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SILICON PHOTOMULTIPLIER GAIN COMPENSATION ALGORITHM IN MULTIDETECTOR MEASUREMENTS

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Abstract

The paper stresses the issue of strong temperature influence on the gain of a Silicon Photomultiplier (SiPM). High sensitivity of the detector to light (single photons) requires stable parameters during measurement, including gain. The paper presents a method of compensating the change of gain caused by temperature variations, by adjusting a suitable voltage bias provided by a precise power module. The methodology of the research takes in account applications with a large number of SiPMs (20 thousand), explains the challenges and presents the results of the gain stabilization algorithm.

Keywords: Silicon photomultiplier, single photons, gain stabilization, temperature influence.

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1. Introduction

The Silicon Photomultiplier (SiPM) is a semiconductor device built as an array of avalanche diodes connected together in parallel. Each element of this array, called a pixel (microcell) consists of a diode and a quenching resistor. A photon falling on the junction of an avalanche diode generates one electron-hole pair. This pair is accelerated in a strong electric field and due to impact ionization produces a large portion of carriers. The total generated charge is called an avalanche. Every photon can stimulate the process of creating an avalanche in a single microcell. What is most important is that each pixel is surrounded by an isolation ring which prevents the avalanche from spreading outside the microcell. A single photon can trigger an avalanche in only one microcell. The total output is the sum of currents from all microcells so it is proportional to the number of photons which have triggered avalanches.

The SiPM operates in the so called Geiger regime, biased about 20% beyond the breakdown voltage. In this regime the total charge of each avalanche is always identical and it always fills the whole capacity of a microcell. Typical gains depend only on the size of pixels. If e.g. two photons fall into arrays of pixels then two avalanches are triggered and the total output signal is twice as high as in the case of one photon. A SiPM is able to detect light on the level of single photons due to high gain (10^6) [1, 2, 3]. The gain of a SiPM is strongly dependent on temperature. SiPMs are used in applications where heat is emitted mainly by other devices. It is hard to control the temperature itself, especially in applications where hundreds or even thousands of detectors are being used. That is why a method of gain stabilization is desired.

In a high electric field carriers crossing the depletion region are transferring part of their energy to optical phonons after passing the mean free path. The mean free path is determining

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the frequency of collisions between an electron and a phonon. It is decreasing with the increase of temperature. In a constant electric field but high temperature, carriers are losing more energy along a given distance to the benefit of the crystal lattice. In these conditions carriers have to pass a greater potential difference in order to have enough energy for electron-hole generation. This effectively increases the breakdown voltage of the junction.

The issue of the impact of temperature on the value of breakdown voltage has to take into account the dependence between breakdown voltage and phonon's mean free path. Moreover, these two parameters are bound by critical electric field and carrier ionization coefficient. The direct relationship between breakdown voltage and temperature can be found in [4, 5]. This leads to the conclusion that with an increase of temperature the breakdown voltage of a SiPM is also increasing.

The main drawback of a SiPM is the existence of dark current. If the temperature of the Silicon Photomultiplier is higher than 0 K, inside the detector, due to vibrations of the lattice, pairs of the electron-hole carriers are created. This is called thermal generation of the carriers. The probability of detecting the photon (detection of the absorption of the photon resulting in the generation of avalanche current) is directly proportional to the value of bias voltage of the detector. The more this voltage exceeds the breakdown voltage of the photodiode, the higher the chance that the avalanche will appear. During the absence of light (lack of photons), high bias voltage enables a single, charged carrier coming from thermal generation in the depletion region to trigger the ionization process resulting in the creation of an avalanche. On the other hand, higher temperature also stimulates the creation of thermally generated avalanches. At room and higher temperatures this effect becomes a challenge that has to be dealt with in order to detect single photons. Nevertheless, this paper does not focus on this issue. The gain stabilization method does not require light detection precision starting from a single photon (very high signal to noise ratio), but only the distinguishability of the number of photons detected.

2. Signals from a Silicon Photomultiplier

Four SiPMs from the Hamamatsu s10362-11-100U series have been used in the research (Serial Numbers: 696, 698, 699 and 700). All measurements have been performed on DAQ built at AGH, Department of Electronics (Fig. 1). The measurement system is equipped with a 1060 nm laser triggered and attenuated by Picosecond's Pulse Generator with a 1 ns pulse duration. Light pulses are converted to a voltage signal using a SiPM. An applied front-end ASIC amplifies the signal from the SiPM and changes it to voltage pulses. The signal coming from the SiPM is proportional to the input light. It is propagating through the ASIC, analog-digital converters and FPGA device respectively. Then these data are saved on PC's hard drive. The system of data acquisition uses 12-bit 40MSPS parallel A-D converters (ADC). They are working with a 40MHz clock and a resolution of 1mV. FPGA controls the flow of data in the system of data acquisition. It accepts data from the ADC and sends them to the Cypress controller connected to the PC. FPGA's internal memory is used for preparing a histogram of the number of avalanches triggered inside the SiPM. The temperature of the SiPM has been measured using a PT100 resistance thermometer which is attached to SiPM's cover. Precision of the readout by a multimeter was equal to $10^{-3}\ \Omega$. LabVIEW software calculates the temperature on the basis of resistance measurements. Based on the temperature and gain compensation parameters of the SiPM (described in Section 3), software calculates the value of voltage that needed to be set on the power module in order to keep the gain of the SiPM stable. The power module enables to bias the SiPM with a precision of 5 mV.

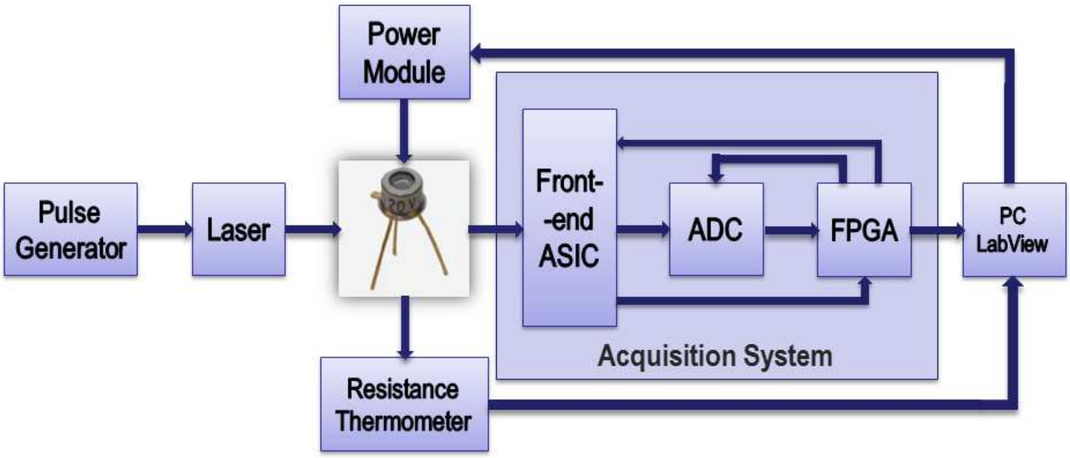

Fig. 1. Data Acquisition System built at AGH [6].

The amplitudes of voltage signals from the SiPM are presented in Fig. 2. Next, they have been converted to the form of a histogram of amplitudes generated by the detector. The histogram shows a sum of Gaussian curves (local maxima). Each curve represents a different number of photons. The height of the first maximum presents how many times light consisting of only one photon has been detected. Its value by far exceeds the value of 30000 because of the additional (dominating) signal representing dark noise. Hence, for the clarity of the plot peak's maximum has not been presented. The second maximum presents how many times light responding to two photons has been detected. The third maximum corresponds to three photons and so on. By determining the integral of the histogram, it would be known what number of photons has been detected during measurement. What is important is that the DAQ is able to detect light, starting from a single photon. By subtracting the values of two following maxima (on the amplitude axis) the amplitude of a single photon can be determined (as it has been shown in Fig. 2). We have called it "Gain per Photon" and based on this value the gain of the SiPM will be described. Such high detection sensitivity is of great importance in low light intensity applications (luminescence, medical, health and nuclear physics applications).

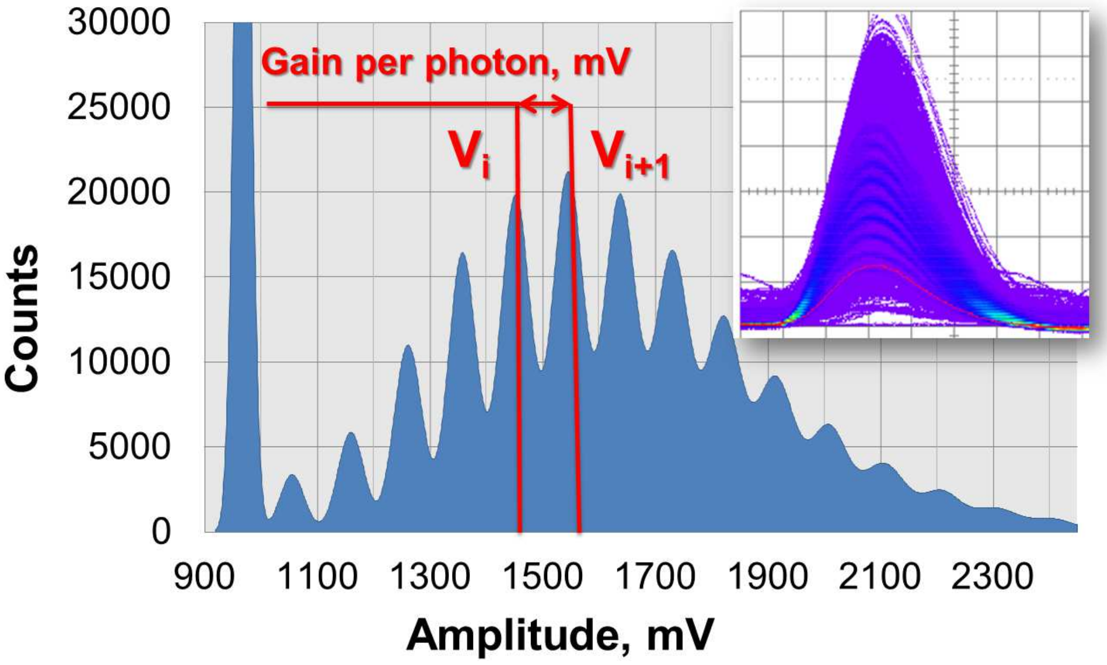

Fig. 2. Signal from a SiPM (amplitude) calculated as a histogram.

3. Gain Stabilization Algorithm

In order to understand why gain compensation is important, it should be described how temperature affects the SiPM's gain. From a set of measurements it has been observed that when temperature increases, the gain decreases (Fig. 3). The dependence is linear and has been presented for various bias values.

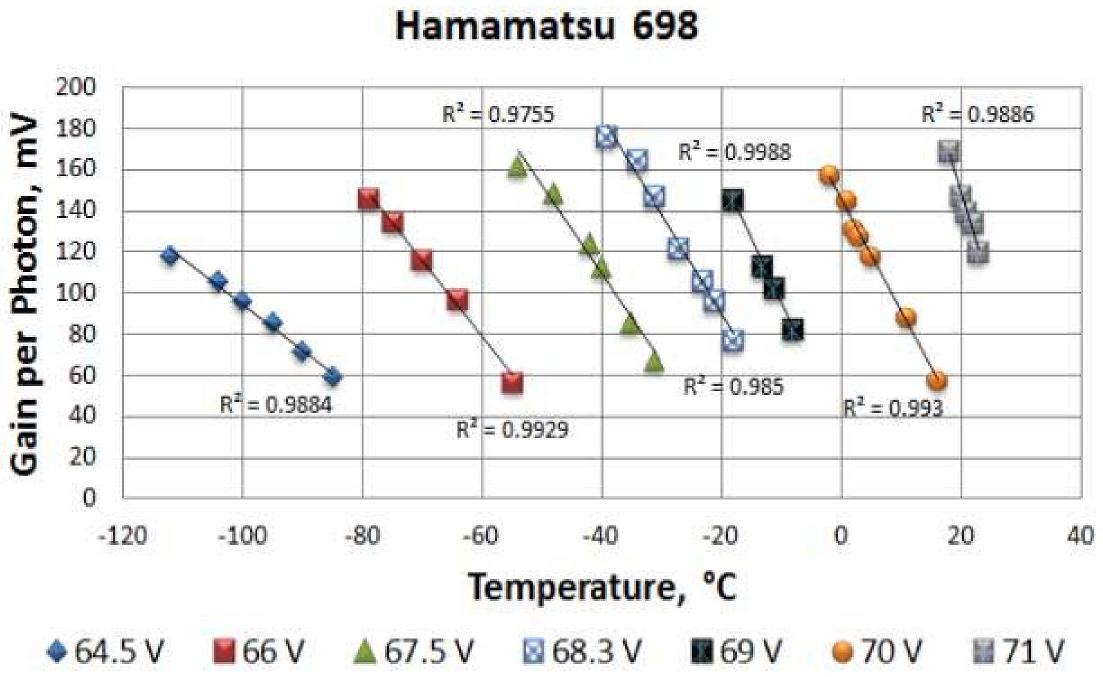

Fig. 3. Gain of a SiPM as a function of temperature.

On the other hand, when the bias is greater, gain rises (Fig. 4). Because both functions are linear (Fig. 3 and Fig. 4), the value of bias could compensate the change in gain caused by temperature fluctuation [7, 8]. Further research confirming the linearity of the dependencies can be found in [7]. During the whole measurement (the range of temperature is 150 °C) the dependencies stayed linear. This wide range could be obtained thanks to the use of liquid nitrogen fumes. The gain stabilization method is intended to be applied in measurement systems operating at temperatures above room temperature, where heat is emitted mainly by surrounding electrical devices. In further research presented in the paper the temperature range has been narrowed down to the required values. The measurements have been taken using Peltier modules and water cooling.

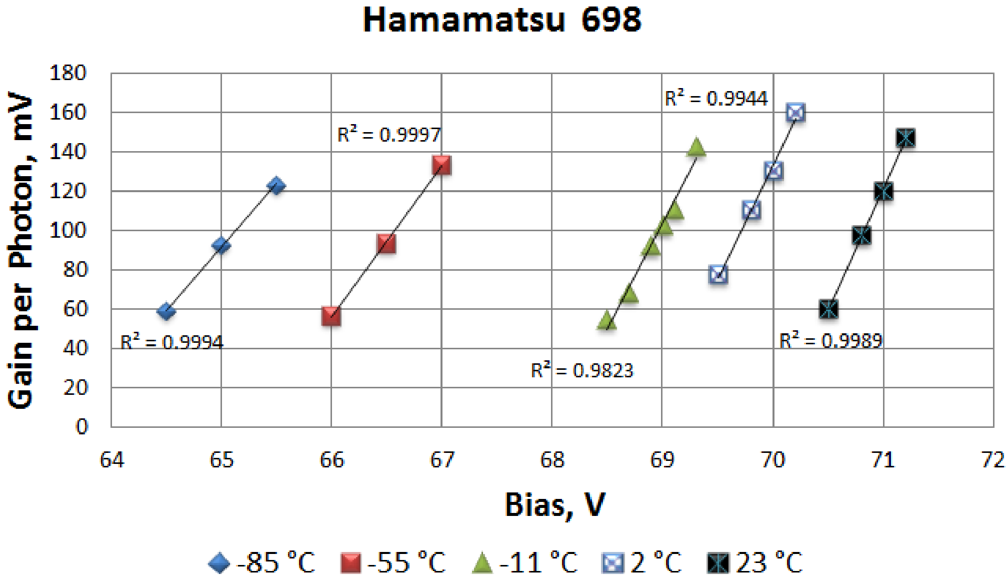

Fig. 4. Gain of a SiPM as a function of bias.

Both functions have been bounded by one linear equation (1).

$$G(V,T) = aV + bT + c\,. \tag{1}$$

Parameters a, b and c have been determined by measuring the same intensity of light at various temperatures and biases. These measurements have been presented in Fig. 5. Each point is a single measurement at specified temperature and bias, resulting in a particular gain. These points form a plane. What is more, linear functions from Fig. 3 and Fig. 4 are presented on a single graph. The easiest way of determining parameters a, b and c is to minimize the weight mean square error between the measured data y_i and the Levenberg-Marquardt best fit function $G(V_i,T_i,a,b,c)$ (2). N is the number of data points.

$$MSE = \sum_{i=0}^{N} \left(y_i - G(V_i,T_i,a,b,c)\right)^2\,. \tag{2}$$

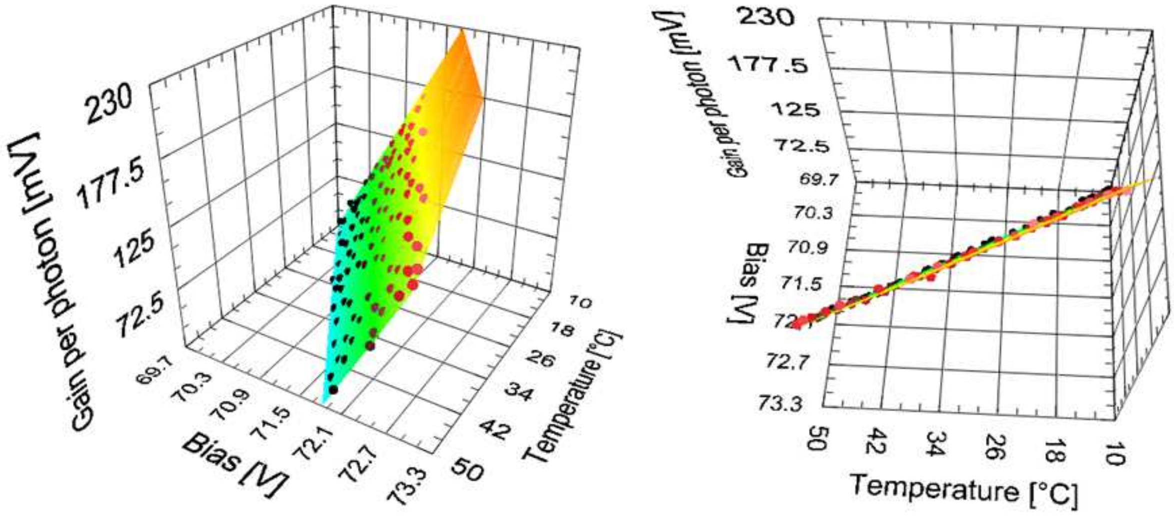

Fig. 5. Set of measurements from a single SiPM. Both graphs present the same data but at a different angle to show that measurements are distributed on a single plane.

By following these steps four sets of parameters a, b and c for each SiPM have been calculated (N≈150, 150 measurements for each set). Each set (for all approaches mentioned below) has been calculated from measurements taken in temperatures ranging from 10 °C to 50 °C. Results are listed in Table 2. Although all detectors are of the same type (Table 1), their parameters are a bit different (Table 2). The values of parameters **a** are much higher than **b**. It shows that a small change in bias influences the value of gain much stronger than a change in temperature. During the preliminary measurements, the power supply used for determining the a, b and c parameters had a resolution of 60 mV. This resolution was too high and the stabilization method did not work properly. A latter power supply (used in obtaining the results in section 4 of this paper) had a resolution of 5 mV. This proved to be enough for the stabilization method which started to work properly. Temperature readout equipment has not been changed since the preliminary measurements.

Table 1. Silicon Photomultipliers used in measurements.

Silicon Photomultiplier	Serial Number	Breakdown Voltage [V]	Number of Microcells	Microcell Gain
Hamamatsu s10362-11-100U	696	69.15	100	2.40×10^6
	698	69.20	100	2.40×10^6
	699	69.32	100	2.40×10^6
	700	69.30	100	2.41×10^6

Table 2. Silicon Photomultipliers' parameters.

Hamamatsu s10362-11-100U	a(V)	b(T)	c	Residue
696	105.27	-5.59	-7261.05	0.074
698	101.33	-5.44	-6983.45	0.057
699	102.38	-5.52	-7058.30	0.078
700	101.46	-5.45	-6991.27	0.091

4. Gain Stabilization Research

4.1. 1st Approach

With parameters a, b and c the user of the SiPM would have to define the value of gain that should be kept stable, measure temperature and calculate proper voltage (from (1)) to bias the detector. This method have been confirmed not only for Hamamatsu but also for a SensL SiPM (Fig. 6). The results show that compensation algorithm works well. For both Hamamatsu the expected value of gain was 110 and for SensL 70. These values have been chosen experimentally so that it would be easy to distinguish following maxima on the histograms for each SiPM individually. In all cases the gain was kept stable during the whole stabilization measurement and the standard deviation of the gain is below 1%.

The gain compensation method will be implemented in various SiPM measurements, especially including international SuperB experiment. One of SuperB detectors (IFR detector) will require about 20 thousand SiPMs connected to scintillators [9]. The IFR detector will register particle showers and it requires a lot of scintillators. Each SiPM will be stabilized separately and it would need individual characterization (determination of parameters a, b and c for each SiPM). It would require a huge amount of time and would be extremely inefficient. To avoid this troublesome situation it needed to be checked if it is required to know the characteristics of all SiPMs. In the following research three approaches have been used. The first has confirmed that the gain compensation algorithm works. The second would present what is the outcome of stabilization when the same parameters are applied to all SiPMs. The final one would or would not confirm that it is not required to know the parameters of all SiPMs in order to stabilize them.

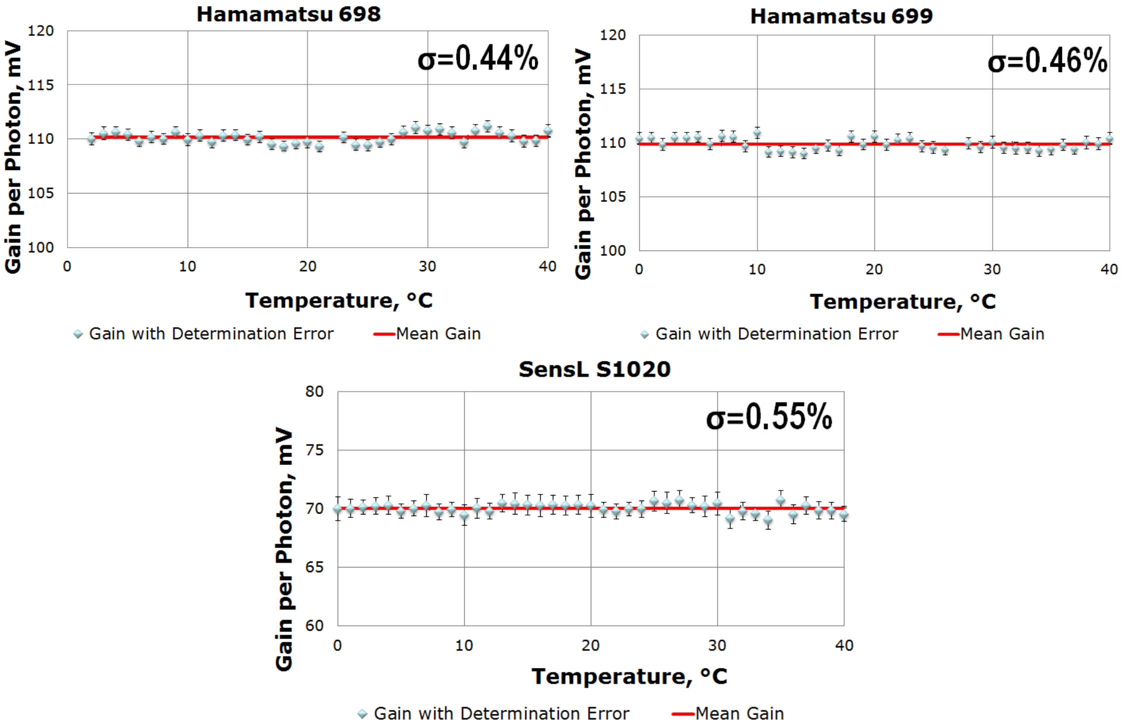

Fig. 6. Gain stabilization results with parameters calculated for each SiPM separately.

The gain compensation method will be implemented in various SiPM measurements, especially including international SuperB experiment. One of SuperB detectors (IFR detector) will require about 20 thousand SiPMs connected to scintillators [9]. The IFR detector will register particle showers and it requires a lot of scintillators. Each SiPM will be stabilized separately and it would need individual characterization (determination of parameters a, b and c for each SiPM). It would require a huge amount of time and would be extremely inefficient. To avoid this troublesome situation it needed to be checked if it is required to know the characteristics of all SiPMs. In the following research three approaches have been used. The first has confirmed that the gain compensation algorithm works. The second would present what is the outcome of stabilization when the same parameters are applied to all SiPMs. The final one would or would not confirm that it is not required to know the parameters of all SiPMs in order to stabilize them.

4.2. 2^{nd} Approach

The next step was to check how well would the stabilization method work for the values of parameters a, b and c that were calculated not directly for the specific SiPMs. The same, averaged parameters to stabilize each SiPM independently have been used (3).

$$a = \frac{a_{696} + a_{698} + a_{699} + a_{700}}{4}, b = \ldots, c = \ldots \,. \qquad (3)$$

Apart from new parameters there are two changes in the measurement approach in comparison to the previous one. Firstly, the new value of gain to be kept stable by the method has been established (from 110 to 100). It has been done to facilitate further calculation. Secondly, the temperature range has been shifted. The stabilization method is intended to work in an environment where temperature is not regulated. That is why a temperature below 10 °C was too low for the discussed purpose. A higher temperature (above 40 °C) seemed more interesting, because in this range it could be tested if dark current would prevent or significantly impede the measurement system from determining the gain of the SiPM (but it did not).

Results have been presented in Fig.7. Standard deviation is still below 1% but for SiPMs number 698 and 700 the mean gain has shifted a bit from the stabilized value of 100. Nevertheless, the outcome is satisfying.

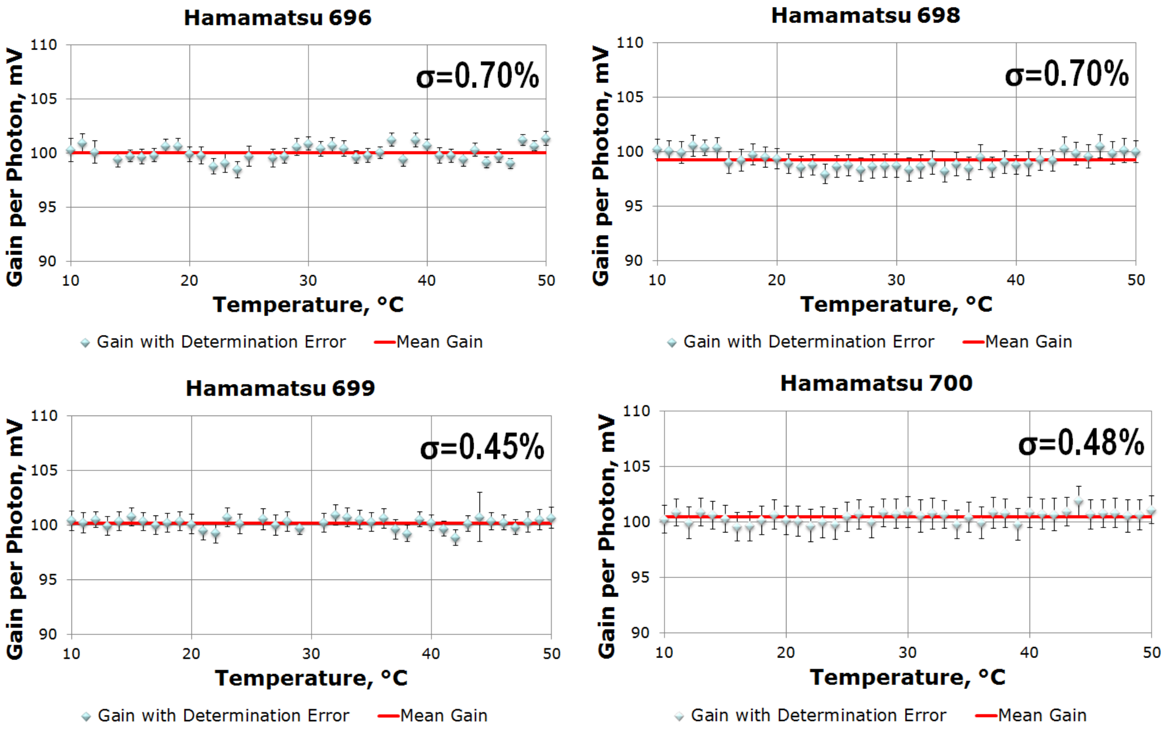

Fig. 7. Gain stabilization results with averaged parameters applied to all SiPMs.

4.3. 3rd Approach

The final research approach is closest to the desired measurement methodology. Having 20 thousand SiPMs it would be desired to characterize only some sample group of detectors (50%, 20% or even less) and use calculated parameters a, b and c to stabilize the gain of each SiPM. To achieve that, a third approach would have to give acceptable results. Each SiPM has been stabilized using averaged parameters calculated from three remaining SiPMs (4).

$$a_{696} = \frac{a_{698} + a_{699} + a_{700}}{3}, b_{696} = \ldots, c_{696} = \ldots \ . \qquad (4)$$

Fig.8 presents the outcome of that approach. Standard deviations exceeded 1% and the offset is noticeable in almost all cases.

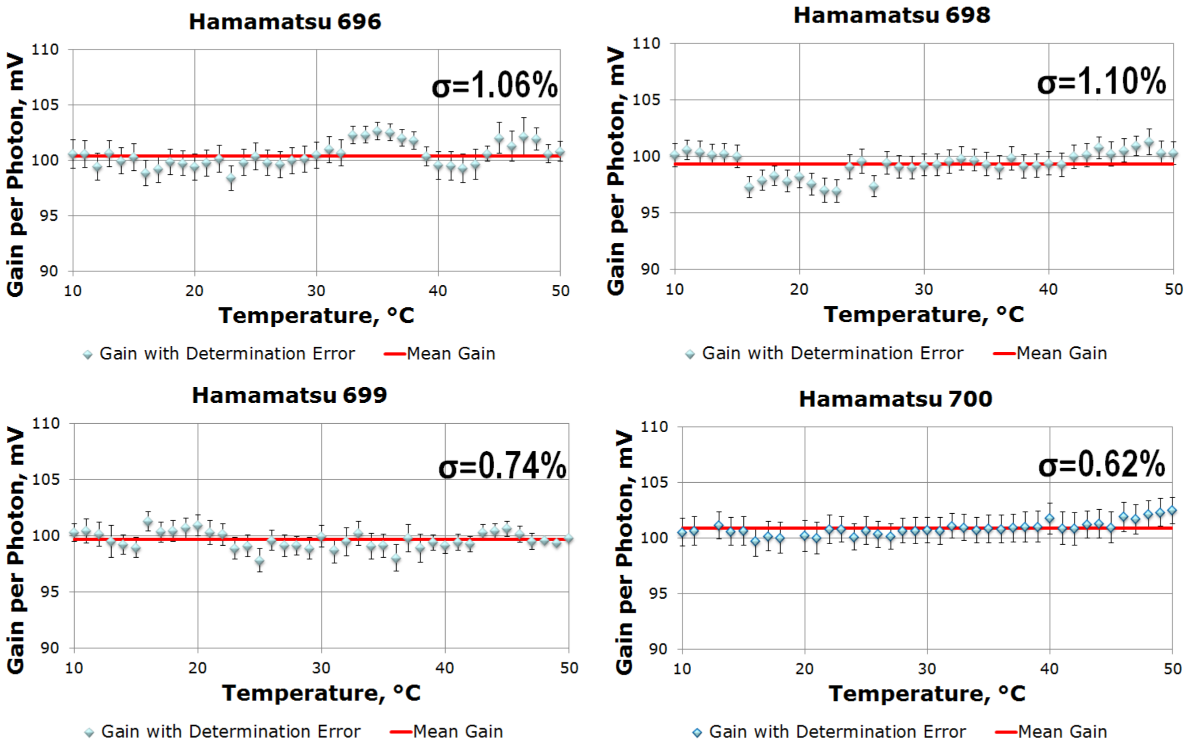

Fig. 8. Gain stabilization results with averaged parameters from three SiPMs applied to the fourth one.

4.4. Comparison of Research Approaches

All measurement results have been assembled in two tables (Table 3 and 4). Hamamatsu 696 has the highest value of the parameter ‘a’, what indicates that it should be the most sensitive to the bias change. Hamamatsu 696 and 700 have not been measured in the first approach domain, that is why some cells in Table 4 are empty.

Table 3. SiPMs’ parameters (1st, 2nd and 3rd Approach).

SIPM:		696	698	699	700
1st Approach	a(V)	105.27	101.33	102.38	101.46
	b(T)	-5.59	-5.44	-5.52	-5.45
	c	-7261.05	-6983.45	-7058.30	-6991.27
2nd Approach	a(V)	102.61			
	b(T)	-5.50			
	c	-7073.52			
3rd Approach	a(V)	101.72	103.04	102.69	102.99
	b(T)	-5.47	-5.52	-5.49	-5.51
	c	-7011.01	-7103.54	-7078.59	-7100.93

Table 4. Comparison of gain stabilization results
(Gain Error - Relative Error between measured and intended gain).

SIPM:		696	698	699	700
1st Approach	Mean Gain, mV	-	110.16	109.90	-
	σ, %	-	0.44	0.46	-
	Gain Error, %	-	0.15	0.09	-
2nd Approach	Mean Gain, mV	100.04	99.24	100.18	100.46
	σ, %	0.70	0.70	0.45	0.48
	Gain Error, %	0.04	0.76	0.18	0.46
3rd Approach	Mean Gain, mV	100.40	99.33	99.63	100.86
	σ, %	1.06	0.67	0.37	0.86
	Gain Error, %	0.40	0.67	0.37	0.86

Over the approaches, for some SiPMs parameters are changing even by 4% (Hamamatsu 696) but it does not impact the gain value so much. On the other hand, the offset between mean gain that is intended to be kept stable and the actual result is changing (it is noticeably higher in the 3rd approach, but the change is still below 1%). Fig. 9 and 10 present the comparison between measured gain stabilization results and simulation results. In simulation the gain was calculated based on (1). Used parameters a, b and c were describing a particular SiPM (Table 3, 1st approach), but the voltage has been calculated from parameters from the current approach (2nd - 2 or 3rd - 3). Simulation shows that Hamamatsu 696 and 698 should have the smallest offset in mean gain. Measurement does not confirm that, because the other two SiPMs give similar results. It is a matter of discussion how low should be both the mean gain offset and standard deviation in order to say that the levels of error are not a concern for the multidetector measurements. From the point of the measurement equipment and stabilization method precision these values vary, but the differences could be significantly influenced by the measurement precision. If the precision of the power supply was better or the resistance thermometer would measure the temperature not on the cover of SiPM but inside the detector, maybe the simulation and stabilization results shown in Fig. 9 and Fig. 10 would fit much better.

In the final analysis all results are very similar. Both the standard deviation and offset are below 2%. The differences between simulation and measurement could be the consequence of the measurement error that is too high for such a precise research.

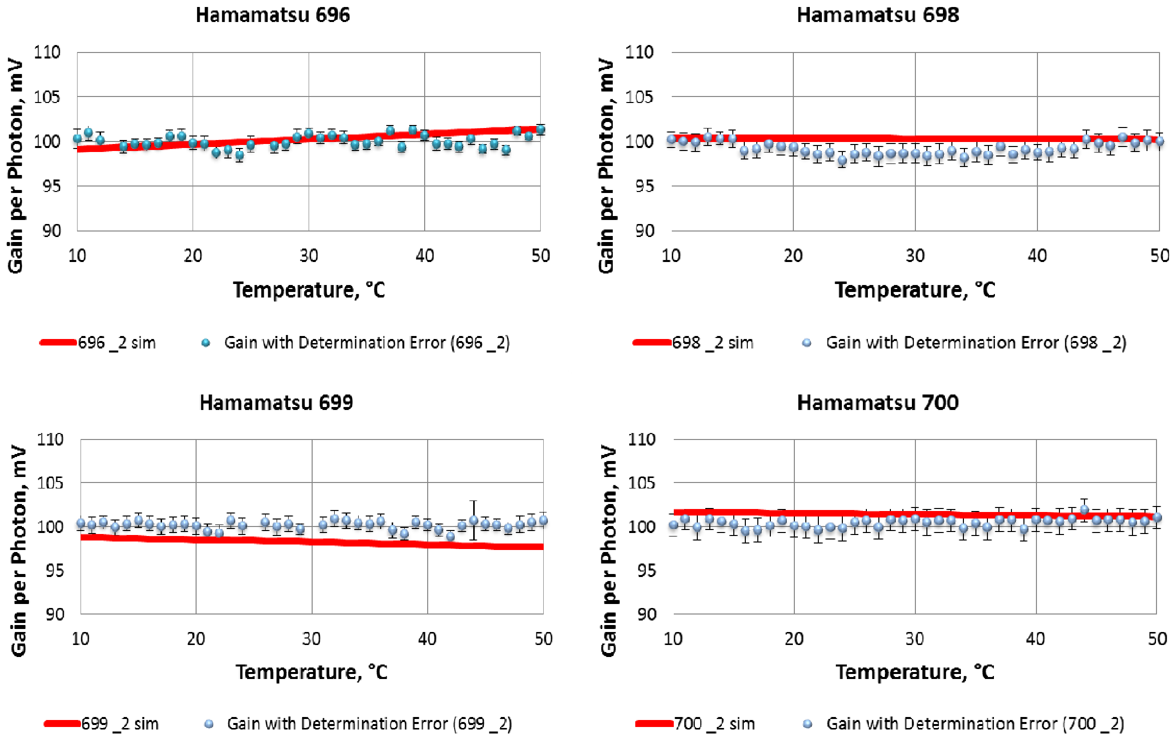

Fig. 9. 2nd approach: Gain stabilization results from measurements compared with simulation results (sim).

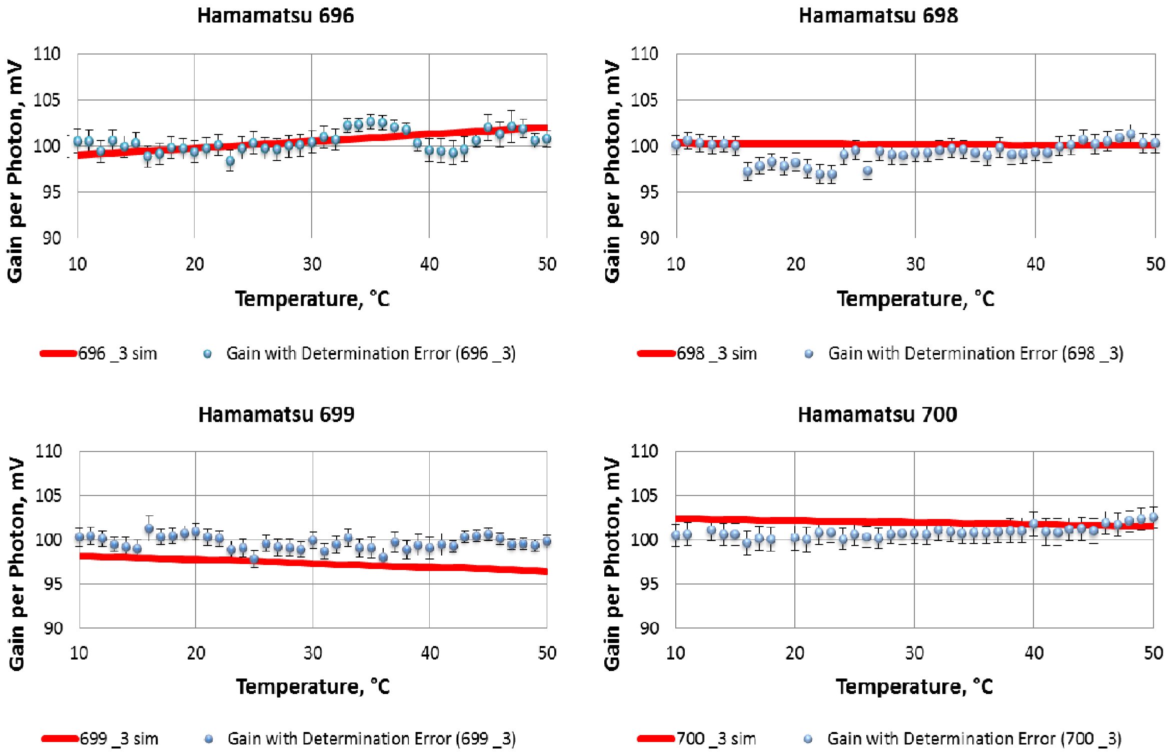

Fig. 10. 3rd approach: Gain stabilization results from measurements compared with simulation results (sim).

5. Conclusions

The paper has shown a possibility of compensating the change of the gain caused by temperature variations by adjusting a suitable bias. It has been confirmed that this method works very well. Moreover, the research has shown that within a group of the same detector model, dependencies between gain, bias and temperature of SiPMs are a bit different. Further tests using various research approaches have indicated that it is not required to know the characteristics of each and every SiPM in order to have its gain well stabilized. Transitions from approach to approach (1^{st} -> 2^{nd} -> 3^{rd}) worsen the results, but they are still very good (below 2%). We can use few sample SiPMs, calculate a set of parameters and then use these parameters for a larger group of SiPMs and the outcome still would be satisfying.

Acknowledgment

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