New beam test results of 3D pixel detectors constructed with pCVD diamond

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Outline of Talk

- Introduction – Motivation, RD42
- Diamond Detectors
- Results of 3D diamond pixel devices constructed with pCVD material
- Summary
- Future Plans

Introduction - Motivation

The Situation:

- Nextgen inner tracking layers → ~10^{16} hadrons/cm^2, ~GHz/cm^2 rates
- Current detectors might survive ~12 months at the HL- LHC

→ R&D for more radiation tolerant detector designs and/or materials

Diamond as a Detector Material:

- Properties:

  radiation tolerance (→ Gregor Kramberger's talk)

  insulating material, high charge carrier mobility

  smaller signal than in same thickness of silicon (larger bandgap)

RD42 work:

- Investigate various detector designs:

  pad → full diamond as a single cell readout

  strip → diamond segmented w/multi-channel readout

  pixel → diamond sensor on pixel chips

  3D → strip/pixel detector with design to reduce drift distance

Introduction - The 2019 RD42 Collaboration

The 2019 RD42 Collaboration

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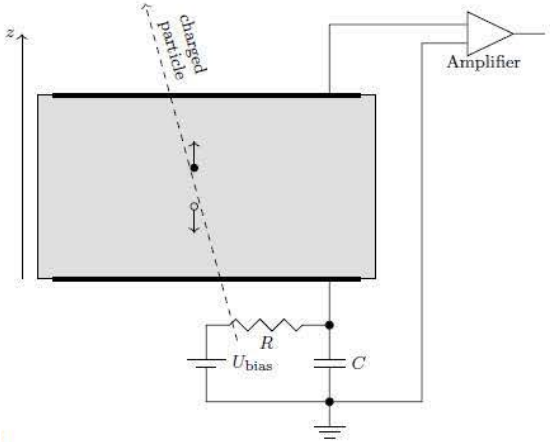
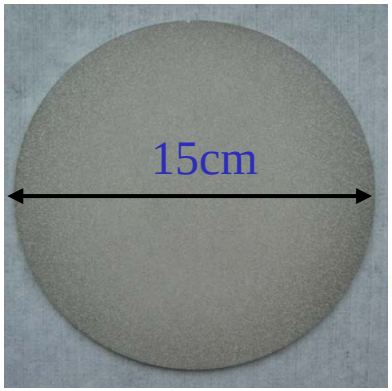
113 participants

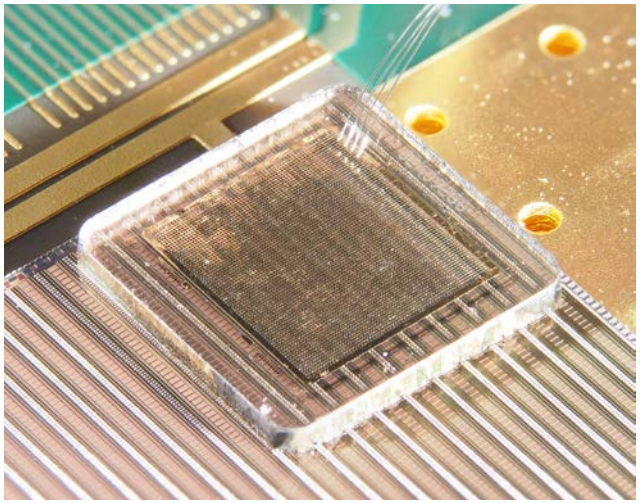
30 institutes

Introduction – Diamond as a Particle Detector

- Diamond detectors are operated as ionization chambers
- Poly-crystalline material comes in large wafers
- Metalization on both sides
  - Pad
  - Strip
  - Pixel (this talk)
- Connected (bump-bonded) to low noise electronics







pCVD diamond with 3D pixel device bump-bonded to ATLAS FE-I4

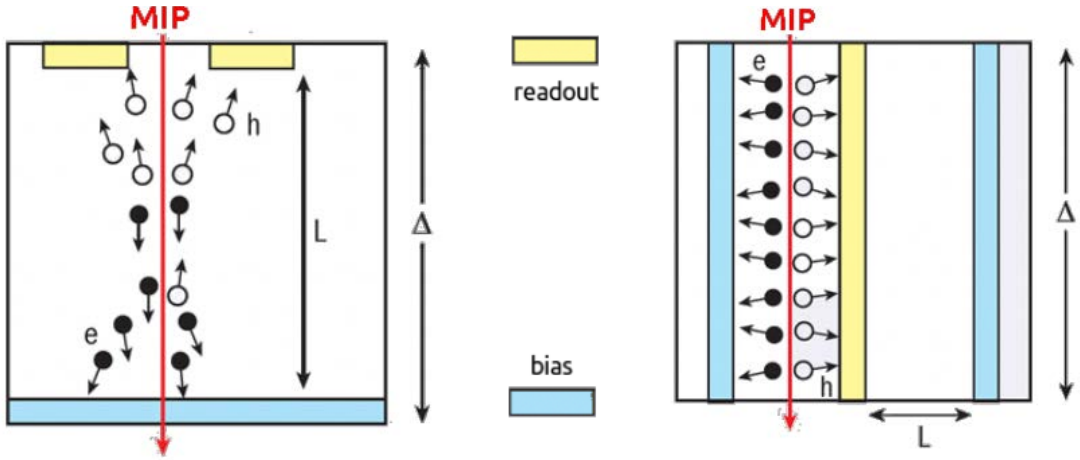
Introduction - 3D Device in Diamond

After large radiation fluence all detectors are trap limited

- Mean free paths (schubweg) λ < 50μm
- Need to keep drift length (L) smaller than mfp (λ)

Comparison of planar and 3D devices

Same $\Delta \rightarrow$ same amount of charge but shorter drift length L!

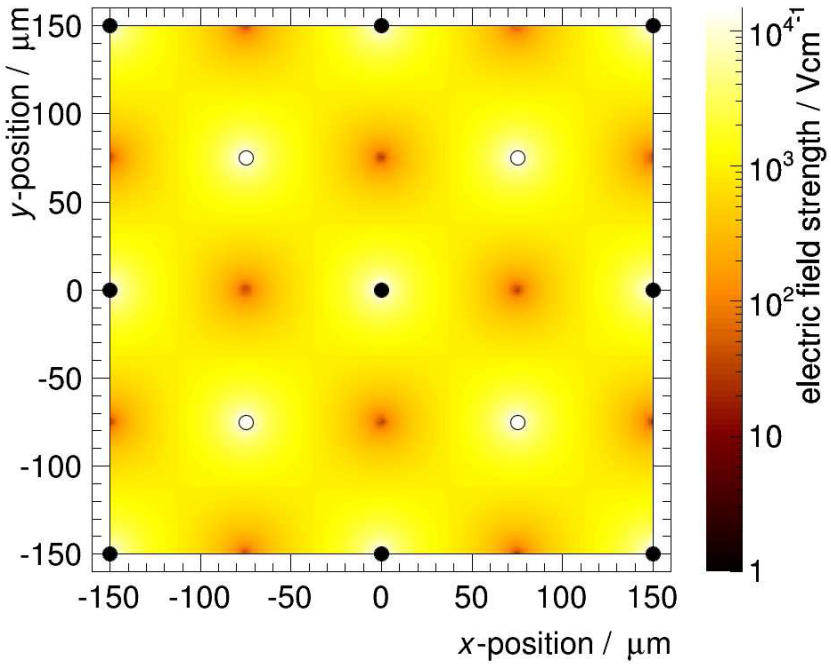


Planar 3D

- 3D geometry increases collected charge in detectors with limited λ
- But 3D geometry introduces low E-field regions

3D Device in pCVD Diamond

- TCAD simulations to compare with measurements:
  - With large cells and large diameter columns → lower field regions in saddle points



Cell size: 150µm x 150µm
Voltage: 25V

from: G. Forcolin, Ph.D. Thesis
Manchester University 2017

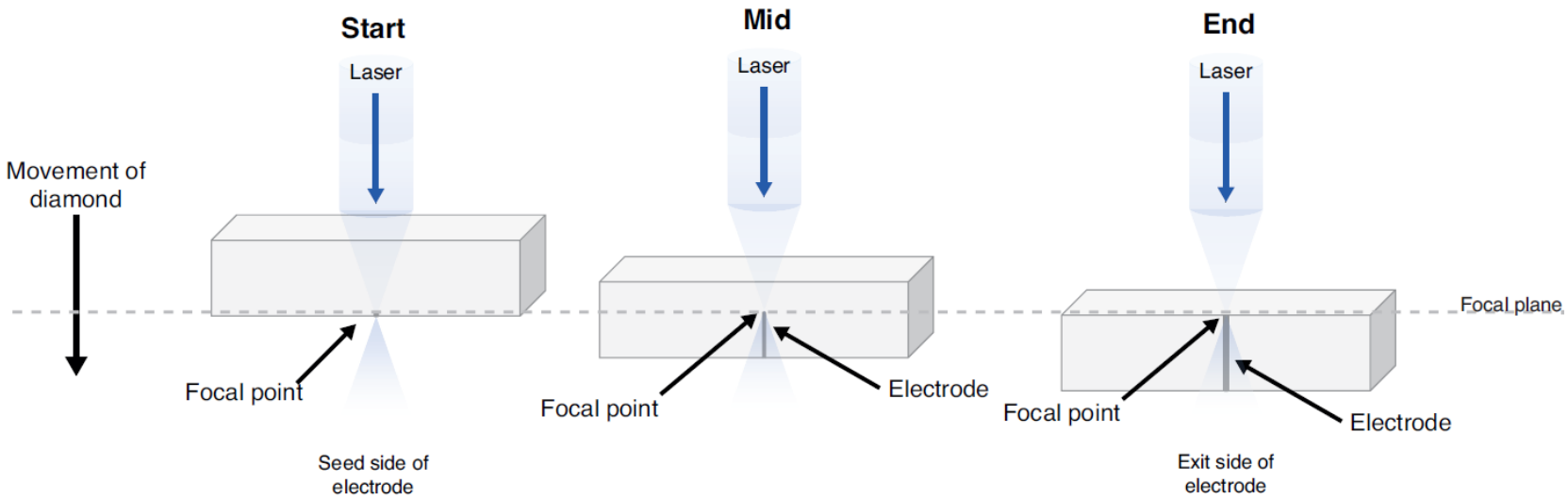
Simulations indicated with present technology, 3D diamond pixel devices would work well enough to test.

3D Device in pCVD Diamond

Femtosecond laser (800 nm) is used to convert insulating diamond into a resistive mixture of various carbon phases:

amorphous carbon, DLC, nano-diamond, graphite.

- Initial methods had 90% column yield → now >99% yield with Spatial Light Modulation (SLM)
- Initial column diameters 6-10μm → now 2.6μm (with SLM)



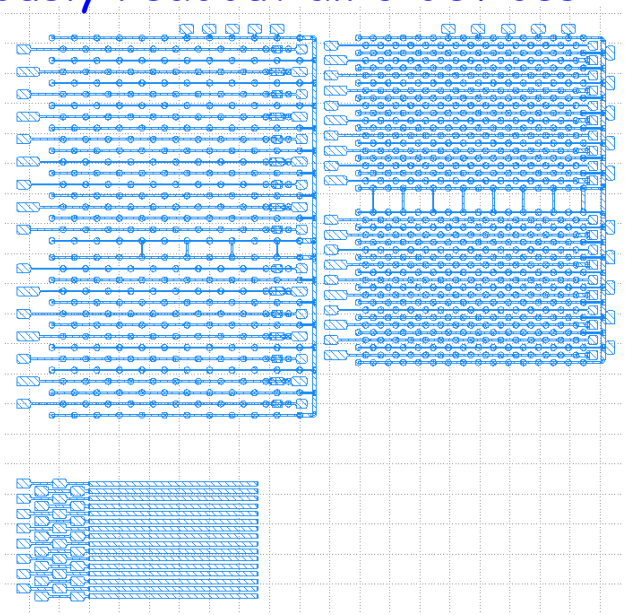
3D Device in pCVD Diamond - History

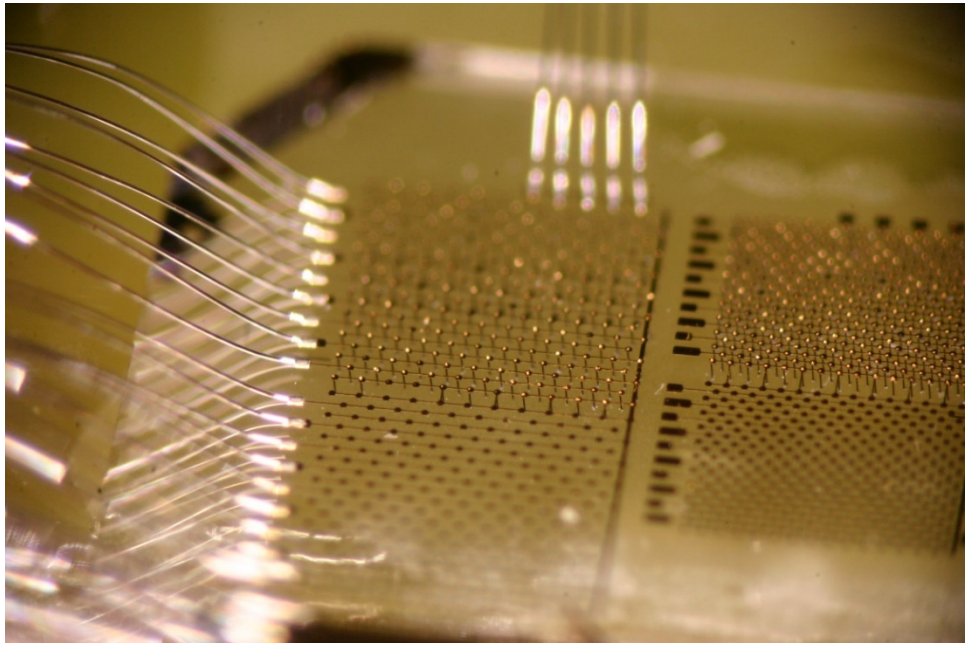
Simultaneously readout all 3 devices

3D

phantom

strip





Four years ago we showed the results in scCVD diamond
- -Compared scCVD strip detector (500V) with 3D (25V)

Three years ago the first 3D device in pCVD diamond
- -Compare pCVD strip detector (500V) with 3D (60V)

Two years ago the first 3D pixel detectors in pCVD diamond

Last year 50μmx50μm 3D cells read out w/ATLAS, CMS electronics

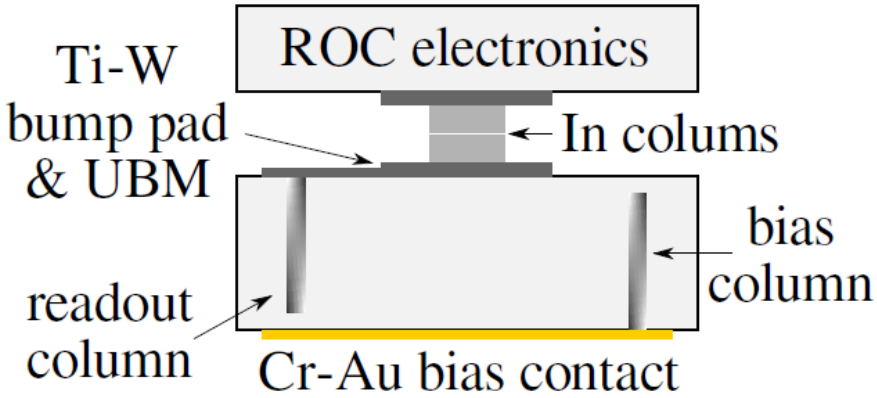
This year first irradiated pCVD 50μmx50μm 3D pixel detector

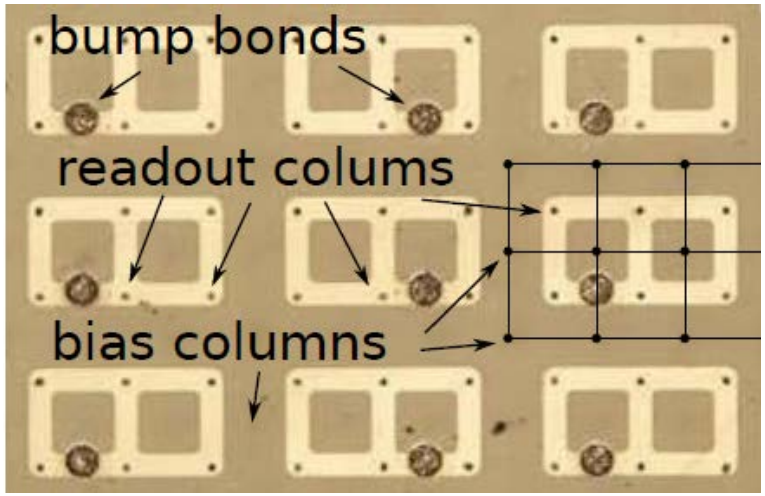
3D Device in pCVD Diamond

- Past Technological Successes:
  - Proved 3D works in pCVD diamond
  - Scaled up number of cells $\mathcal{O}(100) \rightarrow \mathcal{O}(4000)$
  - Reduced cell size: 150μm x 150μm → 50μm x 50μm → 25μm x 25μm (soon)
  - Reduced column diameter: 6~10μm → 2.6μm → 1~2μm (soon)
  - Increased column yield $\mathcal{O}(90\%) \rightarrow \mathcal{O}(99\%)$
  - Tested first 50μm x 50μm 3D device irradiated to 3.5×10^{15} 800MeV p/cm^2 → Small (if any) loss of charge
- Visible improvements at each device
  - Measurements consistent with TCAD predictions to first order

Results of CMS, ATLAS 3D pCVD Pixel Devices

Preliminary Results (50μmx50μm cells)

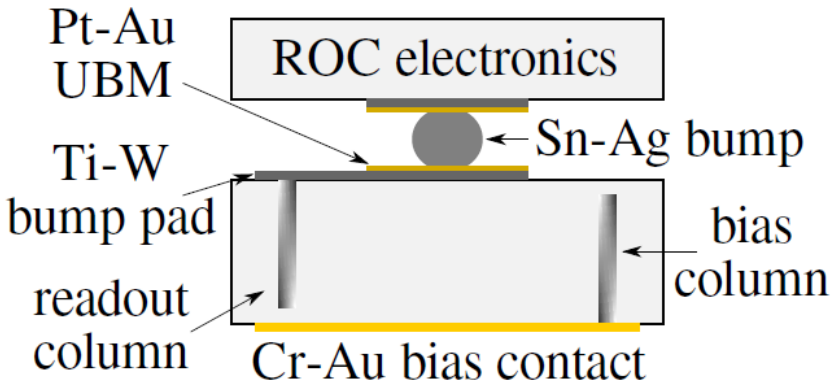


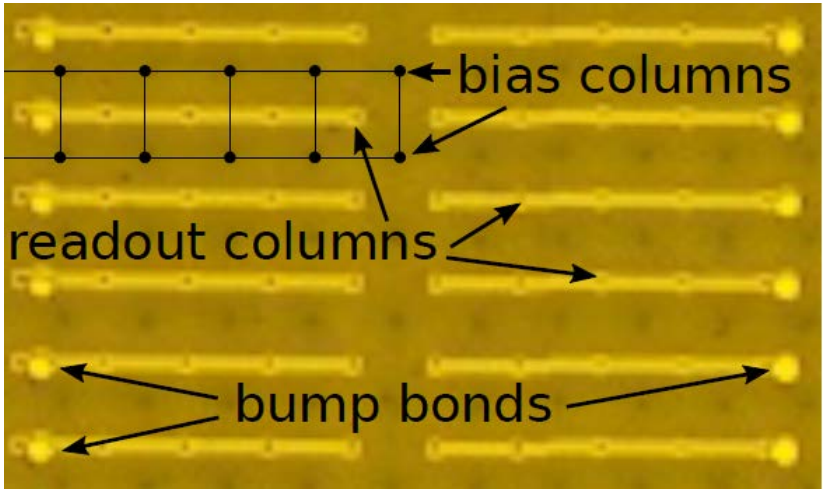


- Connection to bias and readout columns w/surface metallization
- Readout with CMS pixel readout - 6 cells (3x2) ganged together
- Indium bumps on both ASIC (PSI46digv2.1respin) and detector
- Small gap (~15 μm) to opposite surface for voltage isolation

Results of CMS, ATLAS 3D pCVD Pixel Devices

Preliminary Results (50μmx50μm cells)



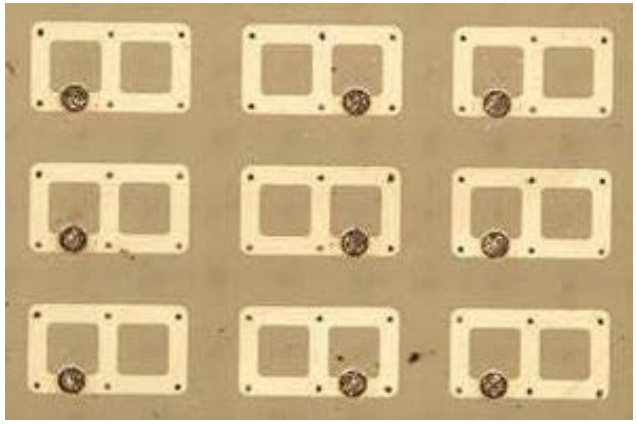


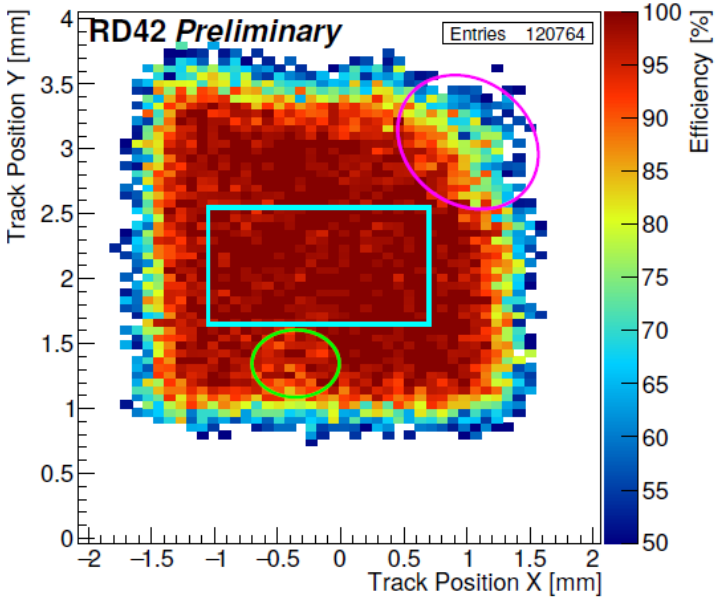
- Connection to bias and readout columns w/surface metallization
- Readout w/ATLAS pixel readout - 5 cells (5x1) ganged together
- Tin-Silver bumps on ASIC (FE-I4); Pt-Au UBM on detector
- Small gap (~15 μm) to opposite surface for voltage isolation

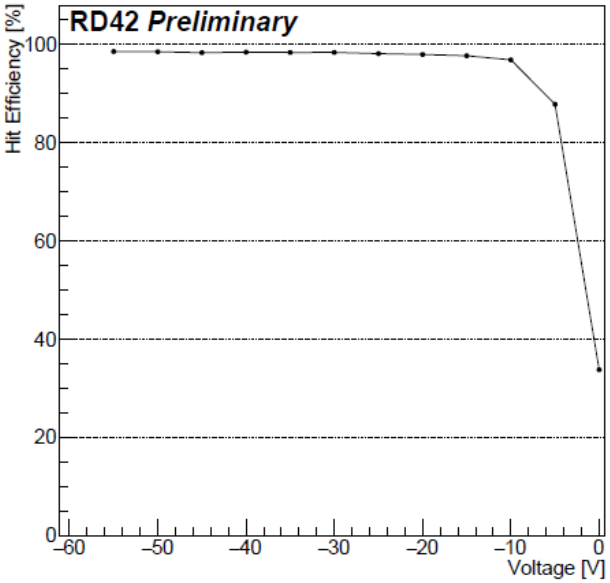
Results of CMS, ATLAS 3D pCVD Pixel Devices

Preliminary Results (50μmx50μm cells)

- CMS pixel readout (3x2) ganging
- Indium bumps
- Magenta area – bump bonding issues
- Green area – void in diamond
- Blue box-efficiency 99.2%; expect 99.6%



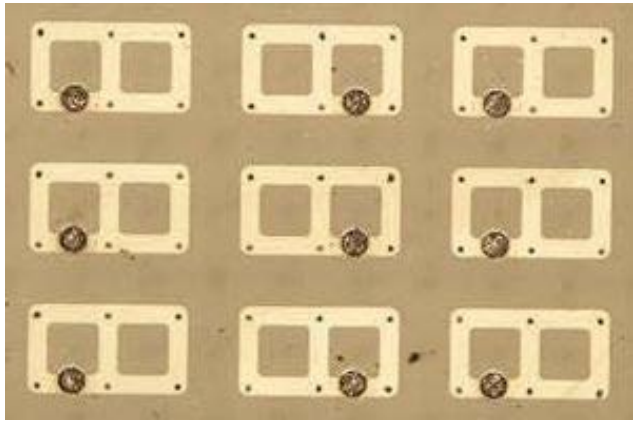


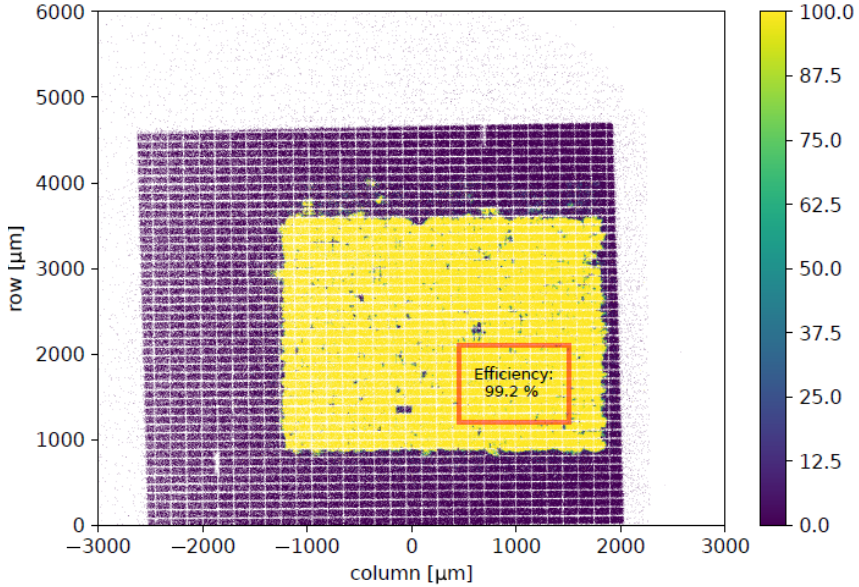


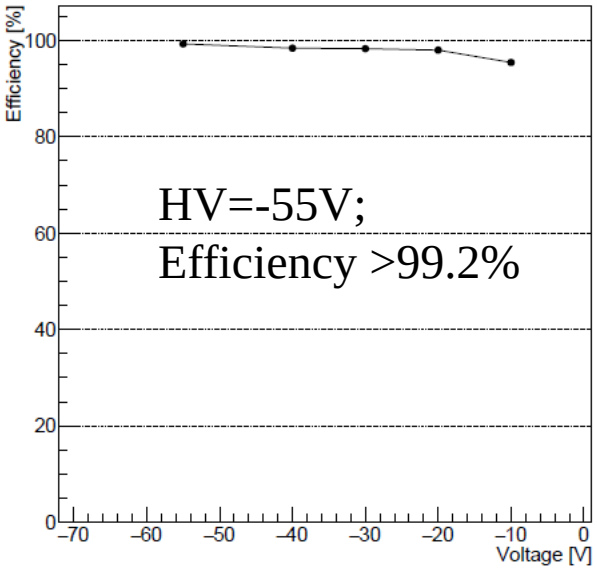
Results of CMS, ATLAS 3D pCVD Pixel Devices

Preliminary Results (50μmx50μm cells)

- CMS pixel readout (3x2) ganging
- Indium bumps
- LJU telescope (resolution ~3 μm)
- Red box-efficiency 99.2%



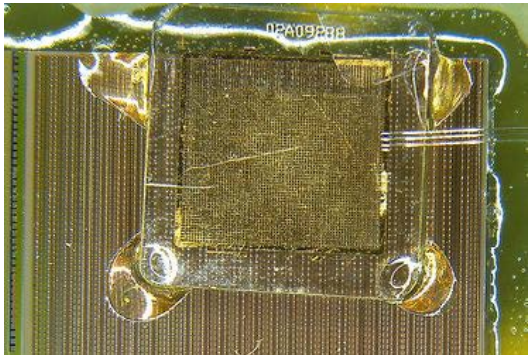


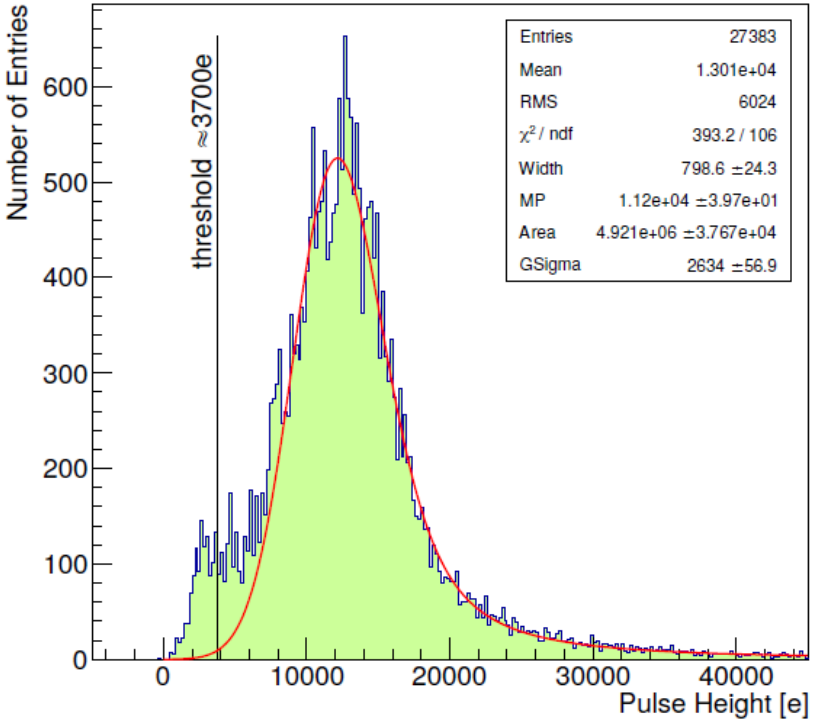


Results of CMS, ATLAS 3D pCVD Pixel Devices

50μm x 50μm 3D diamond with CMS pixels

- Results w/PSI46digv2.1 readout-(3x2) ganging





Mean PH = 14,500e

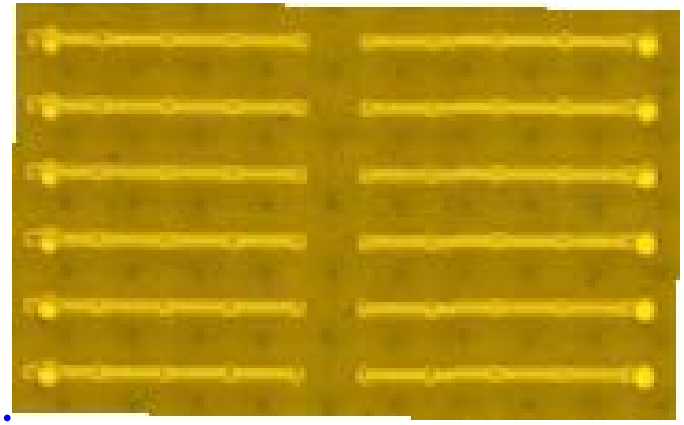
Threshold still needs to be calibrated

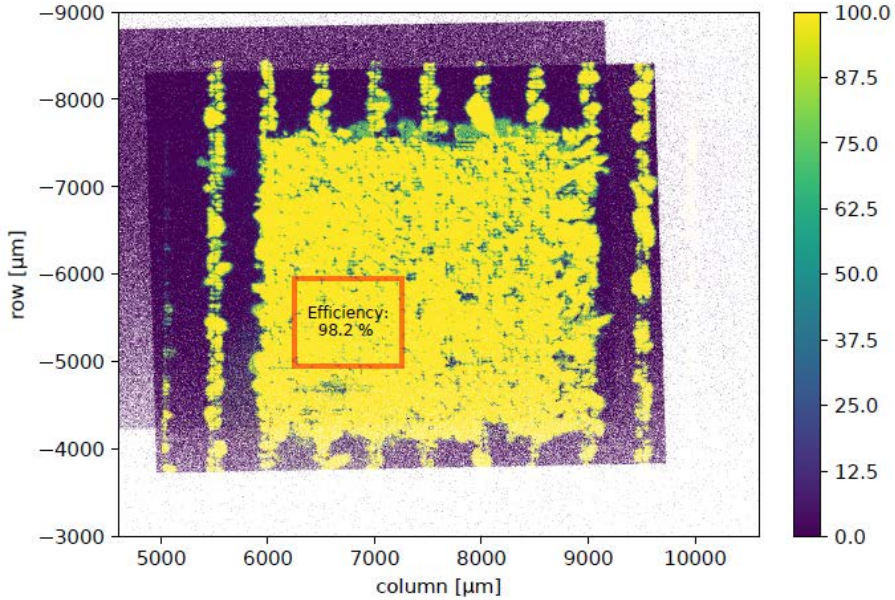
Distribution below threshold being worked on – recent DESY beam test finished last week

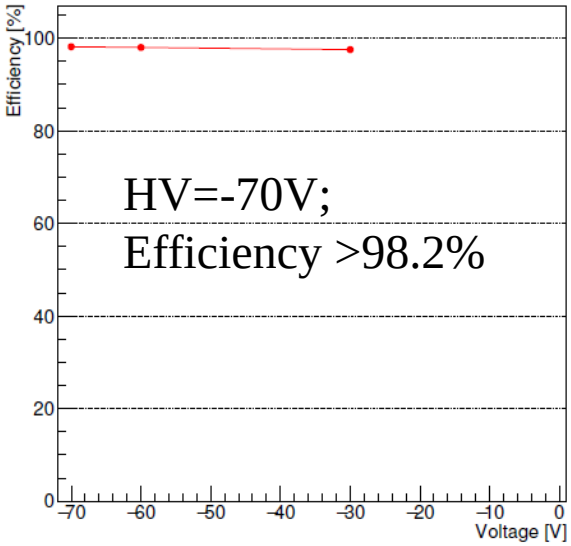
Results of CMS, ATLAS 3D pCVD Pixel Devices

Preliminary Results (50μmx50μm cells)

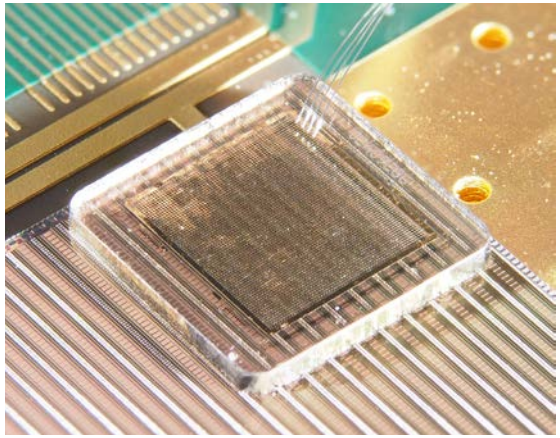
- ATLAS pixel readout (5x1) ganging
- Tin-Silver solder bumps
- LJU telescope (resolution ~3 μm)
- Red box - efficiency >98.2%
- Inefficiencies most likely due to processing







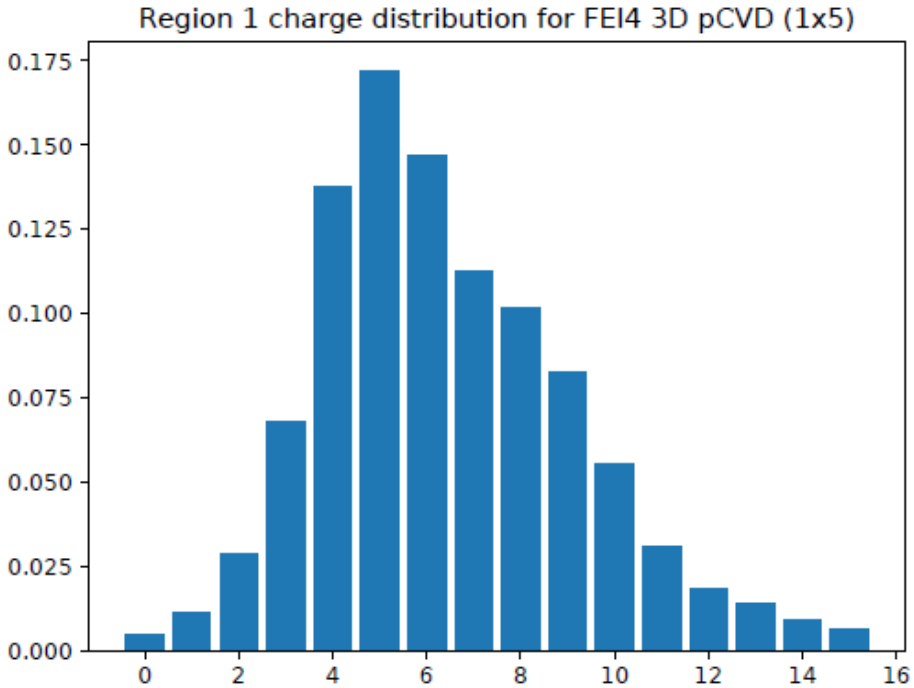
Results of CMS, ATLAS 3D pCVD Pixel Devices



50μmx50μm 3D diamond with ATLAS pixels

- Results w/FE-I4 pixel readout-(5x1) ganging

TOT Distribution (5 TOT ~ 11,000e)



Mean TOT = 6.73 → 14,800e

Small TOT bins still need to be calibrated

Summary

Lots of progress in 3D diamond pixel detectors

- 3D diamond pixel detector prototypes
  - Parameter space now well defined
    - 3D works in pCVD diamond
    - Scale up (x40) worked
    - Smaller cells (50μm x 50μm) worked
    - Thinner columns (2.6μm) worked
- 3D diamond pixel devices being produced
  - Steps from 150μm → 100μm → 50μm … 25μm next
  - Visible improvements with each step
  - Efficiencies look good, still a bit to be understood
  - Simulation needs some effort
  - All devices produced work, to first order, as expected

Future Plans

- 3D diamond device irradiations to 10^{17} hadrons/cm^2
  - Tested 50μm x 50μm device irradiated @3.5x10^{15} 800MeV p/cm^2
  - Continue irradiations to 10^{16}/cm^2 this coming year
  - Test both (50μm x 50μm) and (25μm x 25μm) pixel detectors
  - Thinner columns (<2μm) may be needed for 25μm x 25μm cells
  - Irradiation to 10^{17}/cm^2 next year
- 3D diamond pixel devices
  - Ready for readout with RD53A chip this coming year
  - Continue scale up (x10)
  - Expand fabrication facilities
  - Begin industrial production