Latest 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 (→ William Trischuk's talk next)
  - 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 2020 RD42 Collaboration

The 2020 RD42 Collaboration

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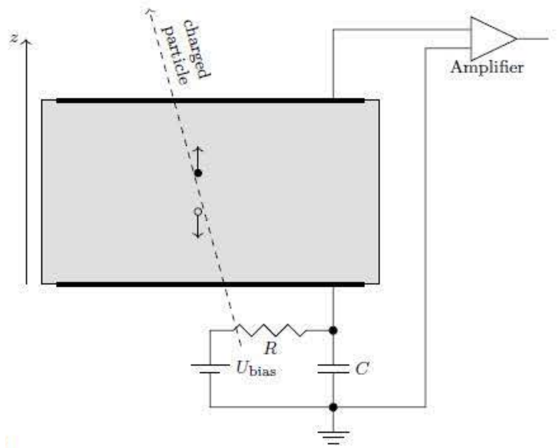
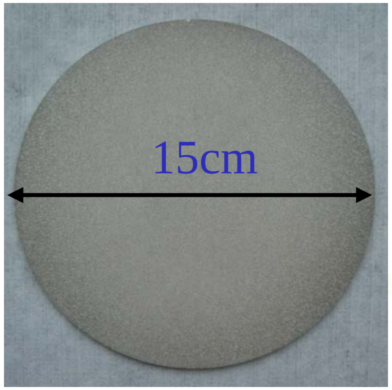
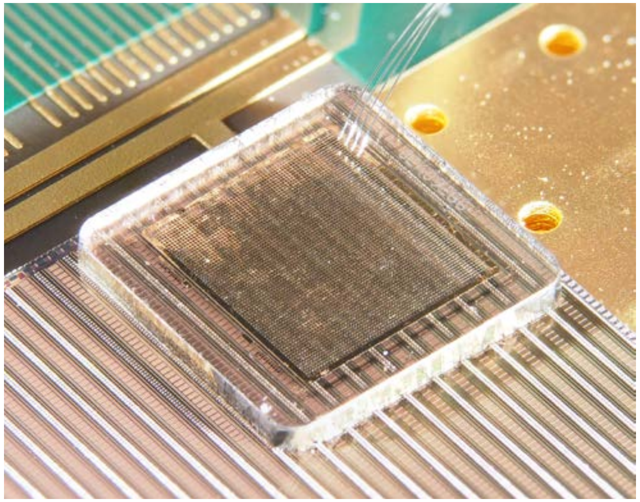
31 Institutes

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







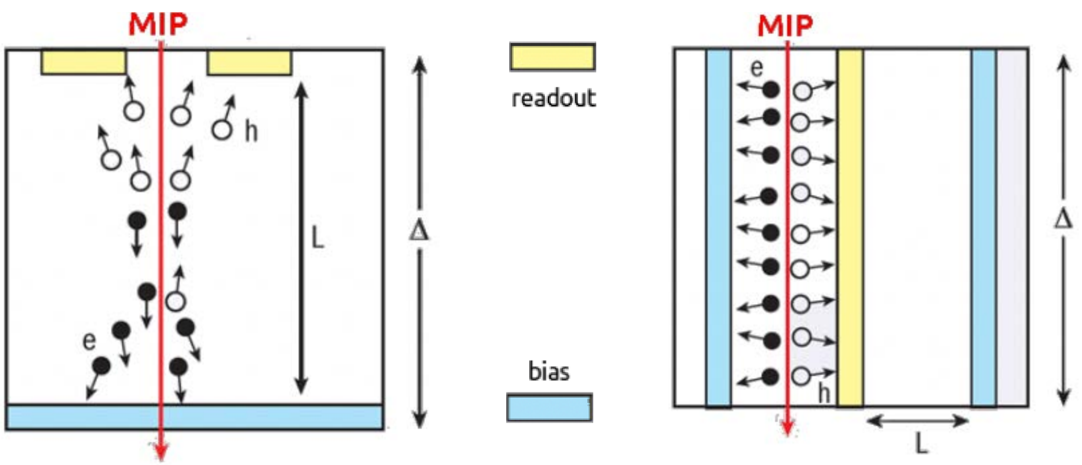
pCVD diamond with 3D pixel device bump-bonded to ATLAS FE-I4

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 Δ → same amount of charge but shorter drift length L!

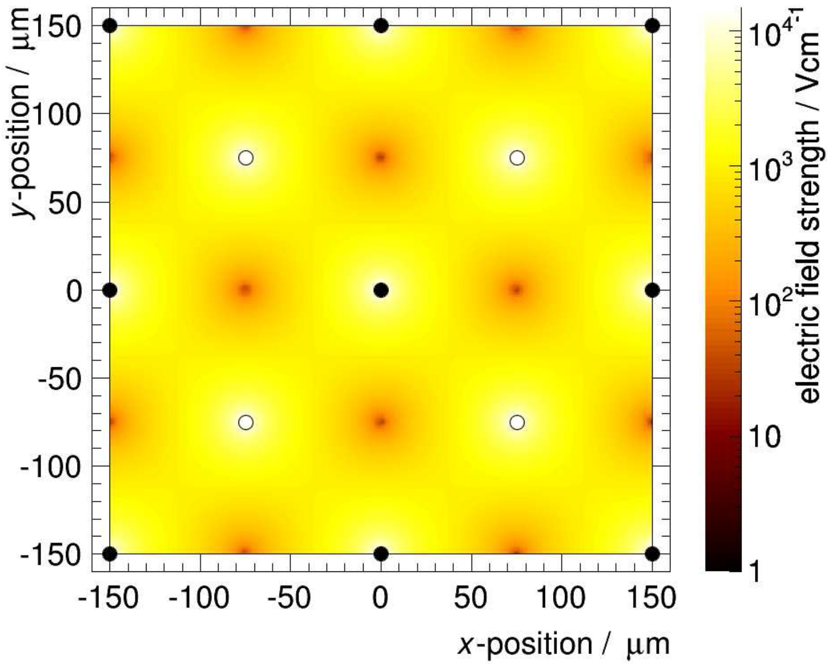


Planar 3D

- 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

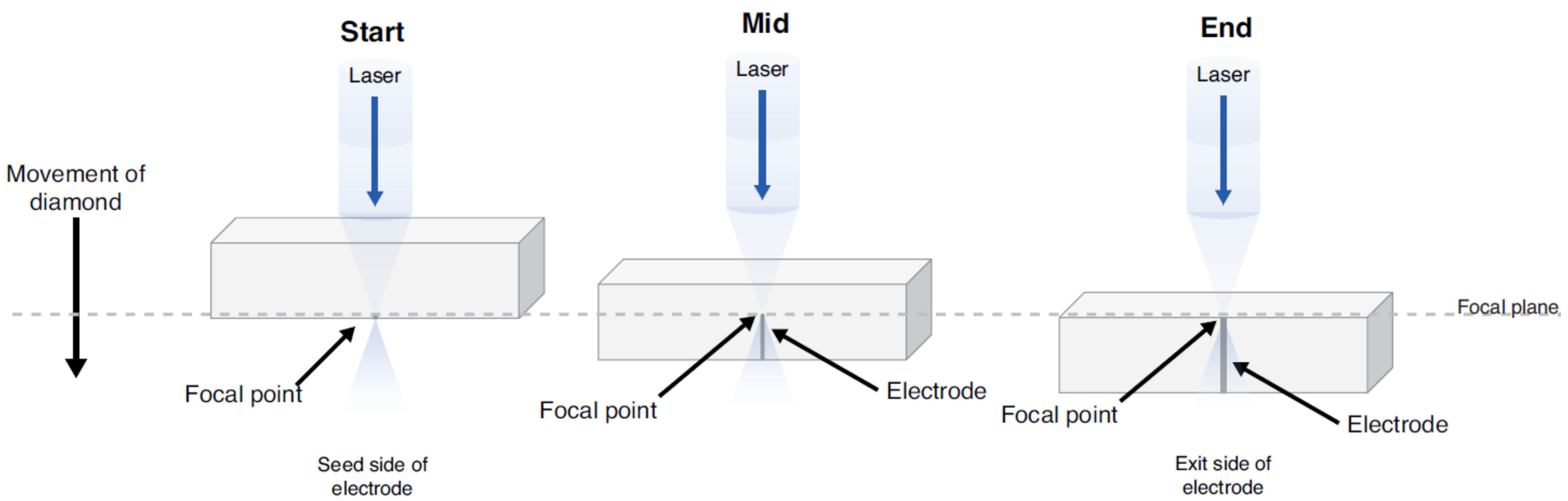
Simulations indicated with present technology, 3D diamond pixel devices would work well enough to test.

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)

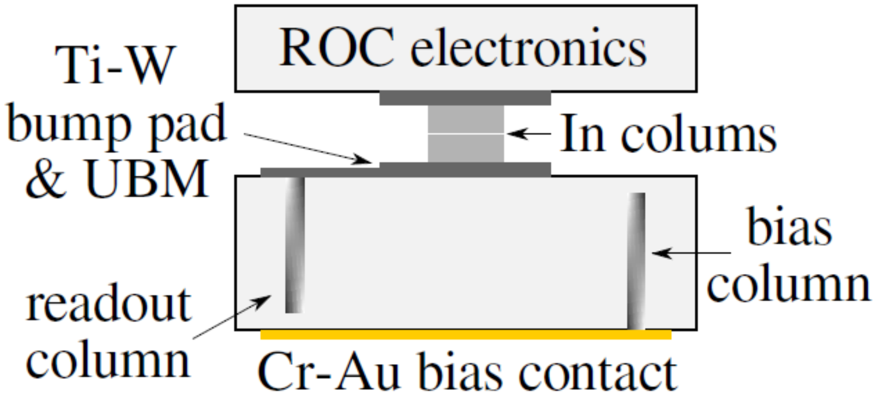


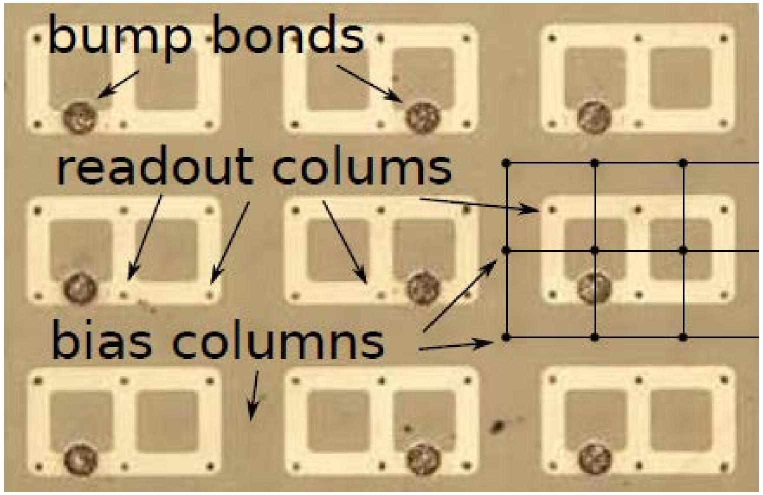
3D Device in pCVD Diamond

- 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)

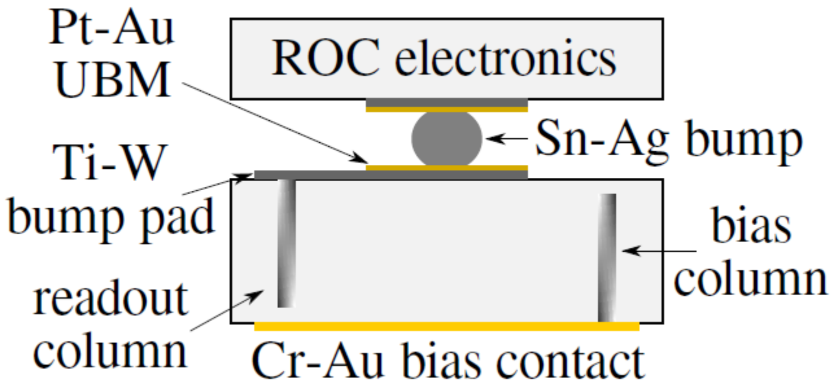


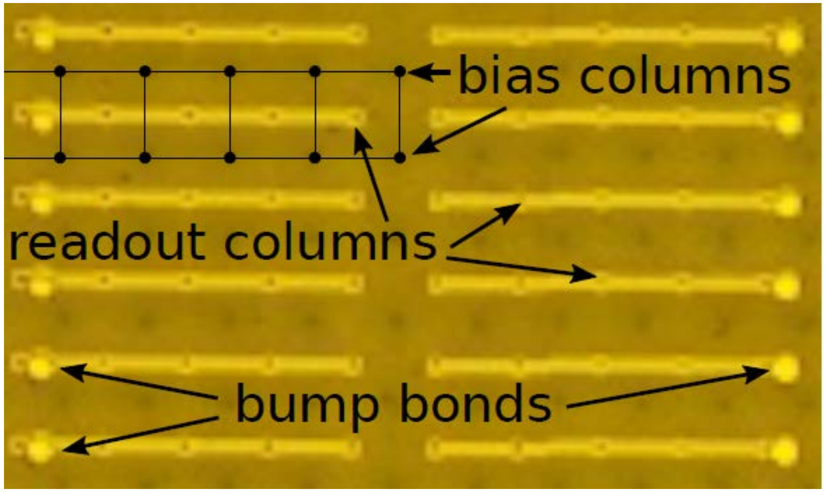


- Connection to bias and readout columns w/surface metallization
- Readout with CMS pixel readout - 6 cells (3x2) ganged together
- Indium bumps on both ASIC (PSI46digv2.1respin) and detector
- Small gap (~15 μm) to opposite surface for voltage isolation

Results of CMS, ATLAS 3D pCVD Pixel Devices

Preliminary Results (50μmx50μm cells)



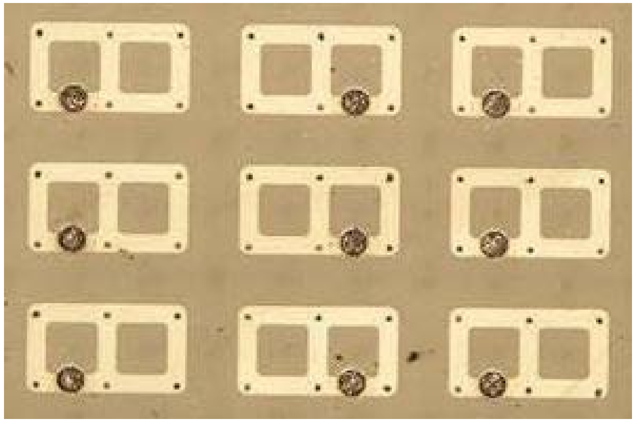


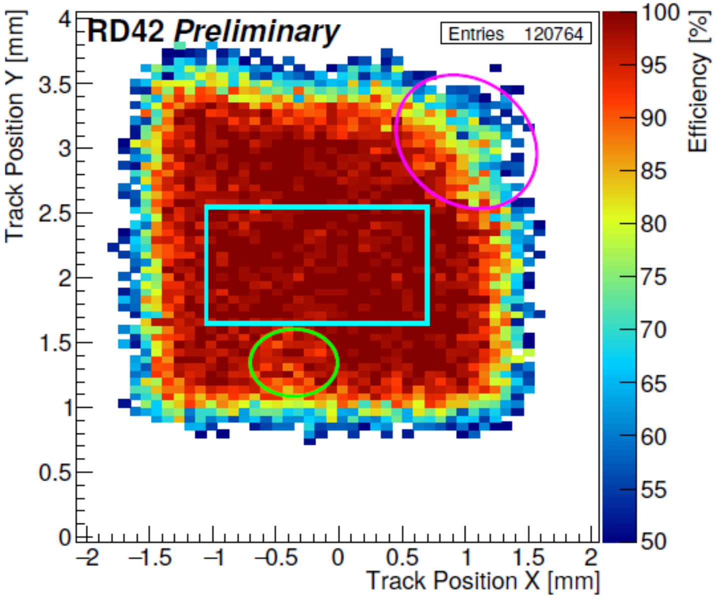
- Connection to bias and readout columns w/surface metallization
- Readout w/ATLAS pixel readout - 5 cells (5x1) ganged together
- Tin-Silver bumps on ASIC (FE-I4); Pt-Au UBM on detector
- Small gap (~15 μm) to opposite surface for voltage isolation

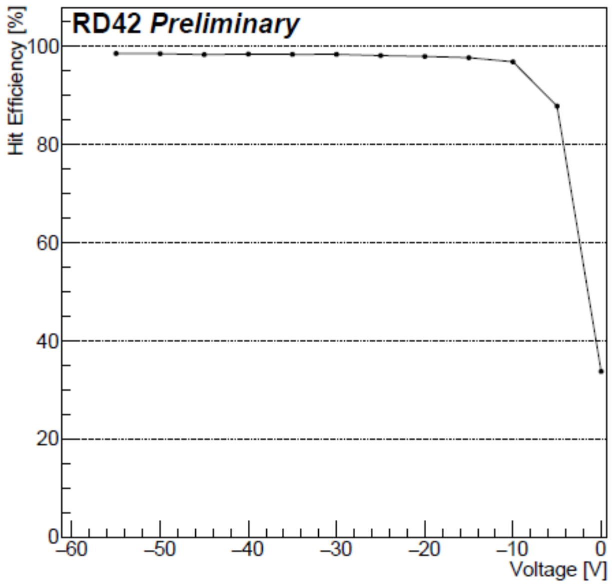
Results of CMS, ATLAS 3D pCVD Pixel Devices

Preliminary Results (50μmx50μm cells)

- CMS pixel readout (3x2) ganging
- Indium bumps – beam test @PSI
- Magenta area – bump bonding issues
- Green area – diamond surface issues
- Blue box-efficiency 99.2%; expect 99.6%



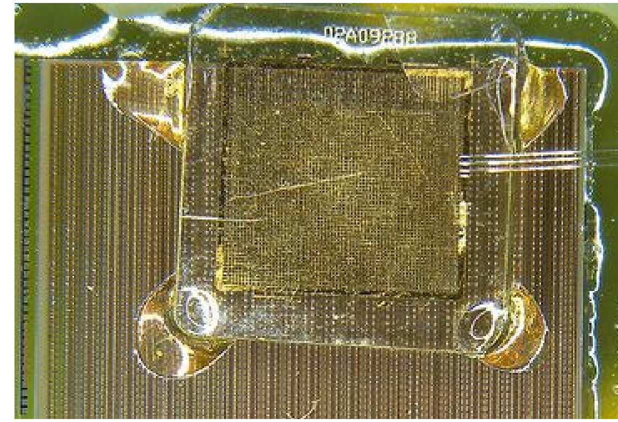


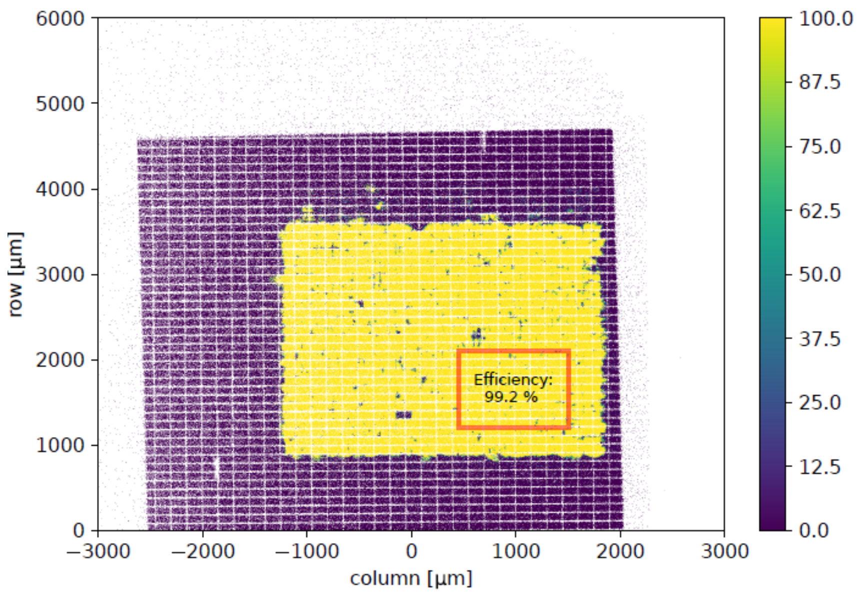


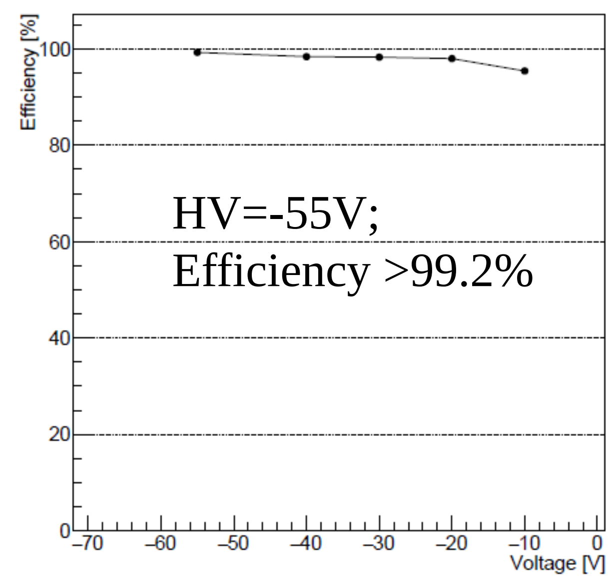
Results of CMS, ATLAS 3D pCVD Pixel Devices

Preliminary Results (50μmx50μm cells)

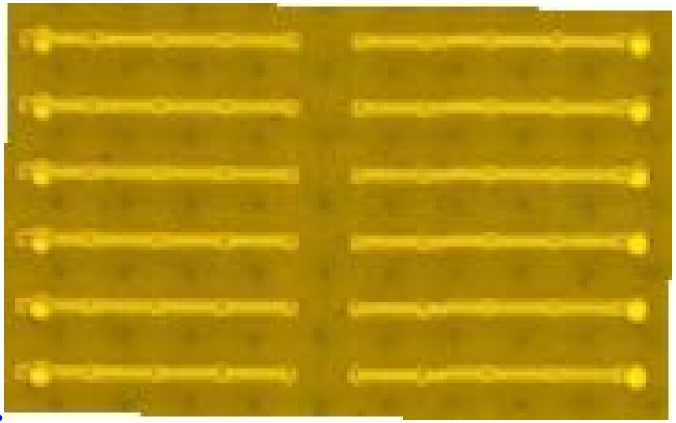
- CMS pixel readout (3x2) ganging
- Indium bumps, re-bump-bonded
- Beam test @CERN
- LJU telescope (resolution ~3 μm)
- Red box-efficiency 99.2%





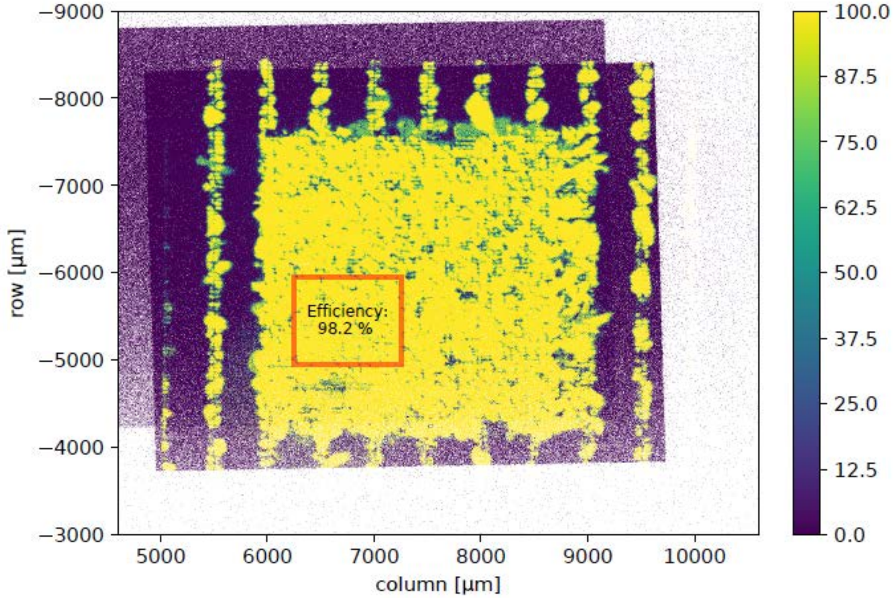


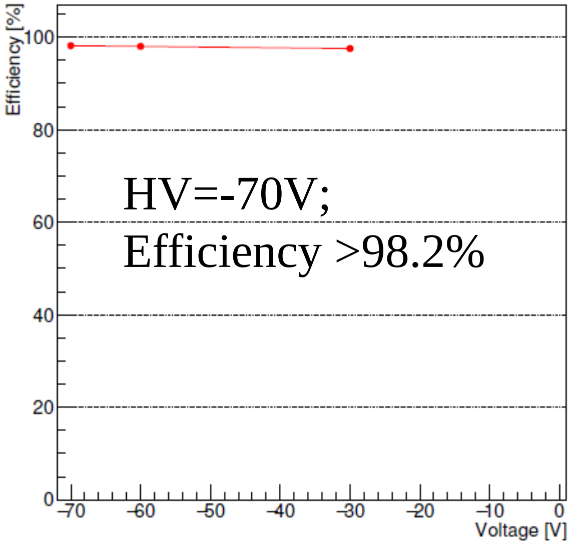
Results of CMS, ATLAS 3D pCVD Pixel Devices



Preliminary Results (50µmx50µm cells)

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

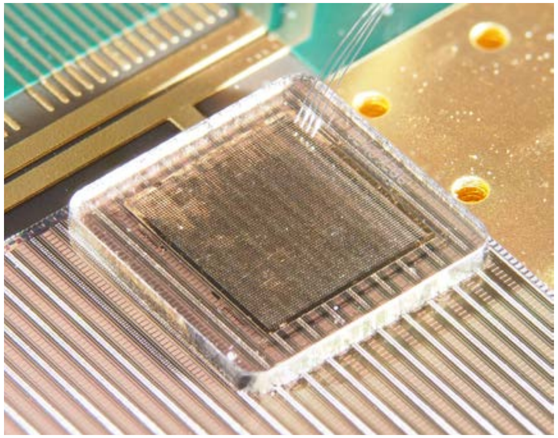




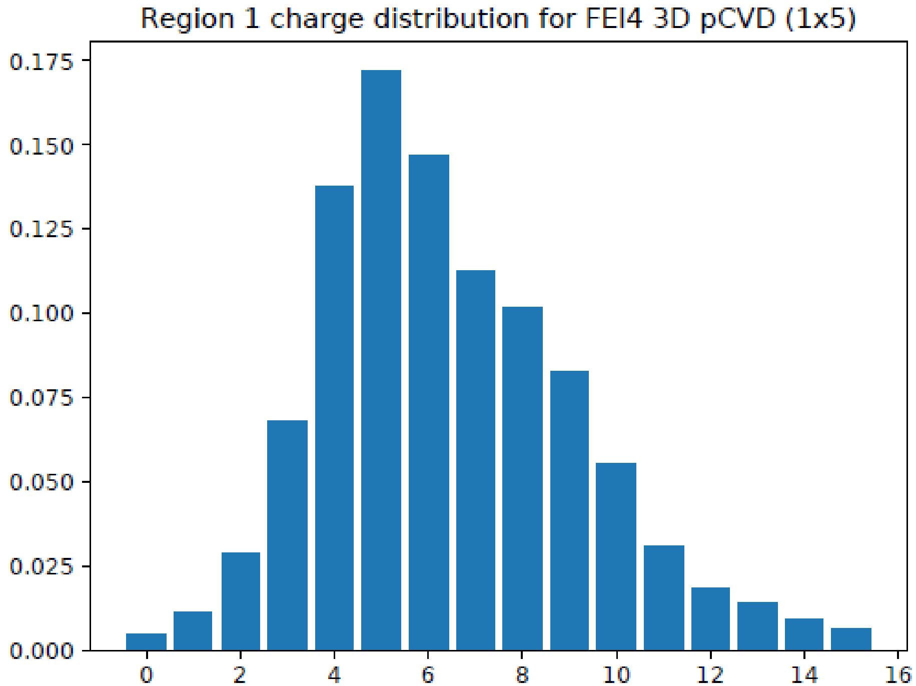
Results of CMS, ATLAS 3D pCVD Pixel Devices

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 in the process of being 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 @3.5×10^{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) will 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