recently tested first irradiated  $50\text{ }\mu\text{m} \times 50\text{ }\mu\text{m}$  3D detector ( $3.5 \cdot 10^{15}\text{ n/cm}^2$ )

## 3D Pixel Detectors:

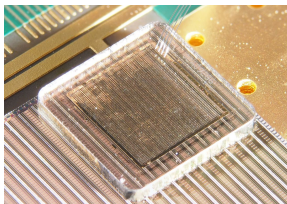
- visible improvements with each step reducing the cell size
- all worked as expected (to first order)

## Section 3

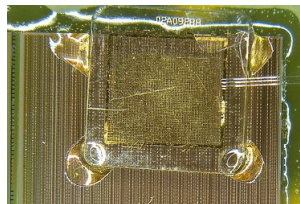
### Results



## Detectors



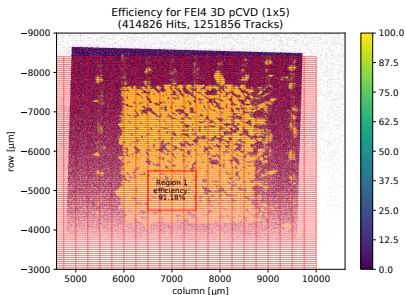
(a) II6-B5



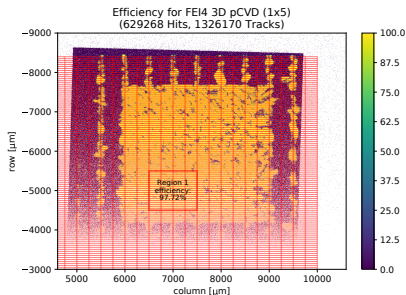
(b) II6-B6

	IIb-B5	II6-B6
readout chip (ROC)	FEI4-b	PSI46digv2.1respin
pixel pitch	$50\text{ }\mu\text{m} \times 250\text{ }\mu\text{m}$	$150\text{ }\mu\text{m} \times 100\text{ }\mu\text{m}$
3D cell size	$50\text{ }\mu\text{m} \times 50\text{ }\mu\text{m}$	$50\text{ }\mu\text{m} \times 50\text{ }\mu\text{m}$
ganging	$1 \times 5$	$3 \times 2$
size	$4.90\text{ mm} \times 4.94\text{ mm}$	$4.85\text{ mm} \times 4.90\text{ mm}$
thickness	$510\text{ }\mu\text{m}$	?
50 pixels $\times$ 50 pixels	$53 \times 67$	$67 \times 53$
3D columns	7223	7223
active area	$3.2\text{ mm} \times 3.5\text{ mm}$	$3.45\text{ mm} \times 3.19\text{ mm}$
bump bonding	tin silver (IFAE)	indium (Princeton)

## II6-B5 - Efficiencies @ CERN



(a) High threshold (1500 e)



(b) Low threshold (1000 e)

- spatial resolution of  $\sim 3\mu\text{m}$
- two different tunings of the FEI4 chip
- efficiency with low threshold significantly higher: 97.7%
- inefficiencies most likely due to bump bonding issues

# Time Over Threshold

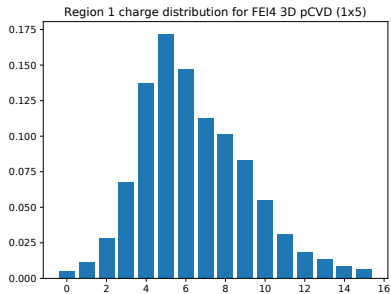
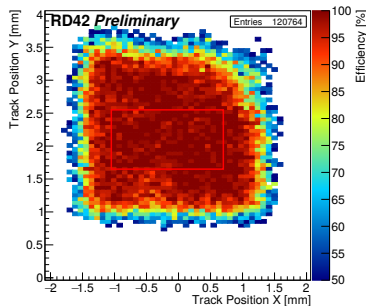


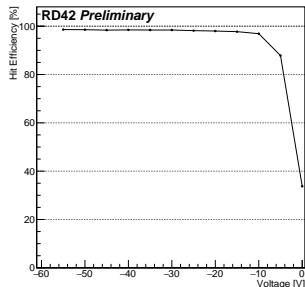
Figure: Time over threshold

- 5 tot  $\approx$  11 000 e
- MPV of the ToT distribution: 5  $\rightarrow$  11 000 e
- roughly 80 % the induced charge was collected

## II6-B6 - Efficiencies @ PSI



(a) Efficiency Map



(b) Efficiency vs. voltage.

- beam test right after the first bump bonding (top right corner badly bonded)
- spatial resolution of  $\mathcal{O}(100\ \mu\text{m})$
- efficiency in red fiducial area: Diamond: 99.2 %
- already fully efficient at 30 V
- ROC stopped working after this beam test

# Pulse Height @ PSI

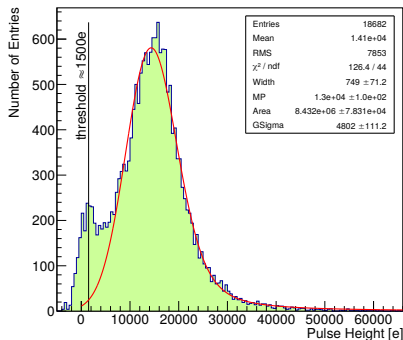


Figure: Pulse height distribution.

- trimmed threshold:  $\sim 1500 \text{ e}$
- Langau MPV:  $13\,500 \text{ e}$
- unreal distribution below threshold most likely due to data transmission problems

# Efficiencies @ CERN

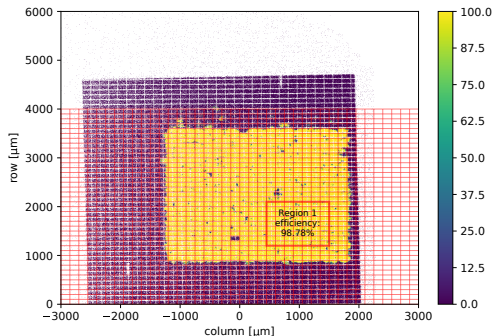


Figure: Efficiency at threshold of  $\sim 3500$  e

- high resolution measurement at CERN
- find non-working/non-connected cells
- sensor twice re-bump-bonded with the same indium (no reprocessing)
  - ▶ no removal of old bumps, no change of surface metallisation
- similar efficiency: 99.1 %

# Pulse Height @ CERN

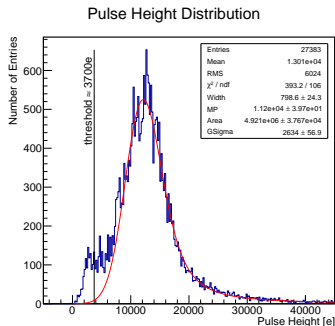


Figure: Pulse height distribution.

- trimmed threshold:  $\sim 3700\text{ e}$
- Langau MPV:  $11\,000\text{ e}$
- pulse height very similar to FEIV-b result at CERN
- beam particles at CERN have less energy loss  $\rightarrow$  lower MPV
- unreal distribution below threshold most likely due to data transmission problems

## Section 4

### Conclusion



# Conclusion

- strongly improved fabrication of 3D diamonds
  - ▶ 40x more cells
  - ▶ smaller cell size
  - ▶ thinner columns
- 3D Detectors work well in pCVD diamond
  - ▶ 99.2 % efficiency
  - ▶ consistent charge measurements for all devices:  $\sim 11\,000\,e$  @ CERN SPS
  - ▶ nearly full charge collection

## Section 5

### Outlook

# Outlook

- results of  $3.5 \cdot 10^{15} \text{ n/cm}^2$  irradiated  $50 \mu\text{m} \times 50 \mu\text{m}$  detectors
- test both  $50 \mu\text{m} \times 50 \mu\text{m}$  and  $25 \mu\text{m} \times 25 \mu\text{m}$  pixel detectors
- reduce column diameter to  $1 \sim 2 \mu\text{m}$
- build pixel device on newest RD53 chip ( $50 \mu\text{m} \times 50 \mu\text{m}$  pixel pitch)
- continue scale up by 10x

# DEL FIN

