



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

Rainer Wallny



on behalf of
the RD42 collaboration

*The help of my RD42 colleagues is gratefully
acknowledged.*

Pixel 2014, Niagara Falls, Canada

Outline



- CMS Experience with a diamond pixel detector (PLT)
- Summary of RD42 radiation hardness results
 - Comparison with FLUKA Displacement Per Atom (DPA)
- PSI Test Beam: Pulse height vs rate study
 - pad detector results
 - pixel detector results
- Conclusions



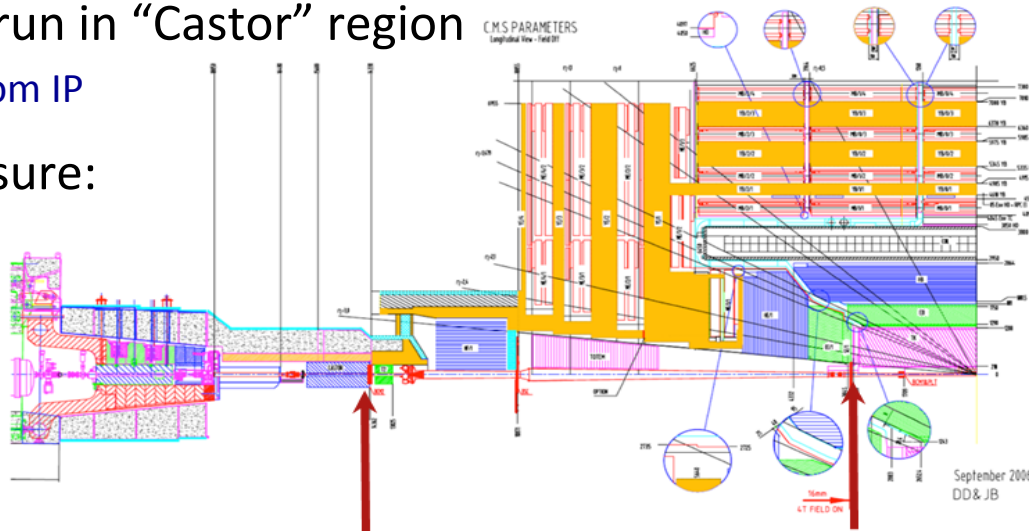
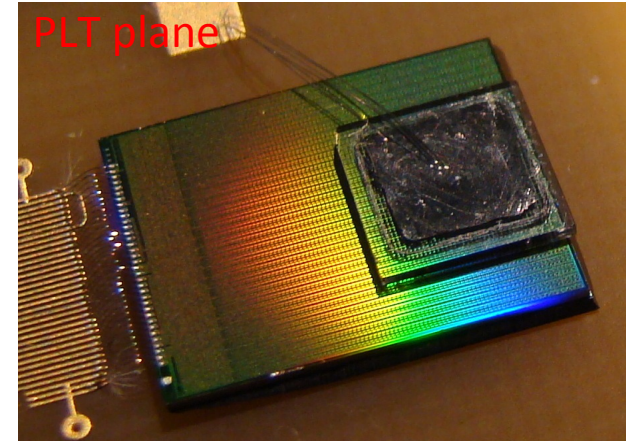
Experience with the PLT during pilot run

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

CMS PLT – Pilot Run Version

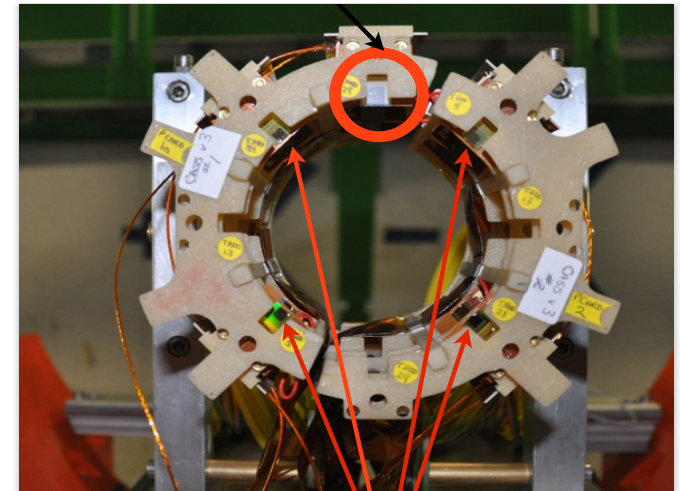


- Dedicated stand-alone **Pixel Luminosity Telescope**
 - Aim to provide high precision bunch-by-bunch luminosity measurement
 - Using “FastOr” readout
- Array of eight 3-plane telescopes in CMS
- Single-crystal diamond pixel sensors by DDL/E6
 - Area 4.7 mm x 4.7 mm, thickness 500 μm
- Pixel readout 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}



Pilot run location

Final location

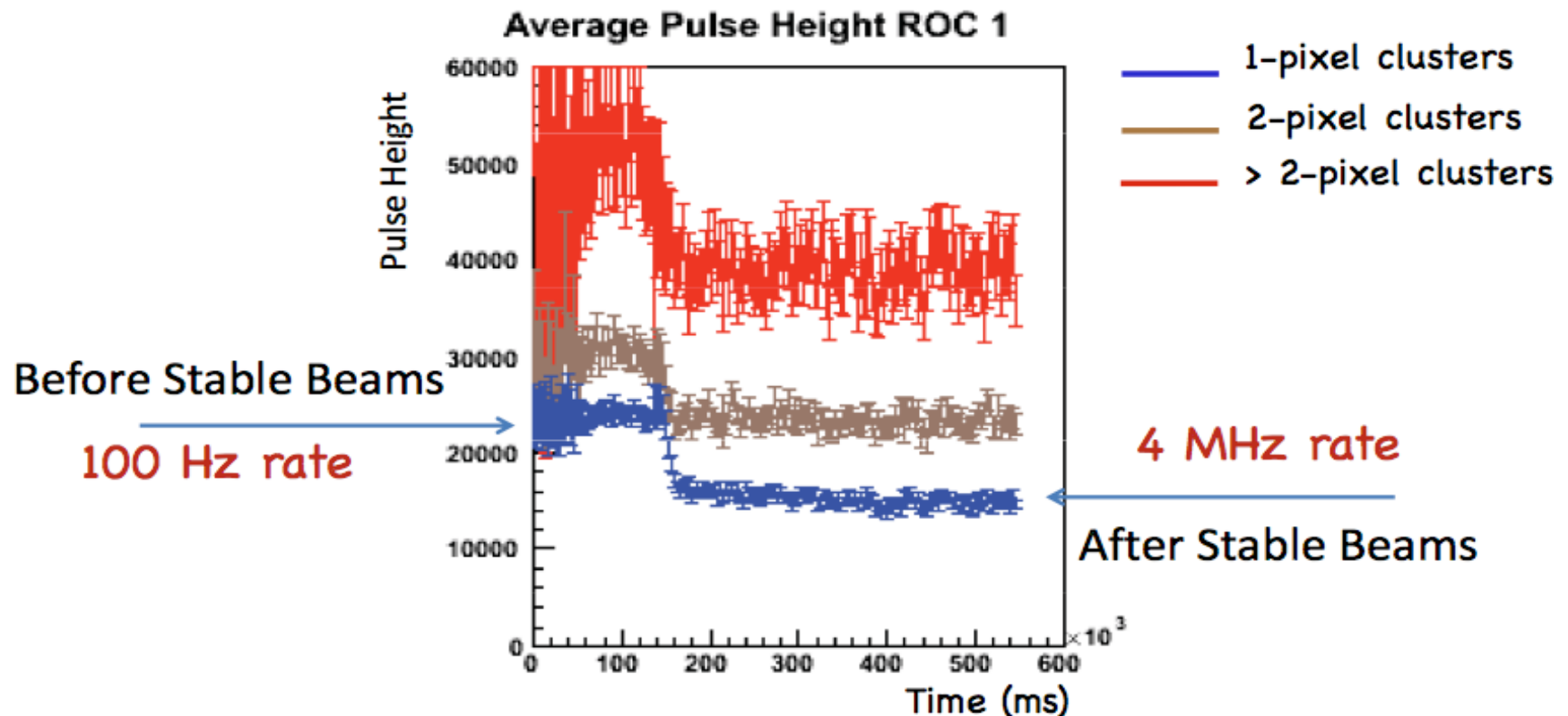


4 diamond pixel telescopes

Diamond PLT Pulse Height Dependence on Rate



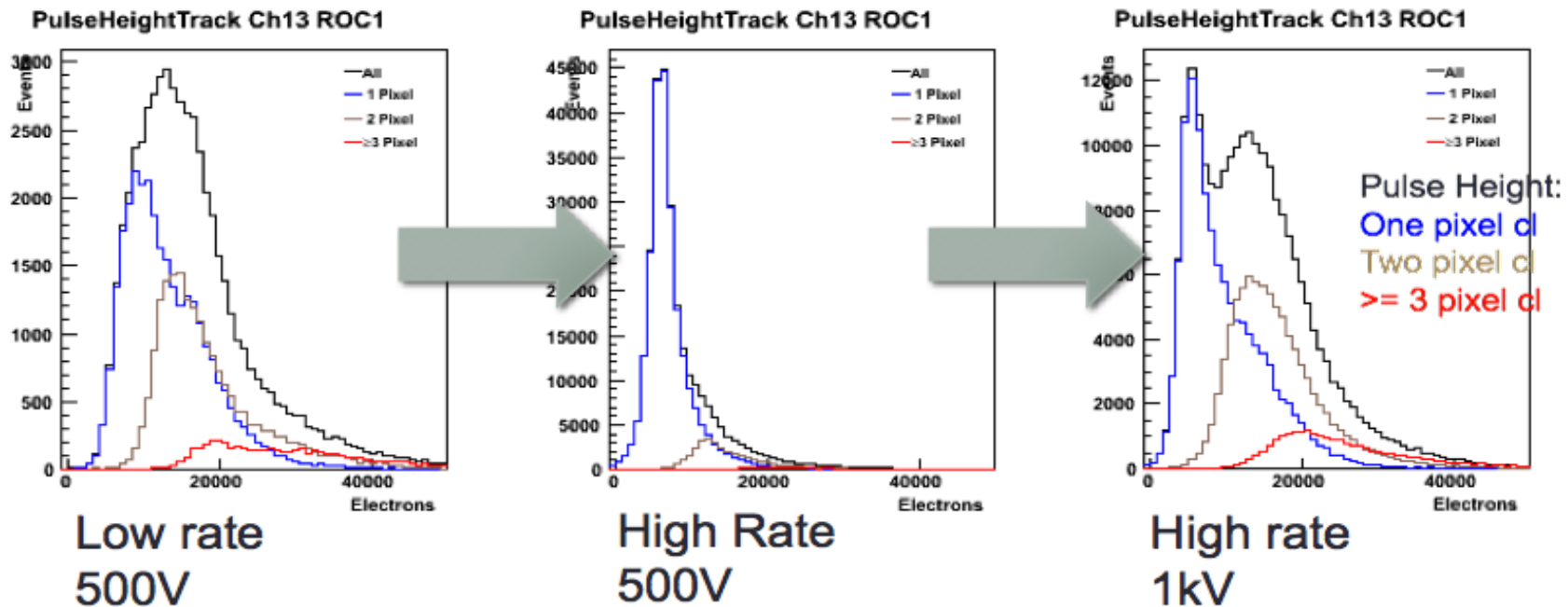
- During pilot run, a shift in pulse height was observed
 - High pulse height before collisions (beam halo)
 - Pulse height drops after beam brought into collision
 - Not seen with silicon planes in CASTOR region



Diamond PLT Pulse Height Dependence on Rate



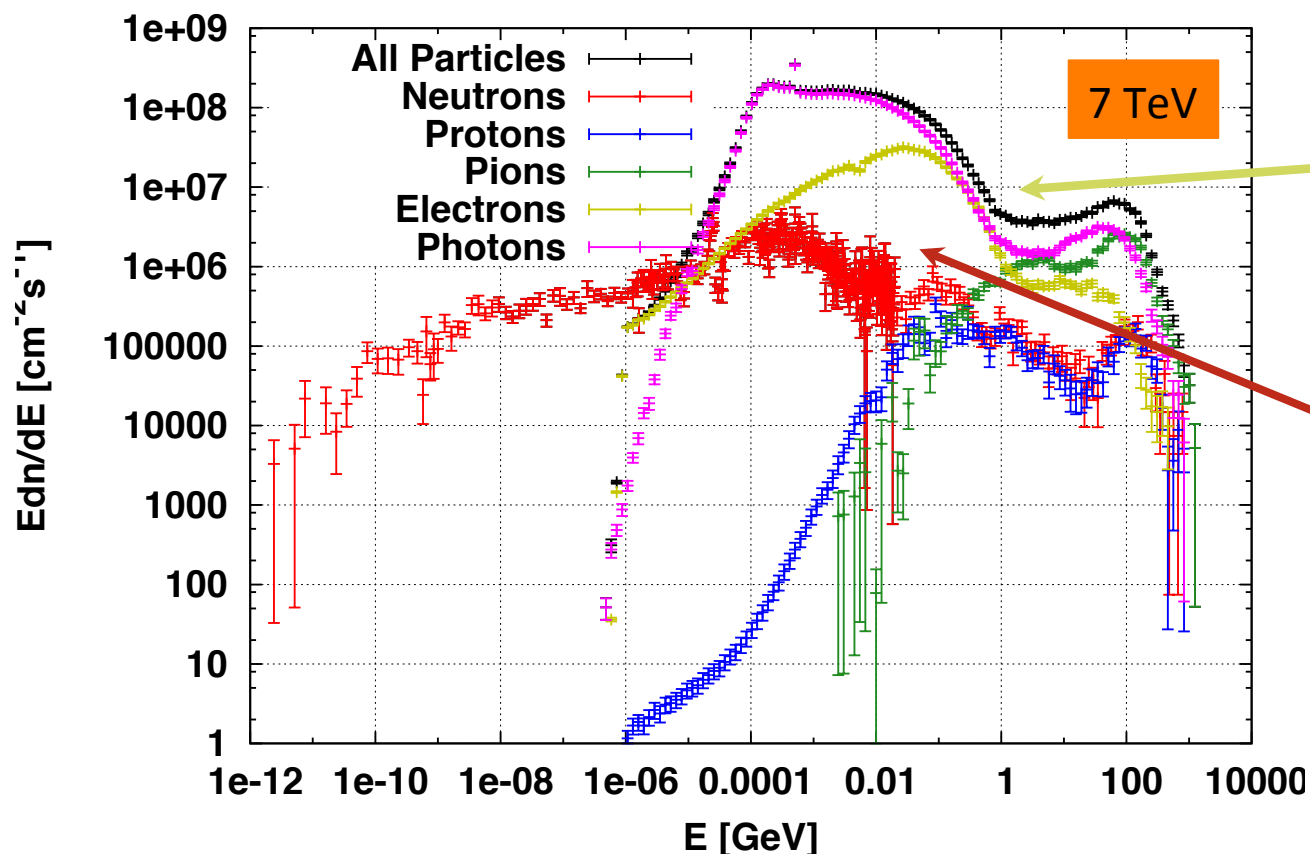
- During pilot run, a shift in pulse height was observed
 - High pulse height before collisions (beam halo)
 - Pulse height drops after beam brought into collision
 - Not seen with silicon planes in CASTOR region
 - Raising HV recovers some of the pulse height => electrostatics



FLUKA Study for CASTOR region



BCM2 inner +Z, 3.5TeV beam energy



Fluences over whole 2012 run

20 fb^{-1}

Charged hadrons: $4 \times 10^{13} \text{ cm}^{-2}$
(mostly pions above 1 GeV)

Neutrons: $5 \times 10^{13} \text{ cm}^{-2}$
(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 $5 \times 10^{13}/\text{cm}^2$ each for charged hadrons and neutrons



Summary of RD42 Results

RD42 Collaboration (2014)



The 2014 RD42 Collaboration

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128 Participants

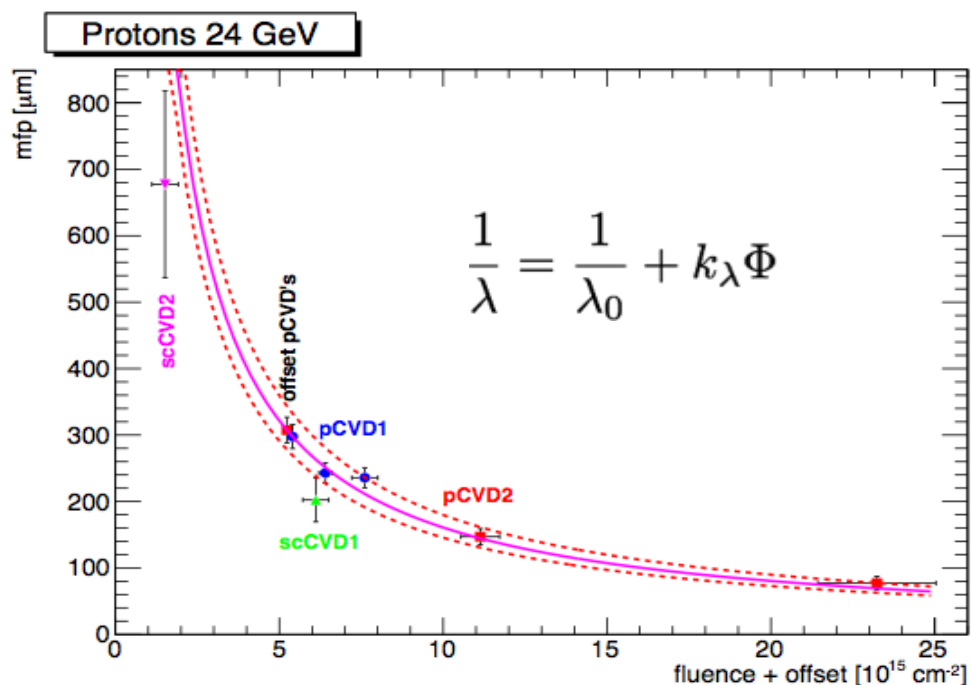
- ¹ Universität Bonn, Bonn, Germany
- ² INFN/University of Catania, Catania, Italy
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- ⁴ FWT, Wiener Neustadt, Austria
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33 Institutes



Summary of RD42 test beam results

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

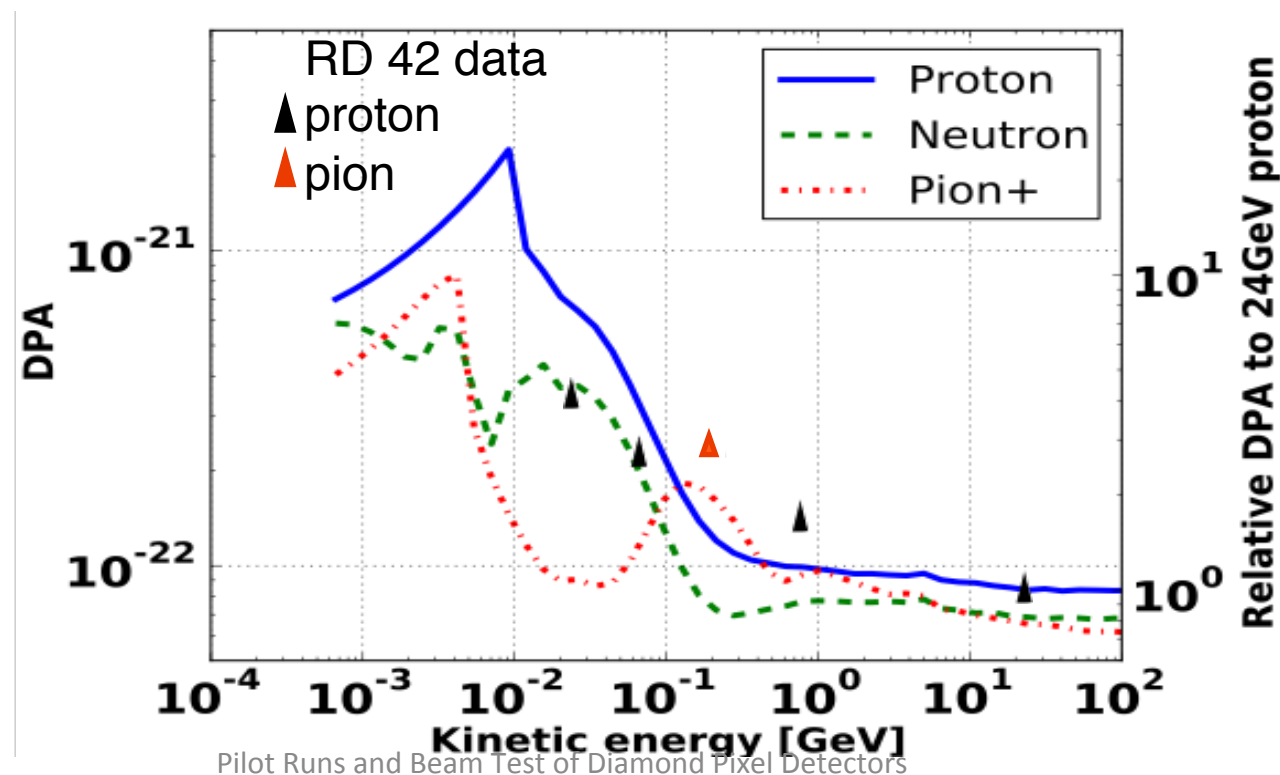


particle	Energy	Relative k_λ
p	24 GeV	1
	800 MeV	1.7
	70 MeV	2.7
	25 MeV	4.2
π^+	300 MeV/c	2.9



Comparison to FLUKA DPA Study

- DPA based on Displacement Energy for Diamond of 43.3 eV
 - M. Guthoff et. al. [arXiv:1308.5419](https://arxiv.org/abs/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

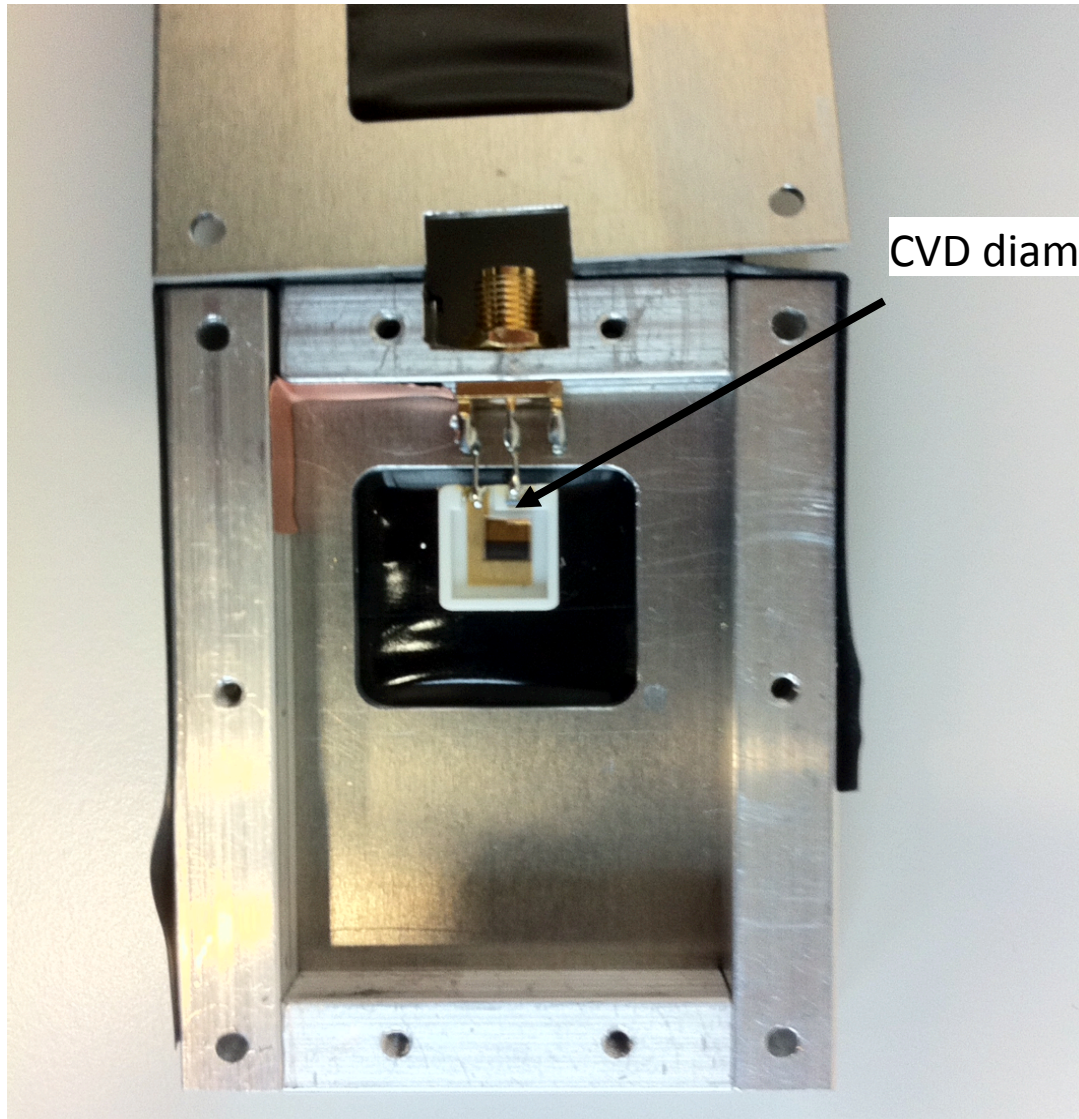


- Several successful test beam campaigns (Dec 2013, May 2014, July 2014)
 - Some Results up to May test beam shown here
- Pad detectors:
 - study sensors w/o threshold effect
 - Quick detector fabrication and turn around
- Pixel detectors:
 - Study effects of pixel threshold
 - Study effects of pixel 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/cm², pixel up to 10 MHz/cm²]
 - Long term pulse height stability at high rate [pad, pixel]
 - Positive and negative bias polarities [pad]

DUT devices

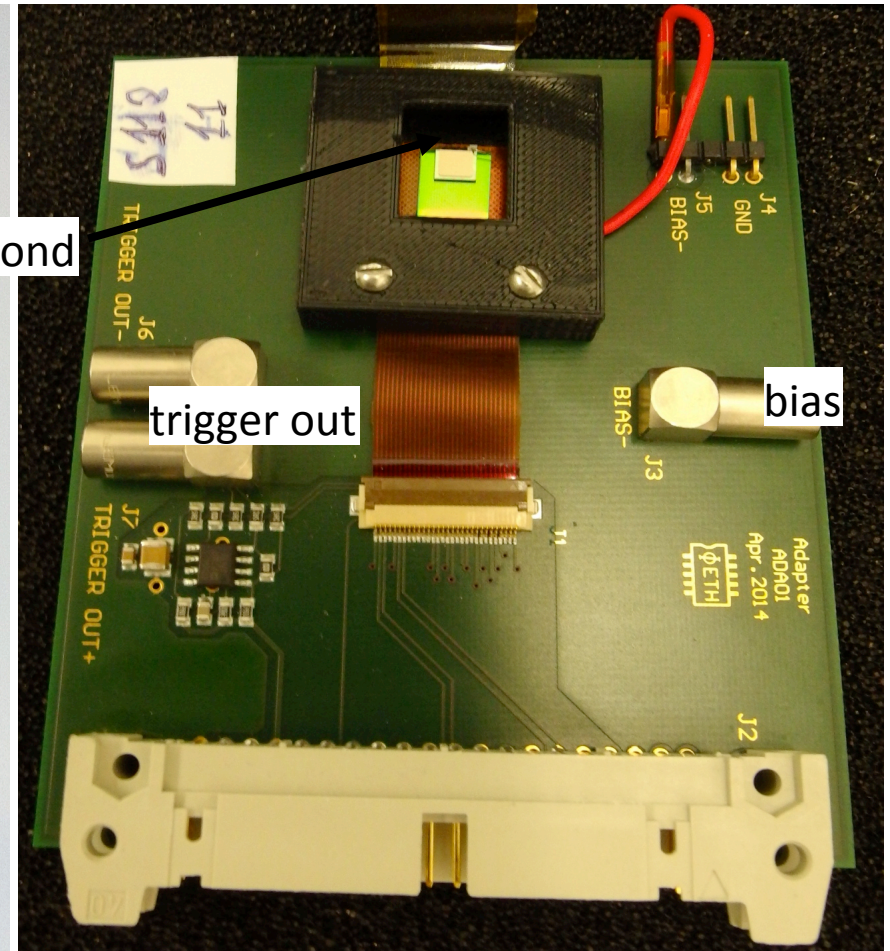


Pad detector box



CVD diamond

Pixel detector plane



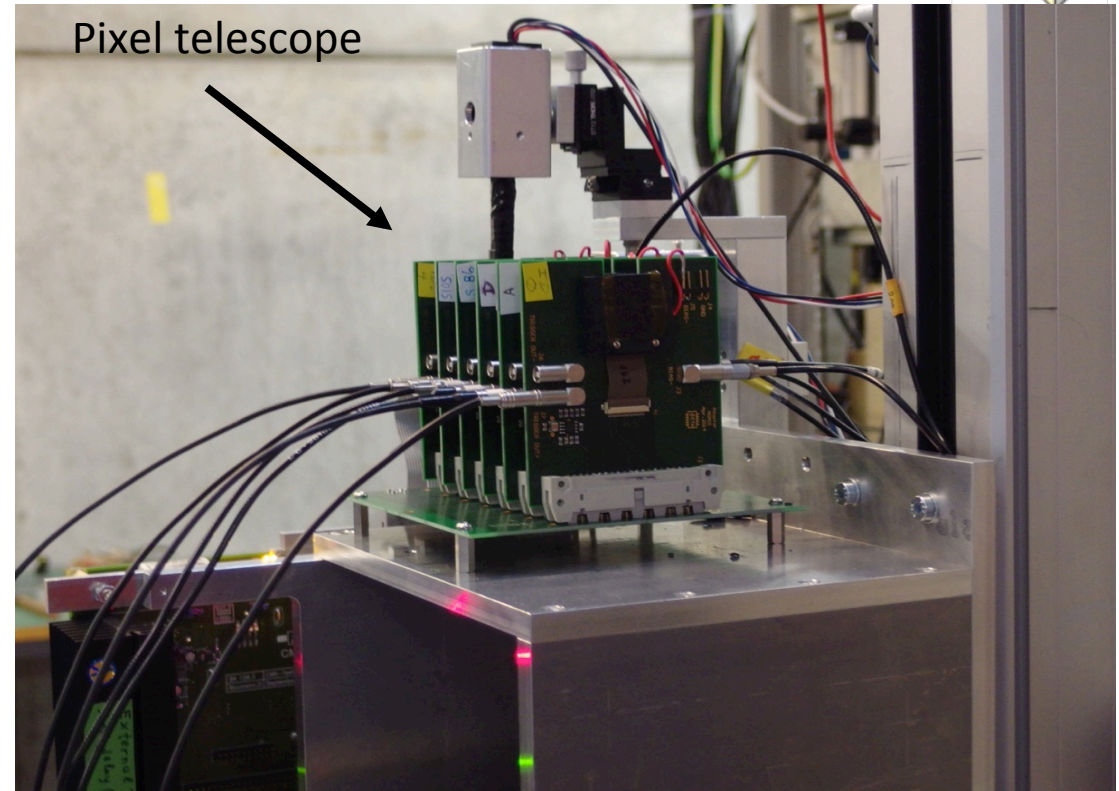
trigger out

bias

- 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 $O(1 \text{ kHz/cm}^2)$ to $O(10 \text{ MHz/cm}^2)$
- test setup reconfigurable into either a “pad” setup or “pixel” setup



Pixel test setup with masked pixel trigger

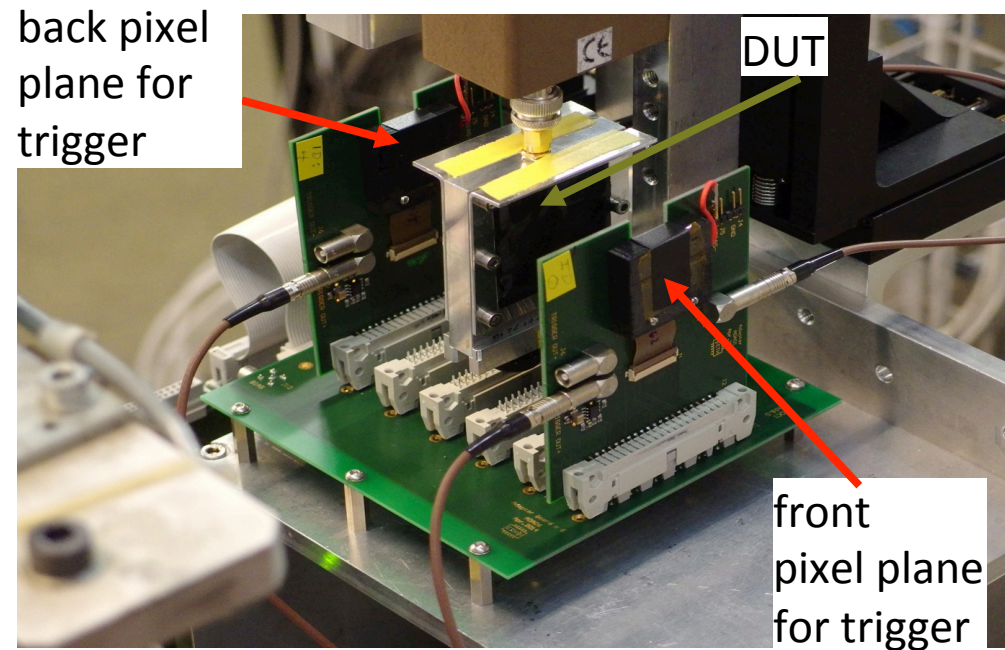
- 6 Tracking planes
 - 2 Trigger planes
 - 4 planes under test

PSI Test beam setup



- 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 $O(1 \text{ kHz/cm}^2)$ to $O(10 \text{ MHz/cm}^2)$
- test setup reconfigurable into either a “pad” setup or “pixel” setup

Pad test setup



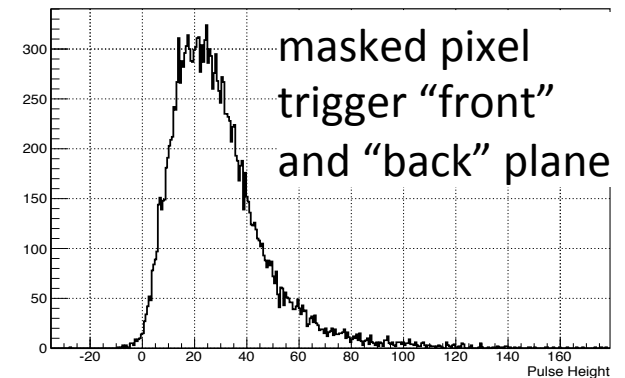
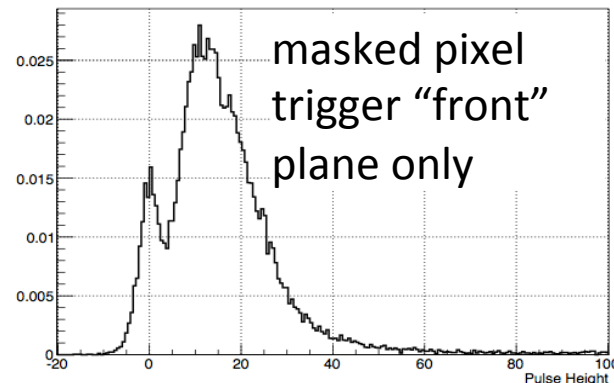
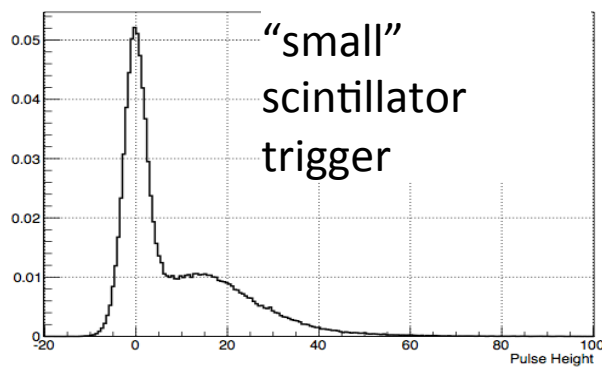
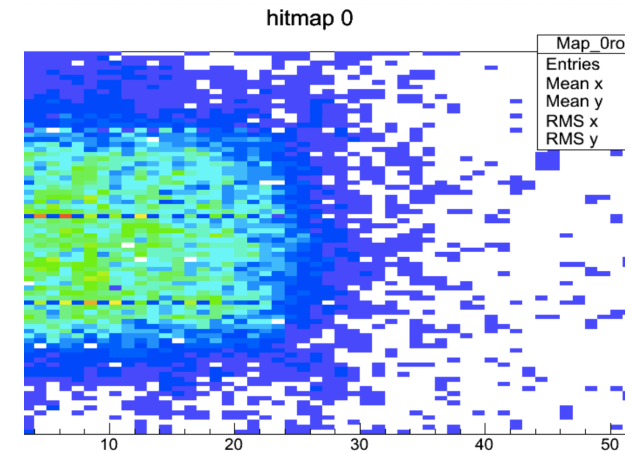
Pad test setup with masked pixel trigger

- 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
 - Baseline practically eliminated



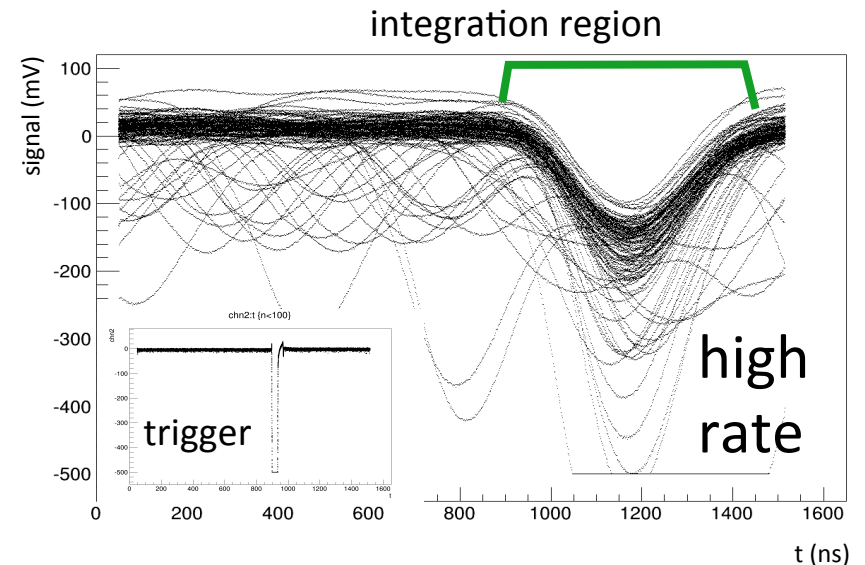
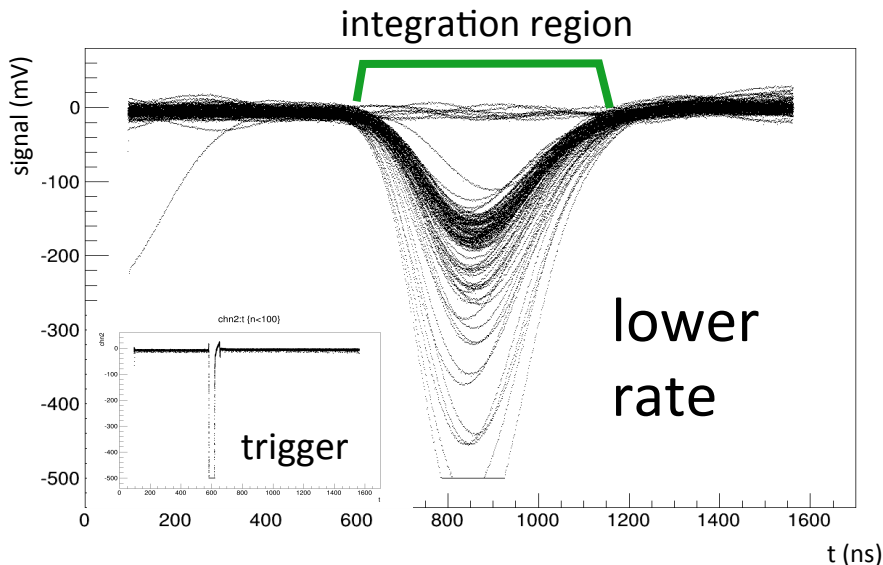
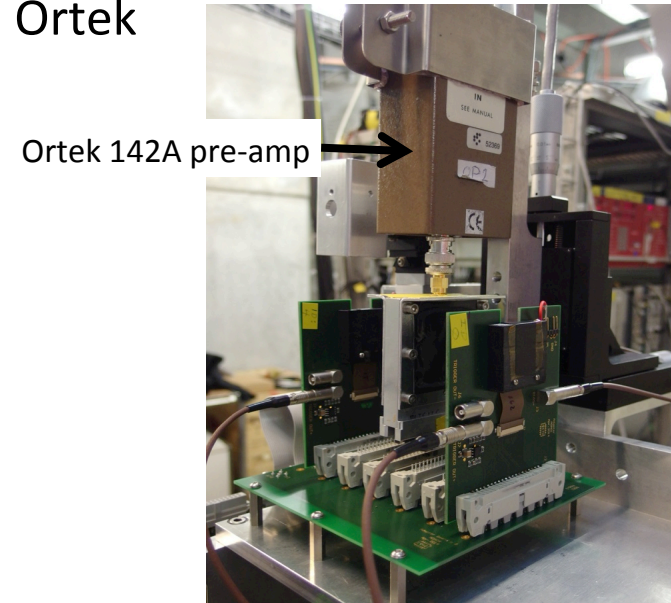


Pad Detector Analysis Results

Pad Analysis Setup



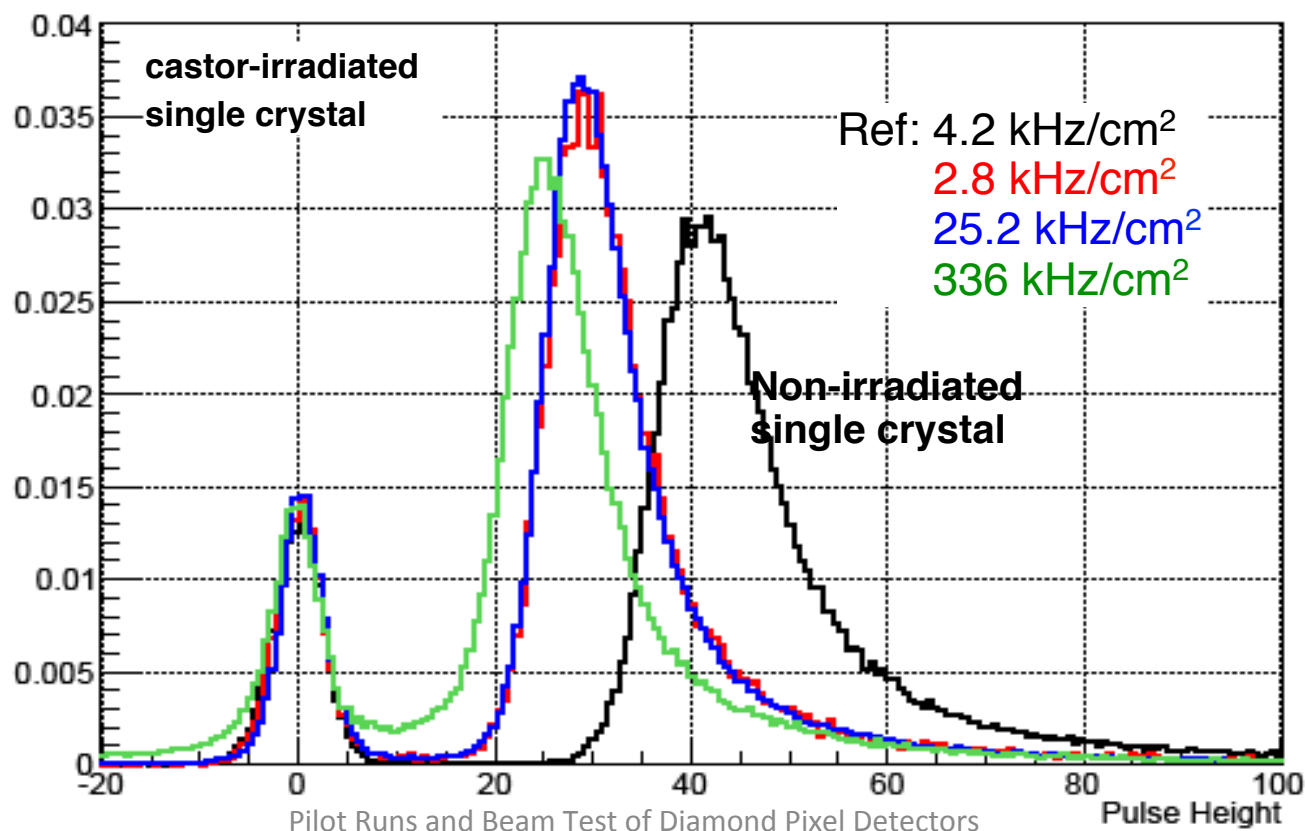
- Pulse height amplified with Ortek 142A pre-amp and Ortek 450 shaping amplifier
 - 300 ns shaping time
- Digitization performed with DRS4 evaluation board
 - 1024 sampling points
 - slowest sampling speed 0.7 GSPS
- Integration region is centered on signal
 - Constant delay with respect to the trigger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



CASTOR single crystal diamond



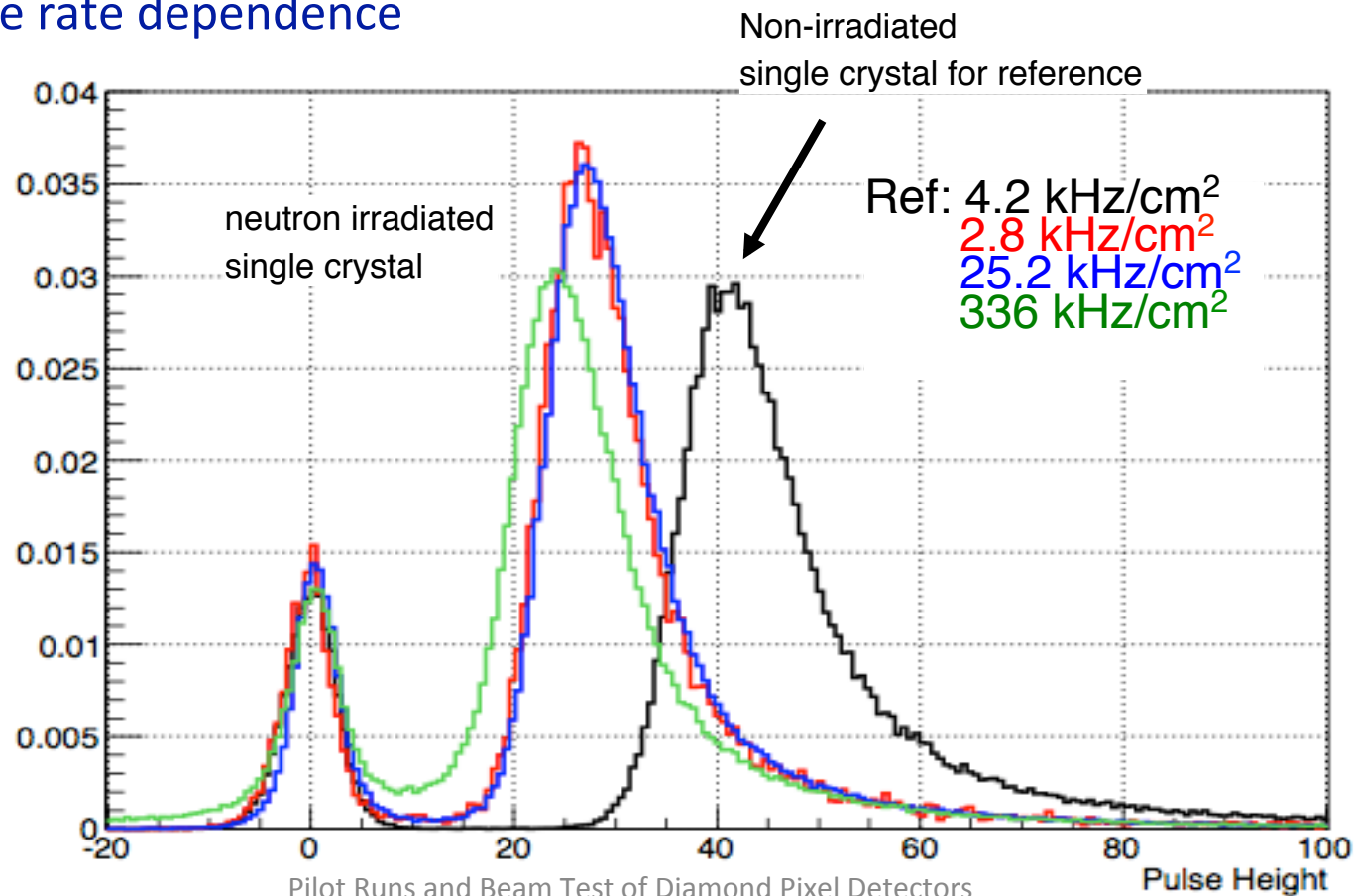
- scCVD diamond produced by Element 6
- FLUKA estimation of dose 5×10^{13} /cm² of each charged hadrons and neutrons
- Run at 500V w/ one plane masked pixel trigger
- Noticeable rate dependence



n-irradiated single crystal diamond



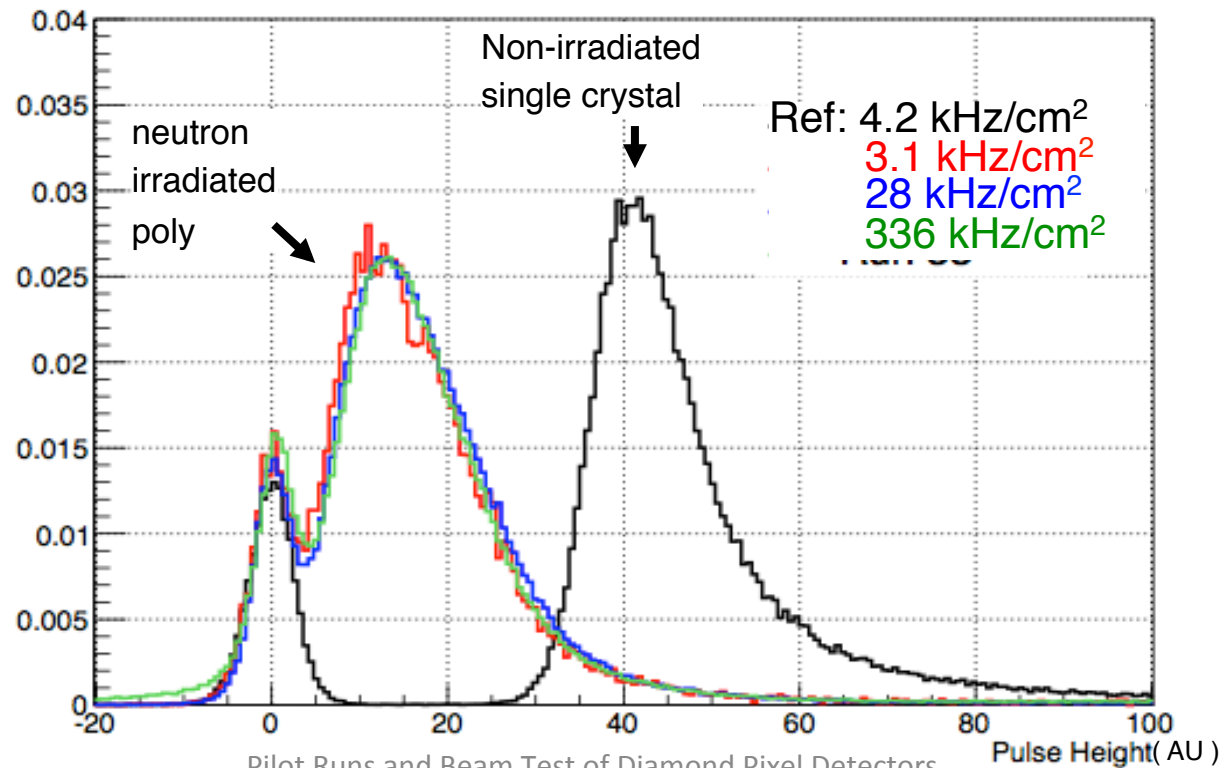
- scCVD diamond produced by Element 6
- Irradiation dose - 5×10^{13} n/cm² at JSI, Ljubljana
- Runs at 500 V with masked pixel trigger
- Noticeable rate dependence



n-irradiated Poly-crystalline diamond



- Irradiation dose - 5×10^{13} n/cm² 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 μ m)
 - Mean for sc: 47.2 (CCD ~ 500 μ m)
- **No noticeable rate dependence**

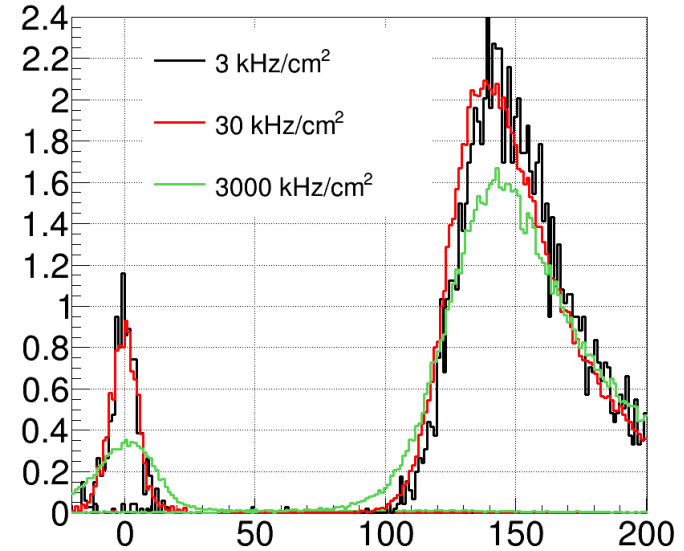




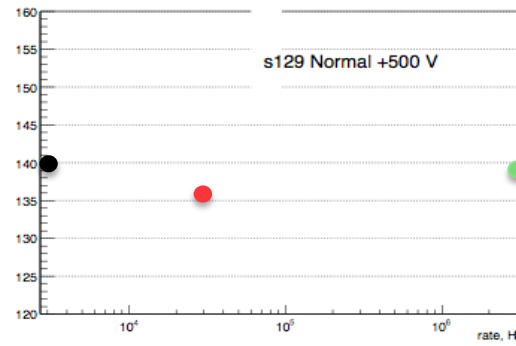
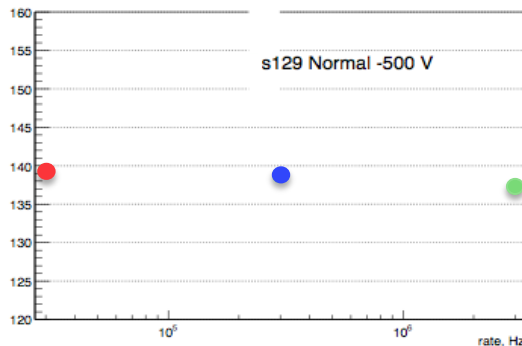
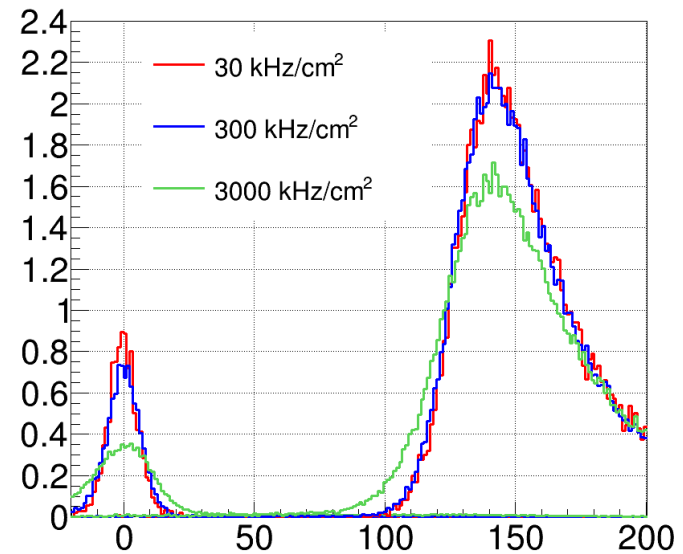
Polarity dependence: non-irrad. single crystal (Ref.)

- 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**

s129, +500 V



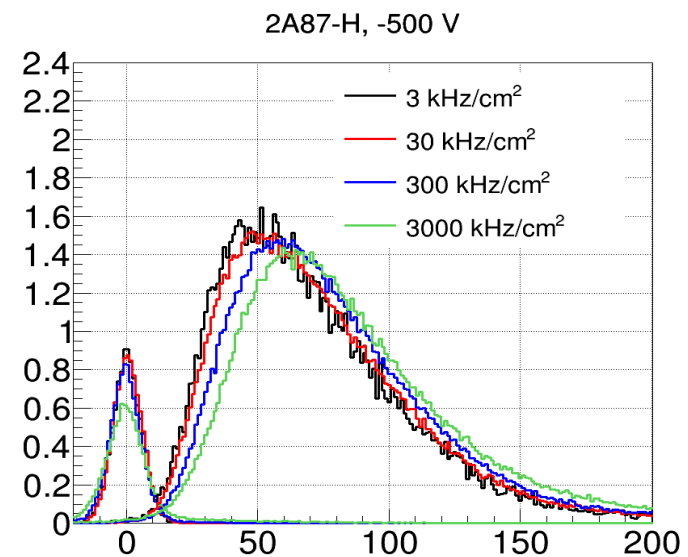
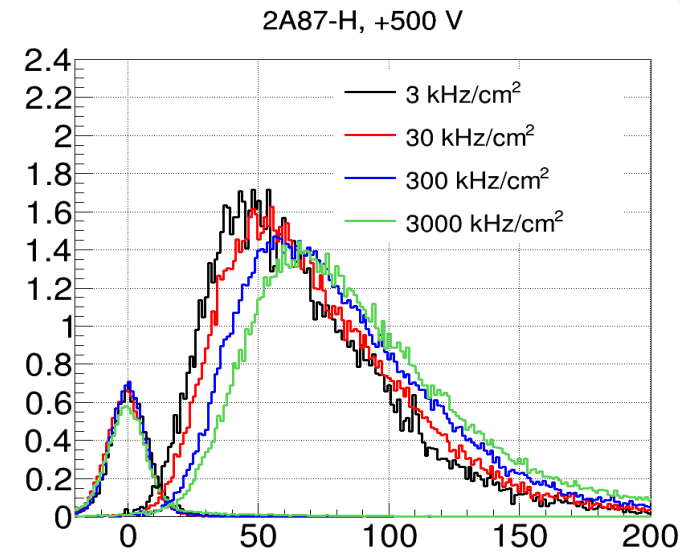
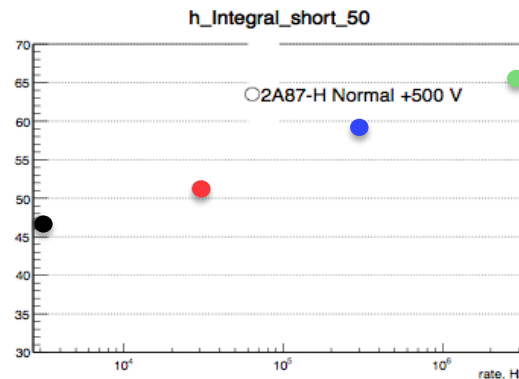
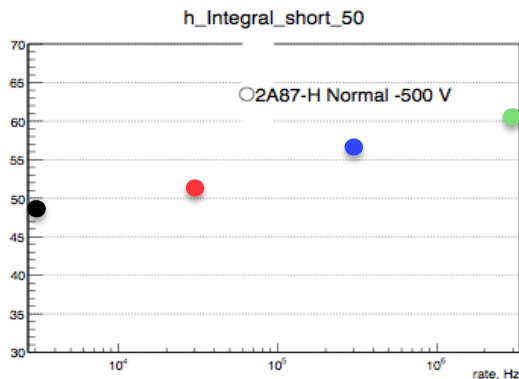
s129, -500 V





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

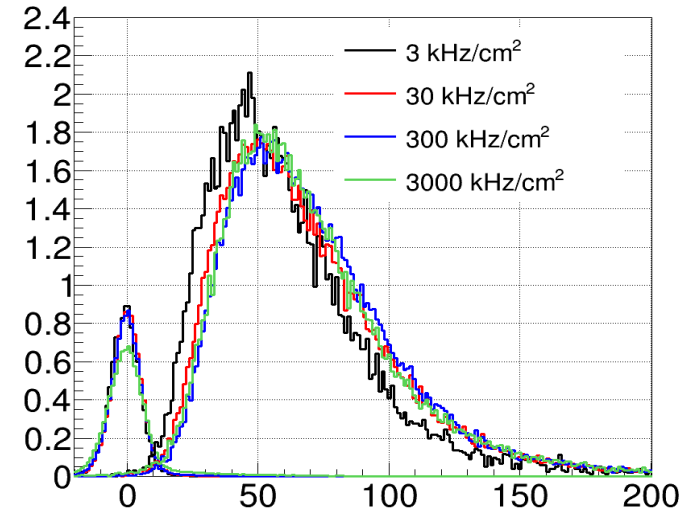




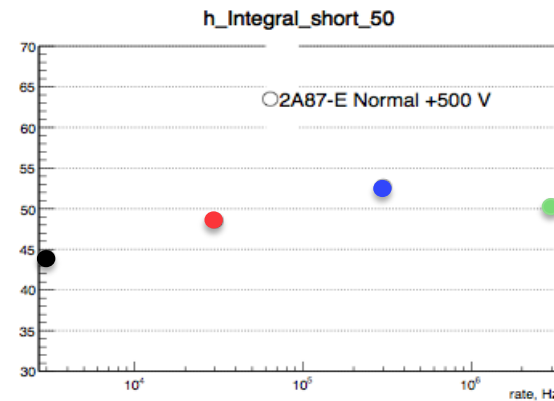
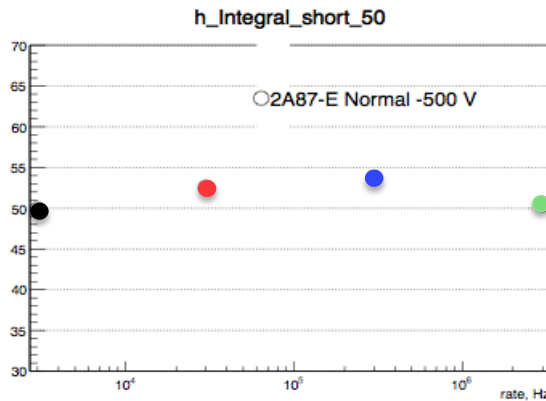
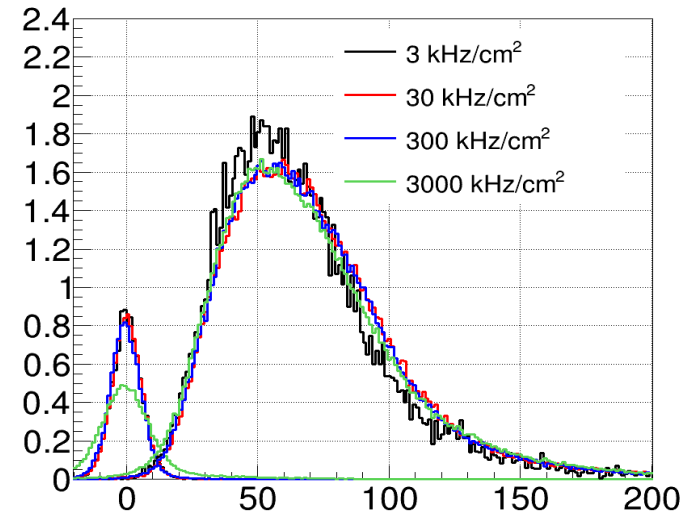
Polarity dependence: Neutron irradiated poly

- Irradiation dose $5 \times 10^{13} \text{ n/cm}^2$
- 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 ?

2A87-E, +500 V



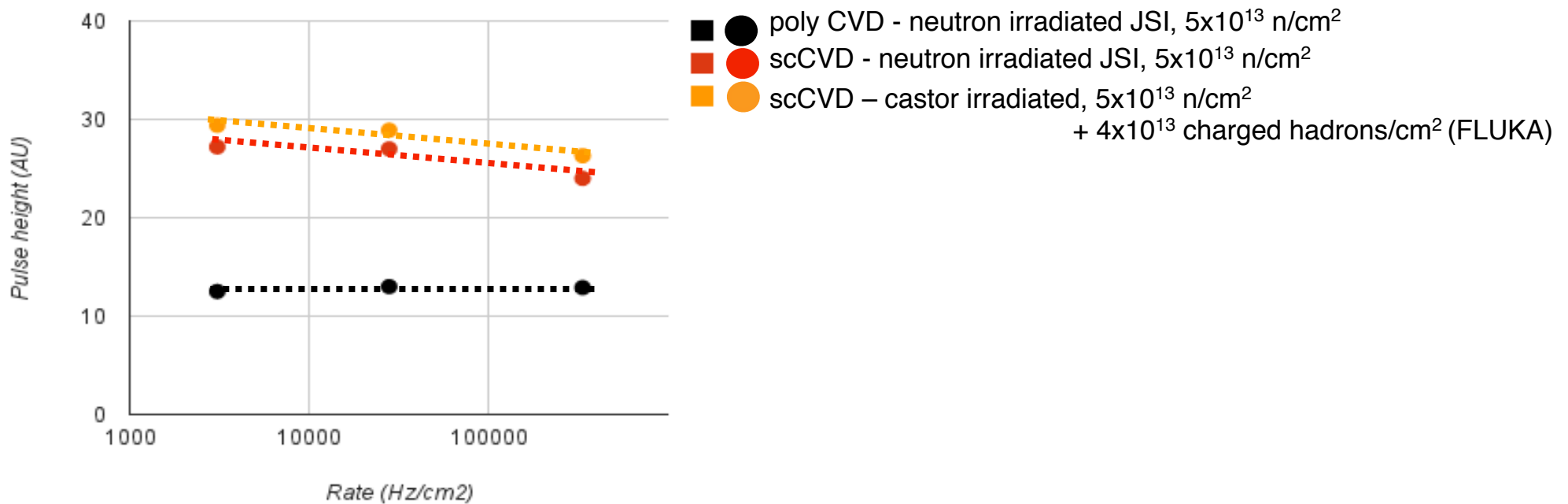
2A87-E, -500 V



Preliminary summary rate dependence



- Plot most probable pulse height versus rate per cm^2
 - Irradiated single crystal diamonds show slight rate dependence
 - Irradiated poly crystalline diamond does not show rate dependence



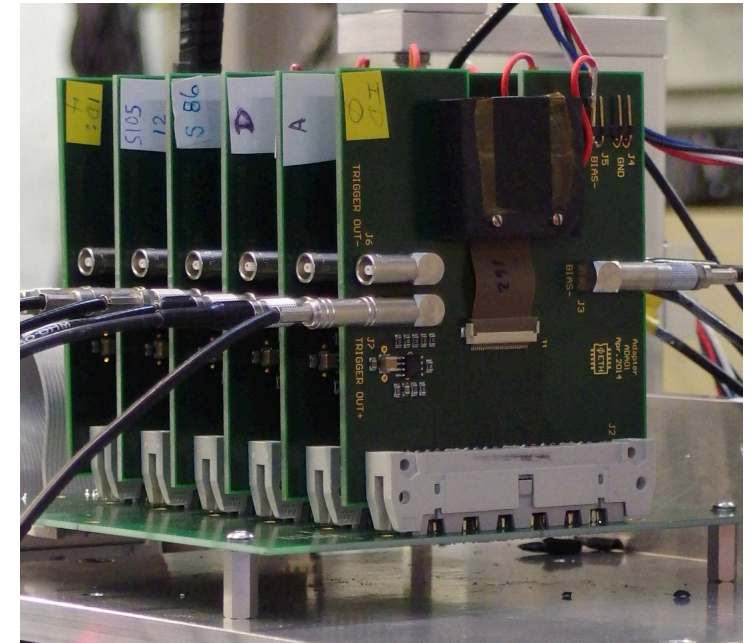


Pixel Detector Analysis Results

Pixel Analysis Setup



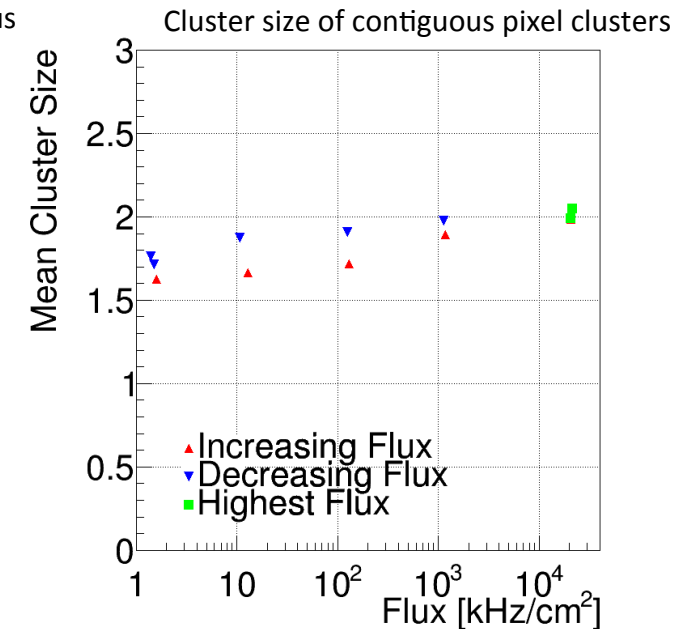
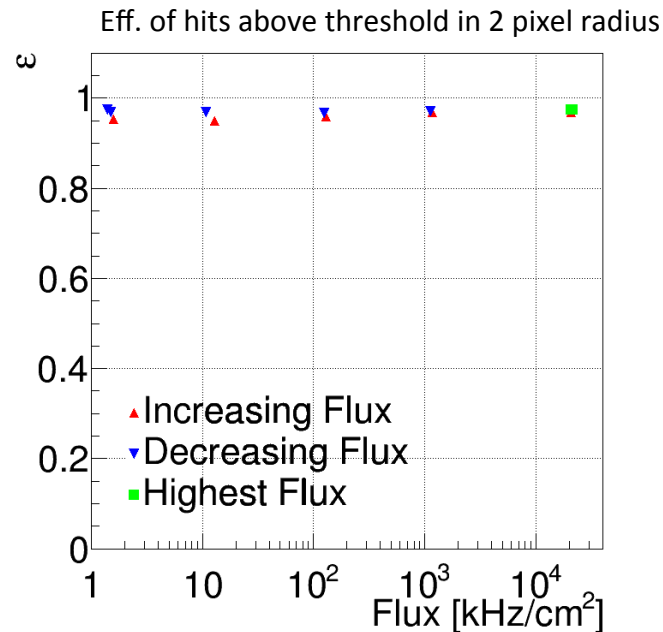
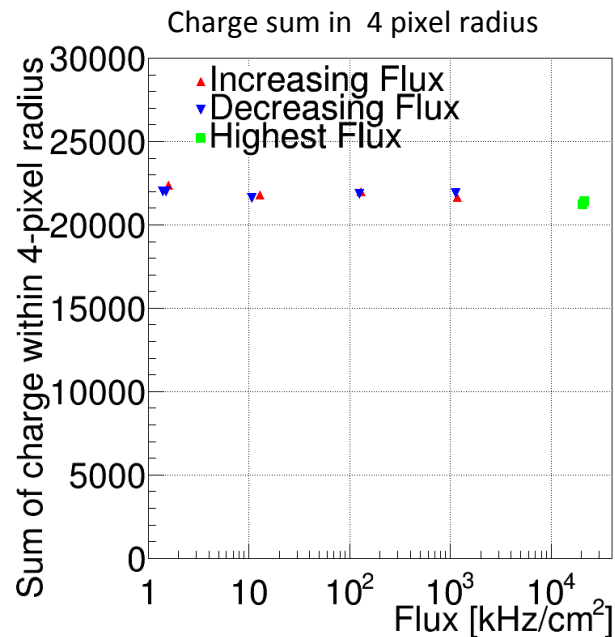
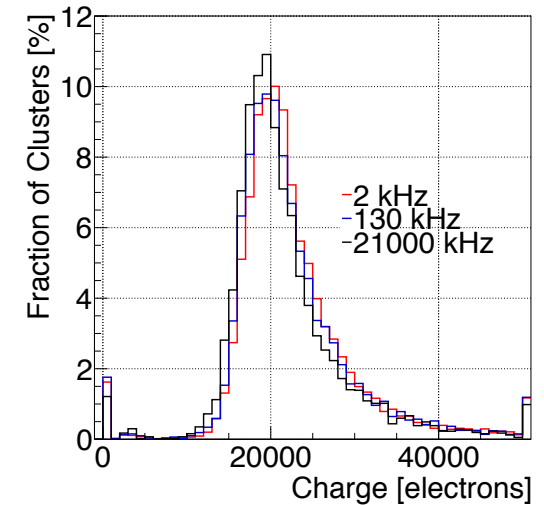
- Two 6-plane telescope arrangements were tested
 - Si : non-irradiated poly-CVD 1 : n-irradiated poly-CVD 1e14 : single-crystal-CVD castor irradiated $\sim 1e14$: single-crystal-CVD non-irradiated : Si
 - Si : non-irradiated poly-CVD 2 : n-irradiated poly-CVD 1e14 : single-crystal-CVD n-irradiated $\sim 5e13$: Si : Si
- Readout with PSI46 analog testboard
 - 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



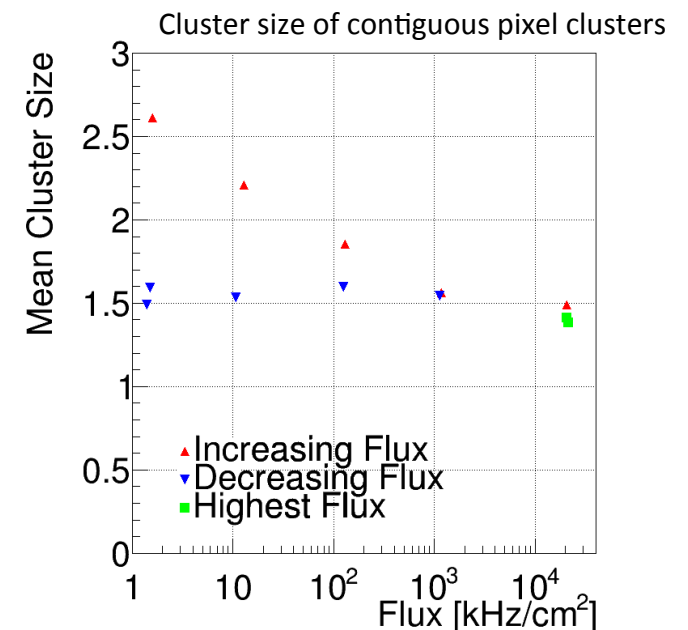
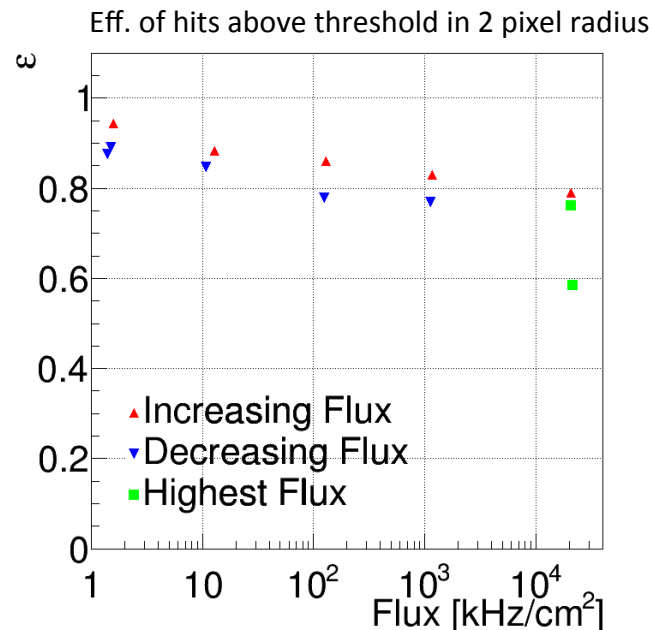
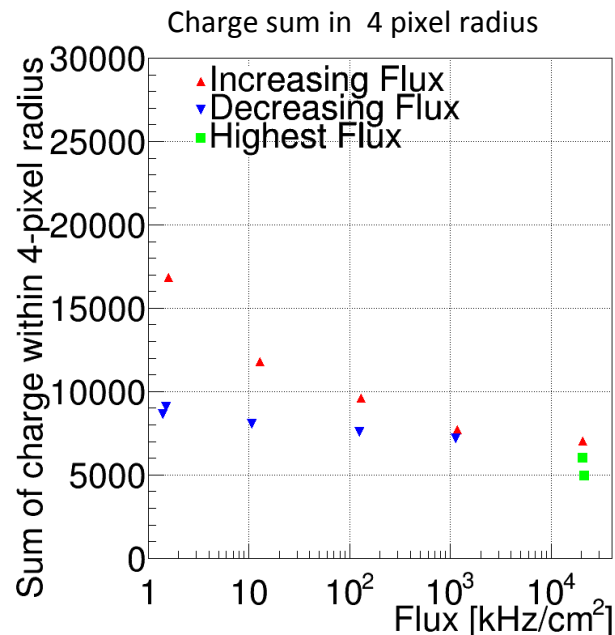
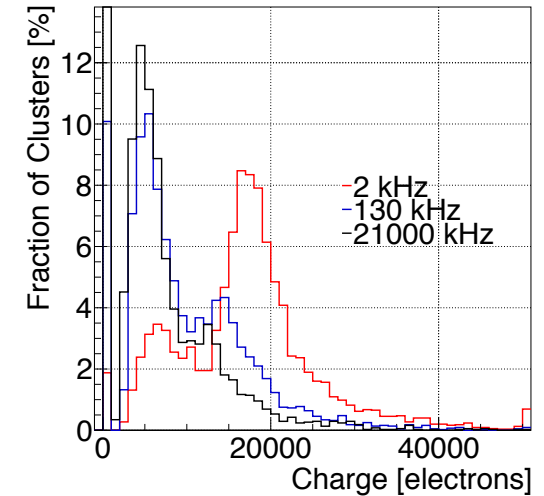
- Total pulse height and efficiency are stable vs rate
- Cluster size is changing
 - surface effects ?



Castor-irradiated single-crystal



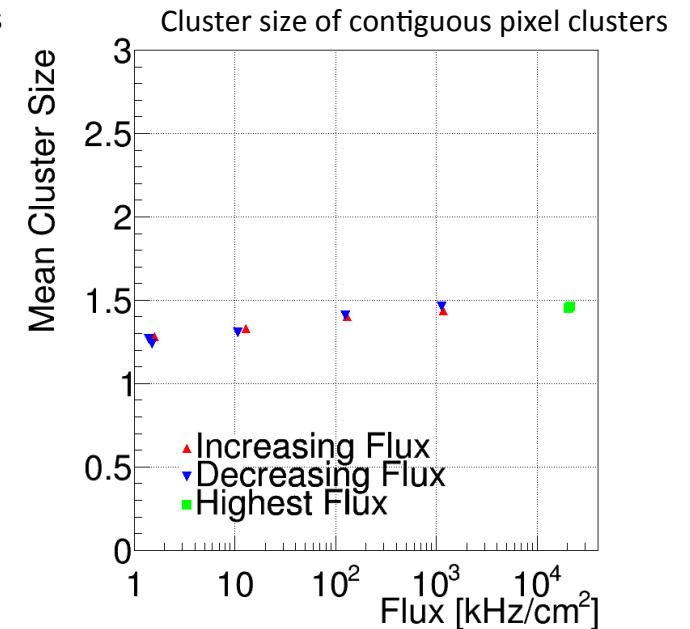
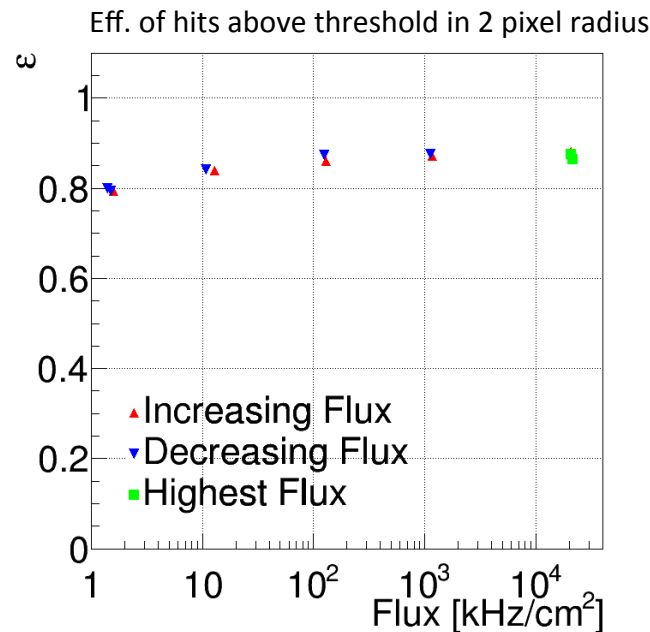
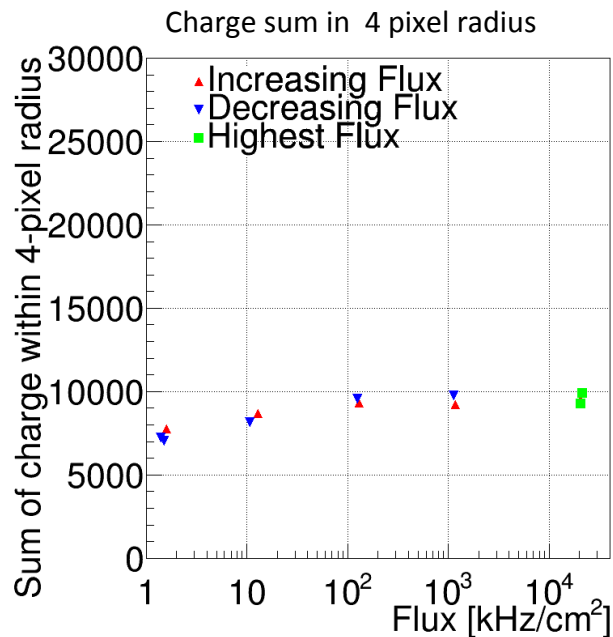
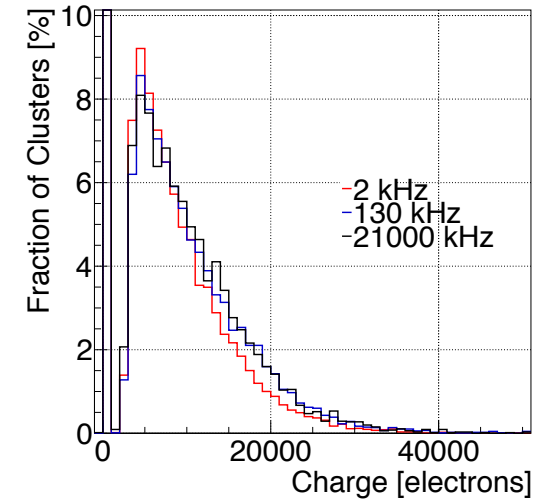
- Irradiation dose: FLUKA estimate 5×10^{13} n/cm² + 4×10^{13} charged hadrons/cm²
- Total pulse height and efficiency are decreasing significantly with rate increase.
- Cluster size is changing
 - low pulse height pixels disappear under threshold, effectively reducing clusters size



Non-irradiated poly



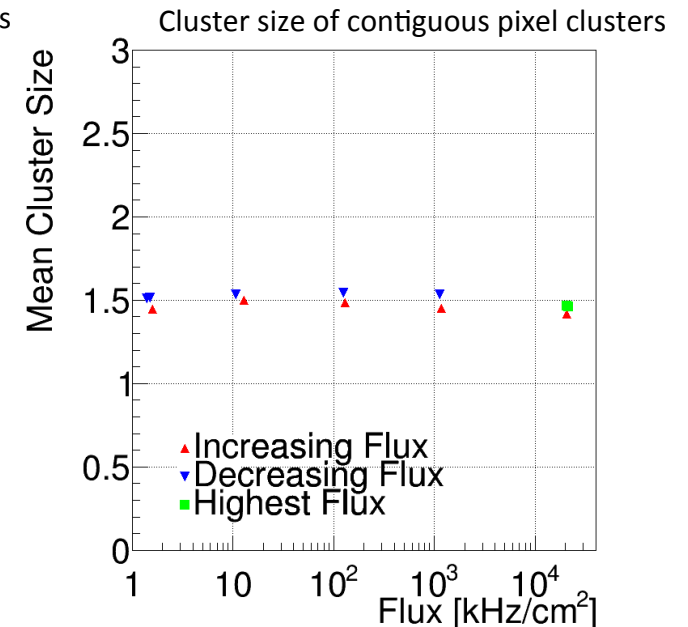
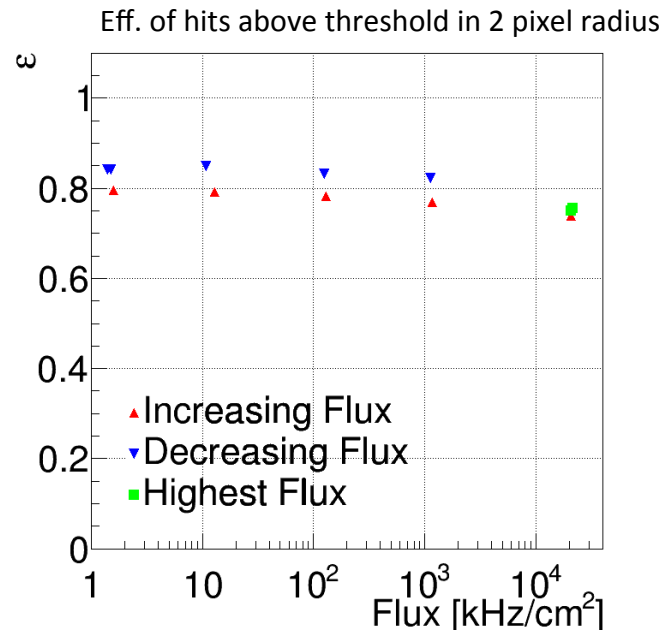
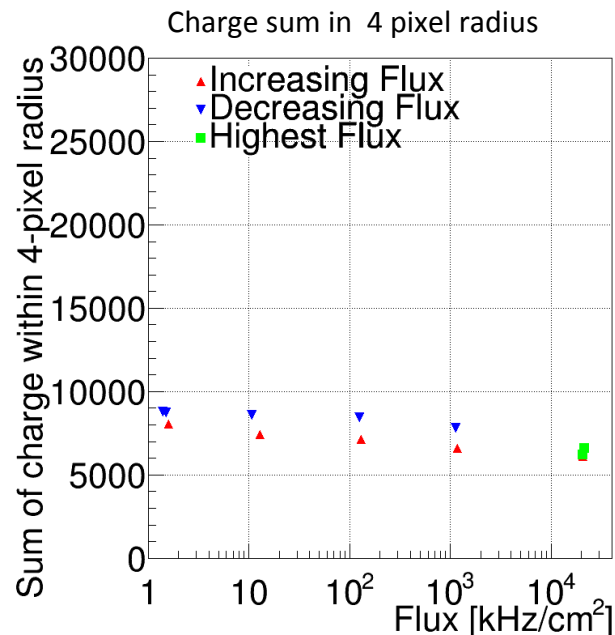
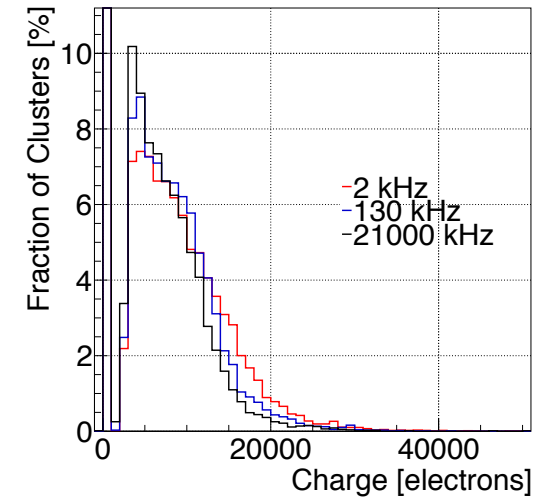
- Total pulse height and efficiency slightly increase, then remain stable
- Cluster size is also slightly increasing vs rate
 - Pumping or systematic bias



neutron-irradiated poly



- Irradiation dose 1×10^{14} n/cm².
- 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



Defects in single crystal diamonds

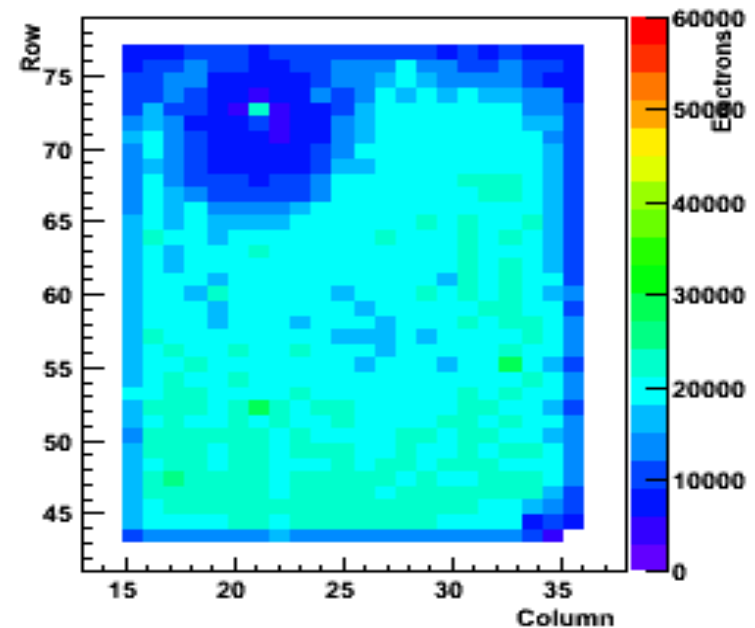


- cross polarizer view of the single crystal CVD diamond showing point defects and high stress regions



*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 sc-CVD 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 1×10^{14} n/cm² to disentangle geometry effects
- Rate dependence could be replicated with sc CVD 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/cm²
 - No dependence on polarity of HV observed (electron or hole carriers)

Outlook



- Study promising new single crystal diamonds from alternate vendor
 - check dependence on manufacturing procedures
- Study latest poly CVD diamonds from II-VI
 - higher collection distance (~ 300 μm)
 - 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					