Diamond Sensors for Future High Energy Experiments

Felix Bachmair on behalf of the RD42 collaboration

ETH Institute for Particle Physics

The RD42 Collaboration

M. Artuso[22], F. Bachmair[26], L. Bäni[26], M. Bartosik[3], J. Beacham[15], 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], C. Chau[18], G. Chiodini[29], D. Chren[20], V. Cindro[11], G. Claus[9], J. Collot[30], S. Costa[2], J. Cumalat[21], A. Dabrowski[3], R. D'Alessandro[5], W. de Boer[12], B. Dehning[3], D. Dobos[3], C. Dorfer[26], M. Dünser[26], V. Eremin[8], R. Eusebi[27], G. Forcolin[24], J. Forneris[17], H. Frais-Kölbl[4], K.K. Gan[15], M. Gastal[3], M. Goffe[9], J. Goldstein[19], A. Golubev[10], L. Gonella[1], A. Gorišek[11], L. Graber[25], E. Grigoriev[10], J. Grosse-Knetter[25], B. Gui[15], M. Guthoff[3], I. Haughton[24], D. Hidas[16], D. Hits[26], M. Hoeferkamp[23], T. Hofmann[3], J. Hosslet[9], J-Y. Hostachy[30], F. Hügging[1], H. Jansen[3], J. Janssen[1], H. Kagan[15,◊], K. Kanxheri[31], G. Kasieczka[26], R. Kass[15], F. Kassel[12], M. Kis[7], G. Kramberger[11], S. Kuleshov[10], A. Lacoste[30], S. Lagomarsino[5], A. Lo Giudice[17], C. Maazouzi[9], I. Mandic[11], C. Mathieu[9], N. McFadden[23], G. McGoldrick[18], M. Menichelli[31], M. Mikuž[11], A. Morozzi[31], J. Moss[15], R. Mountain[22], S. Murphy[24], A. Oh[24], P. Olivero[17], G. Parrini[5], D. Passeri[31], M. Pauluzzi[31], H. Pernegger[3], R. Perrino[29], F. Picollo[17], M. Pomorski[13], R. Potenza[2], A. Quadt[25], A. Re[17], G. Riley[28], S. Roe[3], M. Sapinski[3], M. Scaringella[5], S. Schnetzer[16], T. Schreiner[4], S. Sciortino[5], A. Scorzoni[31], S. Seidel[23], L. Servoli[31], A. Sfyrla[3], G. Shimchuk[10], D.S. Smith[15], B. Sopko[20], V. Sopko[20], S. Spagnolo[29], S. Spanier[28], K. Stenson[21], R. Stone[16], C. Sutera[2], 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], P. Weilhammer[3], J. Weingarten[25], C. Weiss[3], T. Wengler[3], N. Wermes[1], M. Yamouni[30], M. Zavrtanik[11]

129 Participants

[1] Universität Bonn, Bonn, Germany
[2] INFN/University of Catania, Catania, Italy
[3] CERN, Geneva, Switzerland
[4] FWT, Wiener Neustadt, Austria
[5] INFN/University of Florence, Florence, Italy
[6] FNAL, Batavia, USA
[7] GSI, Darmstadt, Germany
[8] Ioffe Institute, St. Petersburg, Russia
[9] IPHC, Strasbourg, France
[10] ITEP, Moscow, Russia
[11] Jožef Stefan Institute, Ljubljana, Slovenia
[12] Universität Karlsruhe, Karlsruhe, Germany
[13] CEA-LIST Technologies Avancees, Saclay, France
[14] MEPHI Institute, Moscow, Russia
[15] The Ohio State University, Columbus, OH, USA
[16] Rutgers University, Piscataway, NJ, USA
[17] University of Torino, Torino, Italy
[18] University of Toronto, Toronto, ON, Canada
[19] University of Bristol, Bristol, UK
[20] Czech Technical Univ., Prague, Czech Republic
[21] University of Colorado, Boulder, CO, USA
[22] Syracuse University, Syracuse, NY, USA
[23] University of New Mexico, Albuquerque, NM, USA
[24] University of Manchester, Manchester, UK
[25] Universität Göttingen, Göttingen, Germany
[26] ETH Zürich, Zürich, Switzerland
[27] Texas A&M, College Park Station, TX, USA
[28] University of Tennessee, Knoxville, TN, USA
[29] INFN-Lecce, Lecce, Italy
[30] LPSC-Grenoble, Grenoble, Switzerland
[31] INFN-Perugia, Perugia, Italy

31 Institutes

Overview

- Diamond as a sensor material
  - Newest developments in chemical vapor deposition (CVD) diamonds
  - Radiation tolerance
- Overview of diamond detectors in HEP
- Latest experiences for
  - CMS PLT pilot run
  - ATLAS DBM
- 3D diamond detectors
  - Single-crystalline (sc)CVD diamond
  - Polycrystalline (p)CVD diamond

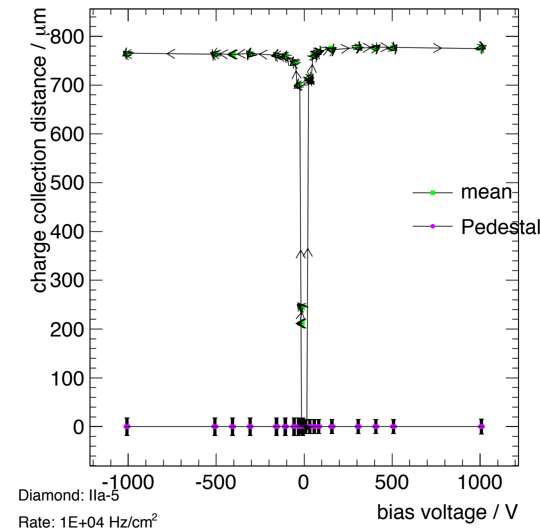
Why diamond?

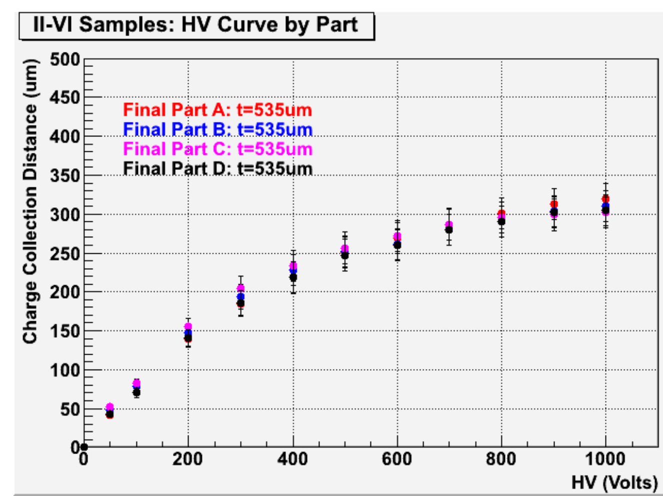
- advantages of diamonds w/r/t silicon
  - large displacement energy → Radiation hard
  - large bandgap → less leakage current & noise
  - high thermal conductivity → less cooling, good heatspread
- there are some disadvantages though
  - Large bandgap → less signal
  - Size of diamonds (scCVD) → Material more expensive than Si

Diamond Manufacturers

- In the past diamonds via DDL from ElementSix (De Beers)
  - DDL out of business, now directly via ElementSix
- New suppliers
  - IIa-Technologies (scCVD)
  - II-VI Incorporated (pCVD)
- IIa has delivered O(10) samples for evaluation
  - committed their self to
    - Further improvement of material
    - pCVD growth
- II-VI improved quality of pCVD over the last years
  - Delivered growing number of final finished parts to CMS and ATLAS
  - Now typically deliver 275 - 300 µm collection distance

IIa scCVD diamond with thickness ~775 µm

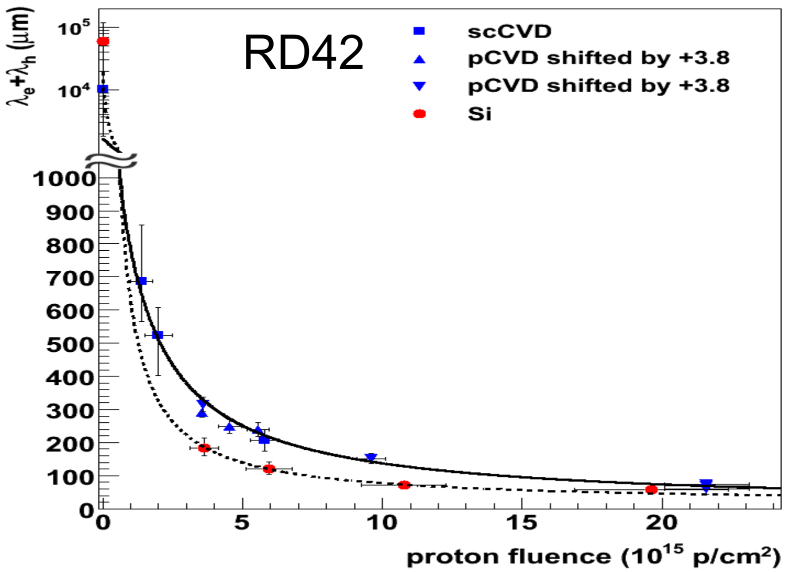




Radiation Hardness

$$\lambda_{e/h}(\Phi) = \frac{\lambda_0}{1 + \lambda_0 \cdot k \cdot \Phi}$$

- 24 GeV protons
- $k_\lambda = 0.62 \pm 0.07 \times 10^{-18}$ $\mu m^{-1} cm^{-2}$
- Polycrystalline diamond sample offset by $\Phi \sim 5 \times 10^{15}$ to account for existing traps.
- Poly and single crystal diamond show consistent damage constants.



http://arxiv.org/pdf/1206.6795v2.pdf

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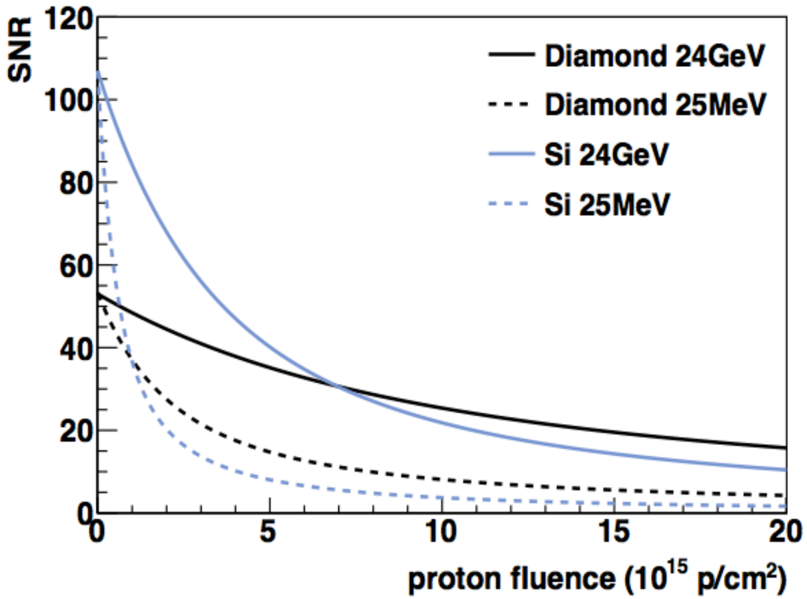

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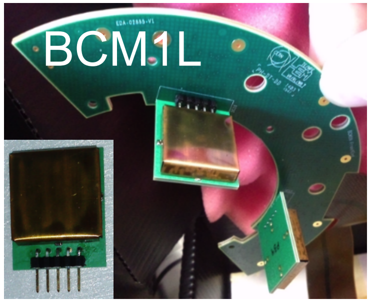
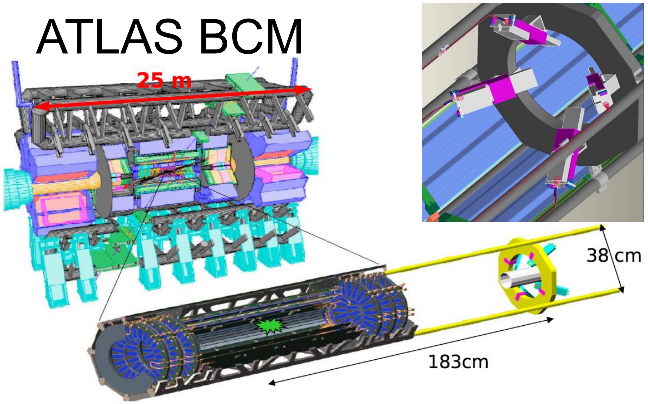
More high energy diamond experiments

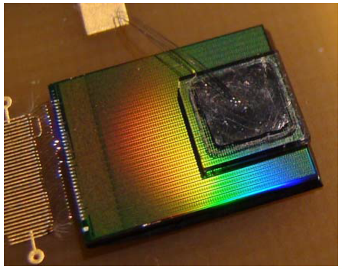


- CMS:
  - BCM1F: for online background and luminosity measurements
    - 24 scCVD diamond sensors, 48 Channels
    - Fast MIP counter, trigger-less readout
  - BCM1L/BCM2L: Beam abort system
    - Based pCVD diamond sensors
- ATLAS:
  - BCM:
    - 4 x 2 pCVD diamonds on each side
    - Single particle counting with σ = 0.7ns.

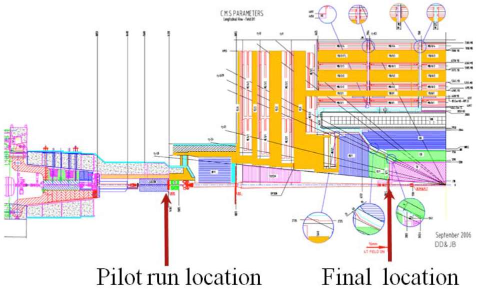
ATLAS BCM

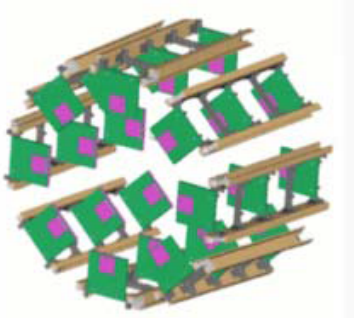


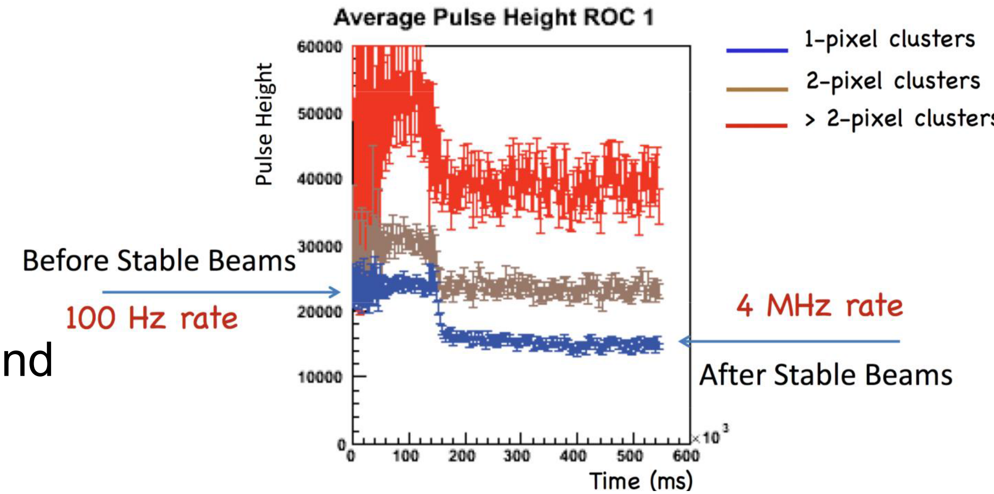
CMS Pixel Luminosity Telescope (PLT)



- High precision bunch-by-bunch luminosity measurement with an array of eight 3-plane telescopes
  - Pilot Run: Diamond sensors
  - Final Installation: Silicon sensors
- Pilot Run while LHC Run 1 in Castor region: 14.5m from IP
  - Total exposure $20 fb^{-1}$
    - 5×10^{13} n/cm^2 and 5×10^{13} charged hadrons/cm^2
- In the Pilot Run:
  - strong rate dependency for this diamonds after a small amount of irradiation
- Major effort was started to understand this issue

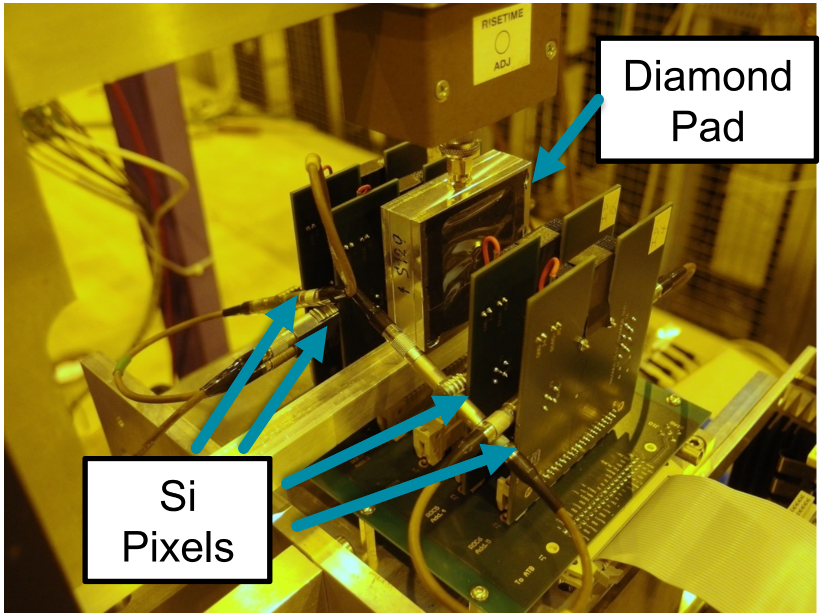






PSI beam test campaign

PAUL SCHERRER INSTITUT PSI

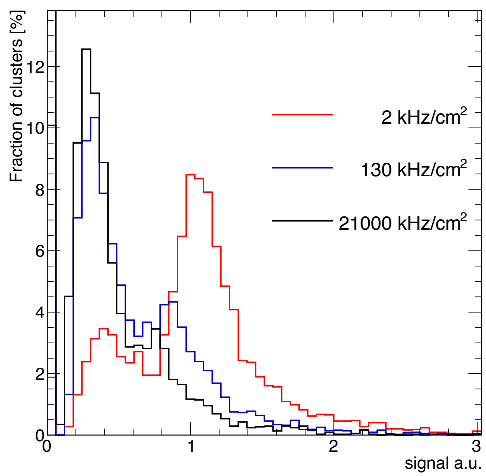


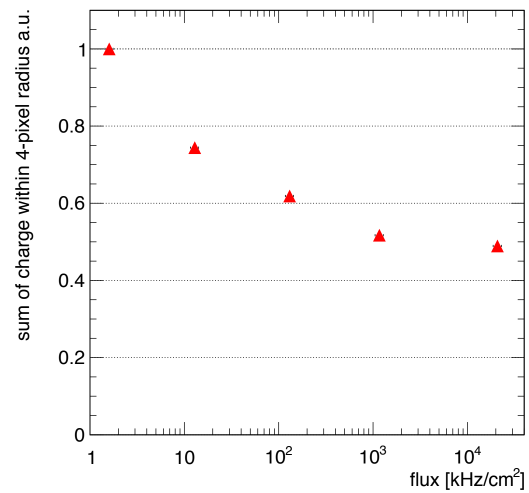
PSI	Paul Scherrer Institute
Beamline	HIPA/PiM1
Beam Energy	250 MeV/c
Particles	Mostly pi^+
Flux	$O(1kHz/cm^2) – O(10 MHz/cm^2)$

- Multiple beam tests at PSI
- Compact Si telescope based on CMS pixel chip PSI46v2
  - Scalable trigger size
  - Readout of pad detectors with Amplifier + DRS4 Evaluation board
- Testing pCVD and scCVD
  - irradiated/non-irradiated/ Pilot Run irradiated
  - Pad detectors:
    - Quick detector fabrication and turn around
    - study sensors w/o threshold effect
  - Pixel detectors:
    - Study effects of pixel threshold
    - Study effects of pixel charge sharing

Pixel Results for rate studies

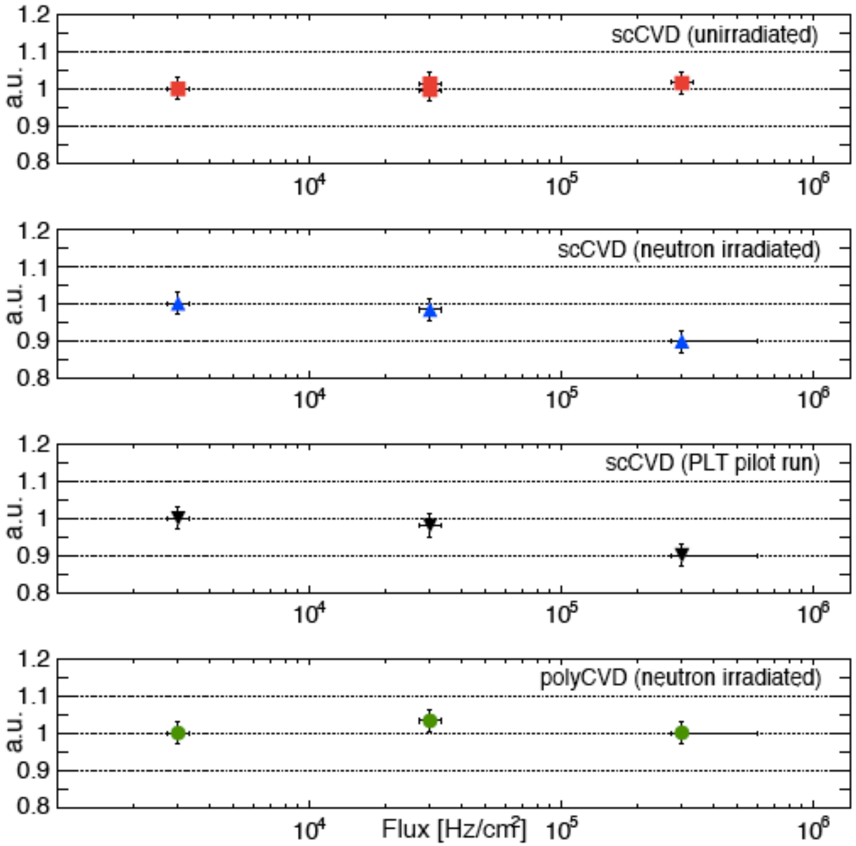
- Testing irradiated scCVD pixel detector
  - Using PSI46v2 readout chip
  - $5x10^{13}$ n/cm^2 and $5x10^{13}$ charged hadrons/cm^2 (PLT pilot run diamond)





- 50% drop in charge with flux
- Similar effect as seen in PLT pilot run

PAD Results for rate studies



- scCVD unirradiated and pCVD irradiated show less than few % signal variation up to O(MHz/cm^2)
- scCVD irradiated with neutrons and in CMS (PLT pilot run 2012) show similar behavior:
  - ~10% drop in signal at flux > 100 kHz/cm^2
- pCVD does not show a rate effect

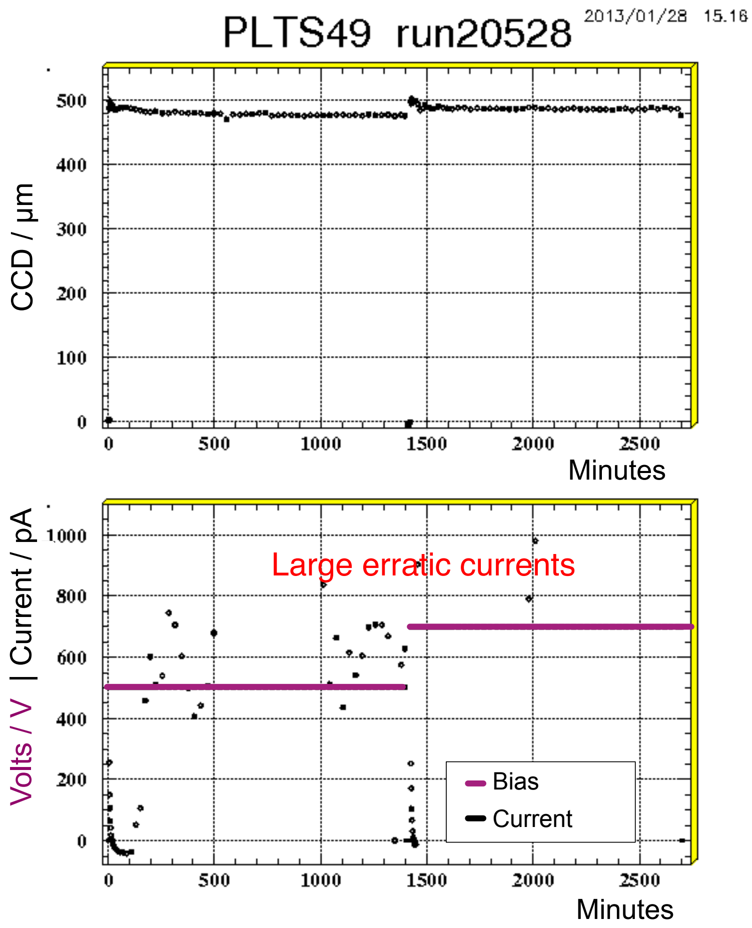
Rate dependency summary

- Also tested irradiated/unirradiated scCVD diamonds from IIa Technology
  - Seems to show less rate dependence than E6 diamonds
- Investigation of rate dependencies is continuing with an improved readout system with
  - Faster amplifiers for PAD readout
  - Lower threshold ROC for Pixel measurements
  - Longer data taking capabilities
- Up to now:
  - **No rate dependence for pCVD diamonds** irradiated with 5e13 neutrons/cm^2 up to 2 MHz/cm^2
  - Rate dependence seems to be a growth dependent

Effect of surface treatment on a leakage current

Lessons learned – leakage current

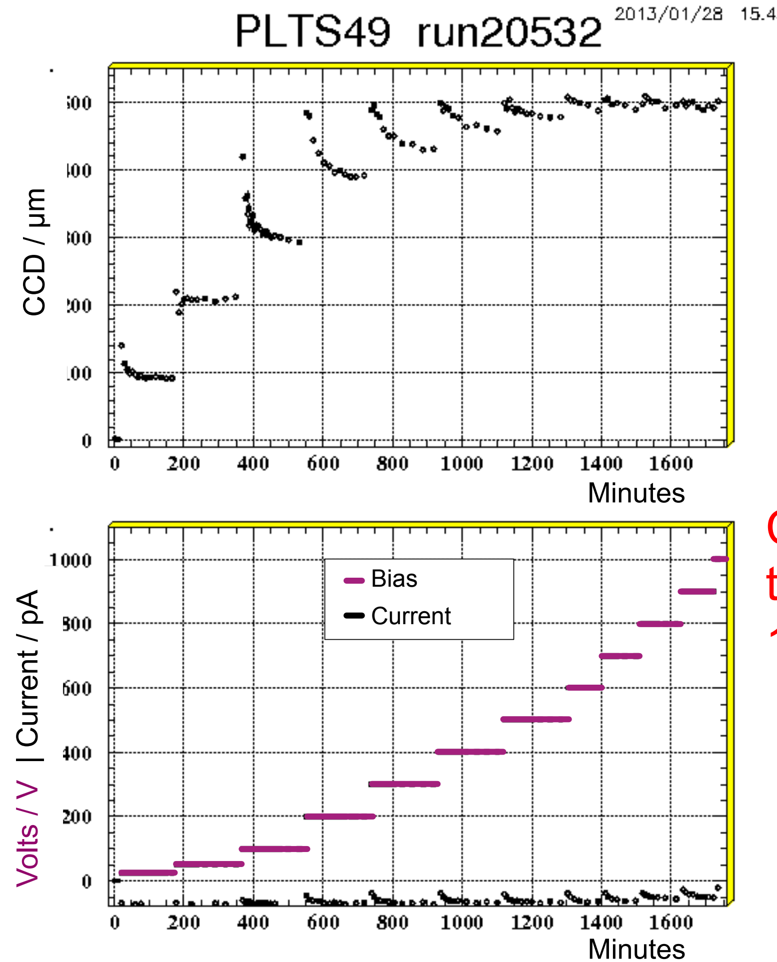
- Observed large erratic currents for several diamonds
  - This diamonds could not hold high bias fields
  - Some scCVD diamonds were not collecting full charge @ 1V/μm
  - Different results for positive and negative polarity



Can't go above 700V

Lessson learned – leakage current

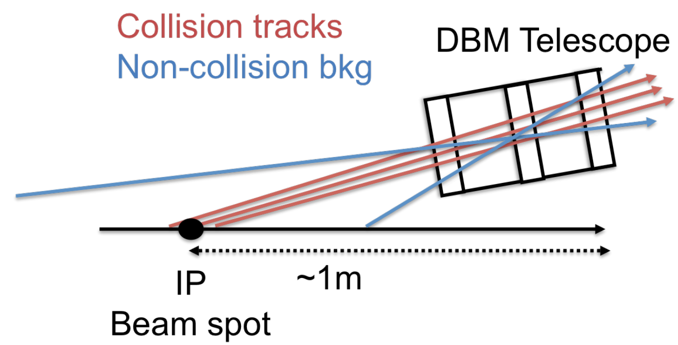
- Surface treatment with reactive ion etching (RIE)
  - Fixing HV problems
    - More stable currents
    - Higher voltages/ electric fields
  - More symmetric charge collection
  - Improving charge collection

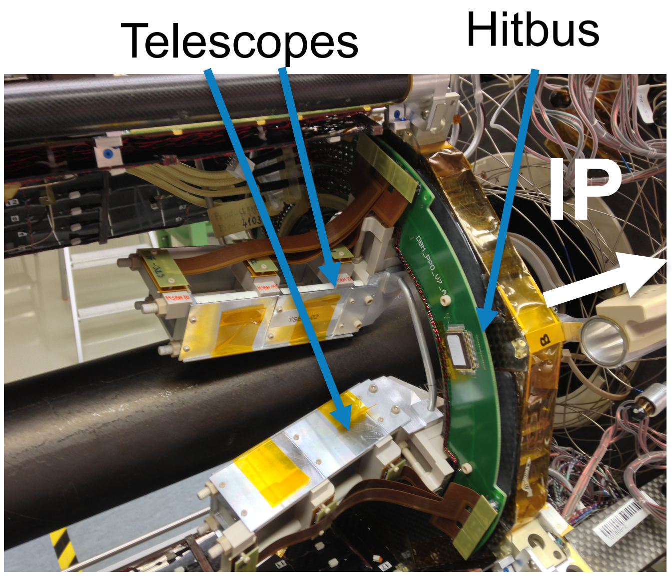


Can go to 1000V

ATLAS Diamond Beam Monitor (DBM)

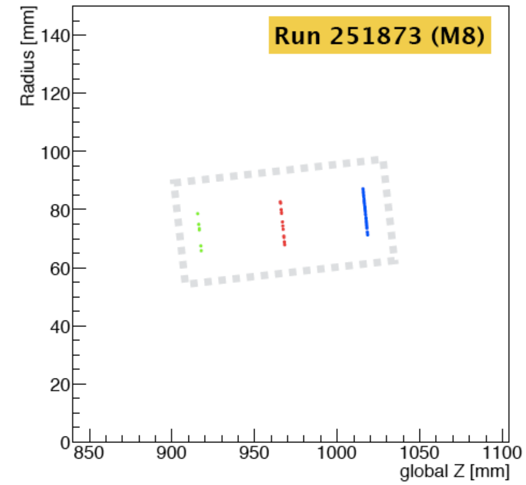
- Purpose:
  - Bunch-by-bunch luminosity monitor (aim <1% per BC per LB)
  - Bunch-by-bunch beam spot monitor
    - Pixelated sensors allow (limited) tracking to distinguish collision tracks from beam halo
- Design:
  - 4 telescope of three FE-I4 modules at η ≅ 3.2 per side ➔ 24 modules
- On each side
  - 3 diamond telescopes with diamonds from 2 suppliers (E6 & II-VI) bump bonded at IZM
  - 1 silicon telescope

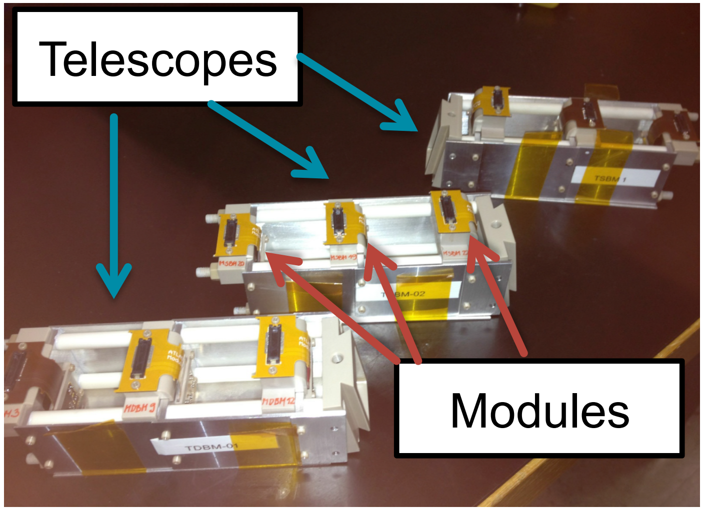




DBM status

- Powered since early February for ATLAS cosmic/ commissioning runs
  - Included in ATLAS central data-taking since mid of February
- Sensors biased at
  - 50 V (silicon telescopes)
  - 500 V (diamond telescopes)
- Thresholds tuned to 2500e for diamond
  - Plan to tune to 1500e
- New experiences with
  - bump bonding
  - Installation



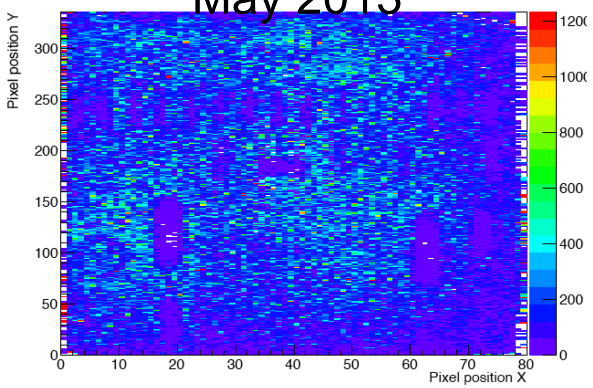


Experience DBM Bump Bonding

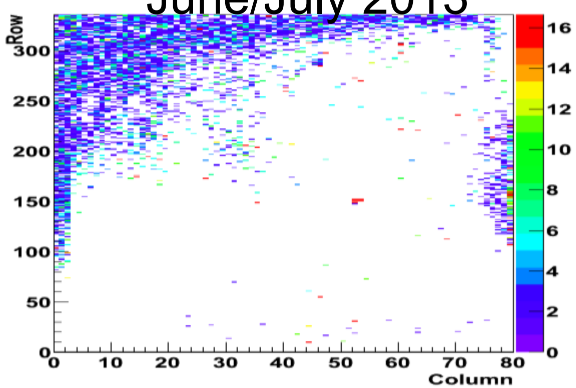
Lessons learned – Bump bonding issues

- FE-I4 – Biggest Pixel chip ever bump bonded to a diamond
  - 26880 pixels with an active area of 341 mm^2
- Bump bonding of diamonds in four batches

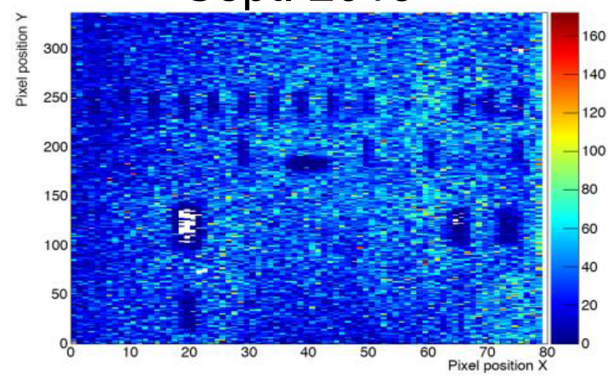
MDBM03
May 2013



MDBM17
June/July 2013



MDBM31
Sept. 2013



- Batch 1 & 4: Similar bump bond efficiencies as for silicon
- Batch 2 & 3: Low bump bond efficencies

Lessons learned – Bump bonding issues

- FE-I4 – Biggest Pixel chip ever bump bonded to a diamond
  - 26880 pixels with an active area of 341 mm^2
- Bump bonding of diamonds in four batches

MDBM03
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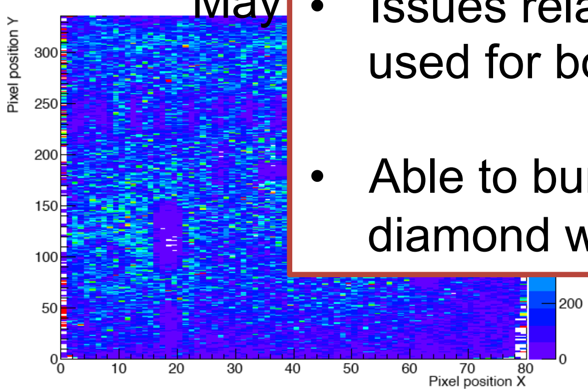
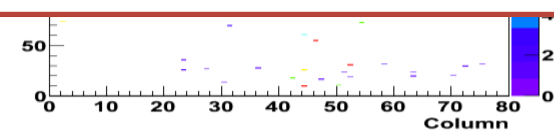
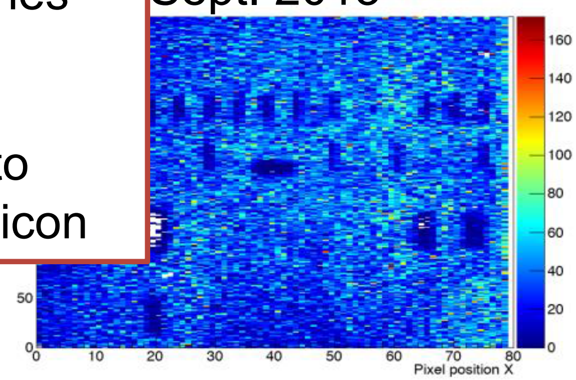


MDBM17



MDBM31
Sept. 2013



- Issues related to the persons and machines used for bonding the chips
- Able to bump bond FEI-4 readout chips to diamond with similar efficiencies as to silicon

- Batch 1 & 4: Similar bump bond efficiencies as for silicon
- Batch 2 & 3: Low bump bond efficencies

Experience DBM Installation

Lesson learned – installation issues

- 'Lost' 3 DBM modules in 2 telescopes during operation
  - 1 diamond module
  - 2 Si modules

- Left modules in an unconfigured state
- Probably wire bonds broke due to high currents and magnetic field

- Investigation is in progress but definitely not a sensor related issue

3D diamond detectors

Supported by
US DoE Grant DE-SC0010061,
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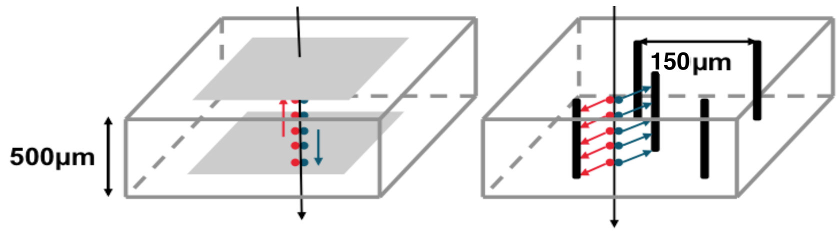
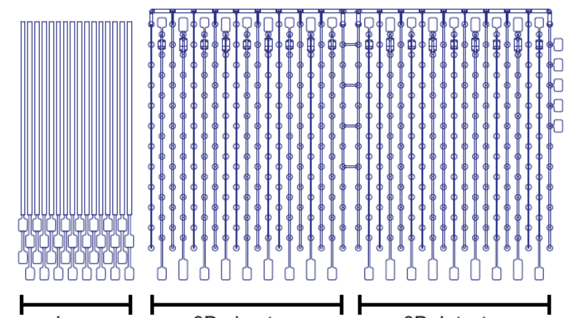
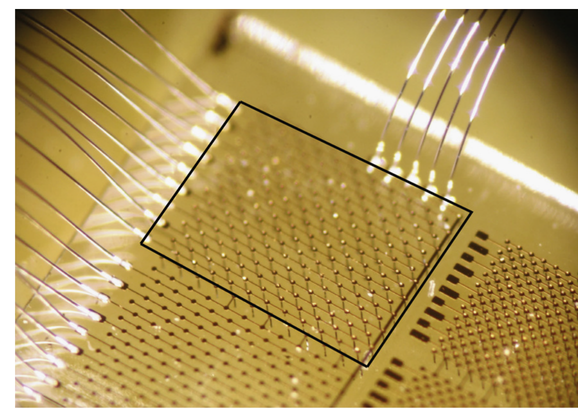
3D diamond detectors

- 3D geometry to shorten the drift distances





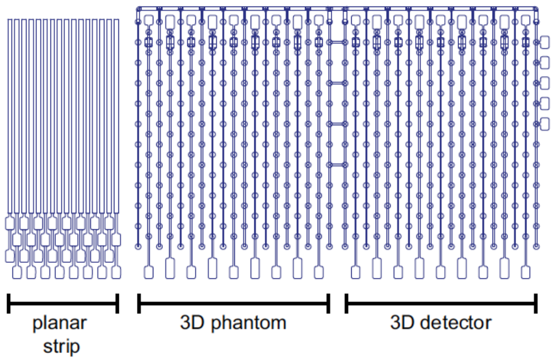
- For 3D geometry using a femto second laser (100fs) with a wavelength of 800 nm
  - phase change of diamond into a combination of diamond-like carbon, amorphous carbon and graphite
- Sizes:
  - Planar strip pitch 50 μm
  - 3D Cell size: 150 x 150 μm^2
- Optical and resistivity measurements show a yield for micromachining columns of ~ 90 %

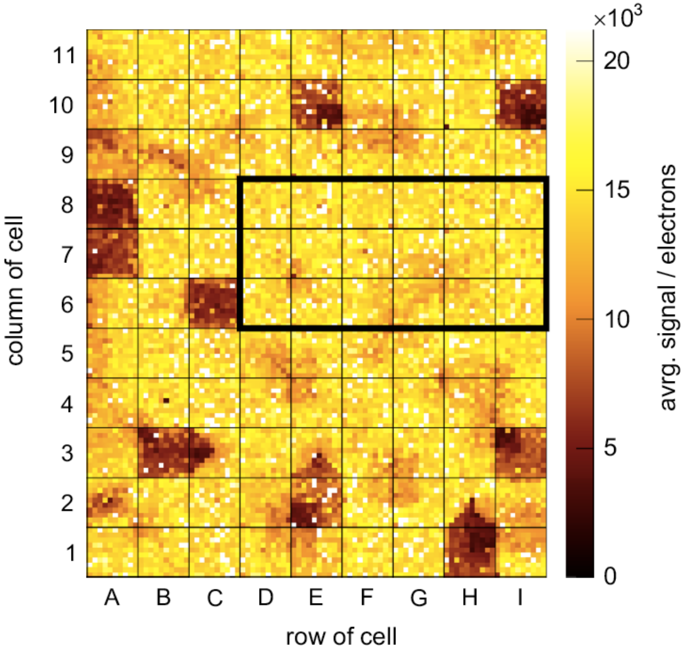


published in NIM A 786 (2015) p97

3D diamond detectors

- 3 different regions on one diamond for comparison
  - Planar strip @ 500V, pitch 50 µm
  - 3D phantom @ 25V, size 150 x 150 $µm^2$
  - 3D detector @ 25V, size 150 x 150 $µm^2$
- Missing charge around ~9 broken readout columns
  - In agreement with other measurements
- See effects of missing bias columns





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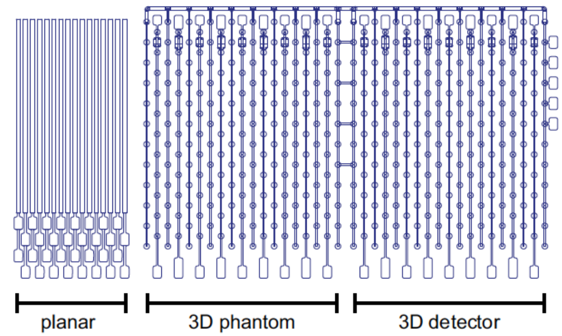

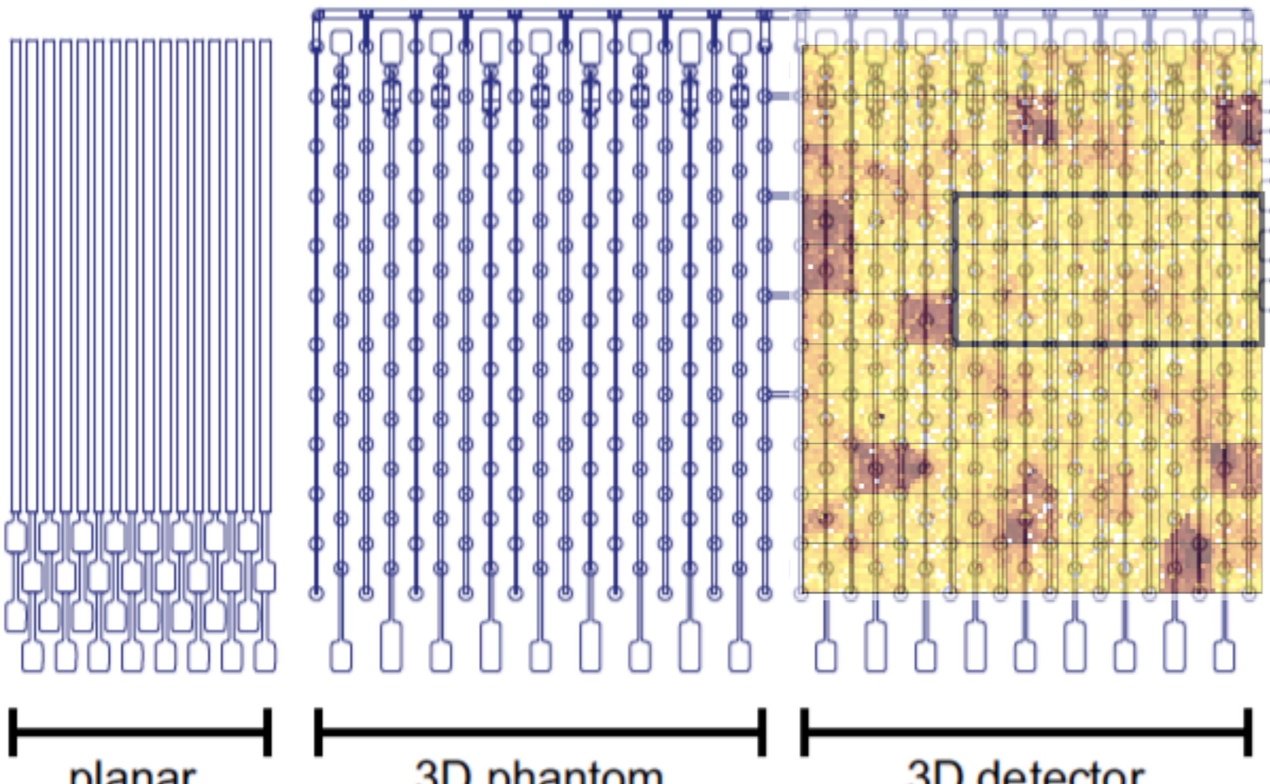

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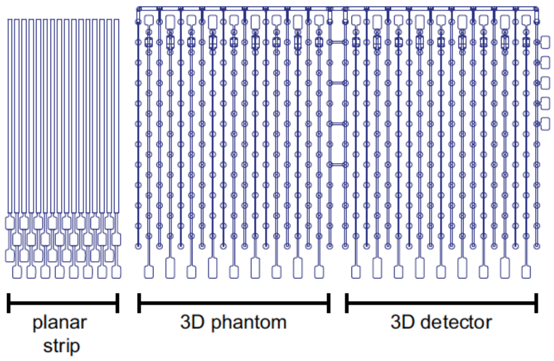

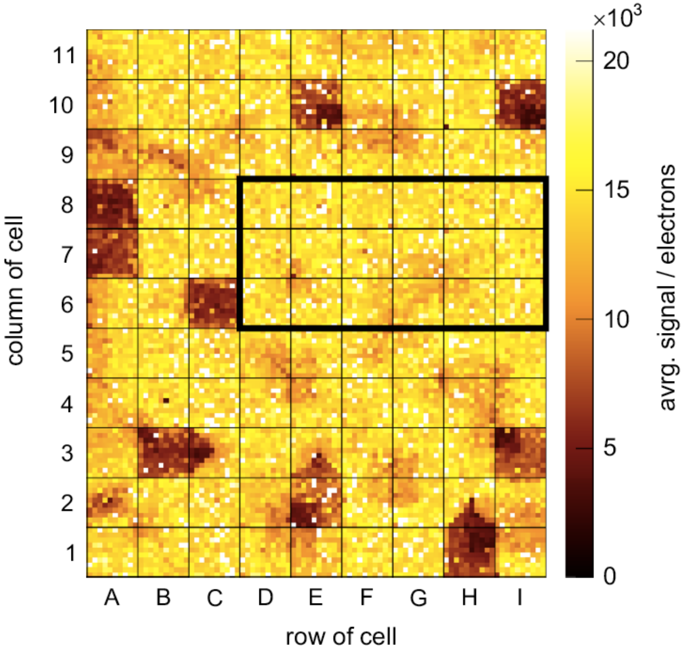

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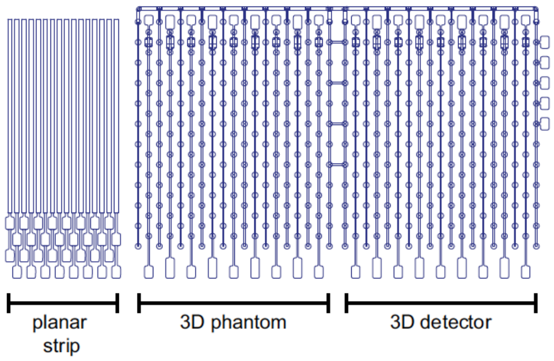

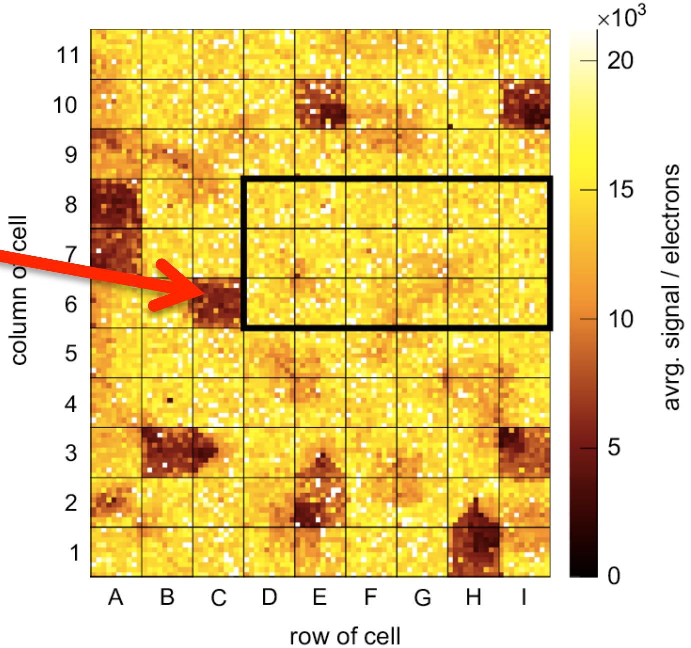

3D diamond detectors

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  - Planar strip @ 500V, pitch 50 µm
  - 3D phantom @ 25V, size 150 x 150 µm²
  - 3D detector @ 25V, size 150 x 150 µm²
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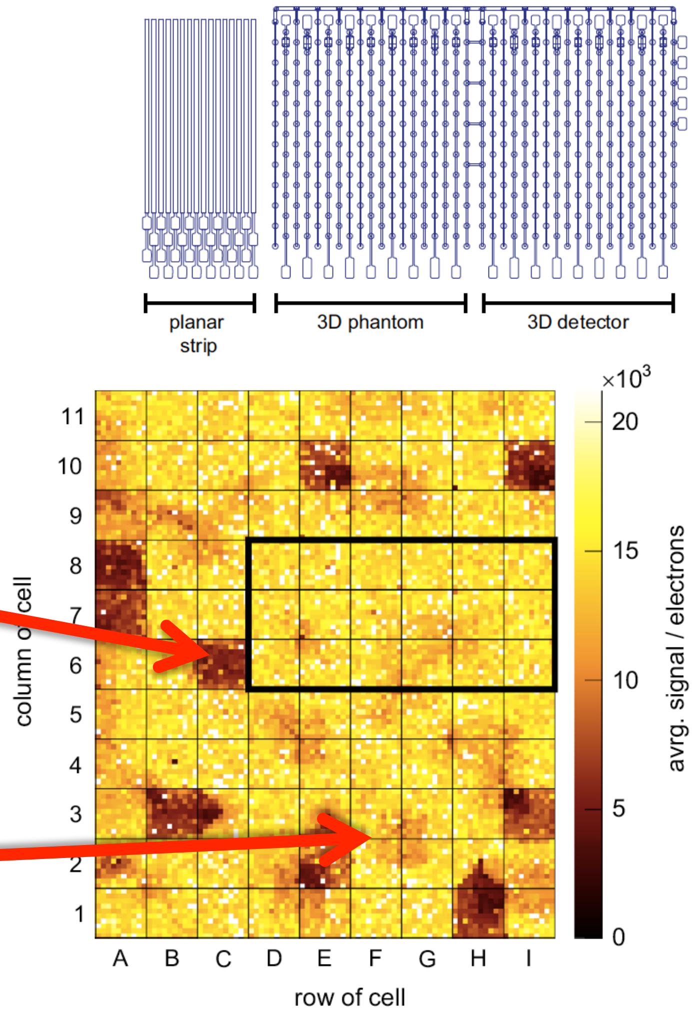
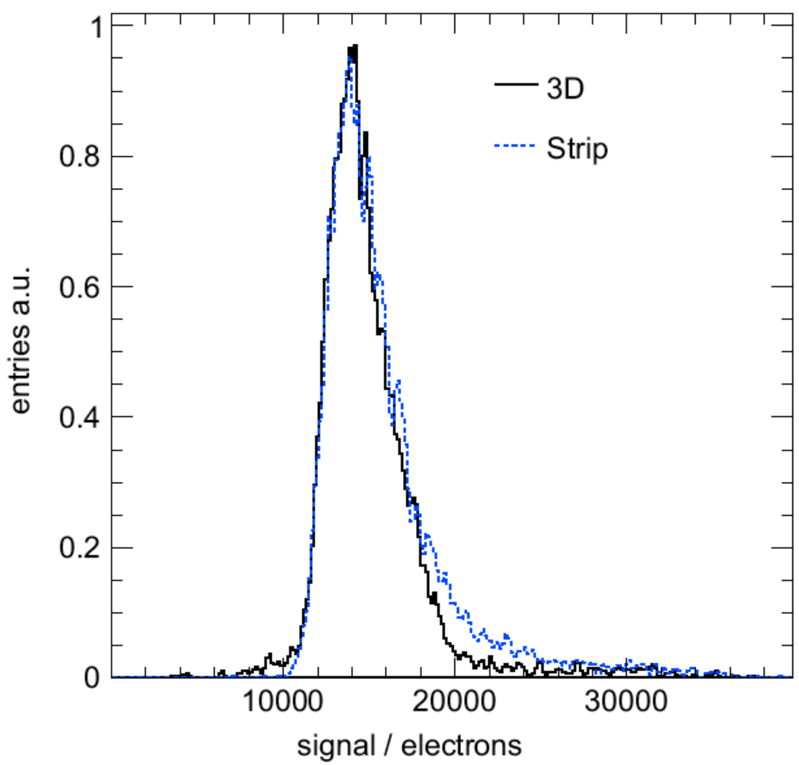
  - In agreement with other measurements
- See effects of missing bias columns



3D diamond detectors

- Remarkable agreement between signal in 3D and planar strip geometry for a good cell region
- full charge at lower avrg. E Field



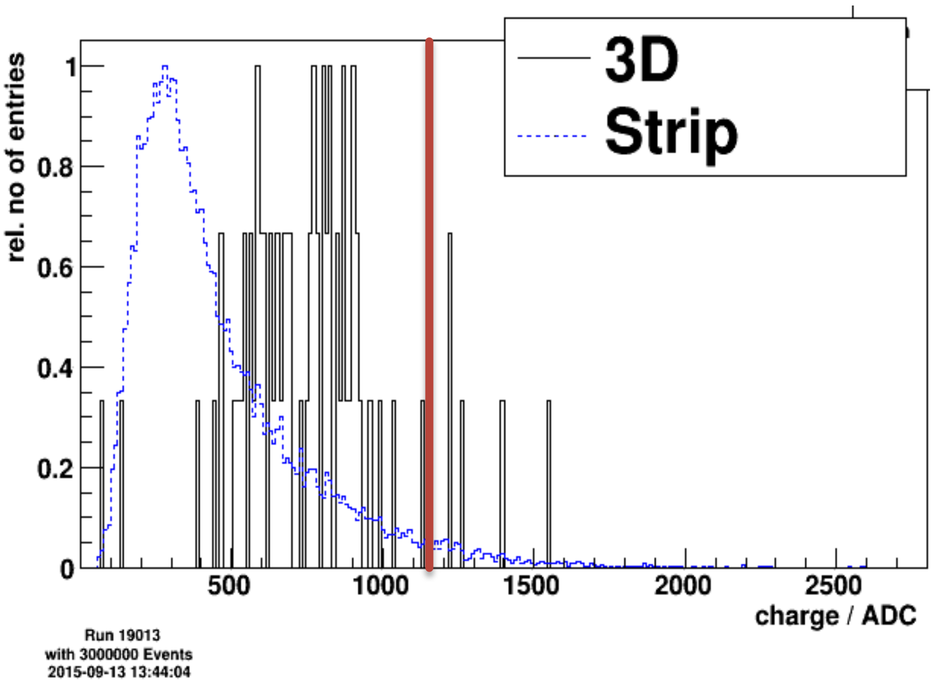
3D pCVD diamond detectors

- 3D pCVD diamond has been tested in beam tests at CERN this summer
- Same layout/mask as for 3D scCVD diamond with Planar Strip/3D-Phantom/3D-Detector
  - Smaller yield in fabrication of columns than for scCVD
  - Smaller yield in contacting the columns with the metallization than for scCVD
- Preliminary result without calibration to electrons
  - 3D-Detector & 3D-Phantom biased @ 75V, planar strip @ 500V
  - Comparison between 3D detector and planar strip
  - Looking at single working cells

Poly 3D

- Red line: estimate for MP of full charge collection (500 μm)

- Collecting more charge than planar strip detector
- ~ 77% of Full charge collection @ 75V
- Highest charge collection ever measured for pCVD diamonds



Summary

- New diamond suppliers, IIa & II-VI, improved situation on the market
- Quality of diamonds has improved strongly over the last years
  - Now reaching 275 - 300 µm CD in pCVD diamonds
- New experiences in using diamonds on bigger scales in CMS PLT Pilot Run and Atlas DBM
  - Most problems has been understood and solved
- Rate dependency still under study,
  - seems to be growth dependent
  - We did not observed a rate dependence for pCVD diamonds
- 3D diamond detectors show a great promise
  - 3D pCVD shows 2.5x the charge of a planar pCVD strip detector at 75V.

Outlook

- Further improvement of diamond quality in cooperation with suppliers
- Continue Rate studies with improved setup
    - Faster amplifiers for PAD readout
    - Lower threshold ROC for Pixel measurements
    - Longer data taking capabilities
- Working on thinner diamond detectors
- R&D for HL-LHC: innermost layer of Tracker
- R&D on 3D devices
  - Improve fabrication of 3D device
    - Higher yield
    - Bigger detectors
  - Test different structures
  - Studies of irradiated 3D CVD diamonds
  - Measure 3D pCVD at higher bias voltages.