Upgrade of the prototype Schwarzschild-Couder Telescope Camera

CTAO School – 28 June, 2024

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UW-Madison

Outline

- Introduction
  - SCTs in CTAO
  - pSCT Background
- Camera Calibration
  - Module Introduction
  - ADC Ramp Tuning
  - CTC DC Transfer Function
  - Finger plots
- Timeline and Conclusion

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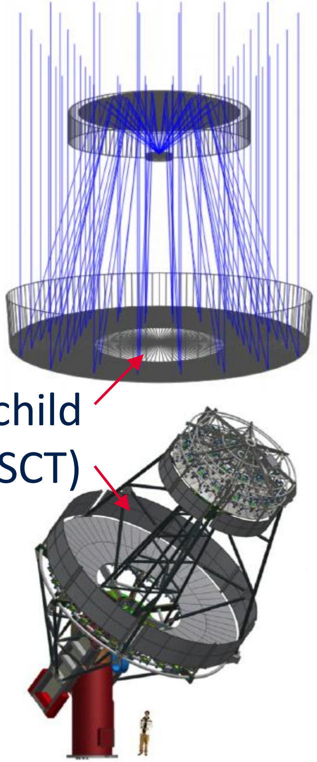
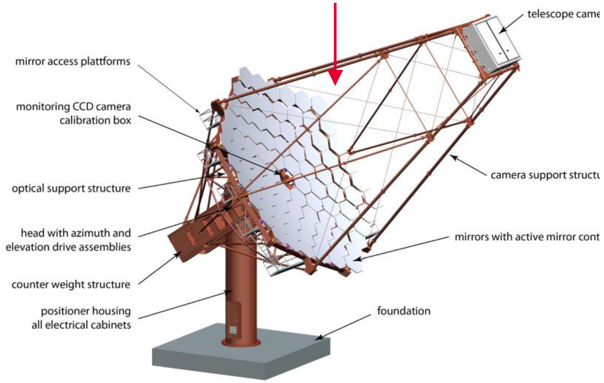
Schwarzschild-Couder vs Davies-Cotton Telescopes

Schwarzschild -Couder (SCT)

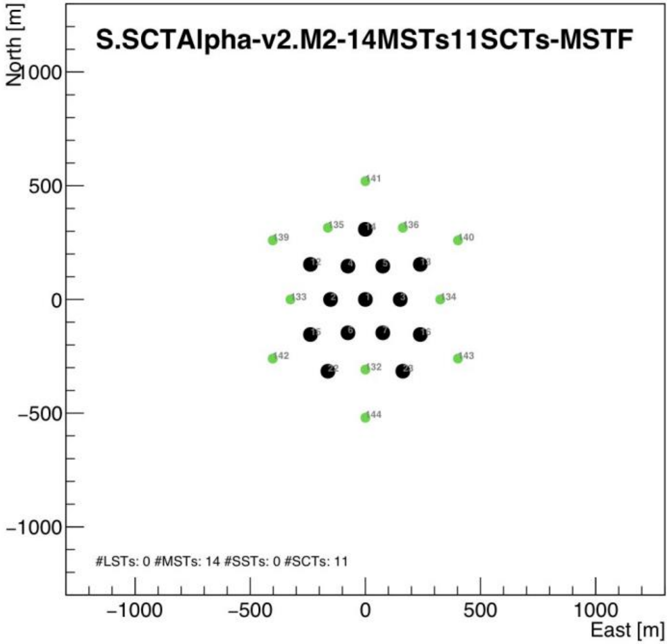


arXiv:1509.02463

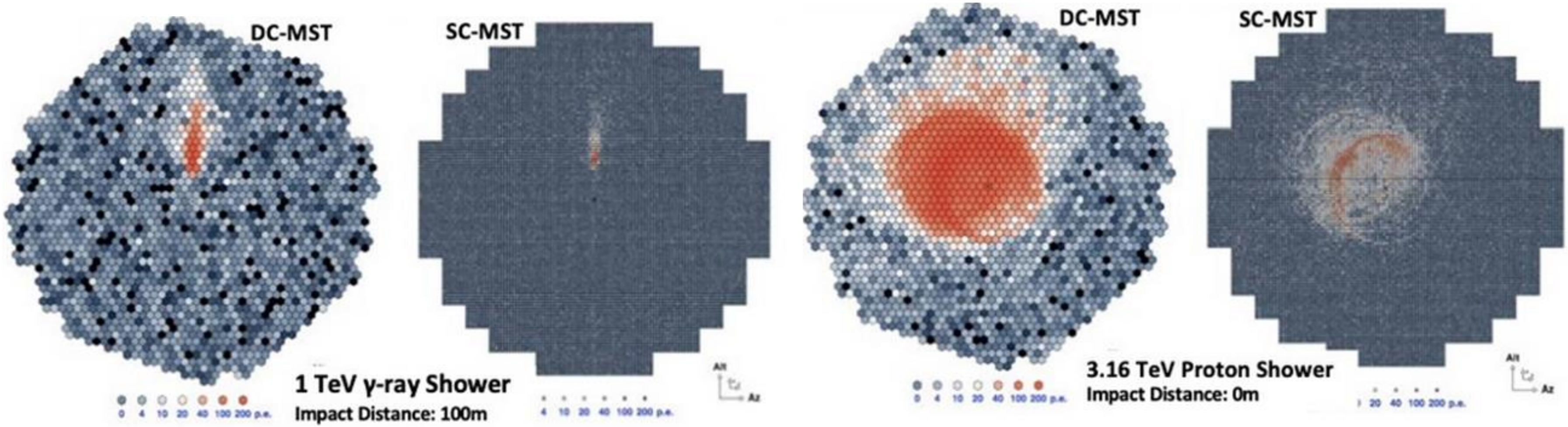
Davies-Cotton (MST)



arXiv:1907.08455



Schwarzschild-Couder vs Davies-Cotton

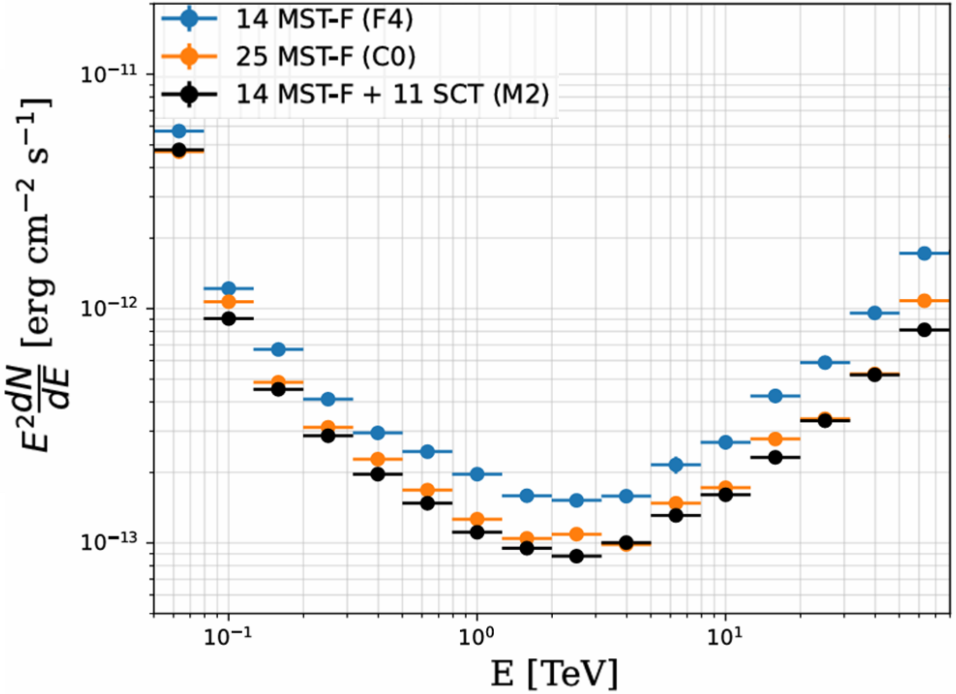


DC-MST: 8 deg /0.18 deg / 1,855 pixels

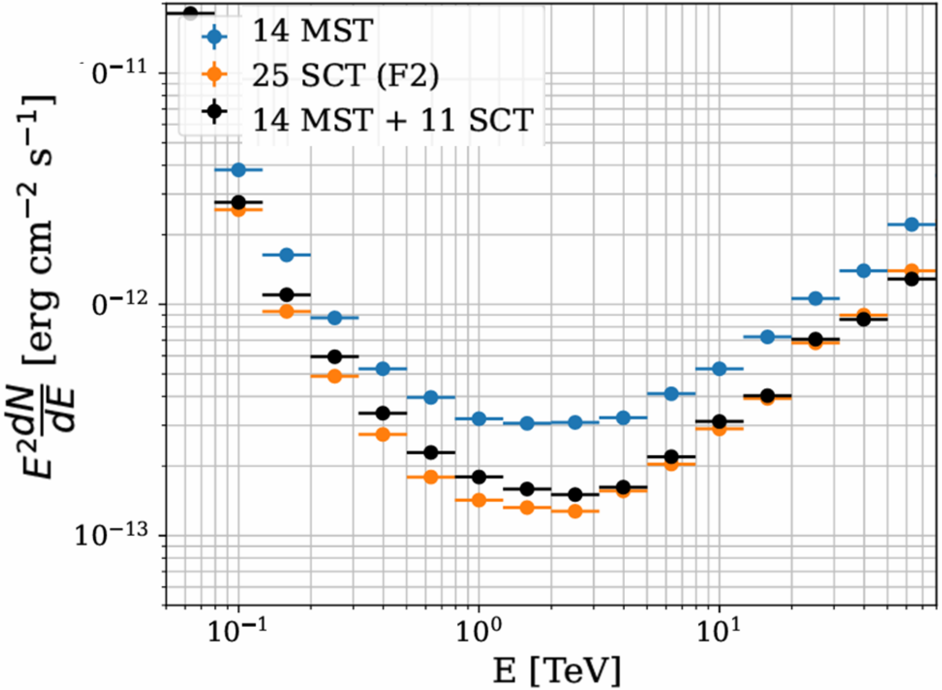
SC-MST: 8 deg /0.067 deg /11,328 pixels

Sensitivity

On-Source

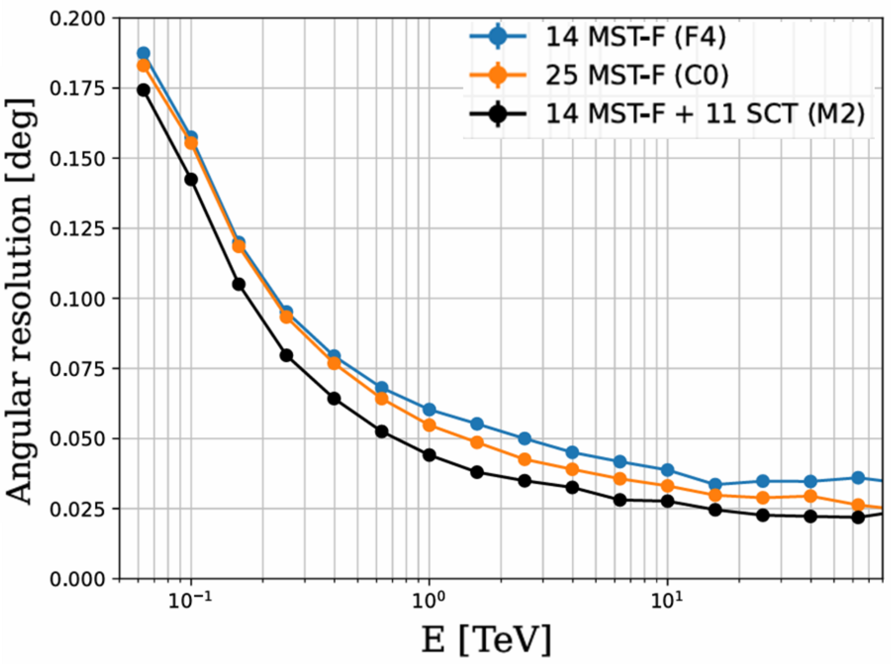


3.5 Degrees Off-Axis



Angular Resolution

On-Source



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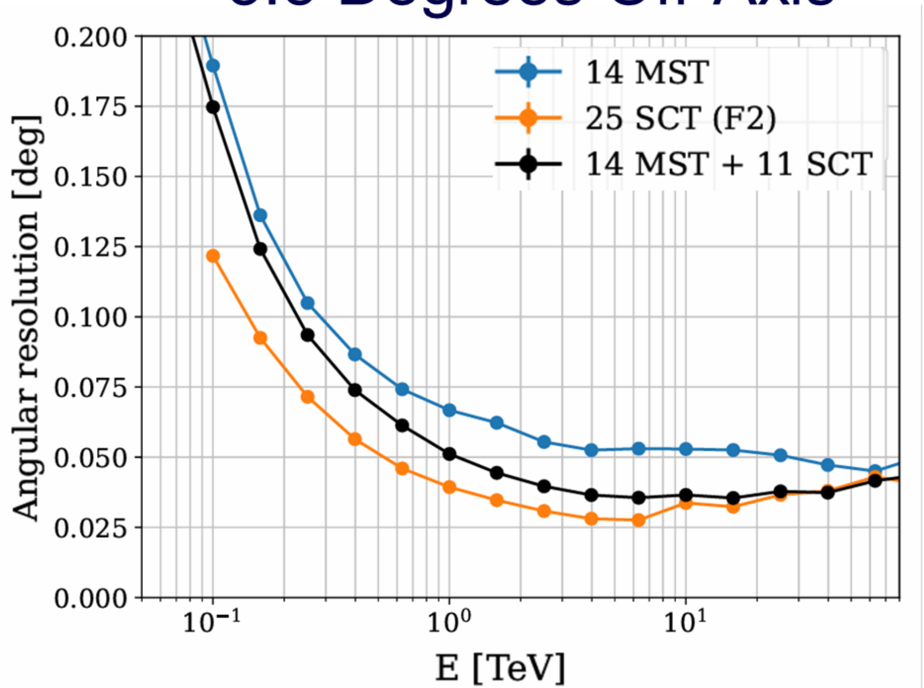

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The Prototype Schwarzschild-Couder Telescope (pSCT)

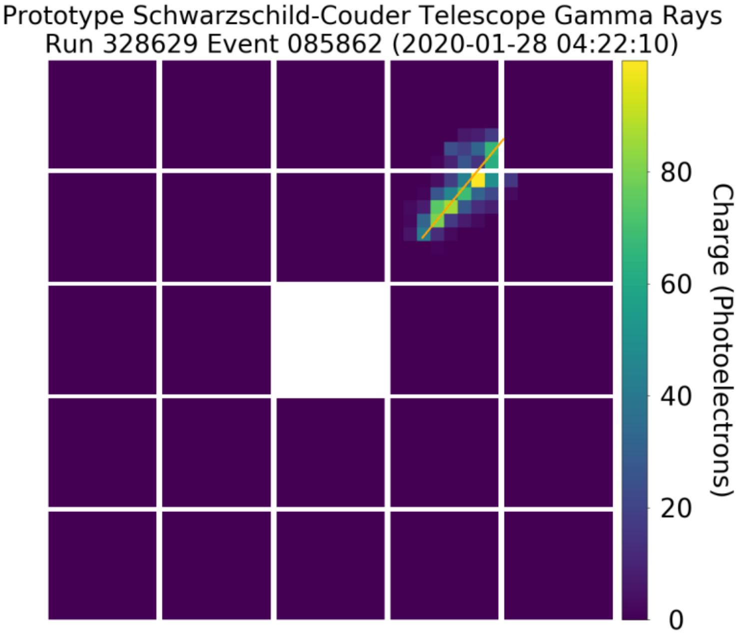
CTAO

- CTAO candidate medium-sized telescope
- Located at Fred Lawrence Whipple Observatory (FLWO)
- 100 GeV to 10 TeV energy range
- Novel dual mirror Schwarzschild-Couder design uses silicon photomultipliers (SiPMs)
- 1600/11,328 pixels populated – 2.7 degree / 8 FOV

Credit: Deivid Ribeiro

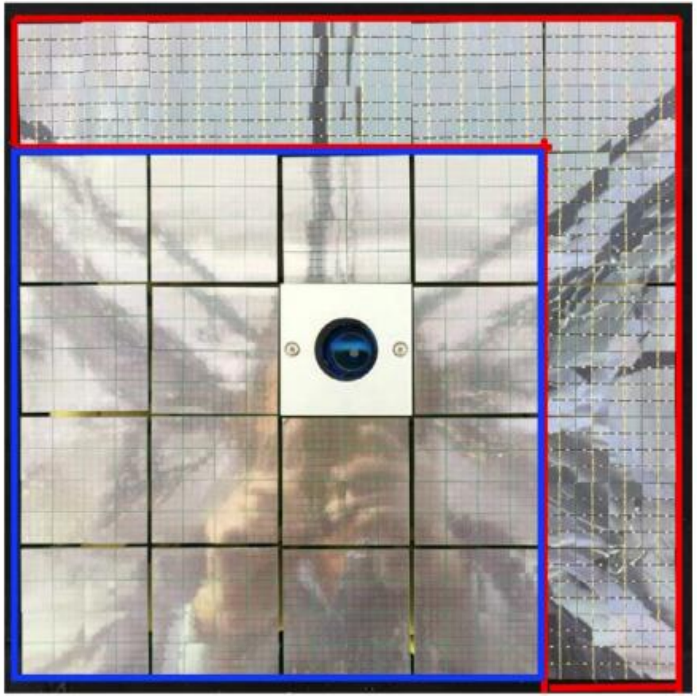
pSCT History

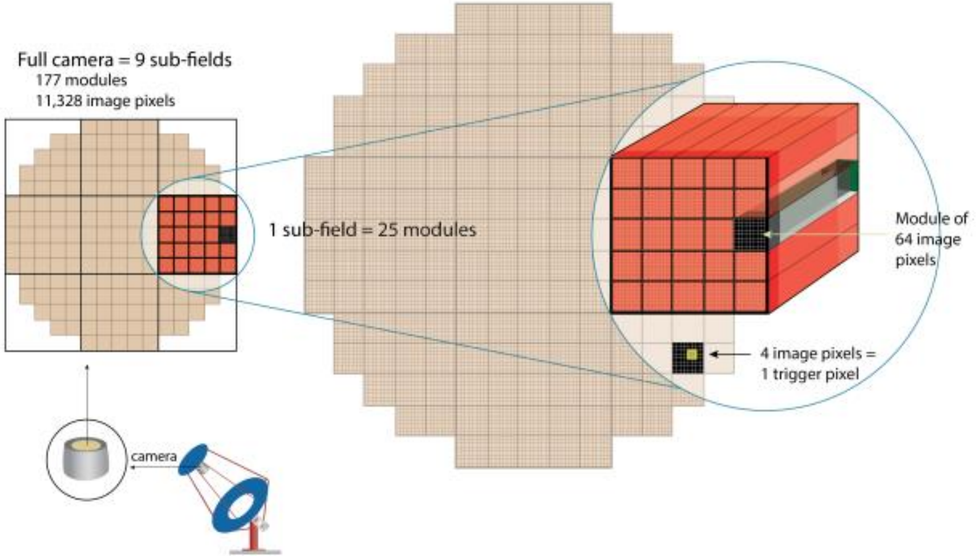
- First light in January 2019
- Detected the Crab Nebula in 2020



Source: Adams et al. Detection of the Crab Nebula with the 9.7 m prototype Schwarzschild-Couder telescope

pSCT Camera

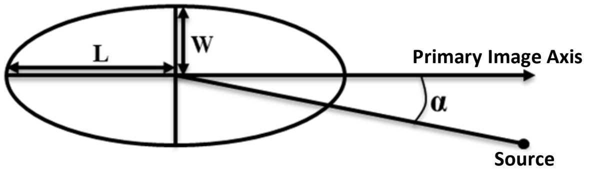




Source: arXiv:1910.00133

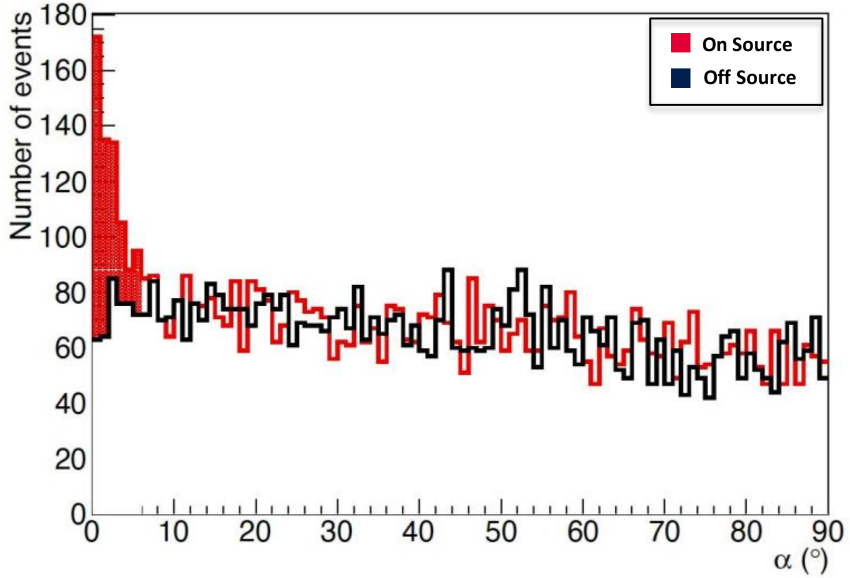
Source: Adams et al. Detection of the Crab Nebula with the 9.7 m prototype Schwarzschild-Couder telescope

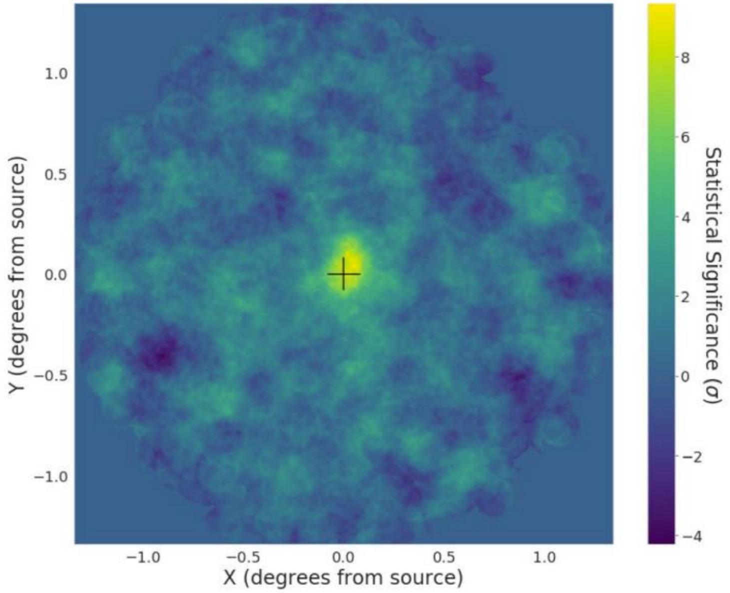
pSCT Crab Detection



- Crab Nebula detected at 8.6 sigma using data from February 2020
- 17.6 hours of on and off source data
- Hillas parameterization used to establish gamma-ray selection cuts

Source: Adams et al. Detection of the Crab Nebula with the 9.7 m prototype Schwarzschild-Couder telescope





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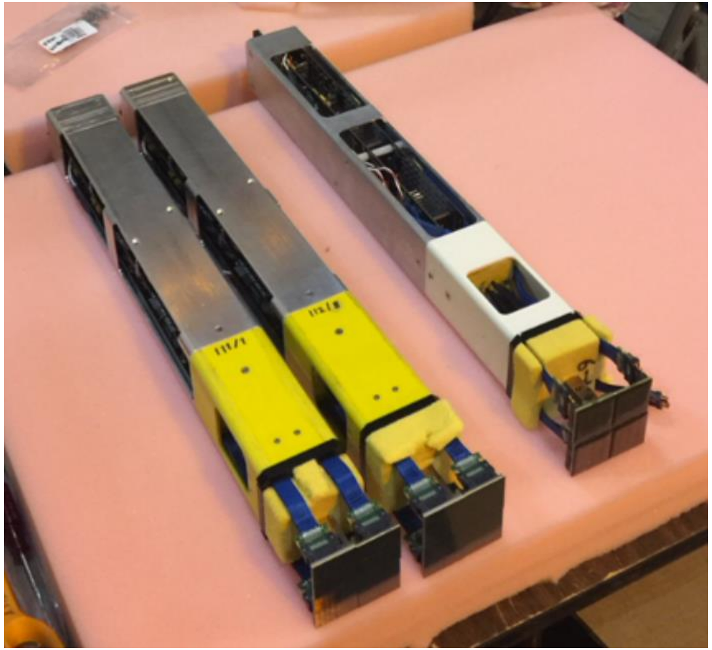
Module Description

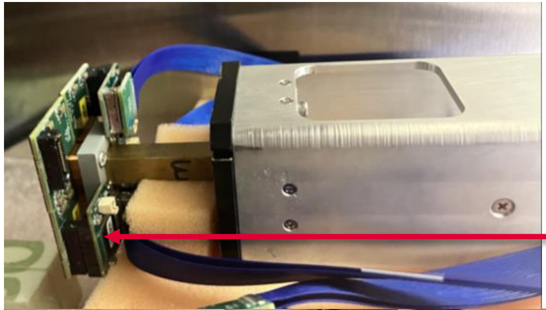
- Camera modules include TARGET Application Specific Integrated Circuits (ASIC) and a Field Programmable Gate Array (FPGA)
- Four quadrants/ASICs per module
- TARGET 7 electronics used on current camera, upgraded camera to use CTC
- T7: Combined triggering and digitization
- CTC: CTC for digitization, CT5TEA for triggering, SMART chip added for pulse shaping and amplification
- Module consists of a Focal Plane Module (FPM) and Front-End Electronics (FEE)



Target 7 Camera Modules

Testing Setup

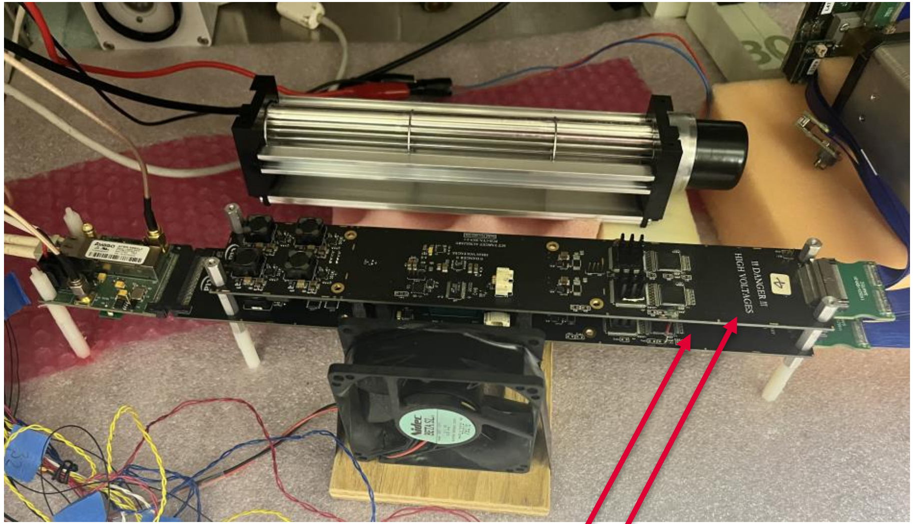
Focal Plane Module



SMART

SiPMs

Front-End Electronics

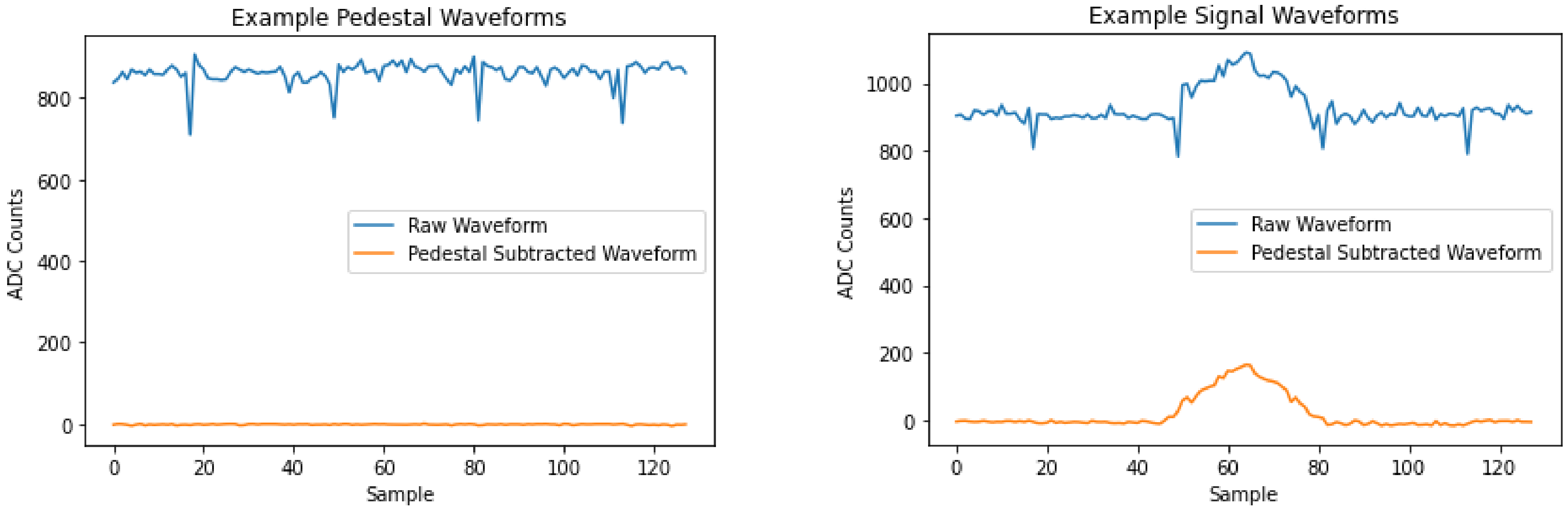


Primary Board

Auxiliary Board

Voltage Pedestal (Vped)

- Vped - DC offset places waveforms in linear range of readout electronics and prevents underflow



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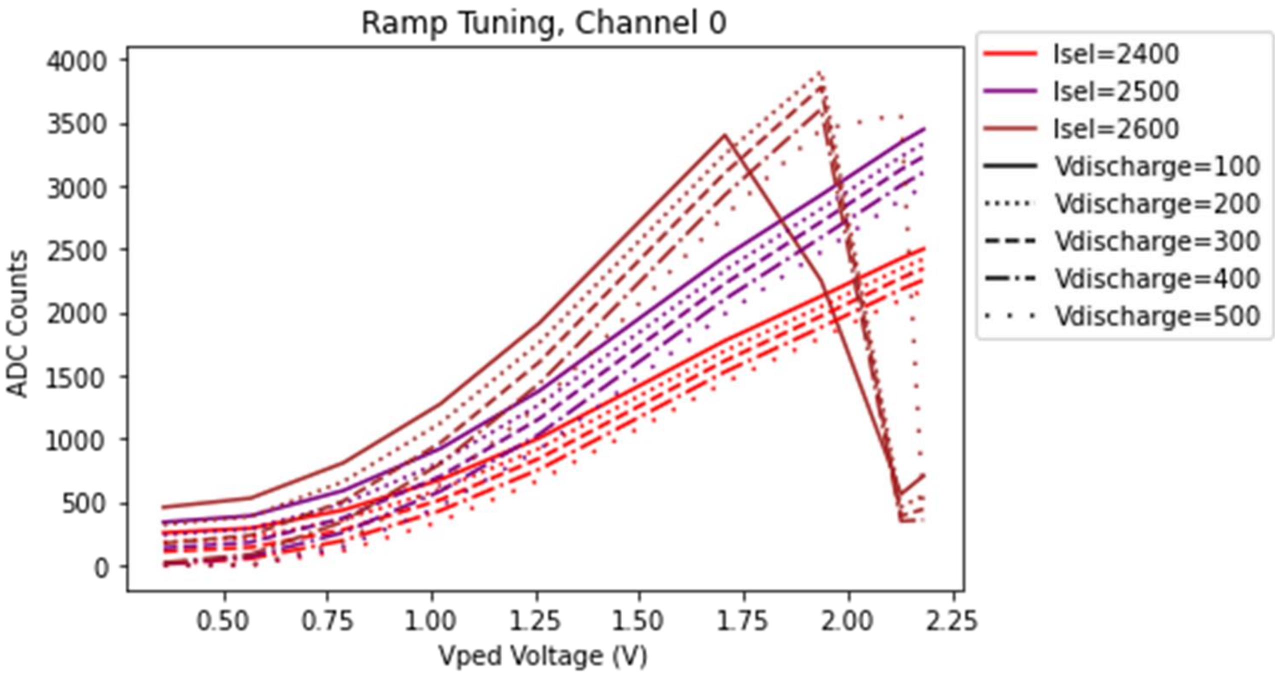
ADC Ramp Tuning

- Wilkinson ramp ADC converts voltage to ADC counts
- Isel and Vdischarge modify ramp shape and should be optimized
- Ideal ramp shape gives maximum voltage resolution while covering the full input dynamic range



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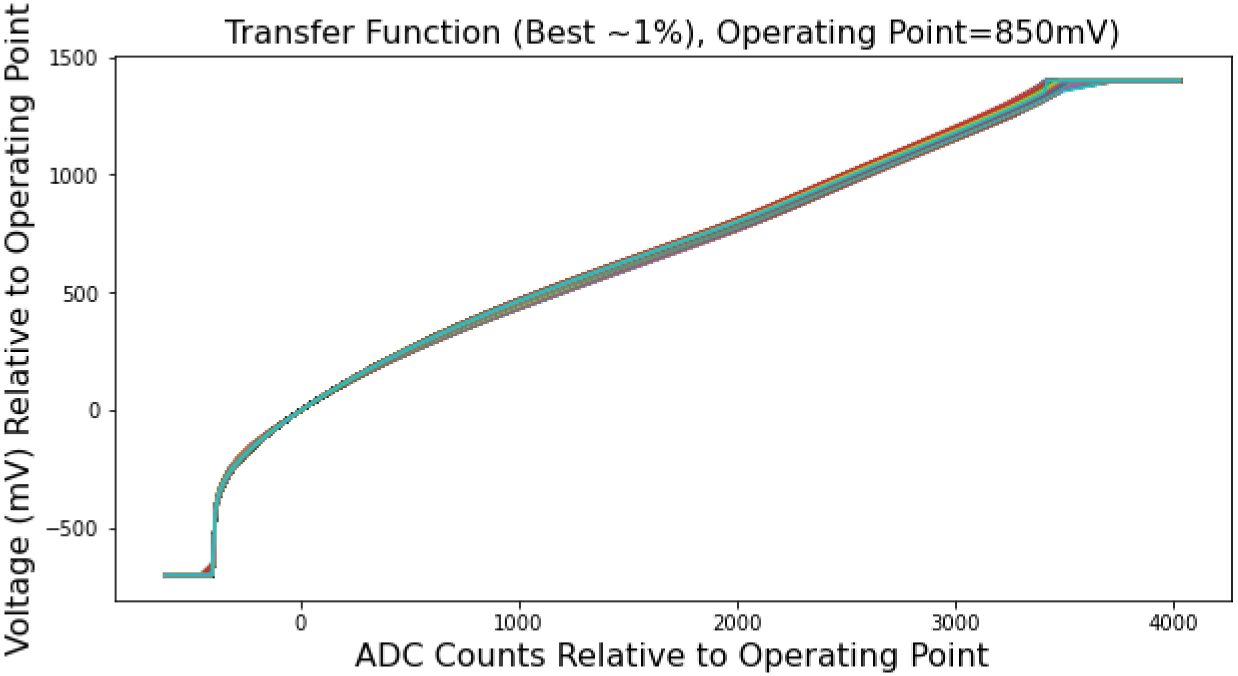
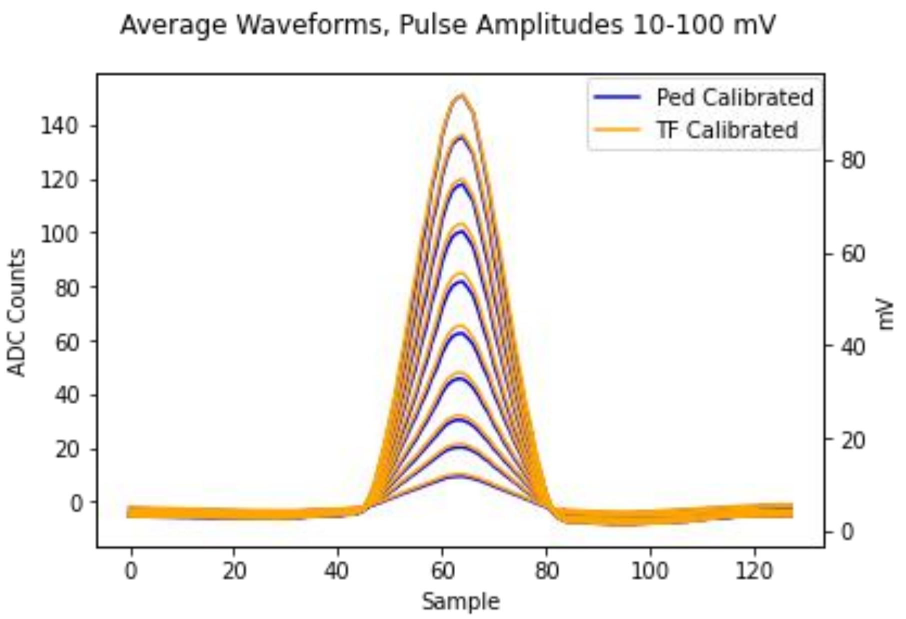
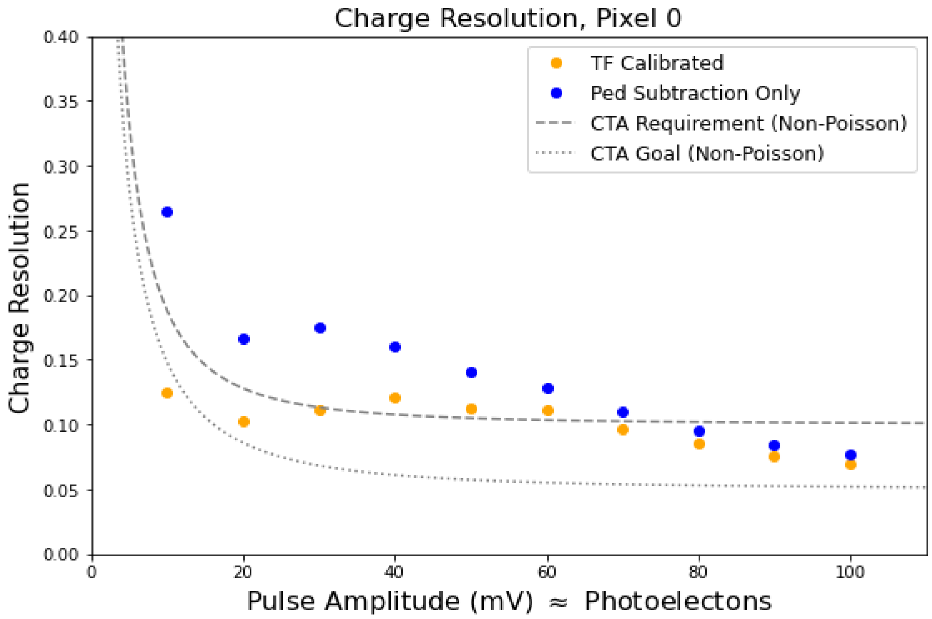
CTC DC Transfer Functions

- Wilkinson ADC in CTC ASIC digitizes analog voltage to ADC counts
- Vped TF provides DAC -> mV
- CTC TF created by measuring DAC -> ADC
- Using Vped we can then get DC TF: ADC -> (DAC ->) mV

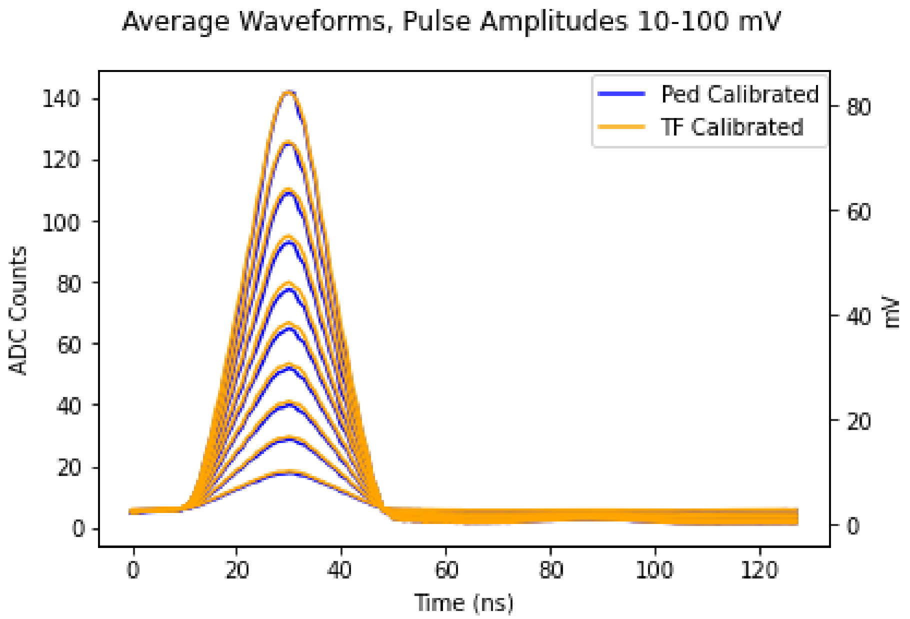


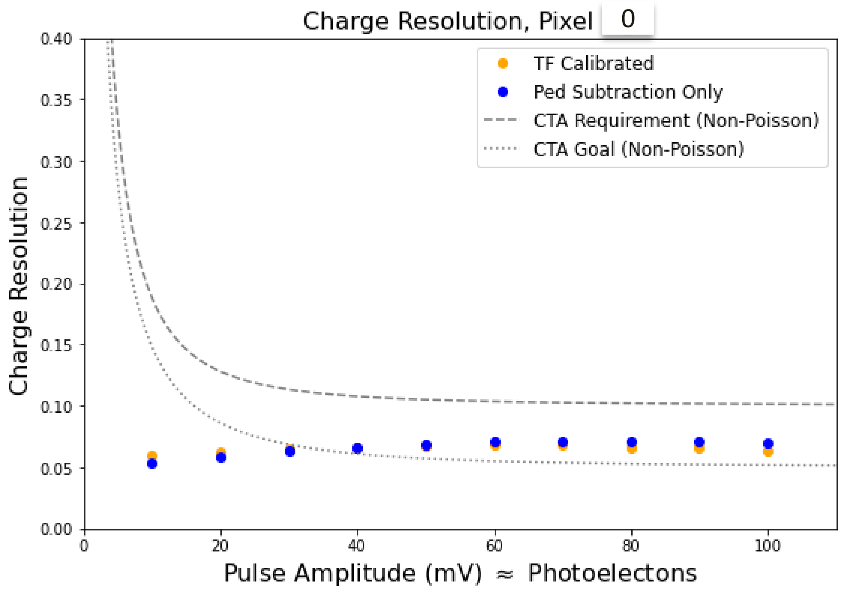
Charge Resolution (TC Module)





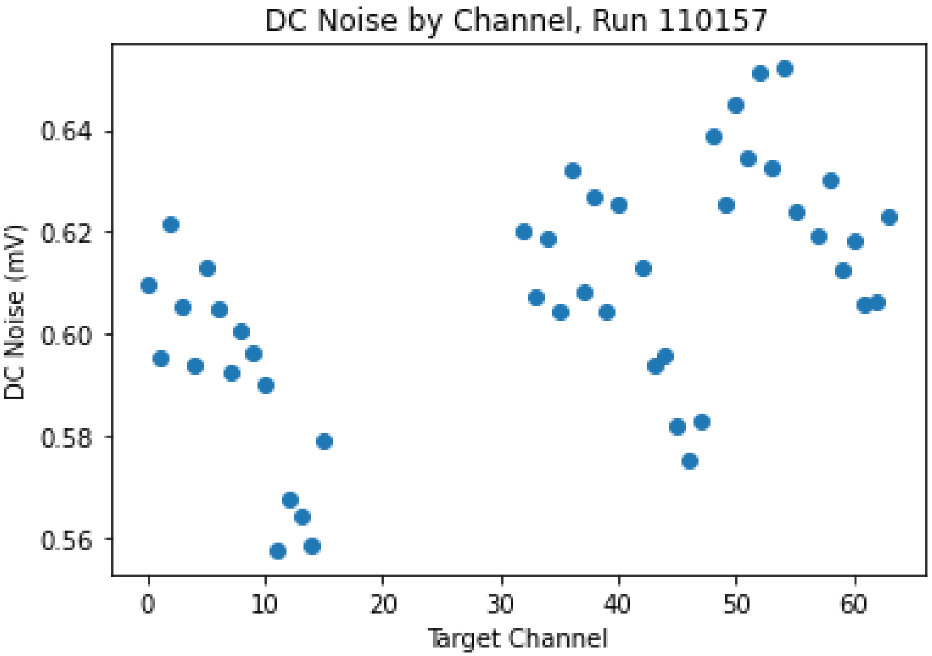
Charge Resolution (CTC Module - Preliminary)





DC Noise

- DC noise calculated as standard deviation over all sample values for a large number of waveforms in pedestal run
- Consistent low DC noise across module channels



1 p.e. approximately 3mV

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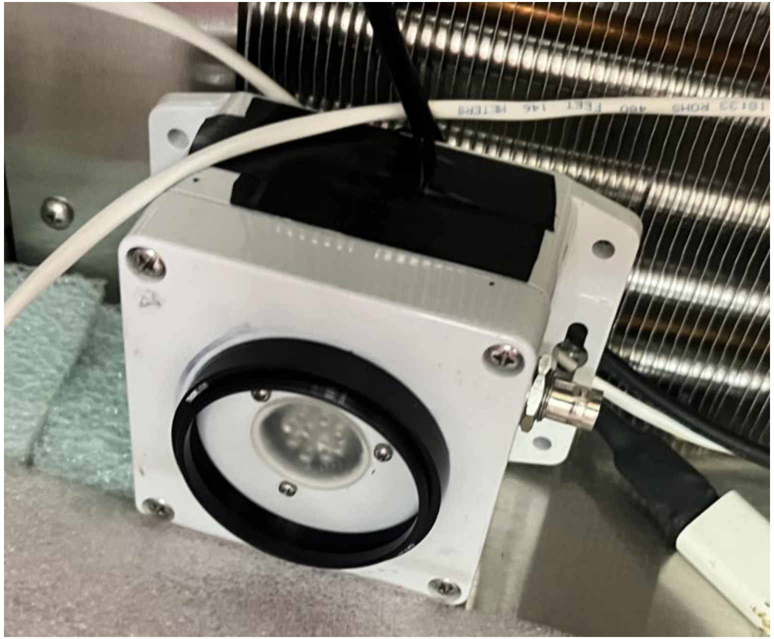
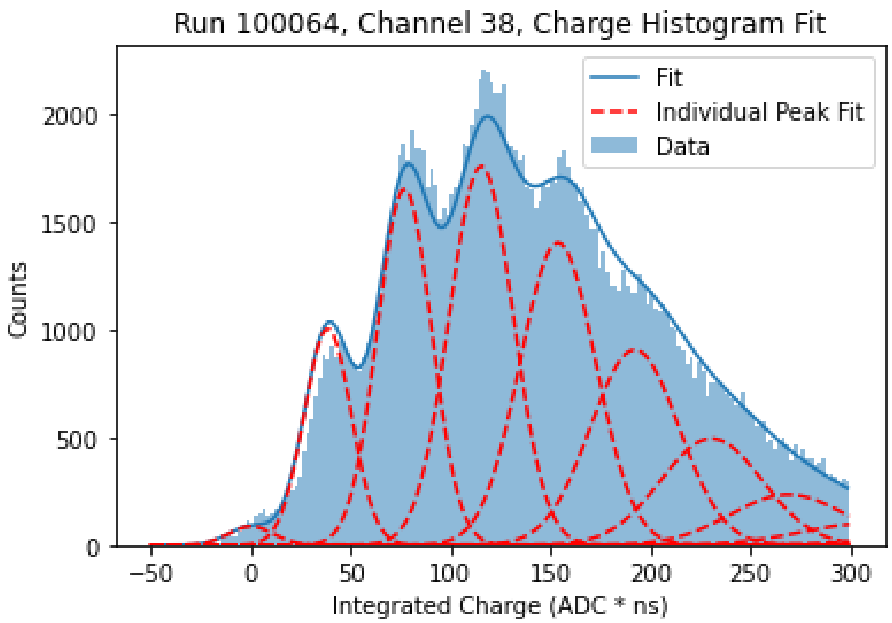
Finger Plots

- Integrating signal waveforms gives the charge deposited by photoelectrons (p.e.)
- A histogram of charges from low intensity light is called a finger plot
- Fitting the finger plot can reveal important information about gain, electronics noise, etc.



Finger Plots



- Camera measures discrete numbers of p.e. - each peak corresponds to an increasing number of p.e.
- Sum of constrained Gaussians fit
- Fit result values:
  - Gain - 38.41 ADC * ns per p.e.
  - Electronics Noise - 11.19 ADC * ns
  - Average Number of p.e. – 3.77 p.e.
  - Sigma Gain / Gain – 0.099

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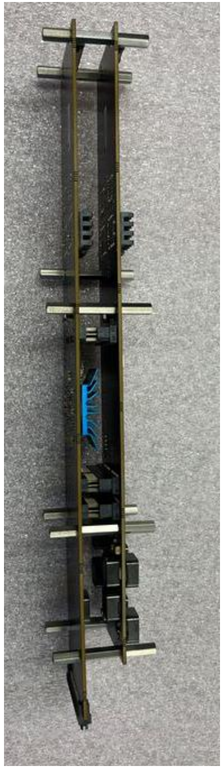
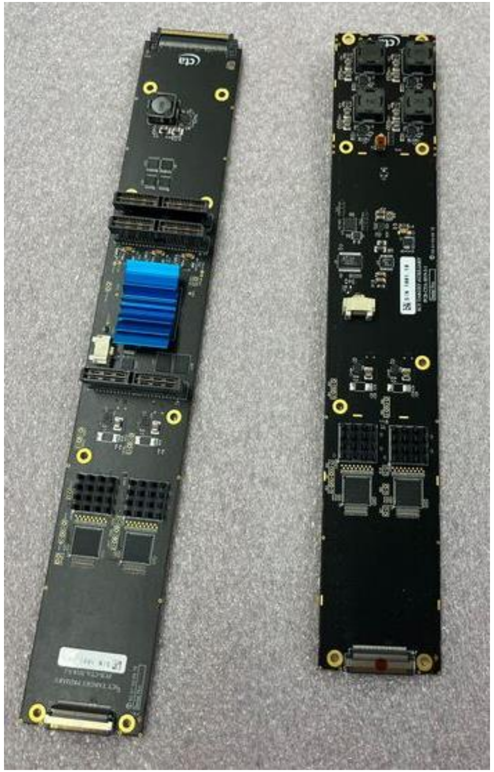
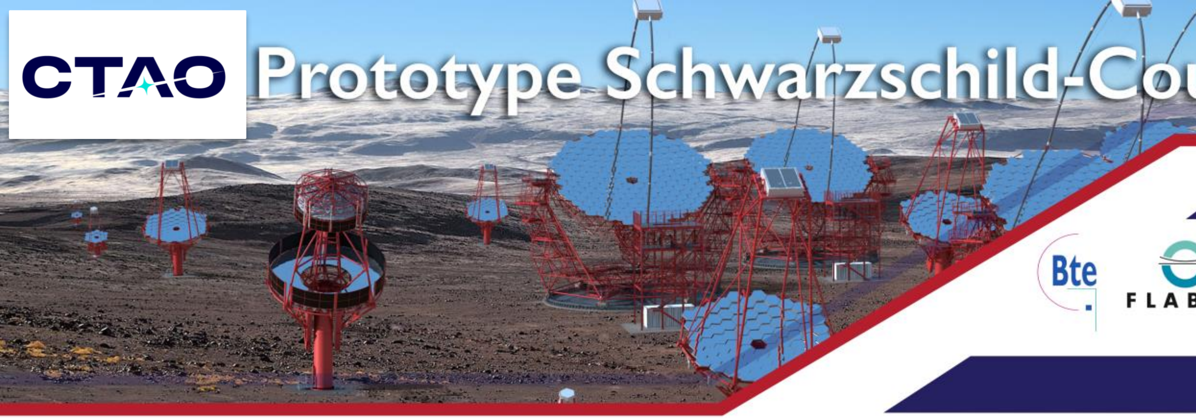
pSCT Outlook

- SCT design results in better sensitivity and angular resolution than Davies-Cotton telescopes
- The pSCT detected the Crab Nebula in 2020 and is currently undergoing a camera upgrade
- Camera upgrade mechanical installation completed in March 2024
- First CTC module arrived in Wisconsin for testing in November 2023





CTAO Prototype Schwarzschild-Couder Telescope



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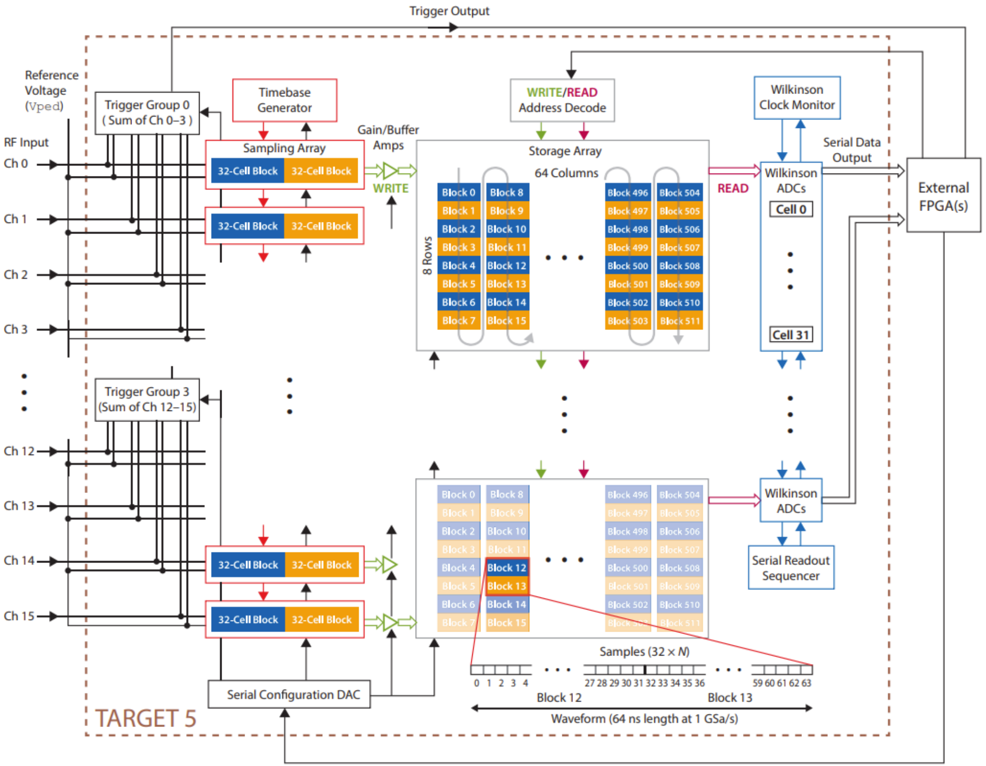
Backup Slides

Data Path Description

- Four quadrants/ASICs per module, 16 channels per ASIC
- Switched-capacitor array stores 512 blocks, each containing 32 cells
- Each cell contains 1ns of charge
- Trigger path monitors four channel sum



Source: Albert et al. TARGET 5: A new multi-channel digitizer with triggering capabilities for gamma-ray atmospheric Cherenkov telescopes

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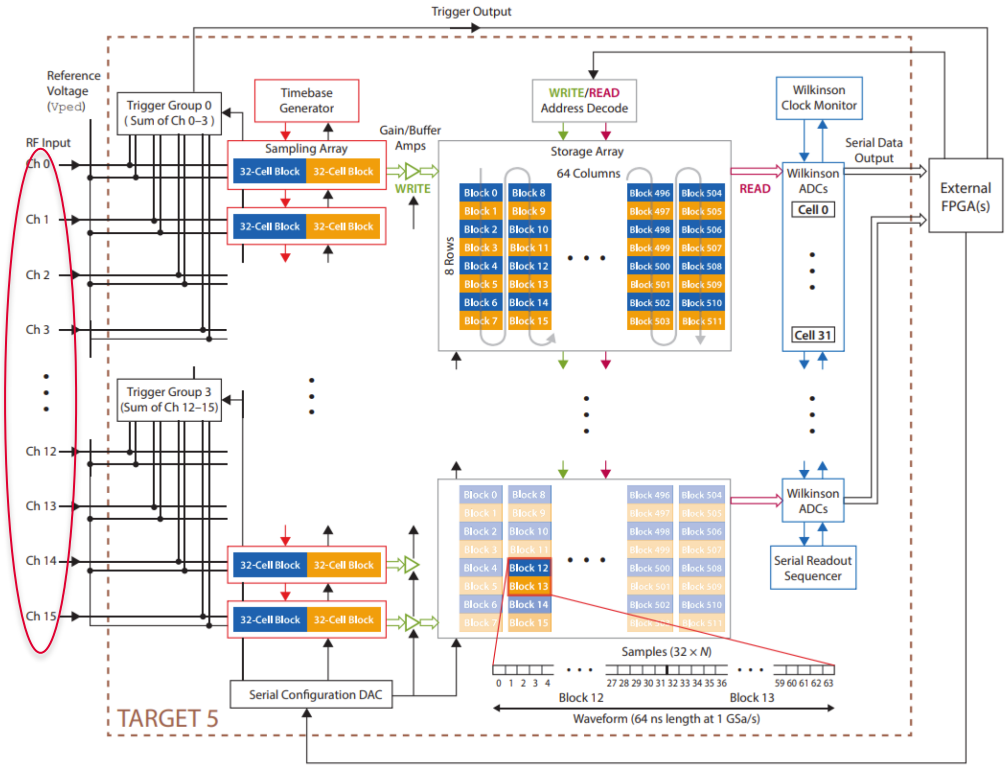

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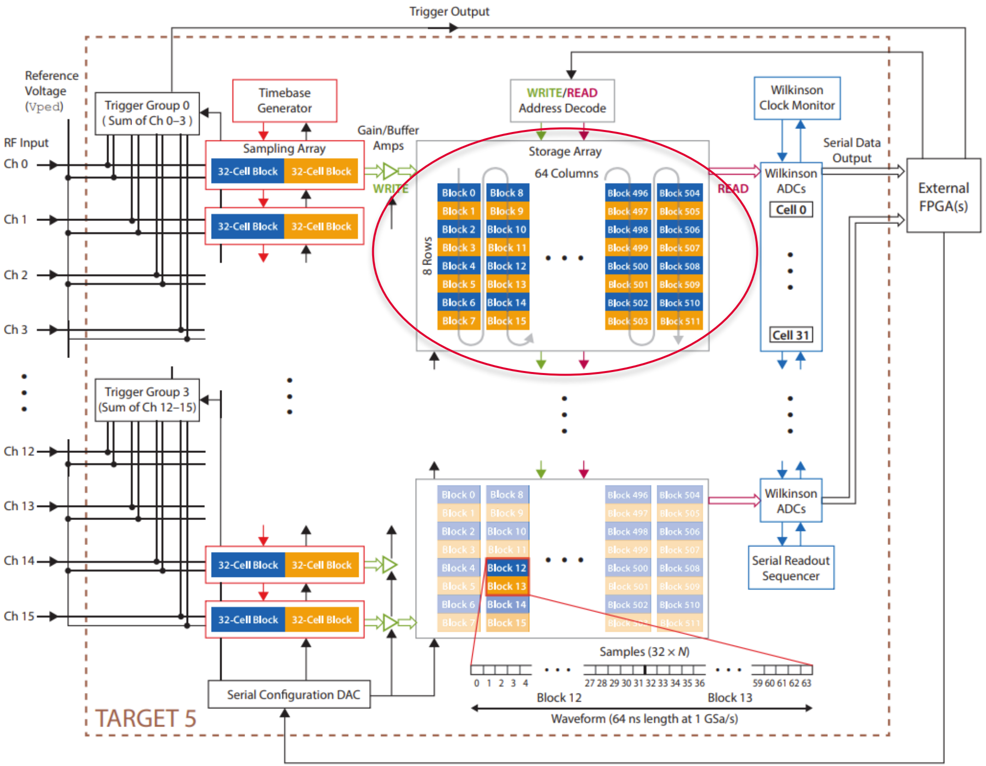

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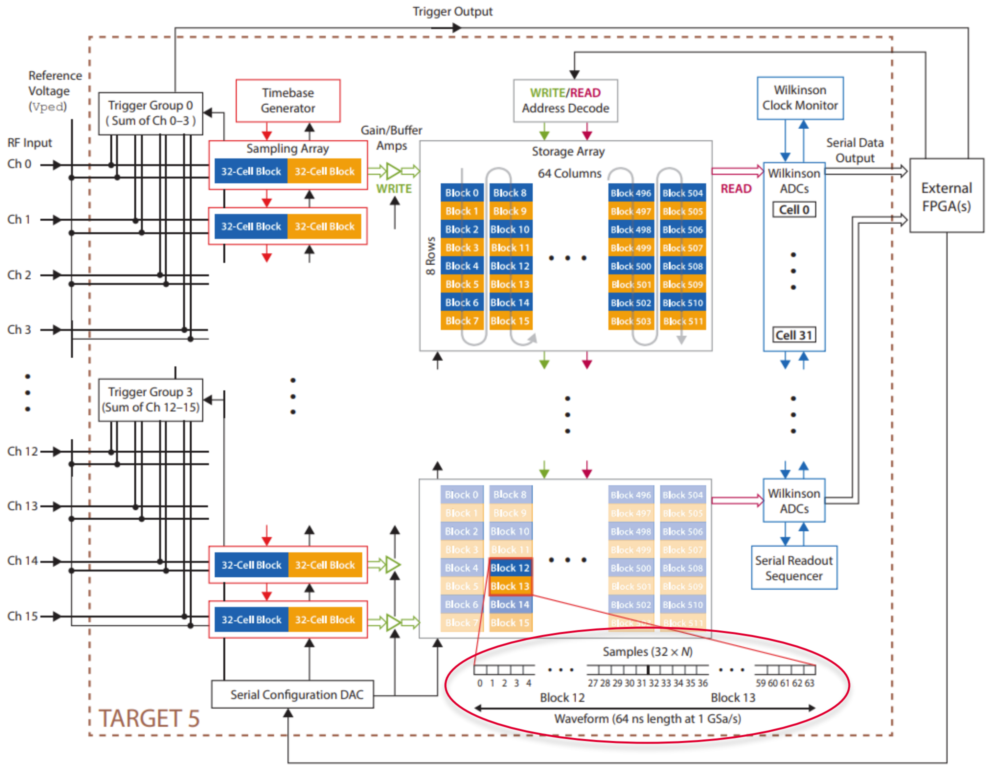

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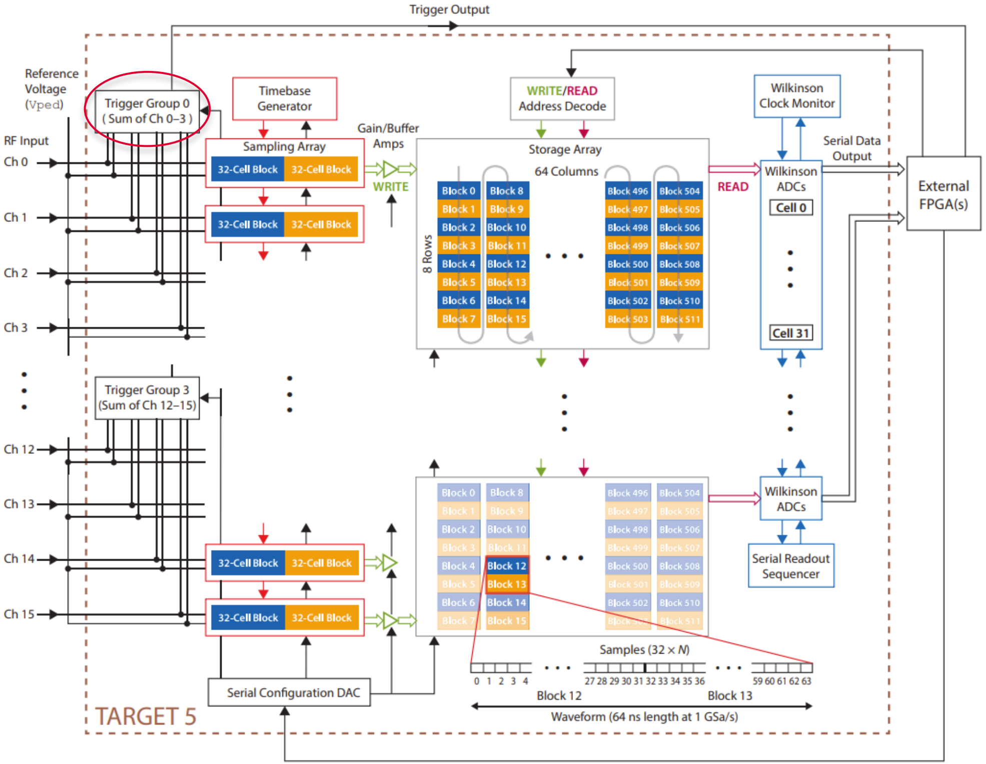
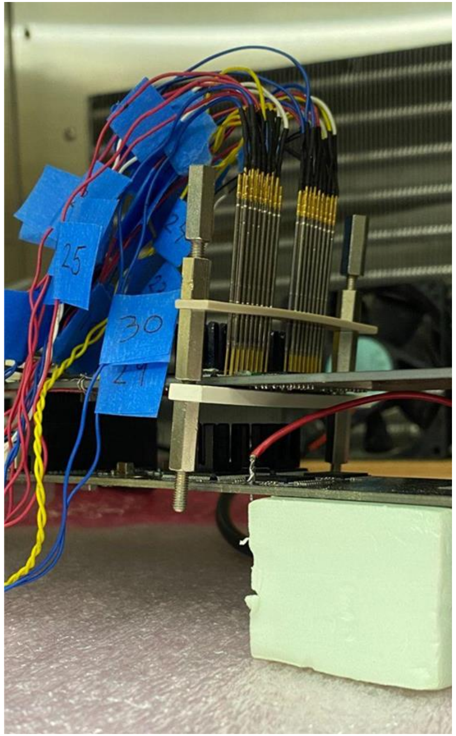
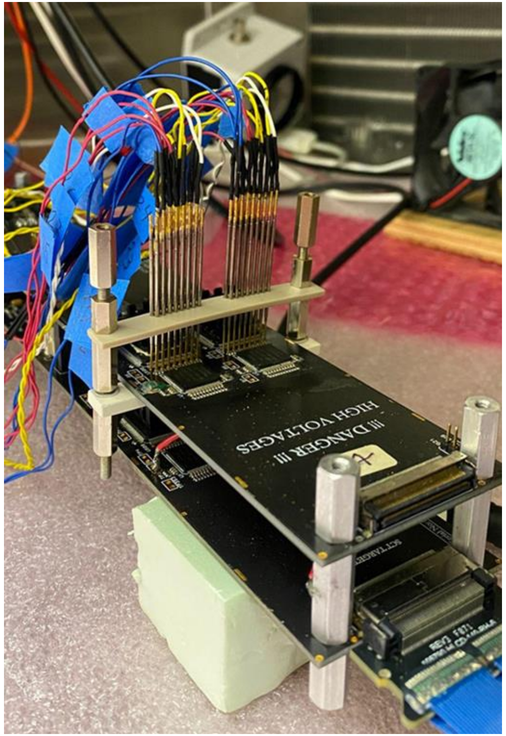


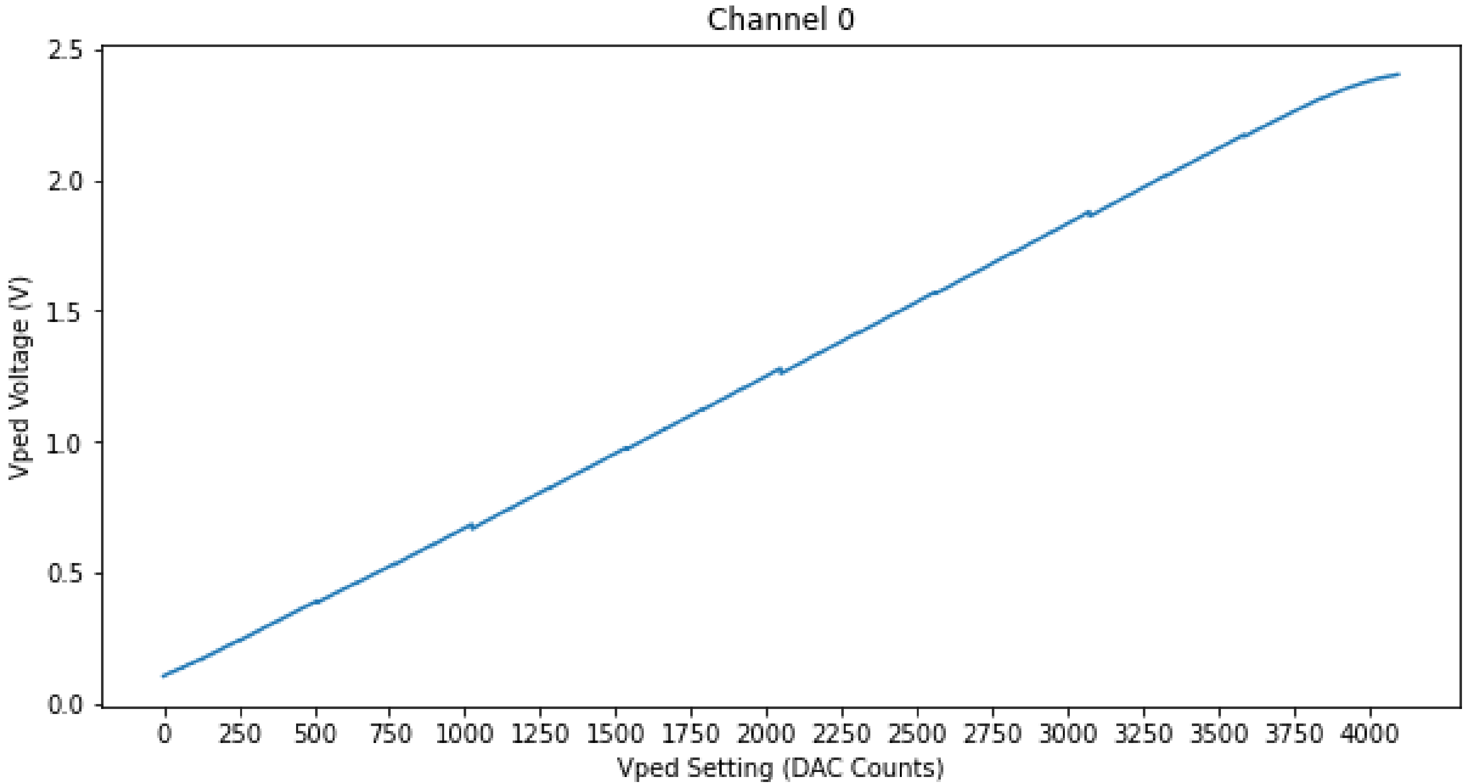
Vped Digital to Analog Converter (DAC) Transfer Function (TF)

- Vped TF converts DAC to mV
- Vped DAC is 12-bit – values from 0 to 4095
- Measured at 25°C, 35°C, 45°C
- Rig setup and measurements done by undergrad Sam Heiman



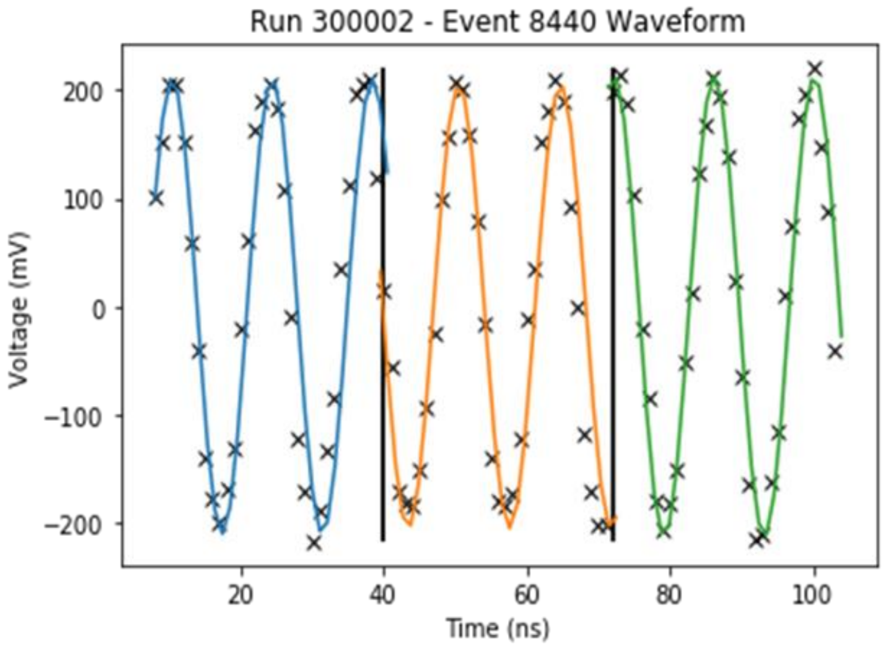


Vped DAC Transfer Function



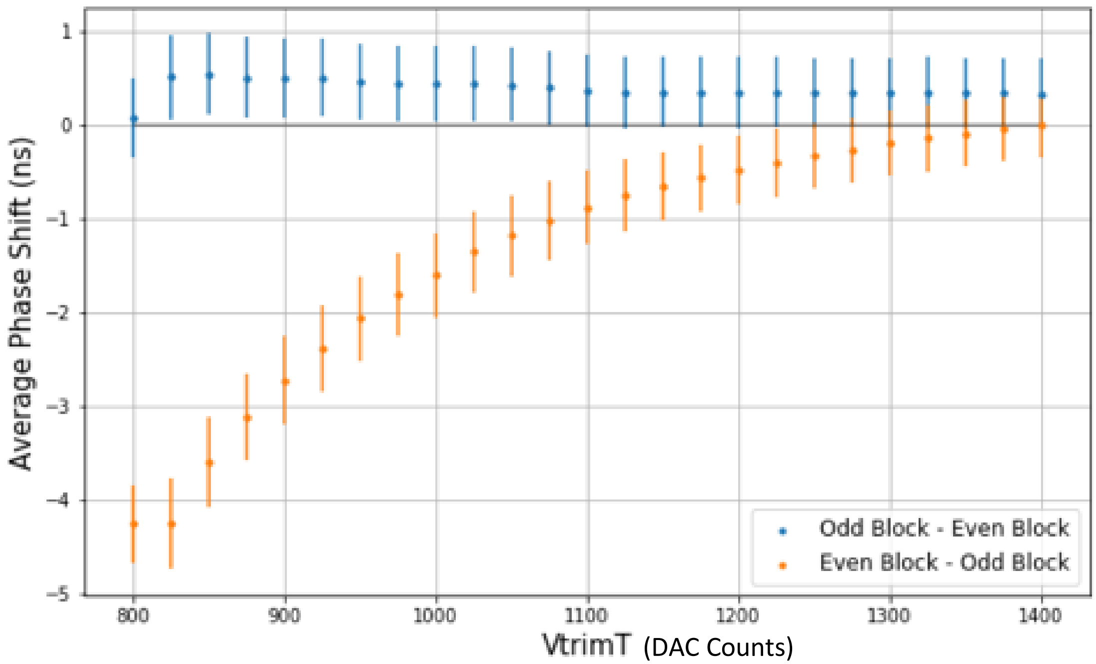
VTrimT Optimization

- Timing of switches for each sampling capacitor controlled by feedback loop
- VTrimT is the fine-tuning setting in feedback control loop
- Best calibrated by fitting injected sine waves
- Phase offset at block boundaries caused by poor calibration

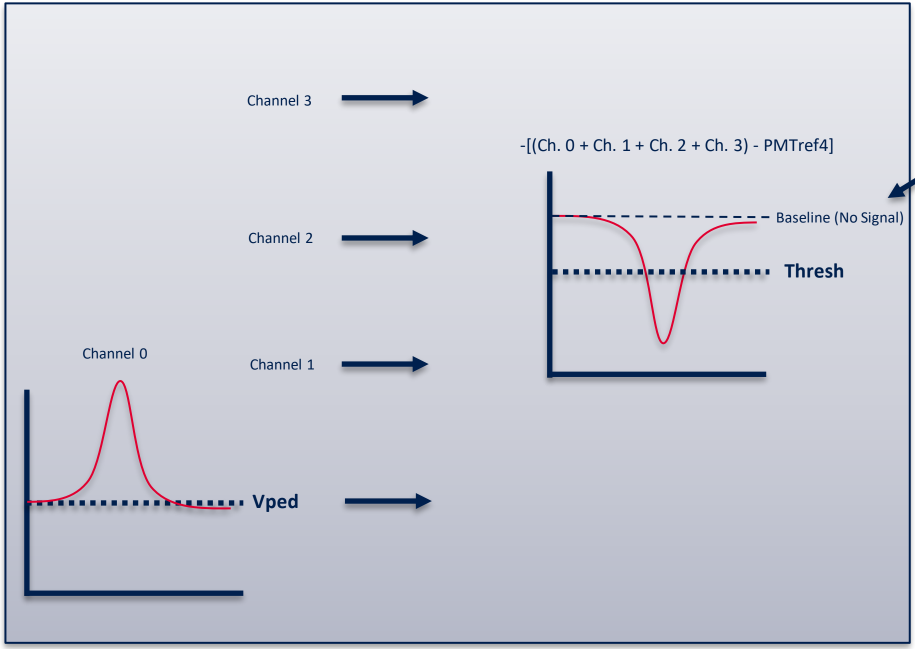


VTrimT Optimization

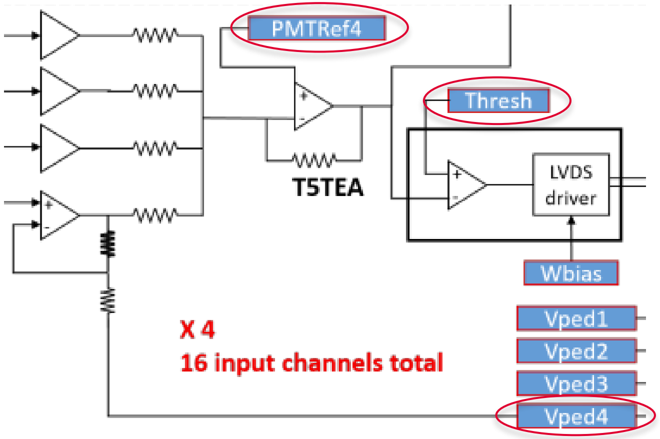
- VTrimT optimization procedure performed by Sam Heiman
- Example VTrimT optimization plot for one ASIC
- VTrimT to be optimized for each ASIC



Trigger Path Description



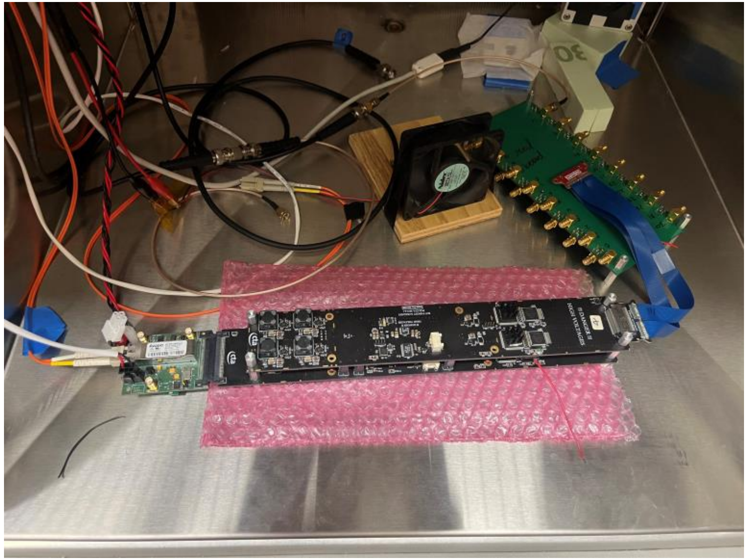
- Increasing PMTref4 will increase physical trigger threshold by moving waveform upward
- Increasing thresh will decrease the physical trigger threshold by moving Thresh towards the baseline
- **Bottom line: Physical trigger threshold increases with PMTref4 but decreases with Thresh**

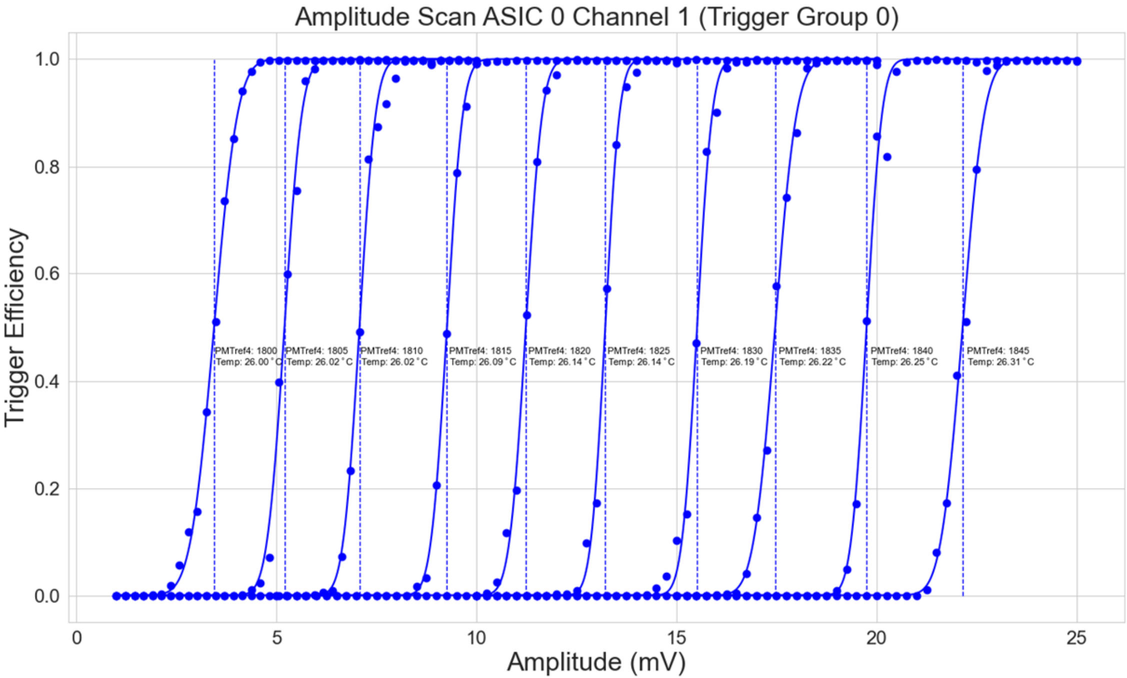


Trigger Threshold Measurement

- Trigger path depends on the Vped (indirectly), Thresh, and PMTref4 parameters
- Four image pixels comprise one trigger pixel
- Precise characterization of the trigger threshold allows for better gamma-ray sensitivity

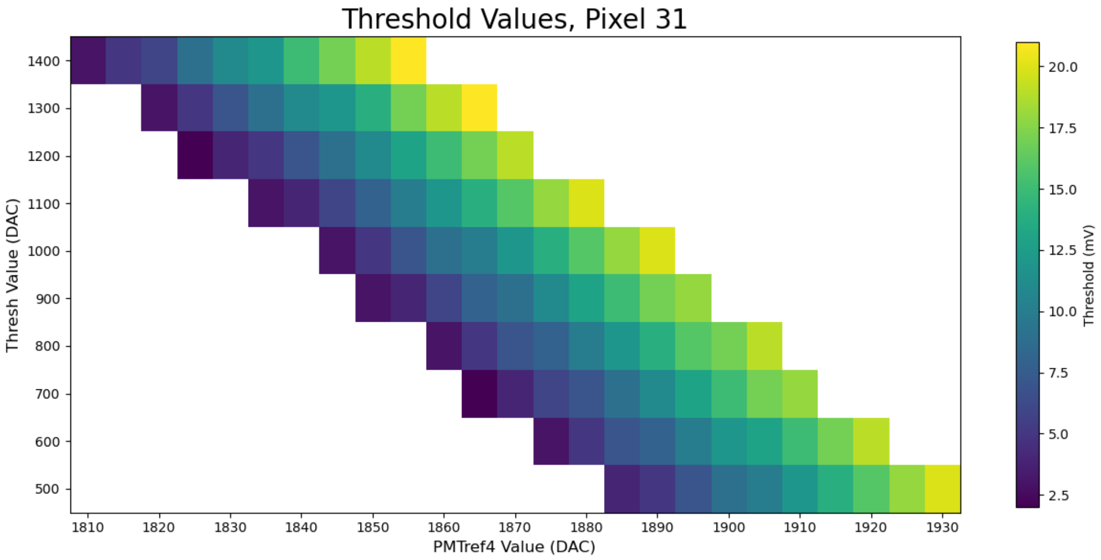
Trigger Threshold Measurement





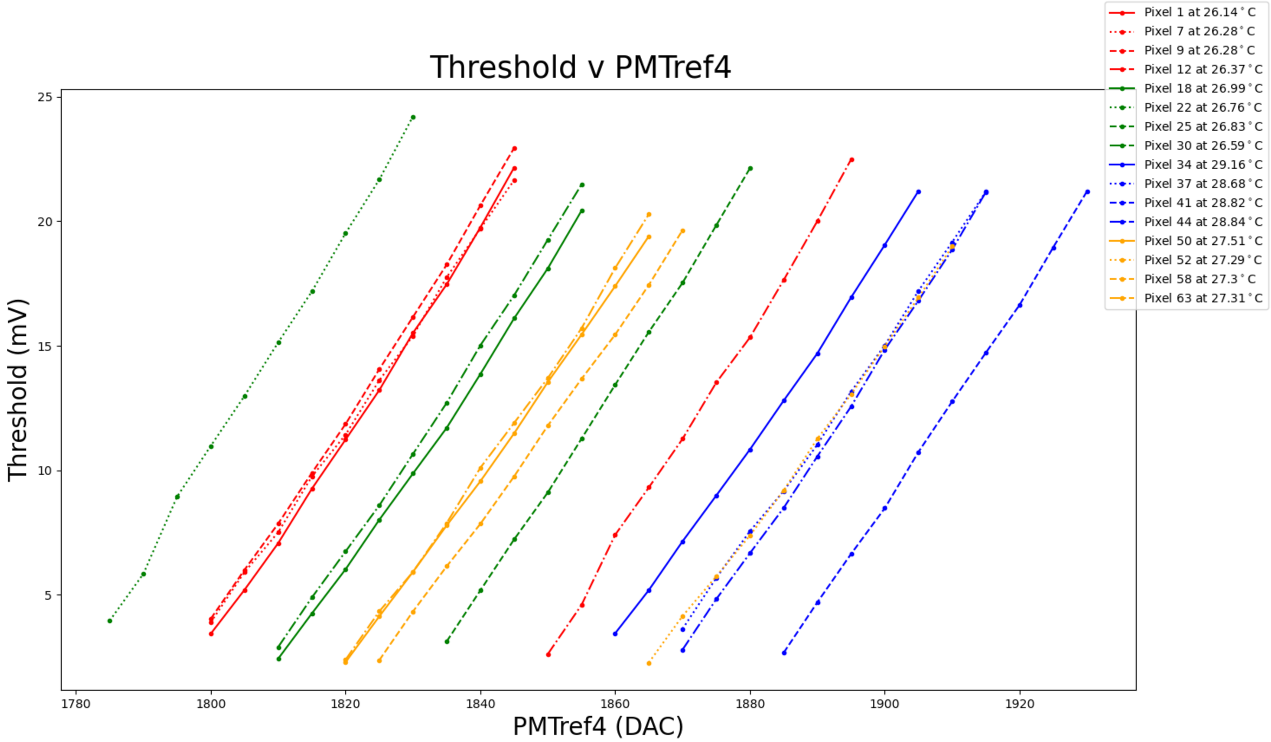
Trigger Threshold Measurement

- Calibration procedure established to determine the trigger threshold in physical units of mV
- Possible to extend the trigger threshold table to third dimension (temperature)
- Tested for T7 but not CTC modules



~3-5 mV / p.e.

Trigger Threshold Measurement



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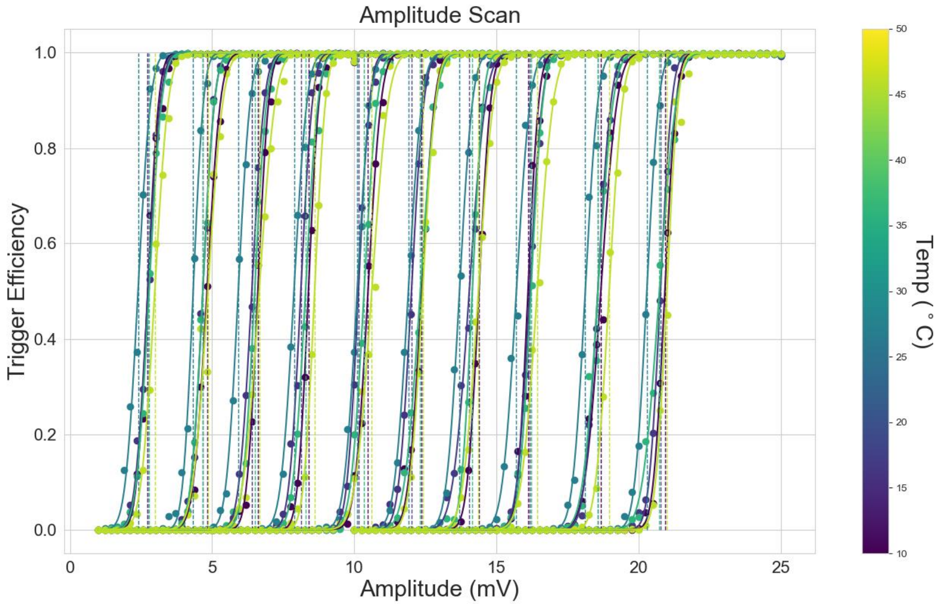
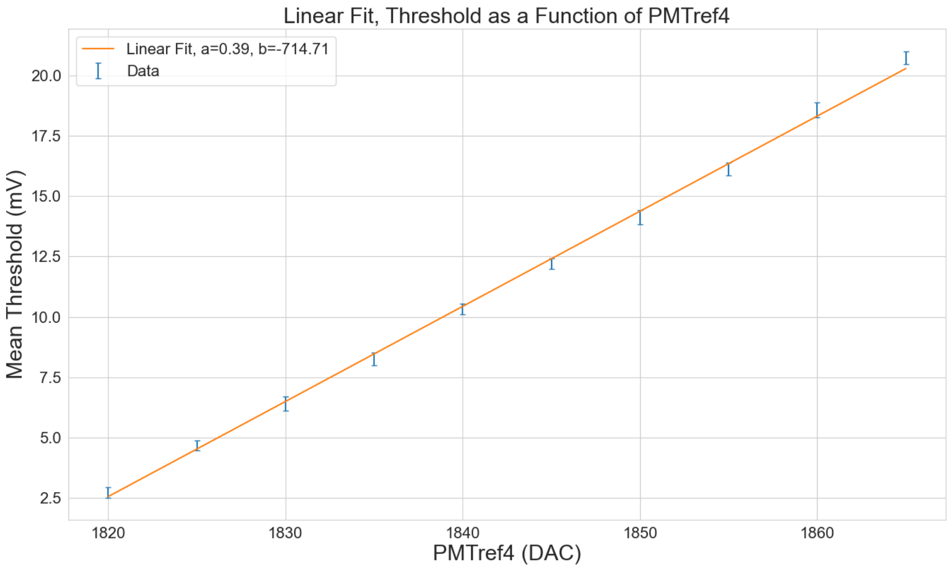
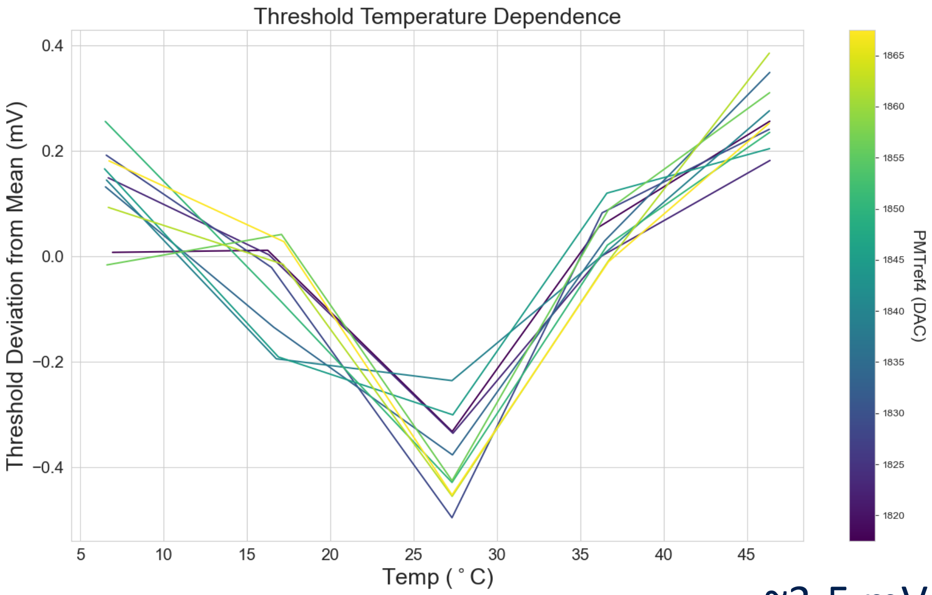




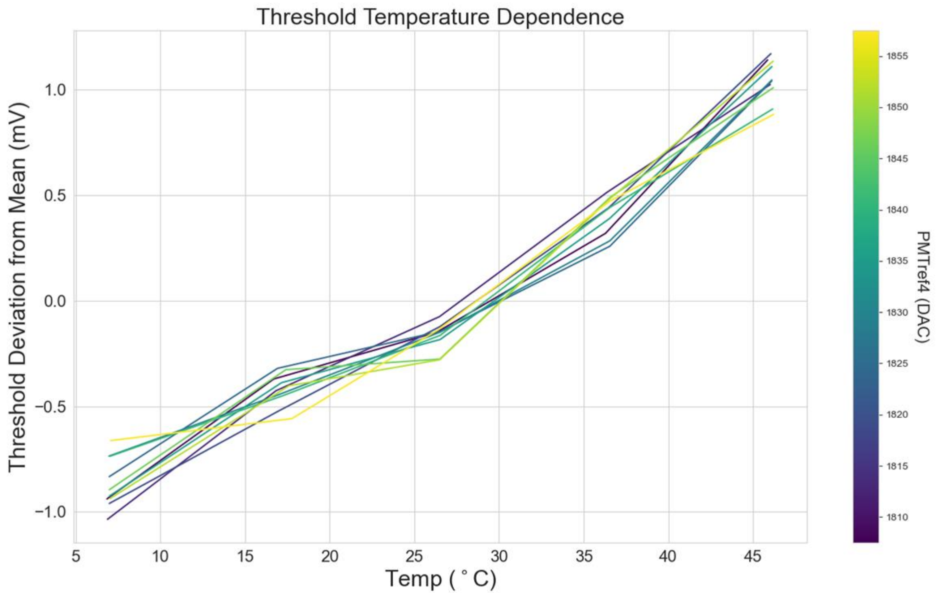
~3-5 mV / p.e.

Trigger Threshold Measurement

Pixel 63



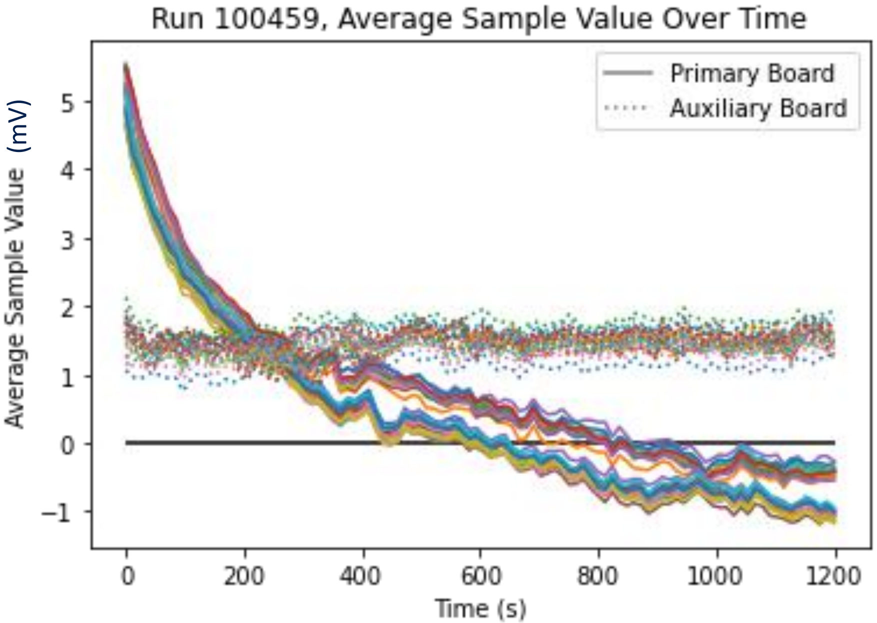
Pixel 31



~3-5 mV / p.e.

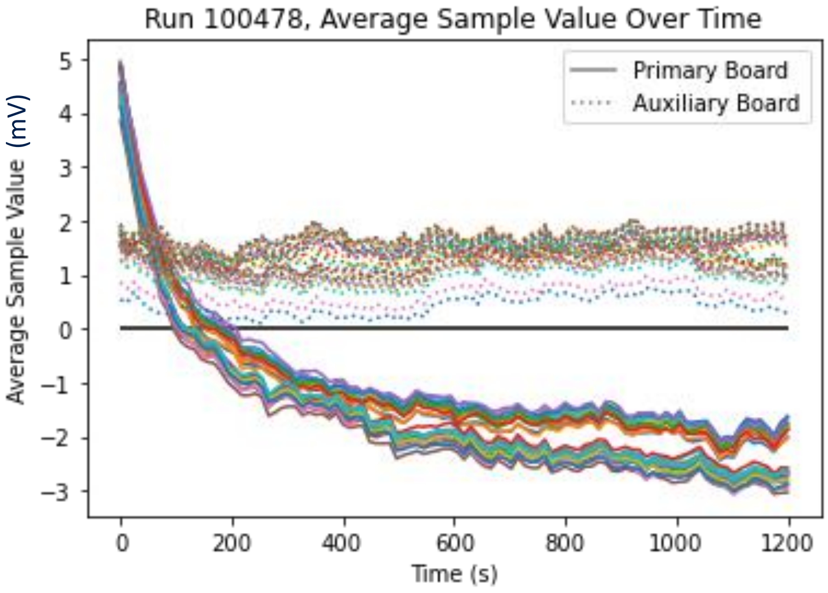
Temperature Effect on Average Pedestal

- Apparent heating effect causing baseline shift in primary board
- Warmup process brings baseline to stable value
- Sufficient warmup requires 1200s
- Run 100459 is triggered at 1kHz – apparent trigger rate dependent baseline shift

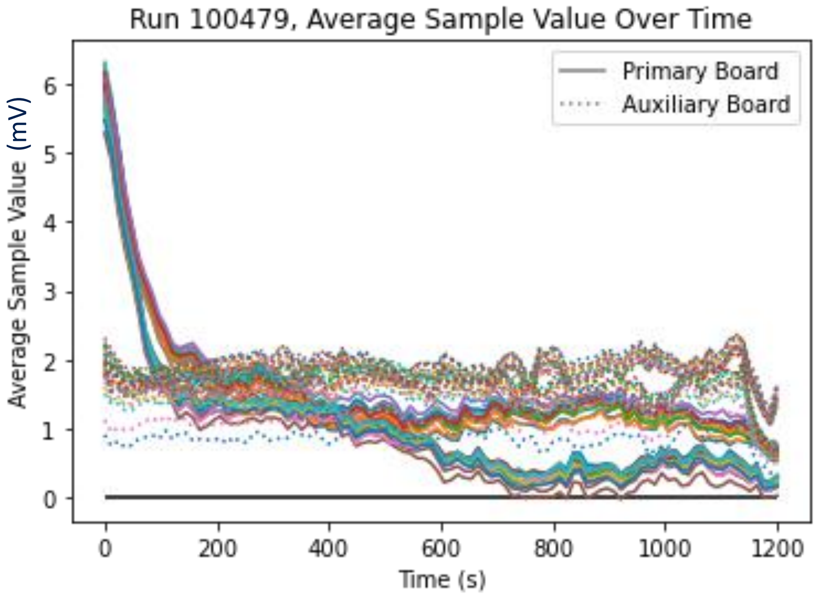


Temperature Effect on Average Pedestal

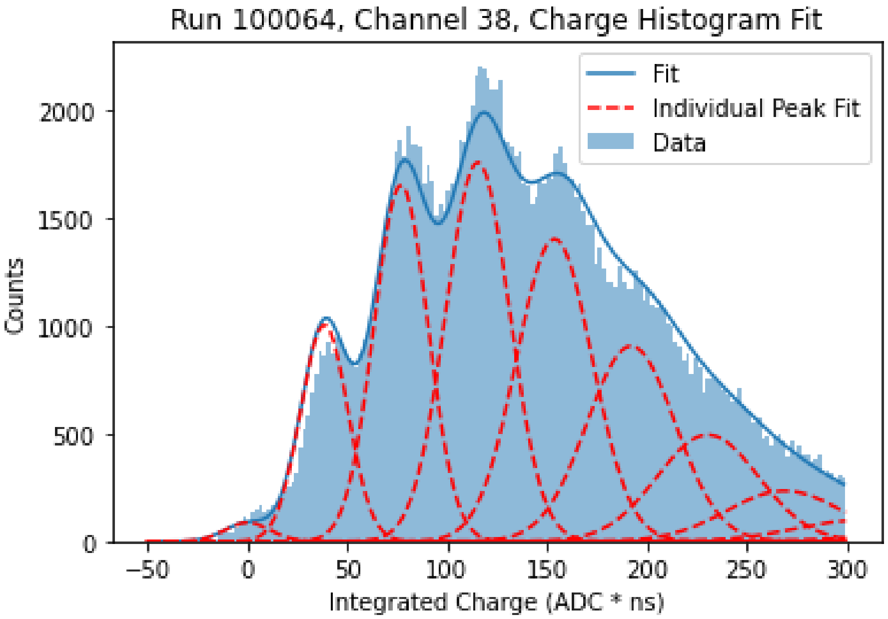
Trigger Rate = 100 Hz



Trigger Rate = 3 kHz



Finger Plots

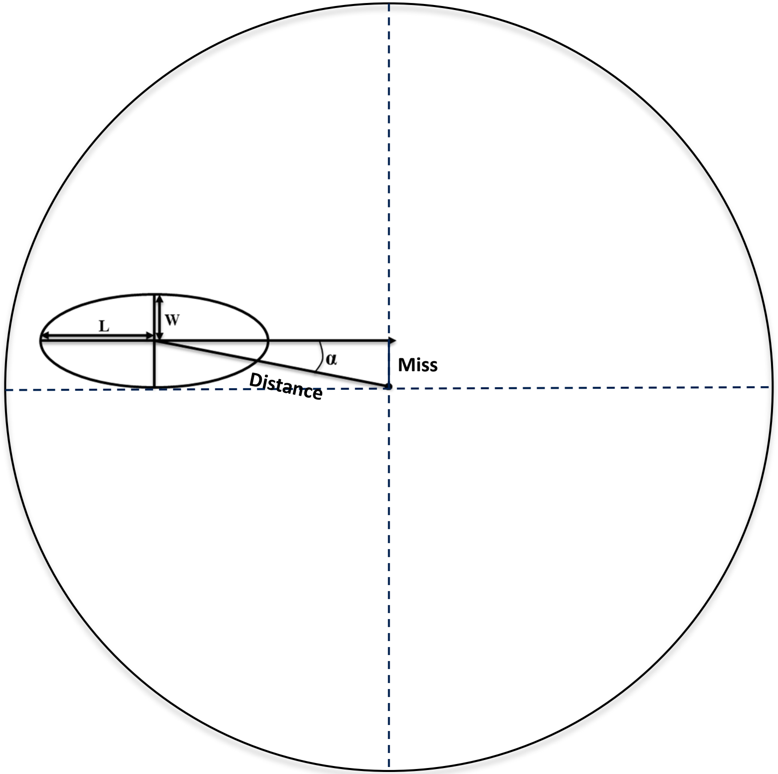


- Camera measures discrete numbers of p.e. - each peak corresponds to an increasing number of p.e.
- Sum of constrained Gaussians fit
- Fit parameters (5 total):
  - Gain – determines mean of Gaussians
  - Electronics Noise – contributes to standard deviation of Gaussian
  - Sigma Gain / Gain – contributes to standard deviation of Gaussian
  - Average Number of Photoelectrons – determines the amount of events in each Gaussian through Poisson distribution
  - Noise Peak Relative Amplitude - determines noise Gaussian relative amplitude
- Fit result values:
  - Gain - 38.41 ADC * ns per p.e.
  - Electronics Noise - 11.19 ADC * ns
  - Average Number of p.e. – 3.77 p.e.
  - Sigma Gain / Gain – 0.099

IACTs

- High Energy Spectroscopic System
- Major Atmospheric Gamma Imaging Cherenkov Telescopes
- Very Energetic Radiation Imaging Telescope Array System

Hillas Parameters



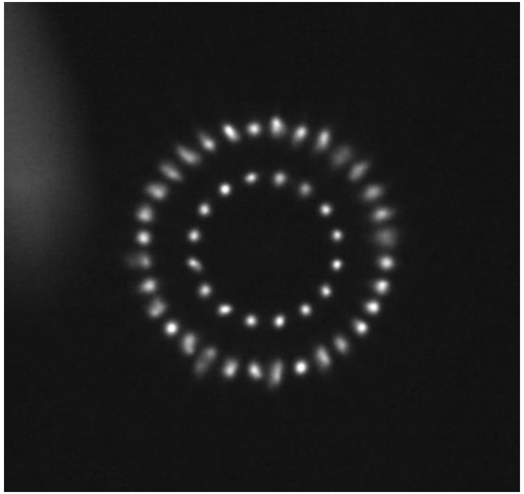
- Length
- Width
- Alpha
- Distance
- Miss
- Disp
- Size

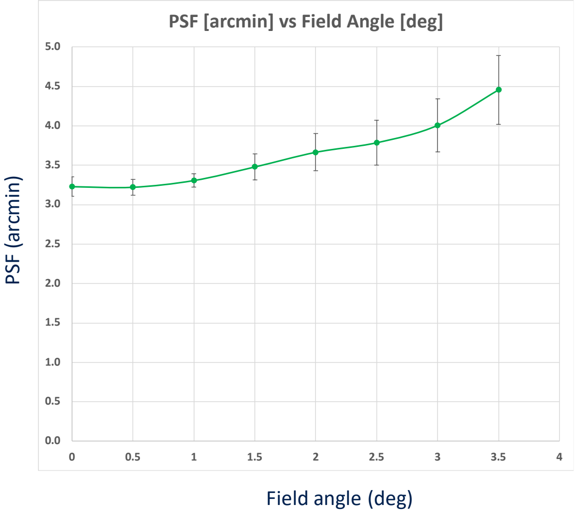
Calibration Tasks

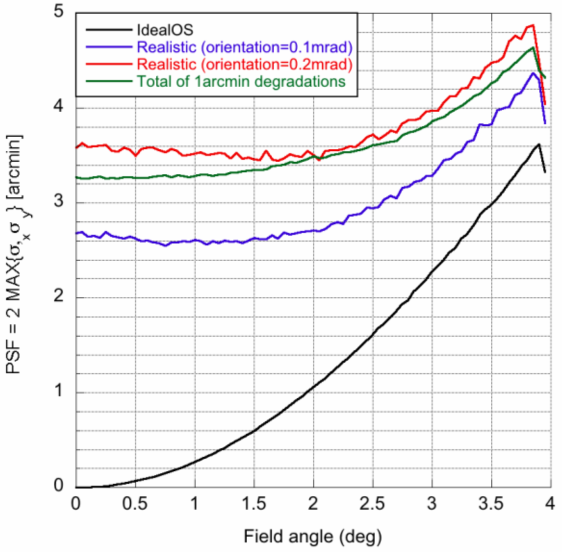
- Measuring the voltage pedestal (Vped) digital-to-analog converter (DAC) transfer function (TF)
- TARGET direct current (DC) transfer function (TF)
- VTrimT – fine control setting for cell integration length feedback loop
- Trigger threshold – precise calibration allows for triggering on low amplitude signals
- Temperature effects – must be understood to prepare for in situ environment
- Finger plots – characterizes gain, electronics noise, etc.

Optics

- 9.7m primary and 5.4m secondary mirror
- 48 segments in primary and 24 segments in secondary
- On-axis point spread function (PSF) - 2.8’
- Excellent off-axis PSF achieved

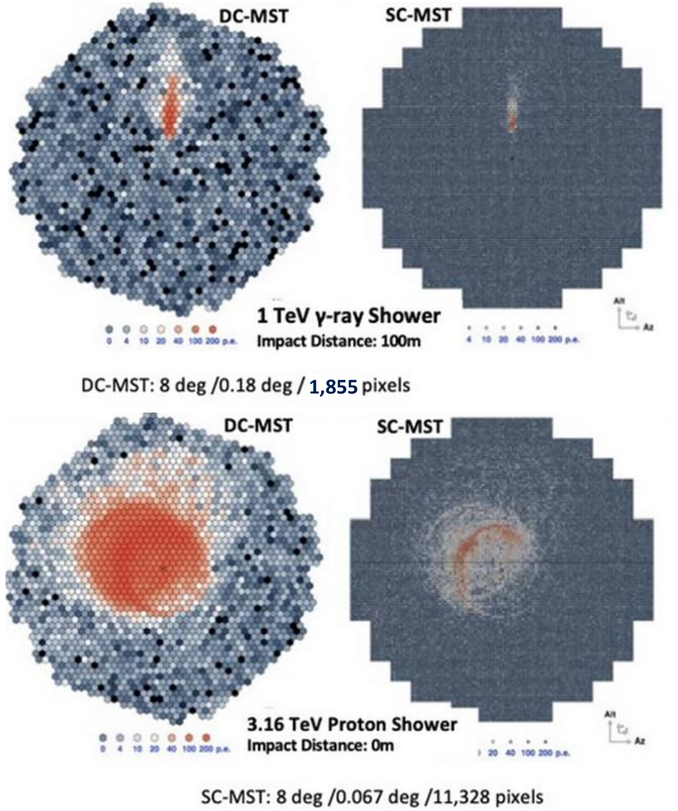






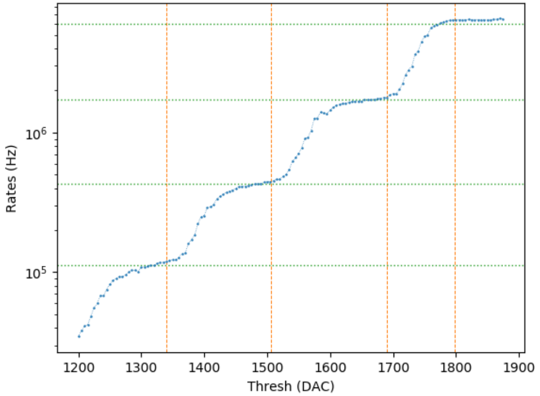
pSCT Future

- Upgrade improvements
  - Lower front-end electronics noise
  - Lower trigger threshold
  - Improved event reconstruction and background rejection
  - Fully populated focal plane
- Camera upgrade funded
  - Full focal plane commissioning – expected early 2024

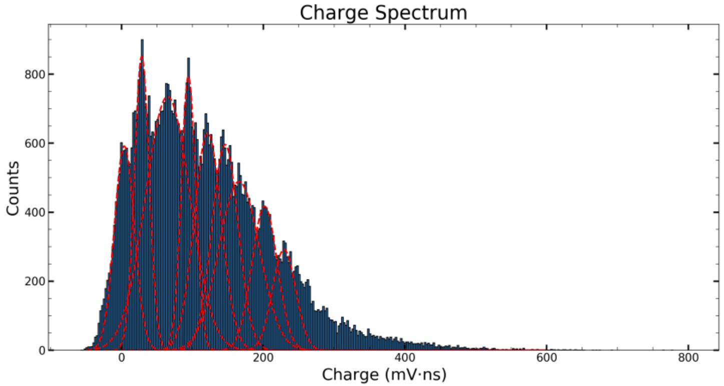


pSCT Camera Upgrade

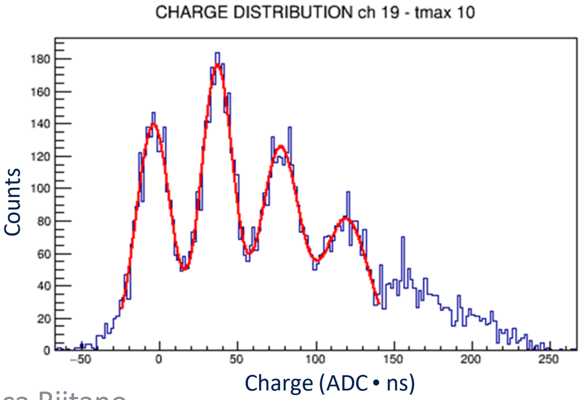
- TeV Array Readout with GSa/s sampling and Event Trigger electronics
- Current module – TARGET7 ASIC
- Upgrade module – T5TEA and TARGETC ASICs
- SMART ASIC pulse shaper and preamp



TARGET 7

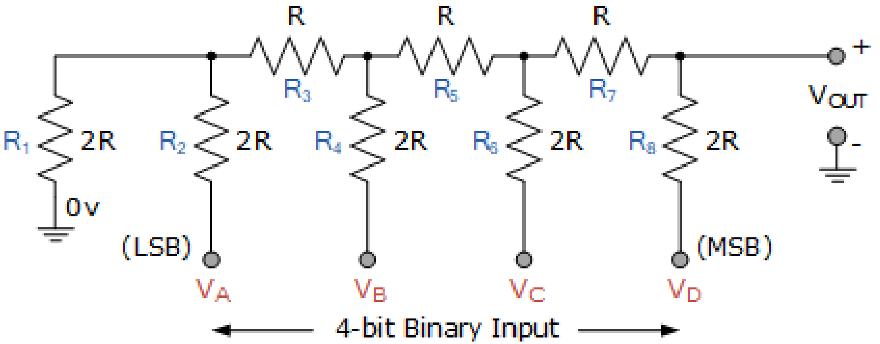


TARGET C



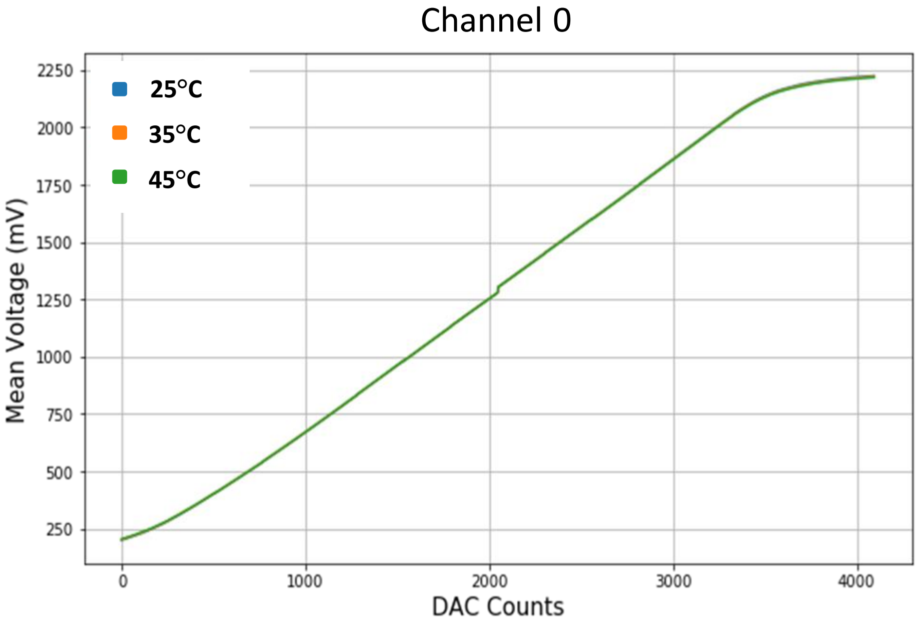
R-2R DAC

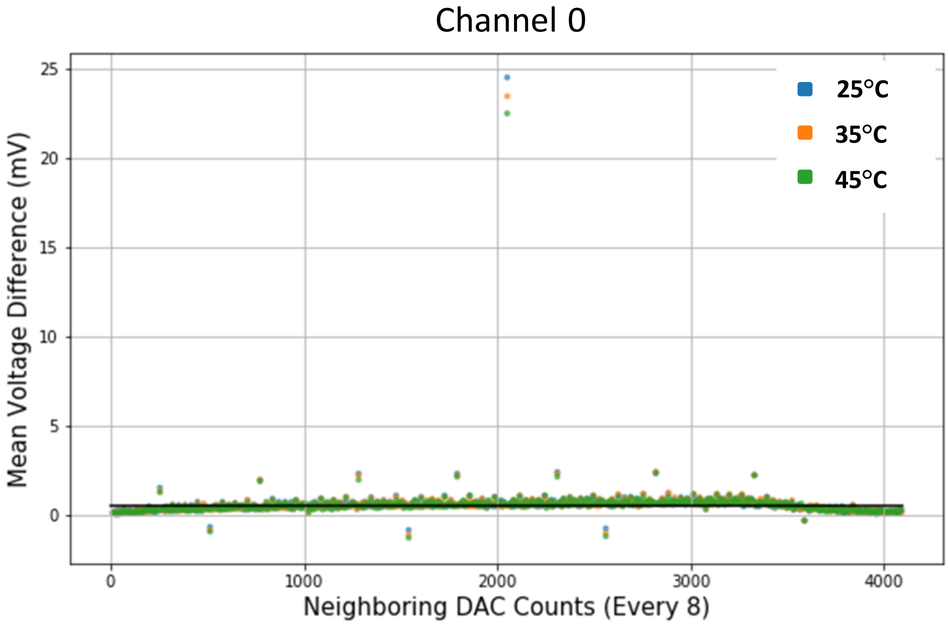
- $V_{out} = (V_A+2V_B+4V_C+8V_D)/16$
- $V_A,V_B,V_C,V_D = V_{in}$ or 0
- $V_{out} / V_{in} = (B_A+2B_B+4B_C+8B_D)/16$ with $B_n = 1$ or 0
- What happens if R is not exact? DAC seams
- Must measure the true analog voltage of the digital input



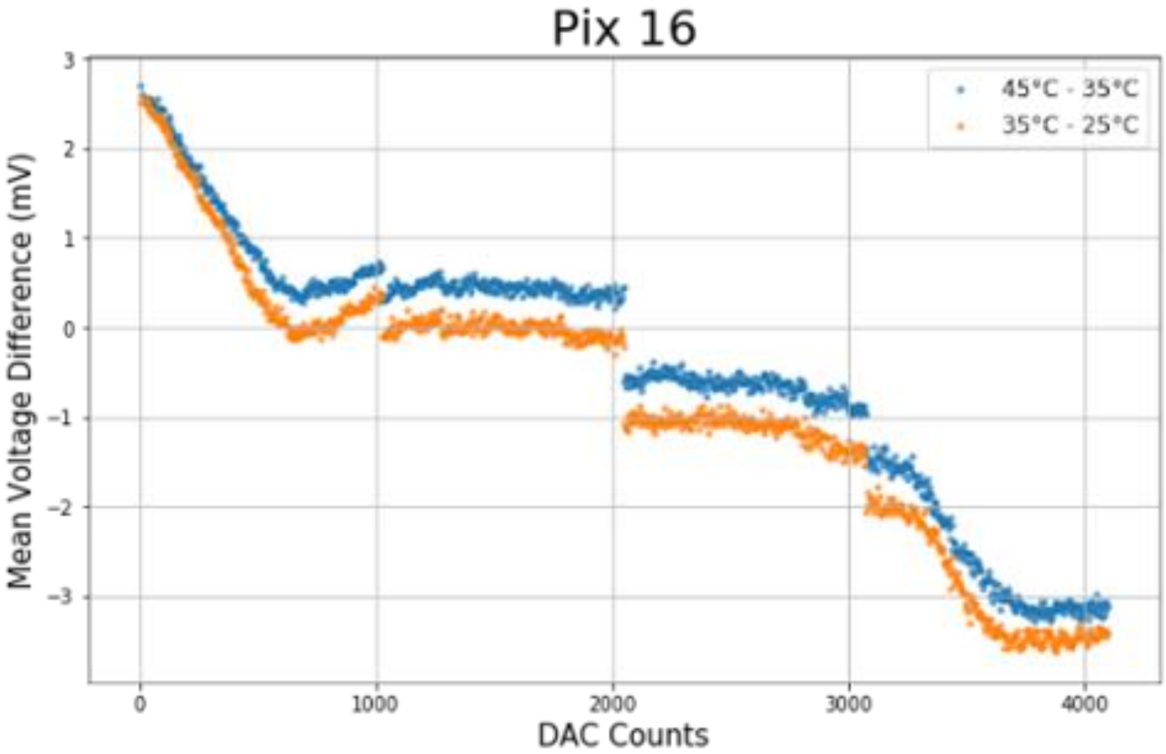
Source: Electronics Tutorials. R-2R DAC.

Vped DAC Transfer Function

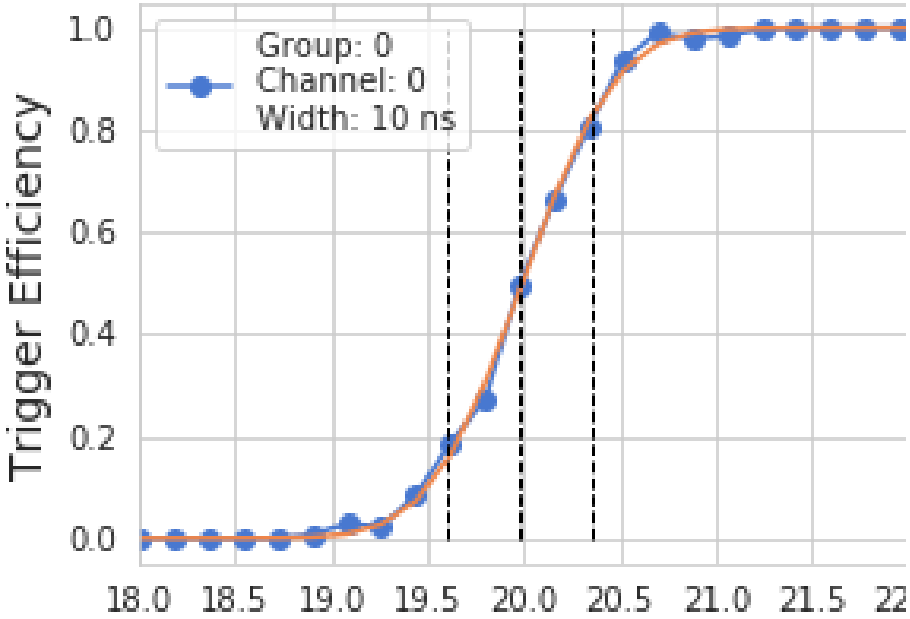




Vped DAC Transfer Function



Trigger Efficiency Plot Example – 2019 Report



Equation to Fit

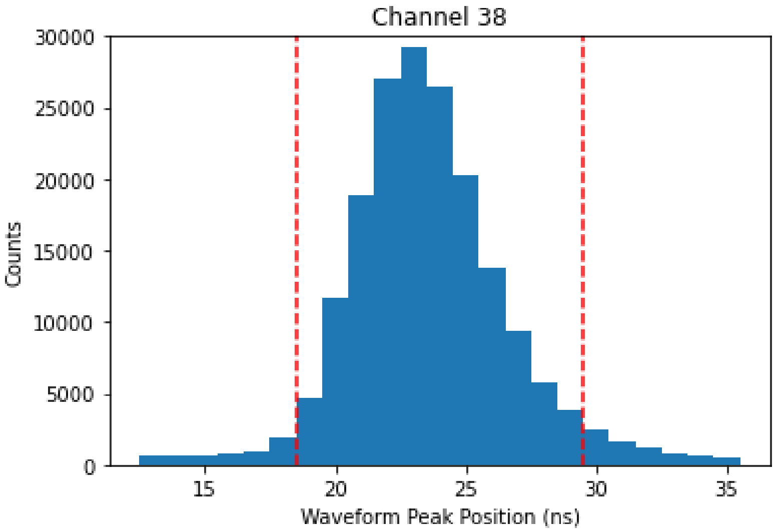
$$y = \frac{1}{2}(1 + erf(\frac{x - \mu}{\sigma\sqrt{2}}))$$

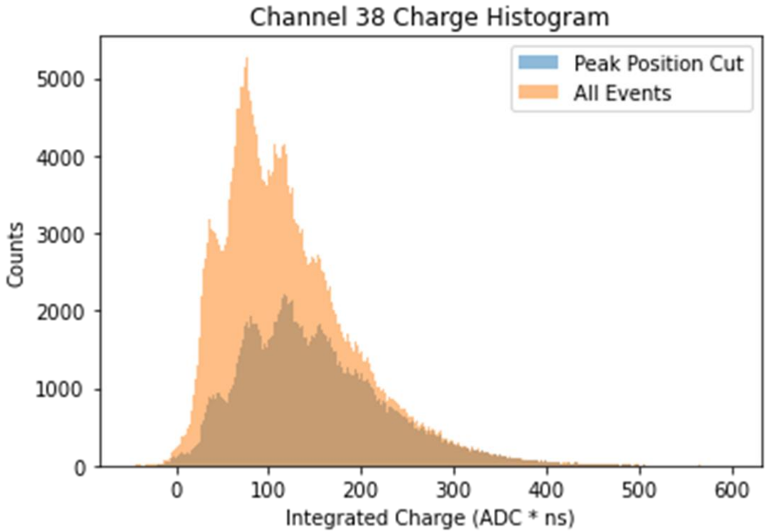
- y is the trigger efficiency, x is the waveform amplitude
- σ, μ are the fit parameters

$$erf(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt$$

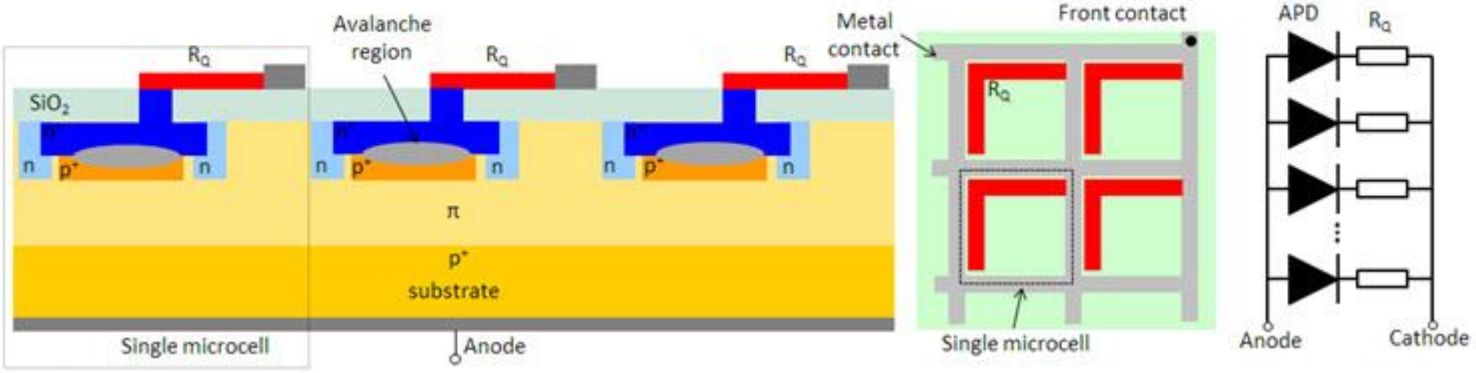
Finger Plots

- Internally triggered on low intensity flasher pulses
- Cut events based on waveform peak position to remove noise events



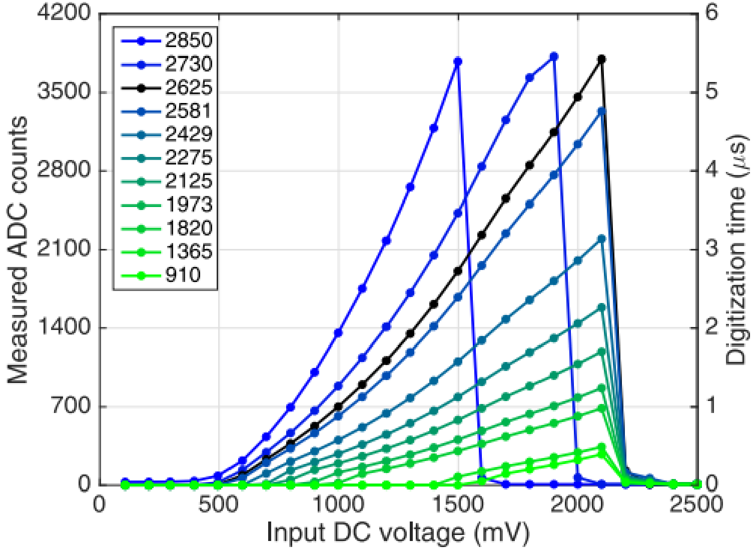


SiPMs



Source: Hamamatsu

Wilkinson ADC



Source: Albert et al. TARGET 5: A new multi-channel digitizer with triggering capabilities for gamma-ray atmospheric Cherenkov telescopes