3D CVD Diamond Sensor Development

APS | DIVISION OF PARTICLES & FIELDS

DPF 2017

MEETING OF THE AMERICAN PHYSICAL SOCIETY DIVISION OF PARTICLES AND FIELDS

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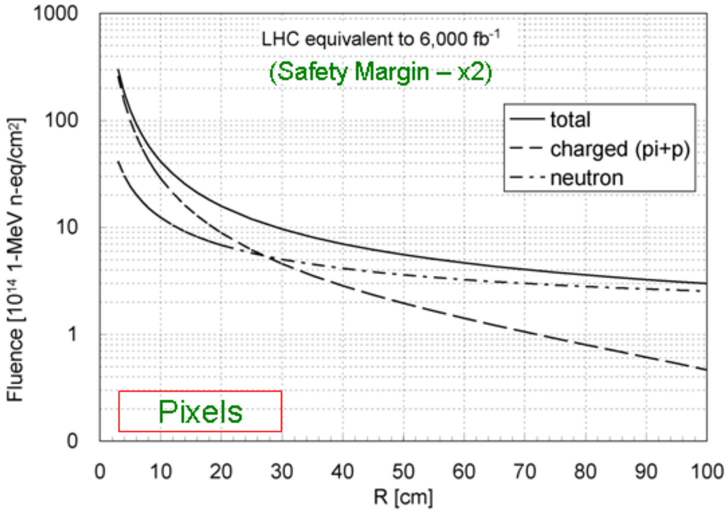
on behalf of the **RD42** collaboration

THE OHIO STATE UNIVERSITY

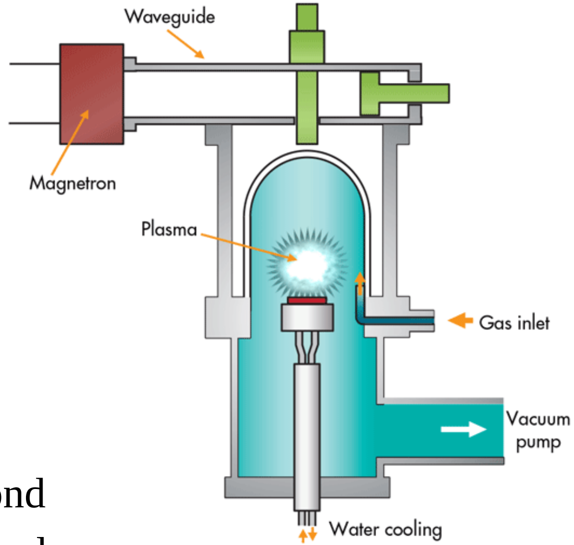
Motivation

- The inner detectors of high energy physics experiments withstand large radiation doses!
  - **Innermost layers**: highest radiation damage (will be 100MHz/cm^2 to 200MHz/cm^2)
  - Current detector is designed to survive 12 month in High-Luminosity LHC (HL-LHC)
  - R&D for more radiation hard detector designs and/or materials



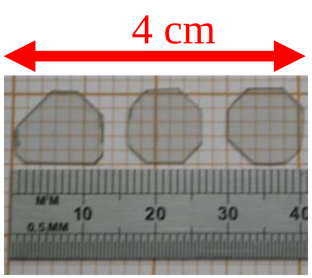
- **Chemical Vapor Deposition (CVD) diamond** as sensor material has been used in almost every experiment, since its
  - *Radiation hardness – no frequent replacements*
  - *Low dielectric constant – low capacitance*
  - *Low leakage current – low readout noise*
  - *Good insulating properties – large active area*
  - *Room temperature operation – no cooling necessary*
  - *Fast signal collection time –no ballistic deficit*
  - *Smaller signal than Silicon – larger energy to create eh-pair*
- **RD42 collaboration** is investigating CVD diamond as material for tracking in extreme radiation environments. Various detector designs have been used in the study of signal independence/dependence on incident particle flux
  - **Pad** → *full diamond as single cell readout*
  - **Pixel** → *diamond sensor on pixel chips*
  - **3D** → *strip/pixel detector with clever design to reduce drift distance*

CVD Diamond Types

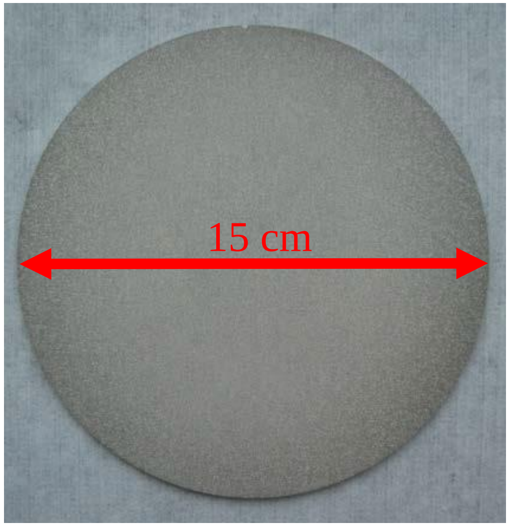


- Diamond produced in an artificial process.
  - Diamonds are “synthesized” from a plama
  - The diamond “copies” the substrate

- Investigation of two different diamond types
  - Polycrystalline Chemical Vapor Deposition **pCVD** diamond
  - Single Crystal Chemical Vapor Deposition **svCVD** diamond



Single crystal CVD diamond



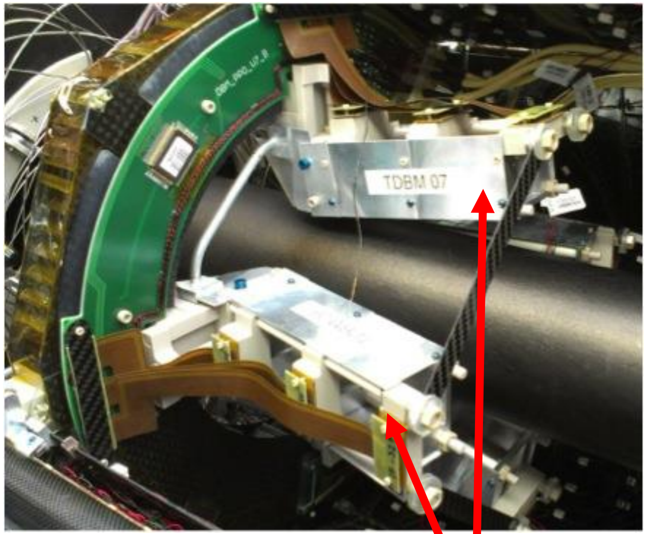
Polycrystalline CVD diamond wafer

- pCVD signals smaller than scCVD in planar configuration

Diamond Detectors in LHC

Large radiation
Little cooling

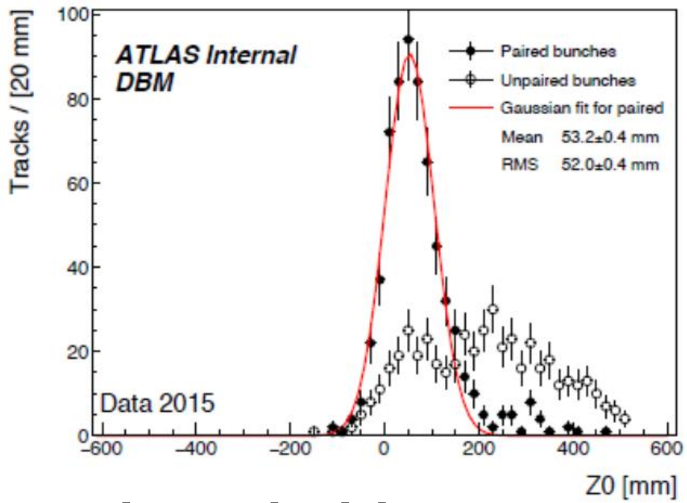
- Beam condition/loss monitors
  - Essential in all modern collider experiments
- ATLAS Diamond Beam Monitor (**DBM**)
  - Diamond pixel detectors in ATLAS (tracking)
  - 45 pCVD diamonds modules with FE-I4b chips
  - Modules assembled at CERN
  - Installed during LS1
  - 8 telescopes (2 Si & 6 Diamond) symmetric around ATLAS IP
    - $854\text{mm} < |z| < 1092\text{mm}$
    - $3.2 < |\eta| < 3.5$
  - ATLAS DBM integrated in ATLAS readout in 2015.
- Future HL-LHC trackers
  - **3D diamond detectors**
- Future beam condition/luminosity monitor
  - Multi-pad design BCM’



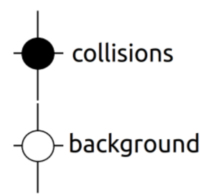
DBM telescopes

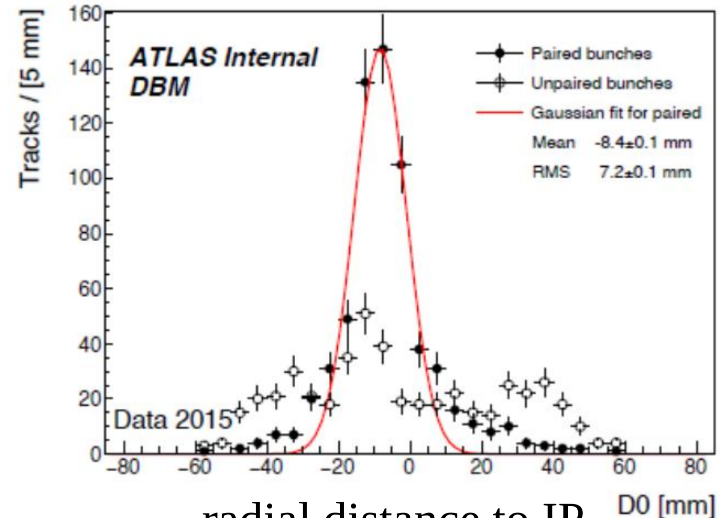
ATLAS Diamond Beam Monitor

- Use hits from the 3 modules to reconstruct tracks



longitudinal distance to IP



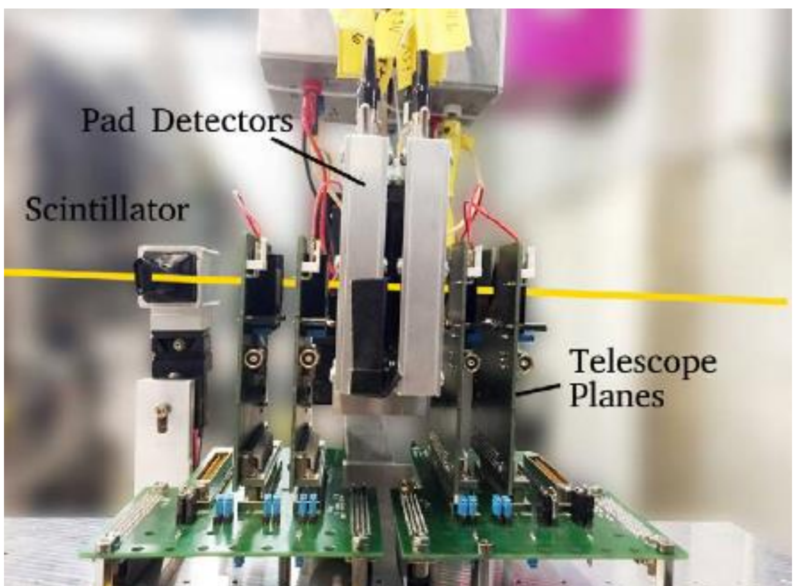


radial distance to IP

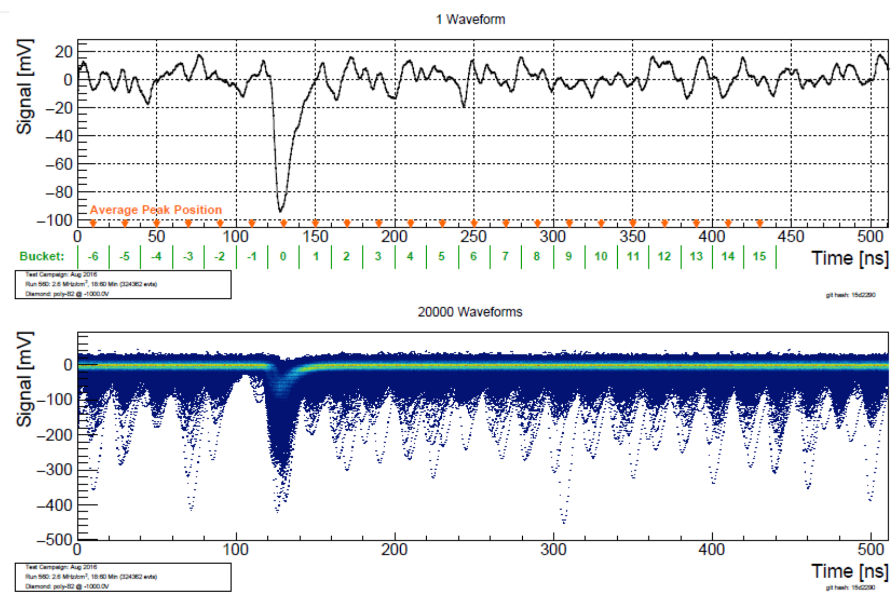
- Plots with initial alignment
- Clear discrimination between **IP** and **background** particles
- 2 electrical incidents in 2015 caused loss of modules (both Si and Diamond)
  - Successful **re-commissioning of surviving modules**
- Diamond and Si modules now part of ATLAS data taking

Rate Studies in pCVD Diamond

- ***Paul Scherrer Institute (PSI)***
  - 260MeV π^+
  - Rate up to **20MHz/cm^2**
  - 50μm position resolution
- Pad detectors tested in **ETH-Z telescope** (CMS pixel, 100μm × 150μm)
- Electronics is pre-prototype for HL-LHC BCM/BLM: luminosity analog board
- 4 tracking planes – the inner 2 planes provide masked trigger
- Scintillator for **precise** ~ **1ns** event time

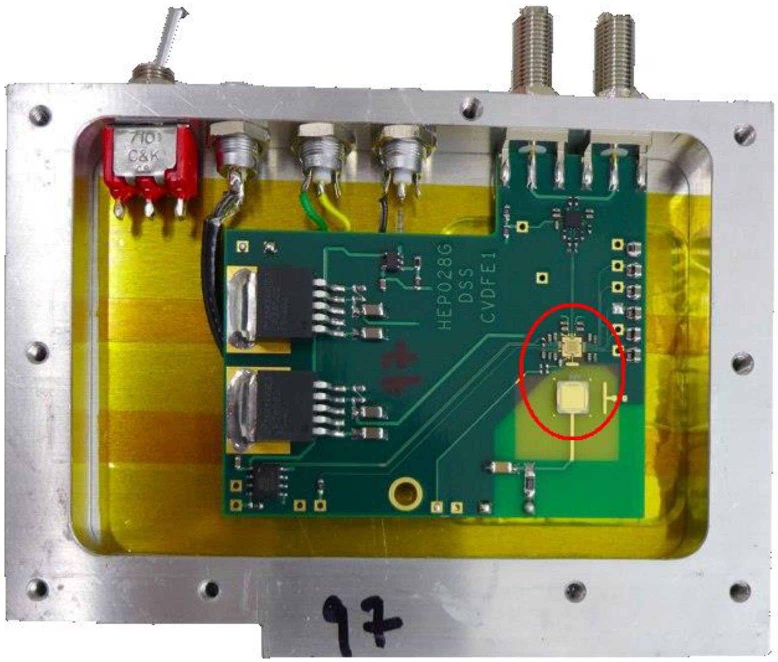


test setup

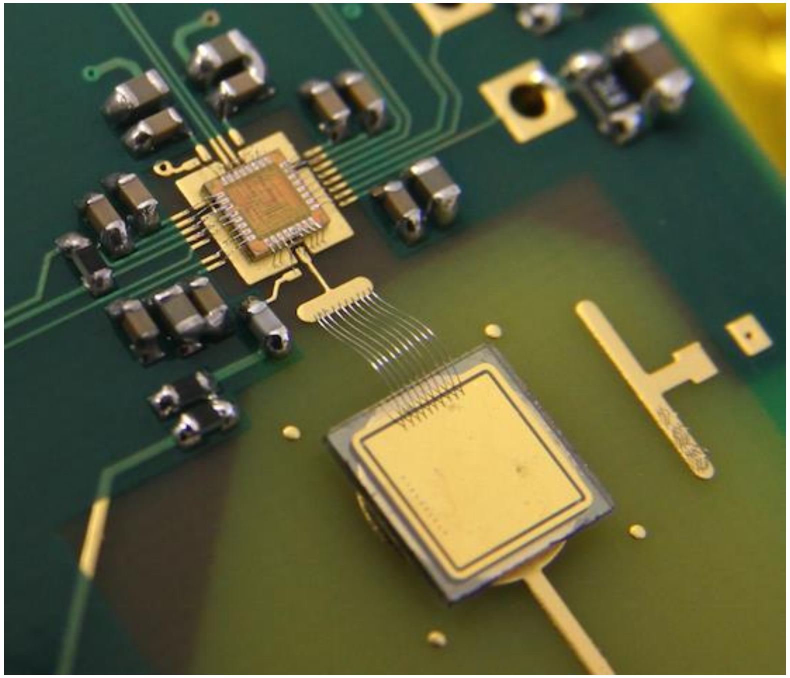


19.8ns bunch spacing clearly visible

Pad Detectors



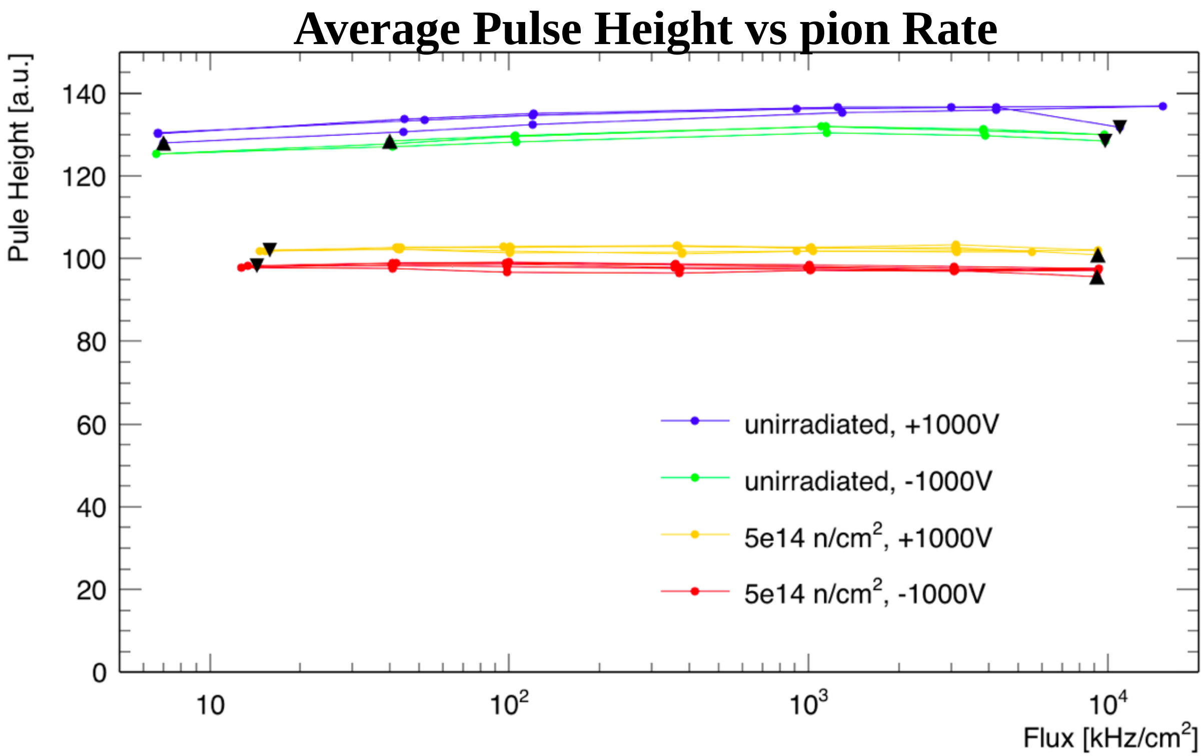
fast amplifier box



Diamond (bottom right) and fast amp (top left)

- Diamonds in custom built amplifier boxes
- Cleaning, photo-lithography and Cr-Au metallization
- Low noise, fast amplifier with *O(5ns) rise time*
- Pre-prototype for HL-LHC BCM/BLM

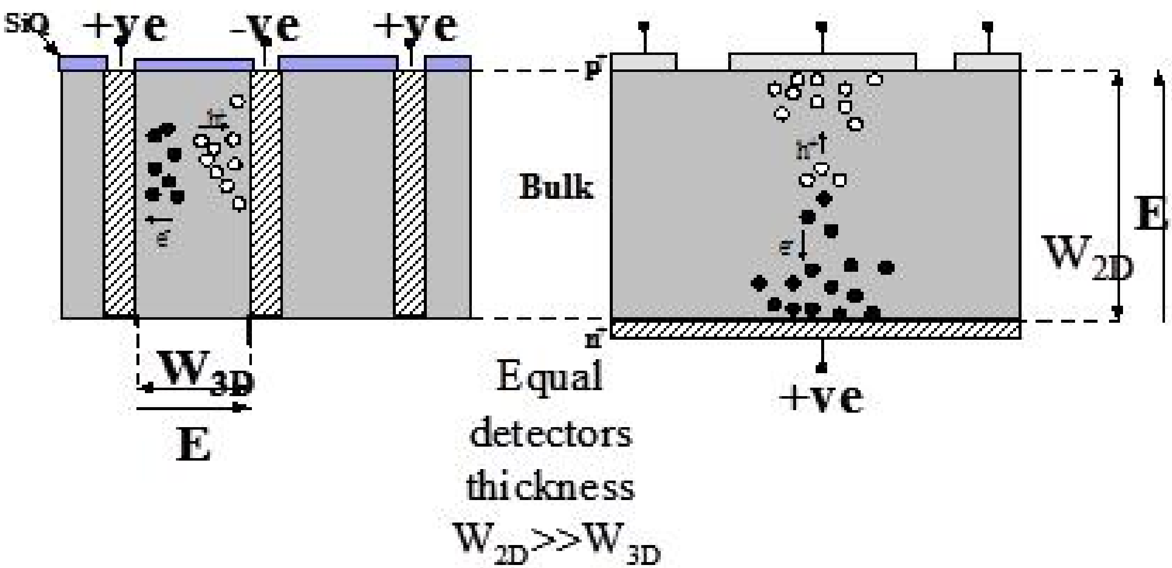
Rate Studies in pCVD Pad Detectors



- Pulse rate was measured at several rate points between 2kHz/cm^2 and 10MHz/cm^2
  - scanned up and down up to 4 times to check repeatability
- No absolute pulse height and noise calibration yet
- **No rate dependence** observed in pCVD up to **10-20MHz/cm^2**
- Now extending dose to **10^{16}n/cm^2**

3D Device in CVD Diamond

- After long radiation fluence all detectors are trap limited.
  - Mean free path < 75µm
  - Would like to keep drift distances smaller than MFP.
    - Thin planar detector, W_{2D} ~50µm
    - 3D detector, W_{3D}~37µm (for 50µm × 50µm cells)



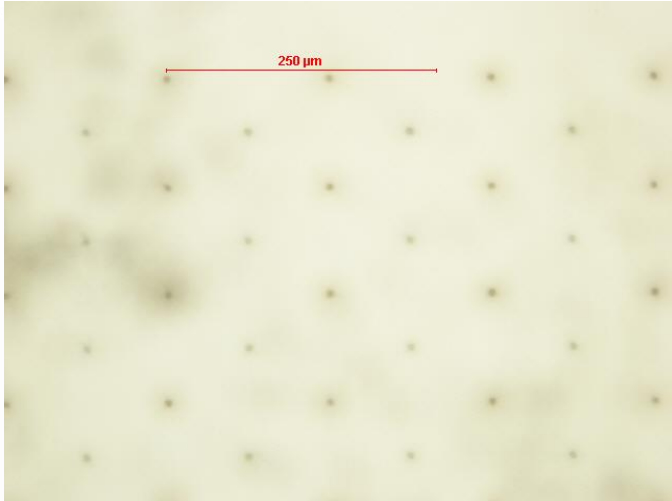
- Incorporate bias and readout electrodes into detector's bulk
  - Same detector thickness (same amount of charge induced by an ionizing particle)
  - Shorter drift distance in 3D detectors
    - Reduced probability of charge trapping in radiation damaged and/or pCVD detector

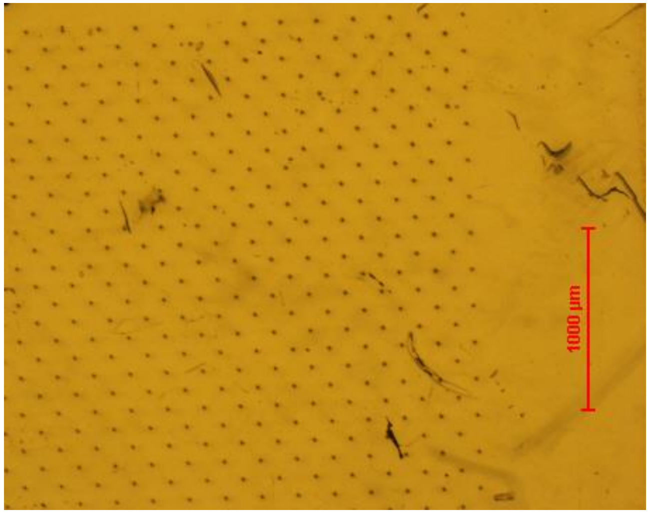
3D Detector Fabrication

- Femtosecond laser converts insulating diamond into a resistive mixture of various carbon phases: DLC, amorphous carbon, graphite, etc
- Spatial Light Modulation (SLM) corrects aberration in diamond, the column yield increased from 90% to >99%

columns made with 800nm femtosecond laser

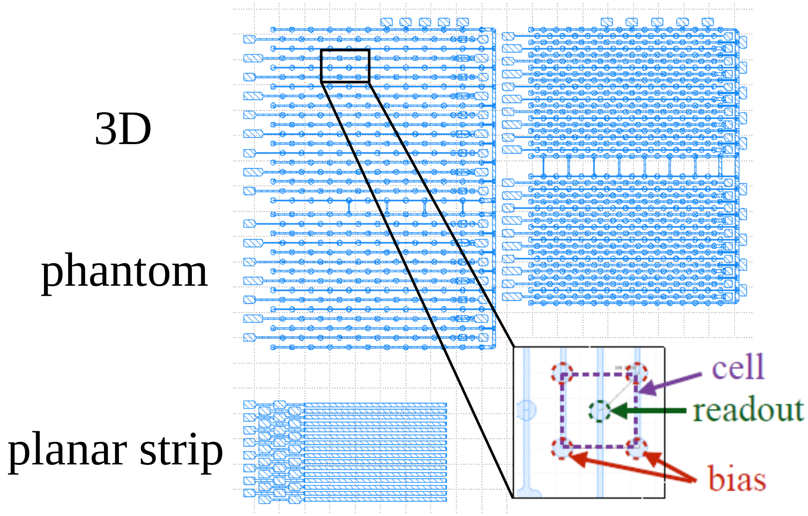
initial cells 150μm × 150μm, columns 6μm diameter

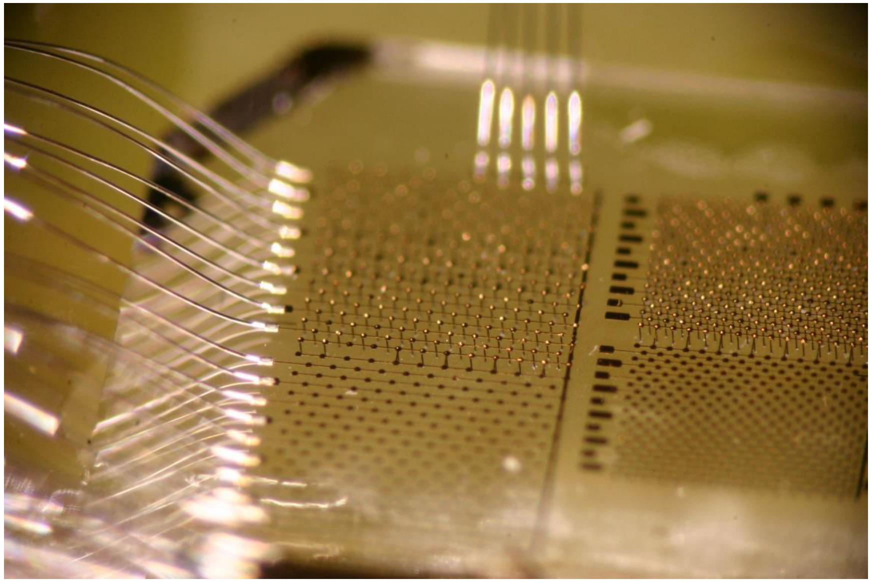




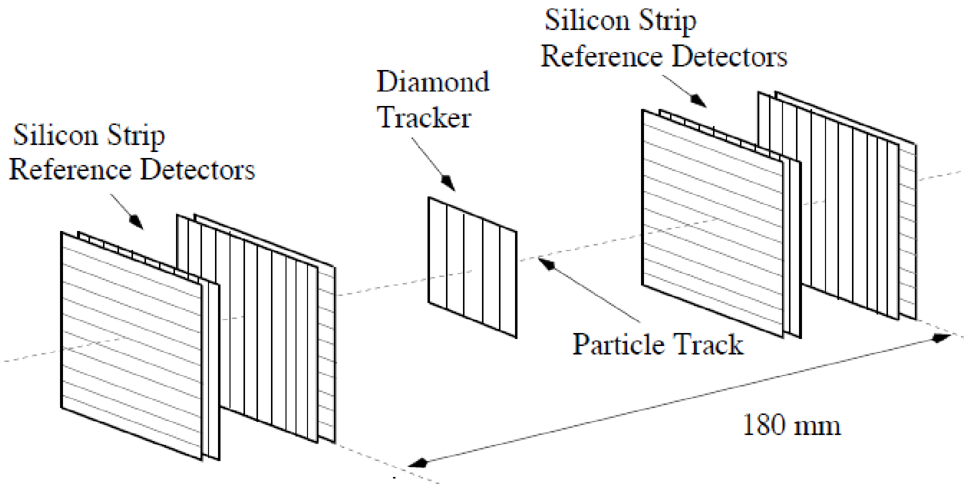
Laser drilled holes, pCVD samples

3D Detector in Polycrystalline CVD Diamond



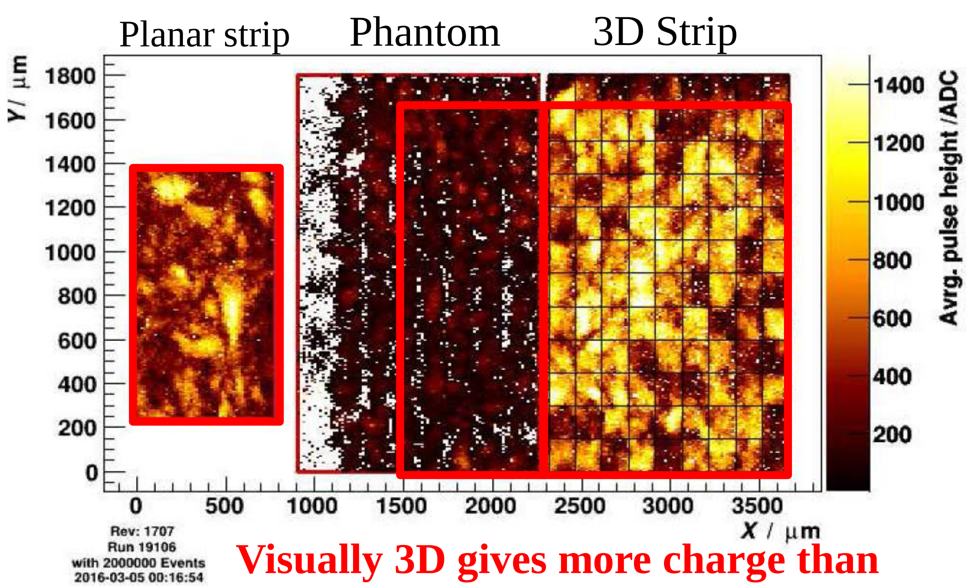


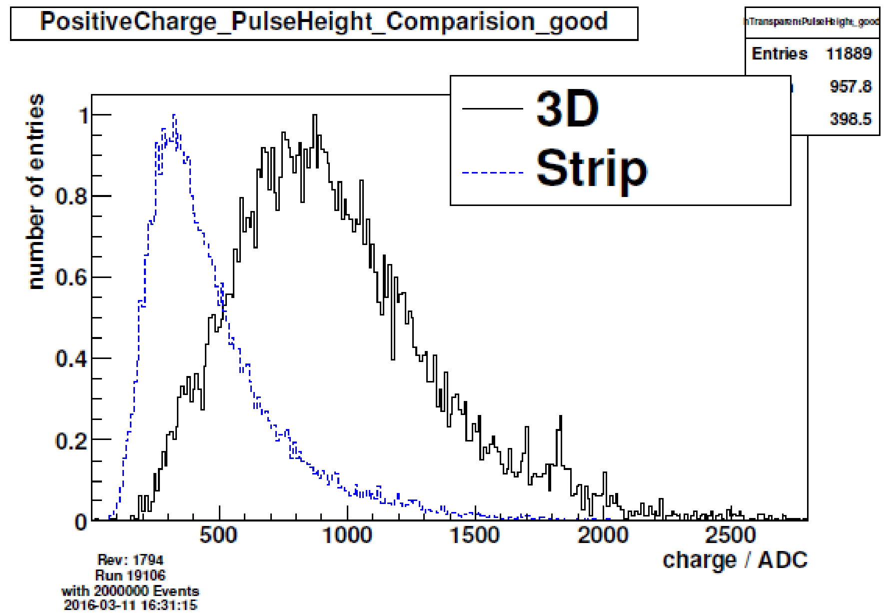
- Simultaneously readout all 3 devices
  - **3D**: bias and readout contacts on the same side (150μm × 150μm cell size)
  - **Phantom**: same metal pattern as 3D strip but <u>without</u> graphitic columns
  - **Planar strip**: bias contact on backside
- Tested at CERN with 120GeV protons
- Beam telescope reconstructs particle tracks and predicts their impact position in the device under test with < 5μm precision
- Low noise VA2 readout



Planar Strip Detector VS 3D Detector

- Measured **column efficiency**: 92%
  - Broken readout columns result in cell with low signal
  - Broken bias columns result in region with lower signal
- Measured **noise**: ~proportional to capacitance
- Measured **signal**: read out as ganged cells



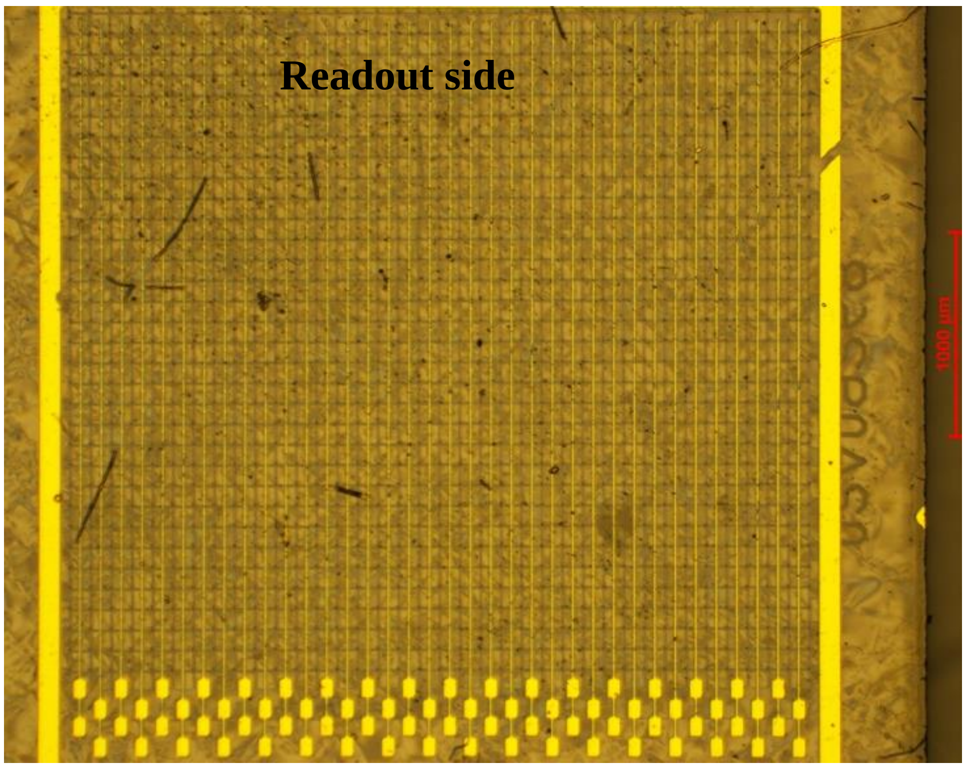


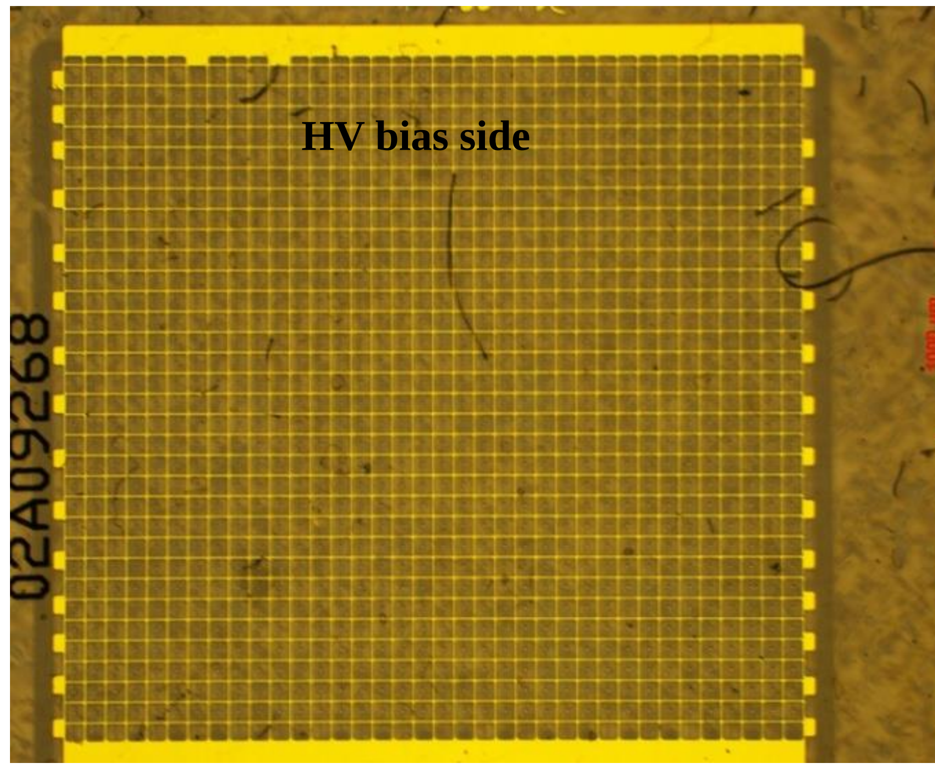
Visually 3D gives more charge than planar strip!

- Measured signal (diamond thickness 500µm)
  - Planar strip detector ave charge : 6900e or ccd=192µm
  - 3D ave charge: 13500e or ccd_{eq}=350-375µm
- **For the first time collect > 75% of charge in pCVD!**

Full 3D Detector in Polycrystalline CVD Diamond

- The first full 3D detector in pCVD diamond was built in May/Sept 2016 with dramatic improvements:
  - An order of magnitude more cells: 99 → **1188**
  - Smaller cell size: 150µm → **100µm**
  - Higher column efficiency: 92% → **99%**

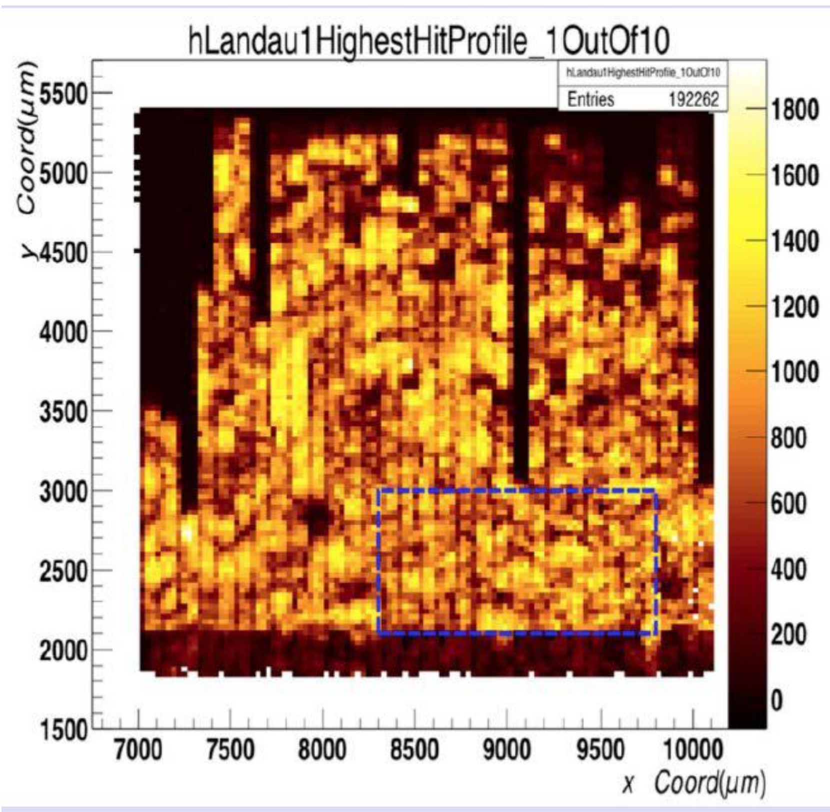


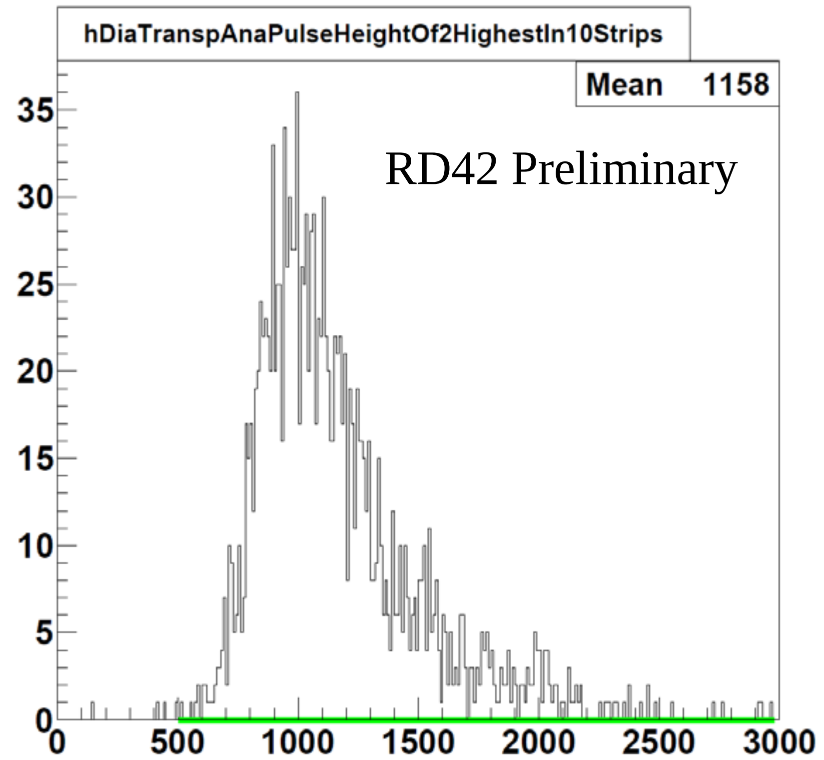


Proved viability (>99%) of new column fabrication procedure

Preliminary Results of Full 3D Detector

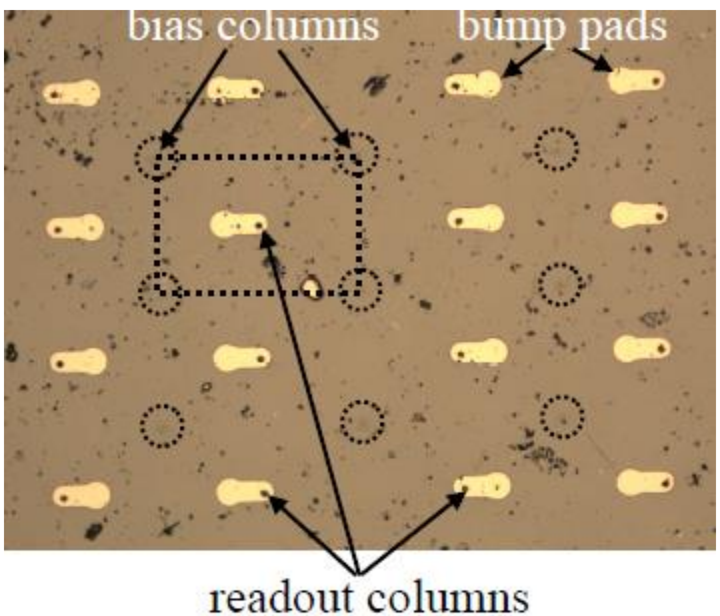
- The detector **works well**
  - First plots of *3D average charge* in entire detector
  - Largest charge collection in pCVD diamond
    Contiguous region shows **> 85% of charge collection**
- Analysis in progress of full detector

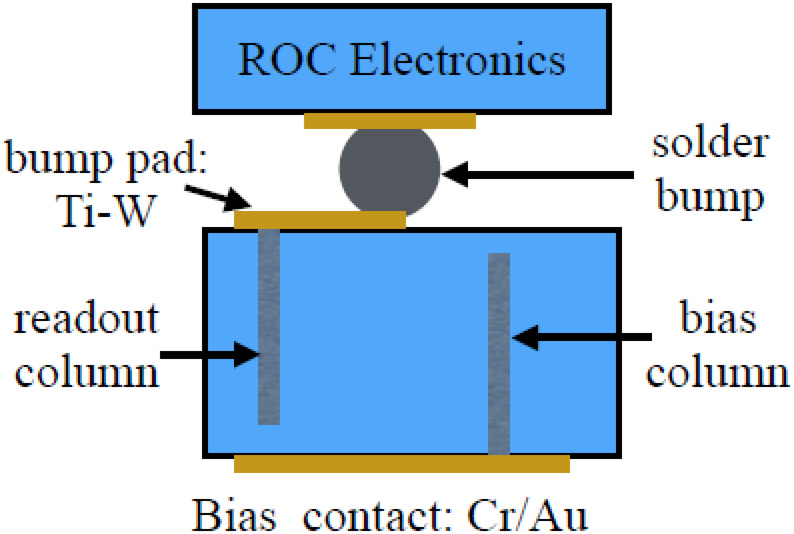




The First 3D Polycrystalline CVD Pixel Detector

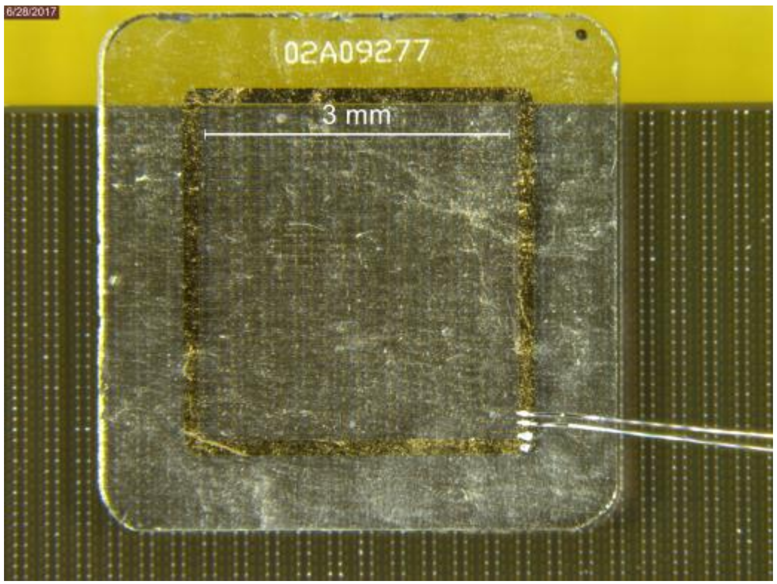
- 3D columns were designed to stop 15μm before the end of the material and drilled from both sides at ***Oxford***
- Mask set by ***Manchester***
- Cleaning and photo-lithography at ***Ohio State***
- Cr-Au metallization of HV back plane at ***Ohio State***
- Photo-lithography and metallization of pixel readout at ***Princeton***
- Bump and wire bonding at ***Princeton***



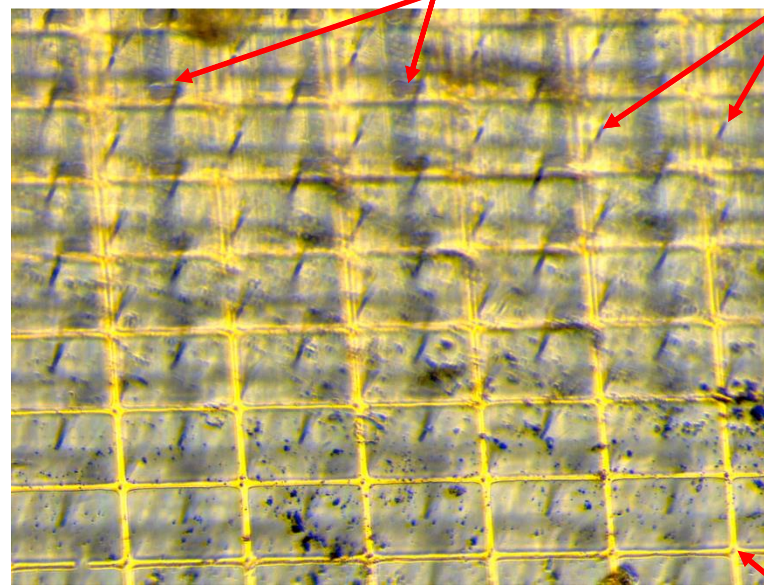


3D Pixel Detector

- Module building/test at ***ETH-Zurich***, ***Rutgers***
- Irradiation at ***JSI/Ljubljana***
- Beam tests at ***ETH-Zurich*** and ***Ohio State***



detector bonded on CMS-Pixel-Chip



tilted view of the 3D detector

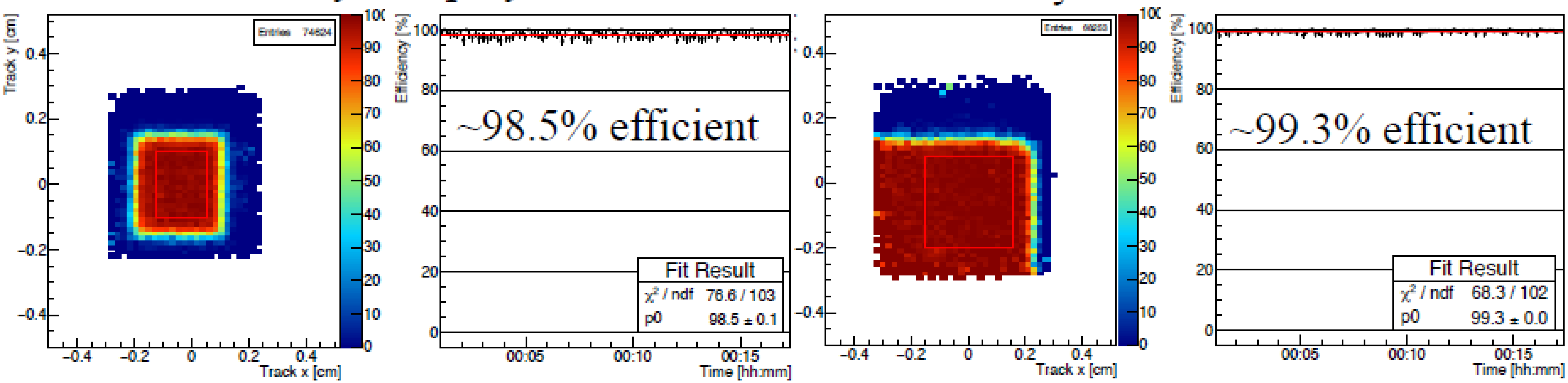
- **Successful production of a working 3D pixel detector**

Beam Test of 3D Pixel Detector

- Readout chip setup: *threshold* for accepting hits ~ **1500e**
- *Efficiency* checked by counting all hits in the device under test and dividing them by the number of tracks predicted by the telescope within a fiducial area
- Preliminary results below

efficiency: 3D poly diamond

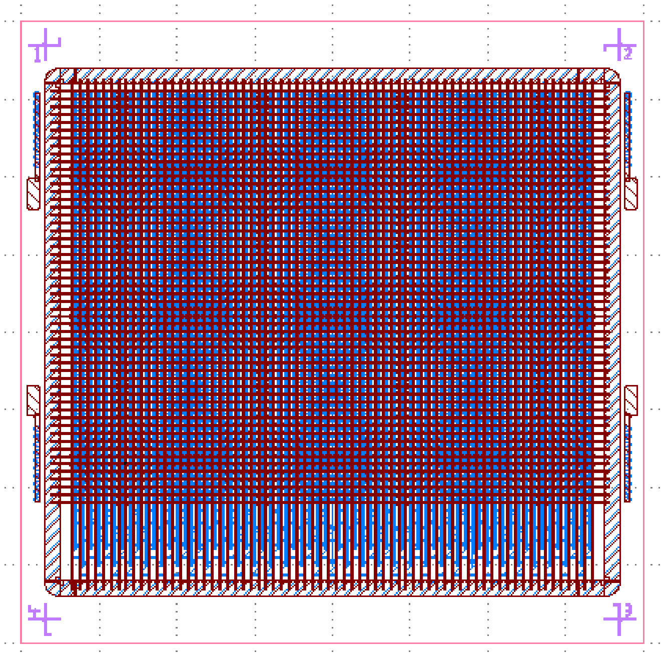
efficiency: silicon reference

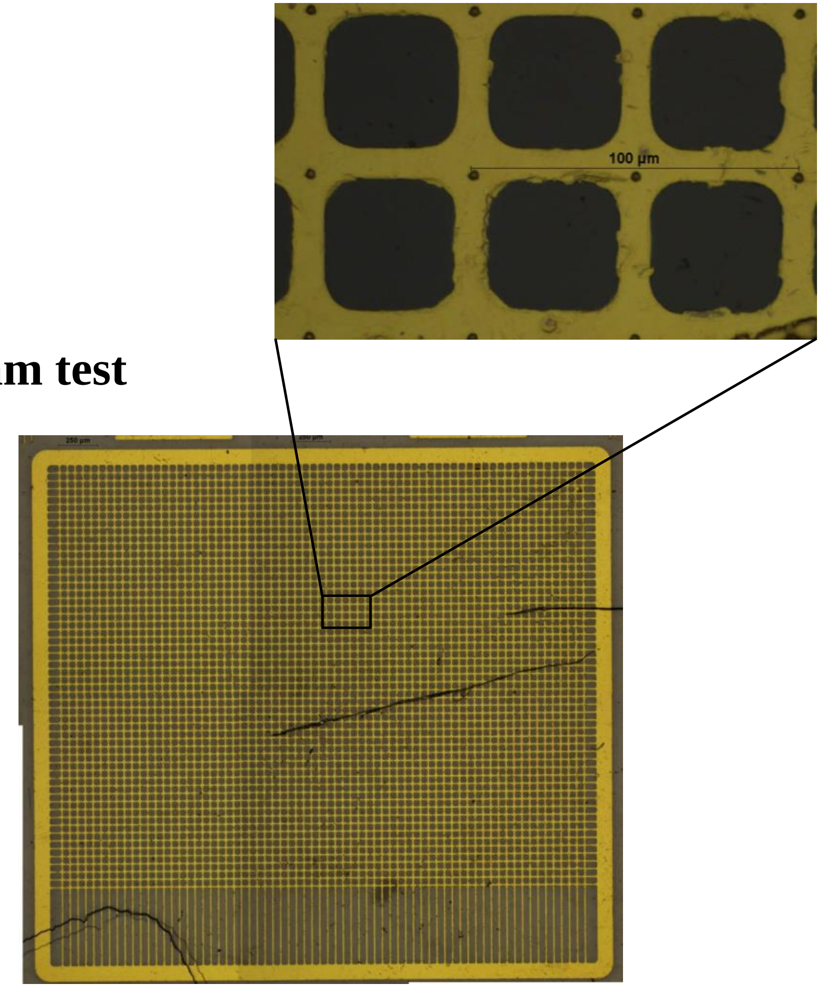


- **Efficiency flat in time**
- Lower efficiency in diamond may be caused by lower field regions (being checked)

Production Plan: CMS, ATLAS 3D pCVD Pixel

- Presently producing 3500 cell pixel prototype
- Two independent drillings
  - Oxford – done
  - Manchester – in progress
- Metallization (done for Oxford part)
- Bump boding
  - CMS @Princeton – being done now
  - ATLAS @IFAE
- **CMS device will be ready for August 7th beam test**





HV bias side @OSU

Conclusion

- Diamonds in the LHC machine making impact moving forward

- One of the first pixel projects started taking data
  - ATLAS DBM re-commissioned for 13TeV collisions

- Observed no pulse height dependence in irradiated pCVD diamonds up to fluence 2×10^{15} reactor neutrons/cm^2.

- 3D detector prototypes made great progress
  - 3D works in pCVD diamond
  - Scale up worked
  - Smaller cells worked

- Successfully tested first 3D diamond with pixel readout
  - Efficiency greater than 98.5%

Back up

The 2017 RD42 Collaboration

The 2017 RD42 Collaboration

A. Alexopoulos[3], M. Artuso[22], F. Bachmair[26], L. Bäni[26], M. Bartosik[3], J. Beacham[15], H. Beck[25], V. Bellini[2], V. Belyaev[14], B. Bentele[21], E. Berdermann[7], P. Bergonzo[13], A. Bes[30], J-M. Brom[9], M. Bruzzi[5], M. Cerv[3], G. Chiodini[29], D. Chren[20], V. Cindro[11], G. Claus[9], J. Collot[30], J. Cumalat[21], A. Dabrowski[3], R. D'Alessandro[5], D. Dauvergne[30], W. de Boer[12], C. Dorfer[26], M. Dunser[3], V. Eremin[8], R. Eusebi[27], G. Forcolin[24], J. Forneris[17], H. Frais-Kölbl[4], L. Gallin-Martel[30], M.L. Gallin-Martel[30], K.K. Gan[15], M. Gastal[3], C. Giroletti[19], M. Goffe[9], J. Goldstein[19], A. Golubev[10], A. Gorišek[11], E. Grigoriev[10], J. Grosse-Knetter[25], A. Grummer[23], B. Gui[15], M. Guthoff[3], I. Haughton[24], B. Hiti[11], D. Hits[26], M. Hoeferkamp[23], T. Hofmann[3], J. Hosslet[9], J-Y. Hostachy[30], F. Hügging[1], C. Hutton[19], H. Jansen[3], J. Janssen[1], H. Kagan[15,◇], K. Kanxheri[31], G. Kasieczka[26], R. Kass[15], F. Kassel[12], M. Kis[7], V. Konovalov[15], G. Kramberger[11], S. Kuleshov[10], A. Lacoste[30], S. Lagomarsino[5], A. Lo Giudice[17], E. Lukosi[28], C. Maazouzi[9], I. Mandic[11], C. Mathieu[9], M. Menichelli[31], M. Mikuž[11], A. Morozzi[31], J. Moss[32], R. Mountain[22], S. Murphy[24], M. Muškinja[11], A. Oh[24], P. Olivero[17], D. Passeri[31], H. Pernegger[3], R. Perrino[29], F. Picollo[17], M. Pomorski[13], R. Potenza[2], A. Quadt[25], A. Re[17], M. Reichmann[26], G. Riley[28], S. Roe[3], D. Sanz[26], M. Scaringella[5], D. Schaefer[3], C. Schmidt[7], S. Schnetzer[16], S. Sciortino[5], A. Scorzoni[31], S. Seidel[23], L. Servoli[31], S. Smith[15], B. Sopko[20], V. Sopko[20], S. Spagnolo[29], S. Spanier[28], K. Stenson[21], R. Stone[16], C. Sutera[2], B. Tannenwald[15], A. Taylor[23], M. Traeger[7], D. Tromson[13], W. Trischuk[18,◇], C. Tuve[2], L. Uplegger[6], J. Velthuis[19], N. Venturi[18], E. Vittone[17], S. Wagner[21], R. Wallny[26], J.C. Wang[22], J. Weingarten[25], C. Weiss[3], T. Wengler[3], N. Wermes[1], M. Yamouni[30], M. Zavrtanik[11]

130 participants

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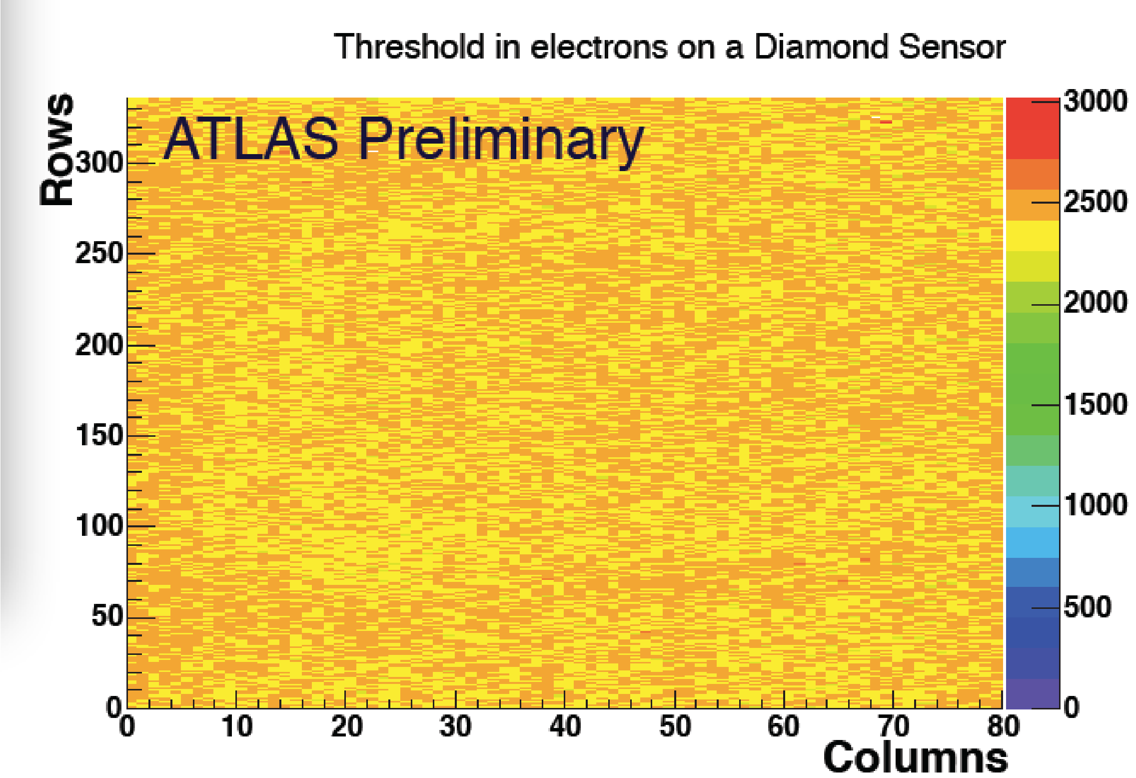
32 institutes

ATLAS Diamond Beam Monitor

- **ATLAS DBM integrated in ATLAS readout in 2015**
- Thresholds tuned to **2500e**



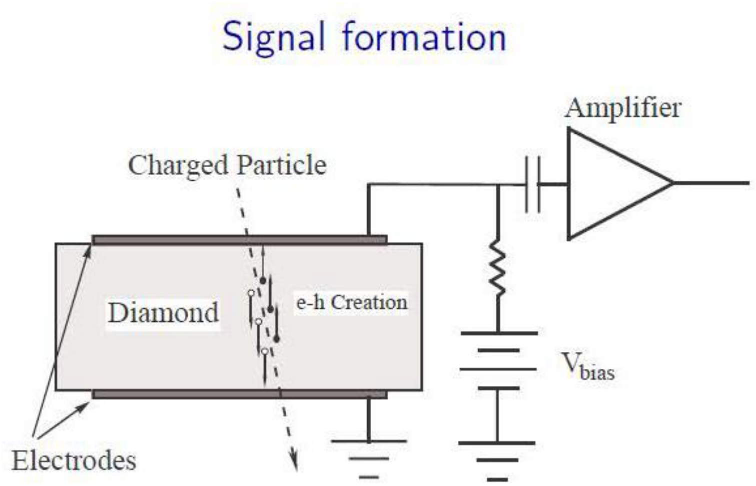
- Would like to lower this (**1100e** possible on bench)

Collection Distance

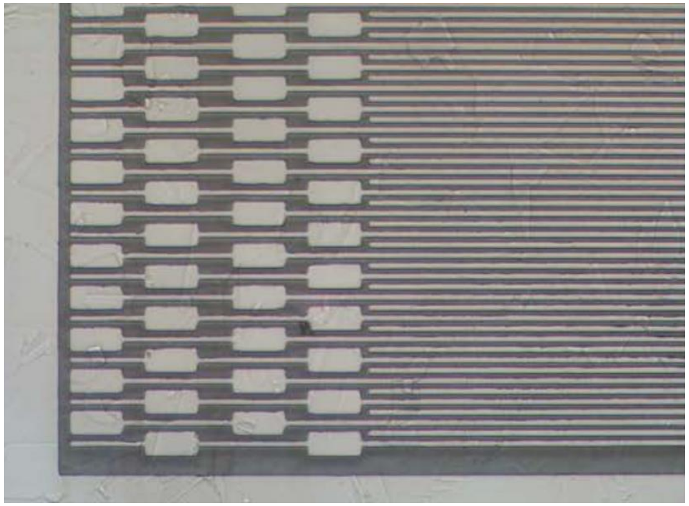
Collection Distance, $d = (\mu_e \tau_e + \mu_h \tau_h) E$, is an average drift distance in the charge collection process which is of interest in the development of radiation detectors.

μ is the mobility of free carriers (electron and hole) and τ is carrier lifetime.

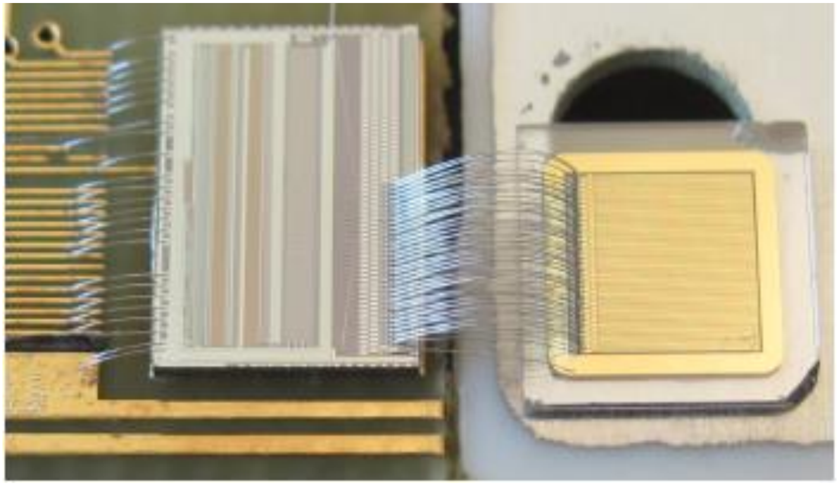
To collect large charge, it needs good collection distance.



Radiation Tolerance

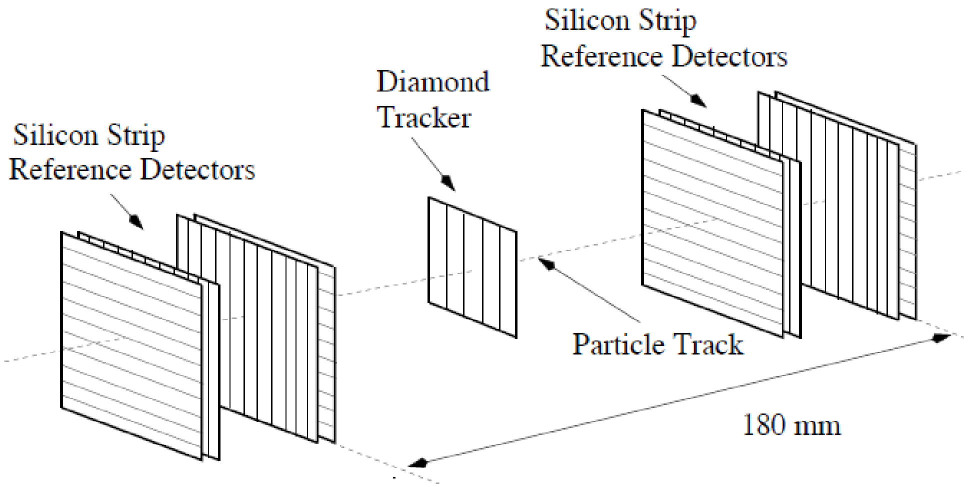


strip pattern



mounted diamond with amplifier

- Patterning the diamonds
  - Pad, strip and pixel devices
- Double –sided metallization
  - edgeless
- Segmentation device critical for radiation studies
  - Charge & position



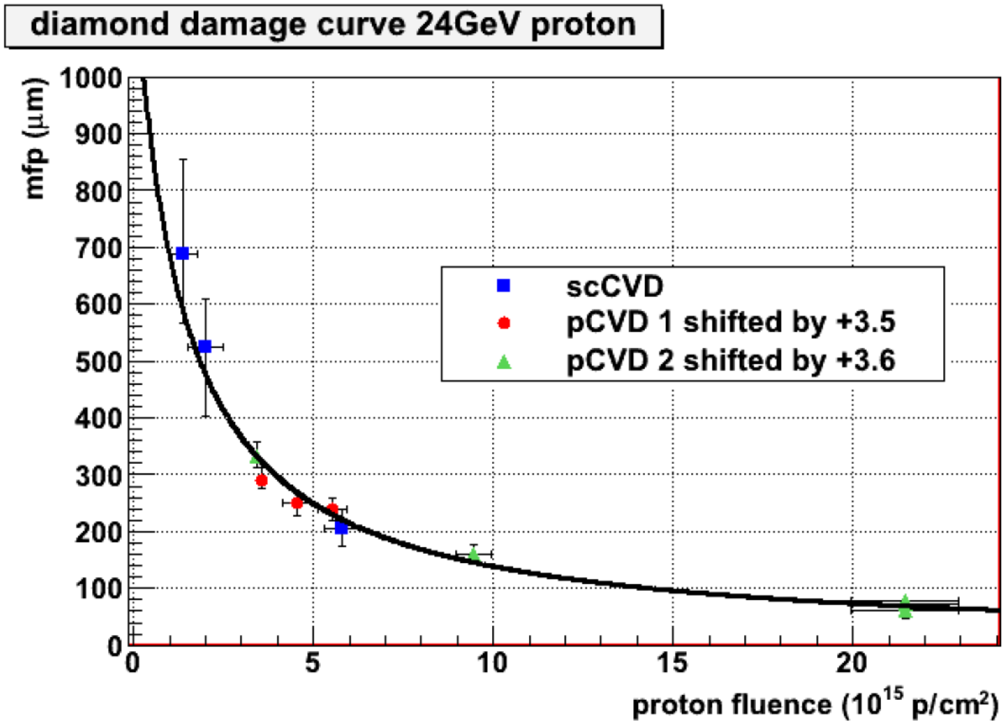
Proton Irradiation at CERN

- CERN PS 24GeV protons
- Damage equation

$$n = n_0 + k\phi$$

$$\frac{1}{\text{mfp}} = \frac{1}{\text{mfp}_0} + k\phi$$

  - mfp_0 initial mean free path (assume $\text{mfp}_e = \text{mfp}_h$)
  - k is damage constant
  - ϕ fluence

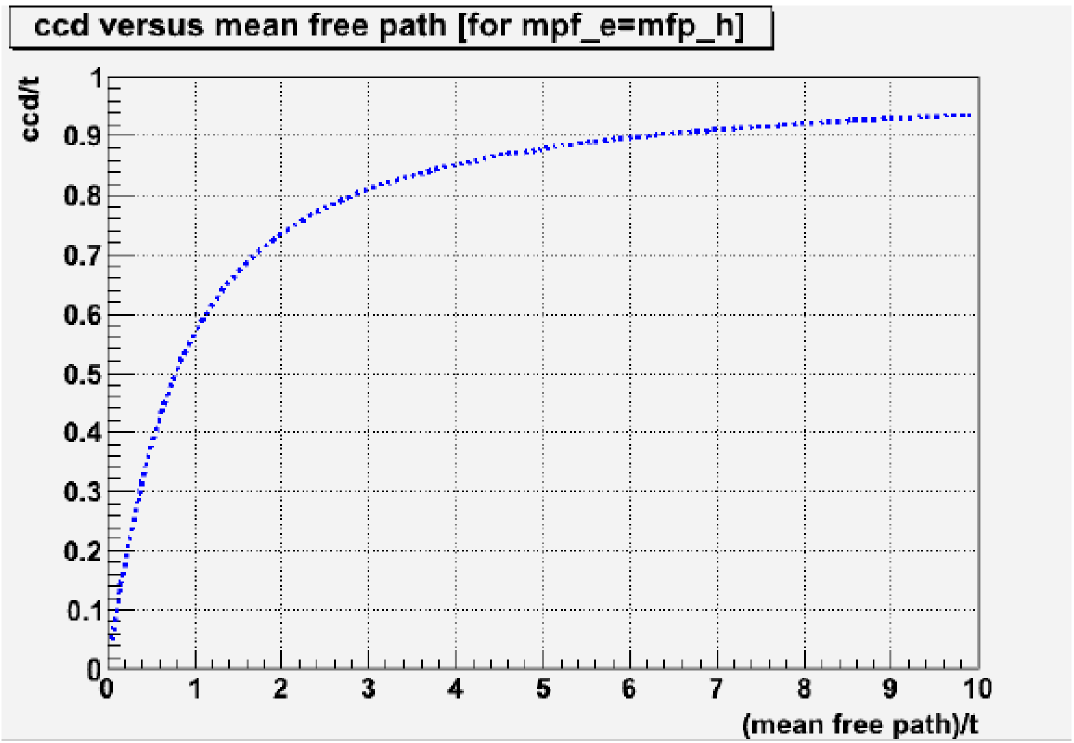


- Irradiation results up to 2.2e16p/cm^2 (~500Mrad)
- Same damage curve, same damage constant (k) for scCVD and pCVD diamond
- Large mfp_0 performs better at any fluence

Charge Collection Distance vs. Mean Free Path

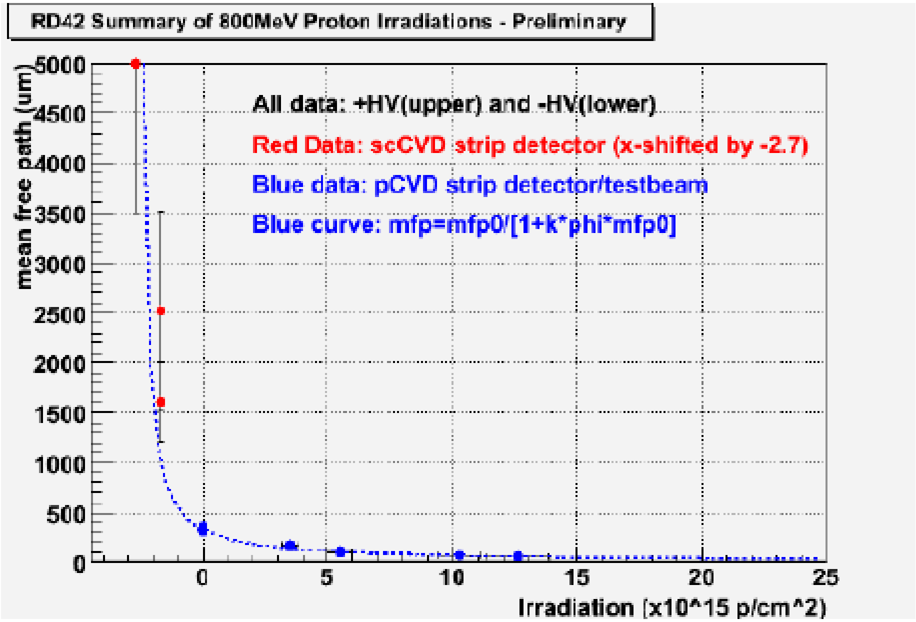
- scCVD ccd ~ thickness; pCVD ccd < thickness
- ccd direct measurement (no correction)
- mfp correct theory: assume $mfp_e = mfp_h$ (correct data)

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



Irradiation at Lower Energy

- LANL 800 MeV protons



- Irradiation results up to 1.4e16p/cm^2
- damage constant k = 1.2e-18μm^{-1}cm^2
- LANL 800 MeV protons damage : CERN 24 GeV protons damage = 1.6~1.8

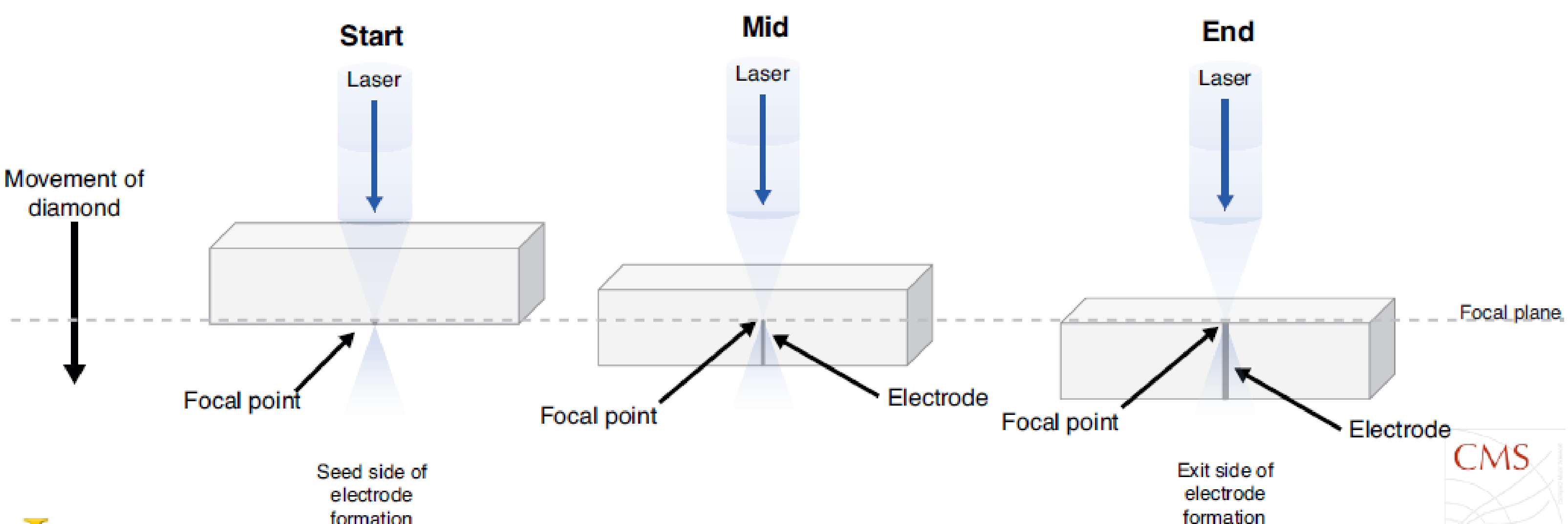
Summary of Radiation Tolerance

Particle	Energy	Relative damage constant k
Proton	24GeV	1.0
	800MeV	1.79 ± 0.13
	70MeV	2.4 ± 0.4
	25MeV	4.5 ± 0.6
Neutron	1MeV	4.5 ± 0.5
Pion	200MeV	2.5 ~ 3.0

3D Detector Fabrication

3D detector fabrication

- Femtosecond laser converts insulating diamond into a resistive mixture of various carbon phases: DLC, amorphous carbon, graphite, etc [Bachmair et al., NIM A, 786 (2015)]
- Early detectors had 90% column yield
  - recently ~100% has been achieved using Spatial Light Modulation to correct for aberration in diamond



Spatial Light Modulation

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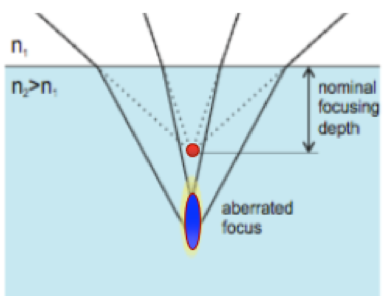
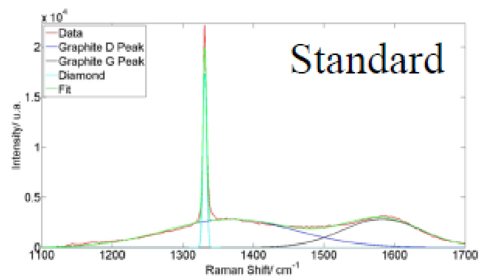
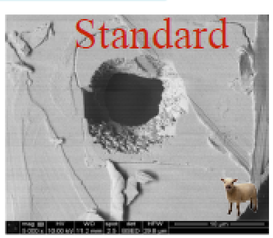
3D detector fabrication

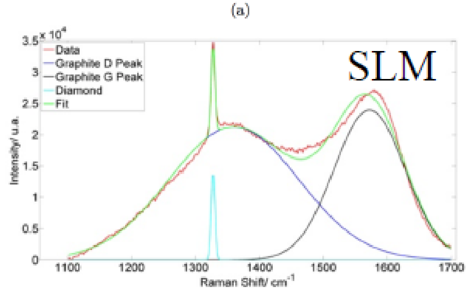
- Femtosecond laser converts insulating diamond into a resistive mixture of various carbon phases: DLC, amorphous carbon, graphite, etc [Bachmair et al., NIM A, 786 (2015)]
- Early detectors had 90% column yield
  - recently >99% has been achieved using Spatial Light Modulation (SLM) to correct for aberration in diamond





(a)





	Standard	SLM
Resistivity	1 Ωcm	0.1 Ωcm
Diameter	~3μm	~1μm
Diamond to graphite ratio	~4	~0.2

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3D Detector in Single Crystal CVD Diamond

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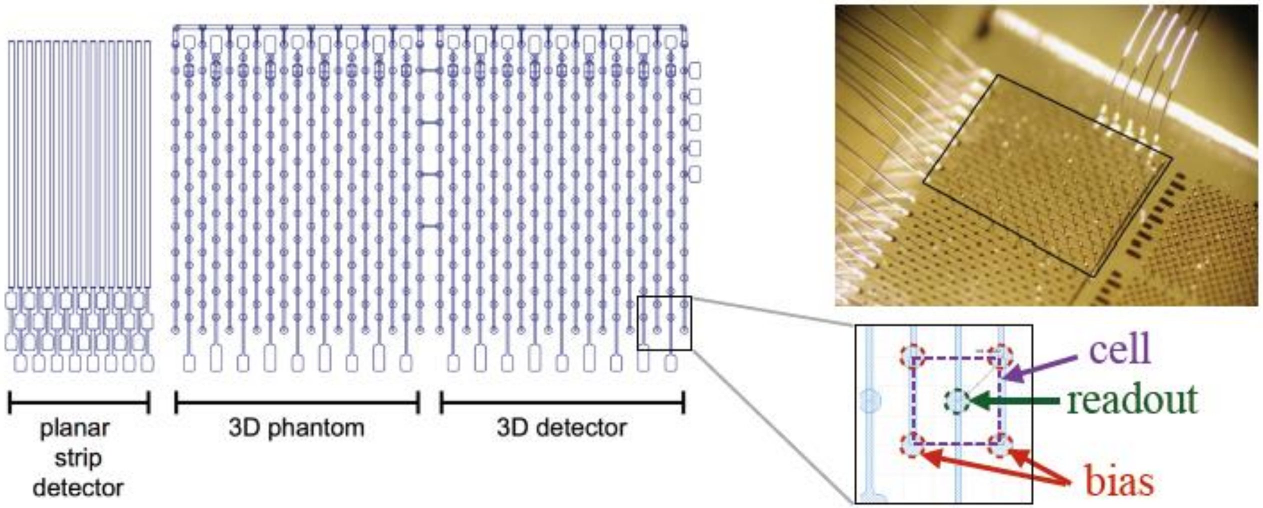
3D detector in single crystal CVD diamond

[Bachmair et al., NIM A, 786 (2015)]



- 3 detectors
  - strip with backside contact for bias
  - 3D with bias and readout contacts on the same side (150μm cell size)
  - 3D phantom (same metal pattern as 3D but without graphitic columns)
- Some broken columns in the detector (90% success rate in column drilling)

3D Detector in Single Crystal CVD Diamond

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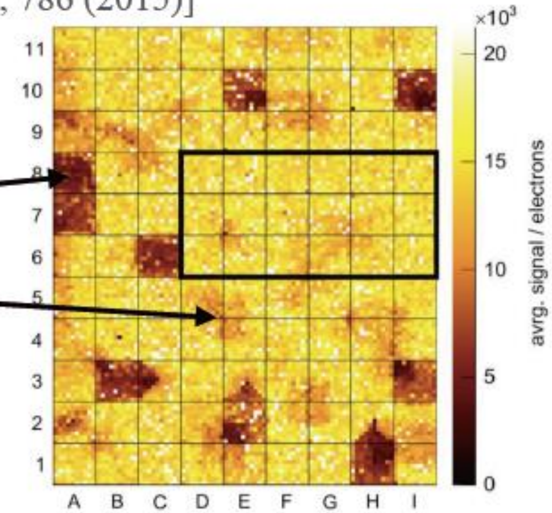
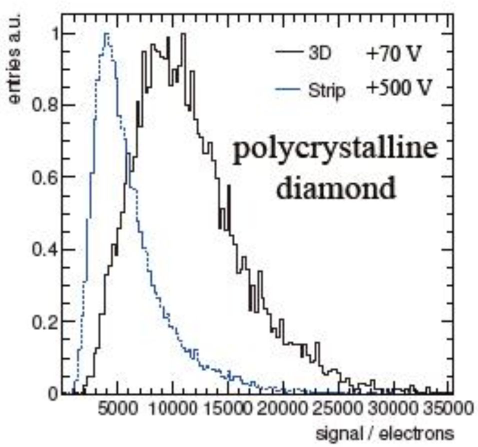
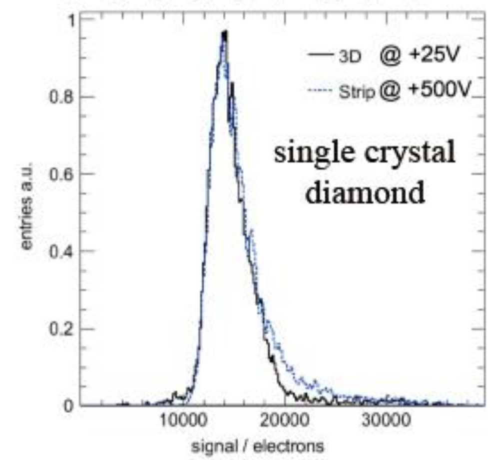
3D detector in single crystal CVD diamond

[Bachmair et al., NIM A, 786 (2015)]

- Some broken columns in the detector (90% success rate in column drilling)
  - Broken readout columns result in cell with low signal
  - Broken bias column result in region with lower signal
- For comparison with the strip detector use contiguous region with no broken signal columns







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