Diamond Detector Development and Plans: RD42 Results and Status

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Outline of Talk

- Introduction – Motivation, Diamond Detectors, RD42
- Radiation Tolerance
- Rate Studies
- Device Development – Test beam results of 3D diamond pixel devices
- Device Development – HL-LHC beam monitoring and abort (BCM')
- Summary

Introduction - Motivation

Present Situation:

- Innermost layers → highest radiation damage (~100's MHz/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

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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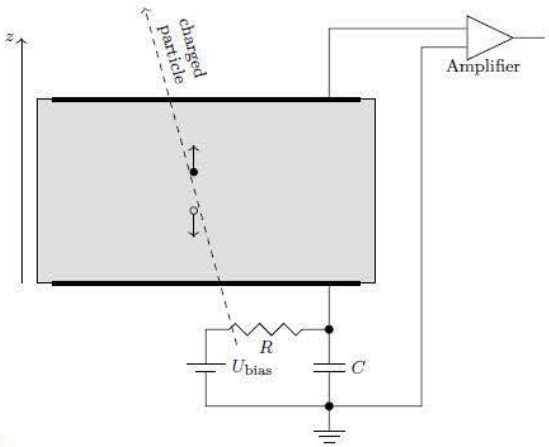
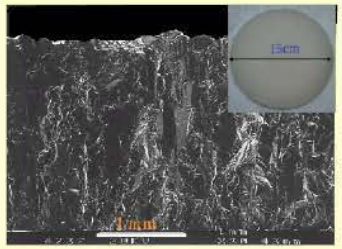
123 participants

30 institutes

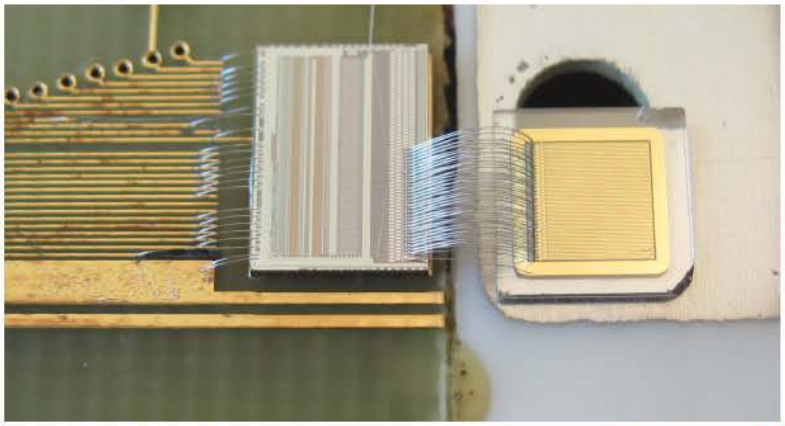
Introduction – Diamond as a Particle Detector

- Diamond detectors are operated as ionisation chambers
- Metalisation on both sides
  - Plate
  - **Strip** (used for presented beam test results)
  - Pixel
- Readout with low noise electronics





Poly-crystalline CVD (courtesy of E6)

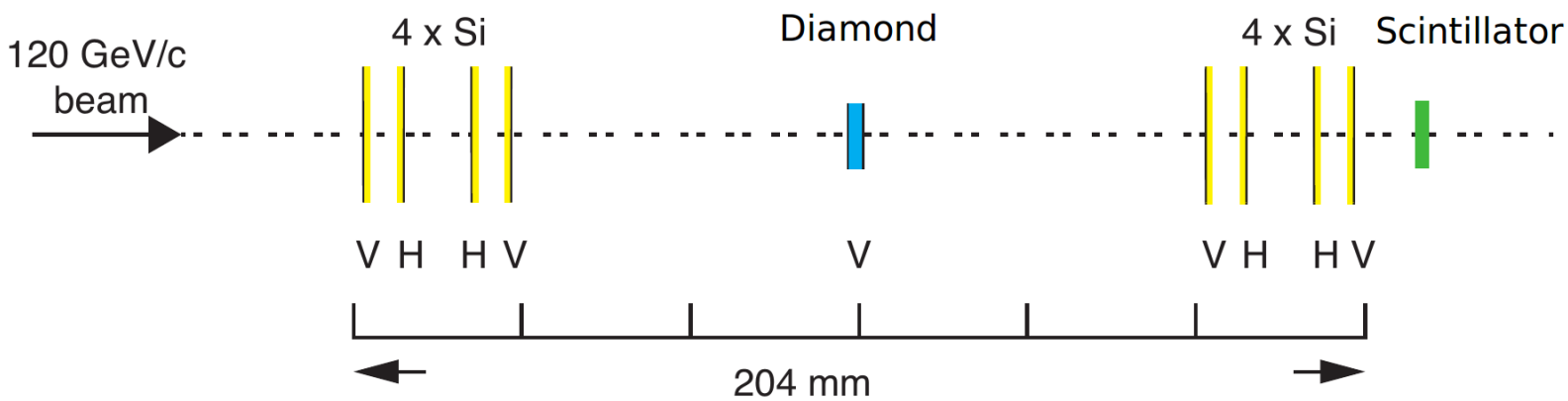


sCVD diamond with strip metalisation and amplifier

Radiation Tolerance

Radiation Tolerance

Test Beam Setup



- characterization of irradiated devices in test beams
- transparent or unbiased hit prediction from telescope
- tracking precision at detector under test: ~2-3μm

Radiation Tolerance – Analysis Strategy

- Measure signal response as a function of predicted position
  - Direct measurement of charge collection distance (CCD)
    - CCD = average distance e-h pairs drift apart under E-field
- Convert CCD to mean free path (MFP) - assume ~same MFP for e,h

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

- Damage equation: $n = n_0 + k\phi$

$$\frac{1}{mfp} = \frac{1}{mfp_0} + k\phi$$

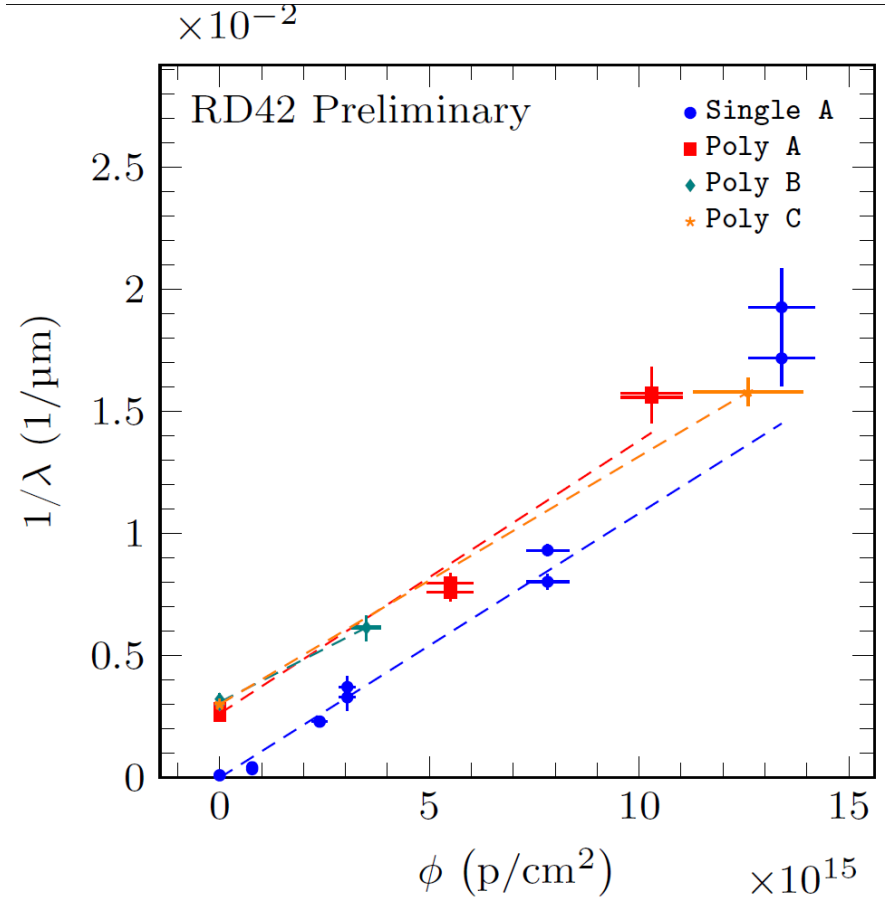
n number of traps
n_0 initial traps in material
k damage constant
ϕ fluence
λ MFP
λ_0 initial MFP

- Fit in $1/\lambda$ (=1/mfp) vs ϕ space

Radiation Tolerance – Analysis Strategy

Example – 800 MeV protons

- Plot single-crystalline and poly-crystalline on same graph
- Fit in 1/λ vs ϕ space
- Damage constant (=slope) for single-crystal and poly the same
- Do the same for all energies, species



Radiation Tolerance – Damage Curve Analysis

Summary of Radiation Tolerance Study
Combined Damage Curve

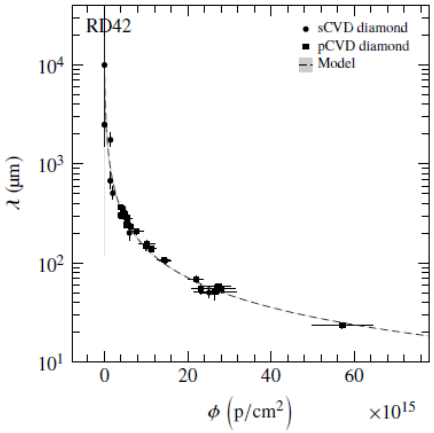
- Obtained radiation damage constants are compared to 24 GeV protons
- Combined damage curve
  - Shift pCVD sample by

$$\varphi_0 = \frac{1}{\lambda_0 k}$$

  - Scale fluence by relative k

$$\phi_{\text{eq.}} = \frac{k_i}{k_{24\,\text{GeV protons}}} \times \phi_i$$

Particle Species	Relative Damage Constant, κ
24 GeV p	1
800 MeV p	1.54 ± 0.13
70 MeV p	2.5 ± 0.4
25 MeV p	4.5 ± 0.6
fast neutrons	4.5 ± 0.5

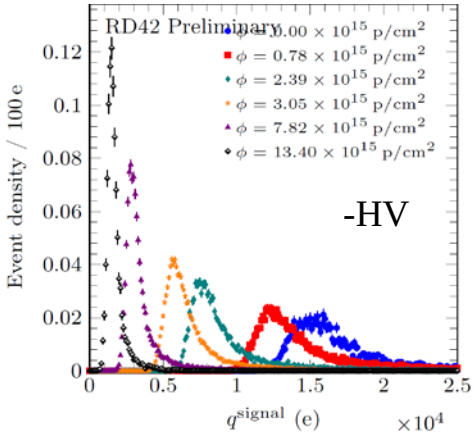


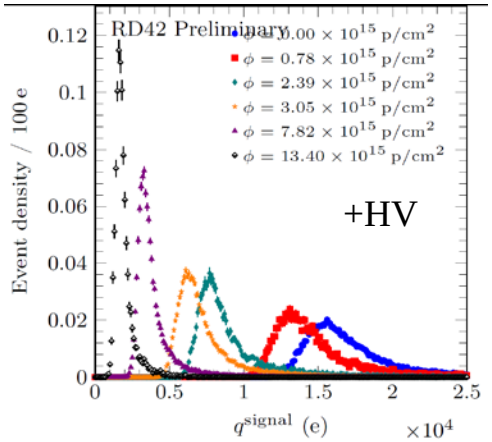
Lukas Bäni, PhD Thesis ETH Zürich, 2017

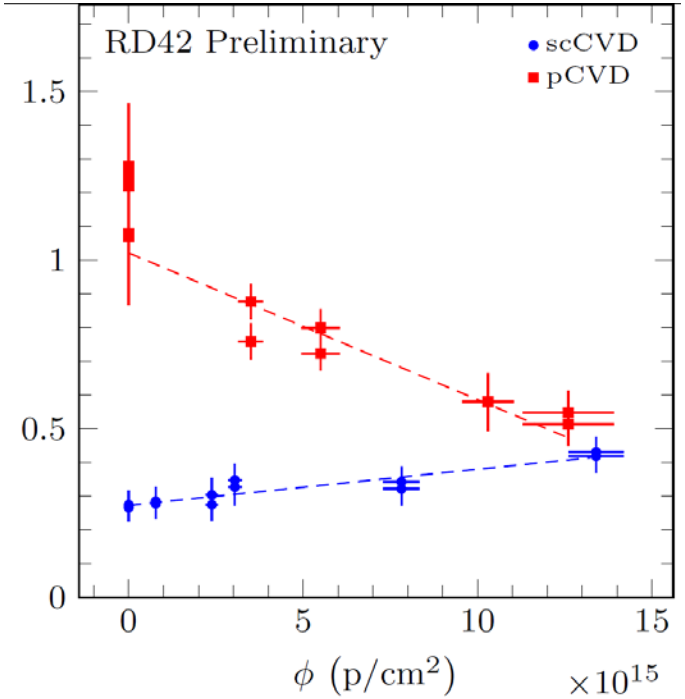
Radiation Tolerance – Shape Analysis

Signal Shape Analysis

- Study the shape of the pulse height distribution after irradiation (5/10 algorithm)
- Use the ratio FWHM/MP which is a measure of the uniformity of the material
- 800 MeV proton irradiated
  - pCVD samples
    - linear decrease of FWHM/MP
  - scCVD samples
    - Smaller initial relative width
    - linear increase towards same value
- See similar results for other irradiation energies, species



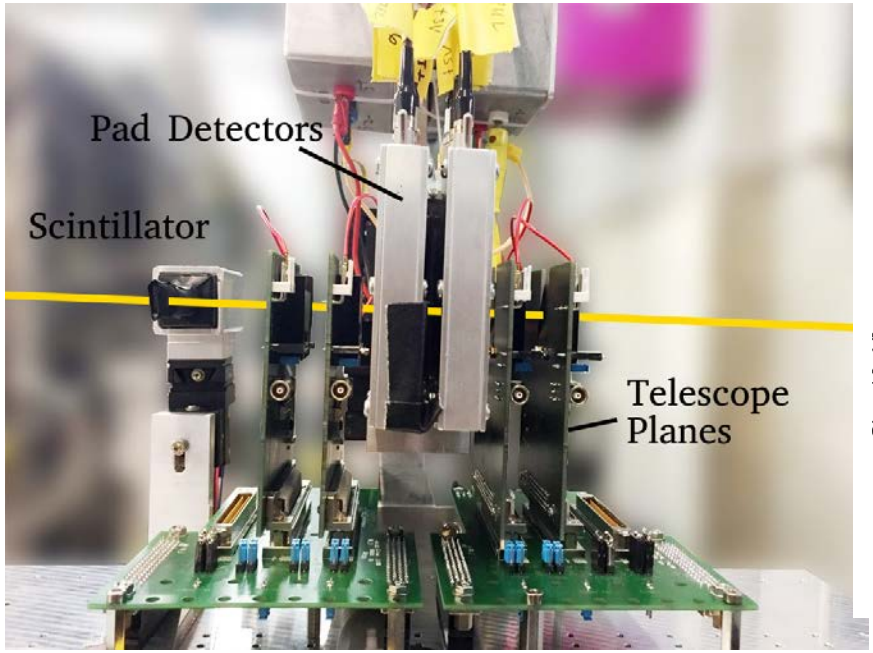


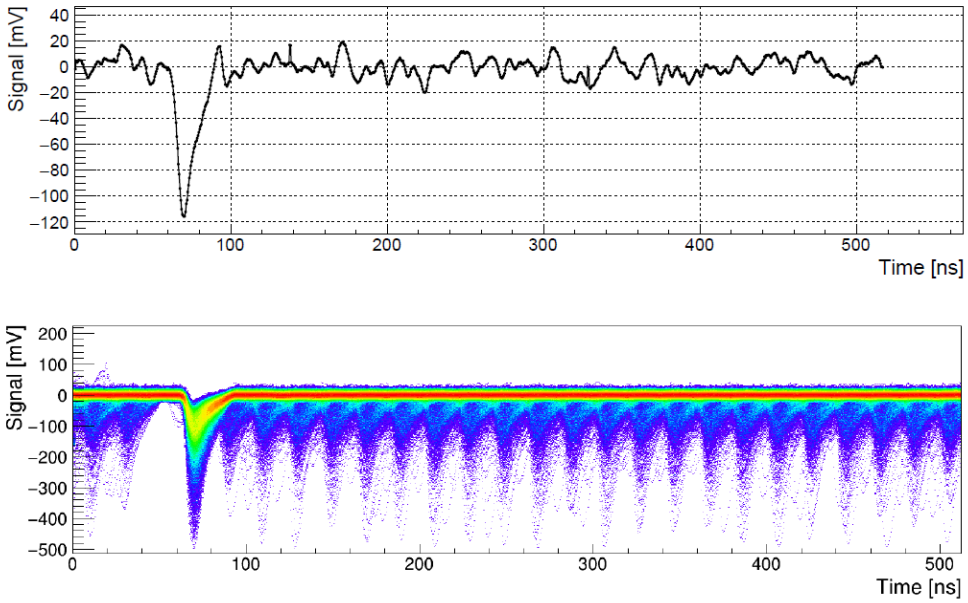


Rate Studies

Rate Studies in pCVD diamond

- Done at PSI - 3 yrs ago published rates up to 300kHz/cm^2
- 2 years ago w/new electronics, rates up to 10-20MHz/cm^2
- Last year measured rate up to fluence of 4x10^{15}n/cm^2
- Pad detector tested in ETH-Z telescope (uses CMS Pixels)
- Electronics is prototype for HL-LHC BCM/BLM

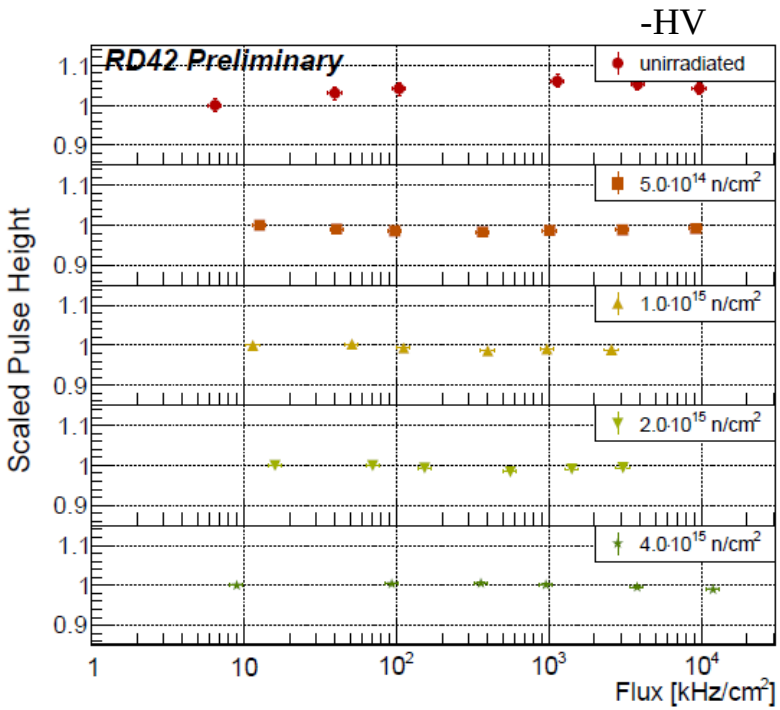


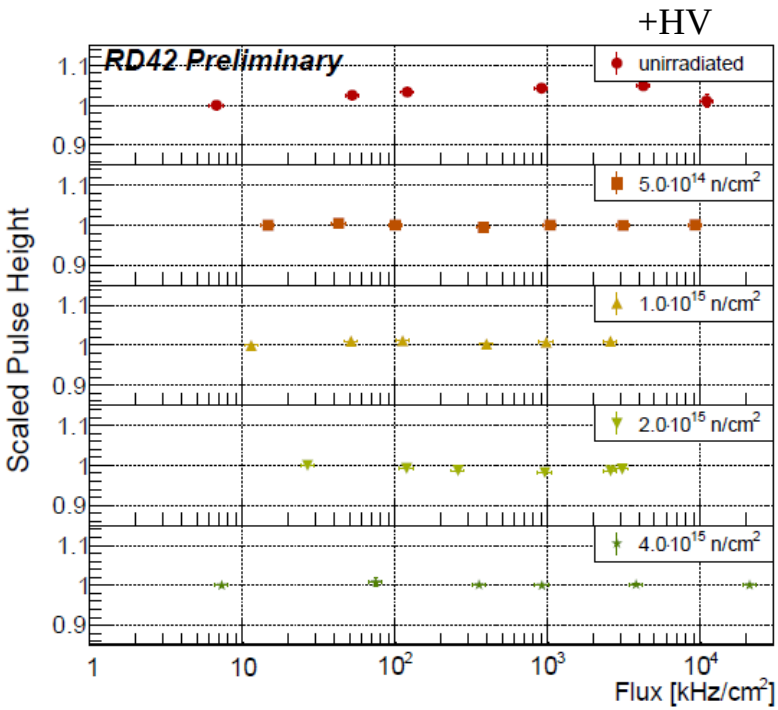


19.8ns bunch spacing clearly visible

Rate Studies in pCVD diamond

Last year rates up to 10MHz/cm^2 + doses to 4x10^{15}n/cm^2





No rate dependence observed in pCVD up to 10-20MHz/cm^2

No rate dependence observed in pCVD up to 4x10^{15}n/cm^2

No absolute pulse height and noise calibration yet

Now extending dose to 10^{16} n/cm^2 then 10^{17} n/cm^2

Device Development: 3D diamond pixel detectors

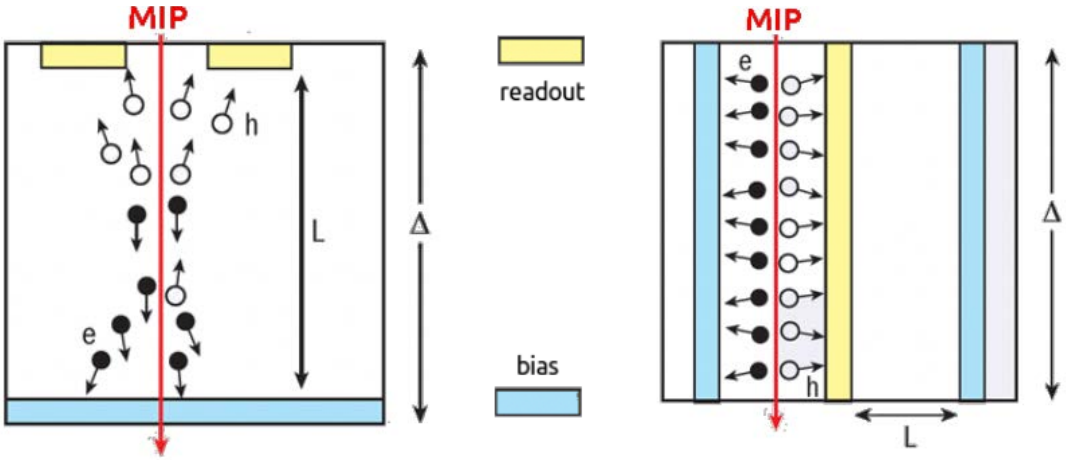
3D Device in pCVD Diamond

After large radiation fluence all detectors are trap limited

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

Comparison of planar and 3D devices

Can one do this in pCVD diamond?



Planar 3D

Have to make resistive columns in diamond for this to work

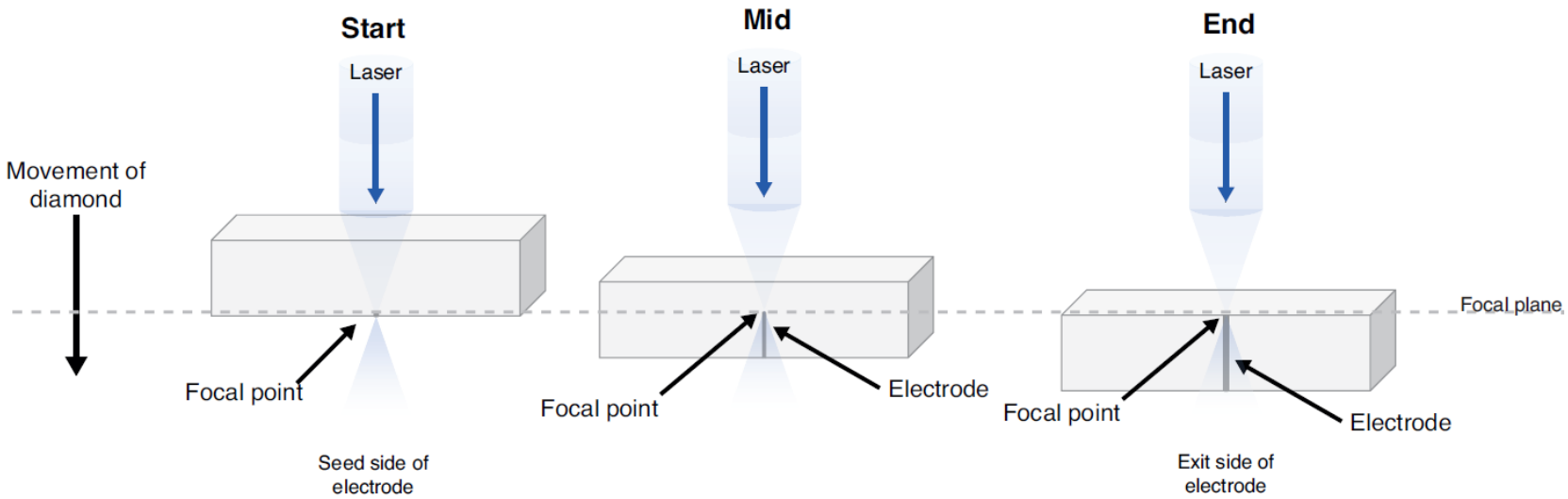
-columns made with 800nm femtosecond laser

-initial cells 150μm x 150μm; columns 6μm 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)



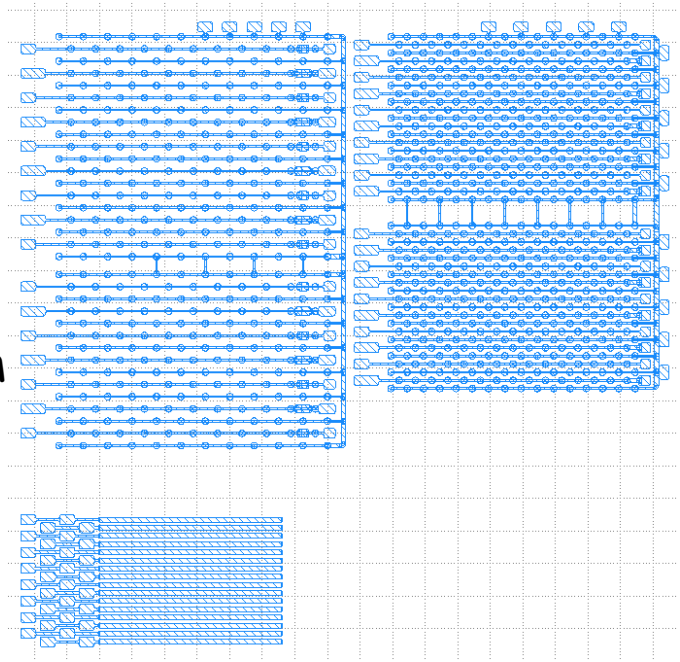
3D Device in pCVD Diamond

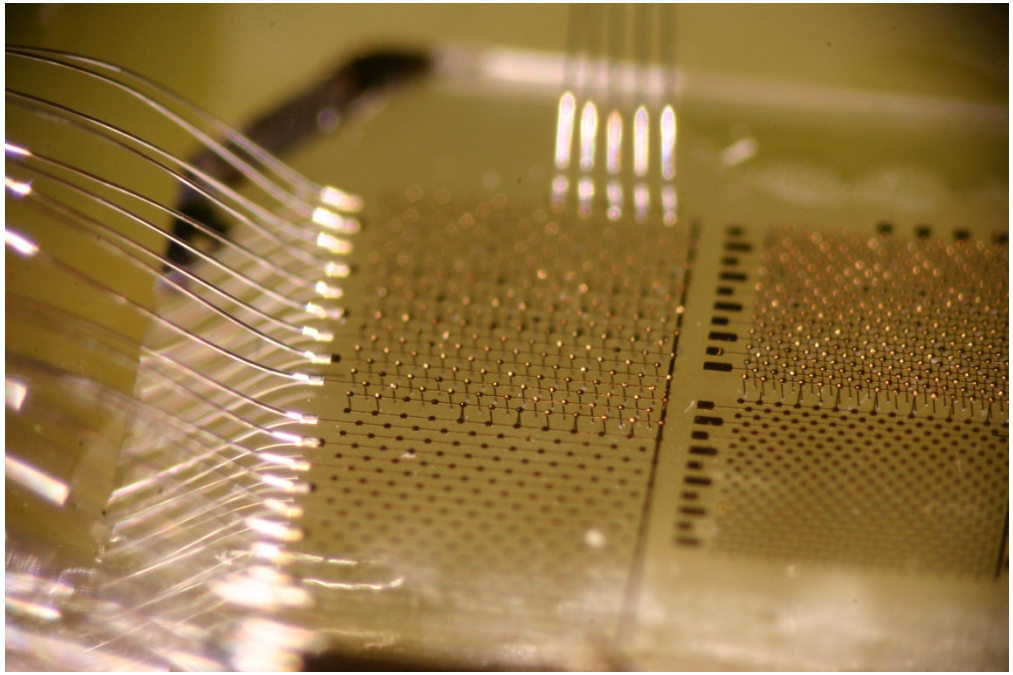
Simultaneously readout all 3 devices

3D

phantom

strip





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

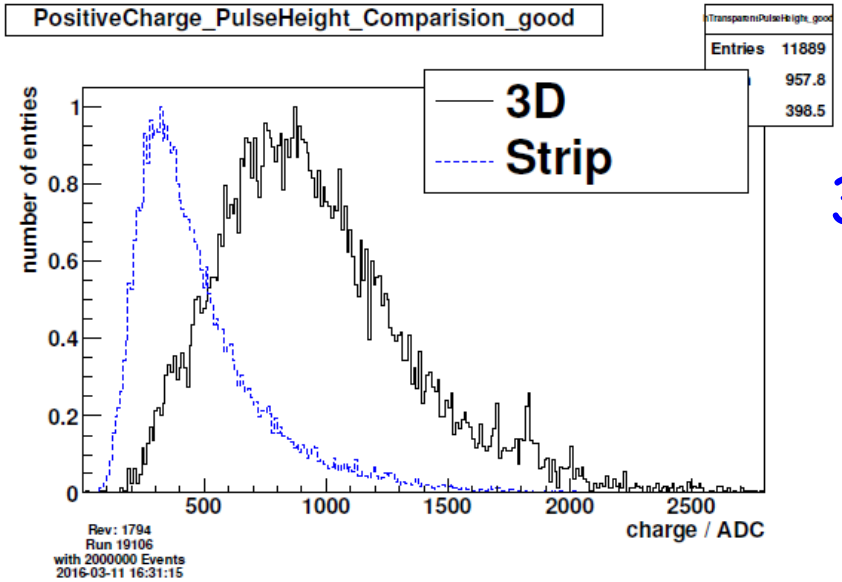
-Compare pCVD strip detector (500V) with 3D (60V)

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

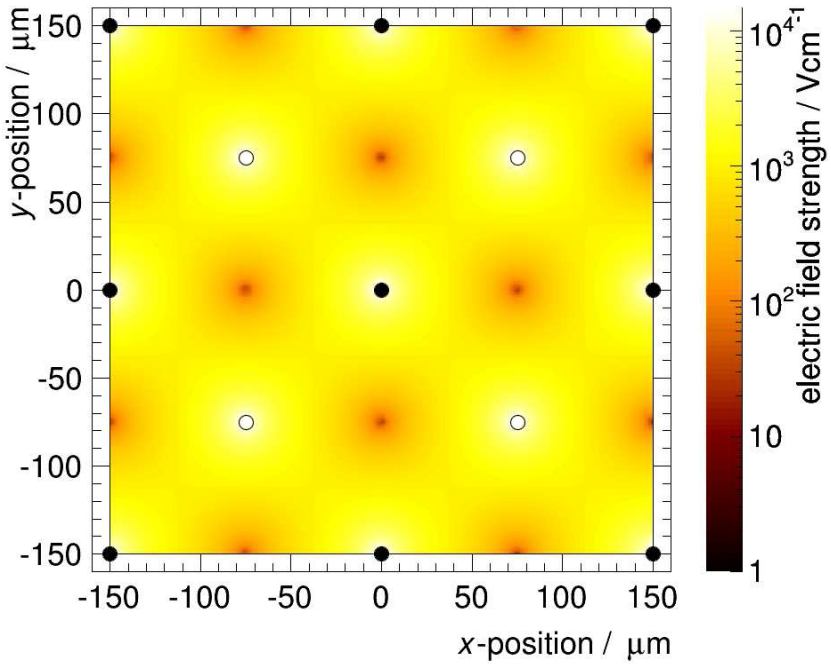
- Measured signal (diamond thickness 500μm):
  - Planar Strip ave charge
    6,900e or ccd=192μm
  - 3D ave charge
    13,500e or ccd_{eq}=350-375μm
- For the first time collect >75% of charge in pCVD



3D cell size:
150μm x 150μm

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

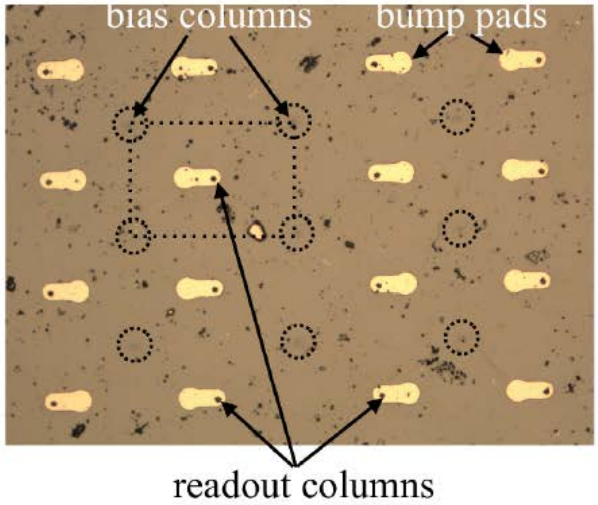
from: G. Forcolin, Ph.D. Thesis
Manchester University 2017

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

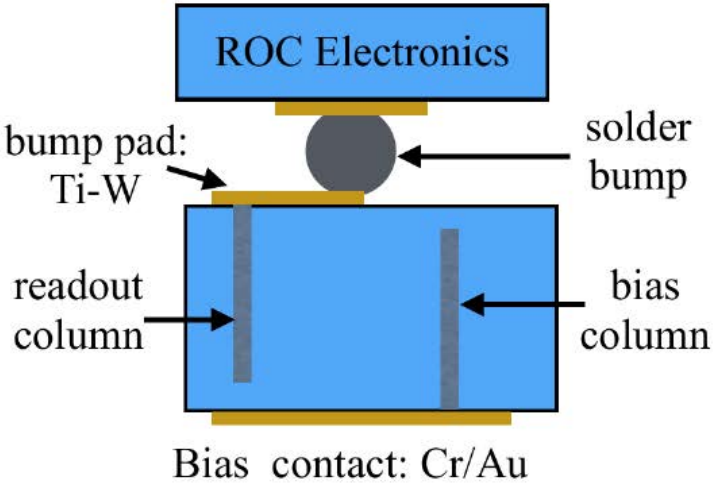
Results of CMS, ATLAS 3D pCVD Pixel Devices

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
- Bump and wire bonding - Princeton



(a) pixel readout metalisation



(b) final scheme

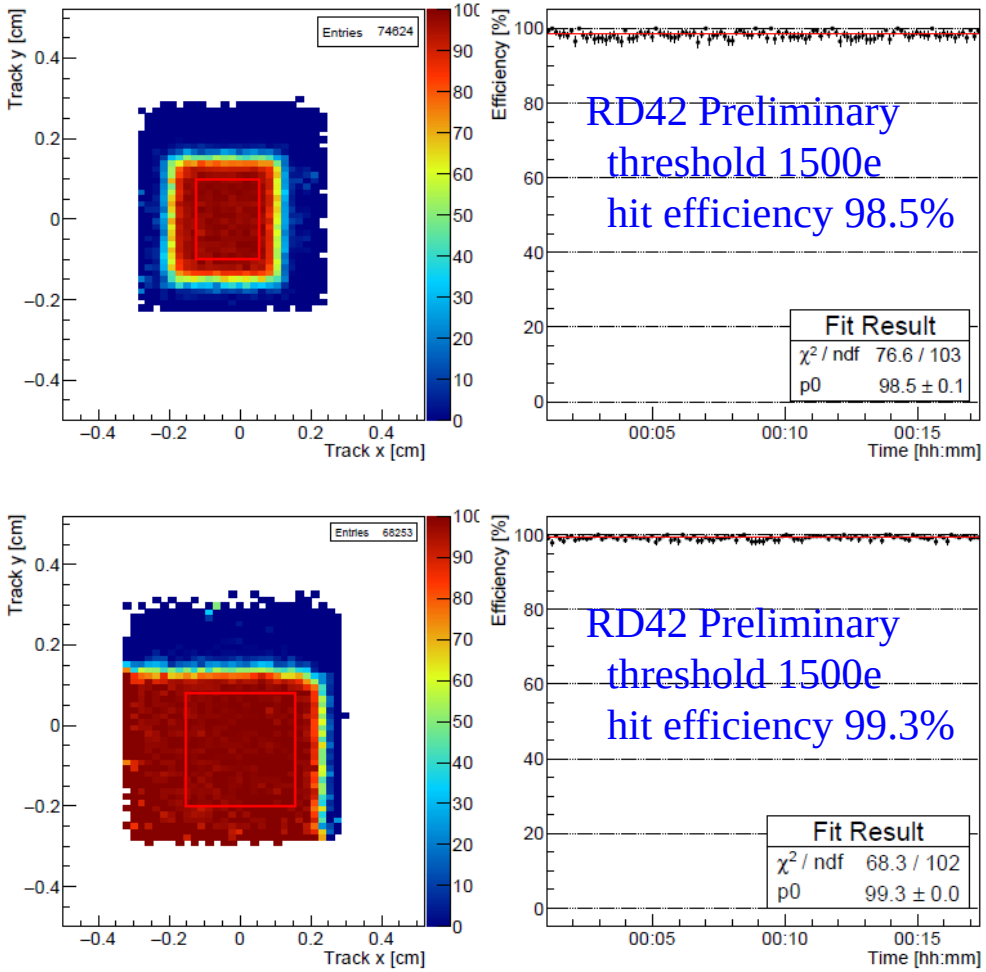
Results of CMS, ATLAS 3D pCVD Pixel Devices

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

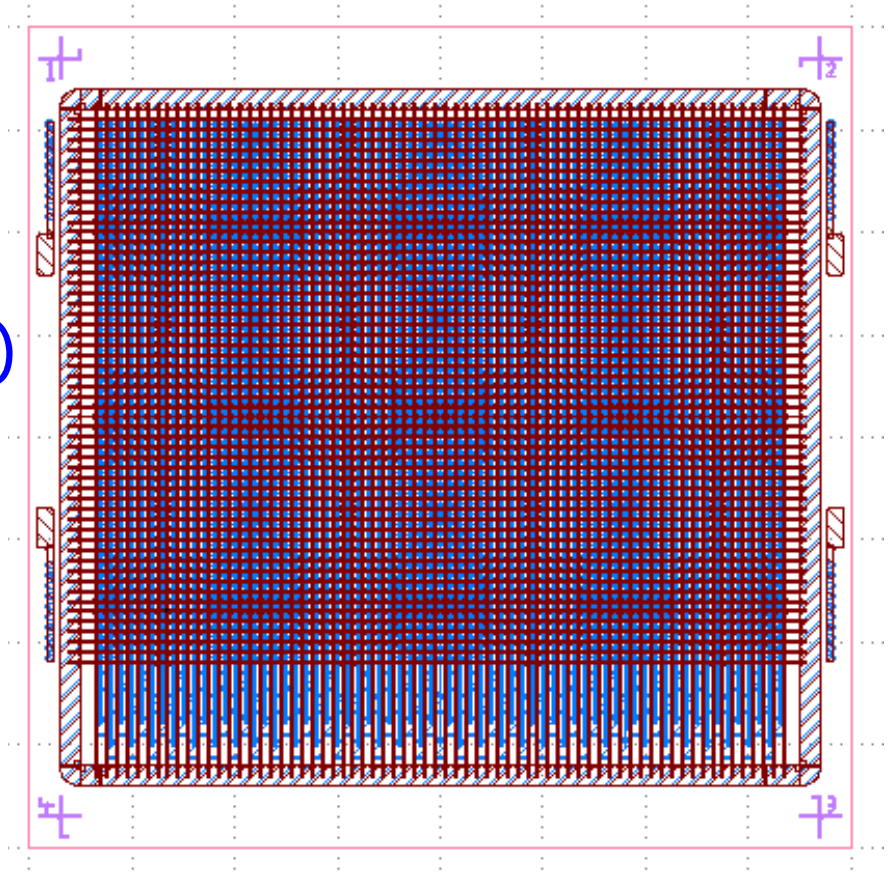


(a) efficiency maps (b) hit efficiencies

Results of CMS, ATLAS 3D pCVD Pixel Devices

Produced 7200 cell pixel prototype w/50μm x 50μm pitch

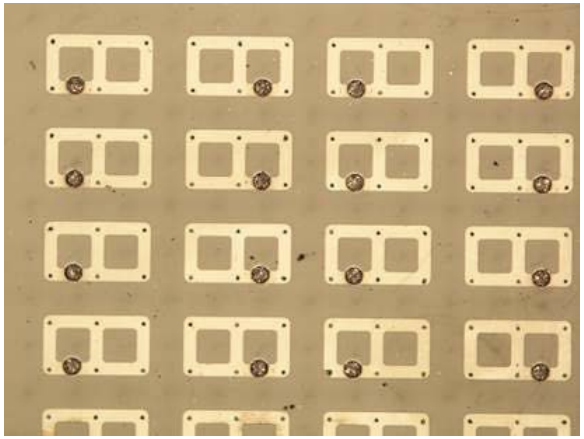
- Three fabricated:
  - Oxford 2 complete
  - Manchester 1 complete
- 50μm x 50μm cells ganged for CMS (3x2) and ATLAS (1x5)
- Metallization
  - CMS complete
  - ATLAS complete
- Bump bonding
  - CMS @Princeton complete
  - ATLAS @IFAE complete
- First one (CMS) tested in Aug 2017 Test Beam @PSI

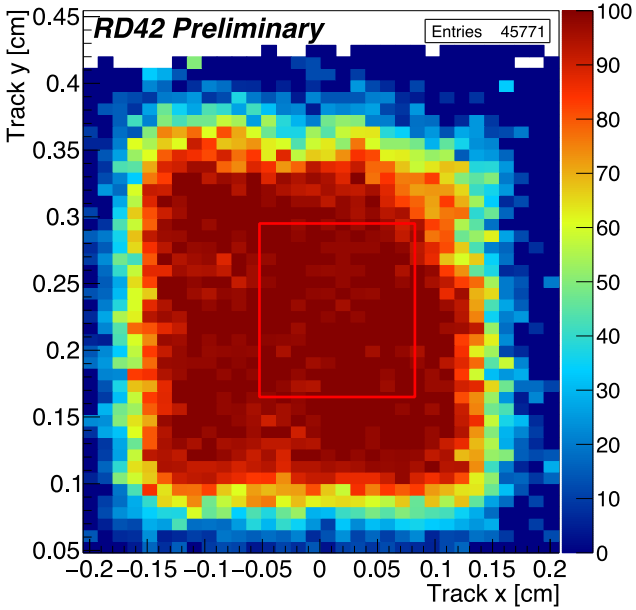


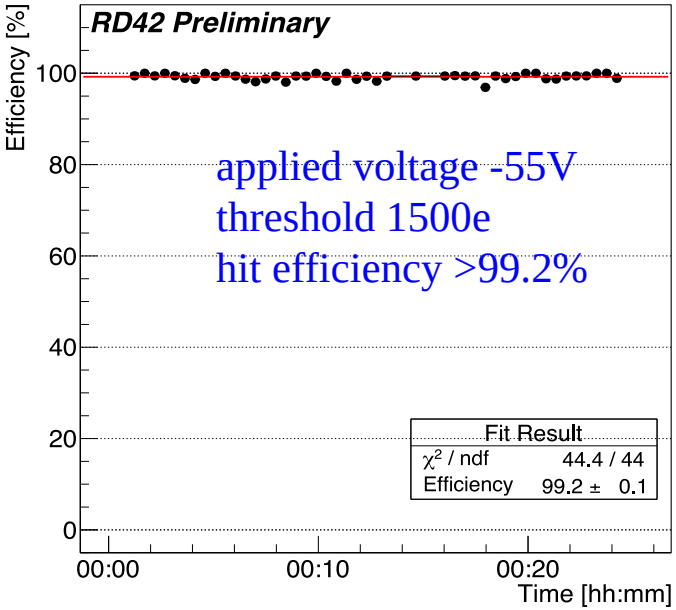
Results of CMS, ATLAS 3D pCVD Pixel Devices

Preliminary Results (50μmx50μm cells)

- Readout with CMS pixel readout
  6 cells (3x2) ganged together
- Preliminary efficiency >99.2%
- Collect >90% of charge!



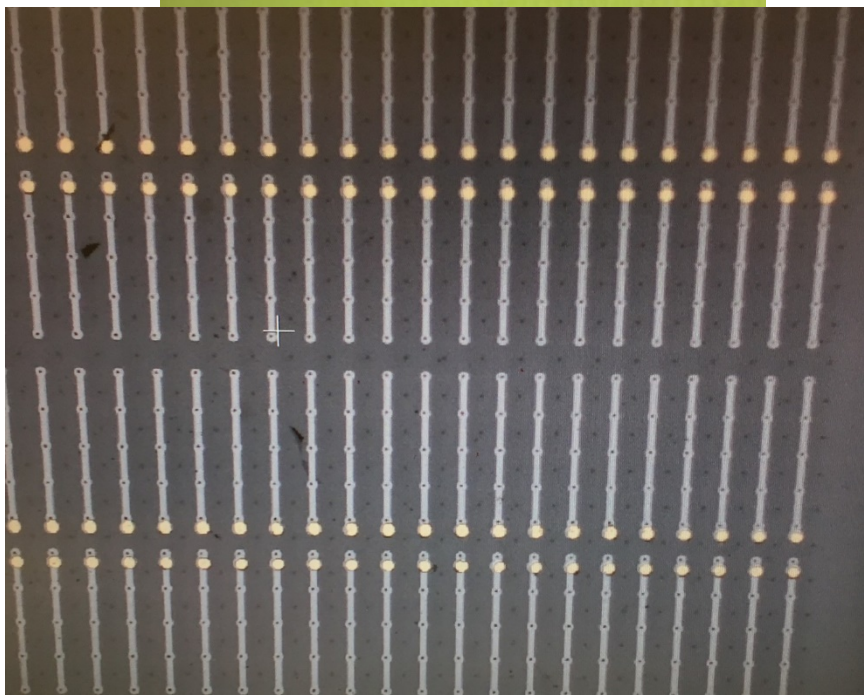


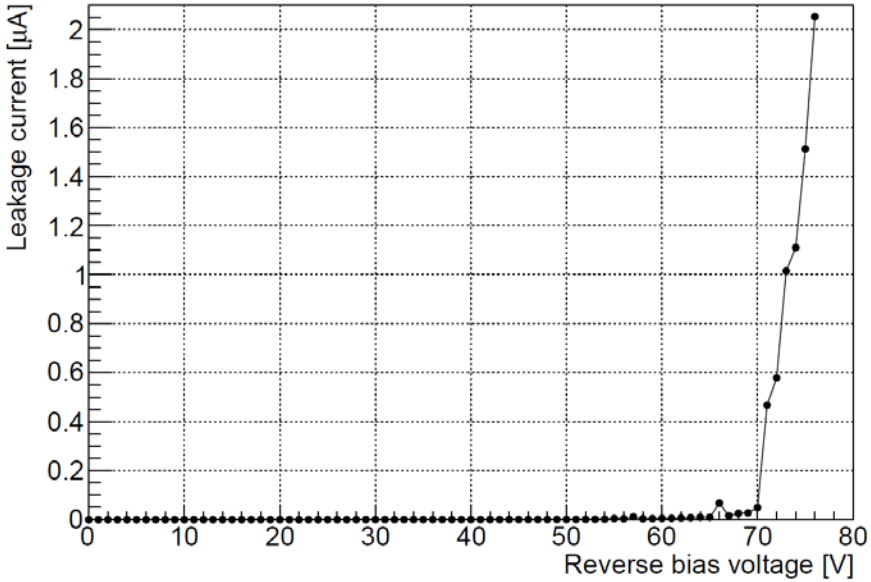


Results of CMS, ATLAS 3D pCVD Pixel Devices

50μmx50μm 3D ATLAS pixels

- Readout w/FE-I4 pixel readout
  5 cells (1x5) ganged
- Tested @CERN Oct 2018
- Worked well, awaiting results





Device Development: HL-LHC BCM'

Device Development: HL-LHC BCM'

Present ATLAS BCM suffers from abort-lumi incompatibility

- Abort thresholds can not be set higher without abandoning lumi
- Fast timing needed for abort lowers S/N thus limiting lumi stability

Separate functions at the HL-LHC

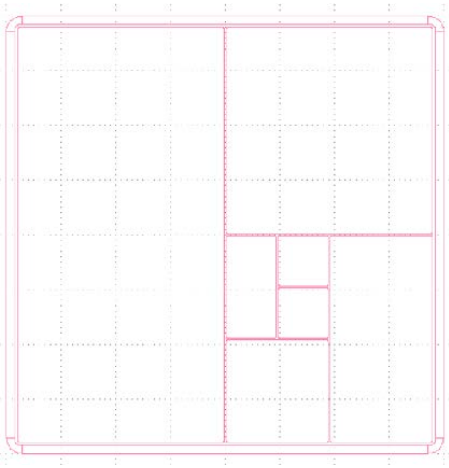
- Two fast devices from sensor to off-detector
- Keep as much commonality as possible
- 4 stations/side with abort, lumi-BCM', BLM

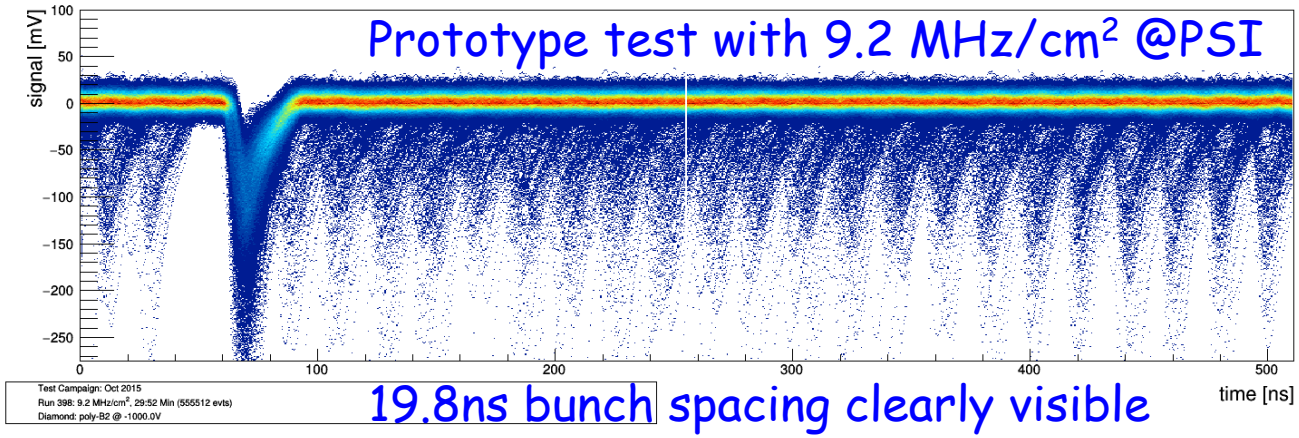
Requires new sensor geometry and appropriate electronics

Device Development: HL-LHC BCM'

Initial Sensor Design Idea

- Build some dynamic range into sensor ✓
  - pad sizes from 1mm^2-32mm^2 work well
- Compare 300μm vs 500μm thick sensors - in progress
  - 500μm thick sensors work well
- Test wire bonding sensor to chip ✘
  - lose sensitivity of small pads – bump bond instead
- Test with existing RD42 fast electronics ✓



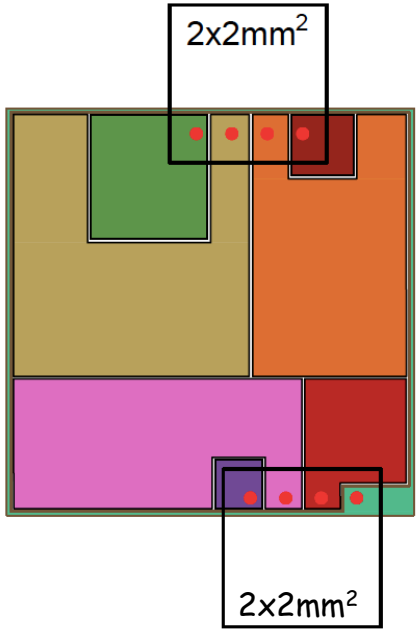


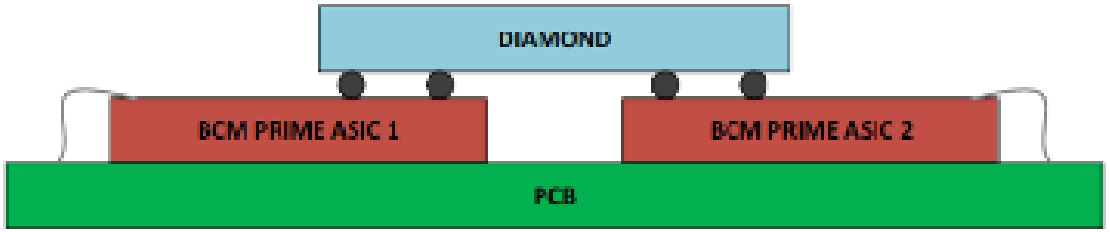
19.8ns bunch spacing clearly visible

Device Development: HL-LHC BCM'

New Sensor Design Idea

- Build some dynamic range into sensor
  - pad sizes from $1mm^2$-$32mm^2$ work well
- Bump bond diamond to electronics to reduce capacitance
- Use TSMC 65nm technology for increased gain-bandwidth

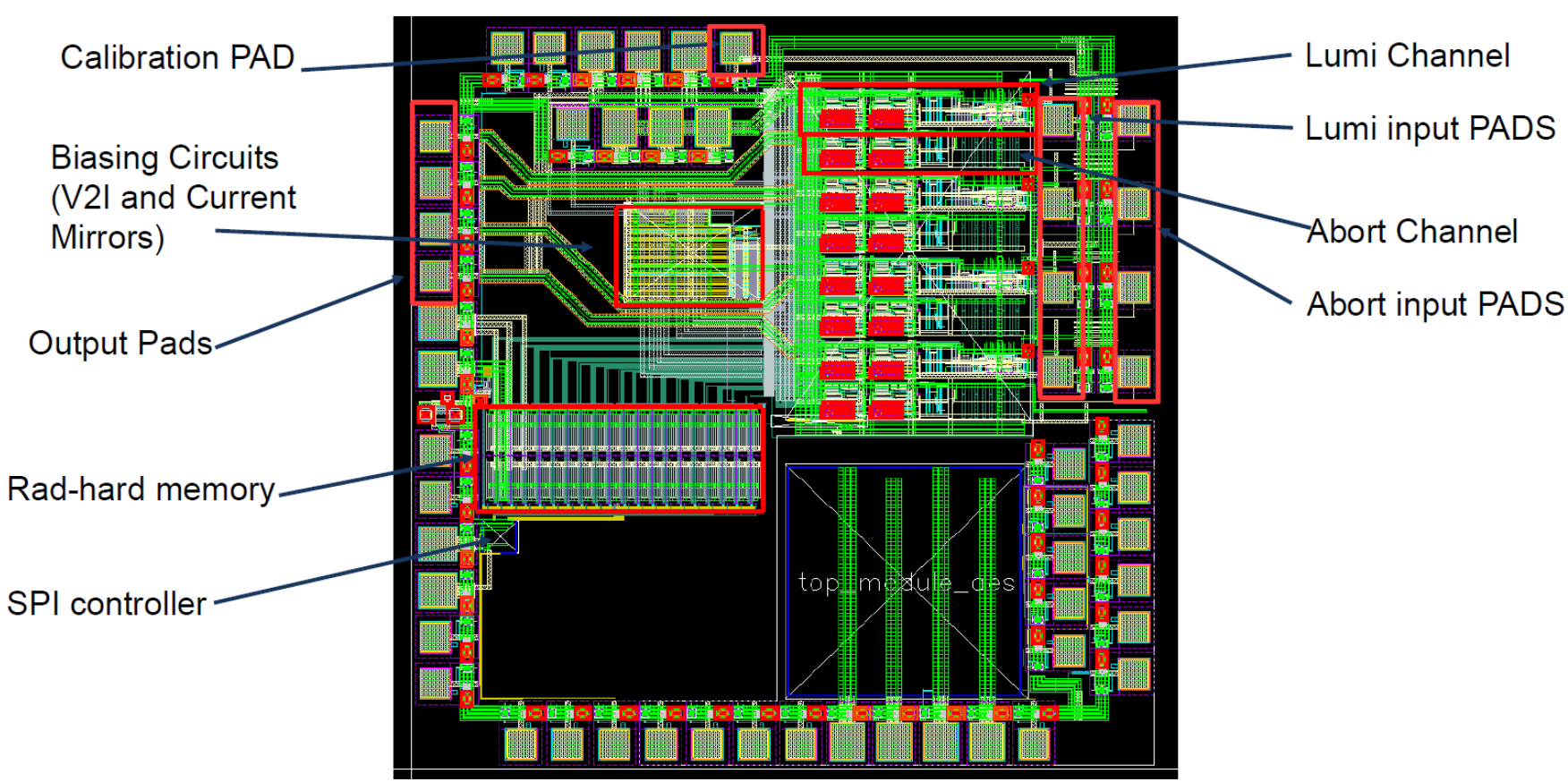




Device Development: HL-LHC BCM'

Electronics Design Path

- First version of preamp layout and simulations

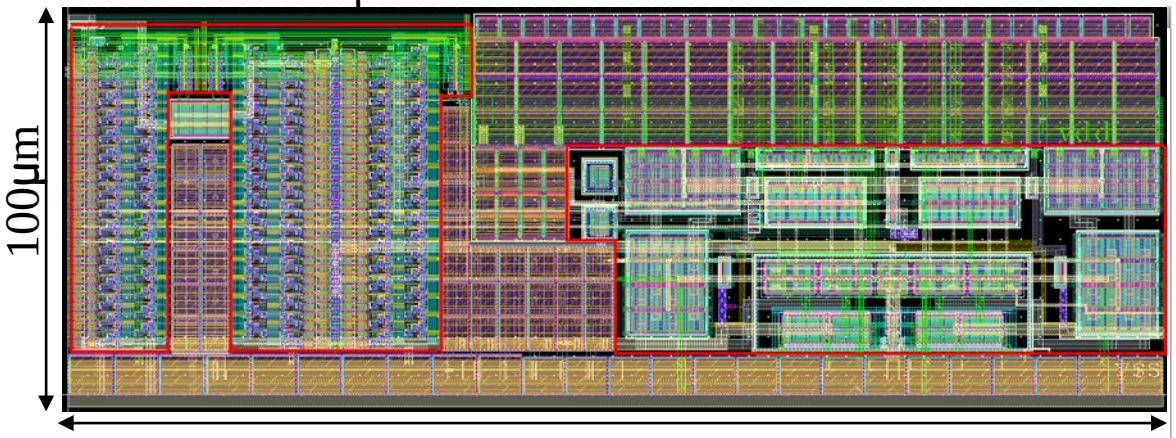


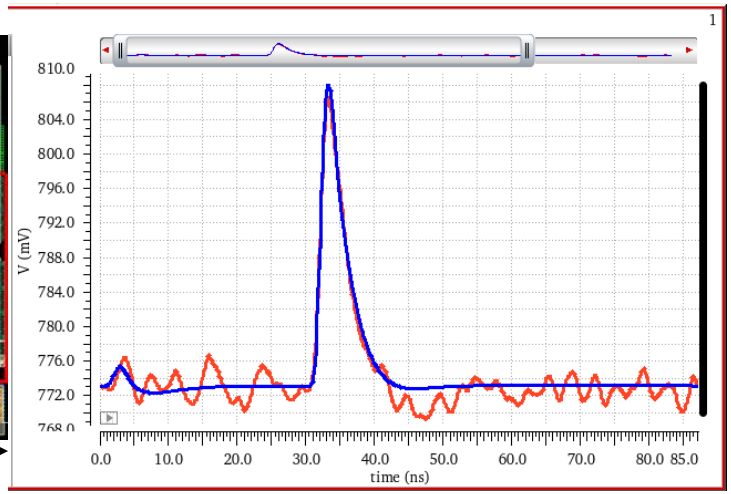
Device Development: HL-LHC BCM'

Electronics Design Path

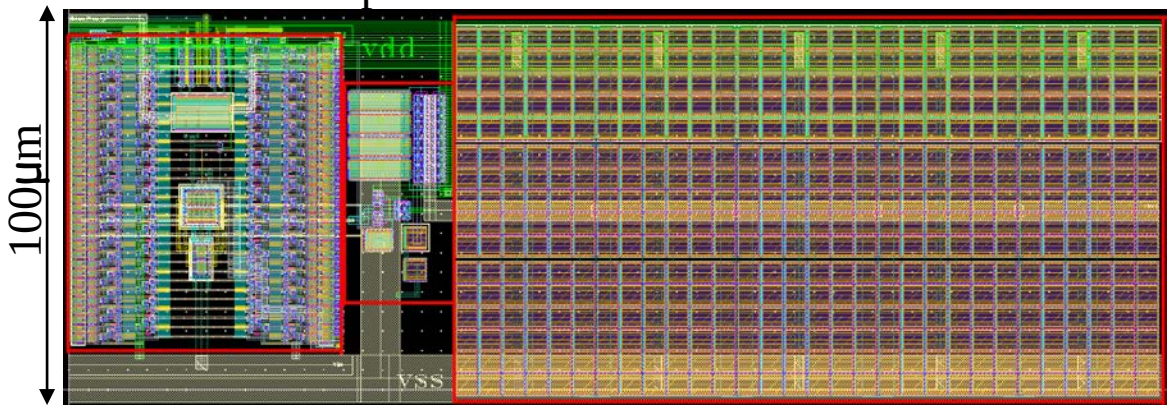
- First version of preamp layout and simulations
- Test in H6a@CERN last week

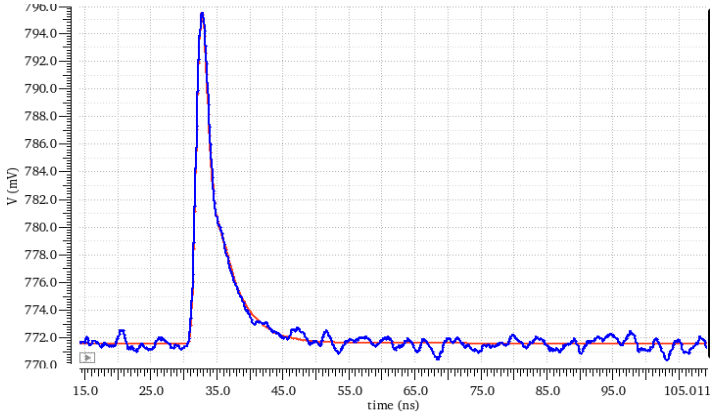
Lumi Preamp





Abort Preamp





Device Development: HL-LHC BCM'

Electronics Design Path

- Start with RD42 fast amp used in rate studies
  - designed in 130nm technology
  - risetime 3-6ns; baseline recovery time 12-18ns
  - noise for 2pf input: 550e
- Design 2 preamps to achieve large dynamic range
  - lumi sensitivity to MIPs at 7ke
  - abort threshold for safety at 25k-7.5M MIPS/cm^2
  - electronics dynamic range 100:1
  - risetime 1-2ns; return to baseline (<2%) 12ns
- Optimize gain and speed vs SNR for lumi, abort separately
  - tune parameters based on beam tests
- End with 8 channel amp (4 lumi, 4 abort) in 65nm

Chip Submitted May 21,2018, back Aug 24, 2018, TB Oct 2018

Summary of RD42 Work

Lots of progress in diamond with HL-LHC in view

- Quantified understanding of radiation and rate effects
  - pCVD shows no rate effect up to 20MHz/cm^2,4x10^{15}n/cm^2 @1000V
  - Irradiate devices to 10^{17} this year, continue rate studies to 10^{16}
- 3D detector prototypes made great progress
  - 3D works in pCVD diamond
  - Scale up (x70) worked; continue scale up (x10) this year
  - Smaller cells (50μm x 50μm) worked; test smaller cells (25μm)
  - Thinner columns (2.6μm) worked; try 2.0μm for 25μm x 25μm cells
- 3D diamond pixel devices being produced
  - All work as expected; just tested 50μm cells irrad@3.5x10^{15}p/cm^2
  - Visible improvements with each step
  - Efficiencies look good, still a bit to be understood
- BCM' design underway

Acknowledgements

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