CHAPTER 10

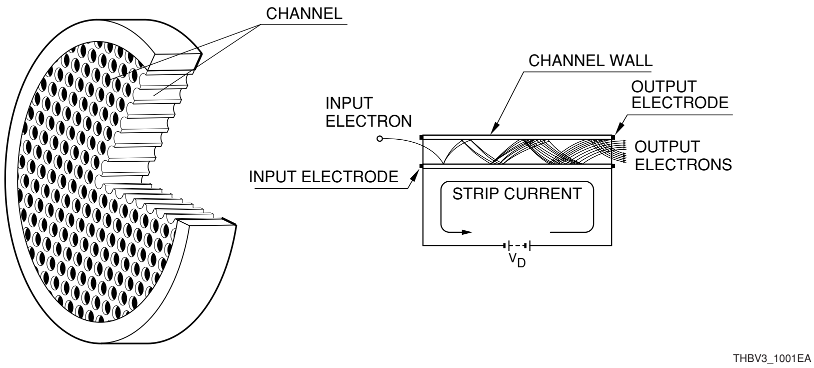
MCP-PMT

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

10.1 Structure

10.1.1 Structure of MCPs

Figure 10-1 (a) 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 10-1 (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 10-1: 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.

10.1.2 Structure of MCP-PMTs

Figure 10-2 shows the cross section of a typical MCP-PMT. This MCP-PMT 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 photocathode to MCP distance is approximately 2 millimeters, forming a close-proximity structure. Two MCPs are stacked to obtain sufficient gain. A thin film called "ion barrier" is usually formed on the photoelectron input side of the MCP in order to prevent ions generated inside the MCP from returning to the photocathode. Figure 10-3 shows an MCP-PMT complete with housing.

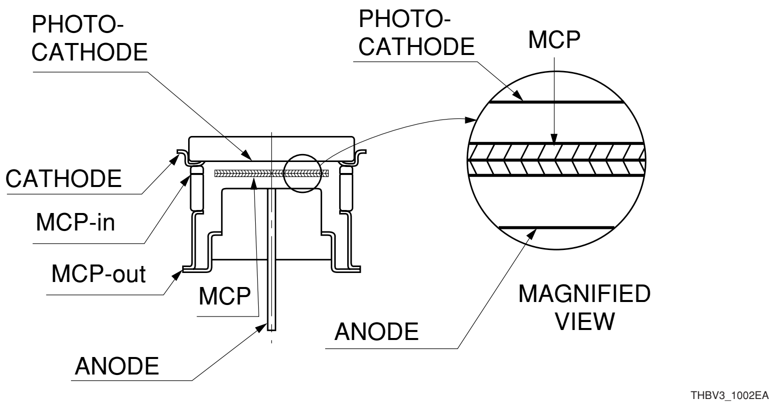


Figure 10-2: Cross section of a typical MCP-PMT

Figure 10-3: External view of an MCP-PMT

10.1.3 Voltage-divider circuit and housing structure

To operate an MCP-PMT, proper voltage must be supplied to each electrode, just as with a photomultiplier tube. A voltage-divider resistor circuit is usually used. Figure 10-4 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.

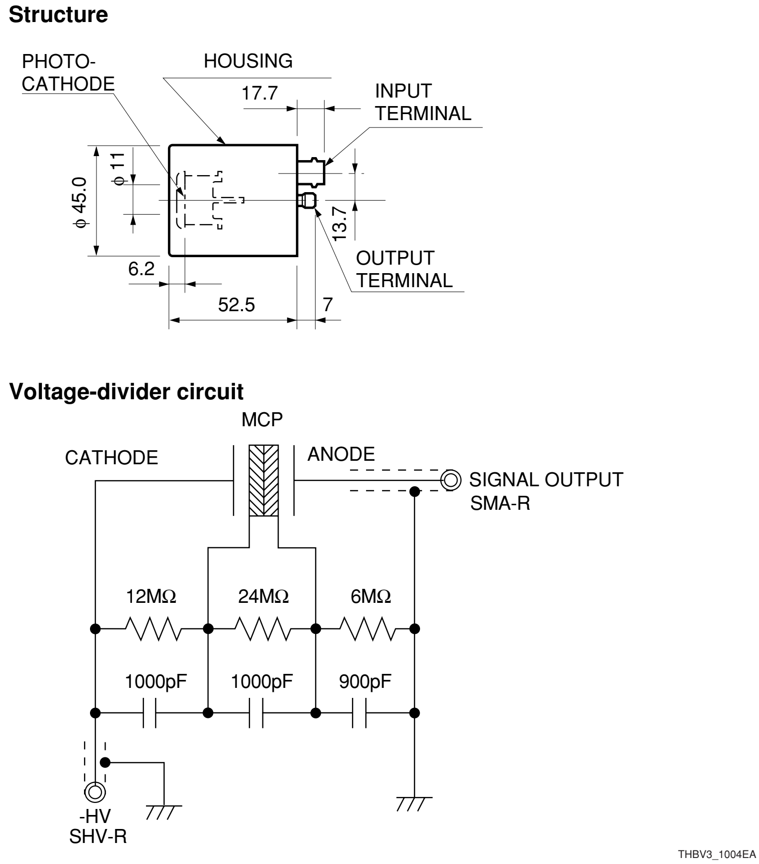


Figure 10-4: Housing configuration and operating circuit for MCP-PMT

10.2 Basic Characteristics of MCP-PMTs

10.2.1 Gain characteristics[1)]

The gain of an MCP-PMT depends on the number of MCPs incorporated in the tube. Figure 10-5 shows the typical gain versus supply voltage characteristics 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:

$$\mu = \mathrm{EXP}\,(G \cdot \alpha)$$

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

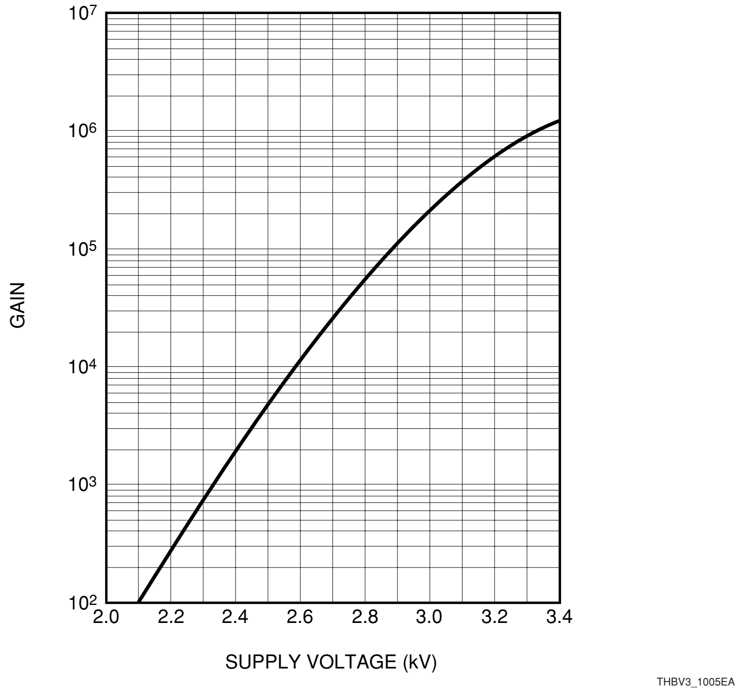


Figure 10-5: Typical gain of an MCP-PMT (using a two-stage MCP of 6 μm channel diameter)

In general, a higher gain can be obtained as α is made greater, though the gain rising point moves to the higher supply voltage side. However, if the gain becomes higher than 10^4, noise begins to increase significantly due to ion feedback effects, which causes 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 1 kV supply voltage.

As shown in Figure 10-5 above, a higher gain can be obtained from a two-stage MCP-PMT. This gain level enables photon counting measurements.

10.2.2 Time characteristics[2)]

As discussed in the previous chapter on photomultiplier tube time characteristics, the signal pulse can broaden during 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 focusing lens. In an MCP-PMT, a strong electric field is applied in nearly parallel from the photocathode to MCPin and the MCPout to anode, so that the emission-angle distribution and initial-velocity distribution of photoelectrons can be almost ignored. Furthermore, since MCP is used in place of conventional dynodes, the electron transit time in the secondary electron multiplication process is very short, allowing a dramatic improvement in the transit time spread. Due to these features, the MCP-PMT offers time response characteristics that are the best among currently available photomultiplier tubes.

(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 4.3.1 in Chapter 4. Figure 10-6 shows an actual waveform obtained with an MCP-PMT.

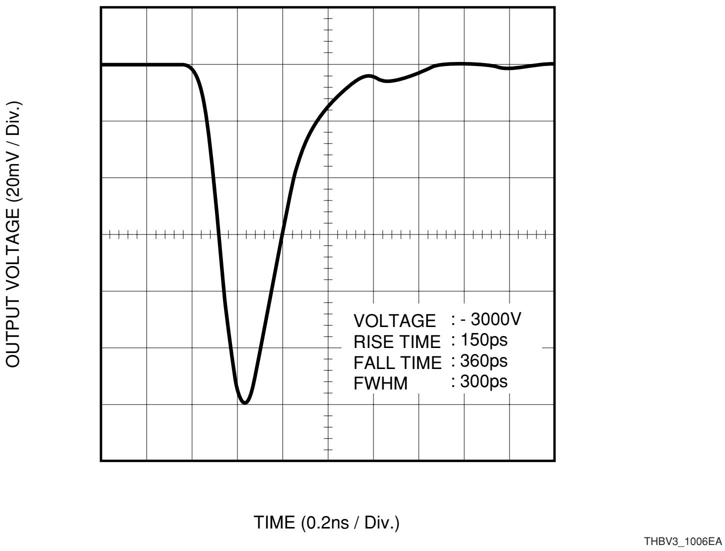


Figure 10-6: Pulse response waveform of MCP-PMT (R3809U-50)

(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 4.3.1 in Chapter 4.

(3) TTS (transit time spread)

When one photon enters an MCP-PMT, the photocathode converts it into an electron which travels to the anode while being multiplied. The transit time of an electron bunch differs depending on each input photon. The distribution of this transit time is referred to as the transit time spread or TTS. This 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 4.3.1 in Chapter 4.

At Hamamatsu Photonics, TTS is evaluated with the measurement system shown in Figure 10-7. 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 acts 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

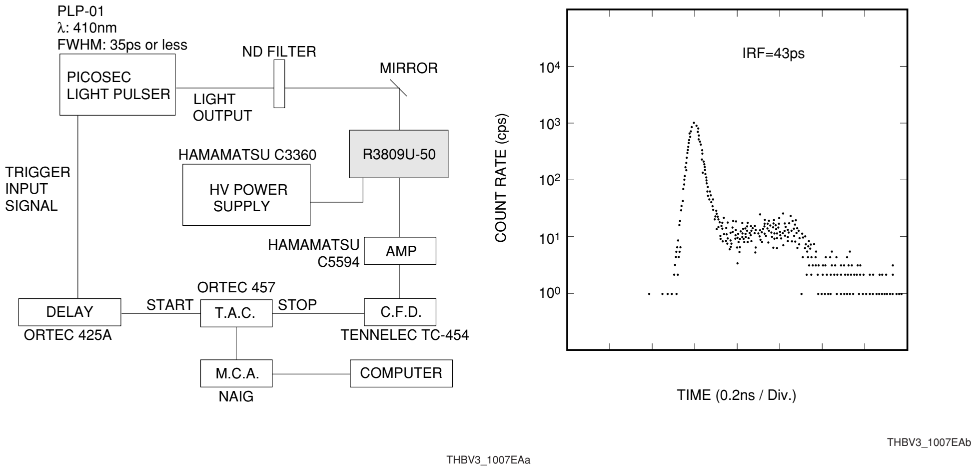


Figure 10-7: IRF measurement using MCP-PMT (R3809U-50)

To evaluate the TTS of an MCP-PMT more accurately, the measurement system shown in Figure 10-8 was 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.

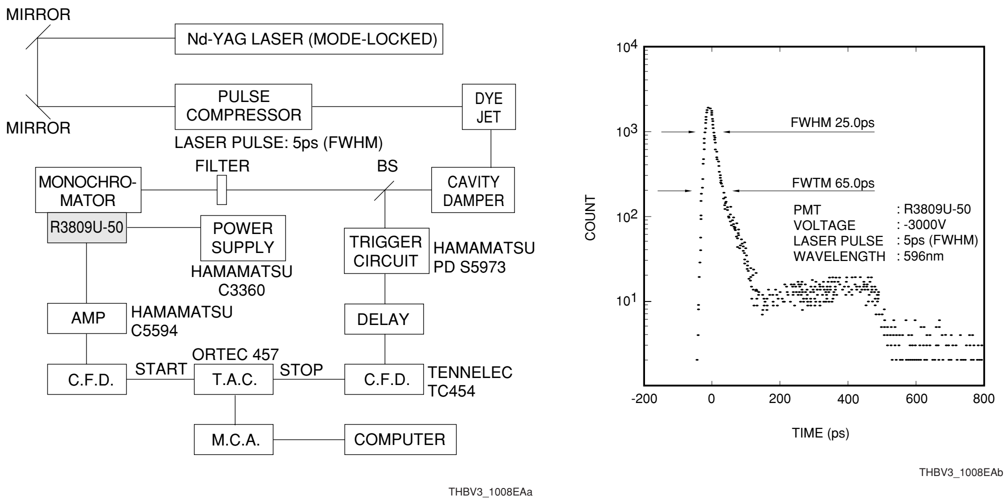


Figure 10-8: Accurate TTS measurement of MCP-PMT (R3809U-50)

(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 4.3.1 in Chapter 4.

(5) Time characteristics of various products

Time characteristics of various MCP-PMTs are summarized in Table 10-1 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 12 µm channel MCPs, the R3809U series using 6 µm 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 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-stage MCP)	150ps	360ps	400ps	45ps
R5916U-50 (6µm, 2-stage MCP)	180ps	700ps	350ps	95ps
R7024U (6µm, 2-stage MCP)	110ps	120ps	400ps	–

Note: Data in the above table shows typical values including the light source and circuit jitters.
A picosecond laser with a pulse width (FWHM) of less than 35 ps is used for IRF measurement.
The R5916U-50 is a gated MCP-PMT. The R7024U is a triode type MCP-PMT (Figure 10-9).

Table 10-1: Comparison of MCP-PMT time characteristics

The R7024 MCP-PMT offers significant improvements in rise and fall times. Its structure is shown in Figure 10-9. This tube has been developed specifically for use in ultra-fast photometry. A mesh electrode is provided between the MCPout and the anode as shown in the figure, and the signal output method differs from ordinary MCP-PMTs. The mesh between the MCPout 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 10-10 shows a typical output waveform from the R7024. Ultrafast time response with 110 picosecond rise time and 120 picosecond fall time is obtained.

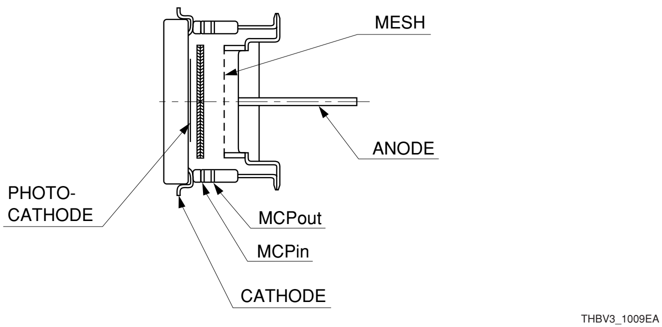


Figure 10-9: Structure of the R7024

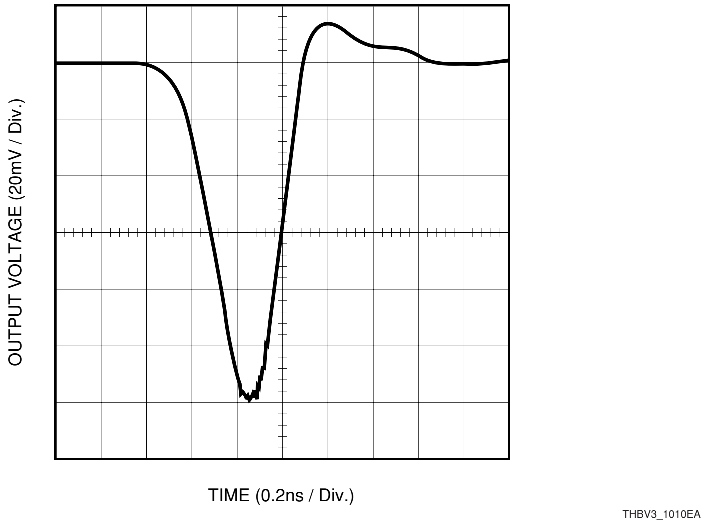


Figure 10-10: Time response waveform of the R7024U

10.2.3 Temperature characteristics and cooling

As with normal photomultiplier tubes, the dark current and dark count of MCP-PMT greatly depend on the photocathode type and operating temperature. In particular, the dark current and dark count of a multialkali photocathode with enhanced red sensitivity (S-25) are relatively high at room temperatures, so MCP-PMTs using such a photocathode may need to be cooled during operation.

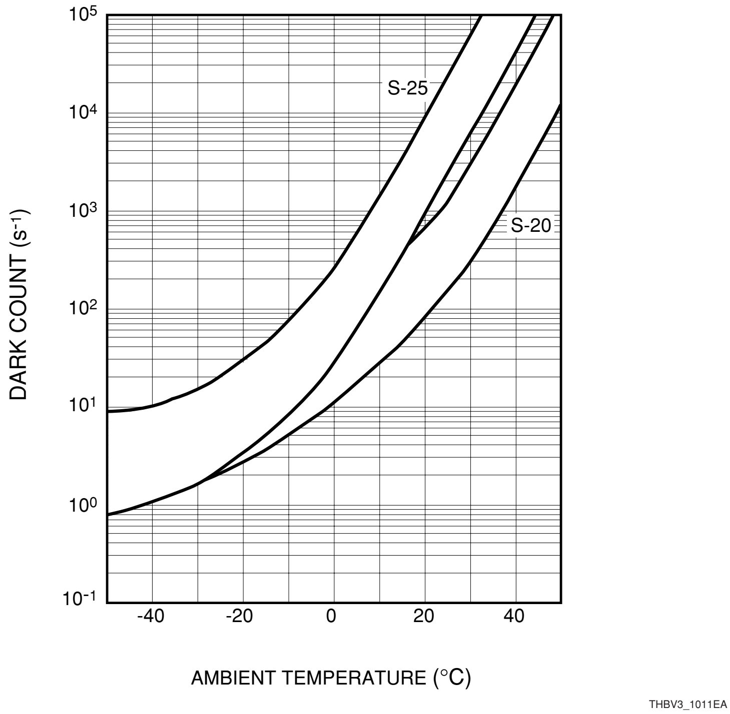


Figure 10-11: Dark count vs. ambient temperature

Hamamatsu Photonics provides an optional thermoelectric cooler and holder specifically designed for MCP-PMT. Using this cooler and the holder allows easy cooling of an MCP-PMT at a constant temperature of -30°C.

10.2.4 Saturation characteristics

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, the causes of this saturation are different from those of normal photomultiplier tubes using multiple stages of discrete dynodes. The saturation is caused by the dead time during which the MCP output current is limited and also by space charge effects inside the MCP. Precautions must be taken so that saturation by the dead time will not occur. Saturation characteristics of MCP-PMT are described in detail below.

(1) 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 weakens 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 τ_d is given by the following relation:

$$\tau_d = Qout / Is$$

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 below. If the MCP-PMT is operated at saturated levels, it cannot exhibit adequate performance, and also degrades the photocathode sensitivity and MCP gain.

(2) Saturation in DC operation

An MCP has a high resistance ranging from tens to 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 10-12 (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 becomes approximately 7 percent or more of the strip current, so use caution.

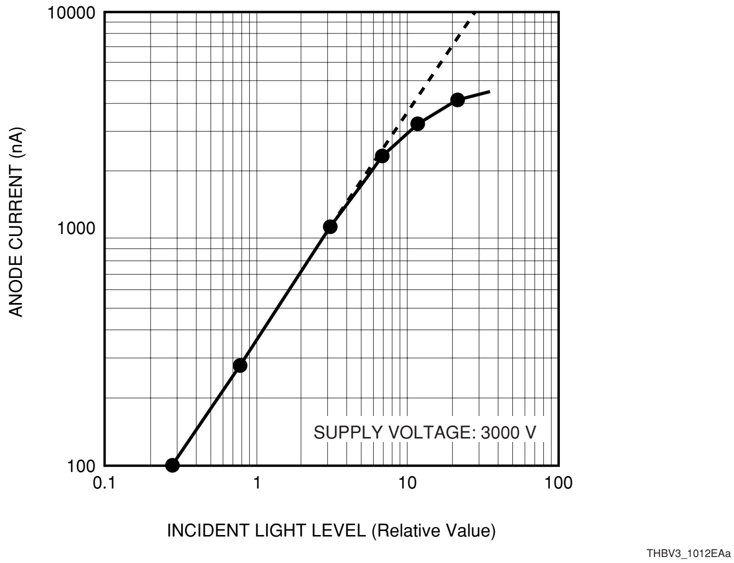


Figure 10-12 (a): Saturation characteristics of MCP-PMT (11 mm effective diameter, 6 μm channel diameter) in DC operation (1)

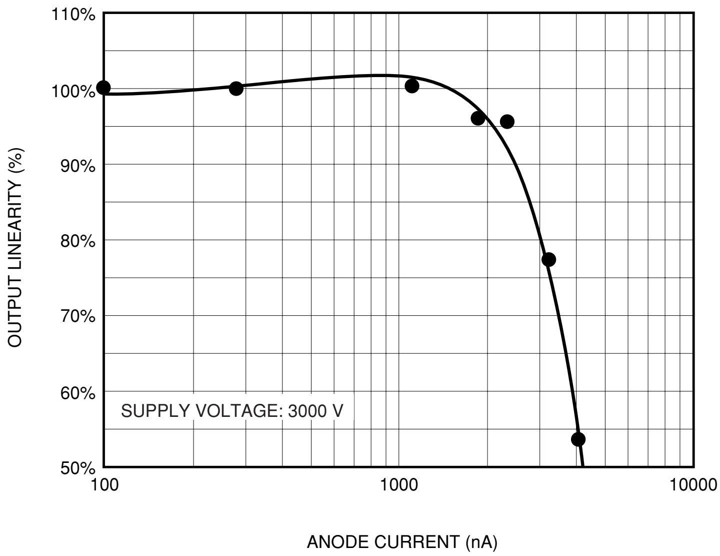


Figure 10-12 (b): Saturation characteristics of MCP-PMT (11 mm effective diameter, 6 μm channel diameter) in DC operation (2)

(3) 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 10-13 shows the linearity data of an MCP-PMT when it detects pulsed light.

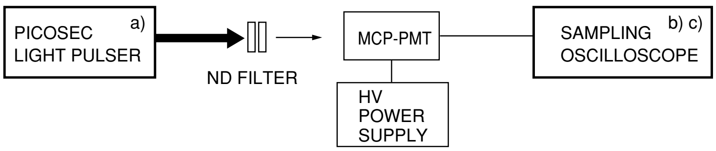


Figure 10-13 (a): Block diagram for MCP-PMT pulse linearity measurement

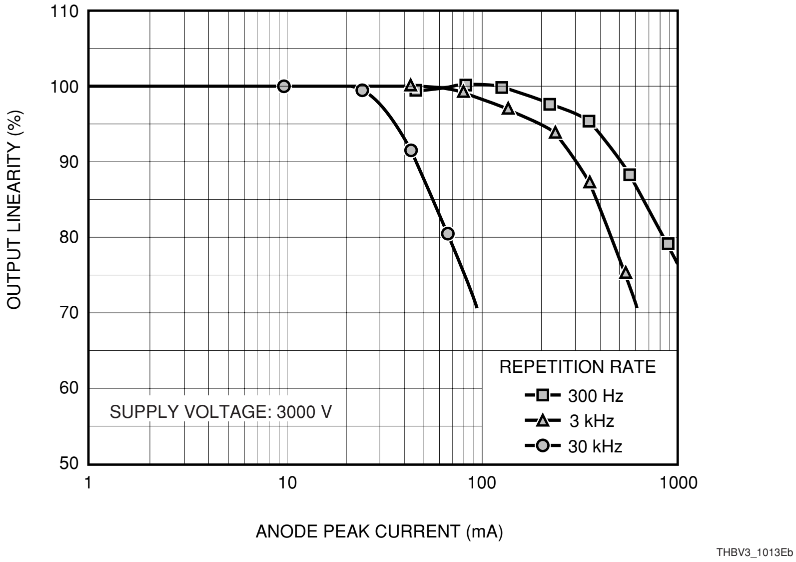


Figure 10-13 (b): Pulse linearity of an MCP-PMT (11 mm effective diameter, 6 mm channel diameter)

Figure 10-13 (a) shows a block diagram for measuring pulse linearity. A picosecond light pulser is used as the light source. The intensity of the pulsed light (FWHM 50 ps) is adjusted by ND (neutral density) filters and input to the MCP-PMT. Figure 10-13 (b) shows a typical pulse linearity plot for a proximity-focused MCP-PMT measured at a pulse repetition rate of 300 Hz to 30 kHz. Pulse currents up to a peak of 350 milliamperes can be extracted at a repetition rate of 300 Hz 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 other hand, 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 (see (1) in 10.2.4), causing output saturation.

(4) Saturation gain characteristics in photon counting mode

Figure 10-14 shows pulse height distributions of photoelectron signals and dark current pulses taken with an MCP-PMT in the photon counting mode. Unlike single-photon pulse height distributions obtained with normal photomultiplier tubes, a distinct peak is formed in the pulse height distribution obtained with the MCP-PMT. This is due to the saturation occurring in the MCP channel by the space charge effect caused by a single photon.

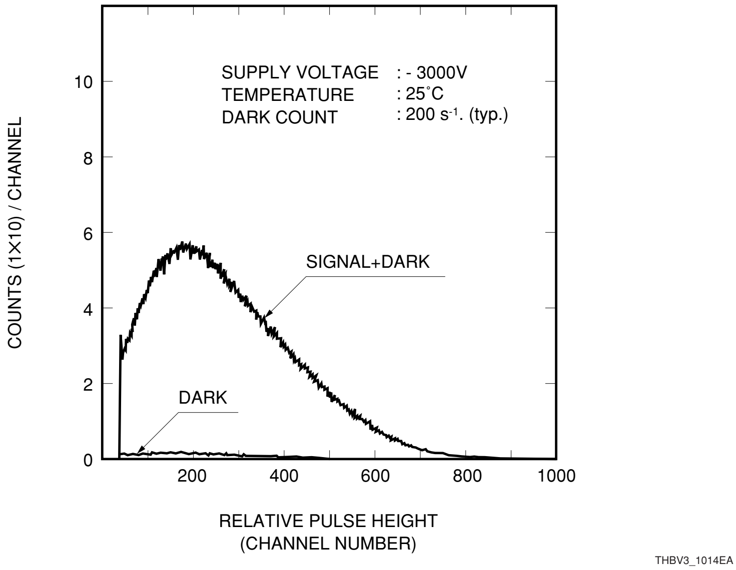


Figure 10-14: Typical pulse height distribution in single photon counting

(5) Count rate linearity in photon counting

Figure 10-15 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.

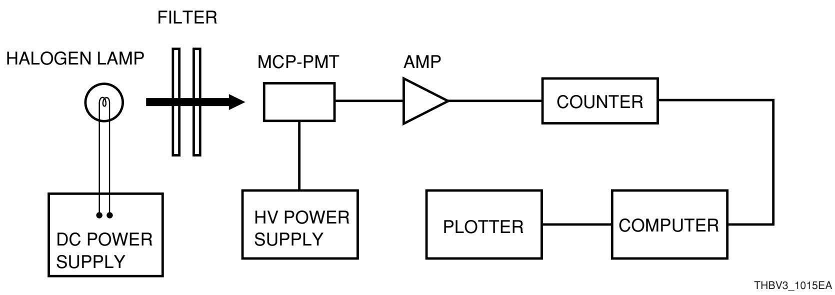


Figure 10-15: Block diagram for measuring count-rate linearity in photon counting mode

Figure 10-16 shows count-rate linearity data measured in photon counting mode. A good linearity is maintained up to 10^7 s^{-1}.

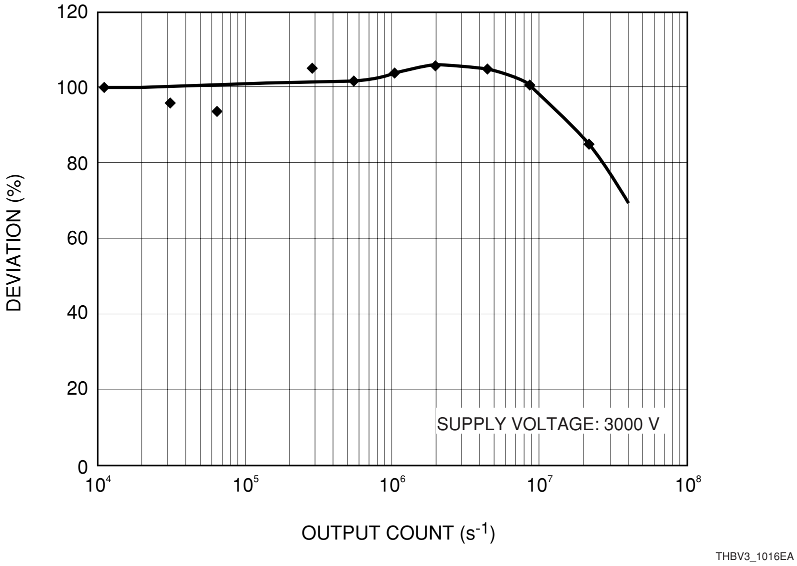


Figure 10-16: Count-rate linearity of an MCP-PMT (11 mm effective diameter, 6 mm channel diameter) in photon counting mode

10.2.5 Magnetic characteristics[2)]

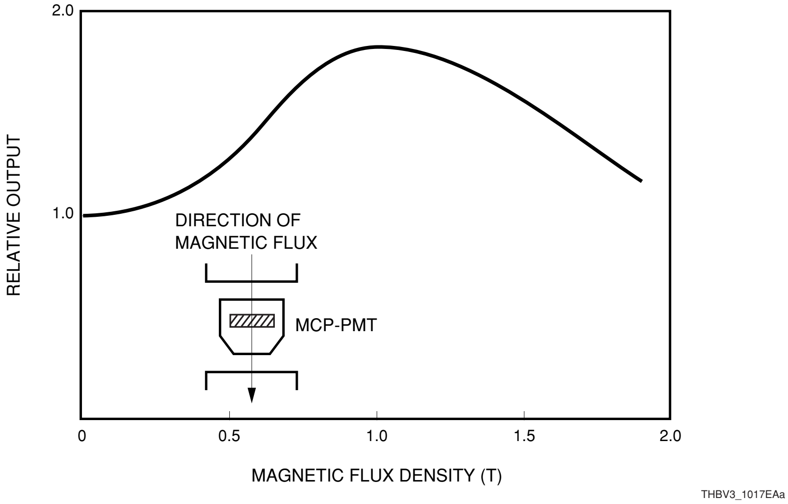
As stated in the section on photomultiplier tubes designed for use in highly magnetic environments, the following points are essential to improve magnetic characteristics.

(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.

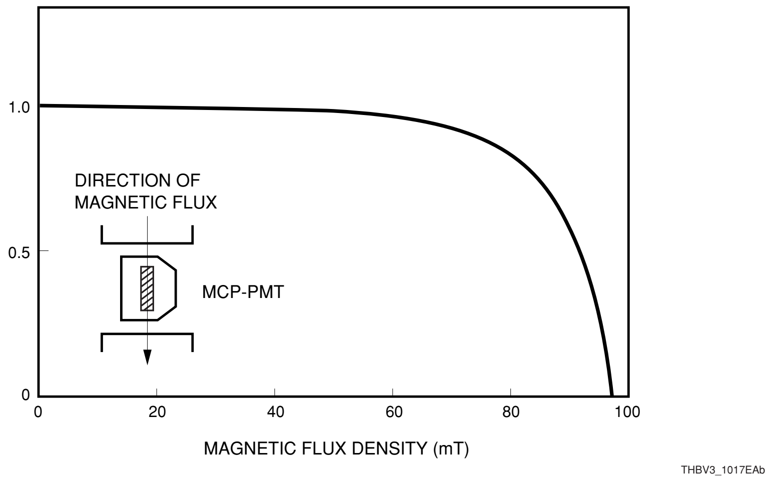
(3) A high electric field intensity should be applied.

The MCP-PMT meets all the above requirements and provides superior magnetic characteristics. Figure 10-17 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 T (20 kilogausses), but in magnetic fields perpendicular to the tube axis, the output drops drastically if fields exceed 70 mT (700 gausses).



(a) When in magnetic fields parallel to tube axis

Figure 10-17: Typical magnetic characteristics of an MCP-PMT (1)



(b) When in magnetic fields perpendicular to tube axis

Figure 10-17: Typical magnetic characteristics of an MCP-PMT (2)

10.3 Gated MCP-PMTs[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 10-18 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 10-18. 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.

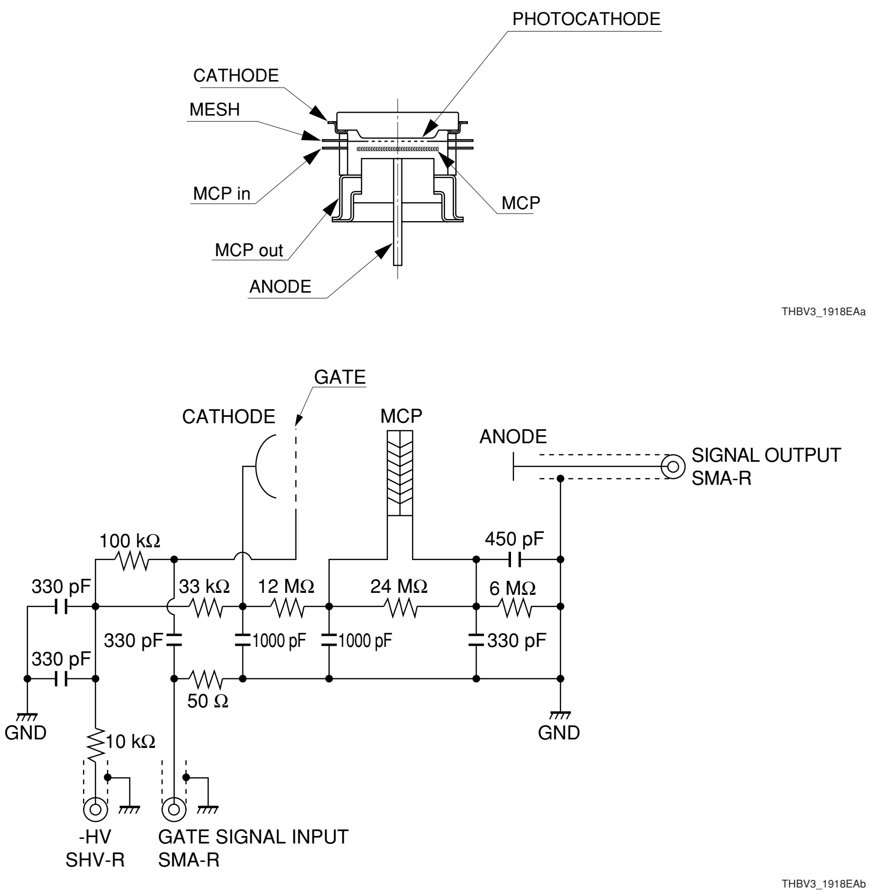


Figure 10-18: Structure of an MCP-PMT with gate mesh and its operating circuit

Figure 10-19 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 is the relation between the anode output and the voltage applied to the gate mesh (input gate bias voltage) when the photocathode potential is maintained at 0 volts and proves that the switching ratio is better than 10^8 (incident light wavelength: 500 nanometers).

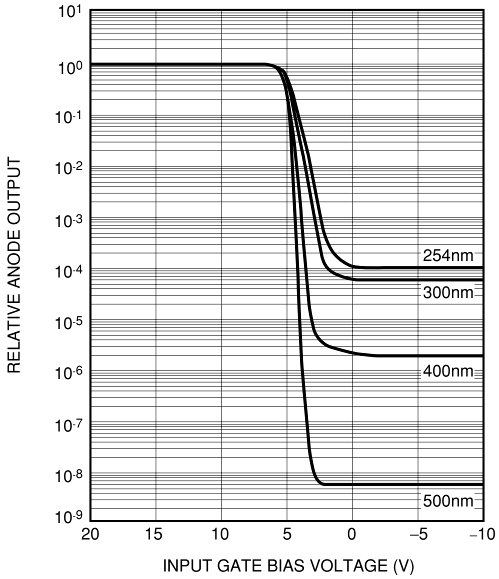


Figure 10-19: Switching ratio characteristic under static operating conditions

Figure 10-20 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 MCP-PMT signal starts rising in approximately 1 nanosecond.

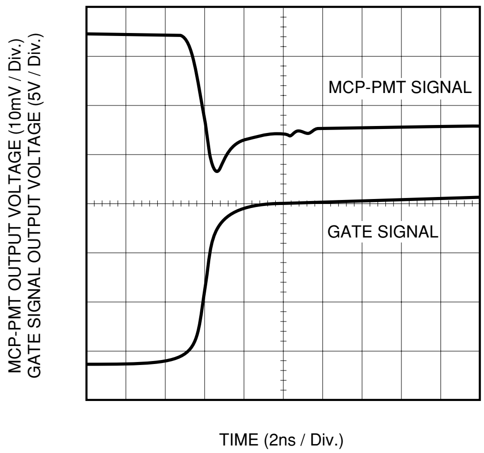


Figure 10-20: Dynamic gate characteristic

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

10.4 Multianode MCP-PMTs[4)]

The previous sections mainly discussed MCP-PMTs having a single anode. A variety of MCP-PMTs with independent multianodes (R4110U, etc.) have been developed and put to 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 10-21.

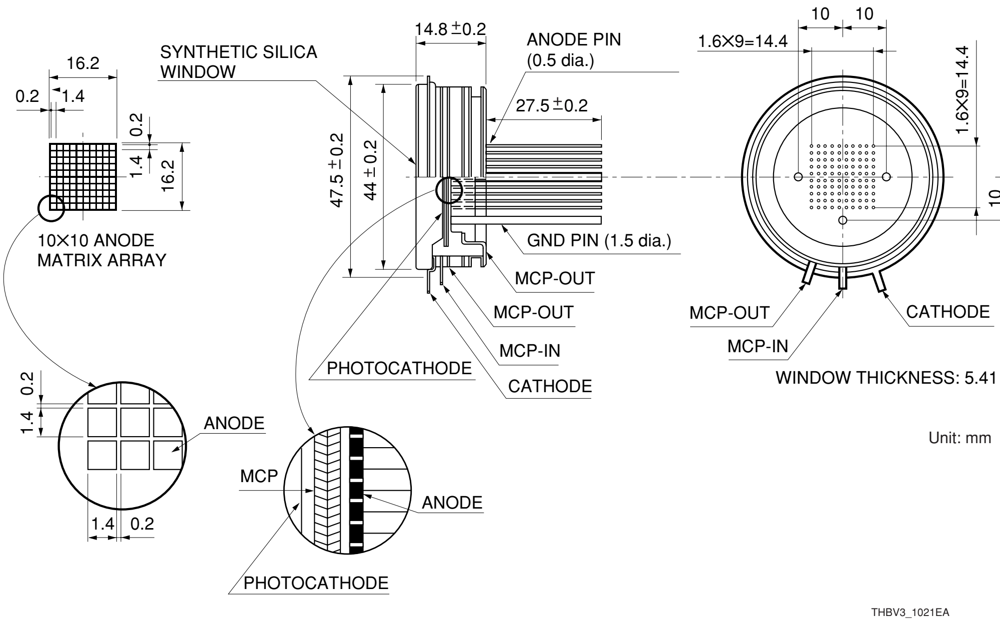
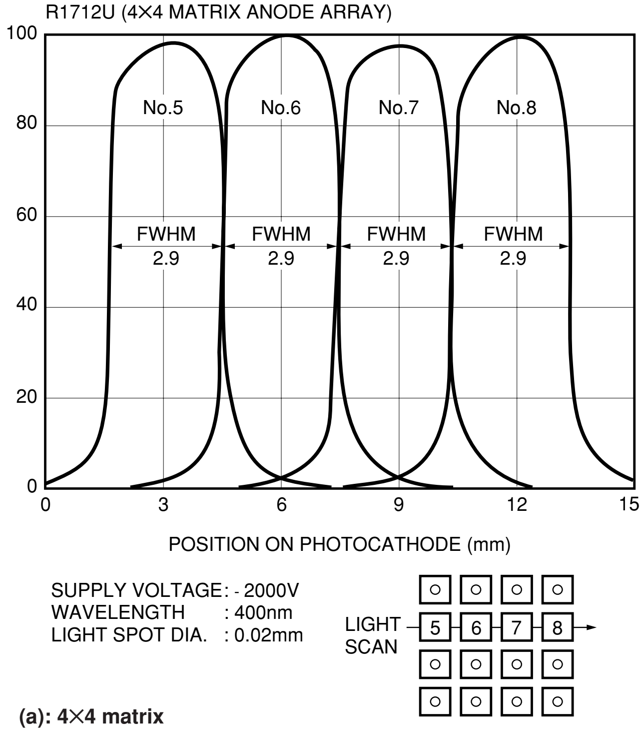


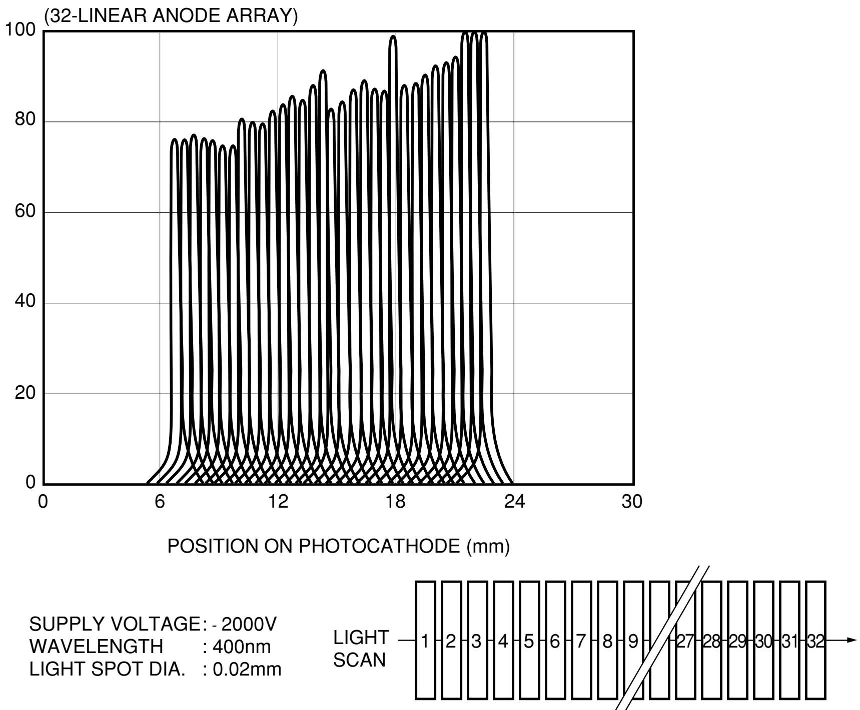
Figure 10-21: Multianode MCP-PMT with 10×10 anode format

Figures 10-22 (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 20 μm diameter is scanned over the photocathode.



(a): 4×4 matrix

THBV3_1022EAa



(b): 32-linear array

THBV3_1022EAb

Figure 10-22: Typical spatial resolution (1)

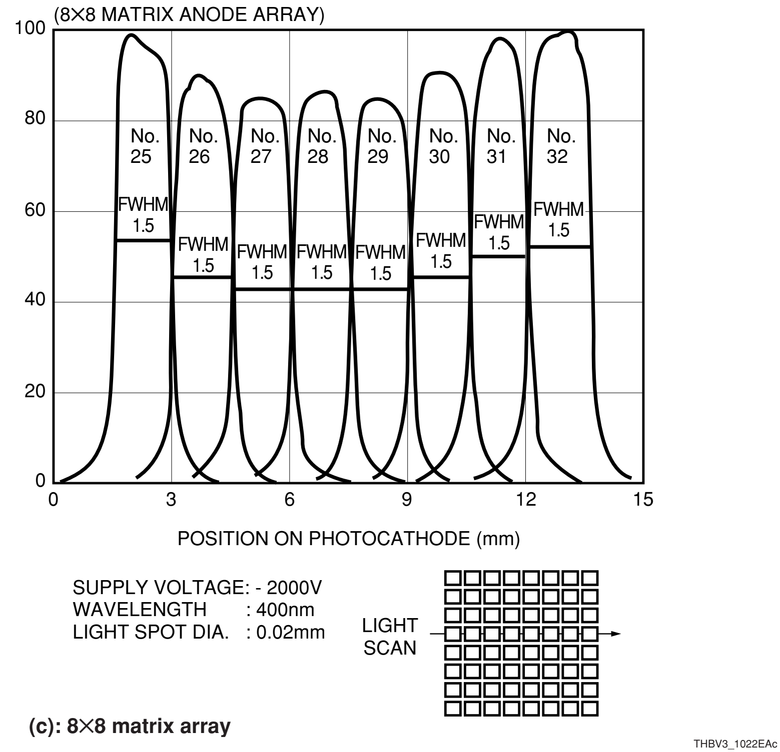


Figure 10-22: Typical spatial resolution (2)

The following applications can take advantage of multianode MCP-PMTs.

(1) Simultaneous, two-dimensional low-light detection of a luminous body which is spread out over a large space

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

(3) Multichannel readout from scintillating fibers

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

Anode Format	
4×4	Matrix anode
8×8	Matrix anode
10×10	Matrix anode
32	Linear anode

Table 10-2: Examples of multianode MCP-PMTs

References in Chapter 10

1) Hamamatsu Photonics Technical Information: MCP assembly, No. TMCP9001E01

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

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