Properties of large SiPM at room temperature

- Experienced acquired operating large area sensors of the SST-1M camera
- Evaluation of main working parameters
- Effect of continuous light illumination on working parameters

Thanks to A. Nagai, M. Heller
A SiPM camera for gamma-ray astronomy

**Entrance window:**
- 3.3 mm Borofloat
- AR coating
- Cut-off filter at 540 nm for NSB rejection

**Photo detection plane:**
- 1296 pixels
- 0.24° angular size
- Power consumption 500 W
- Analogue signals over CAT5/RJ45

**Digital electronics (DigiCam):**
- 12 bits FADC @ 250 MS/s
- Fully digital trigger, decision every 4 ns
- Trigger path with reconfigurable algorithms and signal preprocessing
- Serial architecture based on multi-Gigabit links (both trigger and ADC data)
- Power consumption 1200 W

operating at room temperature!
The photo-sensing plane

### Hollow light guides:
- Plastic substrate (2592 halves glued) - injection molding
- Dichroic coating
- Cut-off at 24°
- 2.32 cm linear size
- Compression factor of ~6

### Sensor:
- 1296 hexagonal Hamamatsu MPPC - same technology of 50 um microcells
- 4 anodes per pixel with one common cathode
- Embedded NTC temperature sensor

### Slow control board:
- 108/camera
- Temperature compensation loop (2 Hz)
- HV generation
- Differential output to DigiCam

### Preamplifier board:
- 108 /camera
- Discrete components
- Trans-impedance topology
- 2 operational amplifiers per sensor to reduce pulse length
- DC coupling
The sensor

Hamamatsu MPPC S10943-2832(X) :
- Low Crosstalk Technology 2 (LCT2)
- 4 anodes per pixel with one common cathode
- Embedded NTC temperature sensor
- PDE (@ 2.8V, 472nm) = 35.5 %

From producer: 
T = 25 °C and over-voltage $\Delta V = V_{op} + 2.8$ V

| Nr. of channels | 4 |
|-----------------|---|
| Cell size       | $50 \times 50 \, \mu m^2$ |
| Nr of cells (per channel) | 9210 |
| Fill Factor     | 61.5% |
| $DCR$ (@$V_{op}$ per channel) | 2.8-5.6 MHz |
| $C_{\mu cell}$ (@ $V_{op}$ per channel) | 85 fF |
| Cross-talk (@$V_{op}$ per channel) | 10% |
| $V_{BD}$ Temp. Coeff. | 54 mV/C° |
| Gain (@$V_{op}$ per channel) | $1.49 \times 10^6$ |
DC coupling motivation

A DC coupled camera is an NSB monitor!

The Digicam can measure the BL before each pulse.

Useful for correcting for changes of SIPM parameters

Rate of NSB in Krakow (including clouds and airplanes…)

$V_{\text{bias}} = 58.3 \text{ V}, T = 25 \degree \text{C}$
Static Characterisation of sensors (DC)

Reading constant current (static or DC)

Advantages:
• Simple;
• Fast;

Disadvantages:
• Limited information (only $V_{BD}$, $R_q$, working range)
• Limited precision

http://arxiv.org/pdf/1810.02275.pdf accepted by NIM
Forward IV: $R_q$ calculation

For a $\mu$cell (deal Shockley law):

\[
I^d = I_s^d \left[ \exp \left( \frac{V_j}{\eta V_T} \right) - 1 \right]
\]
\[
V_j = V_{bias} - I^d \cdot R_s
\]
\[
R_s \approx 100 \, \Omega
\]

diode reverse bias saturation current

For SiPM = array of $N_{\mu\text{cells}}$ G-APDs connected in parallel, each is in series with a quenching resistor $R_q$

\[
V_{bias} = \eta V_T \left[ \ln \left( \frac{I}{I_s} + 1 \right) \right] + I \frac{(R_s + R_q)}{N_{\mu\text{cell}}}
\]

Since $b$ is not constant $R_q$ measurement has a systematic bias of about 17%

\[
R_q + R_s = \frac{N_{\mu\text{cell}}}{b} \approx \frac{R_q}{|R_q > > R_s|}
\]

$R_q = 182.9 \pm 0.3 \, \text{(stat.)} \pm 31 \, \text{(sys.)} \, \text{k}\Omega$
Logarithmic derivative

Inverse log derivative:

Fit with a Landau function to extract peak value
DC (static) methods: Reverse IV

2nd log derivative:
Commonly used: seek for max of second derivative but the Gaussian fit is not perfect

Third derivative method:
2 separate breakdown voltages are assumed. The turn-on is determined by the avalanche triggering probability $P_G$ and the turn-off by the voltage at which quenching starts.

IV model
Fit with 4 regions identified and fit functions physically motivated (exponential for Geiger probability + increase of correlated noise)
AC (dynamic) measurement: $V_{BD}$

**Pulsed light**

- LED`s: 280, 340, 375, 405, 420, 455, 470, 505, 525, 530, 565 & 572nm
- Photodiode 10x10 mm$^2$ (S1337-1010BQ)
- ND filters (81.3% ± 0.01%)

Read 10'000 x 10 µs WFs with an oscilloscope sampled at 500 MHz. Trigger at 5 µs adjusted to have ‘dark’ interval before and LED interval after.

Advantages:
- In dark it is possible to measure $V_{BD}$, work range, G, DCR, $C_{\mu cell}$, $P_{XT}$, $P_{ap}$
- In light: PDE

Disadvantages:
- Relatively complicated set up
- Lots of data and DAQ time
AC measurements: Gain

Each ucell detects photons identically and independently => the sum of the photocurrents from each ucell combines to form an output providing the magnitude of photon flux

Practically, G can be measured from the time integration of the pulse in time subtracting the BL

\[ G = \frac{Q}{e} = \frac{1}{G_{Amp}} \cdot \frac{1}{e} \cdot \frac{1}{R} \int (V(t) - BL) \, dt, \]

Parasitic capacitance

\[ G = \frac{Q}{e} = \left( C_{\mu \text{cell}} + C_q \right) \cdot \left( V_{bias} - V_{BD}^{AC} \right) \]

Gain vs. \( V_{bias} \)

Amplifier input impedance

Parasitic capacitance

Charge spectrum

1 \( \mu \text{cell} \) fired

2 \( \mu \text{cell} \) fired

3 \( \mu \text{cell} \) fired

G is defined by the number of charges created by one avalanche in a ucell

\( Q = N_{\text{fired}} \cdot G \cdot e \)

- \( V_{BD} \) extrapolation of linear fit to 0

- \( V_{bias}^{AC} = 54.699 \, V \)
Comparison of $V_{BD}$ methods

In the IV model and the Inverse log derivative we see the breakdown defined as the voltage at which the avalanche process starts.

In AC $V_{BD}$ corresponds to the value when $G = 0$.

These values are close to the value close of the turn-off voltage of the 3rd derivative when still the gain is 0, though the AC value is commonly used with the meaning of breakdown voltage.
Uncorrelated noise DCR: Counting method from WF

\[ V_{\text{bias}} = 59.2 \, \text{V}, \, T = 25 \, ^{\circ}\text{C} \]

Count all pulses which cross given threshold within given time interval \( L \):

\[ DCR = \frac{N_{\text{pulses}}(Thr.)}{L} \]

This is affected by afterpulses.
DCR: Poisson method

Count how many times in interval $L$ the minimum is higher than 0.5 p.e.

$V_{bias} = 59.2 \, V, \, T = 25 \, ^{0}C$

Poisson statistics is used to estimate purely uncorrelated noise

$D_{CR, Poisson} = -\frac{ln \left( P_{dark}(0) \right)}{L} = -\frac{1}{L} \ln \left( \frac{N_{dark}(0)}{N_{dark}(total)} \right)$

Prob. Not to have any SiPM pulse

WF wo SiPM pulse in $L$
Poisson method caveat:

Window length $L$ should be long enough to include all after pulses corresponding to primary pulse, otherwise $DCR_{\text{Poisson}}$ will be overestimated.

Can correspond only to 0.5 p.e threshold
AC measurements: Uncorrelated Noise

\[ DCR = N_{car} \cdot P_{G}^{DCR} \cdot e^{b \cdot V_{bias}} \]

Geiger prob. Of DCR

Increase of DCR with \( V_{bias} \)

Counting method from WF:
- Commonly used;
- Affected by correlated noise (e.g., after pulses)

Poisson statistics:
- Unaffected by correlated noise
- Should be used with precaution (see previous slide)
AC measurements: Correlated Noise

- Correlated noise:
  - Afterpulses;
  - Optical cross-talk (OCT)

OCT: the avalanche process in a ucell emits secondary IR photons that are then detected by the surrounding ucells with a certain probability ($P_{XT}$).

(Pagano, 2010)
AC measurements: Optical cross-talk

The correction is due to the probability that 2 or more dark pulses pile up in the time interval of 10 ns where afterpulses can be neglected.

\[ R_{total} = 2 \cdot \tau \cdot DCR_{0.5p.e.}^2 + 2 \cdot \tau^2 \cdot DCR_{0.5p.e.}^3 + \ldots = \frac{2 \cdot \tau \cdot DCR_{0.5p.e.}^2}{1 - \tau \cdot DCR_{0.5p.e.}} \]
DCR and afterpulses

Data acquisition:
• Measurements in dark;
• 20 $\mu$s length;
• 0.5 p.e. amplitude trigger and no pulses 5 $\mu$s before trigger @ 10 $\mu$s
AC measurements: Afterpulses

Afterpulses: Afterpulses can be seen as a secondary pulse that follows the primary pulse by a certain time delay. The amplitude of the afterpulse can be calculated using the formula:

\[ A_{AP} = A_{1 \text{p.e.}} - A_{1 \text{p.e.}} \exp \left( -\frac{t}{\tau_{rec}} \right) \]

Where:
- \( A_{1 \text{p.e.}} \) is the amplitude of the primary pulse.
- \( \tau_{rec} \) is the recovery time constant.
- \( t \) is the time delay.

Being 1 p.e. they should come from another cell than the oe recovering, so they are most probably cross-talk since the DCR probability at such short delay is small.
AC measurements: Afterpulses

\[ DCR = \frac{1}{\tau_{DCR}} \]

\[ N_{DCR}(\Delta t) = \frac{n_{DCR}}{\tau_{DCR}} \cdot \exp\left(\frac{-\Delta t}{\tau_{DCR}}\right) \]

\[ N_{AP} = \frac{n_{AP}}{\tau_{AP}} \cdot \exp\left(\frac{-\Delta t}{\tau_{AP}}\right) \cdot \left(1 - \exp\left(\frac{-\Delta t}{\tau_{rec.}}\right)\right) \]

\[ \tau_{AP} : \text{Afterpulses livetime} \]

Term due to decrease of PDE due to cell recovery

\[ N_{total}(\Delta t) = N_{DCR}(\Delta t) + N_{AP}(\Delta t) \]
AC measurements: Afterpulses

- Afterpulse lifetime: average time of charge trapping in impurities
- Afterpulse probability increase with over voltage but lifetime is constant

\[
P_{AP} = \int_{0}^{5 \times \langle \tau_{AP} \rangle} N_{AP}(\Delta t) dt
\]

\[
\tau_{AP} = 5 \times 10^{-9}
\]

\[
P_{AP} = \frac{\int_{0}^{5 \times \langle \tau_{AP} \rangle} N_{AP}(\Delta t) dt}{N_{prim}}
\]

\[
6.769 \pm 0.110 \text{ ns.}
\]
Optical measurements: set-ups

**Pulsed light**

- LED
- Pulse generator
- Photodiode
- Integration sphere
- ND Filter & Diffuser
- Ampl.
- Oscilloscope
- MPPC
- Trigger
- LabVIEW

**Continuous light**

- Xe lamp
- Monochromator
- Integration sphere
- Photodiode
- MPPC
- Source meter
- HV
- LabVIEW

**Light disuniformity < 2%**

- Xe 75 W lamp: 250 ÷ 1800 nm

**ND filters**

- (81.3% ÷ 0.01%)

**LED’s:**

- 280, 340, 375, 405, 420, 455, 470, 505, 525, 530, 565 & 572nm

**Calibrated Photodiode 10x10 mm²**

- (S1337-1010BQ) 5% precision

**PDE = QE(λ) × ε × PG(ΔV, λ)**
### Pulsed light: absolute PDE from photon counting

- **Poisson distribution:**
  \[
P(n_{p.e.}) = \frac{(k)^{n_{p.e.}}}{n_{p.e.}!} \times e^{-k}
  \]

- **Probability to have 0 p.e. on the SiPM:**
  \[
P(0) = e^{-k} = \frac{N(0)}{N(total)}
  \]

- **Average number of detected photons:**
  \[
k = - \ln(P(0)_{LED}) + \ln(P(0)_{dark})
  \]

**PDE**

\[
PDE = \frac{k}{N_{photons}} = k \times \frac{f \cdot QE_{PD} \cdot e}{I_{PD} \cdot R}
\]
Continuous light: Relative PDE

\[ PDE(\Delta V, \lambda) = \frac{I_{\text{light}}^{\text{SiPM}} - I_{\text{dark}}^{\text{SiPM}}}{e \times N_{\text{Ph}} \times G^{\text{eff.}}_{\text{SiPM}}(\Delta V)} \propto \frac{I_{\text{light}}^{\text{SiPM}} - I_{\text{dark}}^{\text{SiPM}}}{I_{PD}(\lambda)} \]

Rate continuous light .

G enhanced by correlated noise

Wavelength (nm)
Comparison from different labs

Average difference
@ $\Delta V = 3V$
6.5%

Nagai et al. Nucl.Instrum.Meth. A912 (2018) 182-185
OXT photons which are going out from SiPM might be reflected by optics and lead to increase of total optical crosstalk. Also coating itself would do the same (Bonanno et al, NIM A908 (2018) 117-12)
Optical crosstalk test

SiPM:

\[ \Delta V = \sim 2.7 \text{ V} \]

No \( P_{XT} \) increase observed

SiPM + lightguide (LG):

SiPM + LG + Window:

Fit Function:

\[ P_{XT} = \text{Gain} \cdot P_{hv} \cdot P_{Geiger} \]
SiPM under continuous light

\[ N_{av} = \frac{B L_{shift} \times \Delta t}{Q_{1p.e.}} \]  
integral of 1 p.e. pulse over time

\[ N_{p.e.} = \frac{N_{av} - DCR \times \Delta t}{(1 + P_{XT})(1 + P_{ap})} \]

\[ N_{ph} = \frac{N_{p.e.}}{PDE} \]
Voltage drop

SiPM devices are usually biased through an RC filter to:

• filter high frequency electronic noise coming from the DC bias source
• limit the current, therefore protect the sensor in case of intense illumination.
• Increase MTBF (mean time before failure) of sensor (usually not provided by producer)
• But this resistor also induces a voltage drop at the sensor cathode in presence of continuous light, which reduces the bias voltage and therefore changes its operation point

Figure 2: Typical schematics to bias SiPM device.

Figure 3: SiPM temperature (upper) and Power consumption (bottom) at initial $\Delta V = 2.8$ V and under $12 \times 10^7$ $\gamma$/s vs. time for $R_{bias} = 0.1 \Omega$ (solid line) and $R_{bias} = 10 \, K \Omega$ (dashed line). The highest acceptable power consumption for a sensor (provided by producer) is represented by red dashed line.
Voltage drop: Toy MC model scheme

Time dependent toy MC simulation was developed to account for these effects:

- Gain (Amplitude) & $\sigma_{\text{Gain}}$
- PDE($\lambda$)
- Noise: $P_{XT}$, $P_{AP}$, DCR
- Baseline Shift & $\sigma_{\text{Baseline Shift}}$
Voltage drop: Toy MC model

Simulation Example:

NSB = 5 \times 10^7 \text{ γ/s}

Transition time (100 ns)

Injected signal

NSB + DCR
Voltage drop: Model Validation @ Cern/Unige

1. @ Unige/Ideasquare

5. With SST-1M camera and CTS

- DC LED (470 nm)/ch mimic NSB
- AC LED (470 nm)/ch mimic Shower

![Voltage drop diagram](image)
AC/DC scan: Model Validation @ Cern/Unige

- **DC intensity scan:**
  - $V_{\text{drop}}$ vs. NSB;
  - Baseline Shift vs. NSB

- AC/DC scan: AC intensity constant and DC intensity changes
  - Amplitude vs. NSB
  - Amplitude vs. Baseline Shift

$$A_{\text{rel.}} = \frac{AC \text{ Ampli.} (NSB)}{AC \text{ Ampli.} (NSB = 0)}$$
The CTS as calibration tool and AC/DC scan

• Pulsed and continuous light for each pixel (2 LEDs)
• Status (On/Off) controllable for each LED
• Calibration of SST-1M camera in 1 day after calibrating the LEDs
• Fully autonomous (just requires 230 V), can be operated on site for camera recalibration (e.g. after module replacement)
Results: SiPM under NSB

Baseline Shift, ADC

Relative Drop

$R_{bias} = 10 \, k\Omega$

- $P_{XT}$
- 1 p.e. Amplitude
- PDE @ 470 nm.

$R_{bias} = 2.4 \, k\Omega$

- $P_{XT}$
- 1 p.e. Amplitude
- PDE @ 470 nm.
Voltage drop: compensation loop

Transition time (100 ns)  NSB = $2 \times 10^9 \, \gamma/s$

No voltage drop after transition time!
Voltage drop: compensation

By increasing $V_{\text{bias}}$ constant $\Delta V$ can be achieved $\rightarrow$ Amplitude stability is $\pm 1.5\%$
Calibration strategy for operation

- Extraction of SiPM and readout parameters per pixel in the laboratory
  - gain, optical cross talk, dark count rate, noise, etc…

- Monitoring of these parameters during operations
  - Dark count run
  - Flasher runs

- Image reconstruction accounts for up to date calibration parameters
Signal shape after preamplifier

Average SiPM pulse for all pixels in the camera for a single photon equivalent (1 p.e.)

30 ns
Calibrations in the lab

Increasing light level

Smeared generalized Poisson evaluated for a given light level $j$:

$$P(C_j = x) = \sum_{k=0}^{\infty} \frac{\mu_j^k \mu_{XT}^{-k}}{k!} \exp(-\mu_{XT}) \frac{1}{\sqrt{2\pi\sigma_k^2}} e^{-\frac{(x-kG-B)^2}{2\sigma_k^2}}$$

With $\sigma_k^2 = f\Delta t\sigma_e^2 + k\bar{G}\sigma_s^2$

- $G$: charge gain, i.e. pulse integral
- $B$: residual charge
- $\mu_{XT}$: Cross talk fraction
- $\sigma_e$: electronic noise
- $\mu_j$: average p.e. number

Maximum log-likelihood estimation per light level and per pixel:

$$\hat{l}(\tilde{\theta}; C_j) = \frac{1}{N_w} \sum_{i=1}^{N_w} \ln \mathcal{L}(\tilde{\theta}; C_{ij}) \quad (\tilde{\theta}: \text{fit parameters})$$

All fitting parameters are independent of the light level (LL), aside from $\mu_j \Rightarrow$ all light levels are combined for the fitting ($N_{LL} + 4$ instead of $5 \times N_{LL}$ free parameters):

$$\tilde{l}(\tilde{\theta}; C) = \frac{1}{N_w N_{AC}} \sum_{j=1}^{N_{AC}} \sum_{i=1}^{N_w} \ln \mathcal{L}(\tilde{\theta}; C_{ij})$$
Verification of performance with prototype in the lab
Verification of performance with prototype in the lab

Charge resolution

Response linearity

Dark conditions

125 MHz/pixel NSB
A vision of the future

- Apply the same pixel technology to larger cameras, e.g. the LST camera for the CTA project

LST with PMTs
1855 pixels (0.1°)

LST with SiPMs
7420 pixels (0.05°)

2 m
A vision of the future

- Apply the same pixel technology to larger cameras, e.g., the LST camera for the CTA project
Application of ASICs: CITIROC

- Combine Front End Boards based on the CITIROC ASIC (Weeroc) and developed at UniGe for the BabyMind experiment with the optical modules developed for the SST-1M camera to build a 144 pixels camera for atmospheric showers detection.
Application of ASICs: CITIROC

- Combine Front End Boards based on the CITIROC ASIC (Weeroc) and developed at UniGe for the BabyMind experiment with the optical modules developed for the SST-1M camera to build a 144 pixels camera for atmospheric showers detection.

**Main advantages:**
- Dual gain + ToT ➡ Large dynamic range
- Variable gain preamplifier per channel ➡ Gain equalisation

**Main drawbacks:**
- Multiplexed amplitude readout ➡ Deadtime of 9.12 μs to read one event
- Different shaper for amplitude and trigger ➡ Single channel calibration
Application of ASICs: CITIROC

- Observation campaign @ OFXB in Saint Luc (Valais, Switzerland)
- Trigger rate scan to determine acquisition threshold
Application of ASICs: MUSIC

- The MUSIC ASIC (ICC-UB) intends to tackle large SiPM surfaces by offering a summation path

**Main advantages:**
- Dual gain ➔ Large dynamic range
- Variable gain preamplifier per channel ➔ Gain equalisation
- Pole Zero Cancelation ➔ Shorter pulses
- Summation of channels ➔ Larger pixels readout, trigger output for group of pixels

**Main drawbacks:**
- Current version has only 8 channels
The MUSIC response has been fully simulated by the ICC-UB group and shows great agreement with measurements.

Example with LVR3 6x6 mm²

Example with LCT5 3x3 mm²