technical reprint

R/P069

voltage divider design

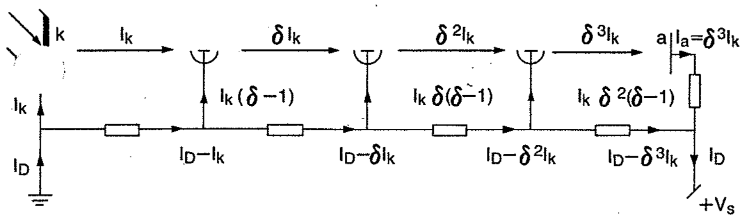
Voltage Divider Design

1. Introduction

In common with most electronic devices, the photomultiplier must be correctly biased. This can be achieved by using an independent voltage supply for each stage but it is more convenient to use a voltage divider network consisting of a series of resistors between earth and high potential. The current flow in this divider network establishes a series of potentials which is applied to the dynodes and focusing elements of the photomultiplier. These potentials create the electrostatic fields required to focus the photoelectrons on to the first dynode and to accelerate the electron cascade between successive dynodes thereby providing current amplification.

The most important factor to bear in mind when designing a voltage divider is that the resistor network is the source of the amplification current for the output signal. An ideal voltage divider network is one which maintains the dynodes at fixed potentials independent of the level of output current. In practice, it is possible to approach, but never completely satisfy, these conflicting requirements, as illustrated in the example of figure 1.

Fig 1. An idealised 3 stage photomultiplier used to illustrate the complex nature of the current division between the signal and the voltage divider. Arrows indicate electron flow.



An input of N photons per second generates a cathode current I_k, which, after amplification by 3 stages each of gain δ, appears as an output current. An increase in I_k causes a decrease in the voltage $\triangle V$ between d_3 and anode and, since the overall voltage is constant, $\triangle V$ will appear as a positive increment on the earlier stages, d_1 and d_2. The net effect is a change in overall gain because the gain voltage characteristic of a dynode follows a power law. The key to successful voltage divider design lies in minimising this feedback effect.

It is convenient to consider two distinct cases: i) direct current operation and ii) transient or pulsed applications.
i) If I_k is continuous, or slowly varying, then we require for a tube of n stages:

$$\textbf{(i)} \quad I_D - I_k\delta^n = I_D - I_a \simeq I_D$$

where I_D is the current drawn from the high voltage supply. Equation [illegible] is satisfied by choosing $I_D >> I_a$ (max.) so that the individual resistor currents $I_D - I_k\delta^n$, $I_D - I_k\delta$ and $I_D - I_k$ are all nearly equal to I_D. Satisfying equation (1) ensures that the interdynode voltages and therefore the gain will remain essentially constant for $I_a \leqslant I_a$ (max.).

ii) If $\hat{i}_a$ is a transient current, then it is necessary to maintain constant interdynode voltages for the duration of $\hat{i}_a$. This can be done by using decoupling capacitors to supply the required charge pulses. In pulsed applications, therefore, we may have:

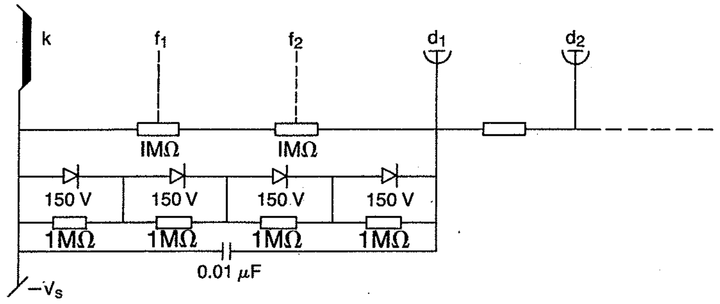
$$\textbf{(ii)} \quad I_D << \hat{i}_a, \text{provided } I_D >> \bar{I}_a$$

where $\bar{I}_a$ is the mean current derived from $\hat{i}_a$ integrated over a suitable time period.

2. Cathode to first dynode considerations

The interface between the photocathode and the input to the electron multiplier is a critical section of the photomultiplier. Certain tubes include focus elements to improve the electron collection efficiency and to minimise the transit time variation for signals originating from different regions of the cathode surface. Most photomultipliers do not have adjustable focus elements — they are either internally connected to the cathode or d_1 or totally absent and the recommendations given in Table 1 should be followed. The performance of tubes with separate focus elements is optimised by setting the focus voltages by experiment, the actual arrangements depending on whether uniformity of collection or speed of response is more critical. In many cases a Zener diode is convenient, especially where the EHT is likely to be changed or the required value is unknown. Potentiometers are useful for providing optimum focusing potentials and they can be replaced later with fixed resistors. The same applies to Zener diodes. An example of a complex front end arrangement is given in figure 2.

Fig 2. Bias arrangement for an elaborately focused 5 inch fast tube type 9823. The 1 MΩ resistors in parallel with the Zener diodes assist in voltage stabilisation and reduce noise.



In most applications it is sufficient to follow the recommendation given in Table 1.

Table 1

Tube diameter	V_{k-d_1}	V_{f-d_1}
Side window types	100	
30 mm, 38 mm and 52 mm	150	
75 mm and 90 mm	300	
130 mm	450	
190 mm	750	
Linear focused types: 19 mm	150	
52 mm	300	$f=d_1$
75 mm	450	$f=d_1$
130 mm	700	120 to 240
Photon counting 52 mm	300	
High d_1 gain 52 mm	600	$f=d_1$
Other special types: 9857	150	60 to 130
9858	300	120 to 260
9618	450	80 to 200
9623	750	160 to 280 (f_1) 300 to 650 (f_2)
9823	700	120 to 240

Recommended voltages for $k-d_1$ and focus where applicable. Measured focus potentials for individual tubes are given on the accompanying test ticket but the optimum values for any particular application are best determined by experiment.

3. Direct Current Applications

It was stated in Section 1 that a purely resistive voltage divider causes voltage redistribution in a complex way depending on the level of I_k but the effect on the gain G will be small provided that $I_D >> I_a$ (max.). If $I_D > 100\,I_a$ (max.) then G will remain essentially constant within a fraction of one percent. Provided I_a (max.) $\leqslant 10\,\mu A$, then $I_D \simeq 1$ mA is entirely satisfactory in most situations. This level of supply current is neither too large for most commercial high voltage supplies nor will it cause excessive heat dissipation in the region of the tube base. Operating with supply currents of the order of several mA can cause heating problems unless the divider network is mounted away from the photomultiplier. A general purpose divider recommended for applications where I_a (max.) $\leqslant 10\,\mu A$ is shown in figure 3(a). This is referred to as a uniform divider because all the resistors except the one between cathode and d_1 have the same value. If I_a (max.) exceeds 10 μA when using box and grid or venetian blind photomultipliers, a standard divider network (Table 3) is recommended. R_k is selected to provide the recommended operating voltage between k and d_1. The circuit of figure 3(b) avoids the need for high series current by using Zener diodes. Modern Zener diodes (e.g. BZX 61C100V) require only a few tens of microamps bias current to establish a reference voltage. The voltage drop across the device does depend on the magnitude of this current but only to a minor extent because of the low Zener resistance, typically $\sim 1\,k\Omega$. The use of a divider such as that shown in figure 3(b) in battery operated equipment offers a significant saving in current drain because the requirement in this case is:

$$I_D \geqslant I_a \text{ (max.)} + 30\,\mu A$$

Fig 3. Uniform voltage divider networks suitable for most d.c. applications.

Fig 3a

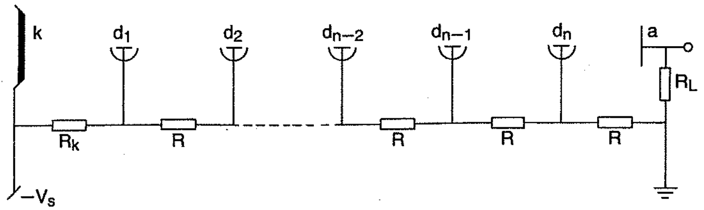
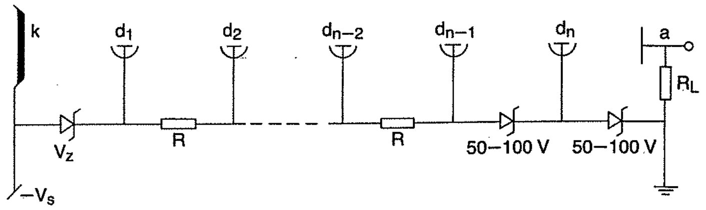


Fig 3b



4.1 Pulsed Applications

The divider circuits of figures 3(a) and (b) are suitable for pulsed operation provided the peak anode current $\hat{i}_a$ satisfies:

$\hat{i}_a << I_D$ referring to figure 3(a)
or $\hat{i}_a < I_D + 30\,\mu A$ referring to figure 3(b)

It is possible to handle pulse currents much larger than I_D by modifying the circuits of figures 3(a) and (b) to include decoupling capacitors on the final 3 stages. For a decoupled network we can have:

$\hat{i}_a >> I_D$ provided $\bar{I}_a << I_D$ figure 3(a)
or $\hat{i}_a >> I_D$ provided $\bar{I}_a < I_D + 30\,\mu A$ figure 3(b)

It is quite acceptable to operate with $\hat{i}_a \simeq 100\,I_D$ provided the signal repetition rate is not excessive. If this is the case then the condition $I_a << I_D$ will not hold and the gain will change with signal rate.

The required capacitance can be estimated from the basic equation relating voltage V, charge Q and capacitance C: Q = CV, from which it follows that the relative voltage drop is:

$$\frac{\Delta V}{V} = \frac{1}{C}\frac{\Delta Q}{V}$$

Taking Q as the output pulse charge, then for stable gain, $\Delta V/V$ should remain <0.01 % so that $C > \left(\frac{\Delta Q}{V}\right) / \left(\frac{\Delta V}{V}\right)$. The value of the capacitors decoupling d_n and d_{n-1} can be reduced because the charge pulse supplied is lower by a factor δ, the stage gain. The same applies to d_{n-1} and d_{n-2} stages but it is usual to use the same value capacitor throughout for convenience.

4.2 Linearity

This refers to the ratio i_a/i_k which under ideal conditions is constant and independent of the value of i_a. Serious departures from linear amplification can occur because of space charge effects emphasised by poor voltage divider design. BeCu dynodes provide linear operation up to higher pulsed currents than their CsSb counterparts operated under similar gain conditions. The range of linear performance also depends on the type of structure. The relative performance in order of decreasing pulsed current capability is: linear focused, circular focused, venetian blind, and box and grid. Applications requiring a large dynamic range of operation are clearly best satisfied with a BeCu, linear focused structure. However, if the maximum pulsed current requirements are modest then a venetian blind structure will give the same results. All photomultipliers give improved linearity when operated with divider networks which provide increased voltages on the last 3 or 4 dynodes. A summary giving typical performance data is given in Table 2.

Table 2

Dynode structure	$\hat{i}_a$ (mA)			
	at V_s = 100 V		at V_s = 300 V	
	CsSb	BeCu	CsSb	BeCu
53 mm linear focused	30	50	100	150
Circular focused	10	20	30	50
Venetian blind	2	4	5	20
Box and grid	0.1	0.2	0.5	1

Note: V_s = voltage d_n to d_{n-1}

Linearity capability of the 4 dynode structures. The table shows the approximate peak currents at which there is a 5 % departure from linear amplification.

4.3 Design Examples

4.3.1 Photon Counting

Design a voltage divider suitable for photon counting using a fa linear focused photomultiplier type 9863, capable of operating up to 1 MHz at a gain of 10^7. The recommended k–d_1 voltage is 300 V and the overall voltage for 10^7 gain is ~ 1900 V (from the catalogue data).

The anode charge produced by each photoelectron is:

$$q_a = 1.6 \times 10^{-19} \times 10^7 \text{ Coulombs}$$

and given that the full width of the output pulse is 5 ns:

$$\hat{i}_a = \frac{q_a}{t} = 0.32 \text{ mA}$$

I_a (max.) corresponding to 1 MHz output rate is:

$$I_a \text{ (max.)} = q_a \times 10^6 = 1.6\,\mu A$$

Taking $I_D = 100\,I_a$ (max.) = 0.16 mA
Space charge saturation is clearly not a problem because the peak anode current is only 0.32 mA and a uniform voltage divider is therefore suitable. Using a 300 V Zener diode for k – d_1, the divider requirement is for 14 equal resistors each of $R\Omega$.

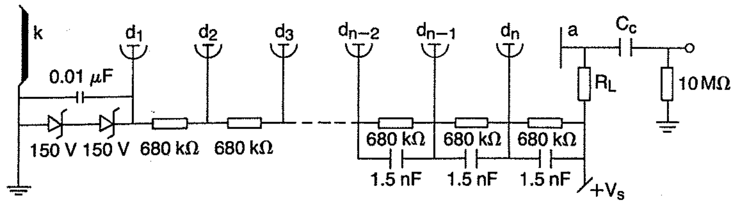
$$R = \frac{1}{14}\,\frac{1900-300}{0.16 \times 10^{-3}} = 714\,k\Omega \text{ or } 680\,k\Omega \text{ using preferred values}$$

$V_n - V_{n-1} = 114$ V and taking $\Delta V/V < 10^{-4}$ (0.01 %)

$$C > \left(\frac{1.6 \times 10^{-12}}{114}\right) / \left(10^{-4}\right) \simeq 150 \text{ pF}$$

It is sensible to take C = 1.5 nF to allow for pulse pile-up. The complete divider is shown in figure 4.

Fig 4. A uniform voltage divider network for low level photon counting applications using positive high voltage.



The value of R_L depends on the electronic circuitry. It is usual practice to use 50 Ω coaxial cable into a matched load. If the length of cable is less than ~ 30 cm, R_L can be >> 50 Ω; otherwise it should be matched to prevent ringing.

4.3.2 Scintillation Counting [NaI(Tl)]

Design a divider network suitable for a range of isotopes with energies up to 1.33 meV (^{60}Co). Photomultiplier non-linearity at a peak anode current of 1 mA should be less than the intrinsic scintillator non-linearity with energy (about 1.5 %). A typical bialkali photocathode provides about 8 photoelectrons/keV energy deposited for a good quality scintillator/photomultiplier combination.
The number of photoelectrons produced by ^{60}Co is:

$$N = 1.33 \times 10^3 \times 8 \simeq 10^4 \text{ photoelectrons}$$

and the decay constant for NaI(Tl) is about 250 ns and it follows that:

$$\hat{i}_a \simeq \frac{G \times 10^4 \times 1.6 \times 10^{-19}}{250 \times 10^{-9}}$$

or

$$G \simeq 1.5 \times 10^5 \text{ for } \hat{i}_a = 1 \text{ mA}$$

A 9956 venetian blind photomultiplier requires about 800 V to provide this gain with a uniform divider network. The tapered divider of figure 5 will ensure good linearity and will require an operating voltage of about 900 V to give 1.5×10^5 gain. Assuming a minimum rate of $n = 10^4\,s^{-1}$, which is a typical upper limit for most NaI(Tl) applications, then:

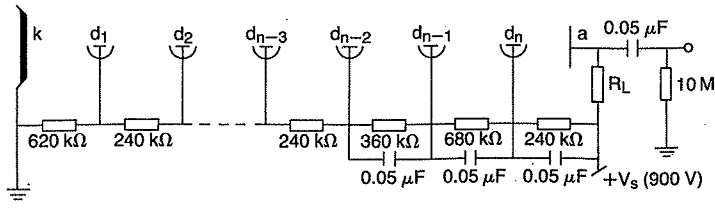
$$\begin{aligned} I_a\text{(max.)} &= NenG \\ &= (10^4 \times 1.6 \times 10^{-19} \times 10^4) \times (1.5 \times 10^5) \\ &= 2.4\,\mu A \end{aligned}$$

Taking $I_D = 100 \times 2.4\,\mu A = 0.24$ mA we have (for the voltage divider of figure 5):

$$13.5\,R = \frac{900-150}{0.24 \times 10^{-3}} \quad \therefore \quad R = 230\,k\Omega,\ R_k = 620\,k\Omega$$

or nearest preferred values, to give $V_{k-d_1} = 150$ V

Fig 5. A typical voltage divider for a venetian blind photomultiplier where good linearity is a requirement.



The most critical decoupling capacitor is that between the last dynode and the supply voltage. For $\Delta V/V < 0.01$ % then:

$$C > (\Delta Q/V)/(\Delta V/V) = \left(\frac{10^4 \times 1.6 \times 10^{-19} \times 1.5 \times 10^{-5}}{55}\right) / 10^{-4}$$

$$= 44 \text{ nF} \simeq 0.05\,\mu F$$

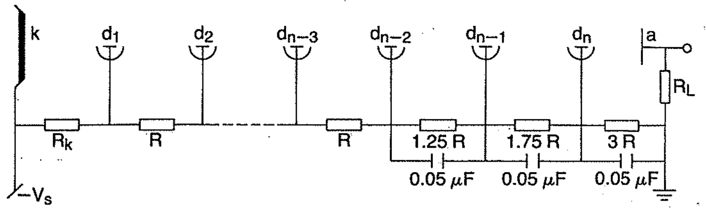
In theory, small capacitance values can be used for C_1 and C_2 although it is usual practice to choose a common value.
The divider current of 0.24 mA is regarded as the minimum that should be used for sodium iodide applications. Note that increasing the source rate from 10^3 to $10^4\,s^{-1}$ changes I_a from 0.24 μA to 2.4 μA. The change in dynode current between d_{10} and anode results in a change of $V(d_{10} - V_s)$ of about $2.2\,\mu A \times 230\,k\Omega = -0.5$ V which is redistributed between d_9 and cathode and causes a gain change of ~ + 1 %. This explains why photopeaks displayed on a multi-channel analyser tend to move to higher channel positions with increasing source strength. If better immunity to changes in source strength is required, it is necesary to increase I_d or use a Zener diode between d_{10} and V_s.

5. Fast pulse applications with linear focused photomultipliers

Photomultipliers used in these applications are invariably operated with the anode at earth potential. The reason is that external circuits can then be directly coupled to the anode, thus avoiding rate effects and overshoot common with capacitative coupling. Good high frequency layout techniques are essential because linear focused photomultipliers provide very fast rise time pulses (1-2 ns). The wiring of the last few stages needs particular care. Most pulse applications make the use of 50 Ω matched coaxial cable essential to preserve signal waveforms without ringing. Fast tubes invariably have the ultimate and penultimate dynode pins located adjacent to the anode pin; these pins should be capacitively decoupled directly to the screen of the coaxial cable using high quality disc ceramic capacitors. These capacitors should be in addition to the normal decoupling capacitors. A uniform divider network is suitable for photon counting and similar low light level applications; but where a large dynamic range (and consequently linearity) up to $i_a \simeq 100$ mA is a requirement, a tapered divider similar to that of figure 6(a) is needed. A 'super' version of this divider is shown in figure 6(b) and includes resistors R′ which provide critical damping of the LC circuit made up of stray capacitance and wiring inductance.
Failure to neutralise this reactance can cause excessive ringing on the output pulse. R′ generally lies in the range 30–300 Ω and needs to be selected for optimum performance.

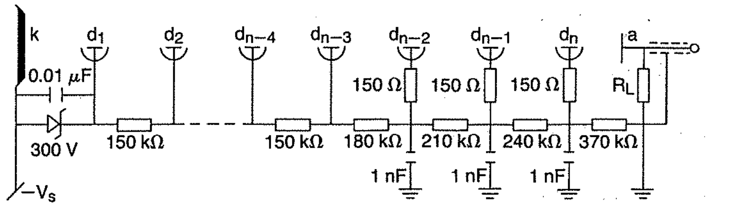
Fig 6. Recommended voltage dividers for linear focused photomultipliers
a) [illegible] test network.

Fig 6a



b) 'Super' version for 'clean' output pulse shapes incorporating 150 Ω damping resistors.

Fig 6b



6. Summary

The number of different divider configurations commonly used is a direct consequence of the extensive range of photomultiplier applications. In general, a divider designed for a particular application will not be optimum for the same tube used for a different purpose.

The difficulties associated with divider network design are often compunded by the fact that the light level is not known and hence the gain required must be determined experimentally. In these cases the user should be prepared to redesign the network using the results obtained from the initial set-up as a guide. Where no information on expected operating conditions is available the 'standard' voltage divider, Table 3, can be used for most applications. Recommended values are: $R_k = 200\ k\Omega$ and $R = 100\ K\Omega$ with decoupling capacitors of 0.01 μF.

A summary listing divider networks is given in Table 3.

Table 3

Ref.	Dynode type	k — d_1	— d_2	— d_3	— d_4		d_{n-4} d_{n-3}	— d_{n-2}	— d_{n-1}	— d_n	— a	Application
A	19 mmLF	2R	1.5R	1.5R	R		R	R	R	R	R	High gain, d.c. $I_a<10\ \mu A$ for 19 mm tubes only.
B	19 mm LF	2R	1.5R	1.5R	R		R	$1.25R+C_1$	$1.5R+C_2$	$1.75R+C_3$	$3R+C_4$	Pulsed, for 19 mm tubes only.
C	All types	Zener or R_k	R	R	R		R	R	R	R	R	High gain, d.c. $I_a<10\ \mu A$.
D	All types	Zener or R_k	R	R	R		R	R	R	Zener	Zener	High current, d.c. $I_a<100\ \mu A$.
E	All types	Zener or R_k	R	R	R		R	$R+C_1$	$R+C_2$	$R+C_3$	$R+C_4$	High gain, pulsed.
F	BG/VB	Zener or R_k	R	R	R		R	$R+C_1$	$R+C_2$	$2R+C_3$	$R+C_4$	Standard, high gain, pulsed.
G	BG/VB	Zener or R_k	R	R	R		R	$R+C_1$	$2R+C_2$	$3R+C_3$	$R+C_4$	High pulse current, $\hat{I}_a<5$ mA.
H	LF/CF	Zener or R_k	R	R	R		R	$1.25R+C_1$	$1.5R+C_2$	$2R+C_3$	$3R+C_4$	High pulse current, $\hat{I}_a<100$ mA.

Recommended voltage dividers. The appropriate k–d_1 voltage (from Table 1) can be provided by a resistor, R_k, if the overall voltage is known, or by a Zener diode.

Zener diodes are particularly useful, both at the cathode and anode ends of the divider, especially where gain adjustment by changing the supply voltage is expected. They are inherently noisy and should be by-passed with a capacitor or resistor to ensure that the noise is not coupled to the anode. The fact that Zener diodes are temperature sensitive is often overlooked; a divider network including Zener diodes can introduce photomultiplier gain variation of between 0.1 to 0.5 % °C^{-1} depending on the number of diodes used.

In conclusion, the user should always be prepared to tailor the voltage divider to the characteristics of the particular photomultiplier or application. When replacing a tube it is important to check that the divider is suitable for the new device. Photomultipliers offer a large dynamic range of operation (for a linear focused tube 1 nA – 0.1 A) and will often operate satisfactorily despite inadequacies in the divider network. However, for demanding applications, where the very best performance is required, the user is well rewarded by careful design.

Further Reading

R/P 021	Dark current in photomultiplier tubes.
R/P 058	Measurement of photocathode spectral response.
R/P 060	Photomultiplier replacement guide.
R/P 061	Gating of photomultipliers.
R/P 062	Reducing noise from photomultipliers.
R/P 063	Basic physics and statistics of photomultipliers.
R/P 064	Photomultipliers - space charge effects and transit time spread.
R/P 065	Design of photomultiplier output circuits for optimum amplitude or time response.
R/P 066	A comparison of current-measurement with photon counting in the use of photomultiplier tubes.
R/P 067	Test parameters and general operating rules for photomultipliers.
R/P 068	Sources of noise in photomultipliers.
R/P 069	Voltage divider design.
R/P 070	Rugged photomultipliers.
R/P 071	An introduction to the photomultiplier tube.

talk to us about your application or choose a product from our literature:

photomultipliers, voltage dividers, signal processing modules, housings and power supplies

ET Enterprises Limited
45 Riverside Way
Uxbridge UB8 2YF
United Kingdom
tel: +44 (0) 1895 200880
fax: +44 (0) 1895 270873
e-mail: sales@et-enterprises.com
web site: www.et-enterprises.com

ADIT Electron Tubes
300 Crane Street
Sweetwater TX 79556 USA
tel: (325) 235 1418
toll free: (800) 521 8382
fax: (325) 235 2872
e-mail: sales@electrontubes.com
web site: www.electrontubes.com

choose accessories for this pmt on our website

ET Enterprises electron tubes

an ISO 9001 registered company

DS_ R/P069 Issue 3 (19/01/11)