First performances of EICROC ASIC to read-out pixelated AC-LGAD sensors for the Electron-Ion Collider (EIC)

Arzoo Sharma

arzoo.sharma@ijclab.in2p3.fr

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EIC QUEST

- Understand nucleon properties like mass and spin emerging from their partonic structure.
- Behavior of sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon.
- Study mechanism through which quark-gluon interactions give rise to nuclear binding.
- Investigating saturation point for the density of gluons in nuclei at high energies.

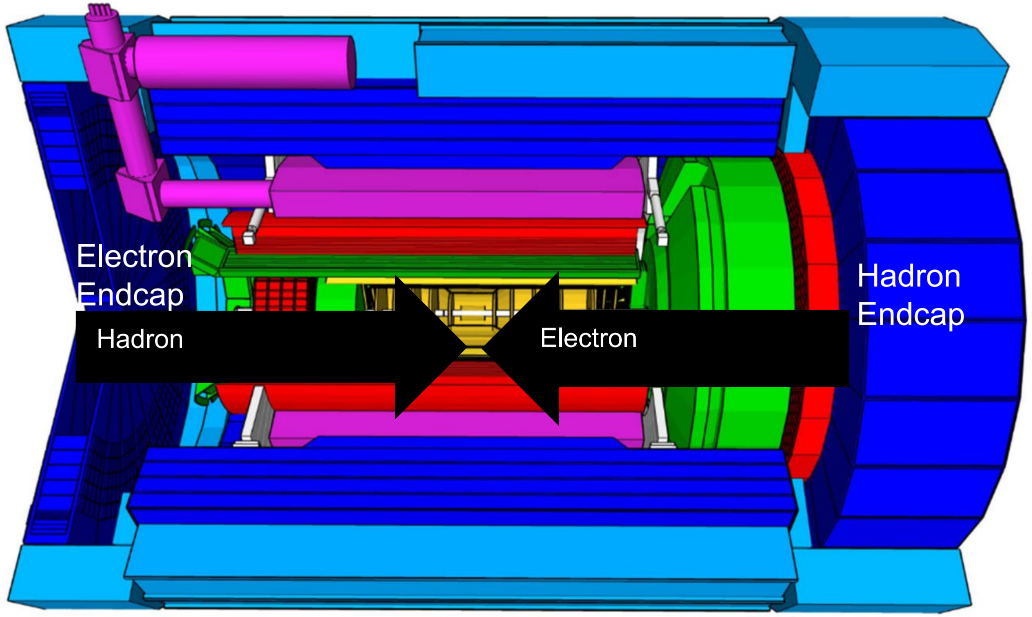

Fig:Electron Proton Ion Collider representation.

Detector Aim: Large rapidity ($-4 < \eta < 4$) coverage;
and far beyond in far-forward/far-backward detector regions

Ref: *Annu. Rev. Nucl. Part. Sci.* 55, no. 1 (2005): 165-228
https://www.bnl.gov/eic/machine.php

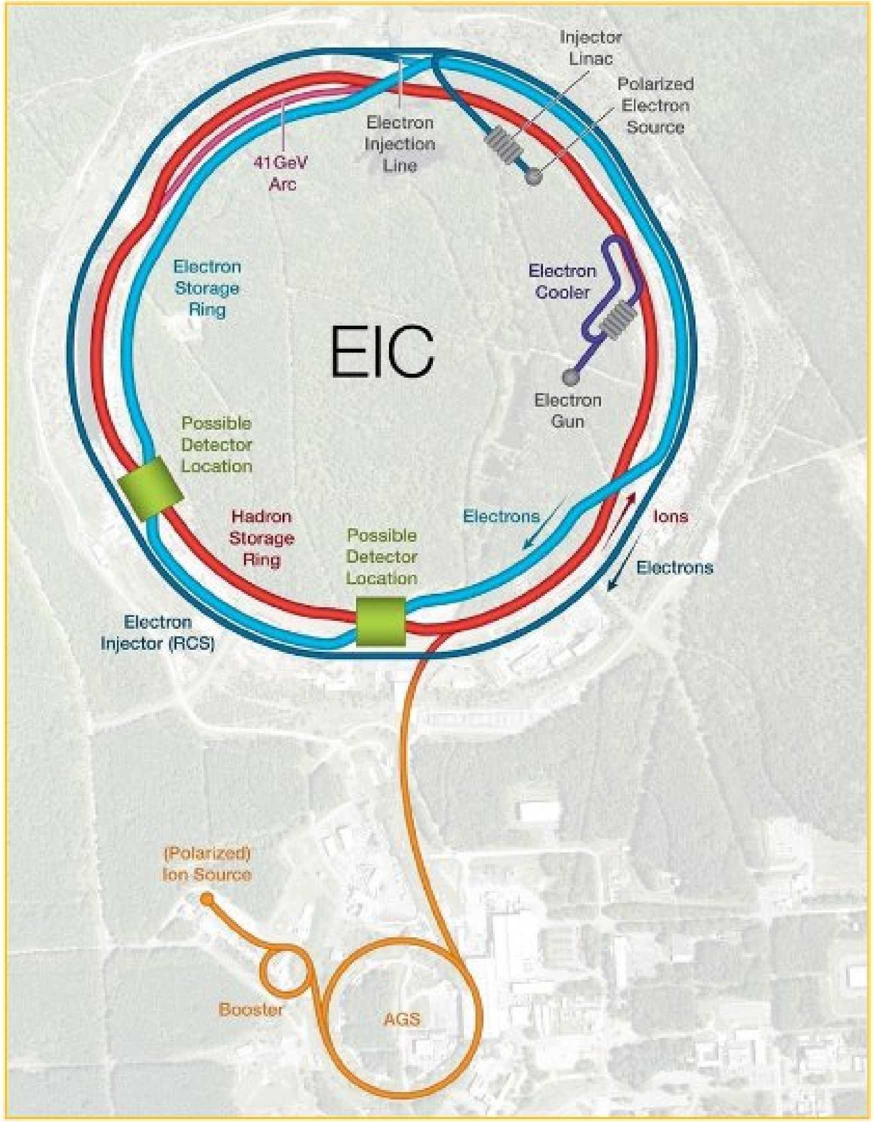

Fig: Large-scale particle accelerator facility under construction at Brookhaven National Laboratory (BNL), New York, USA.

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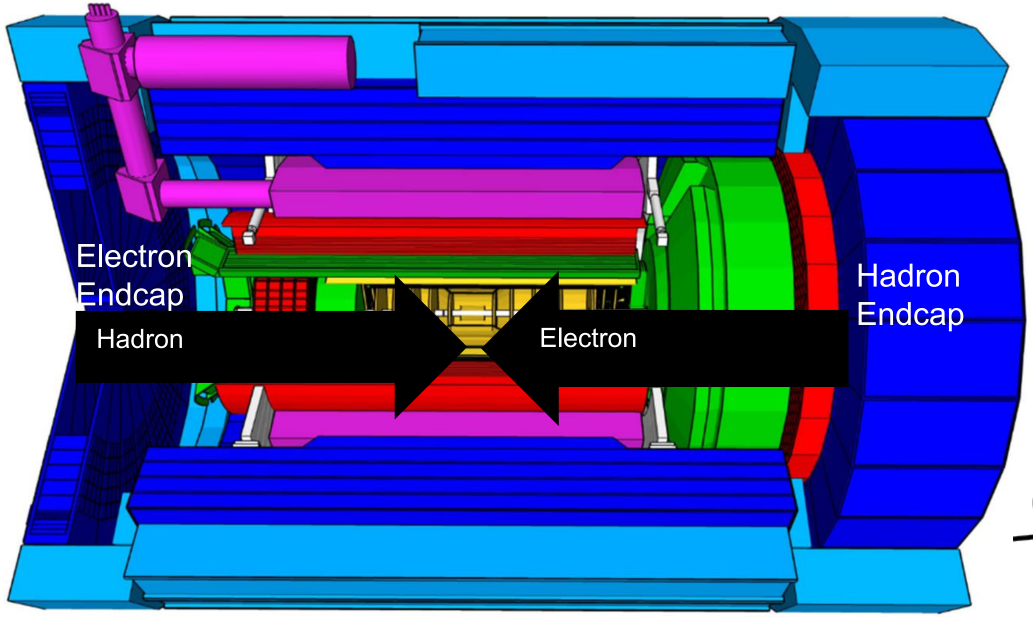

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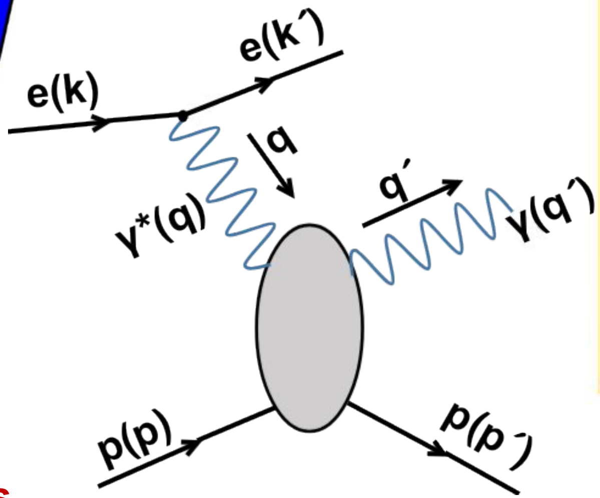
and far beyond in far-forward/far-backward detector regions

Far-Forward: ~37 mrad → DVCS studies

Deep Virtual Compton Scattering (DVCS)



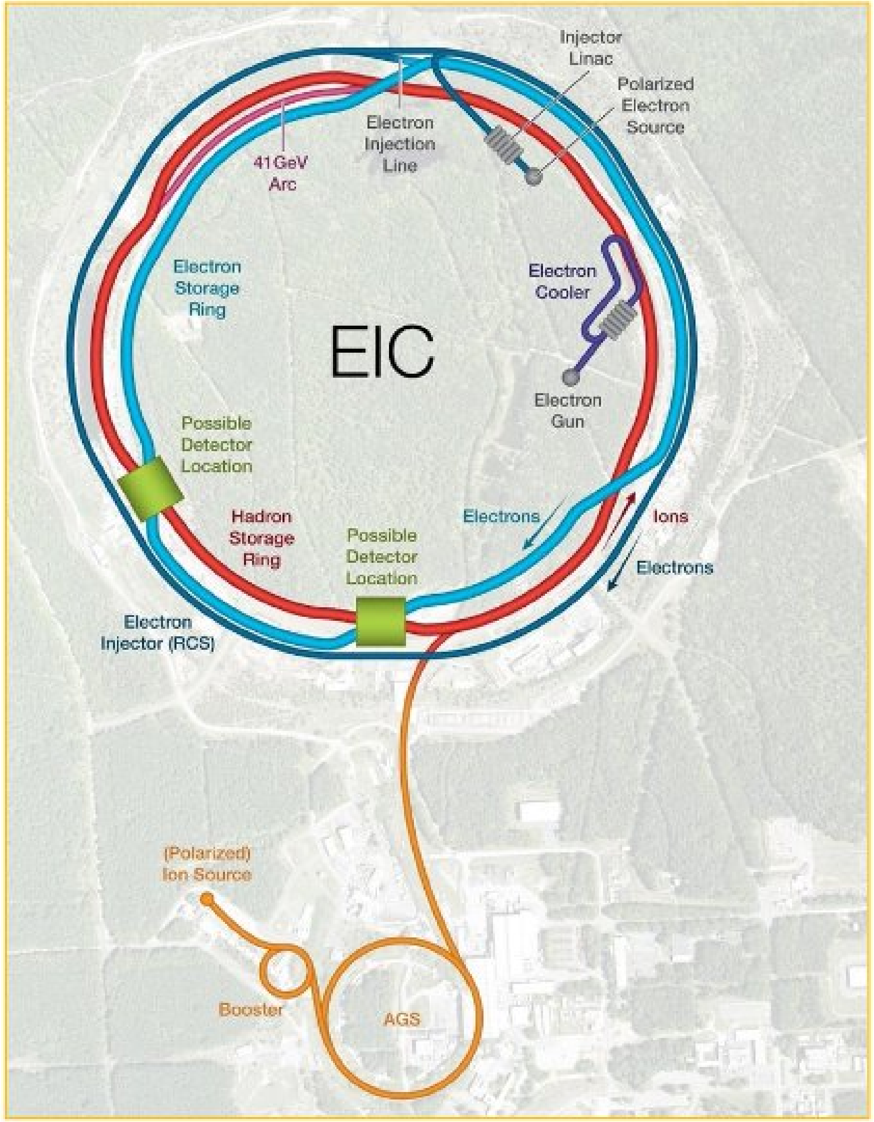
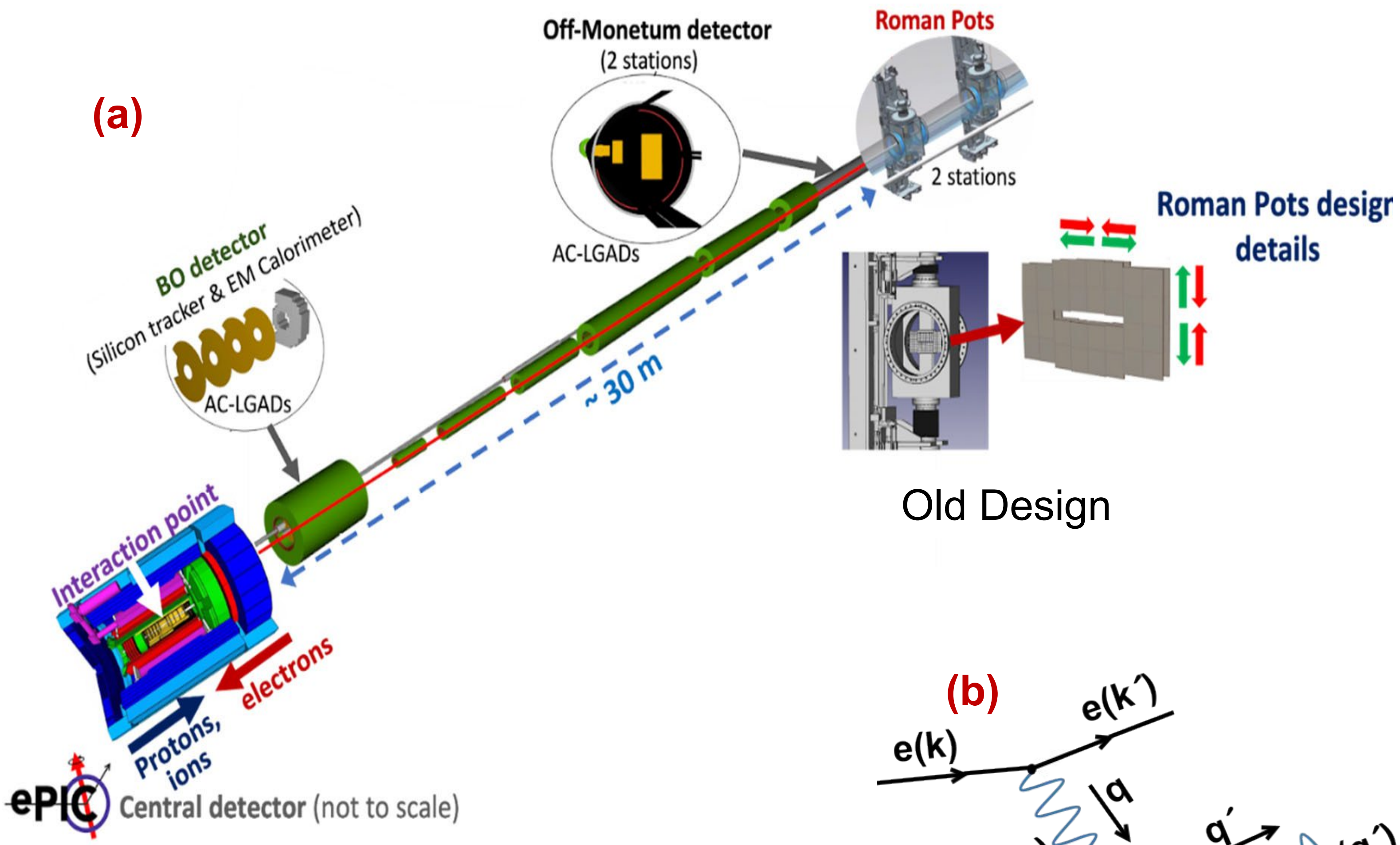


Fig: Large-scale particle accelerator facility under construction at Brookhaven National Laboratory (BNL), New York, USA.

Roman Pots: Essential for exclusive processes



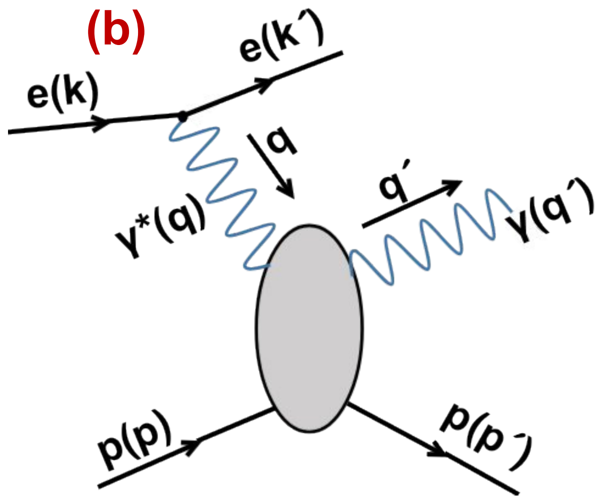


Fig: (a) Roman pots at far-forward angles in the beamline, (b) Deep Virtual Compton Scattering (DVCS) process.

- Aim is to identify and characterize exclusive, diffractive, and tagged events using detectors integrated with the outgoing hadron beamline, (**far-forward detectors**).
- Scattered angle < 5 mrad
- To be placed directly in vacuum around the hadron beam to detect intact hadrons with transverse momenta down to a couple hundred MeVs.

Essential Features:

- Obtain a position resolution of < 50 μm.
- Time resolution ~ 30 ps to account for head on collision between the electron and proton beam.

EICROC Project

Design & performance characterization of EICROC2 (32x32) chip intended to readout large surface pixelated AC-LGAD (Simultaneous time and spatial study)

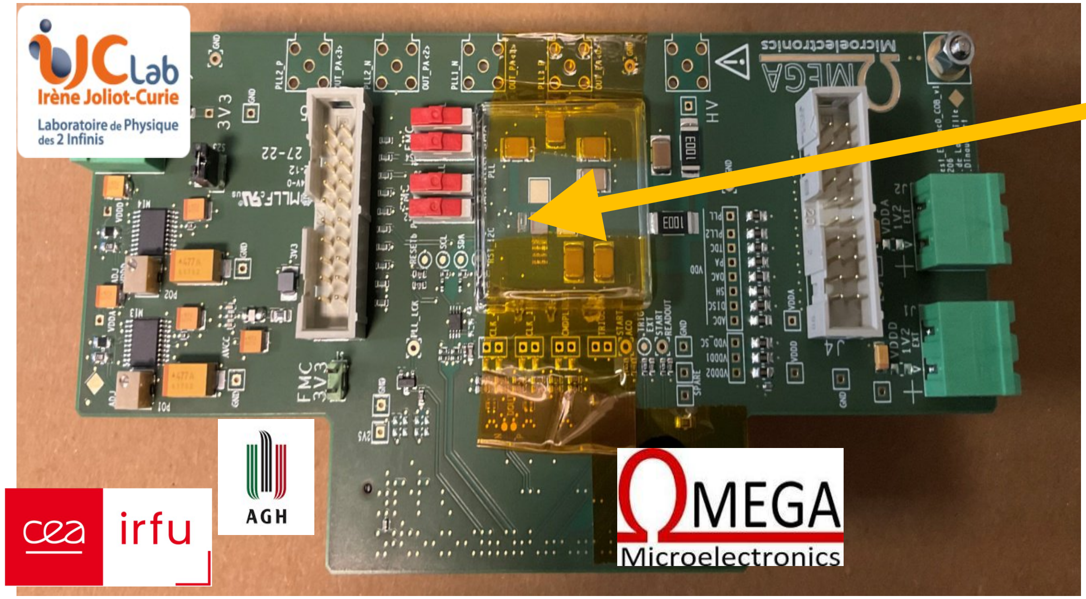
- Design challenge is to fit all the components within a 0.5x0.5 mm^2 pad.
- Goal to accommodate for low sensor capacitance (< 1 pF), low electronic noise (~ 1 mV/channel) and jitter to reach the required timing resolutions (20-30 ps), sensitivity to small charges (~ 3 fC) per pixel, and to estimate the amplitude of the central hit pixel for time-walk correction but also of its neighbors (containing the induced cross-talk and charge sharing).
- Achieve good position resolution (< 50 microns) while ensuring a very low power dissipation, << 1 mW/channel.
- Cooling mechanism in vacuum: studies being performed @ IJCLab.
- EICROC0: 1st ASIC prototype has 16 channels

Design Credit for ASIC Development: @ OMEGA withTDC @ CEA/Irfu/DEDIP, ADC @ AGH Krakow.

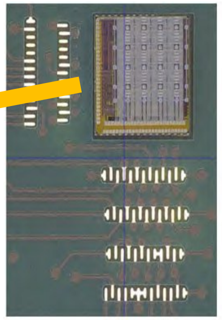
EICROC0 1st prototype (4x4 pads)

Fig.: EICROC0 Testbench

Fig.: EICROC0 Testboard setup.



EICROC0 chip



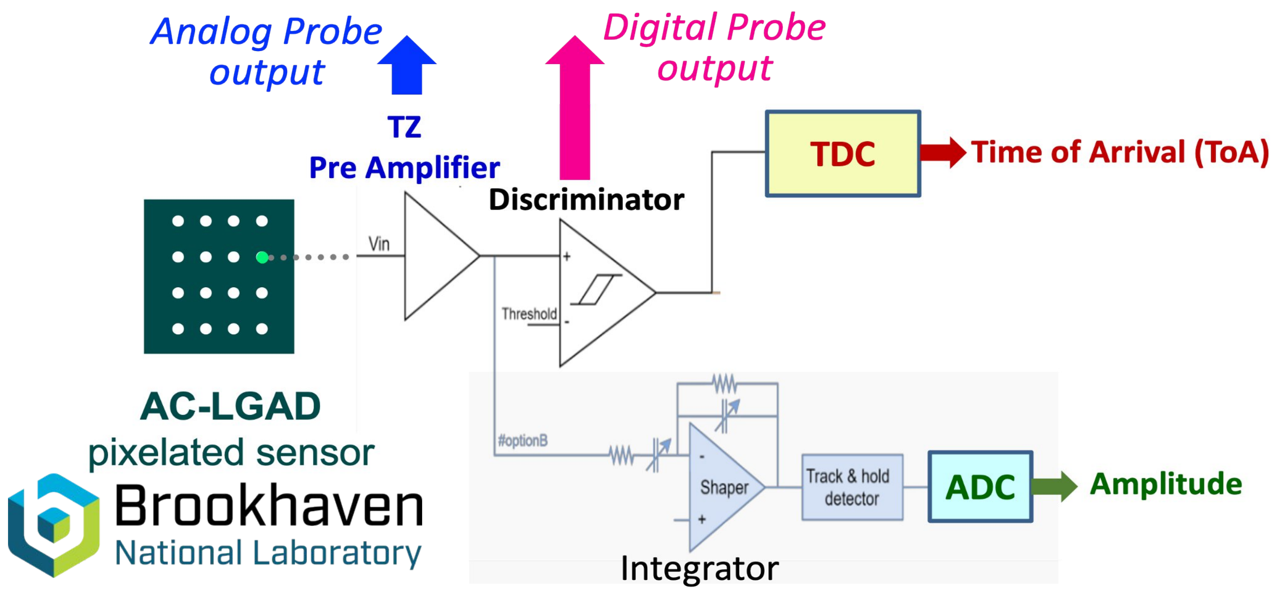
Pixel / Channel Mapping	Column 0	Column 1	Column 2	Column 3
Line 0	Pixel (0,0) #00	Pixel (1,0) #04	Pixel (2,0) #08	Pixel (3,0) #12
Line 1	Pixel (0,1) #01	Pixel (1,1) #05	Pixel (2,1) #09	Pixel (3,1) #13
Line 2	Pixel (0,2) #02	Pixel (1,2) #06	Pixel (2,2) #10	Pixel (3,2) #14
Line 3	Pixel (0,3) #03	Pixel (1,3) #07	Pixel (2,3) #11	Pixel (3,3) #15

Fig.: EICROC0 chip channel map.

EICROC0 features

- An analogical fast Transimpedance (TZ) pre-amplifier and a discriminator taken from ALTIROC ASIC design (ATLAS/HGTD).
- 10-bit Time-to-Digital Converter (TDC) measuring the Time-of-Arrival (ToA), designed by CEA/Irfu/DEDIP.
- 8-bit (40 MHz) Analogical-to-Digital Converter (ADC), designed and adapted by AGH University of Science and Technology (Krakow, Poland) from the HGCROC 10 bit ADC.
- Compared to the ALTIROC chip, holding 2 TDCs, one to measure the TOA and the second one associated to the Time-over-Threshold, an ADC has been preferred to measure the signal amplitude to avoid nonlinear behavior of a ToT TDC as a function of injected charge.
- I^{2}C communication (firmware + software developments)
- Digital readout: FIFO depth 8(200ns)
- 5 slow control bytes per pixel:
  - 6 bits local threshold,
  - 6 bits ADC pedestal,
  - 16 TDC calibration bits,
  - several on/off and probes.

1 channel (1 pixel) schematics



EICROC Characterization

1. Charge injection system, referred as CMD Pulse signal (**0.7-25 fC**).
2. Digital output data consist of 8 time samples;
   [TDC, ADC, Hit bit] / time sample for each of the 16 channels.
3. Discriminator threshold correction is performed by measuring S-curve, i.e., efficiency as a function of threshold.
4. TDC calibration performed.
5. TDC is characterized by measuring average time and jitter as a function of injected charge.
6. Determination of minimum detectable charge (plotting efficiency as a function of charge).
7. ADC waveforms studied with pedestal subtraction.

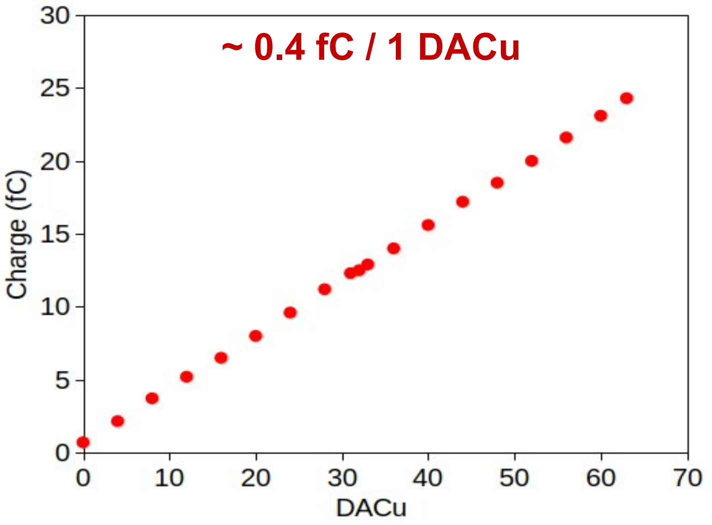
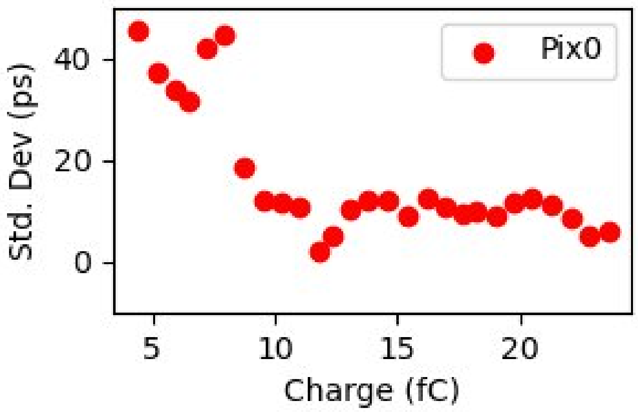


Fig.: Internal Injected charge calibration.



At 23 fC,σ ~ 10 ps

Fig.: Jitter study as a function of charge.

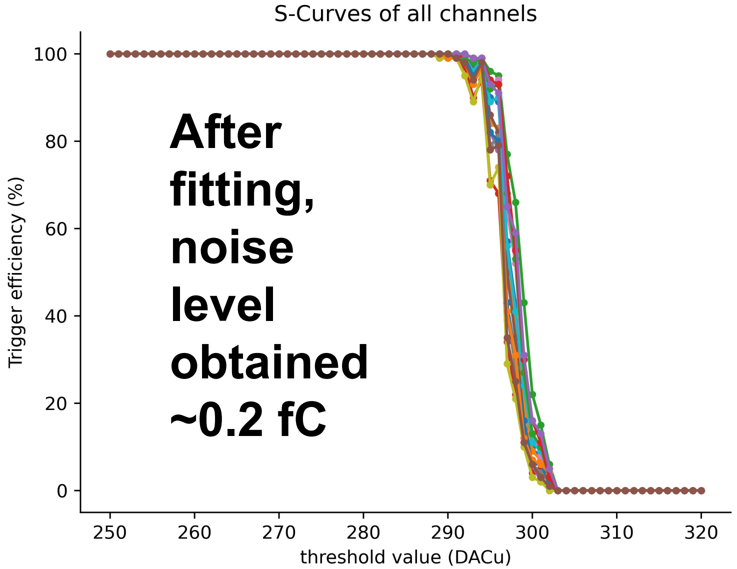


Fig.: Discriminator threshold optimization.

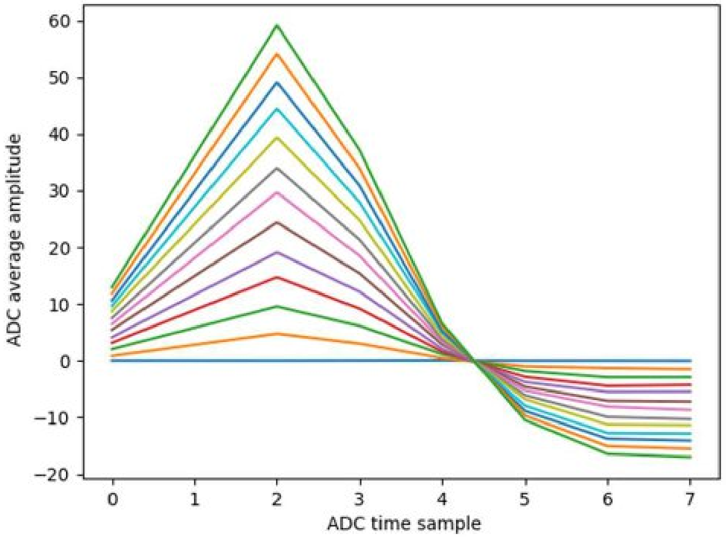


Fig.: ADC waveform studies for different charge injected.

Setup for Beta Source Measurements

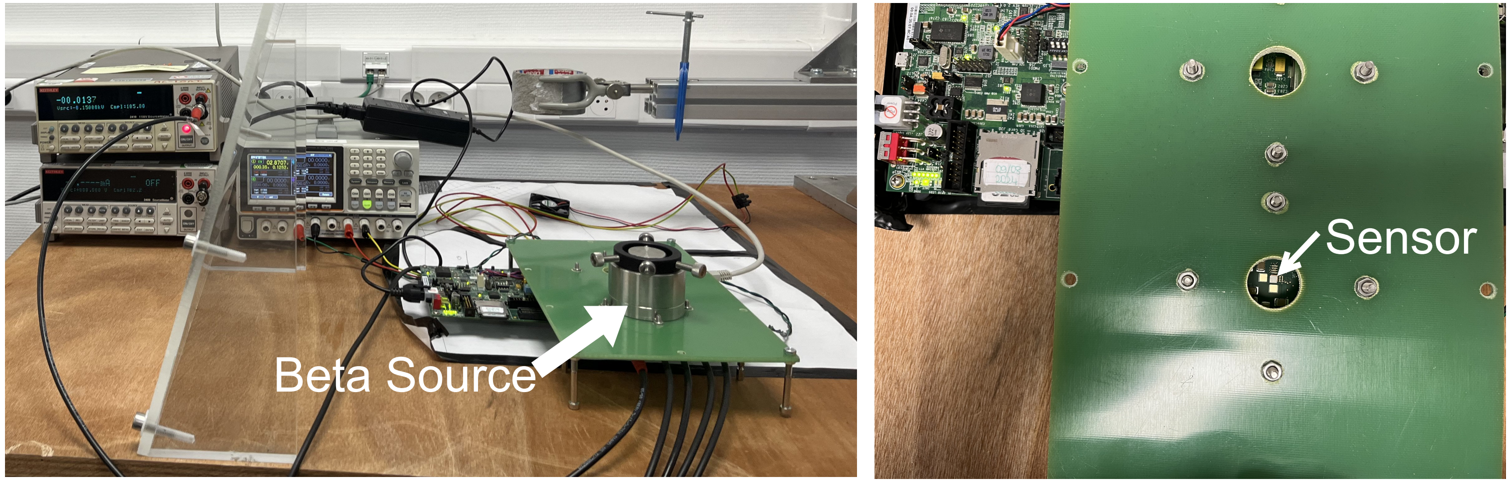


Fig.: Beta Source Setup. (a) Source placed on the stand with a hole on top of the sensor as shown in (b).

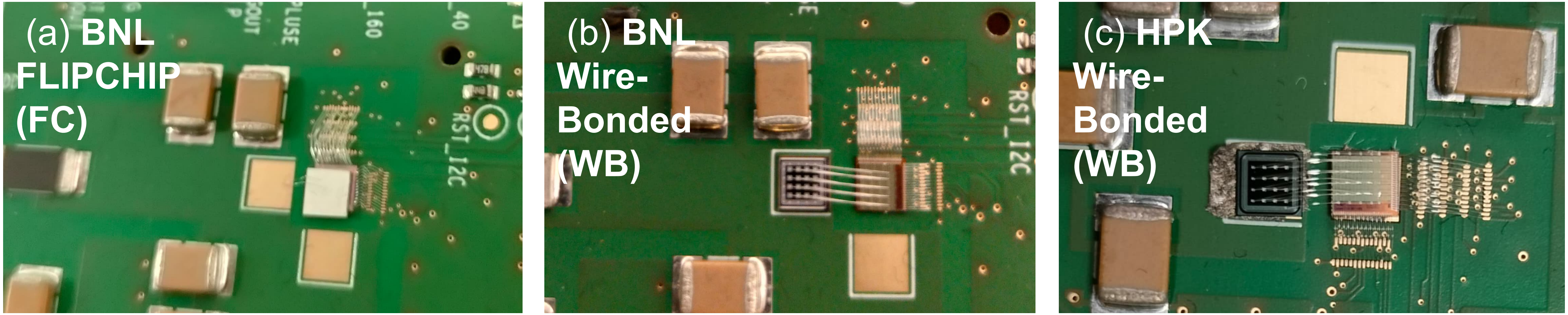


Fig.: Different Sensor Boards present @IJCLab for testing, (a) BNL FlipChip (FC), (b) BNL Wire-Bonded (WB), and (c) HPK WB @KEK.

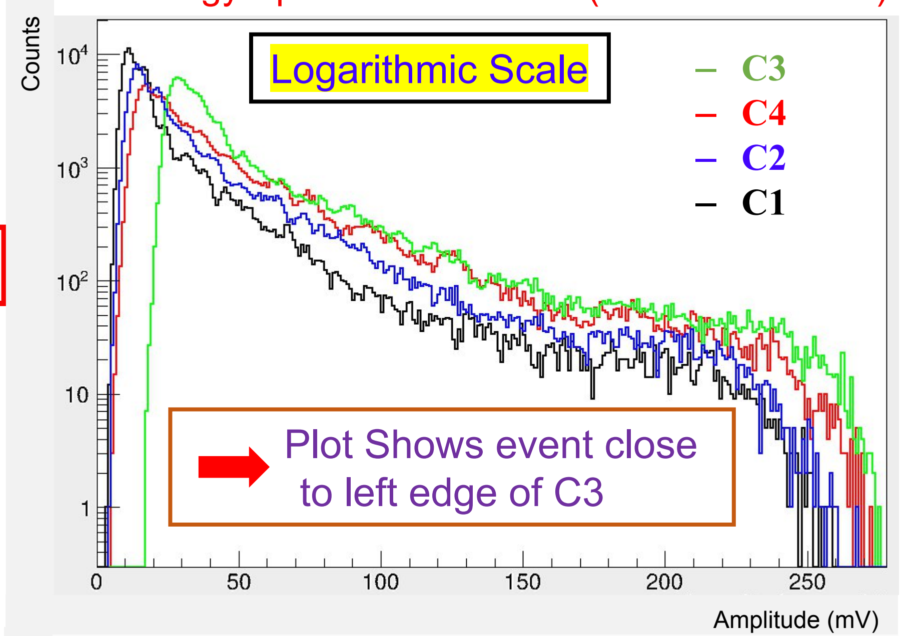
PA Measurements with ^{90}Sr β source

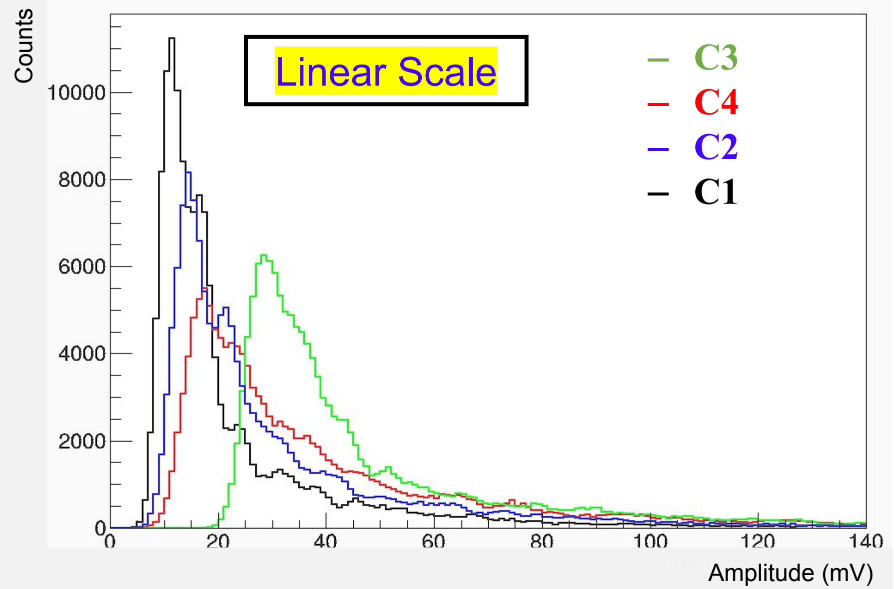
- **Probe Pre-Amplifier signal on oscilloscope**
  - Proper functioning of each of the channels confirmed.
  - Analysis shown for line 1. More Amplitude in C3 confirms hit occured in C3.
  - Implies **Hit location are reflected in the amplitude differences between the pixels**.

Pixel / Channel Mapping	Column 0	Column 1	Column 2	Column 3
Line 0	Pixel (0,0) #00	Pixel (1,0) #04	Pixel (2,0) #08	Pixel (3,0) #12
Line 1	C4	C3	C2	C1
Line 2	Pixel (0,2) #02	Pixel (1,2) #06	Pixel (2,2) #10	Pixel (3,2) #14
Line 3	Pixel (0,3) #03	Pixel (1,3) #07	Pixel (2,3) #11	Pixel (3,3) #15

Fig.: Channel map for scope.

Energy Spectrum for Line 1 (HPK WB Sensor).





- **ADC + TDC data**
  - 16 channels at a time
  - Require a specific firmware

Updated Firmware :
Acquiring TDC and ADC data for all 16 channels when **at least** a hitbit is set to 1 among all 16 channels (meaning that PA signal amplitude passes the discriminator threshold).
(courtesy: Beng-Yun Ky)

Measurements with ^{90}Sr β source : Digital Readout

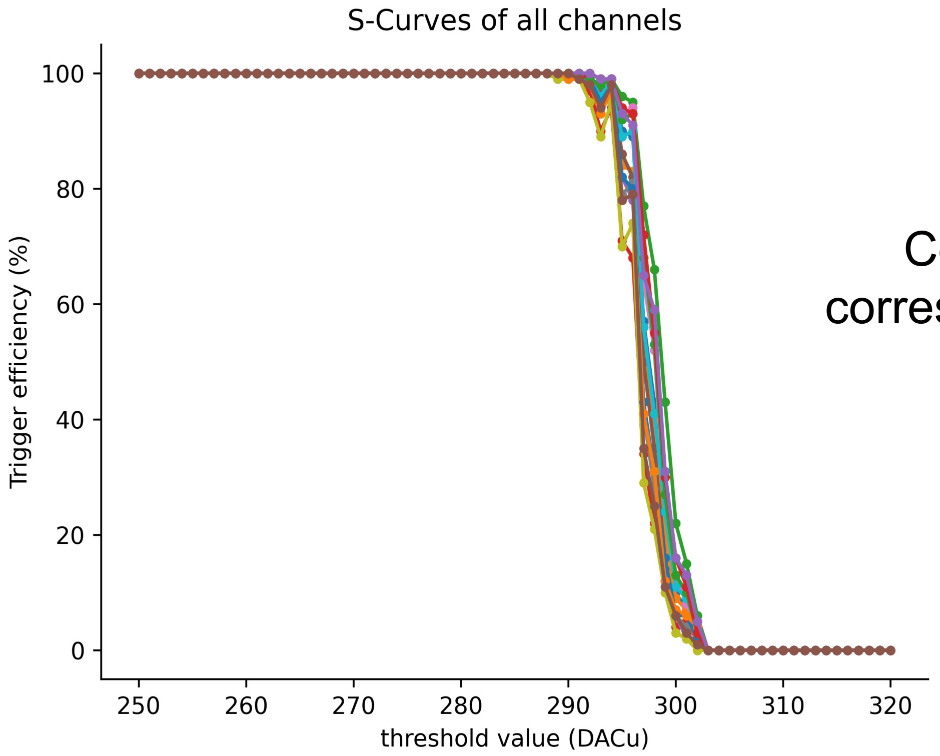
Pix-to-Pix Adjustment

- **Threshold adjustment** channel-by-channel performed.
- **Baseline adjustment** channel-by-channel done.

EICROC0 + wire-bonded BNL AC-LGAD

Detector Bias = -200 V
I ~ 0.06 microA

Adjustments performed for lower charge DAC Pulser 12 (~5 fC) [CMD pulse] and setting global threshold 300 DACu



Color map corresponds to all pixels

Computed data
50% value = 297.4
50% spread = 2.21

Fig.: Discriminator threshold optimization for all channels.

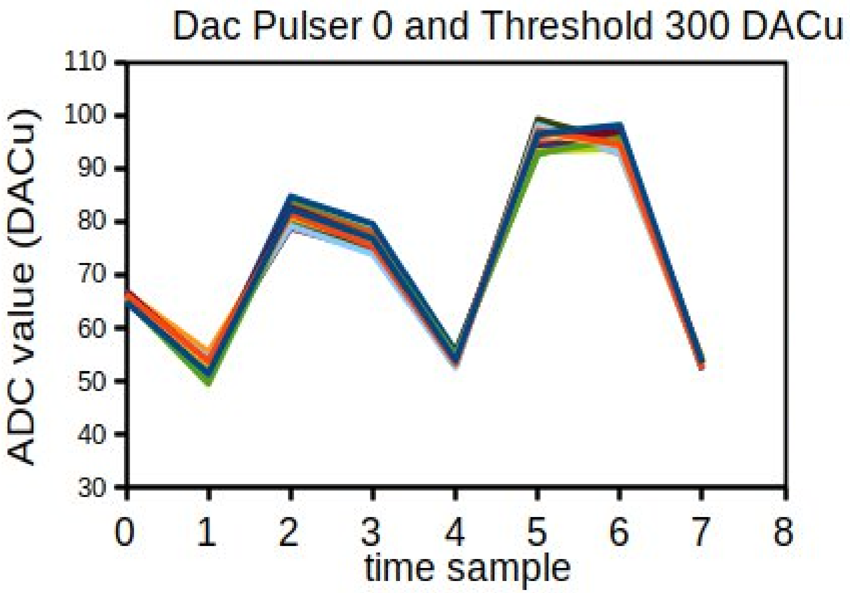


Fig.: ADC offset correction for all channels.

Event Filtering in Digital Readout: Hit Map Evaluation

- Self-Triggered System: An event in any pixel is recorded when Discriminator crosses the threshold. (1 event corresponds to recording data for the all 16 channels)
- **OFFLINE Event Selection:** Hit Map (hit bit = 1) for one of the pixels + same pixel has maximum amplitude recorded after pedestal subtraction.

Condition: Hitbit for Pix #05=1 and Pix #05 with Max

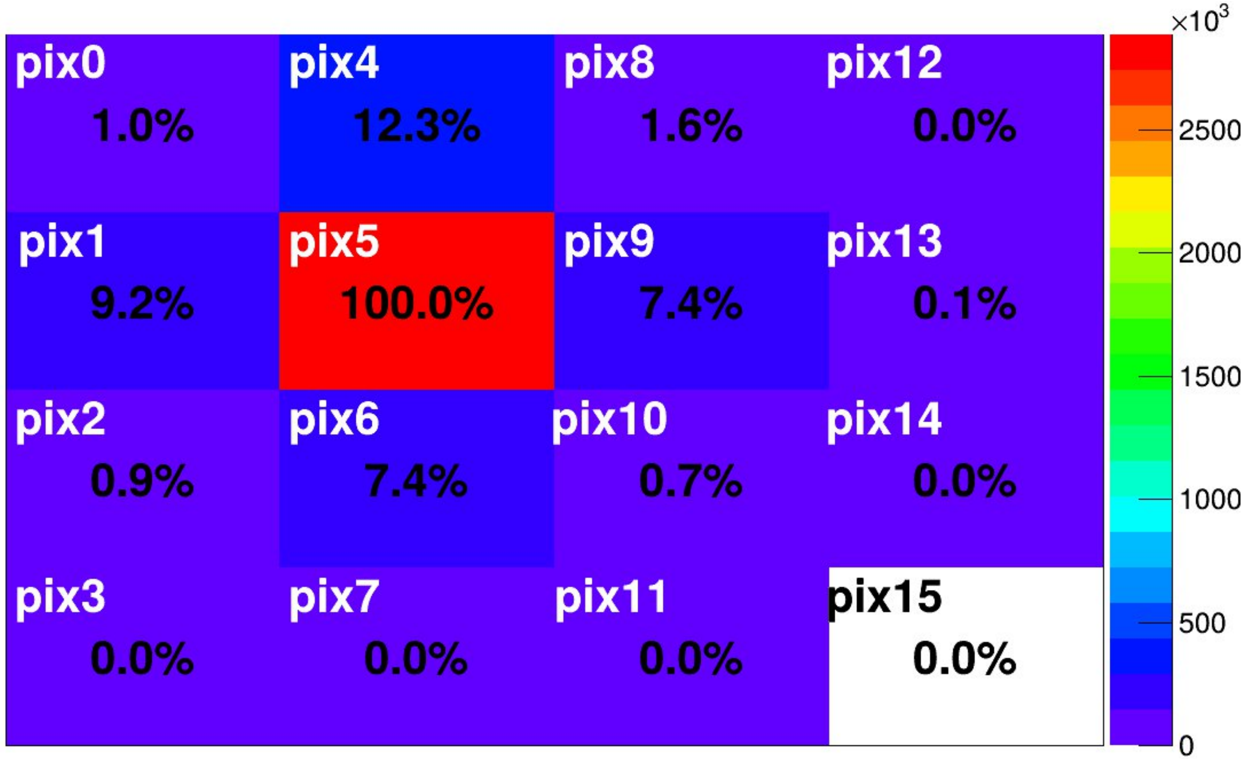
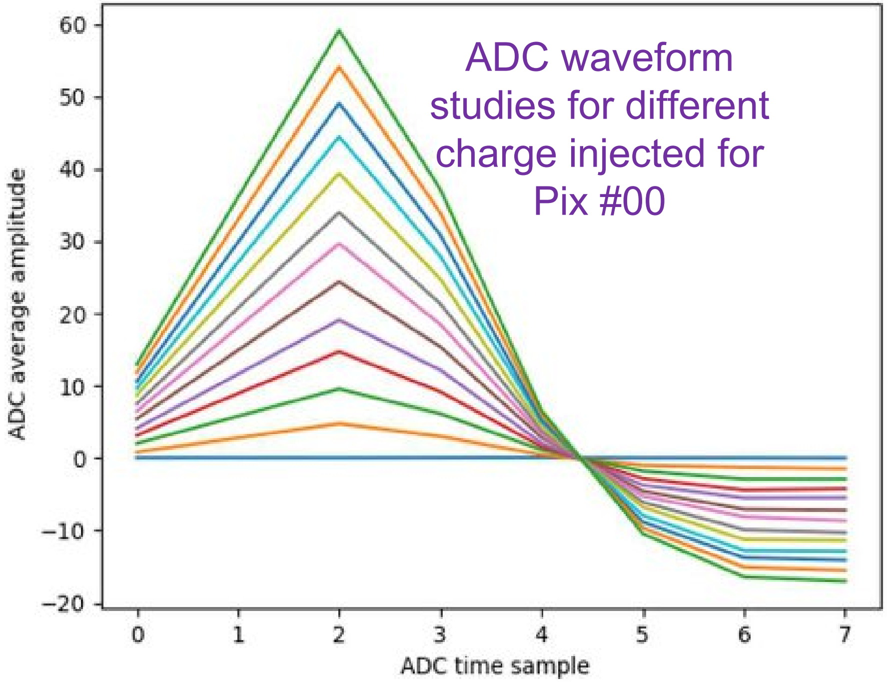


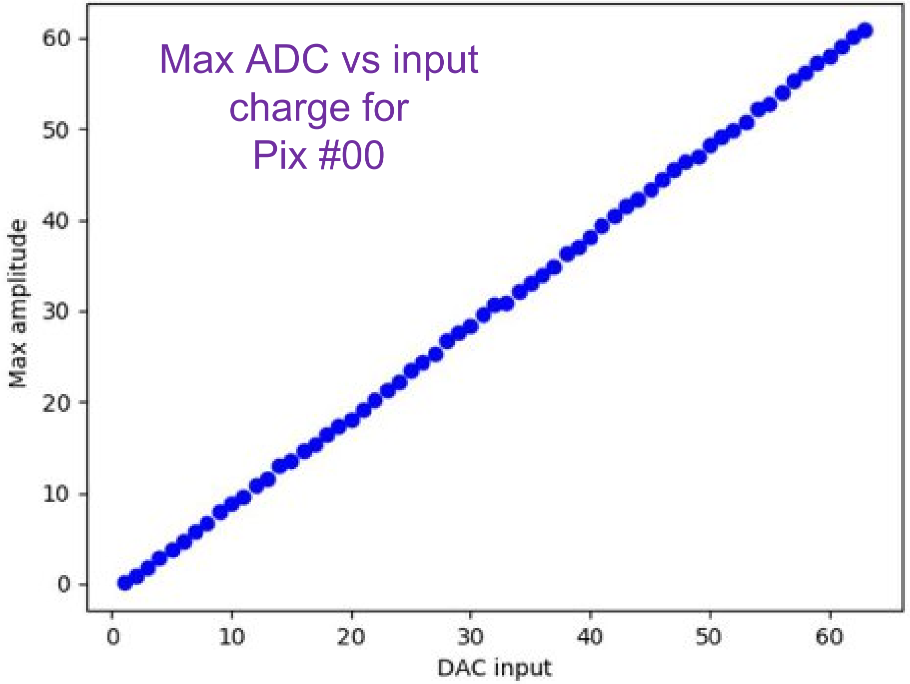
Fig.: Hit Map for event selection in Pix #05 (hit bit = 1 and maximum amplitude).

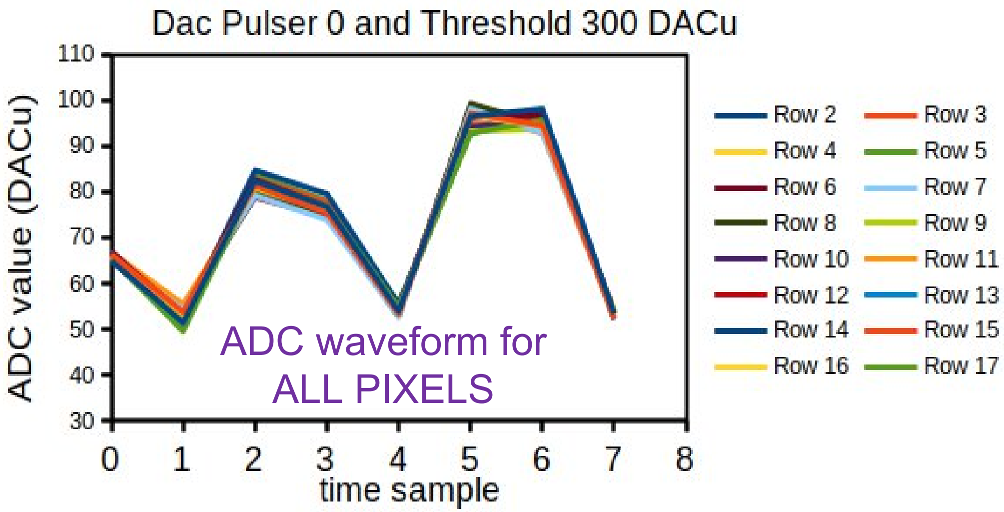
- Only 4% of the events remaining after the selection of events with **hit bit = 1 in pixel #05 and has max amplitude**.
- With this condition the first neighbors having hit bit = 7% w.r.t. the selected hit pixel. (**Not the Measurement of Charge Sharing**)
- **Takeaway:** The far neighbor, almost never crosses the threshold -> **The ADC data corresponds to the noise.**

ADC Waveform Analysis/Overview

- ADC is 8 bit. ADC waveform is constructed for 8 time samples at 25 ns -> 8 points in the waveform.
- Only interest is the Maxima in the ADC waveform.
- Analysis performed with Internal Charge Injection to understand the behavior at different charge values (Linear behavior attained).
- Pedestal Subtraction for ADC is necessary because of noise contribution from electronic couplings.







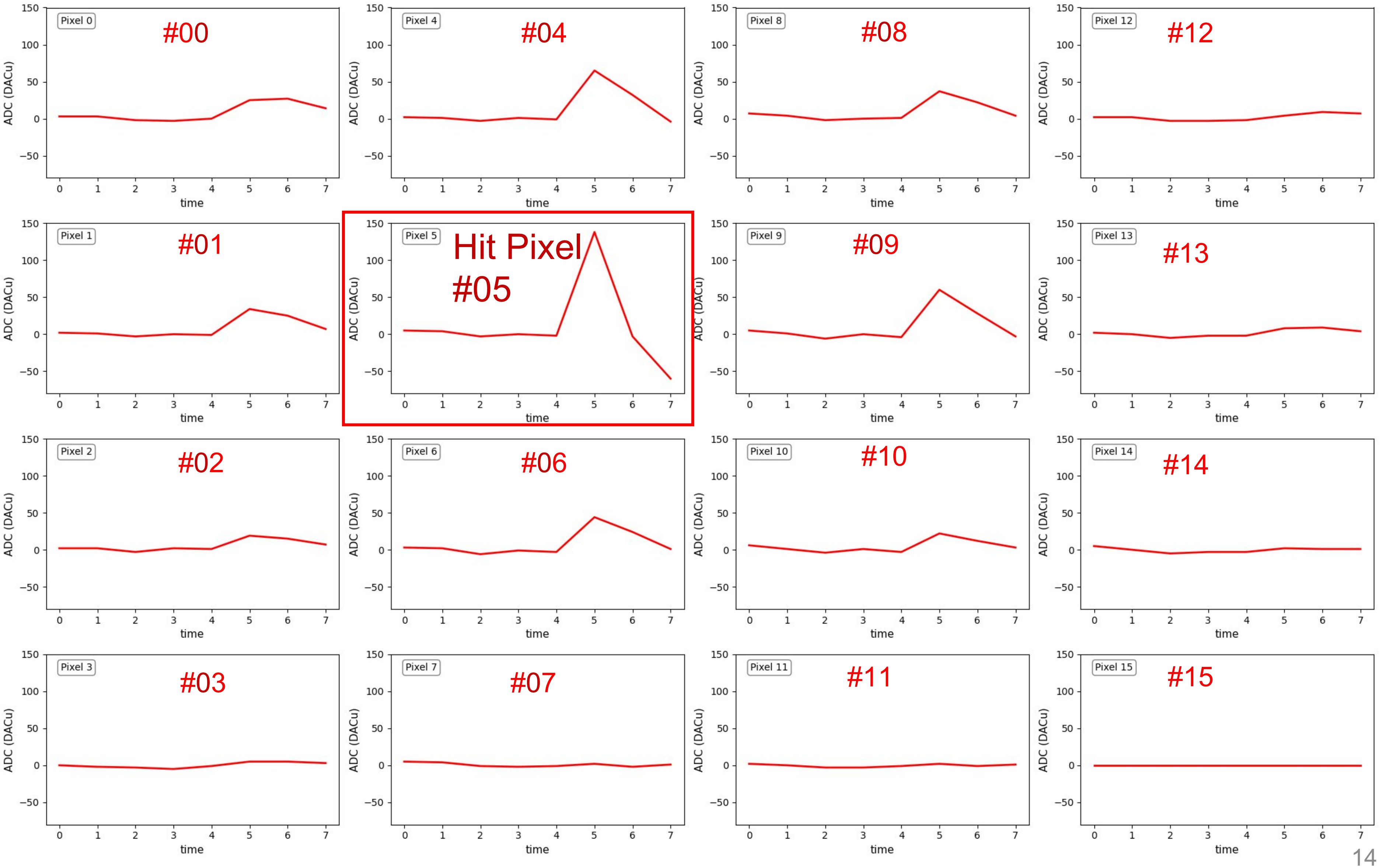
At DAC pulse 0, ADC distribution suggests the contribution from noise

Pedestal Subtraction Needed

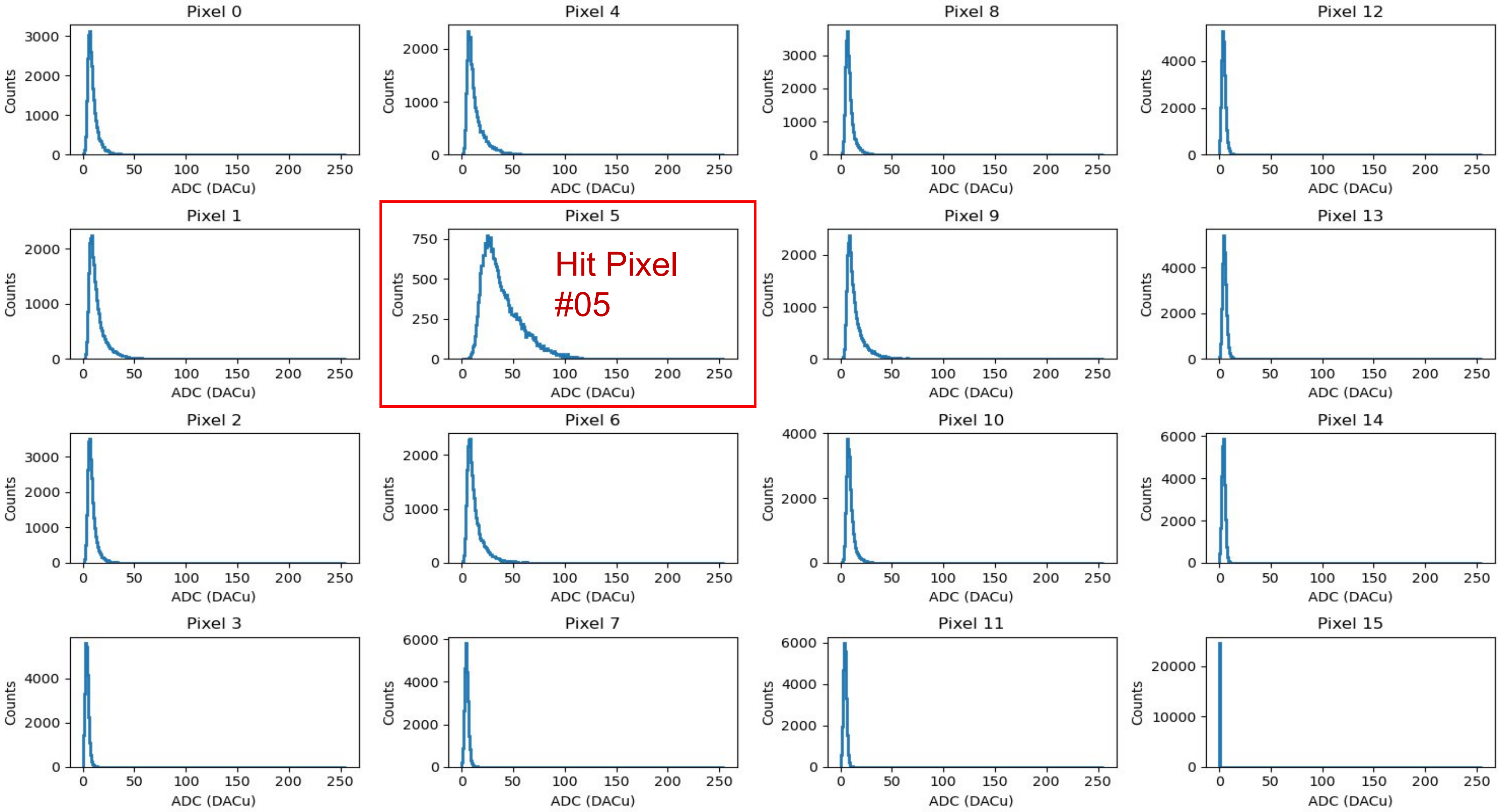
ADC Waveform (Beta Measurements): Pedestal Subtracted

- Code adapted to select events with specific channel with a hit bit = 1 and same channel has maximum amplitude. No condition on the rest of the channels.
- Pedestal Subtraction for ADC performed using a Pix far from the hit pixel on **event-by-event basis**.
- Analysis shown for hit in Pix #05 for one event after pedestal subtraction w.r.t. Pix #15.

Fig: ADC waveform for each pixel with a condition Pix #05 has hit bit = 1 and max amplitude.



Energy spectrum : After Pedestal Subtracted



- The Maximum amplitude in the neighboring channels is less as compared to the hit pixel.
- The Width of the spectrum is reduced for pixels away from the hit pixel.

Fig.: Max ADC distribution for hit in Pix #05 (represented by red rectangle).

ADC Correlation study between different neighbors

Pixel / Channel Mapping	Column 0	Column 1	Column 2	Column 3
Line 0	Pixel (0,0) #00	Pixel (1,0) #04	Pixel (2,0) #08	Pixel (3,0) #12
Line 1	Pixel (0,1) #01	Pixel (1,1) #05	Pixel (2,1) #09	Pixel (3,1) #13
Line 2	Pixel (0,2) #02	Pixel (1,2) #06	Pixel (2,2) #10	Pixel (3,2) #14
Line 3	Pixel (0,3) #03	Pixel (1,3) #07	Pixel (2,3) #11	Pixel (3,3) #15

Fig.: Channel Map. Selected Hit Pix #05 represented in red rectangle.The neighboring pixels selected for correlation study in this slide are represented in blue rectangle.

ADC Correlation study between different neighbors

Pix #04 vs Pix #05 (I neighbor)

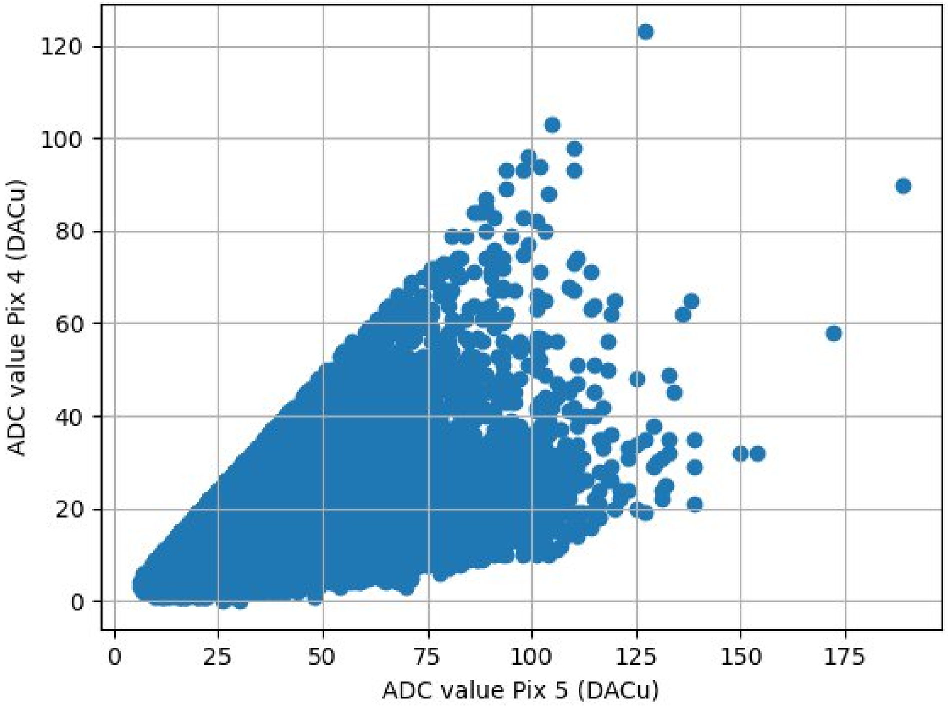


Fig.: ADC #04 vs ADC #05 for hit in Pix #05.

Pixel / Channel Mapping	Column 0	Column 1	Column 2	Column 3
Line 0	Pixel (0,0) #00	Pixel (1,0) #04	Pixel (2,0) #08	Pixel (3,0) #12
Line 1	Pixel (0,1) #01	Pixel (1,1) #05	Pixel (2,1) #09	Pixel (3,1) #13
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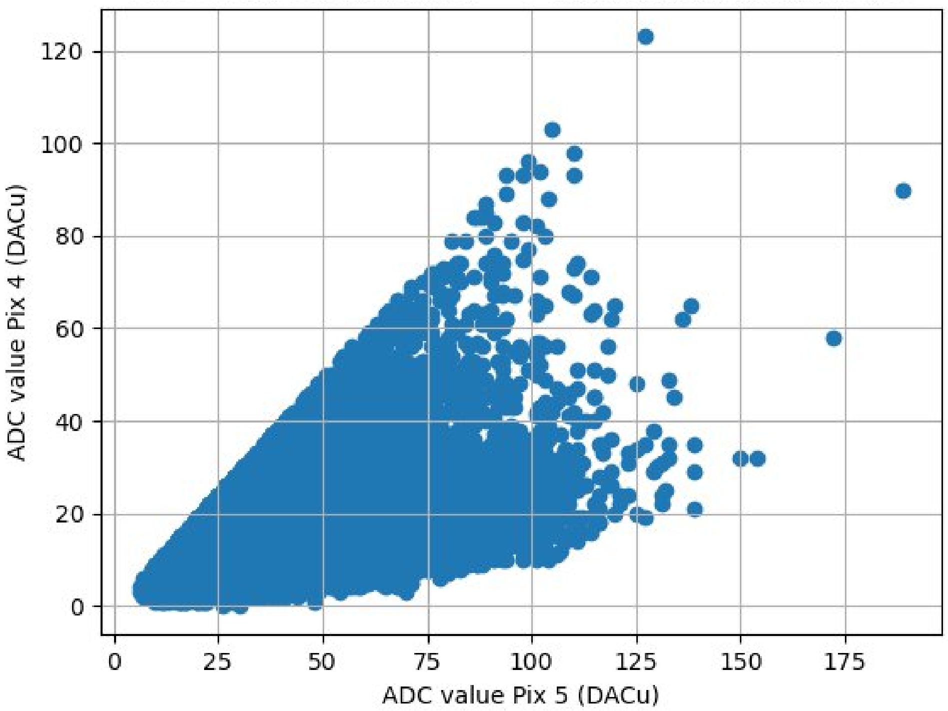

Fig.: ADC 4 vs ADC 5 for hit in Pix 05.

Pixel / Channel Mapping	Column 0	Column 1	Column 2	Column 3
Line 0	Pixel (0,0) #00	Pixel (1,0) #04	Pixel (2,0) #08	Pixel (3,0) #12
Line 1	Pixel (0,1) #01	Pixel (1,1) #05	Pixel (2,1) #09	Pixel (3,1) #13
Line 2	Pixel (0,2) #02	Pixel (1,2) #06	Pixel (2,2) #10	Pixel (3,2) #14
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Fig.: Channel Map. Selected Hit Pix #05 represented in red rectangle.The neighboring pixels selected for correlation study in this slide are represented in blue rectangle.

Pix #03 vs Pix #05 (far neighbor)

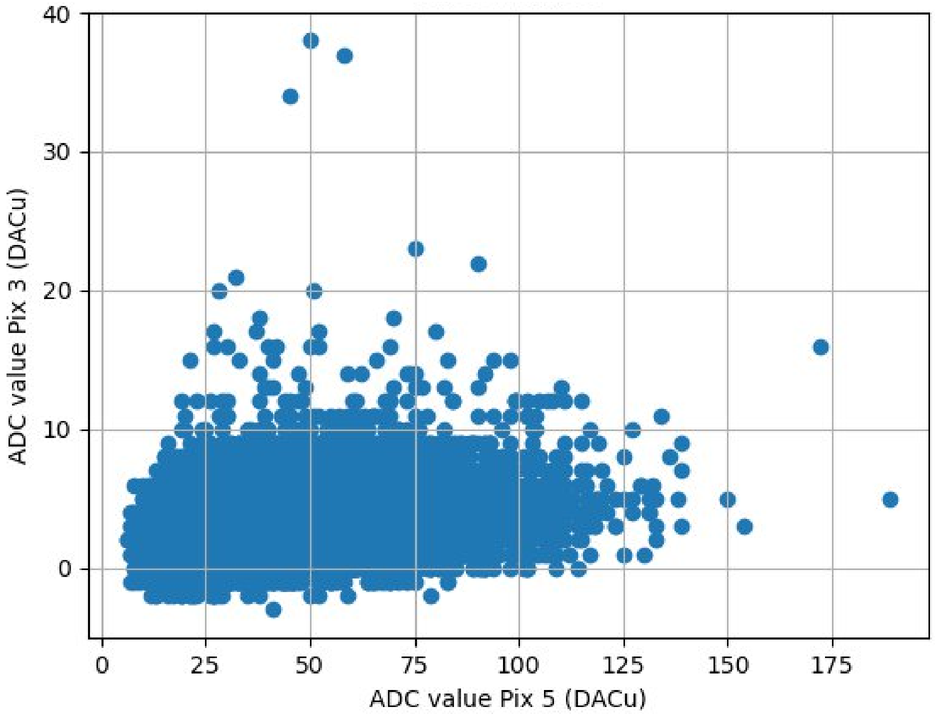


Fig.: ADC 3 vs ADC 5 for hit in Pix 05.

- The results appear consistent with the scope data.
- The correlations are neighbor order dependent, i.e., first neighbor shows clear correlations with hit pixel.

Normalized ADC spectrum w.r.t. hit pixel #05

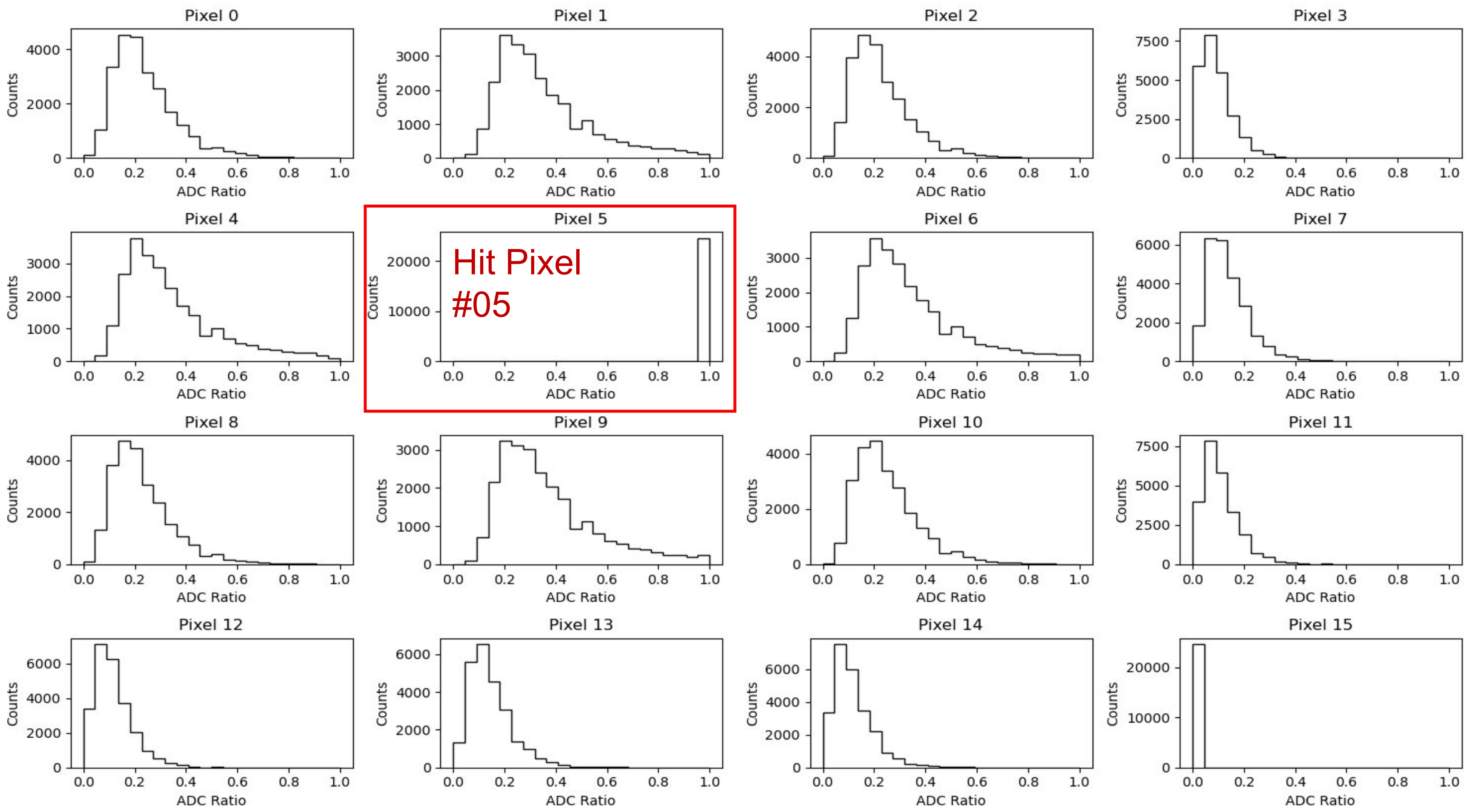
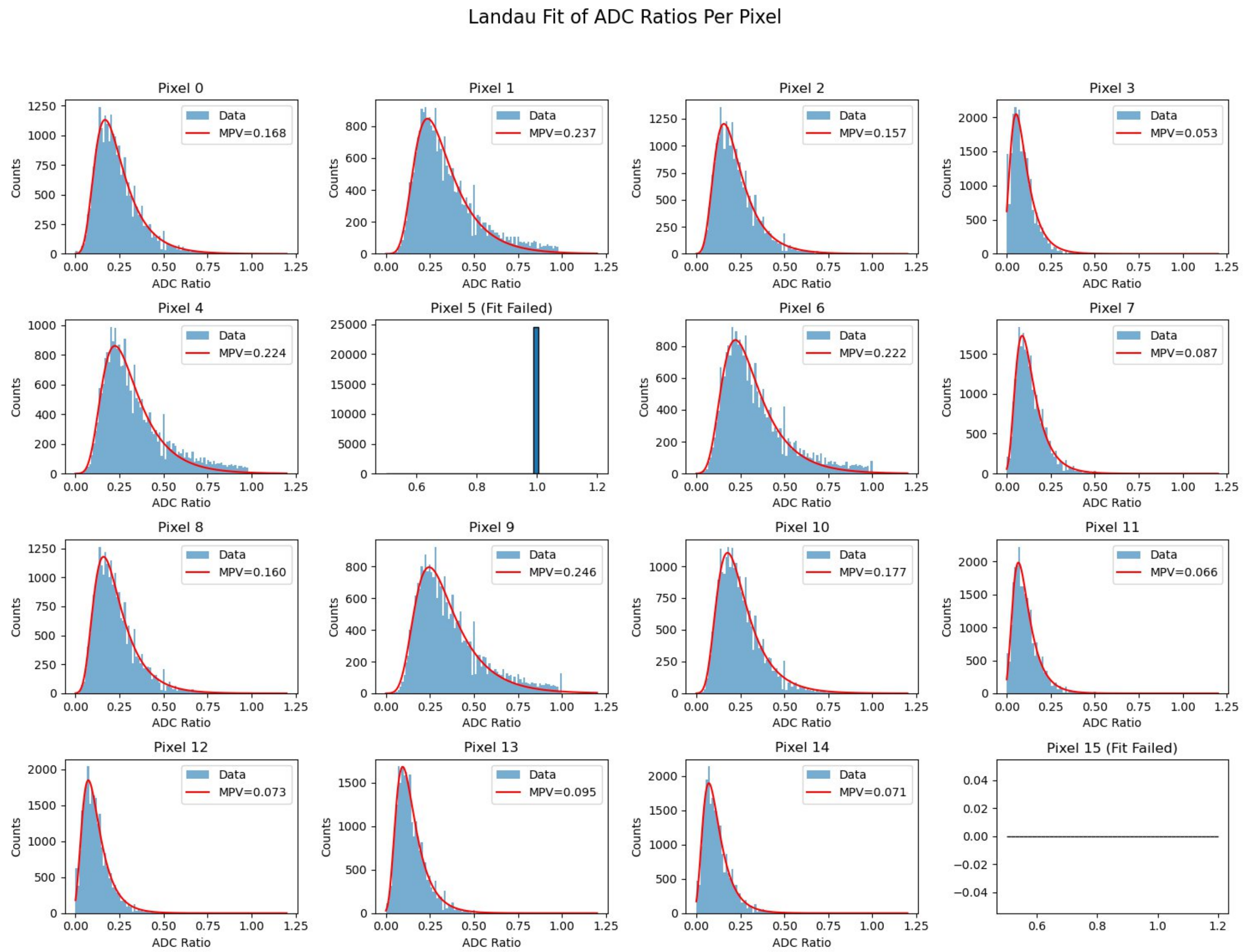


Fig.: Normalized ADC distribution w.r.t. Pix #05 for hit in Pix #05.

#The first neighbors show more tailing, and it reduces for pixels away from the hit pixel..

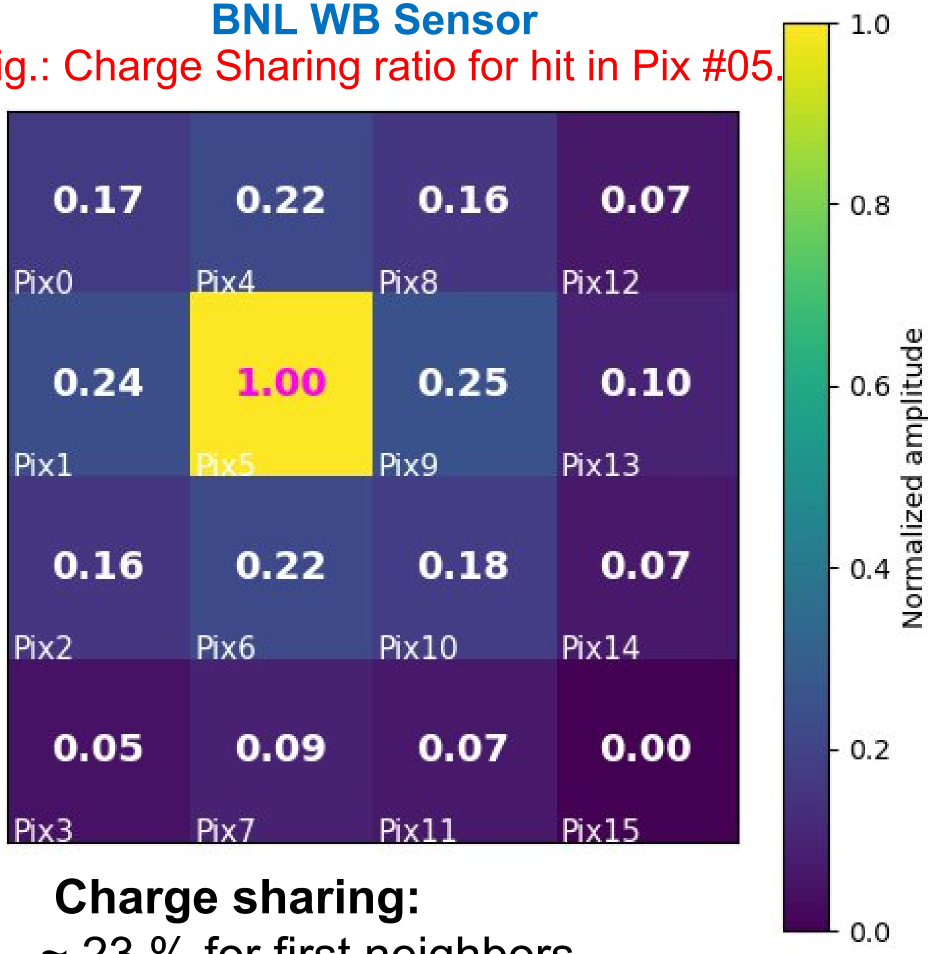
Charge sharing ratio using MPV from Landau Fit

- **Event Selection: Hitbit for Pix #05 = 1 and Pix #05 with Max Amp after Pedestal subtraction.**
- **Landau Fitting to ADC distribution Normalized w.r.t. amplitude in Pix #05.**



BNL WB Sensor

Fig.: Charge Sharing ratio for hit in Pix #05.



Charge sharing:

~ 23 % for first neighbors

~ 16% for first diagonal neighbors.

Fig.: Landau Fit to Normalized ADC distribution for hit in Pix #05. Fit is represented in red color.

Charge Sharing Ratio Comparison

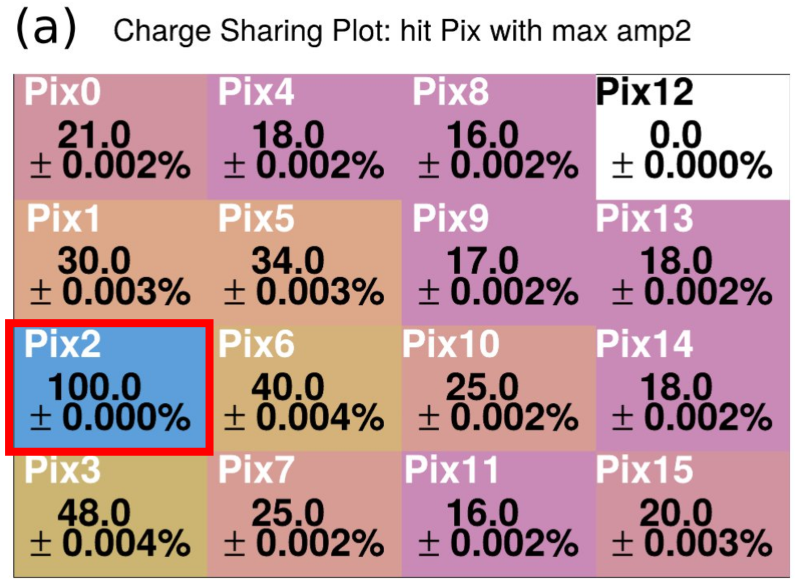
Pixel/ Channel Mapping	Column0	Column1	Column2	Column3
Line0	Pixel(0,0) #00	Pixel(1,0) #04	Pixel(2,0) #08	Pixel(3,0) #12
Line1	Pixel(0,1) #01	Pixel(1,1) #05	Pixel(2,1) #09	Pixel(3,1) #13
Line2	Pixel(0,2) #02	Pixel(1,2) #06	Pixel(2,2) #10	Pixel(3,2) #14
Line3	Pixel(0,3) #03	Pixel(1,3) #07	Pixel(2,3) #11	Pixel(3,3) #15

Fig.:Pixel Mapping.

Charge Sharing Ratio Comparison (Sensor: BNL FC)

Pixel/ Channel Mapping	Column0	Column1	Column2	Column3
Line0	Pixel(0,0) #00	Pixel(1,0) #04	Pixel(2,0) #08	Pixel(3,0) #12
Line1	Pixel(0,1) #01	Pixel(1,1) #05	Pixel(2,1) #09	Pixel(3,1) #13
Line2	Pixel(0,2) #02	Pixel(1,2) #06	Pixel(2,2) #10	Pixel(3,2) #14
Line3	Pixel(0,3) #03	Pixel(1,3) #07	Pixel(2,3) #11	Pixel(3,3) #15

Pix	Charge sharing First Direct Neighbor	Charge sharing First Diagonal	Charge sharing Far Pixel
(a) 02	~40 %	~30 %	~17 %



- **More Charge Sharing ratio observed in the direct neighbor as compared to the first neighbor.**

Fig.: Charge Sharing for selection of hit in different Pixels (a) Pix #02.

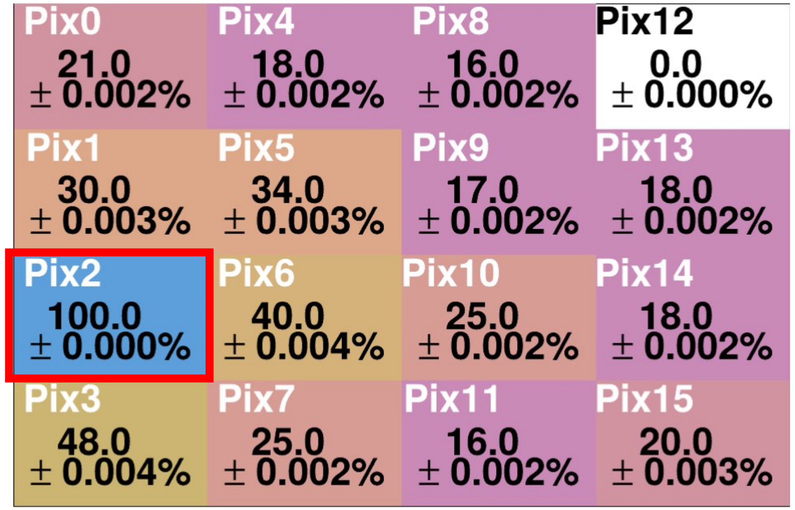
Charge Sharing Ratio Comparison (Sensor: BNL FC)

Pixel/ Channel Mapping	Column0	Column1	Column2	Column3
Line0	Pixel(0,0) #00	Pixel(1,0) #04	Pixel(2,0) #08	Pixel(3,0) #12
Line1	Pixel(0,1) #01	Pixel(1,1) #05	Pixel(2,1) #09	Pixel(3,1) #13
Line2	Pixel(0,2) #02	Pixel(1,2) #06	Pixel(2,2) #10	Pixel(3,2) #14
Line3	Pixel(0,3) #03	Pixel(1,3) #07	Pixel(2,3) #11	Pixel(3,3) #15

Pix	Charge sharing First Direct Neighbor	Charge sharing First Diagonal	Charge sharing Far Pixel
(a) 02	~40 %	~30 %	~17 %
(b) 03	~41 %	~31 %	~16 %

❖ **More Charge Sharing ratio observed in the direct neighbor as compared to the first neighbor.**

(a) Charge Sharing Plot: hit Pix with max amp2



(b) Charge Sharing Plot: hit Pix with max amp3

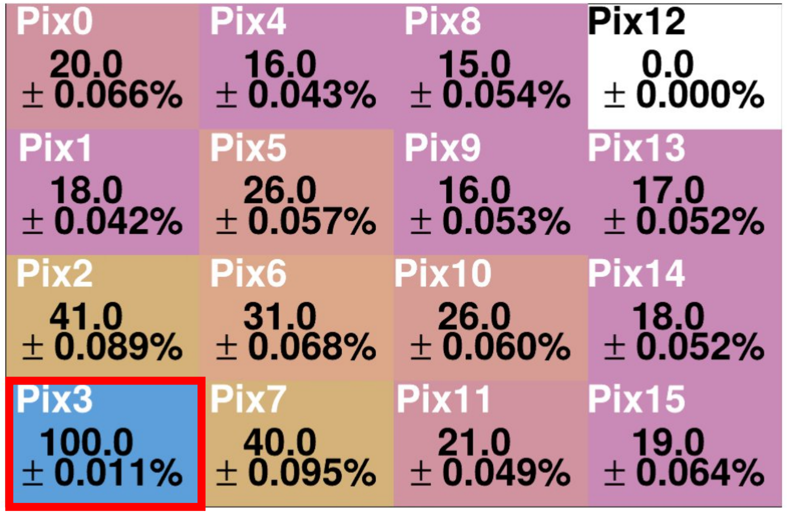


Fig.: Charge Sharing Ratio for selection of hit in different Pixels (a) Pix #02, (b) Pix #03.

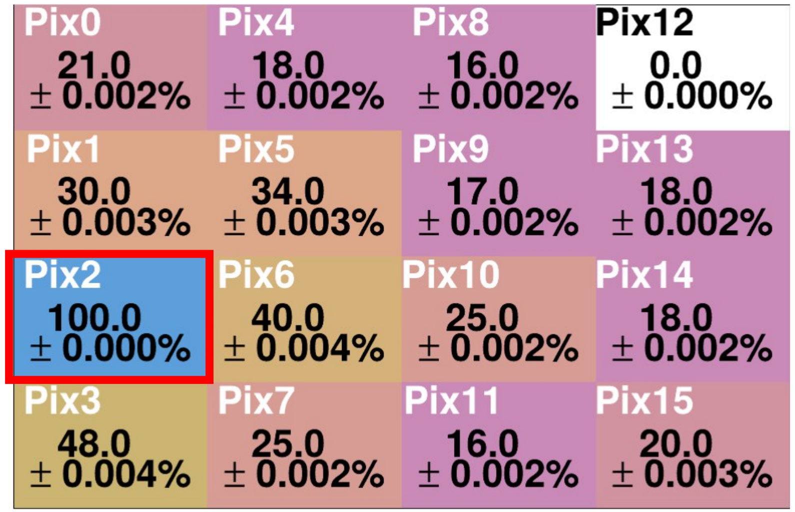
Charge Sharing Ratio Comparison (Sensor: BNL FC)

Pixel/ Channel Mapping	Column0	Column1	Column2	Column3
Line0	Pixel(0,0) #00	Pixel(1,0) #04	Pixel(2,0) #08	Pixel(3,0) #12
Line1	Pixel(0,1) #01	Pixel(1,1) #05	Pixel(2,1) #09	Pixel(3,1) #13
Line2	Pixel(0,2) #02	Pixel(1,2) #06	Pixel(2,2) #10	Pixel(3,2) #14
Line3	Pixel(0,3) #03	Pixel(1,3) #07	Pixel(2,3) #11	Pixel(3,3) #15

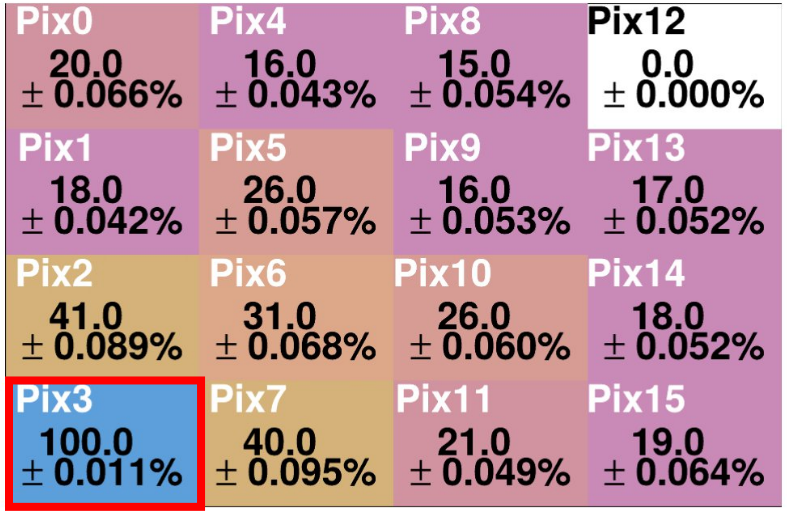
Pix	Charge sharing First Direct Neighbor	Charge sharing First Diagon al	Charge sharing Far Pixel
(a) 02	~40 %	~30 %	~17 %
(b) 03	~41 %	~31 %	~16 %
(c) 06	~33%	~19%	~13%

❖ **More Charge sharing in corners as compared to centre.**

(a) Charge Sharing Plot: hit Pix with max amp2



(b) Charge Sharing Plot: hit Pix with max amp3



(c) Charge Sharing Plot: hit Pix with max amp6

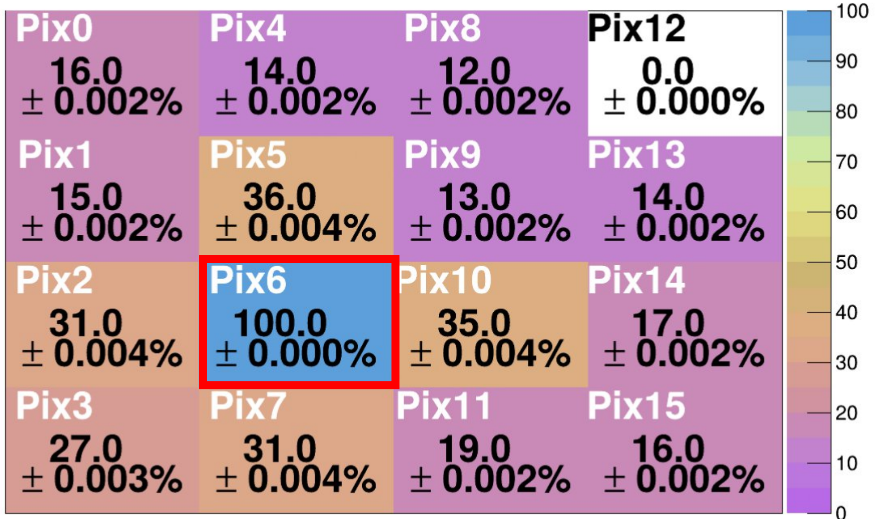


Fig.: Charge Sharing for selection of hit in different Pixels (a) Pix #02, (b) Pix #03, (c) Pix #06.

Charge Sharing Ratio Comparison (Sensor: BNL FC)

Pixel/ Channel Mapping	Column0	Column1	Column2	Column3
Line0	Pixel(0,0) #00	Pixel(1,0) #04	Pixel(2,0) #08	Pixel(3,0) #12
Line1	Pixel(0,1) #01	Pixel(1,1) #05	Pixel(2,1) #09	Pixel(3,1) #13
Line2	Pixel(0,2) #02	Pixel(1,2) #06	Pixel(2,2) #10	Pixel(3,2) #14
Line3	Pixel(0,3) #03	Pixel(1,3) #07	Pixel(2,3) #11	Pixel(3,3) #15

Pix	Charge sharing First Direct Neighbor	Charge sharing First Diagonal	Charge sharing Far Pixel
(a) 02	~40 %	~30 %	~17 %
(b) 03	~41 %	~31 %	~16 %
(c) 06	~33%	~19%	~13%
(d) 07	~39 %	~30%	~15%

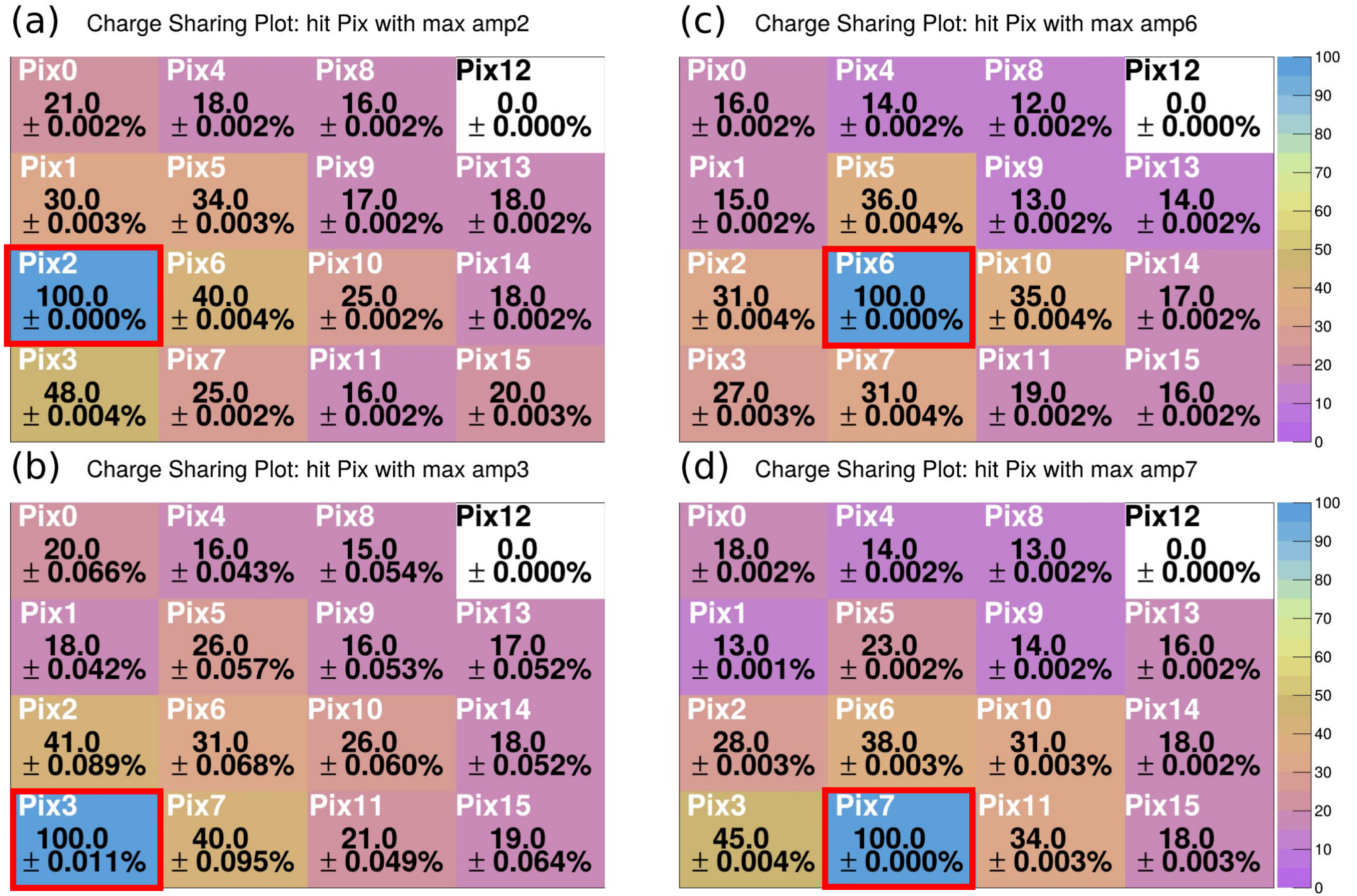


Fig.: Charge Sharing for selection of hit in different Pixels (a) Pix #02, (b) Pix #03, (c) Pix #06, and (d) Pix #07.

- **Pix #07, #02, #03 show similar behavior.**

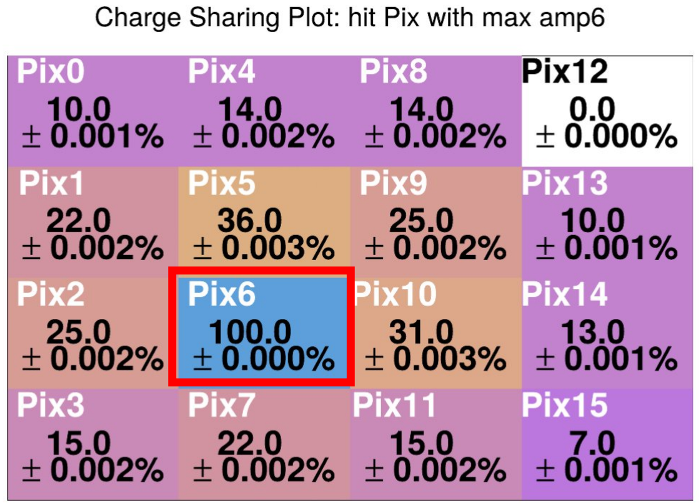
Charge Sharing Ratio Comparison between Sensors (Central Pix #06)

Pixel/ Channel Mapping	Column0	Column1	Column2	Column3
Line0	Pixel(0,0) #00	Pixel(1,0) #04	Pixel(2,0) #08	Pixel(3,0) #12
Line1	Pixel(0,1) #01	Pixel(1,1) #05	Pixel(2,1) #09	Pixel(3,1) #13
Line2	Pixel(0,2) #02	Pixel(1,2) #06	Pixel(2,2) #10	Pixel(3,2) #14
Line3	Pixel(0,3) #03	Pixel(1,3) #07	Pixel(2,3) #11	Pixel(3,3) #15

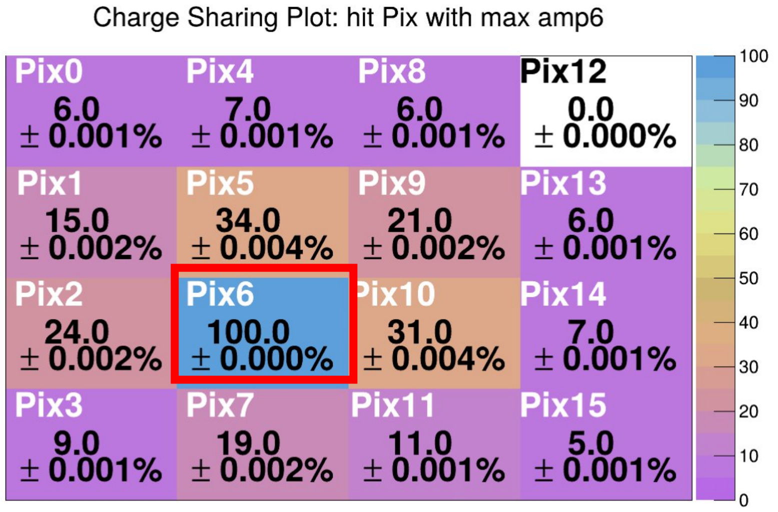
Sensor	Charge sharing First Direct Neighbor	Charge sharing First Diagonal	Charge sharing Far Pixel
(a) WB	~28 %	~20 %	~14%
(b) HPK	~29 %	~16%	~7 %
(c) FC	~33%	~19%	~13%

The Flip Chip features larger charge sharing ratio for #reference_pixel chosen at the centre.

(a)BNL WB



(b)HPK WB



(c)BNL FC

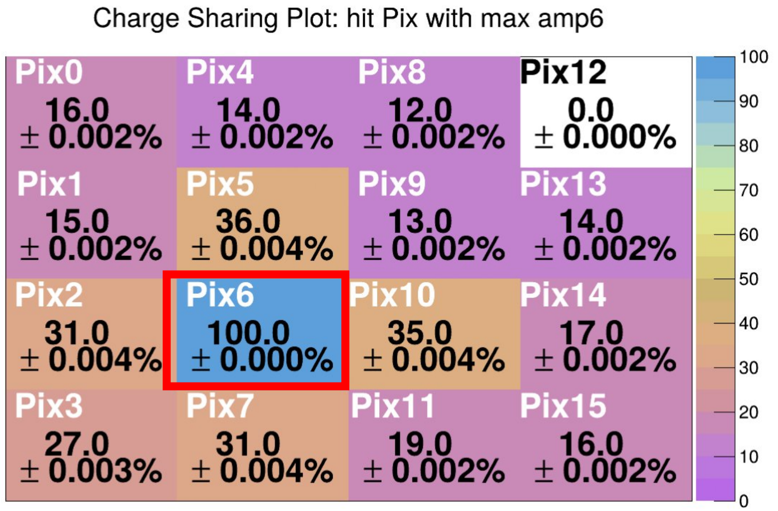


Fig.: Charge Sharing for selection of hit in same Pixel Pix #06 for (a)BNL WB, (b) HPK WB, (c) BNL FC.

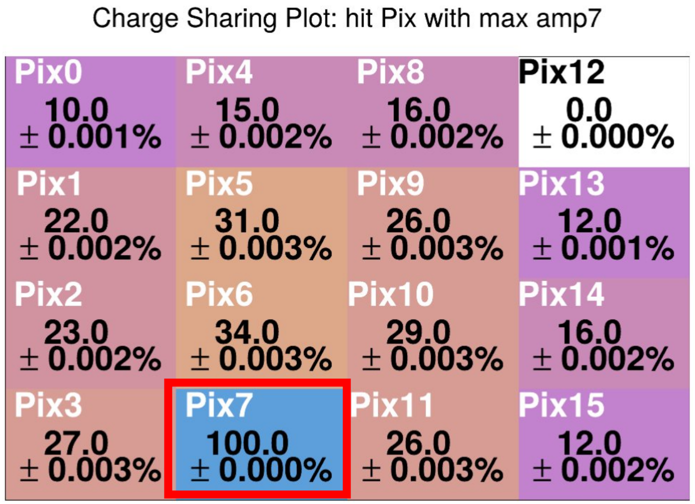
Charge Sharing Ratio Comparison between Sensors (Edge Pix #07)

Pixel/ Channel Mapping	Column0	Column1	Column2	Column3
Line0	Pixel(0,0) #00	Pixel(1,0) #04	Pixel(2,0) #08	Pixel(3,0) #12
Line1	Pixel(0,1) #01	Pixel(1,1) #05	Pixel(2,1) #09	Pixel(3,1) #13
Line2	Pixel(0,2) #02	Pixel(1,2) #06	Pixel(2,2) #10	Pixel(3,2) #14
Line3	Pixel(0,3) #03	Pixel(1,3) #07	Pixel(2,3) #11	Pixel(3,3) #15

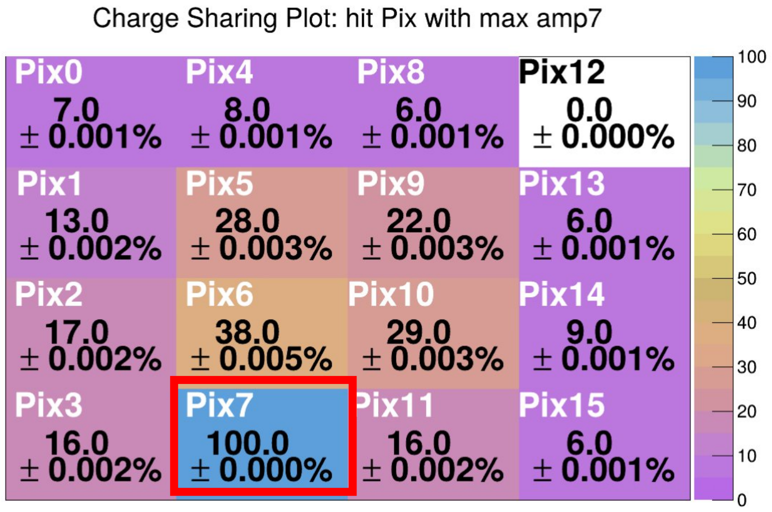
Sensor	Charge sharing First Direct Neighbor	Charge sharing First Diagonal	Charge sharing Far Pixel
(a) WB	~29 %	~26%	~14%
(b) HPK	~23%	~23%	~6 %
(c) FC	~39 %	~30%	~15%

The Flip Chip features larger charge sharing ratio for #reference_pixel chosen at the edge.

(a)BNL WB



(b)HPK WB



(c)BNL FC

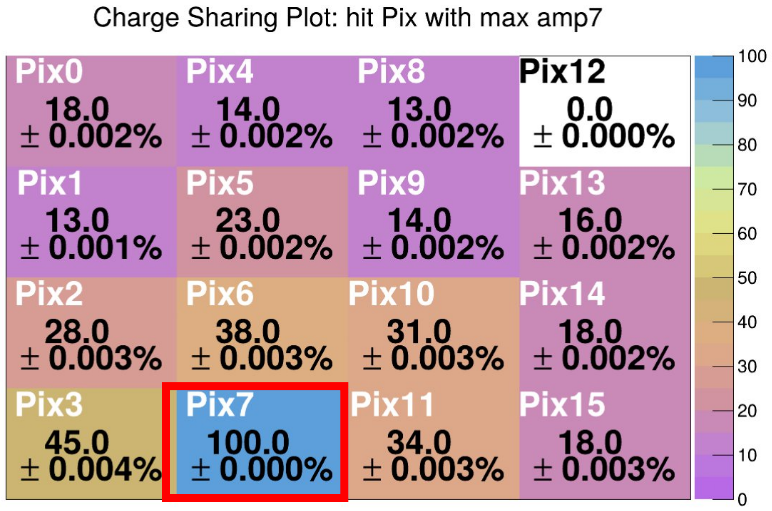


Fig.: Charge Sharing for selection of hit in same Pixel Pix #07 for (a)BNL WB, (b) HPK WB, (c) BNL FC.

Conclusions

- ✓ Beta source measurements performed with EICROC0 ASIC coupled to 4x4 pixelated three different sensors : BNL WB, BNL FC, and HPK WB.
- ✓ 95 % of the events are cut with event selection cut (hit bit =1 in pixel of interest and has max amplitude).
- ✓ Hit map for each of the pixels show ~7% of the events have hit bit = 1 in the first direct neighborhood of the hit pixel (implying they crossed the discriminator threshold). This implies most 93% of the times events is recorded for only one pixel firing.
- ✓ For pedestal subtraction, the far pixel is chosen, which almost never crosses the threshold (implying corresponds to the noise).
- ✓ The analysis shows consistency with the scope data, while the method is more reliable.
- ✓ Charge sharing studied using Landau fitting.
- ✓ More charge sharing observed with FC sensor. For hit in central pixel, ~33% and for edge pixel, ~39% with first neighbor.
- ✓ First direct neighbor shows more charge sharing as compared to first diagonal. E.g., for hit in Pix #06 in FC, it is ~60 % as compared to first direct neighbors.

Future perspectives

- ➢ Further analysis Ongoing to extract timing resolution.
- ➢ Charge sharing ratio extension to achieve required position resolution (AC-LGAD property).
- ➢ LASER setup completed; measurements commenced to investigate detector position and timing resolution.

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