Calibration of a pnCCD Detector at European XFEL

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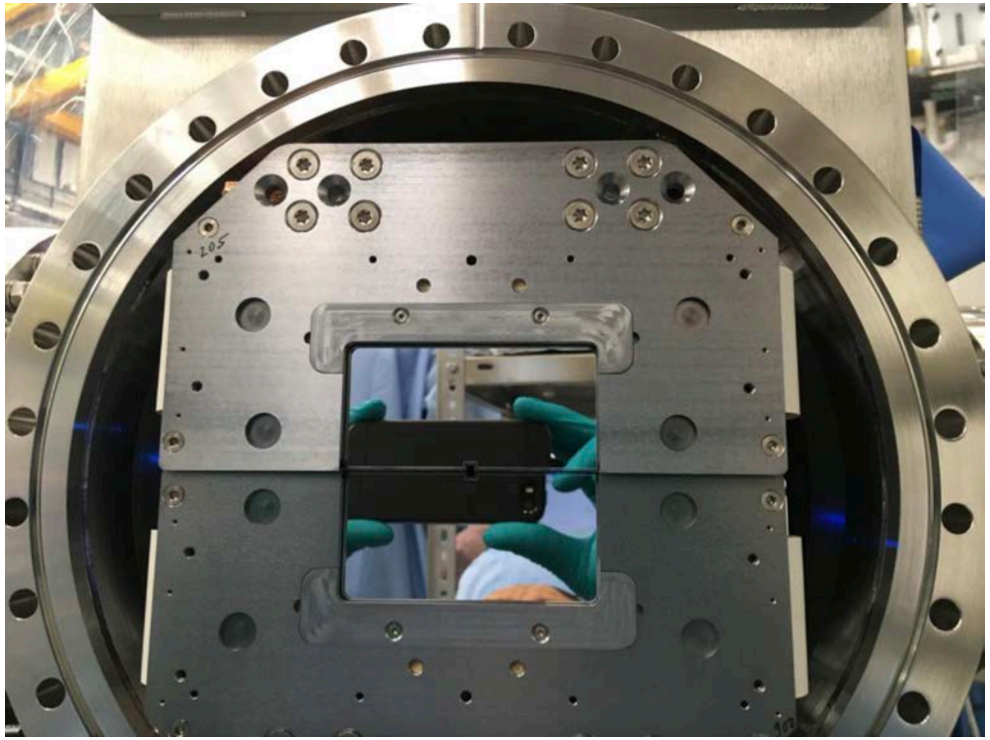
Used with Soft X-rays up to 3 keV

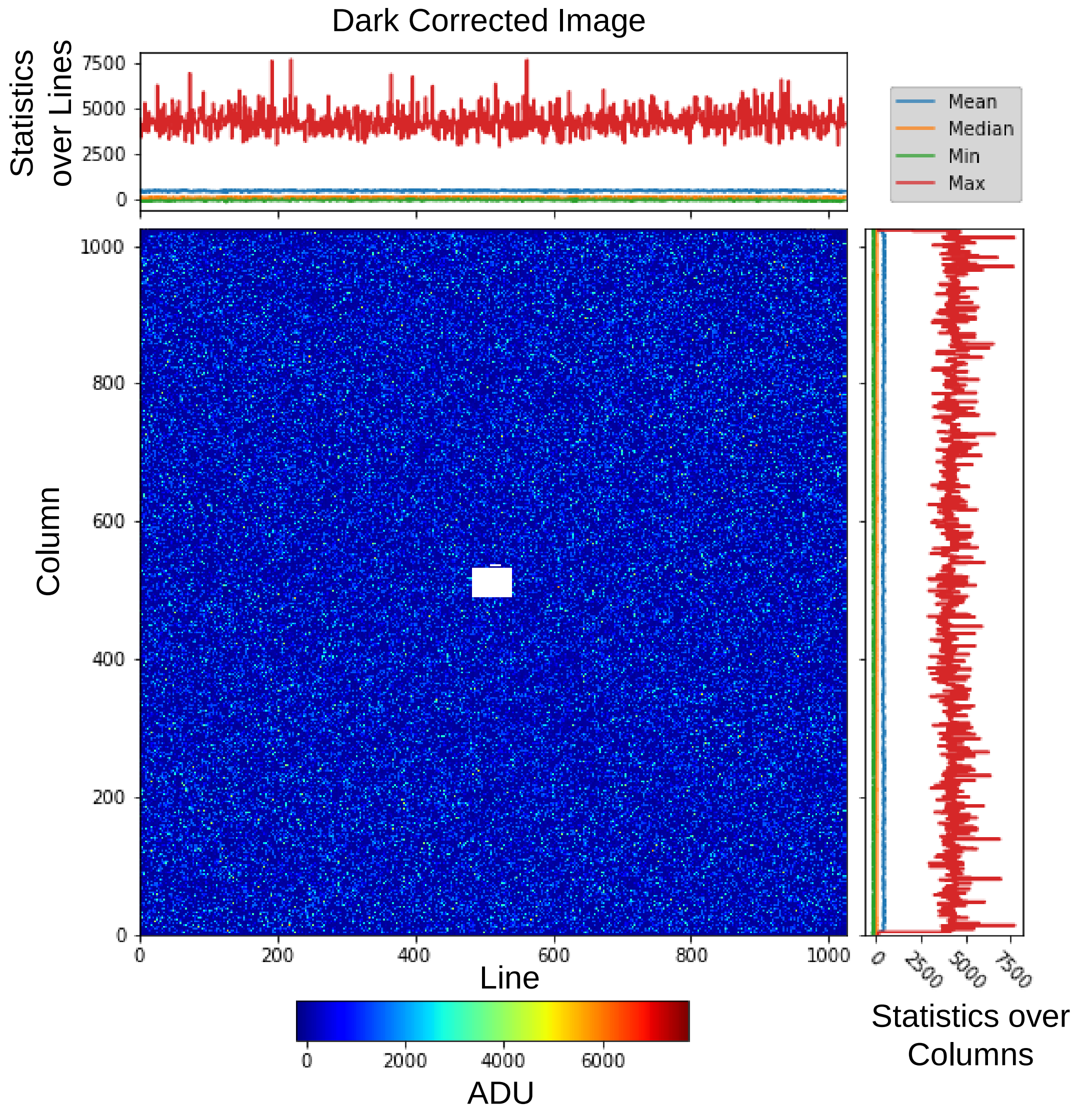
Property	Value
Photon Energy Range	0.3 – 25 keV
Pixel Size	75 µm × 75 µm
Sensor Size	1024 × 1024 pixels
Dynamic Range	< 3000 photons at 1 keV
Beam Hole Size	2 mm
Speed	Up to 150 Hz
Quantum Efficiency	> 80% for 0.7 < E_γ < 12 keV
Thickness	450 µm
Noise	$3e^-$ at High gain

Sensitive Area = 7.7 × 7.7 cm^2



Developed by PNSensor GmbH (Munich)

Flat-Field Illumination and Calibration of pnCCD at –30 °C – August 2020

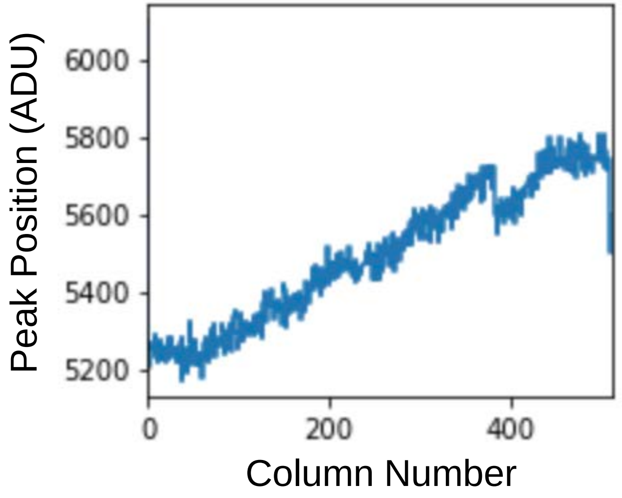


- Using Al fluorescence with an aluminum target
- Using FEL beam at 1.6 keV
- 4 gains are calibrated for bias voltage of –400 V.
- 1 gain is calibrated for bias voltage of –470 V.

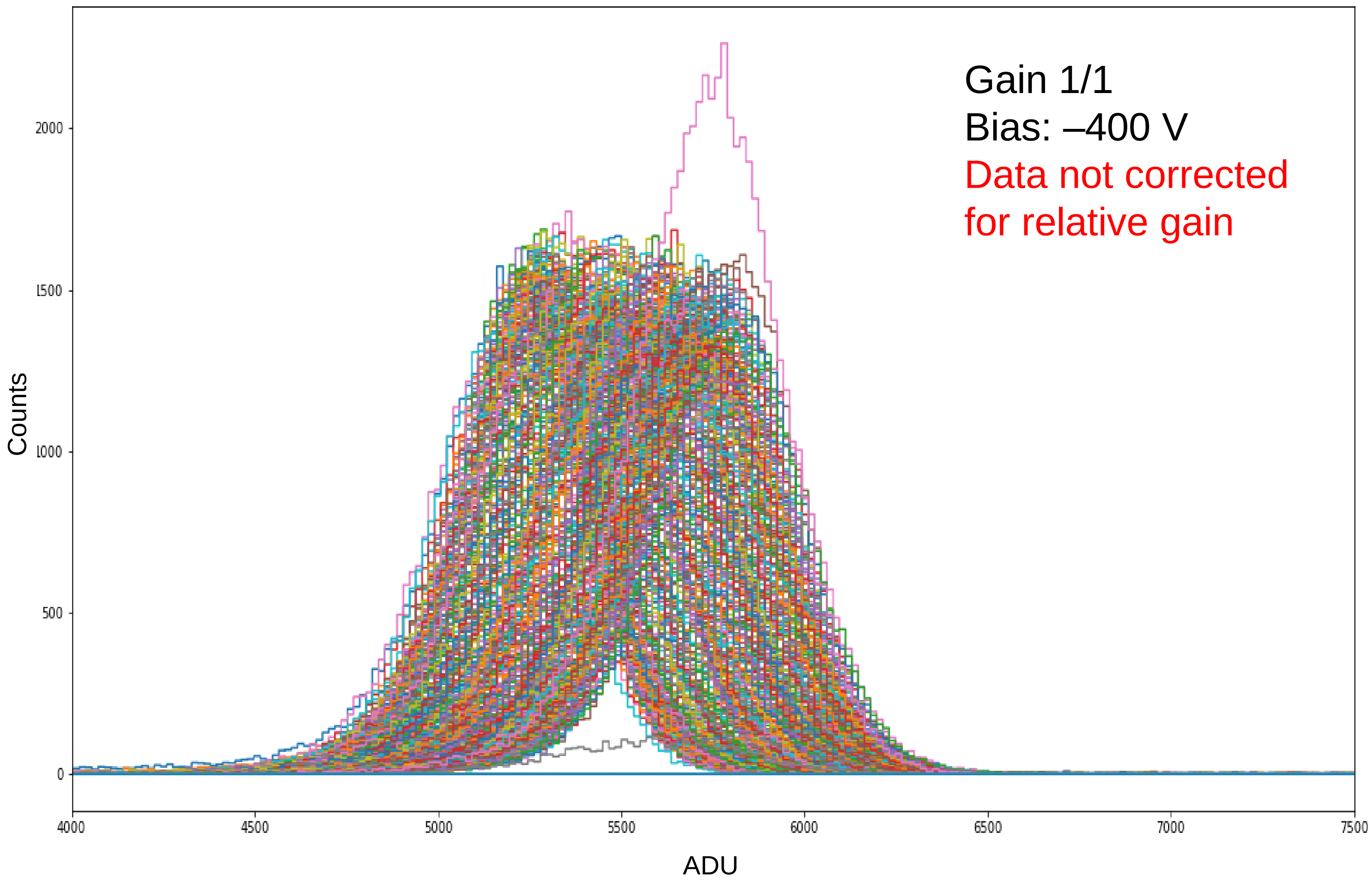
Parameter	Value
Sensor Temperature	-30°C: very stable
Frame Rate	10 Hz
Bias Voltage	-400 V
Gain	1/1, 1/4 , 1/16, 1/64 (one at the time)
Bias Voltage	-470 V
Gain	1/64

Relative Gain Calibration

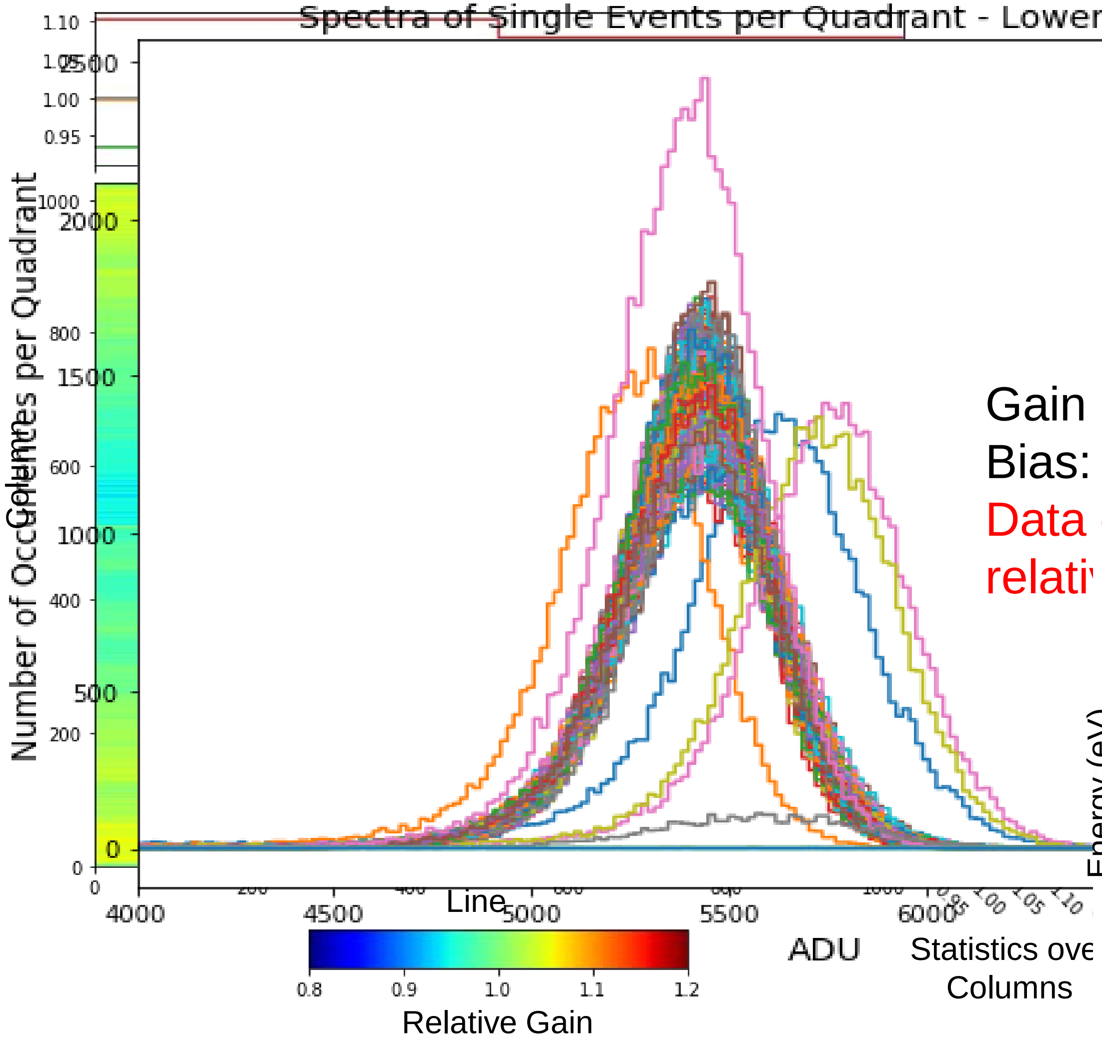
- One can obtain per column (readout axis) spectrum of single events and fit Gaussian functions to the peaks per column.



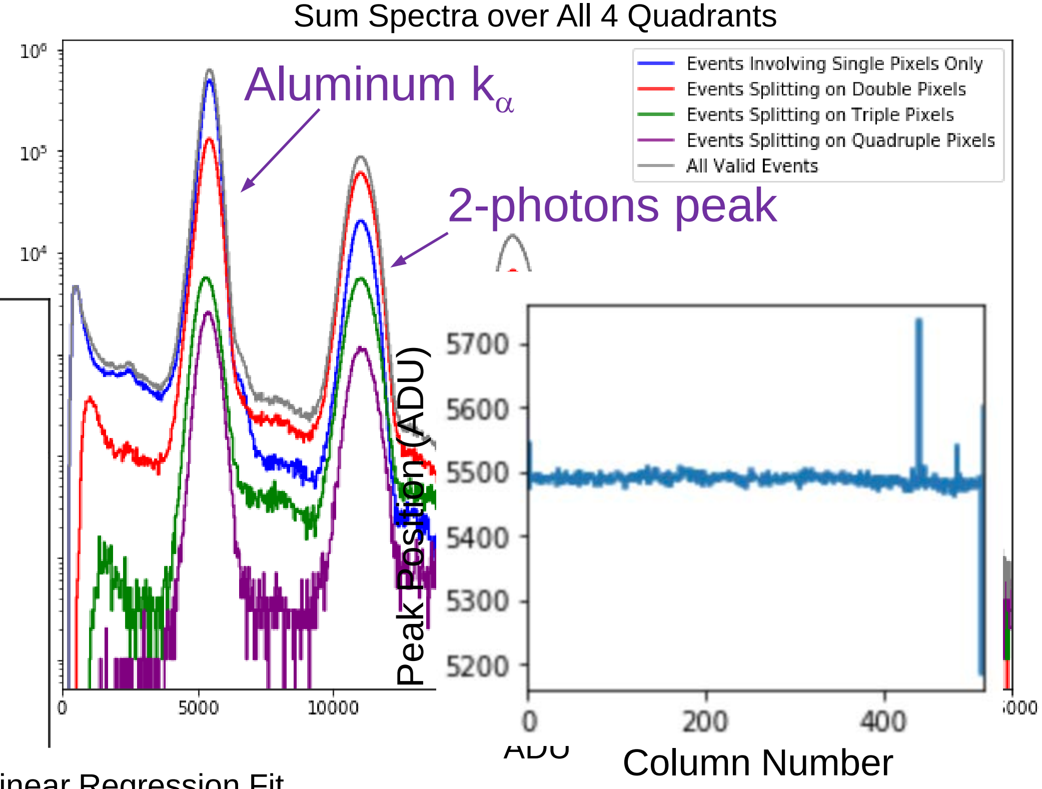
Spectra of **Single Events** for the Lower Left Quadrant

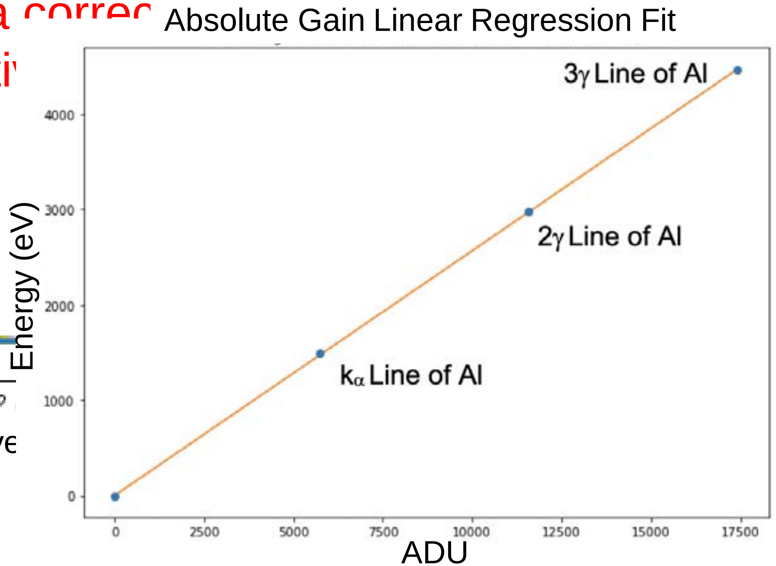


Calibration Results



Gain 1/1
Bias: –400 V
Data correc
relati





Parameter	Value
Absolute Gain for gain = 1/1	0.25659(53) eV/ADU
Energy Resolution	σ = 71.1(2) eV
Conversion Factor	0.07 e-/ADU

Outlook

- Detector was installed and commissioned in summer – 2020

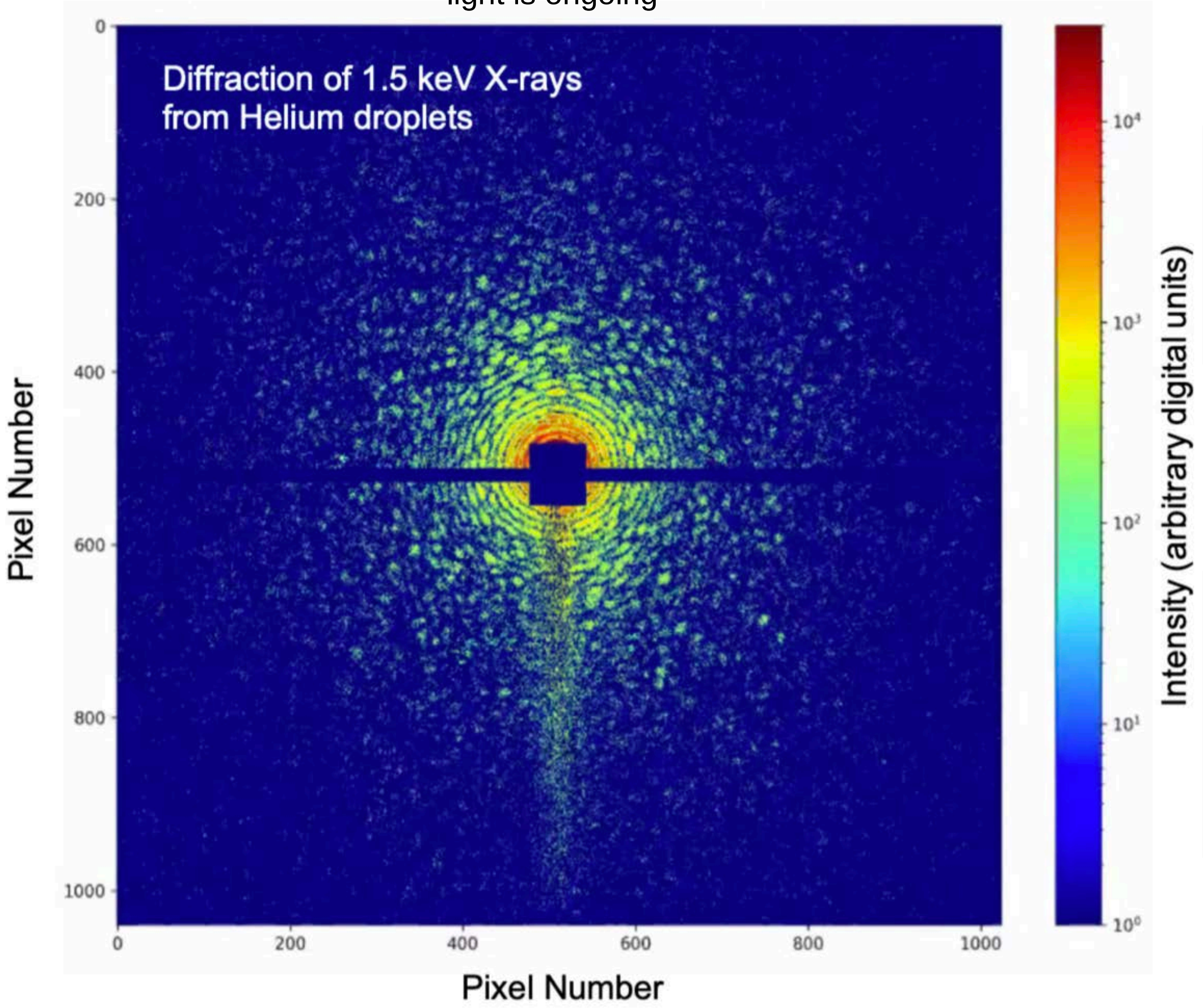
Also see M. Kuster et al., J. Synchrotron Rad. **28** (2021) 576.

- It was used in a following user run (09/2020)
- Experiment was very successful

- More calibration data will be obtained in 2021
- Spectroscopic capabilities are being investigated now using Xe data at 3 photon energies (1.2, 1.5, and 1.9 keV)

- More experiments are planned for 2nd half of 2021

Some stray light remained – improvements to eliminate stray light is ongoing

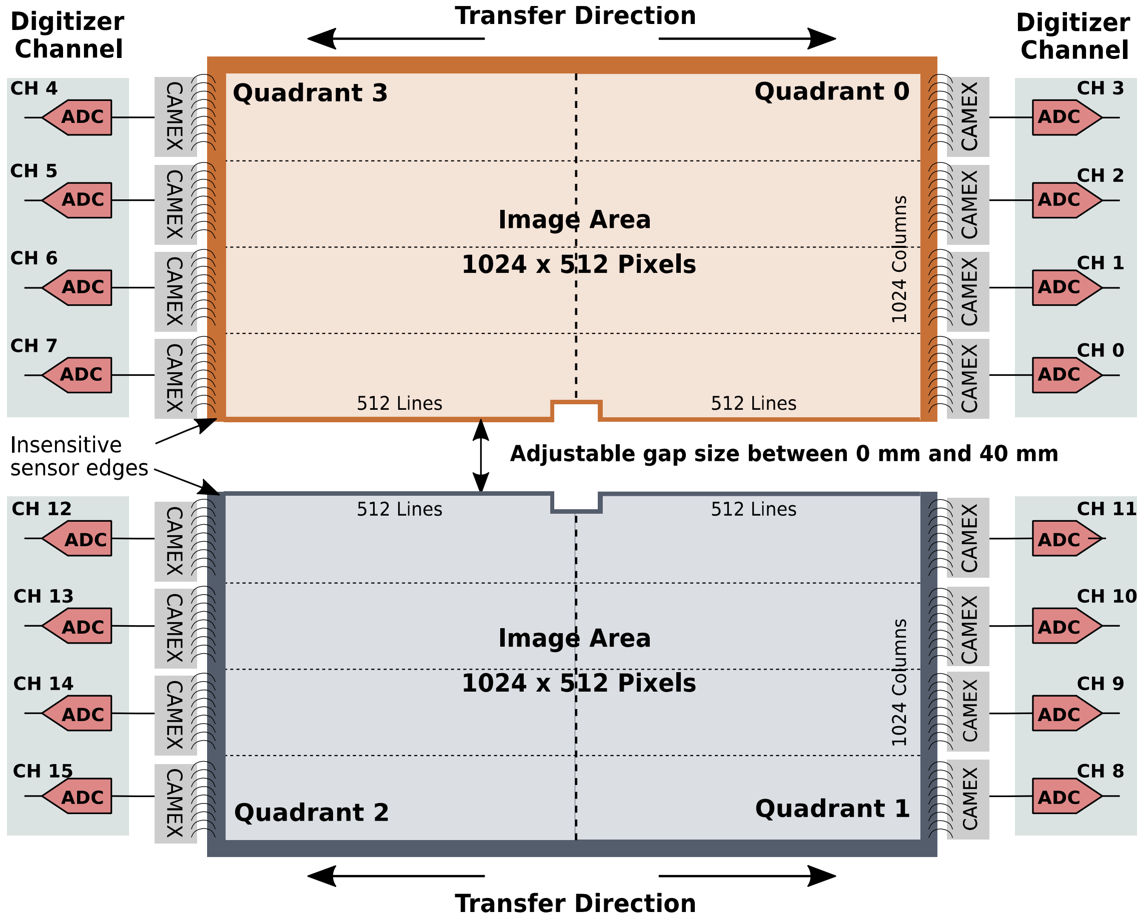


Backup Slides

pnCCD Readout and Operation Modes

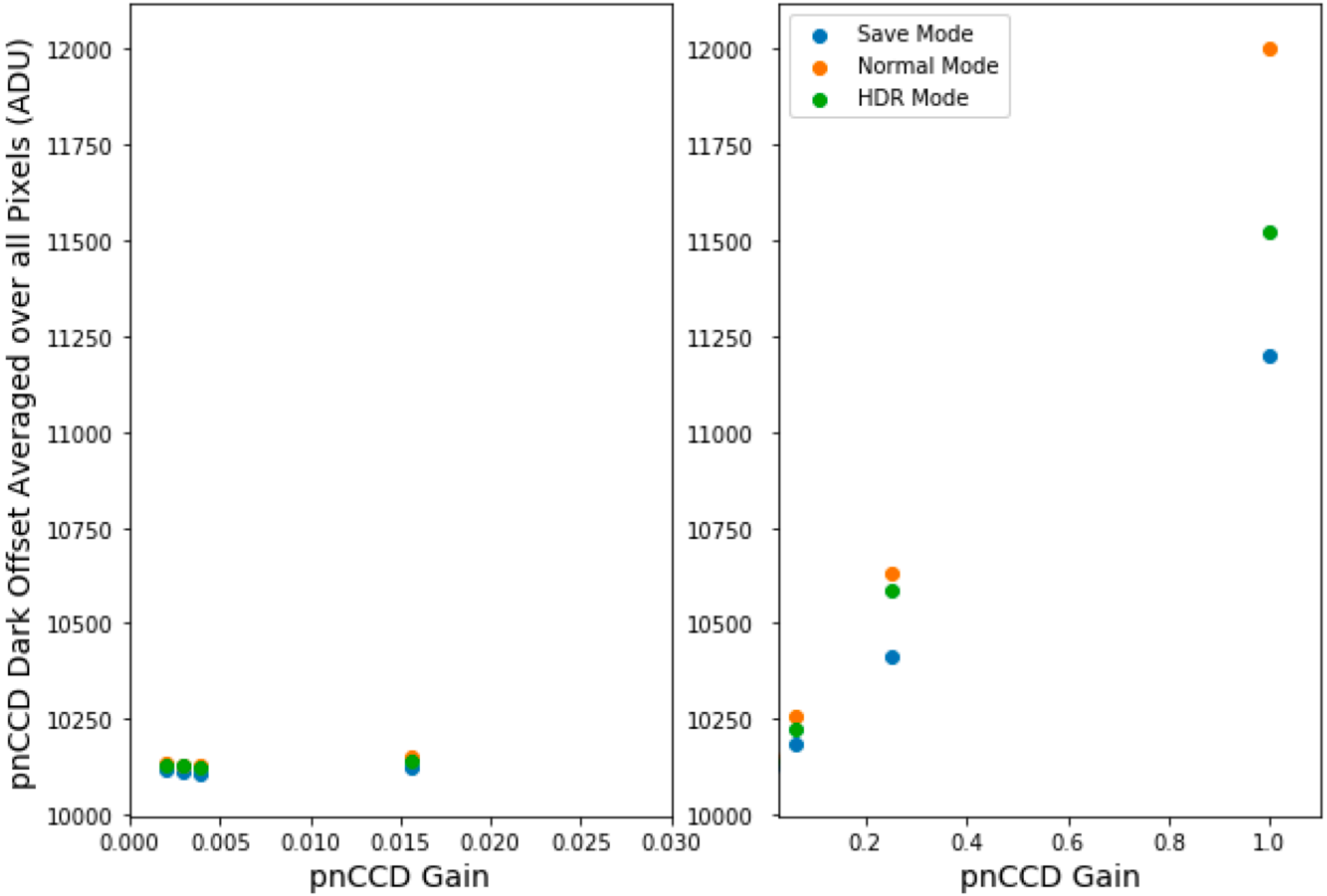
- Has 4 quadrants
- Charge is transferred per column along lines
- Readouts are on the left and right
- Every 128 columns share readout electronics: CAMEX

- pnCCD has 3 modes of operation (3 bias voltages)
- Each mode has 7 gains

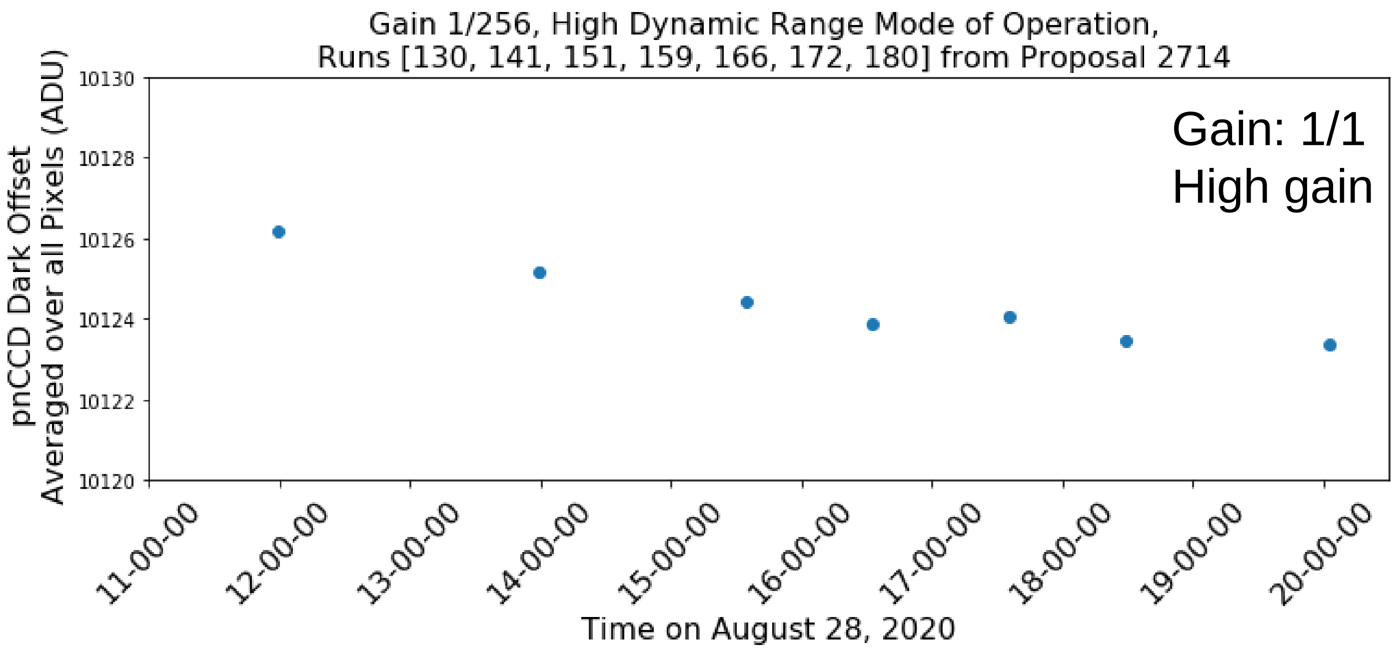


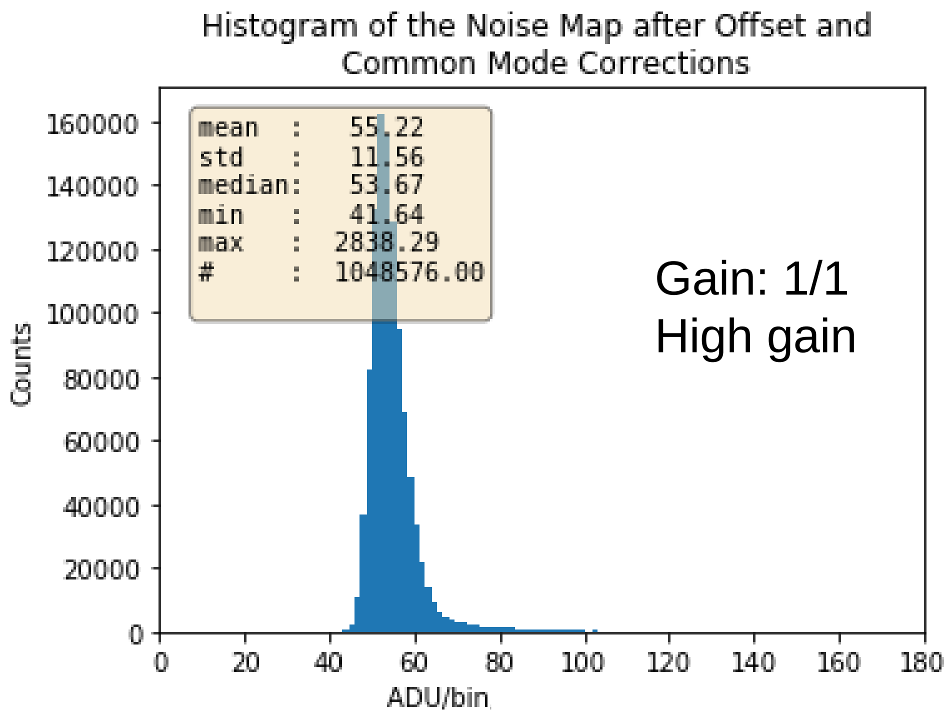
Dark Characterization

- Dark pedestal is the highest for Normal mode of operation (highest power output @ –400 V)
- Pedestal decreases with decreasing gain
- At very low gains, pedestal remains constant



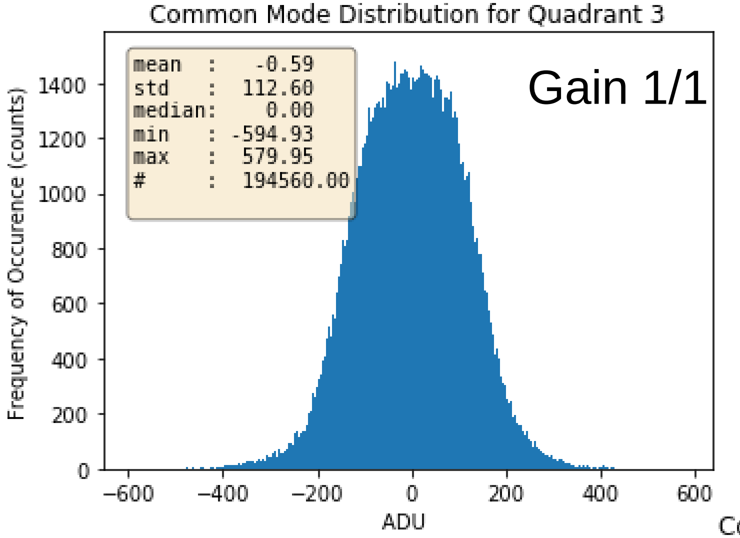
Dark Pedestal and Noise Characterizations

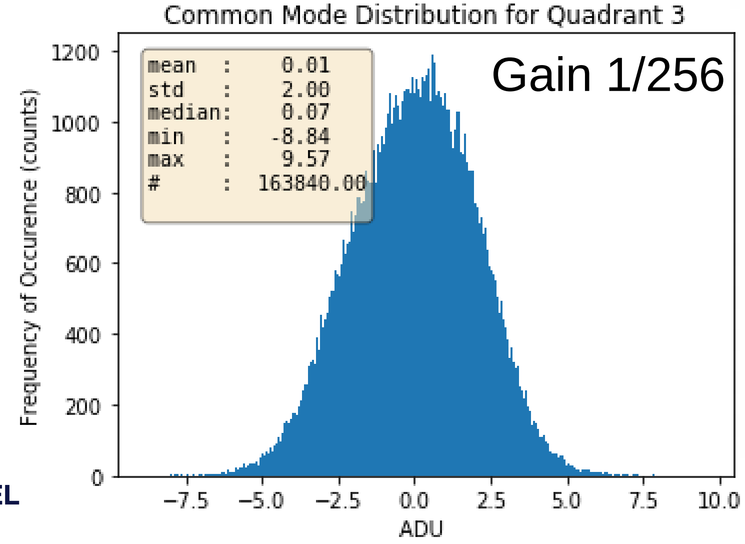


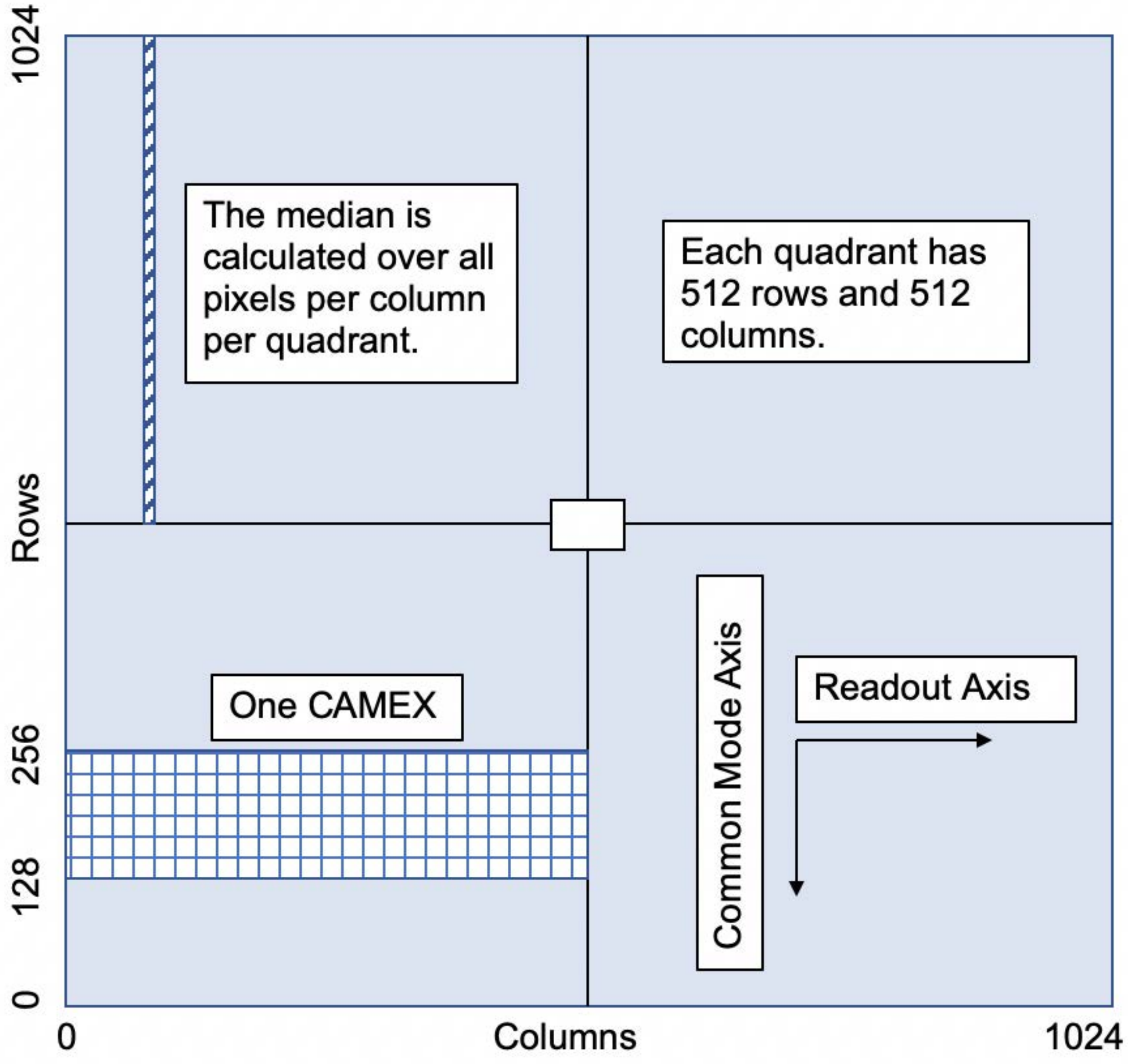


- Dark pedestal is rather stable
- Noise is dominated by the CCD noise in gains 1/1 and 1/4 (high gains): gain = 1/1: 55 ADU, gain = 1/4: 27 ADU
- Noise is dominated by electronics noise in gains <= 1/16 (remains constant around ~8 – 9 ADU)

Common Mode Characterization

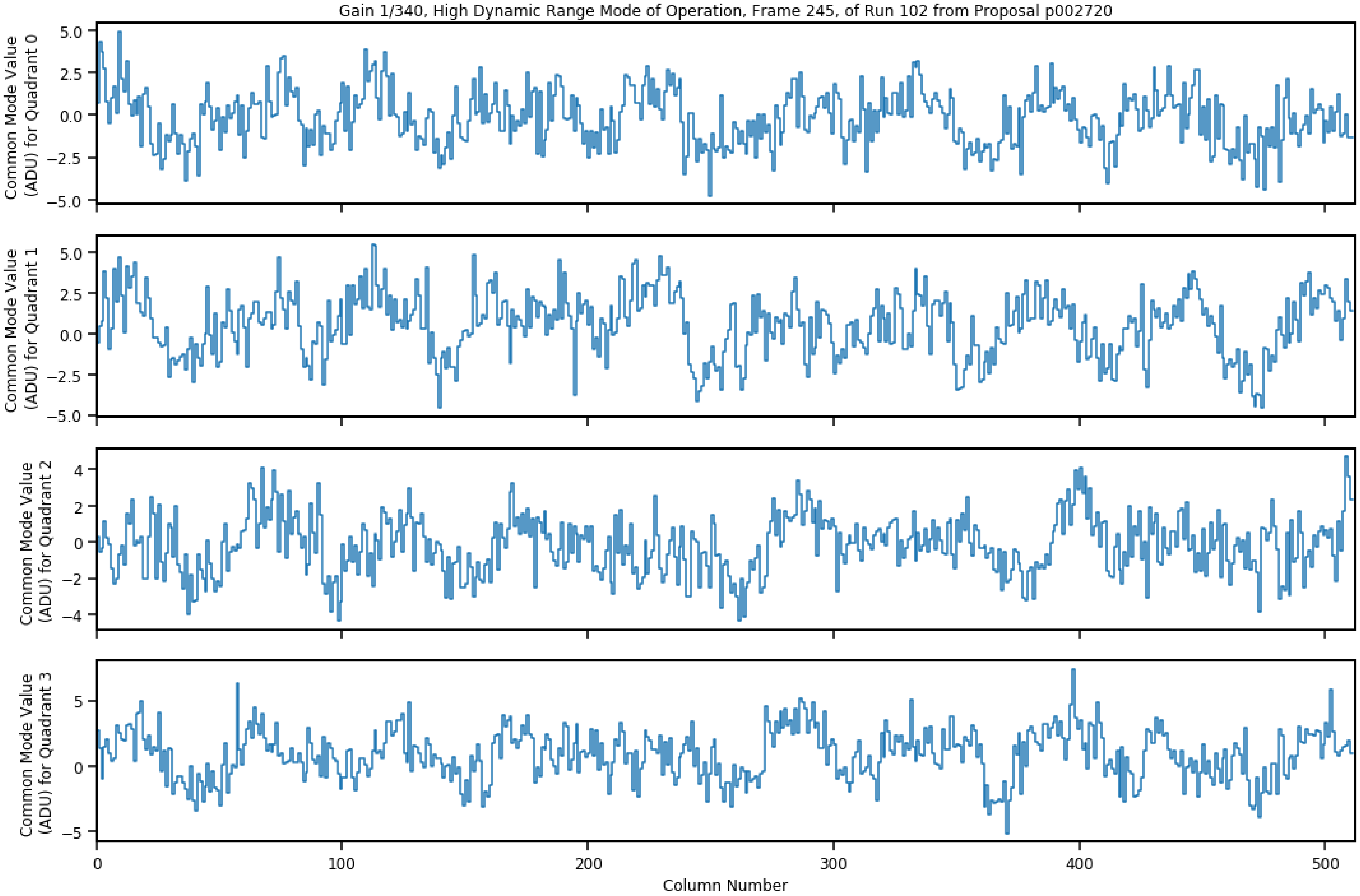






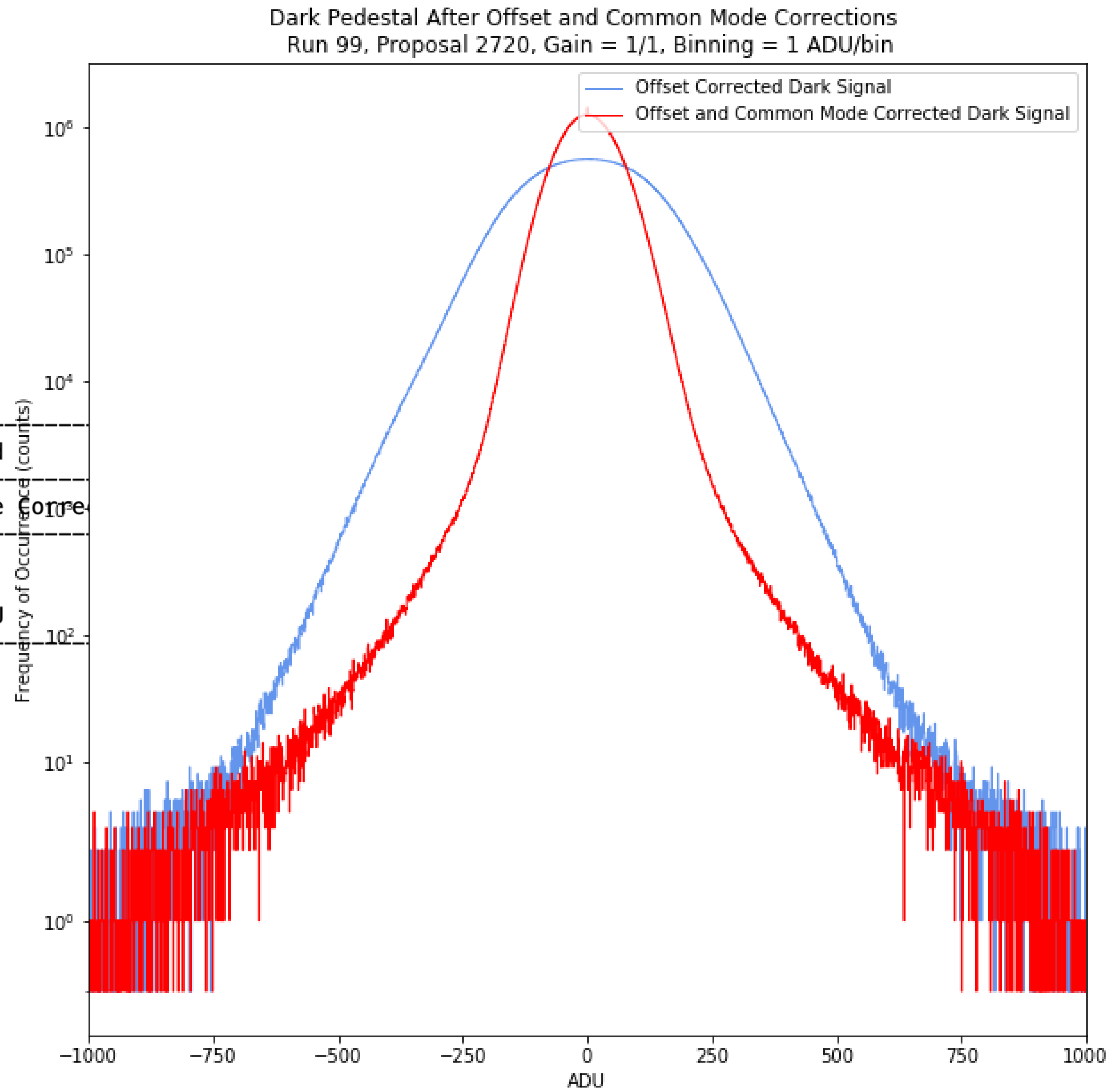
Common Mode Characterization

Distribution changes from image to image and run to run

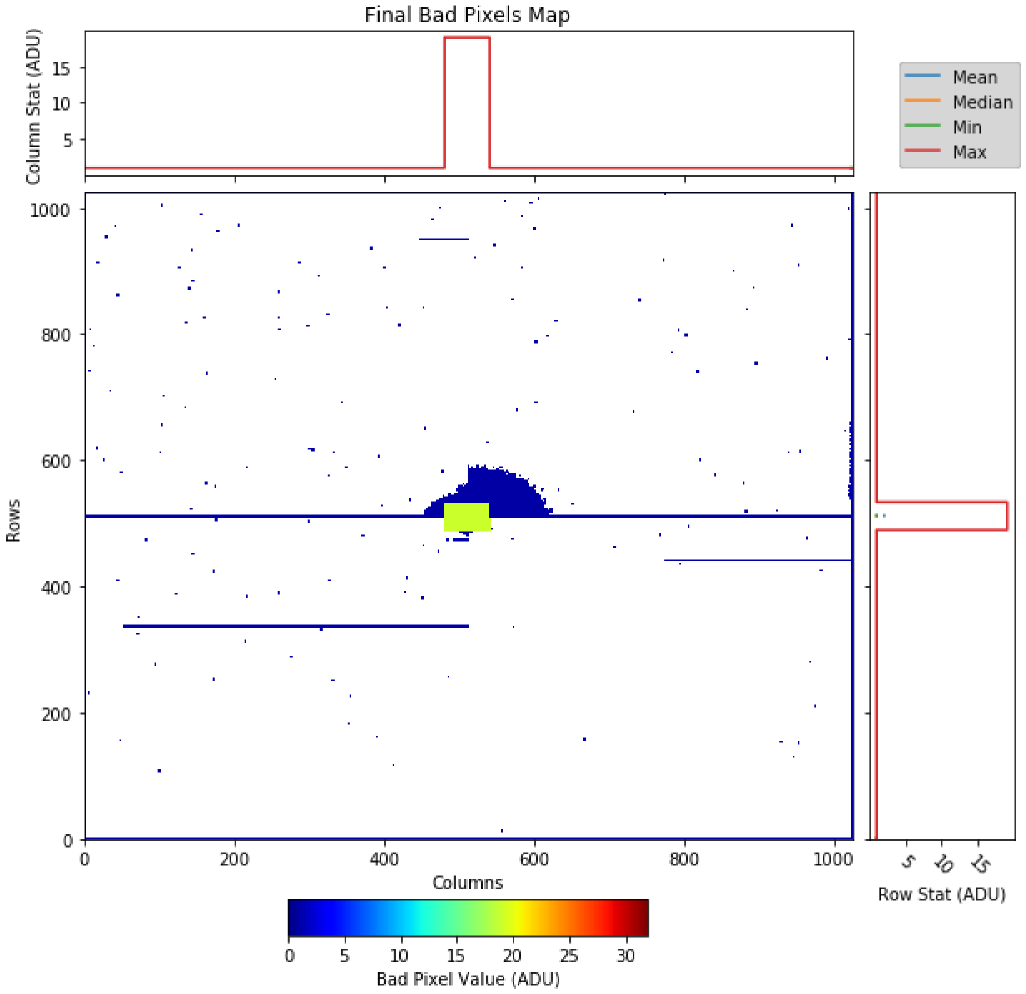


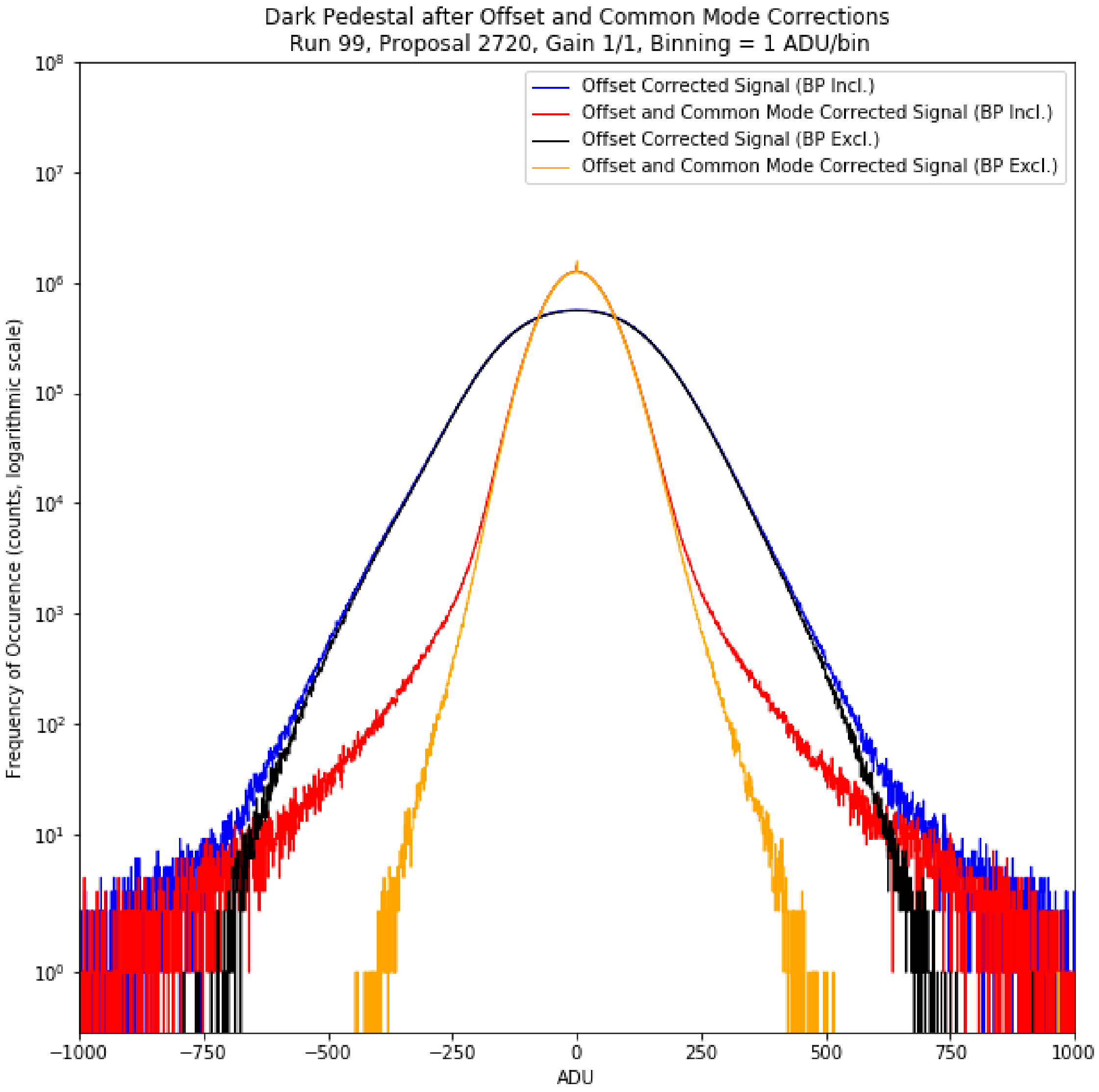
Common Mode Effect

Comparison of the First Round of Corrections – Bad Pixels Not Excluded	
Dark Pedestal After Offset Correction	Dark Pedestal After Offset and Common Mode Corre
Mean: 0.111 ADU Median: 0.221 ADU Standard Deviation: 116.852 ADU	Mean: 0.412 ADU Median: 0.000 ADU Standard Deviation: 55.962 ADU



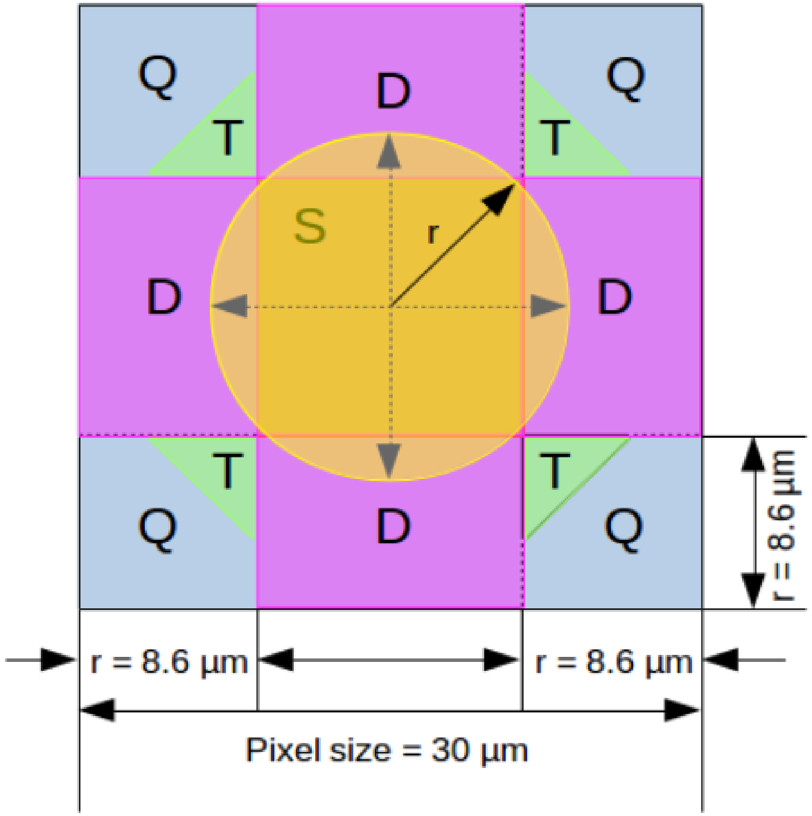
Bad Pixels Removal Effect





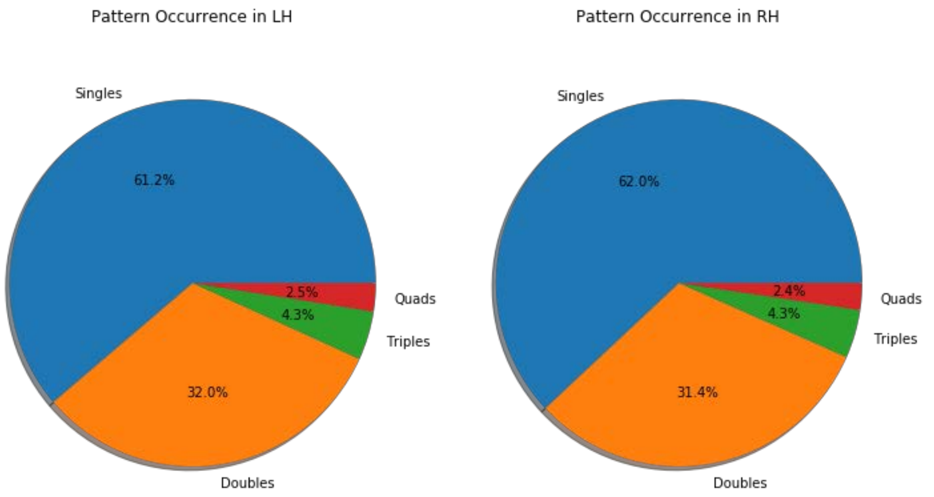
Illuminated Frame Characterization

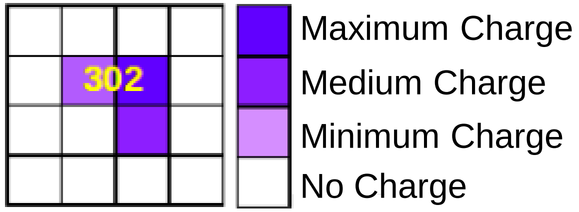
- Bad pixels are masked (in the analysis)
- Offset is corrected for
- Common mode is calculated and corrected for
- Charge sharing (due to small pixel size) is evaluated
  - Events are classified into different patterns
  - Single **events with no charge sharing** are identified
- Single events are used for charge transfer inefficiency and gain characterization



S: Singles, D: Doubles,
T: Triples, Q: Quadruples

Diagram is for another CCD with different pixel size!



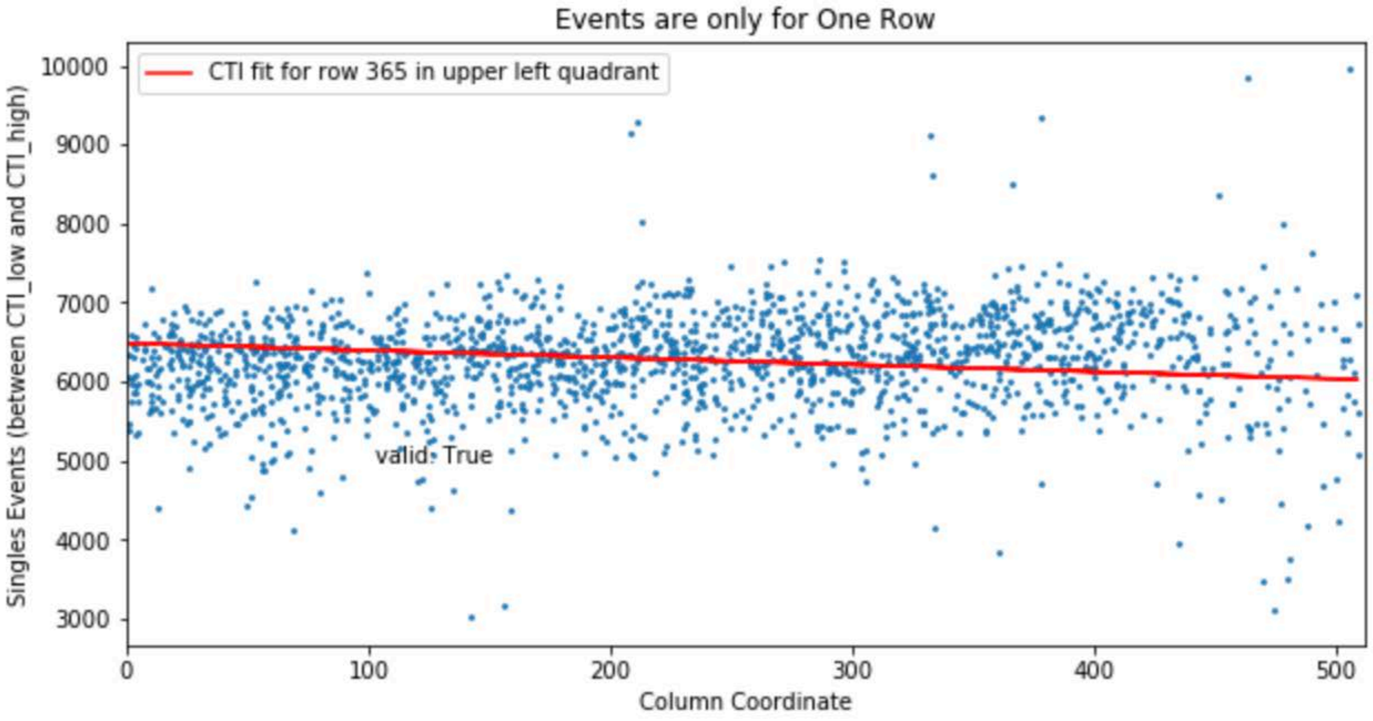


Charge Transfer Inefficiency

CTI: Fractional loss of charge during charge transfer due to existence of traps in the pixel structure

- To evaluate CTI, single events are plotted vs. columns, for each row. Plots are then fitted using a linear function:

$$y = m \times x + b \qquad CTI = \frac{m}{b}$$



CTI Correction

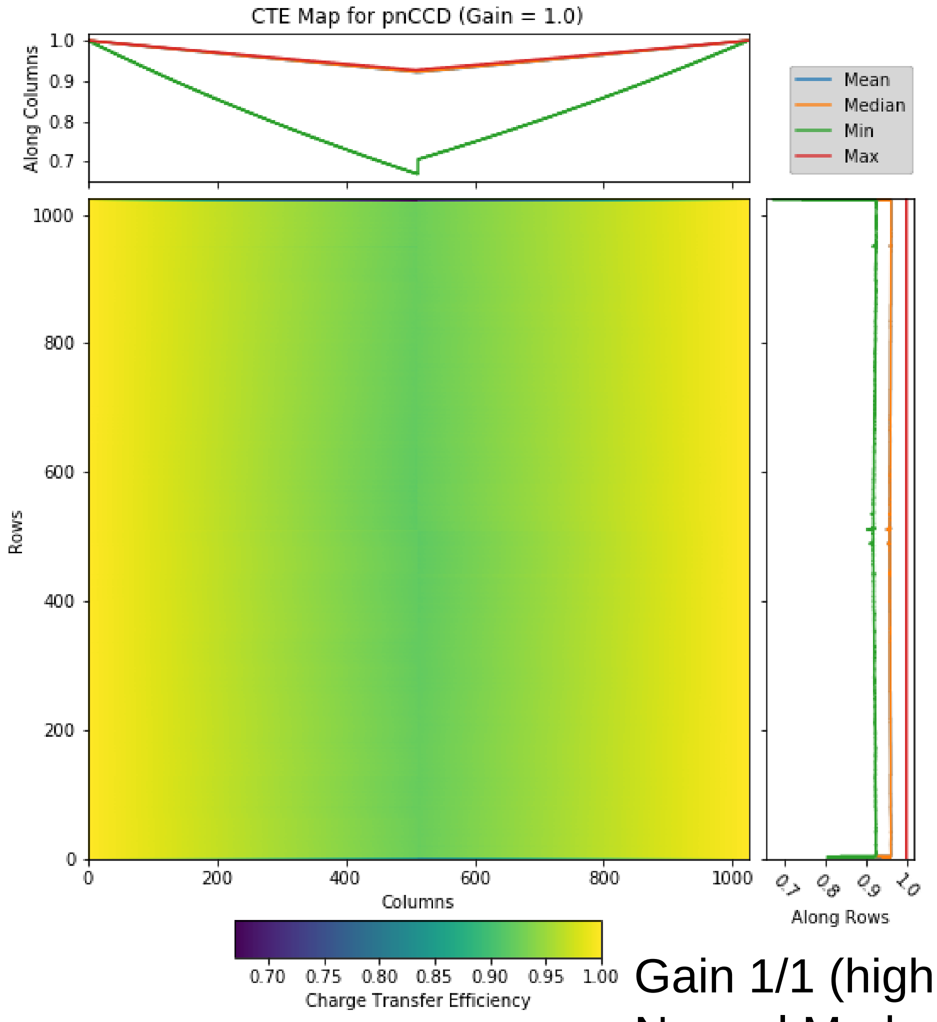
- From the CTI fits, one value of CTI is obtained per each row

- CTE map is then computed as follows: CTE Map = $(1 - \text{CTI})^{\text{columns}}$

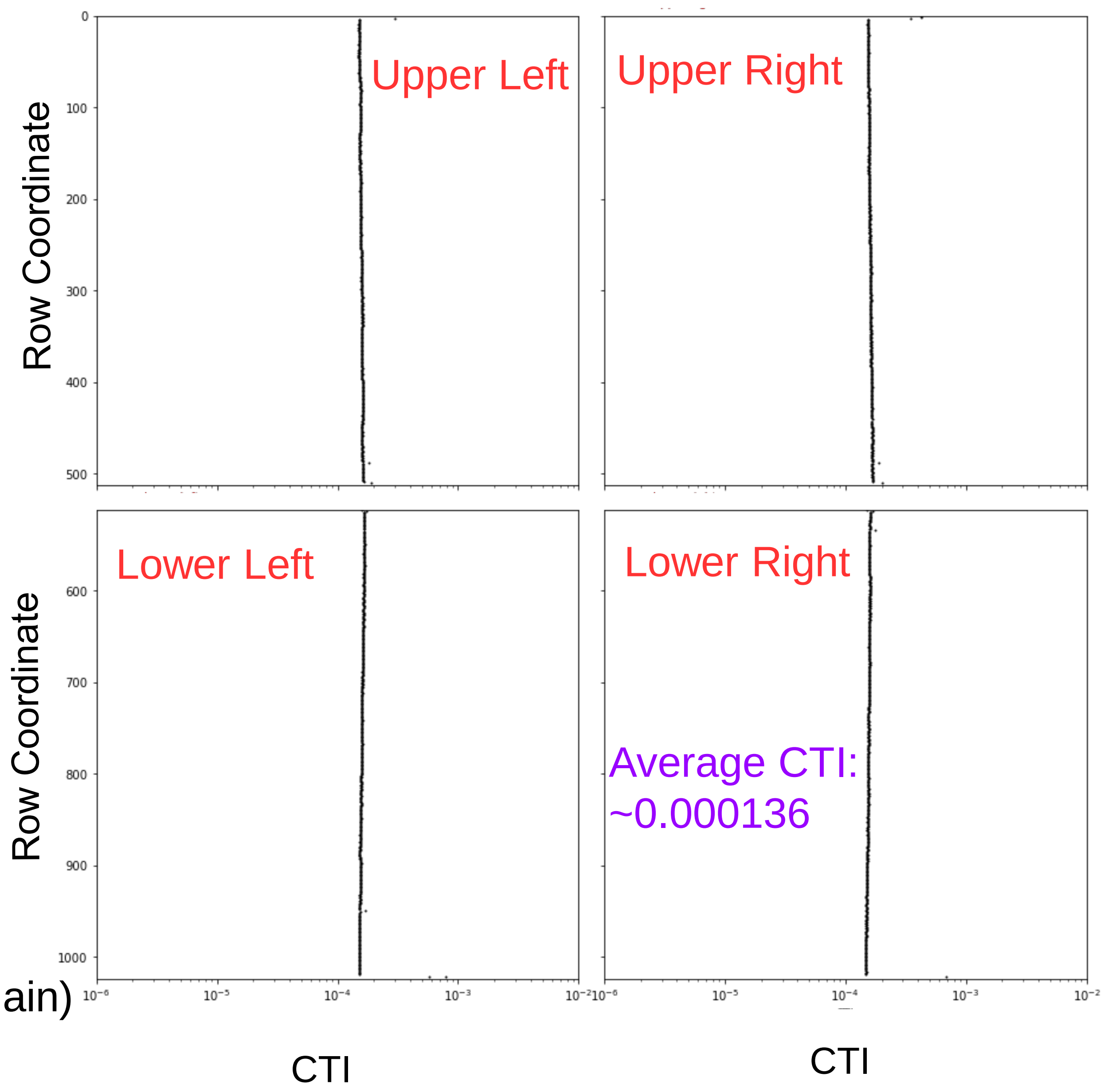
- The created CTE map is then used for correction of the CTI effects by multiplication of data and the CTE map on a per pixel basis

- CTI is rather insignificant and when corrected, it does not really have any noticeable effect on the images
    - We ignore this correction for pnCCD

pnCCD Charge Transfer (In)Efficiency



Gain 1/1 (high gain)
Normal Mode



Gain Characterization and Gain Correction

Relative gain: the relative difference in the amplification of charge due to different output amplifiers. It is calculated as:

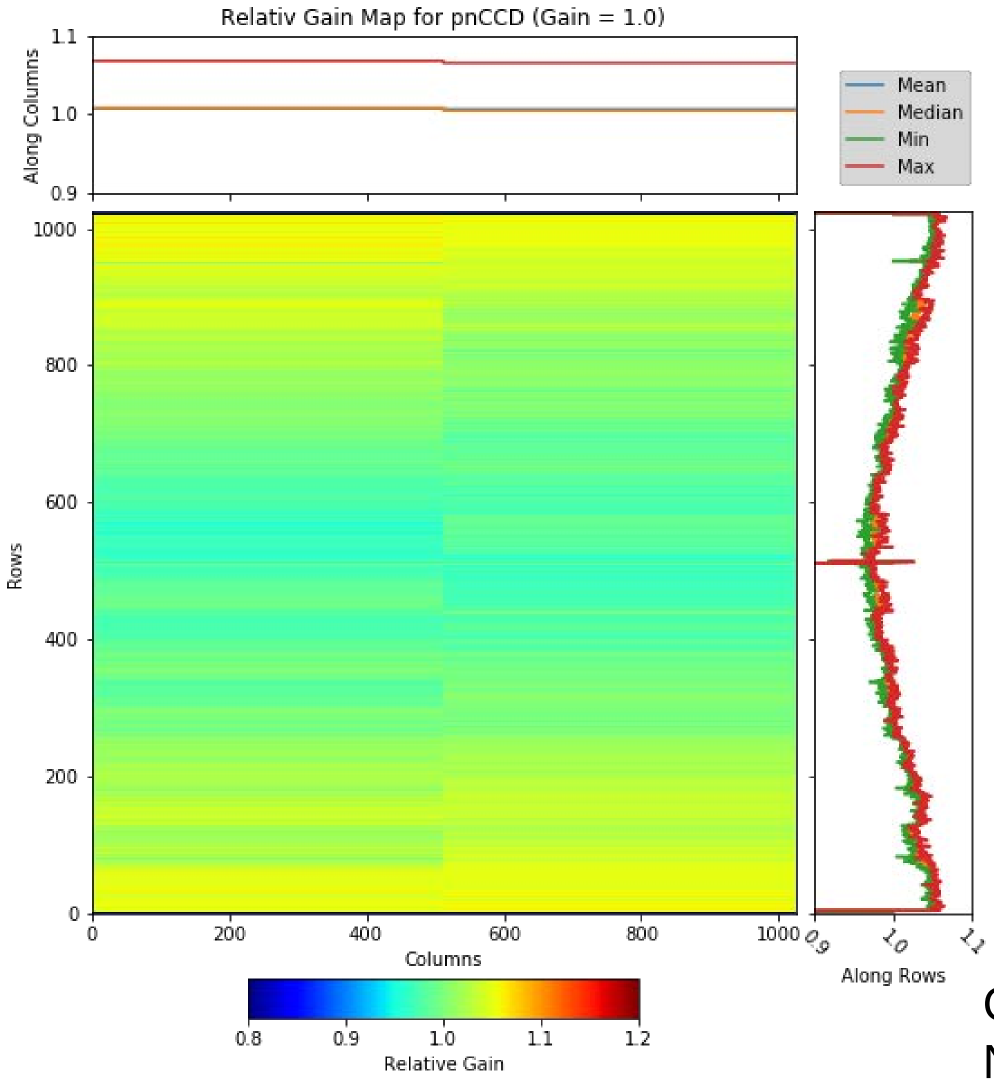
$$relative\,gain = \frac{b(i)}{\frac{1}{N}\sum_{i=0}^{N} b(i)}$$, b = intercept of linear fits; N = total # of columns per quadrant

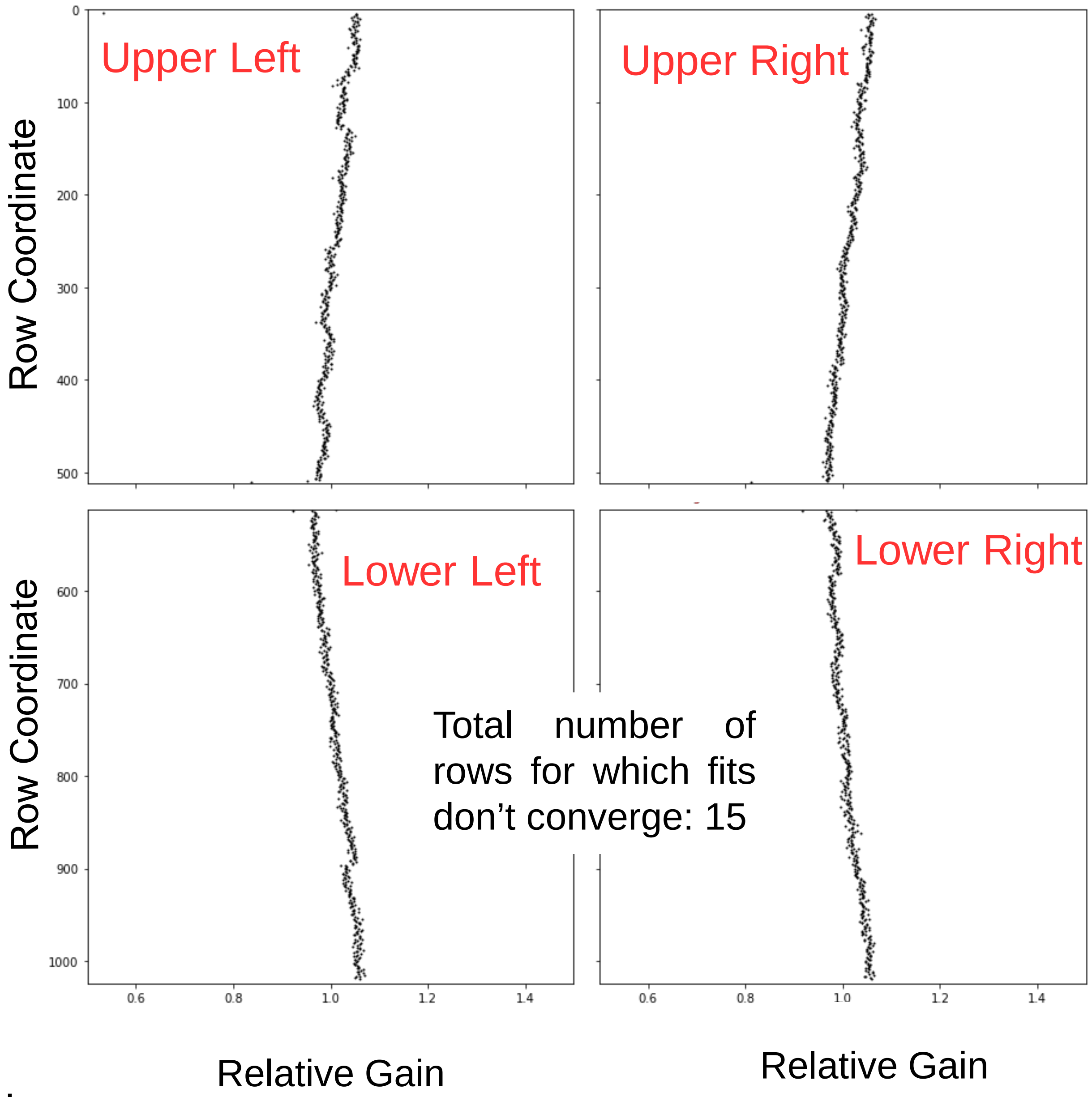
Once we obtain the relative gain map, we can correct for it:

- Mask bad pixels and cosmic ray events in the analysis
- Correct for offset
- Calculate common mode and correct for it
- Divide the data by the gain map
- Divide data into 4 quadrants and correct for split events (pattern classification)
- Arrive at final corrected spectrum of singles events
- Fit the above spectrum with Gaussian peaks
- Now we have energy (eV) vs. ADU: Fit these data to obtain absolute gain information

Uncertainty is less than ±2%

pnCCD Gain Characterization

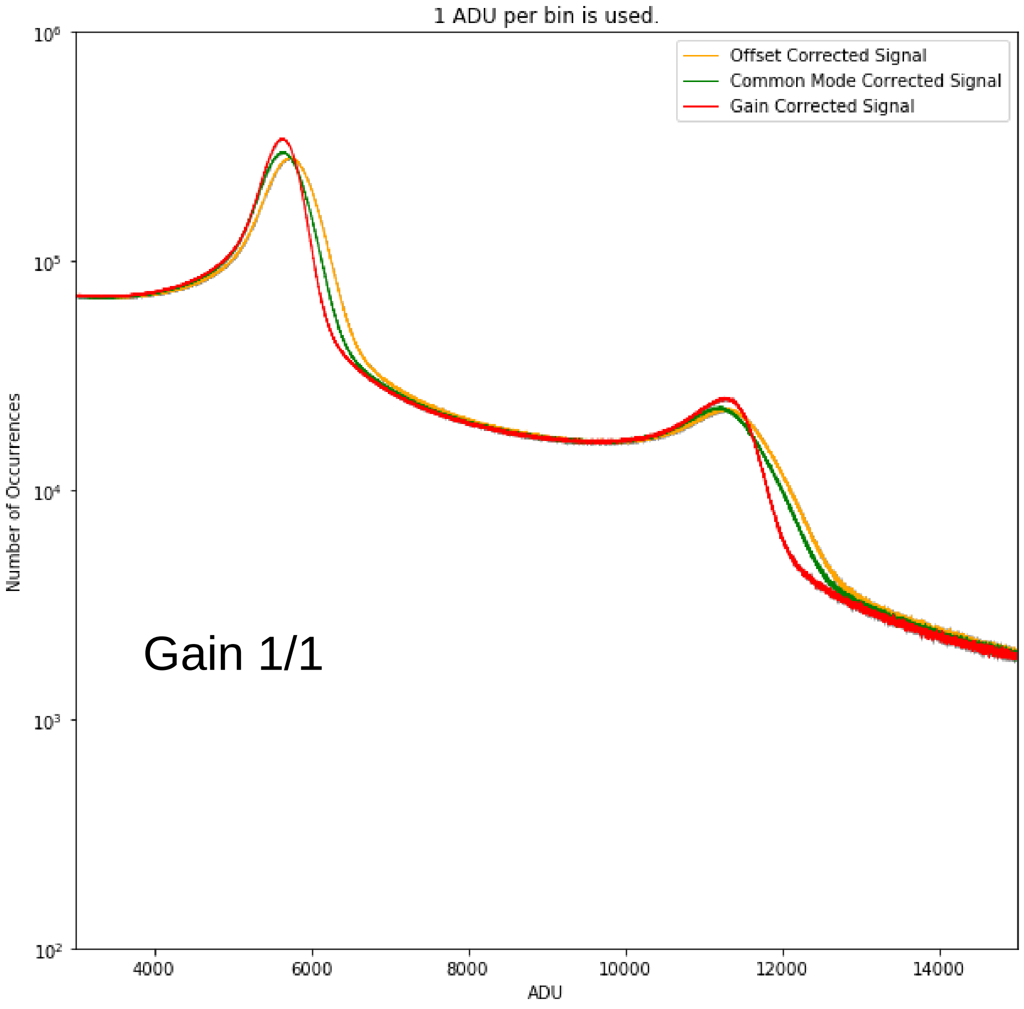


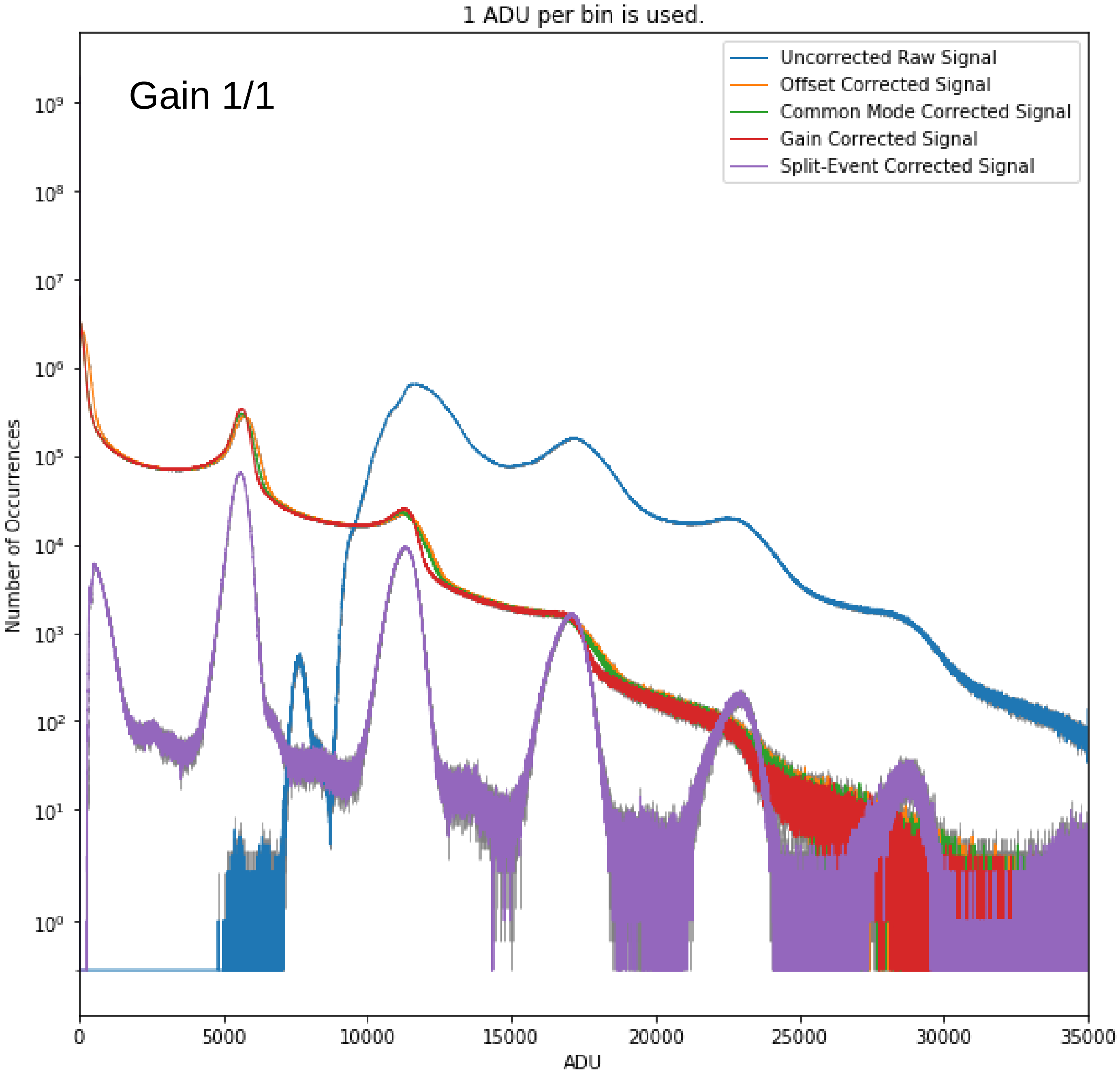


Total number of rows for which fits don't converge: 15

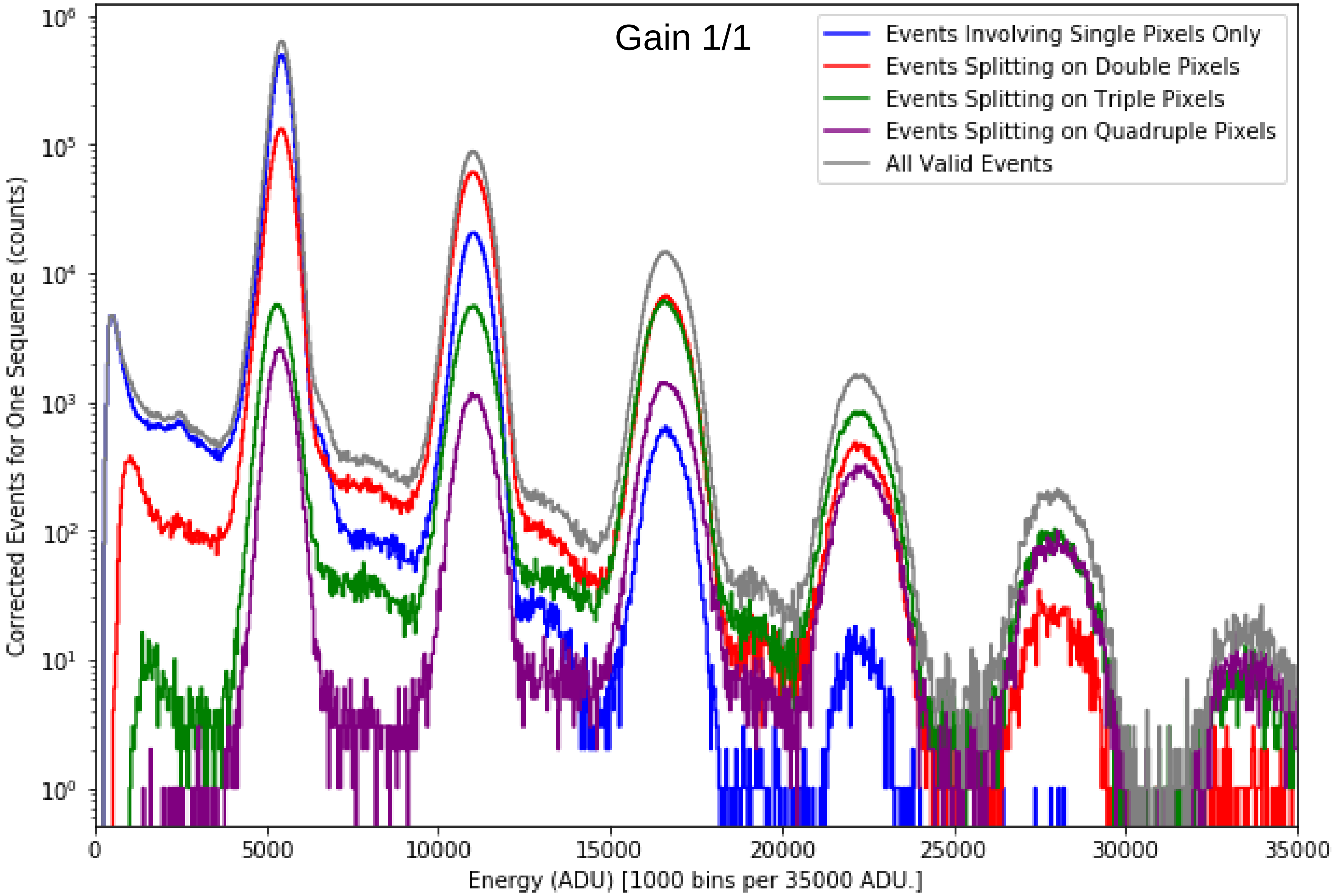
Gain 1/1
Normal Mode

Various Data Corrections





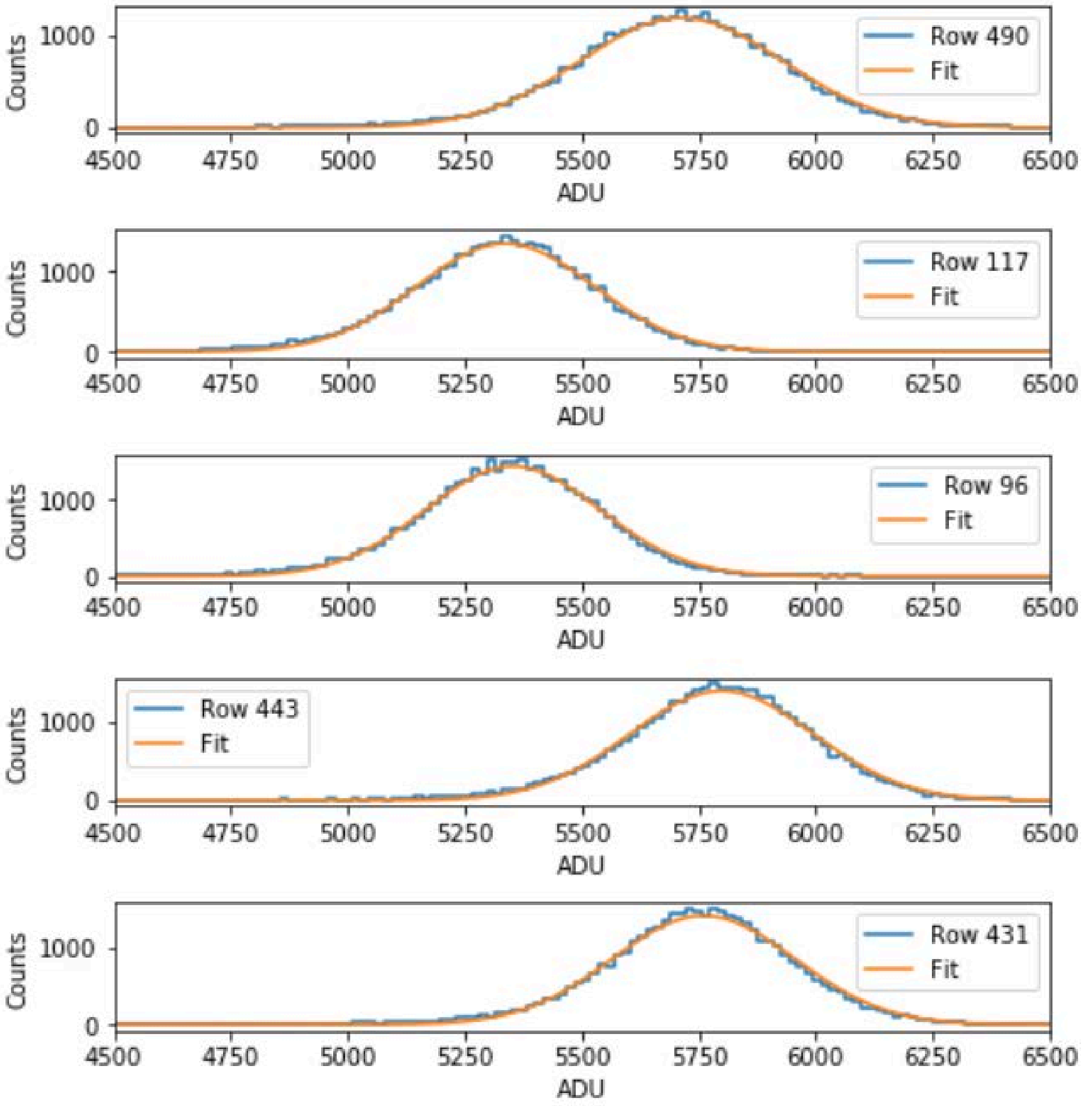
Valid Events Spectra After All Corrections



Aluminum Fluorescence

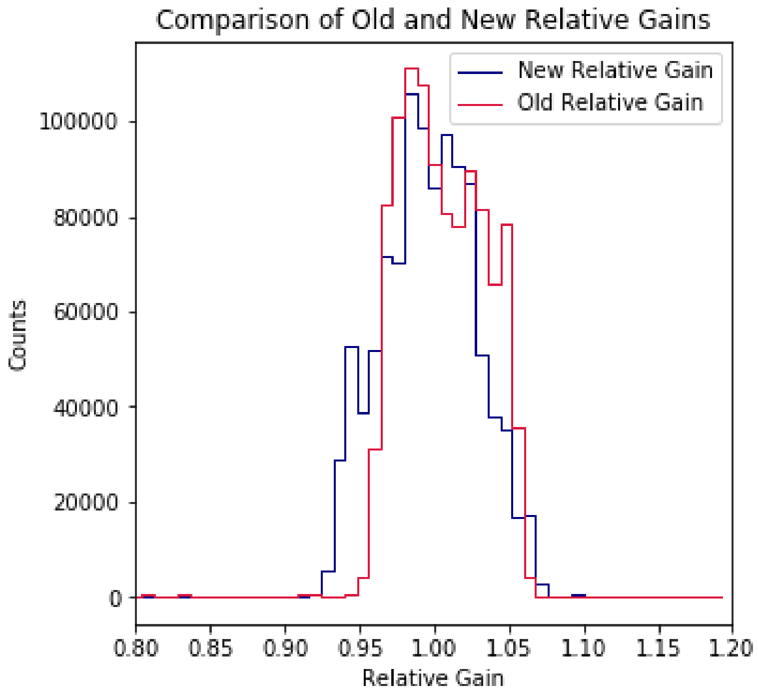
Fitting Gaussian Peaks to Spectra

- I only fit the k_{α} peak of Al
- 512 columns per quadrant
- 4 quadrants
- Fits take about ~20 minutes

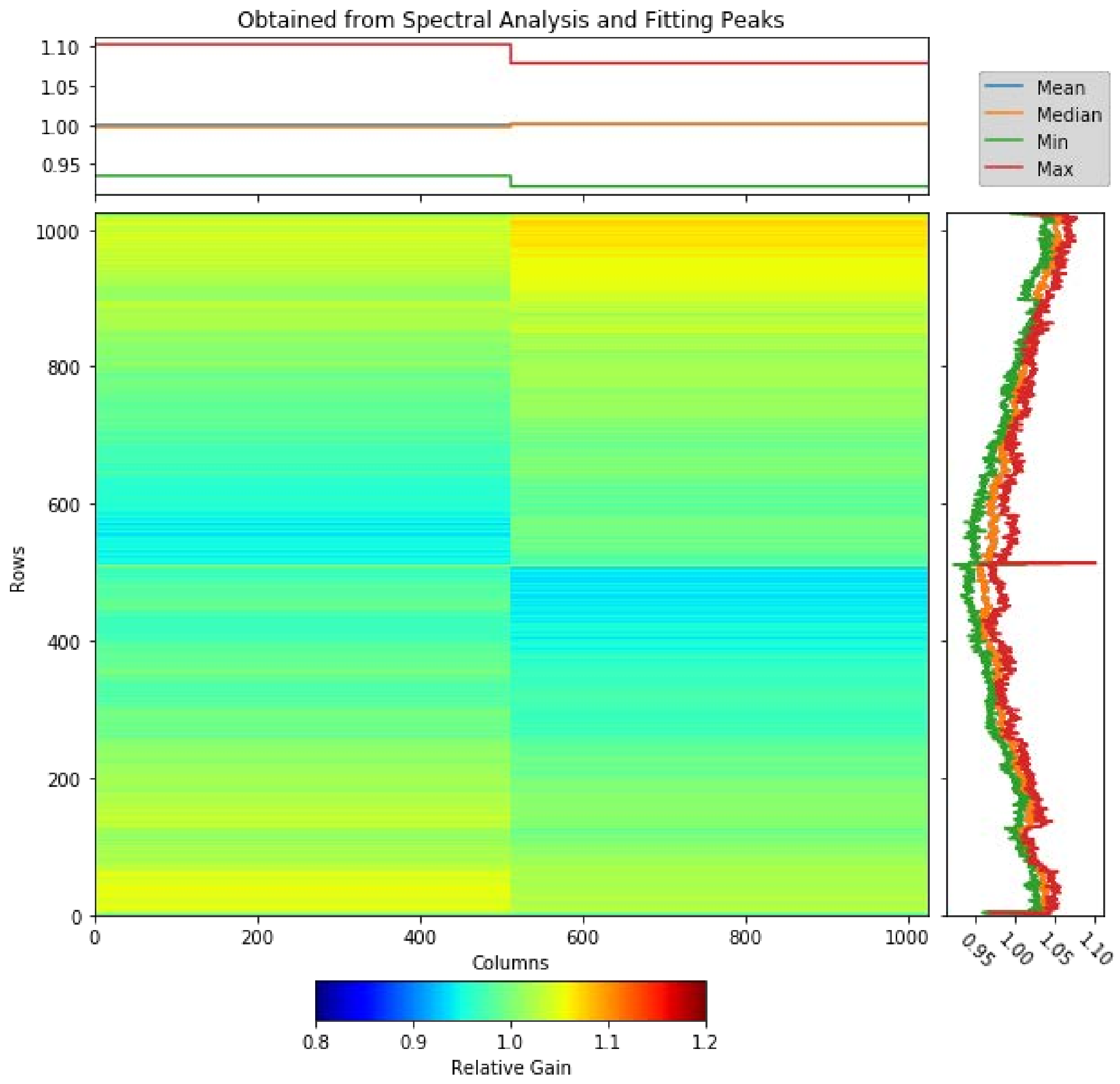


Row-wise Relative Gain Calibration

- By fitting Gaussian functions to each column spectrum of single events, one can derive a relative gain map

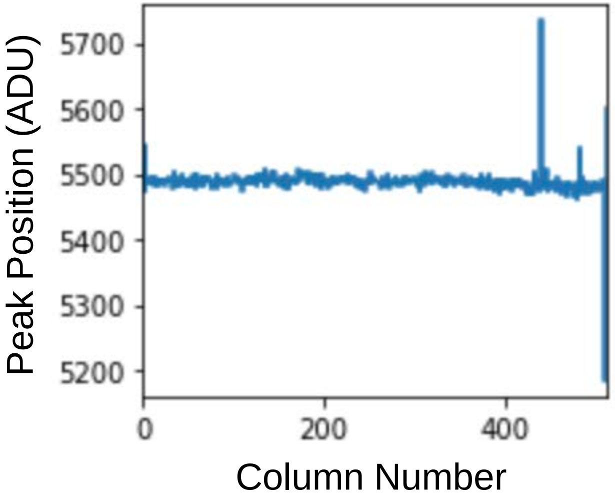


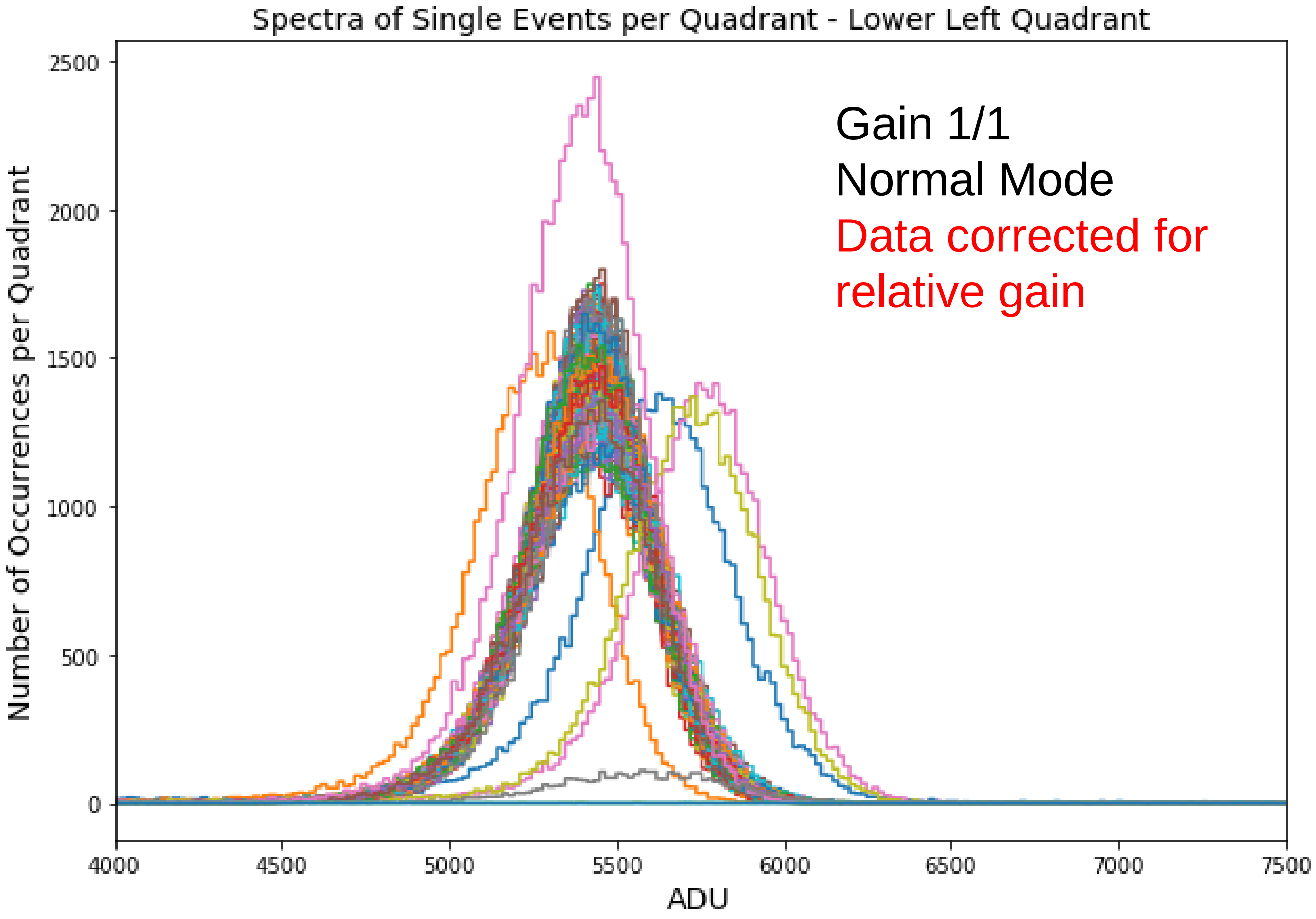
Gain 1/1
Normal Mode



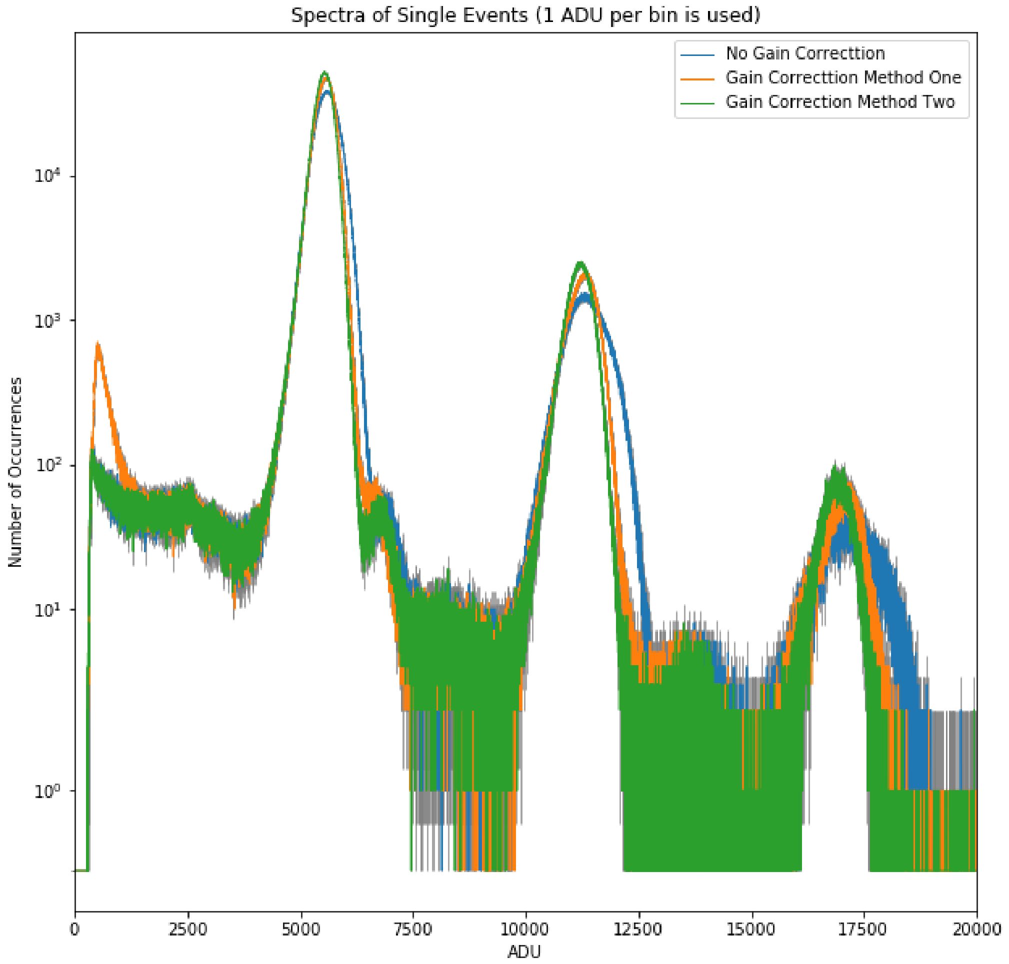
Relative Gain Calibration Validation

- After gain correction, one can look at row-wise corrected spectra of single events, and the peaks must all be on the same position corresponding to a photon energy.

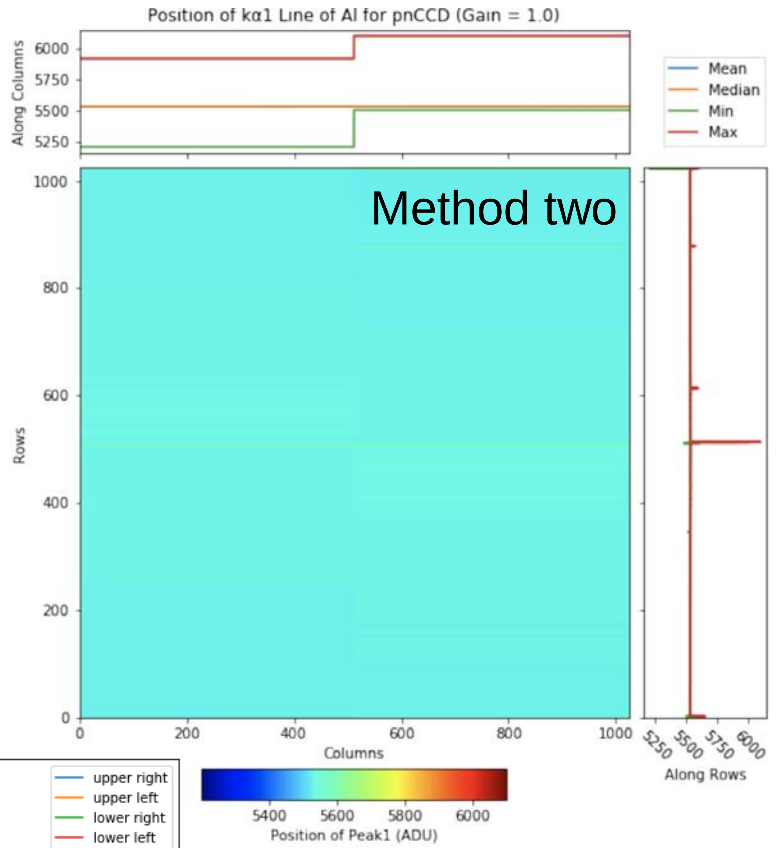


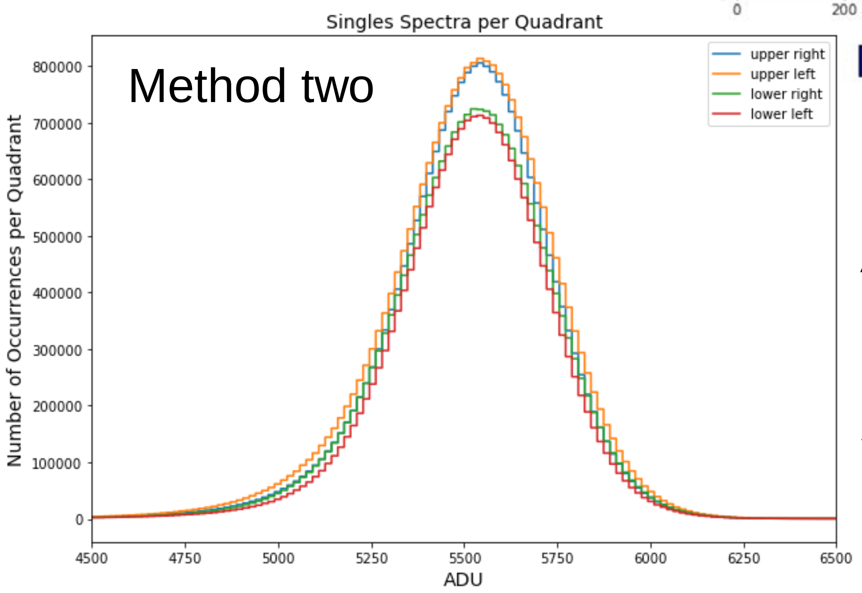


Relative Gain Calibration: Comparison of Methods



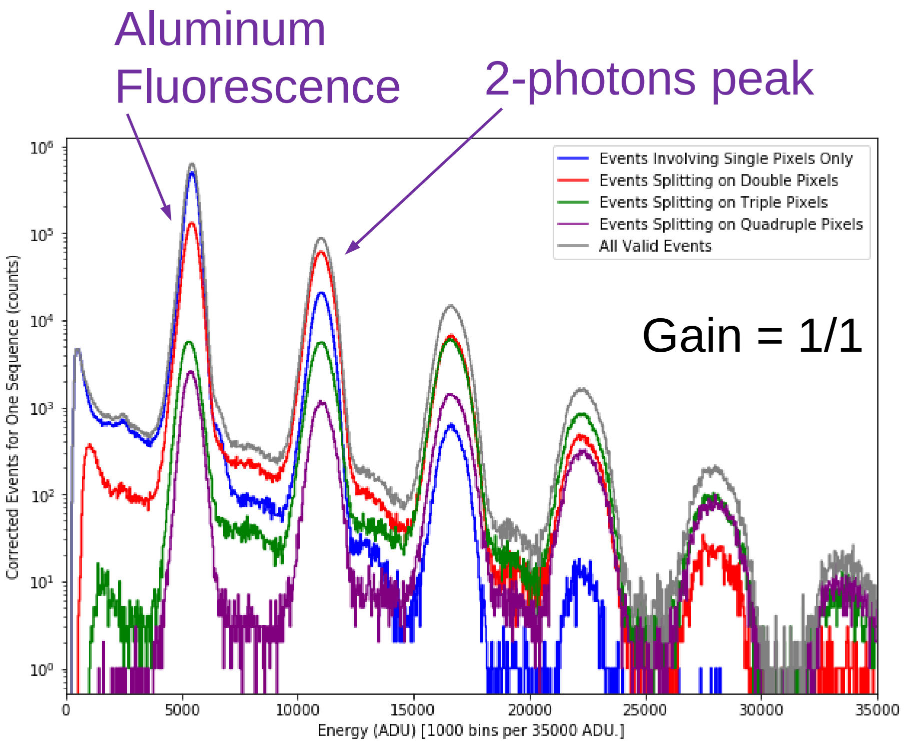
Method one: via CTI Fits
Method two: Row-wise calibration

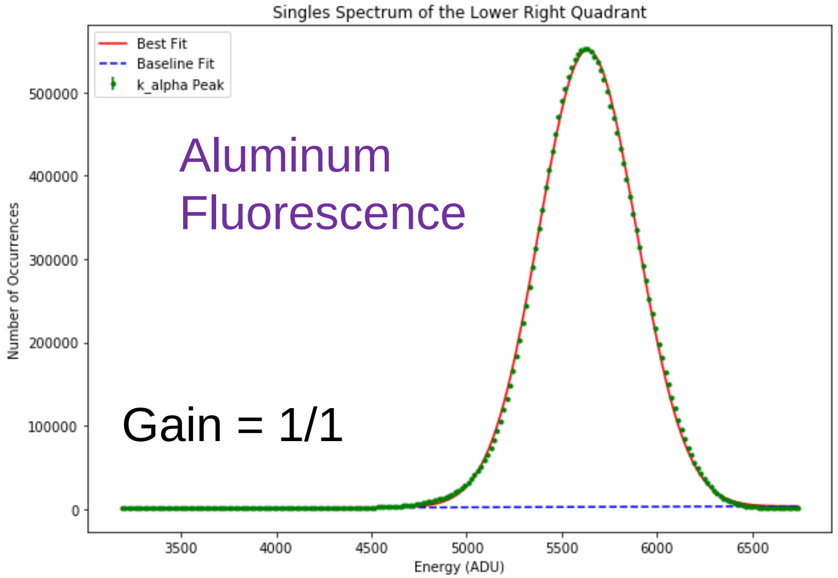


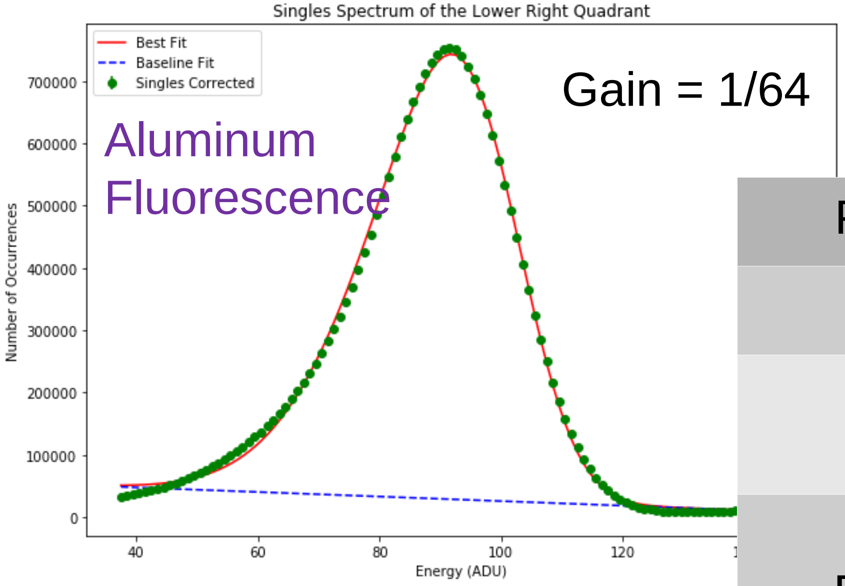


After gain correction, we get a homogeneous map of peak position (top) and the sum spectra per quadrant are all lined up nicely (left).

Absolute Gain

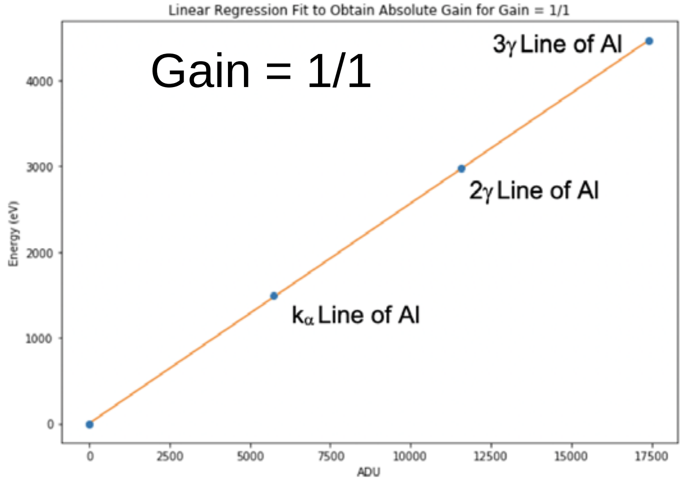






At lower gains, the peaks get skewed, but I still get good fits.

Such results are also obtained for 5 gains out of 21.



Parameter	Value
χ^2/d.o.f	1.2
Gain 1/1	0.25659(53) eV/ADU
Energy Resolution	σ = 71.1(2) eV

Available Calibrations

Bias Voltage (V)	Temperature (°C)	Gain	Absolute Gain (eV/ADU)	σ (eV)	Conversion Factor (e^-/ADU)
- 400	-30	1/1	0.25659(53)	71.1(2)	0.07
- 400	-30	1/4	1.06109(426)	74.2(5)	0.29
- 400	-30	1/16	3.38260(169)	101.0(4)	1.08
- 400	-30	1/64	15.33222(7731)	257.3(29)	4.26
- 470	-30	1/64	15.19430(3813)	247.1(27)	4.22

- I have set the notebooks such that, if desired, the gain of each individual quadrant can also be obtained for any of the above settings.