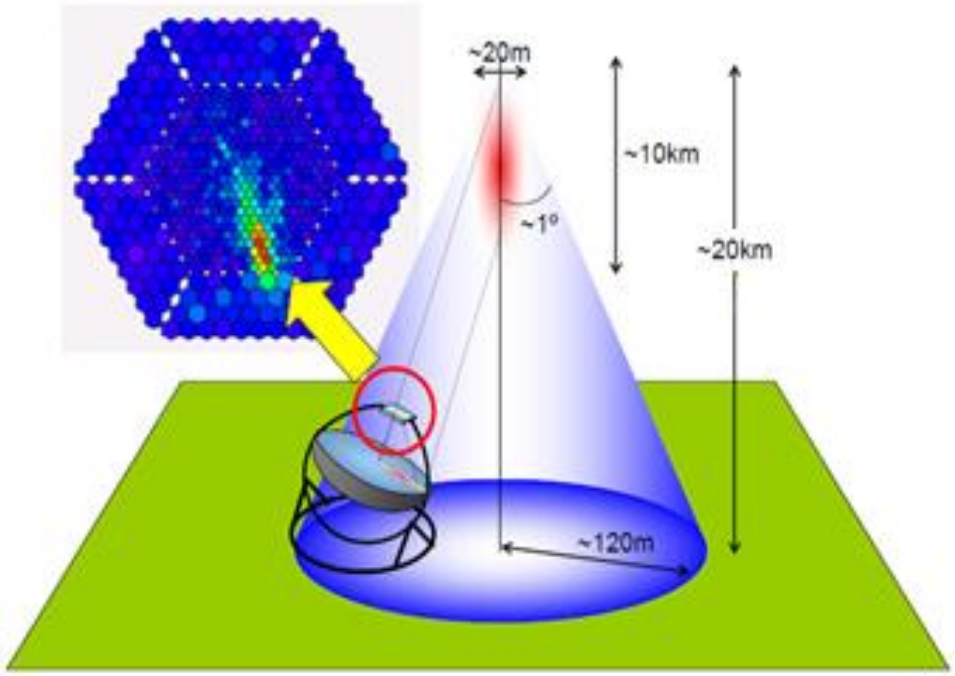
Development of an SiPM-based camera for a 4 m class Atmospheric Cherenkov Telescope

Sandeep Duhan

(On behalf of VHE Gamma Ray Astronomy Group)

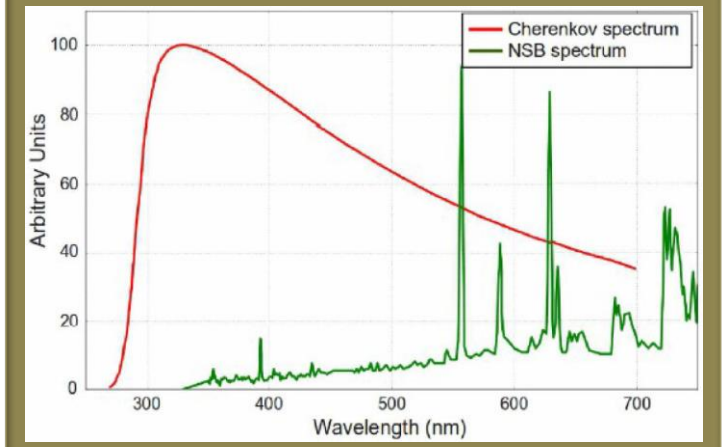
Imaging Atmospheric Cherenkov Telescope (IACT)



Detection of gamma-ray showers by an IACT

Cherenkov light Characteristics:

- ✓ **Wavelength:** 280 nm – 700 nm range, peak at ~350 nm
- ✓ In the form of light flashes
- ✓ **Duration of the flashes:** 5 – 10 ns
- ✓ **No. of photons per flash:** ~100 photons/m^2 at 1 TeV energy
- ✓ **Rate of flashes:** Depends on the source type and its energy.



Cherenkov light and NSB spectrum
(https://pos.sissa.it/252/006/pdf)

Key Detection Challenges:

- Faint & fast signals: Nanosecond-scale Cherenkov flashes
- Large signal variation (from single photoelectron to strong shower pulses)
- High night-sky-background (NSB)

Camera Requirements:

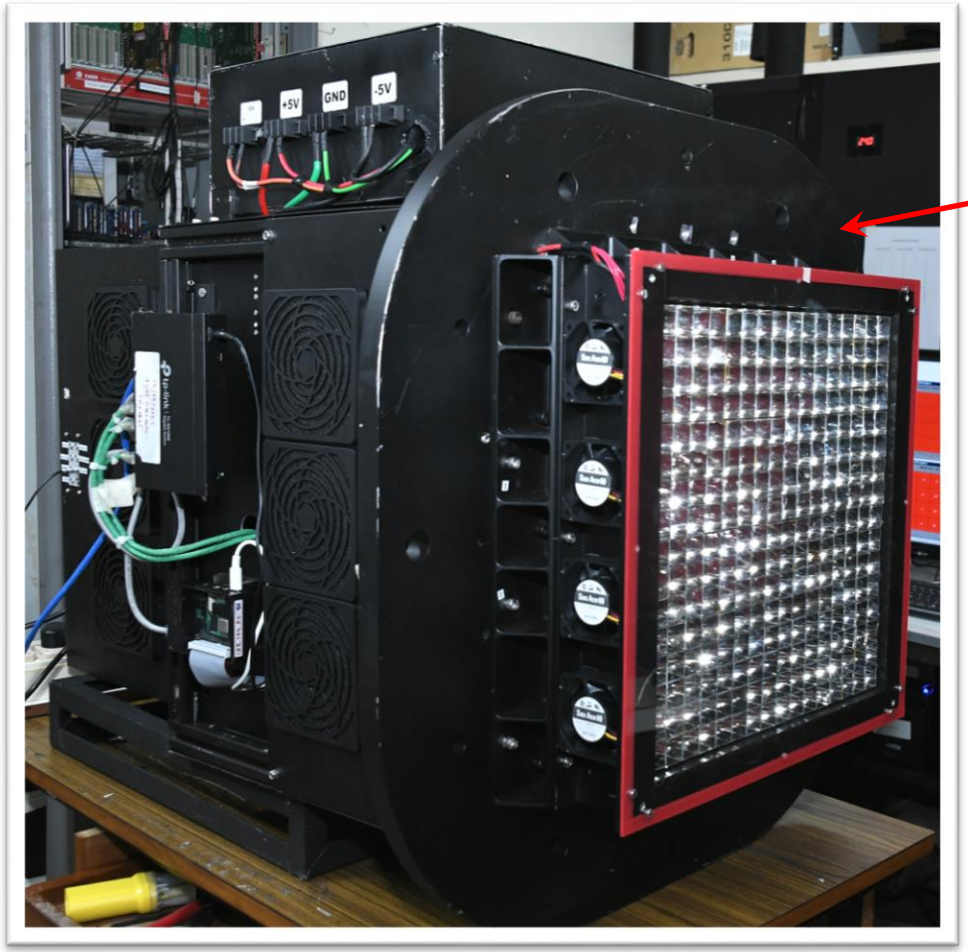
- **High sensitivity:** Ability to detect weak, nanosecond-scale Cherenkov flashes
- **Large dynamic range:** Adequate signal-to-noise ratio (SNR) for weak to strong Cherenkov signals
- **Fast timing:** Few nanosecond timing precision to correlate signals across camera pixels
- **Topology-based trigger system:** To reject events due to NSB
- **Minimal dead time and stable long-duration operation**
- **Configurable, modular, scalable, and compact design**

Major IACT Experiments World-wide

PMT as pixel sensor

SiPM as pixel sensor

SiPM-based 256-pixel IACT camera



- Entire electronics integrated into the camera body
- Physical size : 70 cm x 72 cm x 85 cm
- Detector area: 33.8 cm x 33.8 cm
- Weight: ~90 KG; Cooling: High-speed fans
- Power consumption < 500 Watt (1.9 W per pixel)
- **Complete hardware and software for the camera developed indigenously at TIFR**

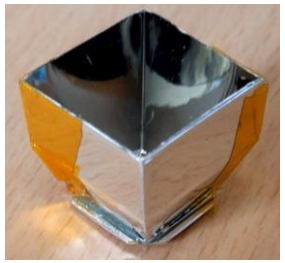
Site: TACTIC, Mount Abu (Rajasthan)

Temperature: 0°C to +30°C over the year and 5°C variation over a night

Camera Sub-systems

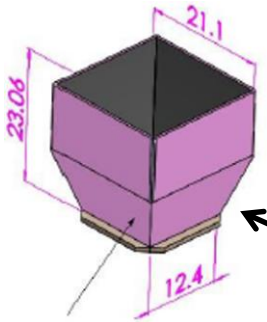
Camera Subsystems:

- ❑ Photon Detection Plane
- ❑ Front-end
- ❑ Back-end



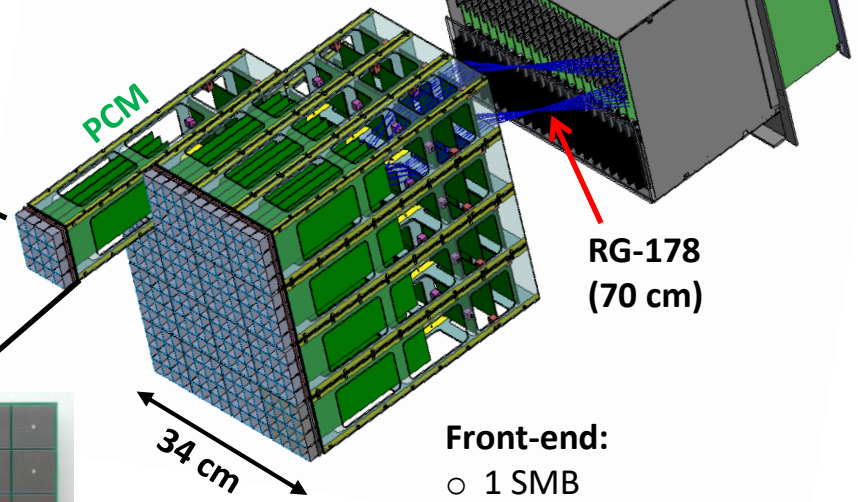
PDP:

- ○ SiPMs
- ○ LCs



Light Concentrator

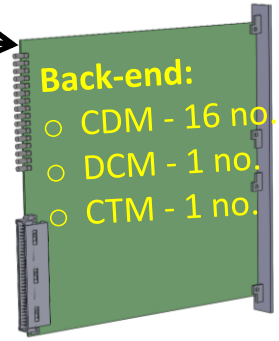
Front-end Size:
(36cm x 36cm x 30 cm)



Back-end Crate size:
(48 cm x 27 cm x 22 cm)

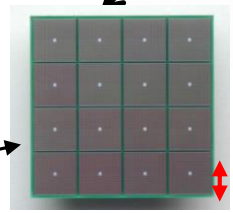
RG-178
(70 cm)

Back-end Module Size:
(23.3cm x 22cm x 2cm)



Front-end:

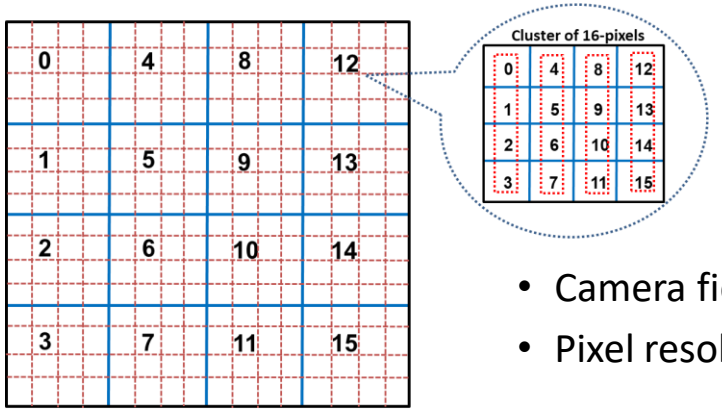
- ○ 1 SMB
- ○ 4 Pre-amplifiers
- ○ 2 Bias voltage boards
- ○ 1 LVPS



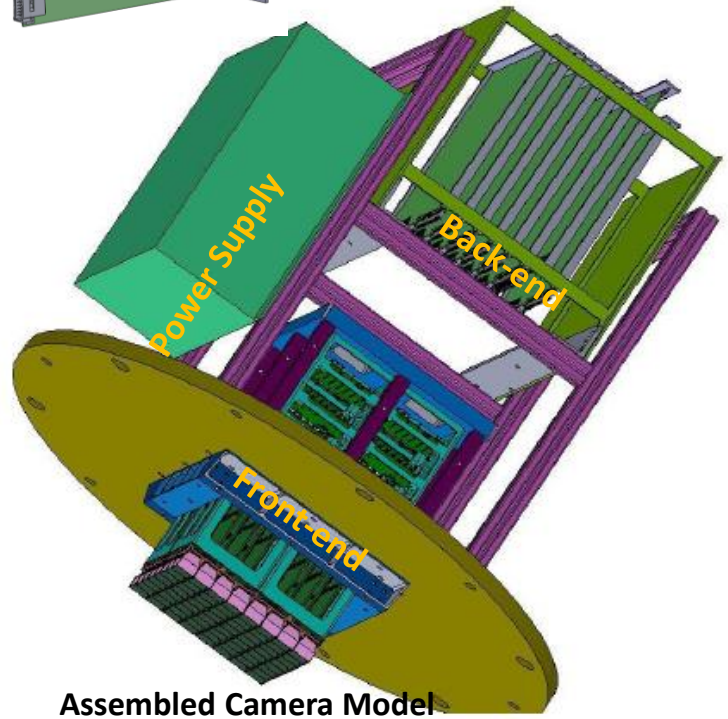
Camera Pixel

3 mm

13 mm



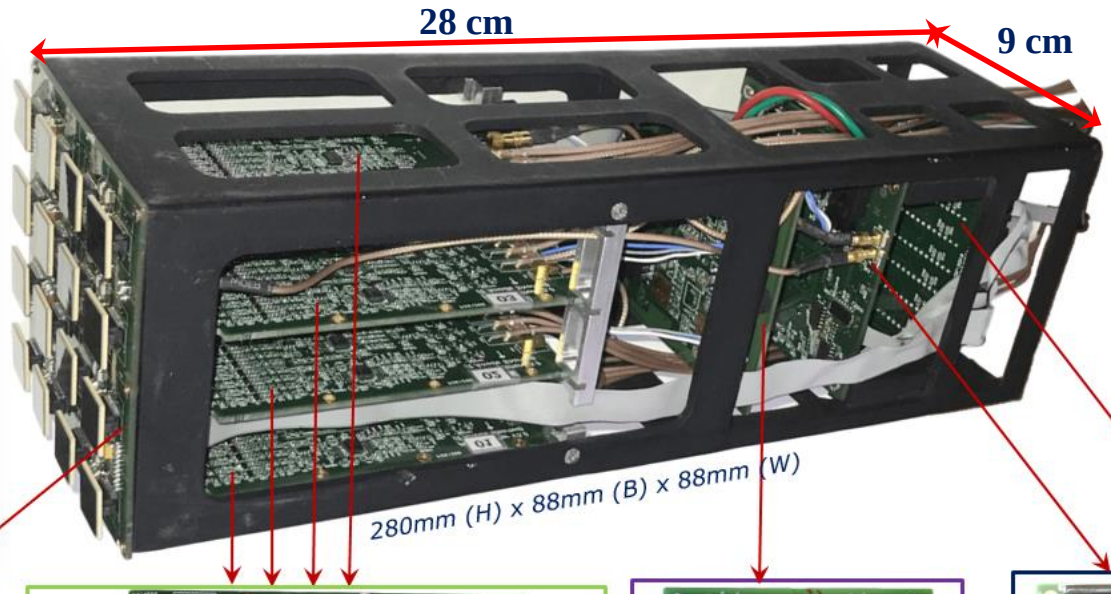
- Camera field-of-view: ~5°
- Pixel resolution: 0.3°



Assembled Camera Model

Pixel Cluster Module (PCM)

Light Concentrator Assembly: Hollow




Sensors Mount Board


4 Channel Preamplifier


Low Voltage Power Supply


8 Channel Bias Supply Board

Bias Supply Board (02 No.):

- Each board caters bias (10 – 80 V @ 4 mA) to 8 pixels
- Resolution: ~5 mV for voltage & ~0.3 µA for current
- SMB ambient temperature monitoring, sub-pixel selection
- Temperature and NSB compensation
- CSPI link to Raspberry Pi for overall control & monitoring

Sensor Mount Board (01 No.):

- 16 - pluggable SiPMs
- 2 Temperature sensors

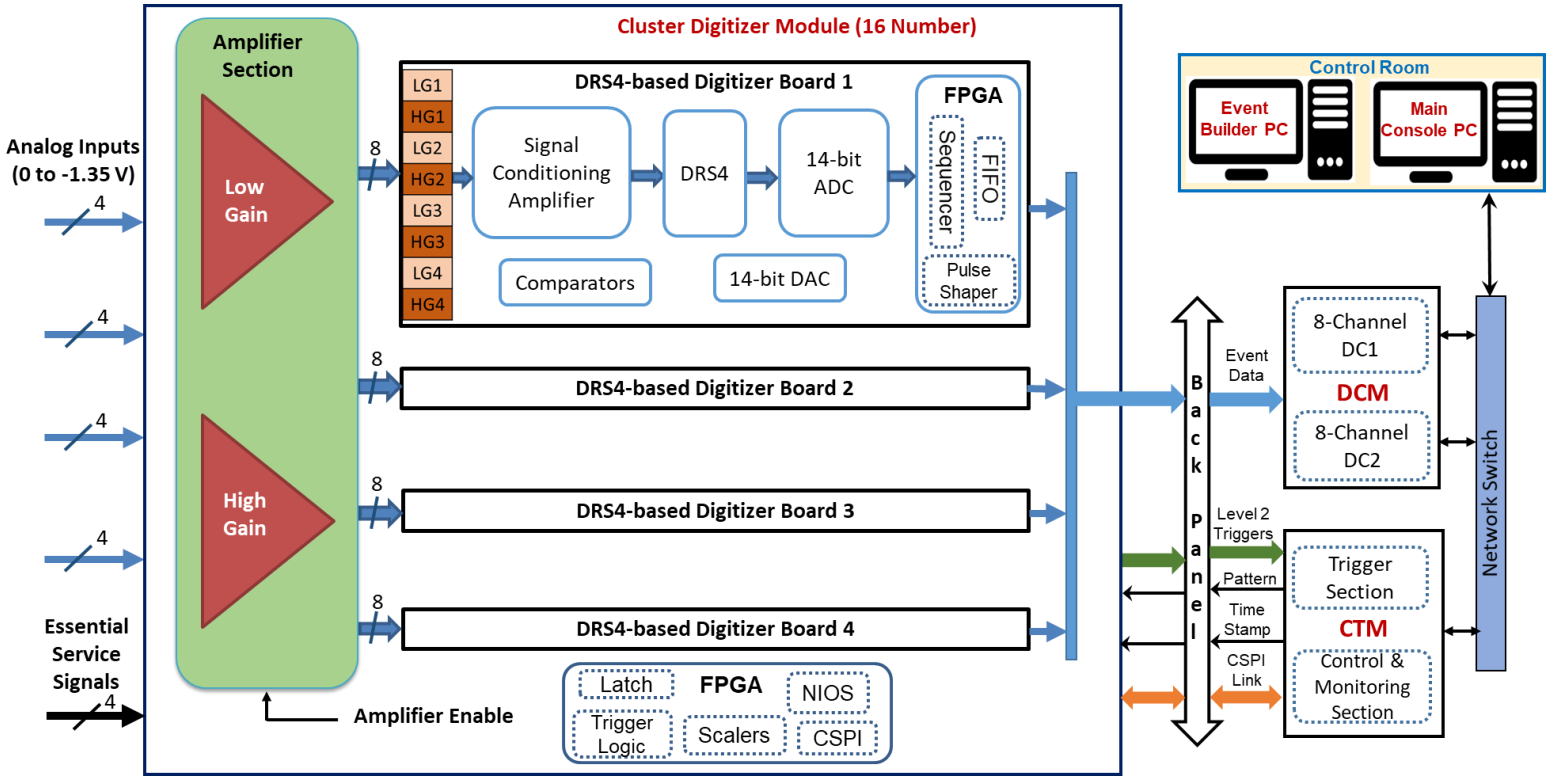
4-channel Pre-amplifier board (04 No.):

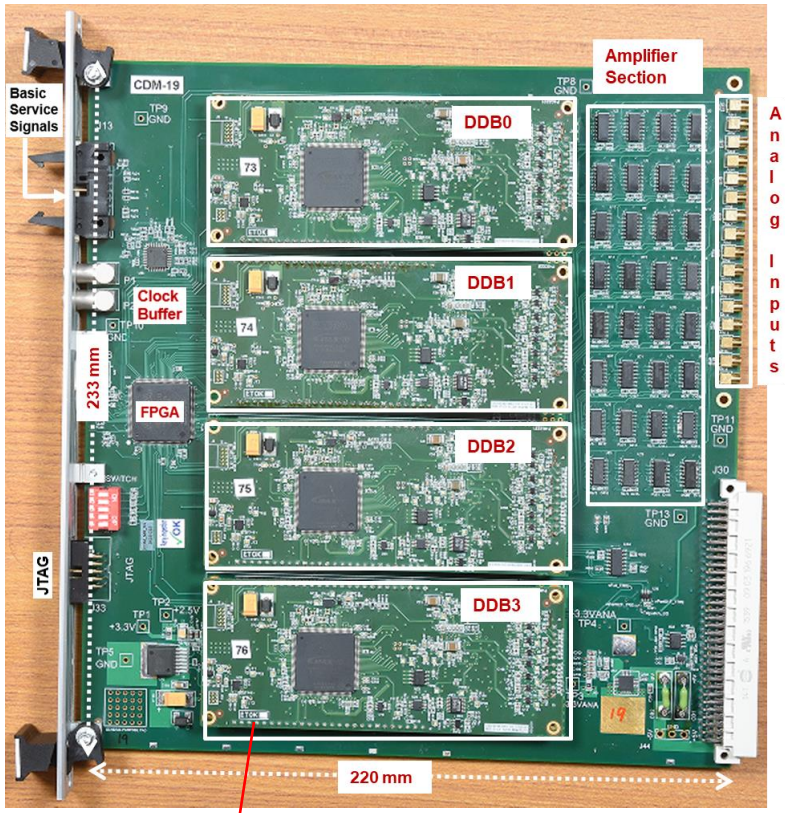
- Each board caters to 4-pixels
- 8 sub-pixel pair pulses are amplified (I2V), shaped and summed to generate a pixel signal output
- Enable/disable facility for sub-pixel pairs
- 0 to -1.3 V signal output corresponding to 0 - 1500 photoelectrons per pixel

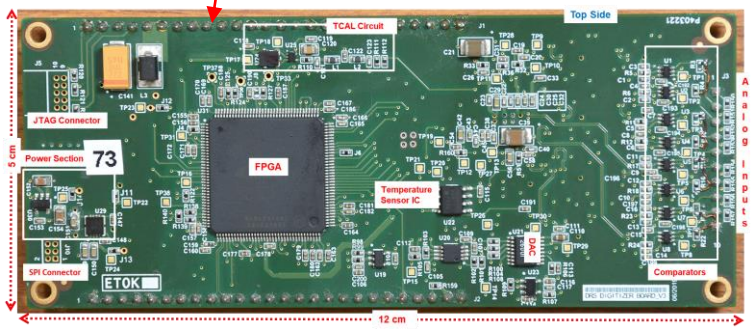
Low Voltage Power Supply Board (01 No.):

- Caters low DC voltages to Pre-amplifiers & bias boards of a PCM

Cluster Digitizer Module (CDM)







DRS4-based Digitizer Board (DDB)

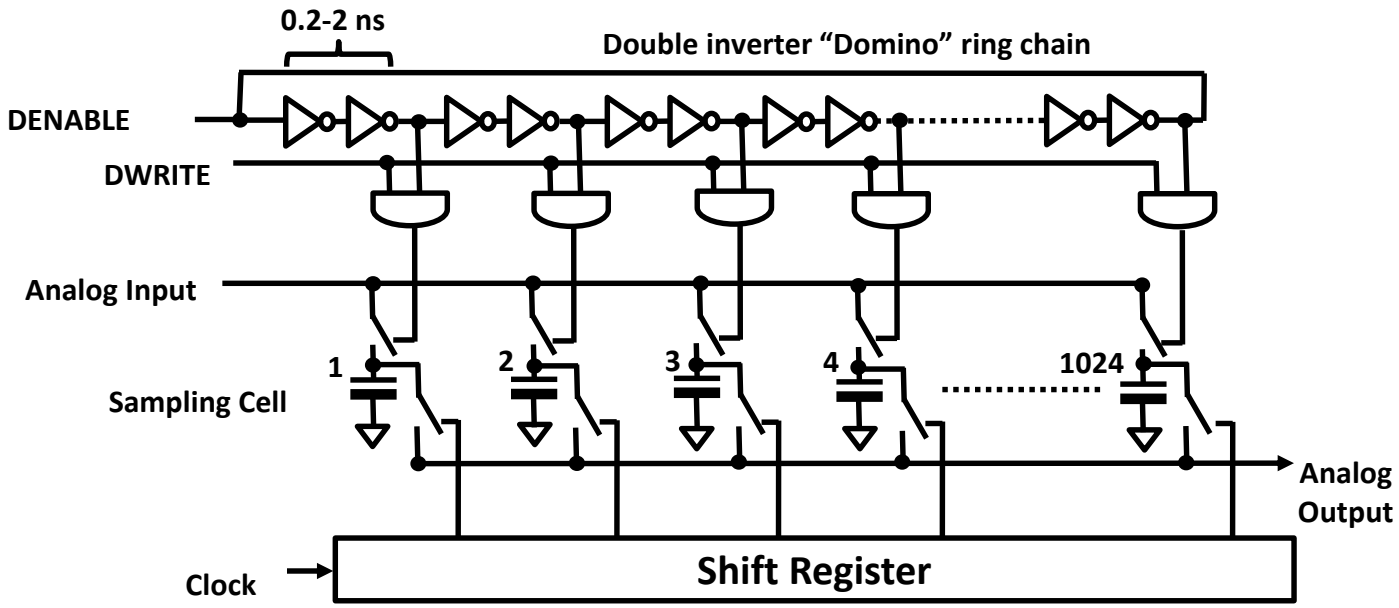
Function: Digitize the pulse profile of 16 pixels with dual gain approach, generate Level-2 triggers

Features:

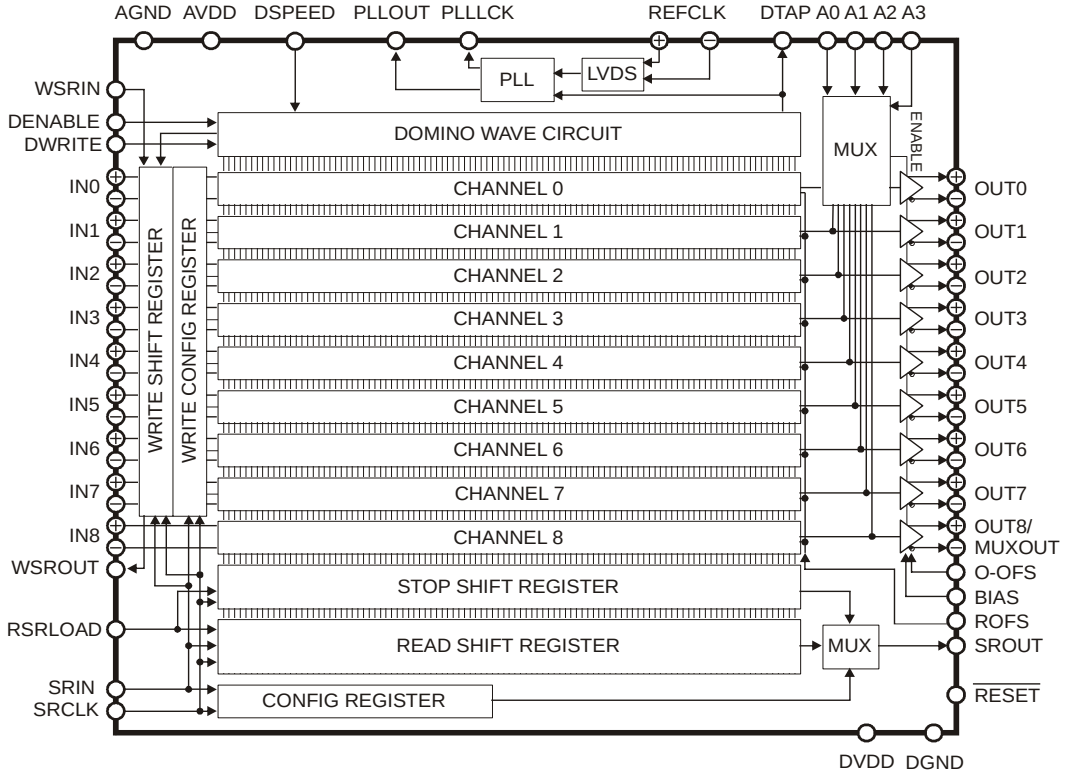
- Dual gain approach for pixel signals: to accommodate the varying intensity of Cherenkov light
- Samples @ 1 GSPS, digitizes @ 33 MHz using a 14-bit ADC
- Level 2 Trigger Logic: identifies possible Cherenkov events at cluster level
- Local data buffering of 16 events at 150 ns ROI: to handle burst of triggers
- Minimal dead time: Parallel data acquisition using mezzanine boards for 4-pixels
- Event marker information embedded to each data packet
- User-selectable ROI & skip cells for pulse digitization (max. 1024 ns): adds flexibility
- Custom SPI link to CTM: to receive configurations parameters, and send monitoring data

Waveform Digitization Using DRS4 Chip

Switched Capacitor Array (SCA)



Functional block diagram of DRS4 chip



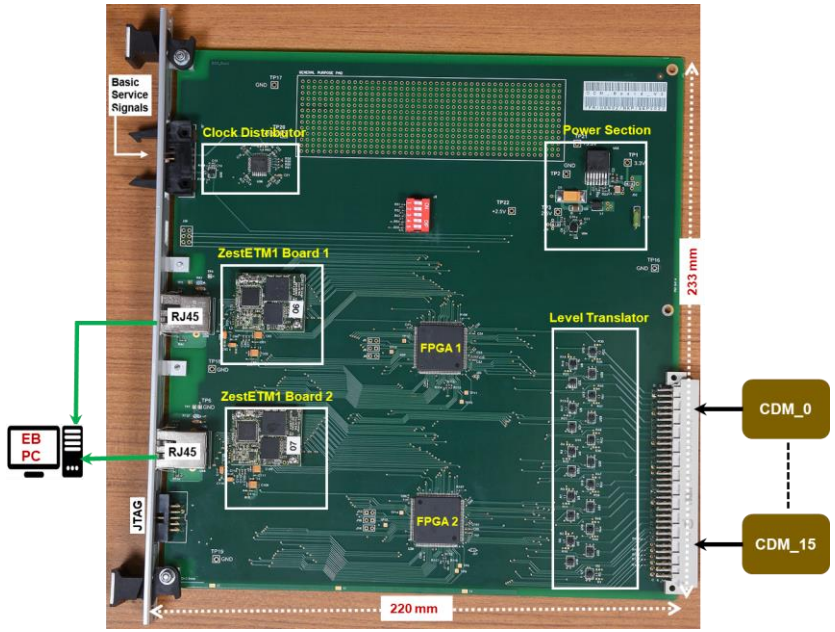
DRS4 chip key features:

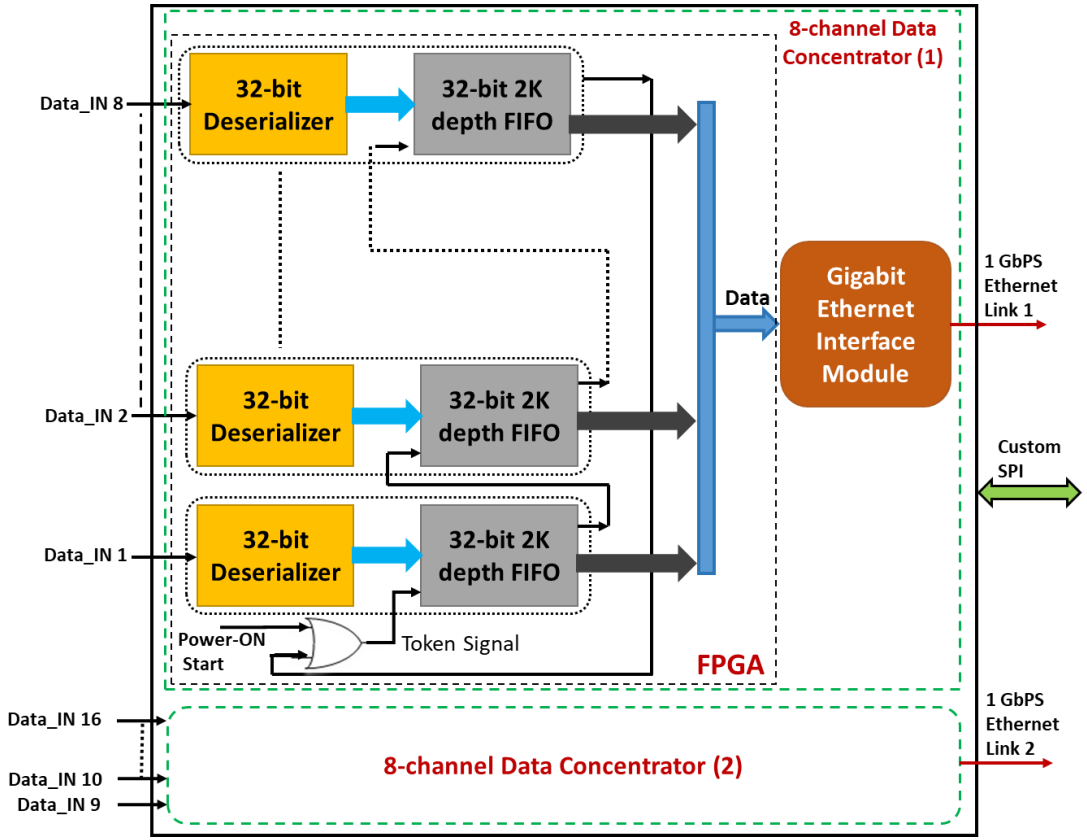
- High channel density: 9 channels with 1024 storage cells each
- Differential analog inputs with 950 MHz bandwidth
- 700 MSPS to 5 GSPS sampling speed
- 1 V dynamic range
- **Region of interest readout**
- Multiplexed or parallel channel readout
- Low power consumption ~ 140 mW at 2 GSPS

Data Concentrator Module

Key Features:

- Central data aggregation module for camera back-end readout
- Receives event data from 16 CDMs via independent LVDS serial links (45 Mbps each)
- Local data buffering to accommodate trigger bursts: Up to 3 event packets per channel (150 ns ROI)
- High-throughput data transfer to remote PC via dual 1-Gbps Ethernet links
- TCP/IP Offload Engine (TOE) for efficient, low-latency data transmission
- Sustained effective data throughput per module up to ~80 MB/s

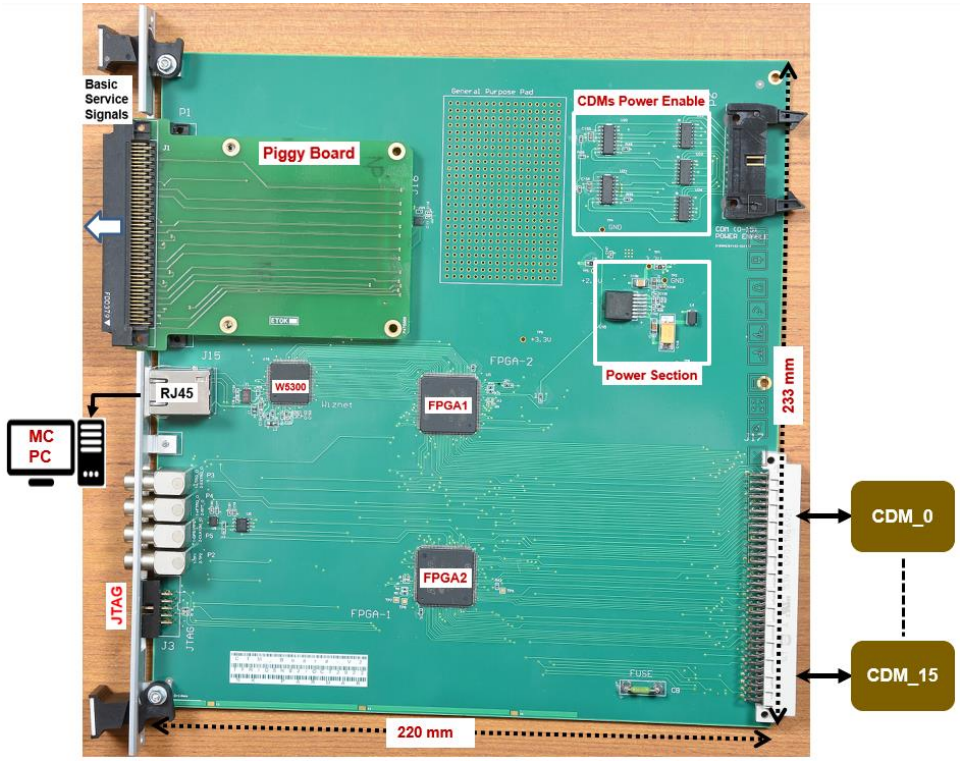


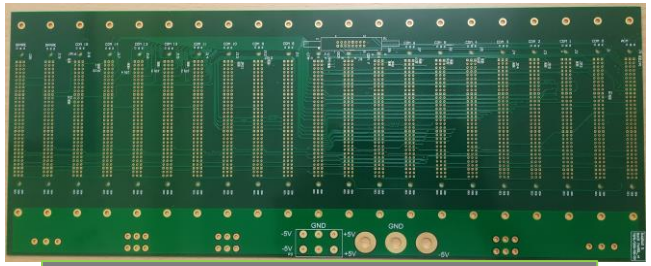


Control & Trigger Module (CTM)

Key Features:

- Central control of camera back-end under supervision of Main Console PC
- FPGA + soft-core processor–based control logic for configuration and monitoring
- Camera trigger generation with user-selectable 3/4-NCNN topology criteria
- Event validation logic to suppress false and spurious triggers
- Precise timing and dead-time monitoring
  - RTC-based trigger timestamping (100 ns resolution)
  - DAQ dead-time measurement (1 µs)
- Communication interfaces:
  - Common serial link to all DDBs for event marker distribution
  - Common CSPI backplane link to all CDMs for configuration and monitoring
  - Dedicated serial links from each CDM for pixel latch data acquisition
- Ethernet interface to Main Console PC for user control, monitoring, and data transfer

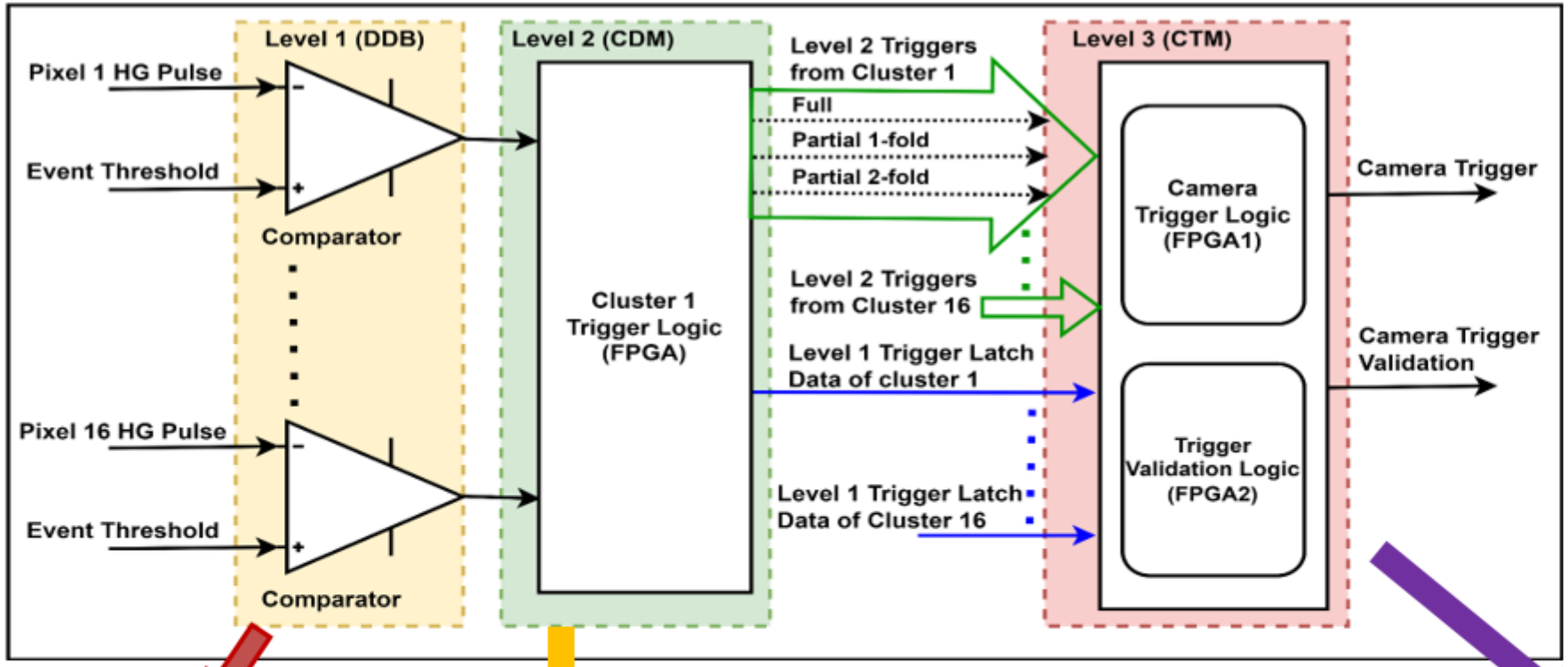




Crate Back Plane Mother Board

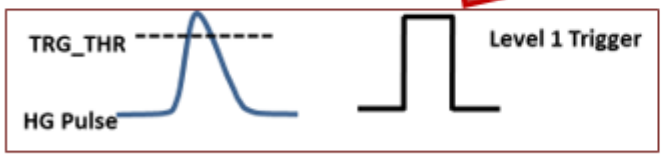
Trigger Scheme

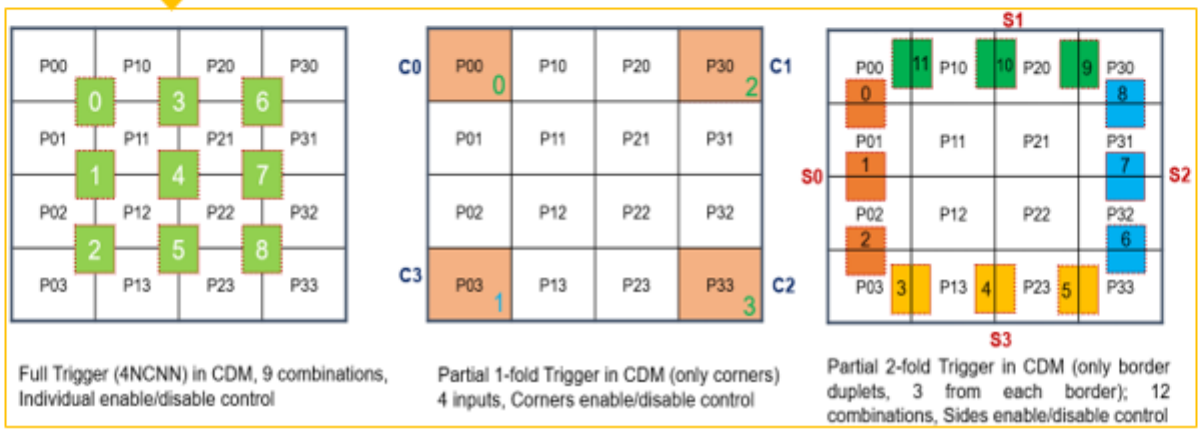
Aim: To discriminate genuine air-shower Cherenkov events from night-sky background (NSB) noise

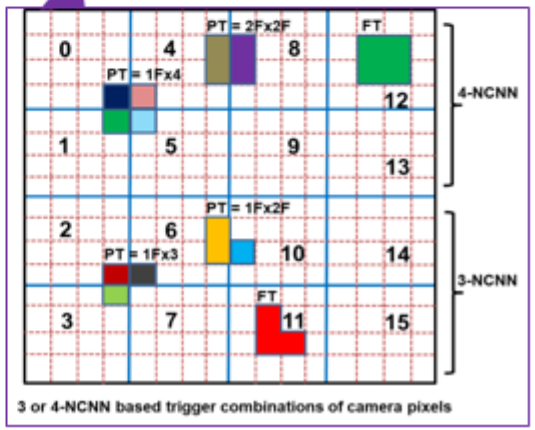


Event Validation:

- Trigger hit patterns of all 256 pixels from respective clusters are received at CTM
- CTM generates the event validation signal as per geographic location of triggered pixels

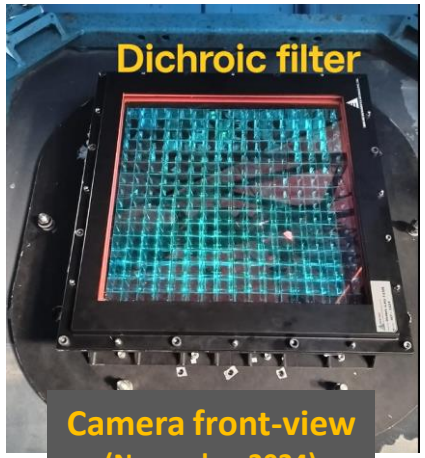






Photographs of Full Camera Installation at Telescope

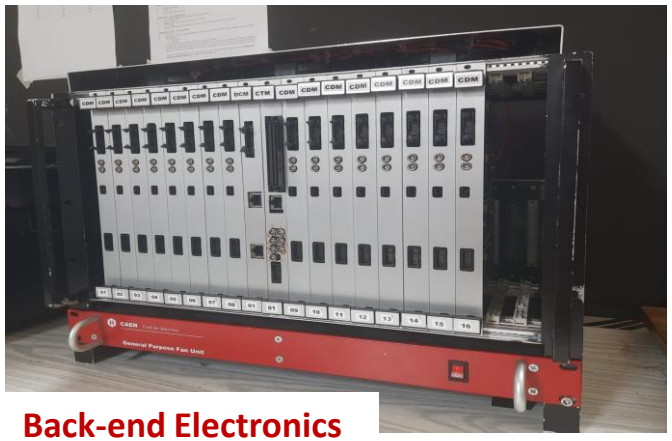
- **256-pixel** camera assembled and tested in lab at TIFR and then installed at vertex telescope of GOALS observatory of BARC at Mount Abu (Rajasthan) in **December 2023.**
- Camera functioning without any major problem.



Camera front-view
(November 2024)

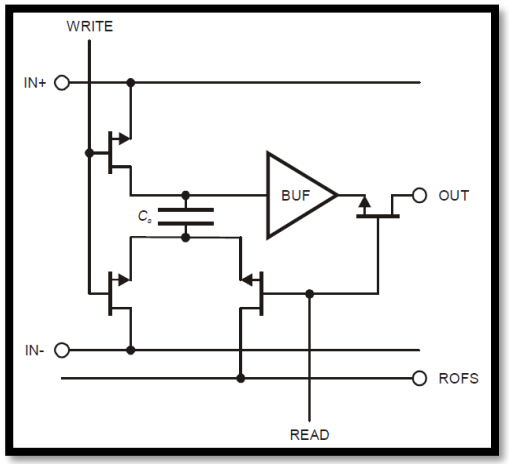
Camera side view

Camera mounted at focal plane of telescope



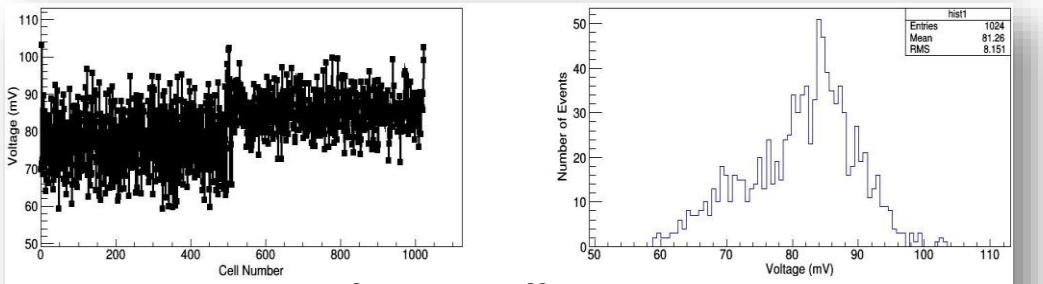
Back-end Electronics

In-lab Performance Results

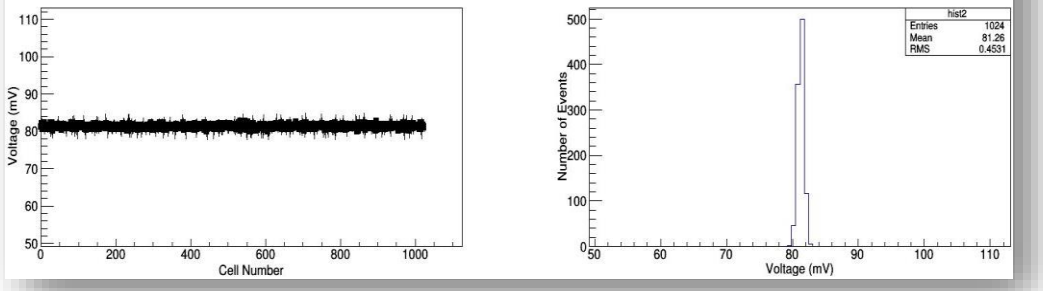


Simplified Schematics of one Sampling Cell

Before DRS4 offset correction

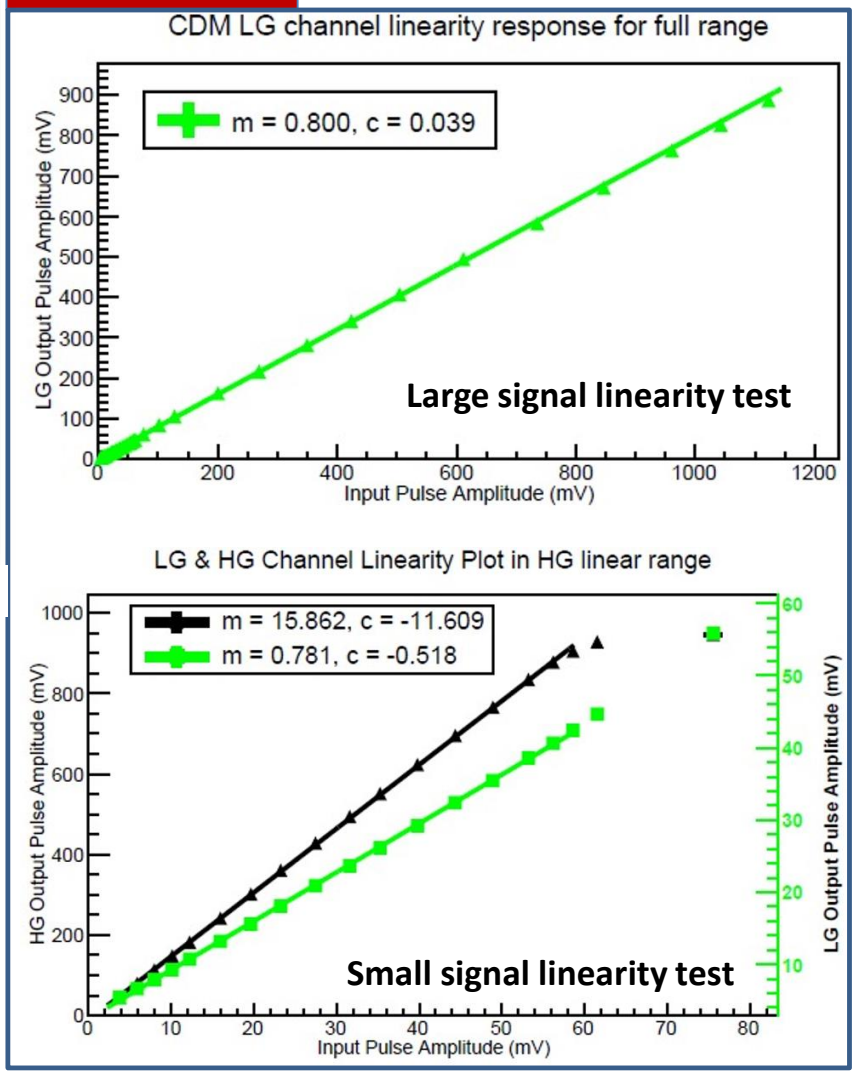


After DRS4 offset correction

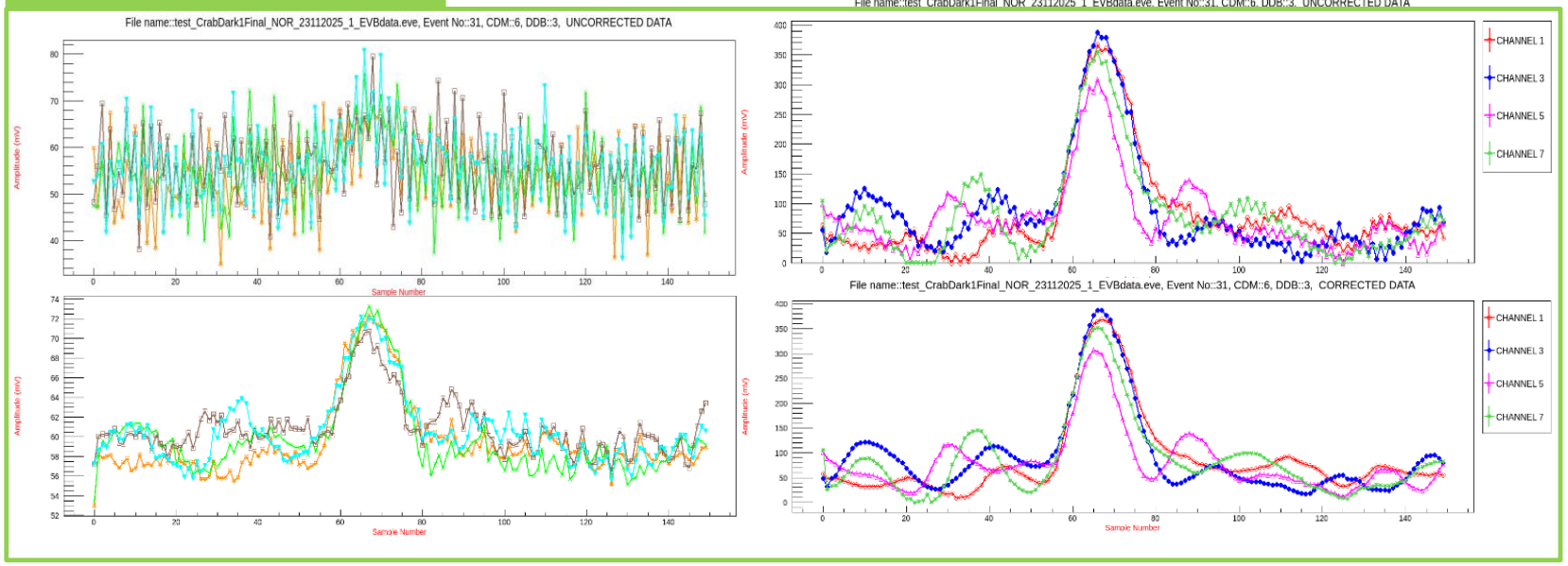


Pattern and distribution of DRS4 cell offsets for a DDB channel before and after offset correction

Linearity Test:



Recorded SiPM Output Pulse



Summary

- ✓ Detector: 256 pixels, **SiPM as photon-sensor**
- ✓ Temperature and NSB compensated bias supply for SiPMs
- ✓ **Dual gain readout:** Pixel dynamic range up to 1500 PEs
- ✓ **Information recorded: Pulse profile** @ 1 GSPS using DRS4 chip (150 ns RoI); Digitization @ 33MHz rate
- ✓ Event Digitization Time (at 150 ns ROI): 40 µs
- ✓ Sustained Trigger Rate (150 ns RoI): ~420 Hz, 16 events in-built buffer
- ✓ Event data size for 1 Hour observation period for 150 ns RoI at 10 Hz event rate: ~6GB
- ✓ **Event trigger time stamp** tagging synchronized with GPS to the accuracy of 0.1 µs
- ✓ **User Configurable hardware:** RoI & skip cells, Trigger threshold, Trigger Scheme (3 or 4-NCNN), Trigger FoV, Bias supply, Individual pixels enable/disable control, option to record data for selective pixels
- ✓ **Monitoring of camera parameters** (trigger rates, temperature, bias voltage, current etc)
- ✓ **Camera pixels calibration:** laser-based calibration device
- ✓ Modular hardware for ease of control and maintenance

Papers Published on Camera Hardware

a) Sandeep et al, Development of a Prototype 16-channel Dual Gain Waveform Readout and Data Transfer System for IACT-based Telescope Camera, **NIM - A**, Volume 1049, **2023**, 168091.

b) Sandeep et al, A 16-channel programmable power supply system with temperature compensation and Ethernet interface for SiPM bias, **JINST**, Volume 18, T01005, **2023**.

c) Shobha K. Rao, K.S. Gothe, S.S. Upadhya, N.K. Parmar, R.L. Deshmukh, B.B. Singh, **Sandeep** et al, Analog Signal Processing for Large Area SiPM in Cherenkov Telescope Camera, **NIM - A**, Volume 1051, **2023**, 168191.

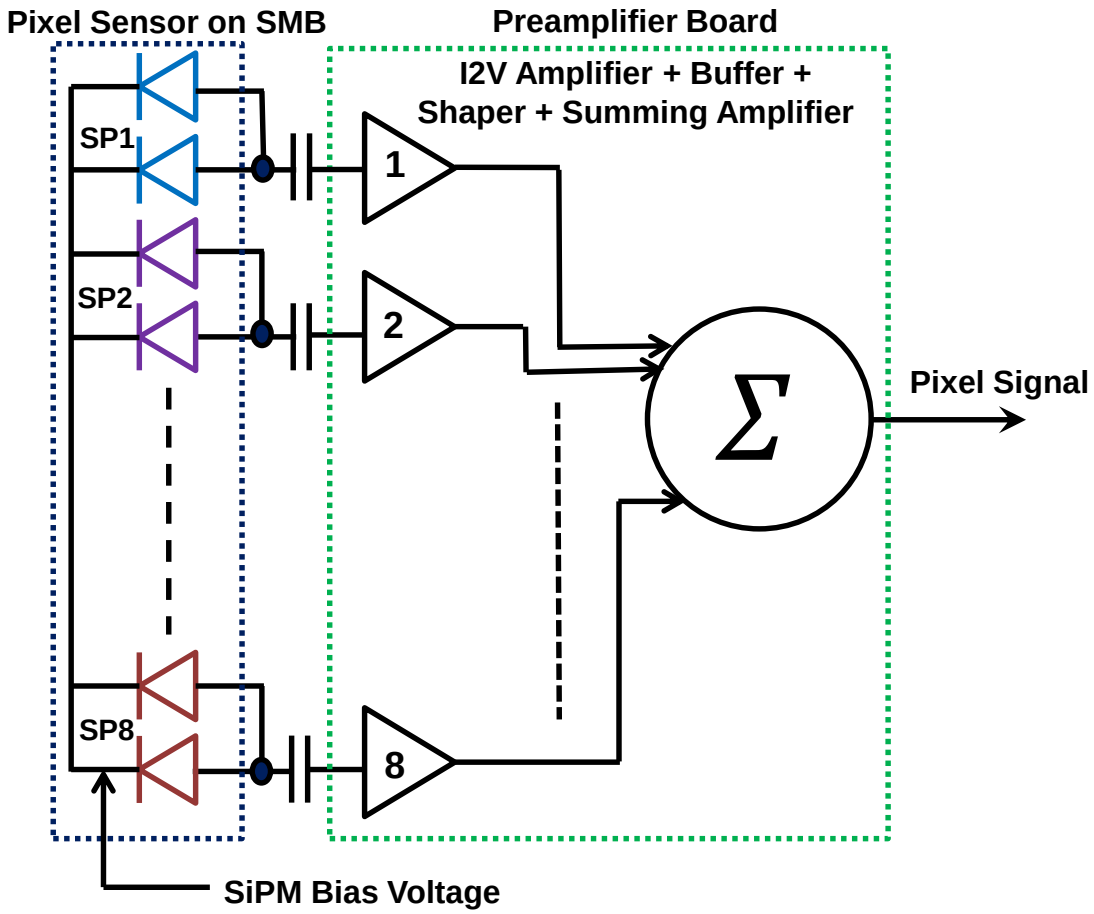
d) Sandeep et al, Development of Control and Trigger Module for a 4-metre class imaging atmospheric Cherenkov telescope camera, **NIM - A**, Volume 1083, Accepted for publication in **March 2026** issue, 171074.

Acknowledgements

- I thank all members of the Camera Development Team at TIFR.
- I also acknowledge GOALS, ApSD-BARC for providing the telescope and for their support in camera testing.

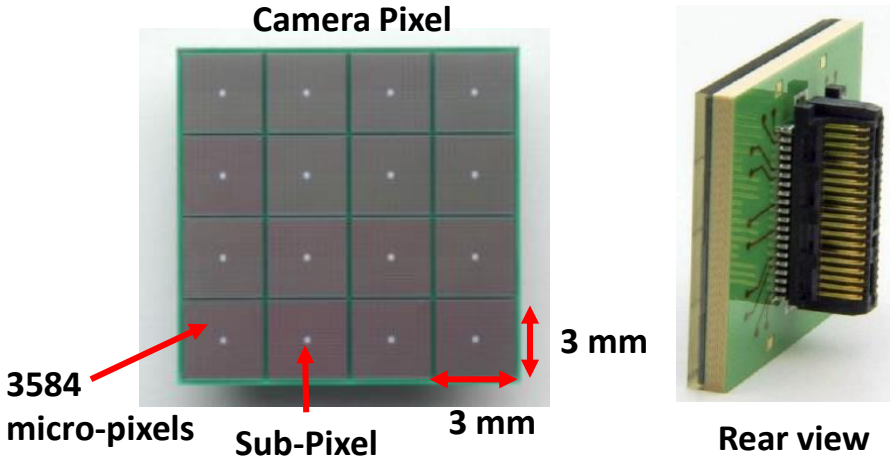
Thank You

Pixel Front-end



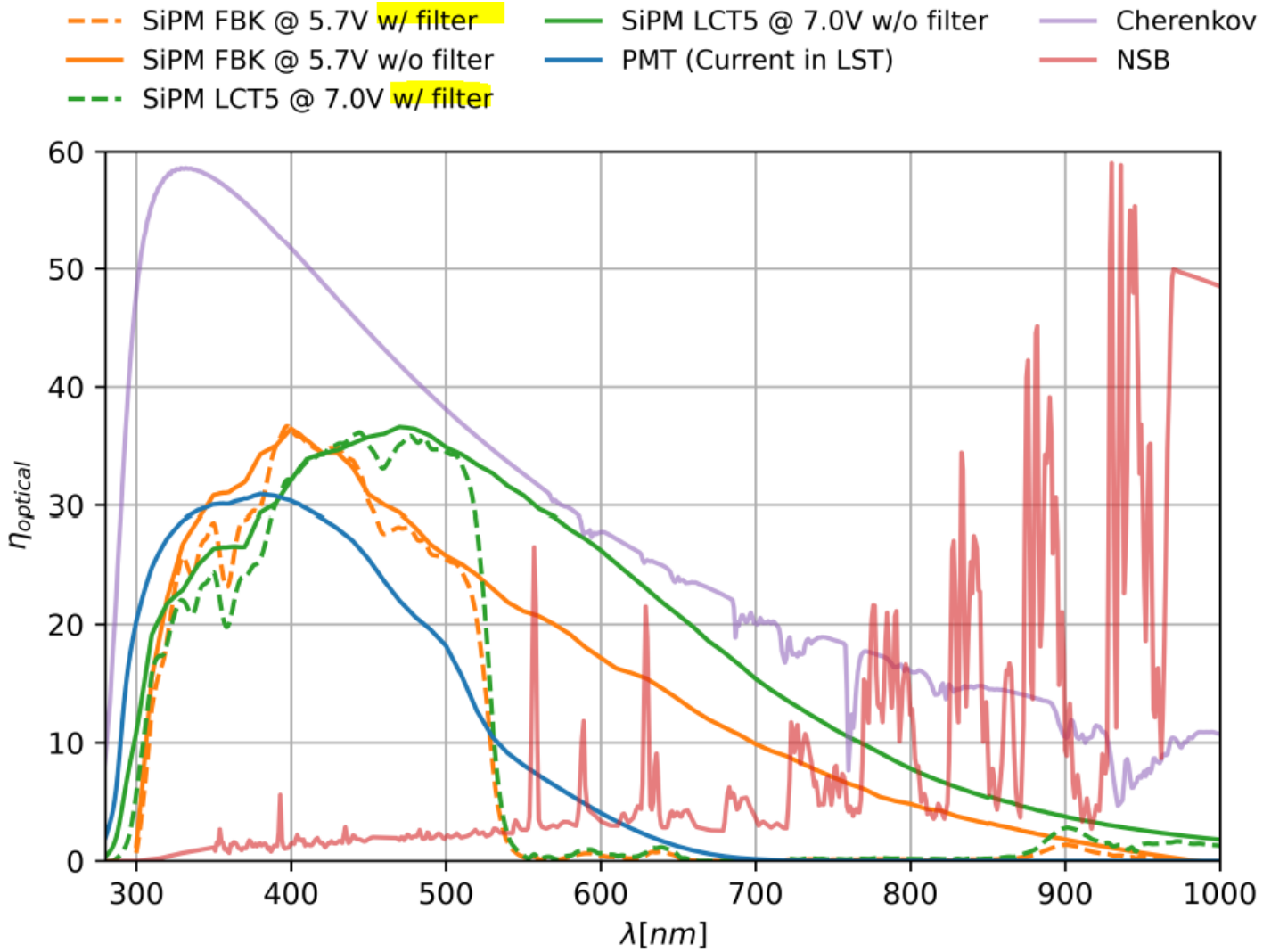
Pixel Sensor Specifications

S13361-3050AS-04 SiPM from Hamamatsu

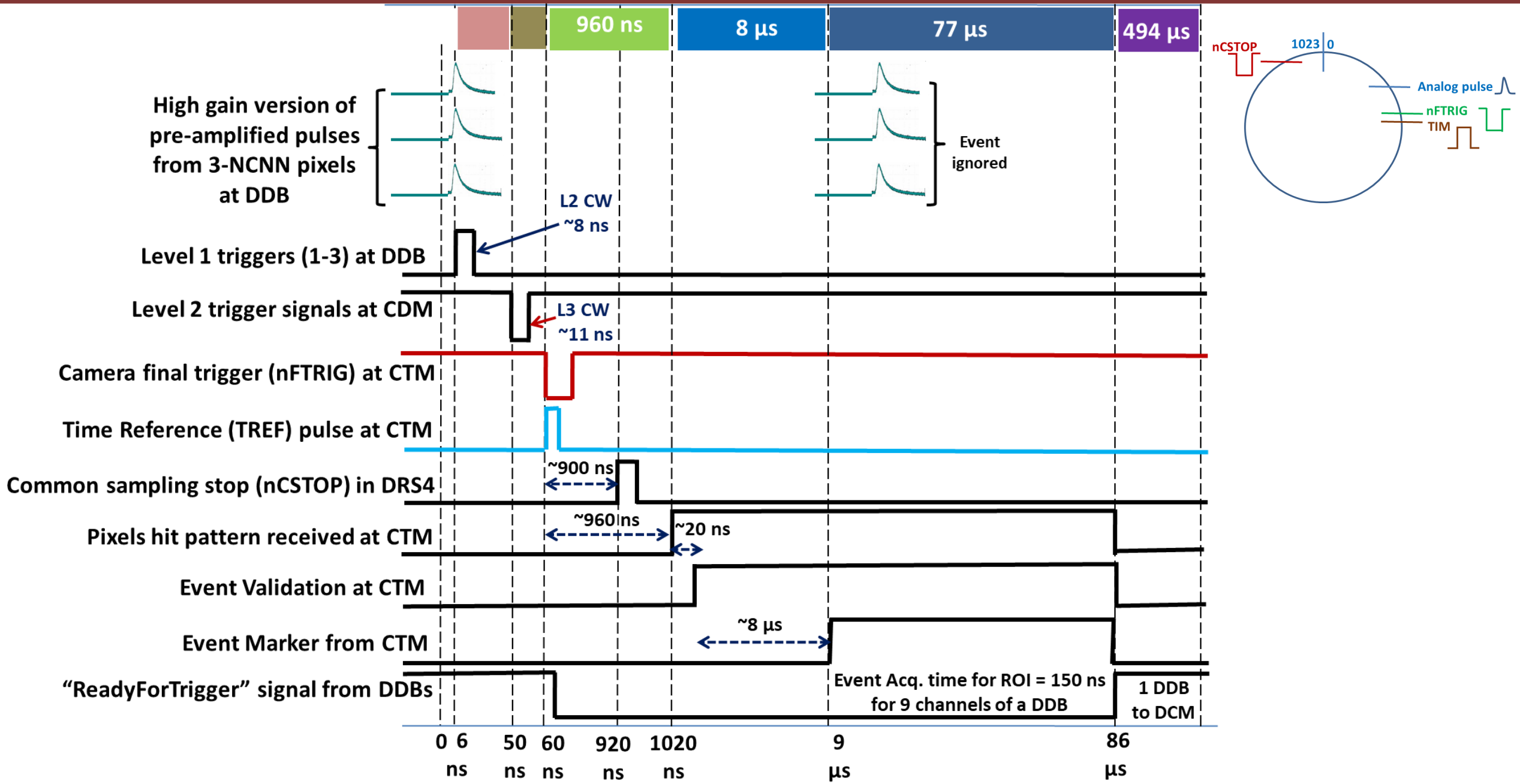


Key Specifications of SiPM S13361-3050AS-04):

- 16 Sub-pixels (3 mm x 3 mm)
- 3584 micro-cells per sub-pixel of 50 µm pitch
- Spectral Response: 270 - 900 nm, Peak (λp) at 450 nm
- PDE at λp = 40%
- Gain at 3 V_{OV} = 1.7 x 10^6
- Typical breakdown voltage (V_{br}) : 53 ± 5 V
- Recommended V_{op} = (V_{br} + 3 V)
- Temp. coeff. of reverse voltage (ΔT_{Vop}): 54 mV/°C
- Dark count rate: 0.5 Mcps (Typ.) at 25°C
- Cross talk Probability: 3%
- Geometrical fill factor: 74%
- Operating temp -20°C to +60°C



Timing Flow Diagram



Recorded Data Types

Data Packet Information Display and Analysis Programs (4 types of recorded data):

1. **Event Builder Pulse Profile Data (Packet size per DDB: ~2.8 kB at 150 ns RoI, ~179 kB for camera):** Event number, event flag, event time stamp, Level-1 trigger latch data, pulse profile, dead time, run & hardware specific info

2. **CTM Event Data (Packet size: 0.6 kB):** Event number, event flag, event time stamp, Level-1 trigger latch data, dead time

3. **Camera Back-end Monitoring Data (Packet size: 2.2 kB):** MON record number, MON time stamp, Level-1 & 2 trigger rates, dead time

4. **Bias MON Data (Packet size: 58 Bytes):** MON record number, bias board & SiPM mount board temperature, individual channel bias voltage, load current, sub-pixel pair enable/disable status, temperature & load compensated channel numbers, hardware specific info

Run Types

Two main types of runs: Science runs and Calibration runs.

1. **Science:** In this type of run, the trigger is generated by the trigger logic (3 or 4-NCNN) at the CTM, mostly due to the Cherenkov light photons from extensive air showers.

2. **Calibration:** Such types of runs are used for the calibration of various camera sub-systems:
   - **Flash:** To establish the relation between the number of photoelectrons and ADC counts, to check stability of ADC counts.
   - **Single Photoelectron (SPE):** To estimate the gain of camera pixels at a given overvoltage using the SPE spectrum method.
   - **Pedestal:** To study the performance of camera electronics by recording the pedestal ADC counts under various operating conditions of the camera, such as pixel bias supply ON/OFF, and camera dome/shutter open/closed.
   - **DRS4 cells offset calibration:** To obtain the cell offset voltage of the analog sampler DRS4 chip used in the DDBs.
   - **DRS4 time calibration:** To obtain the fixed delta time offset in the inter-cell sampling interval of the DRS4 chip.