# PHOTON COUNTING

## Using Photomultiplier Tubes

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# INTRODUCTION

Recently, non-destructive and non-invasive measurement using light is becoming more and more popular in diverse fields including biological, chemical, medical, material analysis, industrial instruments and home appliances. Technologies for detecting low level light are receiving particular attention since they are effective in allowing high precision and high sensitivity measurements without changing the properties of the objects.

Biological and biochemical examinations, for example, use low-light-level measurement for cell qualitative and quanlitative by detecting fluorescence emitted from cells labeled with a fluorescent dye. In clinical testing and medical diagnosis, techniques such as in-vitro assay and immunoassay have become essential for blood analysis, blood cell counting, hormone inspection and diagnosis of cancer and various infectious diseases. These techniques also involve low-light-level measurement such as colorimetry, absorption spectroscopy, fluorescence photometry, and detection of light scattering or luminescence measurement. In RIA (radioimmunoassay) which has been used in immunological examinations using radioisotopes, radiation emitted from a sample is converted into low level light which must be measured with high sensitivity. In addition, fluorescence and luminescence measurements are used for rapid hygienic testing and monitoring processes in inspections for bacteria contamination in water or in food processing.

Photomultiplier tubes, photodiodes and CCD image sensors are widely used as “eyes” for detecting low level light. These detectors convert light into analog electrical signals (current or voltage) in most applications. However, when the light level becomes extremely low so that the incident photons are detected as separate pulses, the single photon counting method using a photomultiplier tube is very effective if the average time intervals between signal pulses are sufficiently wider than the time resolution of the photomultiplier tube. This photon counting method is superior to analog signal measurement in terms of stability, detection efficiency and signal-to-noise ratio.

This technical manual explains how to use photomultiplier tubes in photon counting to perform low-light-level measurement with high sensitivity and high accuracy. This manual also describes the principle of photon counting, its key points and operating circuit configuration, as well as characteristics of photomultiplier tubes and their selection guide.

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# 1. Photon Counting ?

## 1-1 Analog Mode and Digital Mode (Photon Counting Mode)

A photomultiplier tube (PMT) consists of a photocathode, an electron multiplier (composed of several dynodes) and an anode. (See Figure 2 for schematic construction.) When light enters the photocathode of a photomultiplier tube, photoelectrons are emitted from the photocathode. These photoelectrons are multiplied by secondary electron emission through the dynodes and then collected by the anode as an output pulse. In usual applications, these output pulses are not handled as individual pulses but dealt with as an analog current created by a multitude of pulses (so-called analog mode). In this case, a number of photons are incident on the photomultiplier tube per unit time as in ① of Figure 1 and the resulting photoelectrons are emitted from the photocathode as in ②. The photoelectrons multiplied by the dynodes are then derived from the anode as output pulses as in ③. At this point, when the pulse-to-pulse interval is narrower than each pulse width or the signal processing circuit is not fast enough, the actual output pulses overlap each other and become a direct current with shot noise fluctuations as shown in.
In contrast, when the light intensity becomes so low that the incident photons are separated as shown in, the output pulses obtained from the anode are also discrete. This condition is called a single photoelectron state. The number of output pulses is in direct proportion to the amount of incident light and this pulse counting method has advantages in signal-to-noise (S/N) ratio and stability over the analog mode in which an average of all the pulses is made.
This pulse counting technique is known as the photon counting method. Since the detected pulses undergo binary processing for digital counting, the photon counting method is also referred to as the digital mode.

**Figure 1 : Output Pulses from Photomultiplier Tube at Different Light Levels**

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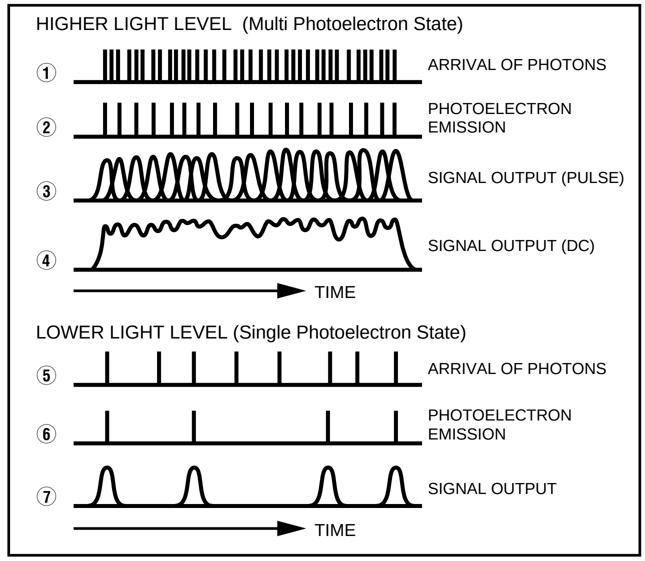
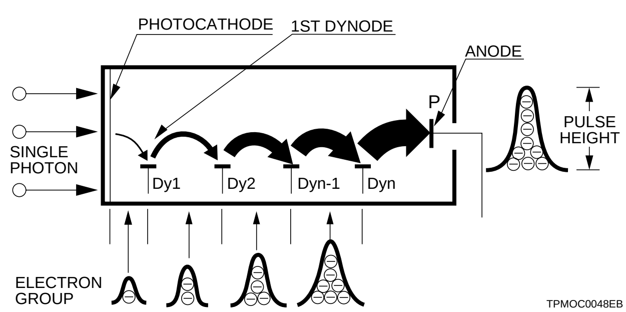



## 1-2 The Principle of Photon Counting

One important factor in photon counting is the quantum efficiency (QE). It is the production probability of photoelectrons being emitted when one photon strikes the photocathode. In a single photoelectron state, the number of emitted photoelectrons (primary electrons) per photon is only 1 or 0. Therefore QE refers to the ratio of the average number of emitted electrons from the photocathode per unit time to the average number of photons incident on the photocathode.

**Figure 2 : Photomultiplier Tube Operation in Single Photoelectron State**

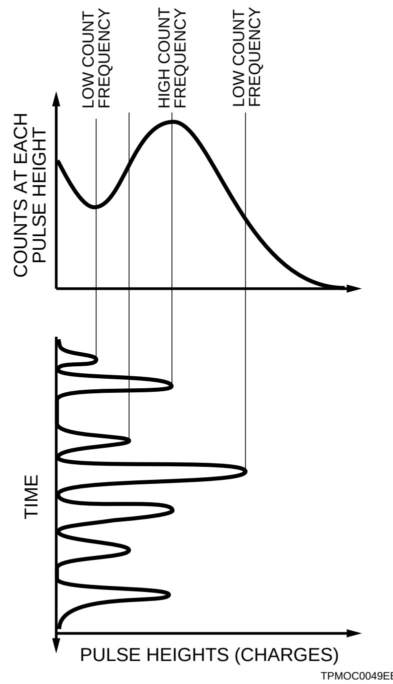


Photoelectrons emitted from the photocathode are accelerated and focused onto the first dynode (Dy1) to produce secondary electrons. However, some of these electrons do not strike the Dy1 or deviate from their normal trajectories, so they are not multiplied properly. This efficiency of collecting photoelectrons is referred to as the collection efficiency (CE). In addition, the ratio of the count value (the number of output pulses) to the number of incident photons is called the detection efficiency or counting efficiency, and is expressed by the following equation :

$$\text{Detection efficiency(\%)} = (Nd/Np) \times 100(\%) = \eta \times \alpha \times 100(\%)$$

where Nd is the count value, Np is the number of incident photons, $\eta$ is the photocathode QE and $\alpha$ is the CE. Although discussed later, detection efficiency also depends on the threshold level that brings the output pulses into a binary signal. Since the number of secondary electrons emitted from the Dy1 varies from several to about 20 in response to one primary electron from the photocathode, they can be treated by Poisson distribution, and the average number of electrons becomes the secondary electoron emission ratio $\delta$. This holds true for multiplication processes in the subsequent dynodes. Accordingly, for a photomultiplier tube having n stages of dynodes, a single photoelectron from the photocathode is multiplied by $\delta^n$ to create a group of electrons and is derived from the anode as an output pulse. In this process, the height of each output pulse obtained at the anode depends on fluctuations in the secondary electron multiplication ratio stated above, so that it differs from pulse to pulse. (Figure 3)
Other reasons why the output pulse height becomes unequal are that gain varies with the position on each dynode and some deviated electrons do not contribute to the normal multiplication process. Figure 3 shows a histogram of the anode pulse heights. This graph is known as the pulse height distribution (PHD).
As illustrated in Figure 3, the photomultiplier tube output exhibits fluctuations in the pulse height and the PHD is obtained by time-integrating these output pulses at different pulse heights. The abscissa of this graph indicates the pulse height that represents the number of electrons contained in one electron group or the pulse voltage (current) produced by that electron group. It is generally expressed in the number of channels used for the abscissa of a multichannel analyzer.

**Figure 3 : Photomultiplier Tube Output and PHD**




## Photomultiplier Tube Output in Single Photoelectron State

The output signal from a photomultiplier tube in the photon counting mode can be calculated as follows:
In the photon counting mode, a single photoelectron $e^-$ (electron charge $1.6 \times 10^{-19}$ coulombs) is emitted from the photocathode. If the photomultiplier tube gain $\mu$ is $5 \times 10^6$, then the anode output charge is given by

$$e \times \mu = 1.6 \times 10^{-19} \times 5 \times 10^6 \text{ (coulombs:C)}$$
$$= 8 \times 10^{-13} \text{ (C)}$$

Here, if the pulse width t (FWHM) of the anode output signal is 10ns, then the output pulse peak current Ip is

$$Ip = e \times \mu \times 1/t \text{ (A)}$$
$$= (8 \times 10^{-13})/(10 \times 10^{-9})$$
$$= 8 \times 10^{-5} \text{ } (\mu A)$$

This means that the anode output pulse width is narrower, we can obtain much higher output peak current. If the load resistance (input impedance of the succeeding amplifier) is 50 ohms, the output pulse peak voltage Vout becomes

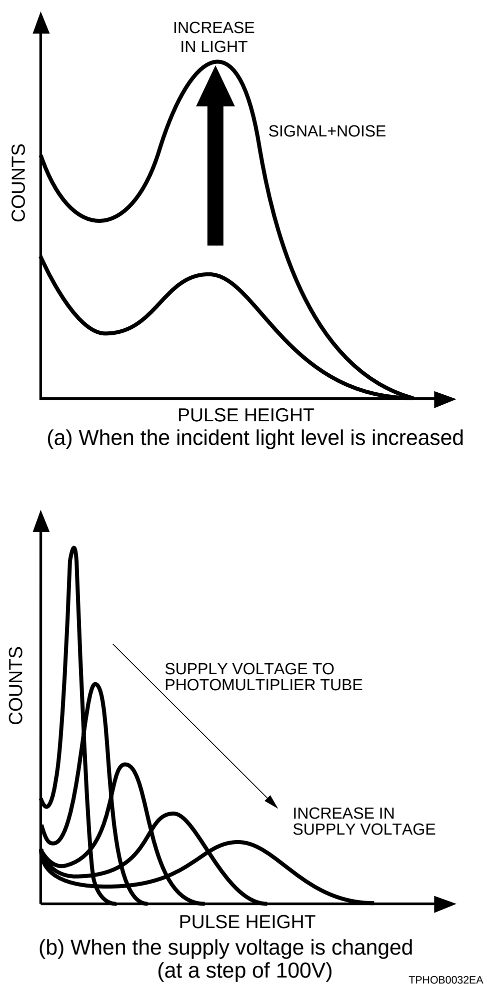
$$Vout = Ip \times 50 \text{ (V)}$$
$$= 4 \text{ (mV)}$$

The photomultiplier tube output in the photon counting mode is extremely small. This requires a photomultiplier tube having a high gain and an amplifier with sufficiently low noise relative to the photomultiplier tube output noise. As a general guide, photomultiplier tubes should have a gain of approximately $1 \times 10^6$ or more.

Figure 4 (a) shows a PHD when the incident light level was increased under single photoelectron conditions, and (b) shows a PHD when the supply voltage was changed.

The ordinate is the frequency of the output pulses that produce a certain height within a given time. Therefore, the distribution varies with the measurement time or the number of incident photons in the upper direction of the ordinate as shown in Figure 4 (a).
As explained above, the abscissa of the PHD represents the pulse height and is proportional to the gain of the photomultiplier tube and becomes a function of the supply voltage of the photomultiplier tube. This means that as the supply voltage V changes, the PHD also shifts along the ordinate, but the total number of counts is almost constant.

**Figure 4 : PHD Characteristics**




(a) When the incident light level is increased

(b) When the supply voltage is changed (at a step of 100V)

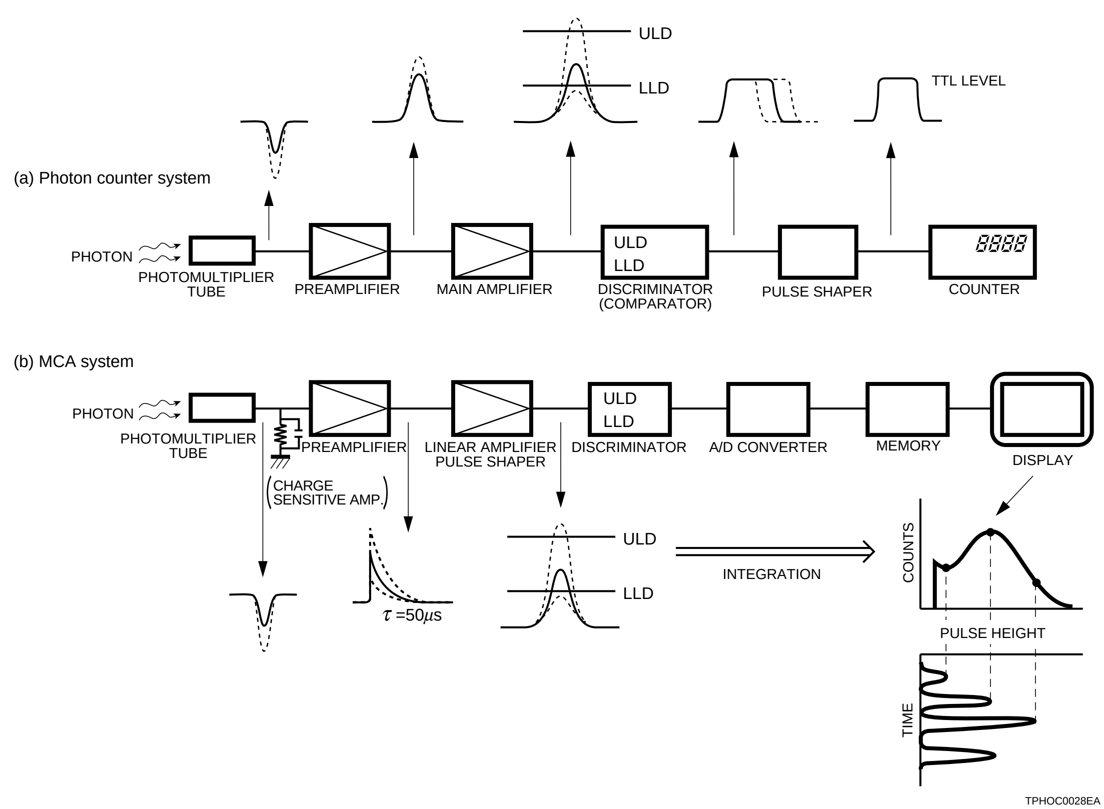
# 2. Operation and Characteristics of Photon Counting

This section describes circuit configurations for use in photon counting and the basic characteristics of photon counting measurements.

## 2-1 Photon Counter and Multichannel Pulse Height Analyzer (MCA)

There are two methods of signal processing in photon counting: one uses a photon counter and the other a multichannel pulse height analyzer (MCA). Figure 5 shows the circuit configuration of each method and the pulse shapes obtained from each circuit system.
In the photon counter system of Figure 5 (a), the output pulses from the photomultiplier tube are amplified by the preamplifier and if necessary, further amplified by the main amplifier. These amplified pulses are then directed into the discriminator in which a comparator IC is usually used. The discriminator compares the input pulses with the preset reference voltage to divide them into two groups: one group is lower and the other is higher than the reference voltage. The lower pulses are eliminated by the lower level discriminator (LLD) and the higher pulses are eliminated by the upper level discriminator (ULD). The output of the comparator takes place at a constant level (usually a TTL level from 0 to 5V, or an ECL level of –0.9 to –1.7V for high-speed output). The pulse shaper cleans the pulses allowing counters to count the discriminated pulses.
In contrast, in the MCA system shown in Figure 5 (b), the output pulses from the photomultiplier tube are generally integrated through a charge-sensitive amplifier, amplified and shaped with the linear amplifier. These pulses are discriminated according to their heights by the discriminator and are then converted from analog to digital. They are finally accumulated in the memory and displayed on the screen. This system is able to output pulse height information and frequency (the number of counts) simultaneously, as shown in the figure.
The photon counter system is used to measure the number of output pulses from the photomultiplier tube corresponding to incident photons, while the MCA system is used to measure the height of each output pulse and the number of output pulses simultaneously. The former system is superior in counting speed and therefore used for general-purpose applications. The MCA system has the disadvantage in not being able to measure high counts, it is used for applications where pulse height analysis is required such as in obtaining the average amount of light per event.

**Figure 5 : Typical Photon Counting Systems**



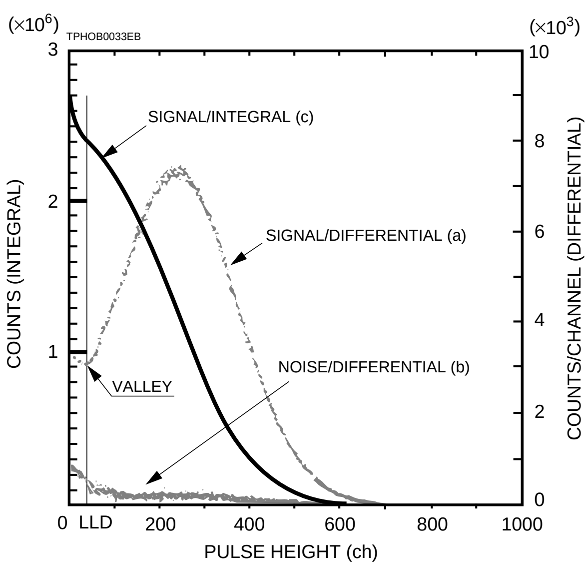
# 2-2 Basic Characteristics in Photon Counting

## (1) Pulse Height Distribution (PHD) and Plateau Characteristics

Figure 6 shows PHD of a photomultiplier tube, obtained with the MCA. The curve (a) is the output when signal light is incident on the photomultiplier tube, while the curve (b) represents the noise when signal light is removed. The major noise component results from thermionic emission from the photocathode and dynodes. The PHD of such noise usually appears on the lower pulse height side. These PHD are the so-called differential curves and the lower level discrimination (LLD) is usually set at the valley of the curve (a). To increase detection efficiency, it is advantageous to set the LLD at a lower position, but this is also accompanied by a noise increase. Therefore the discrimination level must be selected according to the application.

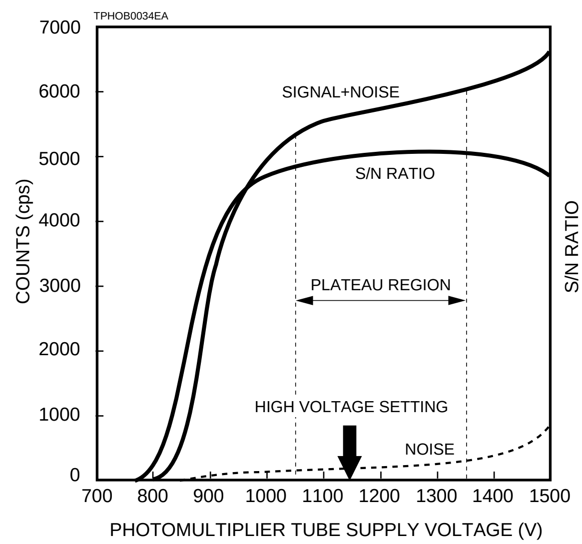
In contrast to the curve (a) in Figure 6, the curve (c) shows an integration curve in which the total number of pulses higher than a certain discrimination level have been plotted while changing the discrimination level. Since this integration curve (c) has an interrelation with the differential curve (a), the proper discrimination levels can be set in the photon counter system without using a MCA, by obtaining the integration curve instead.

**Figure 6 : Differential and Integral Displays of PHD**




The LLD stated above corresponds to a pulse height on a gentle slope portion in the integration curve. But this is not so distinct from other portions, making it difficult to determine the LLD. Another method using plateau characteristics is more commonly used. By counting the number of pulses with the LLD fixed while varying the supply voltage to the photomultiplier tube, a curve similar to the "SIGNAL+NOISE" curve shown in Figure 7 can be plotted. The exponential relationship between the supply voltage and the output pulse height of the photomultiplier tube makes the slope of this curve gentle, which makes the supply voltage setting easier. These curves are known as the plateau characteristics. The supply voltage for the photomultiplier tube should be set within this plateau region. It is also clear that plotting the signal-to-noise (S/N) ratio shows a plateau region in the same supply voltage range. (See Section 3-8 (2).)

**Figure 7 : Plateau Characteristics**



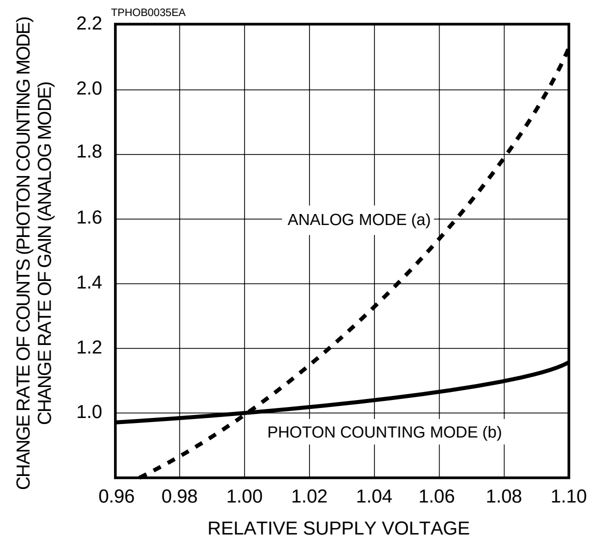
## (2) Output Instability vs. Variations in Photomultiplier Tube Gain

If the photomultiplier tube gain varies for some reason (for example, a change in supply voltage or fluctuations in the ambient temperature, etc.), the output current of the photomultiplier tube is also affected and exhibits variations. In the analog mode the output current (or gain) of the photomultiplier tube changes with variations in the supply voltage as shown in Figure 8 (a). In the photon counting mode, the output current changes, but this is significantly smaller than in the analog mode.

By setting the supply voltage in the plateau region as shown in Figure 7, the photon counting mode can minimize changes in the count rate with respect to variations in the supply voltage, without sacrificing the signal-to-noise (S/N) ratio. This means that the photon counting mode ensures high stability even when the gain of the photomultiplier tube varies, as the gain is a function of the supply voltage.

For the above reasons, the photon counting mode offers several times higher stability than the analog mode versus variations in the operating conditions.

**Figuer 8 : Output Variation vs. Supply Voltage**

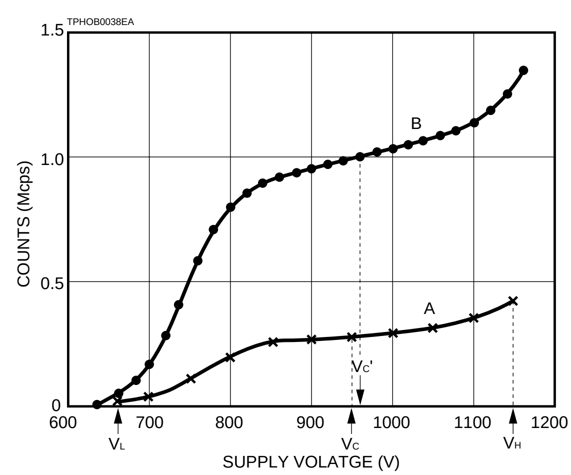



## How to Obtain the Plateau

Speaking it in a broad sence, the integration curve explained in Section 2-2 (1) has plateau characteristics. Here we describe a more common method for obtaining the plateau characteristics by varying the photomultiplier tube supply voltage.

1. Set up the photomultiplier tube, photon counter, high-voltage power supply, and dark box, light source, etc, required to perform photon counting. Preferably, the photomultiplier tube should be stored in the dark box for about one hour after the setup has been completed.
2. Set the discrimination level (LLD) according to the instruction manual for the photon counter being used. Then allow a very small amount of light to strike the photomultiplier tube.
3. Gradually increase the photomultiplier tube supply voltage starting from about 500V. When the photon counter begins to count any signal, halt there and make a plot of the supply voltage ($V_L$) and the counted value at that point, on a graph with the abscissa showing the supply voltage and the ordinate representing the number of counts.
4. Increase the supply voltage with a 50V step until it reaches about 90% ($V_H$) of the maximum supply voltage while making plots on the graph. This will create a curve like "A" shown in Figure 9.
5. With the photomultiplier tube operated at a voltage (Vc) in the middle of the flat portion of curve "A", adjust the light source intensity so that the counted value is set to 10 to 30% of the maximum count rate of the photon counter.
6. Readjust the photomultiplier tube supply voltage to set at $V_L$, then make fine plots while changing the photomultiplier tube supply voltage with a 10 to 20V step. This will be a curve like "B" shown in Figure 9.
7. In the flat range (plateau range) on curve "B", the voltage Vc' at a point where the differential coefficient is smallest (minimum slope) will be the optimum supply voltage.

**Figure 9 : Plotting Plateau characteristics**



## (3) Linearity of Count Rate

The photon counting mode is generally used in very low-light-level regions where the count rate is low, and exhibits good linearity. However, when the amount of incident light becomes large, it is necessary to take the linearity of the count rate into account. The upper limit of the bandwidth of photomultiplier tubes ranges from 30MHz to 300MHz for periodical signal. Therefore, the maximum count rate in the photon counting mode where random signals enter the photomultiplier tube is determined by the type of photomultiplier tube and the time resolution of the signal processing circuit connected to the photomultiplier tube. The time resolution referred to here is defined as the minimum time interval between successive pulses that can be counted as separate pulses.

Figure 10 shows a typical linearity of the count rate obtained from a Hamamatsu H6180-01 Photon Counting Head. As can be seen from the figure, the dynamic range reaches as high as $10^7$ cps. In this case, the linearity of the count rate is limited by the time resolution (pulse pair resolution) of the built-in circuit (18ns).

If we let the measured count rate be n' (cps) and the time resolution be t (seconds), the real count rate n (cps) can be approximated as follows:

$$n = \frac{n'}{1-n't}$$

Figure 11 shows the actual data measured with the H6180-01 Photon Counting Head, along with the corrected data obtained with the above equation. This proves that after making correction, the photon counting mode provides an excellent linearity with a count error of less than 1%, even at a high count rate of $10^7$ cps.

**Figure 10 : Linearity of Count Rate**

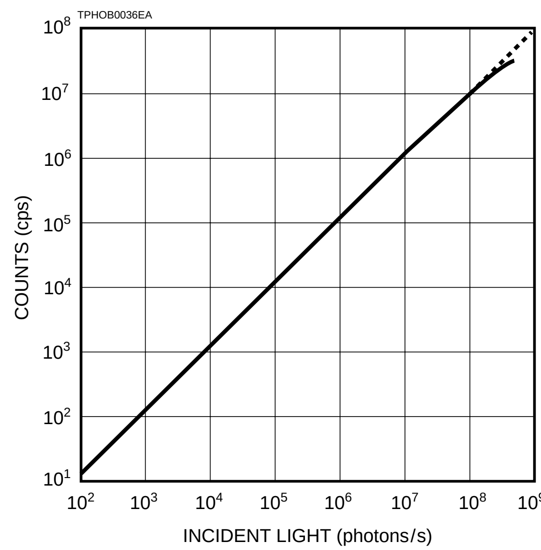
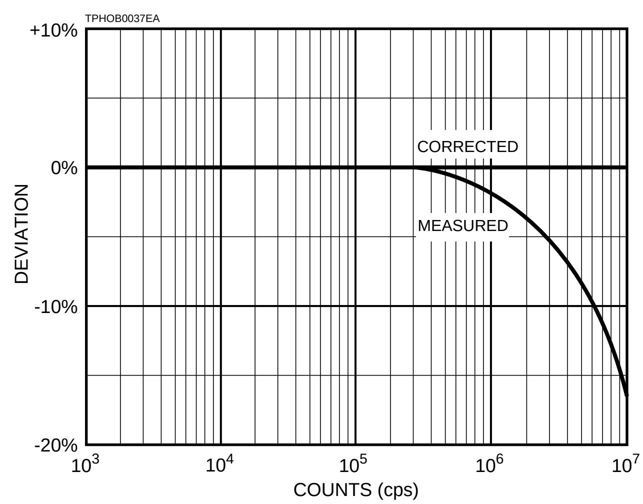



**Figure 11 : Correction of Count Rate Linearity**



# 3. Characteristics of Photomultiplier Tubes

## 3-1 Spectral Response (Quantum Efficiency : QE)

When n number of photons enter the photocathode of a photomultiplier tube, the n × QE number of photoelectrons on average are emitted from the photocathode. The QE depends on the incident light wavelength and so exhibits spectral response.
Figures 12 (a) and (b) show typical spectral response characteristics for various photocathodes and window materials. The spectral response at wavelengths shorter than 350nm is determined by the window material used, as shown in Figure 13.
In general, spectral response characteristics are expressed in terms of cathode radiant sensitivity or QE. The QE and radiant sensitivity have the following relation at a given wavelength.

$$QE = \frac{S \times 1240}{\lambda} \times 100(\%)$$

where S is the cathode radiant sensitivity in amperes per watt (A/W) at the given wavelength $\lambda$ in nanometers.

**Figure 12 : Typical Spectral Response Characteristics**

**Figure 12-1: Transmission Mode Photocathodes**

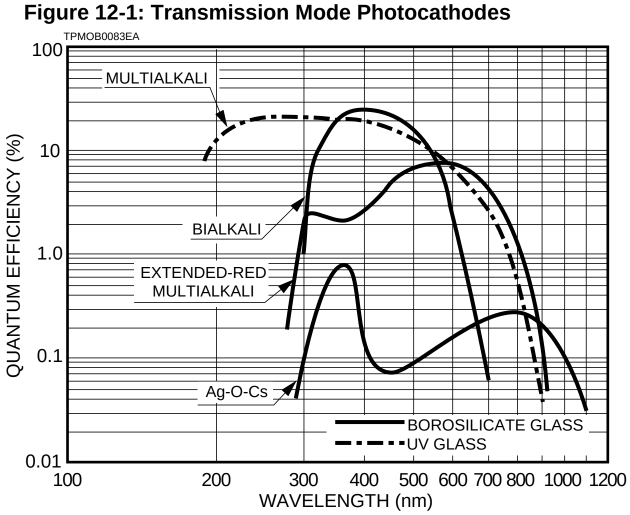



**Figure 12-2: Reflection Mode Photocathodes**

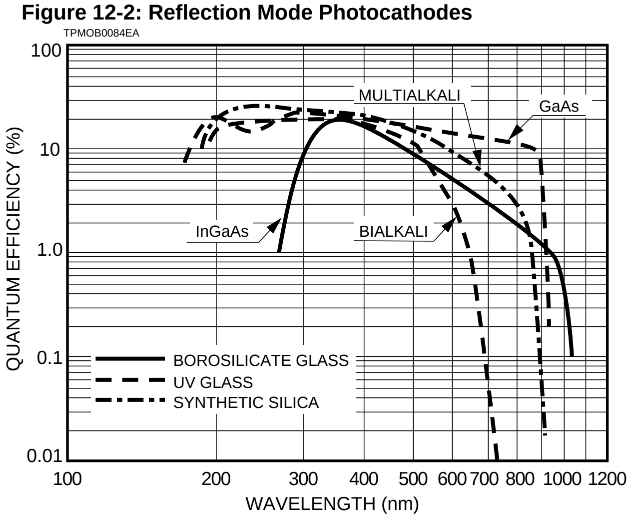
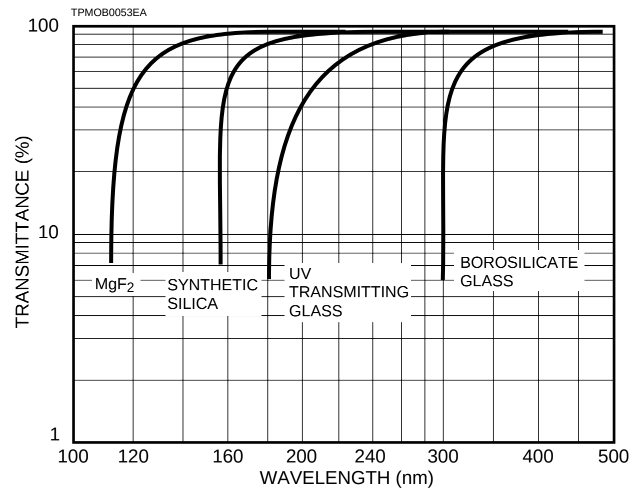



**Figure 13 : Typical Transmittance of Window Material**

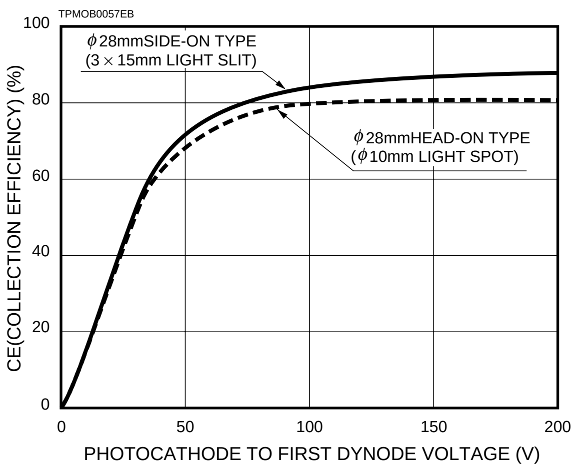



## 3-2 Collection Efficiency (CE)

The CE is the probability in percent, that single photoelectrons emitted from the photocathode can be finally collected at the anode as the output pulses through the multiplication process in the dynodes. In particular, the CE is greatly affected by the probability that the photoelectrons from the photocathode can enter the first dynode. Generally, the CE is from 70 to 90% for head-on photomultiplier tubes and 50 to 70% for side-on photomultiplier tubes at full cathode illumination.
The CE is very important in photon counting measurement. The higher the value of the CE, the smaller the signal loss, thus resulting in more efficient and accurate measurements. The CE is determined by the photocathode shape, dynode structure and voltage distribution for each dynode.
As stated earlier, the ratio of the number of signal pulses obtained at the anode to the number of photons incident on the photocathode is referred to as the detection efficiency or counting efficiency.

Figure 14 shows the relation between the CE and the photocathode to first dynode voltage of 28mm (1-1/8") diameter photomultiplier tubes, measured in the photon counting mode with the discrimination level kept constant and at a small area illumination. As can be seen, the CE sharply varies with at voltages lower than 100V, but becomes saturated and shows little change when the voltage exceeds this. This means that a sufficient voltage should be applied across the photocathode and the first dynode to obtain a stable CE.

**Figure 14 : CE vs. Photocathode to First Dynode Voltage**




## 3-3 Supply Voltage and Gain(Current Amplification)

The output pulse height of a photomultiplier tube varies with the supply voltage, even when the light level is constant. This means that the gain of the photomultiplier tube is a function of the supply voltage. The secondary emission ratio $\delta$ is the function of voltage E between dynodes and is given by

$$\delta = A \cdot E^{\alpha}$$

where A is the constant and $\alpha$ is determined by the structure and material of the electrodes, which usually takes a value of 0.7 to 0.8.

Here, if we let n denote the number of dynodes and assume that the $\delta$ of each dynode is constant, then the change in the gain $\mu$ relative to the supply voltage V is expressed as follows:

$$\mu = \delta^n = (A \cdot E^{\alpha})^n = \left\{A \cdot \left(\frac{V}{n+1}\right)^{\alpha}\right\}^n$$

$$= \frac{A^n}{(n+1)^{\alpha n}} = V^{\alpha n} = K \cdot V^{\alpha n}$$

(K is a constant.)

Since typical photomultiplier tubes have 9 to 12 dynode stages, the output pulse height is proportional to the 6th to 10th power of the supply voltage. The curve previously shown in Figure 8 for the analog mode represents this characteristic.

**Figure 15 : Gain vs. Supply Voltage**

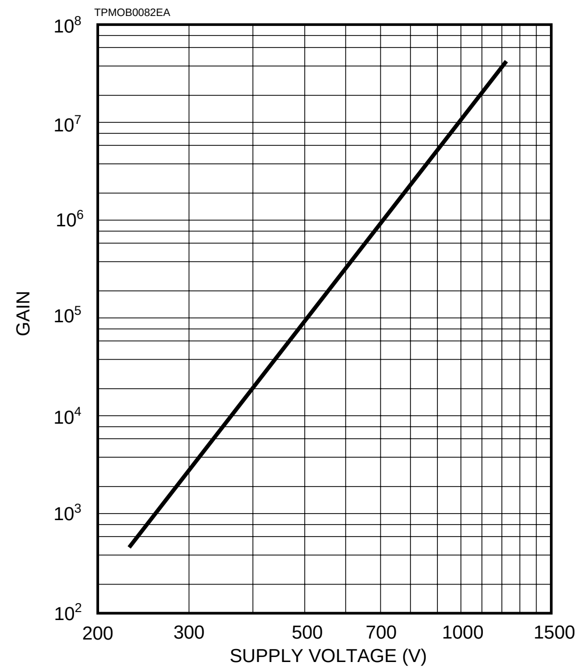
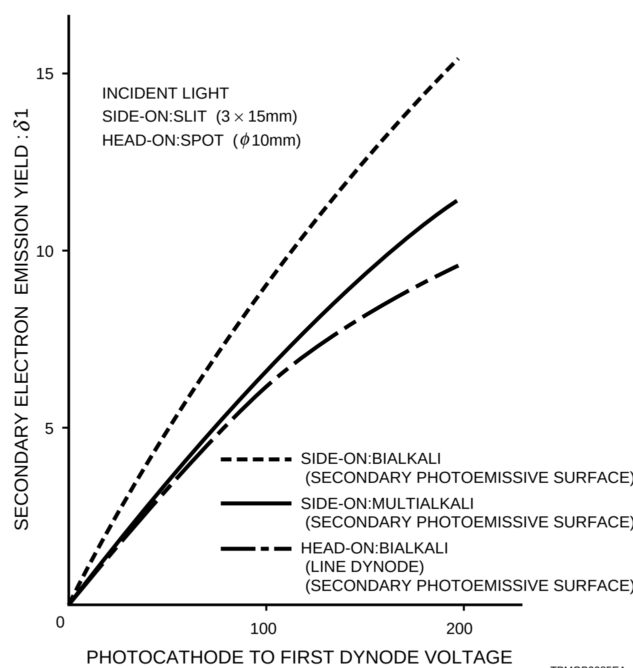



Figure 16 shows the relation between the secondary electorn emission ratio ($\delta 1$) and the photocathode to first dynode voltage. The incident light is passed through a slit of 3 × 15mm for side-on photomultiplier tubes, or is focused on a spot of 10mm diameter for head-on photomultiplier tube. It is clear that the secondary electorn emission ratio depends on the material of the secondary electorn emission surface. Generally, the larger the secondary electorn emission ration, the better the PHD will be.

**Figure 16 : Secondary Electron Emission Yield vs. Supply Voltage**



# 3-4 Noise

Various types of noise may exist in a photomultiplier tube even when it is kept in complete darkness. These noises adversely affect the counting accuracy, especially in cases where the count rate is low. The following precautions must be taken to minimize the noise effects.

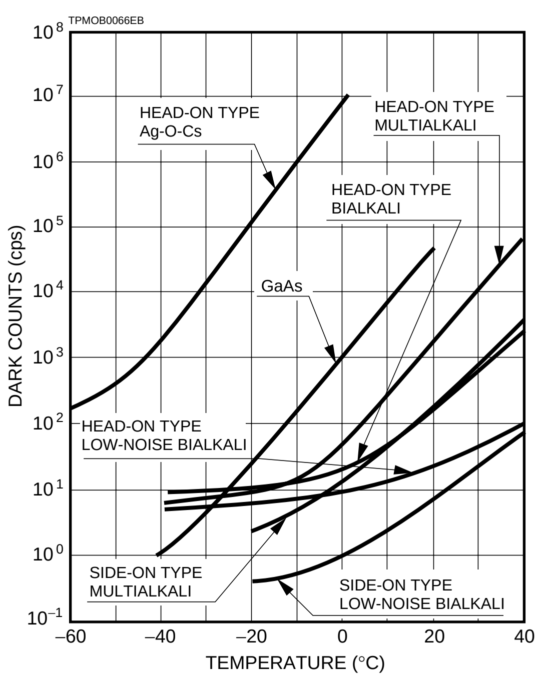
## (1) Thermionic Emission of Electrons

Materials used for photocathodes and dynodes have low work functions (energy required to release electrons into vacuum), so they emit thermal electrons even at room temperature. Most of the noise is caused by these thermal electrons mainly being emitted from the photocathode and amplified by the dynodes. Therefore, cooling the photocathode is the most effective technique for reducing noise in applications where low noise is essential such as photon counting. In addition, since thermal electrons increase in proportion to photocathode size, it is important to select the photocathode size as needed.

Figure 17 shows temperature characteristics of dark counts measured with various types of photocathodes. These are typical examples and actual characteristics vary considerably with photocathode size and sensitivity (especially red sensitivity).

The head-on type Ag-O-Cs, head-on type GaAs and head-on type multialkali photocathodes have high sensitivity in the near infrared to infrared region, but these photocathodes tend to emit large amounts of thermal electrons even at room temperature, so usually cooling is necessary.

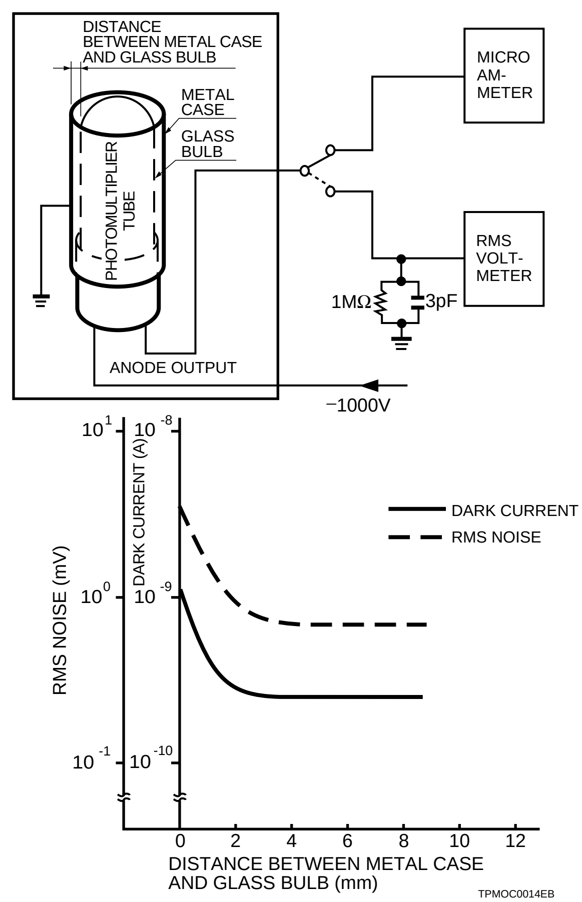
**Figure 17 : Temperature Characteristics of Dark Counts**




## (2) Glass Scintillation

When electrons deviating from their normal trajectories strike the glass bulb of a photomultiplier tube, glass scintillation may occur and result in noise. Figure 18 shows typical dark current (RMS noise) versus the distance between the photomultiplier tube and the metal housing case at ground potential. This implies that glass scintillation noise is caused by stray electrons which are attracted to the glass bulb at a higher potential. This is particularly true when the tube is operated with a voltage divider circuit with the anode grounded. To minimize this problem, it is necessary to reduce the supply voltage for the photomultiplier tube, use a voltage divider circuit with the cathode grounded, or make longer the distance between the photomultiplier tube and the housing. Another effective measure is to coat the outer surface of the glass bulb with a conductive paint which is maintained at the photocathode potential, in order to prevent stray electrons from being attracted to the glass bulb. In this case, however, the photomultiplier tube must be covered with an insulating material since a high voltage is applied to the glass bulb. We call this technique "HA coating". Although Figure 18 is an example of a side-on photomultiplier tube, the same characteristics will be taken with a head-on photomultiplier tube.

**Figure 18 : Dark Current vs. Distance Between Photomultiplier Tube and Housing Case at Ground Potential**



However, in most cases, the input window of the photomultiplier tube is exposed even with the HA coating. Therefore, in anode grounded scheme, use of good insulating material such as fluorocarbon polimers or polycarbonate is necessary around the input window at negative HV operation. Otherwise, a large potential difference may be created at the input window, and could result in irregular and high dark counts.
To avoid this problem, adopting an cathode grounded scheme is strongly recommended.

### (3) Leakage Current

Leakage current may be another source of noise. It may increase due to imperfect insulation of photomultiplier tube lead base or socket pins, and also due to contamination on the circuit board. It is therefore necessary to clean these parts with alcohol.
In addition, when a photomultiplier tube is used with a cooler and if high humidity is present, the photomultiplier tube leads and socket are subject to frost or condensation. This also results in leakage current and therefore special attention should be paid.

### (4) Field Emission Noise

This is voltage-dependent noise. When a photomultiplier tube is operated at a high voltage near the maximum rating, a strong local electric field may induce a small amount of discharge causing dark pulses. It is therefore recommended that the photomultiplier tube be operated at a voltage sufficiently lower than the maximum rating.

### (5) External Noise

Beside the noise from the photomultiplier tube itself, there are external noises that affect photomultiplier tube operation such as inductive noise. Vibration may also result in noise mixing into the signal. Use of an electromagnetic shield case is advisable.

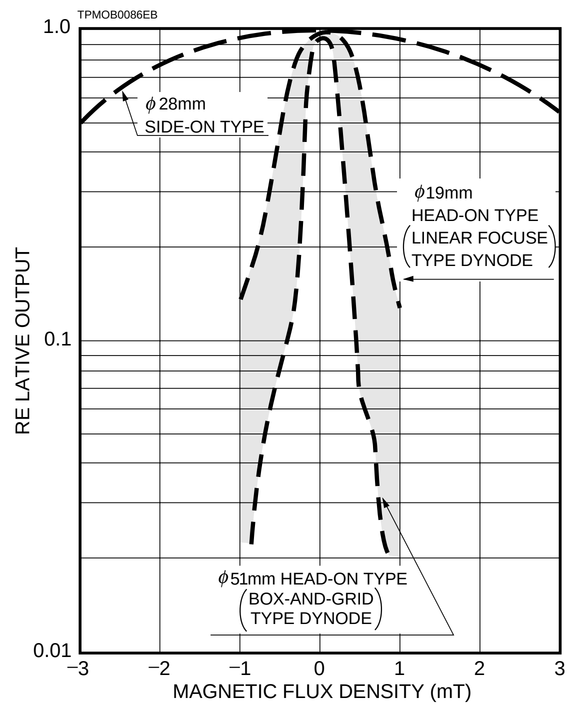
### (6) Ringing

If impedance mismatching occurs in the signal output line from a photomultiplier tube, ringing may result, causing count error. This problem becomes greater in circuits handling higher speeds. The photomultiplier tube and the preamplifier should be connected in as short a distance as possible, or proper impedance matching should be provided at the input of the preamplifier.

## 3-5 Magnetic Shield

Most photomultiplier tubes are very sensitive to magnetic fields and the output varies significantly even with terrestrial magnetism (approx. 0.04mT : ie 0.4 Gauss). Figure 19 shows typical examples of how photomultiplier tubes are affected by the presence of a magnetic field. Although photomultiplier tubes in the photon counting mode are less sensitive to a magnetic field than in the analog mode, photomultiplier tubes should not be operated near any device producing a magnetic field (motor, metallic tools which are magnetized, etc.). When a photomultiplier tube has to be operated in a magnetic field, it is necessary to cover the photomultiplier tube with a magnetic shield case.

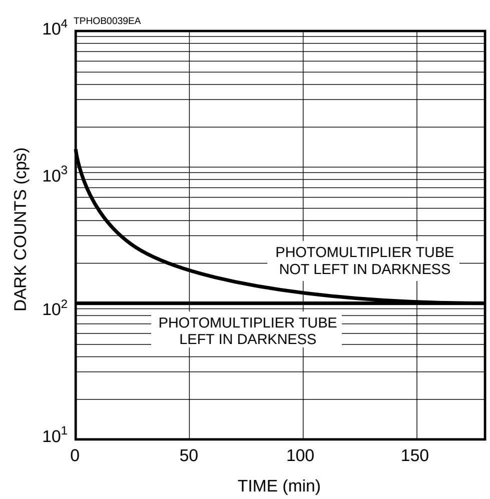
**Figure 19 : Typical Effects by Magnetic Fields Perpendicular to Tube Axis**




## 3-6 Stability and Dark Storage

In either the photon counting mode or analog mode, the dark current and dark count of a photomultiplier tube usually increase just after strong light is irradiated on the photocathode. To operate a photomultiplier tube with good

**Figure 20 : Effect of Dark Storage Noise Reduction**

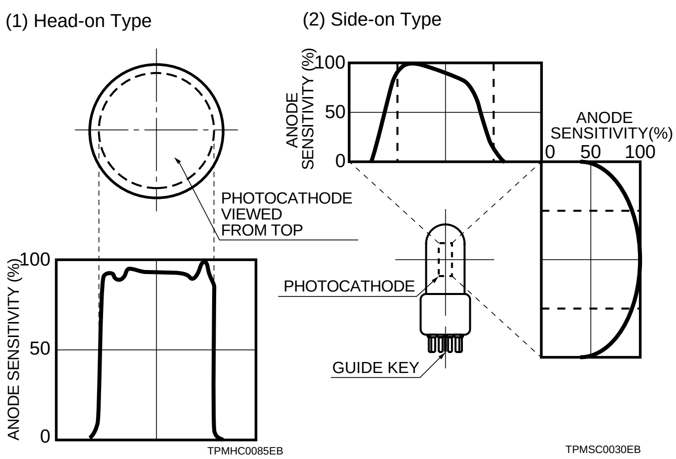


stability, it is necessary to leave the photomultiplier tube in dark state without allowing the incident light to enter the photocathode for about one or more hours. (This is called "dark storage".) As Figure 20 shows, dark storage is effective in reducing the number of dark counts.

## 3-7 Uniformity

Uniformity is the variation in photomultiplier tube output with respect to the photocathode position at which light enters. As stated in 3-2 "Collection efficiency (CE)", even if uniform light enters the entire photocathode of a photomultiplier tube, some electrons emitted from a certain position of the photocathode are not efficiently collected by the first dynode (Dy1). This phenomenon causes variations in uniformity as shown in Figure 21. If photons enter a position of poor uniformity, not all the photoelectrons emitted from there are detected, thus lowering the detection efficiency. In general, head-on photomultiplier tubes provide better spatial uniformity than side-on photomultiplier tubes. For either type, good uniformity is obtained when light enters around the center of a photocathode.

**Figure 21 : Typical Uniformity**




## 3-8 Signal-to-Nose (S/N) Ratio

This section describes theoretical analysis of the signal-to-noise (S/N) ratio in both photon counting and analog modes. The noise being discussed here is mainly shot noise superimposed on the signal.

### (1) Analog Mode

When signal light enters the photocathode of a photomultiplier tube, photoelectrons are produced. This process occurs accompanied by statistical fluctuations. The signal current or average photocurrent $I_{ph}$ therefore includes an AC component which is equal to the shot noise $i_{ph}$ expressed below.

$$i_{ph}=\sqrt{2eI_{ph}B}$$

where $e$ is the electron charge and B is the bandwidth of the measurement system.
The shot noise which is superimposed on the signal can be categorized by origin as follows.

a) Shot Noise Resulting from Signal Light
Since the secondary electron emission in a photomultiplier tube occurs with statistical probability, the resulting output also has statistical fluctuation. Thus the noise current, $i_s$, is given by

$$i_s=\sqrt{2eI_{ph}FB}\cdot\mu$$

where $\mu$ is the gain of the photomultiplier tube, F is the noise figure of the photomultiplier tube. If we let the secondary electron emission ratio per dynode stage be $\delta$, the noise figure for the photomultiplier tube having n dynode stages can be expressed as follows:

$$F=\left(1+\frac{1}{\delta_1}+\frac{1}{\delta_1\,\delta_2}+\cdots\cdots+\frac{1}{\delta_1\cdots\cdots\delta_n}\right)$$

Supposing that $\delta_1$=5, $\delta_2=\delta_3=\cdots\cdots=\delta_n$=3, the noise figure takes a value of approximately 1.3 .
At this point, the photocurrent $I_{ph}$ is given by

$$I_{ph}=\frac{P_i\,\eta(\lambda)\,\alpha e}{h\nu}$$

where $P_i$ is the average light level entering the photomultiplier tube, $\eta(\lambda)$ is the photocathode QE at wavelength $\lambda$, $\alpha$ is the photoelectron CE and $h\nu$ is the energy per photon.

b) Shot Noise Resulting from Background
As with the shot noise caused by signal light, the shot noise resulting from background $P_b$ can be expressed as follows:

$$i_b=\sqrt{2eI_bFB}\cdot\mu$$

$$I_b=\frac{P_b\,\eta(\lambda)\alpha e}{h\nu}$$

where Ib is the equivalent average cathode current produced by the background light.

c) Shot Noise Resulting from Dark Current
Dark current may be categorized by cause as follows:
① Thermionic emission from the photocathode and dynodes.
② Fluctuation by leakage current between electrodes.
③ Field emission current and ionization current from residual gases inside the tube.
Among these, a major cause of the dark current is thermionic emission from the photocathode.

Therefore the shot noise resulting from dark current can be expressed as shown below.

$$i_d = \sqrt{2eI_dFB} \cdot \mu$$

where $I_d$ is the equivalent average dark current from the photocathode.

d) Noise from Succeeding Amplifier

When an amplifier with noise figure $F_a$ is connected to the photomultiplier tube load, the noise converted into the input of the amplifier is given by

$$I_a = \sqrt{\frac{4F_akTB}{R_{eq}}}$$

where $R_{eq}$ is the equivalent resistance used to connect the photomultiplier tube with the amplifier, T is the absolute temperature and k is the Boltzmann constant.

e) Signal-to-Noise (S/N) Ratio

Taking into account the background noise ($I_b+I_d$), the signal-to-noise (S/N) ratio of the photomultiplier tube output becomes

$$S/N = \frac{I_{ph}}{\sqrt{2eFB\{I_{ph}+2(I_b+I_d)\}+(4F_akTB/R_{eq})/\mu^2}} \quad \text{... (1)}$$

Among the above equations, the amplifier noise can be generally ignored because the gain $\mu$ of the photomultiplier tube is sufficiently large, so the signal-to-noise (S/N) ratio can be expressed as follows:

$$S/N \fallingdotseq \frac{I_{ph}}{\sqrt{2eFB\{I_{ph}+2(I_b+I_d)\}}} \quad \text{................. (1)'}$$

f) Noise Equivalent Power (NEP)

In addition, the noise can also be expressed in terms of noise equivalent power (NEP). The NEP is the light level required to obtain a signal-to-noise (S/N) ratio of 1, that is, the light level to produce a signal current equivalent to the noise current. The NEP indicates the lower limit of light detection and is usually expressed in watts.

From equation (1)' above, the NEP at a given wavelength can be calculated by using $I_b = 0$ and S/N=1, as follows:

$$NEP = \frac{2e\mu FB + \sqrt{4eI_{da}\mu FB}}{Sp}$$

where

$I_{da}$ ($\fallingdotseq I_d \times \mu$) : photomultiplier tube anode dark current (A)

Sp : photomultiplier tube anode radiant sensitivity (A/W)

In a low bandwidth region up to several kHz, the NEP mainly depends on the shot noise caused by dark current (the latter component in the above equation). In a high bandwidth region, the noise component (the former component in the above equation) resulting from the cathode radiant sensitivity ($Sp/\mu$ in the equation) predominates the NEP.

The noise can also be defined as equivalent noise input (ENI). The ENI is basically the same parameter as the NEP, and is expressed in lumens (Sp is measured in units of amperes per lumen in this case) or watts.

## (2) Photon Counting Mode

In the analog mode, all pulse height fluctuations occurring during the multiplication process appear on the output. However, the photon counting mode can reduce such fluctuations by setting a discrimination level on the output pulse height, allowing a significant improvement in the signal-to-noise (S/N) ratio.

In the photon counting mode in which randomly generated photons are detected, the number of signal pulses counted for a certain period of time exhibits a temporal fluctuation that can be expressed as a Poisson distribution. If we let the average number of signal pulses be N, it includes fluctuation (mean deviation) which is expressed in the shot noise $n = \sqrt{N}$. The amplifier noise can be ignored in the photon counting mode by setting the photomultiplier tube gain at a sufficiently high level, so that the discrimination level can be easily set higher than amplifier noise level.

As with the analog mode, dark current may be grouped by cause as follows:

(a) Shot noise resulting from signal light

$$n_{ph} = \sqrt{N_{ph}}$$

($N_{ph}$ is the number of counts by signal light)

(b) Shot noise resulting from background light

$$n_b = \sqrt{N_b}$$

($N_b$ is the number of counts by background light)

(c) Shot noise resulting from dark counts

$$n_d = \sqrt{N_d}$$

($N_d$ is the number of dark counts)

In actual measurement, it is not possible to detect $N_{ph}$ separately. Therefore, the total number of counts ($N_{ph}+N_b+N_d$) is first obtained and then the background and dark counts ($N_b+N_d$) are measured for the same period of time by removing the input light. Then $N_{ph}$ is calculated by subtracting ($N_b+N_d$) from ($N_{ph}+N_b+N_d$). From this, each noise component can be regarded as an independent factor, so the total noise component can be analyzed as follows:

$$n^2_{tot} = \left(\sqrt{(n_{ph})^2+(n_b)^2+(n_d)^2}\right)^2 + \left(\sqrt{(n_b)^2+(n_d)^2}\right)^2$$

$$n_{tot} = \sqrt{(n_{ph})^2+2\{(n_b)^2+(n_d)^2\}}$$

Here, substituting $n_{ph} = \sqrt{N_{ph}}$, $n_b = \sqrt{N_b}$ and $n_d = \sqrt{N_d}$

$$n_{tot} = \sqrt{N_{ph} + 2(N_b + N_d)}$$

Thus the signal-to-noise (S/N) ratio becomes

$$S/N = \frac{N_{ph}}{n_{tot}} = \frac{N_{ph}}{\sqrt{N_{ph} + 2(N_b + N_d)}} \ \ldots\ldots\ldots\ldots\ (2)$$

The number of counts per second for $N'_{ph}$, $N'_b$ and $N'_d$ is easily obtained as shown below, respectively. T is the measurement time in seconds.

$$N'_{ph} = N_{ph}/T,\ N'_b = N_b/T \text{ and } N'_d = N_d/T$$

Accordingly, the equation (2) can be expressed as follows:

$$S/N = \frac{N'_{ph}\sqrt{T}}{\sqrt{N'_{ph} + 2(N'_b + N'_d)}} \ \ldots\ldots\ldots\ (2)'$$

This means that the signal-to-noise (S/N) ratio can be improved as the measurement time is made longer.

By replacing the measurement time and the number of counts per second with the corresponding frequency and current, with T(s)=1/2B(Hz) and $N'_x = I_x/e$ ($e = 1.6 \times 10^{-19}$C) respectively, it becomes clear that equation (1)' is equivalent to equation (2)' except for the noise figure term.

In photon counting mode, if we define the detection limit as the light level where the signal-to-noise (S/N) ratio equals 1, the number of signal counts $N'_{ph}$ (cps) at the detection limit can be approximated below, from equation (2)' under the condition that the measurement time is one second and the background light can be disregarded.

$$N'_{ph} \fallingdotseq \sqrt{2N'_d} \quad \text{(cps)}$$

At this point, if the dark count $N'_d$ is more than several counts per secound, the detection limit can be approximated with an error of less than around 30%.

If we let the QE at a wavelength $\lambda$ (nm) be $\eta(\lambda)$, the incident light power $P_o$ at detection limit can be approximated as follows:

$$P_o \fallingdotseq \frac{2.8 \times 10^{-16} \times \sqrt{N'_d}}{\lambda \times \eta(\lambda)} \quad \text{(W)}$$

For your reference, let us calculate the power (P) of a photon per second as follows:

$$P = \frac{1 \times h \times c}{\lambda} \fallingdotseq \frac{2 \times 10^{-16}}{\lambda} \quad \text{(W)}$$

As an example, the table below shows the relation between the light power and the number of photons at a wavelength of 550nm.

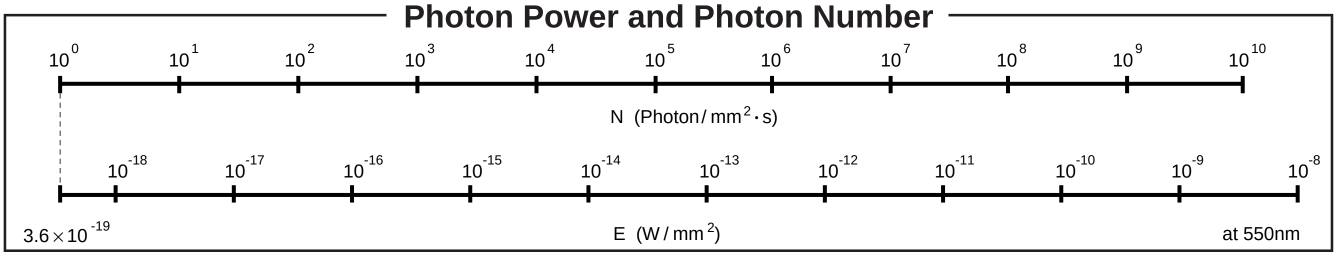
In contrast to the signal pulse height distribution (PHD) similar to a Poisson distribution, the dark current pulses are distributed on the lower pulse height side. This is because the dark current includes thermal electrons not only from the photocathode but also from dynodes. Therefore, most of the dark current component can be effectively eliminated by setting a proper discrimination level without reducing the signal component. Furthermore, by placing an upper discrimination level, the photon counting mode can also eliminate the influence of environmental radiation which produces higher noise pulses and often cause significant problems in the analog mode. It is now obvious that the photon counting mode allows the measurement with a higher signal-to-noise (S/N) ratio than in the analog mode, which is even greater contribution than that obtained from the noise figure F.

## Reference

### ● Physical Constants

| Constant | Symbol | Value | Units |
|---|---|---|---|
| Electron Charge | $e$ | $1.602 \times 10^{-19}$ | C |
| Speed of Light in Vacuum | $c$ | $2.998 \times 10^{8}$ | m/s |
| Planck's Constant | $h$ | $6.626 \times 10^{-34}$ | Js |
| Boltzmann's Constant | k | $1.381 \times 10^{-23}$ | J/K |
| 1eV Energy | eV | $1.602 \times 10^{-19}$ | J |
| Wavelength in Vacuum Corresponding to 1eV | – | 1240 (1.240) | nm ($\mu$m) |

**Photon Power and Photon Number**



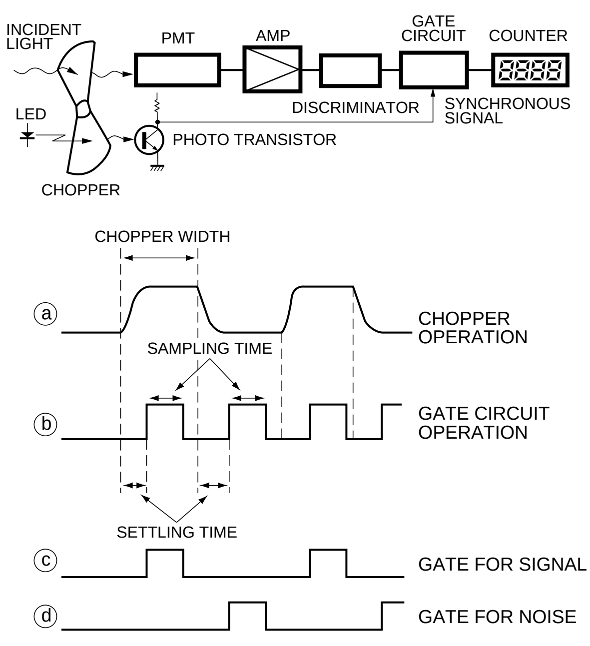
# 4. Measurement Systems

Photon counting can be performed with several measurement systems, including simple sequential measurement and sampling measurement depending on the information to be obtained or the light level and signal timing conditions.

## 4-1 Synchronous Photon Counting Using Chopper

Using a mechanical chopper to interrupt incident light, this method makes light measurements in synchronization with the chopper operation. More specifically, signal pulses and noise pulses are both counted during the time that light enters a photomultiplier tube, while noise pulses are counted during light interruption for subtracting them from signal pulses and noise pulses. This method is effective when a number of noise pulses are present or when extremely low level light is measured. However, since this method uses a mechanical chopper, it is not suitable for the measurement of high-speed phenomena. This method is also known as the digital lock-in mode. Figure 22 shows a block diagram for this measurement system, along with the timing chart.

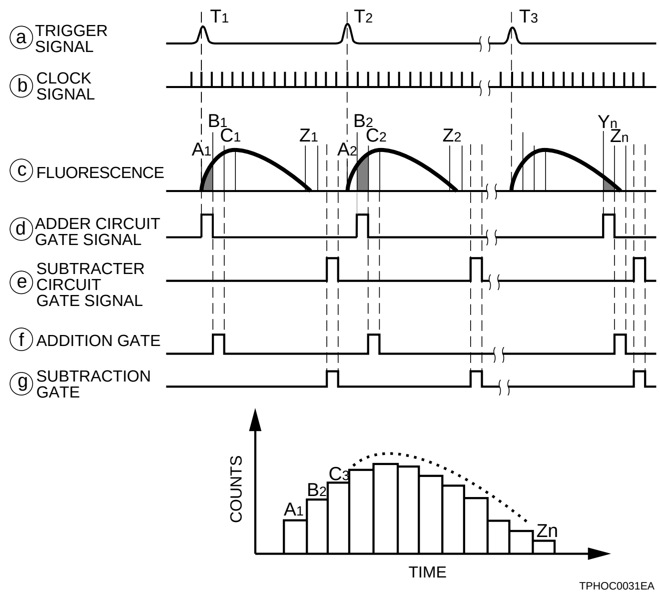
**Figure 22 : Synchronous Photon Counting Using Chopper**




## 4-2 Time-Resolved Photon Counting by Repetitive Sampling

This method uses a pulsed light source to measure temporal changes of repetitive events.
Each event is measured by sampling at a gate timing slightly delayed from the repetitive trigger signals. The signal measured at each gate is accumulated to reproduce the signal waveform. This method is sometimes called the digital boxcar mode and is useful for the measurement of high-speed repetitive events. Figure 23 shows the time chart of this method.

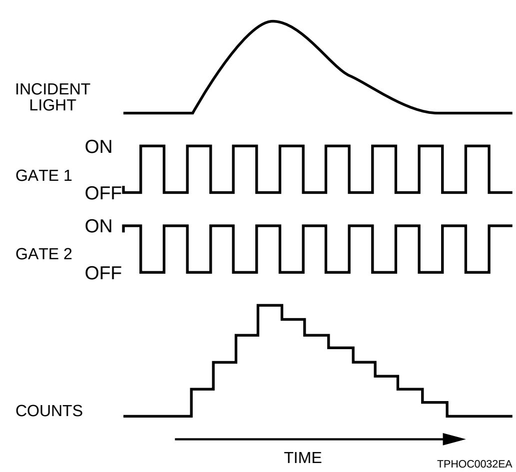
**Figure 23 : Time-Resolved Photon Counting by Repetitive Sampling**




## 4-3 Time-Resolved Photon Counting by Multiple Gates

This method sequentially opens multiple gates and measure the light level in a very short duration of the open gate, allowing a wide range of measurement from slow events to fast events. This method can also measure single events and random events by continuously storing data into memory. The time chart for this method is shown in Figure 24.

**Figure 24 : Time-Resolved Photon Counting by Multiple Gates**



# 4-4 Time-Correlated Photon Counting (TCPC)

Time-correlated photon counting (TCPC) is used in conjunction with a high-speed photomultiplier tube for fluorescence lifetime measurement (in picoseconds to nanoseconds). By making the count rate sufficiently small relative to repetitive excitation light from a pulsed light source, this method measures time differences with respect to individual trigger pulses synchronized with excitation signals in the single photoelectron state.

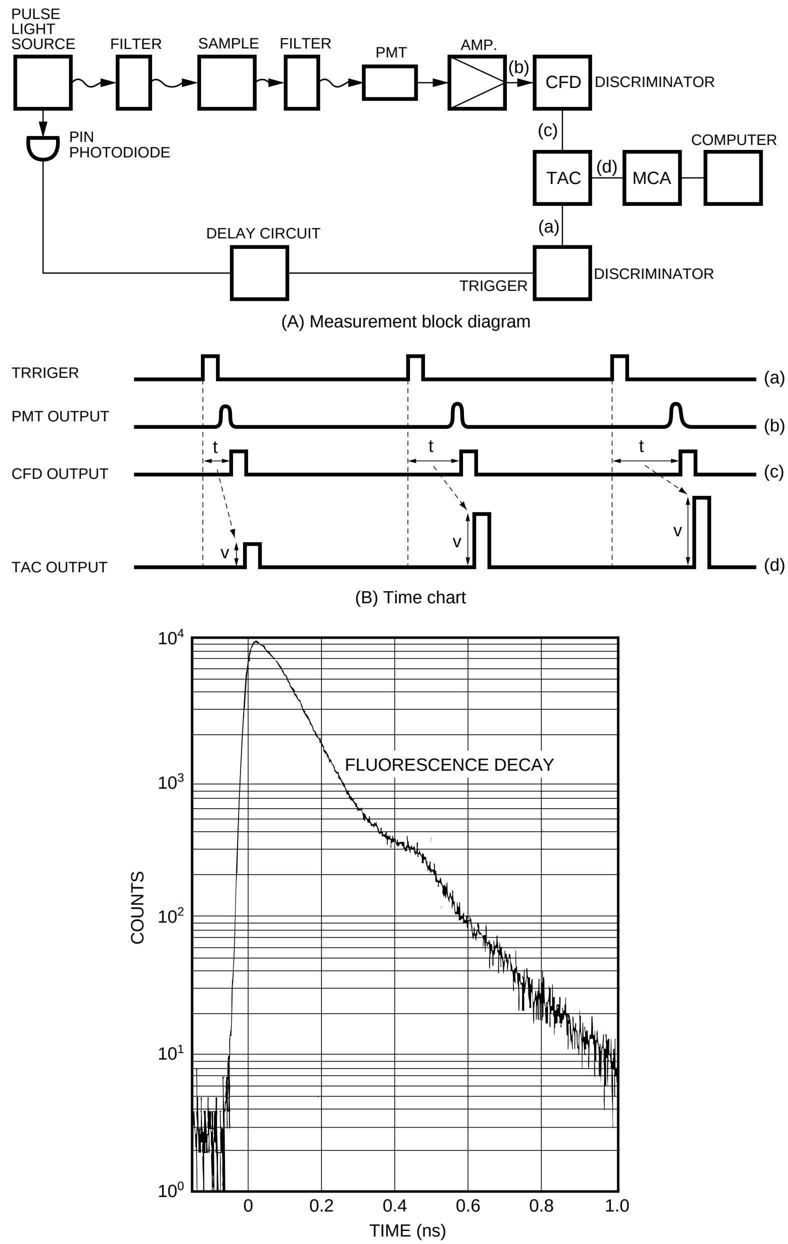
Actual fluorescence and emission can be reproduced with good correlation by integrating the signals. Since this method only measures the time difference, it provides a better time resolution than the pulse width obtainable from a photomultiplier tube. A typical system for the TCPC consists of a high-speed preamplifier, a discriminator with less time jitter called a constant fraction discriminator (CFD), a time-to-amplitude converter (TAC), a multichannel pulse height analyzer (MCA) and a memory or computer. Figure 25 shows the block diagram, time chart for this measurement system and one example data for fluorescence decay time.

Besides TCPC, time-resolved measurement also includes phase difference detection using the modulation method. This method is sometimes selected due to advantages such as a compact light source and simple operating circuits.

**Reference**: ● Application of MCP-PMTs to time-correlated single photon counting and related procedures (available from Hamamatsu).

● Modulated Photomultiplier Tube module H6573 (available from Hamamatsu)

**Figure 25 : TCPC System**




(C) Example TCPC Measurement (Sample : Cryptocyanine in ethanol)

TPHOC0033EC

# 5. Selection Guide

This section describes how to select the optimum photomultiplier tube for photon counting, along with their brief specifications and related products. The following notes should be taken into account in selecting the photomultiplier tube that matches your needs.

## 5-1 Selecting The Photomultiplier Tube

### (1) Photomultiplier Tube Structure

Photomultiplier tubes are roughly grouped into side-on and head-on types, so it is important to select the photomultiplier tube structure type according to the optical measurement conditions.
Side-on photomultiplier tubes have a rectangular photosensitive area and are therefore suitable for use in spectrophotometers where the output light is in the form of a slit, or for the detection of condensed light or collimated light.
Head-on photomultiplier tubes offer a wide choice of photosensitive areas from 8mm to 120mm in diameter and can be used under various optical conditions. Note, however, that selecting the photomultiplier tube with a photosensitive area larger than necessary may increase dark counts, thus deteriorating the signal-to-noise (S/N)ratio.

### (2) Photocathode Quantum Efficiency (QE)

The QE has direct effects on the detection efficiency. It is important to select a photomultiplier tube that provides high QE in the desired wavelength range.

### (3) Gain

Gain required of the photomultiplier tube differs depending on the gain or equivalent noise input of the amplifier connected. As a general guide, it is advisable to select a photomultiplier tube having a gain higher than $1 \times 10^6$, although it depends on the pulse width of the photomultiplier tube.

### (4) Single Photoelectron Pulse Height Distribution (PHD)

Although not listed in the catalog, the PHD is an important factor since it relates to photomultiplier tube detection efficiency and stability. Hamamatsu designs photomultiplier tubes for photon counting, while taking the PHD into account. As a guide for estimating whether PHD is good or not, the P/V ratio (the ratio of the peak count to the valley count in PHD) is sometimes used. (See Figure 6.)

### (5) Dark Count → Lower Detection Limit

Dark count is an important factor for determining the lower detection limit of a photomultiplier tube. Selecting the photomultiplier tube with minimum dark counts is preferred. In general, for the same electrode structure, dark count tends to increase with a larger photocathode and higher sensitivity in a long wavelength range. When a photomultiplier tube is used in a long wavelength range above 700nm, cooling the photomultiplier tube is recommended.

### (6) Response Time → Maximum Count Rate, Time Resolution

The maximum count rate (cps) in the photon counting mode is determined by the time response of a photomultiplier tube and the frequency characteristics of the signal processing circuit, or by pulse width.
Most photomultiplier tubes have no problem with the time response up to a maximum count rate (random pulse) of 30Mcps. However, in applications where the maximum count rate higher than this level is expected, a photomultiplier tube with the rise time (Tr) faster than 5ns must be selected. In time-correlated photon counting (TCPC), the electron transit time spread (TTS) is more important than the rise time (Tr).

## 5-2 Photomultiplier Tubes for Photon Counting

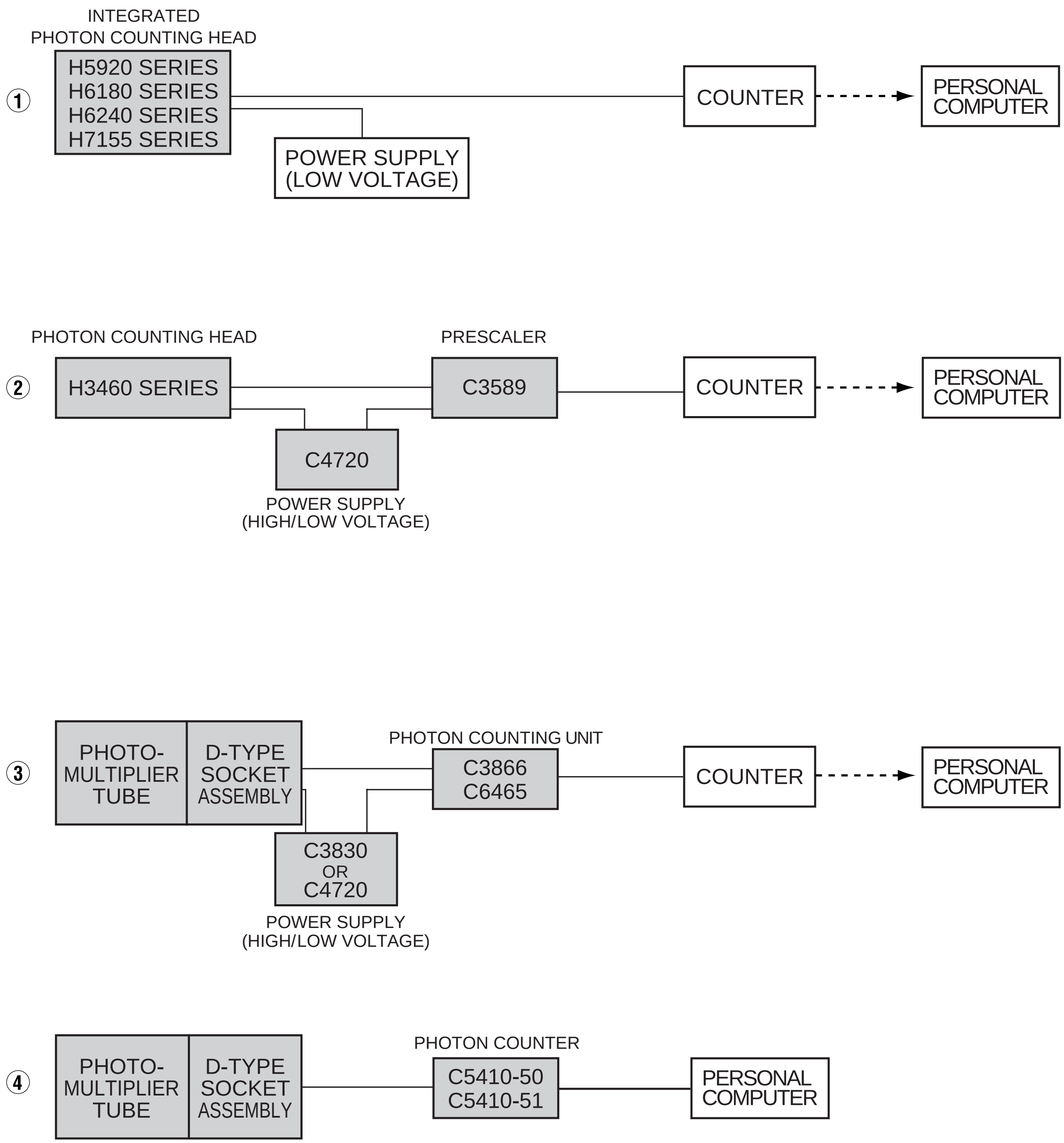
Table 1 (on page 26 and 27) is a listing of typical Hamamatsu photomultiplier tubes designed or selected for photon counting, showing general specifications for the spectral response and configurations. For more information, refer to the Hamamatsu photomultiplier tubes catalog. In addition to photomultiplier tubes listed in Table 1, you can choose from Hamamatsu photomultiplier tubes for photon counting. Please consult our sales office.

## 5-3 Related Products

There are many related products used in photon counting. The following sections introduce major products for photon counting available from Hamamatsu: preamplifiers, photon counting units, photon counting heads, photon counters, high-voltage power supplies, coolers and housings. For further details, refer to individual catalogs.

# Related Products for Photon Counting

## <Sample Configurations>




Notes : In the cases of ③ and ④ a D-type socket assembly is required for operation of a photomultiplier tube.

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# ● Photon Counting Heads

## <H5920 series, H6180 series, H6240 series>

These photon counting heads consist of a photomultiplier tube, a voltage divider, an amplifier, a discriminator and a high-voltage power supply, all included in a compact metallic case. The H5920 series and the H6180 series are similar. The H5920 series needs ±5V and adds a divide by 10 prescaler for improval dynamic range. The H6180 and H6240 just require +5V. All of these photon counting heads output TTL signal, for easy combination with pulse counter. Since the photomultiplier tube supply voltage and discrimination voltage are preset at the optimal levels, there is no need for adjustment before use. For the H5920 and H6180 series, the E6264 mount flange is optionally provided for connection to other equipment.

### SPECIFICATIONS

| Parameter | H5920-01 | H6180-01 | H6240 | H6240-01 | H6240-02 | Unit |
|---|---|---|---|---|---|---|
| Spectral Response Range | 300 to 650 | 300 to 650 | 185 to 680 | 185 to 850 | 185 to 900 | nm |
| Effective Area | $\phi$ 15 | $\phi$ 15 | 4 x 20 | | 4 x 6 | mm Min. |
| Counting Linearity Ⓐ (Random Pulse) | 10 Ⓑ | 6 | 2.5 | | | Mcps |
| Dark Counts (at +25°C) | 10 Ⓑ | 10 | 30 | 80 | 400 | cps Typ. |
| Output Pulse Width | Positive Logic TTL 25ns | Positive Logic TTL 9ns | Positive Logic TTL 30ns | | | — |
| Input Voltage/Current | +5Vdc/125mA, –5Vdc/50mA | +5Vdc/125mA | +5Vdc/80mA | | | — |

Ⓐ At –10% deviation from linear output.
Ⓑ The actual counts are 1/10 of those indicated.

## <H7155 series>

H7155 series are compact photon counting heads comprising a metal package PMT, high-speed photon counting circuit, and high voltage power supply. The operation requires only connecting a +5Vdc power supply and a pulse counter. There is no need for discrimination level or high voltage adjustment by users.
H7155 series accept direct light input or an optical fiber adaptor E5776.

### SPECIFICATIONS

| Parameter | H7155 | H7155-01 | Unit |
|---|---|---|---|
| Spectral response Renge | 300 to 650 | 300 to 820 | nm |
| Effective Area | 8 | | mm |
| Counting Linearity (Random Pulse) Ⓐ | 1.5 | | Mcps |
| Dark Counts (at +25C) | 100 | 600 | cps Typ. |
| Output Pulse Width | Positive Logic TTL 30 | | ns |
| Input Voltage / Current | +5Vdc / 50mA Max. | | — |
| Dimensions (W x H x D) | 22 x 50 x 50 | | mm |

Ⓐ At –10% deviation from linear output.

## <H3460 series>

The H3460 series photon counting heads incorporate a photomultiplier tube and a high-speed amplifier/discriminator into a compact metallic case. By connecting to an external high-voltage power supply for the photomultiplier tube and a low-voltage power supply for the amplifier/discriminator, photon counting can easily be performed.
Hamamatsu also offers the C3589 prescaler that divides the count rate by 10, for use with the H3460-53 and -54, allowing measurement over a wide dynamic range without using a high-speed counter.

### SPECIFICATIONS

| Parameter | H3460-53 | H3460-54 | Unit |
|---|---|---|---|
| Spectral response Renge | 300 to 650 | | nm |
| Effective Area | $\phi$ 21 | | mm Min. |
| Counting Linearity (Random Pulse) | 13 | | Mcps |
| Dark Counts (at +25°C) | 20 | 40 | cps Typ. |
| Output Pulse Width | ECL Balanced Line 3ns | | — |
| Recommened High Voltage/Current (For Photomultiplier Tube) | Approx. +1000 / 230 | | Vdc/$\mu$A |
| Input Voltage/Current (For Preamplifier and Discriminator) | +5Vdc / 35mA, –5Vdc / 150mA | | — |

Ⓐ At –10% deviation from linear output.

# ● Photon Counting Unit

## <C3866>

The C3866 photon counting unit converts photomultiplier tube photoelectron pulses into 5V digital signal with a built-in amplifier/discriminator. The C3866 allows photon counting with a high signal-to-noise (S/N) ratio by connecting to an external pulse and supplying a low voltage. The high-speed electronic circuit used in the C3866 ensures accurate photometry with high linearity up to $10^7$ cps. The built-in prescaler (divided by 10) makes use of a high-speed pulse counter unnecessary.

### SPECIFICATIONS

| Parameter | Descripton / Value |
|---|---|
| Input Impedance | 50Ω |
| Discrimination Level (Converted into input) | –0.5 to –16mV |
| Prescaler | ÷1, ÷10 |
| Maximum Count Rate (Random Pulse:–10% down) | (÷1) 4Mcps, (÷10) 10Mcps |
| Pulse Pair Resolution | (÷1) 25ns, (÷10) 10ns |
| Output Pulse | C-MOS 5V |
| Output Pulse Width | (÷1) 10ns, (÷10) Depend on Count Rate |
| Input Voltage / Current | +5Vdc / 150mA, –5Vdc / 300mA |
| Dimensions (W × H × D) | 88 × 32 × 170mm |

# ● Photon Counting Unit

## <C6465>

The C6465 is a photon counting unit which converts photomultipliertube output signal to 5V digital signal (TTL) by using an amplifier/discriminator. By connecting a pulse counter to the C6465, photon counting with high S/N ratio will be easily performed. For general applications, thus it excludes the 1/10 prescaler.

### SPECIFICATIONS

| Parameter | Value |
|---|---|
| Input Impedance | 50Ω |
| Discrimination Level (Converted into input) | –2.2 to –31 mV |
| Maximum Count Rate (Random Pulse:–10% down) | 1 Mcps (Typ.) |
| Pulse Pair Resolution | 60ns |
| Output Pulse Level | Positive TTL |
| Output Pulse Width | 30ns |
| Input Voltage/Current | +5Vdc/60mA, –5V/120mA |
| Dimensions (W × H × D) | 60 × 43.2 × 105mm |

# ● Photon Counters

## <C5410 -50, -51>

The C5410 -50, -51 photon counter includes an amplifier, a discriminator and a high-voltage power supply, which allow photon counting to be performed by simply connecting to a photomultiplier tube coupled to a D-type socket assembly.
The time-resolved measurement mode with no dead time has been added to the conventional, gated single photon counting mode. A profile of the measured result can be displayed on the large-size liquid crystal screen, thus allowing real-time analysis. The RS232C interface permits simple connection to a personal computer, enabling data transfer or remote control of the C5410 from the computer.

### SPECIFICATIONS

| Parameter | | Value |
|---|---|---|
| Input Impedance | | 50Ω |
| Built-in Amplifier Gain | | 42dB (125Times) |
| Discrimination Level | | –0.4 to –16mV |
| Maximum Count Rate (Random Pulse) | | 2.5Mcps |
| Pulse Pair Resolution | | 40ns |
| Gate Time | | 50$\mu$s to 50s (1, 2, 5steps) |
| Counter Capacity | | 27 Bits/Gate |
| Memory Capacity | | 1024 Gate Data |
| Integration | | 65535 Times |
| High Voltage Output | C5400-50(–HV Specification) | –360 to –2000V (1mA) |
| | C5400-51(+HV Specification) | +360 to +2000V (1mA) |
| Input Voltage | | 120/230Vac±10% (50/60Hz) |

# High Voltage Power Supplies

## <C4900 (on-board type)>

Aiming at compactness, low cost yet high performance, the C4900 series is a modular high-voltage power supply that can be directly mounted on a PC board. The newly designed circuitry ensures both high performance and low power consumption. Enhanced protective functions are also included as standard features.

### SPECIFICATIONS

| Parameter | | C4900 | C4900-01 | C4900-50 | C4900-51 | Unit |
|---|---|---|---|---|---|---|
| Input Voltage | | +15±1 | +12±0.5 | +15±1 | +12±0.5 | Vdc |
| Input Current Ⓐ | with no load | 14 | 15 | 14 | 15 | mA (Typ.) |
| | with full load | 90 | 95 | 90 | 95 | mA (Typ.) |
| Output Voltage Range | | 0 to –1250 | | 0 to +1250 | | Vdc |
| Output Current Ⓐ | | 0.6 | 0.5 | 0.6 | 0.5 | mA (Max.) |
| Line Regulation Ⓑ Ⓒ | | ±0.01 | | | | % (Typ.) |
| Load Regulation Against 0 to 100% Load Change Ⓐ | | ±0.01 | | | | % (Typ.) |
| Ripple Noise (p-p) Ⓑ | | 0.007 | | | | % (Typ.) |
| Dimensions (W × H × D) | | 46 × 24 × 12 | | | | mm |

NOTE : Ⓐ At maximum output voltage.
Ⓑ At maximum output voltage and current.
Ⓒ C4900, -50 : +15±1 Vdc/C4900-01, -51 : +12±0.5 Vdc

## <C4710 (on-board type)>

The C4710 series is an on-board type high-voltage power supply designed for photomultiplier tube operation.
It combines high performance with ease of use, yet offers low cost.

### SPECIFICATIONS

| Parameter | | C4710 | C4710-01 | C4710-02 | C4710-50 | C4710-51 | C4710-52 | Unit |
|---|---|---|---|---|---|---|---|---|
| Input Voltage | | +15±1 | +12±1 | +24±1 | +15±1 | +12±1 | +24±1 | Vdc |
| Input Current Ⓐ | with no load | 95 | 120 | 65 | 95 | 120 | 65 | mA (Typ.) |
| | with full load | 260 | 340 | 145 | 260 | 340 | 145 | mA (Typ.) |
| Output Voltage Range | | –240 to –1500 | | | +240 to +1500 | | | Vdc |
| Output Current | | 1 | | | | | | mA (Max.) |
| Line Regulation Ⓑ Against ±1V Input Change | | ±0.01 | ±0.015 | ±0.015 | ±0.02 | ±0.02 | ±0.015 | % (Typ.) |
| Load Regulation Ⓐ Against 0 to 100% Load Change | | ±0.01 | ±0.015 | ±0.01 | ±0.01 | ±0.01 | ±0.01 | % (Typ.) |
| Ripple Noise (p-p) Ⓑ | | 0.005 | | | | | | % (Typ.) |
| Dimensions (W × H × D) | | 65 × 27.5 × 45 | | | | | | mm |

NOTE : Ⓐ At maximum output voltage.
Ⓑ At maximum output voltage and current.

# <C3830, C4720 (bench-top type)>

The C3830 and C4720 are multipurpose power supplies that provide a high voltage output for photomultiplier tube operation and low voltage outputs (±5V, ±15V) for peripheral devices such as the Hamamatsu preamplifier and photon counting unit.

### SPECIFICATIONS

| Parameter | | High Voltage Power Supply Section | | ±5V Power Supply Section | ±15V Power Supply Section | Value |
|---|---|---|---|---|---|---|
| | | C3830 | C4720 | | | |
| Output Voltage | | –200 to –1500 (Variable) | +200 to +1500 (Variable) | ±4.75 to ±5.25 (Fixed) | ±14.25 to ±15.75 (Fixed) | Vdc |
| Output Current Ⓐ | | 1 | | 500 | 200 | mA Max. |
| Line Regulation Against ±10% Line Voltage Change Ⓑ | | ±0.005 | | ±0.005 | ±0.015 | % Typ. |
| Load Regulation Against 0 to 100% Load Change Ⓐ | | ±0.01 | | ±0.5 | ±0.5 | % Typ. |
| Ripple / Noise (p-p) Ⓑ | | 0.005 | | 0.16 | 0.06 | % Typ. |
| Input Voltage | C3830 | 100/120/230 ±10% | | | | Vac |
| | C4720 | 100/115/220 ±10% | | | | |

NOTE : Ⓐ At maximum output voltage.
Ⓑ At maximum output voltage and current.

# <C2633 (bench-top type)>

The C2633 is a programmable high-voltage power supply with a built-in GP-IB interface. The output voltage settings and on/off operations can be controlled with a personal computer by simple programming.

### SPECIFICATIONS

| Parameter | Value |
|---|---|
| Output Voltage | ±200 to ±3071Vdc |
| Output Current Ⓐ | 5mA Max. |
| Line Regulation Against ±10% Line Voltage Change Ⓑ | ± (0.001%+0.01V) Max. |
| Load Regulation Against 0 to 100% Load Change Ⓐ | ± (0.005%+0.05V) Max. |
| Ripple / Noise (p-p) Ⓒ | 0.0005%p-p Max. |
| Output Voltage Resolution | 1V |
| Built-in Computer Interface | IEEE-488 (GP-IB) |
| Input Voltage | 100/120/230Vac (50/60Hz) |

NOTE : Ⓐ At maximum output voltage.
Ⓑ At maximum output voltage and current.
Ⓒ Excluding switching noise.

# <C3350 (bench-top type)>

The C3350 is a bench-top high-voltage power supply designed for general-purpose photomultiplier tube applications.

### SPECIFICATIONS

| Parameter | Value |
|---|---|
| Output Voltage | 0 to ±3000Vdc |
| Output Current Ⓐ | 10mA Max. |
| Line Regulation Against ±10% Line Voltage Change Ⓑ | ± (0.005%+10mV) Max. |
| Load Regulation Against 0 to 100% Load Change Ⓐ | ±(0.01%+50mV) Max. |
| Ripple / Noise (p-p) Ⓑ | 0.0007%p-p Max. |
| Input Voltage | 100/115/220/230Vac ±10% (50/60Hz) |

NOTE : Ⓐ At maximum output voltage and current.
Ⓑ At maximum output voltage.

## <C3360 (bench-top type)>

The C3360 is a bench-top high-voltage power supply specifically designed for the MCP-PMT operation.

**SPECIFICATIONS**

| Parameter | Value |
|---|---|
| Output Voltage | 0 to –5000Vdc |
| Output Current Ⓐ | 1mA Max. |
| Line Regulation Against ±10% Line Voltage Ⓑ | ± (0.001%+0.05V) Max. |
| Load Regulation Against 0 to 100% Load Change Ⓐ | ± (0.001%+0.05V) Max. |
| Ripple / Noise Ⓑ | 0.0004%p-p Max. |
| Input Voltage | 85 to 132Vac / 170 to 264Vac |

NOTE : Ⓐ At maximum output voltage.
Ⓑ At maximum output voltage and current.

# ● Coolers

## <C4877 series, C4878 series>

In addition to high cooling capability, the C4877 series and C4878 series thermoelectric coolers are constructed with enhanced electrostatic and magnetic shielding. This minimizes the influence of external noise on the photomultiplier tube and thus significantly improves photometric accuracy. These coolers offer user-friendly functions such as easy temperature control and pilot lamp blanking.
The C4877 series are designed for use with 38mm (1-1/2") or 51mm (2") diameter head-on photomultiplier tubes and can be used with the E2762 series socket assembly or the C2759 series socket assembly with a built-in preamplifier ideal for photon counting. The C4878 series cooler are specifically designed for MCP-PMTs. (The E3059-500 holder is available.)

**SPECIFICATIONS**

| Parameter | Description / Value |
|---|---|
| Cooling | Thermoelectric Effect |
| Heat Exchange Medium | Water |
| Flow Rate | 1 to 3L/min |
| Temperature Controllable Range (with cooling water at +20°C) | –30 to 0°C |
| Input Voltage | 100/120/230Vac ±10% (50/60Hz) |

## <C659 series>

The C659 series is a water-cooled thermoelectric cooler that reduces photomultiplier tube temperature to –20°C (C659-50) or –15°C (C659-70). The C659-50 is designed for 28mm (1-1/8") and 38mm (1-1/2") diameter head-on photomultiplier tubes. The C659-70 is specifically intended for use with 28mm (1-1/8") diameter side-on photomultiplier tubes. The E1135 series D-type socket assemblies are also provided for exclusive use with the C659 series coolers.

**SPECIFICATIONS**

| Parameter | C659-50 series | C659-70 series |
|---|---|---|
| Cooling | Thermoelectric Effect | |
| Heat Exchange Medium | Water | |
| Flow Rate | 1 to 3L/min | |
| Cooling Temperature Ⓐ | Approx. –20°C | Approx. –15°C |
| Input Voltage | 115/220Vac ±10% (50/60Hz) | |

Ⓐ Cooling water :+20°C, Cooling temperature differs depending on photomultiplier tube type.

# Housing

## <E1341 series>

The E1341 series housing can contain a 51mm (2") diameter head-on photomultiplier tube or an E4512 D-type socket assembly, and is intended for use at room temperature. The E1341 series provides complete light shielding and magnetic shielding to eliminate external noise. It can be easily attached to such equipment as a monochromator by the aid of a simple adapter and also allows an optical shutter (Copal No.3) to be installed.

# High-Speed Amplifier

## <C5594 series>

The C5594 series is a wide-band amplifier with a high gain. The frequency cutoff is as high as 1.5GHz, enabling amplification of high-speed output pulses from all types of photomultiplier tubes with good fidelity. In particular, the C5594 series is ideally suited for fluorescence lifetime measurement in single photon level using an MCP-PMT and other timing property measurements using high-speed photomultiplier tubes. The input/output connectors are available in either BNC or SMA configuration. For more details, refer to the individual catalog.

**SPECIFICATIONS**

| Parameter | Value |
|---|---|
| Input Voltage | +12 to +16V |
| Maximum Input Signal Power | +10dBm |
| Frequency Bandwidth (–3dB) | 50k to 1.5GHz |
| Gain | 36dB (63 Times) |
| Input / Output Impedance | 50Ω |
| Current Consumption | 95mA |

# D-type Socket Assemblies

Hamamatsu provides D-type socket assemblies using a voltage divider circuit tailored for photon counting. A variety of types are available for use with different size photomultiplier tubes.

13mm (1/2") diameter side-on tubes ............ E850-22
28mm (1-1/8") diameter side-on tubes ......... E717-500, -501
10mm (3/8") diameter head-on tubes .......... E1761-21, -22
13mm (1/2") diameter head-on tubes .......... E849-52, -90
19mm (3/4") diameter head-on tubes .......... E974-17, -18, -22
25mm (1") diameter head-on tubes ............. E2924-500
28mm (1-1/8") diameter head-on tubes ....... E990-500, E2624-500
52mm (2") diameter head-on tubes ............. E2979-501, E4512-500, -501, -502

Besides those listed above, D-type socket assemblies specifically designed for use with coolers are provided. Please contact our sales office.

For C659 series coolers .............................. E1135-500, -501, -502, -503, -504
For C4877 series coolers ............................ E2762-500, -502, -503, -504, -506

We have C6270, which has built-in high voltage power supply with divider, for 28mm (1-1/8") diameter side-on photomultiplier tube available so please contact our sales office.

## ⚠WARNING

HIGH VOLTAGE

- High voltage power supplies and other products contained in this brochure generate or exhibit hazardous voltage and may present an electric shock hazard.
- The products contained in this brochure should be installed, operated, or serviced only by qualified personnel that have been instructed in handling high voltages.
- The products contained in this brochure should be installed, operated, or serviced in accordance with what are instructed in their instruction manuals and other relevant Hamamatsu publications.
- Designs of equipment utilizing the products contained in this brochure should incorporate appropriate interlocks to protect the operator and service personnel from electric shocks.

**Subject to local technical requirements and regulations, availability of products included in this promotional material may vary.**
**Please consult with our sales office.**

## Table 1 : Typical Photomultiplier Tubes for Photon Counting

| Type No. | Wavelength Region | Configuration | Spectral Response (nm) | Effective Area (mm) | Photocathode QE | | Maximum Supply Voltage (V) |
|---|---|---|---|---|---|---|---|
| | | | | | QE Peak (%) | Wavelength (nm) | |
| R166P | VUV to UV | 28mm side | 160 to 320 | 8×24 | 35 | 200 | 1250 |
| R1259P | | 28mm side | 115 to 195 | 8×14 | 24 | 120 | 1250 |
| R7207-01 | UV to Visible | 28mm head | 160 to 650 | ϕ 10 | 22 | 420 | 1500 |
| R585 | | 52mm head | 160 to 650 | 5×8 | 22 | 390 | 1500 |
| R3235-01 | | 52mm head | 160 to 650 | ϕ 10 | 22 | 390 | 2500 |
| R3809U-52 | | MCP-PMT | 160 to 650 | ϕ 11 | 18 | 420 | 3400 |
| R6353P | | 13mm side | 185 to 680 | 4×13 | 23 | 330 | 1250 |
| R3810P | | 13mm side | 185 to 650 | 3×4 | 20 | 270 | 1250 |
| R1527P | | 28mm side | 185 to 680 | 8×24 | 19 | 300 | 1250 |
| R2693P | | 28mm side | 185 to 650 | 18×16 | 22 | 270 | 1250 |
| R4220P | | 28mm side | 185 to 710 | 8×24 | 23 | 320 | 1250 |
| R1635P | Visible | 10mm head | 300 to 650 | ϕ 8 | 26 | 390 | 1500 |
| R647P | | 13mm head | 300 to 650 | ϕ 10 | 26 | 390 | 1250 |
| R2557 | | 13mm head | 300 to 650 | ϕ 10 | 20 | 375 | 1500 |
| R7400P | | 16mm head | 300 to 650 | ϕ 8 | 21 | 360 | 1000 |
| R2295 | | 19mm head | 300 to 650 | ϕ 4 | 22 | 390 | 1250 |
| R5610 | | 19mm head | 300 to 650 | ϕ 15 | 20 | 375 | 1250 |
| R1924P | | 25mm head | 300 to 650 | ϕ 21 | 26 | 390 | 1250 |
| R3550 | | 25mm head | 300 to 650 | ϕ 21 | 20 | 375 | 1250 |
| R7205-01 | | 28mm head | 300 to 650 | ϕ 10 | 22 | 420 | 1500 |
| R6095P | | 28mm head | 300 to 650 | ϕ 25 | 28 | 390 | 1000 |
| R464 | | 52mm head | 300 to 650 | 5×8 | 22 | 390 | 1500 |
| R329P | | 52mm head | 300 to 650 | ϕ 46 | 26 | 390 | 2700 |
| R3234-01 | | 52mm head | 300 to 650 | ϕ 10 | 22 | 390 | 2500 |
| 1P21(P) | | 28mm side | 300 to 650 | 8×24 | 15 | 340 | 1250 |
| R7400P-01 | Visible to Near Infrared | 16mm head | 300 to 850 | ϕ 8 | 19<br>0.19 | 370<br>800 | 1000 |
| R1878 | | 19mm head | 300 to 850 | ϕ 4 | 20<br>0.3 | 340<br>800 | 1250 |
| R2262P | | 25mm head | 300 to 900 | ϕ 21 | 6<br>1 | 600<br>800 | 1250 |
| R7206-01 | | 28mm head | 300 to 850 | ϕ 10 | 20<br>0.4 | 420<br>800 | 1500 |
| R2228P | | 28mm head | 300 to 900 | ϕ 25 | 6<br>1 | 600<br>800 | 1500 |
| R649 | | 52mm head | 300 to 850 | 5×8 | 20<br>0.3 | 340<br>800 | 1500 |
| R3310-02 | | 52mm head | 300 to 1010 | 10×10 | 13<br>0.25 | 340<br>1000 | 2200 |
| R1463P | UV to Near Infrared | 3mm head | 185 to 850 | ϕ 10 | 22<br>0.3 | 270<br>800 | 1250 |
| R1104P | | 28mm head | 185 to 850 | ϕ 25 | 23<br>0.3 | 270<br>800 | 1500 |
| R3237-01 | | 52mm head | 160 to 850 | ϕ 10 | 23<br>0.3 | 420<br>800 | 2500 |
| R943-02 | | 52mm head | 160 to 930 | 10×10 | 22<br>12 | 300<br>800 | 2200 |
| R3809U-50 | | MCP-PMT | 160 to 850 | ϕ 11 | 18<br>7 | 420<br>600 | 3400 |
| R6358P | | 13mm side | 185 to 830 | 4×13 | 24<br>13 | 240<br>600 | 1250 |
| R4632 | | 28mm side | 185 to 850 | 8×24 | 26<br>11 | 270<br>600 | 1250 |
| R928P | | 28mm side | 185 to 900 | 8×24 | 25<br>2.7 | 260<br>800 | 1250 |
| R2949 | | 28mm side | 185 to 900 | 8×6 | 25<br>2.7 | 260<br>800 | 1250 |
| R636P | | 28mm side | 185 to 930 | 3×12 | 24<br>8 | 330<br>800 | 1500 |
| R2658P | | 28mm side | 185 to 1010 | 3×12 | 14<br>0.13 | 330<br>1000 | 1500 |

Ⓐ Characteristics are measured at a supply voltage giving a gain of $2\times10^5$.

Ⓑ Characteristics are measured at 1500V, regardless of gain.

| Supply Voltage (Giving gain of 1×10⁶) | Dark Count | | | Rise Time (ns) | TTS (ns) | Remark | Type No. |
|---|---|---|---|---|---|---|---|
| | Typ. (cps) | Max. (cps) | Temp. (°C) | | | | |
| 800 | 5 | 20 | 25 | 2.2 | 1.2 | $MgF_2$ R1220P | R166P |
| 900 | 5 | 20 | 25 | 2.2 | 1.2 | | R1259P |
| 770 | 10 | 30 | 25 | 1.7 | 1.2 | Compact, Low Dark Counts | R7207-01 |
| 800 | 5 | 15 | 25 | 13.0 | – | Can be selectable for Low Dark Counts (3cps Max.) | R585 |
| 1500 | 200 | 600 | 25 | 1.3 | 0.45 | Fast Time Response | R3235-01 |
| 3000 Ⓐ | 20 | – | 25 | 0.15 | 0.025 | Fast Time Response | R3809U-52 |
| 800 | 10 | 30 | 25 | 1.4 | 0.75 | Compact , Low Dark Counts | R6353P |
| 750 | 5 | 10 | 25 | 1.4 | 0.75 | Compact | R3810P |
| 780 | 10 | 50 | 25 | 2.2 | 1.2 | Low Dark Counts | R1527P |
| 900 | 15 | 50 | 25 | 1.2 | 1.0 | Transparent Photocathode | R2693P |
| 730 | 10 | 50 | 25 | 2.2 | 1.2 | High Sensitivity , Low Dark Counts | R4220P |
| 1200 | 100 | 400 | 25 | 0.8 | 0.7 | | R1635P |
| 900 | 80 | 400 | 25 | 2.5 | 1.6 | | R647P |
| 1000 | 10 | 30 | 25 | 2.2 | – | Low Noise Bialkali Photocathode | R2557 |
| 800 | 80 | 400 | 25 | 0.78 | 0.23 | Metal Package | R7400P |
| 900 | 2 | 5 | 25 | 2.5 | 1.0 | Low Afterpulse | R2295 |
| 850 | 15 | 45 | 25 | 1.5 | – | Compact | R5610 |
| 1000 | 100 | 300 | 25 | 2.0 | – | Ruggedized | R1924P |
| 800 | 20 | 60 | 25 | 2.0 | – | For Ruggedized | R3550 |
| 770 | 10 | 30 | 25 | 1.7 | 1.2 | Compact, Low Dark Counts | R7205-01 |
| 900 | 100 | 250 | 25 | 4.0 | – | Replace R268P | R6095P |
| 1000 | 5 | 15 | 25 | 13.0 | – | Can be selectable for Low Dark Counts (3cps Max.) | R464 |
| 1500 | 200 | 600 | 25 | 2.6 | 1.0 | | R329P |
| 1500 | 50 | 150 | 25 | 1.3 | 0.45 | Fast Time Response | R3234-01 |
| 800 | 30 | 100 | 25 | 2.2 | 1.2 | | 1P21(P) |
| 800 | 500 | 1000 | 25 | 0.78 | 0.23 | Metal Package | R7400P-01 |
| 1100 | 100 | 250 | 25 | 2.5 | 1.0 | Low Dark Counts | R1878 |
| 1100 | 100 | 300 | –20 | 2.0 | – | Ruggedized | R2262P |
| 770 | 300 | 1000 | 25 | 1.7 | 1.2 | Compact, Low Dark Counts | R7206-01 |
| 1100 | 150 | 500 | –20 | 15.0 | – | Extended-Red Multialkali Photocathode | R2228P |
| 800 | 200 | 350 | 25 | 13.0 | – | Can be selectable for Low Dark Counts (100cps Max.) | R649 |
| 1700 | 30 | 150 | –20 | 3.0 | – | High Quantum Efficiency (at 1$\mu$ m) | R3310-02 |
| 1000 | 900 | 1000 | 25 | 2.5 | – | | R1463P |
| 750 | 4500 | 7000 | 25 | 15.0 | – | High Gain | R1104P |
| 1500 | 2000 | 5000 | 25 | 1.3 | 0.45 | Fast Time Response | R3237-01 |
| 1700 | 20 | 50 | –20 | 3.0 | – | For Raman Spectroscopy | R943-02 |
| 3000 Ⓐ | 200 | – | 25 | 0.15 | 0.025 | Fast Time Response | R3809U-50 |
| 830 | 20 | 50 | 25 | 1.4 | 0.75 | Compact , Low Dark Counts | R6358P |
| 830 | 50 | 100 | 25 | 2.2 | 1.2 | Low Dark Counts | R4632 |
| 720 | 500 | 1000 | 25 | 2.2 | 1.2 | | R928P |
| 720 | 300<br>3 | 500<br>– | 25<br>–20 | 2.2 | 1.2 | | R2949 |
| 1300 | 15 | 50 | –20 | 2.0 | 1.2 | | R636P |
| 1500Ⓑ | 50 | 300 | –20 | 2.0 | 1.2 | For Raman Spectroscopy | R2658P |

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