Gain Stabilization of SiPMs and Afterpulsing

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Introduction

- The gain of SiPMs increases with bias voltage $V_{bias}$ and decreases with temperature $T$.

- To operate SiPMs at stable gain, $V_{bias}$ can be readjusted to compensate for $T$ changes.

- This requires the knowledge of $dV/dT$, which is obtained from measurements of $G$ vs $V_b$ for different $T$ to extract $dG/dV$ and $dG/dT$ and in turn $dV/dT$.

- Gain stability is important for large detector arrays such as an analog hadron calorimeter for ILC detector.

- We tested this procedure in a climate chamber at CERN:
  1. For each of 30 SiPMs we measured $G$ vs $V_b$ for different $T$ to extract $dV_b/dT$.
  2. We performed gain stabilization of 30 SiPMs from Hamamatsu, KETEK & CPTA, stabilizing 4 SiPMs simultaneously with one $dV/dT$ compensation value.

- Goal: achieve stable gain if $\Delta G/G < \pm 0.5\%$ in 20°-30°C range.
Temperature Measurements

- We shine blue LED light via optical fibers on each SiPM.
- At a rate of 10kHz, the light is pulsed using sinusoidal pulse above a fixed threshold; signal is 3.4 ns wide.
- Each signal of the 4 SiPMs is recorded with a 12 bit digital scope after amplification by a 2-stage preamp.
- Hamamatsu & KETEK SiPMs are illuminated directly.
- CPTA sensors are glued to a WLS fiber placed in a groove in a scintillator tile. Light has to pass through the tile and WLS fiber.
- Vary $T$ from 48°-2°C (20°-30°C) in 2.5°C (2°C) steps.
  - $T_{SiPM} = T_{set} \pm 0.5°C$ (ramp up/down); accuracy $\sim \pm 0.2°C$.

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Study of Hamamatsu MPPCs with Trenches

- Waveform and pe spectra of 4 S13360 MPPCs (trenches)

  - S13360-3025 (10103)  
  - S13360-3025 (10104)  
  - S13360-1325 (10143)  
  - S13360-1325 (10144)
We remove a parasitic noise signal caused by a defective light pulse cable.

First, we sample 21 points before the signal waveform starts (8.4 ns).

We fit the distribution with a Gaussian function and define a threshold by $\mu - 3\sigma$.

We select all pedestal distributions that lie above the threshold.

We determine the average and subtract it from all waveforms.
Removing the parasitic noise signal improves the shape of the waveforms.

This, in turn, improves the determination of the peak positions.

We then extract photoelectron spectra using 2 methods:
- Integrate waveform
- Determine minimum of the waveform
Two Methods to Extract Photoelectron Spectra

- We take 50000 waveforms at each \( V_b \) and \( T \) point and store them for offline analysis.
- Integrate each waveform over \( t_2-t_1 \) window → total charge, integer # of pe.
- Determine minimum of waveform amplitude → \( A_{peak} \), typically integer # of pe.

\( t_2 : \text{variable} \)  
\( t_1 : \text{fixed} \)

Hamamatsu 12571-10

CPTA #922

\( G = 0.04718 \pm 0.00010 \)
\( G_{ped} = 0.04780 \pm 0.00007 \)
\( \sigma_1 = 0.00684 \pm 0.00006 \)
\( \sigma_2 = 0.00721 \pm 0.00006 \)
\( \sigma_3 = 0.00740 \pm 0.00007 \)
\( f_{SB} = 0.915 \pm 0.008 \)
\( \chi^2/\text{dof} = 0.954 \)

\( G = 4.901 \pm 0.019 \)
\( G_{ped} = 4.882 \pm 0.010 \)
\( \sigma_1 = 0.356 \pm 0.005 \)
\( \sigma_2 = 0.561 \pm 0.007 \)
\( \sigma_3 = 0.769 \pm 0.021 \)
\( f_{SB} = 0.388 \pm 0.008 \)
\( \chi^2/\text{dof} = 5.776 \)
\( T = 25.40 \degree C \)

Data  
Total fit  
Signal  
Background

T=25\degree C
Gain Determination

- **Gain:** distance between two adjacent photoelectron peaks
- We choose distance between first and second photoelectron peaks
- Distance between pedestal and first photoelectron peak yields the same gain
- We fit the photoelectron spectra extracted from 500000 waveforms with a likelihood function

\[
L = \prod_{i=1}^{50000} \left[ f_s F_{\text{sig}}(w^i) + (1-f_s) F_{\text{bkg}}(w^i) \right]
\]

- We use two different fit models
  - **First model:**
    separate Gaussian \( G_i \) for pedestal, first p.e. & second pe peaks and fractions \( f_{\text{ped}}, f_1 \);
    include background \( F_{\text{bkg}} \) determined by a sensitive nonlinear iterative peak-clipping algorithm (SNIP) available in ROOT
  - **Second model:**
    fit pedestal and all visible peaks with Gaussians \( G_{\text{ped}} \) and \( G_i \), where all widths and fit fractions are kept as free parameters, use no background pdf
Use first fit model for bias voltage scans of all SiPMs and gain stability tests of Hamamatsu MPPCs with trenches.

Use second fit model for gain stability tests of all Hamamatsu MPPCs without trenches, all KETEK and CPTA SiPMs, for bias voltage scans of some MPPCs without trenches.

- **First fit model**
  - Hamamatsu S12571

- **Second fit model**
  - Hamamatsu B1

Second fit model yields poor fits without modeling of tails on right-hand side.

- **First fit model**
  - Hamamatsu S13360 with fit model 1

- **Second fit model**
  - Hamamatsu S13360 with fit model 2

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Typically, we explore the 2°C-48°C temperature range.

At fixed temperature, we measure $G$ vs $V_b$ at each point we take 50k waveforms.

The $G$ vs $V_b$ dependence is linear for all $T$, with similar slopes.

Except for low overvoltages $V_o$, all gains show linear dependence on $V_o$ independent of $T$.
For each temperature point, we perform a linear fit for $G$ vs $V_b$ to extract
- breakdown voltage
- $dG/dV$

Breakdown voltage increases linearly with $T \rightarrow dV_b/dT$

$dG/dV \sim C$, for some SIPMS it shows a clear linear $T$ dependence

Fit $dG/dV_b$ vs $T$ with linear functions but only use constant term
$\Rightarrow$ variation from constant is $<3\%$

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For fixed $V_b$, we plot $G$ vs $T \Rightarrow \frac{dG}{dT}$

Fit $\frac{dG}{dT}$ vs $V_b$ with linear functions, use only constant term

$\Rightarrow$ variation from constant is $<3$

We extract $\frac{dV}{dT}$ from simultaneous fit of the gain to $V_b$ and $T$

$$V_0 = V_{\text{nom}}(T_0) + \frac{dV_b}{dT}(T - T_0) \quad \& \quad G = G(V_0, T_0) + \frac{dG}{dV_b}(V - V_0)$$

Fit yields: $\frac{dV}{dT} = (59.1 \pm 0.1) \text{ mV/°C}$

From the breakdown voltage $V_{\text{break}}$ vs $T$

we extract $\frac{dV}{dT} = 58.7 \pm 0.3 \text{ mV/°C}$

For stabilization of Hamamatsu type A MPPCs we used $\frac{dV}{dT} = 59.0 \text{ mV/°C}$

$G_{\text{a.u.}}$ vs $T$ [Hamamatsu A1-20]

$\frac{dG}{dT} = -(2.0274 \pm 0.0033) \times 10^5 \text{/°C}$

$\frac{dV_b}{dT}$ vs $T$

$V_0 = V_{\text{nom}}(T_0) + \frac{dV_b}{dT}(T - T_0)$

$G = G(V_0, T_0) + \frac{dG}{dV_b}(V - V_0)$

$\frac{dG}{dT}$ vs $V_b$
Gain Stabilization: Hamamatsu MPPCs w/o Trenches

- Fit p.e. spectra of all MPPCs without trenches with fit model 2
- All 12 MPPCs satisfy our requirement of $\Delta G/G < \pm 0.5\%$ in $20^\circ - 30^\circ C$ $T$ range
- Some MPPCs satisfy this requirement in the entire $T$ range $2^\circ - 48^\circ C$
Fit photoelectron spectra of all MPPCs with trenches with **fit model 1**

- All 6 MPPCs satisfy our requirement of $\Delta G/G < \pm 0.5\%$ in 20° – 30°C $T$ range
- All LCT4 and some S13360 sensors show stabilization in 2° – 48°C $T$ range
Simultaneous gain stabilization for 4 KETEK SiPMs in two batches: $dV/dT=18.2$ mV/°C

- Fit all photoelectron spectra with fit model 2
- KETEK SiPMs show more complicated $V(T)$ behavior
  - Linear correction is not sufficient
  - Sensors do not function above 30°C
  - $G$ rises (1-18°C); uniform $G$ (18-22°C); $G$ falls off (22-30°C)
- No SiPM satisfies the $<\pm0.5\%$ requirement for $T=20^\circ - 30^\circ$C

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Gain Stabilization of CPTA SiPMs

- CPTA SiPMs are illuminated via scintillator tile
- We adjust $V_b$ with regulator board using $dV/dT=21.2 \text{ mV/°C}$ to stabilize 4 CPTA SiPMs simultaneously
- We test gain stability within $T=2°-48°C$ taking $\geq 18$ samples of 50k waveform samples at each $T$
- The gain is nearly uniform up to 30°C
- SiPMs in ch#2 and ch#4 look fine; ch#1 is noisy, ch#3 changed gain at $T=45°C$ but looks ok
- All 4 SiPMs satisfy our requirement of $>\pm 0.5\%$ within $20°C - 30°C$ $T$ range

Gain vs $T$ Average over 18 points
Look for correlations between operating voltage and measured $dV/dT$ for all SiPMs.

For most SiPMs $dV/dT$ increases linearly with $V_b$.

Exceptions:
- Hamamatsu B type MPPCs
- Hamamatsu MPPCs with trenches
- They have lower $V_b$ for similar $dV/dT$

KETEK & CPTA SiPMs have larger $dV/dT$ spread than Hamamatsu MPPCs without trenches.

**Measured $dV/dT$ Values vs $V_{bias}$**

![Graph showing measured $dV/dT$ values vs $V_{bias}$](attachment:image.png)
We determine the pe spectra from the waveforms in 2 ways
- integrated charge $Q$
- magnitude of the peak $A_{\text{peak}}$

We analyze the scatter plot of $Q$ versus $A_{\text{peak}}$

Signal without afterpulsing lies on the diagonal

Signal with afterpulsing is shifted upwards since waveform is broadened due to delayed secondary signal

Set slope with 2pe & 3pe peaks

Dashed line is chosen to be in valley between the 2 regions $\Rightarrow$ best separation

Redo analysis for region below dashed line
The $dG/dV$ & $dG/dT$ distributions for sample with reduced afterpulsing look similar as those for all data. Within errors get the same fit results. Visually slopes of red lines are the same.
Afterpulsing of LCT4 MPPCs

- Define afterpulsing
  \( R = \text{events above dashed line/all events} \)
- Study \( R \) as a function of \( V_{\text{bias}} \) for each \( T \)
- \( R \) shows rapid increase with \( V_{\text{bias}} \)
- \( R \) shows no explicit \( T \) dependence
  ➡ Spread indicates systememetic effects of procedure

\[ \begin{align*}
\Delta U [\text{V}] \\
R [%] \\
\text{Area}
\end{align*} \]

LCT4#6

LCT4#9

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Conclusions and Outlook

- We successfully completed gain stabilization tests for 30 SiPMs and demonstrated that batches of similar SiPMs can be stabilized with one $dV_b/dT$ compensation value.

- All 18 Hamamatsu MPPCs satisfy the stabilization goal: $\Delta G/G < \pm0.5\%$ for $T=20^\circ C-30^\circ C$.
  - Most MPPCs satisfy $\Delta G/G < \pm0.5\%$ in the extended $T$ range 2°C-48°C.

- Gain stabilization of KETEK SiPMs is more complicated.
  - Range of stabilization is limited to 2°C-30°C $T$ range.
  - No SiPM satisfies our requirement $\Rightarrow$ need individual $dV/dT$ values.

- Gain stabilization of CPTA SiPMs works fine.
  - For all 4 SiPMs, $\Delta G/G < \pm0.5\%$ is satisfied in 20°C-30°C range.

- Afterpulsing does not affect gain stabilization results.

- Afterpulsing strongly depends on overvoltage not temperature.

- Results will be published in JINST.

- In the analog HCAL, $V_b$ adjustment can be implemented on the electronics board $\Rightarrow$ need array of temperature sensors to monitor $T$ adequately in entire AHCAL.
Acknowledgment

- We would like to thank L. Linssen, Ch. Joram, W. Klempt, and D. Dannheim for using the E-lab and for supplying electronic equipment.

- We further would like to thank the team of the climate chamber at CERN for their support.
Backup

Slides
\[ \frac{dG}{dV_b}, \frac{dG}{dT} \& \frac{dV_b}{dT} \text{ Results with Fit Model 1} \]

- For fixed \( T \), measure \( G \) vs \( V_b \) \( \Rightarrow \) \( \frac{dG}{dV_b} \)
- For fixed \( V_b \) plot \( G \) vs \( T \) \( \Rightarrow \) \( \frac{dG}{dT} \)
- Extract all \( \frac{dV_b}{dT} \) for fixed \( T \)& average them
- Do this for each SiPM
- Fit \( \frac{dG}{dV_b} \) and \( \frac{dG}{dT} \) with linear functions, use only constant (slope are small <1%)

\[ \frac{dG}{dV_b} = (46.36 \pm 0.02_{\text{stat}}) \times 10^5/V \]
\[ \frac{dG}{dT} = (2.6775 \pm 0.004) \times 10^5/^{\circ}\text{C} \]
\[ \frac{dV_b}{dT} = (57.8 \pm 0.1_{\text{sys}}) \text{ mV/}^{\circ}\text{C} \]

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We obtain the **same** $dV/dT$ for Hamamatsu A, B & S12571 MPPCs within errors for both fitting strategies.

For KETEK and CPTA SiPMs we have tested the new fitting methodology on one channel so far.

For these two SiPMs, $dV/dT$ values agree within two agree within 2 standard deviations.

We will do the remaining KETEK and CPTA SiPMs soon.
## SiPM Properties

Test 18 Hamamatsu MPPCs (6 w trenches), 8 KETEK SiPMs and 4 CPTA SiPMs

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Use 3 types of MPPCs with trenches
- Two experimental samples (LCT4)
- Two 1.3 × 1.3 mm² sensors
- Two 3 × 3 mm² sensors