Results from the Pilot Runs and Beam Tests of Diamond Pad & Pixel Detectors

Harris Kagan
Ohio State University
on behalf of
the RD42 collaboration

Outline

- CMS Experience with a diamond pixel detector (PLT)
- PSI Test Beam: Pulse height vs rate study
  - pad detector results
  - pixel detector results
- Conclusions

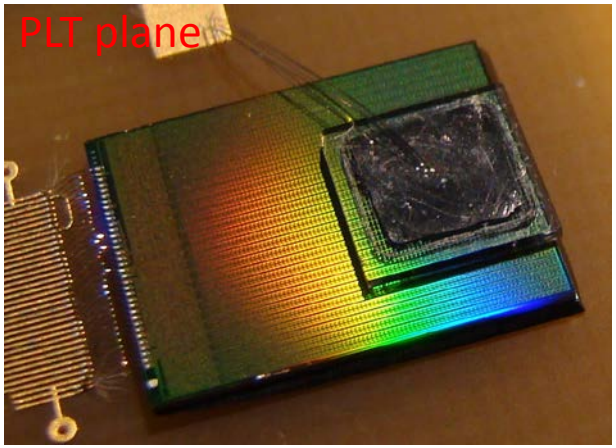
RESMDD 2014, Firenze, Italy

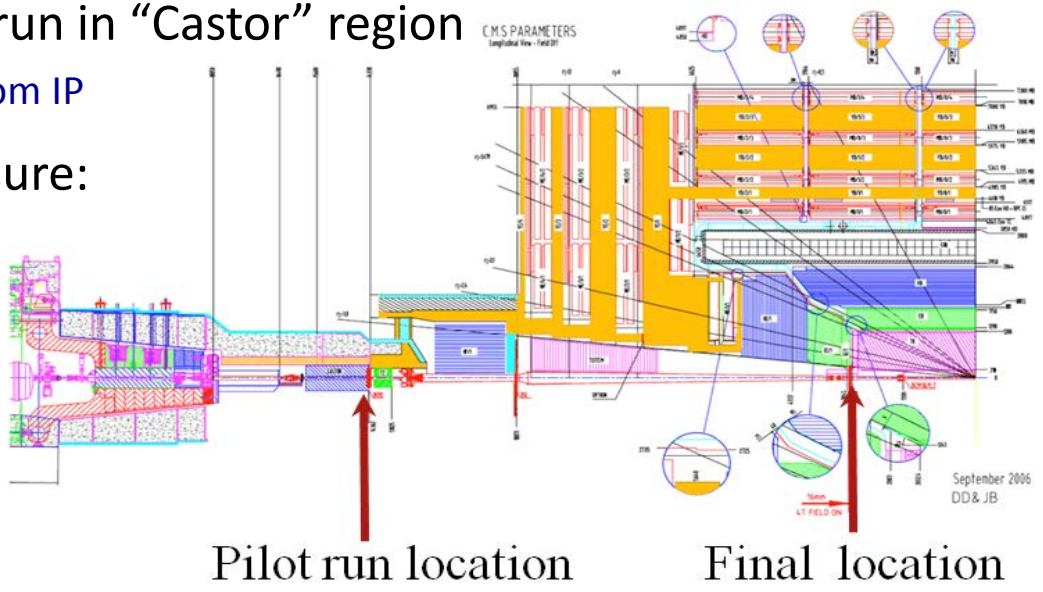
Experience with the PLT during pilot run

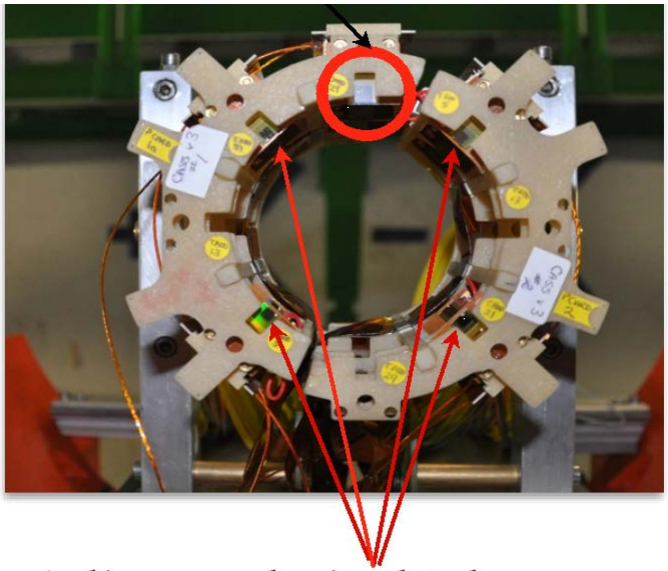
For original details see talk by Dean Hidas at Pixel 2012
and RD42 LHCC Status Report 2014

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}

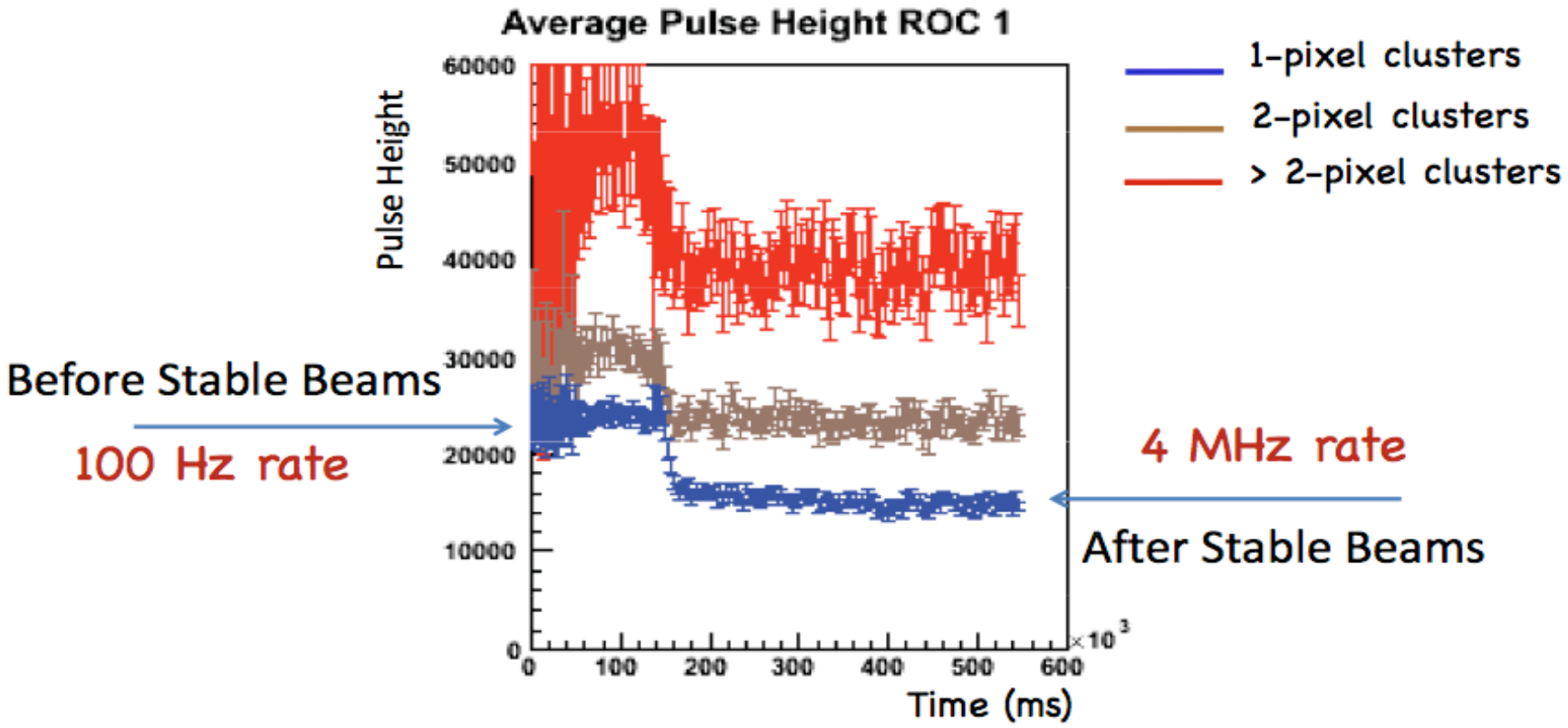






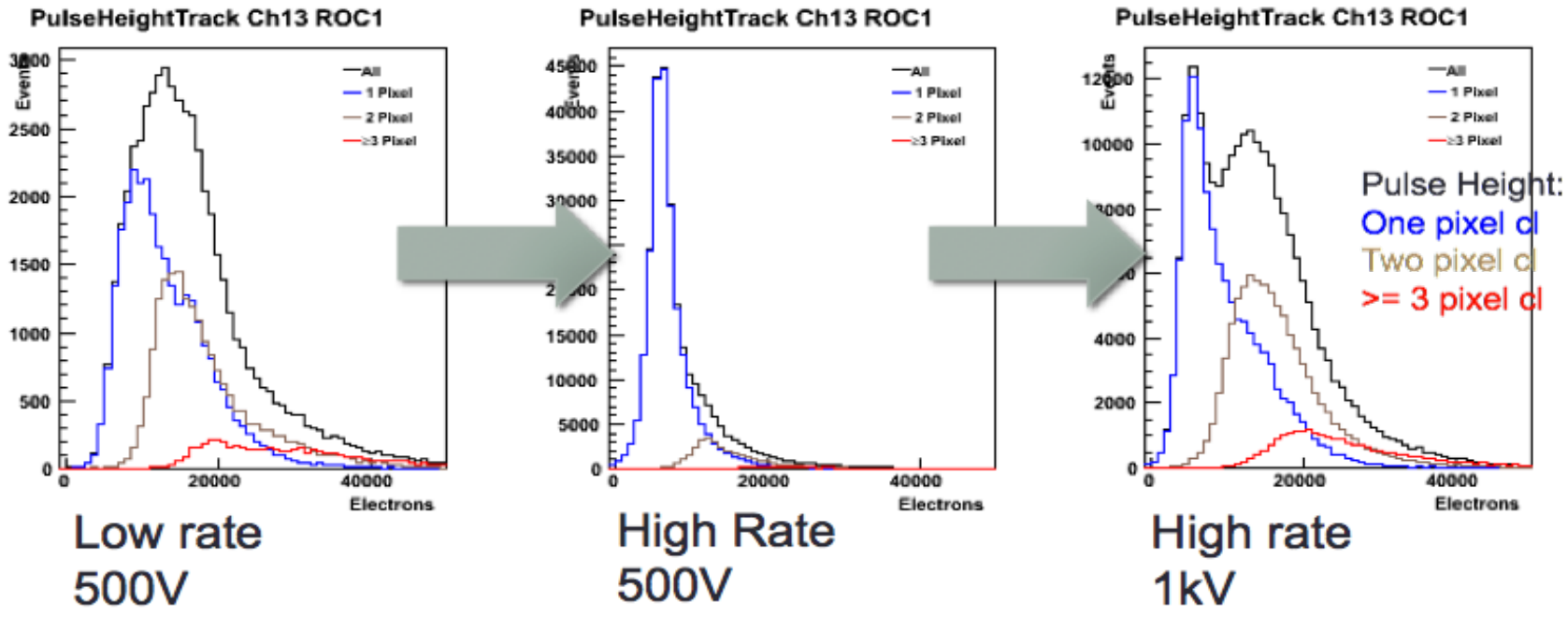
Diamond PLT Pulse Height Dependence on Rate

- 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 in CASTOR region

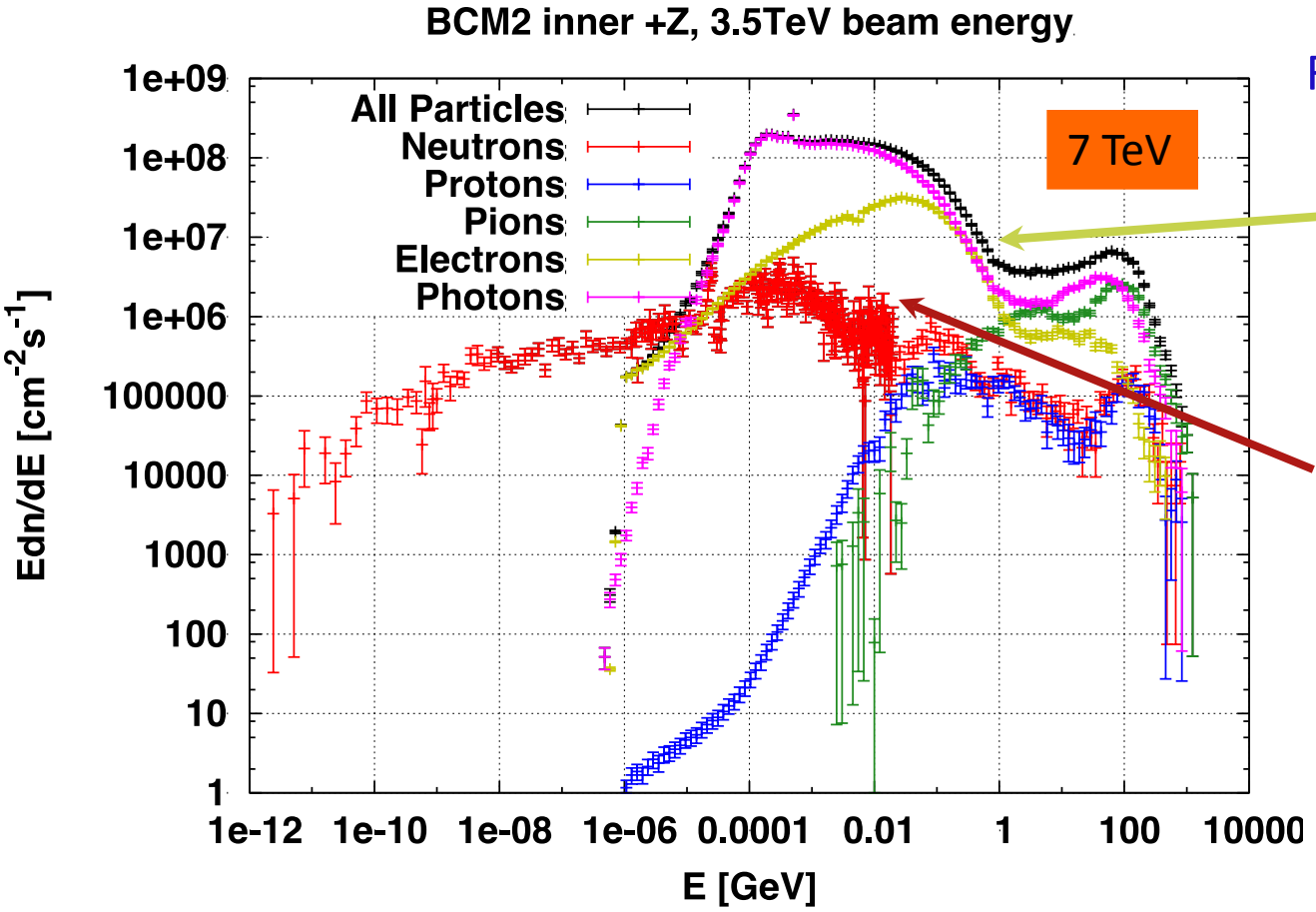


Diamond PLT Pulse Height Dependence on Rate

- 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 in CASTOR region
  - Raising HV recovers some of the pulse height => electrostatics



FLUKA Study for CASTOR region



Fluence 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, to appear)

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

Summary of RD42 Results

For original details see the RD42 LHCC Status Report 2014

RD42 Collaboration (2014)

The 2014 RD42 Collaboration

M. Artuso[24], F. Bachmair[28], L. Bäni[28], M. Bartosik[3], V. Bellini[2], V. Belyaev[15], B. Bentele[23], E. Berdermann[8], P. Bergonzo[14], A. Bes[32], J-M. Brom[10], M. Bruzzi[5], M. Cerv[3], C. Chau[19], G. Chiodini[31], D. Chren[22], V. Cindro[12], G. Claus[10], J. Collot[32], S. Costa[2], J. Cumalat[23], A. Dabrowski[3], R. D'Alessandro[6], W. de Boer[13], B. Dehning[3], D. Dobos[3], W. Dulinski[10], V. Eremin[9], R. Eusebi[29], G. Forcolin[26], J. Forneris[18], H. Frais-Kölbl[4], K.K. Gan[16], M. Gastal[3], M. Goffe[10], J. Goldstein[20], A. Golubev[11], L. Gonella[1], A. Gorišek[12], L. Graber[27], E. Grigoriev[11], J. Grosse-Knetter[27], M. Guthoff[3], I. Haughton[26], D. Hidas[17], D. Hits[28], M. Hoeferkamp[25], T. Hofmann[3], J. Hosslet[10], J-Y. Hostachy[32], F. Hügging[1], H. Jansen[3], J. Janssen[1], H. Kagan[16,◇], K. Kanxheri[33], G. Kasieczka[28], R. Kass[16], F. Kassel[13], M. Kis[8], G. Kramberger[12], S. Kuleshov[11], A. Lacoste[32], S. Lagomarsino[6], A. Lo Giudice[18], C. Maazouzi[10], I. Mandic[12], C. Manfredotti[18], C. Mathieu[10], N. McFadden[25], G. McGoldrick[19], M. Menichelli[33], M. Mikuž[12], A. Morozzi[33], J. Moss[16], R. Mountain[24], S. Murphy[26], G. Oakham[21], A. Oh[26], P. Olivero[18], G. Parrini[6], D. Passeri[33], M. Pauluzzi[33], H. Pernegger[3], R. Perrino[31], F. Picollo[18], M. Pomorski[14], R. Potenza[2], A. Quadt[27], A. Re[18], G. Riley[30], S. Roe[3], M. Sapinski[3], M. Scaringella[5], S. Schnetzer[17], T. Schreiner[4], S. Sciortino[6], A. Scorzoni[33], S. Seidel[25], L. Servoli[33], A. Sfyrla[3], G. Shimchuk[11], S. Smith[16], B. Sopko[22], V. Sopko[22], S. Spagnolo[31], S. Spanier[30], K. Stenson[23], R. Stone[17], C. Sutera[2], A. Taylor[25], M. Traeger[8], D. Tromson[14], W. Trischuk[19,◇], C. Tuve[2], L. Uplegger[7], J. Velthuis[20], N. Venturi[19], E. Vittone[18], S. Wagner[23], R. Wallny[28], J.C. Wang[24], P. Weilhammer[3], J. Weingarten[27], C. Weiss[3], T. Wengler[3], N. Wermes[1], M. Yamouni[32], M. Zavrtanik[12]

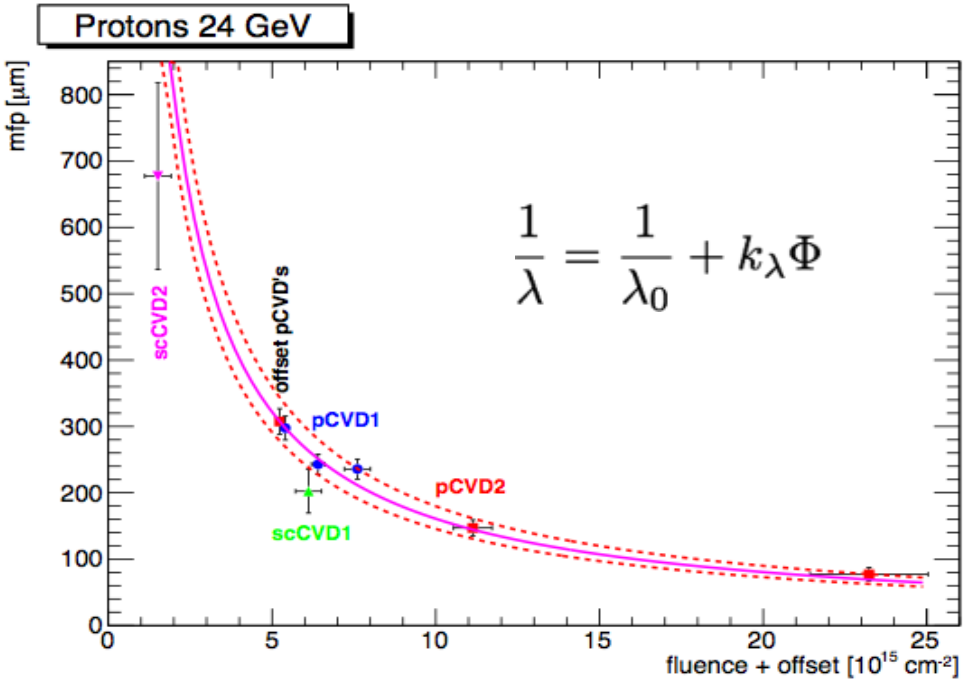
128 Participants

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

33 Institutes

Summary of RD42 test beam results

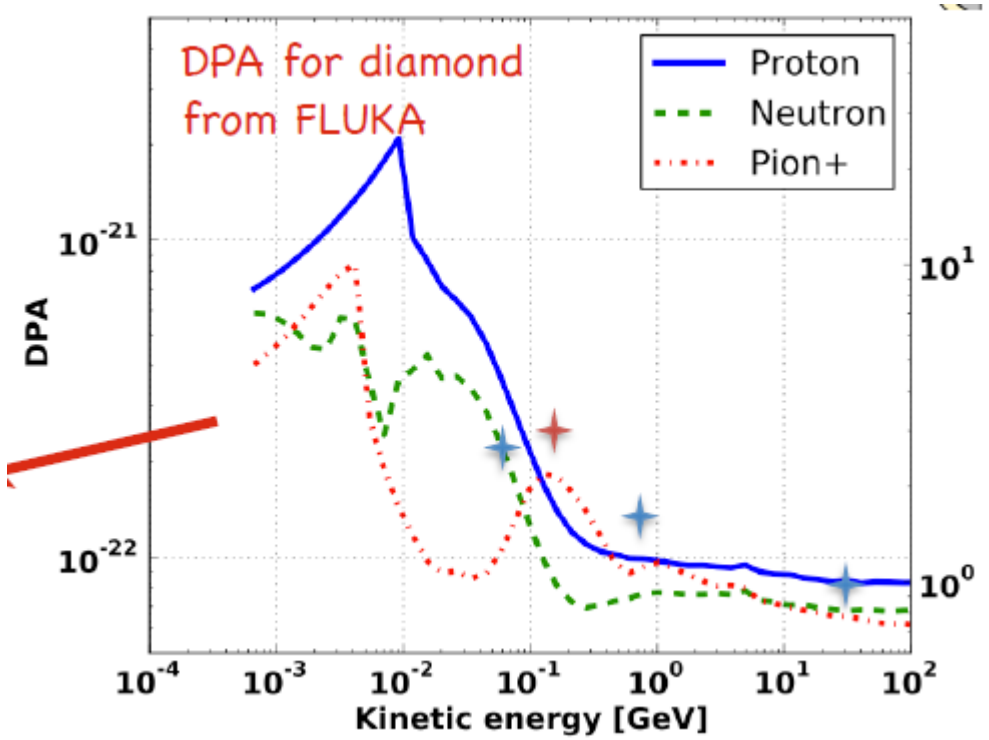
- Damage factor determined from change in pule height vs irradiation fluence
  - multiple test beam campaigns in CERN SPS
- k_λ (24 GeV p) ~ $0.62 \pm 0.07 \times 10^{-18}$ $\mu m^{-1} cm^{-2}$
  - ~10% uncertainty on relative k_λ



particle	energy/momentum	relative k to 24 GeV p
p	24 GeV	1
p	800 MeV	1.7
p	70 MeV	2.7
p	25 MeV	4.2
π	300 MeV/c	2.9

Comparison to FLUKA DPA Study

- DPA based on Displacement Energy for Diamond of 43.3 eV
  - M. Guthoff et. al. arXiv:1308.5419
- Reasonable agreement between RD42 Data and Simulation
  - According to this scaling we expect only 10% signal loss in the PLT from dose received in CASTOR region



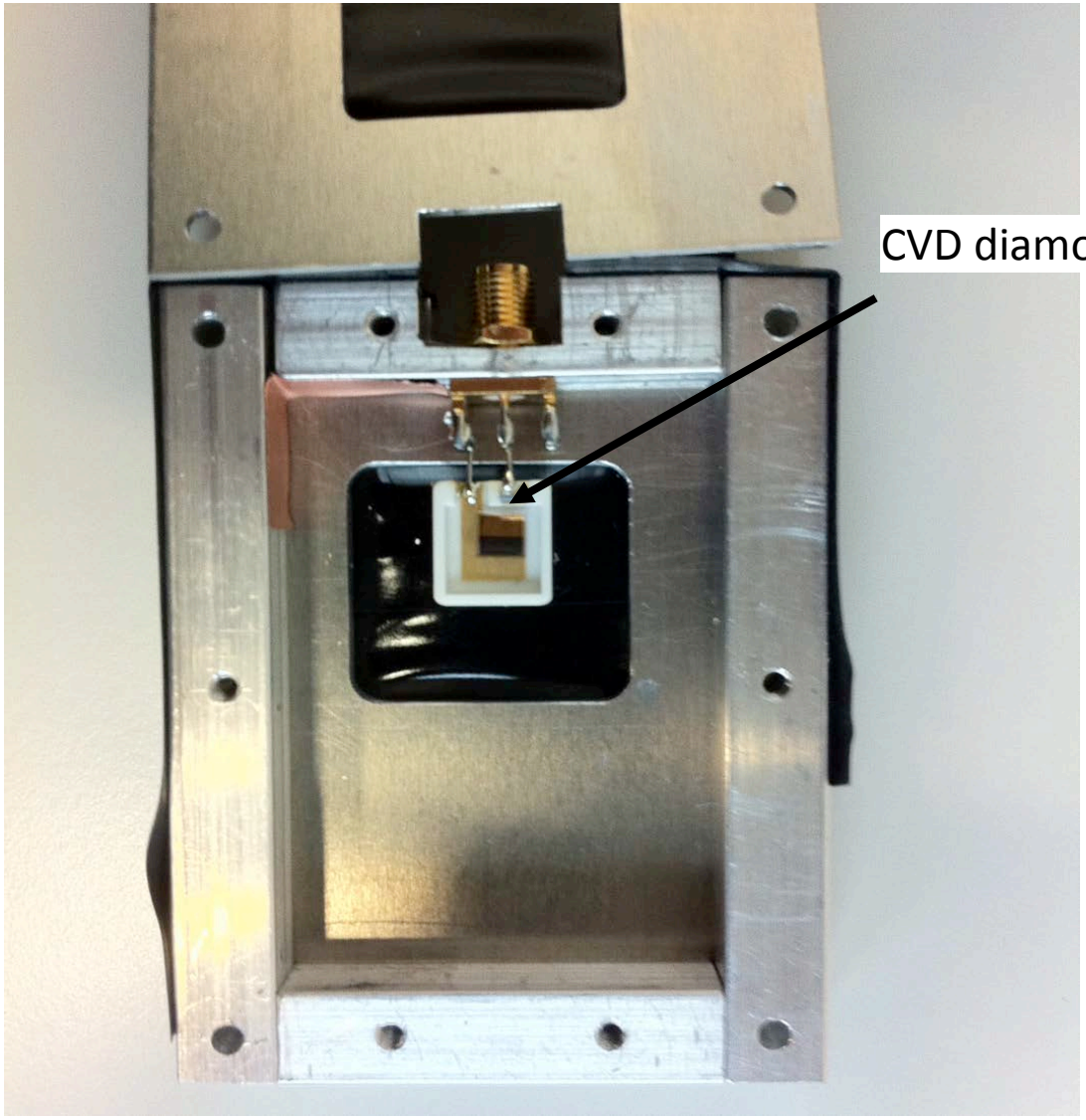
RD42 Test Beams at PSI

PSI Test Beam Campaign

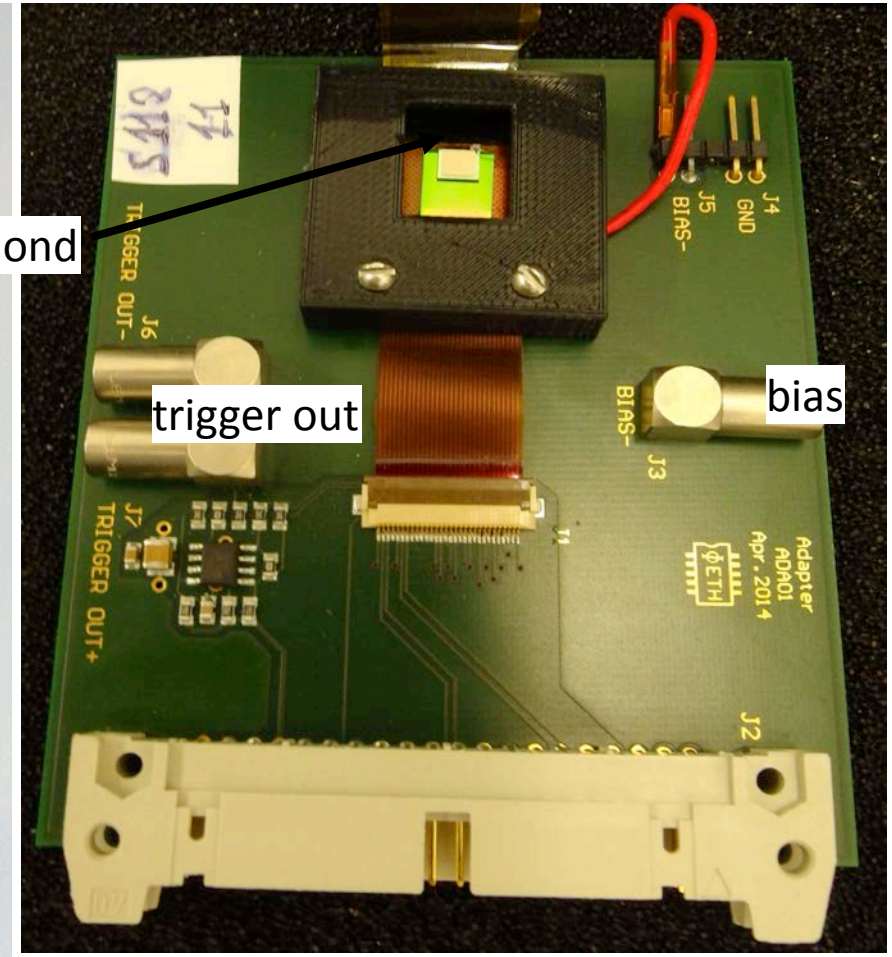
- Several successful test beam campaigns (Dec 2013, May 2014, July 2014)
  - Some Results up to May test beam shown here
- Pad detectors:
  - study sensors w/o threshold effect
  - Quick detector fabrication and turn around
- Pixel detectors:
  - Study effects of pixel threshold
  - Study effects of pixel charge sharing
- Samples:
    - E6 scCVD non-irradiated (Reference) [pad, pixel]
    - E6 scCVD neutron irradiated (5e13), [pad, pixel]
    - E6 scCVD proton irradiated (5e13), [pad]
    - E6 scCVD castor-irradiated (PLT pilot run) [pad, pixel]
    - pCVD non-irradiated [pad, pixel]
    - pCVD neutron irradiated (pad 5e15, pixel 1e14)
  - Tests
    - Pulse height versus rate scan [pad 1-3 MHz/cm^2, pixel up to 10 MHz/cm^2]
    - Long term pulse height stability at high rate [pad, pixel]
    - Positive and negative bias polarities [pad]

DUT devices

Pad detector box



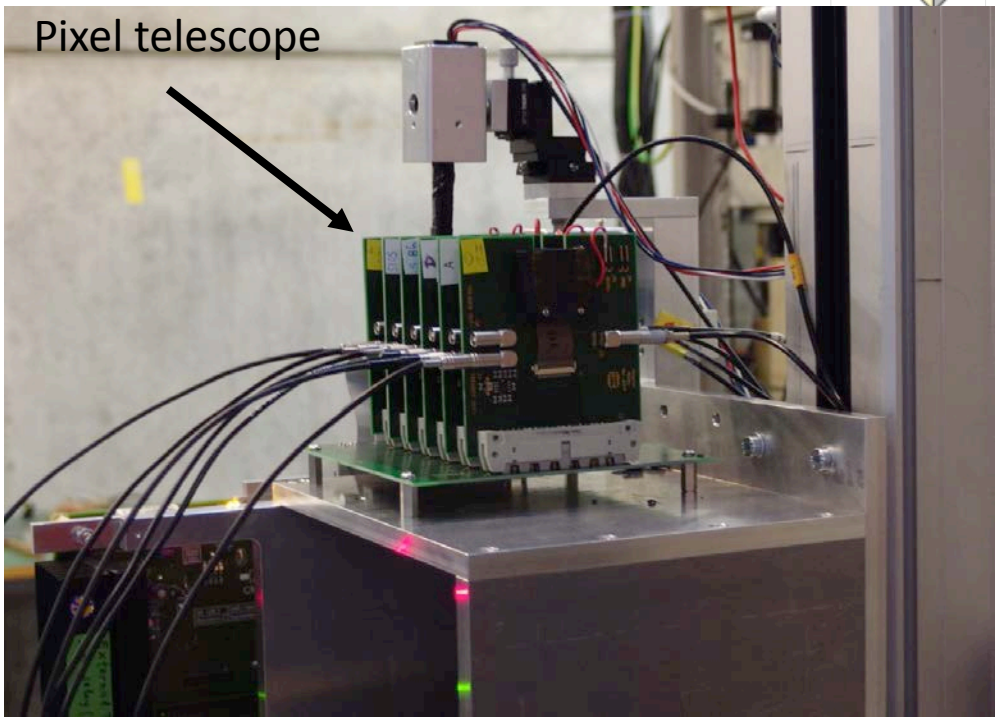
Pixel detector plane



- Readout with PSI46v2 chip
  - analog readout
  - fastOr trigger out at 40 MHz

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



Pixel test setup with masked pixel trigger

- 6 Tracking planes
  - 2 Trigger planes
  - 4 planes under test

PSI Test beam setup

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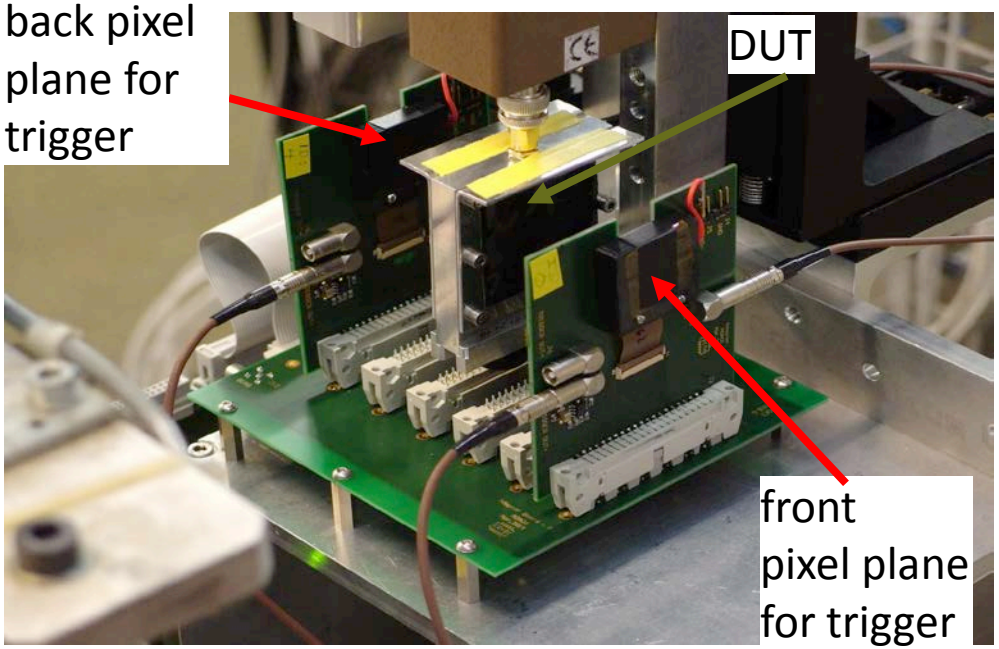
Pad test setup

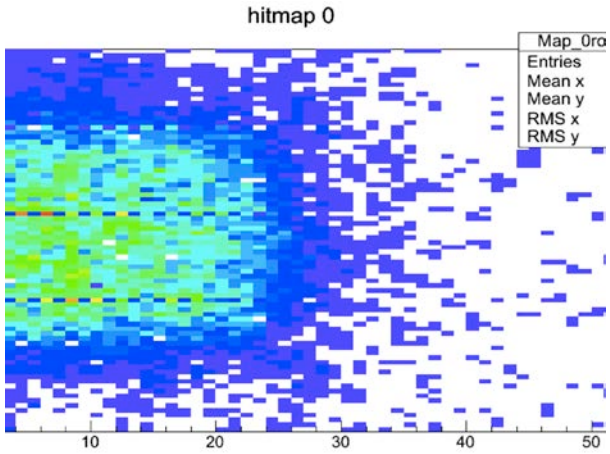


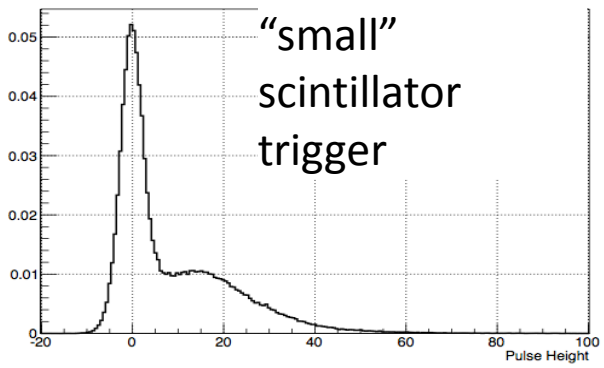
Pad test setup with masked pixel trigger

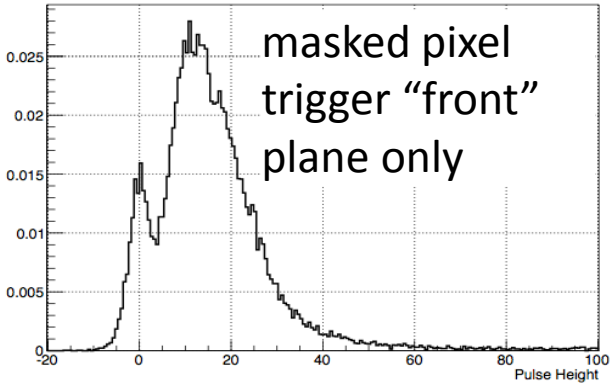
- 2 Tracking/Trigger planes
  - 2 Trigger planes
  - 1 plane under test

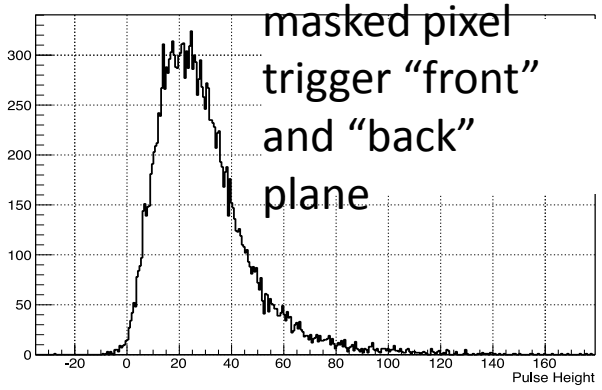
Masked pixel trigger

- Using diamond as a signal to pixel detector to find a “shadow” of the diamond
  - Mask all pixels outside the diamond shadow
- Use “FastOr” of the masked pixel detector as a trigger for the diamond
  - **Large improvement in signal to background ratio**
- In later runs both front and back trigger planes were masked
  - Pedestal events practically eliminated





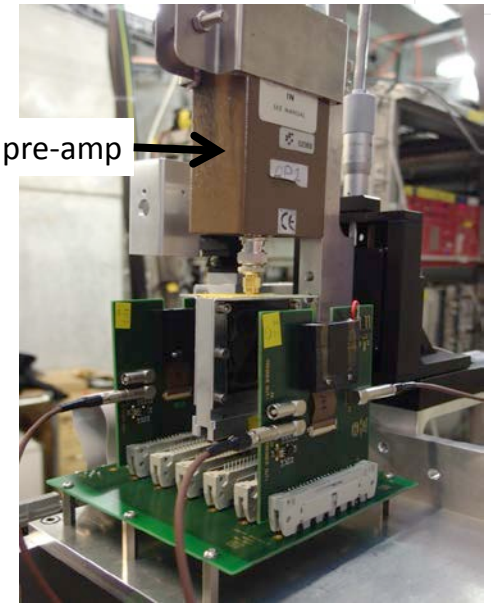




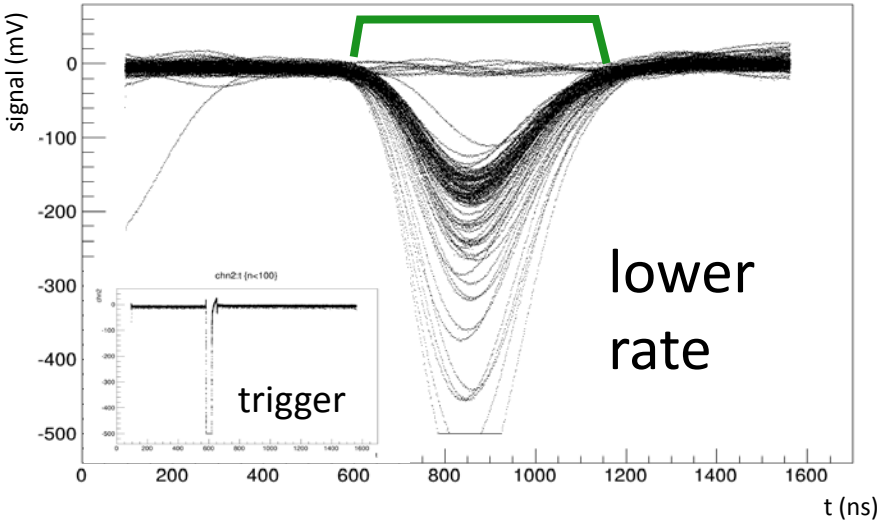
Pad Detector Analysis Results

Pad Analysis Setup

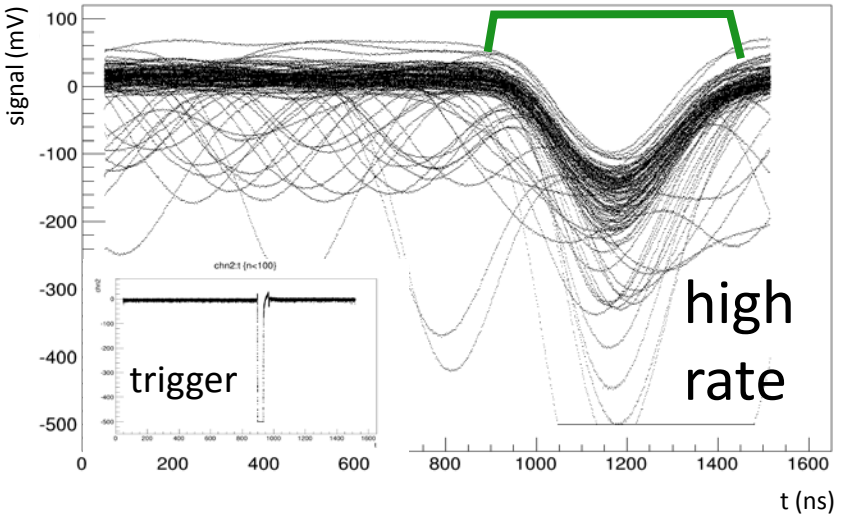
- Pulse height amplified with Ortek 142A pre-amp and Ortek 450 shaping amplifier
  - 300 ns peaking time
- Digitization performed with DRS4 evaluation board
  - 1024 sampling points
  - slowest sampling speed 0.7 GSPS
- Integration region is centered on signal
  - Constant delay with respect to the trigger for all runs



integration region

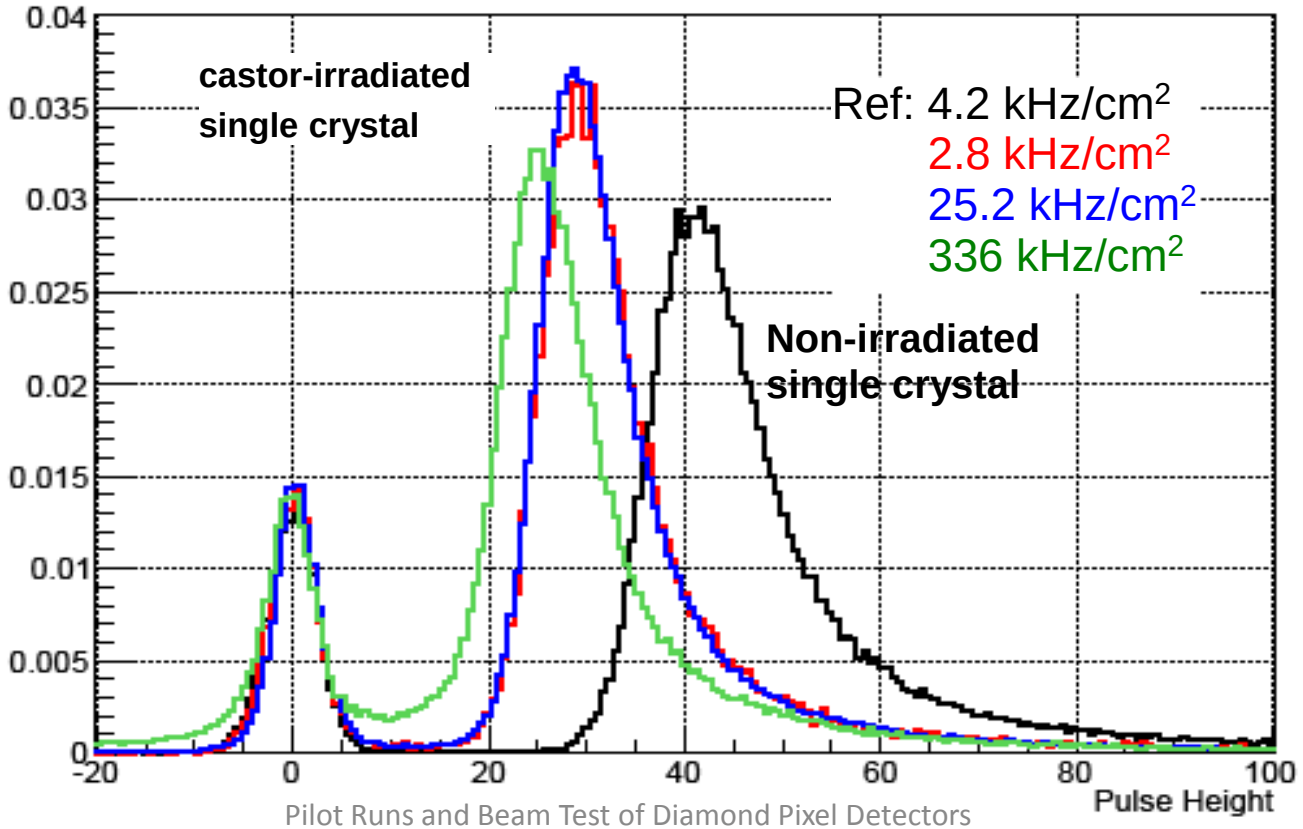


integration region



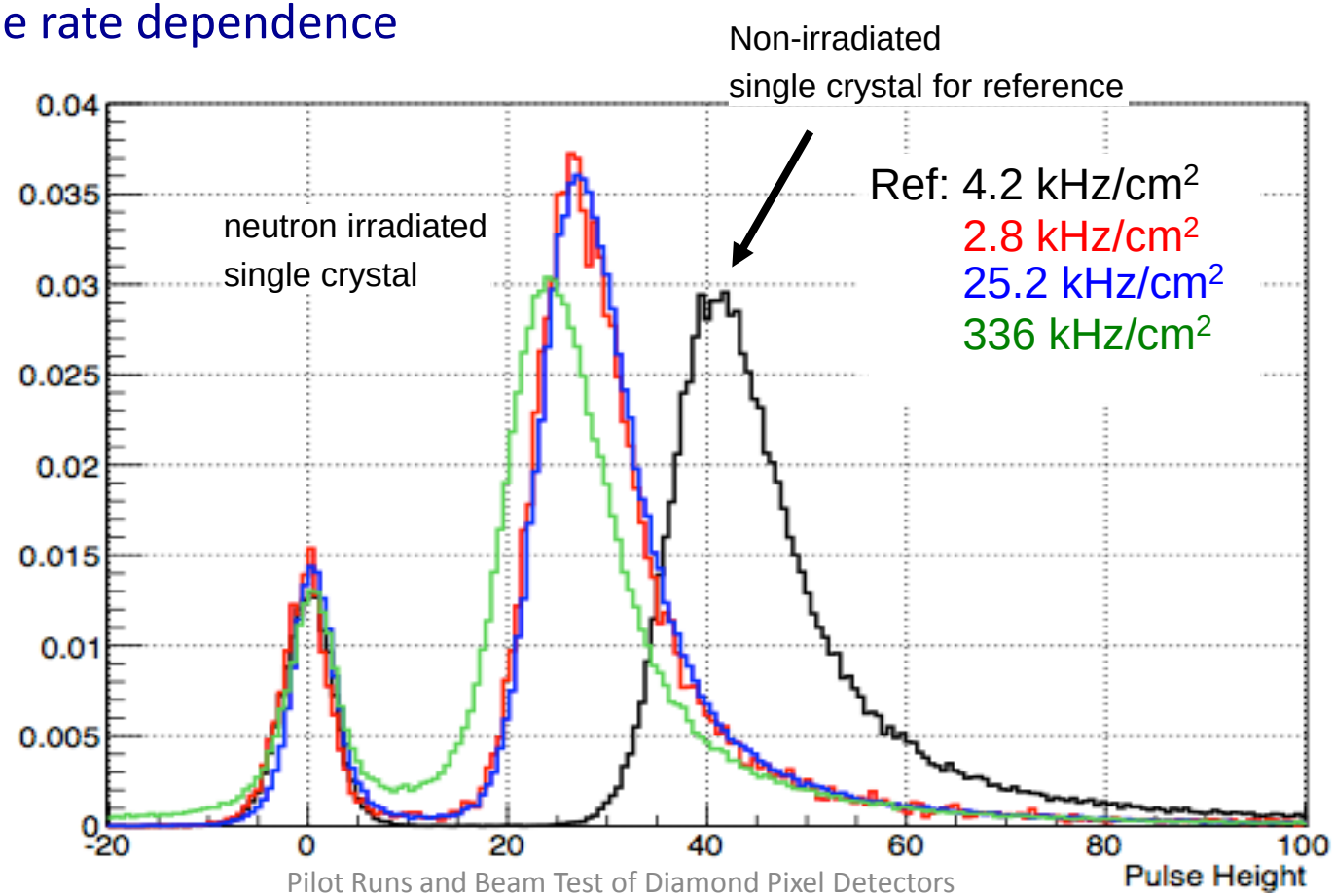
CASTOR single crystal diamond

- scCVD diamond produced by Element 6
- FLUKA estimation of dose 5×10^{13} /cm^2 of each charged hadrons and neutrons
- Run at 500V w/ one plane masked pixel trigger
- Noticeable rate dependence



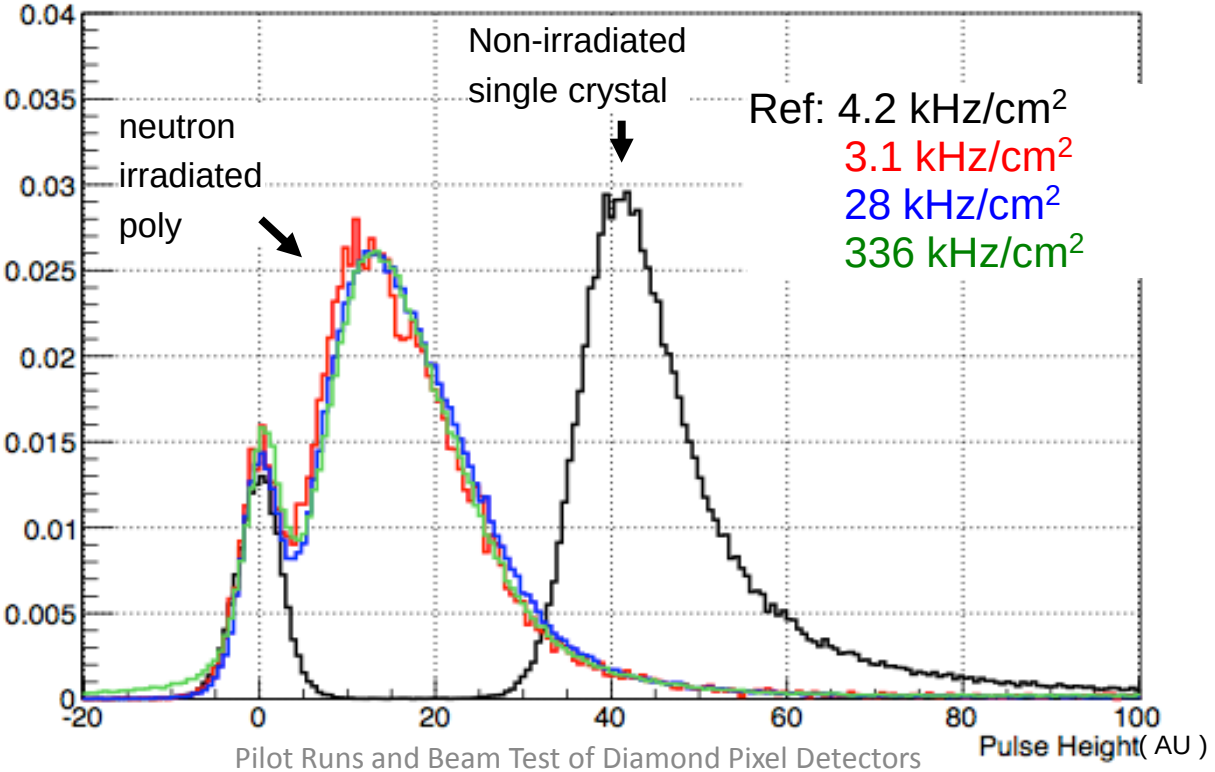
n-irradiated single crystal diamond

- scCVD diamond produced by Element 6
- Irradiation dose - 5×10^{13} n/cm^2 at JSI, Ljubljana
- Runs at 500 V with masked pixel trigger
- Noticeable rate dependence



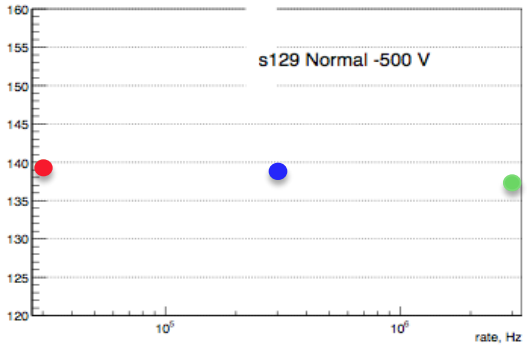
n-irradiated Poly-crystalline diamond

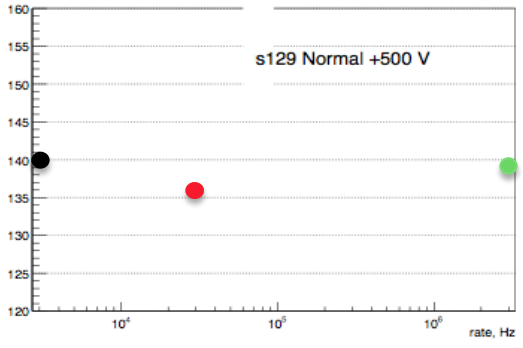
- Irradiation dose - 5x10^{13} n/cm^2 at JSI, Ljubljana
- Runs are at 500 V with masked pixel trigger
  - Use non-irradiated single crystal for calibration
    - Mean for poly: 18.9 (CCD ~ 200 um)
    - Mean for sc: 47.2 (CCD ~500 um)
- **No noticeable rate dependence**

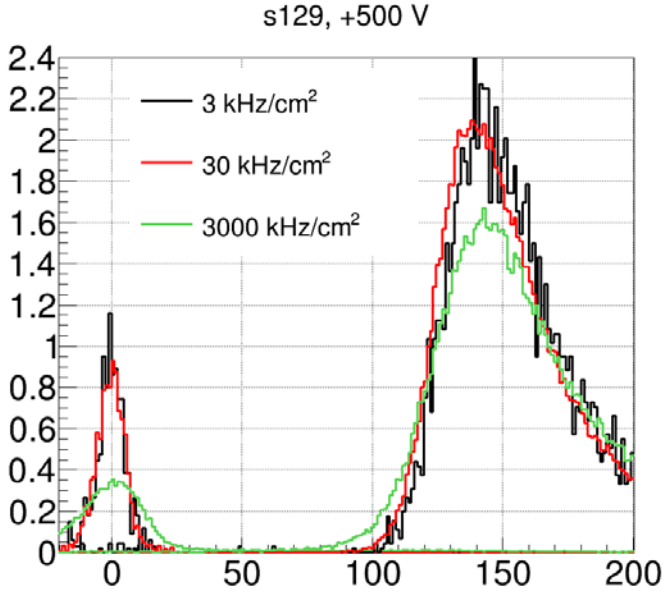


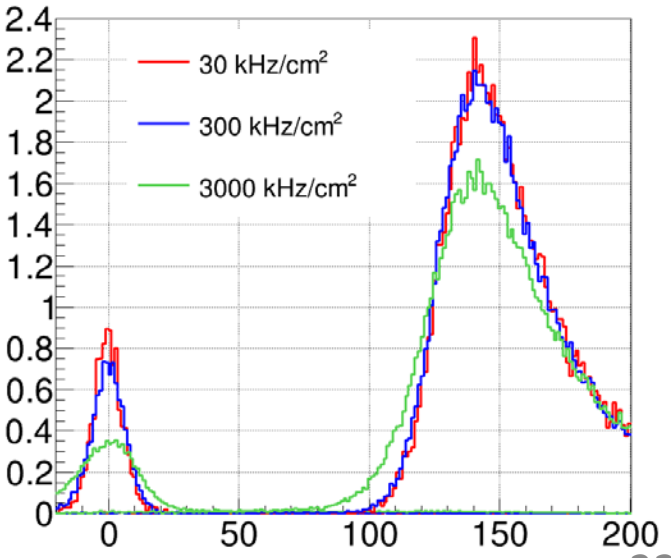
Polarity dependence: Non-irradiated single crystal (Ref.)

- Non-irradiated.
- Test polarity dependence:
  - Bias HV +/- 500 V @ 3, 30, 300, 3000 kHz
- Baseline is found to be rate dependent:
  - Pedestals are fitted with Gaussian at the peak +/-RMS/2
  - the mean of the pedestal shifted to 0 (+/- bin width)
  - Both pedestal and pulse height distribution for the same rate are shifted by the same amount
- Pulse height distribution are fitted with a convolution of Gaussian and Landau.
  - The MP of the Landau distribution is plotted
  - Error is the error from the fit
    - Take spread as systematics uncertainty
- No Polarity dependence observed



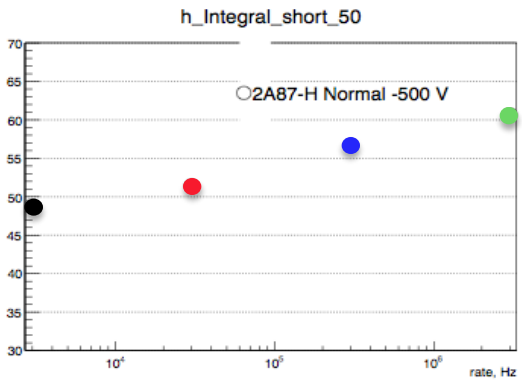


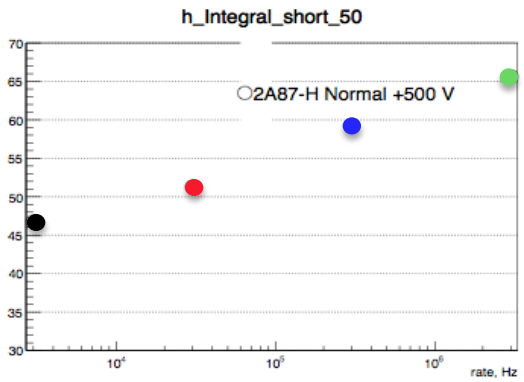


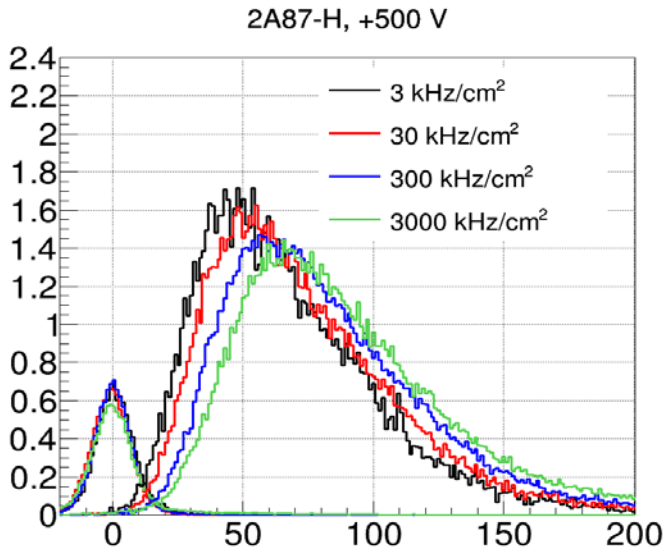


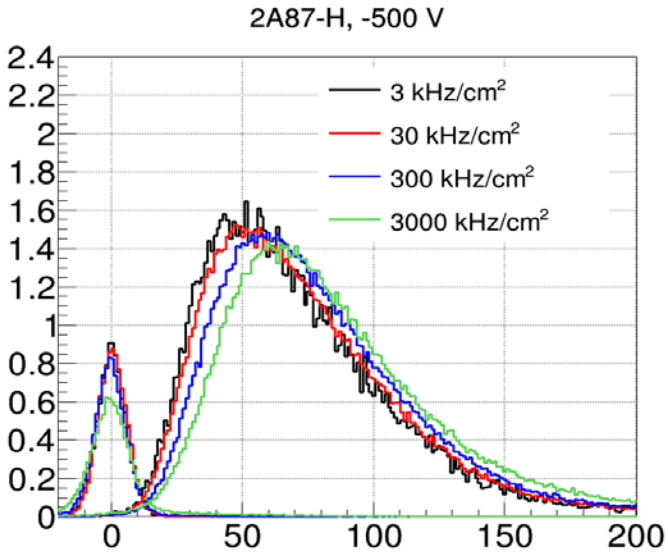
Polarity dependence: Non-irradiated poly

- Non-irradiated.
- Test polarity dependence:
  - Bias HV +/- 500 V @ 3, 30, 300, 3000 kHz
- Baseline is found to be rate dependent:
  - Pedestals are fitted with Gaussian at the peak +/-RMS/2
  - the mean of the pedestal shifted to 0 (+/- bin width)
  - Both pedestal and pulse height distribution for the same rate are shifted by the same amount
- Pulse height distribution are fitted with a convolution of Gaussian and Landau.
  - The MP of the Landau distribution is plotted
  - Error is the error from the fit
- Stronger rise in pulse height: pumping effect



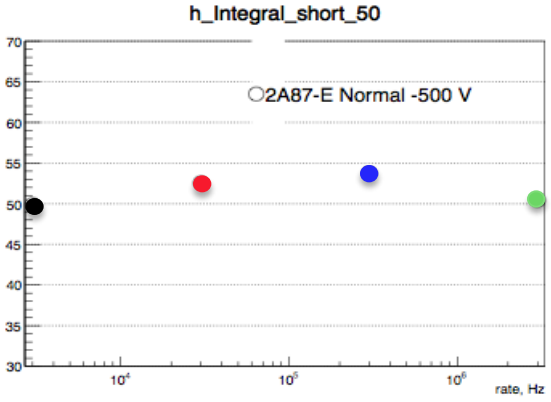


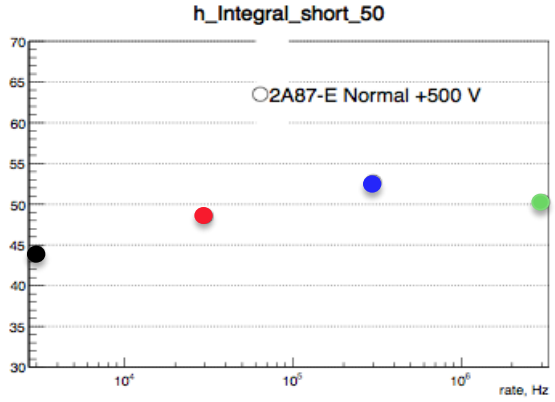


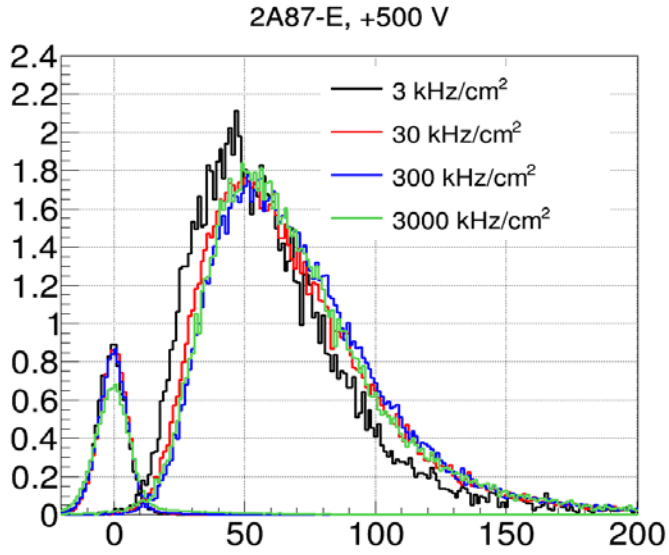


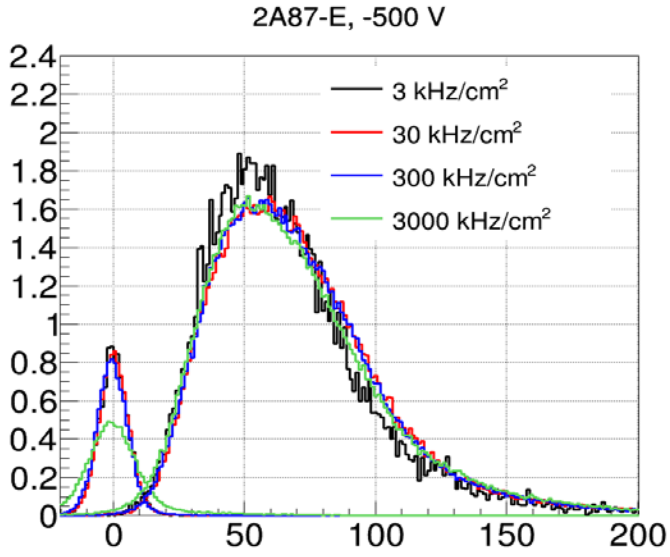
Polarity dependence: Neutron irradiated poly

- Irradiation dose $5x10^{13}$ n/cm ^{2}
- Test polarity dependence:
  - Bias HV +/- 500 V @ 3, 30, 300, 3000 kHz
- Baseline is found to be rate dependent:
  - Pedestals are fitted with Gaussian at the peak +/-RMS/2
  - the mean of the pedestal shifted to 0 (+/- bin width)
  - Both pedestal and pulse height distribution for the same rate are shifted by the same amount
- Pulse height distribution are fitted with a convolution of Gaussian and Landau.
  - The MP of the Landau distribution is plotted
  - Error is the error from the fit
- Slight rise in pulse height - pumping effect ?



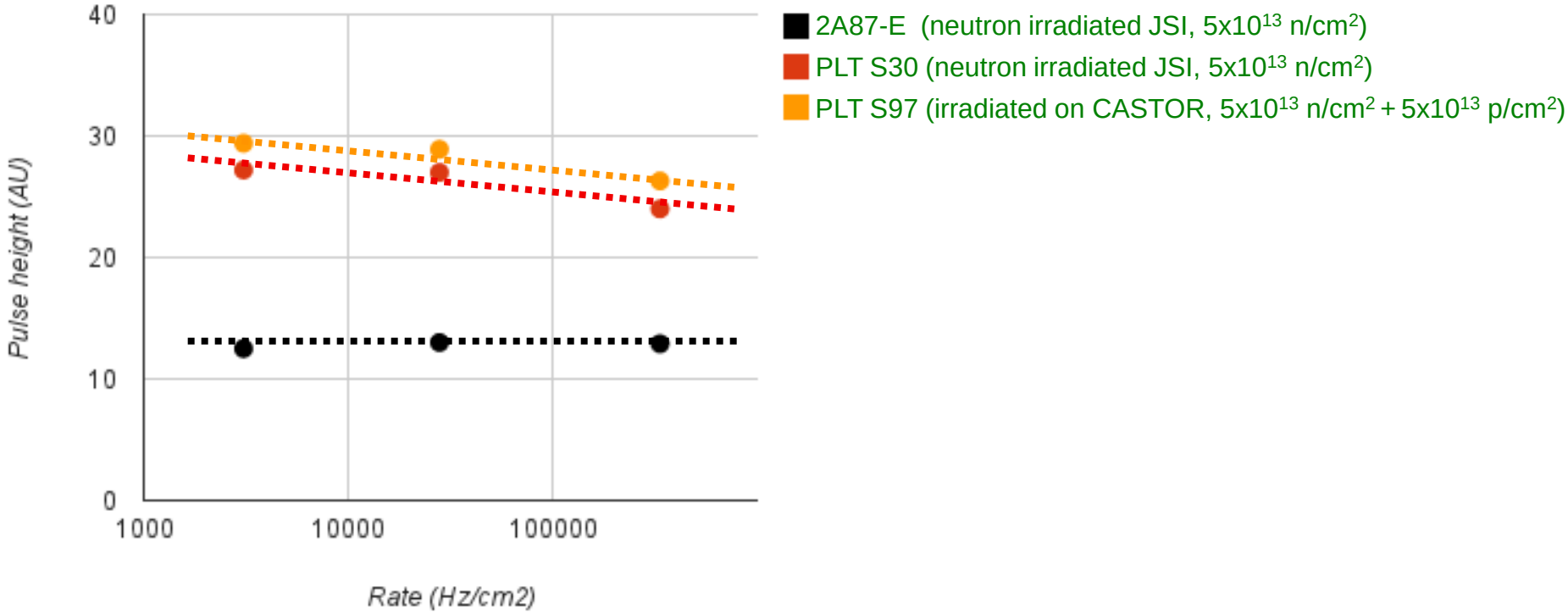






Preliminary summary rate dependence

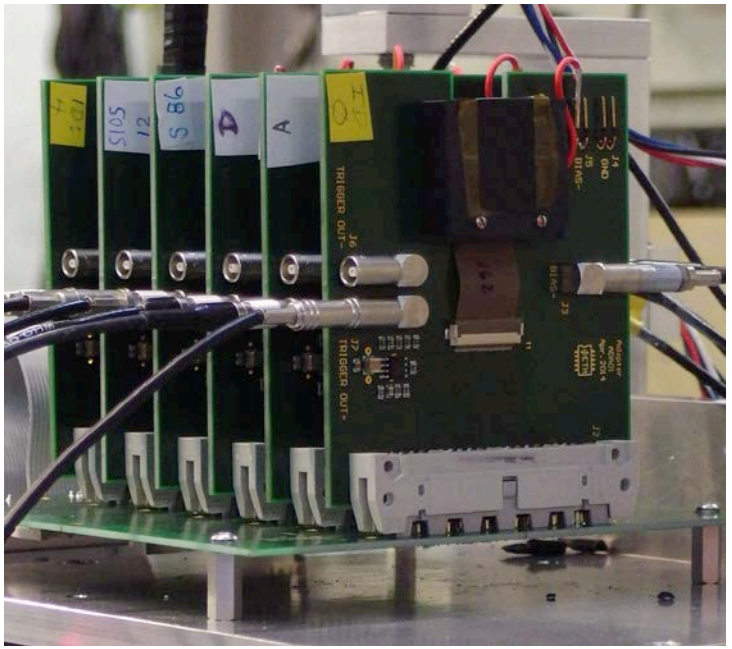
- Plots for Most Probable PH vs Rate
- CASTOR single crystal CVD diamonds (E6) show rate dependence
- Irradiated single crystal CVD diamonds (E6) show rate dependence
- Irradiated poly CVD diamond does NOT show rate dependence



Pixel Detector Analysis Results

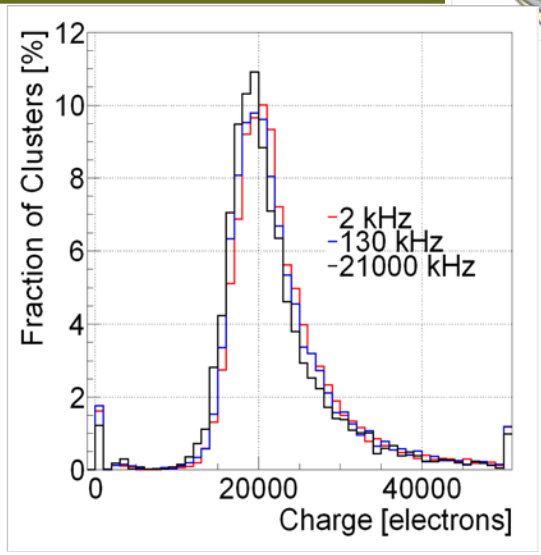
Pixel Analysis Setup

- Two 6-plane telescope arrangements were tested
  - Si : non-irradiated poly-CVD 1 : n-irradiated poly-CVD 1e14 : single-crystal-CVD castor irradiated ~1e14 : single-crystal-CVD non-irradiated : Si
  - Si : non-irradiated poly-CVD 2 : n-irradiated poly-CVD 1e14 : single-crystal-CVD n-irradiated ~5e13 : Si : Si
- Readout with PSI46 analog test board
  - zero suppressed readout
  - individual pixel thresholds 2500 +/- 500 electrons
- Trigger provided by forming a coincidence of fast-OR of front and back masked telescope planes
- Each plane individually biased

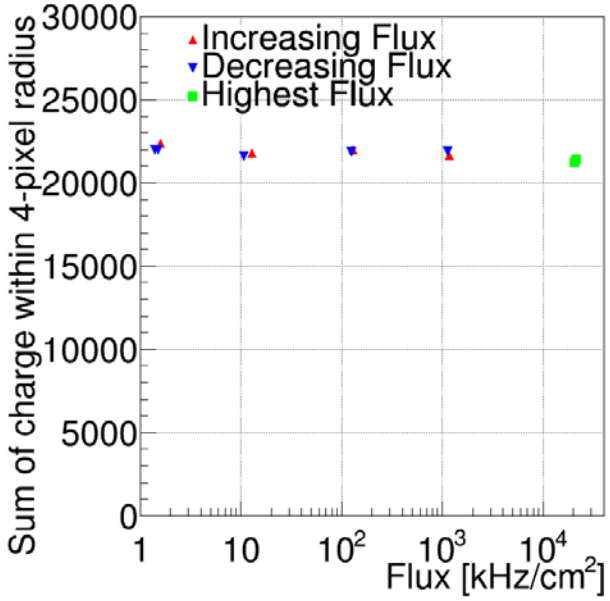


Reference: non-irradiated single-crystal

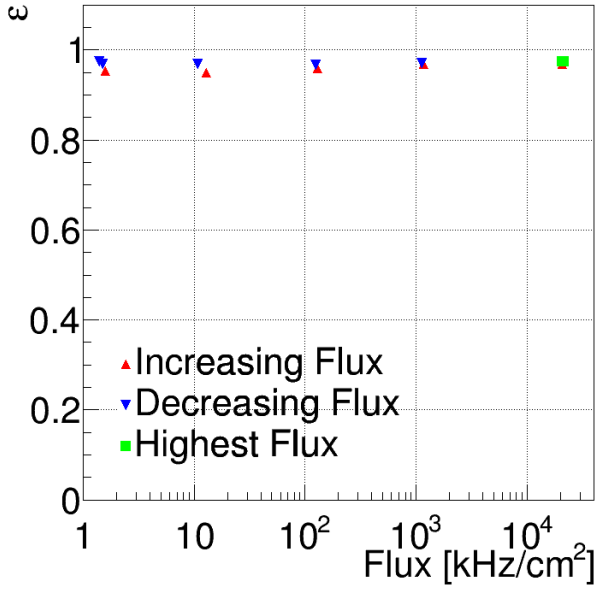
- Total pulse height and efficiency are stable vs rate
- Cluster size is changing
  - surface effects ?



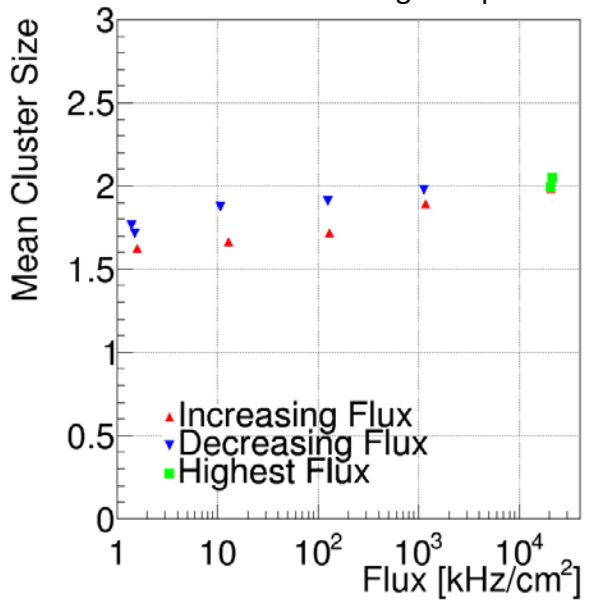
Charge sum in 4 pixel radius



Eff. of hits above threshold in 2 pixel radius

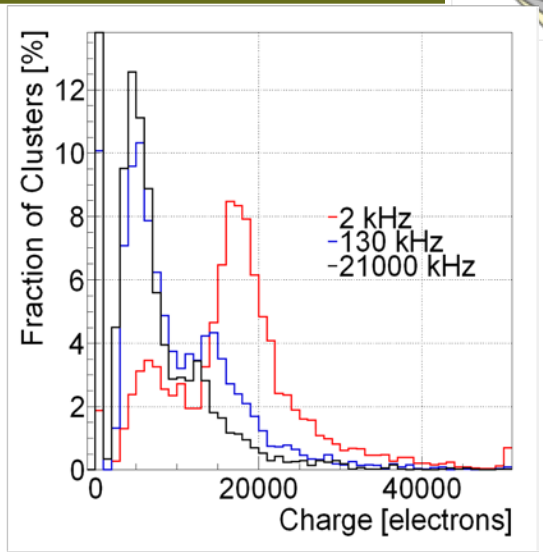


Cluster size of contiguous pixel clusters

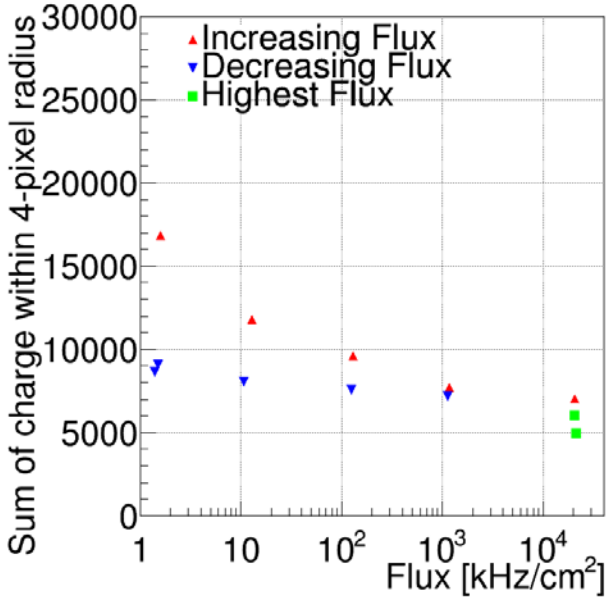


Castor-irradiated single-crystal

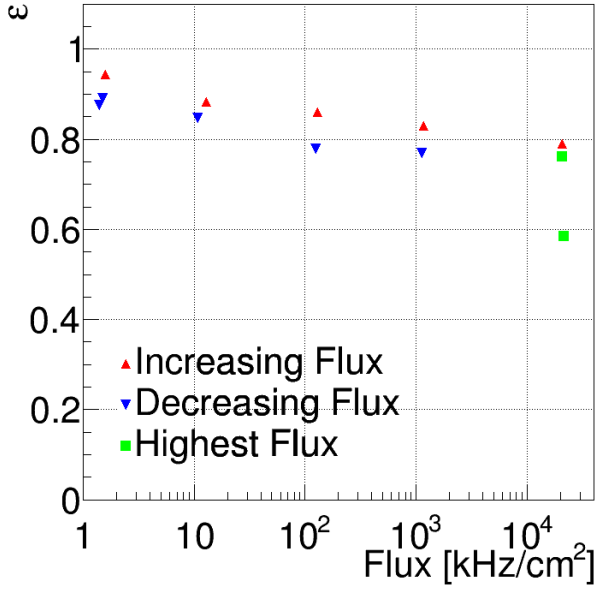
- Irradiation dose: FLUKA estimate $5x10^{13}$ n/cm^2 + $4x10^{13}$ charged hadrons/cm^2
- Total pulse height and efficiency are decreasing significantly with rate increase.
- Cluster size is changing
  - low pulse height pixels disappear under threshold, effectively reducing clusters size



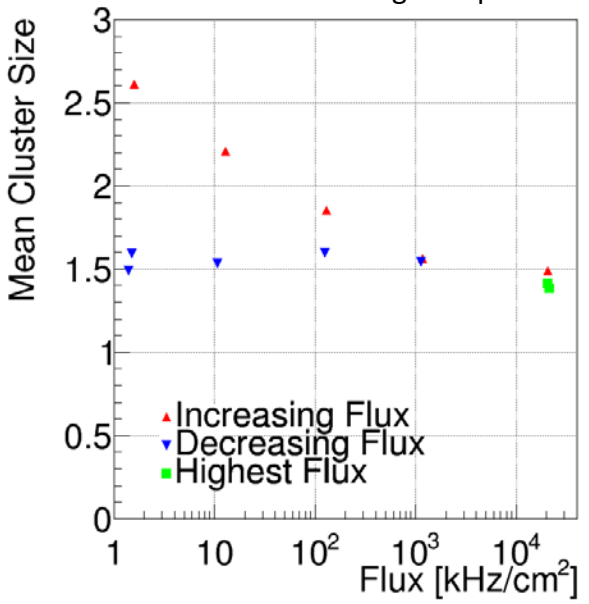
Charge sum in 4 pixel radius



Eff. of hits above threshold in 2 pixel radius

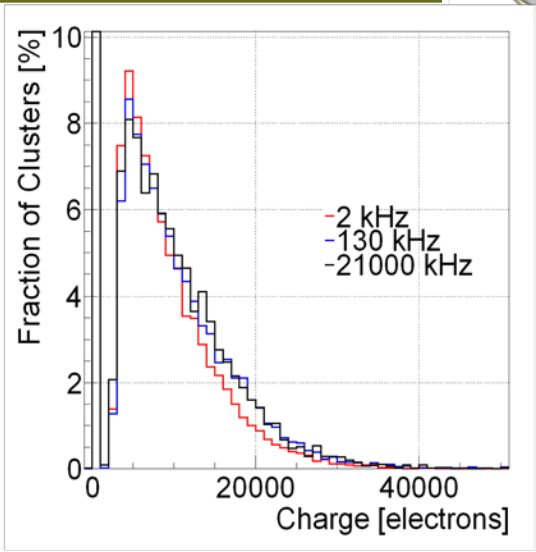


Cluster size of contiguous pixel clusters

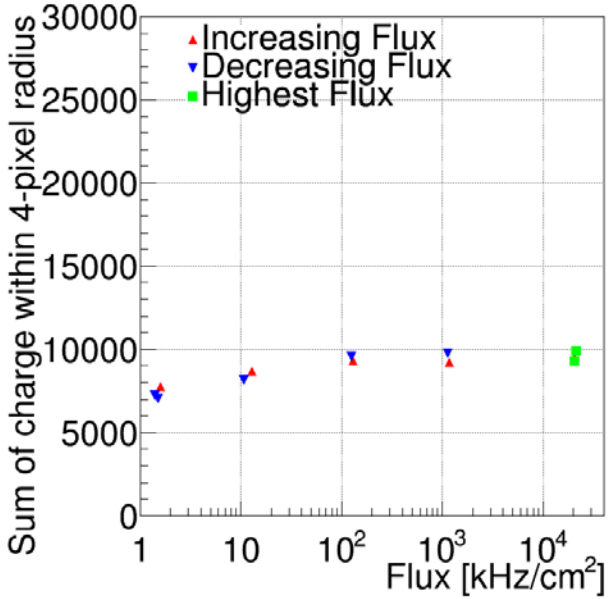


Non-irradiated poly

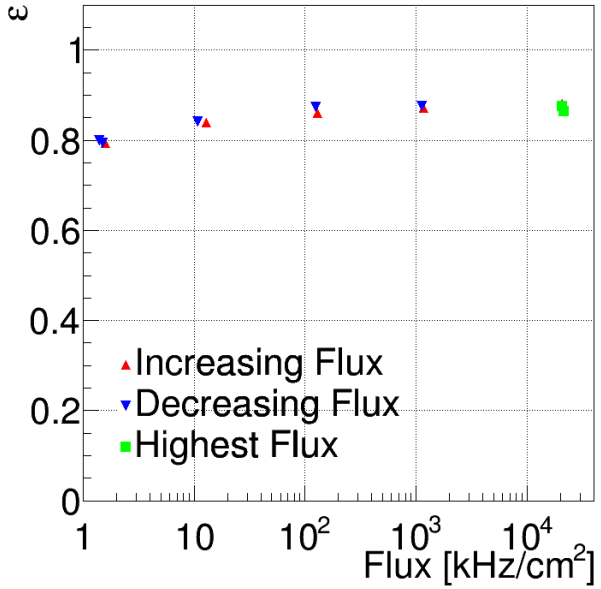
- Total pulse height and efficiency slightly increase, then remain stable
- Cluster size is also slightly increasing vs rate
  - Pumping or systematic bias



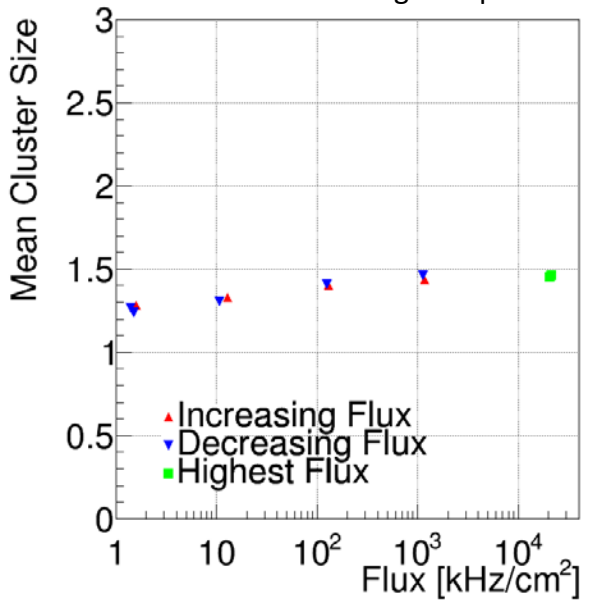
Charge sum in 4 pixel radius



Eff. of hits above threshold in 2 pixel radius

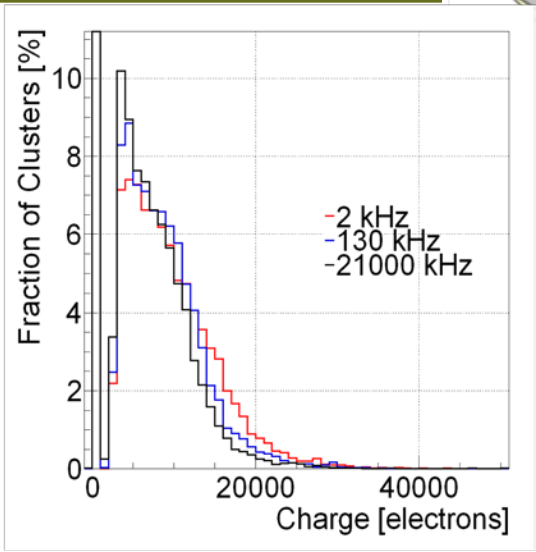


Cluster size of contiguous pixel clusters

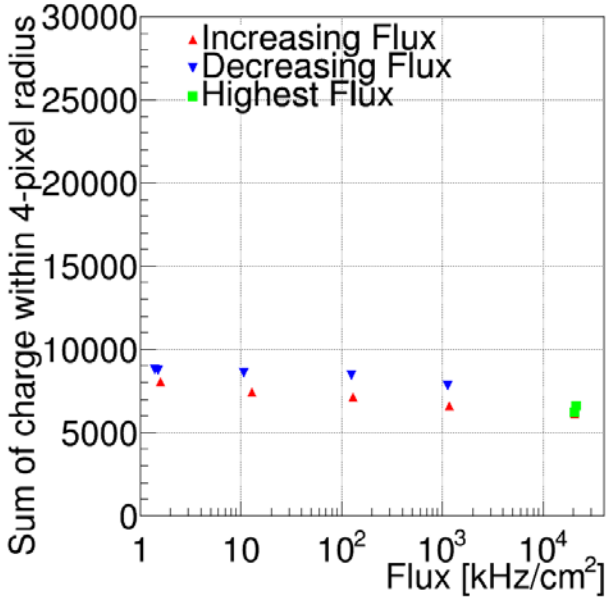


neutron-irradiated poly

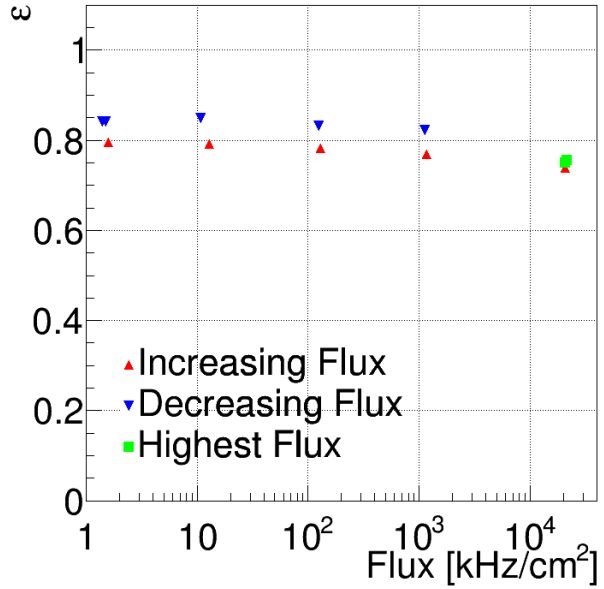
- Irradiation dose $1x10^{14}$ n/cm^2.
- Total pulse height and efficiency decrease only slightly with rate
  - Only tail of Landau is visible due to high threshold
- Cluster size is stable with rate



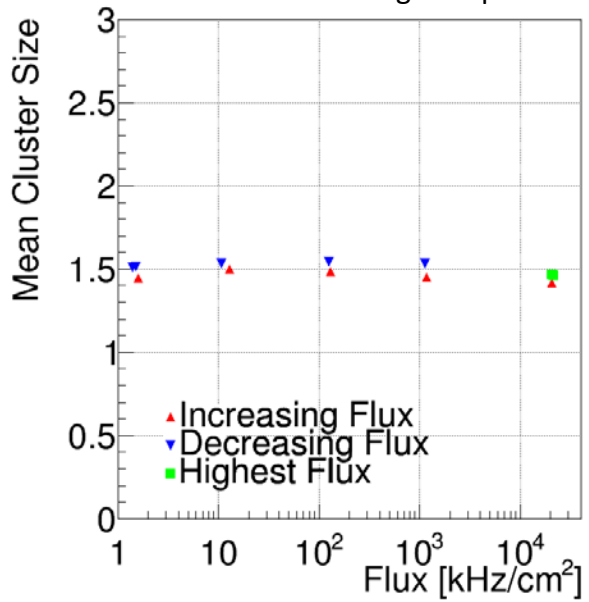
Charge sum in 4 pixel radius



Eff. of hits above threshold in 2 pixel radius



Cluster size of contiguous pixel clusters

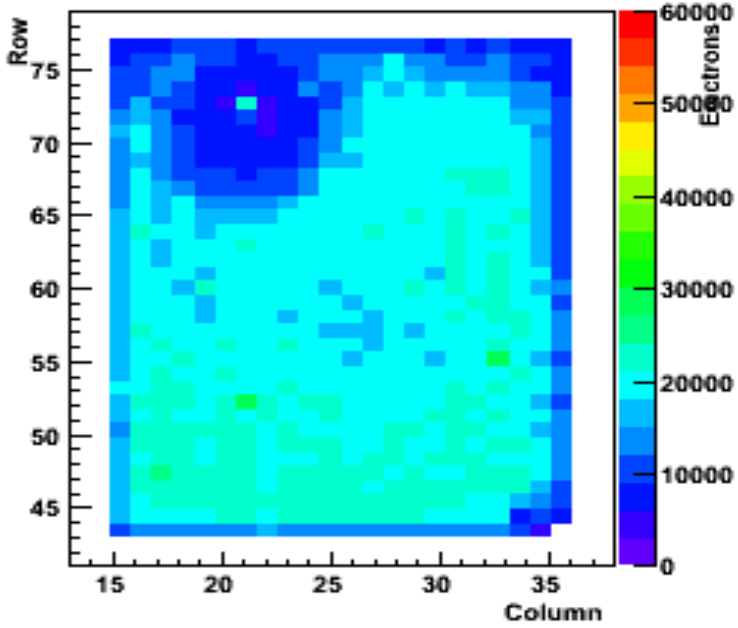


Defects in single crystal diamonds

- Cross polarizer view of the single crystal CVD diamond showing point defects and high stress regions

For illustration – not the same diamond.

- Average pulse height in PLT diamond during pilot run indicating holes



- Holes not seen in poly diamond pixel detectors

Conclusions

- A rate dependence of the pulse height was observed in the PLT using scCVD diamond sensors operating in the CASTOR region of CMS during a pilot run
  - Disappearing signal inconsistent with radiation hardness expectations by RD42
  - Partial signal recovery with increased HV
- RD42 performed dedicated test beam campaigns to study the effect
  - Pad and pixel detectors were studied with diamond samples irradiated up to $1x10^{14}$ n/cm^2 to disentangle geometry effects
- Rate dependence could be replicated with scCVD sensors with neutron irradiation of roughly comparable dose
  - Effect not visible (or very small) in poly-crystalline diamond up to particle rates of 3 MHz/cm^2
  - No dependence on polarity of HV observed (electron or hole carriers)

Outlook

- Study promising new single crystal diamonds from alternate vendor IIa
  - check dependence on manufacturing procedures
- Study latest poly CVD diamonds from II-VI
  - higher collection distance (~ 300 um)
  - Use readout chip with lower threshold (digital ROC for CMS phase 1 upgrade)
- Study time evolution of pulse height
- Study irradiated pad & pixel diamond detectors to higher doses

Backup

PSI Test Beam Campaign

Type of diamonds		Sample	Rate Up	Rate Down	Metallization	Long Term Stability	Low/High Voltage	Voltage Polarity
Poly non-irradiated	Pixel	A,B	X	X		X		
	Pad	H	X	X	X	X	X	X
Poly n-irradiated	Pixel	D	X	X		X		
	Pad	E	X					X
Poly p-irradiated	Pixel							
	Pad							
Single non-irradiated	Pixel	s105	X	X		X		
	Pad	s129	X					X
Single n-irradiated	Pixel	s108	X	X		X		
	Pad	s30	X	X		X	X	
Single p-irradiated	Pixel							
	Pad	S66, S125	X	X		X	X	
Single castor irradiated	Pixel	s86	X	X		X		
	Pad	s97	X					