CHAPTER 5
HOW TO USE PHOTOMULTIPLIER TUBES AND PERIPHERAL CIRCUITS

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

5.1 Voltage-Divider Circuits

5.1.1 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 5-1, but this method is not practical.

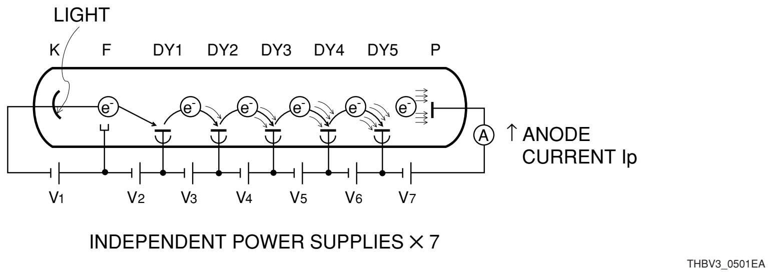


Figure 5-1: Schematic diagram of photomultiplier tube operation

In practice, as shown in Figure 5-2 (1), the interstage voltage for each electrode is supplied by using voltage-dividing resistors (100 kΩ to 1 MΩ) connected between the anode and cathode. Sometimes Zener diodes are used with voltage-dividing resistors as shown in Figure 5-2 (2). These circuits are known as voltage-divider circuits.

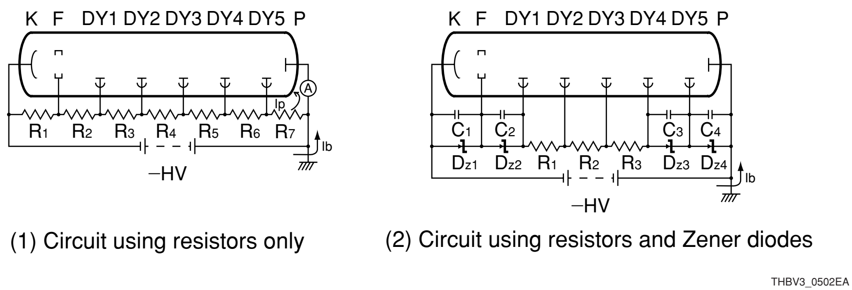


Figure 5-2: Voltage-divider circuits

The current Ib flowing through the voltage-divider circuits shown in Figures 5-2 (1) and (2) is called divider current, and is 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:

$$I_b = \frac{V}{(R_1+R_2+\cdots+R_6+R_7)} \quad \text{(Eq. 5-1)}$$

The Zener diodes (D_z) shown in Figure 5-2 (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. In this case, Ib is obtained by using Eq. 5-1.

$$I_b = \frac{V - (\text{Sum of voltages generated at } D_{z1} \text{ to } D_{z4})}{R_1+R_2+R_3} \quad \text{(Eq. 5-2)}$$

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.

5.1.2 Anode grounding and cathode grounding

As shown in Figure 5-2, 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 photocathode, 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 5-3. 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.

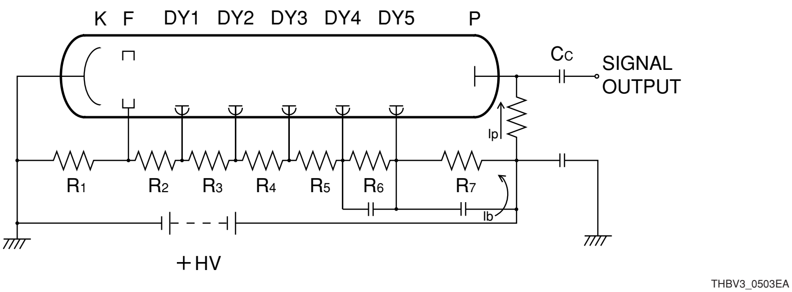


Figure 5-3: Grounded-cathode voltage-divider circuit

5.1.3 Voltage-divider current and output linearity

In both the anode grounding and cathode grounding schemes and in both DC and pulse operation, when the light level incident on the photocathode is increased to raise the output current as shown in Figure 5-4, 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).

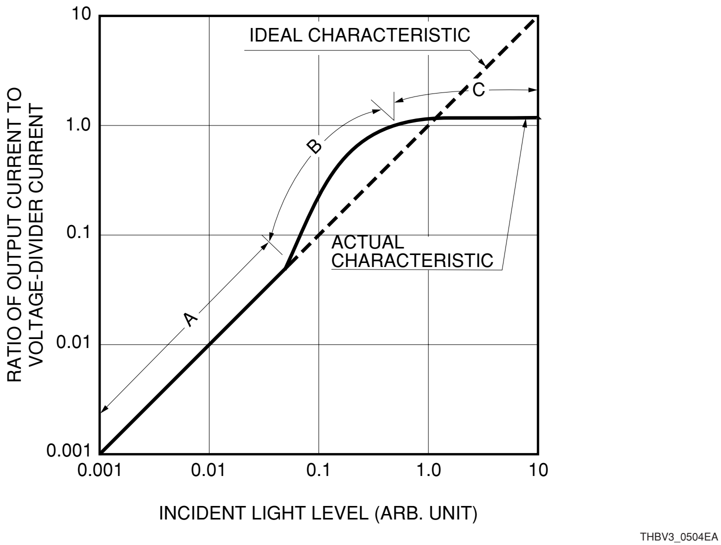


Figure 5-4: Output linearity of a photomultiplier tube

(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 5-5, 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.

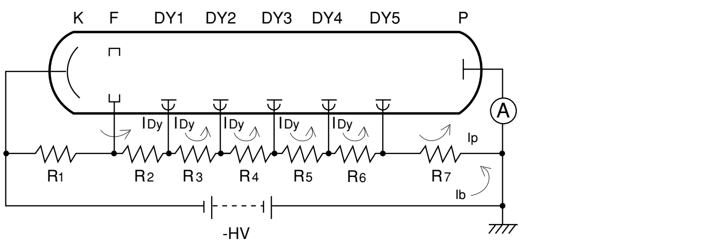


Figure 5-5: Basic operating circuit for a photomultiplier tube

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 5-6. 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.

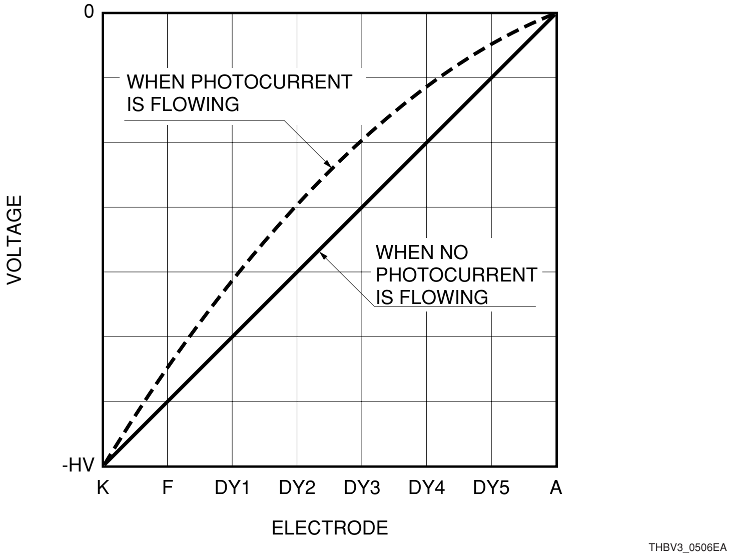


Figure 5-6: Influence of photocurrent on voltage applied to each electrode

The loss of the interstage voltage by means of the multiplied electron current appears most significantly between the last dynode (Dy_5 in Figure 5-5) 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 5-4. 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 5-4.

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 5-2 (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 resulting in detrimental effects of 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 advisable to increase the divider current more than necessary. To solve the above problems in applications where a high linear output is required, individual power supply boosters may be used in place of the voltage-divider resistors at the last few stages.

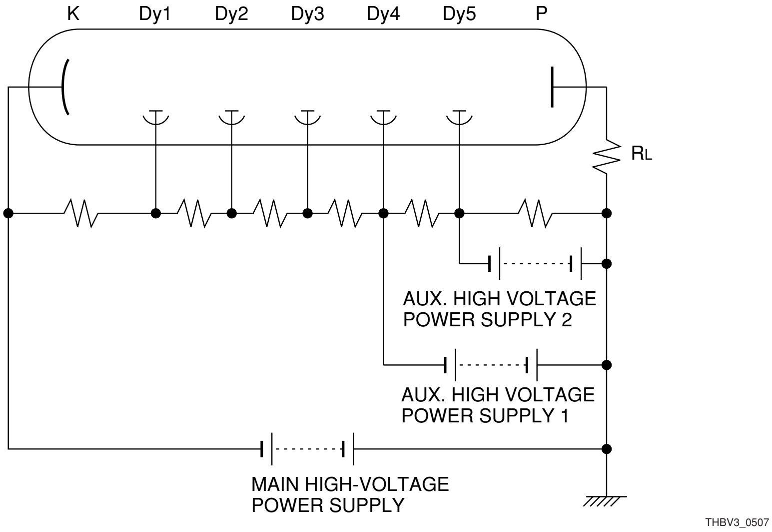


Figure 5-7: Booster circuit

(2) Pulse-operation output linearity and its countermeasures

When a photomultiplier tube is pulse-operated using the voltage-divider circuit shown in Figure 5-2 (1) or Figure 5-3, 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 5-8 (1) and (2). These capacitors supply the photomultiplier tube with an electric charge during the forming of signal pulse and restrain the voltage drop between the last dynode and the anode, 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 Chapter 4. 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 5-8 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 5-8 (1) as an example.

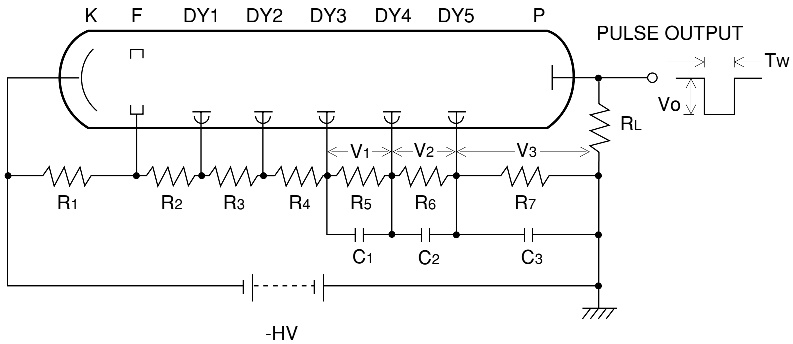


Figure 5-8 (1): Divider circuit with serial-connected decoupling capacitors

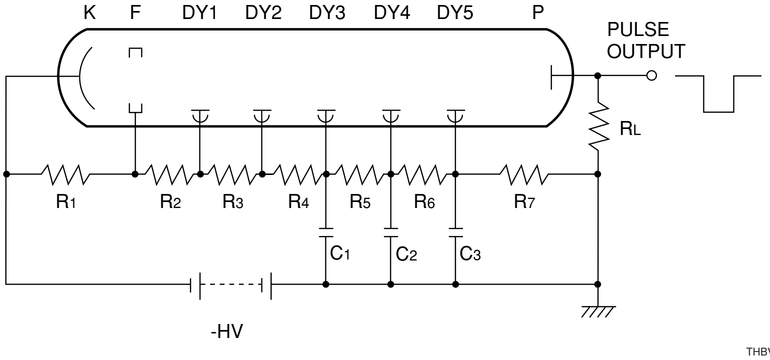


Figure 5-8 (2): Voltage-divider circuit with parallel-connected decoupling capacitors

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. 5-3), as follows:

$$Q_0 = Tw \frac{V_0}{R_L} \quad \text{(Eq. 5-3)}$$

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:

$$Q_3 \geqq 100\ Q_0 \quad \text{(Eq. 5-4)}$$

From the common relation of Q=CV, C_3 is given by Eq. 5-5.

$$C_3 \geqq 100 \frac{Q_0}{V_3} \quad \text{(Eq. 5-5)}$$

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.

$$C_2 \geqq 50 \frac{Q_0}{V_2}$$

$$C_1 \geqq 25 \frac{Q_0}{V_1}$$

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=50 mV, pulse width T_W=1 μs, load resistance R_L=50 Ω, interstage voltages V3=V2=V1=100 V, each capacitor value can be calculated in the following steps:

First, the amount of charge per output pulse is obtained as follows:

$$Q_0 \geqq \frac{50\text{mV}}{50\Omega} \times 1\mu\text{s} = 1\text{nC}$$

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

$$C_3 \geqq 100 \frac{1\text{nC}}{100\text{V}} = 1\text{nF}$$

$$C_2 \geqq 50 \frac{1\text{nC}}{100\text{V}} = 0.5\text{nF}$$

$$C_1 \geqq 25 \frac{1\text{nC}}{100\text{V}} = 0.25\text{nF}$$

The above capacitance values are minimum values required for proper operation. It is therefore 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. Particular care is required when operating at high counting rates even if the output peak current is low.

5.1.4 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 5-9 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.

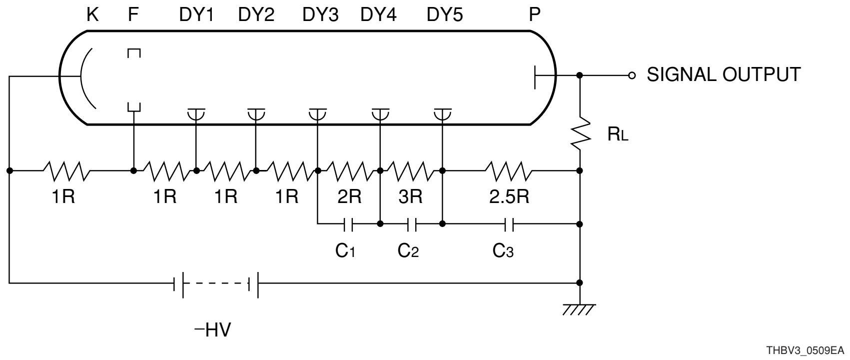


Figure 5-9: Pulse output linearity countermeasures using decoupling capacitors and tapered voltage-divider circuit

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 more than that obtained with normal voltage-divider circuits (equally divided circuits). Figure 5-10 shows a comparison of pulse linearity characteristics measured with a tapered voltage-divider circuit versus that of 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 1/3rd to 1/5th in comparison with the normal voltage-divider anode output. Therefore, adjustment is required to increase the supply voltage for the photomultiplier tube.

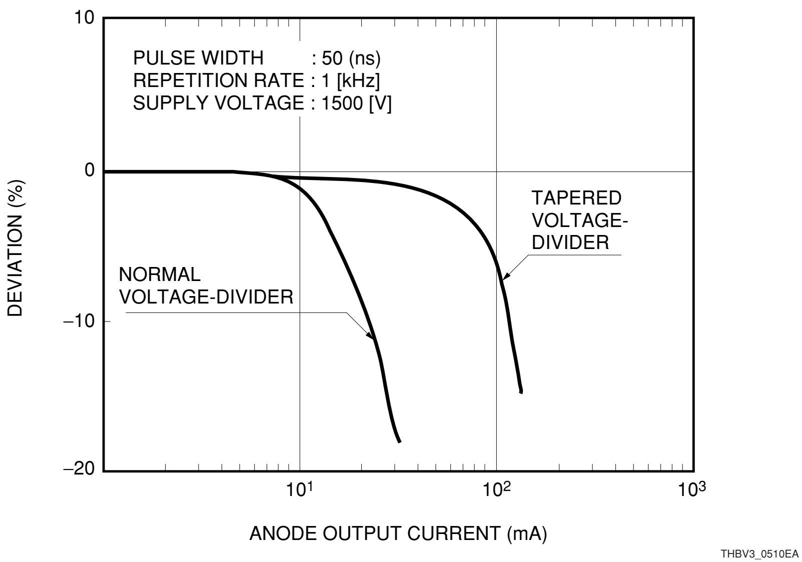


Figure 5-10: Linearity characteristic using a tapered and a normal voltage-divider circuit

The methods discussed 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.

(2) Voltage distribution for the cathode and earlier stages

As mentioned in the previous section, 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 where 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 4.

Figure 5-11 shows a variant of the voltage-divider circuit shown in Figure 5-9, which provides the above measures for the cathode to the first dynode.

In applications such as very low-light-level measurement and single photon counting where shot noise may create a problem, and TOF (time-of-flight) trigger counters and hodoscopes requiring fast time response, it is very important to apply the correct voltage to the cathode, focusing electrode and the precisely designed electron lens system near the first dynode.

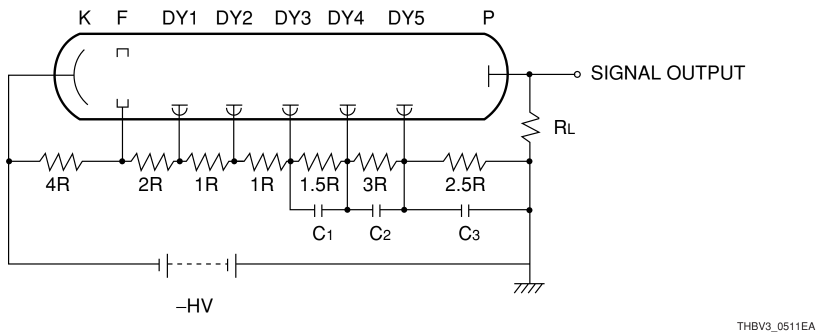


Figure 5-11: Voltage-divider circuit with tapered configurations at both the earlier and latter stages

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.

5.1.5 Countermeasures for fast response circuits

As shown in Figure 5-12, 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 resistor R_1 is usually several tens of kilohms, and a ceramic capacitor of 0.001 to 0.05 microfarads which withstands high voltage is frequently used as C_1.

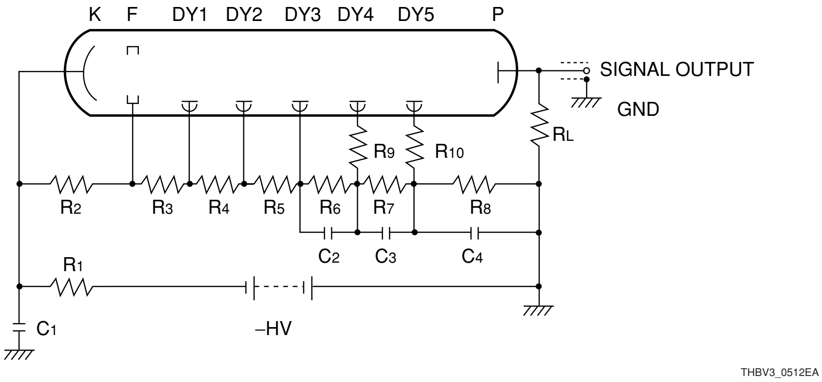


Figure 5-12: Voltage-divider circuit with countermeasure against pulse output linearity, ringing and high-voltage power supply noise

In applications handling a fast pulsed output with a rise time of less than 10 nanoseconds, inserting damping resistors R_{10} into the last dynode as shown in Figure 5-11 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 200 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 5-13 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.

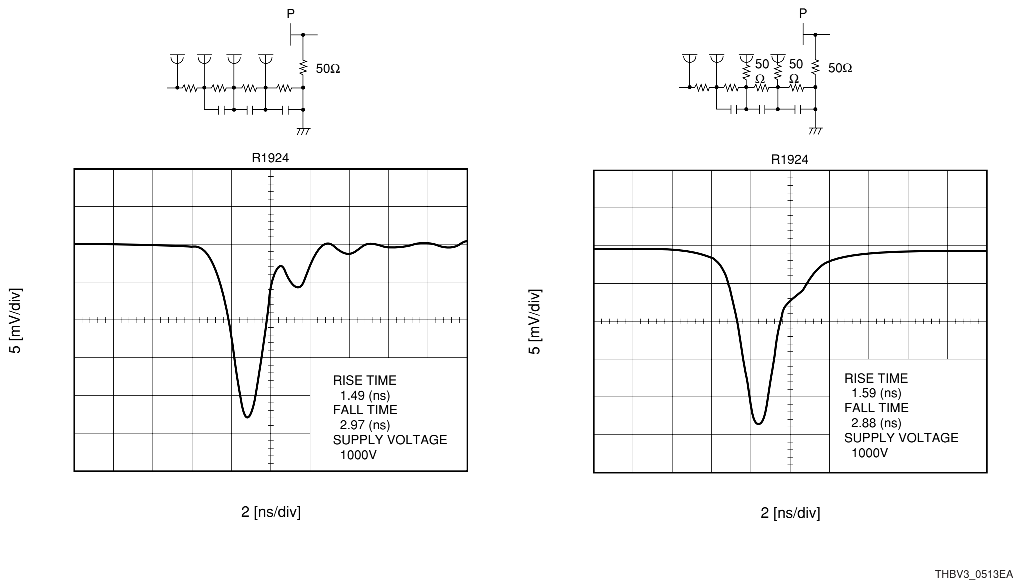


Figure 5-13: Effect of damping resistors on ringing

5.1.6 Practical fast-response voltage-divider circuit

The circuit diagrams of the Hamamatsu H2431-50 photomultiplier tube assembly is shown in Figure 5-14 below as practical examples of fast-response voltage-divider circuits which have been designed based on the description in the preceding section.

H2431-50 circuit diagram

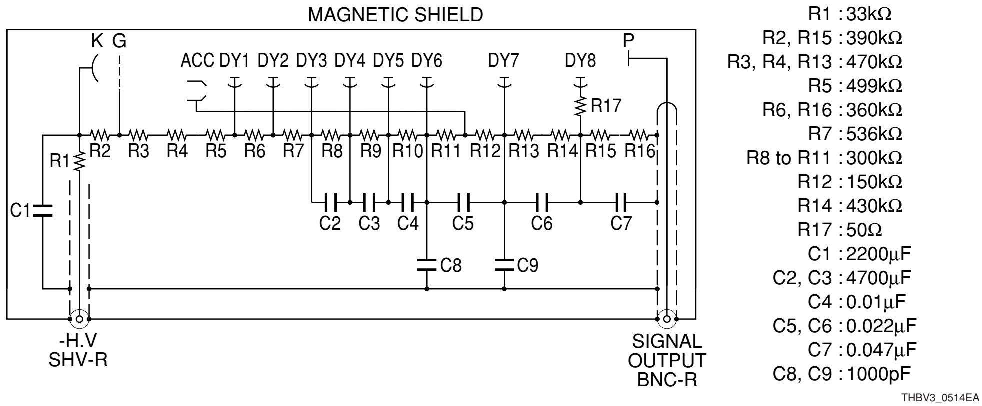


Figure 5-13: Fast-response voltage-divider circuits

5.1.7 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 5-14 shows a voltage-divider circuit for the Hamamatsu R329 photomultiplier tube, devised by FNAL (Fermi National Accelerator Laboratories)[3].

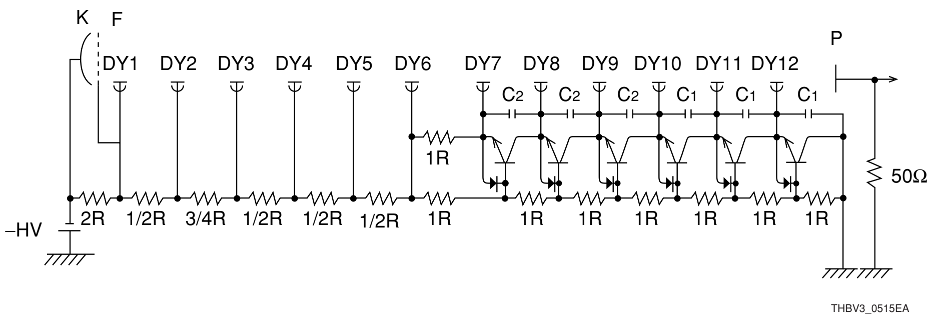


Figure 5-15: Voltage-divider circuit using transistors

In the circuit shown in Figure 5-15, 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.

Figure 5-16 shows output linearity of a voltage-divider circuit (E5815-01) using transistors

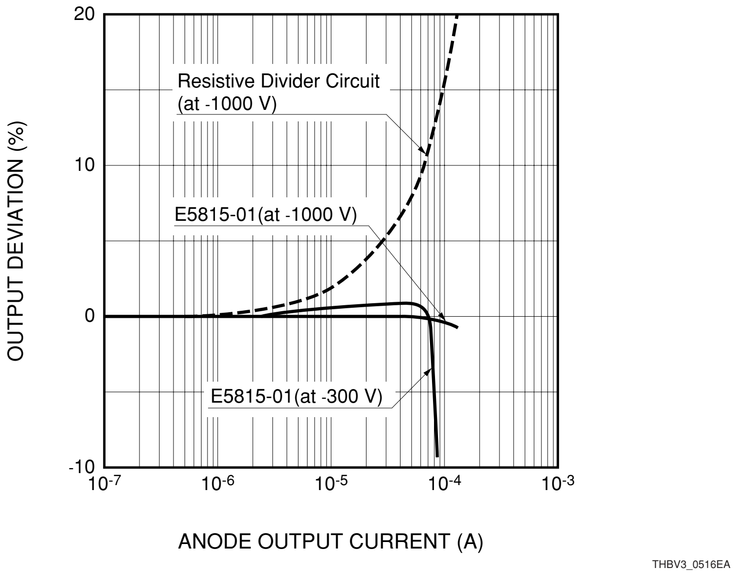


Figure 5-16: Output linearity of a voltage-divider circuit (E5815-01) using transistors

5.1.8 High output linearity voltage-divider circuit (2)

As shown in Figure 5-17, 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 5-18 shows, the Cockcroft-Walton circuit assures higher DC linearity than that obtained with a resistive voltage-divider circuit.

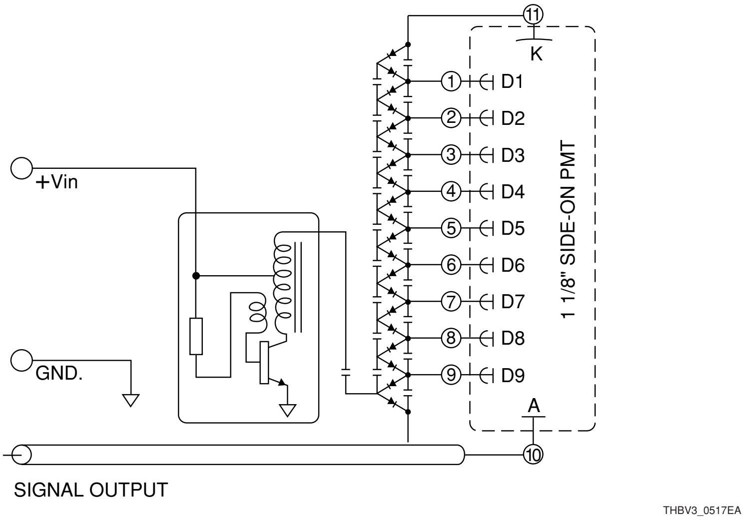


Figure 5-17: Cockcroft-Walton circuit

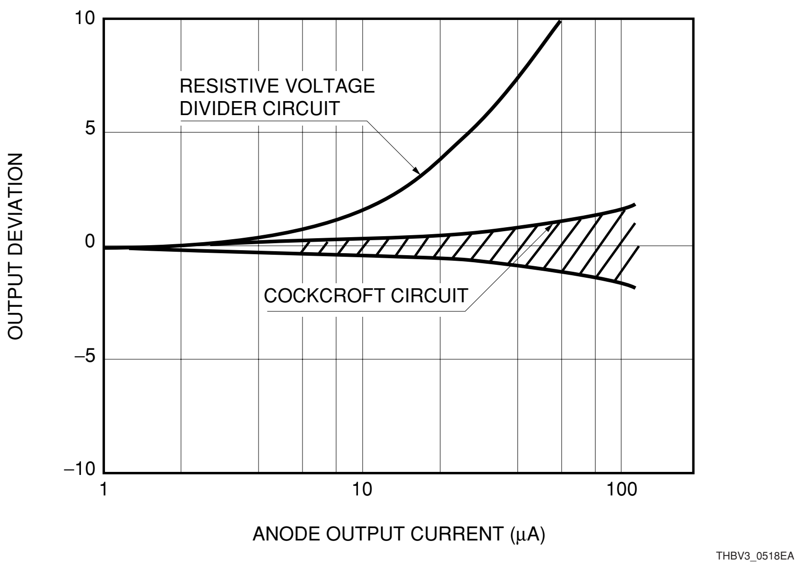


Figure 5-18: Output linearity

5.1.9 Gating circuit

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

In general, in applications such 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.

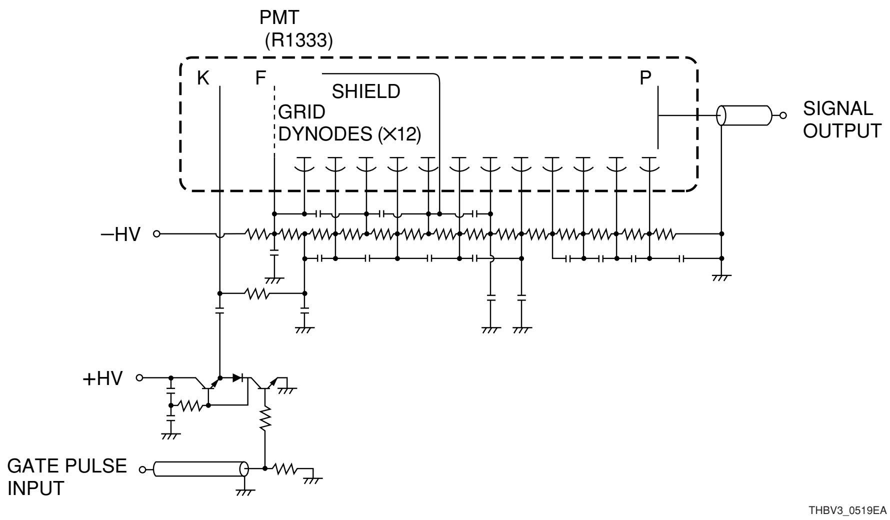


Figure 5-19: Circuit diagram of the C1392 socket assembly with a gating circuit

Figure 5-19 shows the circuit diagram of the Hamamatsu C1392 socket assembly with a gating circuit. 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 when 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. This prevents photoelectrons, if emitted by 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.

5.1.10 Anode sensitivity adjustment circuits

The photomultiplier tube anode sensitivity is usually adjusted by changing the supply voltage. In some applications, however, a single power supply is used to operate two or more photomultiplier tubes or a sensitivity adjustment 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 a sensitivity adjustment circuit, using the circuits shown in Figure 5-20 as examples.

With the circuits shown in Figure 5-20, there are three techniques for adjusting the voltage applied to the photomultiplier tube. The first is, as shown in (1) in the figure, to use a variable resistor connected between the cathode and the negative high-voltage power supply so that the 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). However, it should be noted that the higher the voltage-divider resistance value, the higher the variable resistance value should be and, in some cases, variable resistors with such a high wattage resistor may not be available. 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.

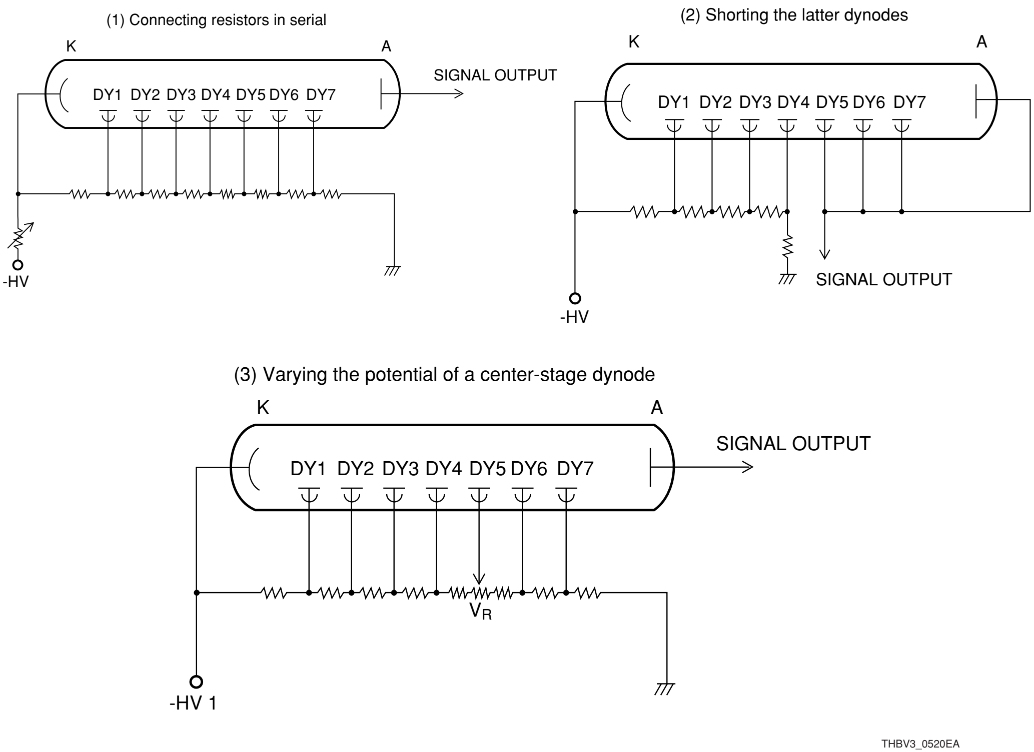


Figure 5-20: Anode sensitivity adjustment circuits

The second technique, as shown in Figure 5-20 (2), is to short the latter dynode stages with the anode so that the signal is derived from a middle dynode. This is effective in cases where 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) reduces the number of dynode stages and assures a higher interstage voltage which 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 sensitivity versus supply voltage characteristic also varies accordingly. The degree of this variation is different from tube to tube.

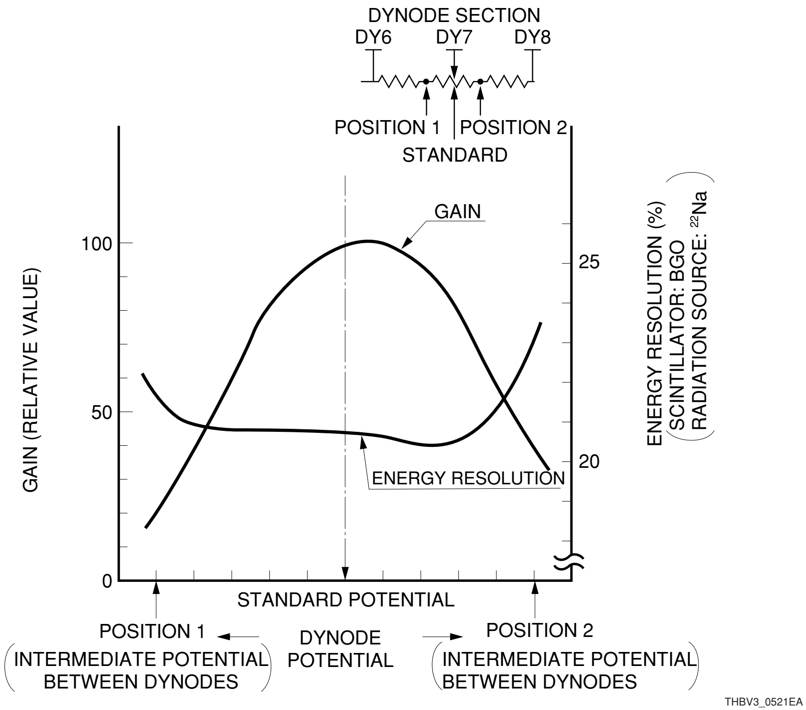


Figure 5-19: Gain variation and energy resolution as a function of dynode potential

The third technique is performed by varying the potential of a mid-stage dynode, as shown in Figure 5-20 (3). This makes use of the fact that with a varying dynode potential, the number of secondary electrons released from the dynode decreases while the collection efficiency between dynodes drops. To adjust the dynode potential, a variable resistor is added between the front and rear adjacent dynodes. Although this method is 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 5-21 dictates the sensitivity 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 sensitivity drops by more than 50 percent. This behavior is not constant but differs depending on individual photomultiplier tubes. In addition, the variable sensitivity range is not so wide. In most cases, the technique (1) or a combination of (1) and (3) is used.

5.1.11 Precautions when fabricating a voltage-divider circuit

This section describes the precautions to take when 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 %, 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 a sufficient power rating 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 typically changes from 100 kΩ to 1 MΩ. For damping resistance and load resistance, use noninduction type resistors designed for operation 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.

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 on a PC board and not on a photomultiplier tube socket, 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.

Leads

For high voltage circuits, use teflon or silicone leads which can withstand a high voltage, or use coaxial cable such as the 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.

Normal lead wires can be used for grounding. However, if there is a possibility that the ground wire may make contact with a high voltage component or socket pins, use a lead wire that withstands high voltage.

(2) Precautions for mounting components

This section describes precautions to be observed when mounting components on a voltage-divider circuit. Refer to Figure 5-12 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 5-12, 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.

5.2 Selecting a High-Voltage Power Supply

Photomultiplier tube operation stability depends on the total stability of the power supply characteristics including drift, ripple, temperature dependence, input regulation and load regulation. The power supply must provide high stability which is at least 10 times as stable as the output stability required of the photomultiplier tube.

Series-regulator type high-voltage power supplies have been widely used with photomultiplier tubes. 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.

The high-voltage power supply should have sufficient capacity to supply a maximum output current which is at least 1.5 times the current actually flowing through the voltage-divider circuit used with the photomultiplier tube.

The following table shows the guide for selecting the correct high-voltage power supply.

High voltage power supply characteristics

(1) Line regulation	±0.1 % or less
(2) Load regulation	±0.2 % or less
(3) Ripple noise	0.05 % or less
(4) Temperature coefficient	±0.05 %/°C or less

(1) This is the percentage (%) change in the output voltage caused by varying, for example, ±10 % the input voltage when the power supply is operated to provide the maximum voltage.

(2) This is the difference between the output voltage at the maximum output (with full load connected) and the output voltage with no load, expressed as a percentage (%) of the output voltage.

(3) Ripple is fluctuations (peak values) in the output caused by the oscillation frequency of the high voltage generating circuit.

(4) This is the rate of output change (%/°C) measured over the operating temperature range at the maximum output.

5.3 Connection to an External Circuit

5.3.1 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 5-22, 5-23 and 5-24.

As described in section 5.1.2 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 5-22 and 5-23. On the other hand, the cathode grounding scheme uses a coupling capacitor to separate the high voltage applied to the anode as shown in Figure 5-24, so that only pulse operation is feasible. But this scheme eliminates DC components produced by such factors as background light, making it suitable for pulse operation.

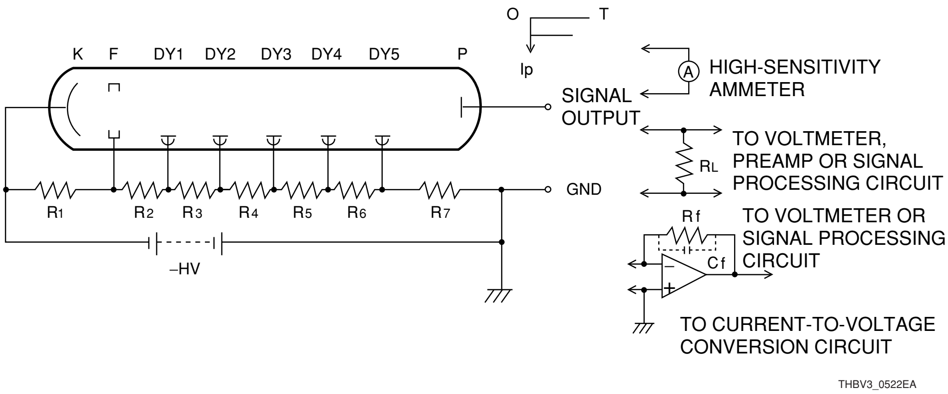


Figure 5-22: Anode grounding scheme in DC operation

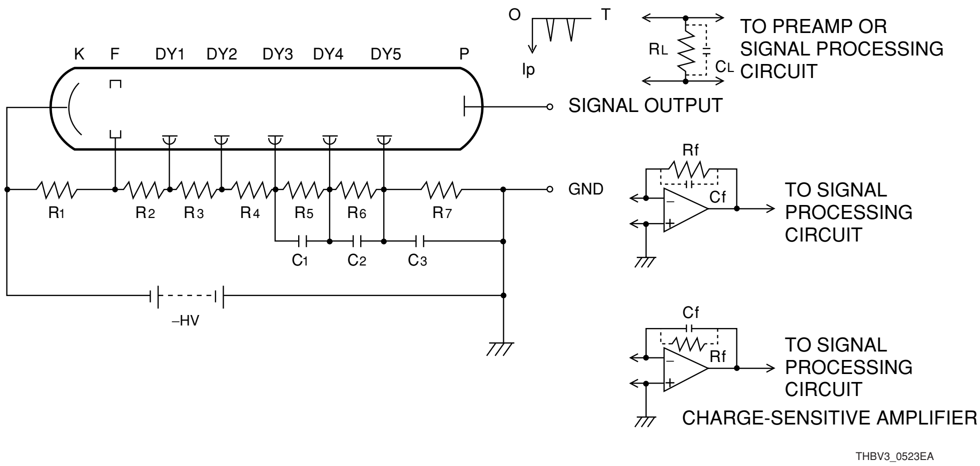


Figure 5-23: Anode grounding scheme in pulse operation

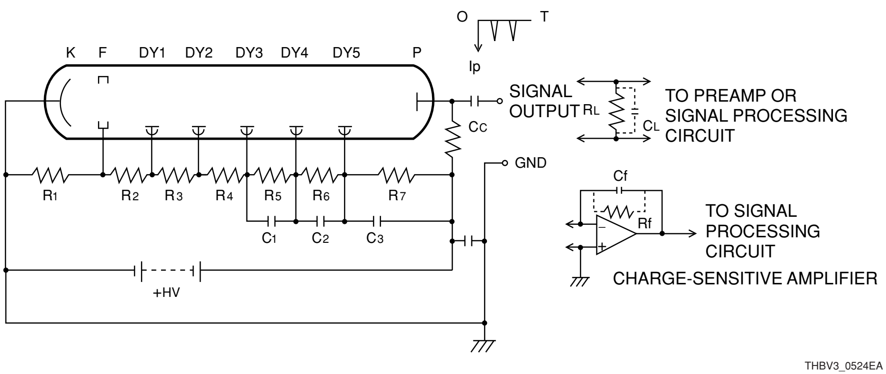


Figure 5-24: Cathode grounding scheme in pulse operation

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, probably leading to damage of the amplifier circuit. Extreme care should be taken when using high speed circuits, as they are more susceptible to damage.

5.3.2 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 5-25, 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 so 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. When a 50-ohm resistor is used for R_a to optimize fast response operation, the time constant C_R becomes small, so 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 $Z_C = \frac{I}{2\pi f_C}$, the output signal decays by 3 dB (approximately to 7/10th of the pulse height) at a frequency $f=1/2\pi CR_L$.

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:

$$V_a = E_0e^{-t/RC} \times \frac{R_a}{R_a+R_L} \quad \text{(Eq. 5-6)}$$

Here, if the signal pulse repetition rate increases, the base line does not return to the true zero level as Figure 5-25 shows. This is known as base-line shift, and can be minimized by reducing the time constant CR. Since the output from a photomultiplier tube is viewed as a current source, reducing the capacitor value increases the initial voltage E_0, 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, so care is required when excessive current including DC current flows.

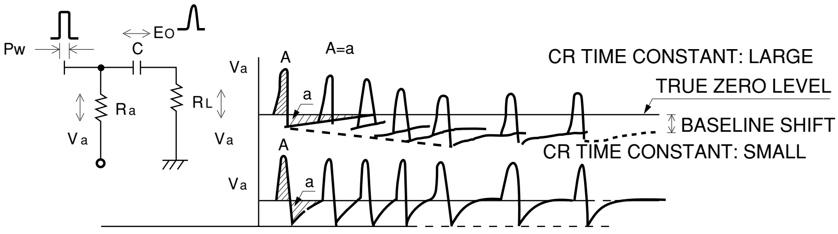


Figure 5-25: Base-line shift

Eventually, when the amount of charge stored on the capacitor (portion A in Figure 5-25) is discharged in a certain time period (portion a in Figure 5-25), 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 pulse 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, the optimum resistor and capacitor values must be selected so 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, some applications utilize a pulse height discriminator to discern the height of individual pulses and in this case the time resolution of the measurement device must be taken into account.

5.3.3 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 and an output voltage of $Ip \times R_L$ can be obtained. In practice, however, the load resistance value is limited by such factors as the required frequency response and output linearity as discussed below.

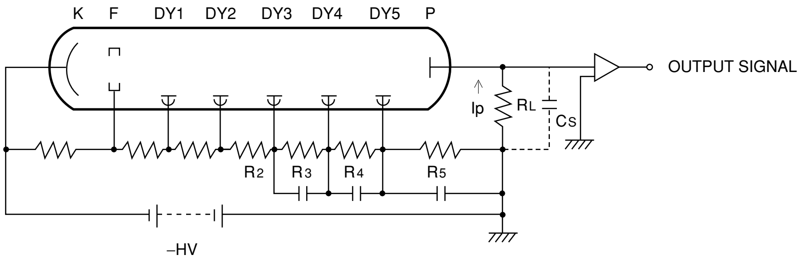


Figure 5-26: Photomultiplier tube and output circuit

If, in the circuit of Figure 5-26, 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 high-range cutoff frequency f_C is given by the following equation:

$$f_C = \frac{1}{2\pi C_S R_L} \text{ (Hz)} \quad \text{(Eq. 5-7)}$$

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. 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. In most cases, therefore, use a load resistance that provides an output voltage of about 1 volt.

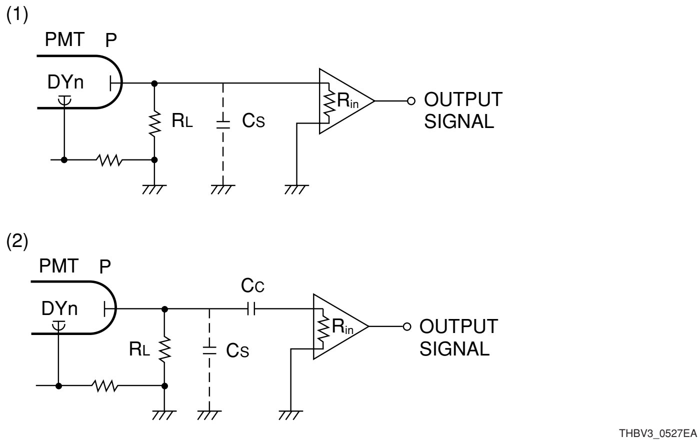


Figure 5-27: Amplifier internal input resistance

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 5-27 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:

$$R_0 = \frac{R_{in} \cdot R_L}{R_{in} + R_L} \quad \text{(Eq. 5-8)}$$

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:

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

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 5-27 (2), 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 (50 ohms). 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 5-28.

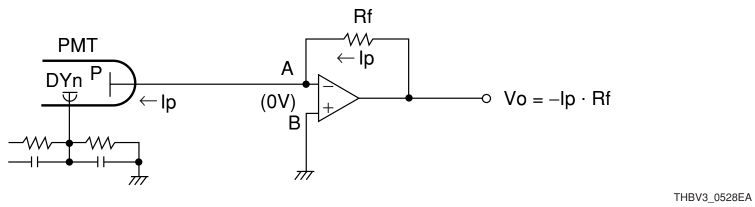


Figure 5-28: Current-to-voltage conversion circuit using an operational amplifier

With this circuit, the output voltage V_0 is given by

$$V_0 = -I_p \cdot R_f \quad \text{(Eq. 5-10)}$$

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 5-28. 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. Use a low-noise type coaxial cable with sufficiently high insulating properties for the signal output cable.
2. Select a connector with adequate insulating properties, for example, a teflon connector.
3. 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.
4. 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.

5. Provide adequate output-offset adjustment and phase compensation for the preamplifier.
6. 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.
7. 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.
8. 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.

A high voltage is applied during photomultiplier tube operation. If for some reason this high voltage is accidentally output from the photomultiplier tube, a protective circuit consisting of a resistor R_p and diodes D_1 and D2 as shown in Figure 5-29 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 5-29 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.

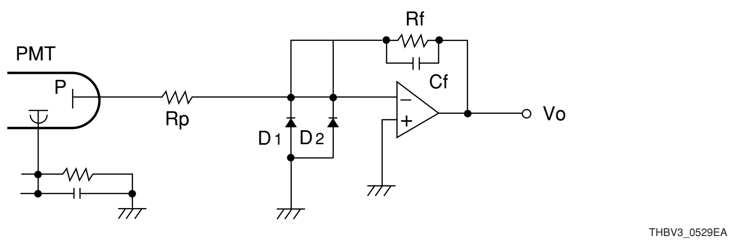


Figure 5-29: Protective circuit for preamplifier

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 5-30, 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.

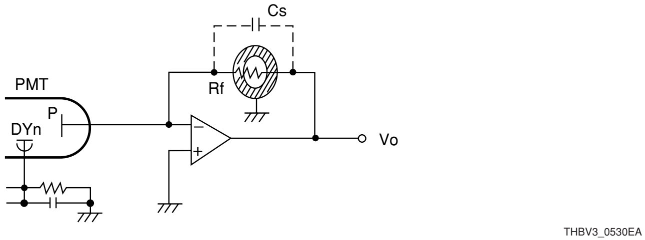


Figure 5-30: Canceling the stray capacitance by Rf

If the signal output cable for a photomultiplier tube is long and its equivalent capacitance is C_C as shown in Figure 5-31, 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 effective in canceling out the rolloff and avoiding this oscillation, but degradation of the response speed is inevitable.

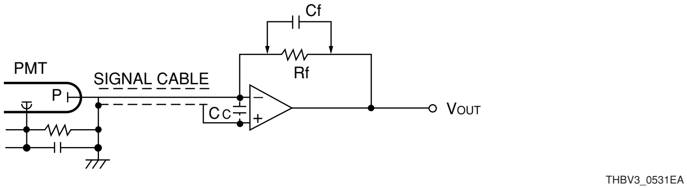


Figure 5-31: Canceling the signal cable capacitance

(3) Charge-sensitive amplifier using an operational amplifier

Figure 5-32 (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

$$V_0 = Q_p/C_f \quad \text{(Eq. 5-11)}$$

Here, if the output current of the photomultiplier tube is I_p, V_0 becomes

$$V_0 = -\frac{1}{C_f}\int_0^t I_p \cdot d_t \quad \text{(Eq. 5-12)}$$

When the output charge is accumulated continuously, V_0 finally increases up to a level near the supply voltage for the preamplifier, as shown in Figure 5-32 (2) and (3).

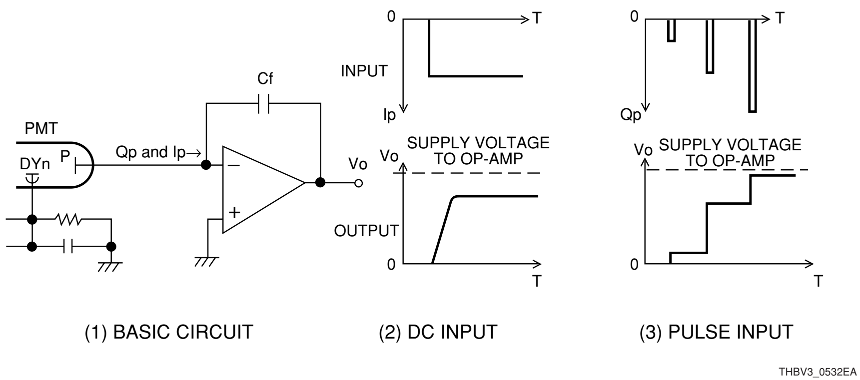


Figure 5-32: Charge-sensitive amplifier circuit and its operation

In Figure 5-32 (1), if a circuit is added by connecting a FET switch in parallel to C_f so that the charge stored in Cf can be discharged as needed, this circuit acts as an integrator that stores the output charge during the measurement time, regardless of whether the photomultiplier tube output is DC or pulse. In scintillation 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 5-33, so that a circuit having a discharge time constant $\tau = C_f \cdot R_f$ is used.

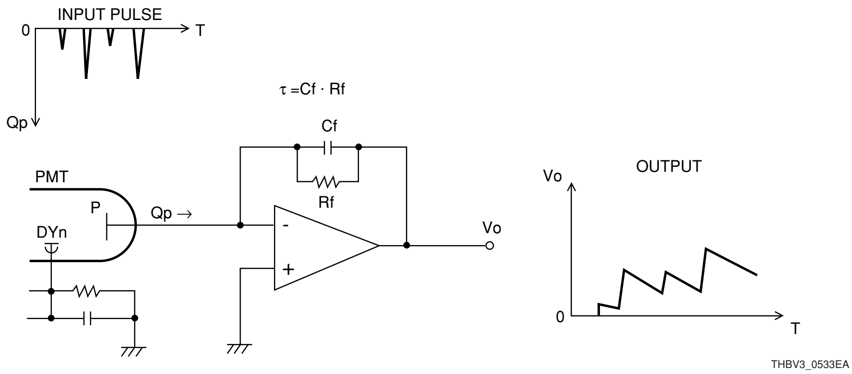


Figure 5-33: Pulse input type charge-sensitive amplifier

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, V_0 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 τ=RC and the fluorescent decay constant of the scintillator τ_S, the output-pulse voltage waveform V(t) is given by[4)]

$$V(t) = \frac{Q \cdot \frac{\tau}{C}}{\tau - \tau_S} \left(e^{-t/\tau} - e^{-t/\tau_S}\right) \quad \text{(Eq. 5-13)}$$

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

$$V(t) \approx \frac{Q}{C} \left(e^{-t/\tau} - e^{-t/\tau_S}\right) \quad \text{(Eq. 5-14)}$$

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

$$V(t) \approx \frac{Q}{C} \cdot \frac{\tau}{\tau_S} \left(e^{-t/\tau_S} - e^{-t/\tau}\right) \quad \text{(Eq. 5-15)}$$

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.

In scintillation counting, 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 with the cable capacitance C_S indicated in Figure 5-34 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 compared to the amount of charge without C_S, so the value of $A \cdot C_f / C_S$ must be large 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.

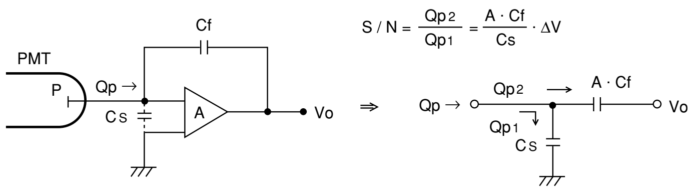


Figure 5-34: Influence of input distribution capacitance

5.3.4 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 as shown in Figure 5-35. This allows the impedance seen from the photomultiplier tube to remain constant, independent of the cable length, 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, and 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.

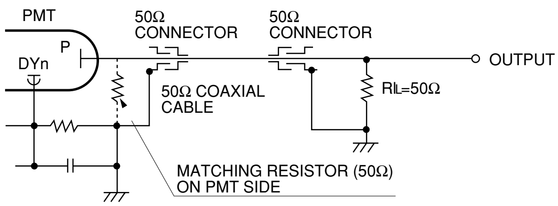


Figure 5-35: Output circuit impedance match

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, so 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 becomes very low. Even so the signal output waveform can be directly observed with an oscilloscope using its internal impedance (50 ohms or 1 megohm), but some cases may require a wide-band amplifier with high gain. Such an amplifier usually has large noise and possibly makes it difficult to measure low-level signals. In this case, to achieve the desired output voltage, it is more advantageous to bring the photomultiplier tube as close as possible to the amplifier to reduce the stray capacitance as shown in Figure 5-36, and also to use a large load resistance as long as the frequency response is not degraded.

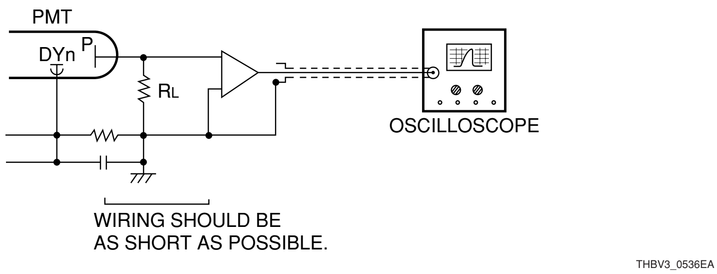


Figure 5-36: Waveform observation using an oscilloscope

It is relatively simple to fabricate a fast amplifier with a wide bandwidth using a video IC or pulse type IC. However, in exchange for such design convenience, these ICs tend 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.

5.4 Housing

A photomultiplier tube housing is primarily used to contain and secure 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

5.4.1 Light shield

Since a photomultiplier tube is a highly sensitive photodetector, the signal light level to be detected is typically very low and therefore 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.

5.4.2 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. 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.

5.4.3 Magnetic shield

As will be described in Chapter 13, photomultiplier tubes are very sensitive to a magnetic field. Even terrestrial magnetism will have a detrimental effect on the photomultiplier tube performance[5)]. 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. Shielding a magnetic field completely is not possible. 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. An optimum shielding material and method must also be selected according to 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.

(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 under stable conditions in a magnetic field, a magnetic shield case must be used. (Also refer to Chapter 13.) 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 5-37.

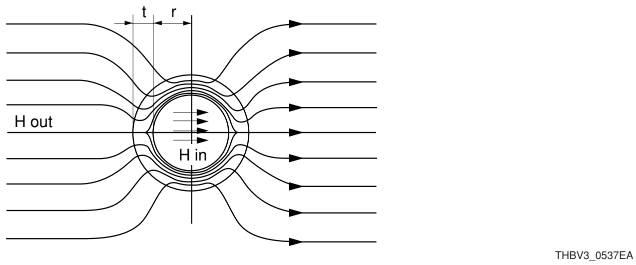


Figure 5-37: Shielding effect of a magnetic shield case

Let us consider the shielding effect of a magnetic shield case illustrated in Figure 5-37. 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:

$$S = \frac{H_{out}}{H_{in}} = \frac{3t\mu}{4r} \quad \text{(Eq. 5-16)}$$

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:

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

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 3 milliteslas, this means that the photomultiplier tube is operated in a magnetic field of 0.3 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 5-38 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.

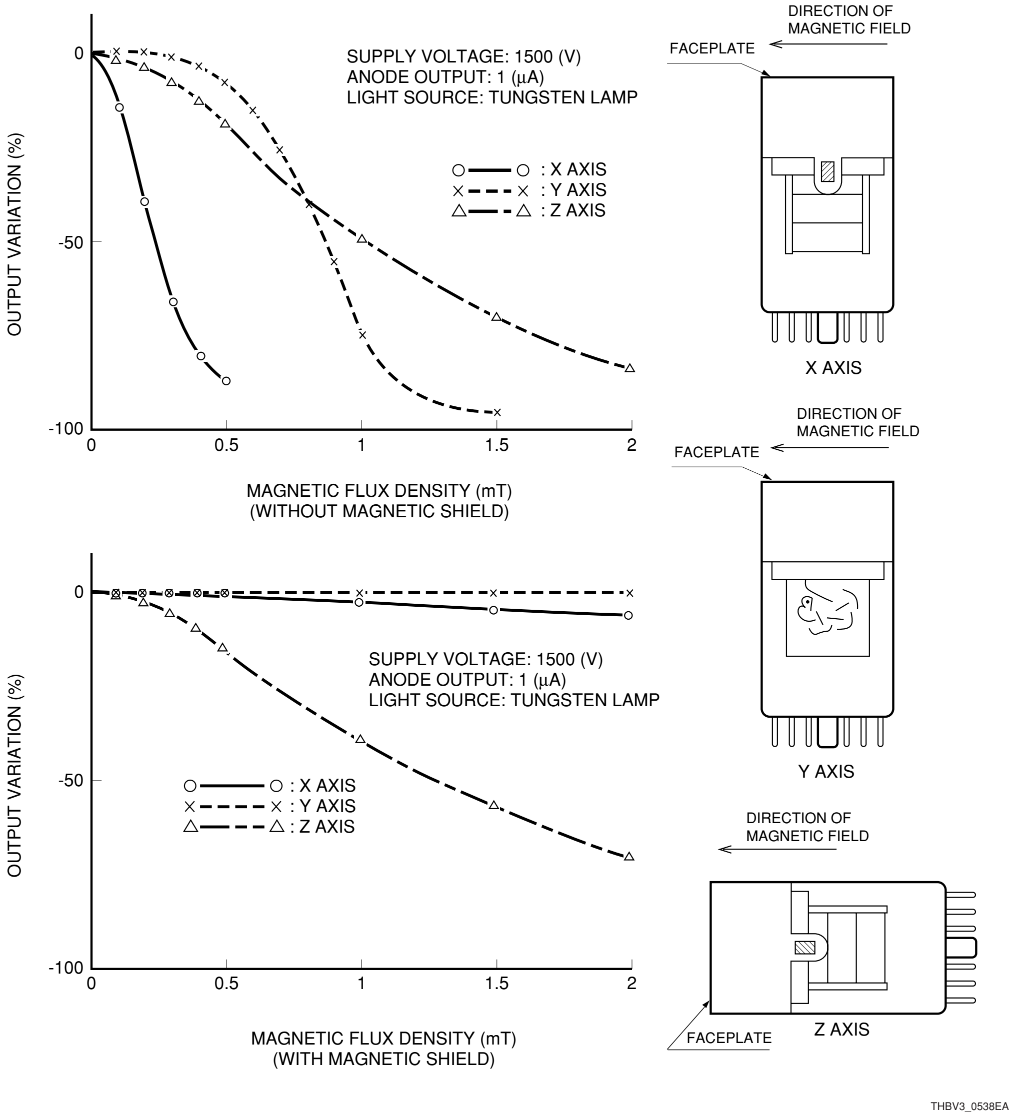


Figure 5-38: Magnetic characteristics of a photomultiplier tube

(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 5-39.

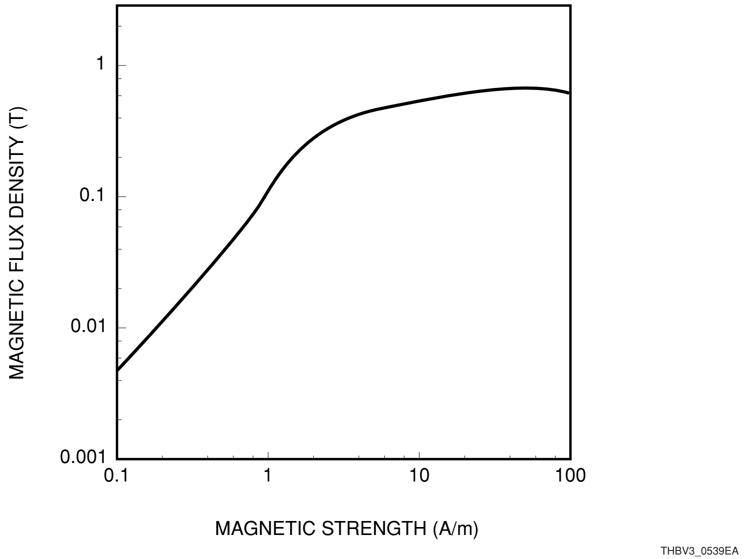


Figure 5-39: DC magnetization curve (B-H curve)

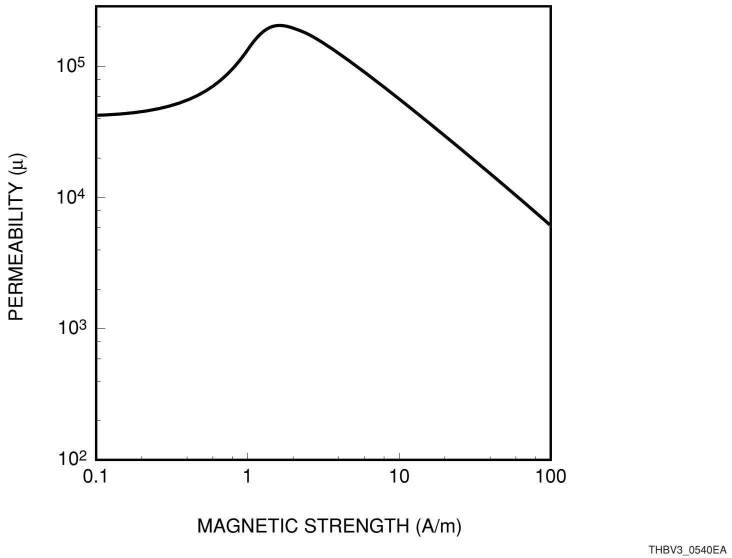


Figure 5-40: Permeability and external magnetic field

Since the permeability μ of a magnetic material is given by the B/H ratio, μ varies with H as shown in

Figure 5-40 with a peak at a certain H level and above it, both μ and the shielding factor degrade sharply. Data shown in Figure 5-40 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.

Magnetic shield cases are made of a "PC" material which contains large quantities of nickel. This material assures very high permeability, but has 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 5-41 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, a "PC" material shield case should be used in conjunction with a shield material such as soft-iron or thick PB material with a thickness of 3 to 10 millimeters, which exhibits a high saturation level of magnetic flux density.

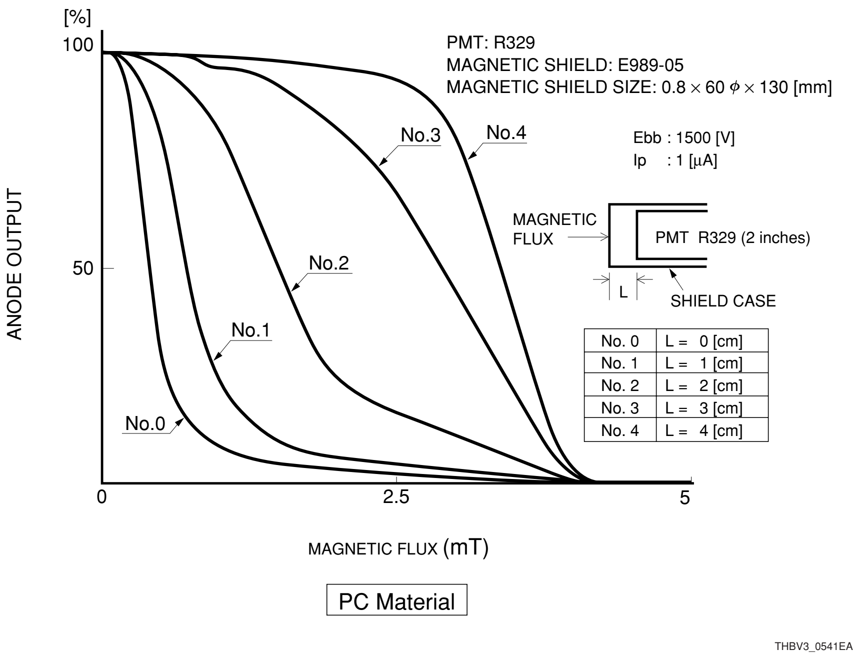


Figure 5-41: Magnetic characteristics of a photomultiplier tube used with magnetic shield case (PC material)

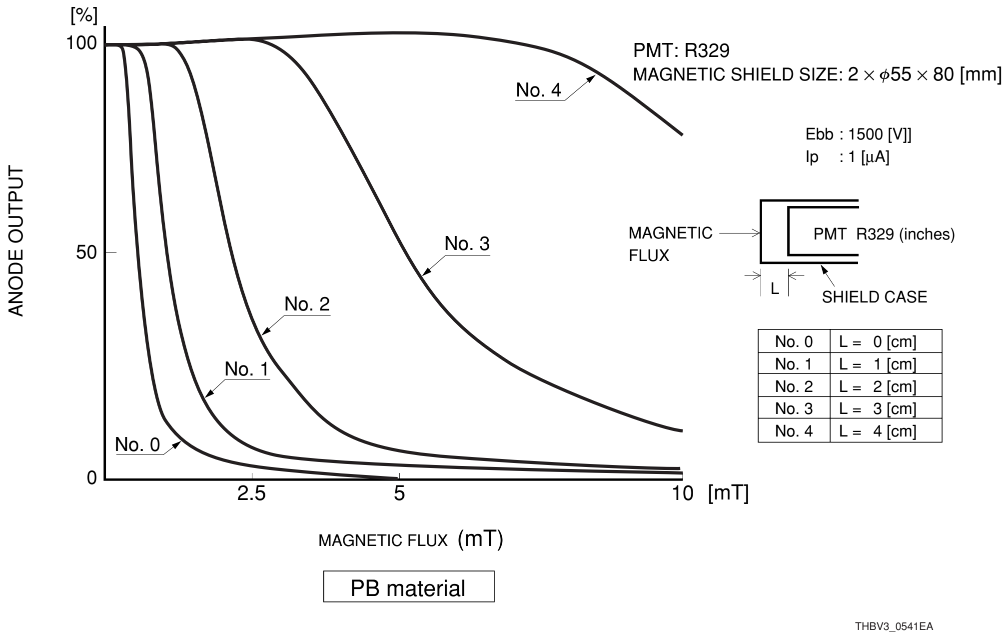


Figure 5-41: Magnetic characteristics of a photomultiplier tube used with magnetic shield case (PB material)

(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 5-42. 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 1 kHz to 10 kHz. 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.

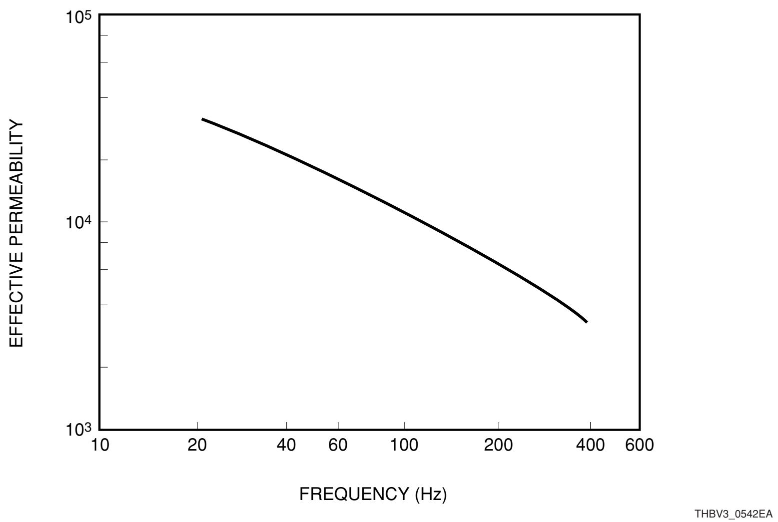


Figure 5-42: Frequency characteristics of a magnetic shield case

(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 5-43. 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 or diameter. (See Figure 5-41.)

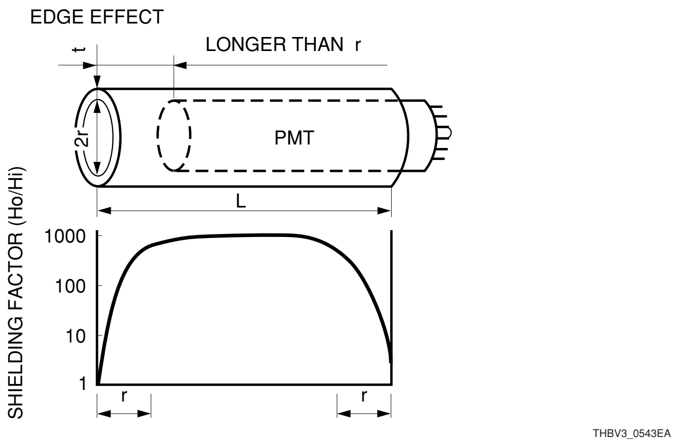


Figure 5-43: Edge effect of a magnetic shield case

(5) Photomultiplier tube magnetic characteristics and shielding effect

Figure 5-44 shows magnetic characteristics of typical photomultiplier tubes (anode output variations versus magnetic flux density characteristics) and the shielding effects of magnetic shield cases (Hamamatsu E989 series). It can be seen from these figures that use of a shield case can greatly reduce the influence of magnetic fields of several milliteslas.

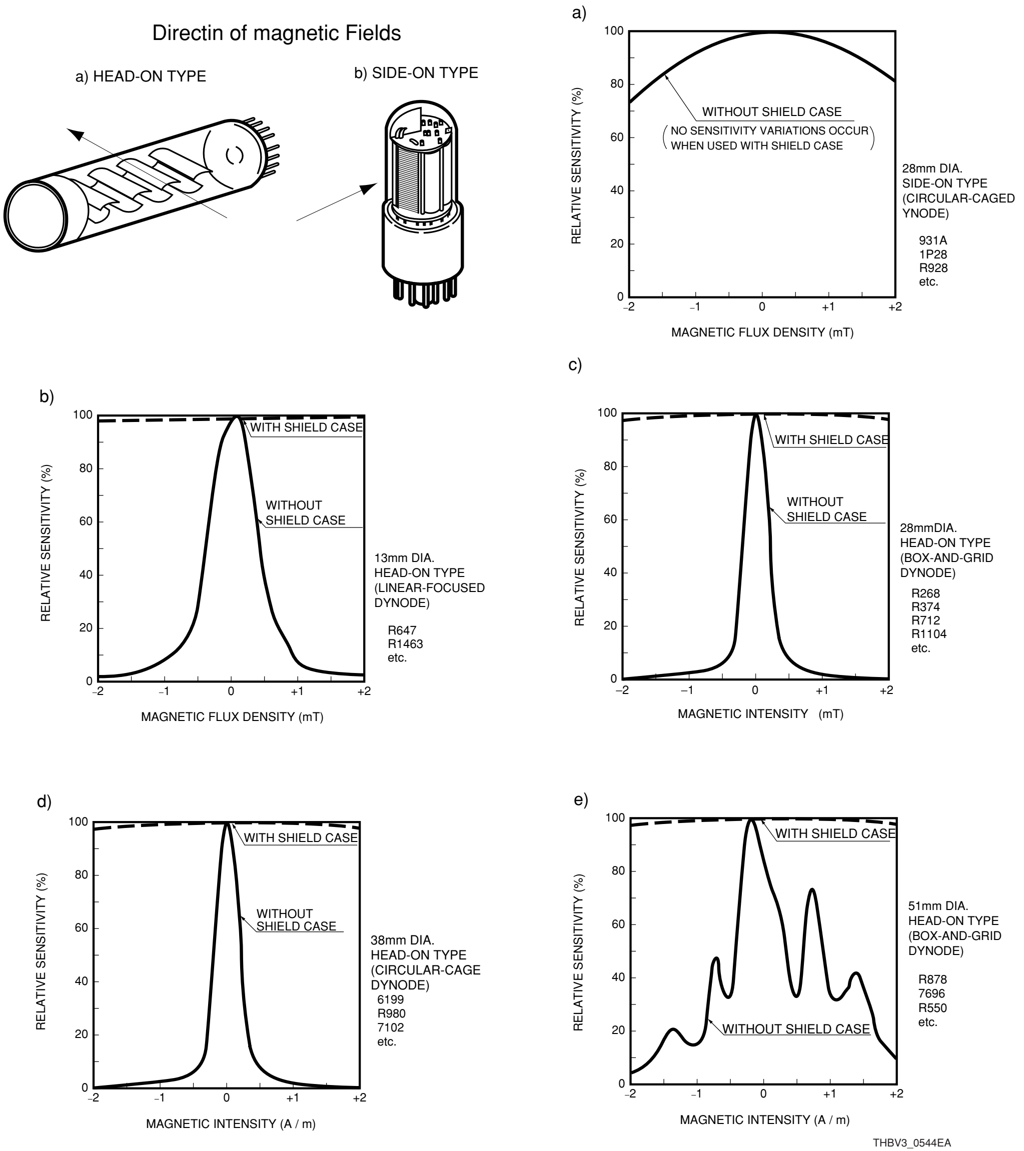


Figure 5-44: Effect of magnetic shield case

(6) Handling the magnetic shield case

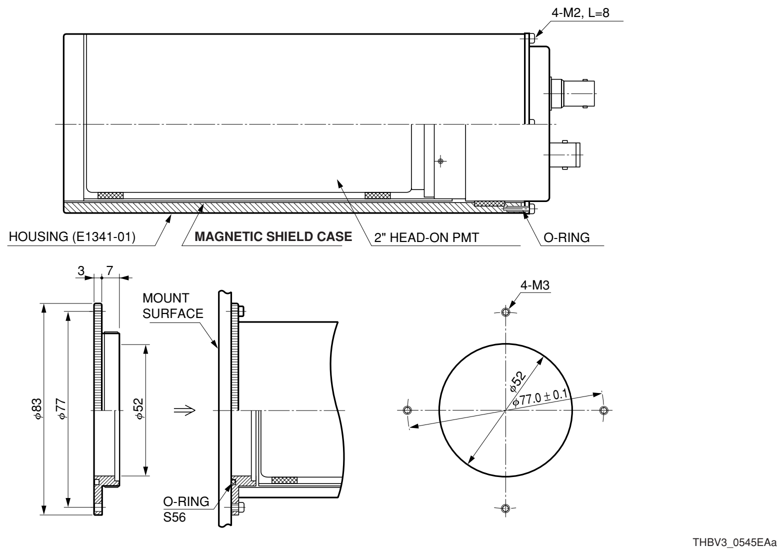
Magnetic shield cases are subject to deterioration in performance due to mechanical shock and deformation therefore sufficient care must be exercised during handling. Once the performance has deteriorated, a special annealing process is required for recovery. In particular, since the permeability characteristics are more susceptible to external shock and stress, avoid any alteration such as drilling and machining the shield case.

If any object at ground potential is brought close to the bulb of a photomultiplier tube, the photomultiplier tube noise increases considerably. Therefore, using a magnetic shield case larger than the photomultiplier tube diameter is recommended. In this case, positioning the photomultiplier tube in the center of the shield case is important, otherwise electrical problem may occur. Foam rubber or similar materials with good buffering and insulating properties can be used to hold the photomultiplier tube in the shield case.

For safety and also for noise suppression reasons it is recommended that the magnetic shield case be grounded via a resistor of 5 to 10 MΩ, although this is not mandatory when a HA-coating photomultiplier tube (See 13.8.2 in Chapter 13) or a photomultiplier tube with the cathode at ground potential and the anode at a positive high voltage is used. In this case, sufficient care must be taken with regards to the insulation of the magnetic shield case.

For your reference when installing a magnetic shield case, Figure 5-45 illustrates the structure and dimensions of a housing and flange assembled with a magnetic shield case, which are available from Hamamatsu Photonics.

Housing: For head-on photomultiplier tube



Flange: For side-on photomultiplier tube

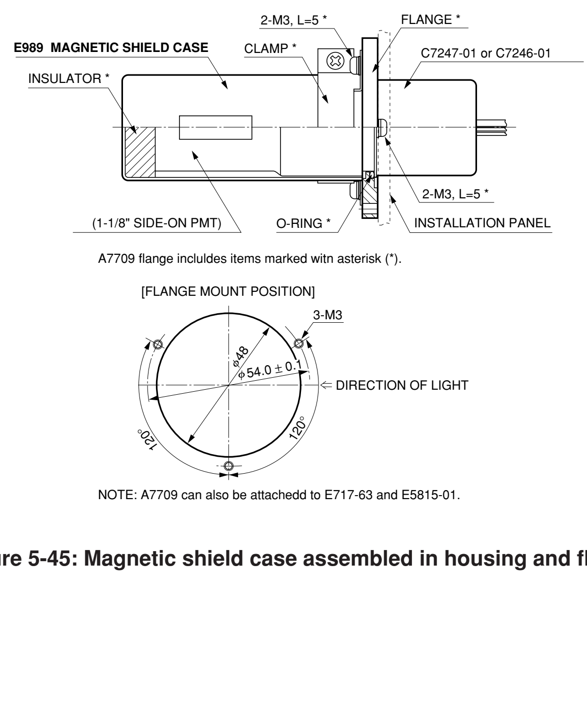


Figure 5-45: Magnetic shield case assembled in housing and flange

5.5 Cooling

As described in Chapter 4, thermionic emission of electrons is a major cause of dark current. It is especially predominant when the photomultiplier tube is operated in a normal supply voltage range. Because of this, cooling the photomultiplier tube can effectively reduce the dark current and the resulting noise pulses, improving the signal-to-noise ratio and enhancing the lower detection limit. However, the following precautions are required for cooling a photomultiplier tube.

Photomultiplier tube cooling is usually performed in the range from 0°C to –30°C according to the temperature characteristic of the dark current. When a photomultiplier tube is cooled to such a temperature level, moisture condensation may occur at the input window, bulb stem or voltage-divider circuit. This condensation may cause a loss of light at the input window and an increase in the leakage current at the bulb stem or voltage-divider circuit. To prevent this condensation, circulating dry nitrogen gas is recommended, but the equipment configuration or application often limits the use of liquid nitrogen gas. For efficient cooling, Hamamatsu provides thermoelectric coolers having an evacuated double-pane quartz window with a defogger and also air-tight socket assemblies.[6] An example of thermoelectric coolers is shown in Figure 5-46, along with a suitable socket assembly.

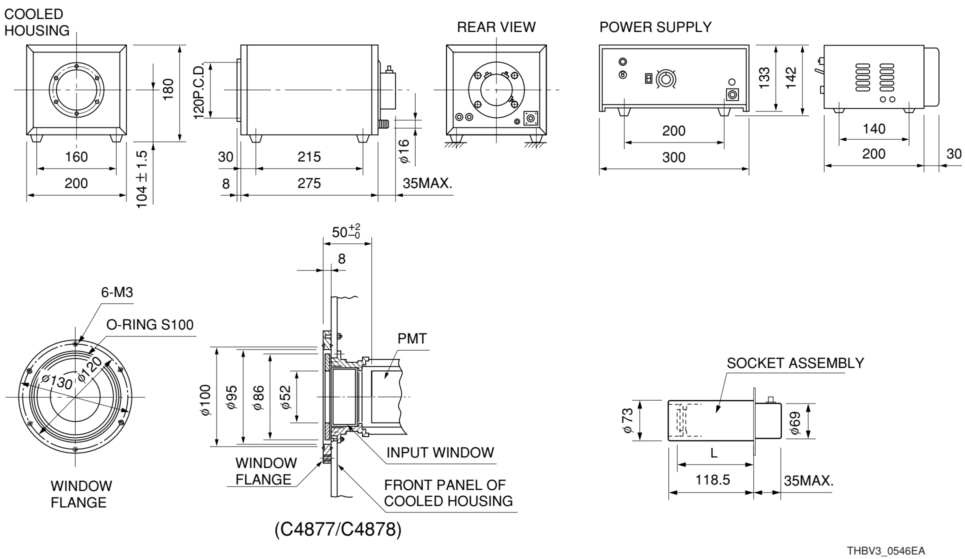


Figure 5-46: Thermoelectric cooler (manufactured by Hamamatsu Photonics)

The cooler shown in the above figure is identical with the Hamamatsu C4877 and C4878 coolers. The C4877 is designed for 51 mm (2”) and 38 mm (1.5”) diameter head-on photomultiplier tubes, while the C4878 is for MCP-PMTs. Either model can be cooled down to -30°C by thermoelectric cooling.

If a socket made by other manufacturers is used with a Hamamatsu photomultiplier tube, the bulb stem of the photomultiplier tube may possibly crack during cooling. This is due to the difference in the thermal expansion coefficient between the socket and the bulb stem. Be sure to use the mating socket available from Hamamatsu. Stem cracks may also occur from other causes, for example, a distortion in the stem. When the bulb stem is to be cooled below –50°C, the socket should not be used, instead, the lead pins of the photomultiplier tube should be directly connected to wiring leads. To facilitate this, use of socket contacts, as illustrated in Figure 5-47, will prove helpful.

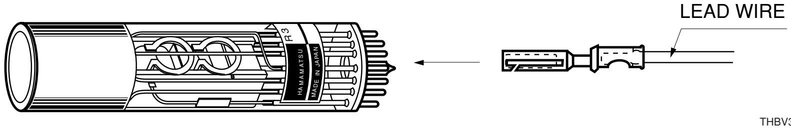


Figure 5-47: Connecting the lead pins to the socket contacts

Thermionic electrons are emitted not only from the photocathode but also from the dynodes. Of these, thermionic emissions that actually affect the dark current are those from the photocathode, Dy_1 and Dy_2, because the latter-stage dynodes contribute less to the current amplification. Therefore cooling the photocathode, Dy1, and Dy2 proves effective in reducing dark current and besides, this is advantageous in view of possible leakage currents which may occur due to moisture condensation on the bulb stem, base or socket.

The interior of a photomultiplier tube is a vacuum, so heat is conducted through it very slowly. It is therefore recommended that the photomultiplier tube be left for one hour or longer after the ambient temperature has reached a constant level, so that the dark current and noise pulses will become constant. Another point to be observed is that, since heat generated from the voltage-divider resistors may heat the dynodes, the voltage-divider resistor values should not be made any smaller than necessary.

References in Chapter 5

1) Hamamatsu Photonics Catalog: Photomultiplier Tubes and Related Products.
2) S. Uda; Musen Kogaku (Wireless Engineering) I, New Edition, Transmission Section, Maruzen.
3) Ref. to “Kerns-type PM base” Produced by R.L. McCarthy.
4) Hamamatsu Photonics Technical Information: Photomultiplier Tubes for Use in Scintillation Counting.
5) H. Igarashi, et al.: Effect of Magnetic Field on Uniformity of Gamma Camera, Nuclear Medicine Vo. 28, No. 2 (1991).
Ref. to "Improvement of 20-inch diameter photomultiplier tubes" published by A. Suzuki (KEK, Tsukuba) and others.
6) Hamamatsu Photonics Catalog: Photomultiplier Tubes and Related Products.

MEMO