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

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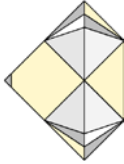
for the RD42 Collaboration

14th Trento Workshop (Tredi 2019)
Trento, Italy
February 26, 2019

Outline of Talk

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

Introduction - Motivation



Present Situation:

- Innermost layers → highest radiation damage (~GHz/cm^2)
- Current detectors designed to survive ~12 months in HL- LHC

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

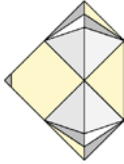
Diamond as a Detector Material:

- Properties:
  - radiation tolerance
  - insulating material
  - high charge carrier mobility
  - smaller signal than in same thickness of silicon (larger bandgap)

RD42 work:

- Investigate signals and radiation tolerance in various detector designs:
  - pad → full diamond as a single cell readout
  - pixel → diamond sensor on pixel chips
  - 3D → strip/pixel detector with design to reduce drift distance

Introduction - The 2018 RD42 Collaboration



The 2018 RD42 Collaboration

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

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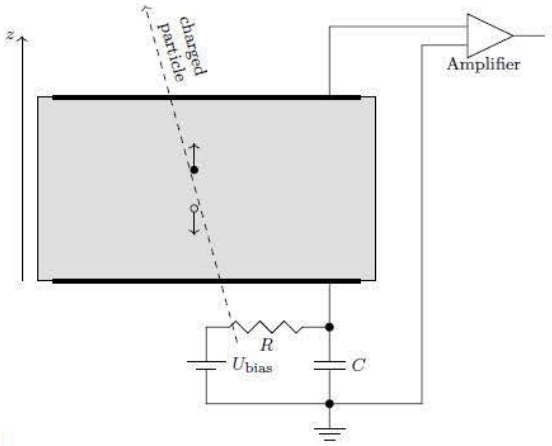
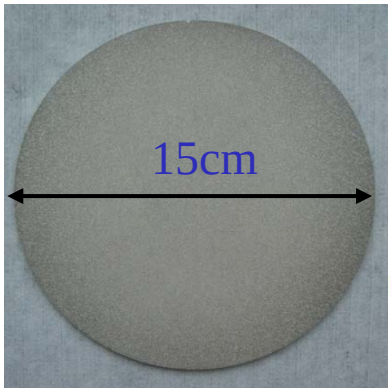
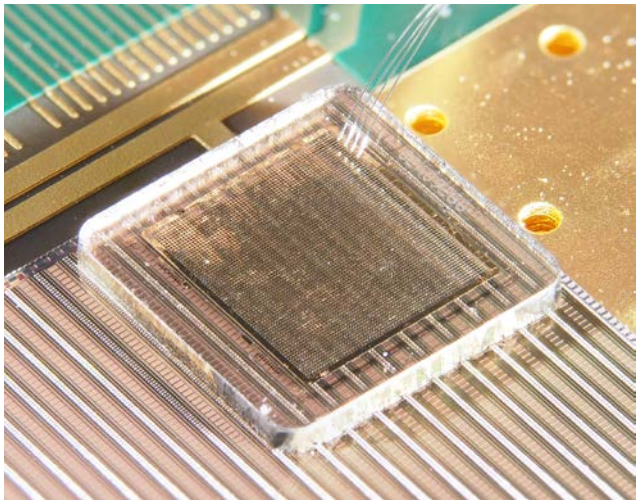
30 institutes

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 FE-I4

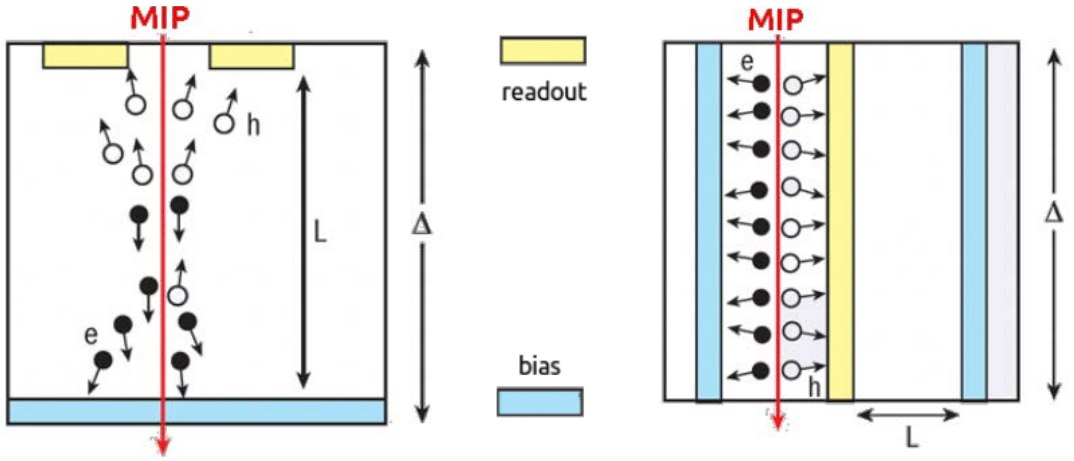
3D Device in pCVD Diamond

After large radiation fluence all detectors are trap limited

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

Comparison of planar and 3D devices

Can one fabricate columns in diamond?



Planar 3D

Have to make resistive columns for this to work:

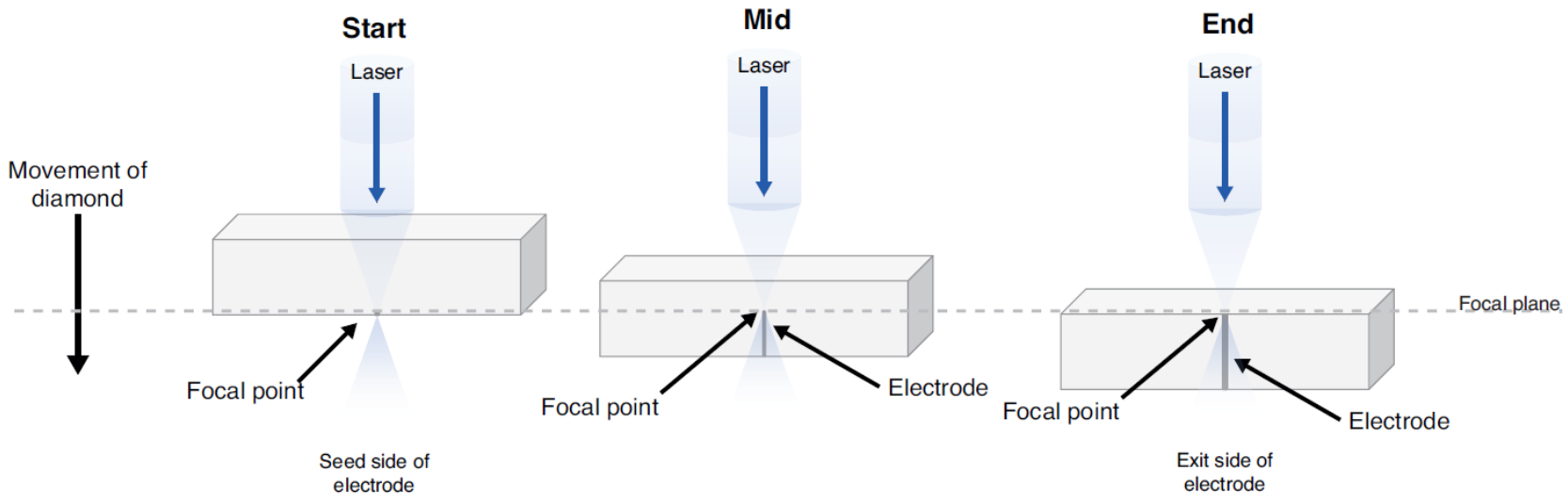
-columns made with 800nm femtosecond laser

-initial cells 150μm x 150μm; columns 6-10μm diameter

3D Device in pCVD Diamond

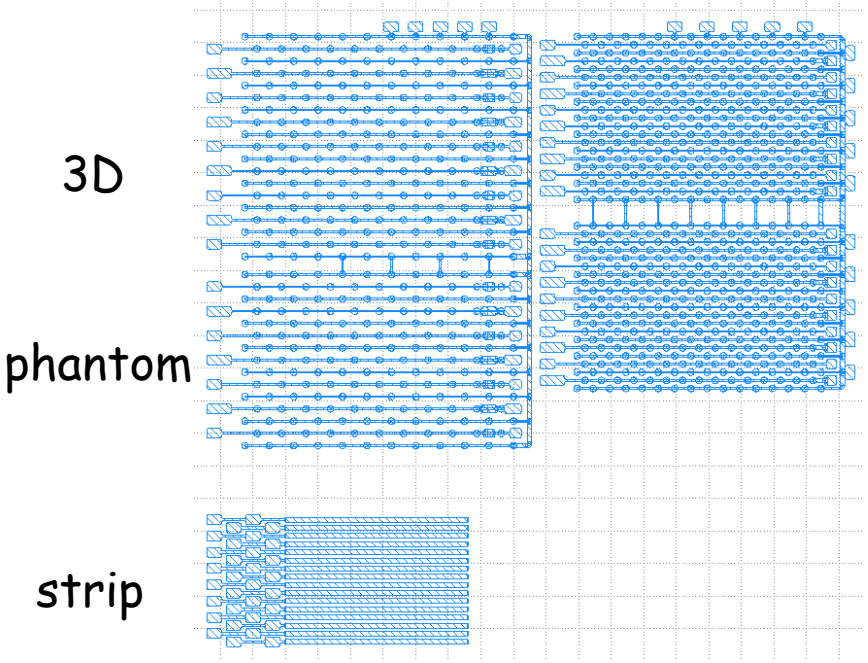
Femtosecond laser converts insulating diamond into resistive mixture of various carbon phases: amorphous carbon, DLC, nano-diamond, graphite.

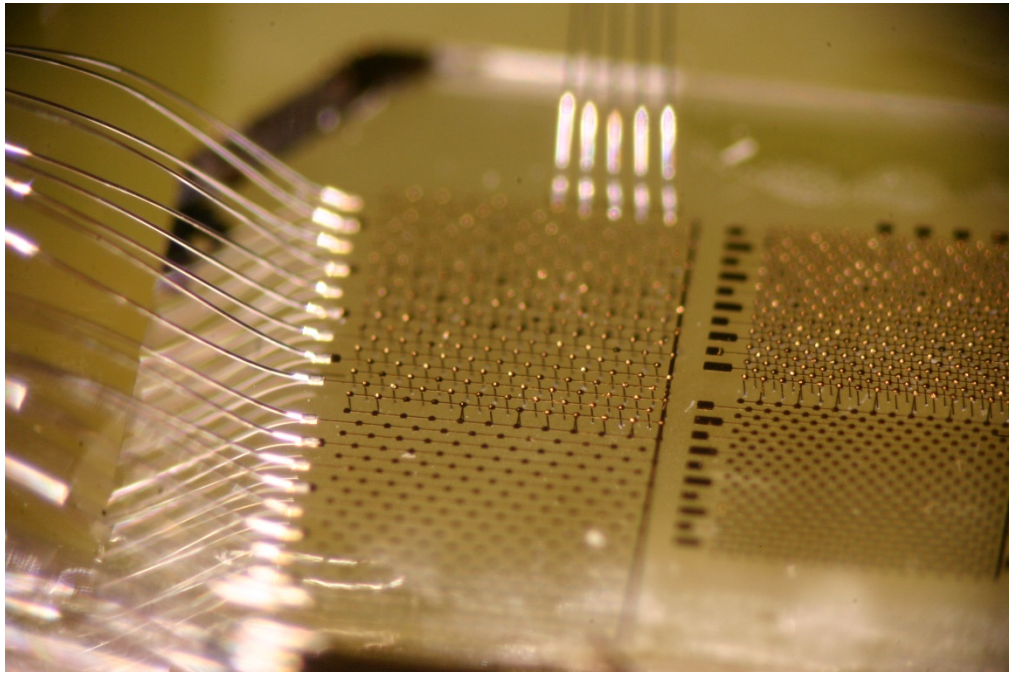
- Initial methods had 90% column yield → now >99% yield with Spatial Light Modulation (SLM)
- Initial column diameters 6-10μm → now 2.6μm (with SLM)



3D Device in pCVD Diamond

Simultaneously readout all 3 devices





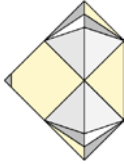
Three years ago we showed the results in scCVD diamond
- -Compared scCVD strip detector (500V) with 3D (25V)

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

Last year the first 3D pixel detectors in pCVD diamond

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

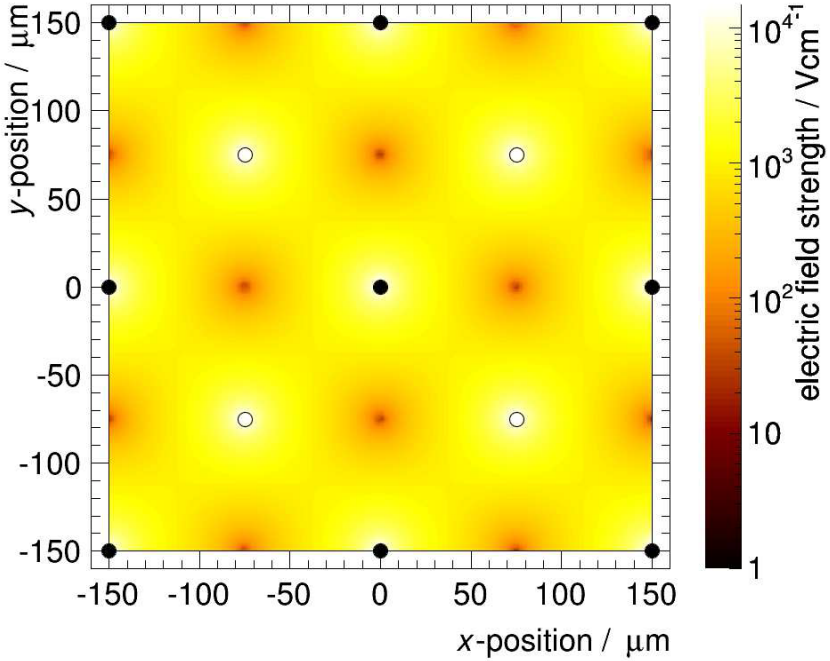
3D Device in pCVD Diamond



- 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

3D Device in pCVD Diamond

- Measurements consistent with TCAD simulations:
  - Large cells, large diameter columns → lower field regions in saddle points



Cell size: 150µm x 150µm
Voltage: 25V

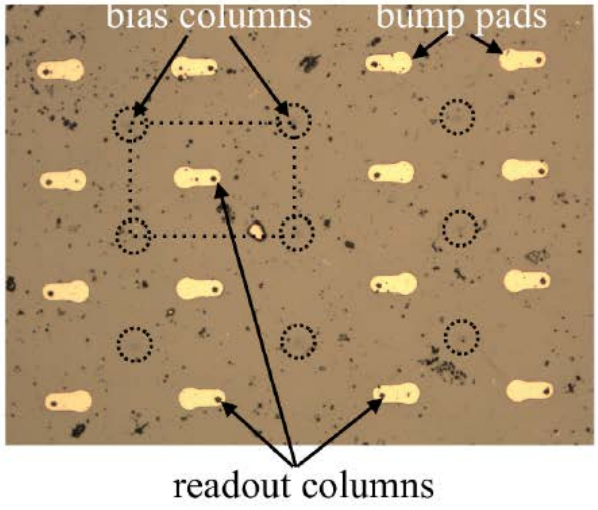
from: G. Forcolin, Ph.D. Thesis
Manchester University 2017

Device worked well enough to construct first pCVD 3D diamond pixel device

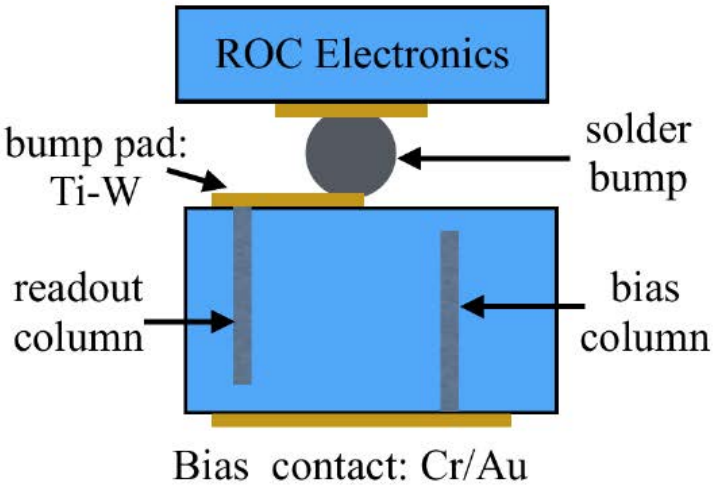
Results of CMS, ATLAS 3D pCVD Pixel Devices

First 3D pixel device in pCVD (2017) – [150μm x 100μm cells]

- Produced cells with 150μm x 100μm size for CMS pixel readout chip
- Cleaning, photolithography, metal contact to pixel and bias – RD42
- Indium Bump and wire bonding - Princeton



(a) pixel readout metalisation



(b) final scheme

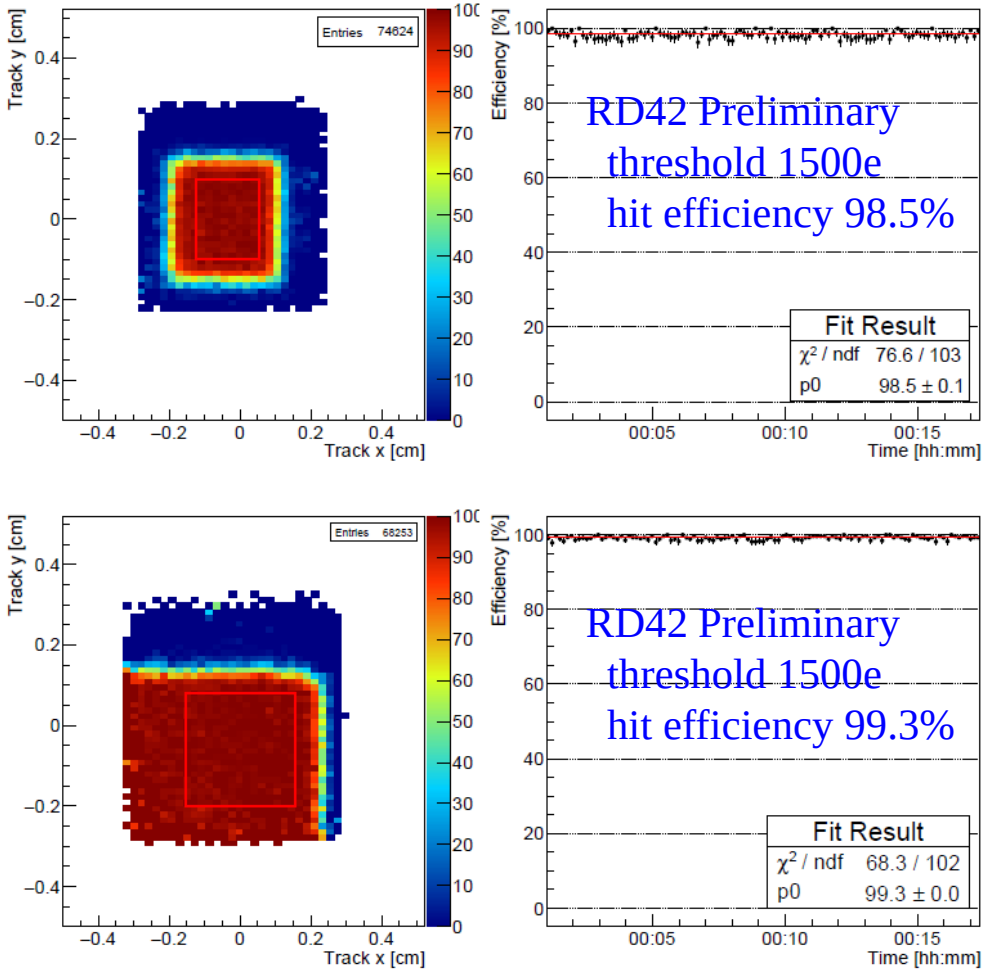
Results of CMS, ATLAS 3D pCVD Pixel Devices

3D Diamond Pixel
>98.5% efficiency

- applied voltage: -55V
- pixel threshold: 1500e
- efficiencies flat in time

Planar Silicon Pixel (ref)
>99.3% efficiency

- lower efficiency in diamond most likely due to low field regions or bad laser columns

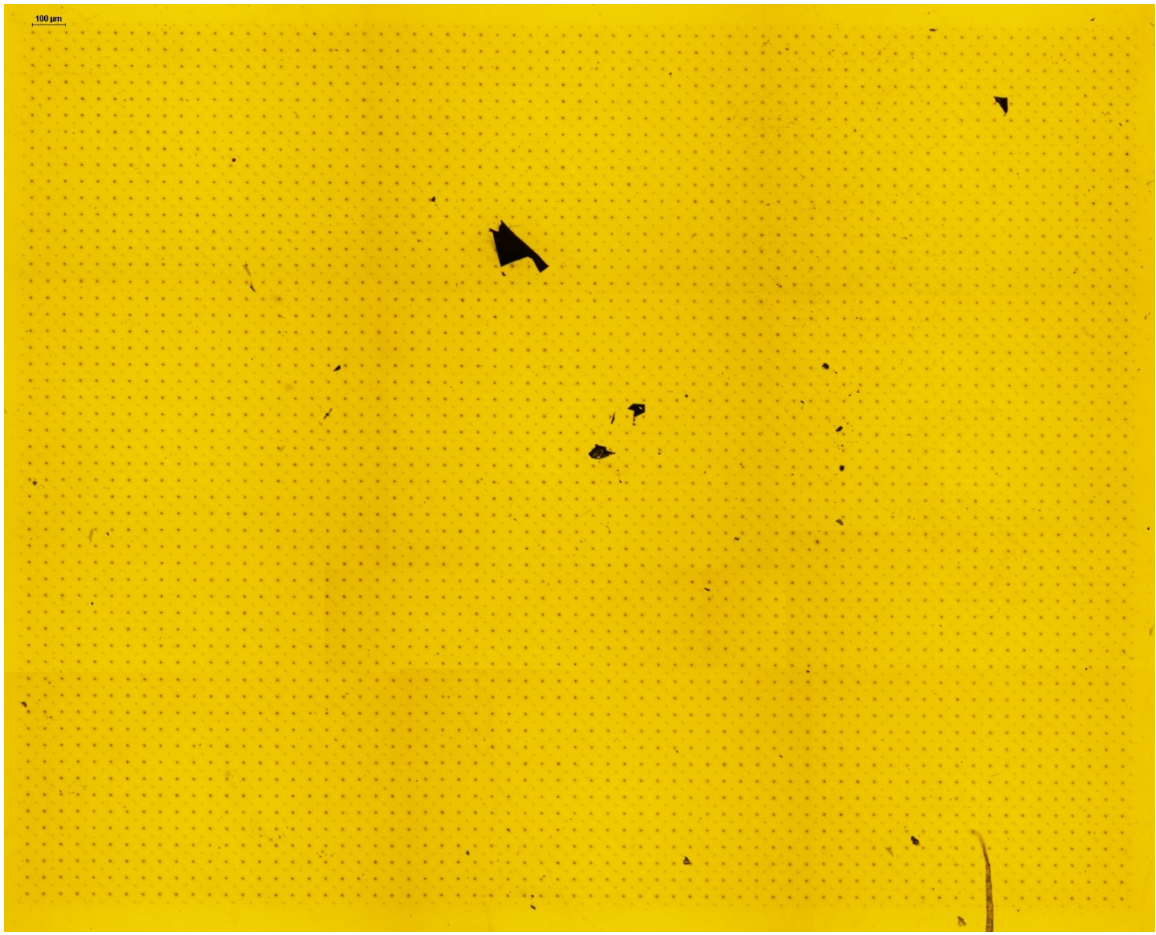


(a) efficiency maps (b) hit efficiencies

Results of CMS, ATLAS 3D pCVD Pixel Devices

Produced ~4000 cell pixel prototype w/50μm x 50μm pitch

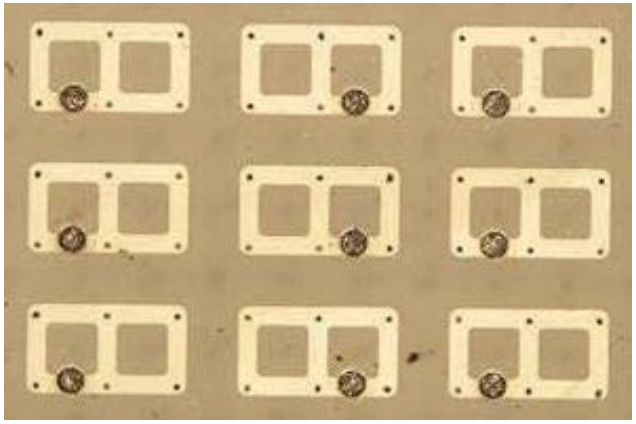
- Three fabricated:
  - Oxford 2;Manchester 1
- Photolith, Metalization
  - CMS, ATLAS
- 50μm x 50μm ganging
  - CMS (3x2),ATLAS (1x5)
- Bump bonding
  - CMS @Princeton
  - ATLAS @IFAE
- Test beam
  - (3x2) Aug 2017 @PSI
  - (3x2) Oct 2018 @CERN
  - (1x5) Oct 2018 @CERN

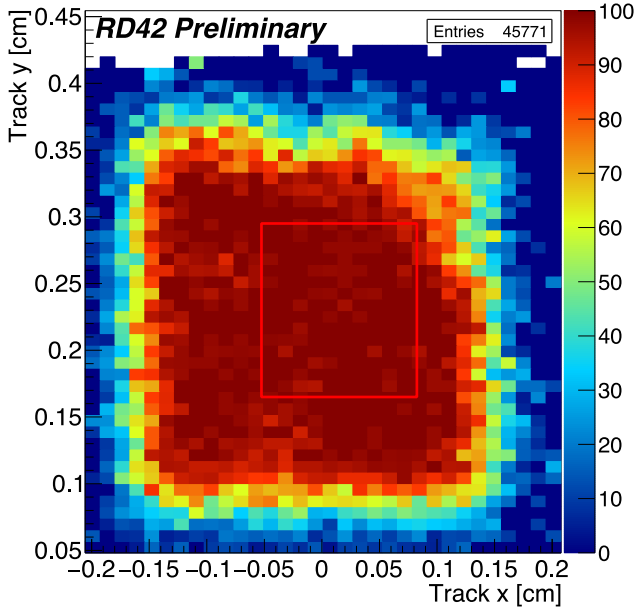


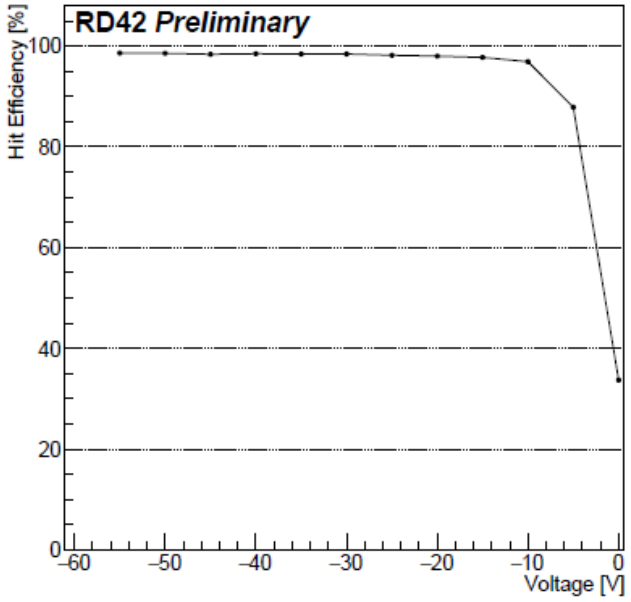
Results of CMS, ATLAS 3D pCVD Pixel Devices

Preliminary Results (50μmx50μm cells)

- Readout with CMS pixel readout
  6 cells (3x2) ganged together
- Indium bumps
- Efficiency 99.2%; plateau at -25V!



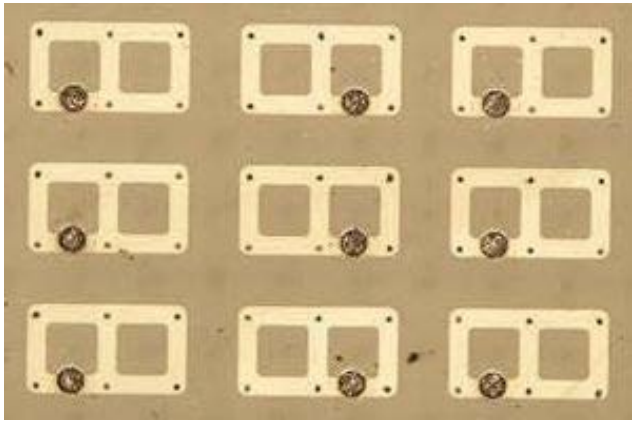


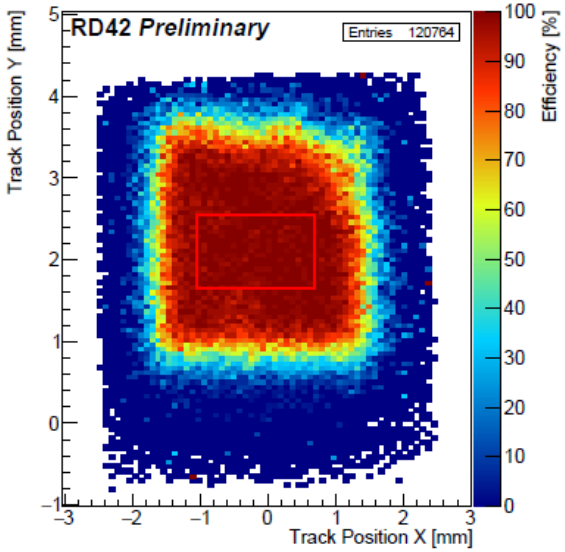


Results of CMS, ATLAS 3D pCVD Pixel Devices

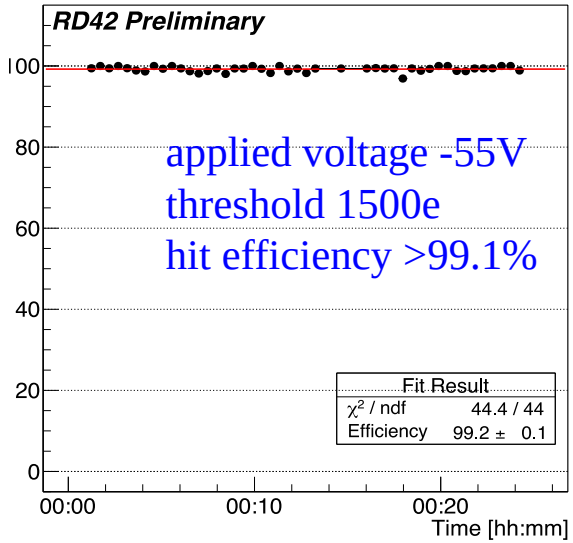
Preliminary Results (50μmx50μm cells)

- Readout with CMS pixel readout
  6 cells (3x2) ganged together
- Efficiency 99.1%; silicon 99.9%
- Collect >80% of deposited charge!

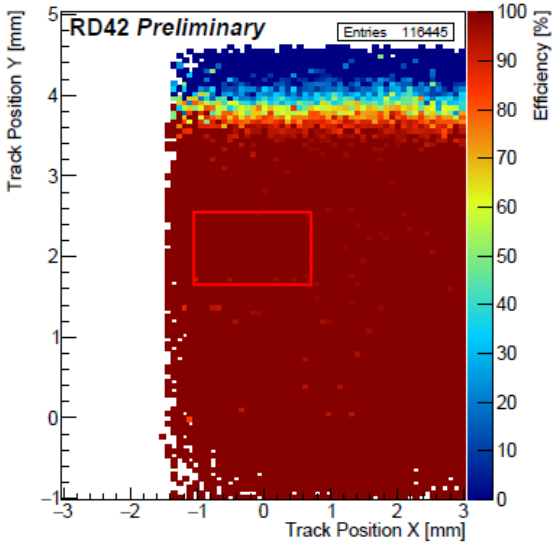




Diamond



Diamond

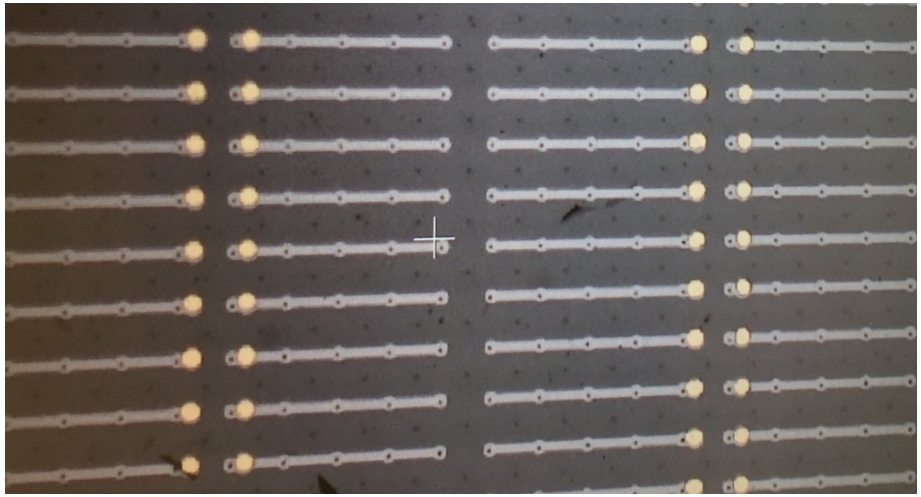


Silicon

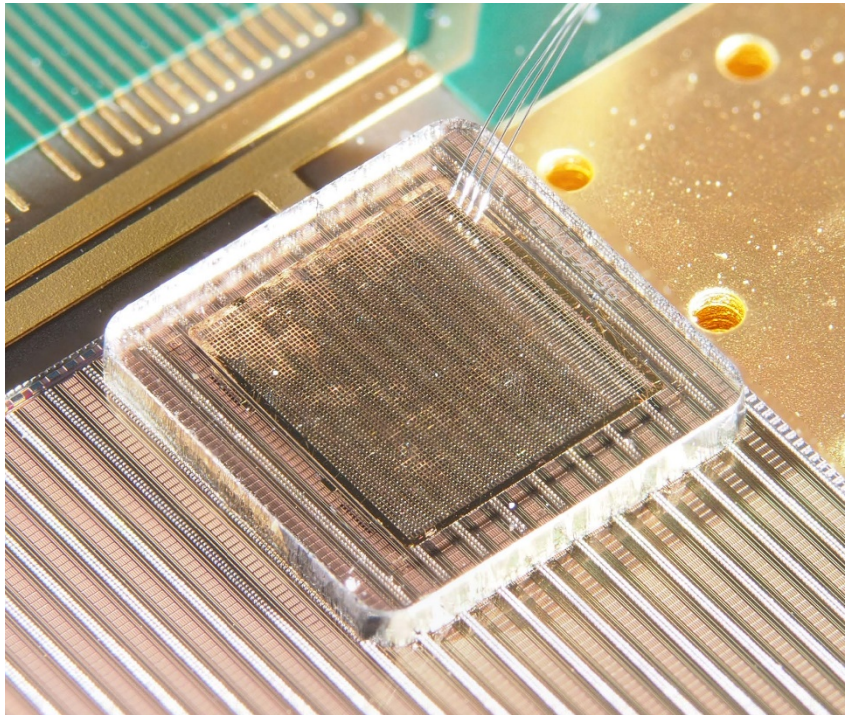
Results of CMS, ATLAS 3D pCVD Pixel Devices

50μm x 50μm 3D diamond with ATLAS pixel readout

- Readout w/FE-I4 pixel chip - 5 cells (1x5) ganged
- Tin-Silver solder bumps
- Tested @CERN Oct 2018



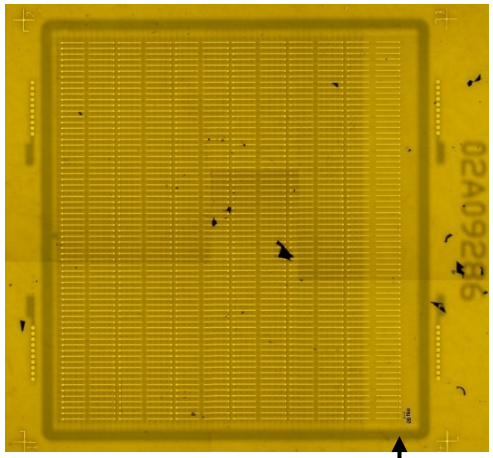
5 cell (1x5) ganging plus UBM



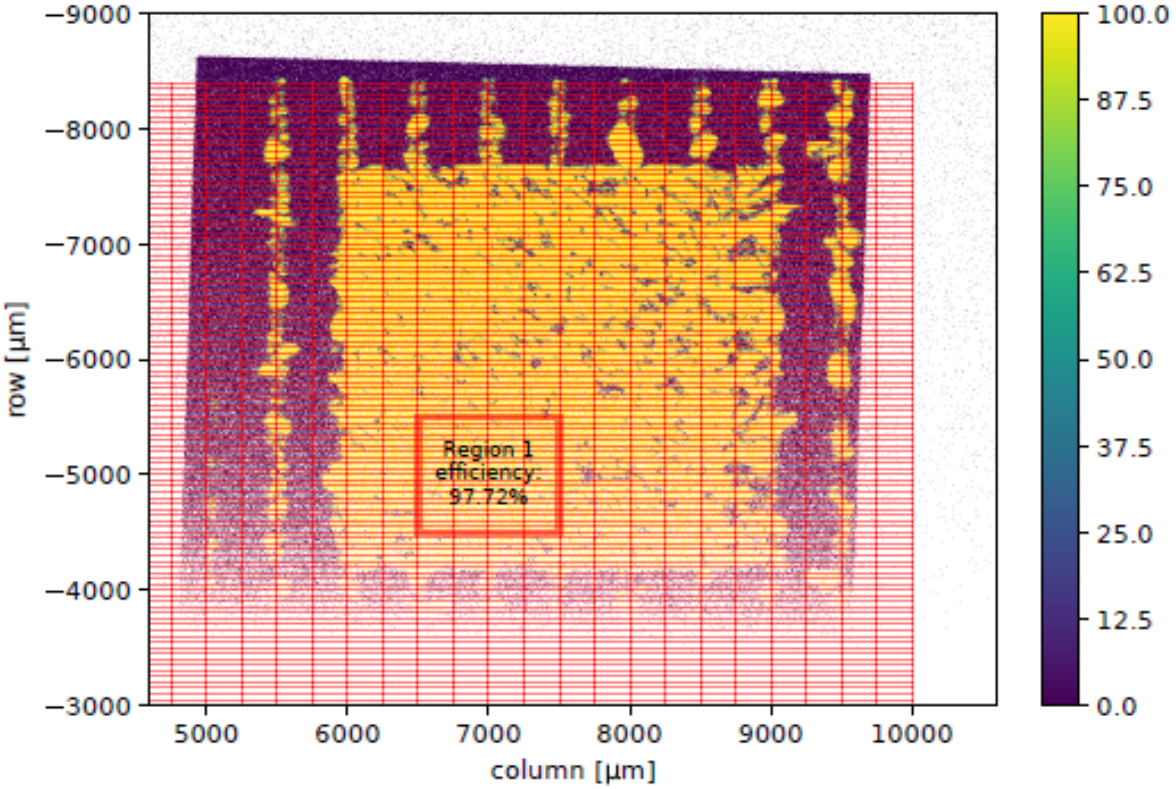
Results of CMS, ATLAS 3D pCVD Pixel Devices

50μm x 50μm 3D diamond with ATLAS pixels

- Results w/FE-I4 pixel readout - 5 cells (1x5) ganged
- LJU Telescope



Missing Columns will be used to check threshold calibration



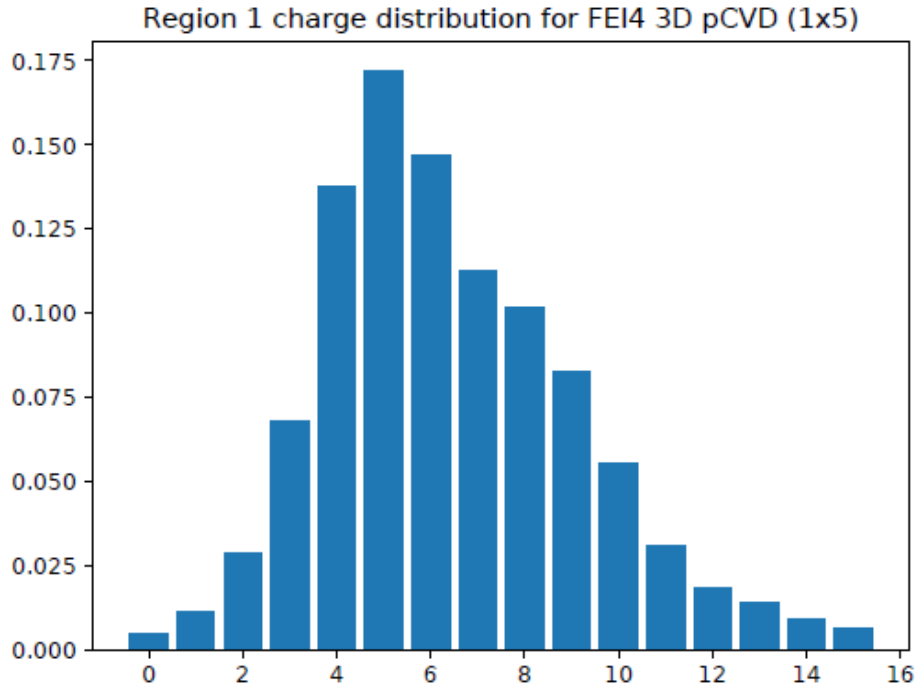
HV=-70V; Efficiency >97.7%

Results of CMS, ATLAS 3D pCVD Pixel Devices

50μm x 50μm 3D diamond with ATLAS pixels

- Results w/FE-I4 pixel readout - 5 cells (1x5) ganged

TOT Distribution (5 TOT ~ 11,000e)



Mean TOT = 6.73 → 14,800e

Threshold still needs to be calibrated

Summary

Lots of progress in 3D diamond

- 3D detector prototypes made great progress
  - 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 x 100μm to 50μm x 50μm
  - Visible improvements with each step
  - Efficiencies look good, still a bit to be understood
  - All work, to first order, as expected
  - More test beam results (irradiated devices) expected soon

Future Plans

Presented to LHCC w/HL-LHC in view

- 3D diamond detector irradiations to 10^{17} hadrons/cm^2
  - Just tested 50μm x 50μm cells irradiated @3.5x10^{15}p/cm^2
  - Continue irradiation to 10^{16}/cm^2 this coming year
  - Test both (50μm x 50μm) and (25μm x 25μm) pixel detectors
  - Thinner columns may be needed-try 1-2μm for 25μm x 25μm cells
  - Irradiation to 10^{17}/cm^2 next year
- 3D diamond pixel devices
  - Ready for RD53A chip readout this coming year
  - Continue scale up (x10)
  - Continue smaller cells (25μm x 25μm)