SiPM Characterization for CTA

Naoya Hidaka
Nagoya University
SiPM Characterization for CTA

- CTA
- Cherenkov Camera
- SiPM (MPPC) Characterization

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Nagoya University
Cherenkov Telescope Array

Gamma-ray Source

Air Shower (~10 km)

θ ~ 1°

Atmospheric Cherenkov Light

Δt ~ 5 ns

R ~ 150 m

Stereo Observation

LST 1

4° – 5°

LST 2

LST 3

LST 4

by MC Simulation Group

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The Next-generation Very-high-energy (VHE) Gamma-ray Observation
- Energy range of \( \sim 20 \text{ GeV} - 100 \text{ TeV} \)
- 10-fold increase in sensitivity over current VHE \( \gamma \)-ray instruments
- Large (\( \sim 8^\circ \)) field of view for surveys
- Improved angular and energy resolution
**Cherenkov Telescope Array**

**SST × (32 + 8)**
- $D = 4 - 6 \text{ m}$
- FOV $\sim 10^\circ$
- $E = 1 \text{ TeV} - 100 \text{ TeV}$

**MST × (23 + 17)**
- $D = 10 - 12 \text{ m}$
- FOV $= 6^\circ - 8^\circ$
- $E = 100 \text{ GeV} - 10 \text{ TeV}$

**LST × (4 + 4)**
- $D = 23 \text{ m}$
- FOV $= 4^\circ - 5^\circ$
- $E = 20 \text{ GeV} - 1 \text{ TeV}$

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- wide FoV, high angular resolution with good off-axis response
- 2-mirror design reduces plate scale allowing multi channel photodetectors and reducing costs
Dual Mirror Telescope

- Wide FoV of 8°
- Angular resolution: 4.0’

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Comparison between LST and Dual-Mirror Cameras

MAPMTs or MPPCs are used instead of regular PMTs (1.5” for LST)
Highly integrated and modular camera electronics are required

11,328 Channels
1,855 Channels

Dual-Mirror Telescope Camera

Single MAPMT or MPPC Array
Camera Module

Focal Plane (SCT)

Single MAPMT or MPPC Array

0.78 m

11,328 Channels

MAPMT
6.08 mm × 6.08 mm /ch
8 ch × 8 ch

Readout module
- Preamp
- ASIC ("TARGET")
- FPGA
- HV etc...

Multi Pixel Photon Counter (MPPC)
Silicone Photomultiplier device of Hamamatsu photonics

Higher Photon Detection Efficiency
Measure ratio of photon detection efficiency (PDE) compared with MAPMT

\[ \rightarrow \sim 60\% \text{ higher light yield than MAPMT} \]

Temperature dependence of MPPC performance
- Need to know operating temperature range of MPPCs at optimum performance conditions
  - Gain, PDE
  - Dark rate, Afterpulse, Crosstalk

\[ \rightarrow \text{Accidental trigger rate} \]
SiPM(MPPC) Characterization

- **Setup**
  - Waveform recording
    - Proper pile up treatments
    - Precise measurement of pulse shape (gain)
    - Removal of accidental dark pulse
    - After pulse detection at small $\Delta t$ by subtraction of primary pulse shape

- **Measurements**
  - PDE, gain, dark rate, crosstalk, after pulse rate
  - Wavelength dependence, temperature dependence

![Diagram of SiPM(MPPC) readout system](image_url)
Integrate current output $V_1 \text{ p.e.} / R_f$

$V_1 \text{ p.e.}$: output voltage / p.e. (from the histogram of pulse height)

$R_f$: feedback resistor
Integrate current output $V_{1\text{ p.e.}} / R_f$

$V_{1\text{ p.e.}}$: output voltage / p.e. (from the histogram of pulse height)

$R_f$: feedback resister
Photon Detection Efficiency

Count the number of detected photons from pulse height distribution

PDE have stable performance under control of bias voltage accidental trigger rate is more important → dark count, crosstalk rate, afterpulse rate measurement
Pixel Trigger Rate

- Dark count + Night Sky Background
- Afterpulse rate \( r_a \)
  - factor \( \frac{1}{1 - r_a} \)

- Crosstalk

→ 4 p.e. threshold

\[
(f_{\text{NSB}} \cdot \text{PDE} + f_{\text{dark}}) \times \frac{1}{1 - r_a} \times \left\{ 1 - (P(0) + P(1) \times P(0) + P(2) \times P(0)^2 + P(1) \times P(1) \times P(0)) \right\}
\]

\( f_{\text{NSB}} \): Night Sky Background rate
\( f_{\text{dark}} \): Darkcount Rate
Dark rate, Afterpulse, Crosstalk

Dark Rate at threshold 0.5p.e. vs Bias Voltage

Count Rate (cps)

Over Voltage (V)

Crosstalk Rate

Over Voltage (V)

Afterpulse Rate

Overvoltage (V)

Afterpulse + dark
• 6mm × 6mm pixel
• NSB = 5 MHz

Pixel Trigger Rate (≧ 4 p.e.)

→ ~10 MHz at high PDE
increase 10 times from 5°C to 40°C
Recent Work

- Evaluation the accidental trigger rate
  - Simulation with trigger logic of telescope
- MPPC with trenches
  - implemented to suppress crosstalk
- evaluation of performance of “camera module”
  - MPPC array + readout
Back up
Measure ratio of MAPMT efficiency compared with MPPC efficiency

- **MPPC**
  - S11827-3344MG
  - 3 mm × 3 mm /ch
  - 4 ch × 4 ch
  - 50 µm GAPDs

- **MAPMT**
  - H8500-D
  - 6.08 mm × 6.08 mm /ch
  - 8 ch × 8 ch

**Diagram:**
- LED
- Fiber
- Pulse Generator
- Diffuse filter
- Oscilloscope
- MPPC Readout
- Thermal chamber
- MPPC Readout
  - 2 mV
  - 20 ns

**Note:**
- MAPMT: H8500-D
- MPPC: S11827-3344MG
- Dimensions and configurations provided.
Pulseheight at the time of LED emission
before average waveform around 8-ns average

Remove events if the baseline (shown in blue) is outside of nominal distribution

Remove off-timing events
Fit to 0 p.e. distribution: \( P(0) \)

- Avoid effect of crosstalk and after-pulse

\[
P(k) = e^{-\lambda} \frac{\lambda^k}{k!}
\]

\[
P(0) = e^{-\lambda}
\]

\[
\lambda = \ln(P(0))
\]
PDE ratio measurements

\[
PDE\ Ratio = \frac{\lambda(MAPMT)}{\lambda(MPPC)} = \frac{\varepsilon(MAPMT)}{\varepsilon(MPPC)}
\]

Black : systematic error
Red : statistic error
Integrate Cherenkov light spectrum weighted by photon detection efficiency up to 550 nm

- Avoid Oxygen fluorescent line
- MPPC PDE from catalog
- MAPMT PDE from MPPC PDE and PDE ratio

\[ \frac{LY(MPPC)}{LY(MAPMT)} = 2.04 \]

Correcting light loss at boundary of each unit

\[ \frac{LY(MPPC)}{LY(MAPMT)} = 1.58 \]

\( \varepsilon(MAPMT) = 89\% \)

\( \varepsilon(MPPC) = 69\% \)

(0.5 mm gap between units)
Current begins to get higher sharply at the voltage over 2 – 3 V of the break-down voltage.
Take 100-ns long waveforms with random trigger
take the maximum of averaged waveform

Pulse Generator → Oscilloscope → read-out circuit → MPPC (masked) → thermal chamber

Diagram:
- Pulse Generator
- Oscilloscope
- Read-out circuit
- MPPC (masked)
- Thermal chamber

Graph:
- Y-axis: 2 mV
- X-axis: 40 ns
Dark Count

max voltage at 10 ns ≤ time ≤ 90 ns

$V_{\text{max}} \text{ (mV)}$

≧ 1 p.e. events

≧ 2 p.e. events

≧ 3 p.e. events

Dark Rate at threshold 0.5 p.e. vs Bias Voltage

Over Voltage (V)

Count Rate (cps)

Dark Rate at threshold 1.5 p.e. vs Bias Voltage

Over Voltage (V)

Count Rate (cps)

Dark Rate at threshold 2.5 p.e. vs Bias Voltage

Over Voltage (V)

Count Rate (cps)
• Cross talk rate
  \[ \frac{\geq 2 \text{ p.e. events}}{\geq 1 \text{ p.e. events}} : \text{crossstalk signals} \]
• No temperature dependence
good agreement → pulse height distribution can be calculated
MPPC Readout

Current sensitive amp

- 2400 SourceMeter
- MPPC Adapter Board
- MPPC Readout Board
- Oscilloscope

Diagram:
- 2400 SourceMeter
- 1 kΩ
- 0.1 μF
- MPPC 16 ch
- 5 MΩ
- 500 Ω
- 50 Ω
- MSO4054B Oscilloscope
Sensitivity of CTA

order of magnitude improvement in sensitivity over HESS and VERITAS