A handy method to monitor outputs from a pulsed light source and its application to photomultiplier's rate effect studies

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Abstract

In order to study photomultiplier's short-term gain stability at high counting rate, we constructed an LED pulsed light source and its output monitor system. For the monitor system, we employed a photon counting method using a photomultiplier as a monitor photon detector. It is found that the method offers a simple way to monitor outputs from a pulsed light source and that, together with an LED light source, it provides a handy way to investigate photomultiplier's rate effects.

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1 Introduction

In high energy physics experiments, photomultipliers are popular devices used as a light-to-charge transducer. Short-term instability (rate effect) of photomultiplier's gain has been a well-known phenomenon [1], which poses one of the major problems to realize good detector performance. For photomultipliers used in our trigger counter [4], stability was one of the major concerns. Roughly speaking, gain stability within $\pm 10\%$ was required up to the counting rate of a few MHz. More detailed accounts will be given in § 4.2.

In order to investigate photomultiplier's gain change, a stable pulsed light source and/or an output light monitor system were needed. Considering pulse rate involved and handiness, the only light source available was LED. However, LED light outputs might vary substantially at a repetition rate of a MHz region. This motivated us to develop a light monitor system, which was suitable to a pulsed light source lit at the repetition rate of MHz or higher. Needed accuracy for our particular application was a few %. We employed a photon counting method for this purpose. We describe the results of studies on the LED light source and its monitor system in the following sections. This report is organized as follows: in § 2 the principle of the photon counting method is described. The experimental setup and the results of test measurements are shown in § 3 and § 4, respectively. The section 5 summarizes our studies.

2 Principle of the Method

Fig. 1 shows a schematic diagram which illustrates our method. A photomultiplier under test, placed in front of a pulsed LED, receives most of the light output. We sample a very small portion of the lights and inject it to a monitor

[4] The trigger counter was used in an experiment (KEK-E162) which searched for rare K_L decay modes such as $K_L \to \pi^+\pi^- e^+ e^-$ [2].

photon detector. Let η_{samp} denotes the sampling fraction of photons; it mainly depends on geometrical factors such as the distance between the light source and detector, and, if exist, an aperture and attenuation filters between them. We regard this fraction to be practically constant during the course of a measurement. The expected number of photons per pulse detected by the monitor detector is given by $\langle n \rangle = \langle N_{LED} \rangle \cdot \eta_{samp} \cdot \eta_{det}$, where $\langle N_{LED} \rangle$ represents the average number of photons per pulse emitted by LED, and η_{det} the monitor's detection efficiency. The probability distribution for n is given by the Poisson distribution. In this method we adjust $\langle n \rangle$, the average number of photons per pulse, to be much less than unity. This can be done at will by changing, for example, aperture size or attenuation filters. Since the probability to detect one or more photons per pulse is given by

$$P(n \geq 1) = 1 - e^{-\langle n \rangle},$$

$\langle n \rangle$ can be represented by

$$\langle n \rangle = -\log\{1 - P(n \geq 1)\}.$$

We can monitor $\langle n \rangle$ by measuring $P(n \geq 1)$, and thus the average LED light output assuming $\eta_{samp} \cdot \eta_{det}$ to be constant. Here an important feature required for the monitor photon detector is capability of discriminating the single photon signal from background noise. In our actual setup we used a photomultiplier as a monitor detector. As described in the following section in detail, we could distinguish clearly a single photoelectron peak from a pedestal [5]. We measured the counts in which outputs from the monitor photomultiplier exceeded some prescribed level set between the pedestal and single photoelectron peak. Then $P(n \geq 1)$ was given by the counts divided by the total number of pulses which triggered the LED light source.

[5] In some photon detectors like a photomultiplier, we actually count photoelectrons instead of photons. We use these two words interchangeably when no confusion occurs.

The principal advantages of the method are the followings:

(i) As long as the single photon signal can be discriminated from background noise, small gain variation of a monitor photon detector itself has almost no effect on $P(n \geq 1)$ and thus $\langle n \rangle$. This is the most important feature in this method. By contrast, if $\langle n \rangle$ is much bigger than one and the monitor photon detector measures the light output every pulse, it is not possible to distinguish the change in the LED output itself from the gain variation in the monitor detector.

(ii) If the peak corresponding to the single photon can be observed, the gain change may be monitored by measuring its peak position. This feature is helpful to demonstrate reliability in the monitor detector.

(iii) The monitor detector must be able to discriminate the single photon from background noise, as mentioned above. However, it is not necessary to resolve single photon from two (or more) photons since the measured quantity is $P(n \geq 1)$. This lessens requirement for the monitor detector.

(iv) The actual counting rate for the monitor detector can be set low by adjusting $\langle n \rangle$ to be much less than unity. We note that monitor detectors are usually more stable at lower counting rates for a fixed gain.

Disadvantages of the method, on the other hand, are that it monitors not instantaneous but average light outputs, and that it takes rather long time to obtain enough statistical accuracy. For example, when an LED is lit at 10 kHz and $\langle n \rangle$ is ~ 0.01, then it takes 100 sec to obtain 10^4 counts, the number of counts needed to reach the statistical accuracy of 1%. It is expected that main source of the systematic errors for the method stems from various backgrounds to the monitor photon detector. It turns out that thermal noises and after-pulses are the two major backgrounds when a photomultiplier is used as a monitor photon detector. We thus studied these backgrounds carefully (see below for the detail).

3 Experimental Setup

As shown in Fig. 2, the system consisted of a light source, a quartz fiber for photon sampling, a monitor photon detector, and a trigger and read-out electronic system. A photomultiplier subject to rate effect studies was placed in front of the light source. A brief description of each component is given below.

3.1 Pulsed light source (LED)

We used a 'blue' LED [3] as a light source. For the present application, it was found advantageous to use blue in two respects. First, the tail of its light output was substantially shorter ($\sim$ 20 nsec) than that of a 'green' LED ($\sim$ 50 nsec) [4] [6]. Secondly, the emission spectrum of the blue LED resembled more to that of the scintillator we used; a desirable property for the photomultiplier gain test.

Fig. 3 shows the LED driver circuit. The circuit provided a constant charge to the LED stored in the capacitor C_{LED}. The discharge was triggered by a differential switch, which in turn initiated by an external NIM pulse. After the discharge, the capacitor C_{LED} was recharged by an external power supply with the charge-up time constant τ of 0.1 μsec.

3.2 Trigger and read-out system

A variable frequency NIM clock generator was used to produce a master pulse. Its output was fed to the LED driver and to a scaler. Output signals from the monitor photon detector, a photomultiplier for the present case, were

[6] Since the number of tested LED types was limited, these observations may not hold for other blue and/or green LEDs.

discriminated and fed into a coincidence circuit. We set the discriminator threshold level at about 1/4 of the single photoelectron peak. The coincidence signal of the discriminator output and the master clock produced a 60-nsec-long gate to a charge sensitive ADC, which integrated the raw signal from the monitor photon detector. The gate signal was also counted by another scaler. Data from the ADC and scalers were read by a computer via a CAMAC system.

3.3 Monitor photon detector

As stated, we used a photomultiplier as a monitor photon detector. Selection of an actual photomultiplier was made by considering (i) single-photoelectron resolution, (ii) thermal noise rate, and (iii) after-pulse rate. We tested the following types of photomultipliers; Hamamatsu R329, R1332, R2165 and R3234 [5]. It was found that backgrounds due to the after-pulse depended strongly upon photomultiplier types, and that, for some of them, they were the source of the most serious systematic errors. We finally chose R3234 from those listed above with an emphasis on this point.

Single-photoelectron resolution Fig. 4 shows the pulse height spectrum obtained with the photomultiplier actually used; the left peak (scaled off) corresponds to a pedestal and the right to the single photoelectron. We defined a signal count as an event above a software cut placed at the bottom of the valley on this spectrum. The actual cut position was 0.4 in units of the single photoelectron, i.e. the ADC counts between the pedestal and single photoelectron peak. It was confirmed that variation of the cut position within a reasonable range from the nominal value resulted a negligible change in the final results [7].

[7] In order to illustrate the effect of the change in the cut position, we take a measurement described in § 4.1 as an example. The maximum change in the normalized

Thermal noise Thermal (random) noises may contribute to a systematic error. We measured the noise rate and found it to be $\sim$ 400 Hz at 15 °C. The background count per pulse is then $\sim$ 400 Hz$\times$60 nsec (ADC gate width) $= 2.4 \times 10^{-5}$. This should be compared with an average signal rate of $\langle n \rangle$. The background is thus severe at small $\langle n \rangle$; however, it is possible to adjust η_{samp} so that $\langle n \rangle$ is much larger than the noise contribution. In our actual measurements (see § 4.2 for an example), the lowest value for $\langle n \rangle$ was chosen to be 0.006. Thus the error due to this noise is negligible ($< 1\%$) [8].

After-pulse An after-pulse is a spurious pulse induced in a photomultiplier by previous pulses [6]. It is induced by positive ion hits on a photocathode which is produced by collisions between electrons and residual gas molecules in the tube. Since original electron currents are initiated by input light, the after-pulse has time and rate correlation with the input light. Let's denote by $\alpha_{a.p}$ the average number of after-pulses per input light which emits single photoelectron. Then, in the worst case, namely when the after-pulse happens to have a complete time correlation with the following signal pulse, $\langle n \rangle$ would increase to $\langle n \rangle (1 + \alpha_{a.p})$. Thus the only way to reduce this error is to choose a photomultiplier with small $\alpha_{a.p}$.

In order to find an appropriate photomultiplier, we measured this quantity $\alpha_{a.p}$. The measurement was done with the same setup shown in Fig. 2 with one minor change; the delay generator started the gate pulse about 200 nsec after the LED light pulse. The gate width determined the time interval to look for the after-pulses. The results are shown in Fig. 5 for the photomultiplier we selected (R3234), together with another type of 2-inch photomultiplier (R2165) for comparison. In the figures, the abscissa represents the integration

photomultiplier gain (i.e. the gain rescaled to 1 at 0.7 MHz) was found to be less than 0.7% when the cut position was varied between 0.3 and 0.5.

[8] The exception was the cross-check measurement described in § 4.1.

period (the gate width) while the ordinate represents the after-pulse probability $\alpha_{a.p}$. As can be seen, the integrated counts saturate around the gate width of 10 μsec. From the results above and similar measurements for the other types of photomultipliers listed above, we concluded that the integration time of 128 μsec was long enough to detect practically all the after-pulses. The selected photomultiplier R3234 has particularly small value ($\alpha_{a.p} \sim 0.001$) [9]. We thus expect the error due to this background is also negligible.

4 Results of Test Measurements

4.1 Cross-check measurement

It is difficult to determine the absolute accuracy of this method experimentally since there is no 'ideal' light source to calibrate with. Nevertheless we wanted to obtain a crude 'estimate' of its accuracy, and thus compared it with one other method.

In place of a test photomultiplier, we set an R329 photomultiplier operated in a diode mode. This was accomplished by keeping the cathode at -300 V while all the other dynodes grounded. The average cathode current was measured by an amplifier and a current monitor. Since there was no electron multiplication involved, the output current was expected to be proportional to the input light even at high rate. At low rate, however, the output was dominated by electronic noise, and the measurement became less accurate. Actually we

[9] We expect that the after-pulse rate depends on, among other things, residual gas pressure of photomultiplier tubes. This means that the quantity $\alpha_{a.p}$ varies from one tube to another within one type of photomultipliers. (In general, old tubes have bigger $\alpha_{a.p}$ due to the increase of residual gas in tubes.) Since the history of the tested tubes was not quite known and the number was limited ($1 \sim 3$ tubes), the selected photomultiplier type may not mean the best type in general. In principle, $\alpha_{a.p}$ may depend on photomultiplier's gain (HV), too. However, very little dependence on the HV was found.

measured the output current produced by the LED light pulse at the repetition rate between 0.7 MHz and 5 MHz [10]. The measured values of the current from R329 were converted to the charge per pulse and then normalized to that at 0.7 MHz. The resultant quantities, namely the normalized LED light outputs per pulse as a function of pulse rate, are displayed in Fig. 6, together with the corresponding quantities obtained with the photon counting method. As seen, they agree fairly well with each other up to 5 MHz. The maximum deviation is found to be about 7%. The origin of the discrepancy is not clear at present [11].

4.2 Example of the stability measurement

In this subsection, we show an example of the gain stability measurement performed with this system. The photomultipliers under test were used in the trigger counter in our experiment [2]. Their short-term stability was one of the major concerns because of the following reasons. The trigger counter was composed of a set of plastic scintillator slabs and was installed in an intense neutral K beam. Scintillation lights from the counter were read by photomultipliers attached at the both ends of the scintillators. We chose Hamamatsu R1398 [5], a photomultiplier with a bialkali photocathode which had a spectral response well matched with an emission spectrum of the scintillator, and a linear focused dynode chain which provided a fast rise time and a good pulse linearity. These properties, together with its cathode diameter (1-1/8″),

[10] As can be seen from the results, the light output from the LED decreased with the repetition rate. A part of the reason could be the long charge-up time constant for the LED capacitor C_{LED} ($1/\tau \sim 9$ MHz). We left it as it was, because we thought it desirable to keep the average cathode current of R329 roughly constant independent of the pulse rate.

[11] For this measurement, the smallest $\langle n \rangle$ was 0.0001 (at 5 MHz). Thus the thermal noise contribution could be as large as 2.4%. If this was the only source of discrepancy between the two sets of the measurement, the discrepancy should become larger as $\langle n \rangle$ decreased. We did not see such behavior; thus we concluded that the thermal noise was not, at least, the main source of the discrepancy.

were well suited to our application. We used an AC-coupled preamplifier and base-line restorer as a part of the read-out circuit. The preamplifier (with $\sim$ 30 db gain) helped to reduce photomultiplier's average anode current while the base-line restorer compensated base-line shifts at high counting rate. If the photomultiplier gains were to be set high to compensate possible gain drop at high counting rate, hit rates would increase by background particles such as neutrons and gammas in the beam. For our experiment (K_L rare decay), these background hits should be avoided as much as possible to reduce trigger rates and to ensure high reconstruction efficiency in off-line analysis. In addition a large pulse would tend to cause a longer dead time for a preamplifier due to saturation, making the counter inefficient. As a consequence the photomultiplier gain should be kept as low as practical while maintaining $\sim$ 100% efficiency for the minimum ionizing particles. This demanded good gain stability (say relative gain change within $\pm$10%) at the expected highest counting rate (i.e., $\sim$ 4 MHz for each photomultiplier).

Fig. 7 shows the result for the R1398 type photomultiplier. It shows the R1398 output divided by $\langle n \rangle$ as a function of the LED pulse rate; the ratio is then rescaled to 1 at 86 kHz. In the measurement, the LED light intensity on R1398 was adjusted to give approximately 100 photoelectrons per pulse independent of the pulse rate, which was approximately equal to the average scintillator light output produced by minimum ionizing particles passing through our trigger counter. We accomplished this by pulsing 7 identical LEDs in turn, thus keeping the effective pulse rate for any individual LED less than 1 MHz [12]. The maximum deviation of the normalized R1398 output from the unity is found to be about 3% in the rage from 86 kHz to 5 MHz. Thus we concluded the photomultiplier, combined with the base used, met our requirements.

We note that the two of the photomultipliers, R3234 (the monitor photon

[12] As can be seen from Fig. 6 the LED light output was roughly constant below 2 MHz.

detector) and R1398, 'see' quite different photons; the former sees mostly single photons with relatively low rates while the latter sees much more intense photons with a rate up to 5 MHz. Thus an accidental cancellation of systematic errors is expected to be uncommon. The result in turn gives good confidence to the monitoring method.

5 Summary and Discussion

In order to study photomultiplier's gain stability at high counting rate, we constructed an LED pulsed light source and its output monitor system. For the monitor system, we employed a photon counting method. It samples a small portion of light output and measures single photon rates with a monitor photon detector. It thus monitors the relative light output from the source. It is virtually insensitive to the gain change of a monitor photon detector because, as long as the discrimination between the signal from background noise is clear, the rate of the single photon count remains constant.

In our actual setup, we used a photomultiplier as a monitor photon detector. Thermal (random) noises and after-pulses were found to be the two main backgrounds. We could make the errors due to these backgrounds sufficiently small ($< 1\%$) by selecting a suitable photomultiplier and a operating condition. We tentatively assign $\sim 7\%$ as an absolute accuracy in this method. This accuracy was estimated by the method described in § 4.1.

Our direct application of this system was to investigate the gain stability of the photomultiplier (R1398) used in our trigger counter. As shown in § 4.2, it was proved that the photomultiplier and base system could satisfy our requirements. At the same time, it is found that the photon counting method offers a simple way to monitor outputs from a pulsed light source. Together with an LED light source, it provides a handy way to investigate photomultiplier's

gain stability at high counting rates.

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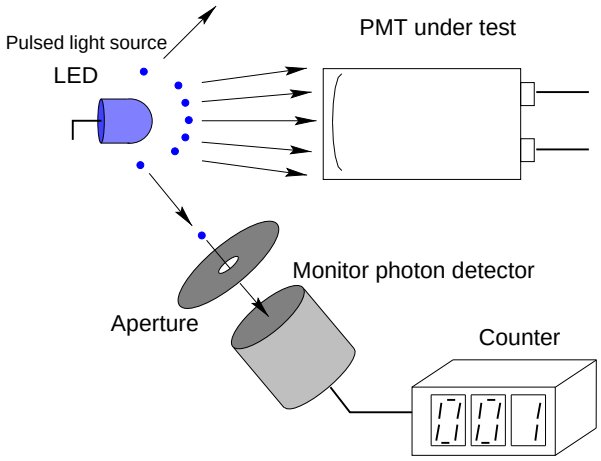

Fig. 1. Schematic diagram showing the principle.

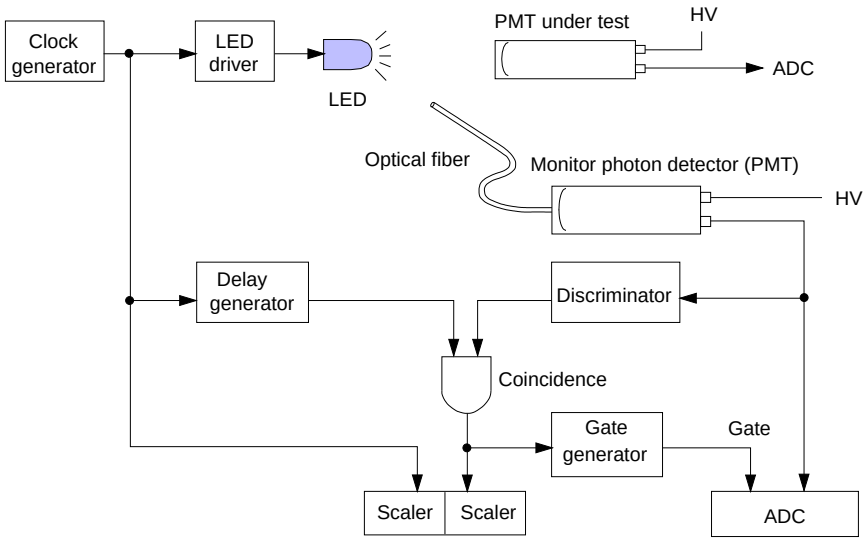

Fig. 2. Schematics of the monitor system.

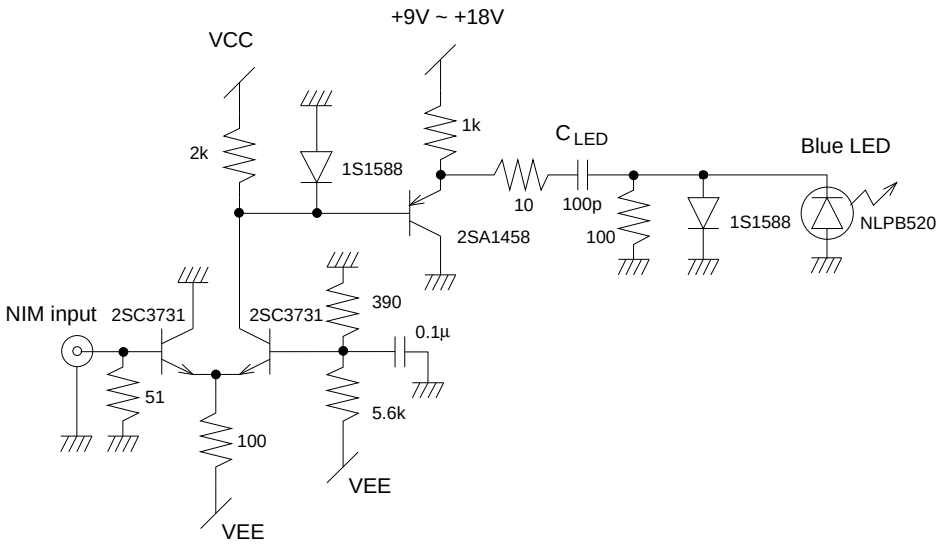

Fig. 3. LED driver circuit.

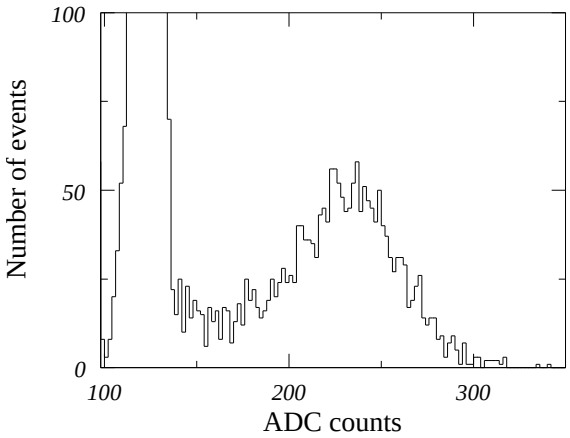

Fig. 4. Pulse height spectrum obtained with R3234.

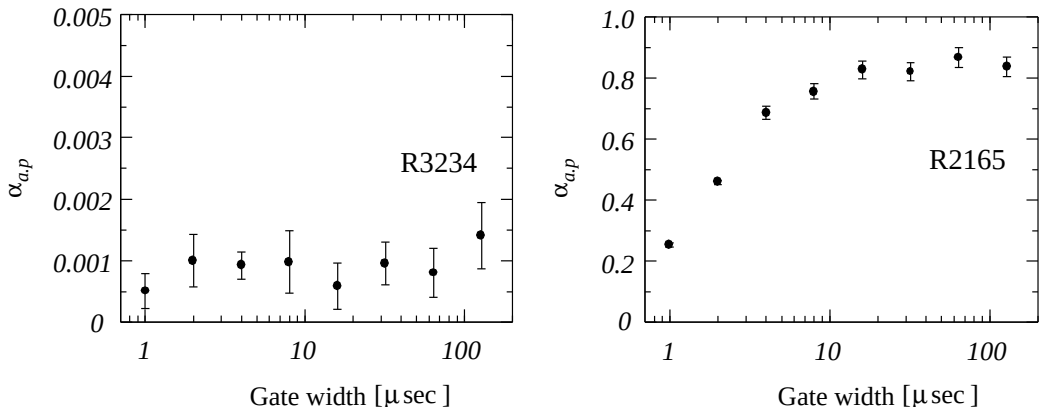

Fig. 5. After-pulse probability $\alpha_{a.p}$ for R3234 (left) and R2165 (right).

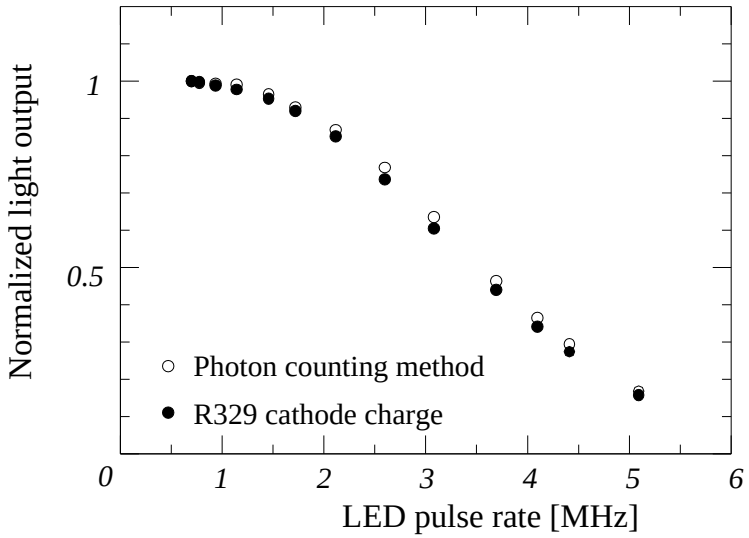

Fig. 6. Normalized LED light outputs measured by R329 and by the photon counting method as a function of pulse rate.

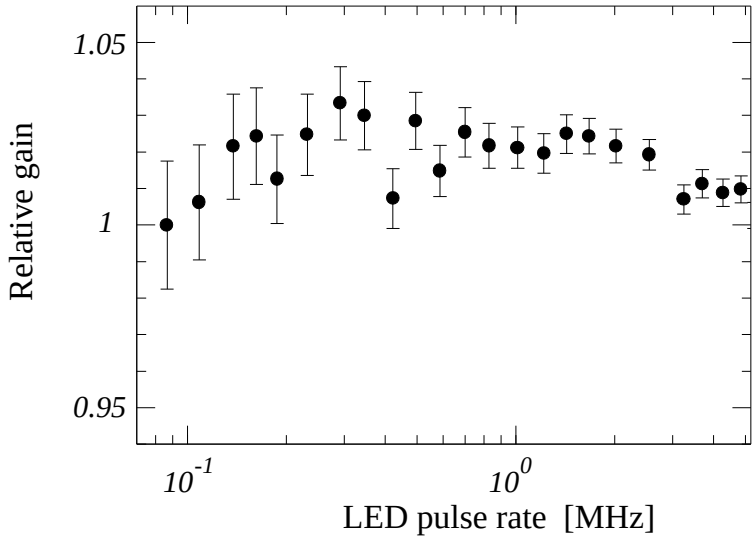

Fig. 7. Gain stability of R1398 as a function of pulse rate.