Recent Results from Beam Tests of 3D & Pad pCVD Diamond Detectors

Rainer Wallny

ETH Institute for Particle Physics

on behalf of the RD42 collaboration

The help of my RD42 colleagues is gratefully acknowledged.

ICHEP 2016, Chicago, USA

RD42 Collaboration (2016)

The 2016 RD42 Collaboration

A. Alexopoulos[3], M. Artuso[22], F. Bachmair[26], L. Bäni[26], M. Bartosik[3], J. Beacham[15], H. Beck[25], 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], G. Chiodini[29], D. Chren[20], V. Cindro[11], G. Claus[9], J. Collot[30], J. Cumalat[21], A. Dabrowski[3], R. D'Alessandro[5], W. de Boer[12], B. Dehning[3], C. Dorfer[26], M. Dunser[3], V. Eremin[8], R. Eusebi[27], G. Forcolin[24], J. Forneris[17], H. Frais-Kölbl[4], K.K. Gan[15], M. Gastal[3], C. Giroletti[19], M. Goffe[9], J. Goldstein[19], A. Golubev[10], A. Gorišek[11], E. Grigoriev[10], J. Grosse-Knetter[25], A. Grummer[23], B. Gui[15], M. Guthoff[3], I. Haughton[24], B. Hiti[11], D. Hits[26], M. Hoeferkamp[23], T. Hofmann[3], J. Hosslet[9], J-Y. Hostachy[30], F. Hügging[1], C. Hutton[19], 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], E. Lukosi[28], C. Maazouzi[9], I. Mandic[11], C. Mathieu[9], N. McFadden[23], M. Menichelli[31], M. Mikuž[11], A. Morozzi[31], R. Mountain[22], S. Murphy[24], M. Muškinja[11], A. Oh[24], P. Olivero[17], D. Passeri[31], H. Pernegger[3], R. Perrino[29], F. Picollo[17], M. Pomorski[13], R. Potenza[2], A. Quadt[25], A. Re[17], M. Reichmann[26], G. Riley[28], S. Roe[3], D. Sanz[26], M. Scaringella[5], D. Schaefer[3], C.J. Schmidt[7], S. Schnetzer[16], T. Schreiner[4], S. Sciortino[5], A. Scorzoni[31], S. Seidel[23], L. Servoli[31], 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]

127 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 Goettingen, Goettingen, 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

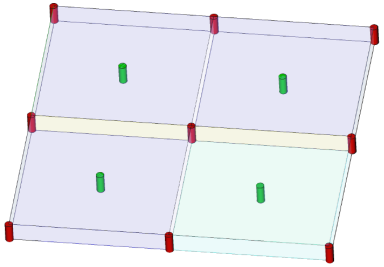
Outline

- 3D diamond detectors beam tests at CERN
  - 3D detector concept in pCVD diamond
  - Large scale 3D detector
- Pulse height vs rate study of pCVD pad/pixel detectors at PSI
  - Setup
  - Results for pCVD pad detectors irradiated to 5e14 n/cm^2
- Conclusions
- Outlook

Diamond 3D Test Beams at CERN

3D Device in pCVD Diamond

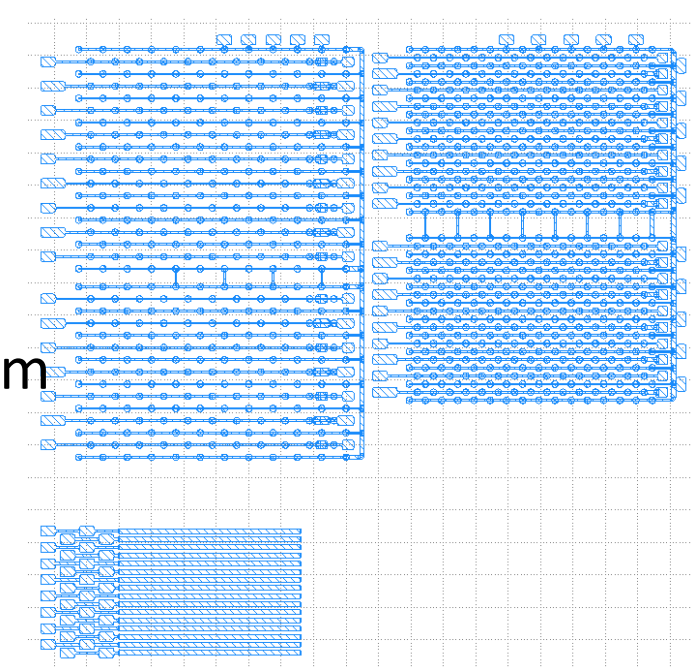
- First 3D device made from polycrystalline (pCVD) diamond!
  - Compare pCVD strip detector (500 V) with 3D (70 V)
  - Same metal mask on top and bottom for 3D and phantom to increase the probability of conductive columns

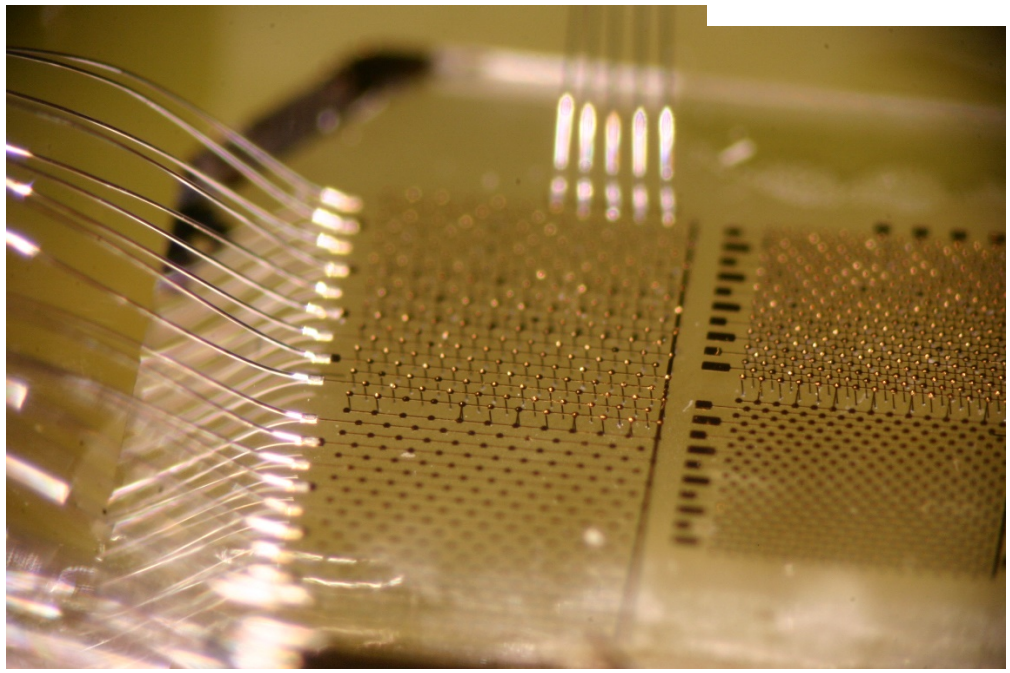


3D

phantom

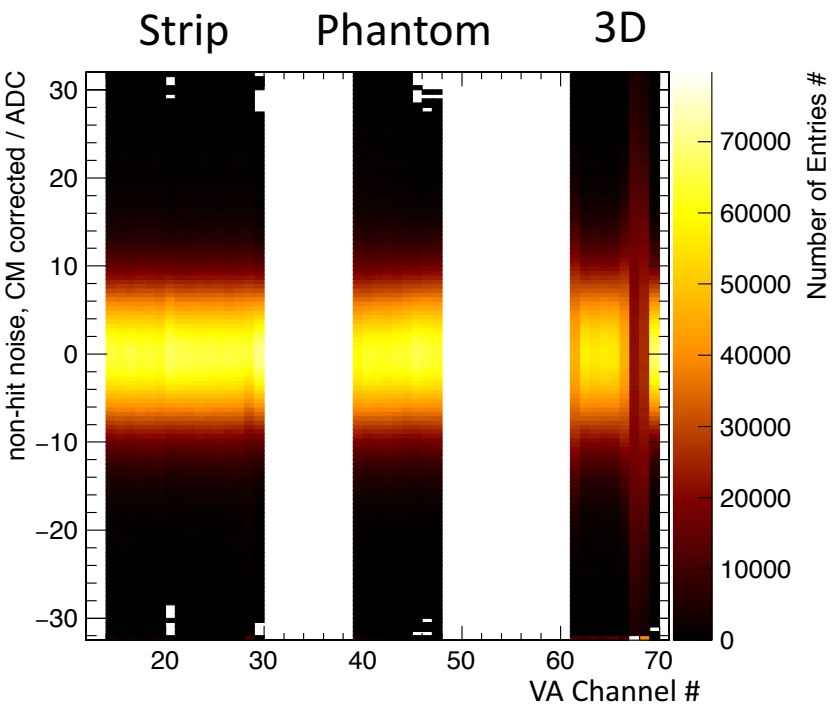
strip



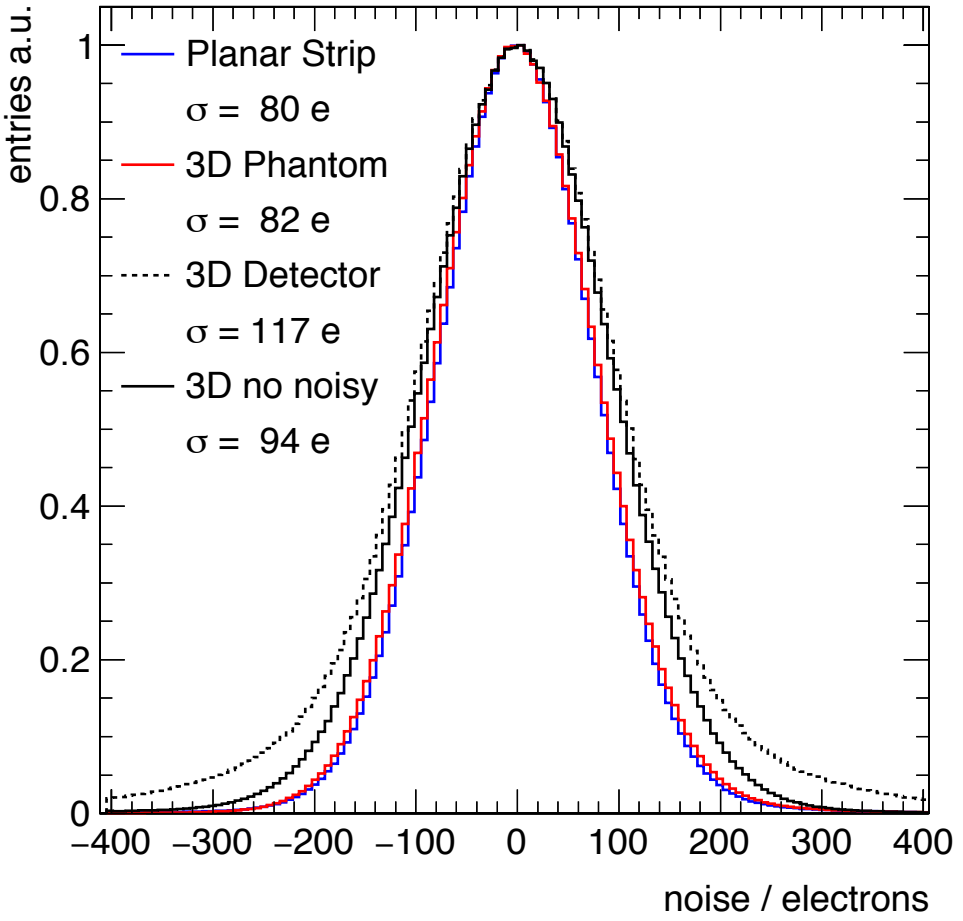


3D Device in pCVD Diamond: Noise

- Measured noise:
  - Planar strip: 80e
  - Phantom: 82e
  - 3D no noisy strips: 94e

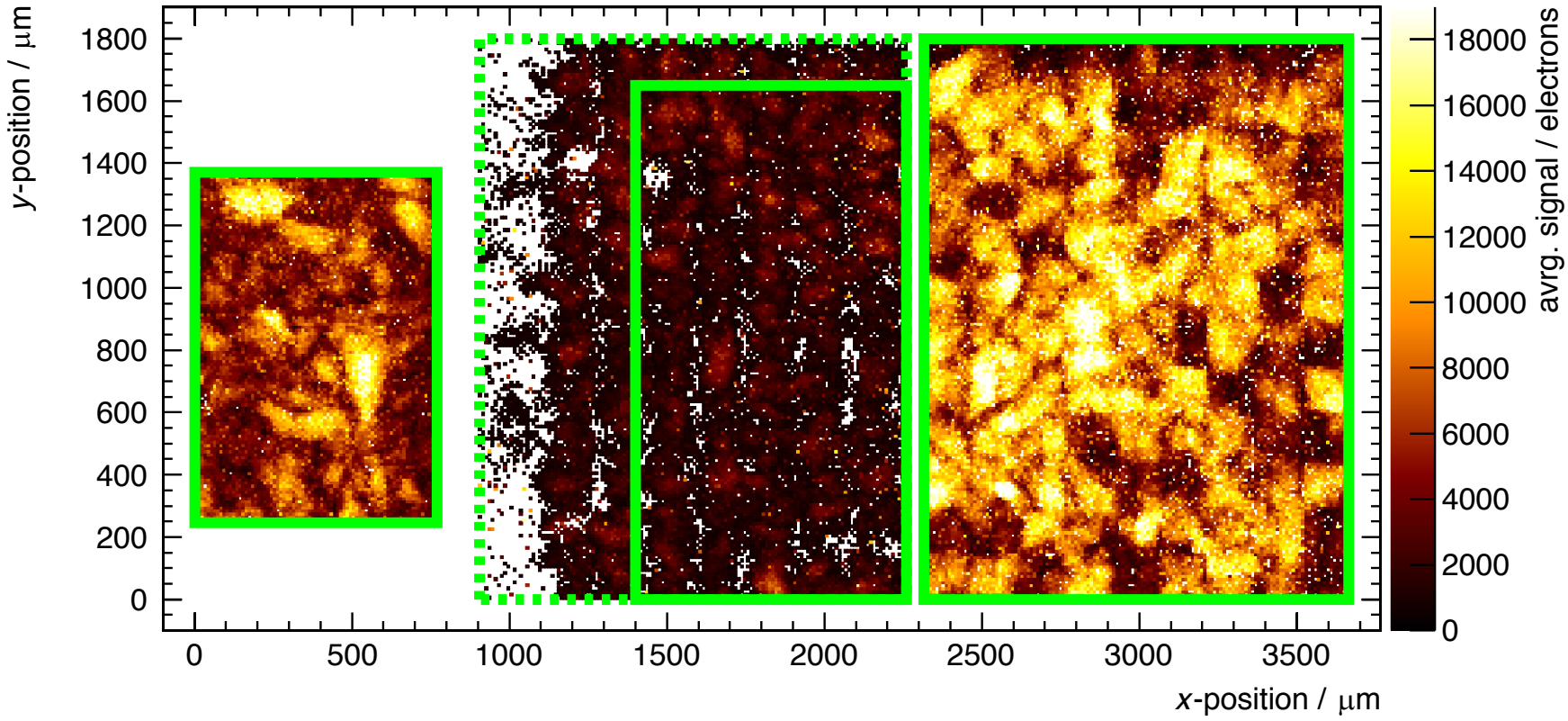


- Noise performance consistent with expectation



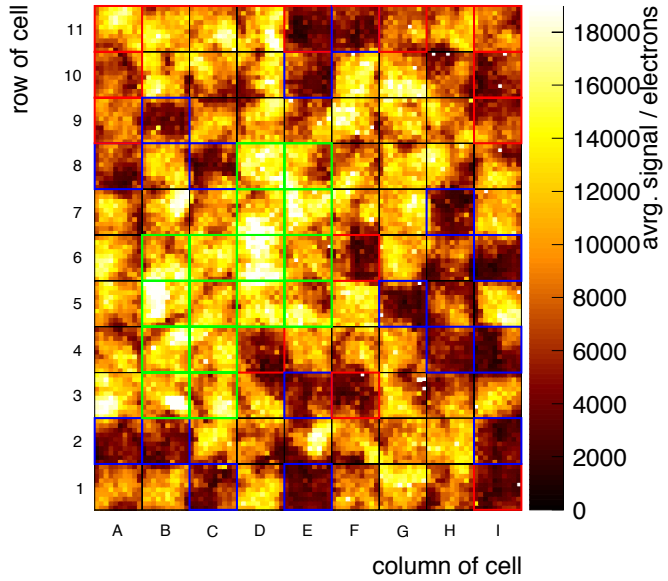
3D Device in pCVD Diamond: Signal

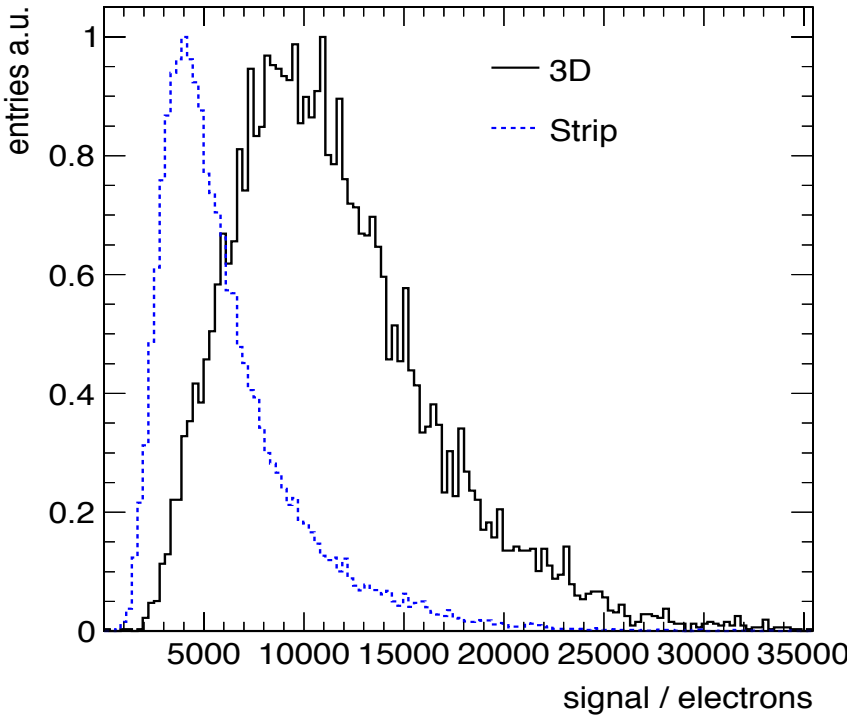
- Measured signal:
  - Visually 3D gives more charge that planar strip!



3D Device in pCVD Diamond:Signal

- Measured signal (diamond thickness 525µm):
  - Planar Strip average charge**: 6,200e**
    or CCD=172 +/- 16 µm
  - 3D average charge: **12,100e**
    or CCD=336 +/- 17 µm



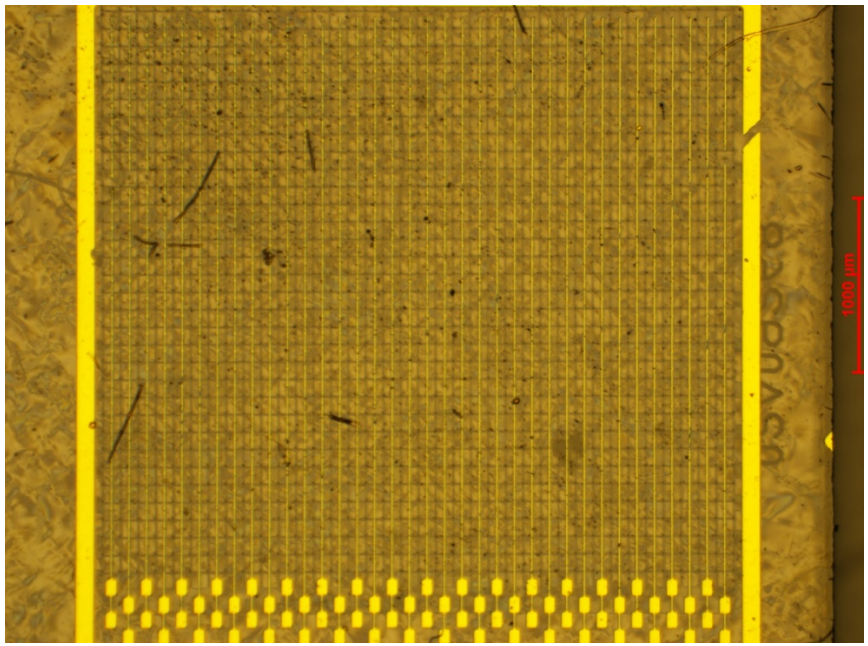


For the first time collect ~65% of charge in pCVD!

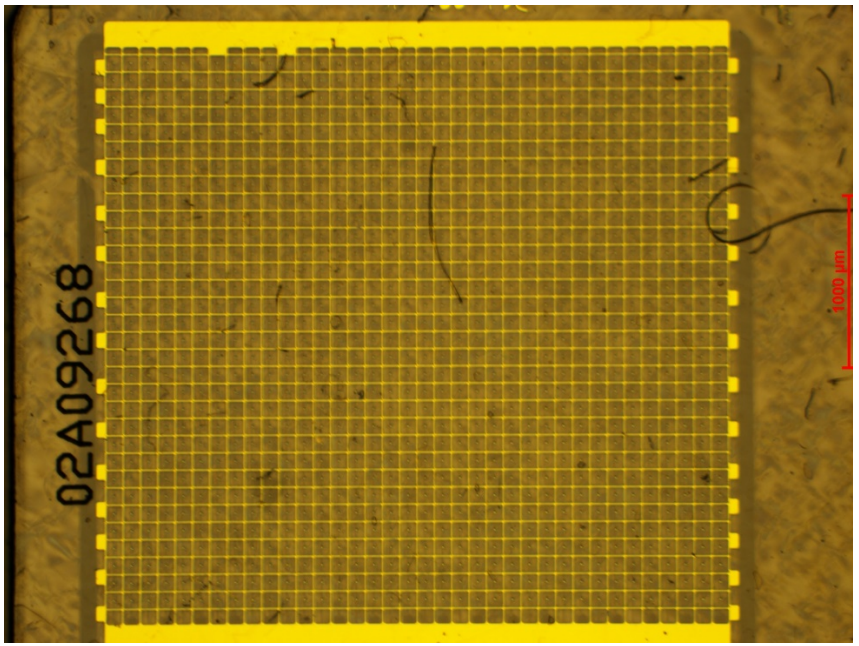
3D Devices in pCVD Diamond

- In May 2016 we tested the first full 3D pCVD detector with two significant improvements:
  - An order of magnitude more cells (1188 vs 99)
  - Smaller cell size (100 µm vs 150 µm)

Readout side

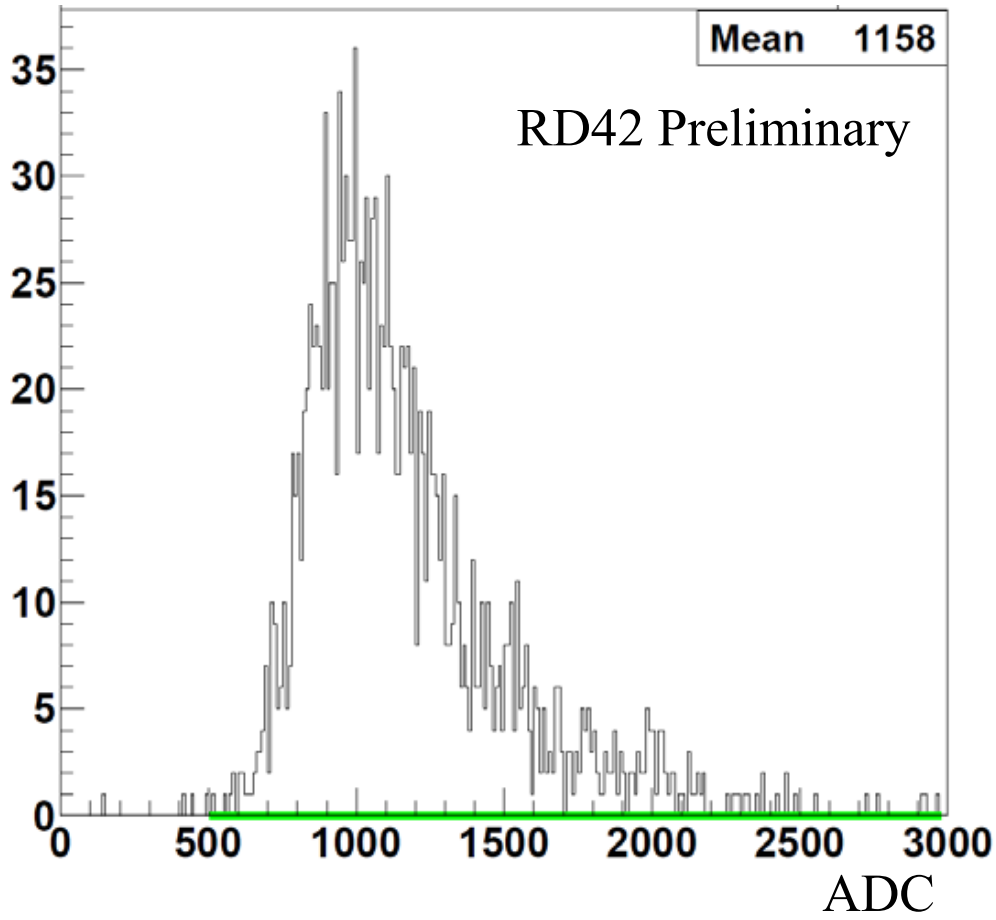


Bias side



3D Device in pCVD Diamond

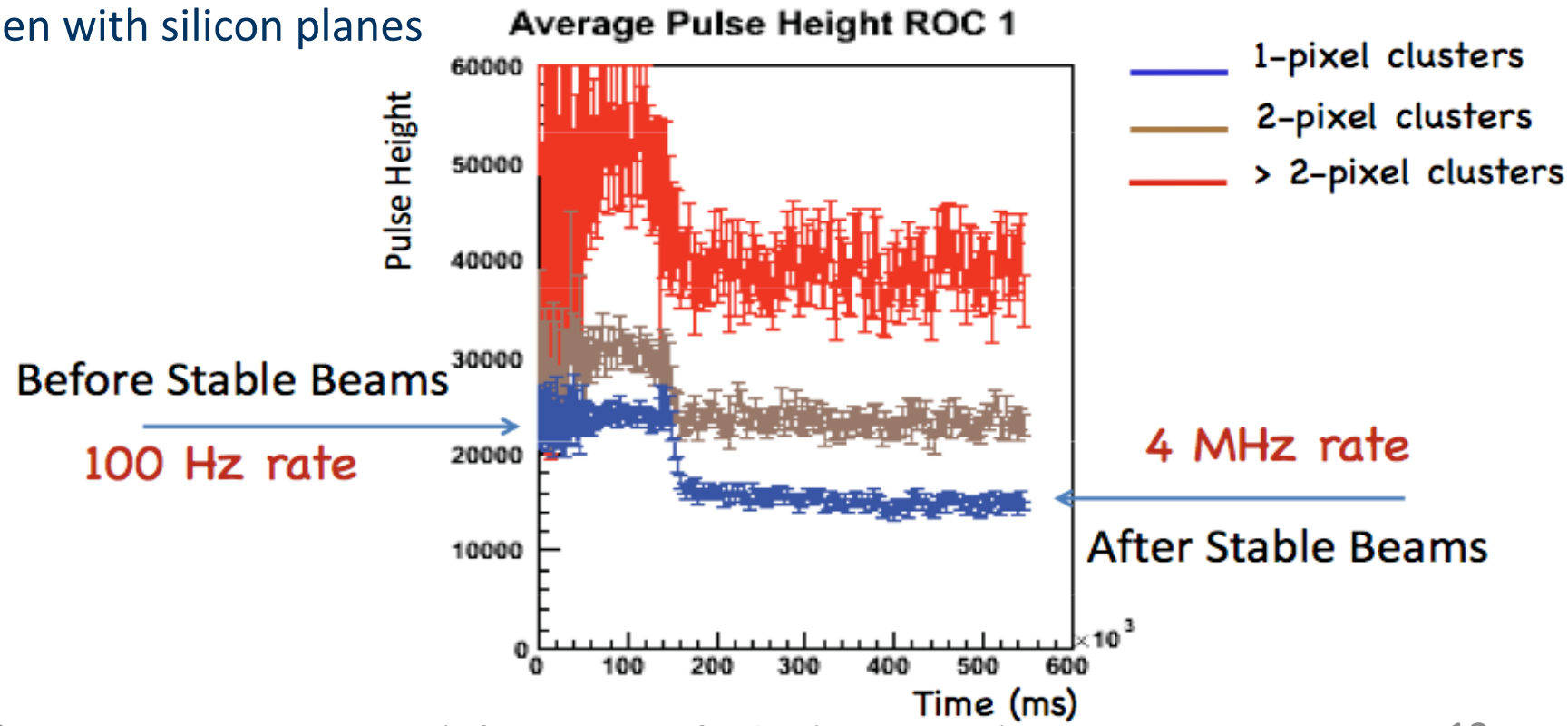
- Preliminary results of full 3D pCVD detector:
  - First plot of 3D average charge in small “good” region
  - Largest charge collection in pCVD diamond:
    ~85% of charge collected!
  - Full analysis in progress



RD42 High Rate Test Beams at PSI

Motivation: Diamond PLT Pulse Height Dependence on Rate

- The first CMS Pixel Luminosity Telescope (PLT) was build using scCVD diamond sensors
- During pilot run, a shift in pulse height was observed
  - High pulse height before collisions (beam halo)
  - Pulse height drops after beam brought into collision
  - Not seen with silicon planes

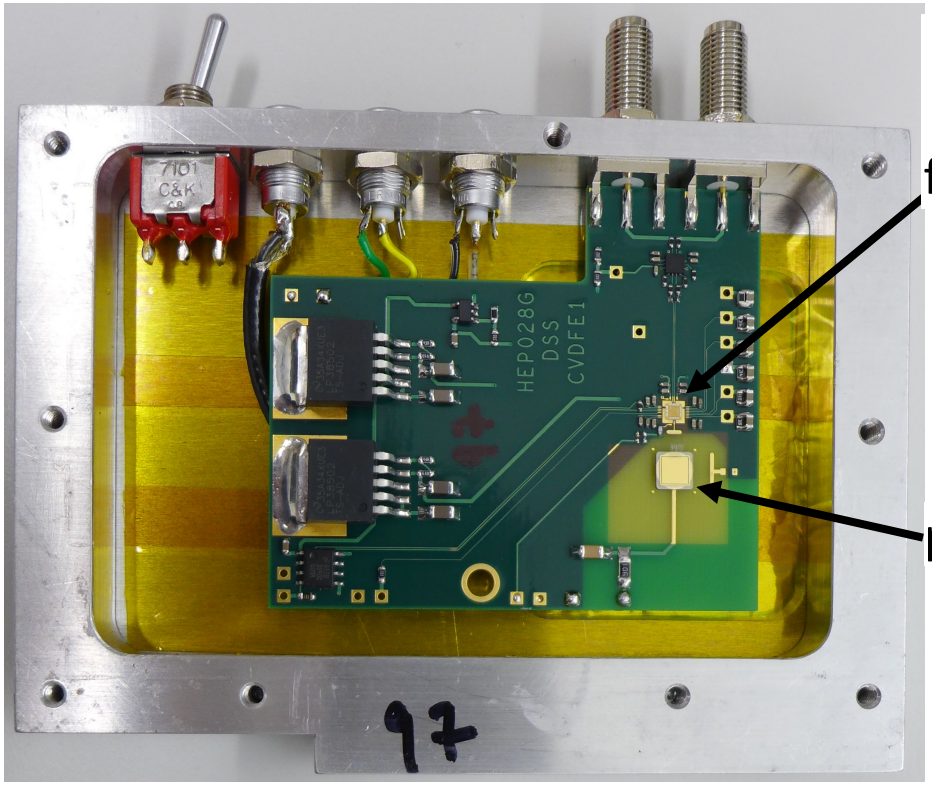


PSI Test Beam Campaign

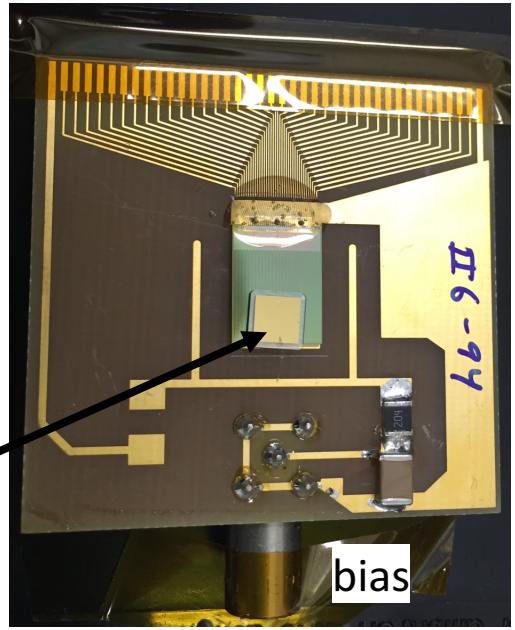
- Several successful test beams in 2015 (May, August, October)
  - Some Pad Detector Results shown here, pixel detector results are being analyzed
- Pad detectors:
  - study sensors w/o threshold effect
  - Quick detector fabrication and turn around
- Pixel detectors:
  - Study effects of pixel threshold
  - Study effects of pixel charge sharing
- Samples:
    - E6 scCVD non-irradiated (Reference) [pad]
    - II-VI pCVD non-irradiated [pad, pixel]
    - II-VI pCVD neutron irradiated (pad 1e14 and 5e14, pixel 5e14)
- Tests:
    - Pulse height versus rate scan [pad 10 MHz/cm^2]
    - Multiple rate up-down scans to determine measurement repeatability [pad, pixel]
    - Positive and negative bias polarities [pad]

DUT devices

Pad detector box



Pixel detector plane

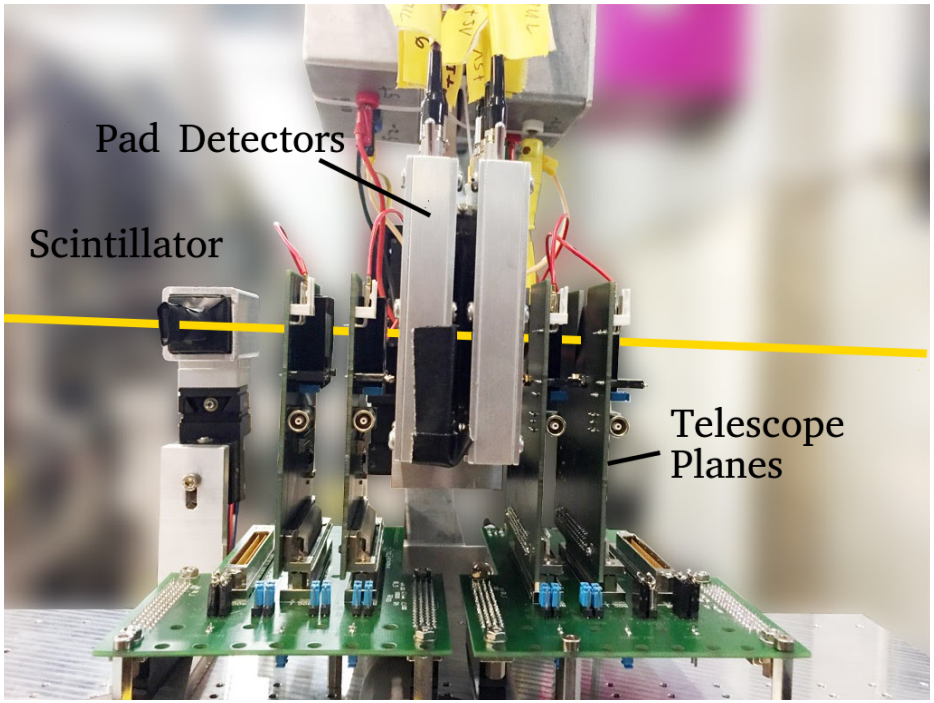


Readout w/ PSI46dig2respin chip

- digital readout
- Low in-time threshold ~1500 electrons

PSI Test beam setup

- piM1 beam line at PSI Proton Accelerator
  - 250 MeV/c “mostly” π+
- Rate determined on the coincidence of front and back silicon planes
- Particle rate easily variable with beam line collimators
  - from O(1 kHz/cm^2) to O(10 MHz/cm^2)
- test setup reconfigurable into either a “pad” setup or “pixel” setup



Pad test setup with masked pixel trigger

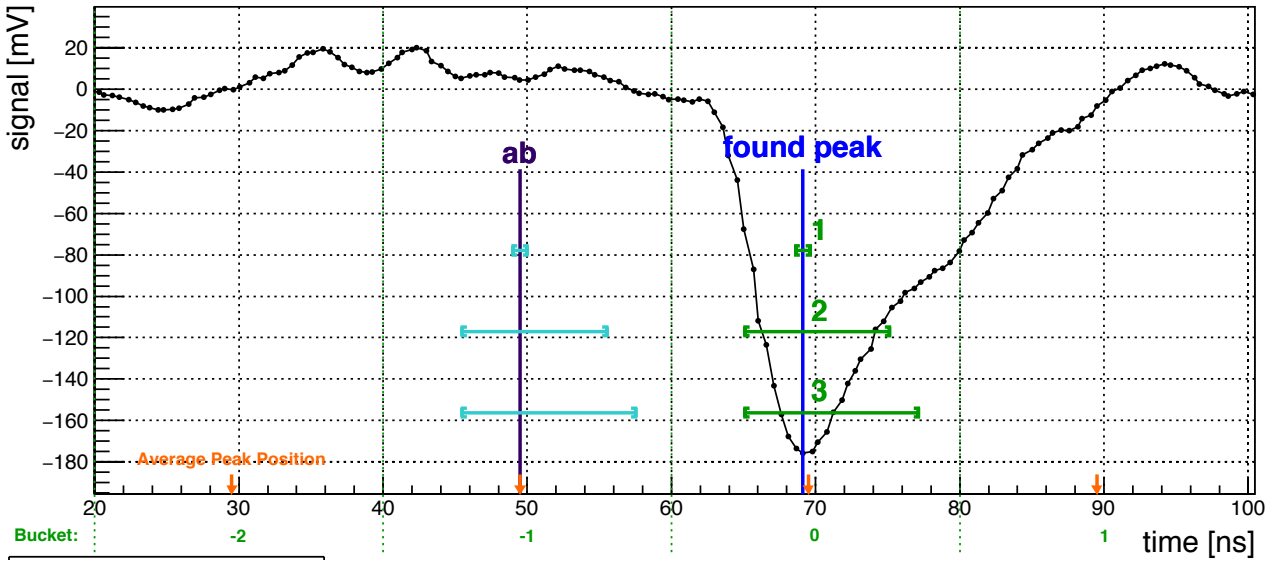
4 Tracking planes:

- 2 Trigger planes
- Scintillator for precise timing (0.7 ns)
- 2 detectors under test

Pad Detector Analysis Results

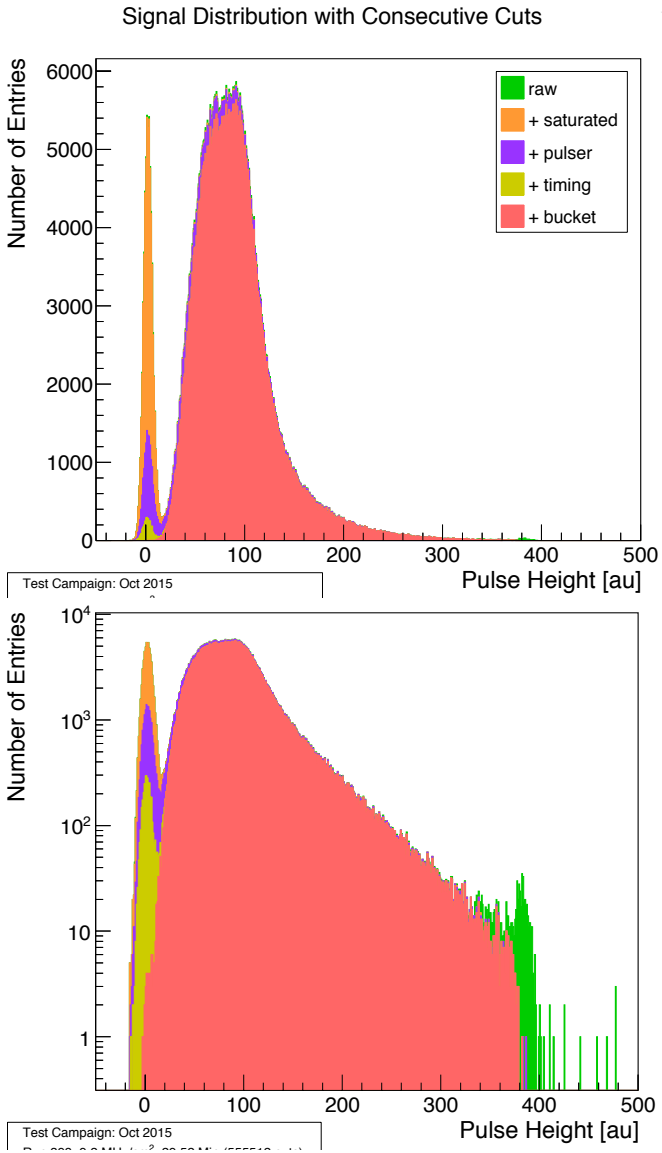
Pad Analysis Setup

- Pulse height amplified with CERN/OSU CVDFE1 fast amp
  - 7 ns rise time, 23 ns fall time
- Digitized by DRS4 evaluation board
  - 1024 sampling points
  - Sampling speed 2 GSPS
- Find peak in the signal region
- Integrate in the window around the peak
  - Integration window optimized to provide best signal to noise ratio
- Subtract pedestal integral
  - Pedestal integrated exactly one bucket in front of the signal



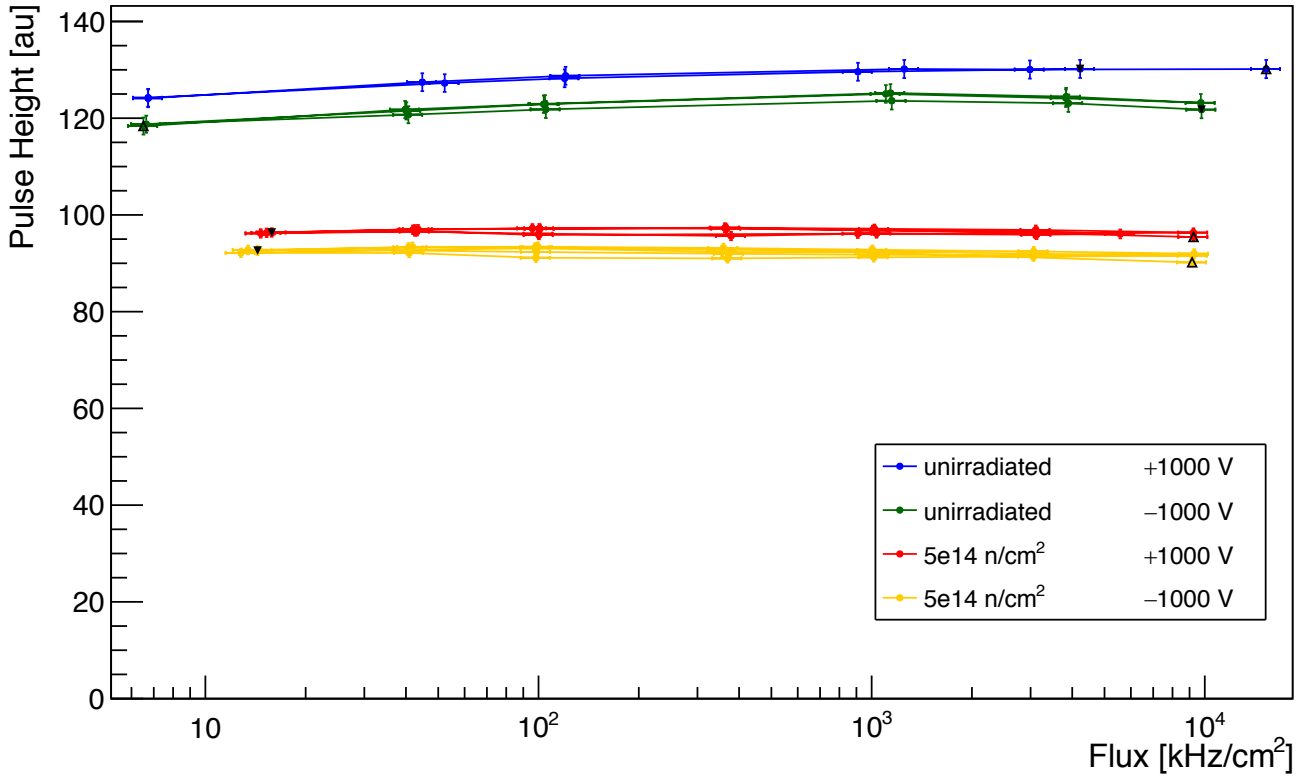
Pad Analysis

- Careful handling of systematic effects
  - **Remove saturated wave forms (heavy ionizing particles)**
  - **Remove calibration events**
  - **Remove residual trigger jitter**
  - **Remove events in wrong bucket**
  - ….
- Remaining pulse height distribution **shown in red** is clean with no remaining pedestal events



Preliminary summary rate dependence

- The particle rate was varied up and down to check reproducibility
  - Systematics on 3% percent level
  - Differences on polarity due to electronics



No significant rate dependence observed in pCVD diamond irradiated to 5e14 n/cm^2 with rates up to 10 MHz/cm^2

Conclusions

- RD42 demonstrated 3D principle on pCVD diamond
  - ~65% of charge collected at 70 V bias
- RD42 demonstrated large-scale (~1200 cells) 3D device
  - Preliminary analysis shows that it is capable of collecting up to 85% of charge!
- A rate dependence (previously observed in a scCVD device) of the pulse height was examined in pCVD diamond sensors:
  - No rate dependence was observed for pCVD detectors irradiated up to 5e14 n/cm^2 and particle rates up to 10 MHz/cm^2

Outlook

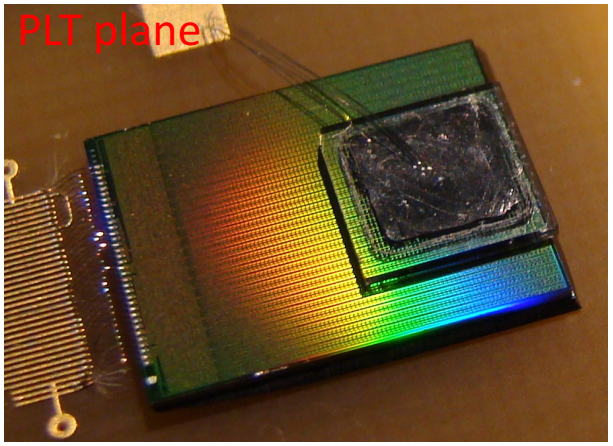
- Study un-irradiated and irradiated 3D devices
- Study 3D device in high rate test beam
- Confirm rate independence of pCVD diamond sensors irradiated to higher doses (up to 2e16 n/cm^2)

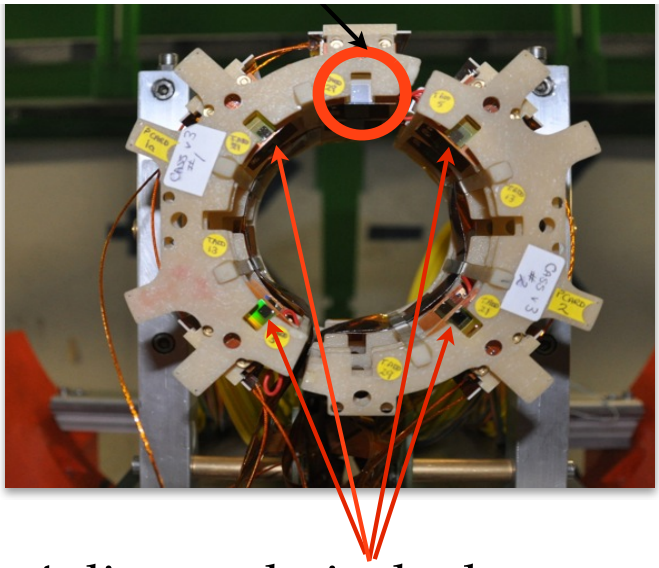
Backup

		silicon [a]		natural diamond [b]	
proton number	[ ]	14		6	
atomic number	[ ]	28.0855	[9]	12.011	[9]
lattice constant	[Å]	5.4310	[10]	3.5668	[10]
mass density	$[\mathrm{g\,cm^{-3}}]$	2.329	[10]	3.515	[10]
cohesive energy	[eV/atom]	4.63	[11]	7.37	[11]
melting point	[K]	1685	[10]	4100 [c]	[10]
band gap	[eV]	1.124	[10]	5.48	[10]
relative dielectric constant [d]	[ ]	11.9	[10]	5.7	[10]
resistivity	[Ωcm]	20×10^3 [e]		$> 10^{13}$	[11]
	[Ωcm]	5×10^{11} [f]	[3.2.3]	$> 10^{14}$ [g]	[3.2.3]
breakdown field	[V/μm]	30		1000	
electron mobility	$[\mathrm{cm^2\,V^{-1}\,s^{-1}}]$			1500..	[12]
		1450	[10]	..2400	[13]
hole mobility	$[\mathrm{cm^2\,V^{-1}\,s^{-1}}]$			1000..	[12]
		≈ 440	[10]	..2100	[13]
electron saturation velocity	[cm/s]			2×10^7	[13]
hole saturation velocity	[cm/s]			10^7	[13]
thermal expansion coefficient	$[10^{-6}\mathrm{K^{-1}}]$	2.59	[10]	0.8..1.0	[14]
thermal conductivity	$[\mathrm{W\,cm^{-1}\,K^{-1}}]$	1.4		20..23	[14]
energy to create *eh*-pair	[eV]	3.6	[15, 16]	13	[13, 17]
radiation length	[cm]	9.4	[9]	12.03	[3.75]
specific ionization loss	[MeV/cm]	3.9	[3.3.1]	6.2	[3.3.1]
ave. no. of *eh*-pairs/*mip*	[pairs/100 μm]	9000	[3.3.5]	3600	[11]
ave. no. of *eh*-pairs/*mip*	[pairs/300 μm]	27000	[3.3.5]	11850	[3.3.5]

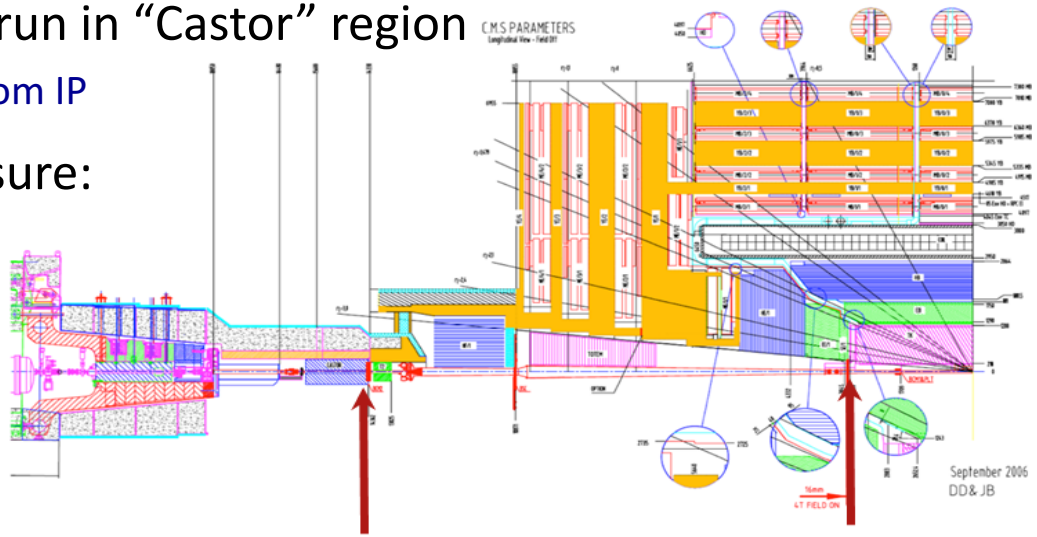
CMS PLT – Pilot Run Version

- Dedicated stand-alone **P**ixel **L**uminosity **T**elescope
  - Aim to provide high precision bunch-by-bunch luminosity measurement
  - Using “FastOr” readout
- Array of eight 3-plane telescopes in CMS
- Single-crystal diamond pixel sensors by DDL/E6
  - Area 4.7 mm x 4.7 mm, thickness 500 µm
- Pixel readout for tracking and minimization of systematics
  - 100 µm x 150 µm pixel pitch
- 2012 Pilot run in “Castor” region
  - 14.5 m from IP
- Total exposure:
  20 fb^{-1}



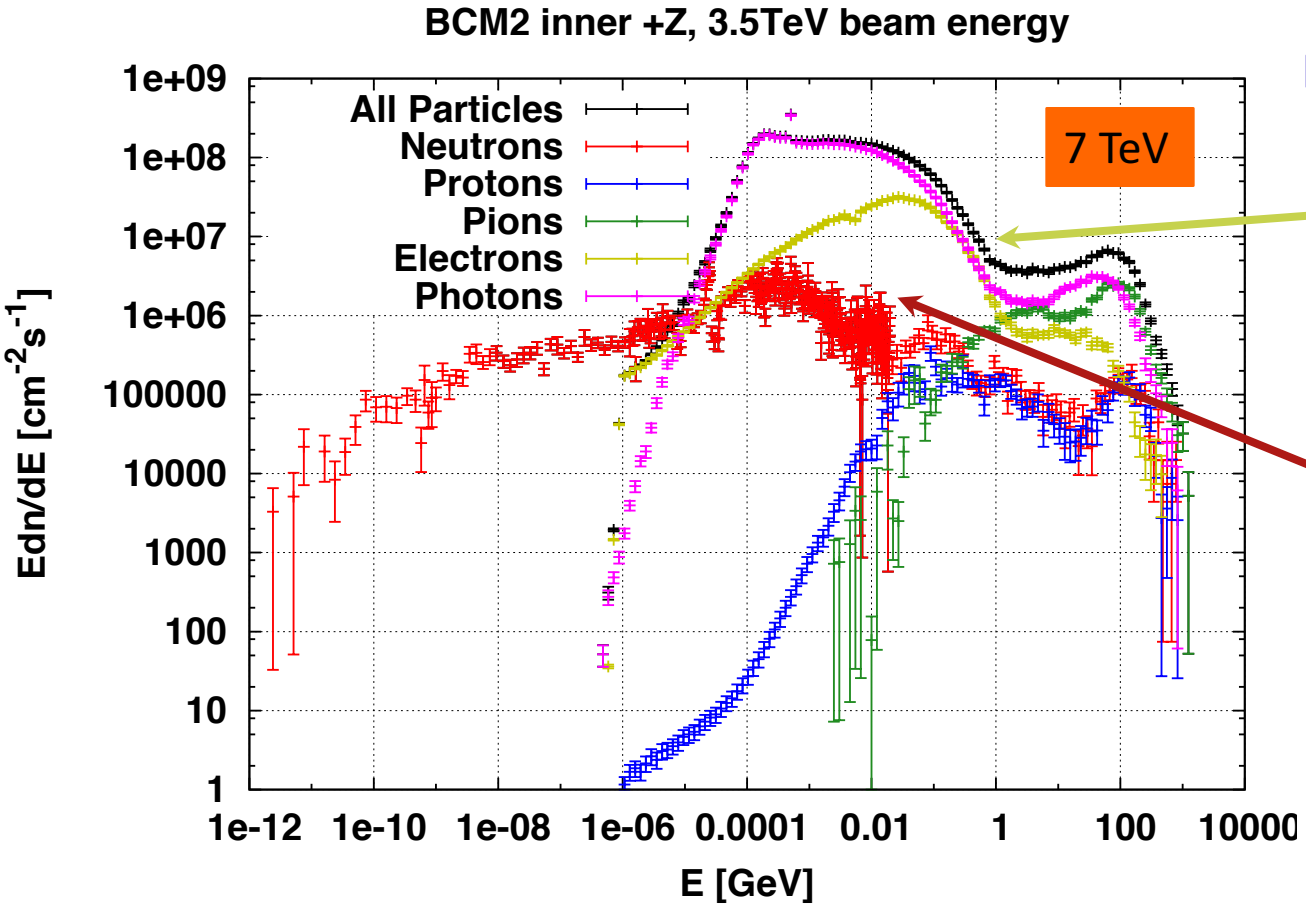


4 diamond pixel telescopes



Pilot run location Final location

FLUKA Study for CASTOR region



Fluences over whole 2012 run

20 fb^{-1}

Charged hadrons: 4 x 10^{13} cm^{-2}

(mostly pions above 1 GeV)

Neutrons: 5 x 10^{13} cm^{-2}

(mostly 100 keV - 10 MeV)

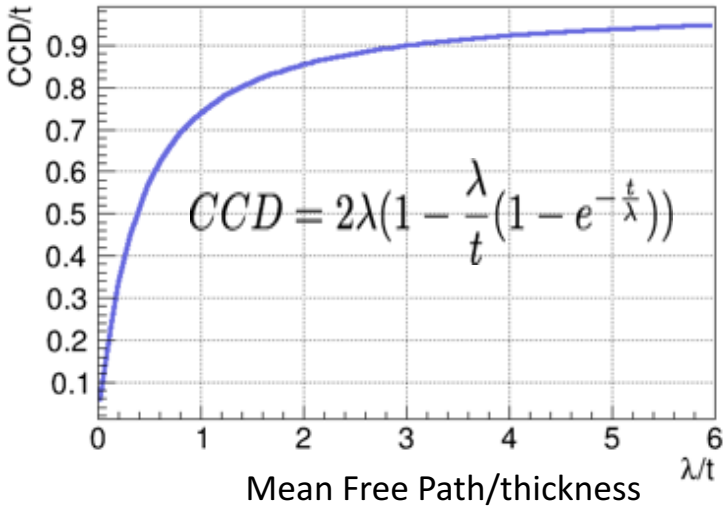
M. Guthoff, Ph.D. Thesis
Univ. Karlsruhe (2014)

FLUKA Simulation suggests the scale of the doses of about 5x $10^{13}/cm^2$ each for charged hadrons and neutrons

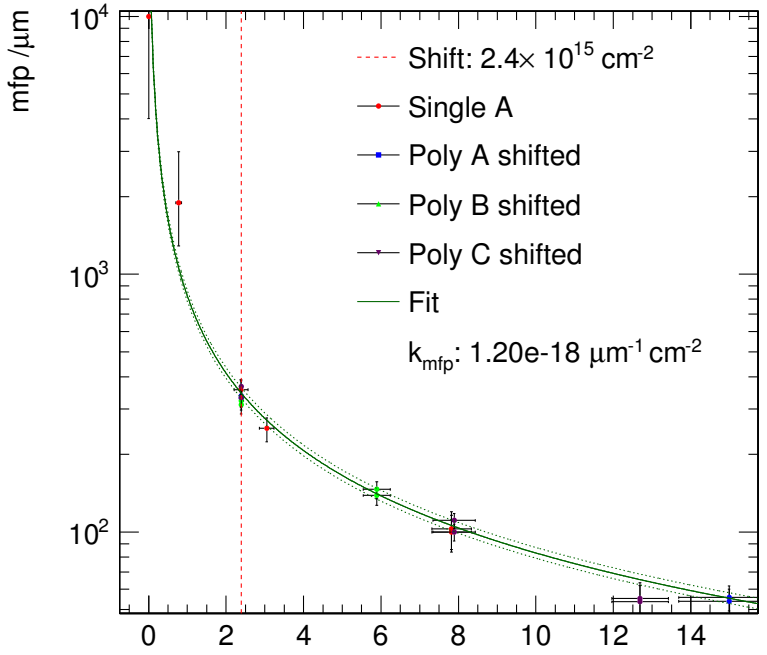
Radiation hardness of diamond

Model: $\frac{1}{\lambda} = \frac{1}{\lambda_0} + k_\lambda \Phi$ $k_{24\ GeV\ p} \sim 0.62 \pm 0.07 \times 10^{-18}\ \mu m^{-1} cm^{-2}$

particle	energy	relative k
proton	24 GeV	1
	800 MeV	2.0 (was 1.7)
	70 MeV	2.7
	25 MeV	4.2
pion	300 MeV/c	2.9

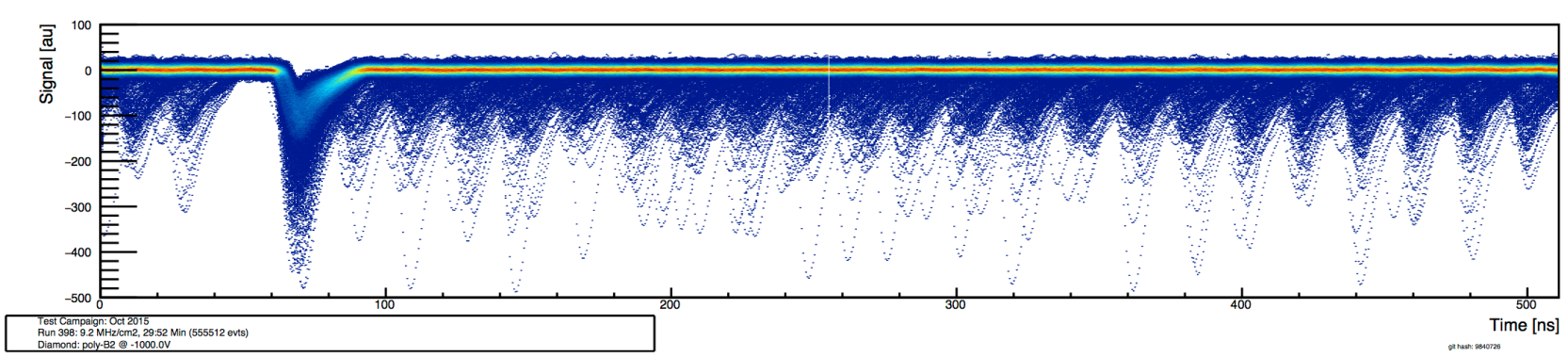


800 MeV protons

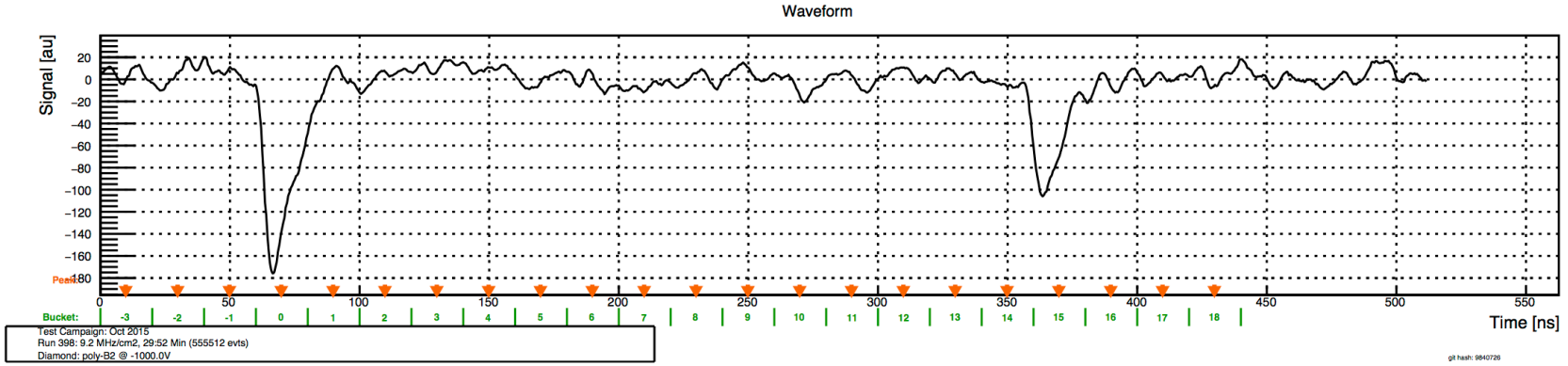


Diamond traces

Many traces overlap



Sample trace



Peak timing