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(7) Plateau characteristic

The plateau characteristic is useful in simple scintillation counting which does not use a pulse height analyzer. The plateau characteristic is measured by setting a discrimination level and counting all pulses with amplitudes greater than that level. This operation is done while changing the supply voltage for the photomultiplier tube. The measured data is plotted on a graph in which the abscissa indicates the supply voltage and the ordinate indicates the total number of counted pulses with amplitudes greater than the discrimination level. Figures 3-66 (a) and (b) show the typical plateau characteristic and pulse height distribution when a NaI(Tl) scintillator and ^{55}Fe radiation source are used.

With the discrimination level kept at a constant value, as the photomultiplier tube supply voltage is increased, the output pulses are counted in order from the photopeak region to the valley and the dark current regions. Plotting the count rate versus the photomultiplier tube supply voltage gives a curve like that shown in Figure 3-66 (a), which consists of three regions (regions A, B and C). Region B is referred to as the plateau and the supply voltage should be set within this region. The count rate will not vary even if the supply voltage is changed within this region, showing a constant photopeak count rate. The wider the plateau region, the less the count rate will be affected by fluctuations in the dark current. This plateau region corresponds to the valley of a pulse height distribution, i.e., region B' in Figure 3-66 (b). photomultiplier tubes with better energy resolution and lower dark current provide a wider region B'. Since the plateau region is expressed in terms of supply voltage range, photomultiplier tubes with smaller gain and lower noise tend to have a wider plateau range. With this method, however, it should be noted that energy analysis cannot be carried out because all pulses with amplitudes higher than the discrimination level are counted.

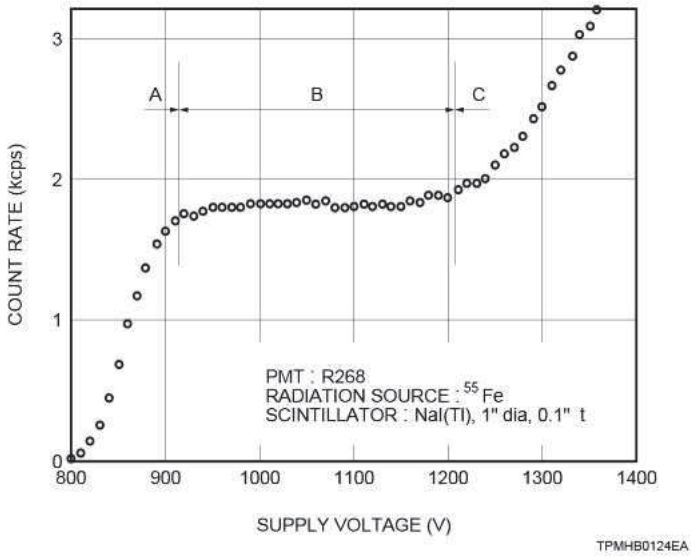


Figure 3-66: Plateau characteristic (a)

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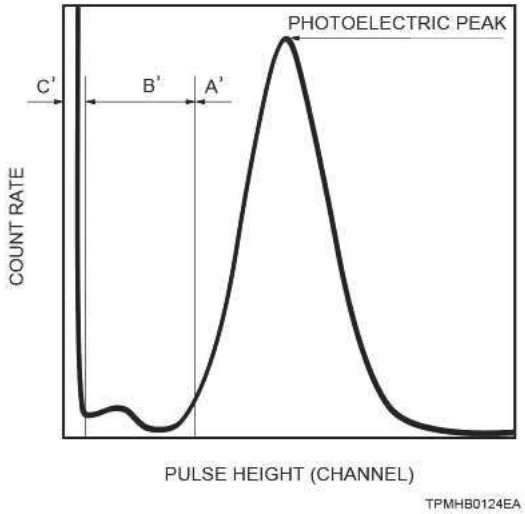


Figure 3-66: Plateau characteristic (b)

As an application example, plateau characteristics are widely employed to evaluate photomultiplier tubes designed for use in oil well logging where geological information is obtained based on the signal produced by Compton scattering. In this case, photomultiplier tubes are also evaluated using a ^{137}Cs radiation source and a NaI(Tl) scintillator. Typical plateau characteristics are shown in Figure 3-67.

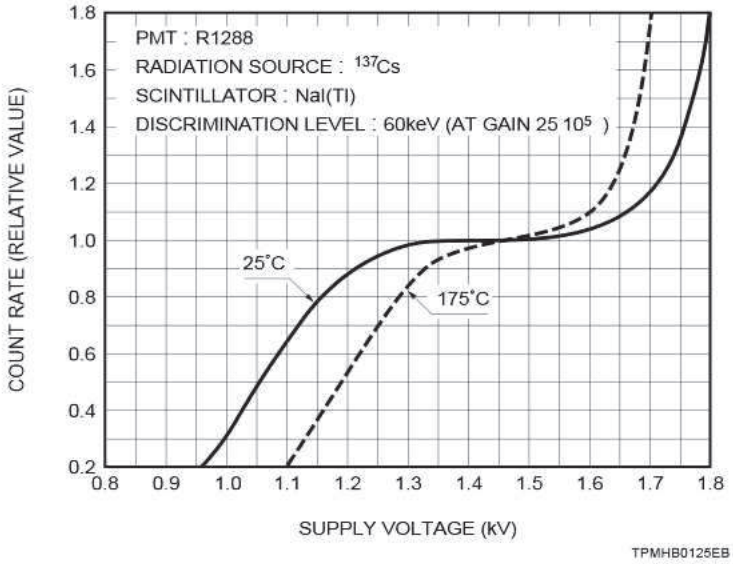


Figure 3-67: Typical plateau characteristics of a photomultiplier tube designed for high temperature operation

To measure the data shown in Figure 3-67, a photomultiplier tube designed for high temperature operation is used. The plateau characteristic taken at 175°C is shown along with that obtained at 25°C. It can be seen from the figure that the supply voltage at which the signal appears (corresponding to region A in Figure 3-66 (a)) shifts to the higher voltage side. This is because the gain of the photomultiplier tube decreases as the temperature increases. On the other hand, since the dark current increases with temperature, the count rate sharply increases (corresponding to region C in Figure 3-66 (a)) at a lower supply voltage. Consequently, the plateau width (supply voltage range) measured at a higher temperature becomes narrow in comparison with that obtained at room temperatures (+25°C).

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MEMO

CHAPTER 4

MCP-PMT

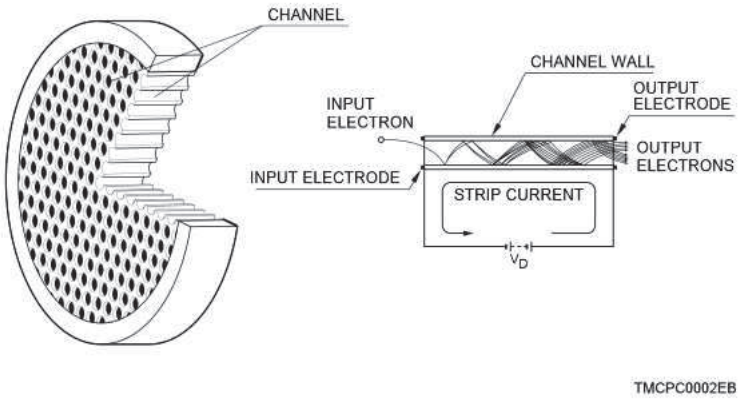
With the advent of the microchannel plate[1] (abbreviated as MCP hereafter), photomultiplier tubes have evolved as more versatile devices. MCP-PMTs - photomultiplier tubes that incorporate an MCP in place of the conventional discrete dynodes - offer wide-bandwidth measurements up to the picosecond region as well as low-light-level detection in the photon counting region. This chapter describes these ultrafast and high-sensitivity MCP-PMTs.[2]

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4. 1 Structure

4. 1. 1 Structure of MCPs

Figure 4-1 illustrates the schematic structure of an MCP. The MCP consists of a two-dimensional array of a great number of glass capillaries (channels) bundled in parallel and formed into the shape of a thin disk. Each channel has an internal diameter ranging from 6 to 20 microns with the inner wall processed to have the proper electrical resistance and secondary emissive properties. Accordingly, each channel acts as an independent electron multiplier. The cross section of a channel and its principle of multiplication are illustrated in Figure 4-1 (b). When a primary electron impinges on the inner wall of a channel, secondary electrons are emitted. Being accelerated by the electric field created by the voltage V_D applied across both ends of the MCP, these secondary electrons bombard the channel wall again to produce additional secondary electrons. This process is repeated many times along the channel and as a result, a large number of electrons are released from the output end.



(a) Schematic structure of an MCP **(b) Principle of multiplication**

Figure 4-1: Schematic structure of an MCP and its principle of multiplication

MCPs are quite different in structure and operation from conventional discrete dynodes and therefore offer the following outstanding features:

1) High gain despite compact size

2) Fast time response

3) Two-dimensional detection with high spatial resolution

4) Stable operation even in high magnetic fields

5) Sensitive to charged particles, ultraviolet radiation, X rays, gamma rays, and neutrons

6) Low power consumption

There are various types of detectors that utilize the advantages offered by MCPs, for example image intensifiers for low-light-level imaging, fast time response photomultiplier tubes that incorporate an MCP (MCP-PMTs), position-sensitive multianode photomultiplier tubes, streak tubes for ultra-fast photometry, and photon counting imaging tubes for ultra-low light level imaging.

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4. 1. 2 Structure of MCP-PMT

Figure 4-2 shows the cross section of a typical MCP-PMT. This tube consists of an input window, photocathode, MCP, and anode. The photoelectrons emitted from the photocathode enter the channels of the MCP and impinge on the inner wall where they are multiplied by means of secondary emission. This process is repeated along the channels, and finally a large number of electrons are collected by the anode as an output signal. The MCP is arranged at a distance of 2 millimeters or less from the photocathode, forming a close-proximity structure. A photograph of an actual MCP-PMT complete with housing is shown in Figure 4-3.

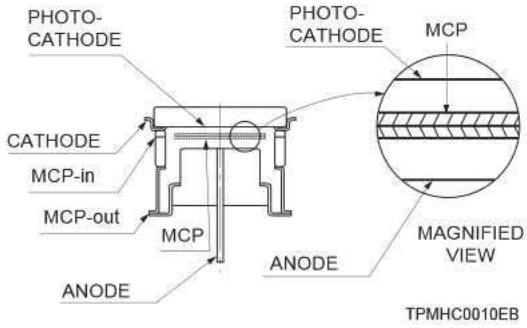


Figure 4-2 Cross section of a typical MCP-PMT



Figure 4-3 External view of an MCP-PMT

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4. 1. 3 Voltage -divider circuit and housing structure

Figure 4-4 shows a basic voltage-divider circuit used to operate an MCP-PMT (with a two-stage MCP) and the configuration of the housing that contains the MCP-PMT with the voltage-divider circuit.

As shown in the figure, a negative high voltage is normally applied to the photocathode, and the voltage-divider circuit gives a voltage gradient between the photocathode, MCP-in, MCP-out, and the anode by dividing the high voltage with properly selected resistors. The voltage-divider circuit and housing are designed with careful consideration given to prevent "ringing" which may be caused by high-frequency signals, so that the output waveform distortion is suppressed to a minimum level.

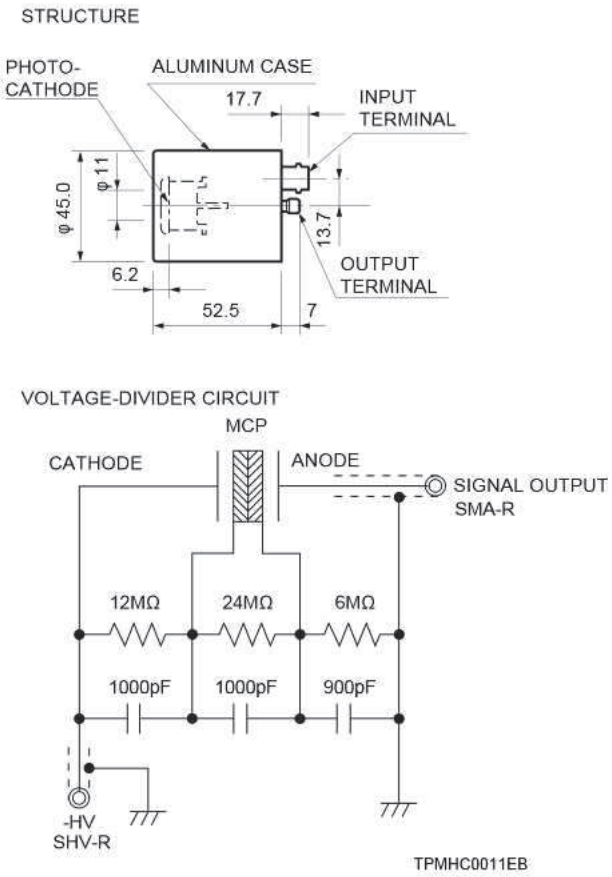


Figure 4-4: Housing configuration and operating circuit for MCP-PMT

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4. 2 Basic characteristics of MCP-PMTs

4. 2. 1 Gain characteristics[1)]

The gain of an MCP-PMT depends on the number of MCPs incorporated in the tube. Figure 4-5 shows a typical current amplification curve of an MCP-PMT.

The gain[1)] (μ) of an MCP is determined by the length-to-diameter ratio α (=L/d) of a channel, and approximated as follows:

$$\mu = EXP\ (G \cdot \alpha)$$

where G is the secondary emission characteristics called the gain factor. This gain factor is an inherent characteristics of the channel wall material and presented by a function of the electric field intensity inside the channel.

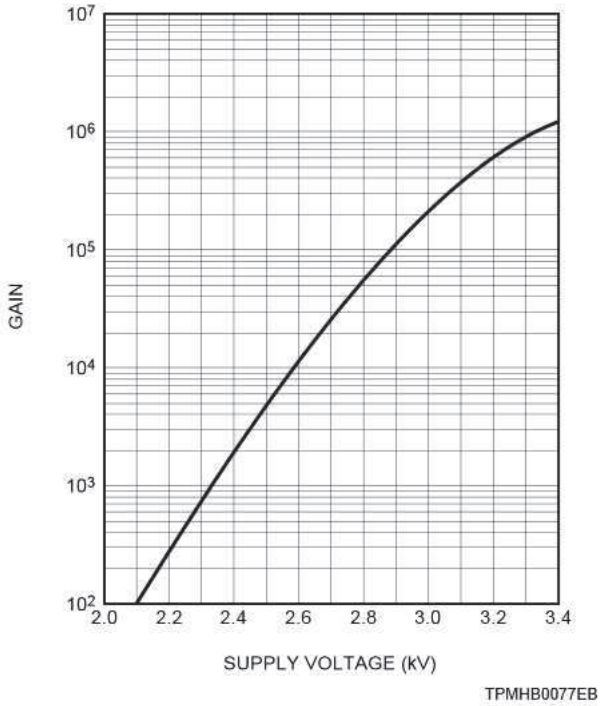


Figure 4-5: Typical gain of an MCP-PMT (using a two-stage MCP of 6μm channel diameter)

In general, the gain rising point moves to the higher voltage side as α is made greater. This also allows obtaining a higher gain. However, if the gain becomes higher than 10^4, noise begins to increase significantly due to ion feedback effects causing a serious problem. To avoid this, α is usually selected to be around 40 so that a single MCP provides a gain of about 10^4 at 1kV supply voltage.

As shown in Figure 4-5 above, a higher gain can be obtained from a two-stage MCP-PMTs. This gain level enables photon counting measurements.

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4. 2. 2 Dead time[1)]

When an MCP is irradiated by a pulsed electron current, a positive charge is generated at the MCP output end in accordance with the released electron current. This phenomenon deforms the potential distribution and enfeebles the electric fields so that the subsequent electron multiplication is suppressed. This charge is neutralized by the strip current flowing through the channel wall. However, a certain amount of time is required for neutralization because the strip current is small due to the high resistance of the MCP. The gain of signals entering within this period is usually low. The time required for neutralization is referred to as the dead time or recovery time. If the output charge per channel is given by Qout and the strip current per channel by Is, then the dead time t_d is given by the following relation:

$$t_d = Qout / Is$$

The dead time can be shortened by using a low resistance MCP which allows the strip current Is to flow in large quantities. This also improves saturation characteristics.

When an MCP-PMT is operated in such a way that the next electron enters the MCP within this dead time, various types of output saturation occur as described in 4.2.3. If the MCP-PMT is operated at saturated levels, it cannot exhibit adequate performance, and also degrades the photocathode sensitivity and MCP gain.

4. 2. 3 Saturation characteristics[1)]

In general, the saturation of a photodetector is defined as the phenomenon in which the amount of output signal is no longer proportional to the incident light intensity. In the case of MCP-PMTs, this saturation is caused by the dead time as described in 4.2.2, disturbed potential distribution and space charge effects inside the MCP, being different from those of normal photomultiplier tubes using multiple stages of discrete dynodes.

(1) Saturation in DC operation

An MCP has a high resistance ranging from several tens to several hundreds of megohms, which limits the output current from the MCP. Because of this, output current saturation occurs as the input current increases, as shown in Figure 4-6 (a) and (b). This is mainly caused by a decrease in the electric field intensity due to variations in the potential distribution at the output end of the MCP which results from large amounts of secondary electrons from the MCP.

The decrease in the electric field intensity is recovered by the strip current flowing through the channel wall. Saturation in DC operation usually begins to occur when the output current reaches 5 or 6 percent of the strip current.

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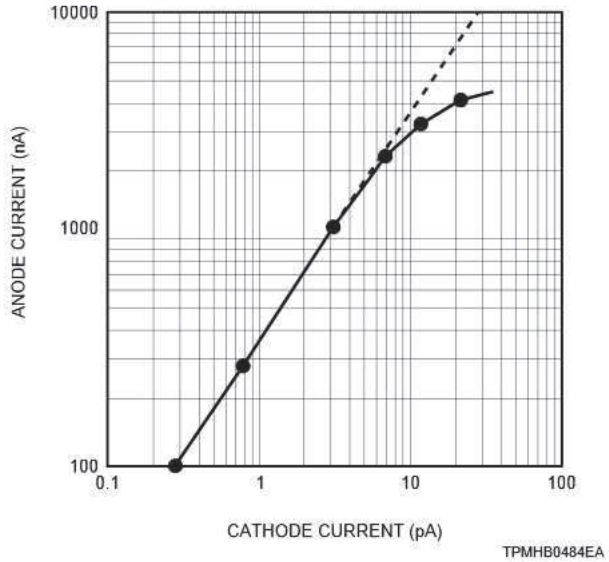


Figure 4-6 (a): Saturation characteristics of MCP-PMT in DC operation

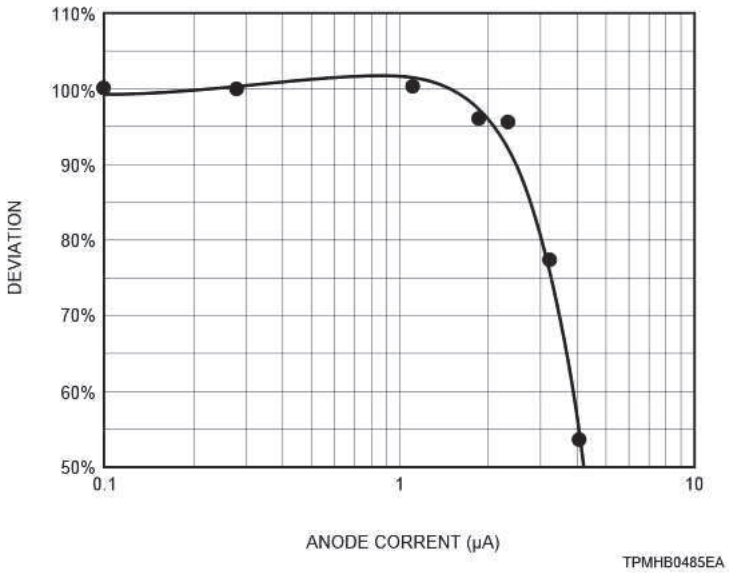
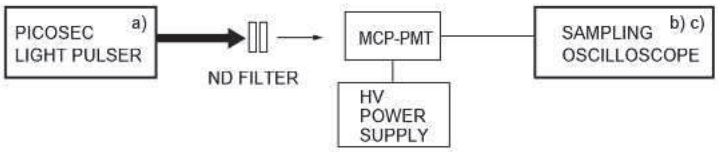


Figure 4-6 (b): Saturation characteristics of MCP-PMT (R3809U-05) in DC operation

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(2) Pulse gain saturation characteristics (pulse linearity)

When pulsed light in an extremely short duration enters the MCP-PMT, the output linearity can be maintained to some extent. Figure 4-7 shows the linearity data of an MCP-PMT when it detects pulsed light.



a) PICOSEC LIGHT PULSER: PLP-01 (HAMAMATSU)
WAVELENGTH: 780nm
FWHM: 50ps
b) SAMPLING OSCILLOSCOPE: 11802 (TEKTRONIX)
FREQUENCY BAND: 20GHz
c) SAMPLING HEA: SD-26D

TPMHB0079EB

Figure 4-7 (a): Block diagram for MCP-PMT pulse linearity measurement

Figure 4-7 (b): Typical pulse linearity of an MCP-PMT (R3809U-50)

Figure 4-7 (a) shows a block diagram for measuring pulse linearity. A picosecond light pulser (Hamamatsu PLP-01) is used as the light source. The intensity of the pulsed light is adjusted by ND (neutral density) filters and input to the MCP-PMT. Figure 4-7 (b) shows a typical pulse linearity plot for a proximity-focused MCP-PMT measured at a pulse repetition rate of 300Hz to 30kHz. Pulse currents up to 350 milliamperes can be extracted at a repetition rate of 300Hz or less. The maximum pulse current at a low repetition rate is determined by the product of the number of electrons released from one channel governed by space charge effects and the number of MCP channels. On the contrary, the maximum pulse current at a high repetition rate is determined by the ratio of the strip current to the total amount of charge which is the product of the charge per pulse and the repetition rate.

When the repetition rate is too high, the MCP gain begins to drop because the next pulse enters within the dead time, causing the output saturation.

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(3) Saturation gain characteristics in photon counting mode

Figure 4-8 shows pulse height distributions of photoelectron signals and dark current pulses taken with an MCP-PMT in the photon counting mode. Since the MCP is operated in the saturation range, a distinct pulse height distribution for the signals is obtained.

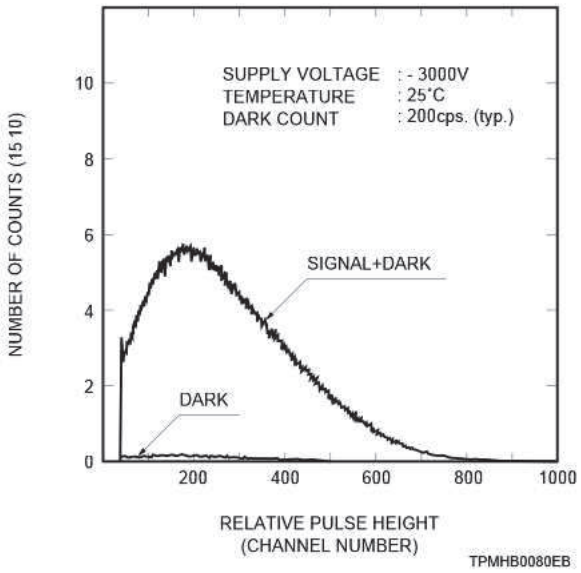


Figure 4-8: Typical pulse height distribution in single photon counting

Figure 4-9 illustrates a block diagram for measuring the count-rate pulse linearity in photon counting. Light intensity is reduced by neutral density filters down to the single photoelectron level. The number of single photoelectron pulses is counted by the counter circuit connected to the MCP-PMT, and the count rate is measured and plotted while changing the number of incident photons.

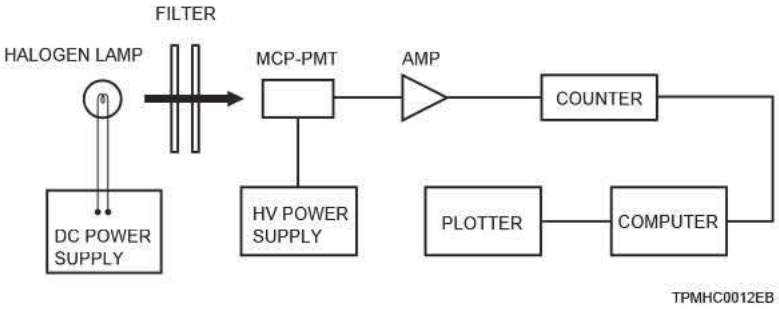


Figure 4-9: Block diagram for measuring count-rate linearity in photon counting mode

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Figure 4-10 shows count-rate linearity data measured in photon counting mode. A good linearity is maintained up to 10^7 counts/second (cps).

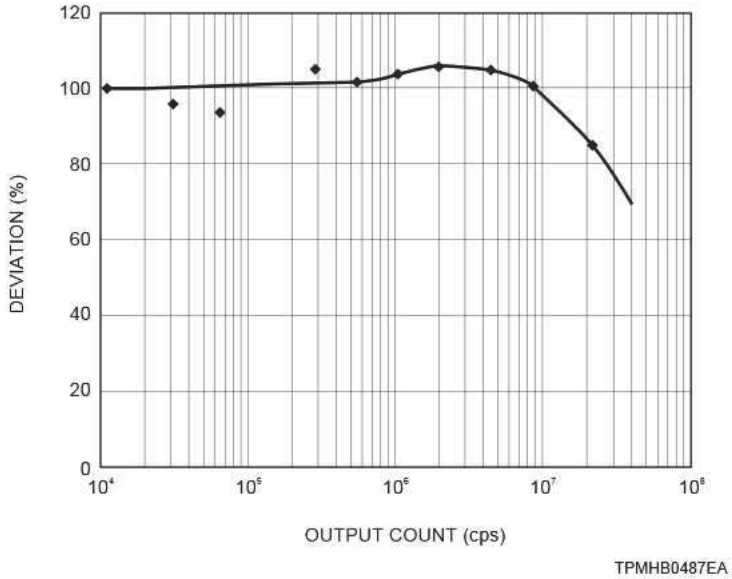


Figure 4-10: MCP-PMT (R3809U-50) count-rate linearity in photon counting mode

4. 2. 4 Time characteristics[2)]

As discussed in the previous chapter on photomultiplier tube time characteristics, the signal pulse broadens along time in the multiplication process from the photocathode to the anode. This is due to the emission-angle distribution and initial-velocity distribution of photoelectrons and secondary electrons, as well as the effects of the accelerating lens. Since MCP-PMTs employ an MCP in place of conventional dynodes, the electron transit time in the secondary electron multiplication process is very short, thus resulting in a significant improvement in the transit time spread. In addition, because a nearly parallel electric field is applied between the photocathode, MCP and anode, the emission-angle distribution and initial-velocity distribution of photoelectrons can be virtually ignored.

(1) Rise/fall times

The rise and fall times of an MCP-PMT are evaluated from the output waveform when the MCP-PMT detects a light pulse whose width is sufficiently short compared to the time response of the MCP-PMT. These parameters are especially important when observing the waveform of ultra-short pulsed light. For the measurement method, refer to Section 3.3.1, "Time characteristics". Figure 4-11 shows an actual waveform obtained with an MCP-PMT.

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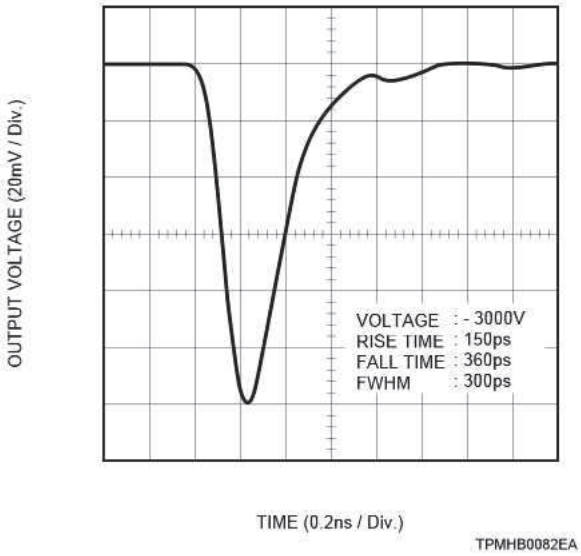


Figure 4-11: Pulse response waveform of MCP-PMT (R3809U-50)

(2) Transit time

The transit time is the time delay between the input of a light pulse at the photomultiplier tube and the appearance of the output pulse from the photomultiplier tube. For the measurement method, refer to Section 3.3.1, "Time characteristics".

(3) TTS (transit time spread)

When a light pulse enters an MCP-PMT, the photocathode converts the light energy into an electron pulse which travels to the anode while being multiplied. The transit time of each pulse differs depending on each event. The distribution of this transit time is referred to as the transit time spread or TTS. The TTS of an MCP-PMT is measured with the incident light intensity reduced down to single photon levels. The TTS is an important parameter, especially in the time-correlated photon counting technique[3)] where the measurement of timing is of prime consideration. For the measurement method, refer to Section 3.3.1, "Time characteristics".

At Hamamatsu Photonics, TTS is evaluated with the measurement system shown in Figure 4-12. In this system, the IRF (instrument response function) value is measured as the time characteristic for the entire system including the MCP-PMT. This is because the measurement system uses a laser pulse with approximately 35 picosecond pulse width, which act as a time jitter equal to the TTS of the MCP-PMT. The relation between the TTS and IRF is given by the following equation.

$$(IRF)^2 = (TTS)^2 + Tw^2 + Tj^2$$

TW : laser pulse width

Ti : other time jitter in the measurement system

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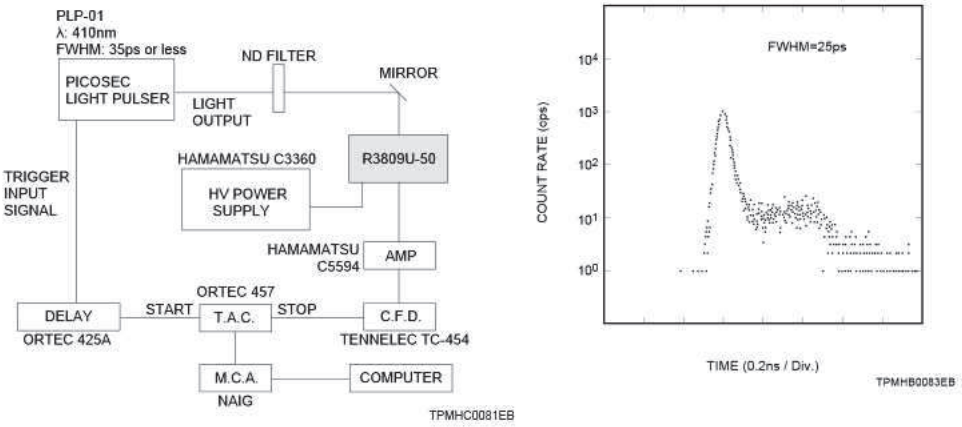


Figure 4-12: IRF measurement using MCP-PMT (R3809U-50)

To evaluate the TTS of an MCP-PMT more accurately, the measurement system shown in Figure 4-13 is used and excellent data of 25.0 picoseconds has been obtained. This system uses a laser pulse with a 5 picosecond pulse width which is shorter than the TTS of the MCP-PMT, therefore enabling accurate measurements.

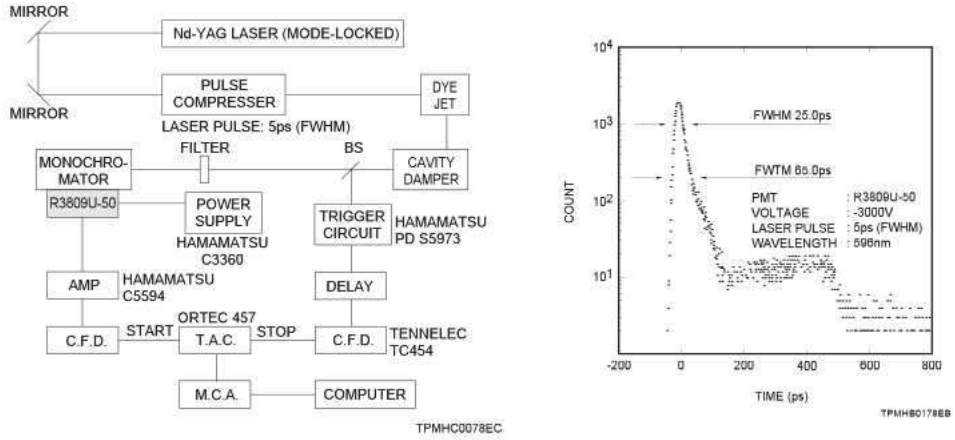


Figure 4-13: Accurate TTS measurement of MCP-PMT (R3809U-50)

(4) Cathode transit time difference

In most photomultiplier tubes, the electron transit time differs with the position of photocathode illumination. When the entire photocathode is uniformly illuminated, the difference in transit time with respect to position is referred to as the cathode transit time difference or CTTD. The CTTD usually affects the TTS, but in the case of proximity-focused MCP-PMTs, it has little effect on the TTS. For the measurement method, refer to Section 3.3.1, "Time characteristics".

(5) Time characteristics of various products

Time characteristics of various MCP-PMTs are summarized in Table 4-1 below. The less the number of MCP stages and the smaller the channel diameter, the better the time characteristics. Compared to conventional MCP-PMTs using 12mm channel MCPs, the R3809U series using 6mm channel MCPs has improved the rise time by 70 picoseconds and the IRF by 25 picoseconds. The fall time does not show a correlation with the rise time. This is probably due to the difference in electrostatic capacity between the

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MCP and the anode. The gated MCP-PMT is slightly inferior in time characteristics compared to other types. This is presumably because the electric field between the gate mesh and the cathode is weak so that the photoelectron emission angle and initial velocity distribution tend to affect the time characteristics adversely to some extent.

MCP-PMT Type No	Rise Time	Fall Time	Transit Time	IRF (FWHM)
R3809U-50 (6μm/2-stages)	150ps	360ps	400ps	45ps
R5916U-50 (6μm/2-stages)	180ps	700ps	350ps	95ps
R7024U (6μm/2-stages)	110ps	120ps	400ps	–

Table 4-1: Comparison of MCP-PMT time characteristics

Here, let us introduce the R7024 MCP-PMT which offers significant improvements in rise and fall times. The structure of the R7024 is shown in Figure 4-14. This tube has been developed specifically for use in ultra-fast photometry. A mesh electrode is provided between the MCP and the anode as shown in the figure, and the signal output method differs from ordinary MCP-PMTs. The mesh between the MCP and the anode cancels out the displacement current generated at the time that the secondary electrons emitted from the MCP are accelerated towards the anode. Figure 4-15 shows a typical output waveform from the R7024. Ultrafast time response with 110 picosecond rise time and 120 picosecond fall time is obtained.

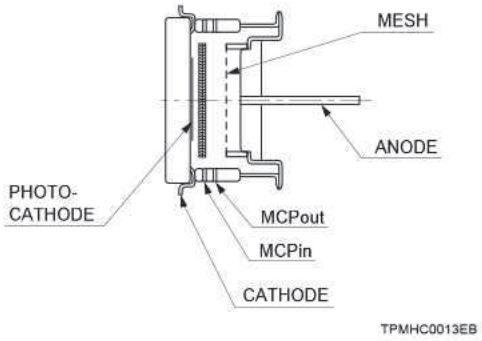


Figure 4-14: Structure of the R7024

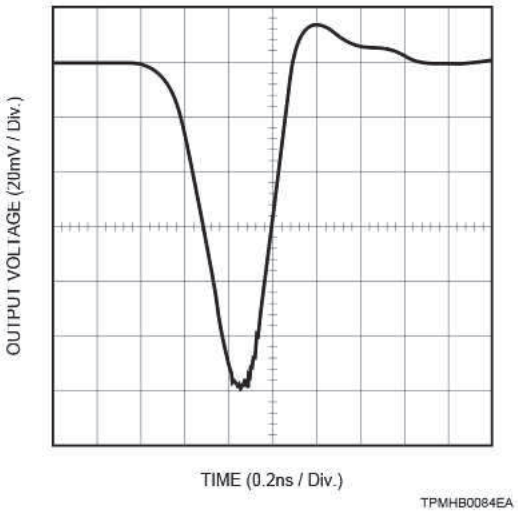


Figure 4-15: Time response waveform of the R7024U

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4. 2. 5 Magnetic characteristics[2)]

As stated in the section on photomultiplier tubes designed for use in highly magnetic environments, the following points are essential to improve magnetic characteristics.

(1) The distance between the photocathode, dynodes and anode should be shortened to minimize the electron transit distance.

(2) The electrodes should be designed to apply a parallel electric field from the photocathode to the anode so that the secondary electrons do not converge but travel in parallel to the tube axis.

(3) A high electric field intensity should be applied.

The MCP-PMT meets all the above requirements and thus provides superior magnetic characteristics. Figure 4-16 shows typical magnetic characteristics of an MCP-PMT. The extent of the effect of a magnetic field on the output depends on the direction of the magnetic field with respect to the MCP axis. In magnetic fields parallel to the tube axis, the MCP-PMT can operate at up to 2.0 Tesla (20 kilogausses), but in magnetic fields perpendicular to the tube axis, the output drops drastically if fields exceed 0.07 Tesla (700 gauss).

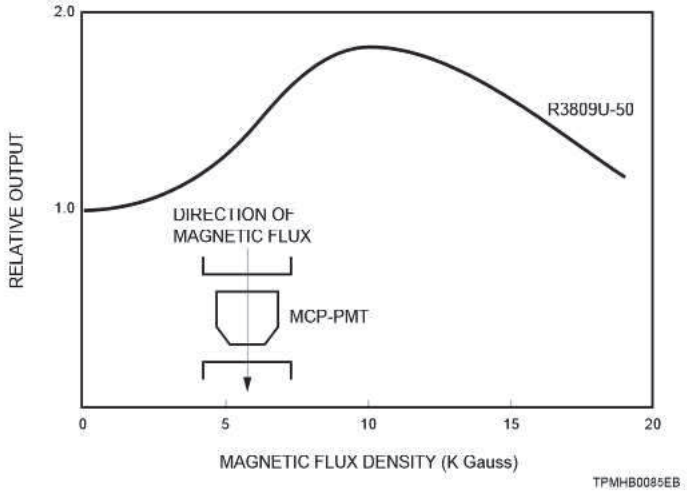


Figure 4-16 (1): Typical magnetic characteristics of an MCP-PMT (in magnetic fields parallel to tube axis)

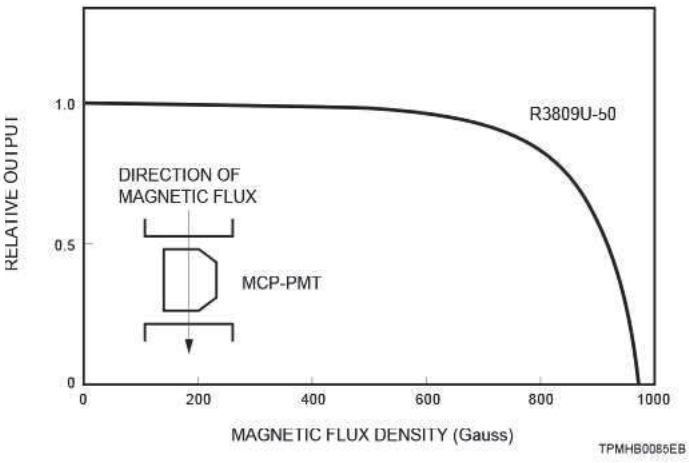


Figure 4-16 (2): Typical magnetic characteristics of an MCP-PMT (in magnetic fields perpendicular to tube axis)

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4. 3 Gated MCP-PMT[2)]

In applications in fields such as fluorescence lifetime measurement, laser Raman spectroscopy, and laser radar, photodetectors with a gate function are often required for more precise measurements. The gate function should have the following performance characteristics:

(1) Highest possible gating speed

(2) Large switching ratio (gate on/off ratio)

(3) Low switching noise

Figure 4-17 illustrates the structure of a gated MCP-PMT (R5916U-50). This tube basically consists of a photocathode, gate mesh, MCP and anode. The gating function is performed by controlling the gate mesh which is positioned in close proximity to the photocathode as shown in Figure 4-17. Applying a reverse potential with respect to the photocathode potential to the gate mesh sets the "off" mode, while applying a forward potential sets the gate operation "on" mode.

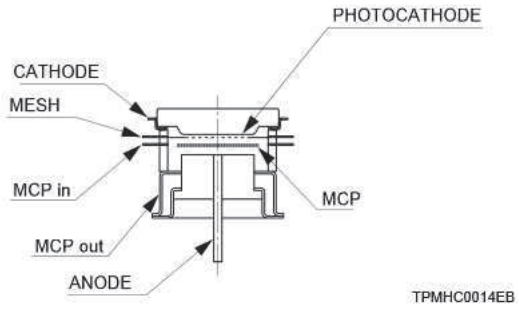


Figure 4-17: Structure of an MCP-PMT with gate mesh

Figure 4-18 shows the basic characteristic of the gate function for a typical switching ratio taken with a gated MCP-PMT operating under static conditions. This data was measured with the photocathode potential maintained at 0 volts and proves that the switching ratio is better than 10^{-8} (incident light wavelength: 500 nanometers).

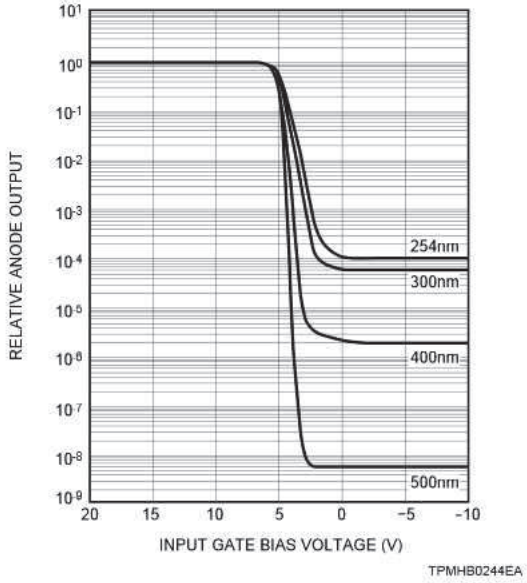


Figure 4-18: Switching ratio characteristic under static operating conditions

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Figure 4-19 shows the dynamic gate performance obtained with a gated MCP-PMT when a gate pulse is applied while continuous light is allowed to strike the tube. The gate operation starts in as little as one nano-second.

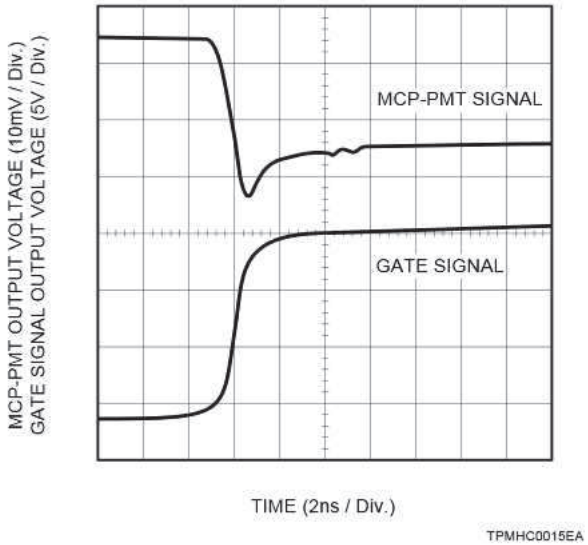


Figure 4-19: Dynamic gate characteristic

As explained above, the gated MCP-PMT offers significant improvement in gate speed and switching ratio in comparison with conventional photomultiplier tubes.

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4. 4 Multianode MCP-PMT[4)]

The previous sections mainly discussed MCP-PMTs having a single anode. A variety of MCP-PMTs with independent multianodes have been developed and utilized in practical use. These multianode MCP-PMTs offer simultaneous, two-dimensional (or one-dimensional) detection as well as fast response speed and low-light-level detection. The structure of a typical multianode MCP-PMT is illustrated in Figure 4-20.

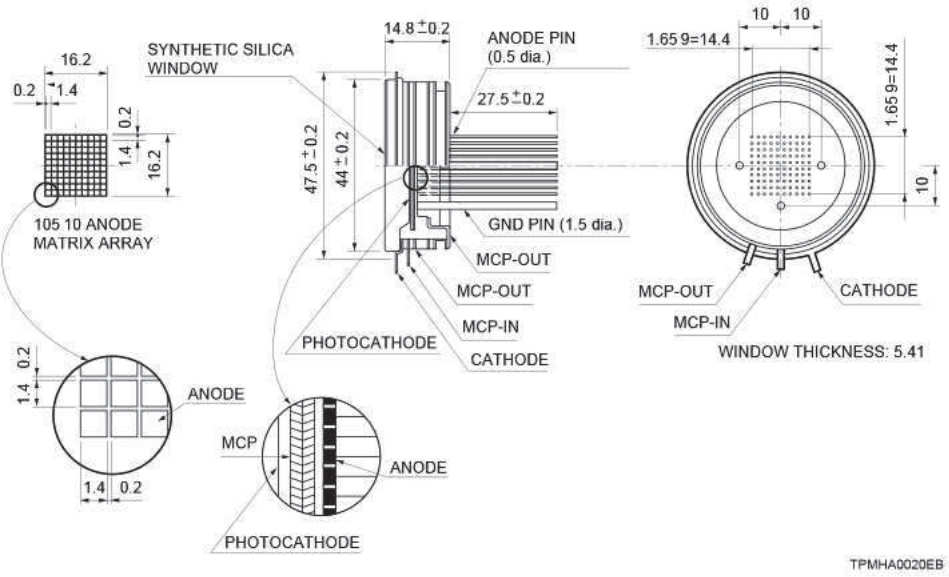


Figure 4-20: Multianode MCP-PMT with 105 10 anode format

Figures 4-21 (a) to (c) show the spatial resolutions of various multianode MCP-PMTs. These consist of the output profile of each anode when a light spot of approximately 20μm diameter is scanned over the photocathode.

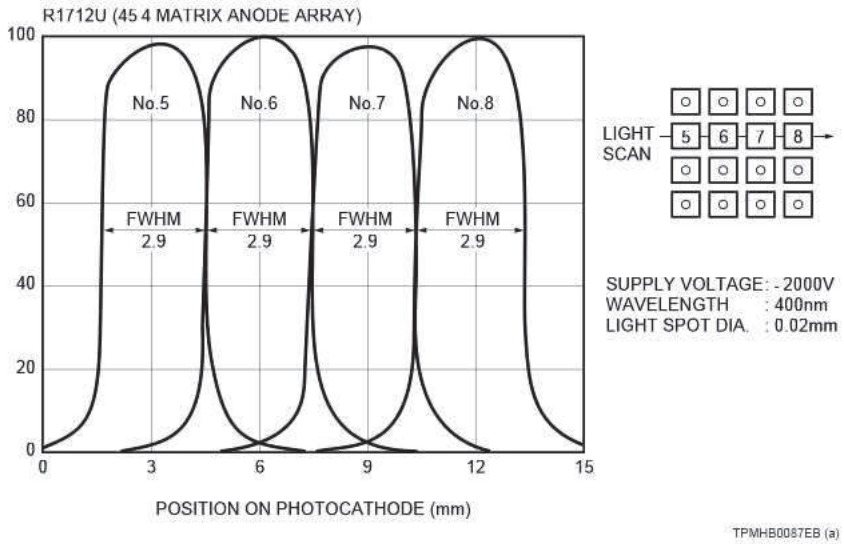


Figure 4-21 (a): Spatial resolution of 454 multianode MCP-PMT

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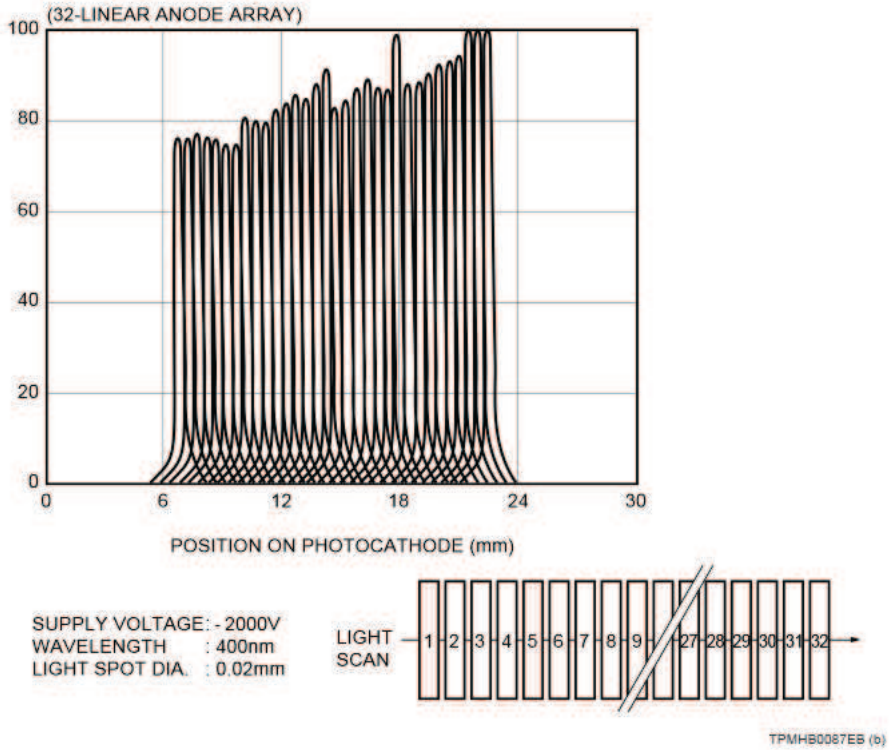


Figure 4-21 (b): Spatial resolution of 32-linear array multianode MCP-PMT

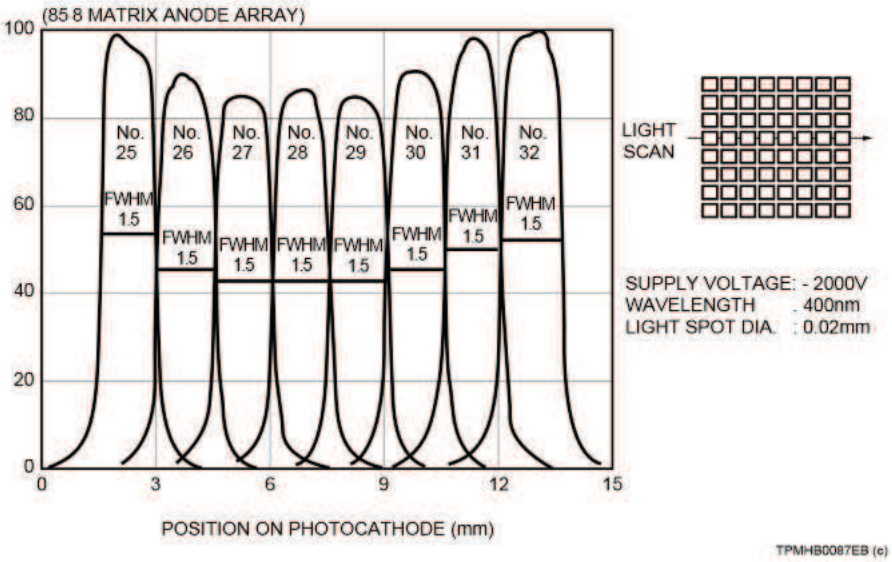


Figure 4-21 (c): Spatial resolution of 858 multianode MCP-PMT

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The following applications are possible by making use of the advantages of multianode MCP-PMTs.

(1) Simultaneous, two-dimensional detection of a luminous body which is spatially spread at low light levels

(2) Simultaneous, multichannel time-resolved spectroscopy using optical fibers

(3) Multichannel readout from scintillating fibers

As listed in Table 4-2, the family of multianode MCP-PMTs includes a 4 5 4 matrix anode type, 8 5 8 matrix anode type, 10 5 10 matrix anode type, and a 32 linear anode type. Furthermore, multianode MCP-PMT assemblies equipped with connectors and cables are available. The anode configurations listed in Table 4-2 are just typical examples. Other anode configurations and the number of anodes are also available upon request.

Type No	Anode Format	Type No	Anode Format
R4110U-XX-M016	4 5 4 matrix anode	R4110U-XX-M100	10 5 10 matrix anode
R4110U-XX-M064	8 5 8 matrix anode	R4110U-XX-L032	32-linear anode

Table 4-2: Examples of multianode MCP-PMTs

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2) Hamamatsu Photonics Catalog: Ultrafast MCP-PMT R3809U (FEB. 1992).

Hamamatsu Photonics Catalog: Microchannel Plate - Photomultiplier Tubes (MCP-PMTs), No.T-112-02 (FEB. 1990)

H. Kume et al.: Ultrafast Microchannel Plate - Photomultiplier Tubes, Applied Optics, Vol. No. 27 (Mar. 15, 1988).

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Desmond V. O'connor, David Phillips: Time-Correlated Single Photon Counting, Academic Press (Harcourt Brace Jovanovich, Publishers), The Royal Institution, London, UK.

4) Hamamatsu Photonics Catalog: Multianode MCP-PMT Series, No.T-1000 (FEB. 1989).

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CHAPTER 5
ELECTRON MULTIPLIER TUBES

Electron multiplier tubes (EMT) are mainly used in various models of mass spectrometers [1) 2) 3)] for detection of ions, electrons, soft X-rays, and vacuum ultraviolet (VUV) radiation.

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5. 1 Electron Multiplier Tubes

5. 1. 1 Electron multiplier tube structure

The structure of an electron multiplier tube is basically identical with the dynode assembly and anode used in a photomultiplier tube. The actual details of the structure differ depending on the materials to be detected and the equipment in which the electron multiplier tube is installed. (See Figure 5-1.)

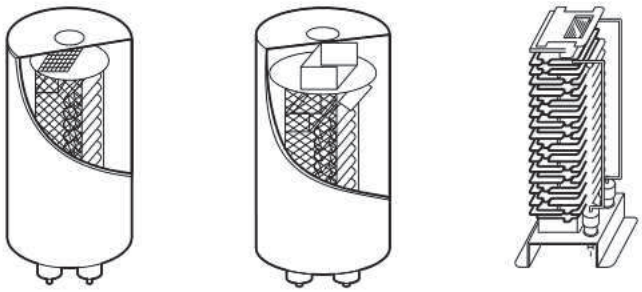




Figure 5-1: Electron multiplier tube structure

An electron multiplier tube is operated in a vacuum, and the ions, electrons, VUV radiation, or soft X-rays to be detected are guided so as to enter the first dynode. The first dynode excited by such particles or radiation emits secondary electrons or photoelectrons. These generated electrons are multiplied in a cascade just as is done in a photomultiplier tube and finally reach the anode. In most electron multiplier tubes, voltage-divider resistors are incorporated to supply an optimum voltage between each dynode.

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5. 1. 2 Composition of the secondary emissive surface

The dynodes of electron multiplier tubes are made of copper containing several percent beryllium. The surface of these copper-beryllium electrodes is activated and a thin film of beryllium oxide is formed on the dynode structure, which emits secondary electrons in response to ions, electrons, VUV radiation and X-rays. This beryllium oxide layer is chemically very stable. Even if exposed to air, it provides stable characteristics with extremely low deterioration.

5. 1. 3 Dynode types

Three kinds of dynodes of box-and-grid, linear-focused and mesh types are commonly used for electron multiplier tubes. (See 3.2.) The number of dynode stages is usually from 15 to 25 depending on the required gain.

5. 2 Characteristics of Electron Multiplier Tubes

5. 2. 1 First dynode sensitivity

Beryllium oxide (BeO) widely used in the first dynode of electron multiplier tubes is sensitive to soft X-ray to ultraviolet radiation at nearly 300 nanometers. Electron multiplier tubes are effectively used in a wavelength range shorter than the cutoff wavelength of the MgF2 window (approximately 115 nanometers). A typical spectral response for beryllium oxide is shown in Figure 5-2, covering a range from 30 to 140 nanometers.

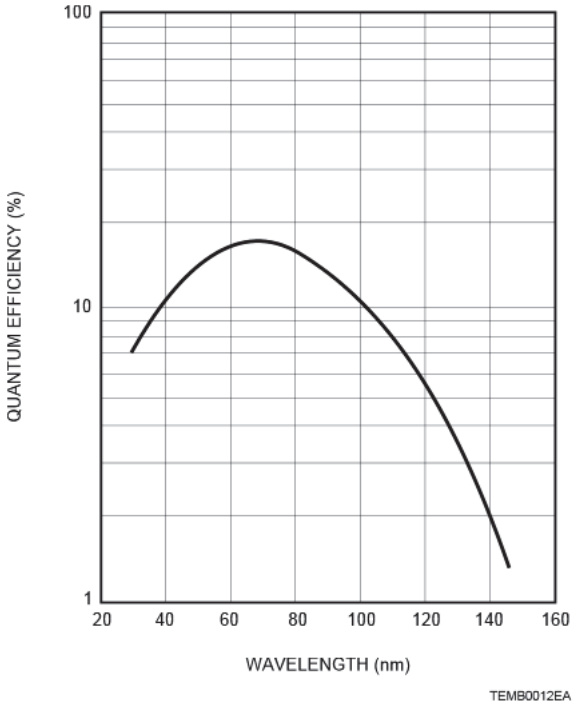


Figure 5-2: Spectral response characteristic of beryllium oxide

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Various spectral response characteristics are available by replacing the first dynode with another type evaporated with a substance optimized for the target wavelength range and operating conditions. Figure 5-3 shows typical spectral response characteristics of beryllium oxide (BeO), cesium iodide (CsI), rubidium bromide (RbBr) and gold (Au) used for the first dynode.

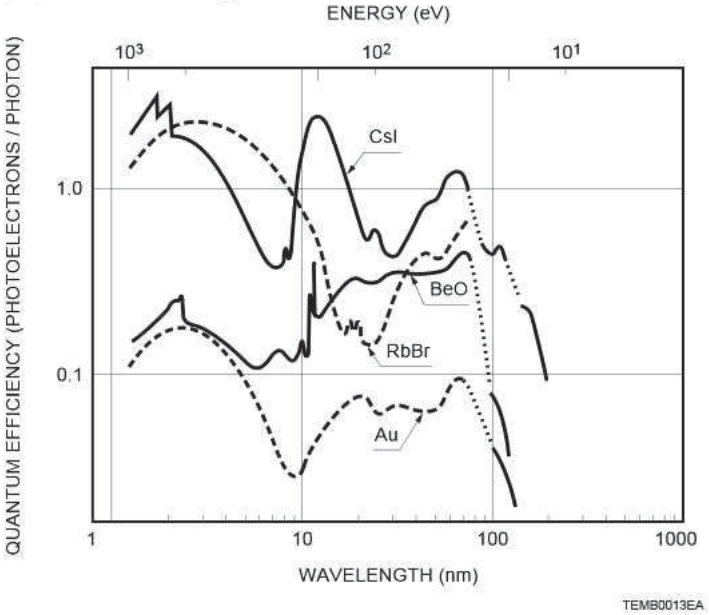


Figure 5-3: Spectral response characteristics of various evaporative substances

The first dynode of electron multiplier tubes is sensitive to electrons with energy, such as Auger electrons, secondary electrons and reflected electrons. (See 2.3.) Since beryllium oxide has a high work function, the high secondary electron emission ratio is much lower than that obtained with alkali-antimonide used for photomultiplier tube dynodes. Figure 5-4 shows typical secondary emission ratio versus primary electron accelerating voltage. The secondary emission ratio peaks at a primary electron accelerating voltage of about 400 volts.

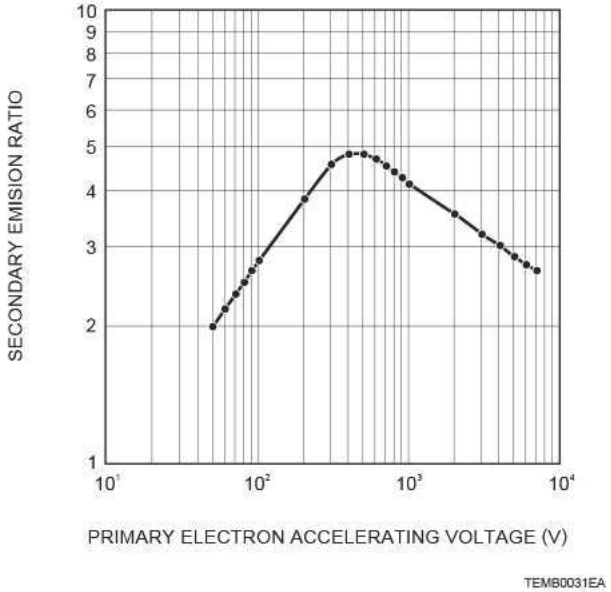


Figure 5-4: Secondary emission ratio vs. primary electron accelerating voltage for beryllium oxide

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The first dynode of electron multiplier tubes is also sensitive to ions. Typically, several electrons are emitted in response to one ion, although this ratio depends slightly on the state of the secondary electron emissive surface on the first dynode. The number of emitted electrons is also affected by the molecular weight (m/e) and ion accelerating voltage. Figure 5-5 shows the relation between the electron emission ratio and the accelerating voltage for nitrogen ion. In Figure 5-6, typical electron emission ratios at an accelerating voltage of 200 volts are plotted along various kinds of ions.

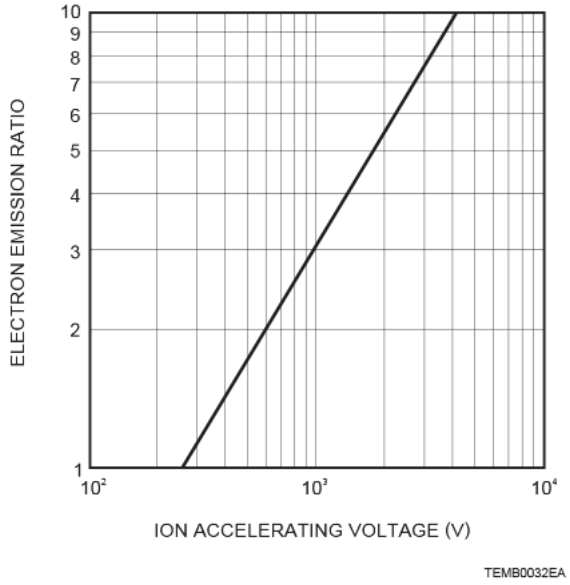


Figure 5-5: Electron emission ratio vs. accelerating voltage for nitrogen ion

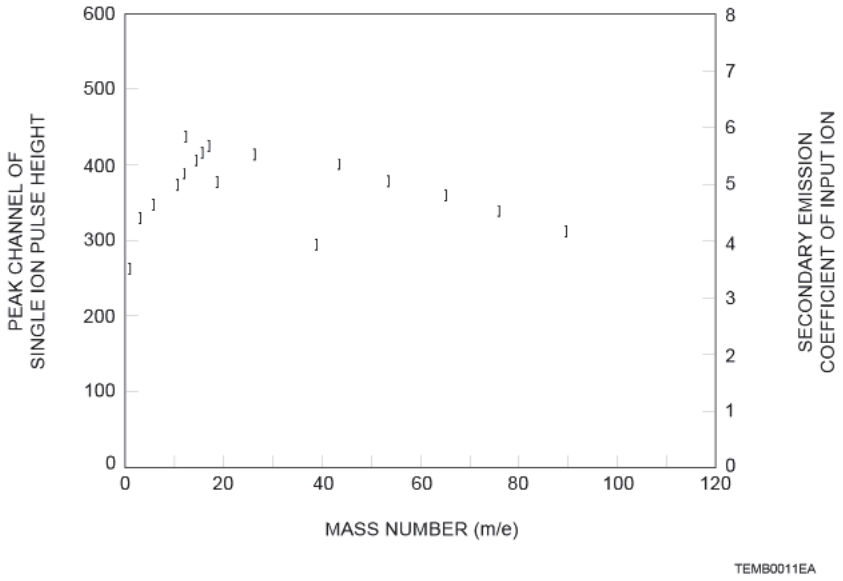


Figure 5-6: Electron emission ratios for various kinds of ions at 200V accelerating voltage

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5. 2. 2 Gain

As in the case of photomultiplier tubes, the current amplification or gain (μ) of an electron multiplier tube is theoretically expressed as follows. (See also 3.2.)

$$\text{Gain } (\mu) = A \cdot E_{bb}^{kn} \quad \cdots\cdots \text{(Eq. 5-1)}$$

Ebb: supply voltage
k : constant determined by electrode structure and material
n : number of dynode stages

It is clear from this equation that the gain μ is proportional to the kn-th power of the supply voltage. Typical gain versus supply voltage characteristics are plotted in Figure 5-7. Since this graph is on logarithmic scales, the slope of each straight line indicates kn.

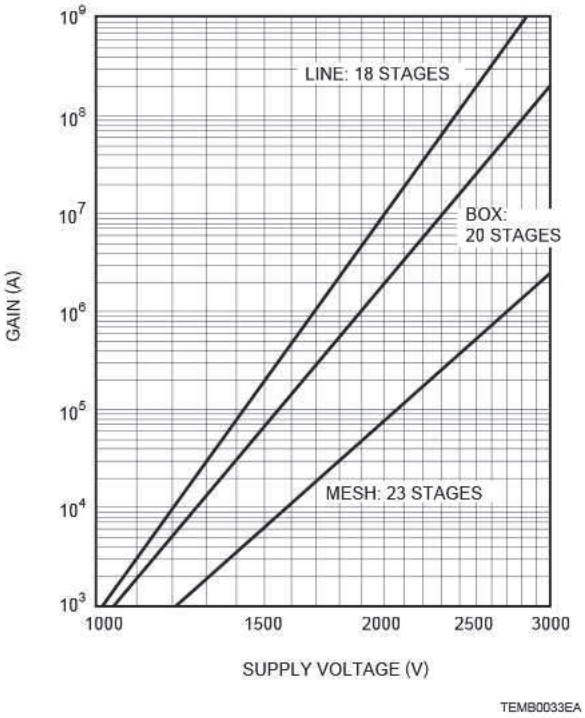


Figure 5-7: Gain versus supply voltage characteristics

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5. 2. 3 Dark current and noise

The secondary electron emissive surface of the dynodes used for electron multiplier tubes has a high work function and therefore exhibits exceptionally low dark current. Even so, small amounts of dark current may be generated by the following factors:

1. Thermionic emission current from the secondary electron emissive surface

2. Leakage current from electrode support materials

3. Field emission current

The dark current of an electron multiplier tube is very low. It is usually less than one picoampere when operated at a supply voltage providing a gain of 10^6.

In ion detection, a sample is ionized by thermal electrons generated from the filament of a lamp such as tungsten lamp. This filament also emits ultraviolet rays and X-rays which then enter the electron multiplier tube along with sample ions. The signals generated by these extraneous rays do not originate from the electron multiplier tube itself. However, they must be handled as noise just like noise of other detectors.

To reduce noise caused by ultraviolet rays and X-rays, some types of electron multipliers have a shield plate above the first dynode, in order to allow only sample ions to enter the first dynode. This design is often called the "off-axis structure". Figure 5-8 shows noise measured with an electron multiplier tube with the off-axis structure. The signal at a molecular weight of 5 (m/e), where no ions exist, appears as noise. This noise level is nearly equal to the intrinsic noise of the electron multiplier tube.

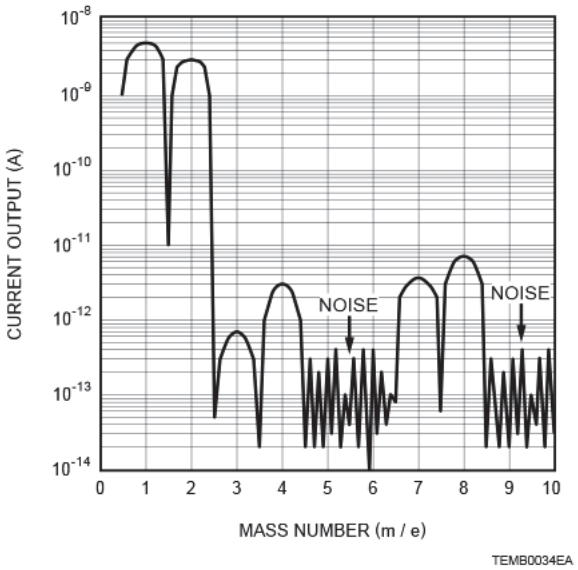


Figure 5-8 Filament noise measured with an electron multiplier tube with the off-axis structure

Because electron multiplier tubes are used in a vacuum, the noise level also depends on the vacuum level. Generally, the higher the vacuum level (for example, 10^{-2}Pa), the less the noise will be. In contrast, the noise increases as the vacuum level degrades. Figure 5-9 shows the relation between the noise count and the vacuum level at which an electron multiplier is operated.

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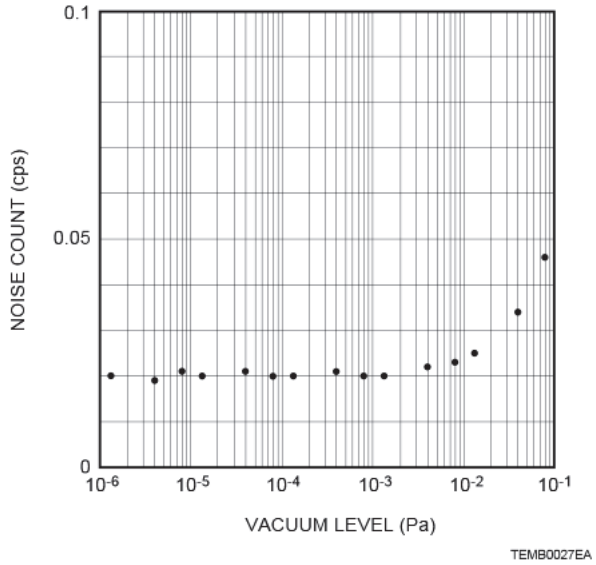


Figure 5-9: Noise count versus vacuum level for typical electron multiplier tube

5 .2. 4 Pulse counting

In applications where high sensitivity is required, the pulse counting technique which counts the number of output pulses is frequently utilized. The principle and advantages of this technique are almost identical with the photon counting technique. (Refer to Section 3.4.) Figure 5-10 shows typical pulse height distribution measured with nitrogen single ions, etc.

As stated previously, the secondary surface of the dynodes used for electron multiplier tubes is made of beryllium oxide (BeO) having a high work function. The dark count is therefore suppressed as low as 0.01 counts per second.

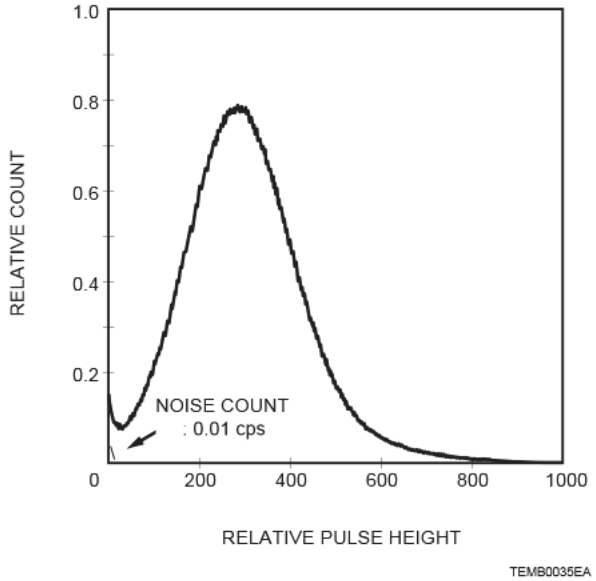


Figure 5-10: Pulse height distribution measured by input of UV, electrons and nitrogen ions

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5. 2. 5 Linearity

Electron multiplier tubes usually incorporate voltage-divider resistors between each successive dynode. This resistor is about 1 megohm per stage, so the total resistance comes to 20 megohms. The value of a linear output current is limited by the voltage-divider current flowing through these voltage-divider resistors. (See Section 7.1.)

Figure 5-11 shows a linearity plot of an electron multiplier tube operated in DC mode. As the output current increases, the gain abruptly drops after increasing slightly. This is a typical pattern for linearity dependent on the voltage-divider current. The linearity can be improved by applying a higher voltage or reducing the total value of the voltage-divider resistors in order to increase the voltage-divider current. To suppress the undesired increase in the gain which tends to occur when the output current becomes large, the resistor value between the last stage and ground should be made smaller.

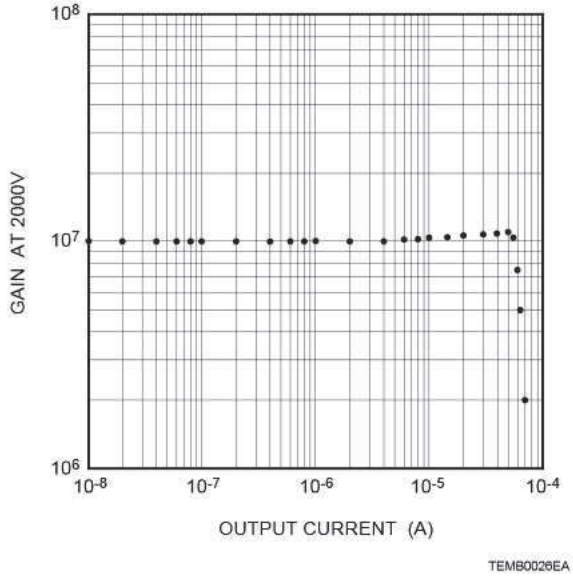


Figure 5-11: Linearity of typical electron multiplier tube in DC operation

In general, the linearity in pulse counting mode is determined by the electron multiplier tube performance and the pulse pair resolution of the signal processing circuit. (See 3.4.) To maintain high pulse count linearity, it is necessary to use an electron multiplier tube having linear focused dynodes with high-speed response.

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5.2.6 Life characteristics

The life of electron multiplier tubes is affected by the gain, output current and operating vacuum level. Two factors that cause gain deterioration are:

1. Sensitivity deterioration in the first dynode by input ions

2. Dust deposition on the secondary electron emissive surface

Figure 5-12 shows typical life characteristics for an electron multiplier tube. This is the supply voltage change required to maintain a preset gain measured with the amount of input ions and output current kept constant. As can be seen, the supply voltage increases as the accumulated output charge increases.

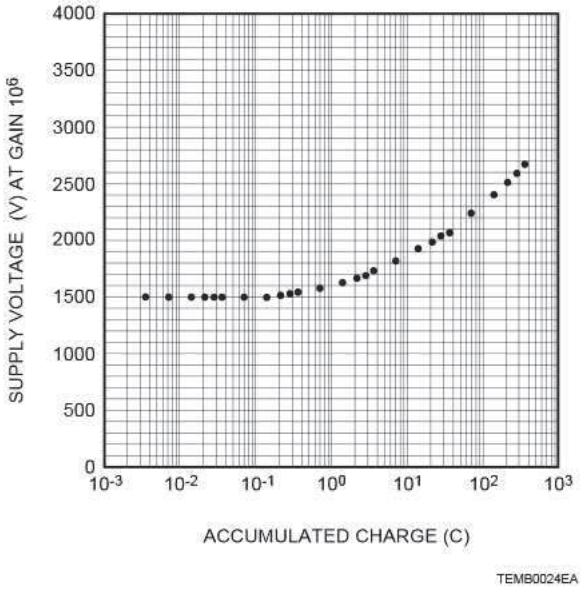


Figure 5-12: Typical life characteristics for gain of an electron multiplier tube

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1) S. Araki: Mass Spectroscopy, 3rd Edition, Modern Chemistry Series 2, Tokyo Chemical Coterie.
2) M. Tsuchiya, M. Ohashi, T. Ueno: New Development of Mass Spectrometry, Modern Chemical, Extra Number 15, Tokyo Chemical Coterie.
3) T. Ueno, K. Hirayama, K. Harada: Biological Mass Spectrometry, Modern Chemical, Extra Number 31, Tokyo Chemical Coterie.

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CHAPTER 6
POSITION-SENSITIVE PHOTOMULTIPLIER TUBES

Applicability of photomultiplier tubes to low-light-level measurement greatly relies on the current multiplication mechanism offered by dynodes. As explained earlier, there are various types of dynode structures available for different photometric purposes.

Popular dynode structures are the box-and-grid type, linear-focused type, circular-cage type and venetian-blind types. Furthermore, the MCP (microchannel plate) is now in use as a dynode with high-speed response.

Two new dynode structures are introduced in this chapter: the "metal channel dynode"[1) 2) 3)] and "fine mesh dynode".[4) 5) 6)] These dynodes provide wide dynamic range, high gain and high position resolution, and are currently used in position-sensitive photomultiplier tubes.

Common methods of reading out the output electron bunch from a position-sensitive photomultiplier tube are illustrated in Figure 6-1. In a multianode, the output signal is read out from independent multiple anodes. The resistive anode has a uniformly distributed resistive layer that allows reading out the signal by means of center-of-gravity detection. The cross-wire (or plate) anode reads out the signal by means of current or charge-dividing center-of-gravity detection.

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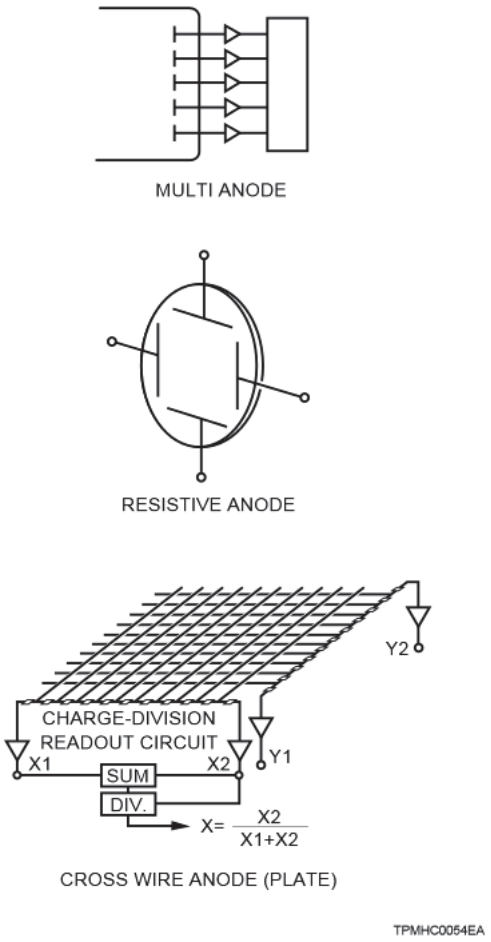


Figure 6-1: Anode output readout methods for position-sensitive photomultiplier tube

The following sections describe position-sensitive photomultiplier tubes using "metal channel dynodes combined with a cross-plate anode", "metal channel dynodes combined with a multianode" and "fine mesh dynodes combined with a multianode"

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6. 1 Position-Sensitive Photomultiplier Tubes Using Metal Channel Dynodes

6. 1. 1 Structure and characteristics

Figure 6-2 shows the electrode structure and electron trajectories in metal channel dynodes. One of the outstanding features offered by the metal channel dynode is very low crosstalk between multiple anodes. After photoelectrons are emitted from the photocathode, they are directed onto the first dynode by the focusing grid and then flow to the second dynode, third dynode, . . . last dynode and finally to the anode, while being multiplied with a minimum spatial spread of the electron flow. Therefore, position data is precisely maintained through the cascade multiplication process.

In addition, the overall length of the tube can be kept short because metal channel dynodes are very thin and assembled in close-proximity to each other.

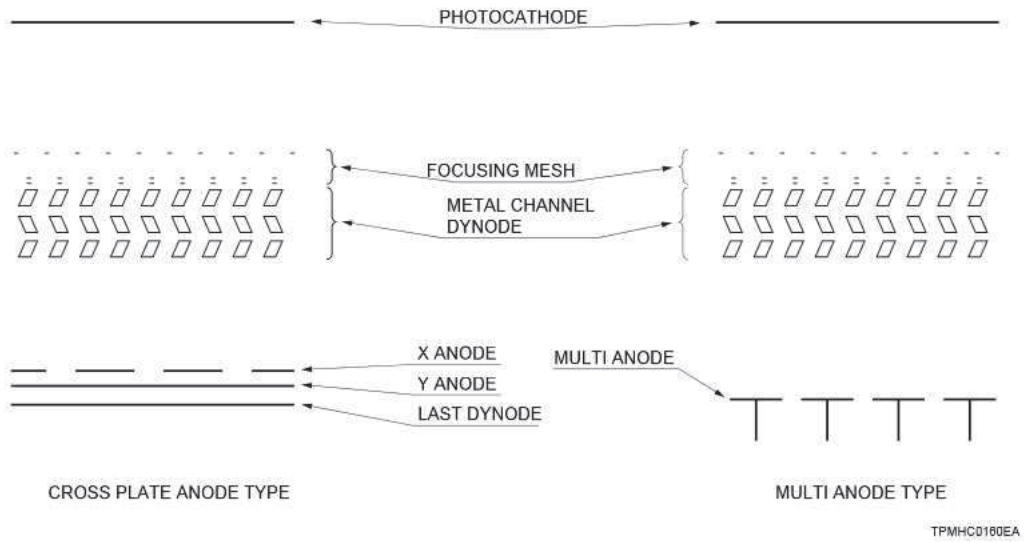


Figure 6-2: Electrode structure of metal channel dynodes and electron trajectories

Figure 6-3 illustrates the center-of-gravity detection method for reading out the output signal from a position-sensitive photomultiplier tube using a cross plate anode. The electron bunch released from the last dynode is collected by anodes linearly arranged in the X and Y directions. Since each anode in the same direction is connected by a resistor chain, the collected electrons are divided into four signal components of X1, X2, Y1 and Y2 corresponding to the anode position at which the electron bunch arrive. By inputting these signals to a summing (SUM) and divider (DIV) circuits, the center of gravity in the X and Y directions can be obtained as follows:

$$X = X_2/(X_1+X_2)$$
$$Y = Y_2/(Y_1+Y_2) \quad \text{(Eq. 6-1)}$$

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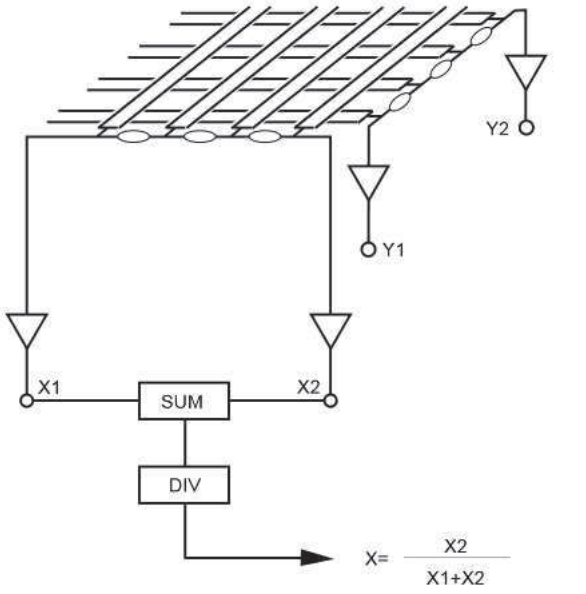
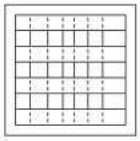
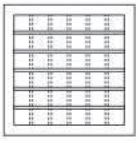
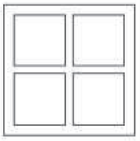
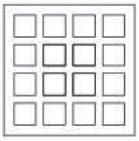
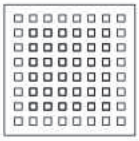


Figure 6-3: Center-of-gravity detection method for position-sensitive photomultiplier tube using cross plate anodes

Hamamatsu has developed the R5900 series position-sensitive photomultiplier tubes housed in a 1"5 1" square metal package. The R5900 series uses 10 to 12 stages of metal channel dynodes and various types of multianodes as shown in Table 6-4, allowing you to make a selection to meet the particular application.

Type No.	R5900-00-C8	R5900-00-C12	R5900-00-M4	R5900-00-M16 (H6568)	R5900-00-L16	R5900-00-M64 (H7546)
Anode Shape						
Number of Anodes	4(X)+4(Y)	6(X)+6(Y)	4	16	16	64
Number of Dynodes	11	11	10	12	10	12
Gain (Supply voltage 800V)	75 10^5	75 10^5	25 10^6	3.35 10^6	25 10^6	35 10^5

TPMHA0432EA

Table 6-4: R5900 series anode patterns

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The R5900 series position-sensitive photomultiplier tube also includes an easy-to-use assembly type with built-in voltage-divider resistors. (Figure 6-5)

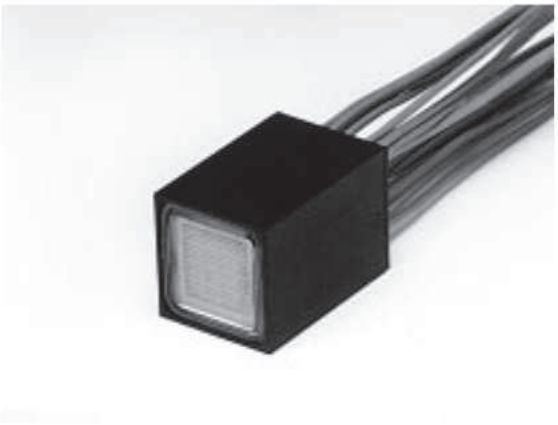


Figure 6-5: R5900-00-M16 assembly (H6568)

As mentioned, when photoelectrons are emitted from the photocathode, they are directed onto the first dynode by the focusing mesh. In this process, the photoelectron flow spreads spatially between the photocathode and the focusing mesh and also between the focusing mesh and the first dynode. Metal channel dynodes are developed to minimize this electron spread.

Figures 6-6 (1) and (2) show typical spatial resolution of the R5900-00-C8 (cross plate multianode type) using the center-of-gravity detection method. This data is measured by irradiating the photocathode surface with a 3mm diameter collimated light beam from a tungsten lamp and plotting the output distribution of each anode. (The light beam is moved along each of the XY directions with the tube axis viewed as the center.)

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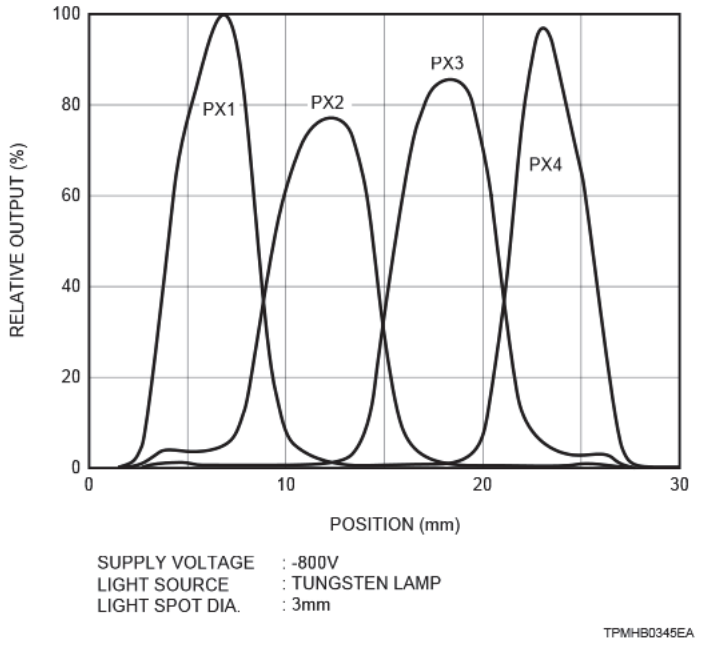


Figure 6-6 (1): Multianode spatial resolution in the X direction (R5900-00-C8)

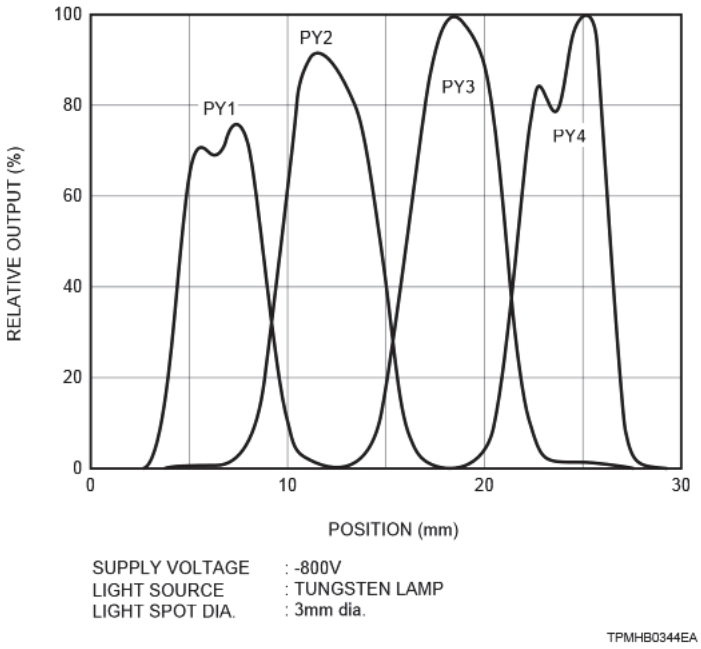


Figure 6-6 (2): Multianode spatial resolution in the Y direction (R5900-00-C8)

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As one sample application, Figure 6-7 (1) shows the measurement diagram for scintillation imaging of 511keV gamma-rays, using the R5900-00-C8 coupled BGO scintillators (arranged in a mosaic pattern of 85 7=56 pieces). An actual image that was taken is shown in Figure 6-7 (2).

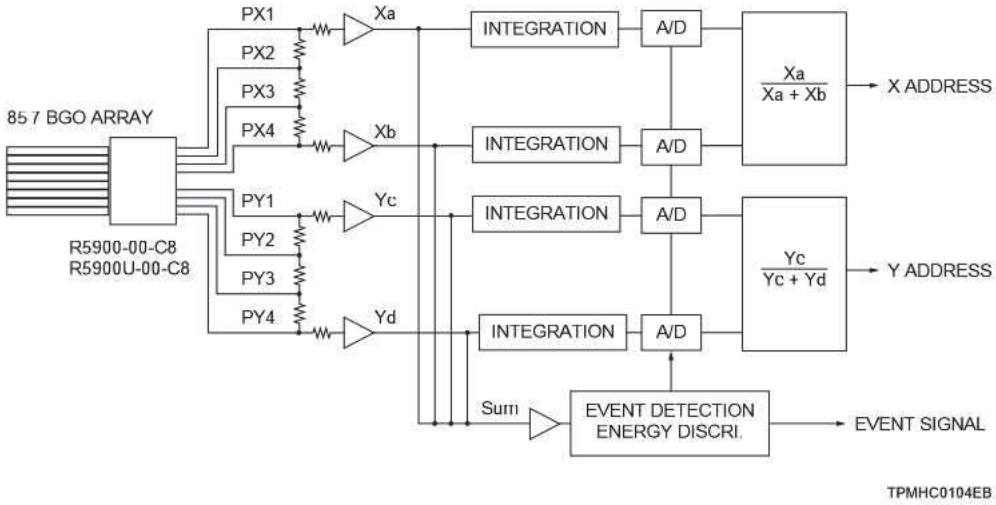
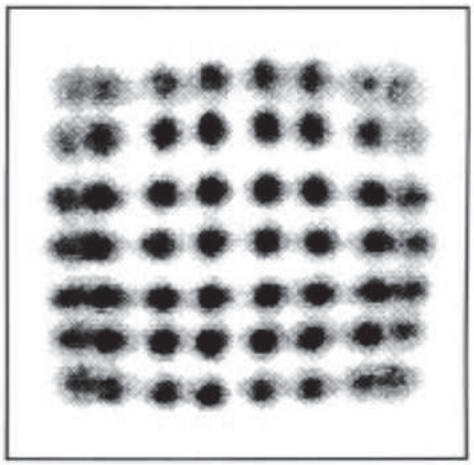


Figure 6-7(1): Scintillation imaging of gamma-rays entering a mosaic pattern of BGO scintillators



Position data after calculation when gamma-rays at 511keV were incident on the 85 7 BGO array (2.8mm5 2.8mm5 30mm)

Figure 6-7(2): Scintillation imaging of gamma-rays entering a mosaic pattern of BGO scintillators

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This scintillation imaging is now possible with position-sensitive photomultiplier tubes. Off-axis distortion in the image can be corrected to some extent by an electronic circuit.

Figure 6-8 shows the external dimensions of the R5900-00-M64 (8 8 multianode[8]), and Figure 6-9 the anode pattern.

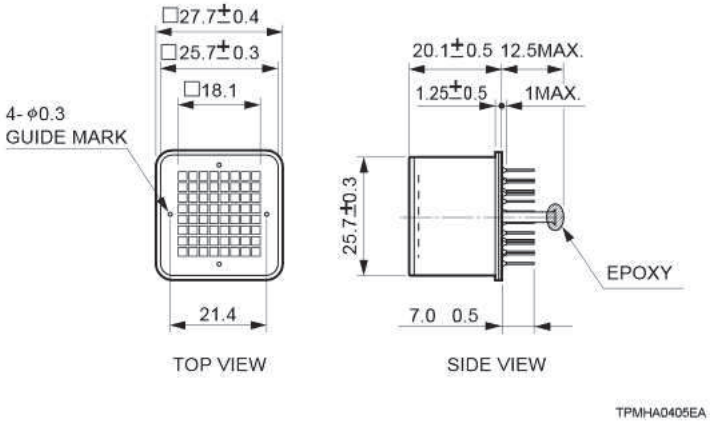


Figure 6-8: R5900-00-M64 external dimensions

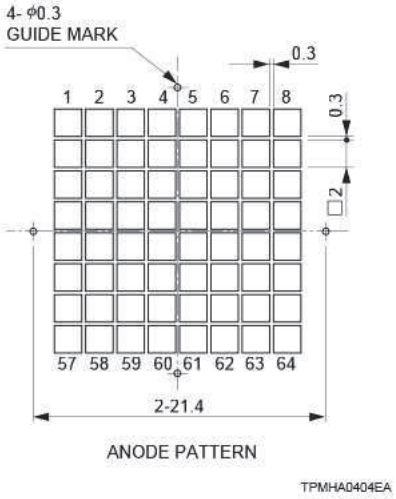


Figure 6-9: R5900-00-M64 anode pattern

Multianode photomultiplier tubes are mainly developed for applications requiring multipoint measurements. Before they are put into practical use, multiple small diameter photomultiplier tubes were used in close arrangement, so that the total cost for using many of these tubes could not be ignored (particularly in huge equipment used in high energy physics experiments and for nuclear medical imaging systems). Simply speaking, one anode of a multianode corresponds to one photomultiplier tube, so using multianode photomultiplier tubes will contribute to a significant reduction in the total cost.

The following paragraphs explain basic characteristics of the R5900-00-M64, such as crosstalk, magnetic immunity and uniformity.[9]

Crosstalk is a measure to indicate how accurately the light (signal) incident on a certain position of the photocathode is detected with the position information still retained. In photomultiplier tube operation, crosstalk is mainly caused by the broadening of electron flow when light is converted into electrons and those electrons

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are multiplied in the dynode section. The incident light spread within the faceplate is another probable cause of crosstalk. A typical setup for measuring crosstalk is shown in Figure 6-10 and the measurement data in Figure 6-11.

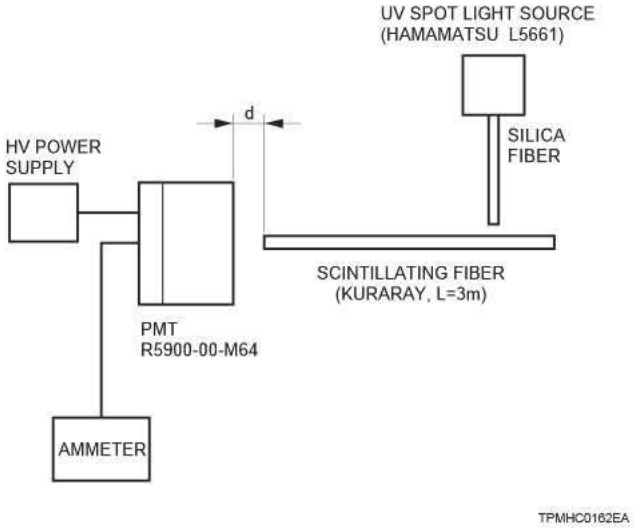


Figure 6-10: Crosstalk measurement method

0.3	1.4	0.4
0.8	100	1.2
0.2	1.1	0.3

SCINTILLATING FIBER (1.0mm dia.)
SUPPLY VOLTAGE: 800(V)
d (DISTANCE): 0mm

0.4	2.6	0.6
1.5	100	1.9
0.3	1.8	0.4

SCINTILLATING FIBER (1.0mm dia.)
SUPPLY VOLTAGE: 800(V)
d (DISTANCE): 0.5mm

Figure 6-11: Crosstalk measurement examples

Data shown in Figure 6-11 is measured by irradiating a light spot (signal) on the photomultiplier tube faceplate, through a 1mm diameter optical fiber placed in close contact with the faceplate. The output of each anode is expressed as a relative value, with 100% being equal to the peak anode output produced from the incident light spot. The results show that crosstalk is "0.2% to 1.4% when the 1mm diameter scintillating fiber is positioned in tight contact with the photomultiplier tube faceplate. However, the crosstalk degrades by 0.3% to 2.6% when the scintillating fiber is placed 0.5mm away from the faceplate. This is of course due to light spread at the scintillating fiber exit. Bringing the optical fiber into tight contact with the photomultiplier tube faceplate is therefore recommended to make accurate measurements using scintillation fibers.

Next, let's discuss magnetic characteristics. The R5900 series photomultiplier tubes have excellent immunity to magnetic fields. This is because all parts except the photocathode are housed in a metal package and also because the distance between dynode electrodes is very short. Figure 6-12 shows how the anode output is adversely affected by external magnetic fields applied to the R5900-00-M16 along the three directions (X, Y, Z). Each data is plotted as a relative output value, with 100% corresponding to an output with no magnetic field applied. It is clear that the output is still maintained as high as 60% versus 13mT of the magnetic field in the X direction.

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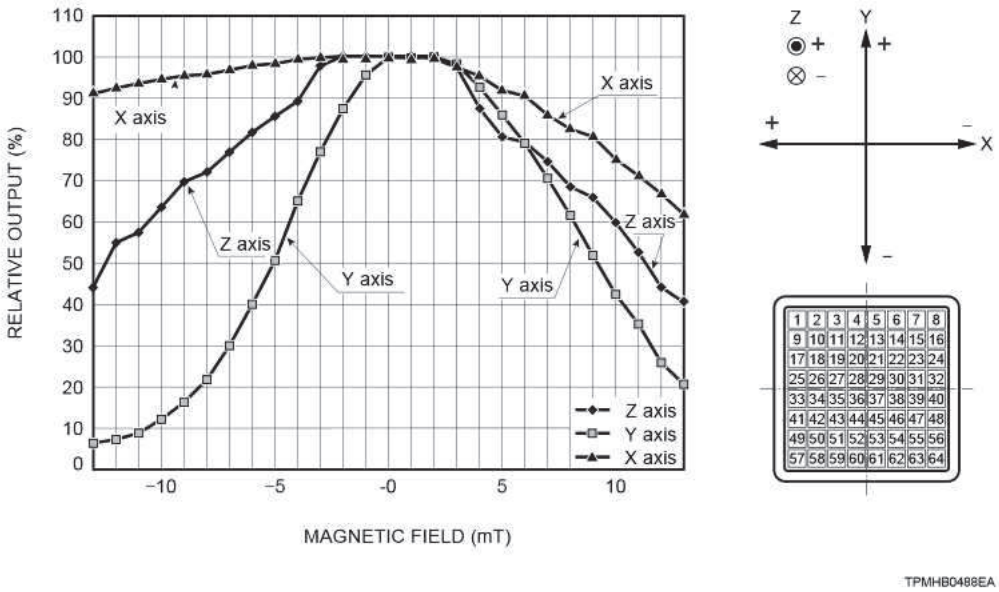


Figure 6-12: Effects of external magnetic fields on anode output (anode channel No. 29)

Figure 6-13 shows typical uniformity data obtained from each anode when uniform light is illuminated over the entire photocathode of the R5900-00-M64. The non-uniformity observed here probably originates from gain variations in the secondary electron multiplier because the photocathode itself has good uniformity. At the current stage, non-uniformity between each anode is about "1:3" on average.

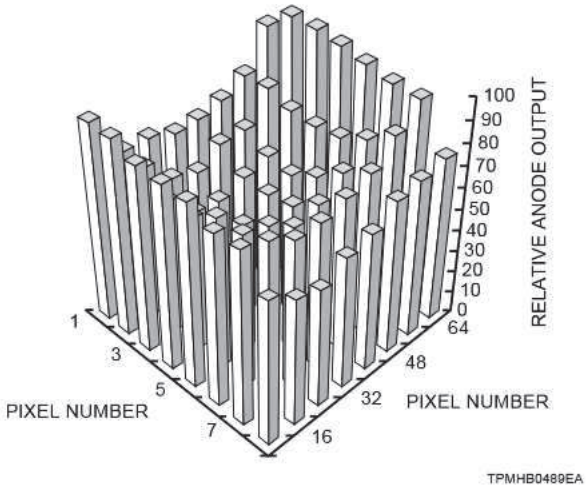


Figure 6-13: R5900-00-M64 anode output uniformity

Uniformity of one anode (one pixel) is shown in Figure 6-14. This data is measured by input of weak DC light to an anode of 2.5 2mm per pixel through a 1mm diameter optical fiber, while scanning the optical fiber every 0.1mm on the photocathode. There are two output peaks as graphically represented. This means that the electrons (signals) extracted from one anode (one pixel) arrive at the anode through the two adjacent paths in the metal channel dynode.

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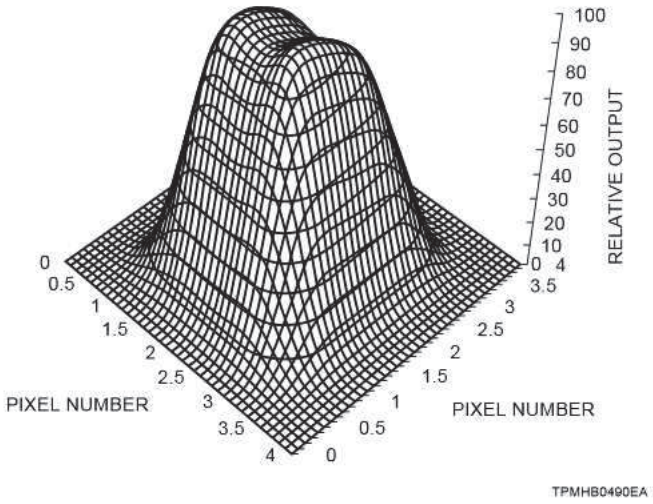


Figure 6-14: Anode output uniformity per pixel

6. 1. 2 Applications

As stated earlier, position-sensitive photomultiplier tubes delivers accurate position information about light falling on the photocathode by center-of-gravity processing. These photomultiplier tubes can be used for scintillation imaging in combination with scintillators. Some recent applications are explained below.

(1) Biometabolic activity imaging using PET (Positron Emission Tomography)[10) 11) 12)]

Nuclear medical instruments 0such as gamma cameras and PET systems have been developed and are now used in hospital facilities. Ordinary gamma cameras use a detector composed of a large scintillator and a number of photomultiplier tubes. To achieve even higher resolution and a smaller instrument, research and development of compact gamma cameras is now under way, using a flat-shaped NaI(Tl), mosaic arrangement of YAP and CsI(Na) scintillators.

PET uses a number of small position detectors arranged to surround the subject and creates tomographic images by detecting gamma rays generated from positron annihilation using the coincidence technique. Recently, scintillation detectors made up of a scintillator coupled to a position-sensitive photomultiplier tube are becoming used as detectors in PET. Major characteristics required of these photomultiplier tubes are high sensitivity, good energy resolution and excellent time resolution. By utilizing position-sensitive photomultiplier tubes having these characteristics, more compact PET systems with better spatial and time resolutions will be available.

As a specific example, Figure 6-15 shows the PET system (Hamamatsu SHR-7700) designed for laboratory animals, which has been already put on the market. This PET system is used for animal studies in pharmacodynamics which are difficult to conduct with the human body, and also for development of new medicines and evaluation of pharmaceutical effects of general medicines. Laboratory animals often used with PET are mice, rats, monkeys and baboons.

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Because these animal organs are relatively small, PET for animal studies must provide high resolution. The SHR-7700 uses scintillation detectors each of which consists of 32 BGO scintillators coupled to a R5900-00-08 position-sensitive photomultiplier (cross-wire anode type). Since 240 photomultiplier tubes are installed in the SHR-7700, a total of 7680 BGO scintillators are required The SHR-7700 provides unprecedented performance with a center resolution of 2.6mm and effective field-of-view of 330mm diameter5 114mm. Fig. 6-15 shows the external view of the SHR-7700.



Figure 6-15: External view of the SHR-7700 (PET system for laboratory animals)

The detector ring and detector unit of the SHR-7700 are shown in Figures 6-16 and 6-17. As a typical example taken with the SHR-7700, Fig. 6-18 shows oxygen metabolic activity images of a monkey brain.

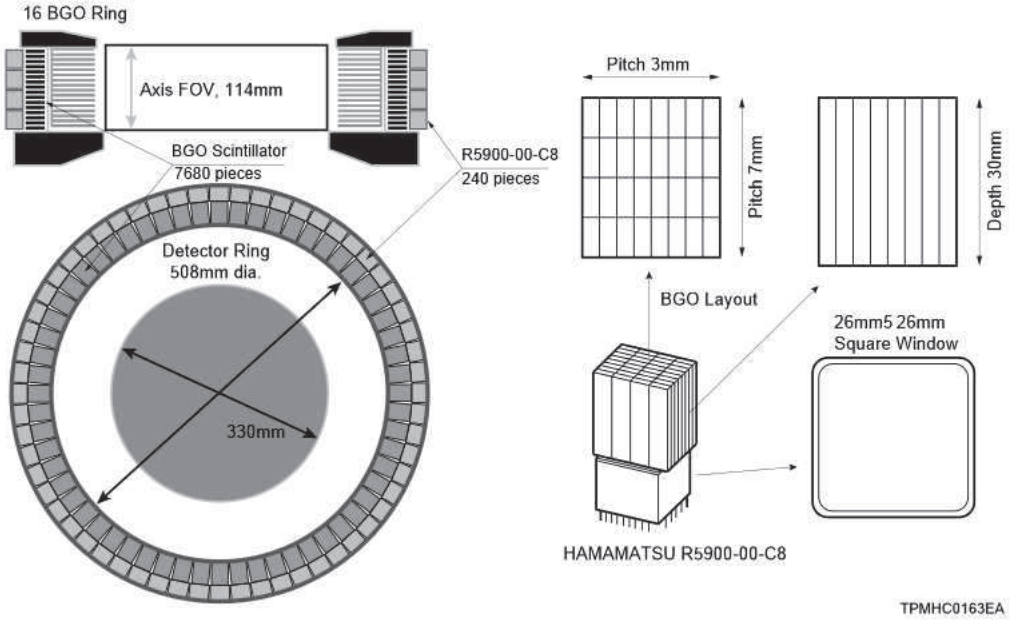


Figure 6-16: Cross section of the SHR-7700 detector ring

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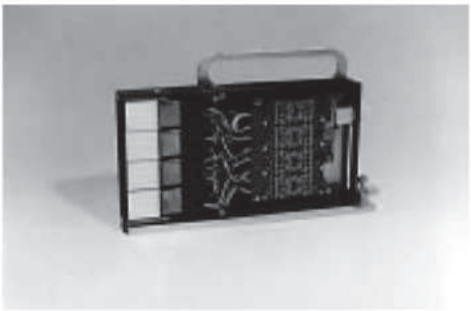


Figure 6-17: Detector unit

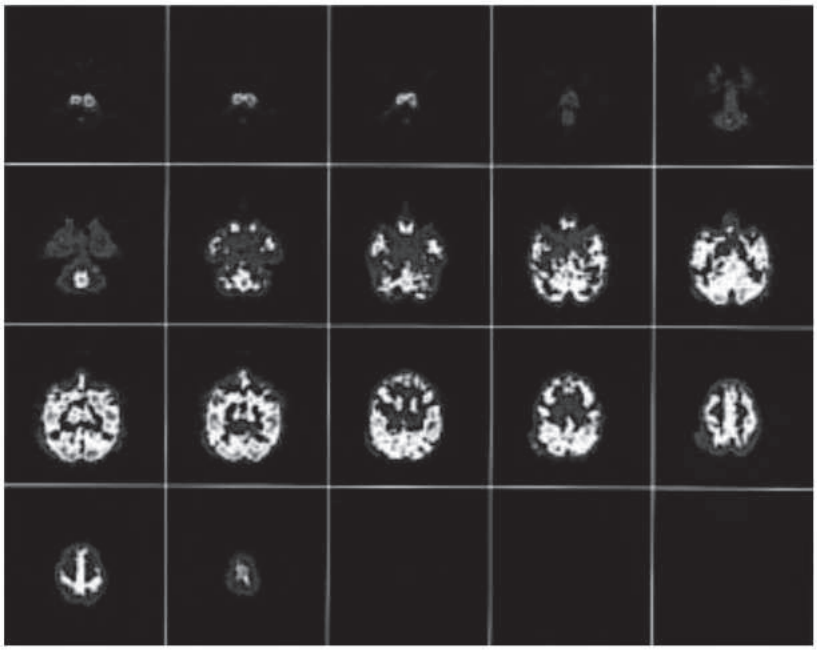


Figure 6-18: Oxygen metabolic activity images of monkey brain (positron imaging system)

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As one application for position-sensitive photomultiplier tubes using grid dynodes, let's take a brief look at a planar detector system for positron imaging developed for studies on metabolism activity inside living plants. The detectors used in this system consists of a BGO scintillator array coupled to a 3-inch square envelope position-sensitive photomultiplier tube. The BGO scintillator array is made up of 275 23 independent scintillators each of which has a prismatic shape measuring 2mm5 2mm5 20mm. As shown in Figure 6-19, a pair of detectors are placed so that they face each other at the front and back of a planar sample such as a plant leaf. To measure real-time images of biological functions within the sample, a positron-emitting tracer is injected into the sample and annihilation gamma-rays emitted from it are captured with the two detectors by coincidence counting technique. Two-dimensional images can be produced by projecting the obtained data onto the same plane (focal plane imaging method).

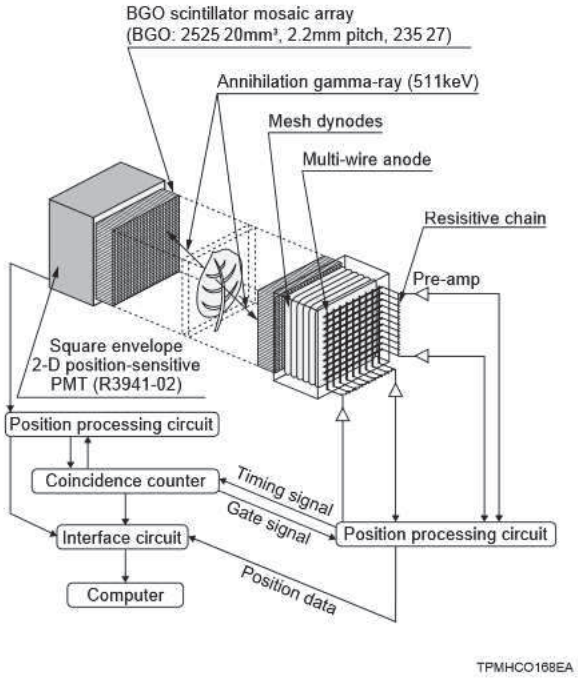


Figure 6-19: Planar detector system for positron imaging of metabolic functions inside plant

A 50 minute integrated image of a rose flower whose stem was cut and given water containing ^{18}F for 2 minutes. Higher concentrations can be seen in the calyxes.

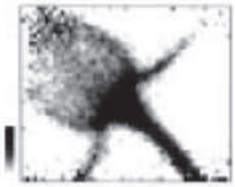


Figure 6-20: Image of metabolic functions inside a plant

One minute images of the stem/leaf separating area of a rose flower whose stem was cut and given water containing ^{18}F for 2 minutes. It is observed that water can be seen to first flow towards the leaf.

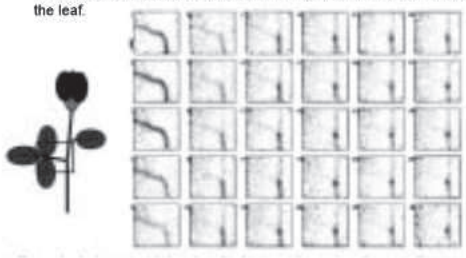


Figure 6-21: Visualization of "water" flow inside a plantflow inside a plant

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6. 2 Position-Sensitive Photomultiplier Tubes Using Fine-Mesh Dynodes

Position-sensitive photomultiplier tubes using fine-mesh dynodes and a multianode have been developed and put on the market.[13)14)] These photomultiplier tubes can be operated near large magnetic field, making them well suited for use in particle track detectors and calorimeters in high energy physics experiments.

6. 2. 1 Structure

Figure 6-22 shows the sectional view of a photomultiplier tube using fine-mesh dynodes. This tube is constructed with an input window, a photocathode, fine-mesh dynodes and an anode. The details of a fine-mesh dynode are illustrated in Figure 6-23. When an electron impinges on the upper part of the mesh, multiple secondary electrons are emitted from the secondary emissive surface deposited on the mesh. This process is repeated through the last dynode stage and finally electrons are multiplied up to a million times.

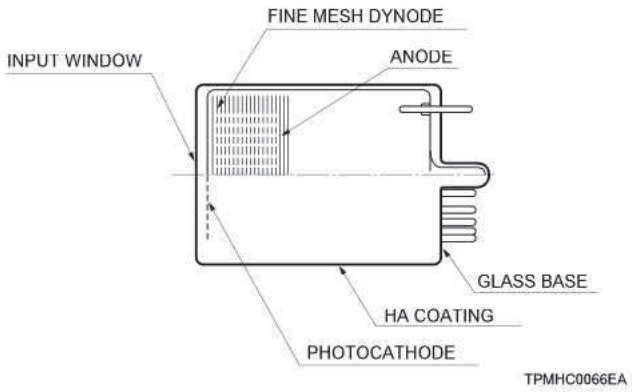


Figure 6-22: Structure of a photomultiplier tube using fine-mesh dynodes

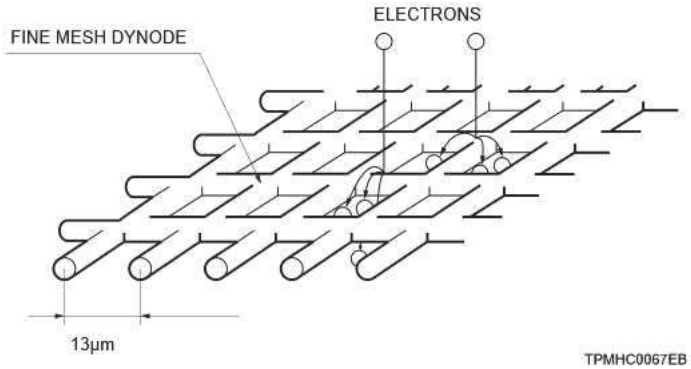


Figure 6-23: Details of a fine-mesh dynode

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Figure 6-24 is a photograph of this type of photomultiplier tube. It provides a gain of 10^6 with 16 dynode stages and 10^7 with 19 dynode stages. Table 6-1 shows typical photomultiplier tubes using fine-mesh dynodes and their major characteristics. A variety of tubes have been marketed, including 1-inch, 1.5-inch, 2-inch, 2.5-inch, 3-inch and 5-inch diameter tubes with 15, 16 or 19 dynode stages.



Figure 6-24: External view of R5924

Size	Type No.	Effective Photo-cathode	Number of Dynodes	Rise Time	TTS	Pulse Linearity
25mm Dia. (1 inch dia.)	R5505 (UV R5506)	17.5mm Dia.	15	1.5ns (2000V)	350ps (2000V)	180mA
38mm Dia. (1.5 inch dia.)	R5946 (Silica R6149) (UV R6148)	27mm Dia.	16	1.9ns (2000V)	350ps (2000V)	350mA
52mm Dia. (2 inch dia.)	R5924 (Silica R6609) (UV R6608)	39mm Dia.	19	2.5ns (2000V)	440ps (2000V)	500mA
64mm Dia. (2.5 inch dia.)	R6504 (UV R6505)	51mm Dia.	19	2.7ns (2000V)	470ps (2000V)	700mA
78mm Dia. (3 inch dia.)	R5542 (UV R5543)	64mm Dia.	19	2.9ns (2000V)	500ps (2000V)	1,000mA

Table 6-1: Photomultiplier tubes using fine-mesh dynodes

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6. 2. 2 Characteristics

The greatest advantage offered by fine-mesh dynodes is that they can be operated in a magnetic field. Figure 6-25 shows the relative output of a photomultiplier tube using fine-mesh dynodes with respect to magnetic flux density. Although the output decreases with increasing magnetic flux density, this tube can be used up to near 1.5 Tesla. This performance is due to the fine-mesh structure with its very minute diameter and also to the close-proximity spacing between dynodes, so that the electron trajectories of the secondary electrons emitted from the fine-mesh dynodes are resistant to external magnetic fields.

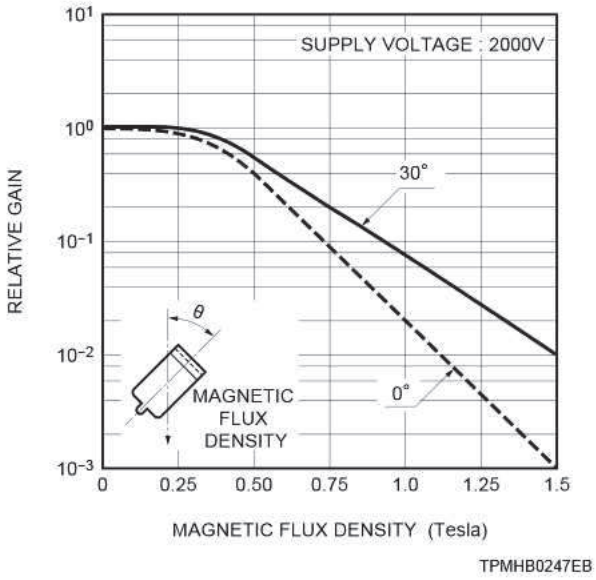


Figure 6-25: Gain vs. magnetic flux density

Next, let us introduce a position-sensitive photomultiplier tube that combines fine-mesh dynodes with a multianode. The configurations of this tube are illustrated in Figure 6-26. The number of fine-mesh dynodes is 19 stages, the multianode consists of 80 independent anodes and these elements are incorporated in a 3-inch diameter cylindrical envelope. A gain of approximately 55 10^{6} can be obtained with this tube. Figure 6-27 shows the spatial resolution of this tube when a 2mm light spot is scanned over the input window along the direction of a row of the anodes. This data was measured with the photomultiplier tube operated in a non-magnetic field and indicates a spatial resolution of approximately 4mm (FWHM).

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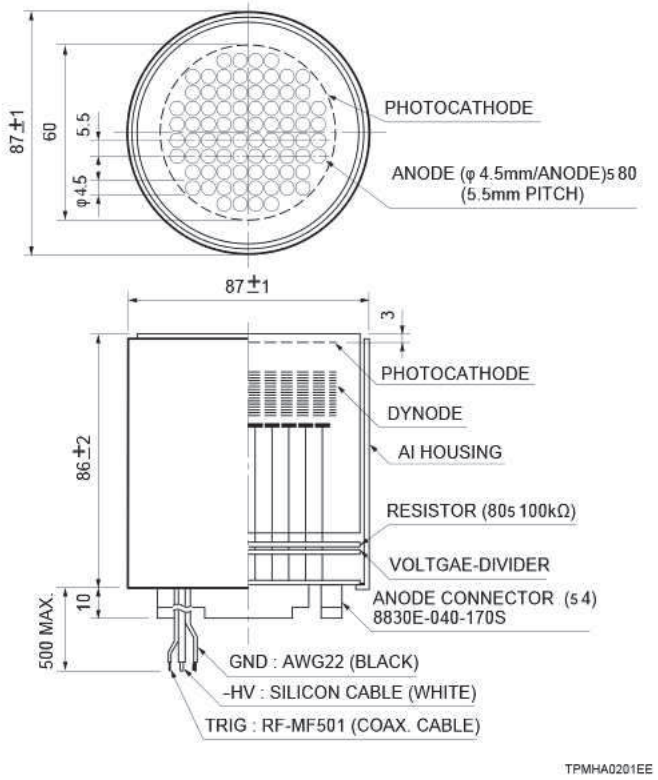


Figure 6-26: Dimensions and internal structure of a multianode photomultiplier tube using fine-mesh dynodes

Figure 6-28 is the photograph of the multianode photomultiplier tube using fine-mesh dynodes described in this section. Figure 6-29 shows the external view of a modular type of photomultiplier tube using fine-mesh dynodes and multianode.

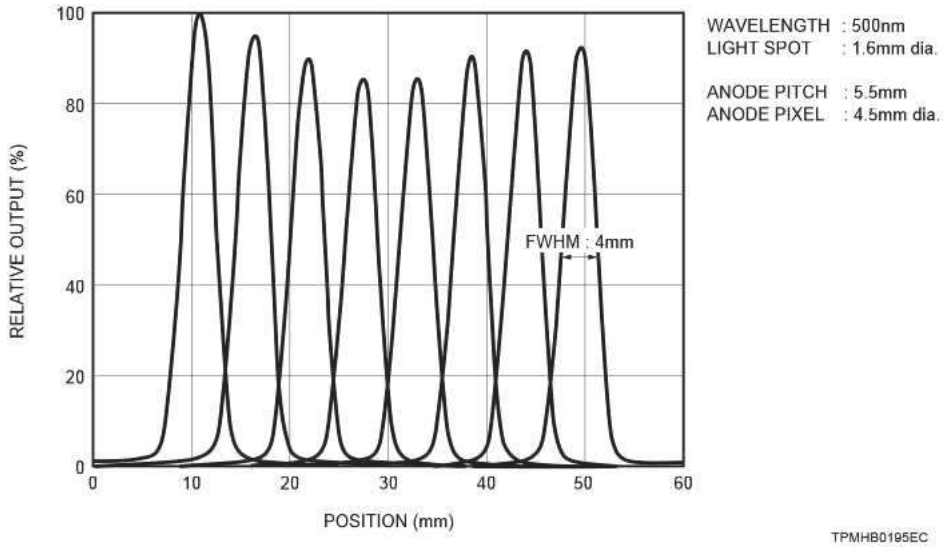


Figure 6-27: Spatial resolution of H5828 (R5635 Assembly) in non-magnetic field

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Figure 6-28: Multianode photomultiplier tube using fine-mesh dynodes



Figure 6-29: Modular type of multianode photomultiplier tube using fine-mesh

Table 6-2 shows a list of major assembly modules of position-sensitive photomultiplier tubes using fine-mesh dynodes and a multianode. In addition to incorporating a voltage-divider circuit, these tubes are equipped with a multiconnector that allows easy connection of the multianode output to an external circuit. The anode configuration of each tube is also listed in this table, 85 8, 165 16 and 80 multianodes are available for tubes with a 3-inch circular and square faceplate.

Size	Type No.	Remarks
75mm, Circuilar (3 inch dia.)	H5828	No. of Anodes . 80 Anode Size . f4.5mm Anode Pitch . f5.5mm
755 75mm, Square (35 3 inch)	H4140-20	No. of Anodes . 165 16 (256) Anode Size . f1.8mm Anode Pitch . 2.54mm
755 75mm, Square (35 3 inch)	H4139-20	No. of Anodes . 64 Anode Size . f4.2mm Anode Pitch . 5.08mm

Table 6-2: Multianode photomultiplier tube using fine-mesh dynodes

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6. 2. 3 Applications

Main applications of the fine-mesh dynode photomultiplier tubes include calorimeters and particle track detectors used in conjunction with scintillators in high energy physics experiments. Figure 6-30 shows a drawing of time resolution measurement using π-mesons at 2GeV and the combination of a rectangular plastic scintillator (Pilot U of 2cm5 1cm5 1cm) with a pair of fine-mesh dynode photomultiplier tubes.[15]

In this measurement, it is anticipated that several thousands of photoelectrons are produced at each photomultiplier tube. The output of each photomultiplier tube is fed into a CFD (constant fraction discriminator) circuit for measurement.

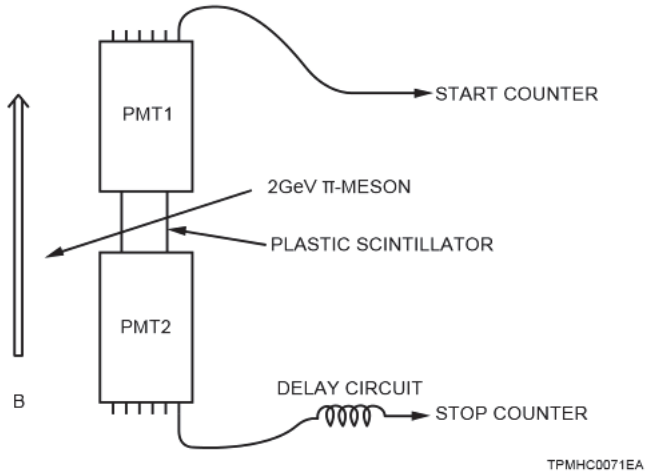


Figure 6-30: Schematic drawing for time resolution measurement using π-mesons

Figure 6-31 shows the time resolution plot obtained with this measurement as a function of magnetic flux density. The time resolution is approximately 100 picoseconds without a magnetic field, and approximately 200 picoseconds in a magnetic field at 0.78 Tesla.

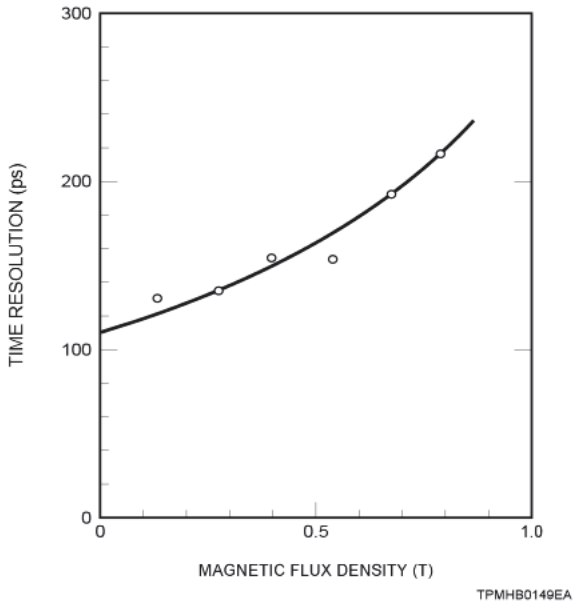


Figure 6-31: Time resolution vs. magnetic flux density

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When the same measurement is made using fast response photomultiplier tubes in place of the fine-mesh dynode photomultiplier tubes, a time resolution of approximately 100 picoseconds is attained. This proves that fine-mesh dynode photomultiplier tubes can be used either in non-magnetic fields or in highly magnetic fields. But it should be noted that as the magnetic field intensity increases, the current amplification of the photomultiplier tube decreases, resulting in deterioration of the time resolution.

Because of their high immunity to magnetic fields and position-detection capability, these photomultiplier tubes find applications in particle track detectors and calorimeters. Figure 6-32 gives an example of a charged particle track detector consisting of a position-sensitive photomultiplier tube with a multianode in combination with a plastic scintillation fiber bundle.[16)]

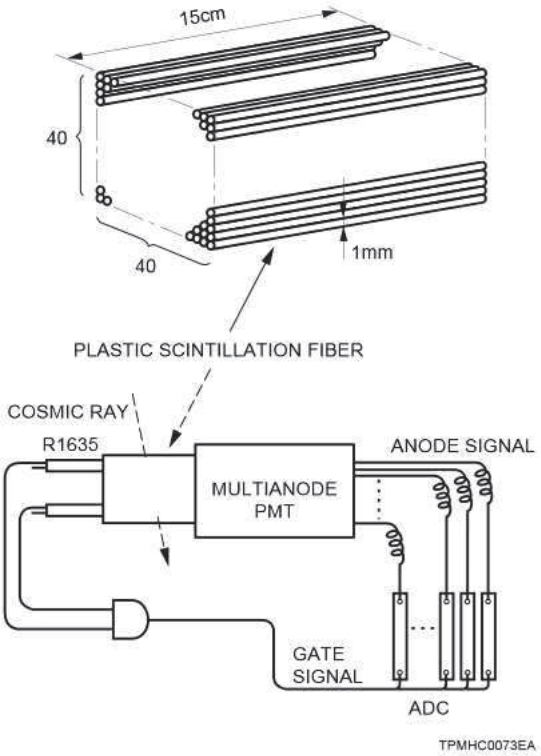


Figure 6-32: Drawing of a particle track detector

This detector uses a fiber bundle measuring 40mm(W)5 40mm(H)5 150mm(L) comprised of individual scintillation fibers (1 millimeter diameter). Figure 6-33 shows the results when the track of cosmic rays is measured with this detector. In the figure, a) are the anode outputs obtained when the photomultiplier tube is operated at 2200 volts, while b) are those at 0 volts. As shown in this figure, a multianode of an 88-matrix array is employed. Here, c) is the output profile of each row of the multianode, indicating the movement of the track. In this case, since no magnetic field is applied to the photomultiplier tube, the electrons broaden to an area equal to three anodes (approximately 8 millimeters). On the other hand, Figure 6-34 shows the results obtained when a magnetic field of 0.05 Tesla is applied to the photomultiplier tube in the direction of the tube axis. Due to the focusing effects of the magnetic field, the electron spread is suppressed to a small area equal to one anode channel (approximately 2.6 millimeters) thus assuring high resolution for the cosmic-ray track measurement.[16)]

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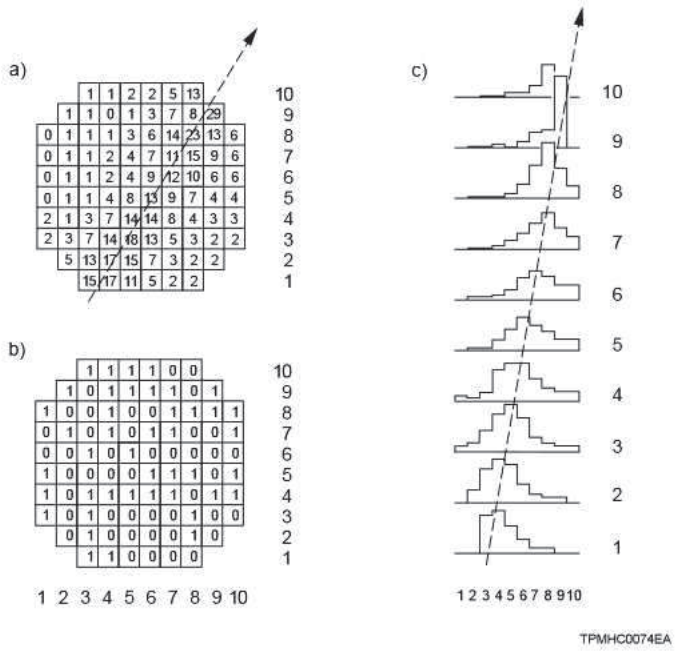


Figure 6-33: Cosmic-ray track measurements with a position-sensitive PMT having fine-mesh dynodes and a multianode (in no magnetic field)

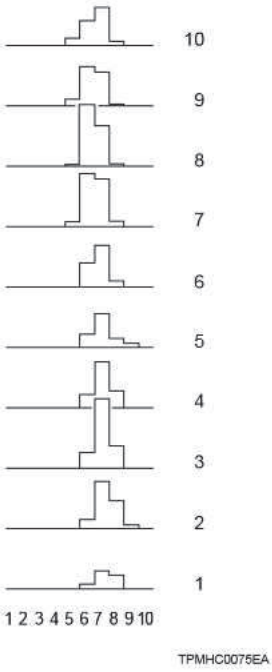


Figure 6-34: Cosmic-ray track measurements with a position-sensitive PMT having fine-mesh dynodes and a multianode (in magnetic field of 0.05 Tesla)

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MEMO

CHAPTER 7
HOW TO USE PHOTOMULTIPLIER TUBES AND ASSOCIATED CIRCUITS

This chapter explains how to use basic circuits and accessories necessary to operate a photomultiplier tube properly.[1)]

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7. 1 Voltage-Divider Circuits

7. 1. 1 Basic operation of voltage-divider circuits

For photomultiplier tube operation, a high voltage from 500 to 3000 volts is usually applied across the cathode (K) and anode (P), with a proper voltage gradient set up between the photoelectron focusing electrode (F), dynodes and, depending on tube type, an accelerating electrode (accelerator). This voltage gradient can be set up using independent multiple power supplies as shown in Figure 7-1, but this is usually not practical.

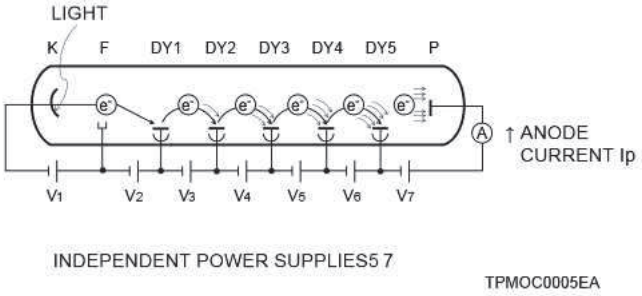


Figure 7-1: Schematic diagram of photomultiplier tube operation

In practice, as shown in Figure 7-2, the interstage voltage for each electrode is supplied by using voltage-dividing resistors (sometimes along with Zener diodes) connected between the anode and cathode. This circuit is known as a voltage-divider circuit or bleeder circuit.

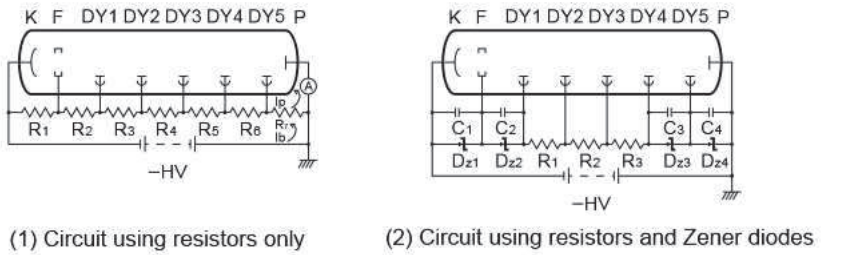


Figure 7-2: Voltage-divider circuits

The current Ib flowing through the voltage-divider circuits shown in Figures 7-2 (1) and (2) is called divider current, and closely related to the output linearity described later. The divider current Ib is approximately the applied voltage V divided by the sum of resistor values as follows:

$$I_b = \frac{V}{(R_1+R_2+\cdots+R_6+R_7)} \quad \text{(Eq. 7-1)}$$

The Zener diodes (D_z) shown in (2) are used to maintain the interstage voltages at constant values for stabilizing the photomultiplier tube operation regardless of the magnitude of the cathode-to-anode supply voltage. The capacitors C_1, C_2, C_3 and C_4 connected in parallel with the Zener diodes serve to minimize noise generated by the Zener diodes. This noise becomes significant when the current flowing through the Zener diodes is insufficient. Thus care is required at this point, as this noise can affect the signal-to-noise ratio of the photomultiplier tube output.

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7. 1. 2 Anode grounding and cathode grounding

As shown in Figure 7-2, the general technique used for voltage-divider circuits is to ground the anode and apply a large negative voltage to the cathode. This scheme eliminates the potential voltage difference between the external circuit and the anode, facilitating the connection of circuits such as ammeters and current-to-voltage conversion operational amplifiers to the photomultiplier tube. In this anode grounding scheme, however, bringing a grounded metal holder, housing or magnetic shield case near the bulb of the photomultiplier tube, or allowing it to make contact with the bulb can cause electrons in the photomultiplier tube to strike the inner bulb wall. This may possibly produce glass scintillation, resulting in a significant increase in noise.

Also, for head-on photomultiplier tubes, if the faceplate or bulb near the photocathode is grounded, the slight conductivity of the glass material causes a small current to flow between the photocathode and ground. This may cause electric damage to the cathode, possibly leading to considerable deterioration. For this reason, extreme care must be taken when designing the housing for a photomultiplier tube and when using an electromagnetic shield case. In addition, when wrapping the bulb of a photomultiplier tube with foam rubber or similar shock-absorbing materials before mounting the tube within its electromagnetic shield case at ground potential, it is very important to ensure that the materials have sufficiently good insulation properties.

The above problems concerning the anode grounding scheme can be solved by coating the bulb surface with black conductive paint and connecting it to the cathode potential. This technique is called "HA coating", and the conductive bulb surface is protected by a insulating cover for safety. In scintillation counting, however, because the grounded scintillator is usually coupled directly to the faceplate of a photomultiplier tube, the cathode is grounded with a high positive voltage applied to the anode, as shown in Figure 7-3. With this grounded cathode scheme, a coupling capacitor (C_c) must be used to separate the positive high voltage (+HV) applied to the anode from the signal, making it impossible to extract a DC signal. In actual scintillation counting using this voltage-divider circuit, a problem concerning base-line shift may occur if the counting efficiency increases too much, or noise may be generated if a leakage current is present in the coupling capacitor. Thus care should be taken regarding these points.

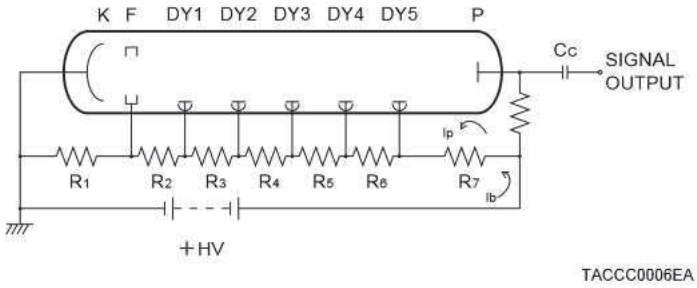


Figure 7-3: Grounded-cathode voltage-divider circuit

7. 1. 3 Voltage-divider current and output linearity

In either the anode grounding or cathode grounding scheme or either DC or pulse operation, when the light level incident on the photocathode is increased to raise the output current as shown in Figure 7-4, the relationship between the incident light level and the anode current begins to deviate from the ideal linearity at a certain current level (region B) and eventually, the photomultiplier tube output goes into saturation (region C).

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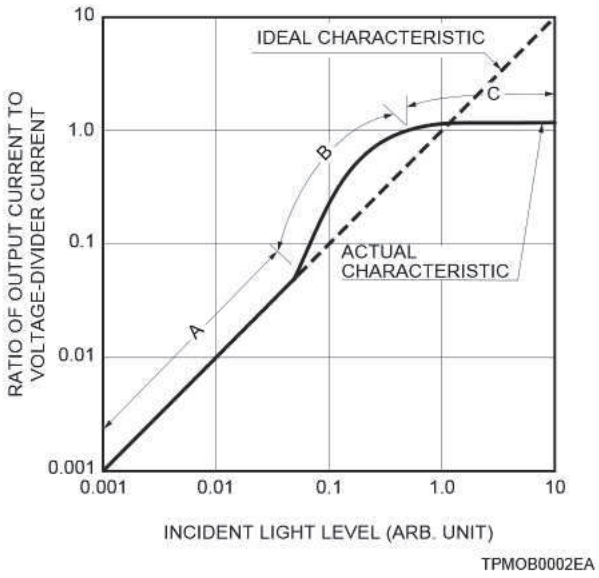


Figure 7-4: Output linearity of a photomultiplier tube

(1) DC-operation output linearity and its countermeasures

In deriving a DC output from a photomultiplier tube using the basic operating circuit shown in Figure 7-5, the current which actually flows through a voltage-divider resistor, for example the current flowing across resistor R_7, equals the difference between the divider current I_b and the anode current I_p which flows in the opposite direction through the circuit loop of P-Dy_5-R_7-P. Likewise, for other voltage-divider resistors, the actual current is the difference between the divider current Ib and the dynode current I_{Dy} flowing in the opposite direction through the voltage-divider resistor. The anode current and dynode current flow act to reduce the divider current and the accompanying loss of the interstage voltage becomes more significant in the latter dynode stages which handle larger dynode currents. Although the dynode current includes current components flowing in the same direction as the divider current Ib, they are of very small amounts and therefore not discussed here.

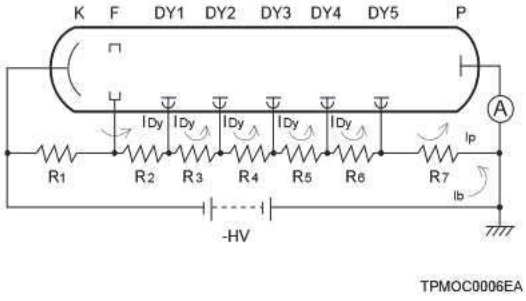


Figure 7-5: Basic operating circuit for a photomultiplier tube

The reduction of the divider current can be ignored if the anode output current is small. However, when the incident light level is increased and the resultant anode and dynode currents are increased, the voltage distribution for each dynode varies considerably as shown in Figure 7-6. Because the overall cathode-to-anode voltage is kept constant by the high-voltage power supply, the loss of the interstage voltage at the latter stages is redistributed to the previous stages so that there will be an increase in the interstage voltage.

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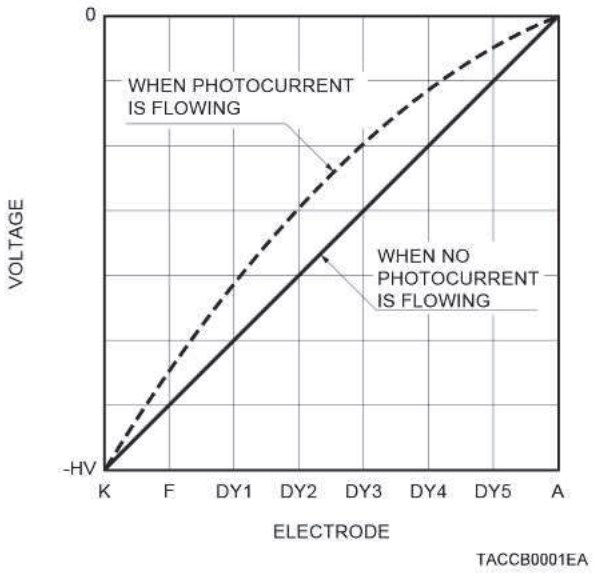


Figure 7-6: Influence of photocurrent on voltage applied to each electrode

The loss of the interstage voltage by the multiplied electron current appears most significantly between the last dynode (Dy_5 in Figure 7-5) and the anode, but the voltage applied to this area does not contribute to the secondary emission ratio of the last dynode. Therefore, the shift in the voltage distribution to the earlier stages results in a collective increase in current amplification, as shown at region B in Figure 7-4. If the incident light level is increased further so that the anode current becomes quite large, the secondary-electron collection efficiency of the anode degrades as the voltage between the last dynode and the anode decreases. This leads to the saturation phenomenon like that shown at region C in Figure 7-4.

While there are differences depending on the type of photomultiplier tube and divider circuit being used, the maximum practical anode current in a DC output is usually 1/20th to 1/50th of the divider current. If linearity better than ±1 percent is required, the maximum output must be held to less than 1/100th of the divider current.

To increase the maximum linear output, there are two techniques: one is to use a Zener diode between the last dynode and the anode as shown in Figure 7-2 (2) and, if necessary, between the next to last or second to last stage as well, and the other is to lower the voltage-divider resistor values to increase the divider current. However, with the former technique, if the divider current is insufficient, noise will be generated from the Zener diode, possibly causing detrimental effects on the output. Because of this, it is essential to increase the divider current to an adequate level and connect a ceramic capacitor having good frequency response in parallel with the Zener diode for absorbing the possible noise. It is also necessary to narrow the subsequent circuit bandwidth as much as possible, insofar as the response speed will permit. With the latter technique, if the voltage-divider resistors are located very close to the photomultiplier tube, the heat emanating from their resistance may raise the photomultiplier tube temperature, leading to an increase in the dark current and possible fluctuation in the output. Furthermore, since this technique requires a high-voltage power supply with a large capacity, it is inadvisable to increase the divider current more than necessary. To solve the above problems in applications where a high linear output is required, individual power supplies may be used in place of the voltage-divider resistors at the last few stages.

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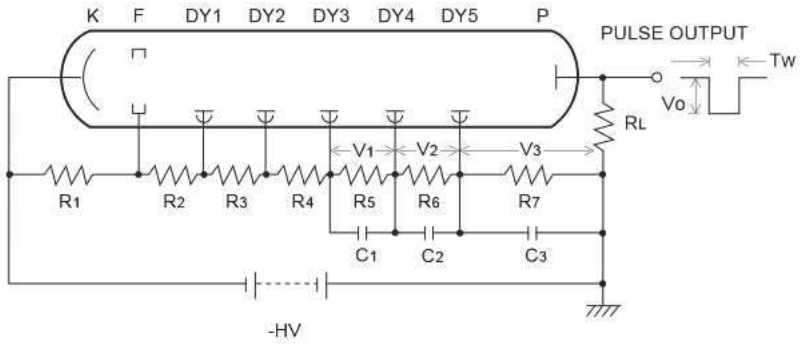
(2) Pulse-operation output linearity and its countermeasures

When a photomultiplier tube is pulse-operated using the voltage-divider circuit shown in Figure 7-2 (1) or Figure 7-3, the maximum linear output is limited to a fraction of the divider current just as in the case of DC operation. To prevent this problem, decoupling capacitors can be connected to the last few stages, as shown in Figures 7-7 (1) and (2). These capacitors supply the photomultiplier tube with an electric charge during the pulse duration and restrain the voltage drop between the last dynode and the anode, thus resulting in a significant improvement in pulse linearity. If the pulse width is sufficiently short so that the duty cycle is small, this method makes it possible to derive an output current up to the saturation level which is caused by the space charge effects in the photomultiplier tube dynodes discussed in Section 3.2, (2) of Chapter 3. Consequently, a high peak output current, more than several thousand times as large as the divider current can be attained.

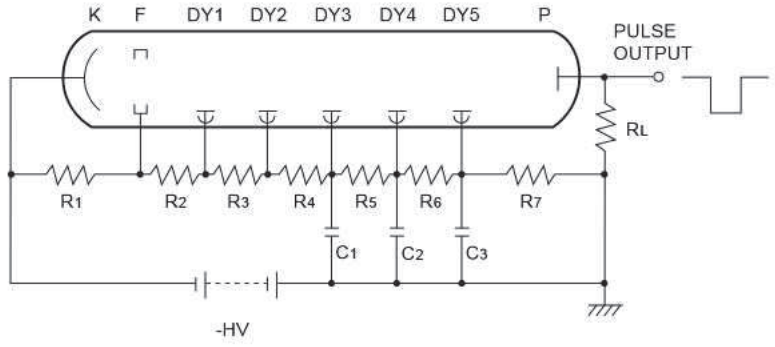
There are two methods of using the decoupling capacitors: a serial connection method and a parallel connection method as illustrated in Figure 7-7 below. The serial connection is more commonly used because the parallel connection requires capacitors which can withstand a high voltage.

The following explains the procedure for calculating the capacitor values, using the circuit shown in Figure 7-7 (1) as an example.

(1) Serial-connected decoupling capacitors



(2) Parallel-connected decoupling capacitors



TACCC0007EA

Figure 7-7: Voltage-divider circuits with decoupling capacitors added

First of all, if we let the output-pulse peak voltage be V_0, and the pulse width be T_W and the load resistance be R_L, the output pulse charge Q_0 per pulse is expressed by Eq. 7-22), as follows:

$$Q_0 = T_W \frac{V_0}{R_L} \quad \text{(Eq. 7-2)}$$

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Next, let us find the capacitance values of the decoupling capacitors C_1 to C_3, using Q_0. If we let the charge stored in capacitor C_3 be Q_3, then to achieve good output linearity of better than ±3 percent, the following relation should generally be established:

$$Q_3 \geqq 100\, Q_0 \quad \text{(Eq. 7-3)}$$

From the common relation of Q=CV, C_3 is given by Eqs. 7-4 and 7-5.

$$C_3 \geqq 100 \frac{Q_3}{V_3} \quad \text{(Eq. 7-4)}$$

then

$$C_3 \geqq 100 \frac{Q_3}{I_b \cdot R_7} \quad \text{(Eq. 7-5)}$$

Normally, the secondary emission ratio δ per stage of a photomultiplier tube is 3 to 5 at the interstage voltage of 100 volts. However, considering occasions in which the interstage voltage drops to about 70 or 80 volts, the charges Q_2 and Q_1 stored in C_2 and C_1 respectively are calculated by assuming that δ between each dynode is 2, as follows:

$$Q_2 = \frac{Q_3}{2} \qquad Q_1 = \frac{Q_2}{2} = \frac{Q_3}{4}$$

Then, the capacitance values of C_2 and C_1 can be obtained in the same way as in C_3.

$$C_2 \geqq 50 \frac{Q_0}{V_2} = 50 \frac{Q_0}{I_b \cdot R_6}$$

$$C_1 \geqq 25 \frac{Q_0}{V_1} = 25 \frac{Q_0}{I_b \cdot R_5}$$

In cases where decoupling capacitors need to be placed in the dynode stages earlier than Dy_3 in order to derive an even larger current output, the same calculation can also be used.

Here, as an example, with the output pulse peak voltage V_0=50mV, pulse width T_W=1μs, load resistance R_L=50Ω, interstage resistor values R_5=R_6=R_7=100kΩ and divider current I_b=1mA, each capacitor value can be calculated in the following steps: First, the amount of charge per output pulse is obtained as follows:

$$Q_0 \geqq \frac{50\text{mV}}{50\Omega} 5\ 1\text{mA} = 1\text{nC}$$

The capacitance values required of the decoupling capacitors C_3, C_2 and C_1 are calculated respectively as follows:

$$C_3 \geqq 100 \frac{1\text{nC}}{100\text{k}\Omega 5\ 1\text{mA}} = 1\text{nF}$$

$$C_2 \geqq 50 \frac{1\text{nC}}{100\text{k}\Omega 5\ 1\text{mA}} = 0.5\text{nF}$$

$$C_1 \geqq 25 \frac{1\text{nC}}{100\text{k}\Omega 5\ 1\text{mA}} = 0.25\text{nF}$$

The above capacitance values are minimum values required for proper operation. Therefore it is usually suggested that the voltage-divider circuit be designed with a safety margin in the capacitance value, of about 10 times larger than the calculated values. If the output current increases further, additional decoupling capacitors should be connected as necessary to the earlier stages, as well as increasing the capacitance values of C_1 to C_3. As with the DC operation, it should be noted that in pulse operation, even with the above countermeasures provided, the output deviates from the linearity range when the average output current exceeds 1/20th to 1/50th of the divider current. In particular, care is required at high counting rates even if the output peak current is low.

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7. 1. 4 Voltage distribution in voltage-divider circuits

(1) Voltage distribution in the anode and latter stages

Even under conditions where adequate countermeasures for pulse output linearity have been taken by use of decoupling capacitors, output saturation will occur at a certain level as the incident light is increased while the interstage voltage is kept fixed. This is caused by an increase in the electron density between the electrodes, causing space charge effects which disturb the electron current. This saturated current level varies, depending on the electrode structures of the anode and last few stages of the photomultiplier tube and also on the voltage applied between each electrode. As a corrective action to overcome space charge effects, the voltage applied to the last few stages, where the electron density becomes high, should be set at a higher value than the standard voltage distribution so that the voltage gradient between those electrodes is enhanced. For this purpose, a so-called tapered voltage-divider circuit is often employed, in which the interstage voltage is increased in the latter stages. But, sufficient care must be taken with regard to the interelectrode voltage tolerance capacity.

As an example, Figure 7-8 shows a tapered voltage-divider circuit used for a 5-stage photomultiplier tube. In this voltage-divider circuit, the Dy_5-to-anode voltage is set at a value lower than the Dy_4-to-Dy_5 voltage. This is because the electrode distance between the last dynode and the anode is usually short so that an adequate voltage gradient can be obtained with a relatively low voltage.

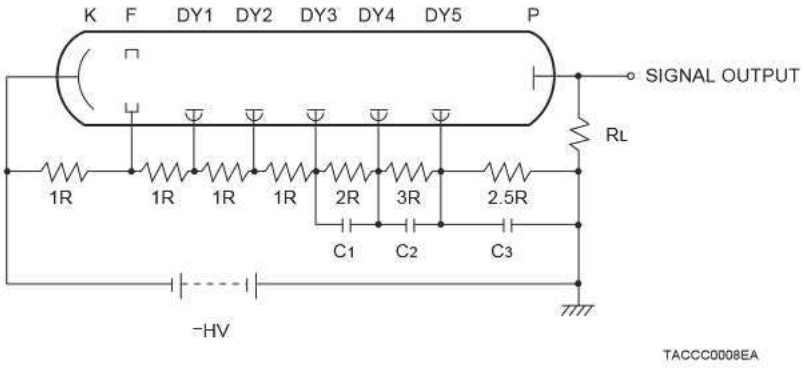


Figure 7-8: Pulse output linearity countermeasures using decoupling capacitors and tapered voltage-divider circuit

The voltage distribution ratio for a voltage-divider circuit that provides optimum pulse linearity depends on the type of photomultiplier tube. In high energy physics applications, a higher pulse output is usually required. Our catalog "Photomultiplier Tubes and Assemblies for Scintillation Counting and High Energy Physics" lists the recommended voltage distribution ratios of individual voltage-divider circuits intended for high pulse linearity (tapered voltage-dividers) and their maximum output current values. Use of these recommended voltage-divider circuits improves pulse linearity 5 to 10 times than that obtained with normal voltage-divider circuits (equally divided circuits). Figure 7-9 shows a comparison of pulse linearity characteristics measured with a tapered voltage-divider circuit and with a normal voltage-divider circuit. It is obvious that pulse linearity is improved about 10 times by using the tapered voltage-divider circuit. Note that when this type of tapered voltage-divider circuit is used, the anode output lowers to about 1/5th in comparison with the normal voltage-divider anode output. Therefore, adjustment is required to increase the supply voltage for the photomultiplier tube.

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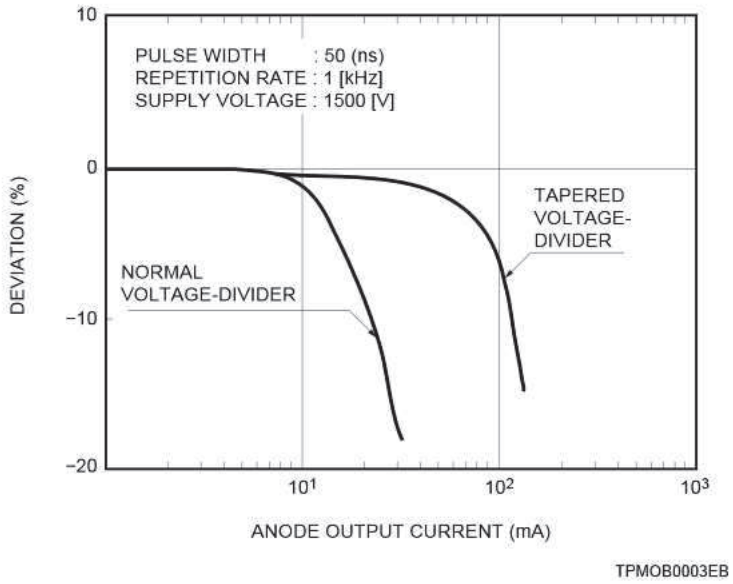


Figure 7-9: Linearity characteristic using a tapered and a normal voltage-divider circuit

The above methods for improving pulse output linearity by use of decoupling capacitors and tapered voltage-divider circuits are also applicable for the voltage-divider circuits with the cathode at ground potential and the anode at a high positive voltage.

The tapered voltage-divider circuit will also prove effective in special applications where a high output voltage is required. For instance, with an anode output current of I_p=100μA and R_L=1MΩ, the output voltage will be 10 volts and the anode potential will drop 10 volts accordingly. This means that the anode-to-last-dynode voltage must be sufficiently greater than 10 volts in order to prevent the output linearity from deviating. Use of a tapered voltage-divider circuit can maintain the anode-to-last-dynode voltage at an adequate level and thus provides a higher output voltage compared to normal voltage-divider circuits.

(2) Voltage distribution for the cathode and earlier stages

As mentioned above, the voltage distribution ratio for the latter stages near the anode is an important factor that determines the output linearity of a photomultiplier tube. In contrast, the voltage distribution between the cathode, focusing electrode and first dynode has an influence on the photoelectron collection efficiency and the secondary emission ratio of the first dynode. These parameters are major factors in determining the output signal-to-noise ratio, pulse height dispersion in the single and multiple photon regions, and also electron transit time spread (TTS).

Furthermore, the voltage distribution at the earlier stages affects the cathode linearity, energy resolution in scintillation counting and magnetic characteristics of a photomultiplier tube, and therefore its setting requires care just as in the case of the latter stages. In general, the voltage distribution ratios for the earlier stages listed in our catalog are determined in consideration of the electron collection efficiency, time properties and signal-to-noise ratio. Note that since they are selected based on the recommended supply voltage, proper corrective actions may be required in cases in which the supply voltage becomes less than one-half that of the recommended voltage. For example, increasing the voltage distribution ratio at the earlier stages or using Zener diodes to hold the dynode voltage constant are necessary. For more information on the photoelectron collection efficiency, output signal-to-noise ratio and other characteristics, refer to Chapter 3.

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Figure 7-10 shows a variant of the voltage-divider circuit shown in Figure 7-10, which provides the above measures for the cathode to the first dynode.

It is quite essential to apply the correct voltage to the cathode, focusing electrode and the first dynode or earlier dynode stages with precision resistors. In applications such as in a magnetic field, or in very low-light-level measurement where shot noise may create a problem, or in single photon counting and in TOF (time-of-flight) trigger counters or hodoscopes requiring good time properties.

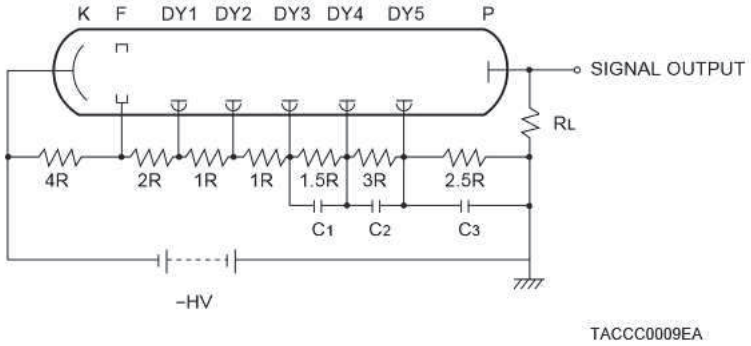


Figure 7-10: Voltage-divider circuit with tapered configurations at both the earlier and latter stages

The recommended voltage distribution ratios listed in our catalog are selected for general-purpose applications, with consideration primarily given to the gain. Accordingly, when the photomultiplier tube must be operated at a lower supply voltage or must provide a higher output current, selecting a proper voltage distribution ratio that matches the application is necessary. As to the resistance values actually used for the voltage-divider circuit, they should basically be selected in view of the photomultiplier tube supply voltage, output current level and required linearity. It should be noted that if the resistance values are unnecessarily small, the resulting heat generation may cause various problems, such as an increase in the dark current, temperature drift in the output and lack of capacity in the power supply. Therefore, avoid allowing excessive divider current to flow.

7. 1. 5 Countermeasures for fast response circuits

As shown in Figure 7-11, inserting a lowpass filter comprised of R_1 and C_1 into the high-voltage supply line is also effective in reducing noise pickup from the high-voltage line. The transistor R_1 is usually several tens of kilohms, and a ceramic capacitor of 0.005 to 0.05 microfarads which withstands high voltage is frequently used as C_1.

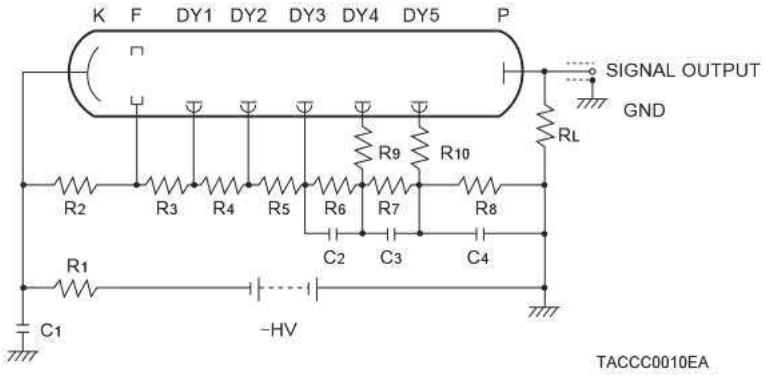


Figure 7-11: Voltage-divider circuit with countermeasure against pulse output linearity, ringing and high-voltage power supply noise

In applications handling a fast pulsed output with a rise time of less than 10 nanoseconds, inserting damp-

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ing resistors R_{10} into the last dynode as shown in Figure 7-11 and if necessary, R_9 into the next to last dynode can reduce ringing in the output waveform. As damping resistors, noninduction type resistors of about 10 to 100 ohms are used. If these values are too large, the time response will deteriorate. Minimum possible values should be selected in the necessary range while observing the actual output waveforms. Figure 7-12 shows typical waveforms as observed in a normal voltage-divider circuit with or without damping resistors. It is clear that use of the damping resistors effectively reduces ringing.

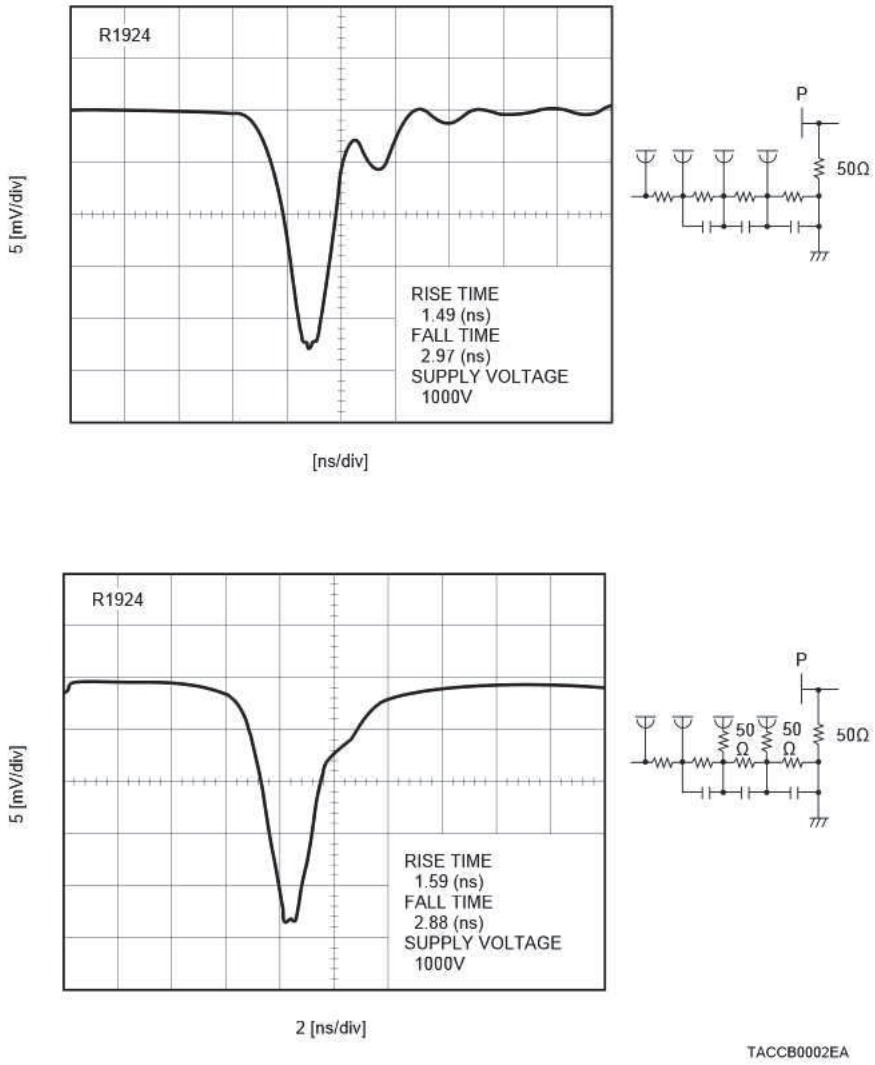


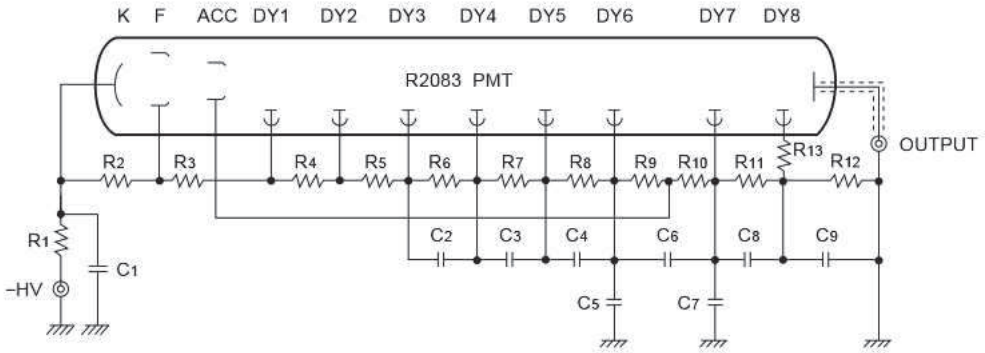
Figure 7-12: Effect of damping resistors on ringing

7. 1. 6 Practical fast-response voltage-divider circuits

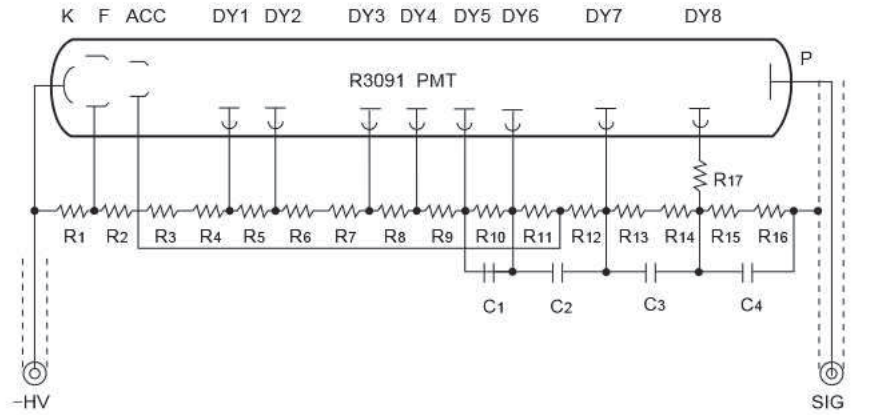
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The circuit diagrams of the Hamamatsu H2431 and H3284 photomultiplier tube assemblies are shown in Figure 7-13 below as practical examples of fast-response voltage-divider circuits which have been designed based on the description in the preceding section.

(a) H2431 circuit diagram



(b) H3284 circuit diagram



TPMHC0016EA

Figure 7-13: Fast-response voltage-divider circuits

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7. 1. 7 High output linearity voltage-divider circuit (1)

In pulse applications such as scintillation counting, when a photomultiplier tube is operated at a high count rate, the output sometimes encounters linearity problems. In this case, use of transistors in place of the voltage-divider resistors at the latter stages can improve the output linearity degradation resulting from the divider current limitation.

As an example, Figure 7-14 shows a voltage-divider circuit for the Hamamatsu R329 photomultiplier tube, devised by FNAL (Fermi National Accelerator Laboratories)[3].

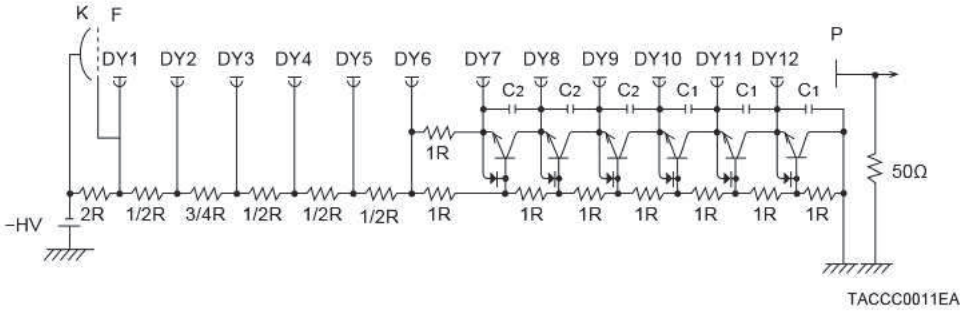


Figure 7-14: Voltage-divider circuit using transistors

In the circuit shown in Figure 7-14, a photoelectron current first flows into the first dynode, then secondary electrons flow through the successive dynodes and into the collector of each transistor. As a result, the emitter potential of each transistor increases while the collector current decreases along with a decrease in the base current. At this point, the decrease in the collector current is nearly equal to the current flowing through the photomultiplier tube and accordingly, the transistors supply the current for the photomultiplier tube.

When using these transistors, the following points must be taken into consideration.

1. Choose transistors having a large h_{fe} so that sufficient current can flow into the collector.
2. Choose transistors having good frequency characteristics.
3. Use capacitors having good frequency characteristics.
4. The number of stages to which transistors are added should be determined in view of the operating conditions of the photomultiplier tube to be used.

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7. 1. 8 High output linearity voltage-divider circuit (2)

As shown in Figure 7-15, this circuit utilizes a Cockcroft-Walton voltage multiplier circuit in which an array of diodes is connected in series. Along each side of the alternate connection points, capacitors are connected in series. If the reference voltage V is placed at the input, this circuit provides voltage potentials of 2V, 3V and so on at each connection point. Therefore, this power supply circuit functions just like a conventional resistive voltage-divider circuit. In addition, this circuit achieves good linearity for both DC and pulsed currents yet with low power consumption, making it suitable for use in compact circuits. As Figure 7-16 shows, the Cockcroft-Walton circuit assures higher DC linearity than that obtained with a resistive voltage-divider circuit.

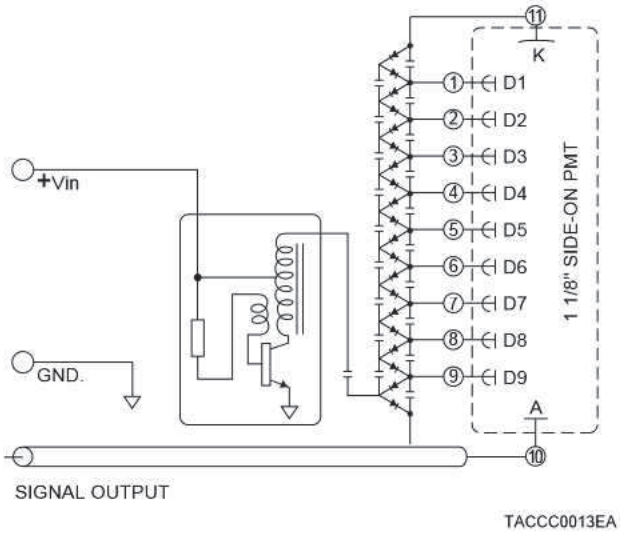


Figure 7-15: Cockcroft-Walton circuit

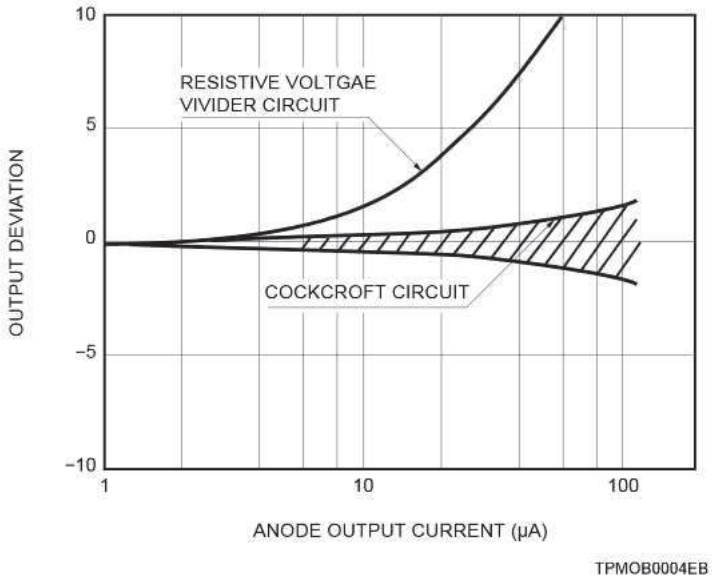


Figure 7-16: Output linearity

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7. 1. 9 Gating circuit

Next, let us introduce gating circuits as a variant of voltage-divider circuits.

In general, in such applications as fluorescence measurement, plasma electron temperature measurement utilizing Thomson scattering, Raman spectroscopy and detection of defects in optical transmission paths, the signal light to be measured is extremely weak in comparison with primary light levels such as the excitation light. For this reason, the detector system is set up to have extremely high sensitivity. If even part of the primary light enters the detector system as stray light, it may cause saturation in the photomultiplier tube output and in the subsequent circuits, degrading their performance. This problem could be solved if only the excessive light was blocked by use of a ultra-fast shutter such as a liquid crystal. But this is not yet practical. A practical technique commonly used is "gating" by which a photomultiplier tube is electronically switched to eliminate the output during unnecessary periods when excess light may be present.

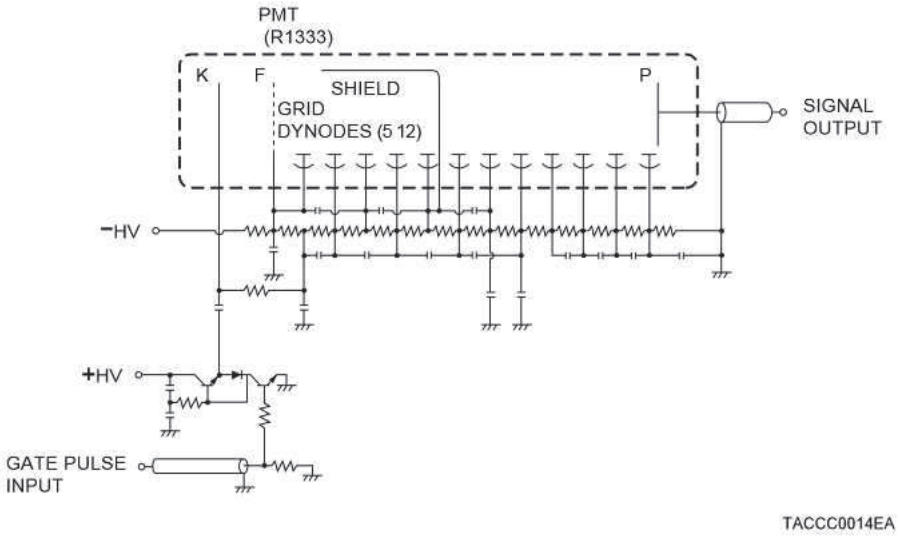


Figure 7-17: Circuit diagram of the C1392 socket assembly with a gating circuit

Figure 7-17 shows the circuit diagram of the Hamamatsu C1392 socket assembly with a gating circuit.[4)] The C1392 is a "normally OFF" type which normally sets the photomultiplier tube output to OFF, and when a gate signal is inputted, sets the photomultiplier output to ON. Also available are variant models with reverse operation, i.e., a "normally ON" type which sets the output to OFF by input of a gate signal.

The following explains the basic operation of the C1392 socket assembly used in conjunction with a photomultiplier tube.

If the photomultiplier tube output is OFF at a gate input of 0V, a reverse bias of about 10 volts with respect to the focusing electrode and first dynode is supplied to the cathode, thereby preventing photoelectrons, if emitted from the cathode, from reaching the dynode section. Here, if a pulse signal of +3 to +4 volts is applied to the gate input terminal, the driver circuit gives a forward bias to the cathode via capacitance coupling, and sets the photomultiplier tube output to ON during the period determined by the gate pulse width and the time constant of the capacitance-coupled circuit. This gating circuit provides a switching ratio (or extinction ratio) of 10^4 of more. The capacitors are connected from the first through the center dynode to absorb the switching noises often encountered with this type of gating circuit.

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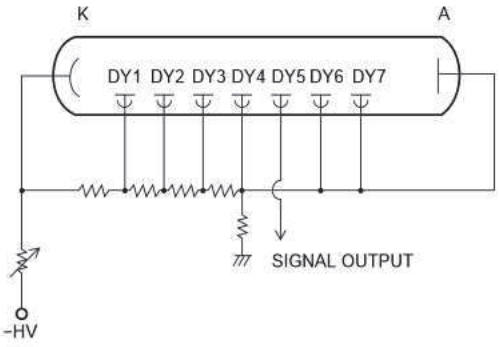
7.1.10 Output control circuit

The photomultiplier tube output is usually controlled by changing the supply voltage. In some applications, however, a single power supply is used to operate two or more photomultiplier tubes or an output control circuit is added to the voltage-divider circuit if the variable range of the high-voltage power supply and amplifier is narrow. The following explains how to provide an output control circuit, using the circuits shown in Figure 7-18 as examples.

With the circuits shown in Figure 7-18, there are three techniques for controlling the photomultiplier tube output. The first is, as shown in both (1) and (2) in the figure, to use a variable resistor connected between the cathode and the negative high-voltage power supply so that the overall voltage applied to the photomultiplier tube can be varied. With this technique, depending on the conditions, the photomultiplier tube gain can be varied within a considerably wide range (up to 10 times). The high voltage supplied from the power supply is divided across this variable resistor and each resistor in the voltage-divider circuit. If the resistance value of the variable resistor is known, the change in the voltage applied to the photomultiplier tube can also be found, thus the signal variation can be predicted. Therefore, this technique is frequently used in many applications. It should be borne in mind that the higher the voltage-divider resistance value, the higher the variable resistance value should be and, in some cases, it might be difficult to obtain a high-quality resistor with high resistance and large rated capacity. On the other hand, if the voltage-divider resistor value is too small, a variable resistor with high rated capacity is required, and problems with contact failure in the variable resistor tend to occur.

Moreover, when a negative high voltage is applied to the cathode as shown in the figure, a high voltage is also impressed on the variable resistor. Thus the housing that contains the photomultiplier tube and associated circuits must also be designed to have sufficiently high dielectric resistance.

(1) Shorting the latter dynodes



(2) Varying the potential of a central-stage dynode

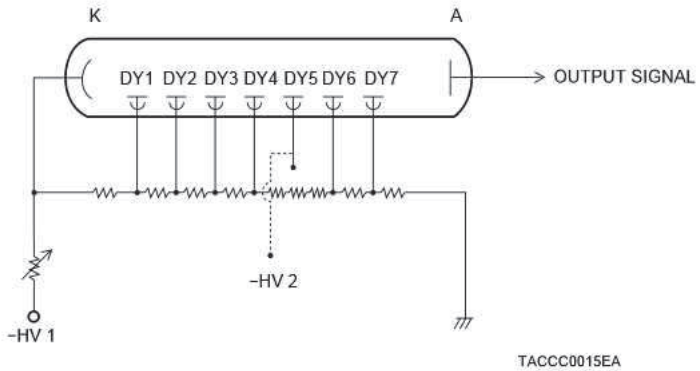


Figure 7-18: Output control circuits

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The second technique is to short the latter dynode stages and anode so that the signal is derived from a middle dynode. This is effective in cases in which the photomultiplier tube gain is so high that the supply voltage may drop considerably and the resultant decrease in the interstage voltage degrades the collection efficiency and secondary electron emission ratio. Shorting the latter dynode stages as shown in (1), that is, essentially, reducing the number of dynode stages, assures a higher interstage voltage and results in an improvement in the signal-to-noise ratio. However, this is accompanied by a sacrifice in linearity characteristics because the output is fetched from an earlier dynode. Furthermore, since the number of stages being used is changed, the gain versus supply voltage characteristic also varies accordingly. The degree of this variation is different from tube to tube, and it is therefore best to select a photomultiplier tube with characteristics optimized for the particular application rather than using this technique.

The third technique is performed by varying the potential of a mid-stage dynode, as shown in Figure 7-18 (2). This makes use of the fact that with a varying dynode potential, the number of secondary electrons released from the dynode decreases and also the collection efficiency between dynodes drops. There are two methods of adjusting the dynode potential. In one method a variable resistor is added between the front and rear adjacent dynodes. The other method is to use an external power supply directly connected to the central dynode. Although both are relatively easy to implement, there is a disadvantage that the signal-to-noise ratio may deteriorate if the dynode potential is varied too much. Figure 7-19 dictates the gain variation and energy resolution of a photomultiplier tube when the dynode potential is varied continuously. It can be seen that the energy resolution begins to deteriorate near the points at which the gain drops by more than 50 percent. This behavior is not constant but differs depending on individual photomultiplier tubes. In addition, the variable gain range is not so wide.

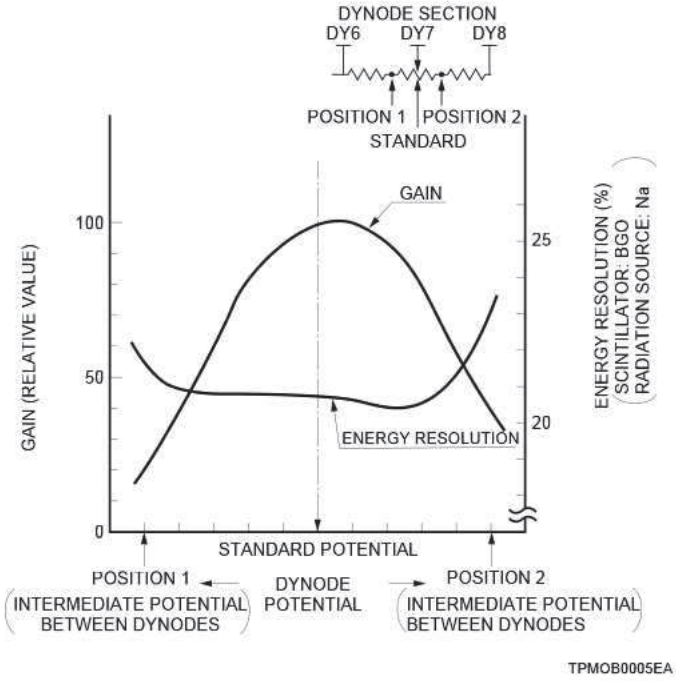


Figure 7-19: Gain variation and energy resolution as a function of dynode potential

As discussed above, it should be noted that using the voltage-divider circuit for controlling the photomultiplier tube output is not recommended. We advise using normal methods by which the power supply voltage is directly changed for controlling the photomultiplier tube output.

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7.1.11 Precautions when fabricating a voltage-divider circuit

In the previous sections, the functions of various voltage-divider circuits and their design consideration have been discussed. This section describes the precautions for actually fabricating a voltage-divider circuit.

(1) Selecting the parts used for a voltage-divider circuit

Since the voltage-divider circuit has a direct influence on the photomultiplier tube operation, careful selection of parts is necessary.

Resistors

Because photomultiplier tubes are very susceptible to changes in the supply voltage and interstage voltage, metal-film resistors with a minimum temperature coefficient should be used. Preferably, use the same type of resistor for all stages, but if not available, select resistors with temperature coefficients which are close to each other. These resistors should also have good temperature characteristics, but their accuracy is not so critical. If non-uniformity between each resistor is held within ±5 percent, it will work sufficiently. This is because the photomultiplier tube gain varies to some degree from tube to tube and also because a voltage difference of several volts will not affect the electron trajectories very much. If possible, we recommend using resistors with sufficient rated power and dielectric resistance, for example, respectively at least 1.7 times and 1.5 times higher than necessary. As a rough guide, the resistance value per stage is typically from 100 kilohms to 1 megohm. For damping resistance and load resistance, use noninduction type resistors designed for use at high frequency.

Decoupling capacitors

In pulsed light applications where a fast response photomultiplier tube handles the output with a rise time of less than 10 nanoseconds, decoupling capacitors are connected between dynodes. For these decoupling capacitors, use ceramic capacitors with sufficiently high impedance at a high frequency range and adequate dielectric resistance at least 1.5 times higher than the maximum voltage applied between dynodes. To prevent the actual capacitance from being lower than the designed value during operation, select capacitors with a minimum minus (-) tolerance.

For the bypass capacitor used to eliminate noise from the power supply connected to the high-voltage input terminal of a photomultiplier tube, use a ceramic capacitor having high impedance at high frequencies and adequate dielectric resistance.

Coupling capacitors

For the coupling capacitor which separates the signal from a positive high voltage applied to the anode in a grounded-cathode voltage-divider circuit, use a ceramic capacitor having minimum leakage current (which may also be a source of noise) as well as having superior frequency response and sufficient dielectric resistance.

PC boards for voltage-divider circuits

When a voltage-divider circuit is assembled not on a photomultiplier tube socket but on a PC board, use a high-quality PC board made of glass epoxy or similar materials which exhibit low leakage current even at a high voltage. If both sides of the PC board are used for assembly, select a board with adequate thickness.

On a glass epoxy board, the wiring space between patterns necessary to hold a potential difference of 1 kilovolt is typically 1 millimeter or more.

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Leads

For high voltage circuits, use teflon or silicone leads which can withstand a high voltage, or use coaxial cable such as RG-59B/U. In either case, take sufficient care with regard to the dielectric resistance of leads or conductor wires.

For signal output lines, use of a coaxial cable such as RG-174/U and 3D-2V is recommended. For high-speed circuits, in particular, a 50-ohm coaxial cable is commonly used to provide the good impedance match with the measurement equipment. However, if the signal current to be derived is not very low (several microamperes or more) and the lead length is no longer than 20 centimeters, using normal leads does not create any problem in practice, as long as a noise source is not located near the photomultiplier tube.

(2) Precautions for mounting components

This section describes precautions to be observed when mounting components on a voltage-divider circuit. Refer to Figure 7-11 while reading the following precautions.

Voltage-divider resistors

Considering heat dispersion, provide adequate space between voltage-divider resistors so as not to allow them to make contact with each other. When a low resistance is used or in low-light-level measurement where an increase in the dark current resulting from temperature rise may create a significant problem, avoid direct connections of voltage-divider resistors to the lead pins of the photomultiplier tube or to the socket so that Joule heat generated from the voltage-divider circuit is not directly conducted to the photomultiplier tube. Be sure to allow a distance between the photomultiplier tube and the voltage-divider circuit.

Decoupling capacitors

The lead length of decoupling capacitors used for fast pulse operation affects the photomultiplier tube time properties and also causes ringing due to the lead inductance. Therefore lead length should be kept as short as possible. Even when mounting voltage-divider resistors remote from a photomultiplier tube, the decoupling capacitors must be mounted directly to the lead pins of the photomultiplier tube or to the socket.

Signal output line

The wiring length of a signal output line including load resistance should be as short as possible. It must be wired away from the high voltage lines and the components to which a high voltage is applied. In particular, when handling fast pulse signals, grounding of the signal circuitry and power supply circuitry, as shown in Figure 7-11, is essential. If extra-low output currents are to be derived from a photomultiplier tube, attention must also be paid to shielding the signal line and to preventing ohmic leakage.

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7.2 Photomultiplier Tube Voltage Dependence and High-Voltage Power Supply

Photoelectrons emitted from the photocathode of a photomultiplier tube are guided by the focusing electrode or accelerating electrode and impinge on the first dynode where several times this number of electrons are released as secondary electrons. These secondary electrons are further multiplied in the successive dynodes and finally a large number of electrons, 0.1 to 10 million times the initial number of photoelectrons, reach the anode. As detailed in Section 2.2 of Chapter 3, when a voltage V is applied between the cathode and the anode of a photomultiplier tube having n dynode stages, the overall current gain μ is expressed in the following relation.

$$\mu = A \cdot V^{kn}$$

Typical photomultiplier tubes employ about 10 stages of dynodes and as shown in Figure 7-20, the current amplification is proportional to the 6th to 10th power of the voltage applied between the cathode and the anode. This means that the photomultiplier tube output is extremely susceptible to variations in the applied voltage and that the power supply used for photomultiplier tubes must be stable.

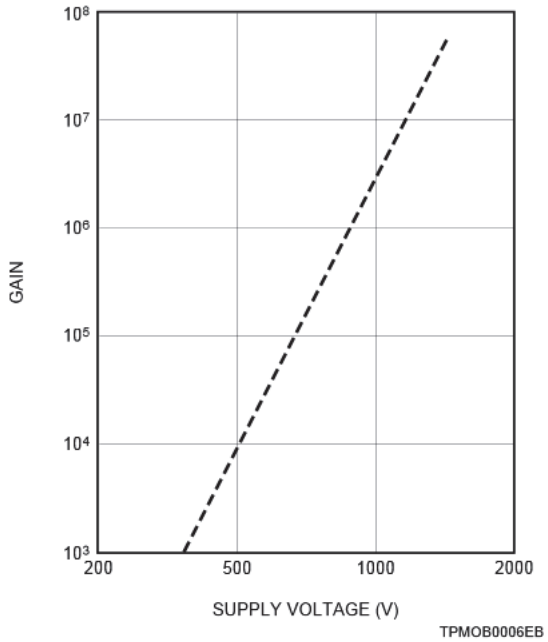


Figure 7-20: Current amplification vs. supply voltage

Including drift, ripple, temperature dependence, input regulation and load regulation, the power supply must provide collective stability which is at least 10 times as stable as the output stability required of the photomultiplier tube.

Series-regulator types regulated high-voltage power supplies optimized for photomultiplier tubes, are extensively used and have gained a good reputation. Recently, a variety of switching-regulator types have been put on the market and are becoming widely used. Most of the switching-regulator type power supplies offer compactness and light weight, yet provide high voltage and high current. However, with some models, the switching noise is superimposed on the AC input and high voltage output or the noise is radiated. Thus, sufficient care is required when selecting this type of power supply, especially in low-light-level detection, measurement involving fast signal processing, and photon counting applications.

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7. 3 Connection to The External Circuit

7. 3. 1 Observing an output signal

To observe the output signal of a photomultiplier tube, various methods are used depending on the operating conditions as illustrated in Figures 7-21 to 7-23.

As described in Section 7.1.2 in this chapter, there are two schemes for voltage-divider circuit operation: the anode grounding and the cathode grounding schemes. The anode grounding scheme permits both DC and pulse operation as shown in Figures 7-21 and 7-22. On the other hand, the cathode grounding scheme uses a coupling capacitor to separate the high voltage applied to the anode, so that only pulse operation is feasible. This scheme eliminates DC components produced by such factors as background light.

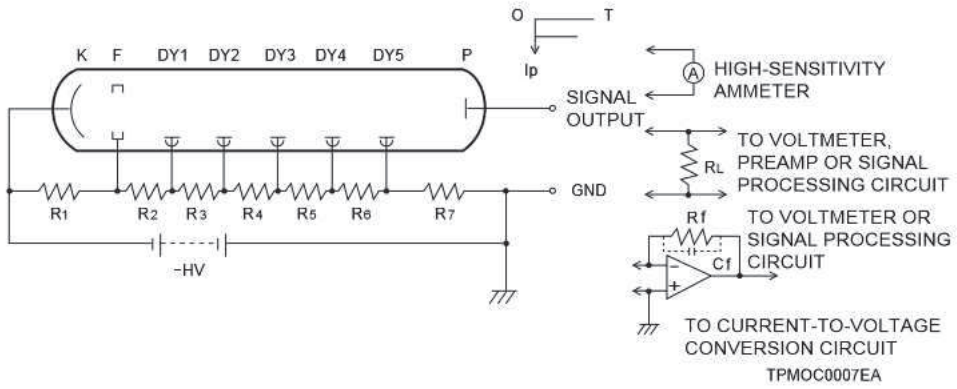


Figure 7-21: Anode grounding scheme in DC operation

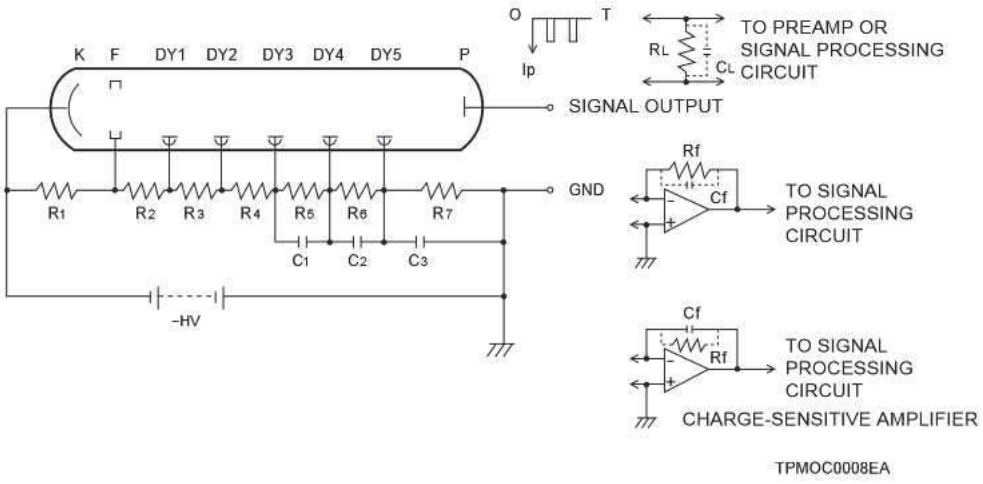


Figure 7-22: Anode grounding scheme in pulse operation

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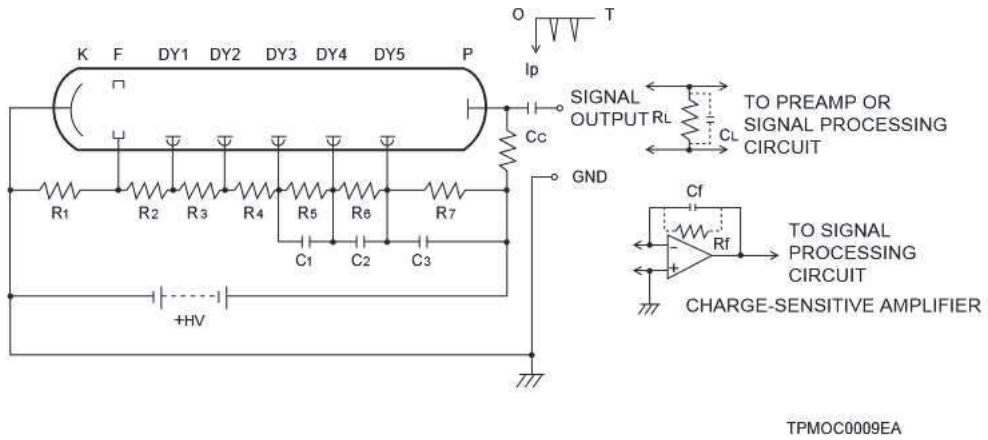


Figure 7-23: Cathode grounding scheme in pulse operation

It should be noted that when wiring the photomultiplier tube output to an amplifier circuit, the amplifier circuit must be wired before turning on the high-voltage power supply. When a high voltage is applied to the voltage-divider circuit even in a dark state, the possible dark current creates a charge on the anode. If the voltage-divider circuit is wired to the amplifier circuit under this condition, the charge will instantaneously flow into the amplifier, thus probably leading to damage of the amplifier circuit. Care should particularly be taken when using high speed circuits, as they are more susceptible to damage.

7. 3. 2 Influence of a coupling capacitor

A coupling capacitor, required by the cathode grounding scheme, can also be used in the anode grounding scheme in order to eliminate the DC components. This section describes precautions for using a voltage-divider circuit to which a coupling capacitor is connected.

Output waveform

When a photomultiplier tube is operated with the circuit shown in Figure 7-24, if the anode output pulse width Pw is sufficiently shorter than the time constant CR (R is parallel resistance of R_a and R_L), the impedance of the coupling capacitor can be ignored and thus the signal pulse current is divided to flow into R_L and R_a. In this case, the input waveform is transmitted to the output waveform without distortion, regardless of the capacitance value of the coupling capacitor. However, if P_W is close to or longer than CR, the output will have a differential waveform.

Because the coupling capacitor is merely used as a coupling element between the voltage-divider circuit and the amplifier circuit, P_W must be at least several tens of times shorter than C_R so that the output waveform has good fidelity to the input waveform. If the output waveform is differentiated, the output pulse height is influenced by the capacitance value and temperature characteristic of the coupling capacitor. In particular, when a 50-ohm resistor is used for R_a to optimize fast response operation, the time constant C_R becomes small and thus care should be taken of this point.

In the case of low frequency applications, the impedance of the coupling capacitor cannot be ignored. Since its impedance $Z_C = \frac{1}{2\pi f_C}$, the output signal decays by 3dB (approximately to 7/10th of the pulse height) at a frequency f=1/2pCR_a.

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Base-line shift

As stated above, the amount of the signal passing through the coupling capacitor is stored as a corresponding charge on the capacitor. This stored charge Q generates a voltage of $E_0=Q/C$ across both sides of the capacitor in the reverse direction of the signal. This voltage E_0 attenuates by a factor of $V=E_0e^{-t/RC}$ related to the time constant C_R which is determined by the capacitance value C and the serial resistance value R of R_a and R_L. The voltage induced in the capacitor is divided by R_a and R_L, and the output voltage Va is given by the following equation:

$$V_a = E_0 e^{-t/RC} 5 \frac{R_a}{R_a+R_L} \quad \text{(Eq. 7-6)}$$

Here, if the signal repetition rate increases, the base line does not return to the true zero level. This is known as base-line shift, and can be minimized by reducing the time constant CR. In this case, reducing the capacitor value increases the initial voltage E0, but shortens the discharge time. Decreasing the resistor value also shortens the discharge time, but this is accompanied by a decrease in the signal voltage, causing a problem with the signal-to-noise ratio. In contrast, increasing the resistor value produces a larger output and results in an improvement in the signal-to-noise ratio, but a base-line shift tends to occur due to the long time constant. If Ra is large, it lowers the anode potential, thus care is required when excessive current including DC current flows.

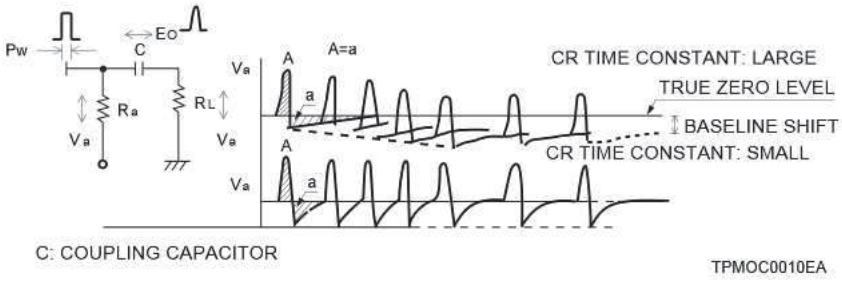


Figure 7-24: Base-line shift

Eventually, when the amount of charge stored on the capacitor (portion A in Figure 7-24) is discharged in a certain time period (portion a in Figure 7-24), the area of portion A is equal to the area of portion a, regardless of the discharge time constant. In general, the circuit time constant is longer than the signal pulse width, so this discharge time will have less effect on the pulse height. However, when the signal repetition rate is extremely high or accurate information on the output pulse height is needed, the discharge time cannot be neglected. If a base-line shift occurs, the signal is observed at an apparently lower level. Therefore, when designing the circuit it is necessary to select the optimum resistor and capacitor values such that the output pulse height exhibits no fluctuations even if the signal repetition rate is increased.

Furthermore, when multiple pulses enter the measurement system including an amplifier, these pulses are added to create a large pulse, and a so-called "pile-up" problem occurs. Because of this, in applications where a pulse height discriminator is used to discern the height of individual pulses, it is important to take into account the time resolution of the measurement device.

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7. 3. 3 Current-to-voltage conversion for photomultiplier tube output

The output of a photomultiplier tube is a current (charge), while the external signal processing circuit is usually designed to handle a voltage signal. Therefore, the current output must be converted into a voltage signal by some means, except when the output is measured with a high-sensitivity ammeter. The following describes how to perform the current-to-voltage conversion and major precautions to be observed.

(1) Current-to-voltage conversion using load resistance

One method for converting the current output of a photomultiplier tube into a voltage output is to use a load resistance. Since the photomultiplier tube may be thought of as an ideal constant-current source at low output current levels, a load resistance with a considerably large value can theoretically be used. In practice, however, the load resistance value is limited by such factors as the required frequency response and output linearity as discussed below.

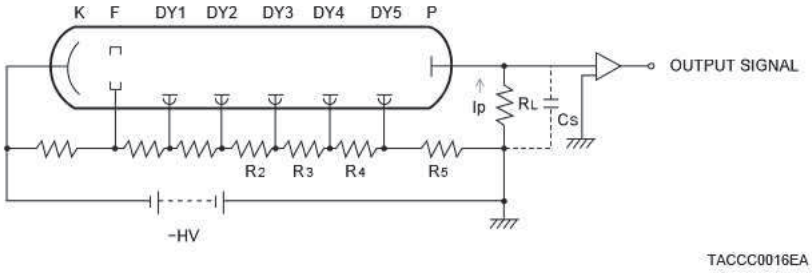


Figure 7-25: Photomultiplier tube and output circuit

If, in the circuit of Figure 7-25, we let the load resistance be R_L and the total electrostatic capacitance of the photomultiplier tube anode to all other electrodes including stray capacitance such as wiring capacitance be C_S, then the cutoff frequency f_C is given by the following equation:

$$f_C = \frac{1}{2\pi C_S R_L} \text{ (Hz)} \quad \text{(Eq. 7-7)}$$

From this relation, it can be seen that, even if the photomultiplier tube and amplifier have fast response, the response is limited to the cutoff frequency f_C determined by the subsequent output circuits. In addition, as described in Section 7.1.4 in this chapter, if the load resistance is made unnecessarily large, the voltage drop by $I_P \cdot R_L$ at the anode potential is increased accordingly, causing the last-dynode-to-anode voltage to decrease. This will increase the space charge effect and result in degradation of output linearity.

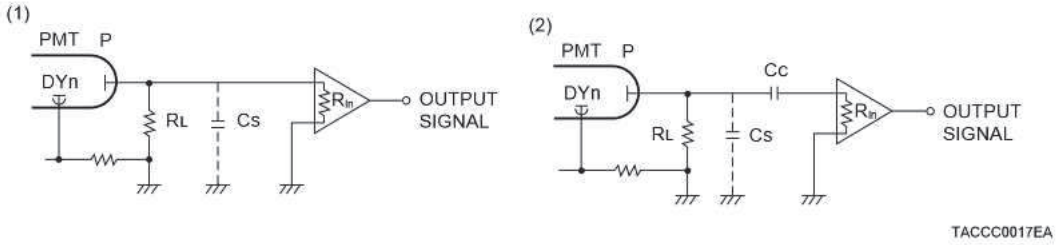


Figure 7-26: Amplifier internal input resistance

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When selecting the optimum load resistance, it is also necessary to take account of the internal input resistance of the amplifier connected to the photomultiplier tube. Figure 7-26 shows equivalent circuits of the photomultiplier tube output when connected to an amplifier. In this figure, if the load resistance is R_L and the input resistance is R_{in}, the resultant parallel output resistance R_0 is calculated from the following relation:

$$R_0 = \frac{R_{in} \cdot R_L}{R_{in}+R_L} \quad \text{(Eq. 7-8)}$$

This value of R_0, less than the R_L value, is then the effective load resistance of the photomultiplier tube. The relation between the output voltage V_0 at $R_{in}=\infty\Omega$ and the output voltage V_0' when the output was affected by Rin is expressed as follows:

$$V_0' = V_0 5 \frac{R_{in}}{R_{in}+R_L} \quad \text{(Eq. 7-9)}$$

With $R_{in}=R_L$, V_0' is one-half the value of V_0. This means that the upper limit of the load resistance is actually the input resistance Rin of the amplifier and that making the load resistance greater than this value does not have a significant effect. Particularly, when a coupling capacitor Cc is placed between the photomultiplier tube and the amplifier, as shown in Figure 7-26, an unnecessarily large load resistance may create a problem with the output level.

While the above description assumed the load resistance and internal input resistance of the amplifier to be purely resistive, in practice, stray capacitance and stray inductance are added. Therefore, these circuit elements must be considered as compound impedances, especially in high frequency operation.

Summarizing the above discussions, the following guides should be used in determining the load resistance:

1. When frequency and amplitude characteristics are important, make the load resistance value as small as possible. Also, minimize the stray capacitance such as cable capacitance which may be present in parallel with the load resistance.
2. When the linearity of output amplitude is important, select a load resistance value such that the output voltage developed across the load resistance is several percent of the last-dynode-to-anode voltage.
3. Use a load resistance value equal to or less than the input impedance of the amplifier connected to the photomultiplier tube.

(2) Current-to-voltage conversion using an operational amplifier

The combination of a current-to-voltage conversion circuit using an operational amplifier and an analog or digital voltmeter enables accurate measurement of the output current from a photomultiplier tube, without having to use an expensive, high-sensitivity ammeter. A basic current-to-voltage conversion circuit using an operational amplifier is shown in Figure 7-27.

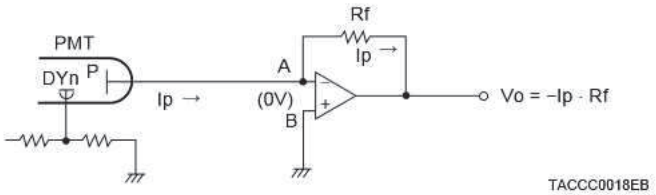


Figure 7-27: Current-to-voltage conversion circuit using an operational amplifier

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With this circuit, the output voltage V_0 is given by

$$V_0 = -I_p \cdot R_f \quad \cdots\cdots \text{(Eq. 7-10)}$$

This relation can be understood as follows:

Since the input impedance of the operational amplifier is extremely high, the output current of the photomultiplier tube is blocked from flowing into the inverting input terminal (-) of the operational amplifier at point A in Figure 7-27. Therefore, most of the output current flows through the feedback resistance R_f and a voltage of $I_p \cdot R_f$ is developed across R_f. On the other hand, the operational amplifier gain (open loop gain) is as high as 10^5, and it always acts so as to maintain the potential of the inverting input terminal (point A) at a potential equal to that (ground potential) of the non-inverting input terminal (point B). (This effect is known as an imaginary short or virtual ground.) Because of this, the operational amplifier outputs voltage V_0 which is equal to that developed across R_f. Theoretically, use of a preamplifier performs the current-to-voltage conversion with an accuracy as high as the reciprocal of the open loop gain.

When a preamplifier is used, factors that determine the minimum measurable current are the preamplifier offset current (I_{OS}), the quality of Rf and insulating materials used, and wiring methods.

To accurately measure a very low current on the order of picoamperes (10^{-12}A), the following points should be noted in addition to the above factors:

1. Connect the photomultiplier tube anode directly to the signal output cable without using any repeater.
2. Use a low-noise type coaxial cable with sufficiently high insulating properties for the signal output cable.
3. Select a connector with adequate insulating properties, for example, a teflon connector.
4. For connection of the photomultiplier tube anode to the input signal pin of the preamplifier, do not use a trace on the printed circuit board but use a teflon standoff instead.
5. For the actual output $V_0=-(I_p+I_{OS})R_f+V_{OS}$, if the R_f value is large, I_{OS} may cause a problem. Therefore, select a FET input preamplifier which has a small I_{OS} of less than 0.1 picoamperes and also exhibits minimum input conversion noise and temperature drift.
6. Provide adequate output-offset adjustment and phase compensation for the preamplifier.
7. Use a metal-film resistor with a minimum temperature coefficient and tolerance for the feedback resistance Rf. Use clean tweezers to handle the resistor so that no dirt or foreign material gets on its surface. In addition, when the resistance value must be 10^9 ohms or more, use a glass-sealed resistor that assures low leakage current.
8. Carbon-film resistors are not suitable as a load resistance because of insufficient accuracy and temperature characteristics and, depending on the type, noise problems. When several feedback resistors are used to switch the current range, place a ceramic rotary switch with minimum leakage current or a high-quality reed relay between the feedback resistance and the preamplifier output. Also connect a low-leakage capacitor with good temperature characteristics, for example a styrene capacitor, in parallel with the feedback resistors so that the frequency range can be limited to a frequency permitted by the application.
9. Use a glass-epoxy PC board or other boards with better insulating properties.

On the other hand, since the maximum output voltage of a preamplifier is typically 1 to 2 volts lower than the supply voltage, multiple feedback resistors are usually used for switching to extend the measurement current range. In this method, grounding the non-inverting input terminal of the preamplifier for each range, via a resistor with a resistance equal to the feedback resistance while observing the above precautions can balance the input bias current, so that the offset current I_{OS} between the input terminals can be reduced.

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If high voltage is accidentally emitted by the photomultiplier tube, a protective circuit consisting of a resistor R_P and diodes D_1 and D2 as shown in Figure 7-28 is effective in protecting the preamplifier from being damaged. In this case, these diodes should have minimum leakage current and junction capacitance. The B-E junction of a low-signal-amplification transistor or FET is commonly used. If R_p in Figure 7-28 is too small, it will not effectively protect the circuit, but if too large, an error may occur when measuring a large current. It is suggested that Rp be selected in a range from several kilohms to several tens of kilohms.

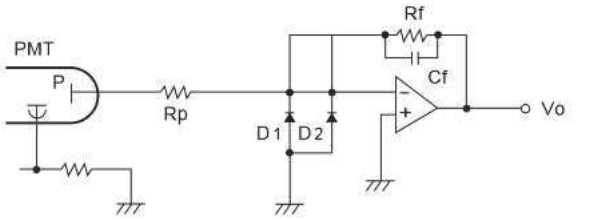


Figure 7-28: Protective circuit for preamplifier

When a feedback resistance, R_f, and of as high as 10^{12} ohms is used, if a stray capacitance, C_S, exists in parallel with R_f as shown in Figure 7-26, the circuit exhibits a time constant of $C_S \cdot R_f$. This limits the bandwidth. Depending on the application. This may cause a problem. As illustrated in the figure, passing Rf through a hole in a shield plate can reduce C_S, resulting in an improvement of the response speed.

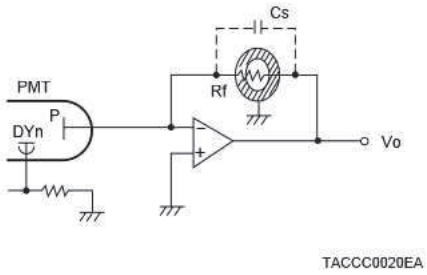


Figure 7-29: Canceling the stray capacitance Cs

The output cable for a photomultiplier tube has an its equivalent capacitance C_C when the cable is long, the C_C and R_f create a rolloff in the frequency response of the feedback loop. This rolloff may be the cause of oscillations. Connecting C_f in parallel with R_f is used in canceling out the rolloff and avoiding this oscillation, but degradation of the response speed is inevitable.

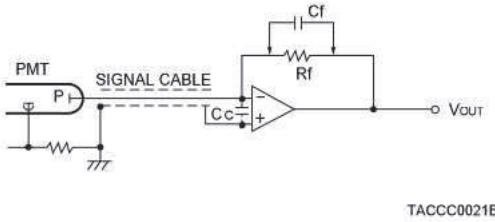


Figure 7-30: Canceling the signal cable capacitance

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(3) Charge-sensitive amplifier using an operational amplifier

Figure 7-31 (1) shows the basic circuit of a charge-sensitive amplifier using an operational amplifier. The output charge Q_p of a photomultiplier tube is stored in C_f, and the output voltage V_0 is expressed by the

$$V_0 = -\int_0^t Q_p \cdot dt \quad \cdots\cdots \text{(Eq. 7-11)}$$

Here, if the output current of the photomultiplier tube is I_p, V0 becomes

$$V_0 = -\frac{1}{C}\int_0^t I_p \cdot dt \quad \cdots\cdots \text{(Eq. 7-12)}$$

When the output charge is accumulated continuously, V0 finally increases up to a level near the supply voltage for the preamplifier, as shown in Figure 7-31 (2) and (3).

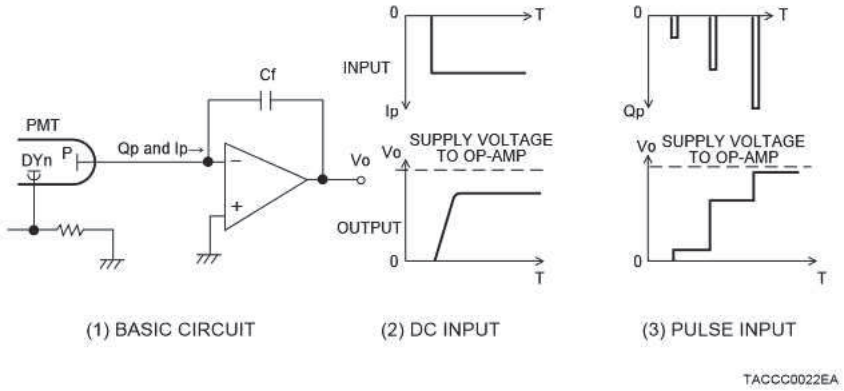


Figure 7-31: Charge-sensitive amplifier circuit and its operation

In Figure 7-31 (1), acts as an integrator that stores the output charge during the measurement time, regardless of whether the photomultiplier tube output is DC or pulse. If a FET switch is added in parallel to C_f, the charge stored in Cf can be discharged at the beginning of a measurement. In scintillation counting or photon counting, the individual output pulses of a photomultiplier tube must be converted into corresponding voltage pulses. Therefore, R_f is connected in parallel with C_f as shown in Figure 7-32, so that a circuit having a discharge time constant $\tau = C_f R_f$ is used.[5)]

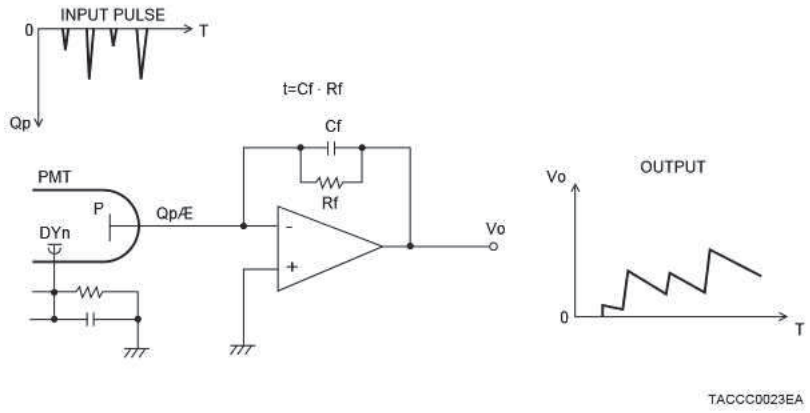


Figure 7-32: Pulse input type charge-sensitive amplifier

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If the time constant τ is made small, the output V_0 is more dependent on the pulse height of the input current. Conversely, if τ is made large, V0 will be more dependent on the input pulse charge and eventually approaches the value of $-Q_p/C_f$. In scintillation counting, from the relation between the circuit time constant $\tau=RC$ and the fluorescent decay constant of the scintillator τ_s, the output-pulse voltage waveform V(t) is given by[2)]

$$V(t) = \frac{Q \cdot \frac{t}{C}}{t-t_s} (e^{-t/t} - e^{-t/t_s}) \quad \cdots\cdots \text{(Eq. 7-13)}$$

when $\tau \gg \tau_s$, V(t) becomes

$$V(t) \approx \frac{Q}{C} (e^{-t/t} - e^{-t/t_s}) \quad \cdots\cdots \text{(Eq. 7-14)}$$

While, when $\tau \ll \tau_s$, V(t) is

$$V(t) \approx \frac{Q}{C} \cdot \frac{t}{t_s} (e^{-t/t_s} - e^{-t/t}) \quad \cdots\cdots \text{(Eq. 7-15)}$$

When the circuit time constant τ is larger than the scintillator decay constant τ_s, the rise of the output waveform depends on τ_s, while the fall depends on τ, with the maximum pulse height given by Q/C. In contrast, when the circuit time constant τ is smaller than τ_s, the rise of the output waveform depends on τ, while the fall depends on τ_s, with the maximum pulse height given by $Q/C \cdot \tau/\tau_s$. In most cases, the condition of $\tau \gg \tau_s$ is used since higher energy resolution can be expected. This is because the output pulse has a large amplitude so that it is less influenced by such factors as noise, temperature characteristics of the scintillator and variations of the load resistance. In this case, it should be noted that the pulse width becomes longer due to a larger τ and, if the repetition rate is high, base-line shift and pile-up tend to occur. If measurement requires a high counting rate, reducing τ is effective in creating an output waveform as fast as the scintillator decay time. However, the output pulse height becomes lower and tends to be affected by noise, resulting in a sacrifice of energy resolution. Under either condition, the output voltage V(t) is proportional to the output charge from the photomultiplier tube anode. Generally, the load capacitance is reduced to obtain higher pulse height as long as the operation permits, and in most cases the resistor value is changed to alter the time constant. When a NaI(Tl) scintillator is used, the time constant is usually selected to be from several microseconds to several tens of microseconds.

As explained above, noise generated in the charge-sensitive amplifier degrades the energy resolution. This noise mainly originates from the amplifier circuit elements, but care should also be taken of the cable capacitance C_S indicated in Figure 7-33 because the output charge of the photomultiplier tube is divided and stored in C_f and C_S. The C_S makes the charge of C_f smaller as compared to the amount of charge without C_S. Thus, it is necessary to increase the value of $A \cdot C_f/C_S$ in order to improve the signal-to-noise ratio. In actual operation, however, since $A \cdot C_f$ cannot be made larger than a certain value due to various limiting conditions, the value of C_S is usually made as small as possible to improve the signal-to-noise ratio.

In scintillation counting measurements, a common method of reducing the cable capacitance is to place the preamplifier in the vicinity of the photomultiplier tube, remote from the main amplifier.

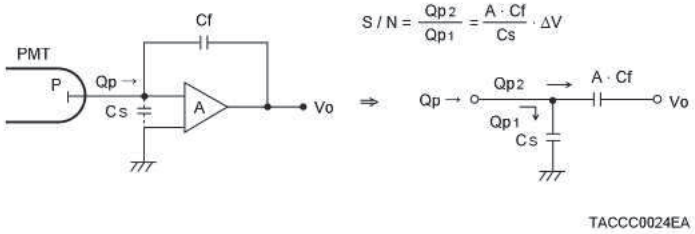


Figure 7-33: Influence of input distribution capacitance

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7. 3. 4 Output circuit for a fast response photomultiplier tube

For the detection of light pulses with fast rise and fall times, a coaxial cable with 50-ohm impedance is used to make connection between the photomultiplier tube and the subsequent circuits.

To transmit and receive the signal output waveform with good fidelity, the output end must be terminated in a pure resistance equal to the characteristic impedance of the coaxial cable. This allows the impedance seen from the photomultiplier tube to remain constant, independent of the cable length, thus making it possible to reduce "ringing" which may be observed in the output waveform. However, when using an MCP-PMT for the detection of ultra-fast phenomena, if the cable length is made unnecessarily long, distortion may occur in signal waveforms due to a signal loss in the coaxial cable.

If a proper impedance match is not provided at the output end, the impedance seen from the photomultiplier tube varies with frequency, and further the impedance value is also affected by the coaxial cable length, as a result, ringing appears in the output. Such a mismatch may be caused not only by the terminated resistance and the coaxial cable but also by the connectors or the termination method of the coaxial cable. Thus, sufficient care must be taken to select a proper connector and also to avoid creating impedance discontinuity when connecting the coaxial cable to the photomultiplier tube or the connector.

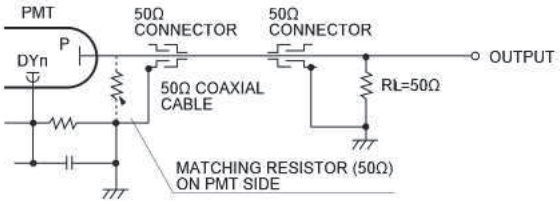


Figure 7-34: Output circuit impedance match

When a mismatch occurs at the coaxial cable ends, all of the output signal energy is not dissipated at the output end, but is partially reflected back to the photomultiplier tube. If a matching resistor is not provided on the photomultiplier tube side, the photomultiplier tube anode is viewed as an open end, thus the signal will be reflected from the anode and returned to the output end again. This reflected signal is observed as a pulse which appears after the main pulse with a time delay equal to the round trip through the coaxial cable. This signal repeats its round trip until its total energy is dissipated, as a result, ringing occurs at the output end. To prevent this, providing an impedance match not only at the output end but also at the photomultiplier tube side is effective to some extent, although the output voltage will be reduced to one-half in comparison with that obtained when impedance match is done only at the output end. When using a photomultiplier tube which is not a fast response type or using a coaxial cable with a short length, an impedance matching resistor is not necessarily required on the photomultiplier tube side. Whether or not to connect this resistor to the photomultiplier tube can be determined by doing trial-and-error impedance matching. Among photomultiplier tubes, there are special types having a 50-ohm matched output impedance. These tubes do not require any matching resistor.

Next, let us consider waveform observation of fast pulses using an oscilloscope. A coaxial cable terminated with a matching resistor offers the advantage that the cable length will not greatly affect the pulse shape. Since the matching resistance is usually as low as 50 to 100 ohms, the output voltage is reduced. While this situation can be corrected by use of a wide-band amplifier with high gain, the inherent noise of such an amplifier makes it difficult to measure low-level signals. In this case, to achieve the desired output voltage, it is more advantageous, as shown in Figure 7-35, to bring the photomultiplier tube as close as possible to the amplifier to reduce the stray capacitance and also to use as a large load resistance as a possible without effecting the frequency response.

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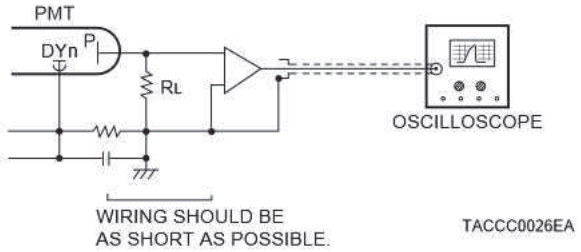


Figure 7-35: Waveform observation using an oscilloscope

It is relatively simple to operate a fast amplifier with a wide bandwidth using a video IC or pulse type IC. However, in exchange for such design convenience, these ICs tends to reduce performance, such as introducing noise. For optimum operation, it is therefore necessary to know their performance limits and take corrective action.

As the pulse repetition rate increases, a phenomenon called "base-line shift" creates another reason for concern. This base-line shift occurs when the DC signal component has been eliminated from the signal circuit by use of a coupling capacitor. If this occurs, the zero reference level shifts from ground to an apparent zero level equal to the average of the output pulses. Furthermore, when multiple pulses enter within the time resolution of the measuring system including the amplifier, they are integrated so that a large output pulse appears. This is known as "pile-up". Special care should be taken in cases where a pulse height discriminator is used to discern the amplitude of individual pulses.

7. 3. 5 Photon counting circuits

Because the basic operating principles of photon counting have already been detailed in Section 3.4 of Chapter 3, this section briefly explains how to connect a photomultiplier tube to the photon counting circuits available from Hamamatsu Photonics. The block diagram of the photon counting circuits connected between the photomultiplier tube anode and a TTL counter is shown in Figure 7-36.

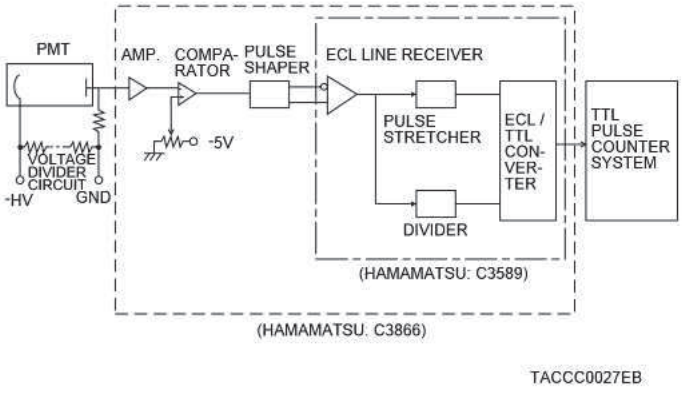


Figure 7-36: Photon counting circuits

After passing through the comparator and pulse shaper, the output signals become ECL output pulses. These are then fed to the ECL line receiver and the pulse width is extended by the pulse stretcher so that the signals are compatible with a TTL counter. If a high-speed counter is not available, use of a prescaler enables photon counting operation without impairing the linearity.

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7. 4 Housing

A photomultiplier tube housing is primarily used to contain and secure in place a photomultiplier tube, but it also provides the following functions:

1. To shield extraneous light
2. To eliminate the effect of external electrostatic fields
3. To reduce the effect of external magnetic fields

The following sections explains each of these functions

7. 4. 1 Light shield

Since a photomultiplier tube is an extremely high-sensitivity photodetector, the signal light level to be detected is very low and therefore particular care must be exercised in shielding extraneous light. For instance, when a connector is used for signal input/output, there is a possibility of light leakage through the connector itself or through its mounting holes and screw holes. Furthermore, light leakage may occur through seams in the housing.

As a corrective action, when mounting connectors or other components in the housing, use black silicone rubber at any location where light leakage may occur. It is also important to use black soft tape or an O-ring so as to fill in any gaps around the components attached to the housing. In addition, it is necessary to coat the inside of the housing with black mat paint in order to prevent reflection of scattered light.

7. 4. 2 Electrostatic shield

Since photomultiplier tube housings are made of metal such as aluminum, maintaining the housing at ground potential provides an effective shield with respect to external electrostatic fields. The inside of the housing is usually coated with black paint to prevent diffuse reflection of light, so care is required to be certain that the point does not interfere with the contact of the ground line. As stated previously, if any object at ground potential is brought close to the bulb of a photomultiplier tube, noise increases, so that the housing should have sufficient separation from the photomultiplier tube.

7. 4. 3 Magnetic shield

As will be described in Section 3.3 of Chapter 8, photomultiplier tubes are very sensitive to a magnetic field. Even terrestrial magnetism will have a detrimental effect on the photomultiplier tube performance[6]. Therefore, in precision photometry or in applications where the photomultiplier tube must be used in a highly magnetic field, the use of a magnetic shield case is essential. However, unlike the electrostatic shield, there exists no conductors that carry the magnetic flux. It is not possible to shield a magnetic field completely. One common technique for reducing the effect of an external magnetic field is to wrap a metal shield having high permeability around the photomultiplier tube bulb, but such a metal shield cannot completely block the magnetic field. It is also necessary to select an optimum shielding material and method, based on both the strength and frequency of the magnetic fields.

In general applications, it is not necessary to fabricate the entire housing from high-permeability materials. Instead, a photomultiplier tube can be wrapped into a cylindrical shield case. Among shielding materials, "Permalloy" is the best and is widely used. The effect of a magnetic shield is described below.

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(1) Shielding factor of magnetic shield case and orientation of magnetic field

Photomultiplier tubes are very sensitive to an external magnetic field, especially for head-on types, the output varies significantly even with terrestrial magnetism. To eliminate the effect of the terrestrial magnetism or to operate a photomultiplier tube more stably in a magnetic field, a magnetic shield case must be used. (Also refer to Section 3.3 of Chapter 8.) Utilizing the fact that a magnetic field is shunted through an object with high permeability, it is possible to reduce the influence of an external magnetic field by placing the photomultiplier tube within a magnetic shield case, as illustrated in Figure 7-37.

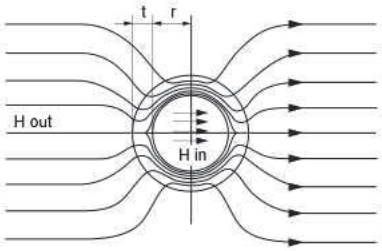


Figure 7-37: Shielding effect of a magnetic shield case

Let us consider the shielding effect of a magnetic shield case illustrated in Figure 7-37. As stated, the magnetic shield case is commonly fabricated from metal with high-permeability such as Permalloy. The shielding factor S of such a magnetic shield case is expressed as follows:

$$S = \frac{H_{out}}{H_{in}} = \frac{3tm}{4r} \quad \text{(Eq. 7-16)}$$

where H_{in} and H_{out} are the magnetic field strength inside and outside the shield case respectively, t is the thickness of the case, r is the radius of the case and μ is the permeability. When two or more magnetic shield cases with different radii are used in combination, the resultant shielding factor S' will be the product of the shielding factor of each case, as expressed in the following equation:

$$S' = S1\,5\,S2\,5\,S3 \cdots S_n$$
$$= \frac{3t_1\mu_1}{4r_1} 5 \frac{3t_2\mu_2}{4r_2} 5 \frac{3t_3\mu_3}{4r_3} 5 \cdots 5 \frac{3t_n\mu_n}{4r_n} \quad \text{(Eq. 7-17)}$$

When a magnetic shield case is used, the magnetic field strength inside the case H_{in}, which is actually imposed on the photomultiplier tube, is reduced to a level of H_{out}/S. For example, if a magnetic shield case with a shielding factor of 10 is employed for a photomultiplier tube operated in an external magnetic field of 30 milliteslas, this means that the photomultiplier tube is operated in a magnetic field of 3 milliteslas. In practice, the edge effect of the shield case, as will be described later, creates a loss of the shielding effect. But this approach is basically correct.

Figure 7-38 shows the output variations of a photomultiplier tube with and without a magnetic shield case which is made of "PC" materials with a 0.6 millimeter thickness. It is obvious that the shielding is effective for both X and Y axes. For these axes the shielding factor of the magnetic shield case must be equal. However, the Y axis exhibits better magnetic characteristics than the X axis when not using a magnetic shield case, so that the Y axis provides a slightly better performance when used with the magnetic shield case. In the case of the Z axis which is parallel to the tube axis, the photomultiplier tube used with the magnetic shield case shows larger output variations. It is thought that, as described in the section on the edge effect, this is probably due to the direction of the magnetic field which is bent near the edge of the shield case.

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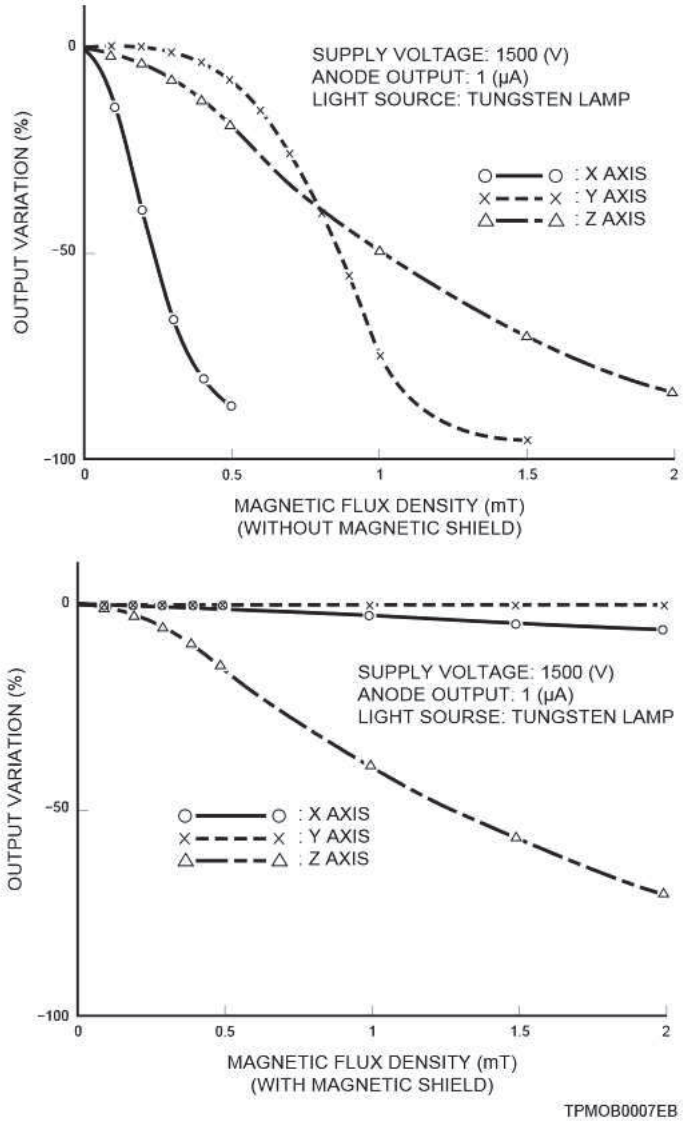


Figure 7-38: Magnetic characteristics of a photomultiplier tube

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(2) Saturation characteristics

When plotting a B-H curve which represents the relationship between the external magnetic field strength (H) and the magnetic flux density (B) traveling through a magnetic material, a saturation characteristic is seen as shown in Figure 7-39.

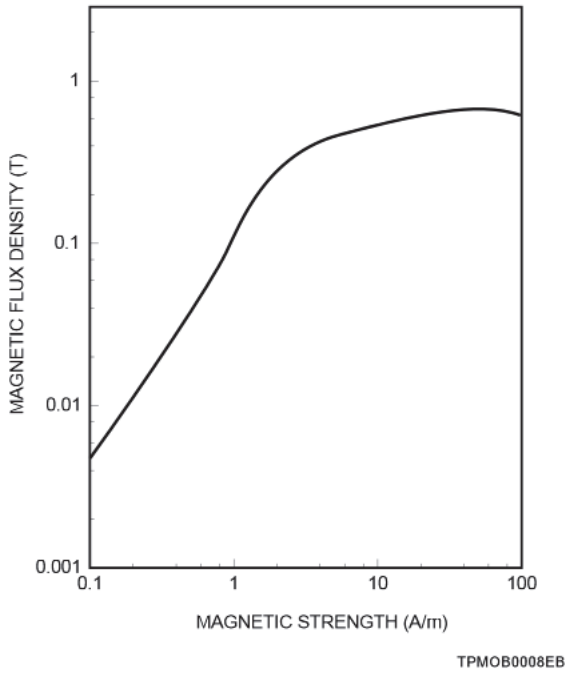


Figure 7-39: DC magnetization curve (B-H curve)

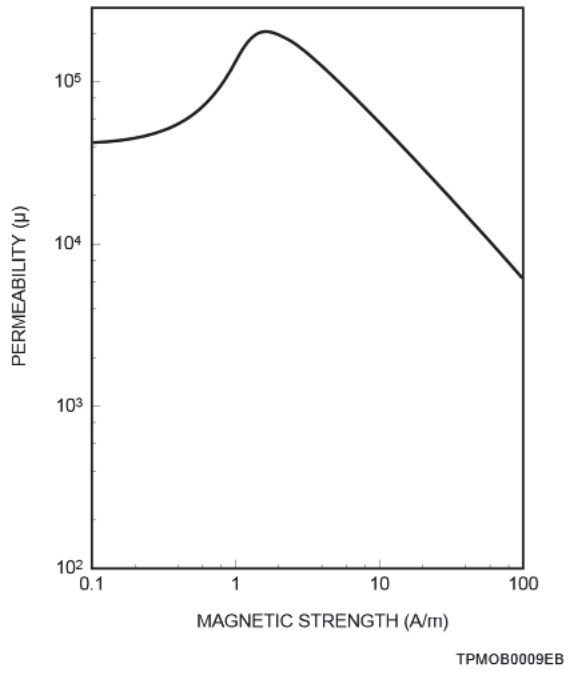
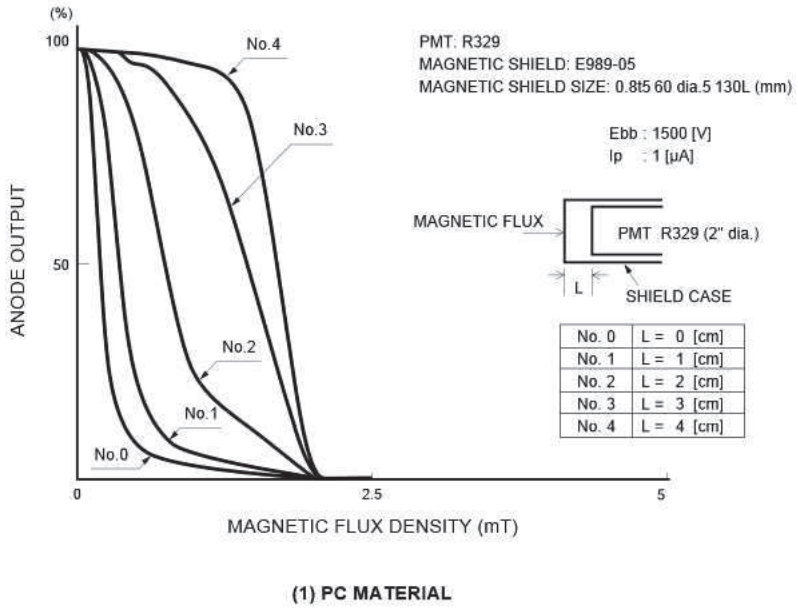


Figure 7-40: Permeability and external magnetic field

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Since the permeability μ of a magnetic material is given by the B/H ratio, μ varies with H as shown in Figure 7-40 with a peak at a certain H level and above it, both μ and the shielding factor degrade sharply. Data shown in Figures 7-39 and 7-40 are measured using a magnetic shield case E989 (0.8 millimeter thick) manufactured by Hamamatsu Photonics when a magnetic field is applied in the direction perpendicular to the shield case axis.

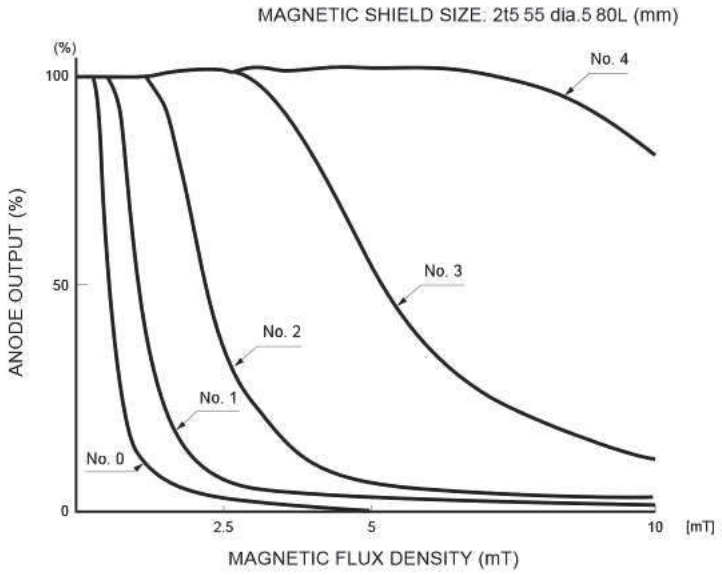
The Hamamatsu E989 series magnetic shield cases are made of a "PC" material which contains large quantities of nickel. This material assures very high permeability, but exhibits a rather low saturation level of magnetic flux density. In a weak magnetic field such as from terrestrial magnetism, the "PC" material provides good shielding factor as high as 10^3 and thus proves effective in shielding out terrestrial magnetism. In contrast, "PB" material which contains small quantities of nickel offers high saturation levels of magnetic flux density, though the permeability is lower than that of the "PC" material. Figure 7-41 shows the anode output variations of a photomultiplier tube used with a magnetic shield case made of "PC" or "PB" material. As the magnetic flux density is increased, the anode output of the photomultiplier tube used with the "PC" material shield case drops sharply while that used with the "PB" material shield case drops slowly. Therefore, in a highly magnetic field, it is necessary to use a "PC" material shield case in conjunction with a shield case made of high-permeability metal such as soft-iron, with a thickness of 3 to 10 millimeters.



(1) PC MATERIAL

Figure 7-41: Magnetic characteristics of a photomultiplier tube used with magnetic shield case (1)

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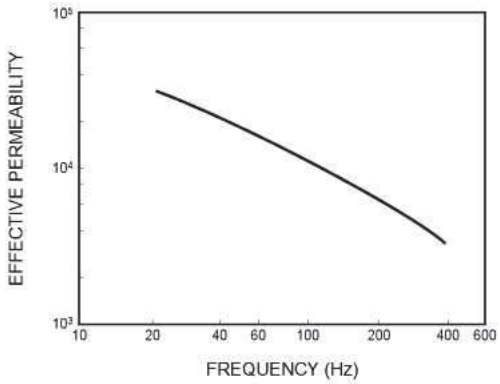
(2) PB MATERIAL

TPMOB0010EB

Figure 7-41: Magnetic characteristics of a photomultiplier tube used with magnetic shield case (2)

(3) Frequency characteristics

The above description concerning the effect of magnetic shield cases, refers entirely to DC magnetic fields. In AC magnetic fields, the shielding effect of a magnetic shield case decreases with increasing frequency as shown in Figure 7-42. This is particularly noticeable for thick materials, so it will be preferable to use a thin shield case of 0.05 to 0.1 millimeter thickness when a photomultiplier tube is operated in a magnetic field at frequencies from 1kHz to 10kHz. The thickness of a magnetic shield case must be carefully determined to find the optimum compromise between the saturated magnetic flux density and frequency characteristics.



TACCB0003EA

Figure 7-42: Frequency characteristics of a magnetic shield case

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(4) Edge effect

The shielding effect given by 3t μ/4r applies to the case in which the magnetic shield case is sufficiently long with respect to the overall length of the photomultiplier tube. Actual magnetic shield cases have a finite length which is typically only several millimeters to several centimeters longer than the photomultiplier tube, and their shielding effects deteriorate near both ends as shown in Figure 7-43. Since the photocathode to the first dynode region is most affected by a magnetic field, this region must be carefully shielded. For example, in the case of a head-on photomultiplier tube, the tube should be positioned deep inside the magnetic shield case so that the photocathode surface is hidden from the shield case edge by a length equal to the shield case radius.

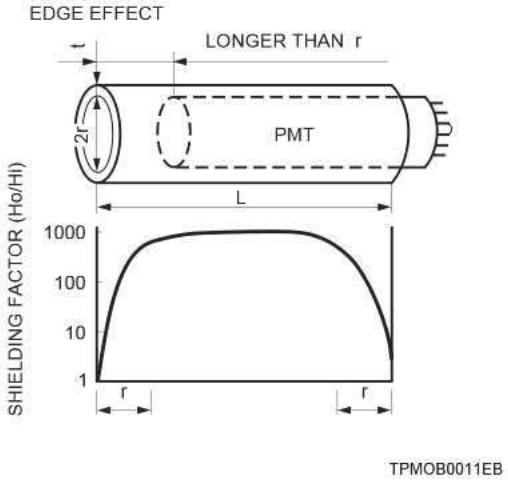


Figure 7-43: Edge effect of a magnetic shield case

Figures 7-44 (1) to (4) show the output variations of a head-on photomultiplier tube operated in magnetic fields in the respective directions of X, Y and Z axes. Also shown in these figures are the output variations measured using a magnetic shield wrapping and a magnetic shield case while moving the photomultiplier tube along the shield case axis at positions a, b and c. When used with the magnetic shield case, in either axis of the magnetic field, the longer the distance from the edge of the shield case to the photocathode, the more the output variations improve. For the Y axis, however, since the photomultiplier tube originally exhibits better magnetic characteristics, no output variations occur, as seen from (2), up to 3 milliteslas even if the photocathode is positioned near the edge of the magnetic shield case. For the Z axis, on the other hand, if the photocathode is positioned at the open edge of the magnetic shield case, the output variations are increased. This is often larger than the case even without using a magnetic shield case, as shown in (3). The reason for this is thought to be that the magnetic field applied along the shield case axis is bent near the open edge, and this bent magnetic field adversely affects the photoelectron collection efficiency from the photocathode to the first dynode. In addition, as shown in (1), the photomultiplier tube output is significantly affected by the magnetic field along the X axis. Therefore, even if the magnetic field along the Z axis is reduced, the resultant magnetic field which is generated along the X axis can cause output variations. This problem will be solved by positioning the photomultiplier tube deeper than the open edge of the magnetic shield case.

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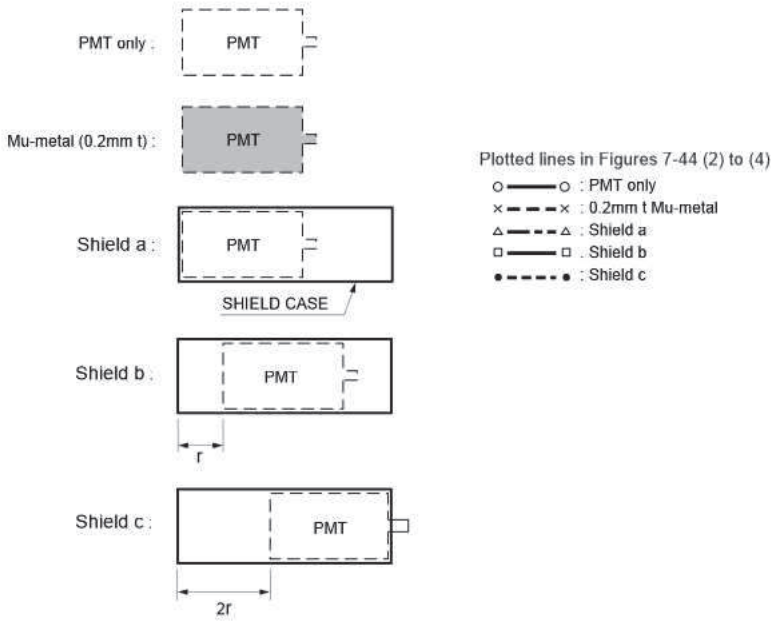


Figure 7-44 (1): Photomultiplier tube shield conditions for magnetic characteristic measurements

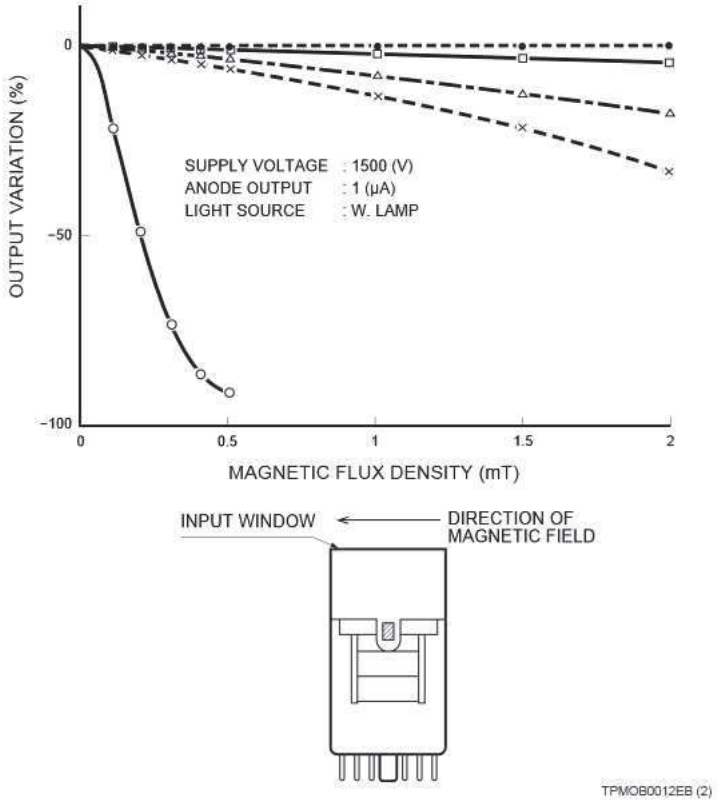


Figure 7-44 (2): Magnetic characteristics of a photomultiplier tube

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